New Physics, EFTs & the on-shell approach

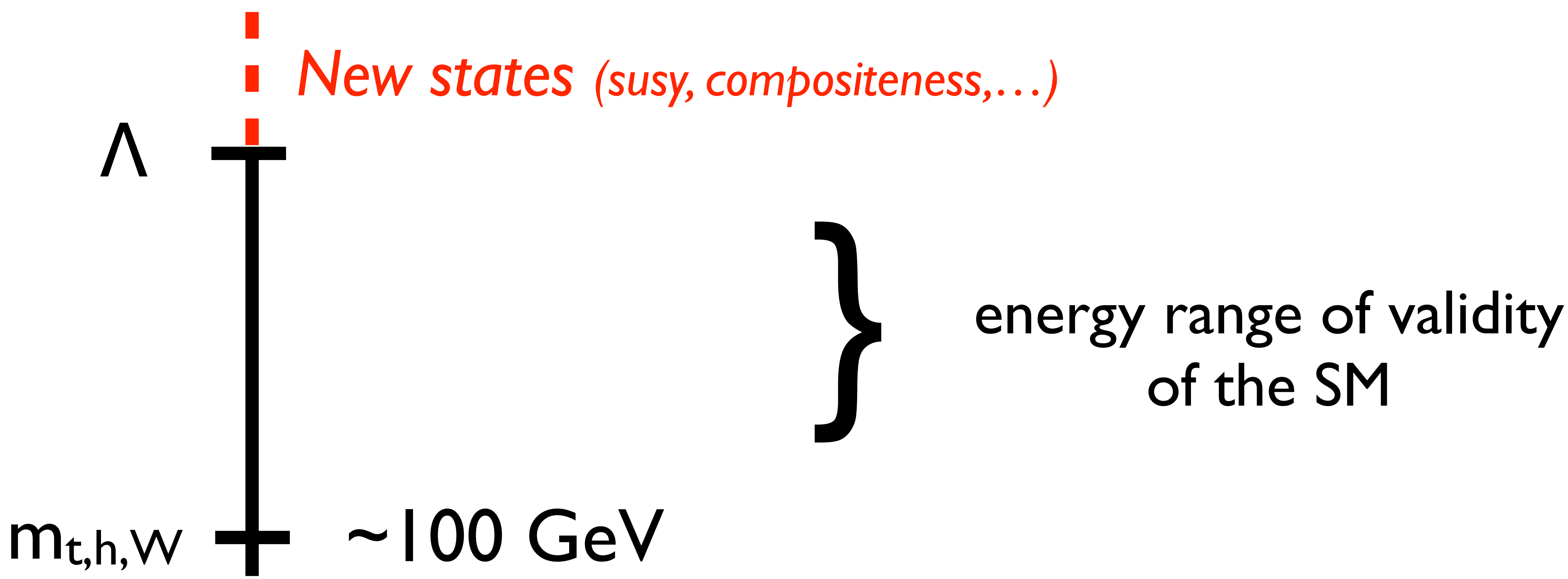
Alex Pomarol, IFAE & UAB (Barcelona) and CERN

EFT approach to new physics

↳ **Effective Field Theory**

To (*humbly*) accept that:

The SM provides a good description of physics at low-energies ($E \ll \Lambda$)



assumption based on the many tests of the SM!

…and that Nature does not conspire to fool us!

We can then Taylor expand (SM fields and derivative over Λ):

(assuming lepton & baryon number)

$$\mathcal{L}_{\rm eff} = \frac{\Lambda^4}{g_*^2}\mathcal{L}\left(\frac{D_\mu}{\Lambda}\ ,\ \frac{g_H H}{\Lambda}\ ,\ \frac{g_{f_{L,R}} f_{L,R}}{\Lambda^{3/2}}\ ,\ \frac{g F_{\mu\nu}}{\Lambda^2}\right) \simeq \mathcal{L}_4 + \mathcal{L}_6 + \cdots$$

dimension-4 terms:

The SM

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dimension-4 terms:

The SM

dimension-6 terms:

Leading deviations from the SM

Grzadkowski et.al. JHEP 1010 (2010) 085

SM EFT:

$$\mathcal{L}_6$$

Dimension-6 operators

assuming L & B

$$\mathcal{O}_H = \tfrac{1}{2}(\partial^\mu |H|^2)^2$$
$$\mathcal{O}_T = \tfrac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$
$$\mathcal{O}_6 = \lambda |H|^6$$

$$\mathcal{O}_W = \tfrac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = \tfrac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$$
$$\mathcal{O}_{2W} = -\tfrac{1}{2}(D^\mu W^a_{\mu\nu})^2$$
$$\mathcal{O}_{2B} = -\tfrac{1}{2}(\partial^\mu B_{\mu\nu})^2$$
$$\mathcal{O}_{2G} = -\tfrac{1}{2}(D^\mu G^A_{\mu\nu})^2$$

$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu}G^{A\mu\nu}$$
$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$\mathcal{O}_{3W} = \tfrac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$$
$$\mathcal{O}_{3G} = \tfrac{1}{3!} g_s f_{ABC} G^{A\,\nu}_{\mu} G^B_{\nu\rho} G^{C\,\rho\mu}$$

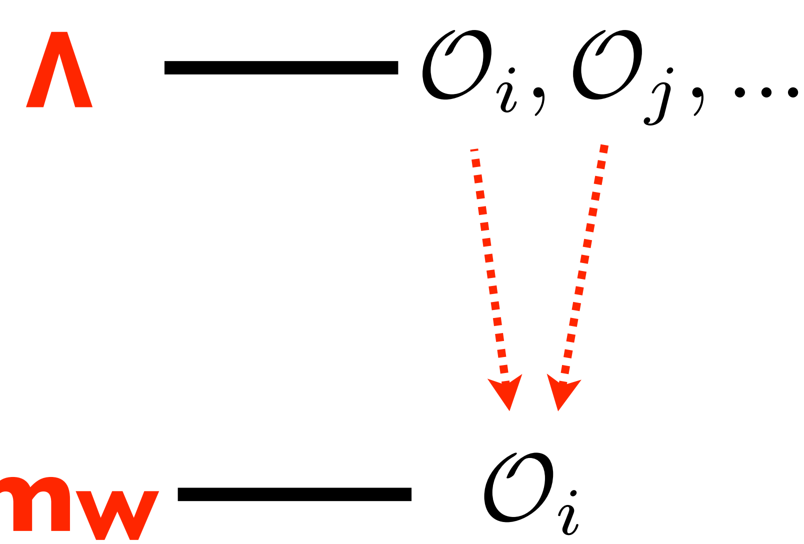
$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$
$\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L)$		$\mathcal{O}_L^l = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu L_L)$
$\mathcal{O}_L^{(3)\,q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu \sigma^a Q_L)$		$\mathcal{O}_L^{(3)\,l} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu \sigma^a L_L)$
$\mathcal{O}_{LR}^u = (\bar{Q}_L\gamma^\mu Q_L)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}_{LR}^d = (\bar{Q}_L\gamma^\mu Q_L)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}_{LR}^e = (\bar{L}_L\gamma^\mu L_L)(\bar{e}_R\gamma^\mu e_R)$
$\mathcal{O}_{LR}^{(8)\,u} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{u}_R\gamma^\mu T^A u_R)$	$\mathcal{O}_{LR}^{(8)\,d} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{d}_R\gamma^\mu T^A d_R)$	
$\mathcal{O}_{RR}^u = (\bar{u}_R\gamma^\mu u_R)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}_{RR}^d = (\bar{d}_R\gamma^\mu d_R)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}_{RR}^e = (\bar{e}_R\gamma^\mu e_R)(\bar{e}_R\gamma^\mu e_R)$
$\mathcal{O}_{LL}^q = (\bar{Q}_L\gamma^\mu Q_L)(\bar{Q}_L\gamma^\mu Q_L)$		$\mathcal{O}_{LL}^l = (\bar{L}_L\gamma^\mu L_L)(\bar{L}_L\gamma^\mu L_L)$
$\mathcal{O}_{LL}^{(8)\,q} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{Q}_L\gamma^\mu T^A Q_L)$		
$\mathcal{O}_{LL}^{ql} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{L}_L\gamma^\mu L_L)$		
$\mathcal{O}_{LL}^{(3)\,ql} = (\bar{Q}_L\gamma^\mu \sigma^a Q_L)(\bar{L}_L\gamma^\mu \sigma^a L_L)$		
$\mathcal{O}_{LR}^{qe} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{e}_R\gamma^\mu e_R)$		
$\mathcal{O}_{LR}^{lu} = (\bar{L}_L\gamma^\mu L_L)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}_{LR}^{ld} = (\bar{L}_L\gamma^\mu L_L)(\bar{d}_R\gamma^\mu d_R)$	
$\mathcal{O}_{RR}^{ud} = (\bar{u}_R\gamma^\mu u_R)(\bar{d}_R\gamma^\mu d_R)$		
$\mathcal{O}_{RR}^{(8)\,ud} = (\bar{u}_R\gamma^\mu T^A u_R)(\bar{d}_R\gamma^\mu T^A d_R)$		
$\mathcal{O}_{RR}^{ue} = (\bar{u}_R\gamma^\mu u_R)(\bar{e}_R\gamma^\mu e_R)$	$\mathcal{O}_{RR}^{de} = (\bar{d}_R\gamma^\mu d_R)(\bar{e}_R\gamma^\mu e_R)$	
$\mathcal{O}_R^{ud} = y_u^\dagger y_d (i\widetilde{H}^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu d_R)$		
$\mathcal{O}_{y_u y_d} = y_u y_d (\bar{Q}_L^r u_R)\epsilon_{rs}(\bar{Q}_L^s d_R)$		
$\mathcal{O}_{y_u y_d}^{(8)} = y_u y_d (\bar{Q}_L^r T^A u_R)\epsilon_{rs}(\bar{Q}_L^s T^A d_R)$		
$\mathcal{O}_{y_u y_e} = y_u y_e (\bar{Q}_L^r u_R)\epsilon_{rs}(\bar{L}_L^s e_R)$		
$\mathcal{O}'_{y_u y_e} = y_u y_e (\bar{Q}_L^{r\alpha} e_R)\epsilon_{rs}(\bar{L}_L^s u_R^\alpha)$		
$\mathcal{O}_{y_e y_d} = y_e y_d^\dagger (\bar{L}_L e_R)(\bar{d}_R Q_L)$		
$\mathcal{O}_{DB}^u = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \widetilde{H} g' B_{\mu\nu}$	$\mathcal{O}_{DB}^d = y_d \bar{Q}_L \sigma^{\mu\nu} d_R H g' B_{\mu\nu}$	$\mathcal{O}_{DB}^e = y_e \bar{L}_L \sigma^{\mu\nu} e_R H g' B_{\mu\nu}$
$\mathcal{O}_{DW}^u = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \sigma^a \widetilde{H} g W^a_{\mu\nu}$	$\mathcal{O}_{DW}^d = y_d \bar{Q}_L \sigma^{\mu\nu} d_R \sigma^a H g W^a_{\mu\nu}$	$\mathcal{O}_{DW}^e = y_e \bar{L}_L \sigma^{\mu\nu} e_R \sigma^a H g W^a_{\mu\nu}$
$\mathcal{O}_{DG}^u = y_u \bar{Q}_L \sigma^{\mu\nu} T^A u_R \widetilde{H} g_s G^A_{\mu\nu}$	$\mathcal{O}_{DG}^d = y_d \bar{Q}_L \sigma^{\mu\nu} T^A d_R H g_s G^A_{\mu\nu}$	

Too many terms to understand the implications?

