HIGGS PRODUCTION AT NLO IN THE STANDARD MODEL EFT

Nicolas Deutschmann

Work in progress with

Claude Duhr, **Fabio Maltoni** and **Eleni Vryonidou**

LHCTheory meeting
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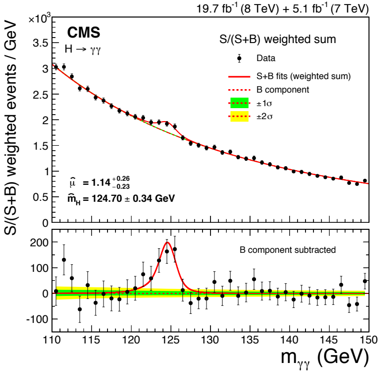
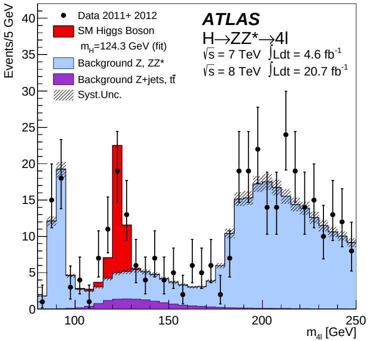
Constraining the Higgs boson at the LHC

Convincing evidence for the new LHC boson to be a CP-even scalar with SM-Higgs like properties.





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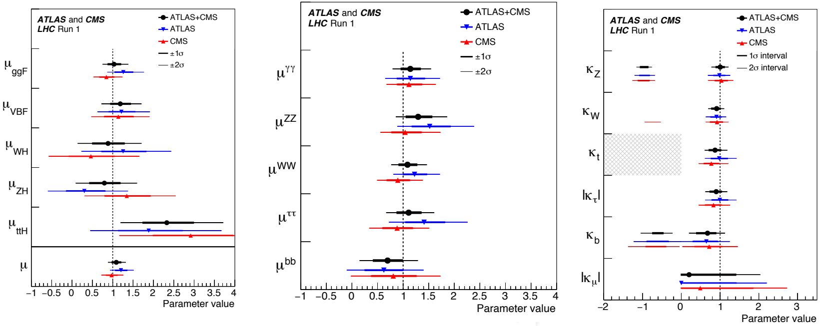

Measurements of signal strengths and κ parameters from Run I

Kappas VS couplings

The κ parameters are not the coefficients of a QFT, they are fit parameters:

$$\mathcal{N}_{\text{events}}\left(pp \to t\bar{t}H \to b\bar{b}\right) \underset{\text{fit}}{\longrightarrow} \kappa_t^2 \kappa_b^2 \left(\sigma \times B\right) \epsilon \mathcal{L} + \ldots$$

Scaling based on LO description

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Scaling based on LO description

- Good tools to test the SM

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- Complex relation to BSM parameters

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Scaling based on LO description

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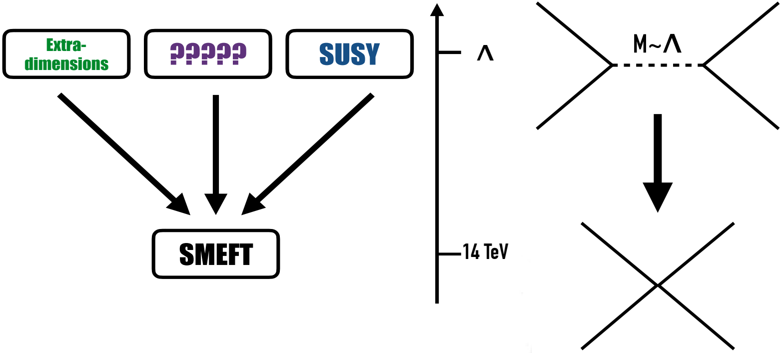
Fit parameters $\rightarrow$ Model parameter:
precise calculation for each channel, for each model

Model independent BSM constraints

As long as new physics is heavy (no direct production), the SMEFT can encapsulate its effect on LHC physics.



