A precise effective Higgs-gluon interaction beyond the Standard Model

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6th Vienna Central European Seminar

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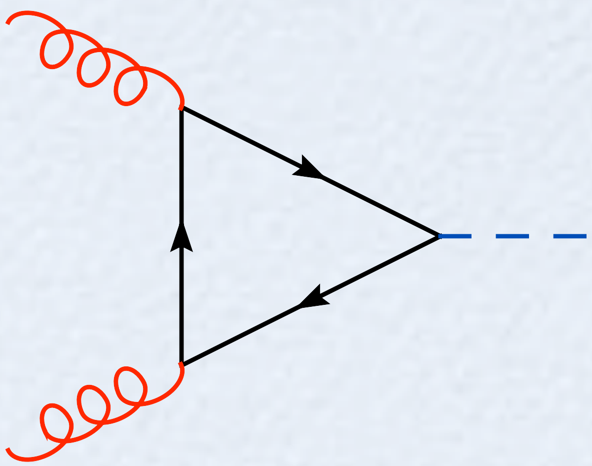
MOTIVATION



- gluon fusion is the main mechanism for Higgs production at hadron colliders
- it is sensitive to *any* coloured particle that couples to the Higgs, e.g. the top
- the Higgs sector is untested

this channel is very sensitive to new physics effects

- the Standard Model Higgs sector is likely to be wrong
- extensions of the SM require new particles which may contribute to gluon fusion

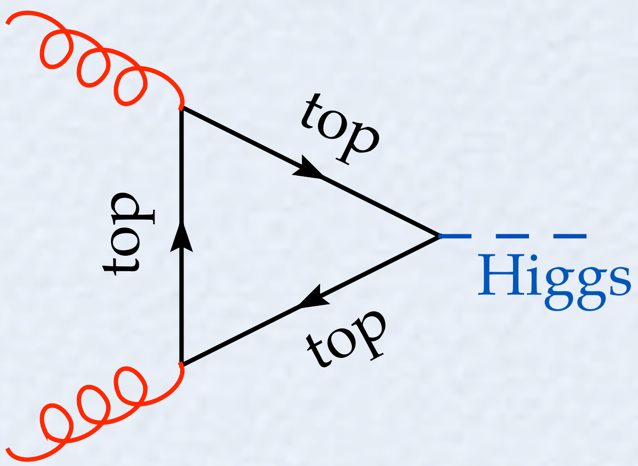
Motivation

- Assume that we find...
  - a relatively light Higgs with a cross section much different than σ_{SM} ($\sigma \sim 0.35\sigma_{SM}$, $\sigma \sim 0.80\sigma_{SM}$?)
  - and/or some new heavy particles

➡ lot of model-building activity ...

➡ ... and of perturbative QCD calculations of the gluon fusion cross section for these models

GLUON FUSION IN THE SM



- it is known very precisely...
- ... but it required tough calculations

$$\sigma^{(SM)}_{NNLO} = \sigma^{(SM)}_{LO}\,(1 + \underbrace{0.7}_{\text{NLO}} + \underbrace{0.3}_{\text{NNLO}})$$

Harlander, Kilgore; Anastasiou, Melnikov; Ravindran, Smith, van Neerven

$$\left(\frac{\Delta\sigma}{\sigma}\right)^{\exp} \sim \pm 10\% \quad , \quad \left(\frac{\Delta\sigma}{\sigma}\right)^{NNLO}_{SM} \sim \pm 10\%$$

... and integrating out the top quark (HQET)

(Chetyrkin, Kniehl, Steinhauser)

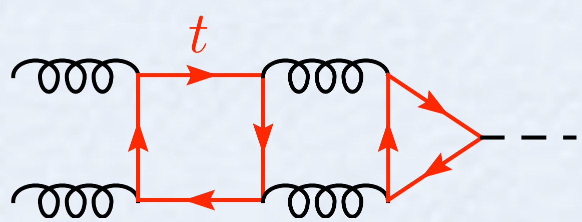
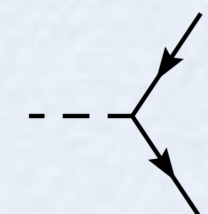
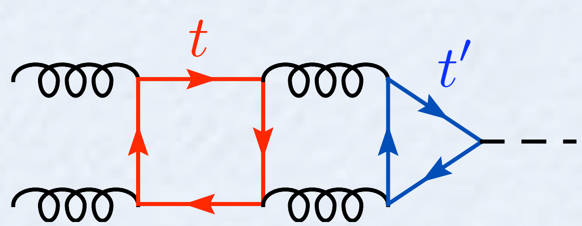
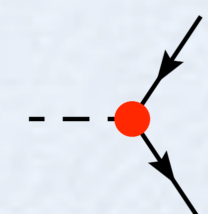
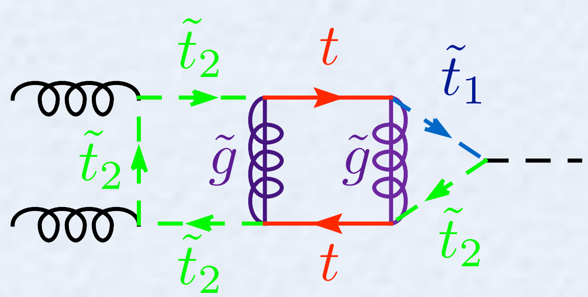
Gluon fusion in BSM

- No NNLO calculation in *any* BSM model, e.g. a fourth fermionic generation
- Why?