The SM EFT is an useful approach as it allows to better understand the interplay of different experiments

Many many examples of correlations:

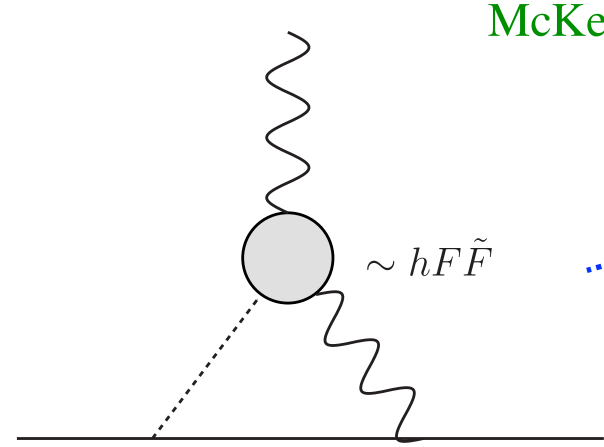
I) Either by operator mixing:



Low-energy experiments can be affected by **different** operators

CP-violating Higgs operators

McKeen,Pospelov,Ritz 12



EDM

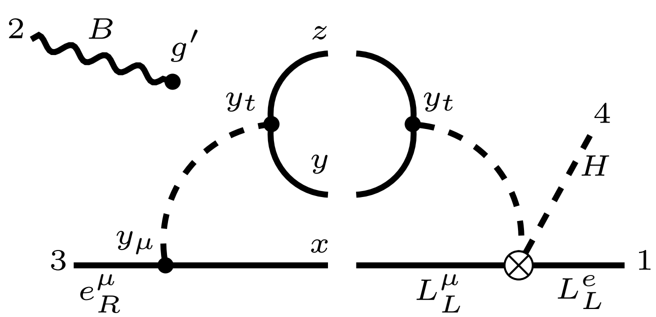
$\kappa_{\gamma\gamma} \lesssim 10^{-5}$

LHC not competitive!

J. Elias-Miro, C. Fernandez, M. Gümüs, AP 2112.12131

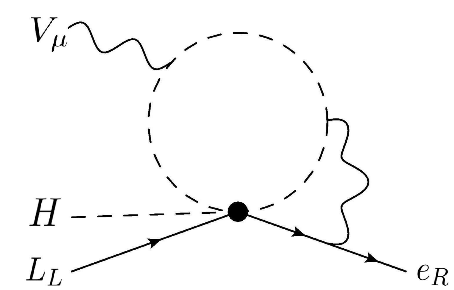
$$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu \mu_R)$$

↳ **Z→μe**



$$H|H|^2 \bar{L}_L \mu_R$$

↳ **h→μe**



μ→eγ,eee

Much better constraints from these observables!

	BR($\mu \to e\gamma$)	BR($\mu \to eee$)
Current	$4.2 \cdot 10^{-13}$ [33]	$1 \cdot 10^{-12}$ [34]
Future	$6.0 \cdot 10^{-14}$ [37]	$1 \cdot 10^{-16}$ [38]

LHC bounds on Z,h→μe orders of magnitude below!

2) Either by accidental symmetries:

- Deviations in Z/W couplings to fermions related:

$Zf_Lf_L \longleftrightarrow Wf_Lf_L'$ *Custodial symmetry in* $\mathcal{L}_6$ *!*

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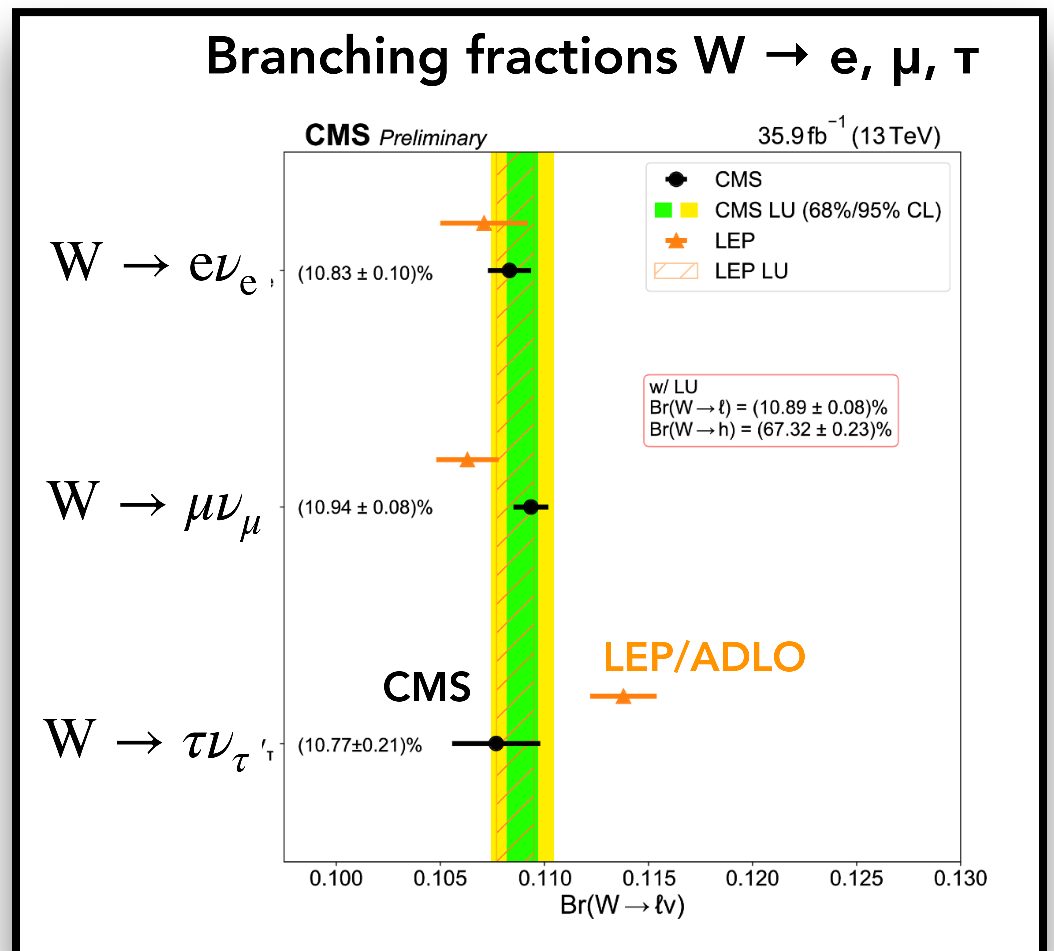
- Deviations in Z/W couplings to fermions related:

Zf_Lf_L ⟷ Wf_Lf_L' *Custodial symmetry in $\mathcal{L}_6$!*

After LEP Z-measurements, not expected deviations in Wf_Lf_L at the LHC



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- Deviations in Z/W couplings to fermions related:

$Zf_Lf_L \longleftrightarrow Wf_Lf_L'$ *Custodial symmetry in $\mathcal{L}_6$!*

- Deviations in $H \to ZZ^*$ and $H \to WW^*$ related:

AP, Riva 308.2803

$$\lambda_{WZ}^2 \equiv \frac{\Gamma(h\to WW^{(*)})}{\Gamma^{SM}(h\to WW^{(*)})}\frac{\Gamma^{SM}(h\to ZZ^{(*)})}{\Gamma(h\to ZZ^{(*)})} \approx 1 + 0.6\,\delta g_1^Z - 0.5\,\delta\kappa_\gamma - 1.6\,\kappa_{Z\gamma}$$

δg_1^Z, $\delta\kappa_\gamma$ → TGC

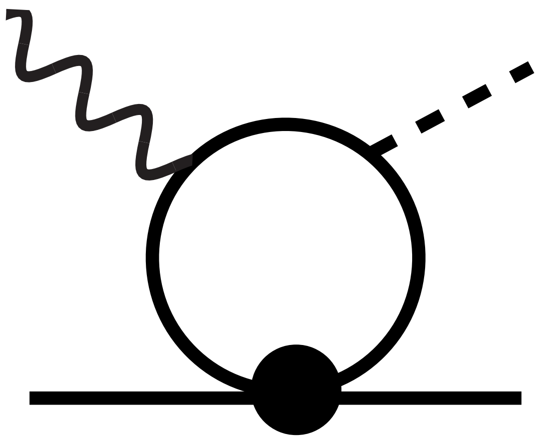
$\kappa_{Z\gamma}$ → $h \to Z\gamma$

Not expected to see these deviations at the LHC!

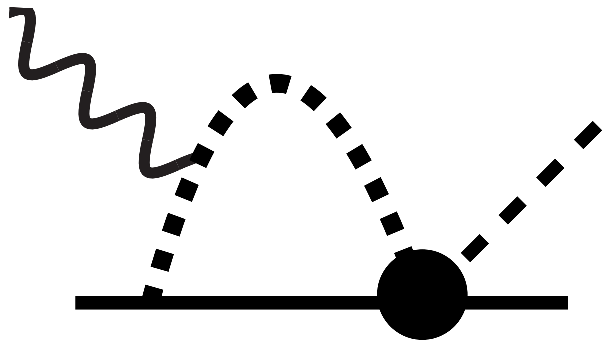
Nevertheless, a lot of *unexplained* cancelations (“***zeros*”)**
reported in the last years…

I. Many absence of mixings to dipoles

$$F^{\mu\nu}\,\psi\sigma_{\mu\nu}\psi\,H$$



$(\bar{\Psi}\gamma^{\mu}\Psi)^2$



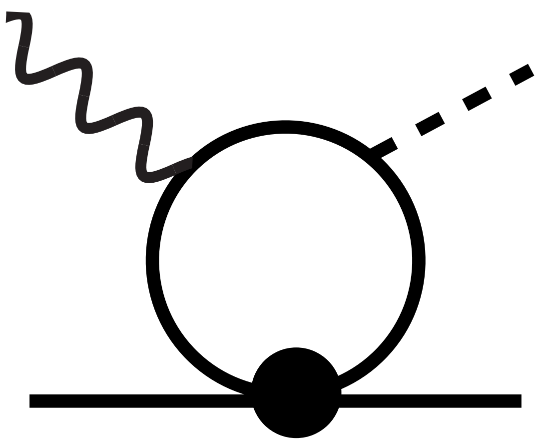
$(\bar{\Psi}\gamma^{\mu}\Psi)H^{\dagger}D_{\mu}H$

☞ give zero mixing

at leading order

I. Many absence of mixings to dipoles

$$F^{\mu\nu}\psi\sigma_{\mu\nu}\psi\, H$$



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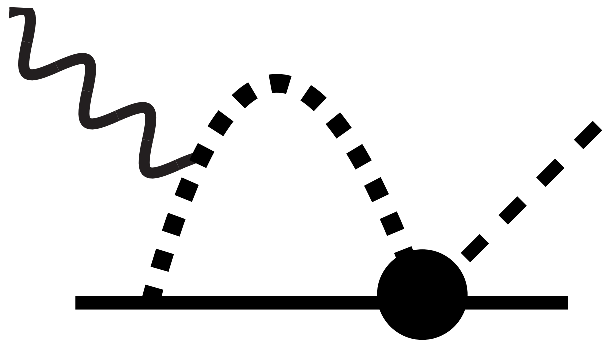


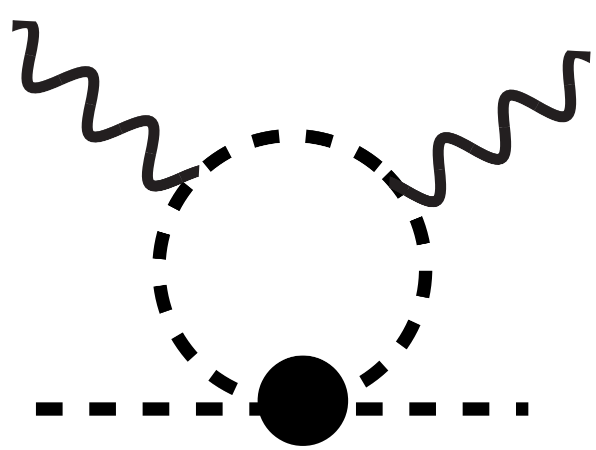
$(\bar{\Psi}\gamma^{\mu}\Psi)H^{\dagger}D_{\mu}H$

