NATIONAL CENTRE FOR SCIENTIFIC RESEARCH "DEMOKRITOS"
INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS

H.F.R.I.
Hellenic Foundation for Research & Innovation

Activities of the HEP-TH group

Giuseppe Bevilacqua
NCSR "Demokritos"

INPP Annual Meeting 2025

April 9, 2025

Based on work in collaboration with:
D. Canko, N. Dokmetzoglou, C. Papadopoulos, M. Reinartz, A. Spourdalakis, M. Worek

Outlook

- Activity 1: Two-loop amplitude reduction
  - Costas Papadopoulos
  - Giuseppe Bevilacqua
  - Aris Spourdalakis
  - Dhimiter Canko
  - Nikos Dokmetzoglou

  NCSR-D

  Eötvös Lorand University, Budapest

  University of Bologna

- Activity 2: Towards SMEFT phenomenology with HELAC
  - Giuseppe Bevilacqua
  - Malgorzata Worek
  - Minos Reinartz

  NCSR-D

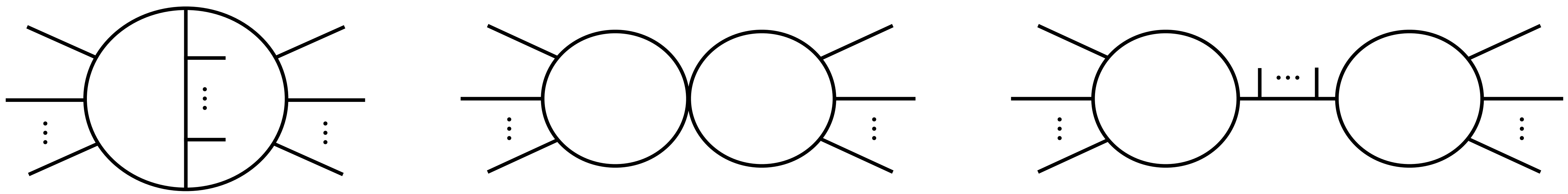
  RWTH Aachen University

Other theory activities → talks by Georgios Savvidis and Stam Nicolis

Part 1.

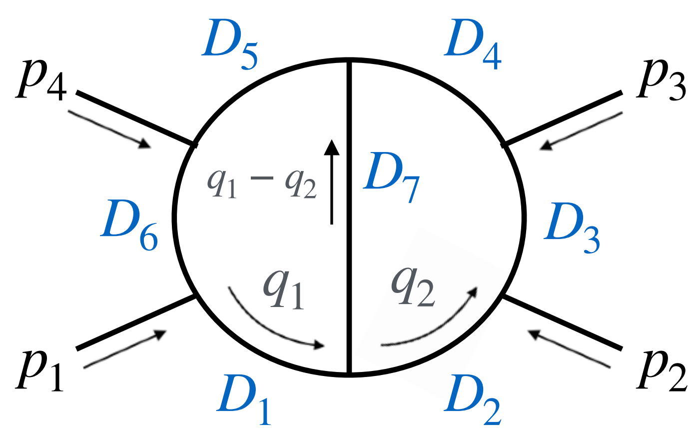
Two-loop amplitude reduction

C. Papadopoulos, G. Bevilacqua, A. Spourdalakis, D. Canko, N. Dokmetzoglou



- **2-loop amplitudes are crucial ingredients (and often bottlenecks) for theory predictions accurate at NNLO**

example: 4-point function



$$A_{2L} = \int d^d\bar{q}_1\, d^d\bar{q}_2 \,\frac{N(\bar{q}_1, \bar{q}_2, \{p\})}{\prod_{i=1}^{7} D_i(\bar{q}_1, \bar{q}_2, \{p\})}$$

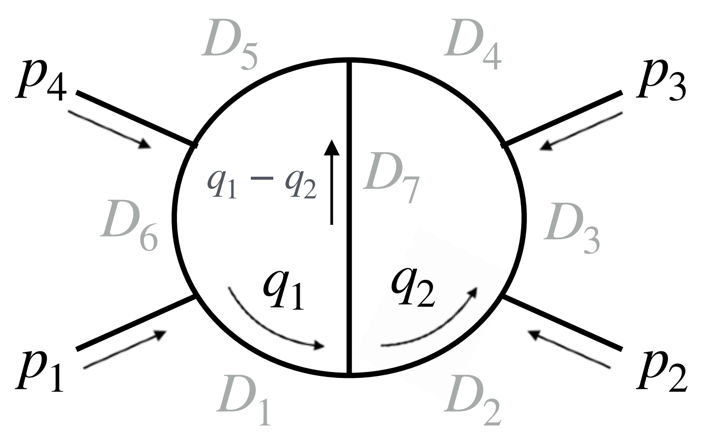
"Propagators"

$$
\begin{aligned}
D_1 &= \bar{q}_1^{\,2} \\
D_2 &= \bar{q}_2^{\,2} \\
D_3 &= (\bar{q}_2 + p_2)^2 \\
D_4 &= (\bar{q}_2 + p_2 + p_3)^2 \\
D_5 &= (\bar{q}_1 + p_2 + p_3)^2 \\
D_6 &= (\bar{q}_1 + p_2 + p_3 + p_4)^2 \\
D_7 &= (\bar{q}_1 - \bar{q}_2)^2
\end{aligned}
$$

Anatomy of 2-loop amplitudes

- 2-loop amplitudes are crucial ingredients (and often bottlenecks) for theory predictions accurate at NNLO

example: 4-point function



Numerator

$$A_{2L} = \int d^d\bar{q}_1\, d^d\bar{q}_2 \frac{N(\bar{q}_1, \bar{q}_2, \{p\})}{\prod_{i=1}^{7} D_i(\bar{q}_1, \bar{q}_2, \{p\})}$$

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D_7 &= (\bar{q}_1 - \bar{q}_2)^2
\end{aligned}$$

The Numerator is a function of few constituents (Lorentz scalars):

$$(\bar{q}_i \cdot \bar{q}_j)\ ,\ (\bar{q}_i \cdot p_j)\ ,\ (p_i \cdot p_j)\ ,\ (\bar{q}_i \cdot \eta)$$

$\rightarrow (\eta \cdot p_j) \equiv 0$

[transverse vector]

2-loop reduction: a toy example

$$N(\bar{q}_1, \bar{q}_2, \{p\}) \equiv (\bar{q}_1 \cdot \bar{q}_2)(p_2 \cdot p_3) + (\bar{q}_2 \cdot p_4)(p_1 \cdot p_2)$$

$$A_{2L} = \int d^d\bar{q}_1\, d^d\bar{q}_2 \frac{N(\bar{q}_1, \bar{q}_2, \{p\})}{\prod_{i=1}^{7} D_i(\bar{q}_1, \bar{q}_2, \{p\})}$$

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$$N(\bar{q}_1, \bar{q}_2, \{p\}) \equiv (\bar{q}_1 \cdot \bar{q}_2)(p_2 \cdot p_3) + (\bar{q}_2 \cdot p_4)(p_1 \cdot p_2)$$

$$= -\frac{1}{2}(D_7 - D_1 - D_2)(p_2 \cdot p_3) + (\bar{q}_2 \cdot p_4)(p_1 \cdot p_2)$$

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D_1 &= \bar{q}_1{}^2 \\
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\end{aligned}$$

- Part of the above scalars can be *reduced* in terms of the D_i's appearing in the Denominator: *Reducible Scalar Products* (RSP)

2-loop reduction: a toy example

$$A_{2L} = \int d^d\bar{q}_1\, d^d\bar{q}_2 \frac{N(\bar{q}_1, \bar{q}_2, \{p\})}{\prod_{i=1}^{7} D_i(\bar{q}_1, \bar{q}_2, \{p\})}$$

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- Part of the above scalars can be *reduced* in terms of the D_i's appearing in the Denominator: *Reducible Scalar Products* (RSP)
- The subset of scalars that cannot be decomposed this way are *Irreducible Scalar Products* (ISP)

2-loop reduction: a toy example

$$A_{2L} = \int d^d\bar{q}_1\, d^d\bar{q}_2 \, \frac{N(\bar{q}_1, \bar{q}_2, \{p\})}{\prod_{i=1}^{7} D_i(\bar{q}_1, \bar{q}_2, \{p\})}$$

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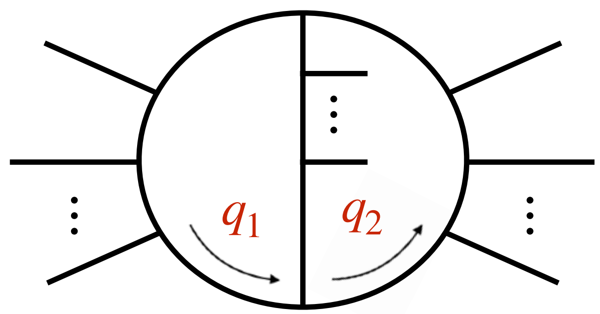
D_7 &= (\bar{q}_1 - \bar{q}_2)^2
\end{aligned}$$

$$A_{2L} = \int d\bar{q}_1\, d\bar{q}_2 \left\{ \frac{-(p_2 \cdot p_3)/2}{D_1 D_2 D_3 D_4 D_5 D_6} + \frac{(p_2 \cdot p_3)/2}{D_2 D_3 D_4 D_5 D_6 D_7} + \frac{(p_2 \cdot p_3)/2}{D_1 D_3 D_4 D_5 D_6 D_7} + \frac{(\bar{q}_2 \cdot p_4)(p_1 \cdot p_2)}{D_1 D_2 D_3 D_4 D_5 D_6 D_7} \right\}$$

- Part of the above scalars can be *reduced* in terms of the D_i's appearing in the Denominator: *Reducible Scalar Products* (RSP)
- The subset of scalars that cannot be decomposed this way are *Irreducible Scalar Products* (ISP)
- After reduction, the 2-loop amplitude is a combination of *simpler* Feynman integrals

- A generic 2-loop amplitude can be *reduced* in the following form:



$$\mathcal{A}_{2L} = \sum_i a_i F_i$$

coefficients (a_i) — Feynman integrals (F_i)

- If we know how to:
  - determine the coefficients, → [Task n.1]
  - decompose all Feynman integrals into *Master Integrals* (using IBP), → [Task n.2]

  then we know how to compute $\mathcal{A}_{2L}$.

