PLANCK 2022

Paris, May 30 - June 3, 2022

Local organizing commitee:

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M. Graña (IPHT)
S. Lavignac (IPHT)
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H. Partouche (CPHT)
D. Steer (APC)

The on-shell way to BSM

Alex Pomarol, IFAE & UAB (Barcelona)
and CERN

Photo by Karim Benakli

Outline

- **Some motivations for on-shell amplitude methods**
- **EFT (EFfective Theories) from amplitudes, instead of Lagrangians**
- **Renormalization of EFT using on-shell methods:**

Loops from tree-level amplitudes

☞ **Simple**, elegant, and **efficient**

Outline

- **Some motivations for on-shell amplitude methods**
- **EFT (EFfective Theories) from amplitudes, instead of Lagrangians**
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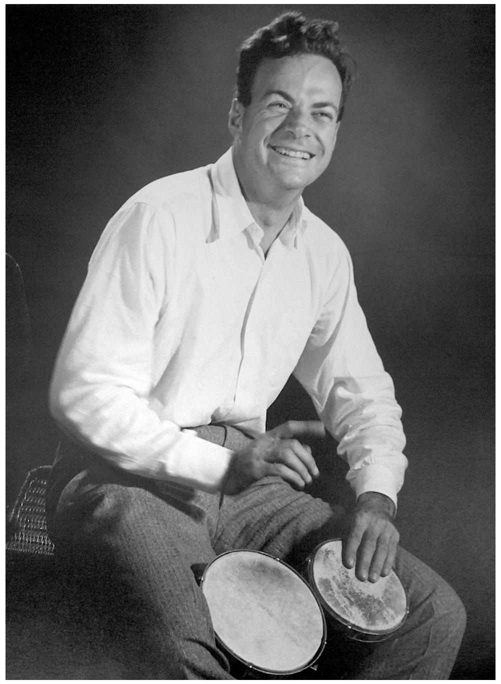
Loops from tree-level amplitudes

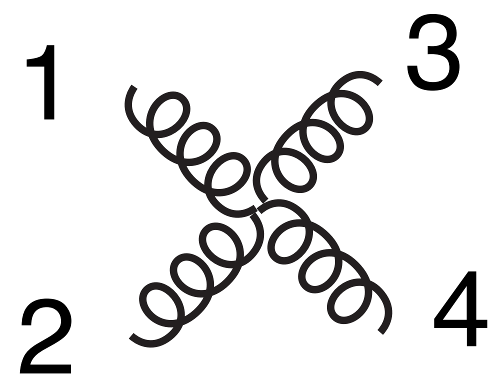
☞ **Simple**, elegant, and **efficient**

Makes explicit a lot of information that one cannot see from the Feynman approach!

1. Some motivation

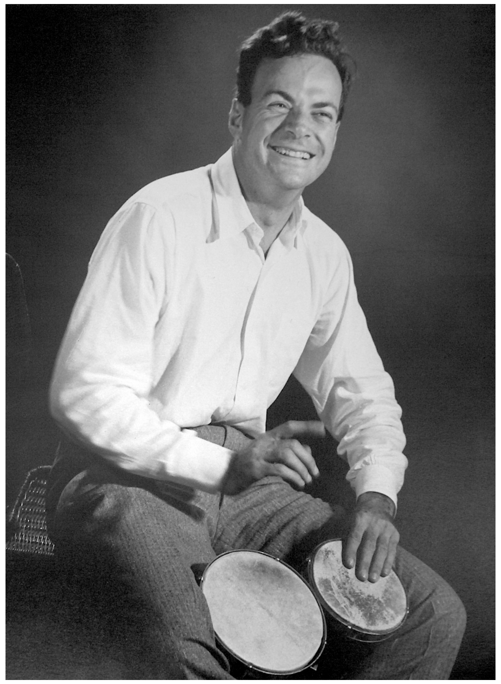
graviton + graviton → graviton + graviton





à la Feynman !

graviton + graviton → graviton + graviton



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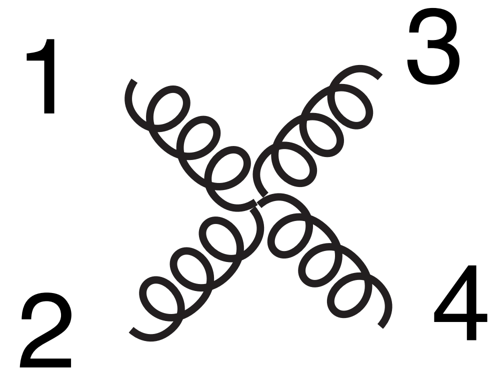
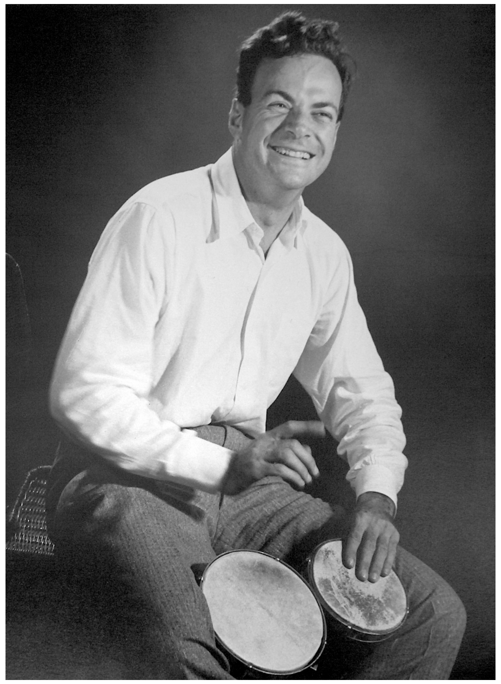
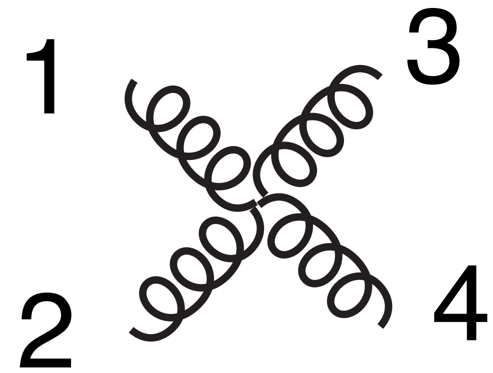


1) Define your fields ($h_{\mu\nu}$)

graviton + graviton → graviton + graviton



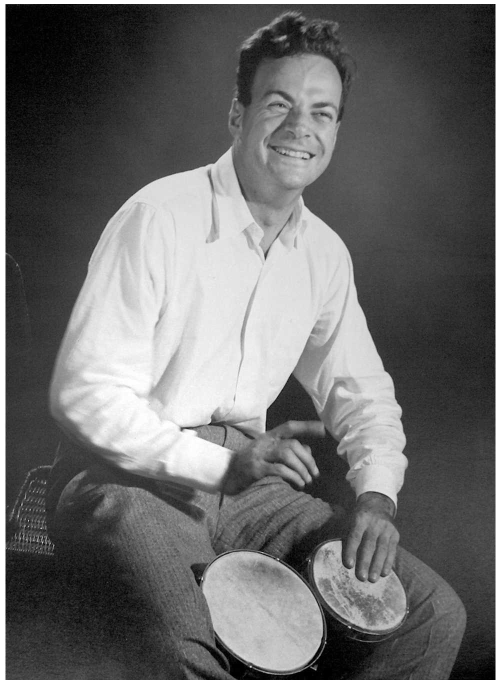


1) Define your fields ($h_{\mu\nu}$)

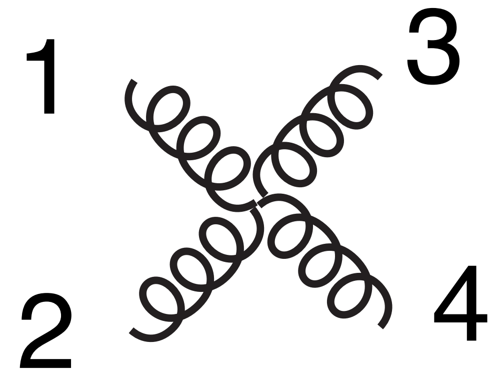
à la Feynman !

2) Get the Lagrangian (GR)

graviton + graviton → graviton + graviton



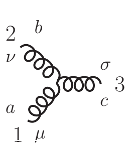
à la Feynman !



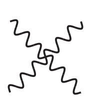
1) Define your fields ($h_{\mu\nu}$)

2) Get the Lagrangian (GR)

3) Get the Feynman rules



$$i\mathrm{Sym}\Big[-\frac{1}{2}P_3(p_1\cdot p_2\eta_{\mu\rho}\eta_{\nu\lambda}\eta_{\sigma\tau})-\frac{1}{2}P_6(p_{1\nu}p_{1\lambda}\eta_{\mu\rho}\eta_{\sigma\tau})+\frac{1}{2}P_3(p_1\cdot p_2\eta_{\mu\nu}\eta_{\rho\lambda}\eta_{\sigma\tau})$$
$$+P_6(p_1\cdot p_2\eta_{\mu\rho}\eta_{\nu\sigma}\eta_{\lambda\tau})+2P_3(p_{1\nu}p_{1\tau}\eta_{\mu\rho}\eta_{\lambda\sigma})-P_3(p_{1\lambda}p_{2\mu}\eta_{\rho\nu}\eta_{\sigma\tau})$$
$$+P_3(p_{1\sigma}p_{2\tau}\eta_{\mu\nu}\eta_{\rho\lambda})+P_6(p_{1\sigma}p_{1\tau}\eta_{\mu\nu}\eta_{\rho\lambda})+2P_6(p_{1\nu}p_{2\tau}\eta_{\lambda\mu}\eta_{\rho\sigma})$$
$$+2P_3(p_{1\nu}p_{2\mu}\eta_{\lambda\sigma}\eta_{\tau\rho})-2P_3(p_1\cdot p_2\eta_{\rho\nu}\eta_{\lambda\sigma}\eta_{\tau\mu})\Big],$$



$$\mathrm{Sym}[-\tfrac{1}{8}P_6(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\tau}\eta^{\rho\lambda}\eta^{\iota\kappa})-\tfrac{1}{8}P_{12}(p^\sigma p^\tau\eta^{\mu\nu}\eta^{\rho\lambda}\eta^{\iota\kappa})-\tfrac{1}{4}P_6(p^\sigma p'^\mu\eta^{\nu\tau}\eta^{\rho\lambda}\eta^{\iota\kappa})+\tfrac{1}{8}P_6(p\cdot p'\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\rho\lambda}\eta^{\iota\kappa})$$
$$+\tfrac{1}{4}P_6(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\tau}\eta^{\rho\iota}\eta^{\lambda\kappa})+\tfrac{1}{4}P_{12}(p^\sigma p^\tau\eta^{\mu\nu}\eta^{\rho\iota}\eta^{\lambda\kappa})+\tfrac{1}{2}P_6(p^\sigma p'^\mu\eta^{\nu\tau}\eta^{\rho\iota}\eta^{\lambda\kappa})-\tfrac{1}{4}P_6(p\cdot p'\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\rho\iota}\eta^{\lambda\kappa})$$
$$+\tfrac{1}{4}P_{24}(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\rho}\eta^{\tau\lambda}\eta^{\iota\kappa})+\tfrac{1}{4}P_{24}(p^\sigma p^\tau\eta^{\mu\rho}\eta^{\nu\lambda}\eta^{\iota\kappa})+\tfrac{1}{4}P_{12}(p^\rho p'^\lambda\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\iota\kappa})+\tfrac{1}{2}P_{24}(p^\sigma p'^\rho\eta^{\tau\mu}\eta^{\nu\lambda}\eta^{\iota\kappa})$$
$$-\tfrac{1}{2}P_{12}(p\cdot p'\eta^{\nu\sigma}\eta^{\tau\rho}\eta^{\lambda\mu}\eta^{\iota\kappa})-\tfrac{1}{2}P_{12}(p^\sigma p'^\mu\eta^{\tau\rho}\eta^{\lambda\nu}\eta^{\iota\kappa})+\tfrac{1}{2}P_{12}(p^\sigma p^\rho\eta^{\tau\lambda}\eta^{\mu\nu}\eta^{\iota\kappa})-\tfrac{1}{2}P_{24}(p\cdot p'\eta^{\mu\nu}\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\sigma})$$
$$-P_{12}(p^\sigma p^\tau\eta^{\nu\rho}\eta^{\lambda\iota}\eta^{\kappa\mu})-P_{12}(p^\rho p'^\lambda\eta^{\nu\iota}\eta^{\kappa\sigma}\eta^{\tau\mu})-P_{24}(p_\sigma p'^\rho\eta^{\tau\iota}\eta^{\kappa\mu}\eta^{\nu\lambda})-P_{12}(p^\rho p'^\iota\eta^{\lambda\sigma}\eta^{\tau\mu}\eta^{\nu\kappa})$$
$$+P_6(p\cdot p'\eta^{\nu\rho}\eta^{\lambda\sigma}\eta^{\tau\iota}\eta^{\kappa\mu})-P_{12}(p^\sigma p^\rho\eta^{\mu\nu}\eta^{\tau\iota}\eta^{\kappa\lambda})-\tfrac{1}{2}P_{12}(p\cdot p'\eta^{\mu\rho}\eta^{\nu\lambda}\eta^{\sigma\iota}\eta^{\tau\kappa})-P_{12}(p^\sigma p^\rho\eta^{\tau\lambda}\eta^{\mu\iota}\eta^{\nu\kappa})$$
$$-P_6(p^\rho p'^\iota\eta^{\lambda\kappa}\eta^{\mu\sigma}\eta^{\nu\tau})-P_{24}(p^\sigma p'^\rho\eta^{\tau\mu}\eta^{\nu\iota}\eta^{\kappa\lambda})-P_{12}(p^\sigma p'^\mu\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\nu})+2P_6(p\cdot p'\eta^{\nu\sigma}\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\mu})]$$