☞ give zero mixing

at leading order

II. No p^2H^4 corrections to Hγγ

$$F^{\mu\nu}F_{\mu\nu}|H|^2$$



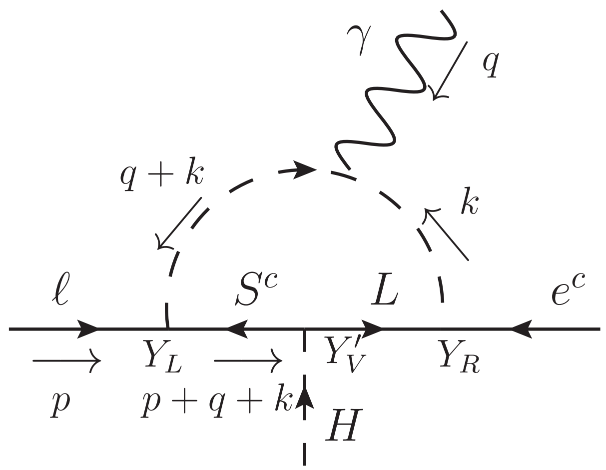
$(H^{\dagger}D_{\mu}H)^2$

☞ give zero mixing

at leading order

Finite terms to g-2

No contribution $O(1/M^2)$ to **dipoles**
from a **heavy singlet + doublet fermion**:



~ $O(1/M^4)$

N. Arkani-Hamed, K. Harigaya 2106.01373

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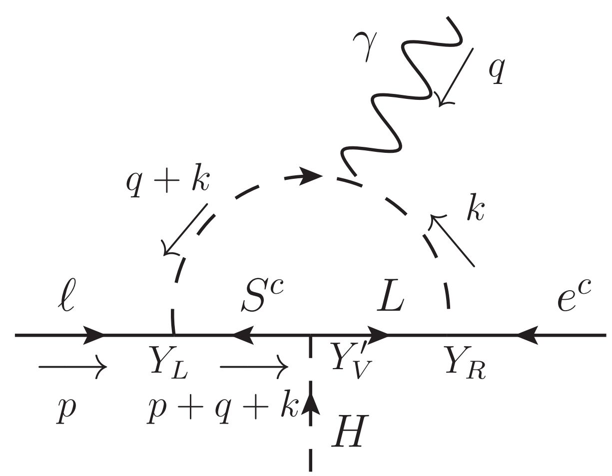

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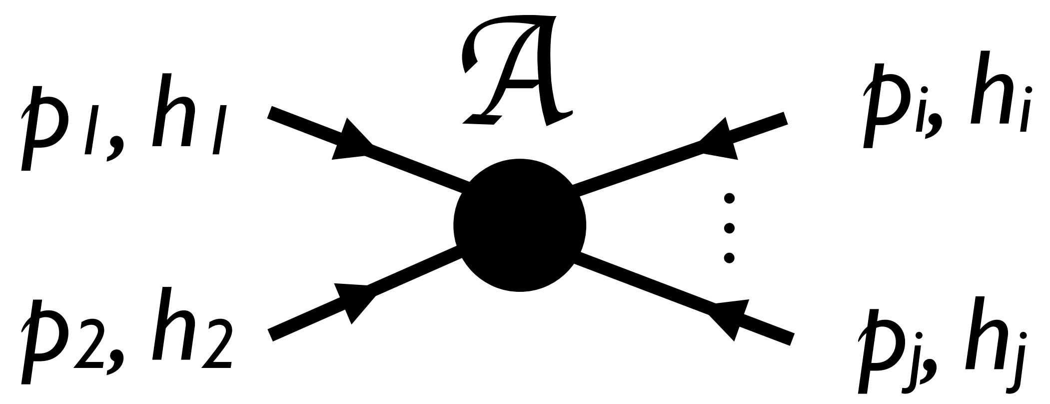
Finite terms to Hγγ

No contribution $O(1/M^2)$ to **dipoles**
from a **heavy E+L fermion**:

L. Delle Rosse, B. von Harling, AP in 2201.10572

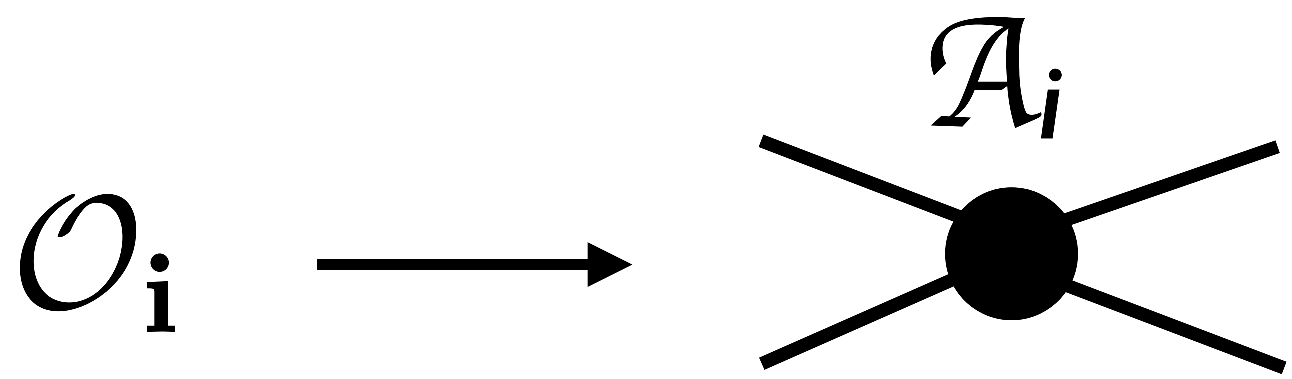
Asking for a better understanding…

II. EFT (EFfective Theories) from on-shell amplitudes



An important gain in simplicity:

the power of being on-shell !



Ghosts, Golstones,…
($p^2 \neq 0$)

only physical states ($p^2=0$)

↳ **definite helicity (h = ∓)**

An important gain in simplicity:

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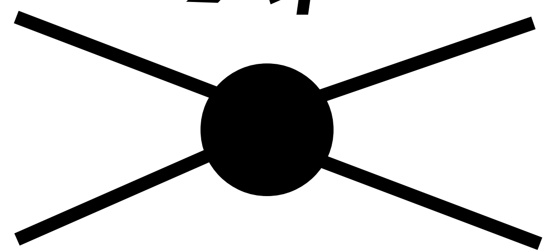
$\mathcal{A}_i$



$\mathcal{O}_i \longrightarrow$

Ghosts, Golstones,…
($p^2 \neq 0$)

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↳ **definite helicity (h = ∓)**

Spinor-helicity formalism

$$p^\mu \longrightarrow p^\mu \sigma_\mu = p_{\alpha\dot{\alpha}} = |p\rangle_\alpha |p]_{\dot{\alpha}}$$

“angle” spinor ($|p\rangle_\alpha$)

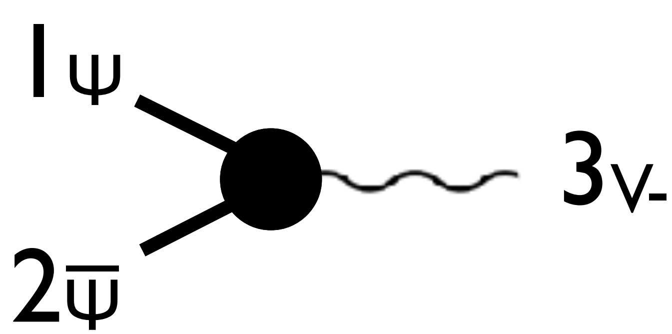
“squared” spinor ($|p]_{\dot{\alpha}}$)

The SM as an EFT

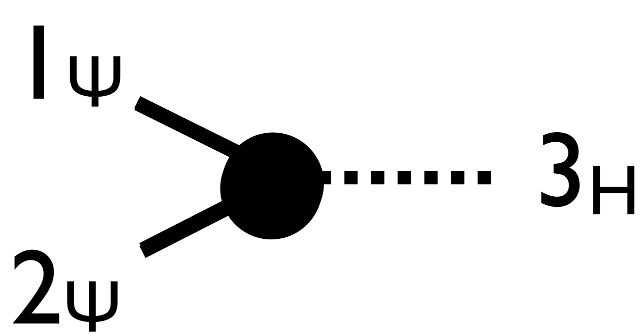
= ***EF**fective **T**heory of Amplitudes*

Expansion: $\langle ij \rangle/\Lambda$, $[ij]/\Lambda$

SM "Building-blocks":



$$= \frac{\langle 13 \rangle^2}{\langle 12 \rangle}$$



$$= \langle 12 \rangle$$

...

At O(E²/Λ²):

***n* = number of external states**
***h* = helicity of the amplitude**

$$\mathcal{A}_{F^3}(1_{V_-}, 2_{V_-}, 3_{V_-}) = \frac{C_{F^3}}{\Lambda^2}\langle 12\rangle\langle 23\rangle\langle 31\rangle$$

} n=3, h=-3

$$\begin{aligned}
\mathcal{A}_{F^2\phi^2}(1_{V_-}, 2_{V_-}, 3_\phi, 4_\phi) &= \frac{C_{F^2\phi^2}}{\Lambda^2}\langle 12\rangle^2\,, \\
\mathcal{A}_{F\psi^2\phi}(1_{V_-}, 2_\psi, 3_\psi, 4_\phi) &= \frac{C_{F\psi^2\phi}}{\Lambda^2}\langle 12\rangle\langle 13\rangle\,, \\
\mathcal{A}_{\psi^4}(1_\psi, 2_\psi, 3_\psi, 4_\psi) &= \left(C_{\psi^4}\langle 12\rangle\langle 34\rangle + C'_{\psi^4}\langle 13\rangle\langle 24\rangle\right)\frac{1}{\Lambda^2}
\end{aligned}$$

} n=4, h=-2

$$\begin{aligned}
\mathcal{A}_{\Box\phi^4}(1_\phi, 2_\phi, 3_\phi, 4_\phi) &= \left(C_{\Box\phi^4}\langle 12\rangle[12] + C'_{\Box\phi^4}\langle 13\rangle[13]\right)\frac{1}{\Lambda^2} \\
\mathcal{A}_{\psi\bar\psi\phi^2}(1_\psi, 2_{\bar\psi}, 3_\phi, 4_\phi) &= \frac{C_{\psi\bar\psi\phi^2}}{\Lambda^2}\langle 13\rangle[23]\,, \\
\mathcal{A}_{\psi^2\bar\psi^2}(1_\psi, 2_\psi, 3_{\bar\psi}, 4_{\bar\psi}) &= \frac{C_{\psi^2\bar\psi^2}}{\Lambda^2}\langle 12\rangle[34]\,.
\end{aligned}$$

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$$\mathcal{A}_{F\psi^2\phi}(1_{V_-}, 2_\psi, 3_\psi, 4_\phi) = \frac{C_{F\psi^2\phi}}{\Lambda^2}\langle 12\rangle\langle 13\rangle ,$$

⟷ $F^{\mu\nu}\psi\sigma_{\mu\nu}\psi\, H$

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$$\mathcal{A}_{\psi\bar\psi\phi^2}(1_\psi, 2_{\bar\psi}, 3_\phi, 4_\phi) = \frac{C_{\psi\bar\psi\phi^2}}{\Lambda^2}\langle 13\rangle[23] ,$$

$$\mathcal{A}_{\psi^2\bar\psi^2}(1_\psi, 2_\psi, 3_{\bar\psi}, 4_{\bar\psi}) = \frac{C_{\psi^2\bar\psi^2}}{\Lambda^2}\langle 12\rangle[34] .$$

} n=4, h=0

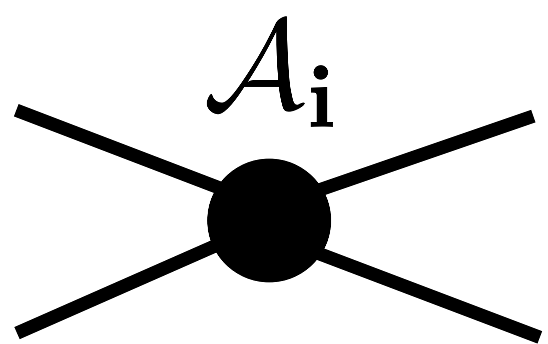
$$\mathcal{A}_{\psi^2\phi^3}(1_\psi, 2_\psi, 3_\phi, 4_\phi, 5_\phi) = \frac{C_{\psi^2\phi^3}}{\Lambda^2}\langle 12\rangle$$