- We are working to establish a *method* which allows to perform the above tasks in *automated* form and for *arbitrary* processes

Currently focusing on Task n.1: extracting coefficients at *integrand* level

Parametrising the Numerator

- The first step is to build a general parametrisation of the Numerator:

$$N(\bar{q}_1, \bar{q}_2, \{p\}) = P^{(m)} + \sum_i P_i^{(m-1)} D_i + \sum_{i<j} P_{ij}^{(m-2)} D_i D_j + \sum_{i<j<k} P_{ij}^{(m-3)} D_i D_j D_k + \cdots$$

- The $P^{(x)}$'s are *polynomials* built out of the available ISP's :

$$P^{(x)} = \sum_k c_k M_k(\bar{q}_1, \bar{q}_2, \{p\}) \quad \rightarrow \quad \text{e.g.: } M_k = (\bar{q}_1 \cdot p_2)(\bar{q}_2 \cdot p_4)^3$$

- The c_k - that we want to extract - are functions of external momenta only:

$$c_k = c_k(\{p\})$$

- We need an *ansatz* to characterise the polynomials:
  - How many terms ?
  - Analytic structure of each term ?
  - Maximal power ? [→ can be deduced from loop integral's *rank*]

Extracting coefficients

$$N(\bar{q}_1, \bar{q}_2, \{p\}) = P^{(m)} + \sum_i P_i^{(m-1)} D_i + \sum_{i<j} P_{ij}^{(m-2)} D_i D_j + \sum_{i<j<k} P_{ij}^{(m-3)} D_i D_j D_k + \cdots$$

$$P^{(x)} = \sum_k c_k M_k(\bar{q}_1, \bar{q}_2, \{p\})$$

Once the ansatz is established, extract coefficients

- <u>Method n.1</u>: global fit

• given the external kinematics ($\{p\}$), sample $N(\bar{q}_1, \bar{q}_2, \{p\})$ with *random* $\{\bar{q}_1, \bar{q}_2\}$

$$\underbrace{\begin{pmatrix} N_1 \\ \vdots \\ N_m \end{pmatrix} = \begin{pmatrix} M_{11} & \cdots & M_{1m} \\ & \ddots & \\ M_{m1} & \cdots & M_{mm} \end{pmatrix} \begin{pmatrix} c_1 \\ \vdots \\ c_m \end{pmatrix}}_{\text{Linear system}} \quad \leftrightarrow \quad \vec{N} = \mathbf{M} \cdot \vec{c}$$

• all coefficients of $\{P^{(m)}, P_i^{(m-1)}, P_{ij}^{(m-2)}, \ldots\}$ are extracted at the same time

↪ *huge* system of equations! Not the most efficient method, but feasible numerically

Extracting coefficients

$$N(\bar{q}_1, \bar{q}_2, \{p\}) \;=\; P^{(m)} \;+\; \sum_i P_i^{(m-1)} D_i \;+\; \sum_{i<j} P_{ij}^{(m-2)} D_i D_j \;+\; \sum_{i<j<k} P_{ij}^{(m-3)} D_i D_j D_k \;+\; \cdots$$

$$P^{(x)} = \sum_k c_k M_k(\bar{q}_1, \bar{q}_2, \{p\})$$

Once the ansatz is established, extract coefficients

- **Method n.2**: iterative fit

Extracting coefficients

$$N(\bar{q}_1, \bar{q}_2, \{p\}) = P^{(m)} + \sum_i P_i^{(m-1)} D_i + \sum_{i<j} P_{ij}^{(m-2)} D_i D_j + \sum_{i<j<k} P_{ij}^{(m-3)} D_i D_j D_k + \cdots$$

$$P^{(x)} = \sum_k c_k M_k(\bar{q}_1, \bar{q}_2, \{p\})$$

Once the ansatz is established, extract coefficients

- Method n.2: iterative fit

  - Sample N using sets of $\{\bar{q}_1, \bar{q}_2\}$ such that *all* D_k's vanish (→ "*maximal-cut solutions*"); extract coefficients of $P^{(m)}$;

$$N(\bar{q}_1, \bar{q}_2, \{p\}) - P^{(m)} = \sum_i P_i^{(m-1)} D_i + \sum_{i<j} P_{ij}^{(m-2)} D_i D_j + \sum_{i<j<k} P_{ij}^{(m-3)} D_i D_j D_k + \cdots$$

$$P^{(x)} = \sum_k c_k M_k(\bar{q}_1, \bar{q}_2, \{p\})$$

Once the ansatz is established, extract coefficients

- Method n.2: iterative fit

  - Sample N using sets of $\{\bar{q}_1, \bar{q}_2\}$ such that *all* D_k's vanish (→ "*maximal-cut solutions*"); extract coefficients of $P^{(m)}$;
  - Sample $N - P^{(m)}$ using sets of $\{\bar{q}_1, \bar{q}_2\}$ such that *all* D_k's *except* D_i vanish (→ "*next-to-maximal cuts*"); extract coefficients of $P_i^{(m-1)}$;

Extracting coefficients

$$N(\bar{q}_1, \bar{q}_2, \{p\}) - P^{(m)} - \sum_i P_i^{(m-1)} D_i = \sum_{i<j} P_{ij}^{(m-2)} D_i D_j + \sum_{i<j<k} P_{ij}^{(m-3)} D_i D_j D_k + \cdots$$

$$P^{(x)} = \sum_k c_k M_k(\bar{q}_1, \bar{q}_2, \{p\})$$

Once the ansatz is established, extract coefficients

- **Method n.2**: iterative fit

  - Sample N using sets of $\{\bar{q}_1, \bar{q}_2\}$ such that *all* D_k's vanish ($\rightarrow$ "*maximal-cut solutions*"); extract coefficients of $P^{(m)}$;
  - Sample $N - P^{(m)}$ using sets of $\{\bar{q}_1, \bar{q}_2\}$ such that *all* D_k's *except* D_i vanish ($\rightarrow$ "*next-to-maximal cuts*"); extract coefficients of $P_i^{(m-1)}$;

  ⋮

  - Proceed iteratively till all polynomials are reconstructed

↪ Consistency check: original Numerator = ansatz Numerator ($\rightarrow$ "$N = N$ test")

Iterative fit: analytic vs numeric approach

$$N(\bar{q}_1, \bar{q}_2, \{p\}) = P^{(m)} + \sum_i P_i^{(m-1)} D_i + \sum_{i<j} P_{ij}^{(m-2)} D_i D_j + \sum_{i<j<k} P_{ij}^{(m-3)} D_i D_j D_k + \cdots$$

- If N is known *analytically* (→ iterative "**linear fit**" method)

  - Cut equations translate into *linear relations* which constrain (part of) the ISPs

e.g.

$$\begin{aligned} D_1 &= \bar{q}_1^{\,2} \\ D_2 &= \bar{q}_2^{\,2} \\ D_3 &= (\bar{q}_2 + p_2)^2 \\ D_4 &= (\bar{q}_2 + p_2 + p_3)^2 \\ &\vdots \end{aligned} \longrightarrow \begin{cases} D_1 = 0 \\ D_2 = 0 \\ \quad\vdots \\ D_m = 0 \end{cases}$$

  - The more D_i's are set zero, the less ISP's are left unconstrained

    ↪ $P^{(m)}$ is simpler than $P_i^{(m-1)}$, which in turn is simpler than $P_{ij}^{(m-2)}$ etc…

  - This method is independent of dimensionality, therefore it works in either $d = 4$ or in $d = 4 - 2\varepsilon$ dimensions

  - However, it cannot be used if N is computed by a fully numerical framework

Iterative fit: analytic vs numeric approach

$$N(\bar{q}_1, \bar{q}_2, \{p\}) = P^{(m)} + \sum_i P_i^{(m-1)} D_i + \sum_{i<j} P_{ij}^{(m-2)} D_i D_j + \sum_{i<j<k} P_{ij}^{(m-3)} D_i D_j D_k + \cdots$$