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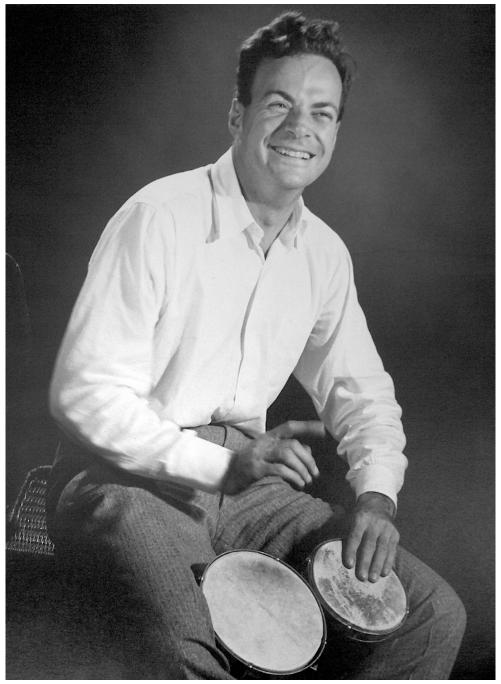
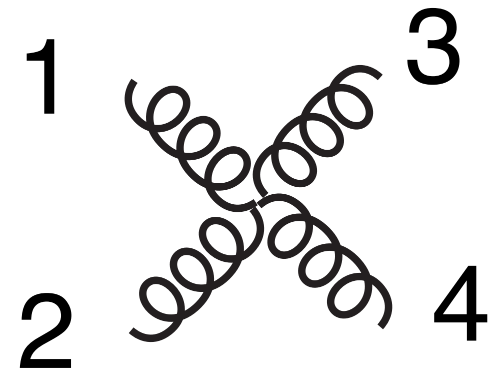
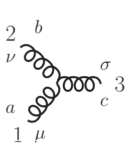
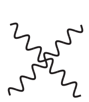


à la Feynman !





$$i\mathrm{Sym}\Big[-\frac{1}{2}P_3(p_1\cdot p_2\eta_{\mu\rho}\eta_{\nu\lambda}\eta_{\sigma\tau})-\frac{1}{2}P_6(p_{1\nu}p_{1\lambda}\eta_{\mu\rho}\eta_{\sigma\tau})+\frac{1}{2}P_3(p_1\cdot p_2\eta_{\mu\nu}\eta_{\rho\lambda}\eta_{\sigma\tau})$$
$$+P_6(p_1\cdot p_2\eta_{\mu\rho}\eta_{\nu\sigma}\eta_{\lambda\tau})+2P_3(p_{1\nu}p_{1\tau}\eta_{\mu\rho}\eta_{\lambda\sigma})-P_3(p_{1\lambda}p_{2\mu}\eta_{\rho\nu}\eta_{\sigma\tau})$$
$$+P_3(p_{1\sigma}p_{2\tau}\eta_{\mu\nu}\eta_{\rho\lambda})+P_6(p_{1\sigma}p_{1\tau}\eta_{\mu\nu}\eta_{\rho\lambda})+2P_6(p_{1\nu}p_{2\tau}\eta_{\lambda\mu}\eta_{\rho\sigma})$$
$$+2P_3(p_{1\nu}p_{2\mu}\eta_{\lambda\sigma}\eta_{\tau\rho})-2P_3(p_1\cdot p_2\eta_{\rho\nu}\eta_{\lambda\sigma}\eta_{\tau\mu})\Big],$$



$$\mathrm{Sym}[-\tfrac{1}{8}P_6(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\tau}\eta^{\rho\lambda}\eta^{\iota\kappa})-\tfrac{1}{8}P_{12}(p^\sigma p^\tau\eta^{\mu\nu}\eta^{\rho\lambda}\eta^{\iota\kappa})-\tfrac{1}{4}P_6(p^\sigma p'^\mu\eta^{\nu\tau}\eta^{\rho\lambda}\eta^{\iota\kappa})+\tfrac{1}{8}P_6(p\cdot p'\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\rho\lambda}\eta^{\iota\kappa})$$
$$+\tfrac{1}{4}P_6(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\tau}\eta^{\rho\iota}\eta^{\lambda\kappa})+\tfrac{1}{4}P_{12}(p^\sigma p^\tau\eta^{\mu\nu}\eta^{\rho\iota}\eta^{\lambda\kappa})+\tfrac{1}{2}P_6(p^\sigma p'^\mu\eta^{\nu\tau}\eta^{\rho\iota}\eta^{\lambda\kappa})-\tfrac{1}{4}P_6(p\cdot p'\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\rho\iota}\eta^{\lambda\kappa})$$
$$+\tfrac{1}{4}P_{24}(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\rho}\eta^{\tau\lambda}\eta^{\iota\kappa})+\tfrac{1}{4}P_{24}(p^\sigma p^\tau\eta^{\mu\rho}\eta^{\nu\lambda}\eta^{\iota\kappa})+\tfrac{1}{4}P_{12}(p^\rho p'^\lambda\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\iota\kappa})+\tfrac{1}{2}P_{24}(p^\sigma p'^\rho\eta^{\tau\mu}\eta^{\nu\lambda}\eta^{\iota\kappa})$$
$$-\tfrac{1}{2}P_{12}(p\cdot p'\eta^{\nu\sigma}\eta^{\tau\rho}\eta^{\lambda\mu}\eta^{\iota\kappa})-\tfrac{1}{2}P_{12}(p^\sigma p'^\mu\eta^{\tau\rho}\eta^{\lambda\nu}\eta^{\iota\kappa})+\tfrac{1}{2}P_{12}(p^\sigma p^\rho\eta^{\tau\lambda}\eta^{\mu\nu}\eta^{\iota\kappa})-\tfrac{1}{2}P_{24}(p\cdot p'\eta^{\mu\nu}\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\sigma})$$
$$-P_{12}(p^\sigma p^\tau\eta^{\nu\rho}\eta^{\lambda\iota}\eta^{\kappa\mu})-P_{12}(p^\rho p'^\lambda\eta^{\nu\iota}\eta^{\kappa\sigma}\eta^{\tau\mu})-P_{24}(p_\sigma p'^\rho\eta^{\tau\iota}\eta^{\kappa\mu}\eta^{\nu\lambda})-P_{12}(p^\rho p'^\iota\eta^{\lambda\sigma}\eta^{\tau\mu}\eta^{\nu\kappa})$$
$$+P_6(p\cdot p'\eta^{\nu\rho}\eta^{\lambda\sigma}\eta^{\tau\iota}\eta^{\kappa\mu})-P_{12}(p^\sigma p^\rho\eta^{\mu\nu}\eta^{\tau\iota}\eta^{\kappa\lambda})-\tfrac{1}{2}P_{12}(p\cdot p'\eta^{\mu\rho}\eta^{\nu\lambda}\eta^{\sigma\iota}\eta^{\tau\kappa})-P_{12}(p^\sigma p^\rho\eta^{\tau\lambda}\eta^{\mu\iota}\eta^{\nu\kappa})$$
$$-P_6(p^\rho p'^\iota\eta^{\lambda\kappa}\eta^{\mu\sigma}\eta^{\nu\tau})-P_{24}(p^\sigma p'^\rho\eta^{\tau\mu}\eta^{\nu\iota}\eta^{\kappa\lambda})-P_{12}(p^\sigma p'^\mu\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\nu})+2P_6(p\cdot p'\eta^{\nu\sigma}\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\mu})]$$

1) Define your fields ($h_{\mu\nu}$)

2) Get the Lagrangian (GR)

3) Get the Feynman rules

4) Obtain the amplitude

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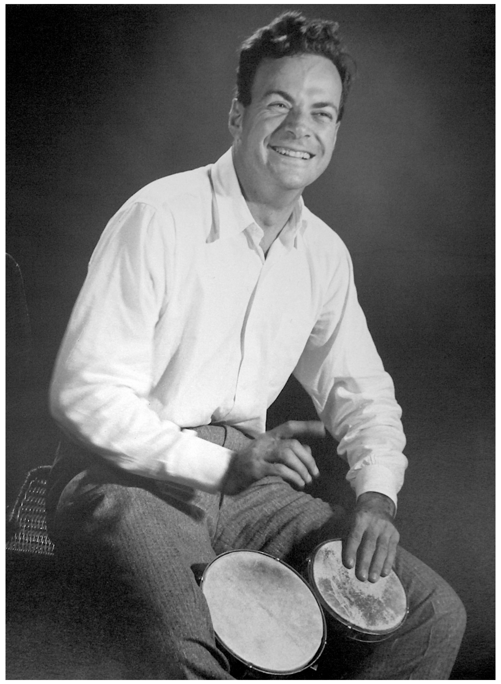

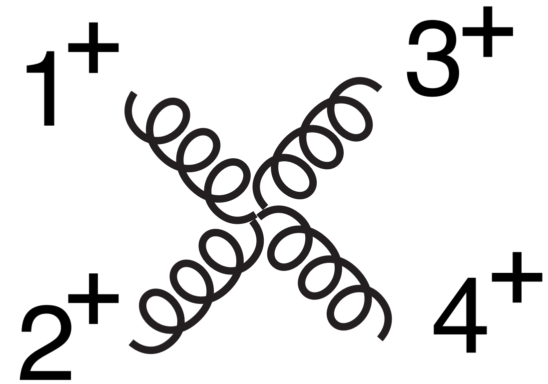

± ☞ h =±2

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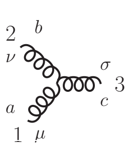
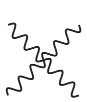


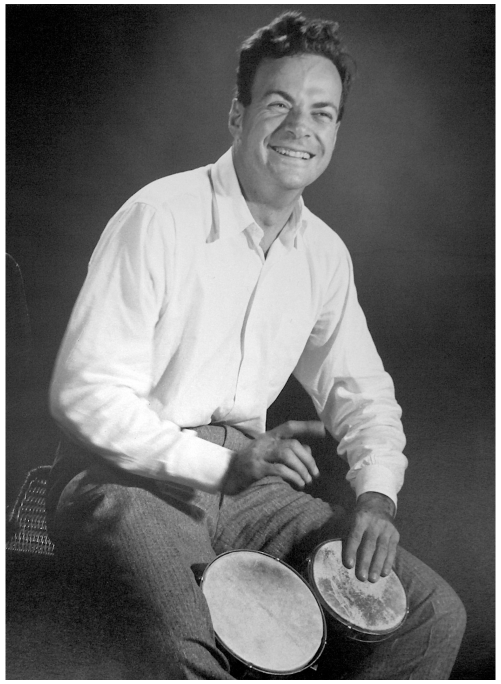
$$i\text{Sym}\Big[-\frac{1}{2}P_3(p_1\cdot p_2\eta_{\mu\rho}\eta_{\nu\lambda}\eta_{\sigma\tau}) - \frac{1}{2}P_6(p_{1\nu}p_{1\lambda}\eta_{\mu\rho}\eta_{\sigma\tau}) + \frac{1}{2}P_3(p_1\cdot p_2\eta_{\mu\nu}\eta_{\rho\lambda}\eta_{\sigma\tau}) + P_6(p_1\cdot p_2\eta_{\mu\rho}\eta_{\nu\sigma}\eta_{\lambda\tau}) + 2P_3(p_{1\nu}p_{1\tau}\eta_{\mu\rho}\eta_{\lambda\sigma}) - P_3(p_{1\lambda}p_{2\mu}\eta_{\rho\nu}\eta_{\sigma\tau}) + P_3(p_{1\sigma}p_{2\tau}\eta_{\mu\nu}\eta_{\rho\lambda}) + P_6(p_{1\sigma}p_{1\tau}\eta_{\mu\nu}\eta_{\rho\lambda}) + 2P_6(p_{1\nu}p_{2\tau}\eta_{\lambda\mu}\eta_{\rho\sigma}) + 2P_3(p_{1\nu}p_{2\mu}\eta_{\lambda\sigma}\eta_{\tau\rho}) - 2P_3(p_1\cdot p_2\eta_{\rho\nu}\eta_{\lambda\sigma}\eta_{\tau\mu})\Big],$$