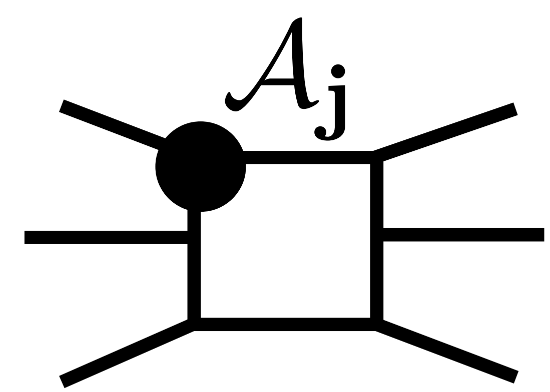
n=5
h=-1

$$\mathcal{A}_{\phi^6}(1_\phi, 2_\phi, 3_\phi, 4_\phi, 5_\phi, 6_\phi) = \frac{C_{\phi^6}}{\Lambda^2}$$

n=6
h=0

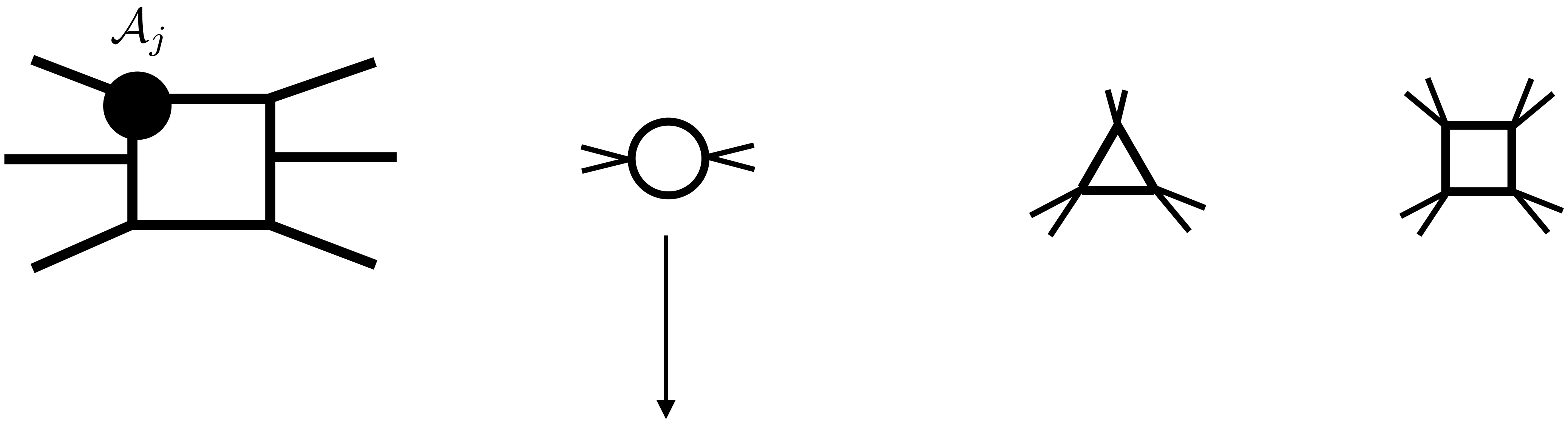
III. EFT renormalization via amplitude methods

$$\mathcal{A}_{\mathbf{i}}^{1-\mathrm{loop}} =$$ 

$+$ 

One-loop reduction to Passarino-Veltman integrals:

$$\mathcal{A}_{\mathbf{i}} = \sum_{\text{bubble}} \mathbf{c_2 I_2} + \sum_{\text{triangle}} \mathbf{c_3 I_3} + \sum_{\text{box}} \mathbf{c_4 I_4} + \mathbf{rational}$$



divergent ☞ c_2 = anomalous dimensions

One-loop reduction to Passarino-Veltman integrals:

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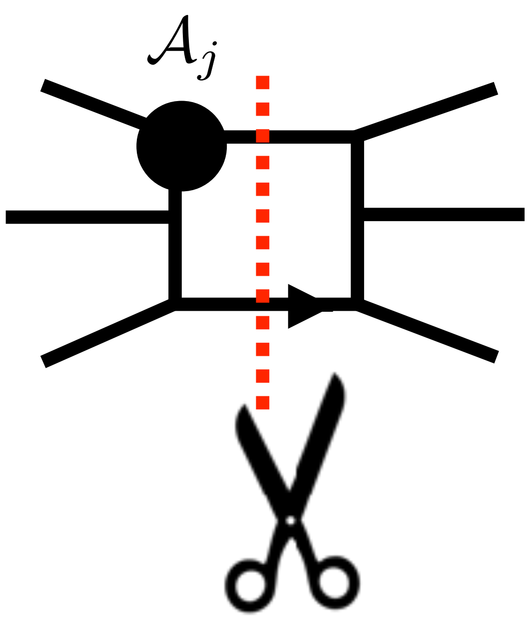
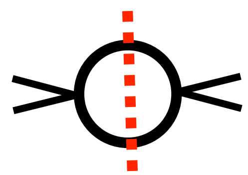
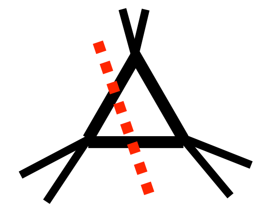
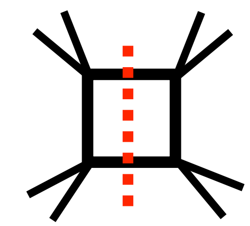






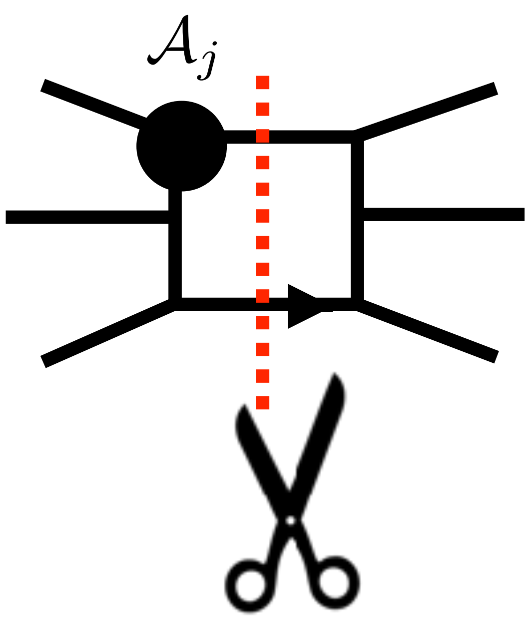


double cut

(internal particles on-shell)

One-loop reduction to Passarino-Veltman integrals:

$$\mathcal{A}_\mathbf{i} = \sum_{\text{bubble}} \mathbf{c_2 I_2} + \sum_{\text{triangle}} \mathbf{c_3 I_3} + \sum_{\text{box}} \mathbf{c_4 I_4} + \mathbf{rational}$$



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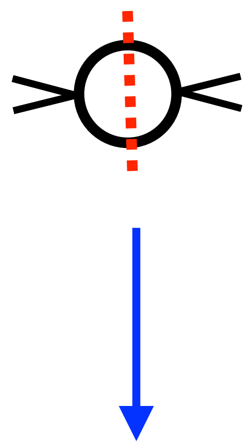
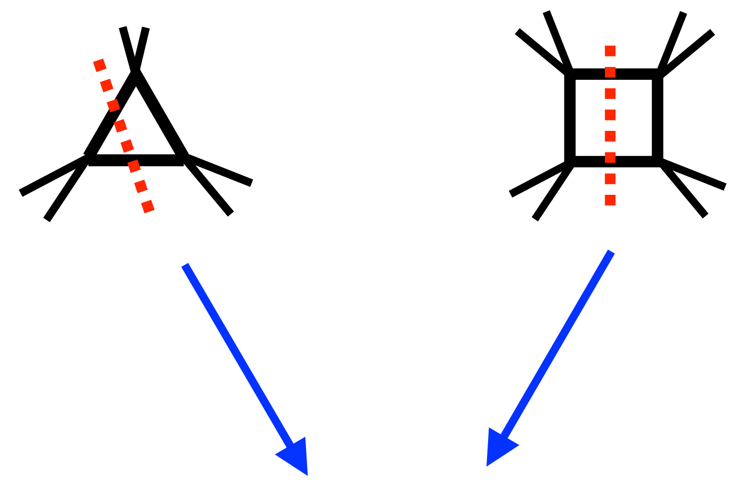


c_2

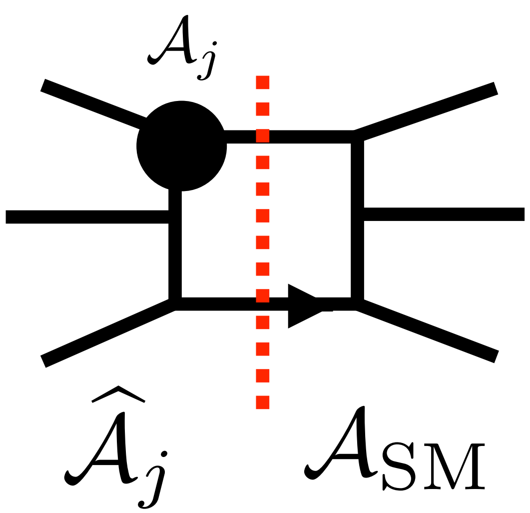


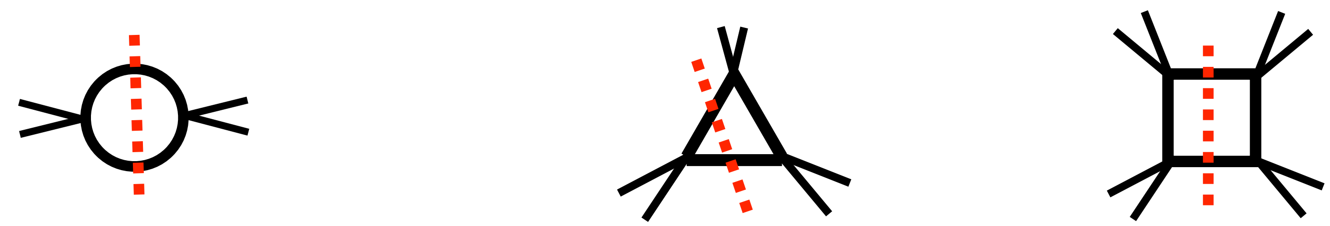
Cancel out in IR safe quantities

P. Baratella, C. Fernandez, AP   2005.07129

One-loop reduction to Passarino-Veltman integrals:

$$\mathcal{A}_\mathbf{i} = \sum_{\text{bubble}} \mathbf{c_2 I_2} + \sum_{\text{triangle}} \mathbf{c_3 I_3} + \sum_{\text{box}} \mathbf{c_4 I_4} + \textbf{rational}$$





$$-\frac{1}{4\pi^3}\frac{C_i}{C_j}\int d\text{LIPS} \sum_{\substack{\text{ext. legs}\\ \text{distrib.}}} \sum_{\ell_1,\ell_2} \widehat{\mathcal{A}}_j(\ldots,-\ell_1,-\ell_2)\times\mathcal{A}_{\rm SM}(\ell_2,\ell_1,\ldots) = \gamma_{ij}\,\mathcal{A}_i(1,2,\ldots,n)$$

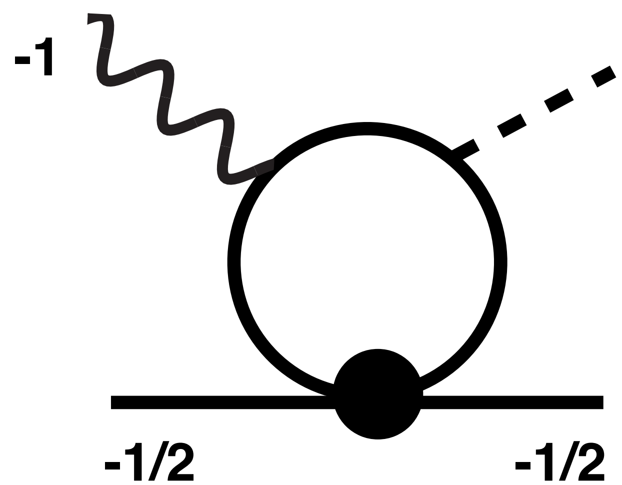
phase space integration & sum over internal states