- If N is known *numerically* (→ iterative "**numerical fit**" method)
  - We need to build *explicit solutions* for $\bar{q}_1, \bar{q}_2$

't Hooft-Veltman scheme

- $p_1, \ldots, p_n$ (ext. momenta) in $d = 4$
- $\bar{q}_1, \bar{q}_2$ (loop momenta) in $d = 4 - 2\varepsilon$

↪ $\bar{q}_1, \bar{q}_2$ have $8 + 3 = \boxed{11}$ d.o.f.

$$\begin{cases} \bar{q}_1^2 = q_1^2 + \mu_{11} \\ \bar{q}_2^2 = q_2^2 + \mu_{22} \\ (\bar{q}_1 \cdot \bar{q}_2) = (q_1 \cdot q_2) + \mu_{12} \end{cases}$$

  - In $d = 4 - 2\varepsilon$, there is sufficient freedom to guarantee that cut equations, at any level, admit a *unique* parametric solution for $\bar{q}_1, \bar{q}_2$:

$$\begin{cases} D_1 = 0 \\ D_2 = 0 \\ \vdots \\ D_m = 0 \end{cases} \quad \rightarrow \quad \begin{array}{l} q_1 = q_1(\{p\}, \vec{x}) \\ q_2 = q_2(\{p\}, \vec{x}) \\ \mu_{11}, \mu_{12}, \mu_{22} \end{array}$$

[$\vec{x}, \mu_{ij}$ = free parameters]

more $D_i \to 0$ ↔ less free parameters

  - Once q_1, q_2, μ_{ij} are known, feed N and solve linear system to extract coefficients…
  - Requires a procedure to supplement evanescent terms ($\propto \mu_{ij}, \varepsilon$) to N *numerically*

Iterative fit: analytic vs numeric approach

- What if we work in $d = 4$? $^{(*)}$

$^{(*)}$ R_2 rational terms must to be provided at some later stage

- Cut solutions do not admit a *unique* parametric solution in general!
  They are structured in different *branches:*

$$\begin{cases} D_1 = 0 \\ D_2 = 0 \\ \vdots \\ D_m = 0 \end{cases} \rightarrow \begin{matrix} \left\{ q_1^{(1)}(\{p\},\vec{x}), q_2^{(1)}(\{p\},\vec{x}) \right\} & \longrightarrow & 1^{\text{st}} \text{ branch} \\ \vdots & & \vdots \\ \left\{ q_1^{(r)}(\{p\},\vec{x}), q_2^{(r)}(\{p\},\vec{x}) \right\} & \longrightarrow & r^{\text{th}} \text{ branch} \end{matrix}$$

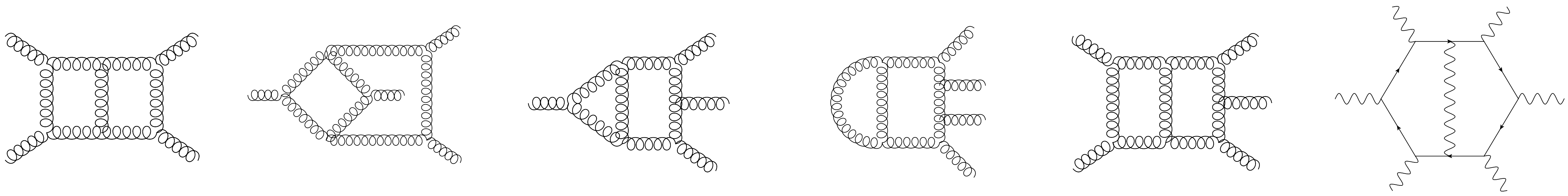
- Solutions from *all* branches need to be considered for coefficient extraction.
  The system has a larger number of rows:

$$\begin{pmatrix} N_1^{(1)} \\ \vdots \\ N_m^{(r)} \end{pmatrix} = \begin{pmatrix} M_{1,1} & \cdots & M_{1,m} \\ & \ddots & \\ M_{m\cdot r,1} & \cdots & M_{m\cdot r,m} \end{pmatrix} \begin{pmatrix} c_1 \\ \vdots \\ c_m \end{pmatrix} \quad \leftrightarrow \quad \vec{N} = \mathbf{M} \cdot \vec{c}$$

- However, there are cases where where the matrix $\mathbf{M}$ is rank deficient.

Status of checks

- Successful reconstruction of numerators ($N = N$ **test**) for the following 2-loop topologies:



"double box" "non-planar double box" "penta-triangle " "hexa-bubble" "penta-box" "six-photon"

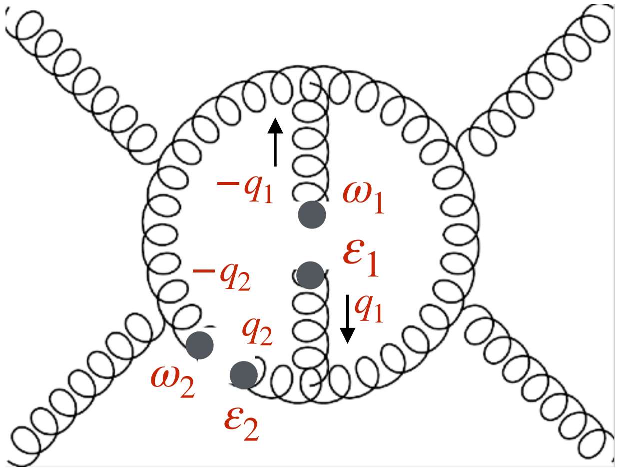
TOPOLOGY	Iterative linear	Iterative numeric ($d = 4 - 2\varepsilon$)	Iterative numeric ($d = 4$)	Global
	FITTING METHOD			
double box	✓	✓	✓	✓
non-planar double box	✓	✓	✓	✓
penta-triangle	✓	✓	⟳	✓
hexa-bubble	✓	✓*	⟳	✓*
penta-box	✓	✓*	⟳	✓*
six-photon	✓	✓*	⟳	✓*

Computing Numerators in $d = 4 - 2\varepsilon$

- Towards numerical computation of dimensionally regularised numerators

  ↪ see also talks at INPP Annual Meeting 2024 and HOCTools mini-workshop

- Basic idea: compute evanescent terms ($\propto \mu_{ij}, \varepsilon$) in the context of $d = 4$ recursive calculation



$$\mathscr{E}[\,(q_i \cdot q_j)\,X\,] = \mu_{ij}\,X \qquad [i,j=1,2]$$

$$\mathscr{E}[\,\sum_{\lambda} (q_i \cdot \varepsilon_{k,\lambda})\,(q_j \cdot \omega_{k,\lambda})\,X\,] = \mu_{ij}\,X \qquad [i,j=1,2]$$

$$\mathscr{E}[\,\sum_{\lambda} (\varepsilon_{i,\lambda} \cdot \omega_{i,\lambda})\,X\,] = (d-4)\,X \qquad [i,j=1,2]$$

$$\mathscr{E}[\,\sum_{\lambda_1,\lambda_2} (\varepsilon_{1,\lambda_1} \cdot \omega_{1,\lambda_1})\,(\varepsilon_{2,\lambda_2} \cdot \omega_{2,\lambda_2})\,X\,] = (d-4)\,X$$

$$\mathscr{E}[\,\sum_{\lambda_1,\lambda_2} (\varepsilon_{1,\lambda_1} \cdot \omega_{2,\lambda_2})\,(\varepsilon_{2,\lambda_2} \cdot \omega_{1,\lambda_1})\,X\,] = (d-4)\,X$$

$$\mathscr{E}[\,\sum_{\lambda_1,\lambda_2} (\varepsilon_{1,\lambda_1} \cdot \varepsilon_{2,\lambda_2})\,(\omega_{1,\lambda_1} \cdot \omega_{2,\lambda_2})\,X\,] = (d-4)\,X$$