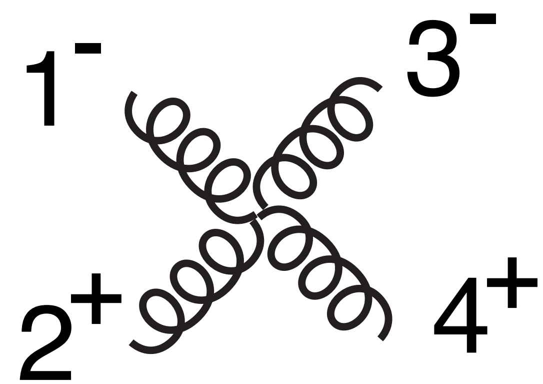


$$\text{Sym}[-\tfrac{1}{8}P_6(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\tau}\eta^{\rho\lambda}\eta^{\iota\kappa}) - \tfrac{1}{8}P_{12}(p^\sigma p^\tau\eta^{\mu\nu}\eta^{\rho\lambda}\eta^{\iota\kappa}) - \tfrac{1}{4}P_6(p^\sigma p'^\mu\eta^{\nu\tau}\eta^{\rho\lambda}\eta^{\iota\kappa}) + \tfrac{1}{8}P_6(p\cdot p'\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\rho\lambda}\eta^{\iota\kappa})$$
$$+\tfrac{1}{4}P_6(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\tau}\eta^{\rho\iota}\eta^{\lambda\kappa}) + \tfrac{1}{4}P_{12}(p^\sigma p^\tau\eta^{\mu\nu}\eta^{\rho\iota}\eta^{\lambda\kappa}) + \tfrac{1}{2}P_6(p^\sigma p'^\mu\eta^{\nu\tau}\eta^{\rho\iota}\eta^{\lambda\kappa}) - \tfrac{1}{4}P_6(p\cdot p'\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\rho\iota}\eta^{\lambda\kappa})$$
$$+\tfrac{1}{4}P_{24}(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\rho}\eta^{\tau\lambda}\eta^{\iota\kappa}) + \tfrac{1}{4}P_{24}(p^\sigma p^\tau\eta^{\mu\rho}\eta^{\nu\lambda}\eta^{\iota\kappa}) + \tfrac{1}{4}P_{12}(p^\rho p'^\lambda\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\iota\kappa}) + \tfrac{1}{2}P_{24}(p^\sigma p'^\rho\eta^{\tau\mu}\eta^{\nu\lambda}\eta^{\iota\kappa})$$
$$-\tfrac{1}{2}P_{12}(p\cdot p'\eta^{\nu\sigma}\eta^{\tau\rho}\eta^{\lambda\mu}\eta^{\iota\kappa}) - \tfrac{1}{2}P_{12}(p^\sigma p'^\mu\eta^{\tau\rho}\eta^{\lambda\nu}\eta^{\iota\kappa}) + \tfrac{1}{2}P_{12}(p^\sigma p^\rho\eta^{\tau\lambda}\eta^{\mu\nu}\eta^{\iota\kappa}) - \tfrac{1}{2}P_{24}(p\cdot p'\eta^{\mu\nu}\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\sigma})$$
$$-P_{12}(p^\sigma p^\tau\eta^{\nu\rho}\eta^{\lambda\iota}\eta^{\kappa\mu}) - P_{12}(p^\rho p'^\lambda\eta^{\nu\iota}\eta^{\kappa\sigma}\eta^{\tau\mu}) - P_{24}(p_\sigma p'^\rho\eta^{\tau\iota}\eta^{\kappa\mu}\eta^{\nu\lambda}) - P_{12}(p^\rho p'^\iota\eta^{\lambda\sigma}\eta^{\tau\mu}\eta^{\nu\kappa})$$
$$+P_6(p\cdot p'\eta^{\nu\rho}\eta^{\lambda\sigma}\eta^{\tau\iota}\eta^{\kappa\mu}) - P_{12}(p^\sigma p^\rho\eta^{\mu\nu}\eta^{\tau\iota}\eta^{\kappa\lambda}) - \tfrac{1}{2}P_{12}(p\cdot p'\eta^{\mu\rho}\eta^{\nu\lambda}\eta^{\sigma\iota}\eta^{\tau\kappa}) - P_{12}(p^\sigma p^\rho\eta^{\tau\lambda}\eta^{\mu\iota}\eta^{\nu\kappa})$$
$$-P_6(p^\rho p'^\iota\eta^{\lambda\kappa}\eta^{\mu\sigma}\eta^{\nu\tau}) - P_{24}(p^\sigma p'^\rho\eta^{\tau\mu}\eta^{\nu\iota}\eta^{\kappa\lambda}) - P_{12}(p^\sigma p'^\mu\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\nu}) + 2P_6(p\cdot p'\eta^{\nu\sigma}\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\mu})]$$

$$\mathcal{A}(1^+2^+3^+4^+) = 0$$

graviton + graviton → graviton + graviton





± ☞ h =±2

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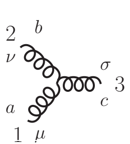
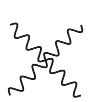


$$i\mathrm{Sym}\Big[-\frac{1}{2}P_3(p_1\cdot p_2\eta_{\mu\rho}\eta_{\nu\lambda}\eta_{\sigma\tau}) - \frac{1}{2}P_6(p_{1\nu}p_{1\lambda}\eta_{\mu\rho}\eta_{\sigma\tau}) + \frac{1}{2}P_3(p_1\cdot p_2\eta_{\mu\nu}\eta_{\rho\lambda}\eta_{\sigma\tau}) + P_6(p_1\cdot p_2\eta_{\mu\rho}\eta_{\nu\sigma}\eta_{\lambda\tau}) + 2P_3(p_{1\nu}p_{1\tau}\eta_{\mu\rho}\eta_{\lambda\sigma}) - P_3(p_{1\lambda}p_{2\mu}\eta_{\rho\nu}\eta_{\sigma\tau}) + P_3(p_{1\sigma}p_{2\tau}\eta_{\mu\nu}\eta_{\rho\lambda}) + P_6(p_{1\sigma}p_{1\tau}\eta_{\mu\nu}\eta_{\rho\lambda}) + 2P_6(p_{1\nu}p_{2\tau}\eta_{\lambda\mu}\eta_{\rho\sigma}) + 2P_3(p_{1\nu}p_{2\mu}\eta_{\lambda\sigma}\eta_{\tau\rho}) - 2P_3(p_1\cdot p_2\eta_{\rho\nu}\eta_{\lambda\sigma}\eta_{\tau\mu})\Big],$$

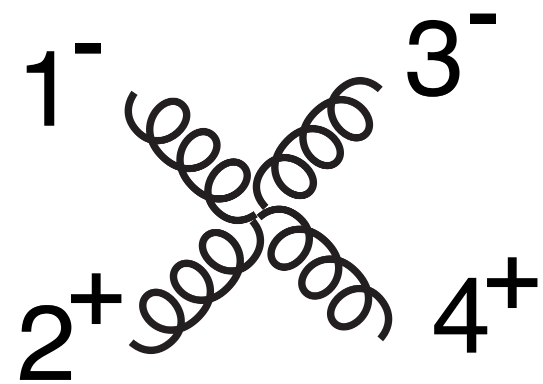


$$\mathrm{Sym}[-\tfrac{1}{8}P_6(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\tau}\eta^{\rho\lambda}\eta^{\iota\kappa})-\tfrac{1}{8}P_{12}(p^\sigma p^\tau\eta^{\mu\nu}\eta^{\rho\lambda}\eta^{\iota\kappa})-\tfrac{1}{4}P_6(p^\sigma p'^\mu\eta^{\nu\tau}\eta^{\rho\lambda}\eta^{\iota\kappa})+\tfrac{1}{8}P_6(p\cdot p'\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\rho\lambda}\eta^{\iota\kappa})$$
$$+\tfrac{1}{4}P_6(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\tau}\eta^{\rho\iota}\eta^{\lambda\kappa})+\tfrac{1}{4}P_{12}(p^\sigma p^\tau\eta^{\mu\nu}\eta^{\rho\iota}\eta^{\lambda\kappa})+\tfrac{1}{2}P_6(p^\sigma p'^\mu\eta^{\nu\tau}\eta^{\rho\iota}\eta^{\lambda\kappa})-\tfrac{1}{4}P_6(p\cdot p'\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\rho\iota}\eta^{\lambda\kappa})$$
$$+\tfrac{1}{4}P_{24}(p\cdot p'\eta^{\mu\nu}\eta^{\sigma\rho}\eta^{\tau\lambda}\eta^{\iota\kappa})+\tfrac{1}{4}P_{24}(p^\sigma p^\tau\eta^{\mu\rho}\eta^{\nu\lambda}\eta^{\iota\kappa})+\tfrac{1}{4}P_{12}(p^\rho p'^\lambda\eta^{\mu\sigma}\eta^{\nu\tau}\eta^{\iota\kappa})+\tfrac{1}{2}P_{24}(p^\sigma p'^\rho\eta^{\tau\mu}\eta^{\nu\lambda}\eta^{\iota\kappa})$$
$$-\tfrac{1}{2}P_{12}(p\cdot p'\eta^{\nu\sigma}\eta^{\tau\rho}\eta^{\lambda\mu}\eta^{\iota\kappa})-\tfrac{1}{2}P_{12}(p^\sigma p'^\mu\eta^{\tau\rho}\eta^{\lambda\nu}\eta^{\iota\kappa})+\tfrac{1}{2}P_{12}(p^\sigma p^\rho\eta^{\tau\lambda}\eta^{\mu\nu}\eta^{\iota\kappa})-\tfrac{1}{2}P_{24}(p\cdot p'\eta^{\mu\nu}\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\sigma})$$
$$-P_{12}(p^\sigma p^\tau\eta^{\nu\rho}\eta^{\lambda\iota}\eta^{\kappa\mu})-P_{12}(p^\rho p'^\lambda\eta^{\nu\iota}\eta^{\kappa\sigma}\eta^{\tau\mu})-P_{24}(p_\sigma p'^\rho\eta^{\tau\iota}\eta^{\kappa\mu}\eta^{\nu\lambda})-P_{12}(p^\rho p'^\iota\eta^{\lambda\sigma}\eta^{\tau\mu}\eta^{\nu\kappa})$$
$$+P_6(p\cdot p'\eta^{\nu\rho}\eta^{\lambda\sigma}\eta^{\tau\iota}\eta^{\kappa\mu})-P_{12}(p^\sigma p^\rho\eta^{\mu\nu}\eta^{\tau\iota}\eta^{\kappa\lambda})-\tfrac{1}{2}P_{12}(p\cdot p'\eta^{\mu\rho}\eta^{\nu\lambda}\eta^{\sigma\iota}\eta^{\tau\kappa})-P_{12}(p^\sigma p^\rho\eta^{\tau\lambda}\eta^{\mu\iota}\eta^{\nu\kappa})$$
$$-P_6(p^\rho p'^\iota\eta^{\lambda\kappa}\eta^{\mu\sigma}\eta^{\nu\tau})-P_{24}(p^\sigma p'^\rho\eta^{\tau\mu}\eta^{\nu\iota}\eta^{\kappa\lambda})-P_{12}(p^\sigma p'^\mu\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\nu})+2P_6(p\cdot p'\eta^{\nu\sigma}\eta^{\tau\rho}\eta^{\lambda\iota}\eta^{\kappa\mu})]$$

$$\mathcal{A}(1^-2^+3^-4^+) \propto \frac{1}{stu}$$

graviton + graviton → graviton + graviton

On-shell amplitude methods



± ☞ h =±2

1) ~~Define your fields ($h_{\mu\nu}$)~~

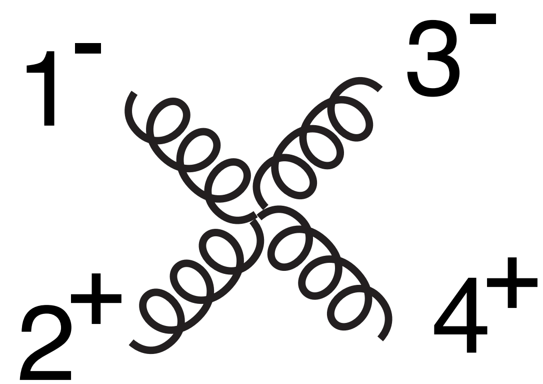
2) ~~Get the Lagrangian (GR)~~

3) ~~Get the Feynman rules~~

4) Obtain the amplitude

graviton + graviton → graviton + graviton

On-shell amplitude methods



± ☞ h =±2

1) ~~Define your fields ($h_{\mu\nu}$)~~

2) ~~Get the Lagrangian (GR)~~

3) ~~Get the Feynman rules~~

4) **Obtain the amplitude**

Demanding:
- Lorentz invariance
- Unitarity & locality:

(single poles & factorization)

Spinor-helicity formalism

Lorentz ⟶ SL(2,C)

p^μ ⟶ $p_{\alpha\dot{\alpha}} = |p\rangle_\alpha [p|_{\dot{\alpha}}$

(1/2,1/2) =(1/2,0)⊗(0,1/2)

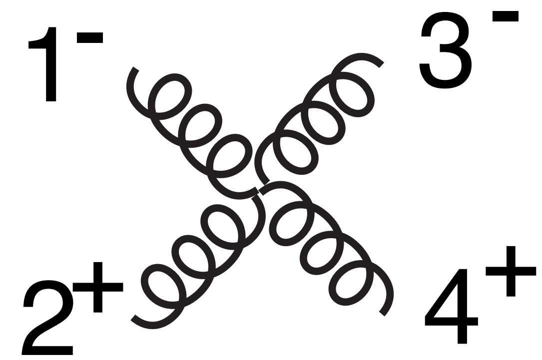
"angle" spinor

"squared" spinor

- **Under Little group** $\begin{cases} |p\rangle_\alpha \to e^{-i\theta/2}|p\rangle_\alpha & \textbf{Helicity -1/2} \\ |p]_{\dot{\alpha}} \to e^{i\theta/2}|p]_{\dot{\alpha}} & \textbf{Helicity +1/2} \end{cases}$

- **Lorentz invariance:** $\langle pq\rangle \equiv \langle p|^\alpha |q\rangle_\alpha$; $[pq] \equiv [p|_{\dot{\alpha}}|q]^{\dot{\alpha}}$

4-graviton amplitude:

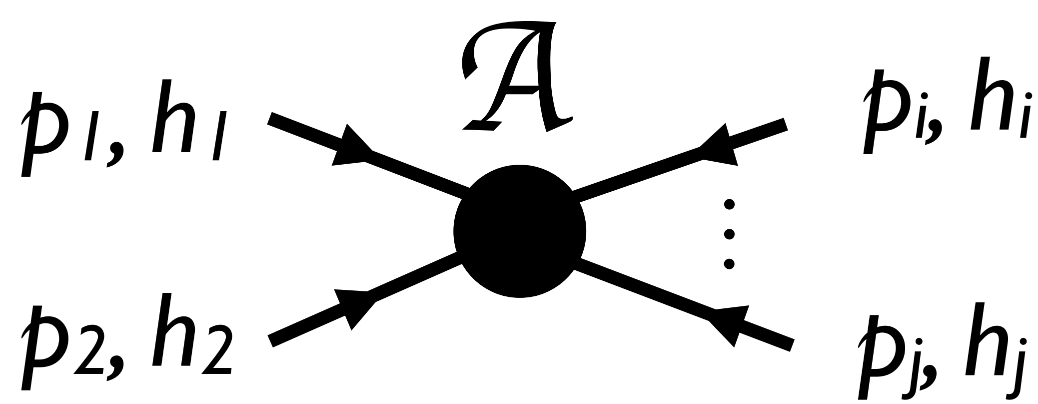


helicities (Little Group)

$$\mathcal{A}(1^-2^+3^-4^+) = \frac{\langle 13\rangle^4[24]^4}{stu} \times G_N$$

dim analysis & single-pole structure

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



Ordinary EFT approach

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

SM → $\mathcal{L}_4$

Ordinary EFT approach

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

SM

One must eliminate redundancies

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

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

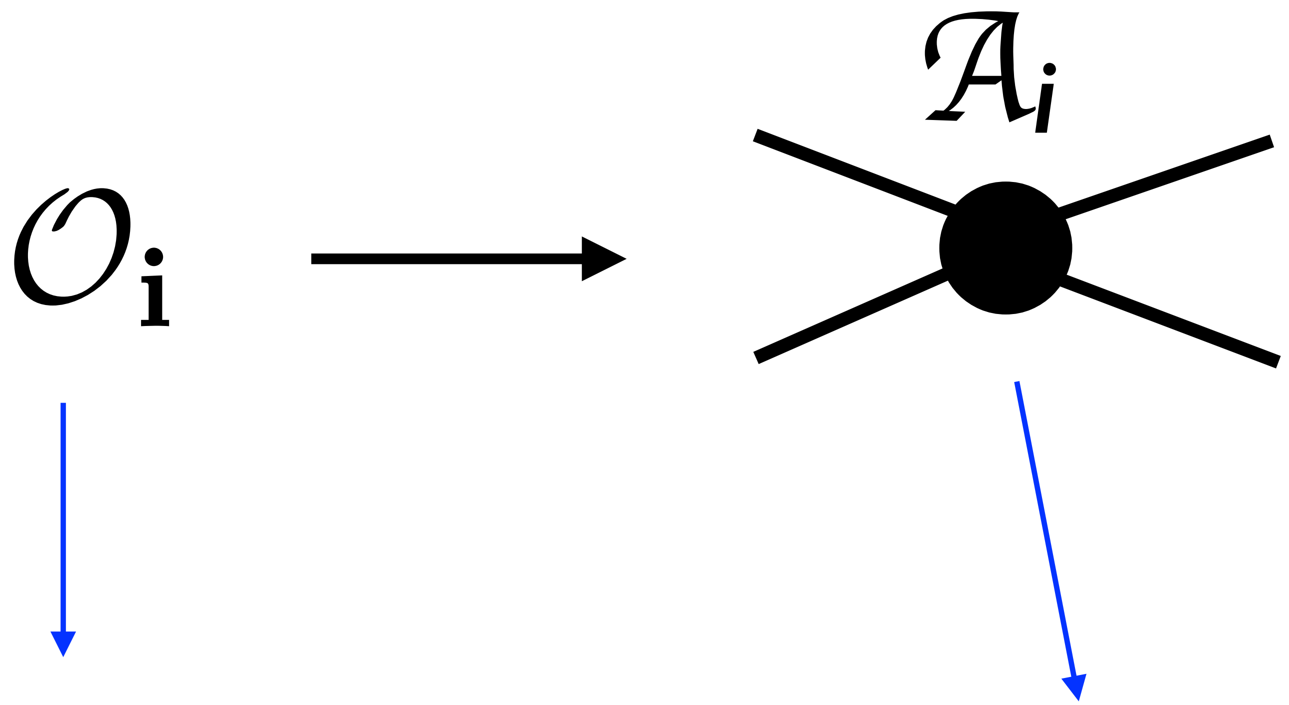
$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$
$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$\mathcal{O}_{3W} = \tfrac{1}{3!} g \epsilon_{abc}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

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

Many missed
in original papers
(Buchmuller,Wyler,…)!

An important gain in simplicity:

the power of being on-shell !



Ghosts, Golstones,…
($p^2 \neq 0$)

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

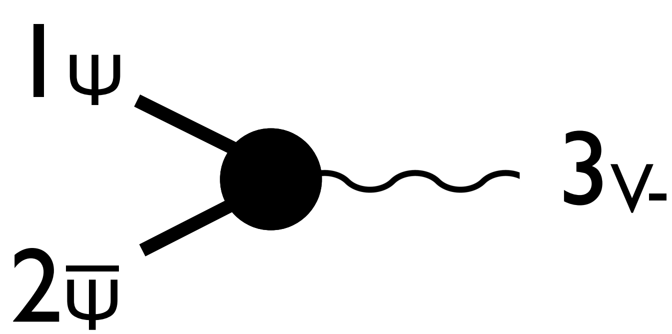
definite helicity
($h = \mp$)

The SM as an EFT

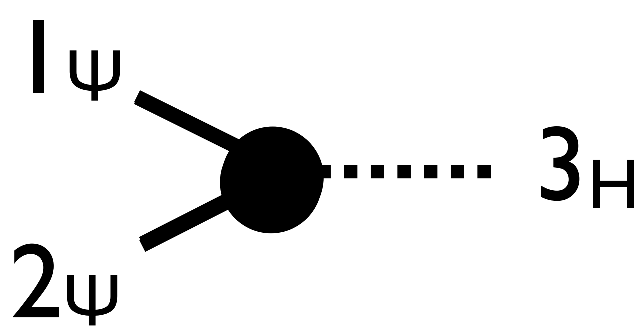
= ***EF**fective **T**heory*

Expansion: $\langle ij\rangle/\Lambda^2$, $[ij]/\Lambda^2$

SM "Building-blocks":



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



$$= \langle 12\rangle$$

...

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

At O(E²/Λ²):

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

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

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

n=4
h=0

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

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

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

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

$$\mathcal{A}_{\psi^4}(1_\psi, 2_\psi, 3_\psi, 4_\psi) = \left(C_{\psi^4}\langle 12\rangle\langle 34\rangle + C'_{\psi^4}\langle 13\rangle\langle 24\rangle\right)\frac{1}{\Lambda^2}$$

$$\mathcal{A}_{\Box\phi^4}(1_\phi, 2_\phi, 3_\phi, 4_\phi) = \left(C_{\Box\phi^4}\langle 12\rangle[12] + C'_{\Box\phi^4}\langle 13\rangle[13]\right)\frac{1}{\Lambda^2}$$

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

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

} 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

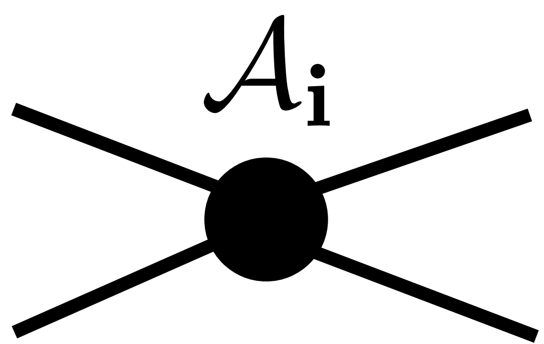
$$\mathcal{A}_{\phi^6}(1_\phi, 2_\phi, 3_\phi, 4_\phi, 5_\phi, 6_\phi) = \frac{C_{\phi^6}}{\Lambda^2}$$

n=6
h=0

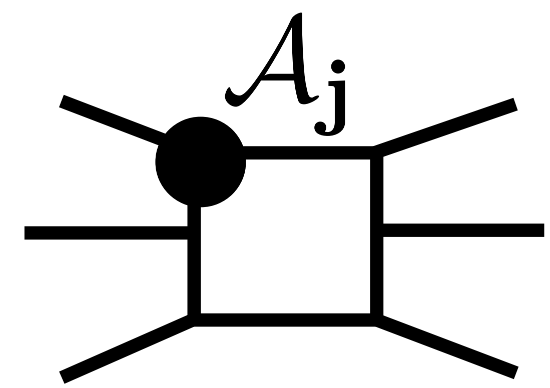
III. EFT renormalization via amplitude methods