“Emergent” selection rules

1505.01844 (also by susy techniques:1412.7151)

No 4-fermion $(\bar{\psi}\gamma^{\mu}\psi)^2$ corrections to dipoles

$$\mathcal{A}(1_e, 2_{l_j}, 3_{W^a_-}, 4_{H_i^\dagger})$$



$$F^{\mu\nu}\bar{\psi}\sigma_{\mu\nu}\psi\, H$$

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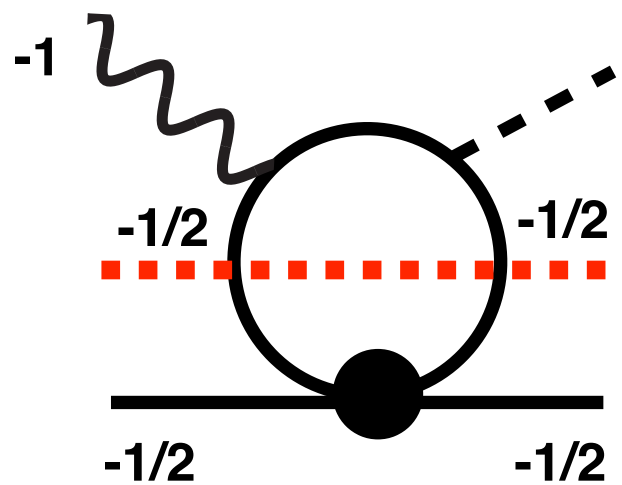

$$F^{\mu\nu}\bar{\psi}\sigma_{\mu\nu}\psi\, H$$

$$\gamma\mathcal{A}_{WHle} = -\frac{1}{4\pi^3}\int d\text{LIPS}\,\mathcal{A}_{luqe}(1_e, 2_l, 3'_{\bar{e}}, 4'_{\bar{l}}) \times \mathcal{A}_{\text{SM}}(4'_e, 3'_l, 3_{W^a_-}, 4_{H^\dagger})$$

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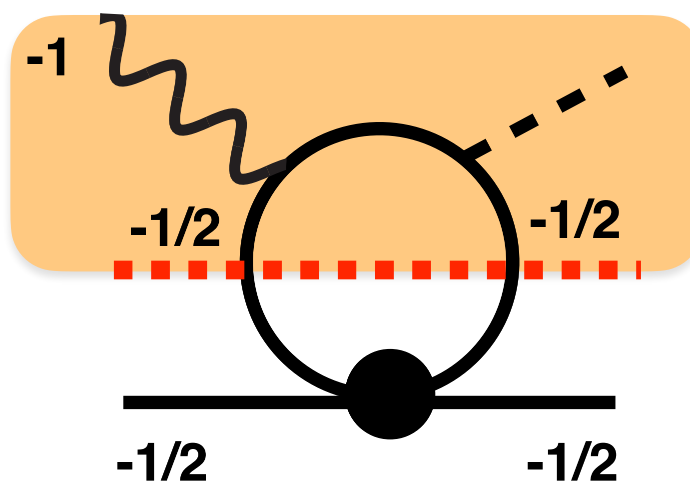

$$F^{\mu\nu}\bar{\psi}\sigma_{\mu\nu}\psi\, H$$

h_{total} = -2

Absent in the SM

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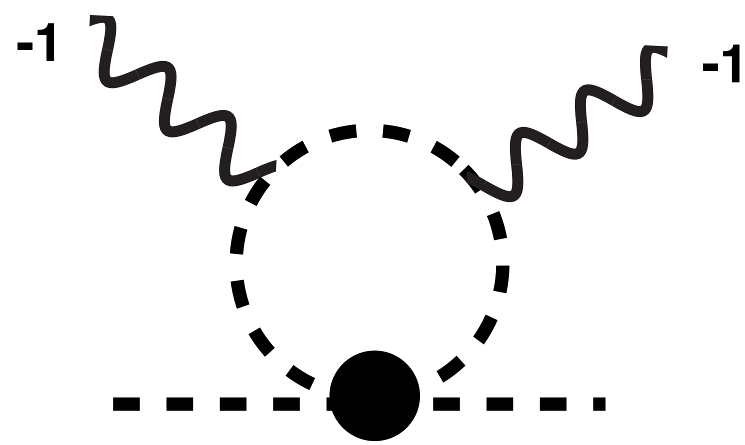
No p^2H^4 corrections to Hγγ

e.g.

$$(H^\dagger D_\mu H)^2$$



$$F_{\alpha\beta}F^{\alpha\beta}h^2$$

No p^2H^4 corrections to $H\gamma\gamma$

e.g.

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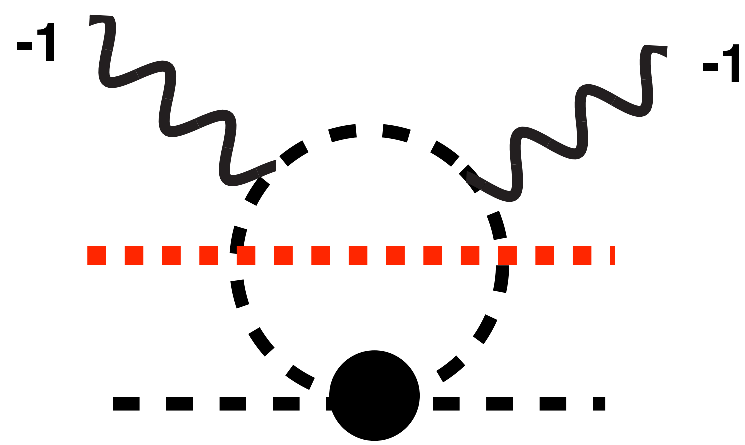

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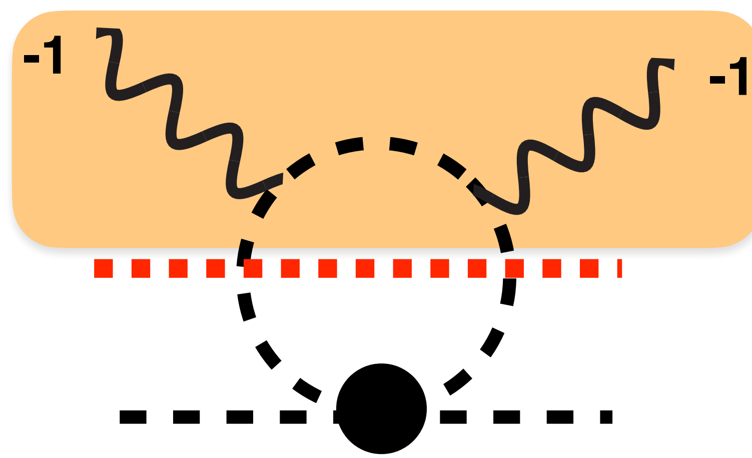

$$F_{\alpha\beta}F^{\alpha\beta}h^2$$

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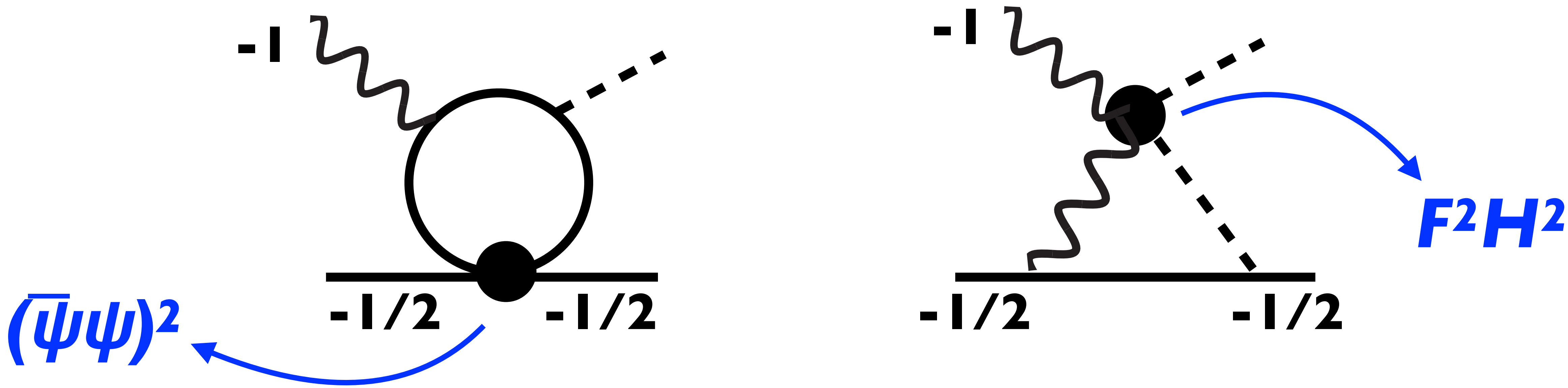
Absent in the SM

But the **on-shell methods** also tell us about the non-zero result

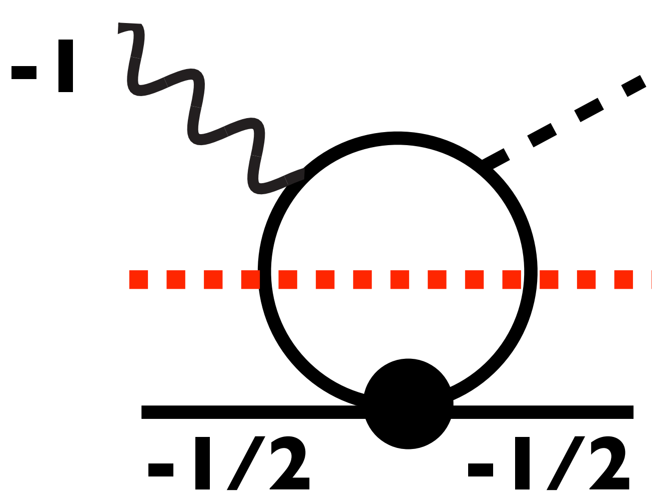
Contributions to **dipoles** from **Feynman** approach:

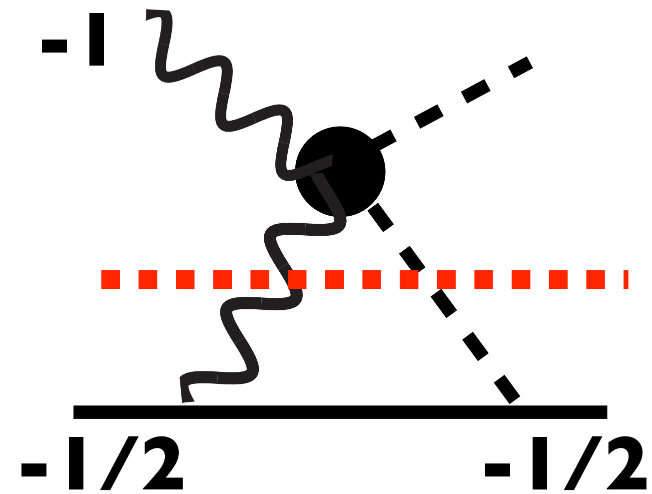


very **different** contributions

But the **on-shell methods** also tell us about the non-zero result

From **on-shell** approach: $\gamma \mathcal{A}_{\mathbf{i}} \sim \sum\!\!\!\!\!\!\int \mathcal{A}_{\mathbf{j}} \mathcal{A}_{\mathbf{SM}}$