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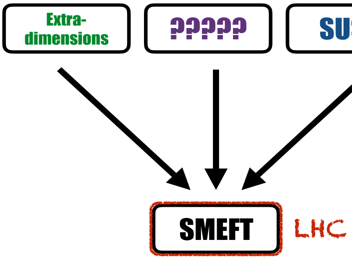

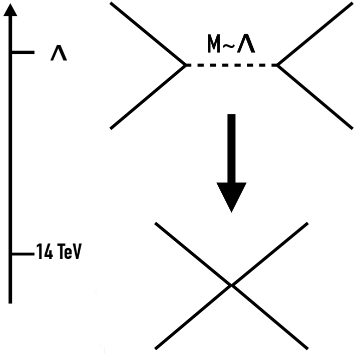

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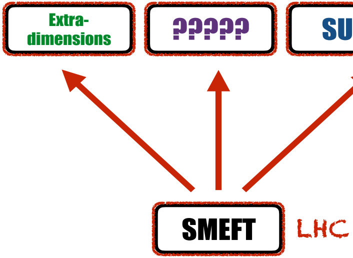

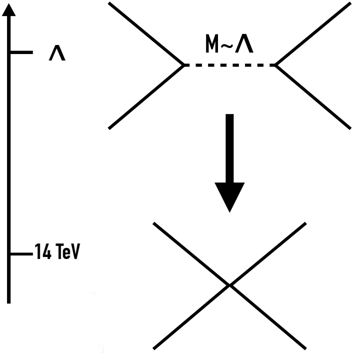

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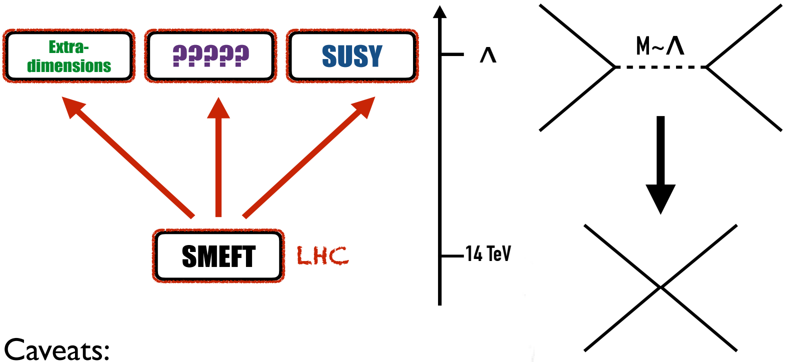


Caveats:

- Standard Model processes (no searches)
- Small deviations: $14\ \mathrm{TeV}/\Lambda \ll 1$

The SMEFT framework

A consistent QFT for parametrizing small BSM effects using higher-dimensional operators with SM fields:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{k=1}^{N} \frac{1}{\Lambda^k} \sum_i C_i \mathcal{O}_i^{[k+4]} \tag{1}$$

Consistent approach to radiative corrections: truncate $\mathcal{L}_{\text{SMEFT}}$ *and* observables at a finite order.

- Dimension 5: 1 operator (neutrino masses)
- Dimension 6: 59 operators or 63, or 84

[Weinberg]
[Buchmuller, Wyler]
[Grzadkowski, Iskrzynski, Misiak, Rosiek]

NLO corrections to SMEFT processes

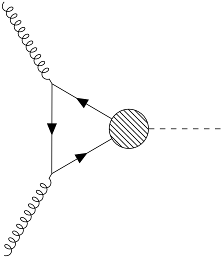
The SMEFT parametrizes possible deviations on precision LHC measurements.
Need for NLO predictions:

- Better accuracy: SM Higgs cross-section changes by 100% from LO to NLO
- Better bounds: typically increased rates at NLO (e.g. bound on one operator involved in $\bar{t}t$ improved by $\times 1.5$ [Buarque Franzosi,Zhang])
- Better precision: reduction of scale uncertainties. SMEFT@LO for $gg \to H$: $15 \sim 25\%$ [Maltoni,Vryonidou,Zhang]