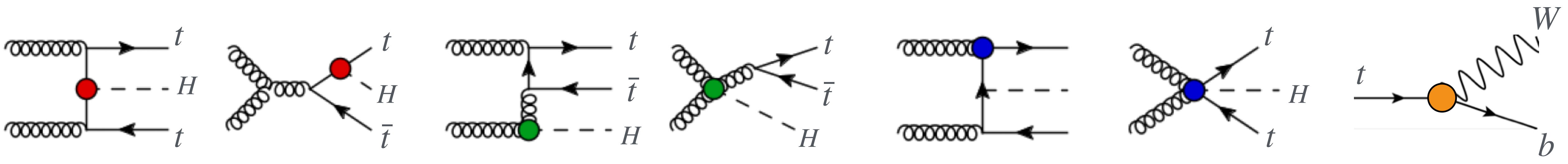
$$\begin{aligned}
\bar{J}^{(N)\,\alpha} = \;& J^{(N)\,\alpha} \\
&+ C_{q_1}{}^{(N)}\,\tilde{q}_1^\alpha + C_{q_2}{}^{(N)}\,\tilde{q}_2^\alpha \\
&+ C_{\varepsilon_1}{}^{(N)}\,\tilde{\varepsilon}_1^\alpha + C_{\varepsilon_2}{}^{(N)}\,\tilde{\varepsilon}_2^\alpha + C_{\omega_1}{}^{(N)}\,\tilde{\omega}_1^\alpha \\
&+ (\tilde{\varepsilon}_1 \cdot \tilde{\varepsilon}_2)\,[\; C^{(N)\,\alpha}_{\varepsilon_1\varepsilon_2,q_1}\,\tilde{q}_1{}^\alpha + C^{(N)\,\alpha}_{\varepsilon_1\varepsilon_2,q_2}\,\tilde{q}_2^\alpha + J^{(N)\,\alpha}_{\varepsilon_1\varepsilon_2} \;] \\
&+ \sum_{i,j=1}^{2} (\tilde{\varepsilon}_i \cdot \tilde{q}_j)\,[\; C^{(N)\,\alpha}_{\varepsilon_i q_j,q_1}\,\tilde{q}_1^\alpha + C^{(N)\,\alpha}_{\varepsilon_i q_j,q_2}\,\tilde{q}_2^\alpha + \\
&\qquad C^{(N)\,\alpha}_{\varepsilon_i q_j,\omega_1}\,\tilde{\varepsilon}_i^\alpha + J^{(N)\,\alpha}_{\varepsilon_i q_j} \;] \\
&+ \sum_{i,j=1}^{2} (\tilde{\varepsilon}_1 \cdot \tilde{q}_i)(\tilde{\varepsilon}_2 \cdot \tilde{q}_j)\,[\; C^{(N)\,\alpha}_{\varepsilon_1 q_i \varepsilon_2 q_j,q_1}\,\tilde{q}_1^\alpha + \\
&\qquad C^{(N)\,\alpha}_{\varepsilon_1 q_i \varepsilon_2 q_j,q_2}\,\tilde{q}_2^\alpha + J^{(N)\,\alpha}_{\varepsilon_1 q_i \varepsilon_2 q_j} \;]
\end{aligned}$$

Completed proof of concept for double-box topology ($gg \to gg$)

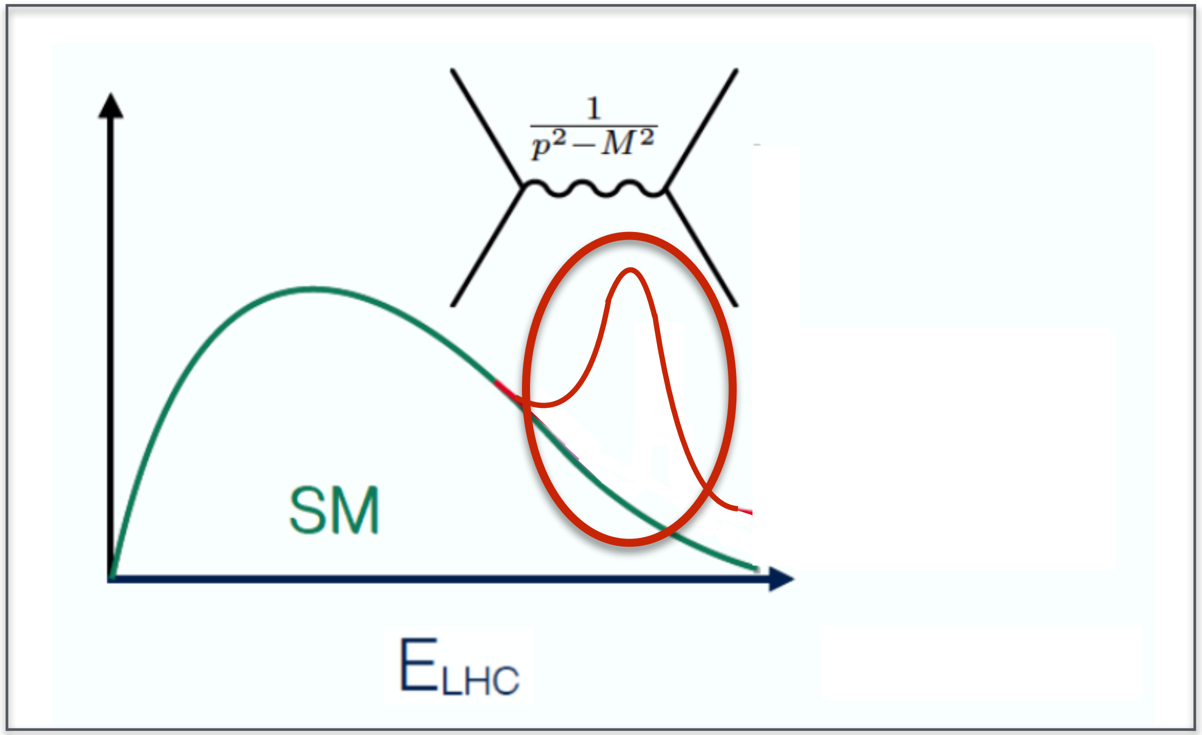
Part II.

Towards SMEFT phenomenology with HELAC

G. Bevilacqua, M. Reinartz, M. Worek



New Physics exploration at the energy frontier

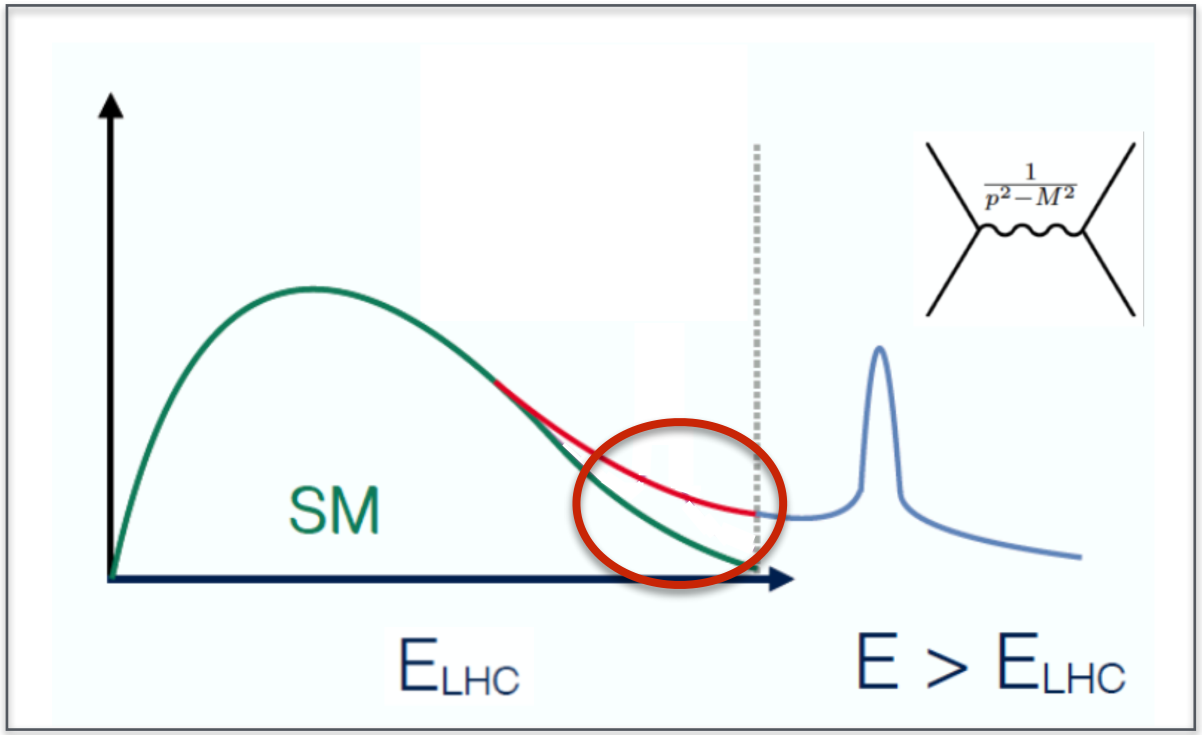


↪ Target: *resonant* signals (bumps)

- "Natural" approach of high-energy colliders: perform *direct* searches of new particles/resonances