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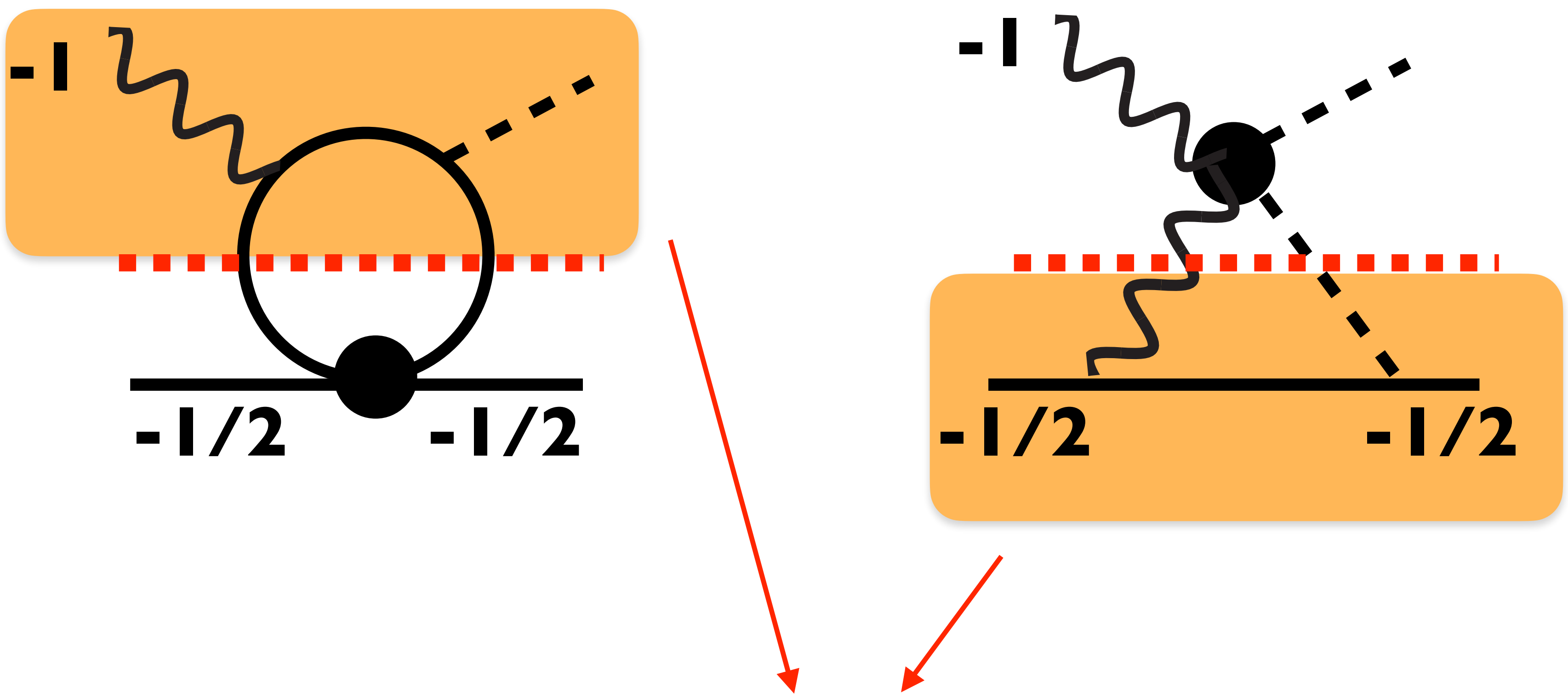

$$\mathcal{A}_{\rm SM}(1_{\bar\psi}, 2_{\bar\psi}, 3_{V_-}, 4_{H^\dagger})$$

from the same SM amplitude!

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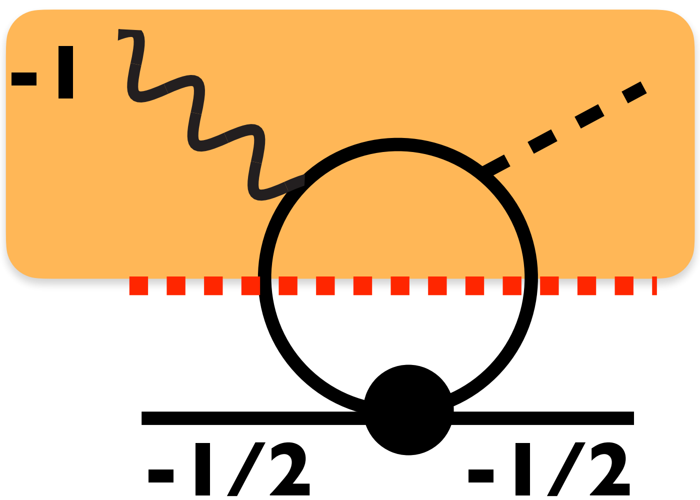
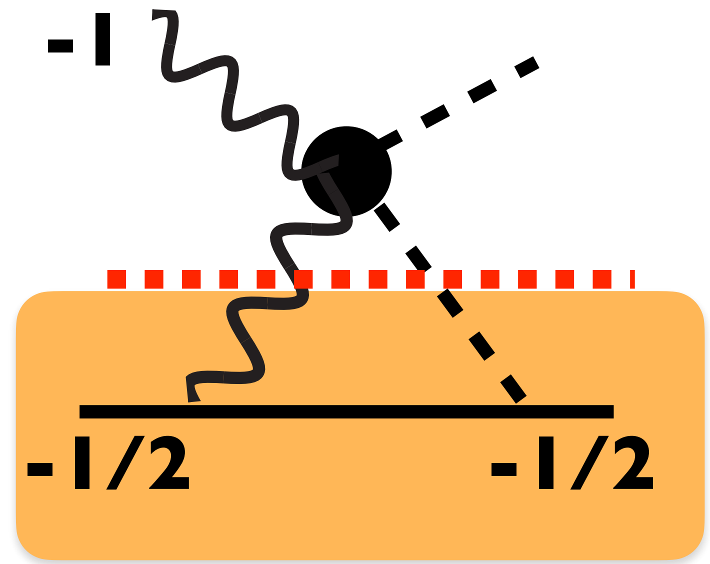
From **on-shell** approach: $\gamma \mathcal{A}_{\mathbf{i}} \sim \sum\!\!\!\!\!\!\int \mathcal{A}_{\mathbf{j}} \mathcal{A}_{\mathrm{SM}}$





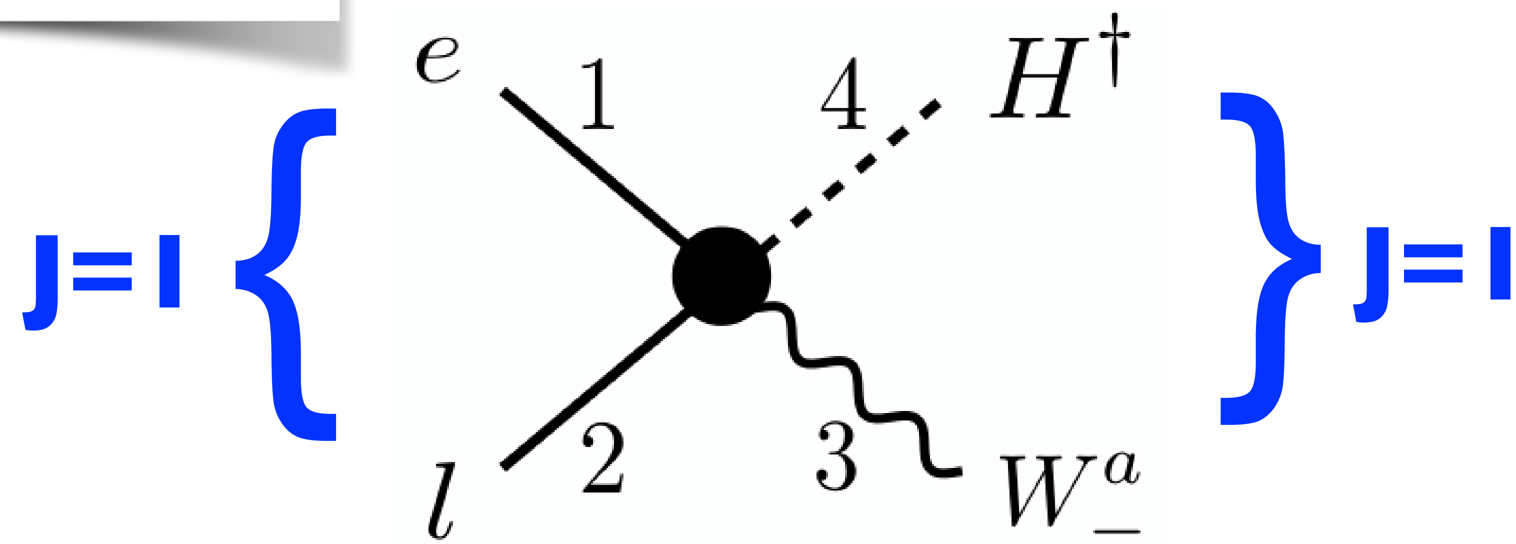
No calculation wasted in the on-shell method

$$\mathcal{A}_{\mathrm{SM}}(1_{\bar{\psi}}, 2_{\bar{\psi}}, 3_{V_-}, 4_{H^\dagger})$$

from the same SM amplitude!

But there is more to say by
angular-momentum decomposition (partial-waves)

Example of dipoles:

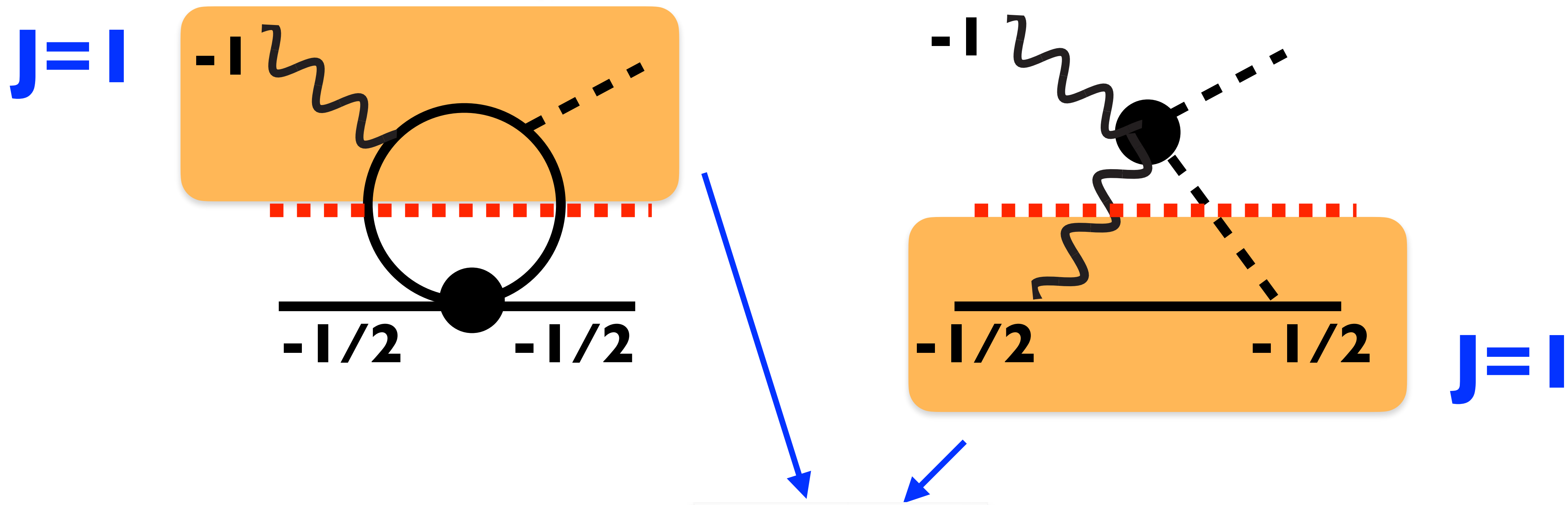


$$\mathcal{A}(1_e, 2_l, 3_{W_-}, 4_{H^\dagger}) = 3e^{-i\phi} d_{01}^{J=1}(\theta)\, a^{J=1}$$

only one partial-wave!