One-loop mixing

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



+



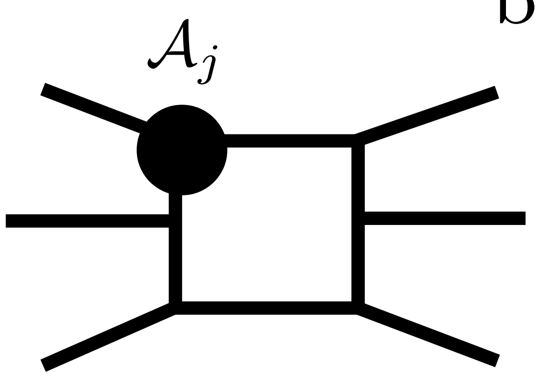
Of great importance:

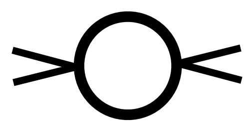
In particular, the **RG-running** of the (Wilson) coefficients of the amplitudes (the anomalous dimensions) needed for making contact with low-energy experiments

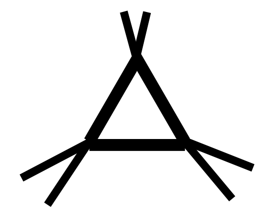
e.g. for muon g-2, they must "run" down to E~m_μ

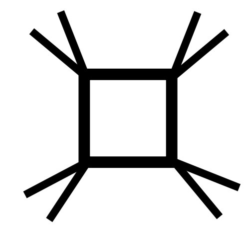
After one-loop reduction to Passarino-Veltman integrals

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





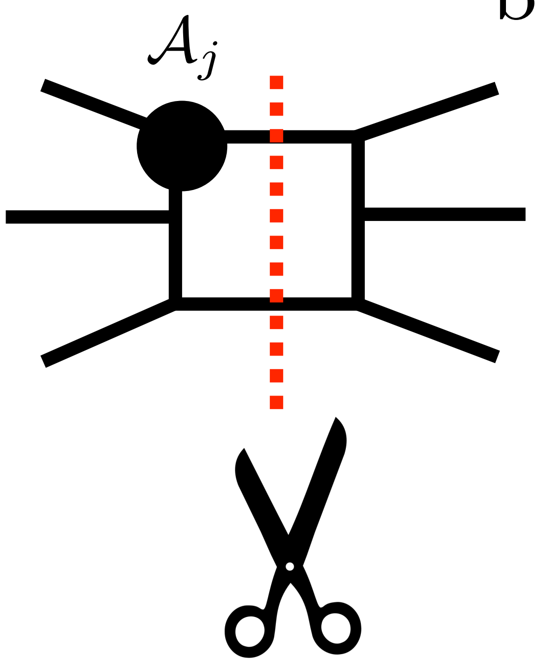


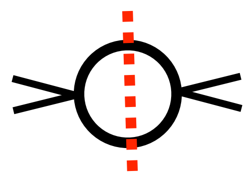


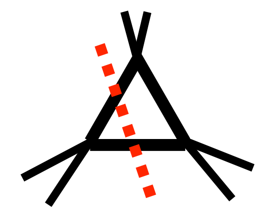
divergent ☞ c_2 = anomalous dimensions

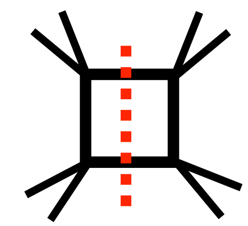
After one-loop reduction to Passarino-Veltman integrals

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







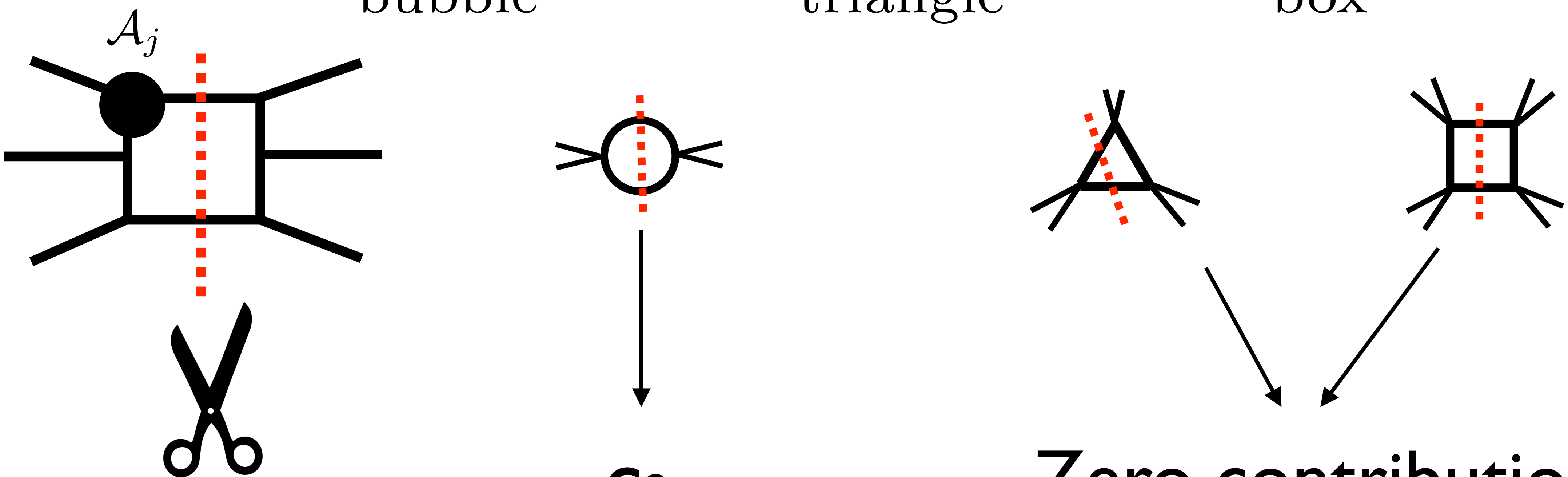


double cut

(internal particles on-shell)

After one-loop reduction to Passarino-Veltman integrals

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



double cut

(internal particles on-shell)

c_2

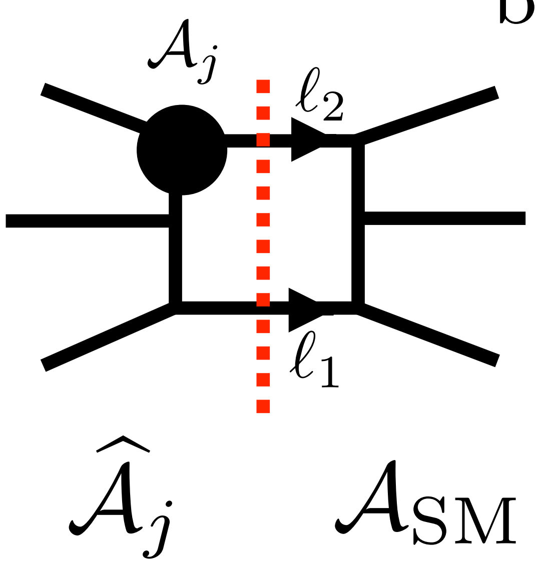
Zero contribution

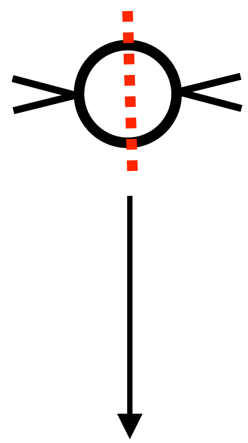
(after extracting IR-div)

P. Baratella, C. Fernandez, AP 2005.07129

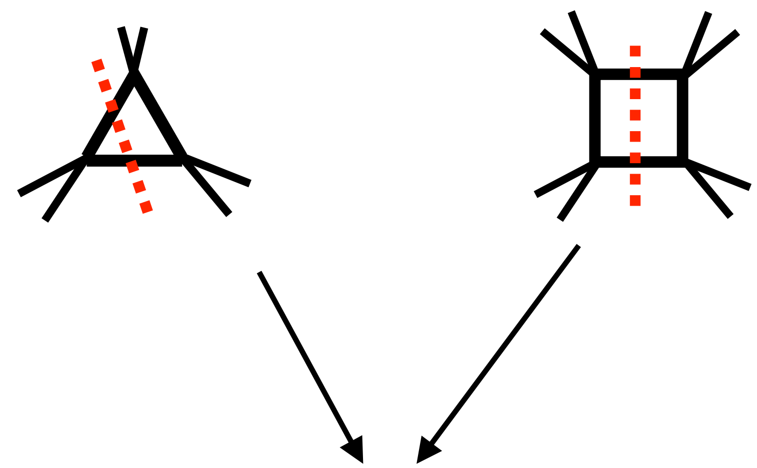
After one-loop reduction to Passarino-Veltman integrals

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





c_2



Zero contribution

(after extracting IR-div)

P. Baratella, C. Fernandez, AP 2005.07129

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

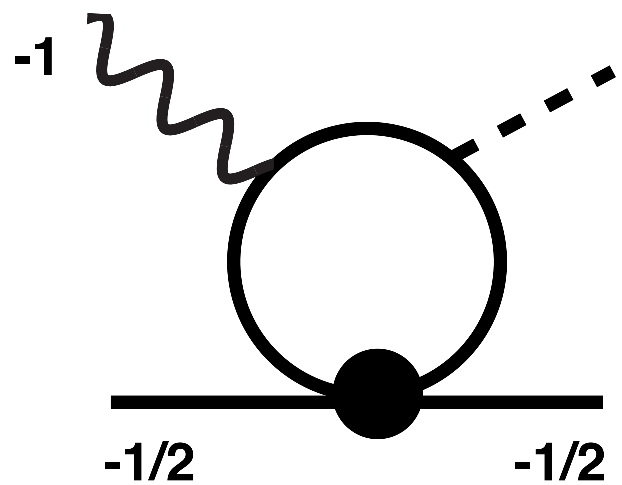
phase-space integration & sum over internal states

“Emergent” selection rules

1505.01844 (also by susy techniques:1412.7151)

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

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



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

"Emergent" selection rules

1505.01844 (also by susy techniques:1412.7151)

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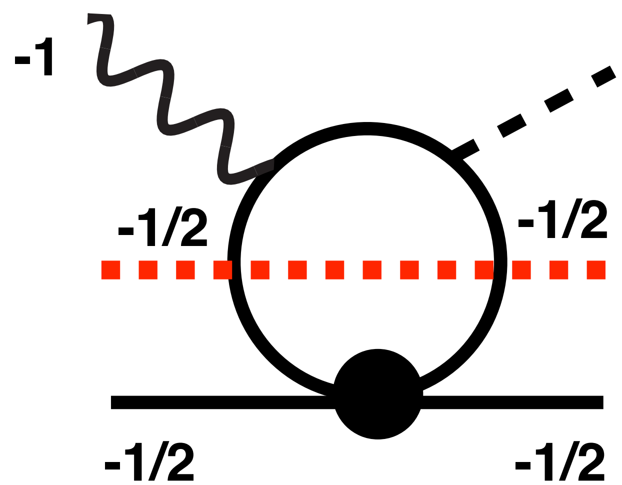

$$F^{\mu\nu}\bar{\psi}\sigma_{\mu\nu}\psi\, H$$

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

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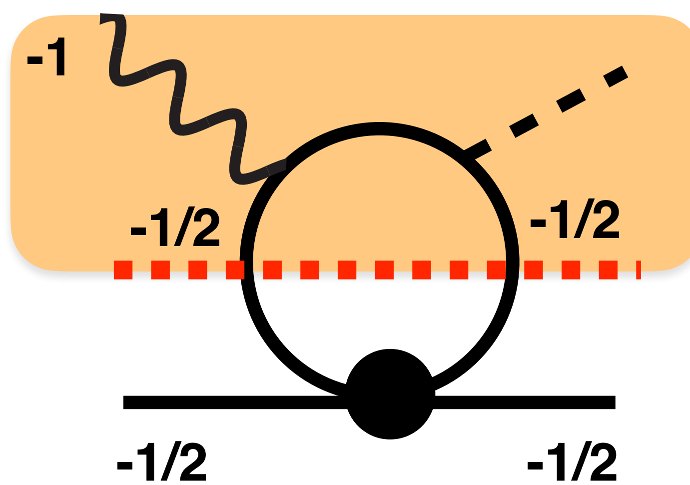

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Absent in the SM

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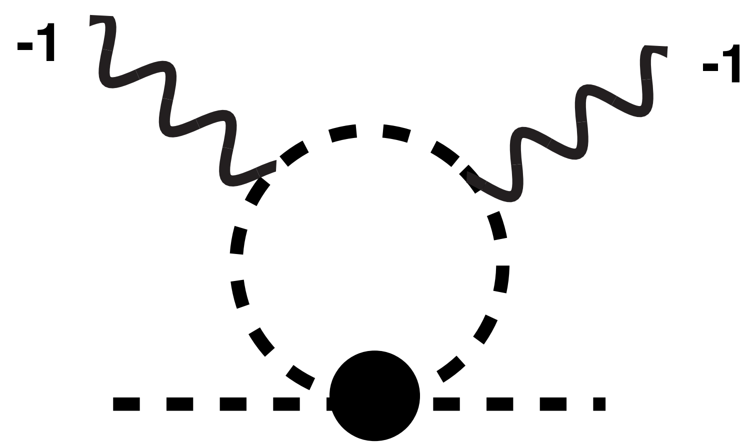
No p^2H^4 corrections to $H\gamma\gamma$

e.g.