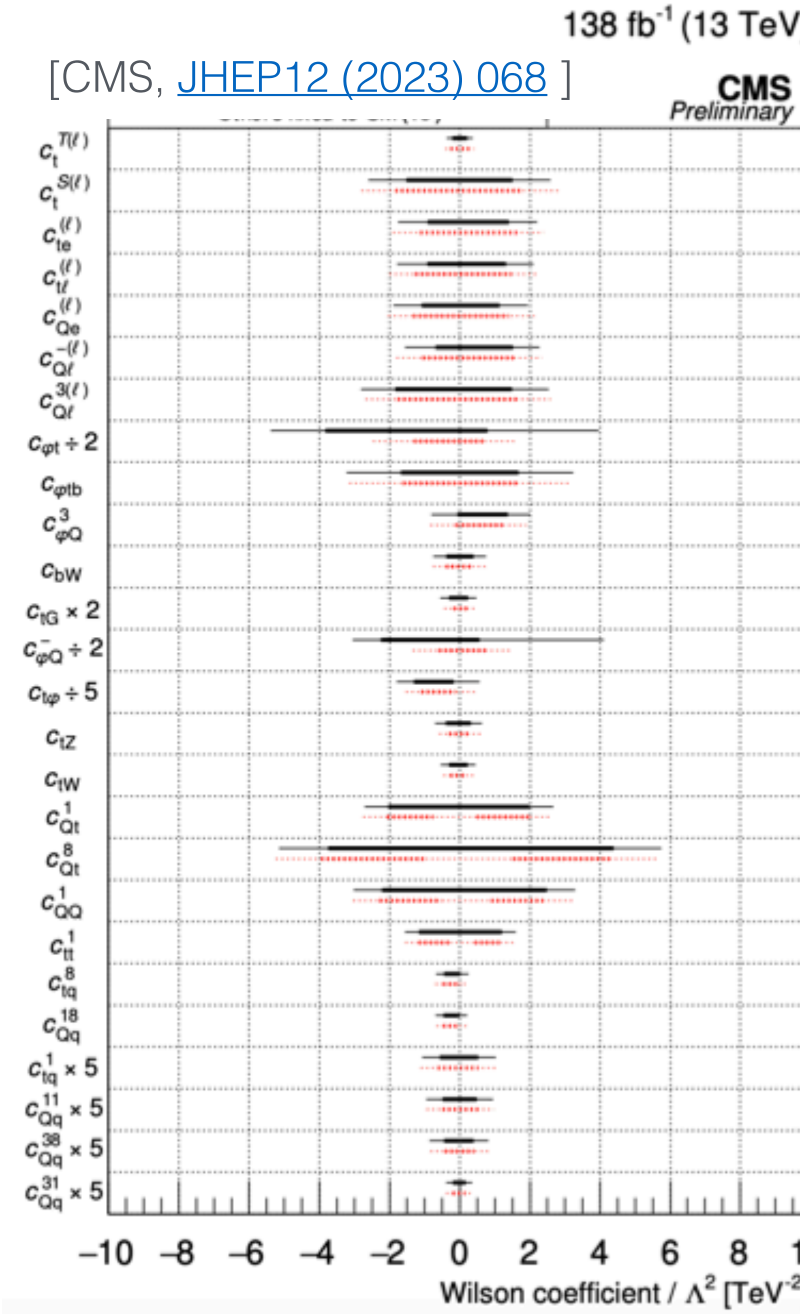
- What if the mass of the new particle(s) is beyond energy reach?

New Physics exploration at the energy frontier



↪ Target: *non-resonant* signals (tails)

- Paradigm shift → BSM effects show up as tiny deviations from SM
- Need for a *model-independent* bridge to underlying theories



[CMS, JHEP12 (2023) 068]

Standard Model Effective Field Theory — SMEFT

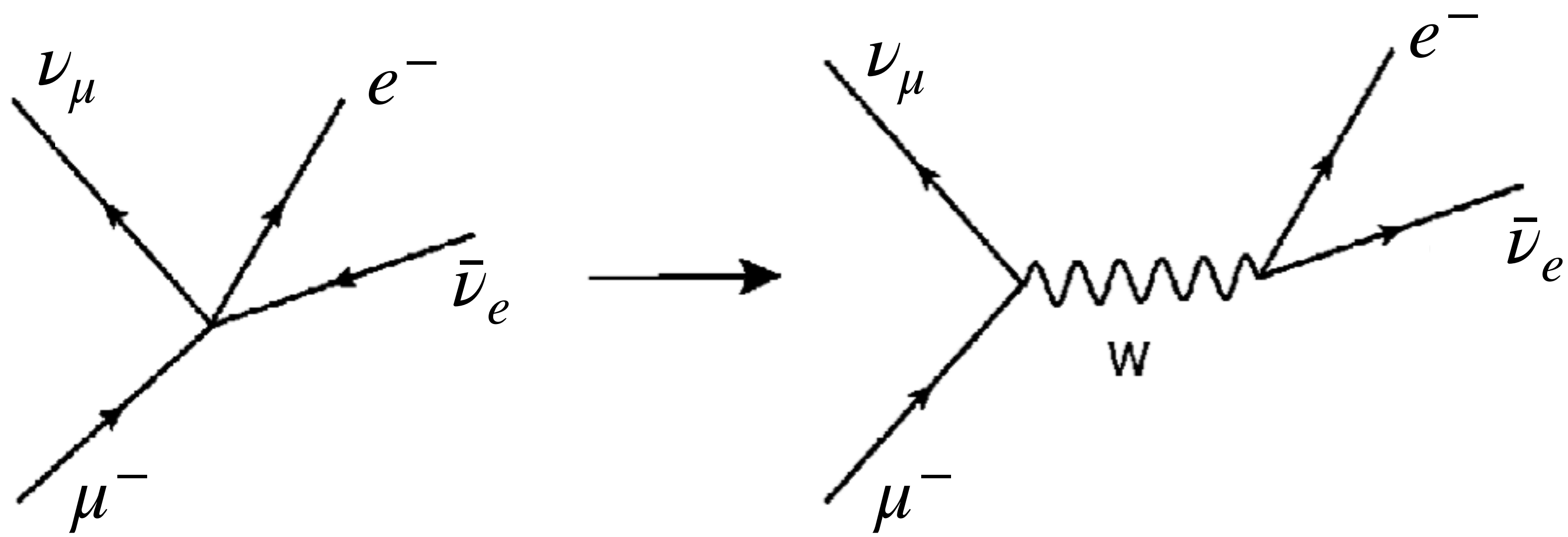
$$\mathscr{L} = \mathscr{L}_{SM} + \sum_i C_i^{(6)} \frac{\mathcal{O}_i^{d=6}}{\Lambda^2} + \sum_i C_i^{(8)} \frac{\mathcal{O}_i^{d=8}}{\Lambda^4} + \cdots$$

- $\mathscr{L}_{SM}$: $\mathcal{O}^{d=4}$
- $C_i^{(6)}$: **Wilson coeff.**
- $\mathcal{O}_i^{d=6}$: **EFT operator**
- Λ^2: **SMEFT scale**

- only SM particles
- new interactions

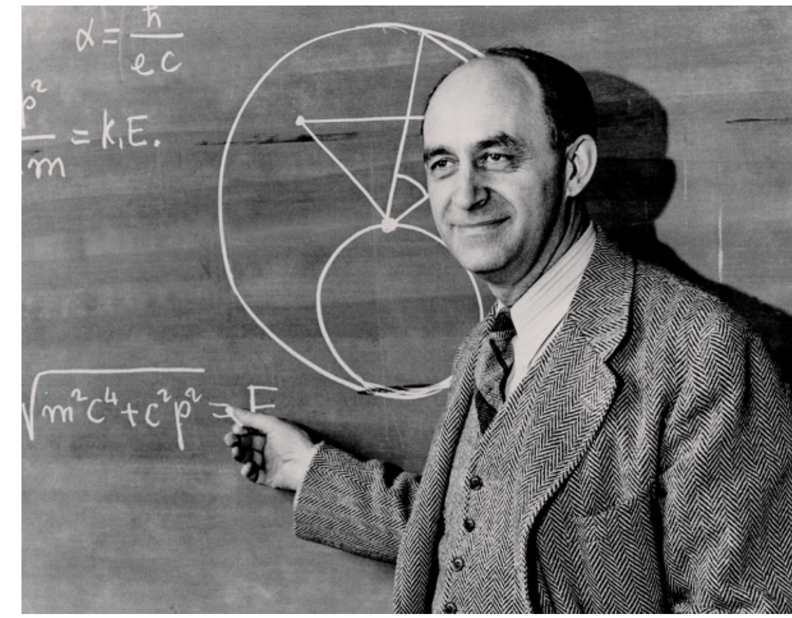
Early example of EFT: Fermi theory

Muon decay



Fermi's theory $[\sqrt{s} \ll M_W]$

W-boson exchange (SM) $[\sqrt{s} \approx M_W]$



Fermi theory → $A = -\frac{4\,G_F}{\sqrt{2}} \left(\bar{\psi}\gamma^\mu P_L \psi\right)\left(\bar{\psi}\gamma^\mu P_L \psi\right)$ → $\frac{G_F}{\sqrt{2}} = \frac{g^2}{8\,M_W^2}$