The top-Higgs sector of the SMEFT

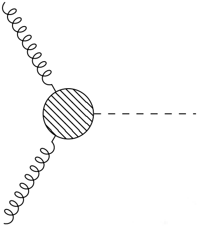
Yukawa correction

$C_1 \bar{Q} \sigma^{\mu\nu} t_R \phi (\phi^\dagger \phi)$



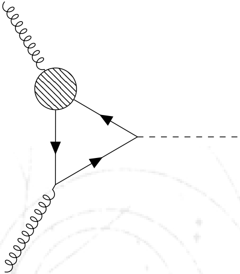
Gluon fusion

$g_s^2 C_2 \phi^\dagger \phi G_{\mu\nu} G^{\mu\nu}$



Chromomagnetic

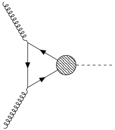
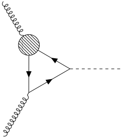
$g_s C_3 \bar{Q} \sigma^{\mu\nu} t_R \phi G_{\mu\nu}$

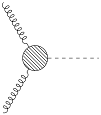


Structure of the LO amplitude

Two unusual features:

- Mix of tree-level and one-loop
- UV divergence in loop contribution

$\mathcal{A}^{(0)}_{\text{EFT}} =$ $C_1 \times$  $+\ C_3 \times$ 

$+\ C_2 \times$ 

[Degrande,Gérard,Grojean,Maltoni,Servant]

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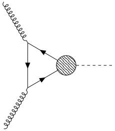
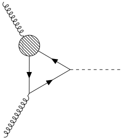


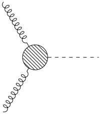
Finite

$+\ C_3 \times$



UV divergent

$+\ C_2 \times$



Finite

[Degrande,Gérard,Grojean,Maltoni,Servant]

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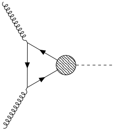

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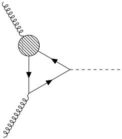
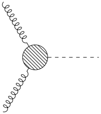


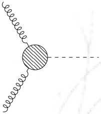
UV divergent

$+ C_2 \times$



Finite

$+ \delta Z_{23} C_3 \times$



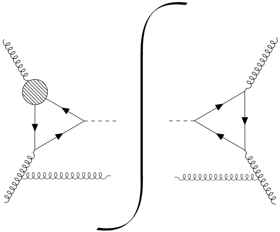
Counter-term

[Degrande,Gérard,Grojean,Maltoni,Servant]

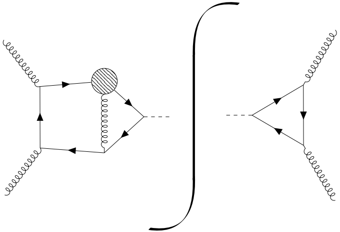
NLO correction to the amplitude

The NLO contribution to the cross-section is composed of

Real emissions



Virtual corrections



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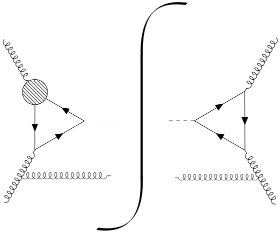
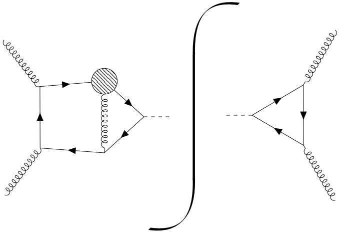


1-loop: automated

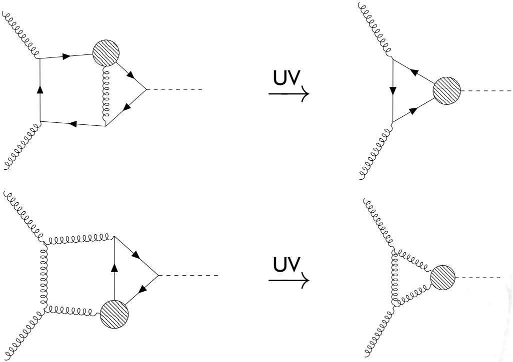
Virtual corrections



2-loop: by hand

Divergence structure: operator mixing

The chromomagnetic operator requires counter-terms from both other operators:



Renormalization matrix:
$C_i^0 = Z^{ij} C_j^R$
[Jenkins, Manohar, Trott]

Divergence structure: IR divergences

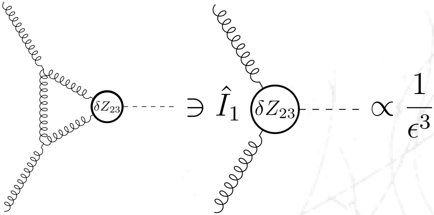
The Infrared divergences factorize:

$$\mathcal{A}_R^{(1)} = \mathcal{A}_{\text{finite}}^{(1)} + \hat{I}_1 \mathcal{A}_R^{(0)}$$

$\hat{I}_1$ is a universal operator encapsulating the IR divergences.