  The low-energy theory is usually the same as in SM HQET, but the matching calculation at NNLO is much more complicated:

  - number of diagrams
  - renormalization
  - dependence on multiple mass scales

… Many possibilities!

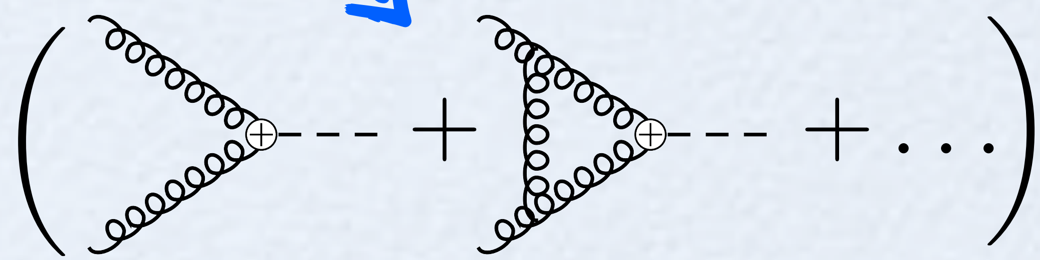
particles in different representations of the Lorentz group	particles of different mass in the loops	particles in different colour representations	different structure of the Higgs coupling
quarks		singlets, triplets, octets	 $\sim \bar{\psi}\psi$
squarks		fundamental, adjoint	 $\sim \bar{\psi}\gamma_5\psi$
Majorana fermions		⋮	⋮
⋮	⋮		

Separating New Physics

- experiments (LEP, Tevatron, ..) indicate that new particles must be heavy, while the Higgs is light
- this allows for an effective-theory approach:

$$\mathcal{L}_{eff} = -\frac{\alpha_S}{4v} C H G^a_{\mu\nu} G^{a\mu\nu}$$

$$\left(C_0 + \left(\frac{\alpha_s}{\pi}\right) C_1 + \left(\frac{\alpha_s}{\pi}\right)^2 C_2 + \ldots \right)$$