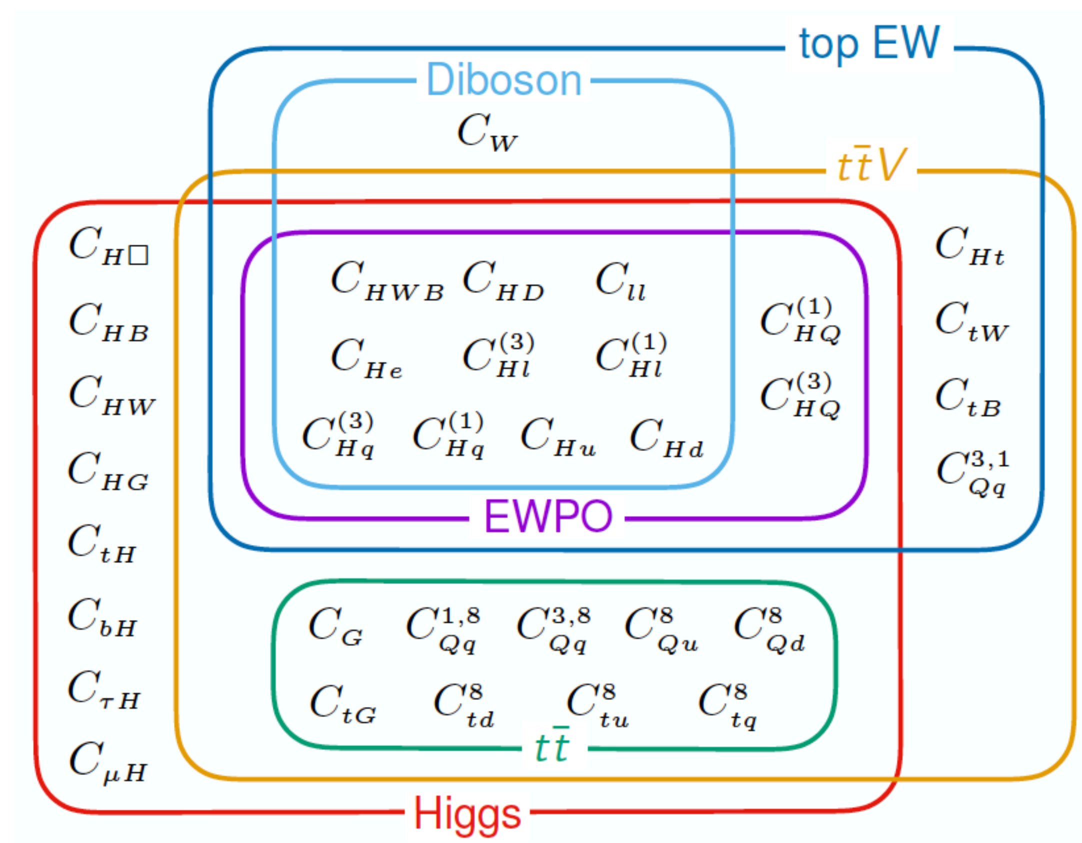
Standard Model → $A = \frac{g^2}{2} \left(\bar{\psi}\gamma^\mu P_L \psi\right)\left(\bar{\psi}\gamma^\mu P_L \psi\right)\left(\frac{1}{p^2 - M_W^2}\right)$

SMEFT operators

[Ellis et al., JHEP 04 (2021) 279]

X^3		H^6 and H^4D^2		ψ^2H^3	
$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar{l}_p e_r H)$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
$\mathcal{O}_W$	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$\left(H^\dagger D^\mu H\right)^\star\left(H^\dagger D_\mu H\right)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar{q}_p d_r H)$
$\mathcal{O}_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
X^2H^2		ψ^2XH		ψ^2H^2D	
$\mathcal{O}_{HG}$	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$\mathcal{O}^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\, W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\, B_{\mu\nu}$	$\mathcal{O}^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)H\, G^A_{\mu\nu}$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I H\, W^I_{\mu\nu}$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde{W}B}$	$H^\dagger\tau^I H\, \widetilde{W}^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}^{(1)}_{qq}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{O}^{(3)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}^{(1)}_{lq}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}^{(3)}_{lq}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}^{(1)}_{qu}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$\mathcal{O}^{(1)}_{ud}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}^{(8)}_{qu}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$\mathcal{O}^{(8)}_{ud}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$\mathcal{O}^{(1)}_{qd}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$\mathcal{O}^{(8)}_{qd}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating			
$\mathcal{O}_{ledq}$	$(\bar{l}^j_p e_r)(\bar{d}_s q^j_t)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$		
$\mathcal{O}^{(1)}_{quqd}$	$(\bar{q}^j_p u_r)\varepsilon_{jk}(\bar{q}^k_s d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$		
$\mathcal{O}^{(8)}_{quqd}$	$(\bar{q}^j_p T^A u_r)\varepsilon_{jk}(\bar{q}^k_s T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$		
$\mathcal{O}^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k_s u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$		
$\mathcal{O}^{(3)}_{lequ}$	$(\bar{l}^j_p\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}^k_s\sigma^{\mu\nu}u_t)$				

- Different processes are most sensitive to different operators



↪ global SMEFT fits

SMEFT operators

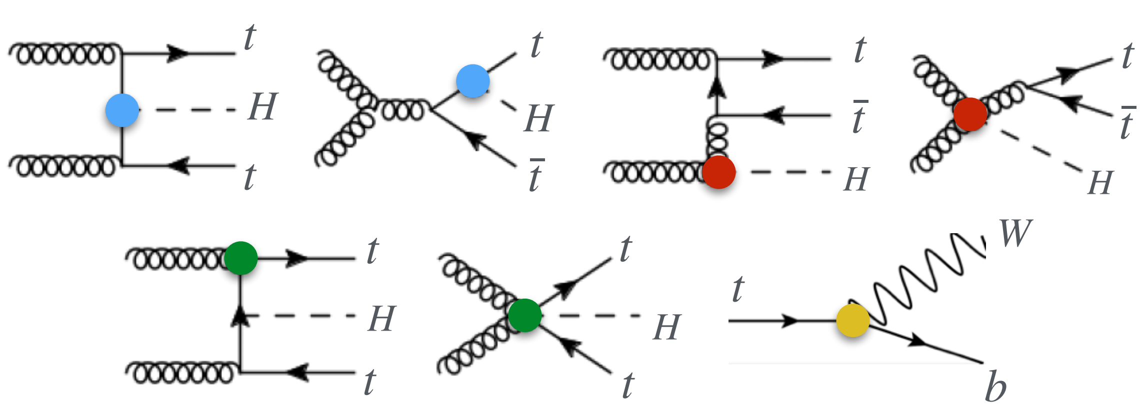
[Ellis et al., JHEP 04 (2021) 279]

X^3		H^6 and H^4D^2		ψ^2H^3	
$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar{l}_p e_r H)$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
$\mathcal{O}_W$	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$\left(H^\dagger D^\mu H\right)^\star\left(H^\dagger D_\mu H\right)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar{q}_p d_r H)$
$\mathcal{O}_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
X^2H^2		ψ^2XH		ψ^2H^2D	
$\mathcal{O}_{HG}$	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$	$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\, W^I_{\mu\nu}$	$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)H\, B_{\mu\nu}$	$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)H\, G^A_{\mu\nu}$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I H\, W^I_{\mu\nu}$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde{W}B}$	$H^\dagger\tau^I H\, \widetilde{W}^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating			
$\mathcal{O}_{ledq}$	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$\mathcal{O}_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$\mathcal{O}_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$\mathcal{O}_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$\mathcal{O}_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$				

- Focus on: $\mathcal{O}_{t\phi}$ $\mathcal{O}_{\phi G}$ $\mathcal{O}_{tG}$ $\mathcal{O}_{tW}$