For $gg \to H$, $$\hat{I}_1 = -\frac{e^{\epsilon\gamma}}{\Gamma(1-\epsilon)}\left(\frac{C_A}{\epsilon^2} + \frac{\beta_0}{\epsilon}\right)\left(\frac{\mu^2}{-s}\right)^{\epsilon}$$

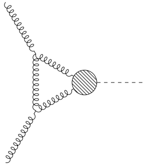
Our LO amplitude already has a pole so an unusual divergence appears :



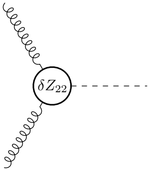
[Catani, Seymour]

Structure of the NLO amplitude

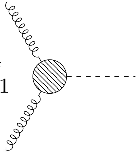
Simplest part of the amplitude: C_2



$= \mathcal{A}^{(1)}_{\text{finite}}\Big|_{C_2} +$



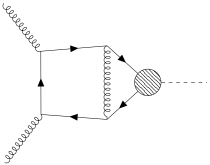
$+ \hat{I}_1$



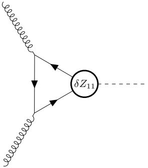
Bare 1-loop — UV divergence — IR divergence

Structure of the NLO amplitude

SM-like two-loop amplitude: C_1



$$= \mathcal{A}^{(1)}_{\text{finite}}\Big|_{C_1} +$$



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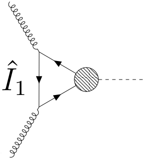
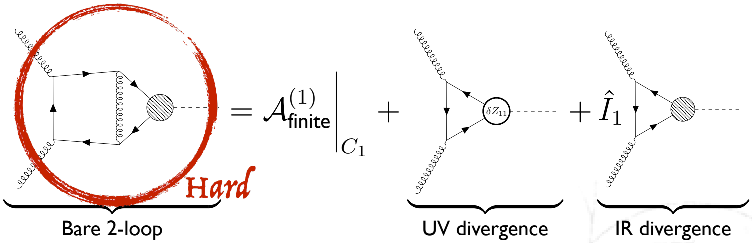


Bare 2-loop — UV divergence — IR divergence

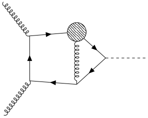
Structure of the NLO amplitude

SM-like two-loop amplitude: C_1



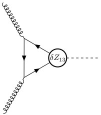
Structure of the NLO amplitude

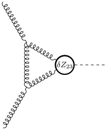
Two-loop and mixing: C_3

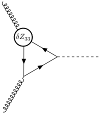


$= \mathcal{A}^{(1)}_{\text{finite}}\Big|_{C_1}$

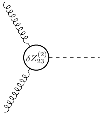
Bare 2-loop

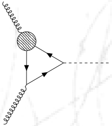
$+$ 

$+$ 

$+$ 

1-loop UV divergences

$+$ 

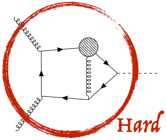
$+ \ \hat{I}_1$ 

2-loop UV divergence

IR divergence

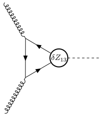
Structure of the NLO amplitude

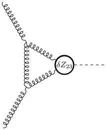
Two-loop and mixing: C_3

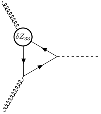


Bare 2-loop

$$= \mathcal{A}^{(1)}_{\text{finite}}\Big|_{C_1}$$

$+$ 

$+$ 

$+$ 

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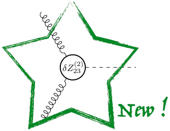
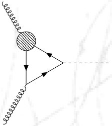
$+$ 