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



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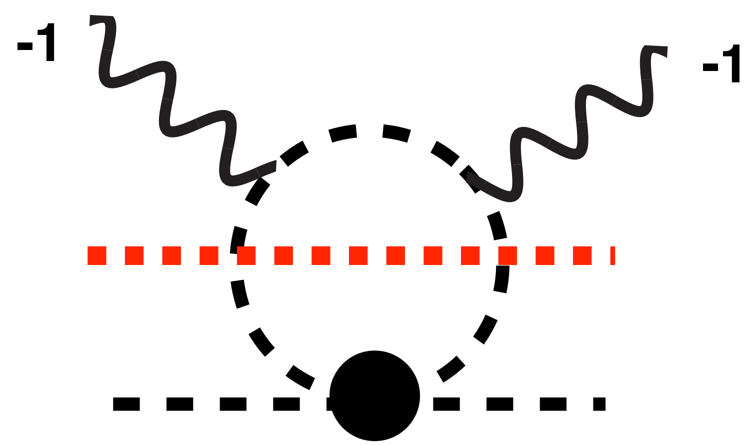

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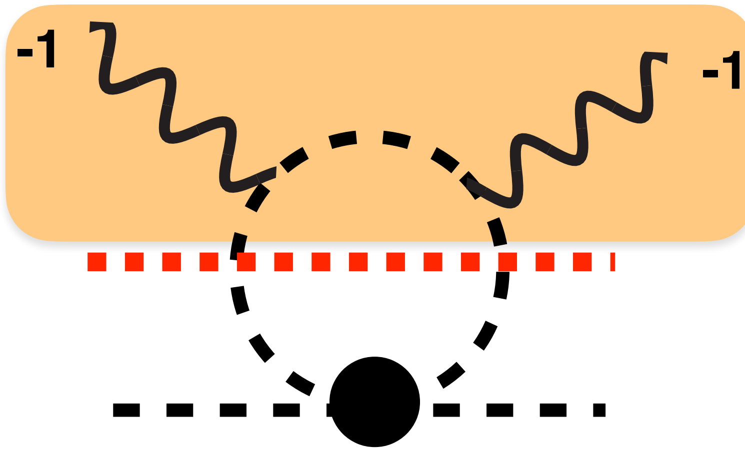

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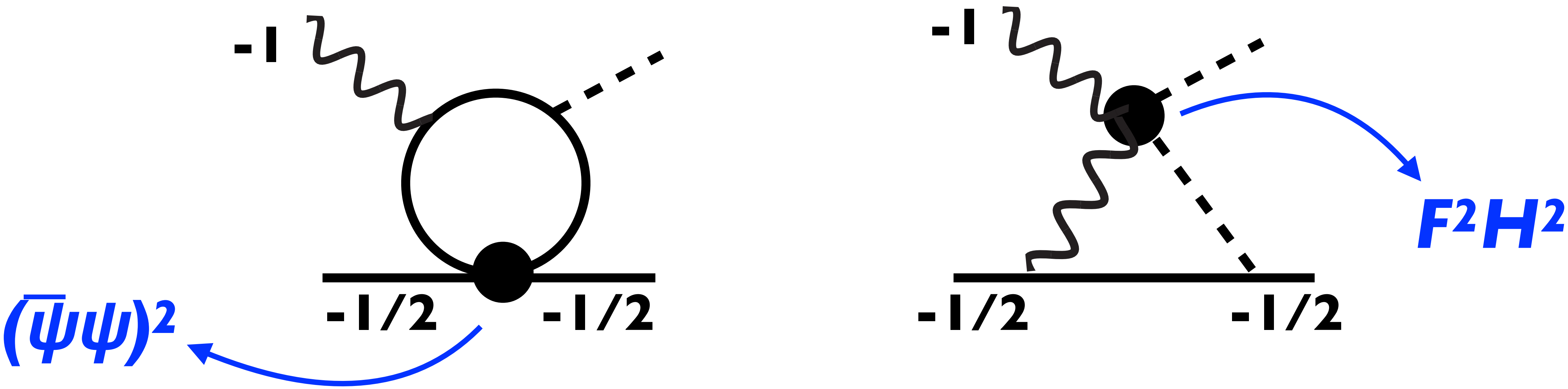
Absent in the SM

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

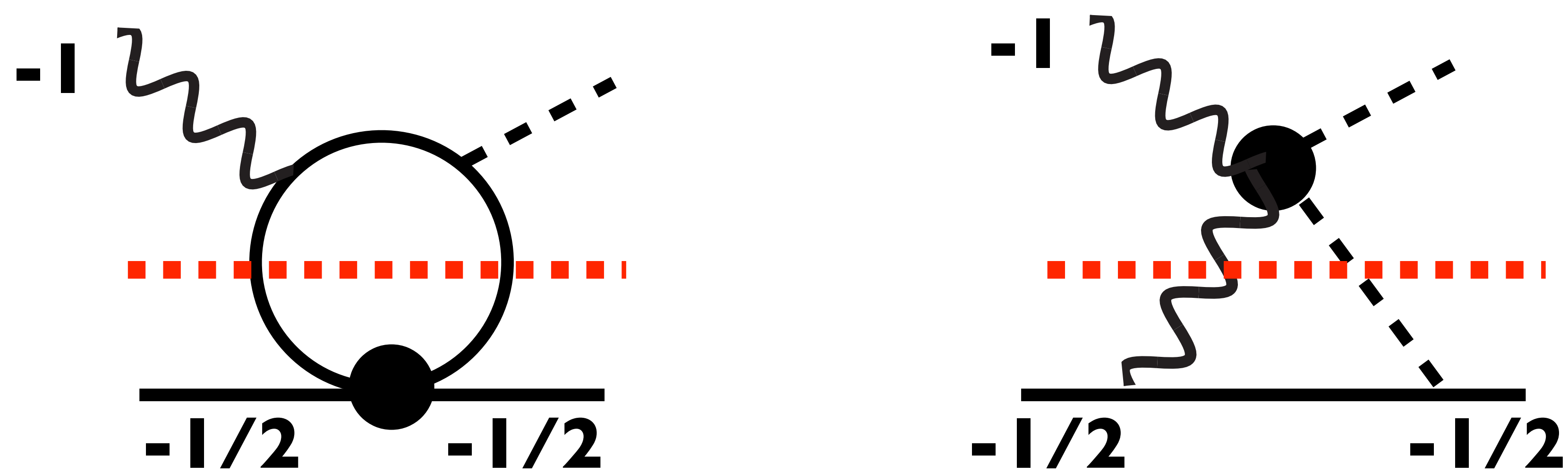
Contributions to **dipoles** from **Feynman** approach:



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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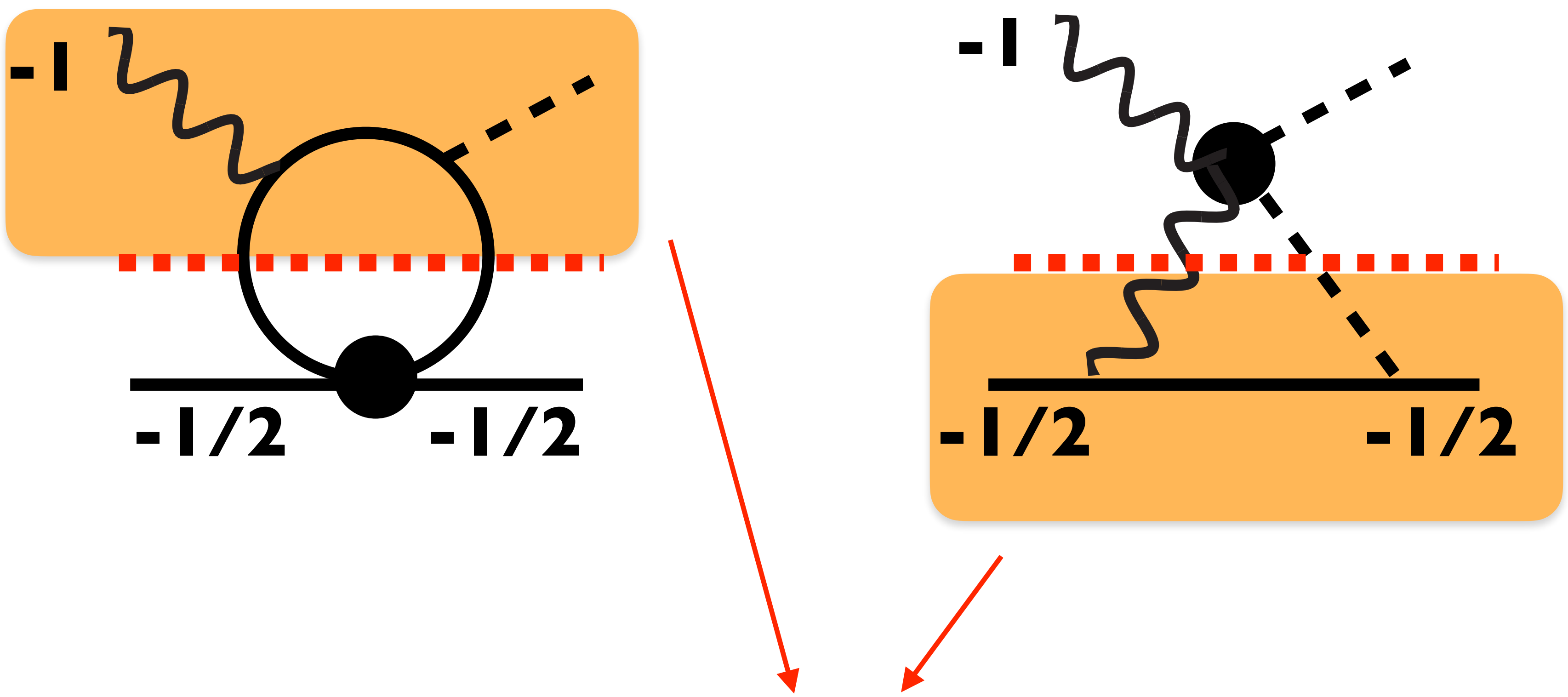

$$\mathcal{A}_{\rm SM}(1_{\bar{\psi}}, 2_{\bar{\psi}}, 3_{V_-}, 4_{H^\dagger})$$

from the same SM amplitude!