But there is more to say by
angular-momentum decomposition (partial-waves)

Example of dipoles:



Not needed the full SM amplitude, only: $a_{\text{SM}}^{J=1}$

B. vonHarling, P. Baratella, C. Fernandez, AP 2010.13809

☞ **angular-momentum selection rules**

see also arXiv:2001.04481

Amplitudes with J≠1 cannot contribute to dipoles

Anomalous Dimensions as a product of partial-waves

B. vonHarling, P. Baratella, C. Fernandez, AP   2010.13809

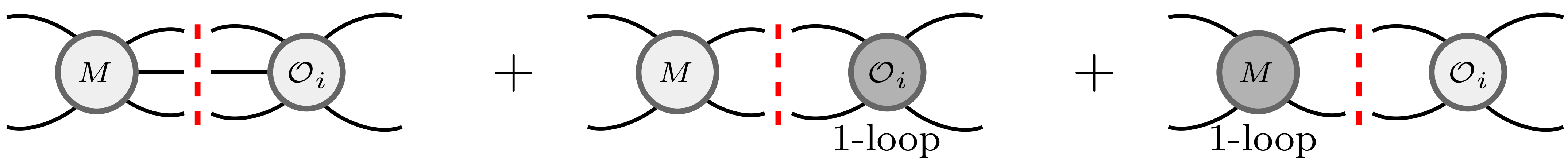
$$\gamma_i \sim a^J_{\rm SM} a^J_{\rm BSM}$$

$\to$ $1/\Lambda^2$ amplitude

Beyond one-loop

2005.06983
2005.12917
2112.12131

Two-loop:

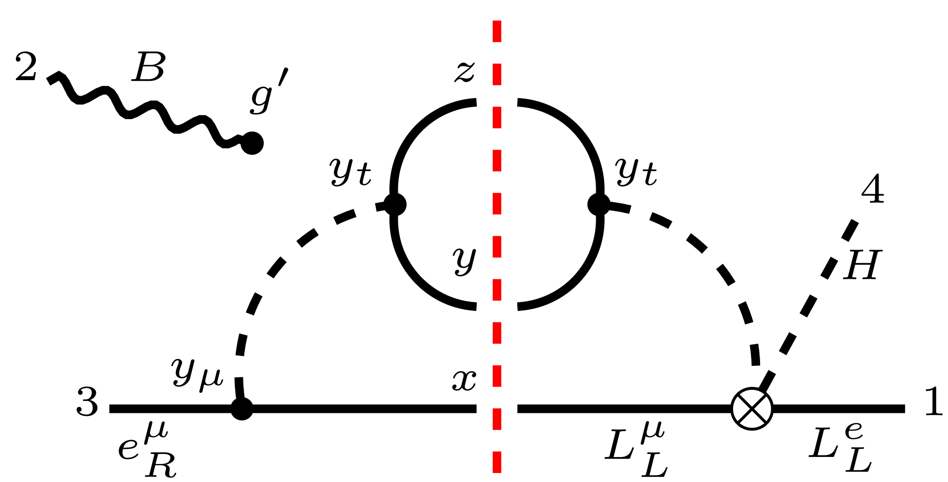


Two-loops for μ→eγ

J. Elias-Miro, C. Fernandez, M. Gümüs, AP 2112.12131

$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu \mu_R)$ affects μ→eγ at the two-loop level:

↳ **Z→μe**



product of tree-level amplitudes

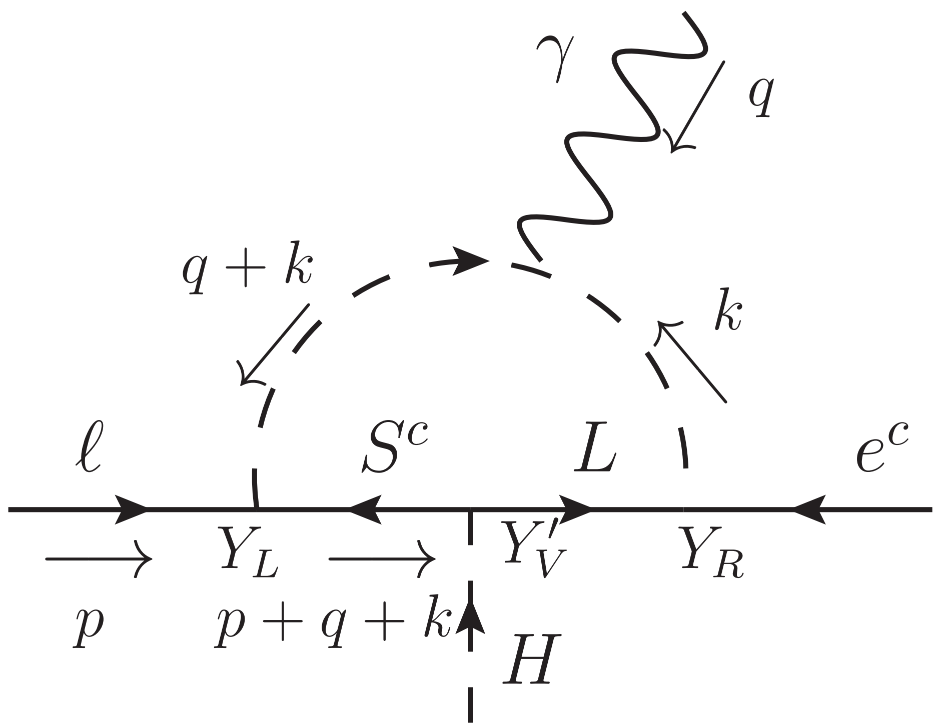
Finite terms?

Difficult in general, **but** simplifies a lot
for BSM calculations, where new physics scale $\mathbf{M \gg E_{exp}}$

New insights from the **amplitude** method!

Finite terms to g-2

No contribution $O(1/M^2)$ to **dipoles**
from a **heavy singlet + doublet fermion**:



~ $O(1/M^4)$

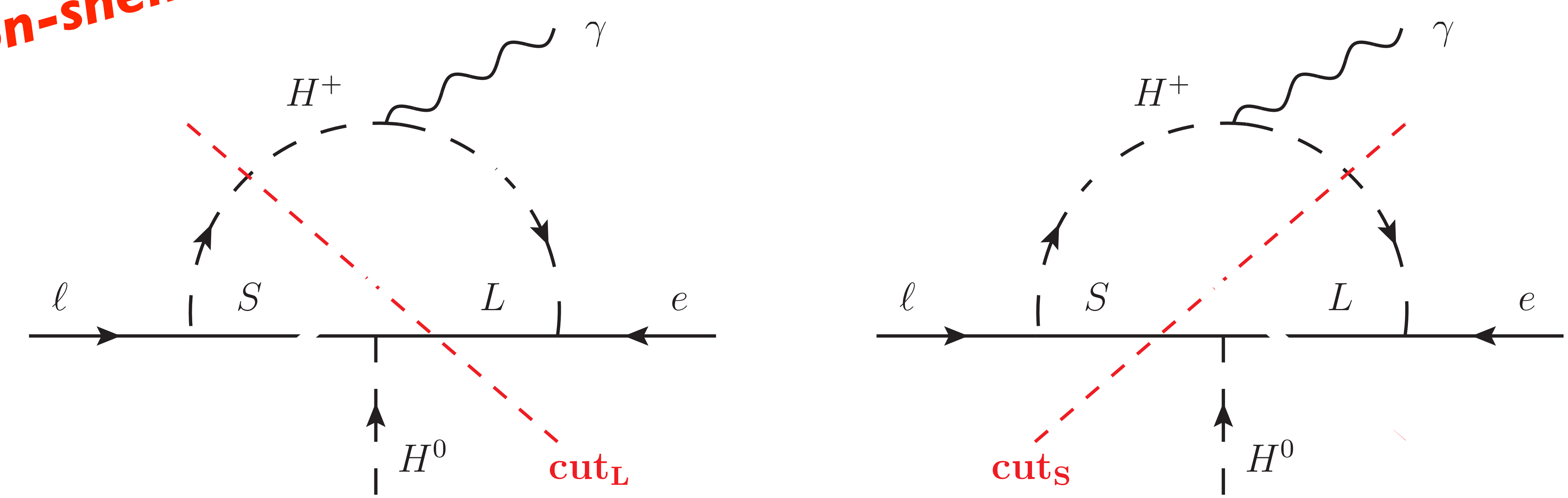
N. Arkani-Hamed, K. Harigaya 2106.01373

Finite terms to g-2

No contribution $O(1/M^2)$ to **dipoles**
from a **heavy singlet + doublet fermion**:

from on-shell methods:

L. Delle Rosse, B. von Harling, AP in 2201.10572



even under S↔L

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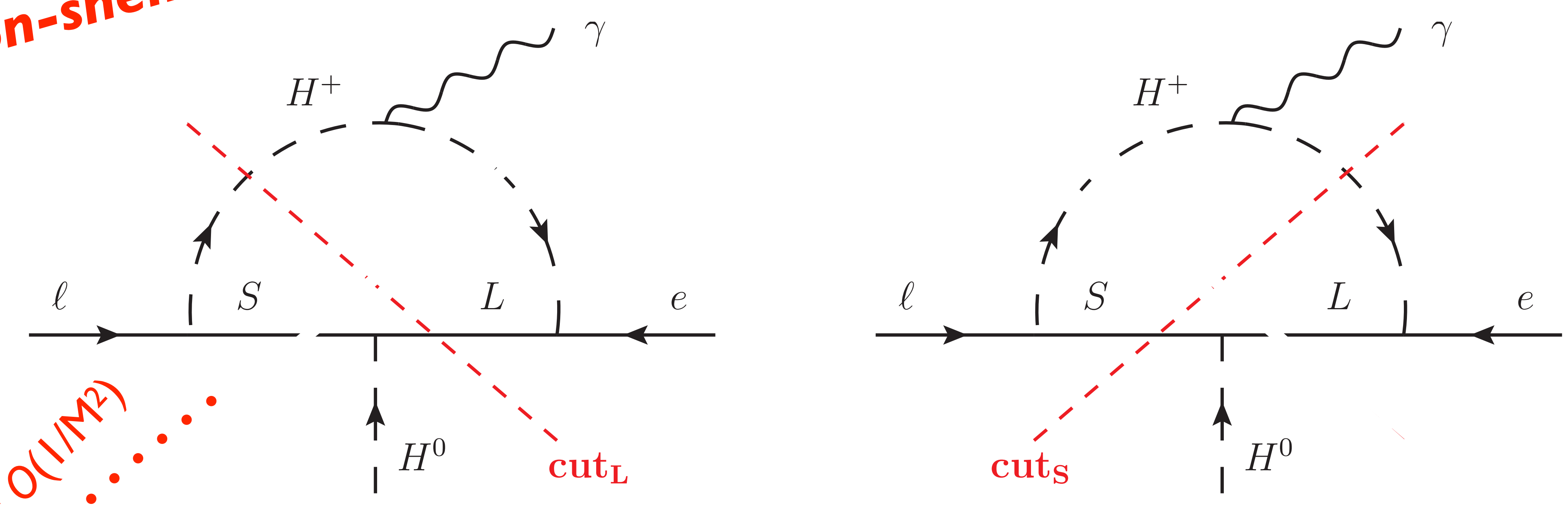