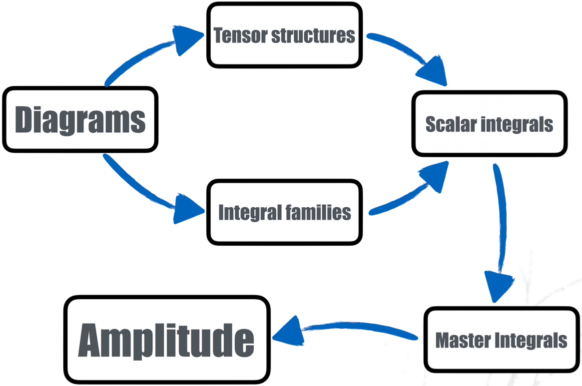
2-loop UV divergence

$+ \ \hat{I}_1$ 

IR divergence

Introduction to modern multi-loop techniques

Workflow of a multi-loop calculation



Integral families

Multi-loop amplitudes contain thousands of loop integrals: need for an organisational principle

Definition: Family

A family of integrals is given by a set of propagators. Scalar integrals with arbitrary powers of this propagators are in the same family

$$I(a_1, \ldots, a_k) = \int d^d k_1 \ldots d^d k_l \frac{1}{D_1^{a_1} \ldots D_k^{a_k}}$$

Arbitrary numerators are included using negative powers

Family bases

Theorem: all integrals in a family can be expressed in terms of a finite basis (!)
How can we reach it?

Integration-by-parts identities (IBP)

In dimensional regularization:

$$\int \prod d^d k_i \frac{\partial}{\partial k_{\hat{j}}^{\mu}} \frac{v_\mu}{D_1^{a_1} \dots D_k^{a_k}} = 0$$

Families are stable under differentiation: generates an infinite linear system

[Chetyrkin, Tkachov]

Going down the ladder

The IBP relation provide a way to reach a basis with low powers

Example: massless bubble integral

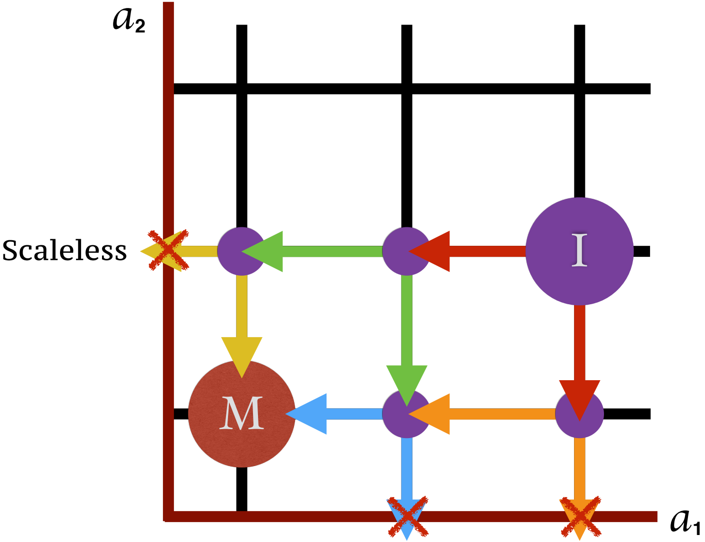
$$I(n_1, n_2) = \int d^d k \frac{1}{(k^2)^{n_1}((k+p)^2)^{n_2}}$$

Two relations:

$$\begin{aligned} I(n_1, n_2) =& \frac{n_1 + n_2 - d - 1}{p^2(n_2 - 1)} I(n_1, n_2 - 1) + \frac{1}{p^2} I(n_1 - 1, n_2) \\ =& \frac{n_1 + n_2 - d - 1}{p^2(n_1 - 1)} I(n_1 - 1, n_2) + \frac{1}{p^2} I(n_1, n_2 - 1) \end{aligned}$$

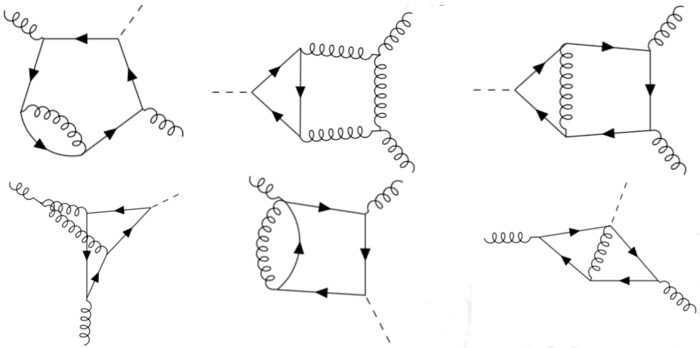
Going down the ladder

Starting from one integral, one can always go back to $I(1,1)$.