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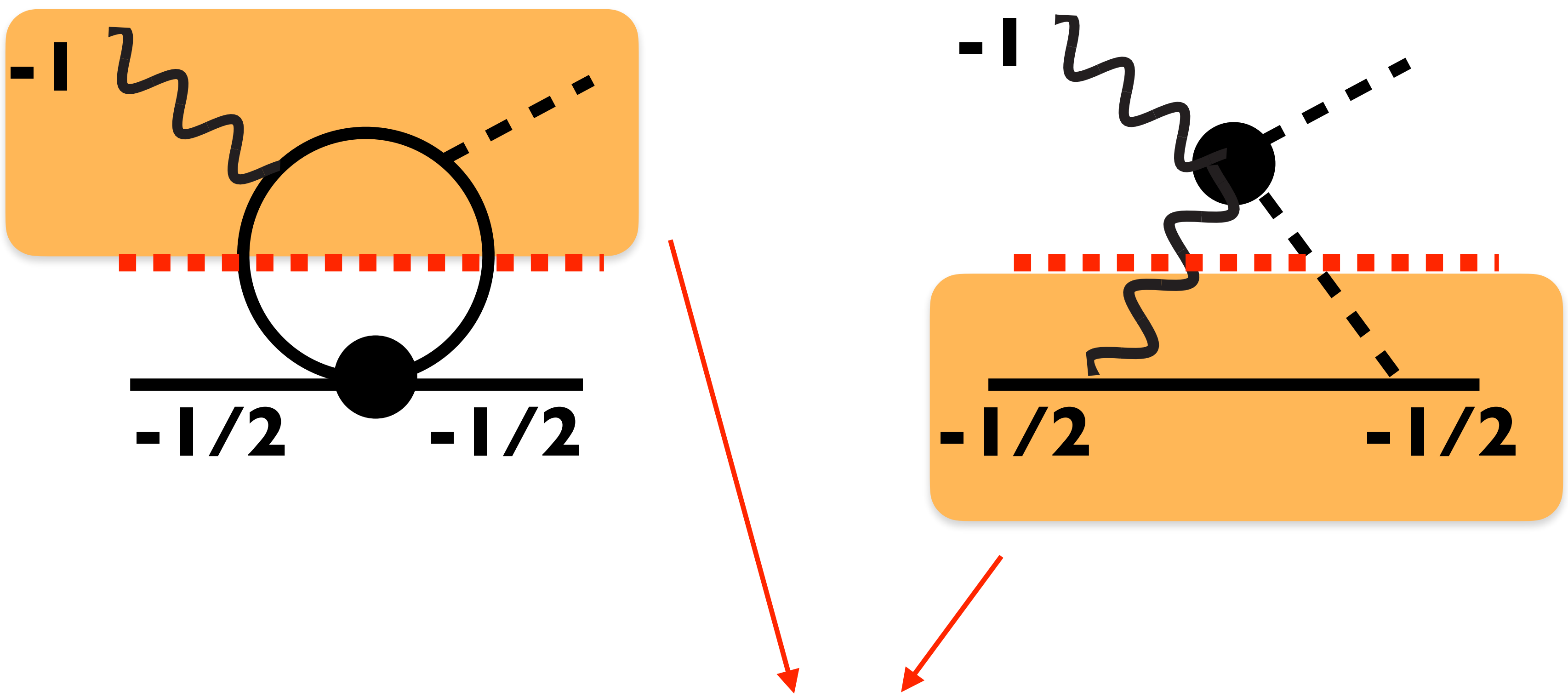


No calculation wasted in the on-shell method

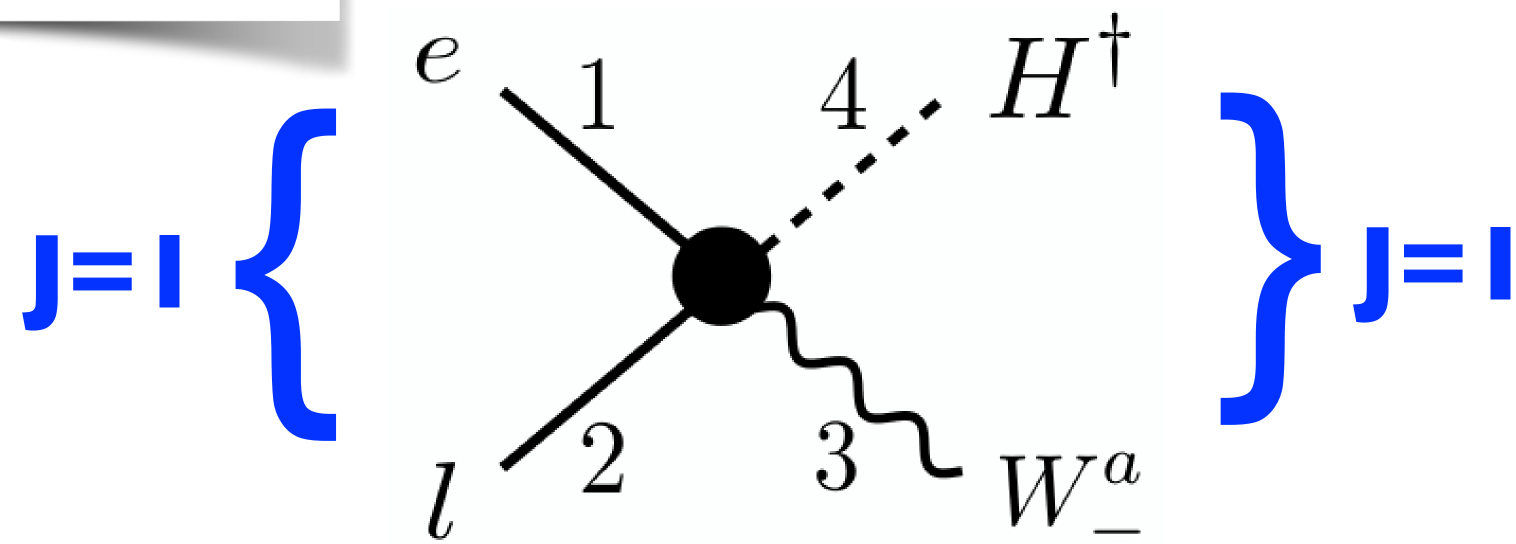
$$\mathcal{A}_{\mathrm{SM}}(1_{\bar{\psi}}, 2_{\bar{\psi}}, 3_{V_-}, 4_{H^\dagger})$$

from the same SM amplitude!

But there is more to say by

angular-momentum decomposition (partial-waves)

Example of dipoles:

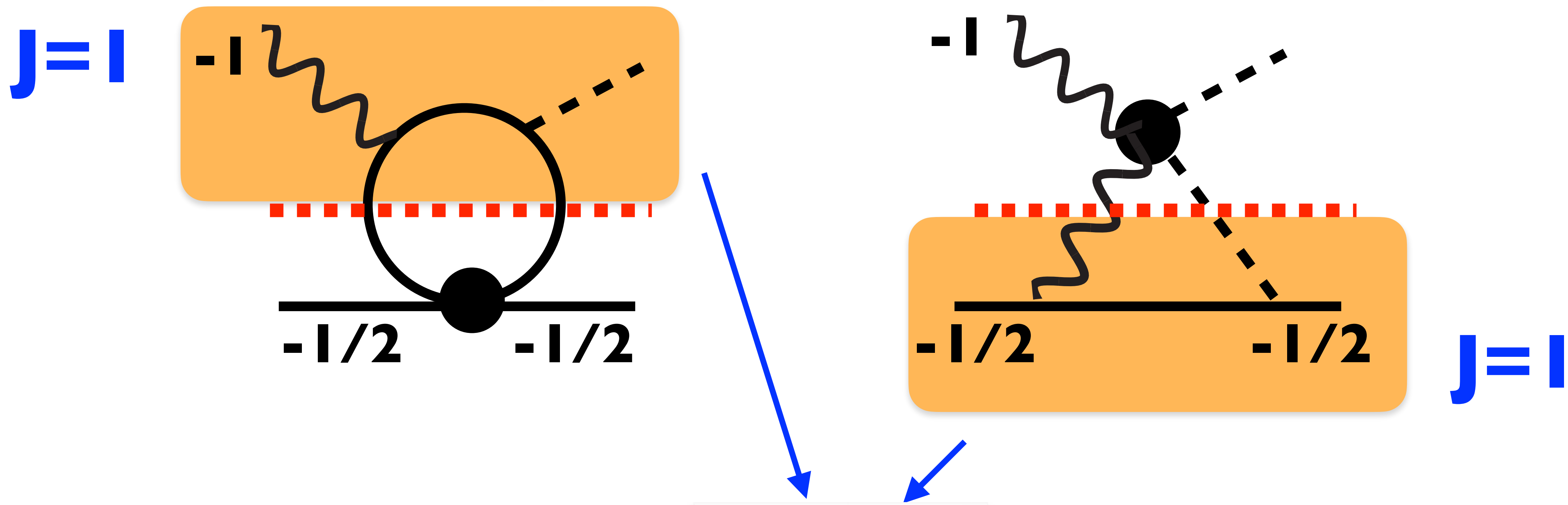


$$\mathcal{A}(1_e, 2_l, 3_{W_-}, 4_{H^\dagger}) = 3e^{-i\phi} d^{J=1}_{01}(\theta)\, a^{J=1}$$

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: $a_{\rm SM}^{J=1}$

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

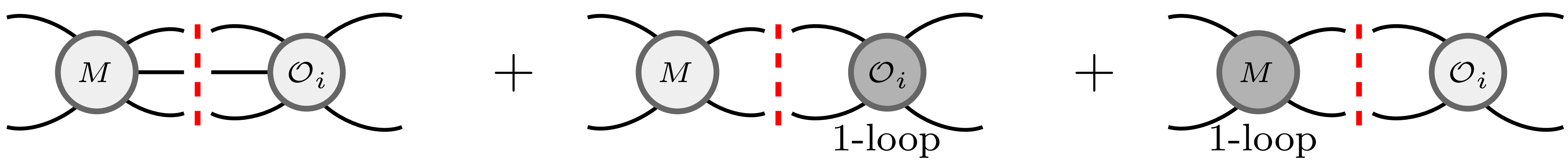
$$\gamma_i \sim a^J_{\rm SM} a^J_{\rm BSM}$$

→ $1/\Lambda^2$ amplitude

Beyond one-loop

2005.06983
2005.12917
2112.12131

Two-loop:

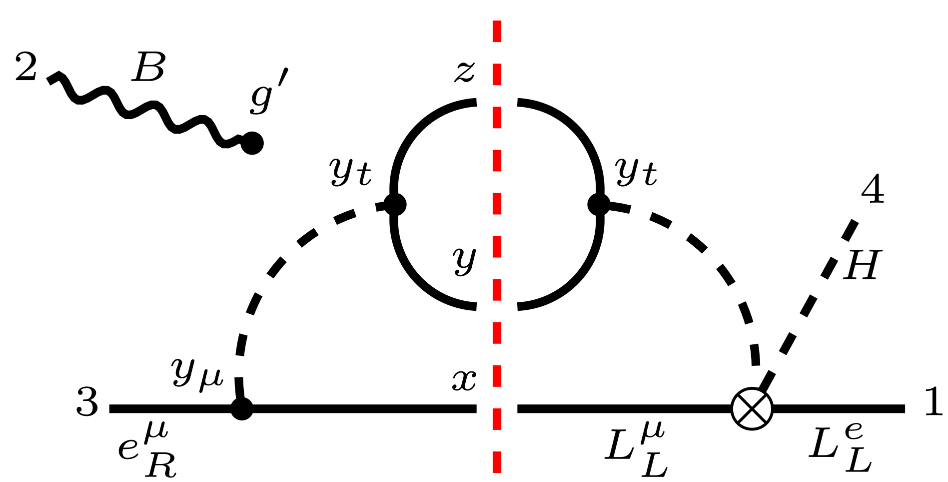


Two-loops for μ→eγ

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

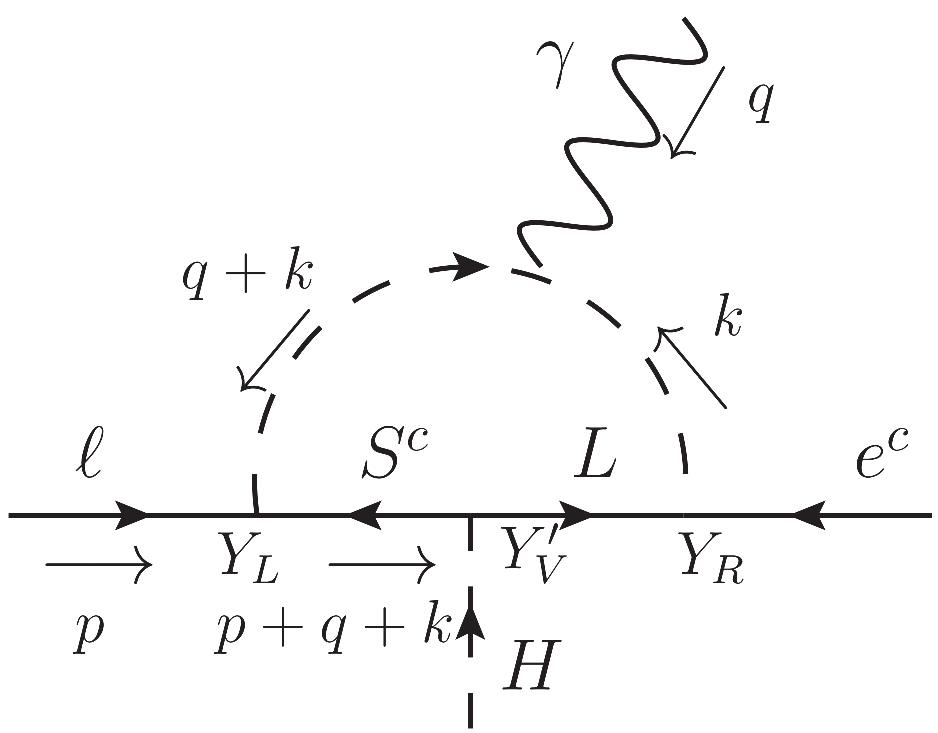
Finite terms?