amplitude at $O(1/M^2)$

even under S↔L

$$\frac{1}{M_L^2 - M_S^2}$$

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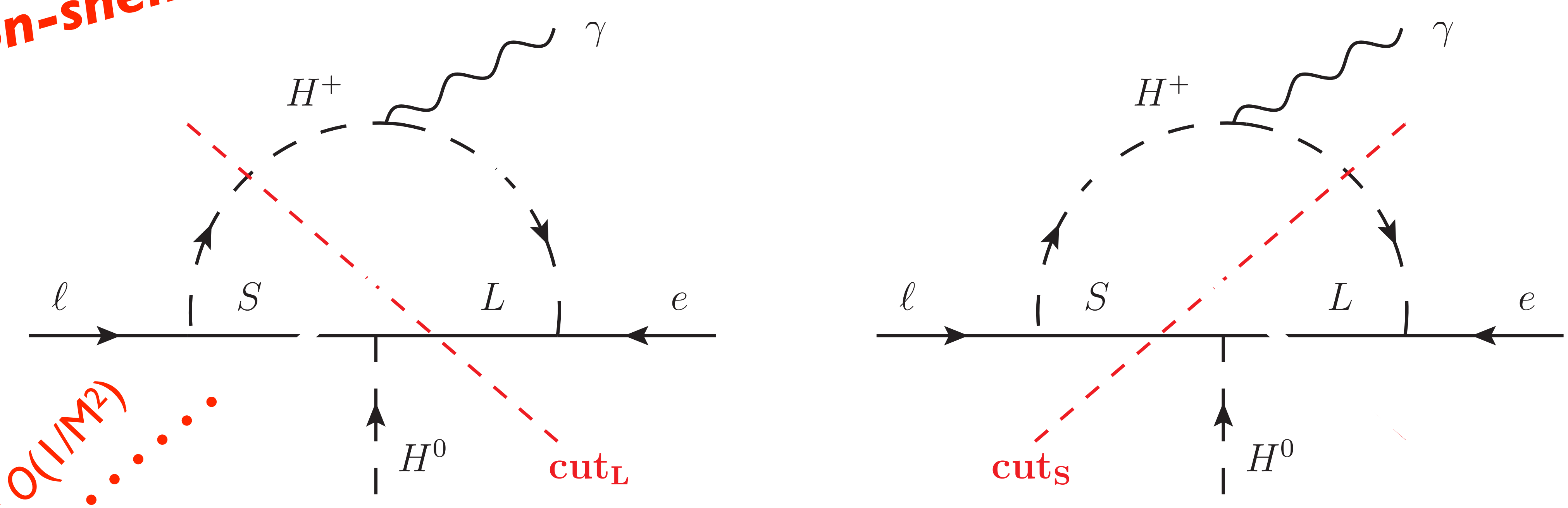


amplitude at $O(1/M^2)$

$$\frac{1}{M_L^2 - M_S^2}$$

even under S↔L

odd under S↔L

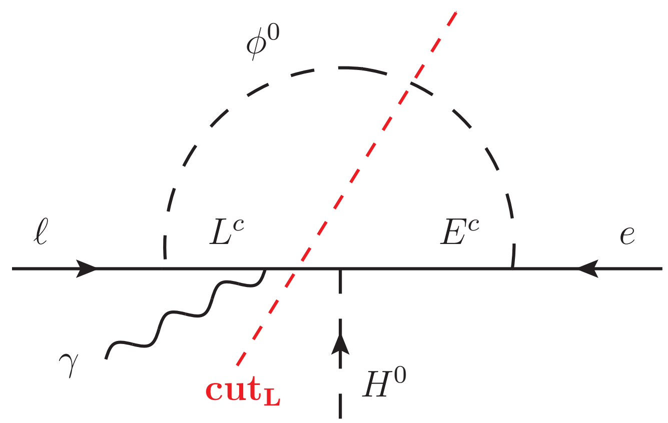
☞ **zero**

Finite terms to g-2

L. Delle Rosse, B. von Harling, AP in 2201.10572

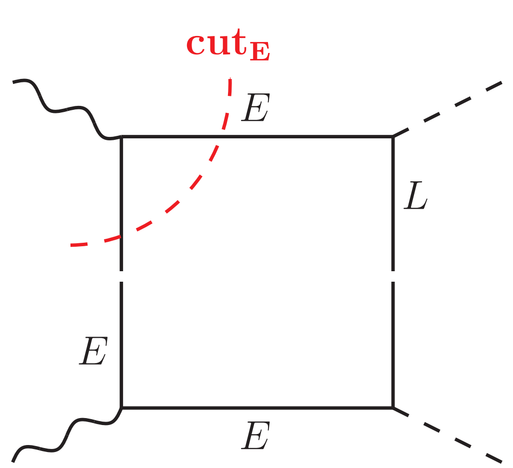
Following the same argument, more zeros can be found:

- **Scalar + heavy doublet + charged fermion**:



+ (L↔E) ☞ **zero**

- **Beyond g-2: Zeros in hγγ**

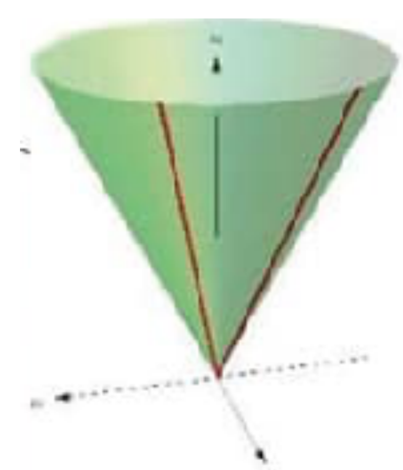


+ (L↔E) ☞ **zero**

Conclusions

- **The SM is an EFT:** dimension-6 interactions are there *waiting* to be discovered (not clear though at which scale)
- EFT approach useful to understand correlations
- Nevertheless, many unexplained patterns (one-loop "zeros")

☞ ***Getting on-shell!***



- Allows to construct **BSM without Lagrangians**
- Calculation of loop effects: ***Simpler with easy recycling***

☞ many "emergent" **selection rules**

☞ many relations **between anomalous dimensions**

Conclusions

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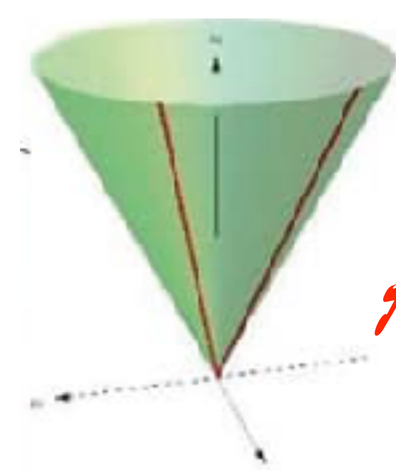


A lot to do! Stay Tuned!

- Allows to construct **BSM without Lagrangians**
- Calculation of loop effects: ***Simpler with easy recycling***

☞ many "emergent" **selection rules**

☞ many relations **between anomalous dimensions**

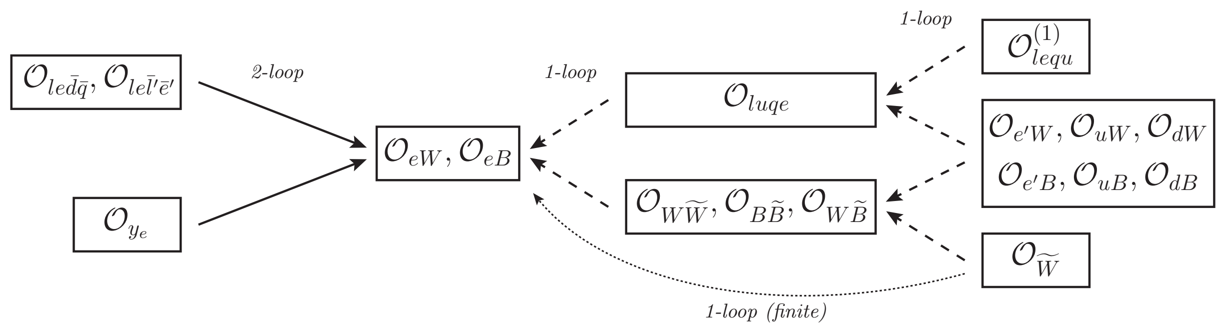

RESTRICTED AREA
MONITORED
BY VIDEO
CAMERA

	BR($\mu \to e\gamma$)	BR($\mu \to eee$)	R($\mu N \to eN$)	BR($h \to \mu e$)
Current	$4.2 \cdot 10^{-13}$ [33]	$1 \cdot 10^{-12}$ [34]	$7 \cdot 10^{-13}$ [35]	$6.1 \cdot 10^{-5}$ [36]
Future	$6.0 \cdot 10^{-14}$ [37]	$1 \cdot 10^{-16}$ [38]	$8 \cdot 10^{-17}$ [39]	

	$\mu \to e\gamma$	$\mu \to eee$	$\mu N \to eN$	$h \to \mu e$
$C_{DB}^{\mu e} - C_{DW}^{\mu e}$	951 TeV (1547 TeV)	218 TeV (2183 TeV)	208 TeV (1812 TeV)	
$C_{DB}^{\mu e} + C_{DW}^{\mu e}$	127 TeV (214 TeV)	26 TeV (309 TeV)	24 TeV (253 TeV)	
$C_{R}^{\mu e}$	35 TeV (59 TeV)	160 TeV (1602 TeV)	225 TeV (1535 TeV)	
$C_{L}^{\mu e} + C_{L3}^{\mu e}$	4 TeV (7 TeV)	164 TeV (1642 TeV)	225 TeV (1535 TeV)	
$C_{L}^{\mu e} - C_{L3}^{\mu e}$	24 TeV (41 TeV)	35 TeV (421 TeV)	50 TeV (395 TeV)	
$C_{LuQe}^{\mu ett}$	304 TeV (510 TeV)	63 TeV (735 TeV)	59 TeV (604 TeV)	
$C_{LeQu}^{\mu ett}$	80 TeV (141 TeV)	14 TeV (209 TeV)	5 TeV (57 TeV)	
$C_{LL(RR),LR(RL)}^{\mu eee}$		207,174 TeV (2070,1740 TeV)		
$C_{LL,RR,LR}^{\mu euu}$			352 TeV (2693 TeV)	
$C_{LL,RR,LR}^{\mu edd}$			376 TeV (2725 TeV)	
$C_{LR}^{\mu dde}$			18 TeV (164 TeV)	
$C_{LL,RR,LR,RL}^{\mu e\tau\tau}$		14,16,14,16 TeV (174,194,174,194 TeV)	22 TeV (200 TeV)	
$C_{LL3}^{\mu e\tau\tau}$		20 TeV (247 TeV)	55 TeV (476 TeV)	
$C_{LL,RR,LR,RL}^{\mu ett}$	122 TeV (214 TeV)	21 TeV (317 TeV)	22,32,32,22 TeV (200,290,290,200 TeV)	
$C_{LL3}^{\mu ett}$	230 TeV (401 TeV)	41 TeV (592 TeV)	100 TeV (851 TeV)	
$C_{LL,RR,LR,RL}^{\mu ebb}$		14,16,14,16 TeV (174,194,174,194 TeV)	22 TeV (200 TeV)	
$C_{y}^{\mu e}$	4 TeV (6 TeV)	1 TeV (9 TeV)	1 TeV (7 TeV)	0.3 TeV

J. Elias-Miro, C. Fernandez, M. Gümüs, AP 2112.12131

$$|d_e| < 1.1 \cdot 10^{-29}\, \mathrm{e} \cdot \mathrm{cm}\,.$$



tree-level

C_{eW}	$5.5 \times 10^{-5}\, y_e g$
C_{eB}	$5.5 \times 10^{-5}\, y_e g'$

one-loop

C_{luqe}	$1.0 \times 10^{-3}\, y_e y_t$
$C_{W\widetilde{W}}$	$4.7 \times 10^{-3}\, g^2$
$C_{B\widetilde{B}}$	$5.2 \times 10^{-3}\, g'^{\,2}$
$C_{W\widetilde{B}}$	$2.4 \times 10^{-3}\, g g'$
$C_{\widetilde{W}}$	$6.4 \times 10^{-2}\, g^3$

two-loops

C_{lequ}	$3.8 \times 10^{-2}\, y_e y_t$
$C_{\tau W}$	$260\, y_\tau g$
$C_{\tau B}$	$380\, y_\tau g'$
C_{tW}	$6.9 \times 10^{-3}\, y_t g$
C_{tB}	$1.2 \times 10^{-2}\, y_t g'$
C_{bW}	$64\, y_b g$
C_{bB}	$47\, y_b g'$
$C_{led\bar{q}}$	$10\, y_e y_t (y_t/y_b)$
$C_{le\bar{e}'\bar{l}'}$	$0.63\, y_e y_t (y_t/y_\tau)$

two-loops finite

C_{y_e}	$14\, y_e \lambda_h$
C_{y_t}	$14\, y_t \lambda_h$
C_{y_b}	$2.9 \times 10^3\, y_b \lambda_h$
C_{y_τ}	$3.4 \times 10^3\, y_\tau \lambda_h$