Our calculation in numbers: diagrams

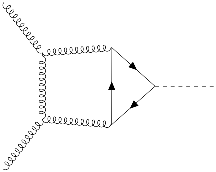
21 diagrams for C_1 and 75 for C_3



Our calculation in numbers: integrals and masters

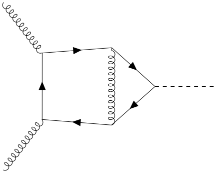
The integrals in our amplitude fall into three families:

Family 1



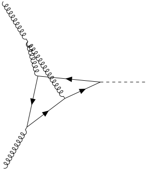
821 Integrals

Family 2



635 Integrals

Family 3



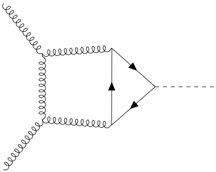
513 Integrals

Total number of master integrals : 17

Our calculation in numbers: integrals and masters

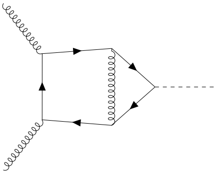
The integrals in our amplitude fall into three families:

Family 1



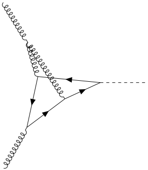
821 Integrals

Family 2



635 Integrals

Family 3



513 Integrals

Total number of master integrals : 17
All known from SM calculation

[Anastasiou, Beerli, Bucherer, Daleo, Kunszt]
[Aglietti, Bonciani, Degrassi, Vicini]

Master integrals in terms of polylogarithms

Many master integrals can be expressed in terms of iterated integrals called multiple polylogarithms:

$$G(a_1, \ldots, a_n; x) = \int_0^x \frac{dt}{t - a_1} G(a_2, \ldots, a_n, dt)$$

With $G(a; x) = \log(1 - x/a)$

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All our integrals are expressed in terms of MPLs with entries in $\{0, \pm 1\}$, depending on the dimensionless variable

$$x = \frac{\sqrt{4m_t^2 - s} - \sqrt{s}}{\sqrt{4m_t^2 - s} + \sqrt{s}}$$

Conclusion and outlook

We have reached the final stages of the calculation of the NLO correction to the Higgs production cross-section by gluon fusion in the SMEFT

- Finished the calculation of the two-loop renormalized amplitude
- Obtained the new two-loop counter-term
- On our way to combine the virtuals with real emissions to compute the cross-section

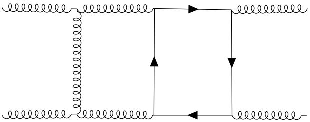
Expected improvement on the precision and accuracy of the prediction, paving the way for future investigations of the Higgs boson properties.

Thank you for your attention

Precise definition of the families

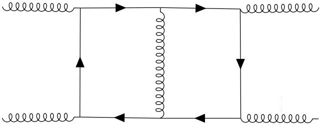
The integrals in our amplitude fall into three families:

Family 1



821 Integrals

Family 2



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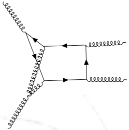


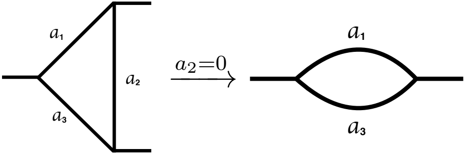
513 Integrals

Integral families: example

One-loop triangle scalar integral family:

$$I(a_1, a_2, a_3) = \int d^d k \frac{1}{(k_1^2)^{a_1}((k_1+p_1)^2)^{a_2}((k_1+p_1+p_2)^2)^{a_3}}$$

Contains sub-topologies:



Numerator example:

$$\int d^d k \frac{k_1.p_1}{(k_1^2)(k_1+p_1)^2(k_1+p_1+p_2)^2} =$$

$$\int d^d k \frac{1}{2}\frac{1}{(k_1^2)(k_1+p_1+p_2)^2} - \frac{1}{2}\frac{1}{(k_1+p_1)^2(k_1+p_1+p_2)^2}$$