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**:



~ $O(1/M^4)$

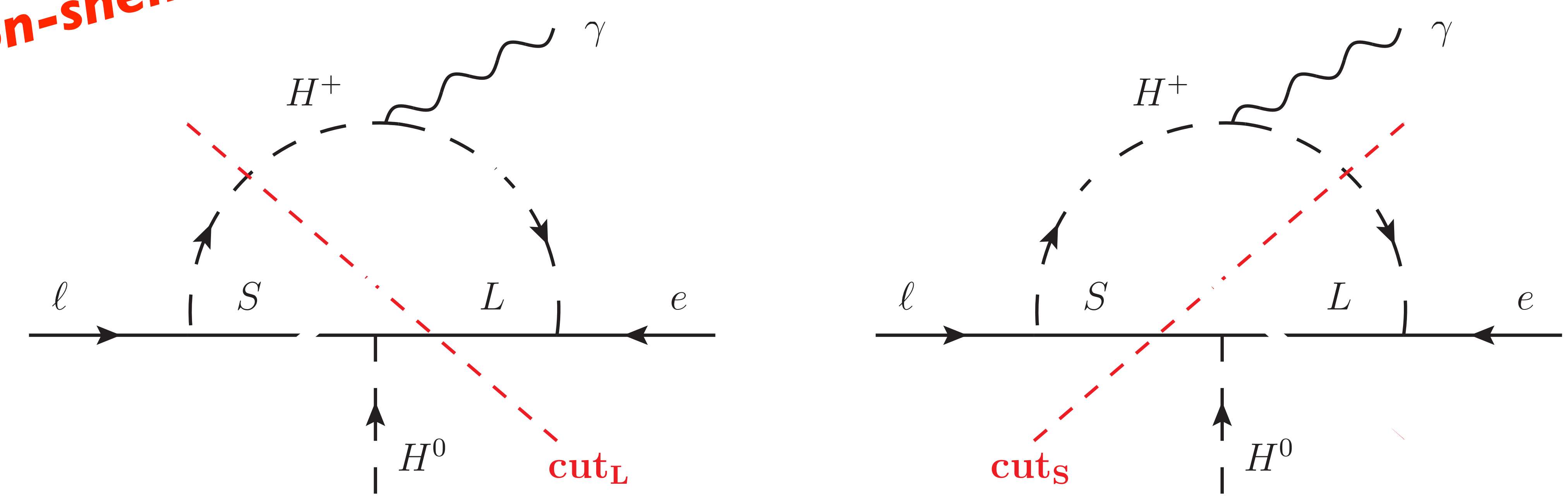
N. Arkani-Hamed, K. Harigaya 2106.01373

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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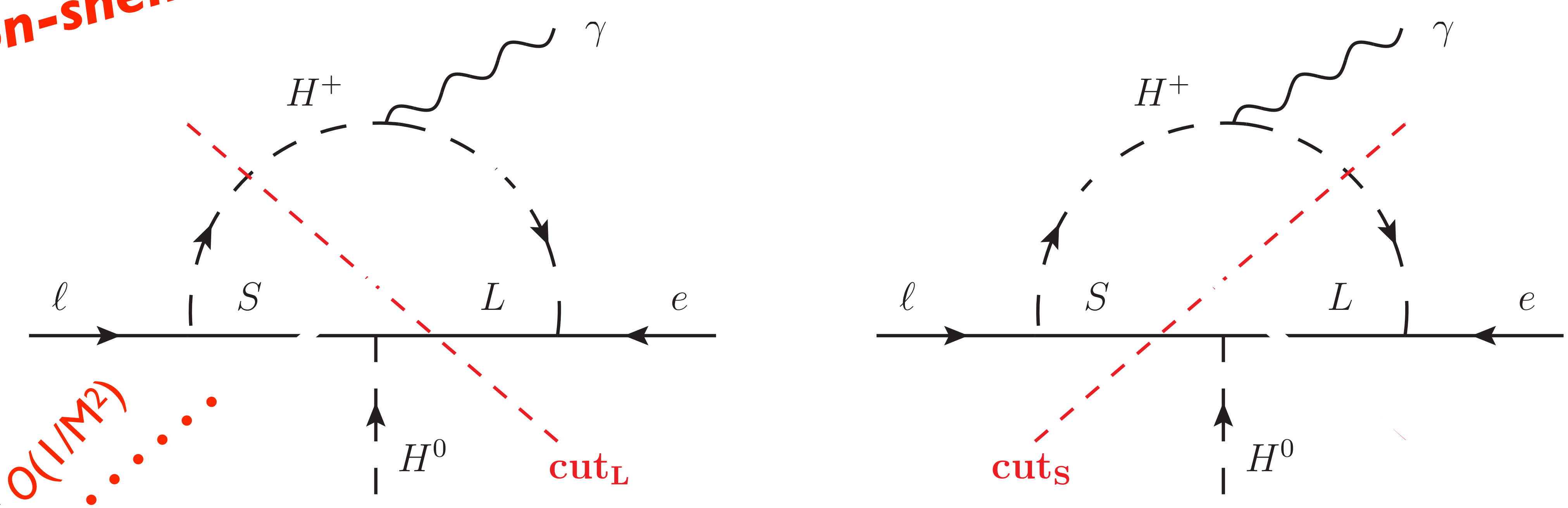

amplitude at O(1/M²)

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

even under S↔L

odd under S↔L

Finite terms to g-2

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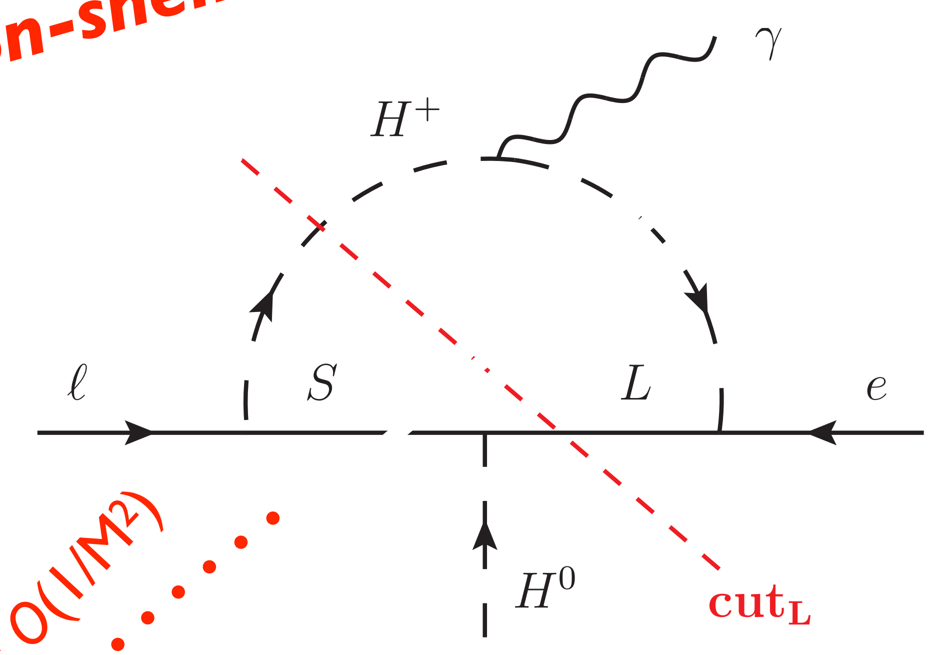
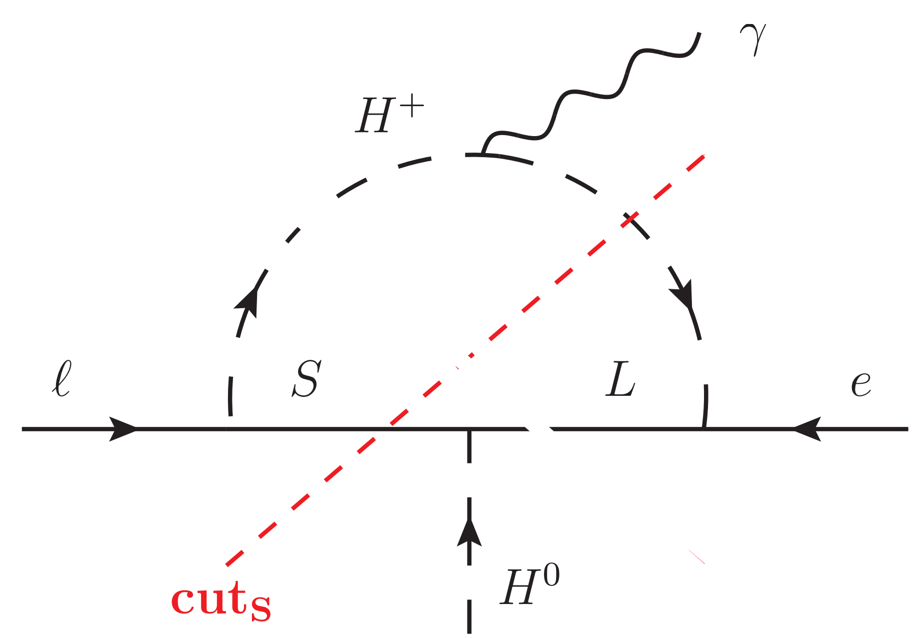




amplitude at $O(1/M^2)$

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

even under S↔L

odd under S↔L

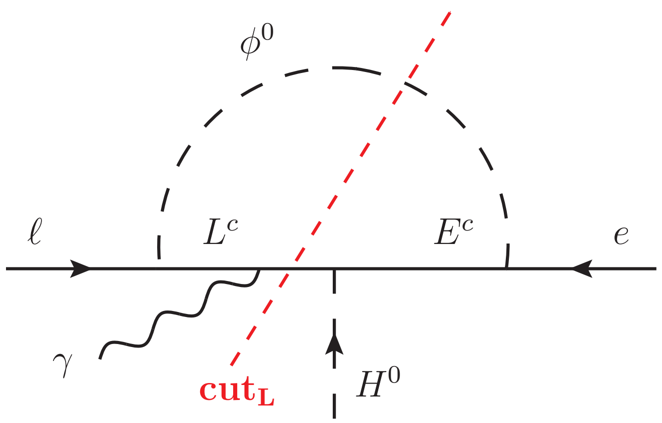
} ☞ **zero**

Finite terms to g-2

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

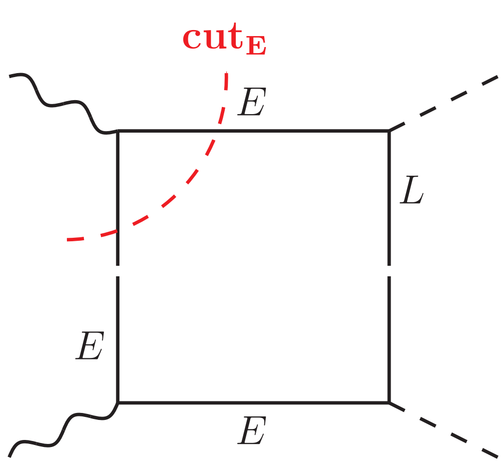
Following the same argument, more zeros can be found:

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



+ (L↔E) ☞ **zero**

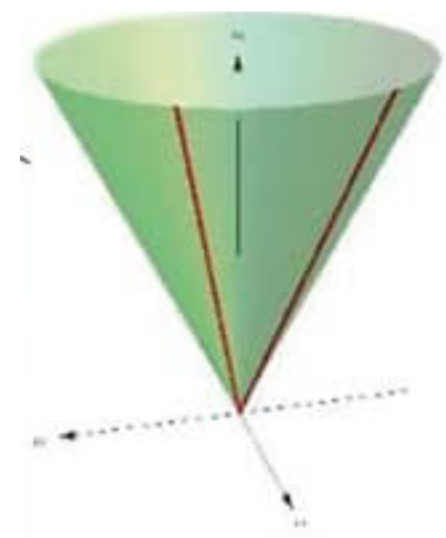
- **Beyond g-2: Zeros in hγγ**



+ (L↔E) ☞ **zero**

Conclusions

Get 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**

where Feynman approach is quite obscure

A lot to do! Stay Tuned!