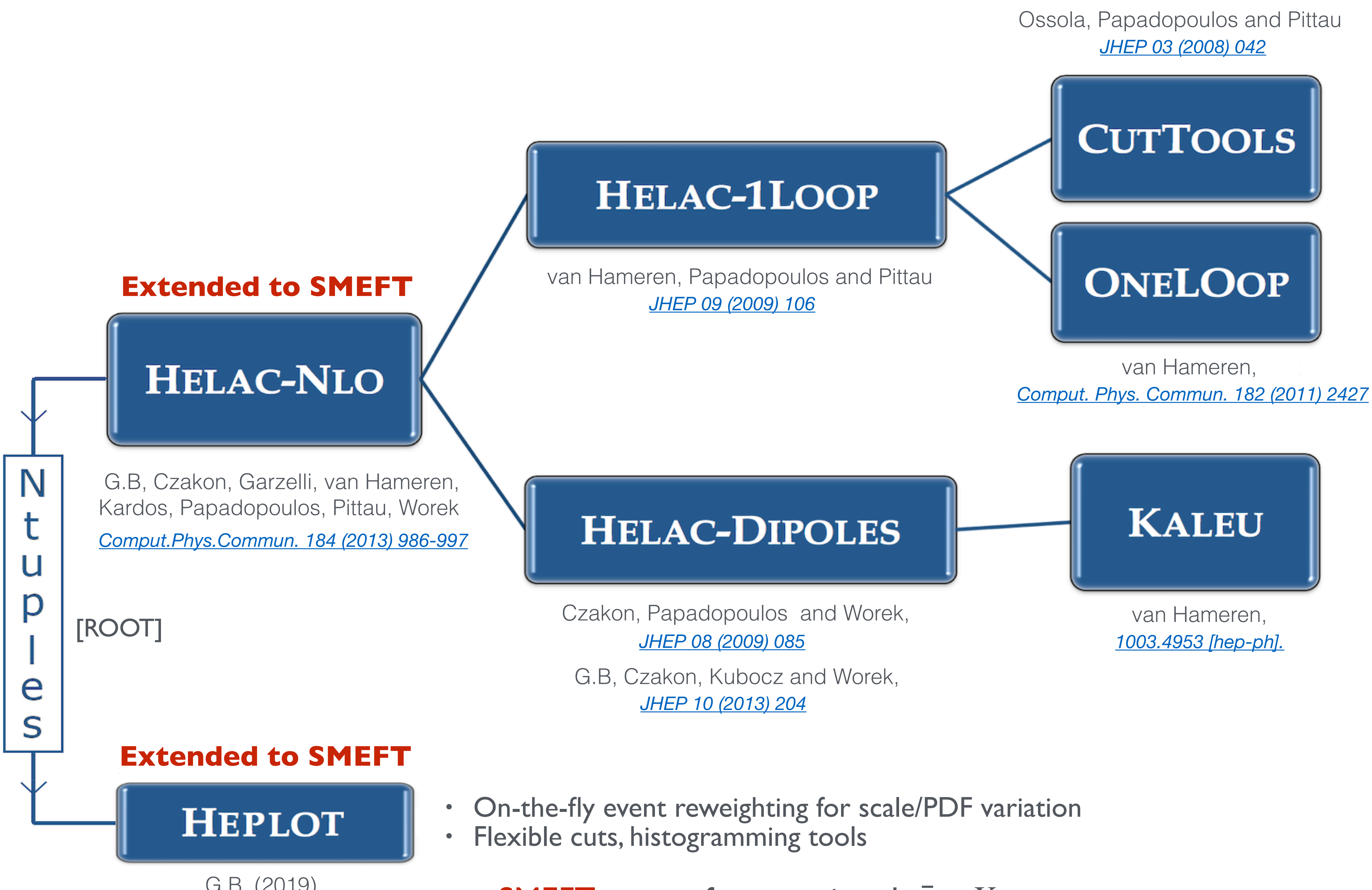
- Interesting applications to:
  - Top quark physics
  - Higgs physics

  ↪ e.g.: study of t-H interaction



Goal: extend HELAC framework to carry out NLO-accurate SMEFT studies

The HELAC-NLO framework



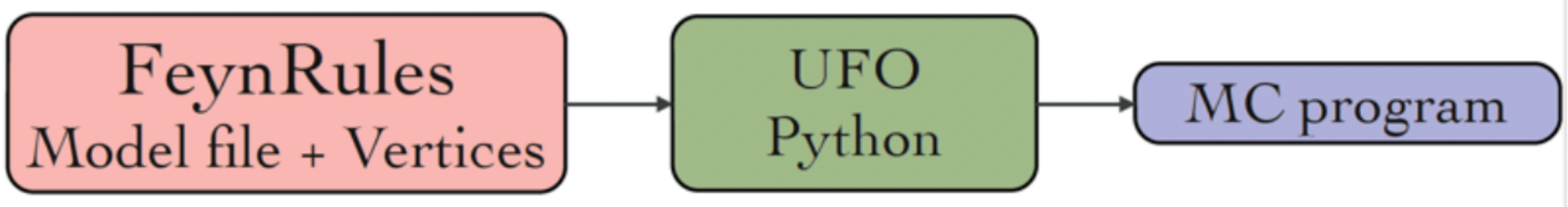
- On-the-fly event reweighting for scale/PDF variation
- Flexible cuts, histogramming tools

$\hookrightarrow$ SMEFT events for associated $t\bar{t} + X$

Extending HELAC to SMEFT

"HELAC-SMEFT"

- Interface to generic BSM models using the UFO format

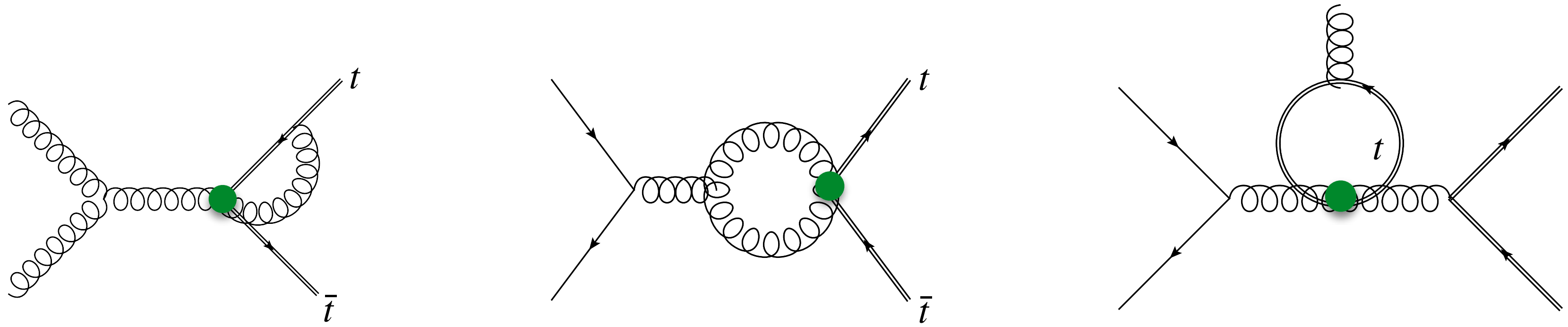


[Alloul, Christensen, Duhr, Degrande, Fuks, '09-'13]

*UFO = **U**niversal **F**eynRules **O**utput

[Darmé et al., Eur.Phys.J.C 83 (2023) 7, 631]

- Steps to development:
  - Automated color-flow decomposition & vertex functions from UFO ✓
  - Automated generation of fortran code to be interfaced to HELAC ✓
  - Updated algorithms for loop-topology generation and optimised recursive computation ✓



Validation: matrix elements

$gg \to t\bar{t}H$

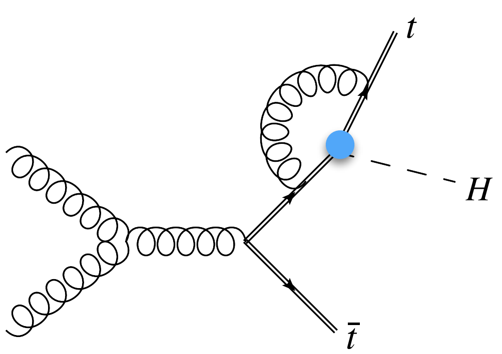
$$\sigma_{\text{SMEFT}} = \sigma_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2}\sigma_i + \sum_{i,j} \frac{C_i\,C_j}{\Lambda^4}\sigma_{ij}$$

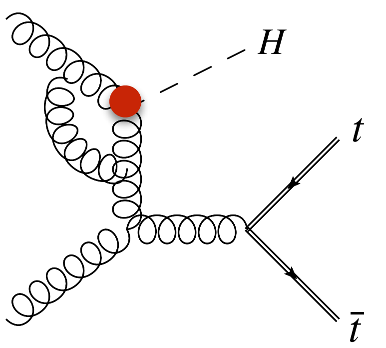
$\mathcal{O}_{t\phi}$ $\mathcal{O}_{\phi G}$ $\mathcal{O}_{tG}$

- 10 partial contributions add up to σ_{SMEFT}

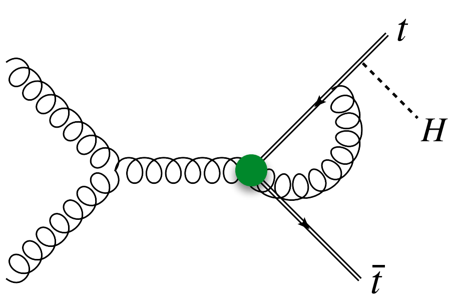
- Checks of IR-pole cancellation (→ KLN theorem)

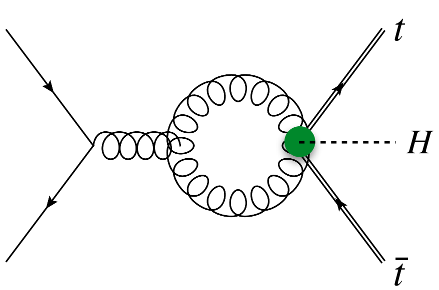
```
LO                        :    0.39001283171747263443496820-03

1-LOOP        (eps^0)     :   -0.16413326968649444020621790-02

1-LOOP        (eps^-1)    :    0.47889491582013217137248720-03
I-operator    (eps^-1)    :   -0.47889491582013217137248720-03

1-LOOP        (eps^-2)    :   -0.65920963578982927447279830-04
I-operator    (eps^-2)    :    0.65920963578982927447279830-04
```

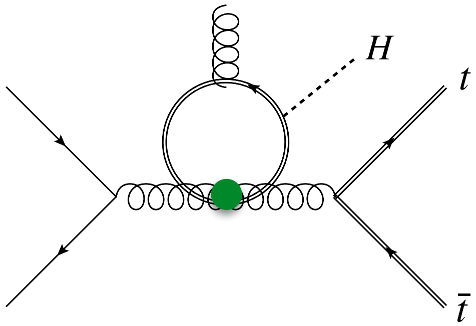




- 1-loop matrix elements checked against Madgraph







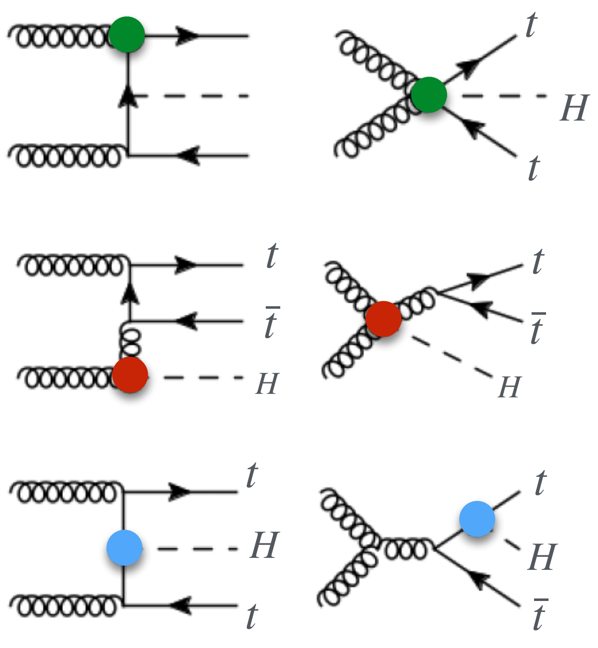
Validation: total cross sections

$pp \to t\bar{t}H$

13 TeV

$$\sigma_{\text{SMEFT}} = \sigma_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2}\sigma_i + \sum_{i,j}\frac{C_i C_j}{\Lambda^4}\sigma_{ij}$$

$\mathcal{O}_{t\phi}$ $\mathcal{O}_{\phi G}$ $\mathcal{O}_{tG}$



LO [pb] →

	Maltoni *et al.*, *JHEP*10 (2016) 123	HELAC-SMEFT
σ_{SM}	0.464	0.464
$\sigma_{t\phi}$	-0.055	-0.055
$\sigma_{\phi G}$	0.627	0.627
σ_{tG}	0.470	0.469
$\sigma_{t\phi,t\phi}$	0.016	0.016
$\sigma_{t\phi,\phi G}$	-0.037	-0.037
$\sigma_{t\phi,tG}$	-0.028	-0.028
$\sigma_{\phi G,\phi G}$	0.646	0.646
$\sigma_{\phi G,tG}$	0.627	0.627
$\sigma_{tG,tG}$	0.645	0.645

→ See also Jonathan Hermann's PhD thesis (RWTH Aachen)

Checks of NLO cross sections in progress

Supervision and local outreach activities

- Master thesis project:

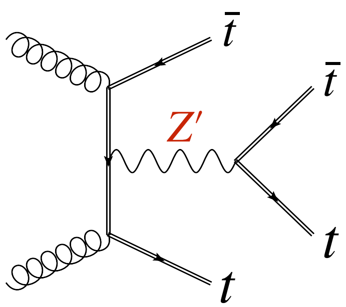
  "Study of Higgs-strahlung process at lepton colliders" (A. Fotopoulos, in progress)

  Supervisor: C. Papadopoulos

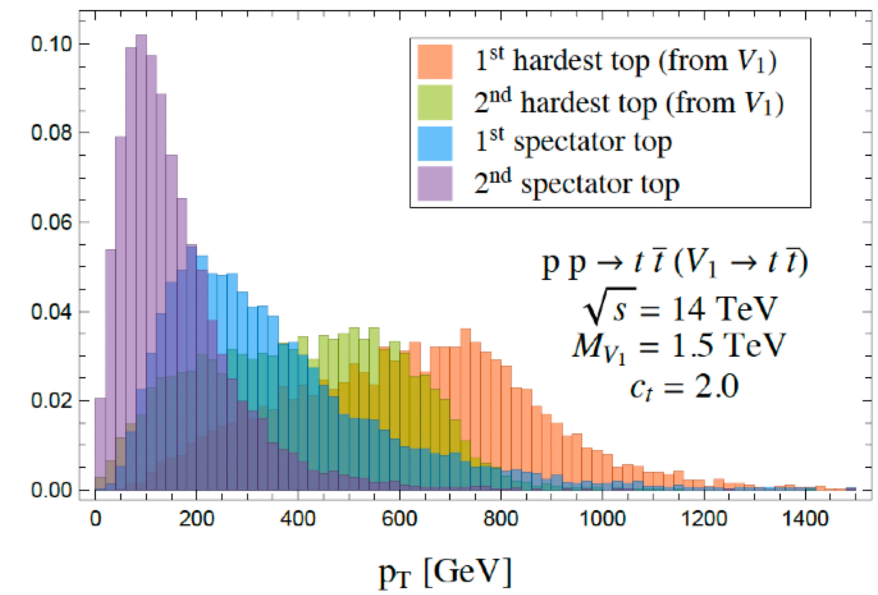
- Internship project:

  "Study of top-philic Z' in four-top production at LHC"
  (G. Zachou, L. Stamatelopoulos)

  Supervisor: G. Bevilacqua



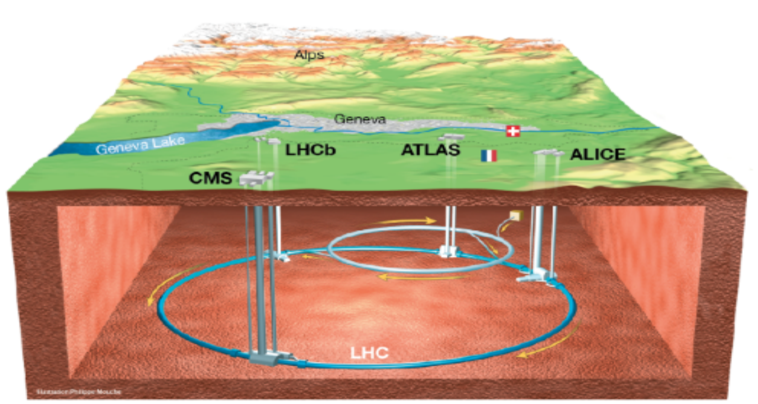
[Kim *et al.*, Phys. Rev. D 94, 035023 (2016)]

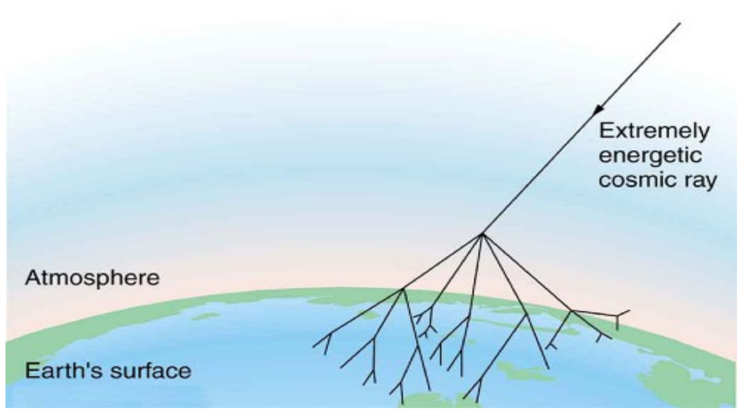


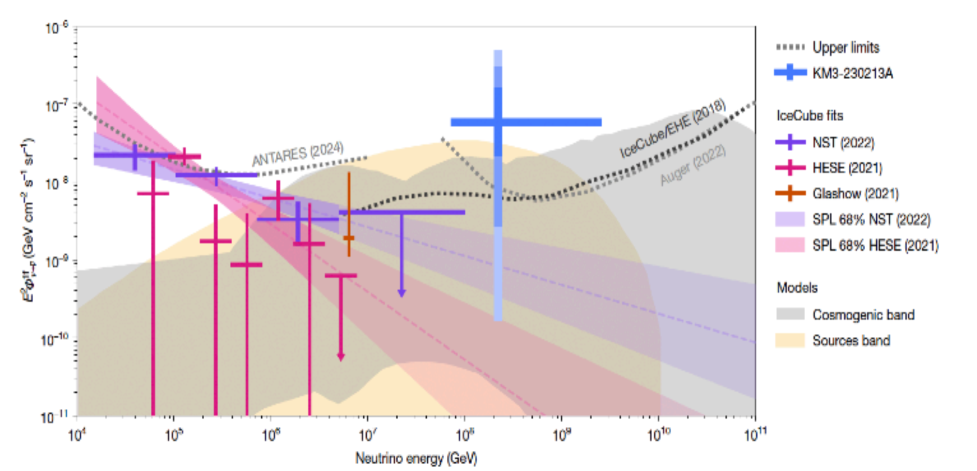
- Outreach talk:

  "A promenade through fundamental interactions and particles"

  G. Bevilacqua, February 2025 → collaboration with Aimilia Smyrli (Γραφείο Εκπαίδευσης)







Thank you for your attention

Ευχαριστώ για τη προσοχή σας