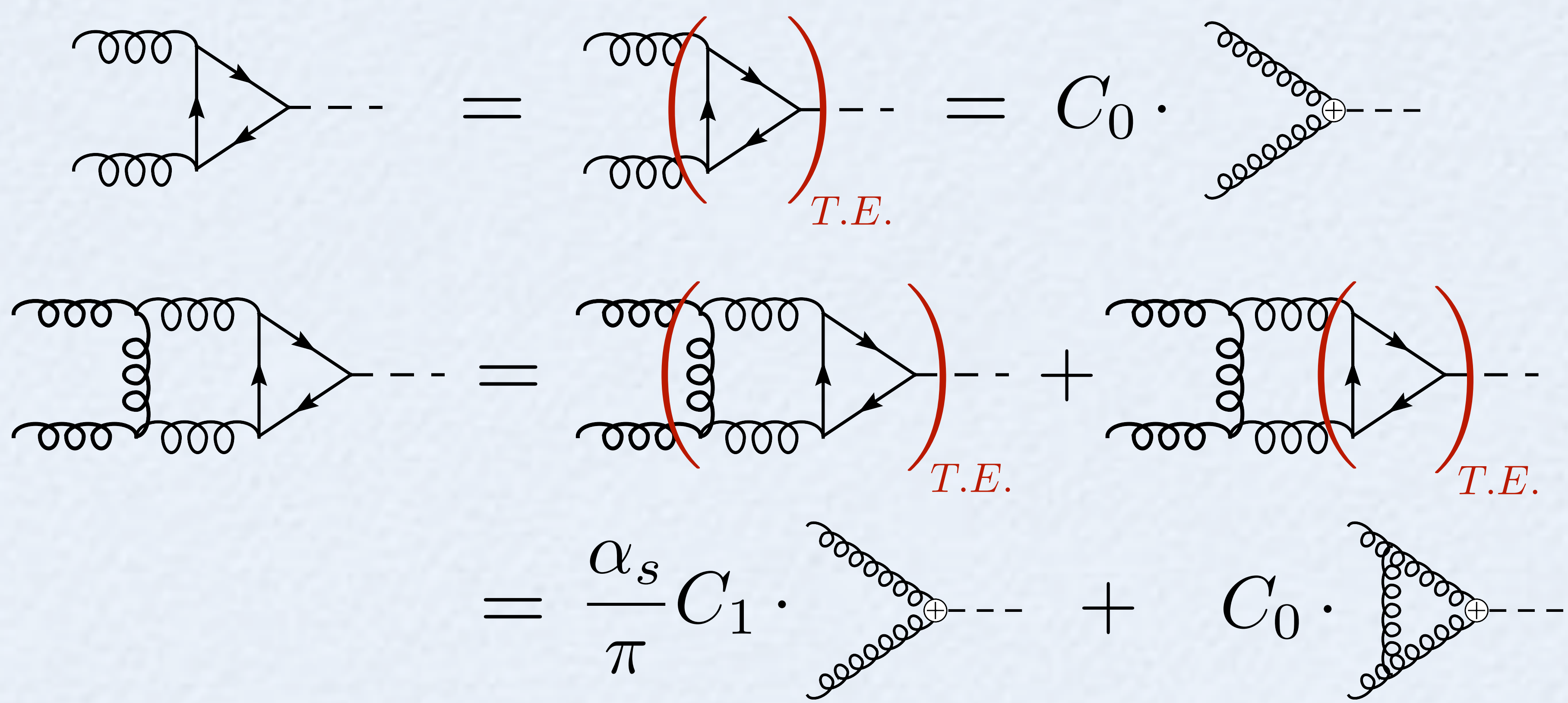
depends on the specific model

QCD only!

→ factorization of QCD and NP effects

METHOD

expansion by subgraphs (Chetyrkin; Gorishny; V. A. Smirnov)
+ small momentum expansion (Fleischer, Tarasov):



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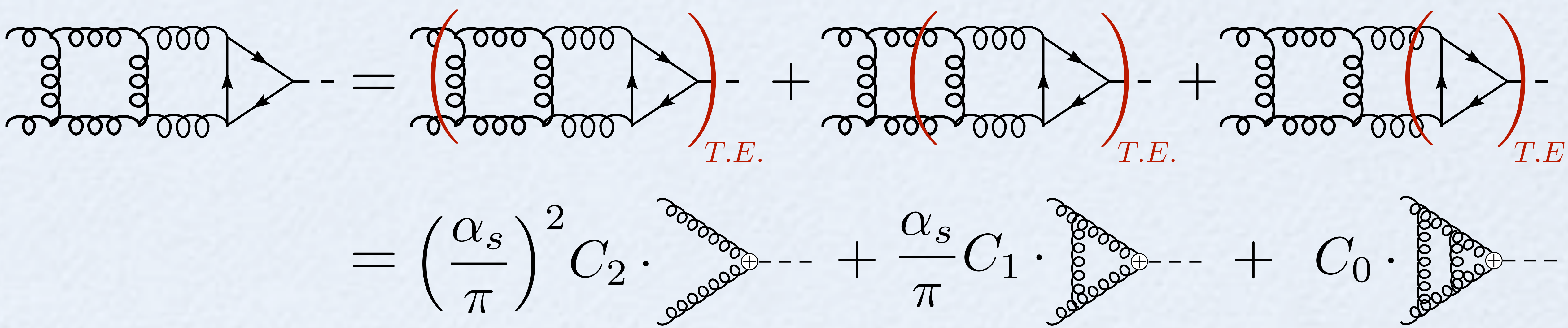
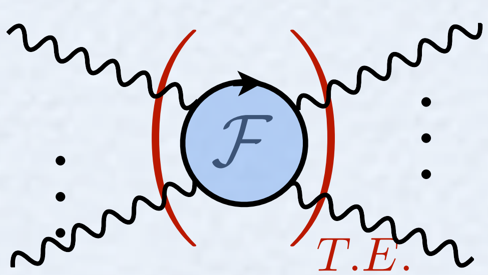




double Taylor expansion:

- in all the momenta external to $\mathcal{F}$
- in the external momenta p_1, p_2 :

$$\mathcal{F} = \sum_{n=0}^{\infty} \mathcal{F}_n (p_1 \cdot p_2)^n \ , \ \mathcal{F}_n = \mathcal{D}_n \mathcal{F} \Big|_{p_1=p_2=0} \left(\mathcal{D}_0 = 1 \, , \mathcal{D}_1 = \frac{1}{d} \Box_{12} \, , \ldots \right)$$

Technical challenges

- Large number of Feynman diagrams

  ~ 500 in the SM, ~ 4000 in MSSM, ~ 6000 in composite Higgs, ...

- Apply costly differentiations for Taylor expansion
- Reduce a large number (~10^5) of integrals to master integrals

  ➡ can be done with

  - ✦ QGRAF (Nogueira)
  - ✦ Mathematica
  - ✦ FORM (Vermaseren)
  - ✦ AIR (Anastasiou, Lazopoulos)

  ➡ same methods for SM and BSM Wilson coefficients

Technical Challenges

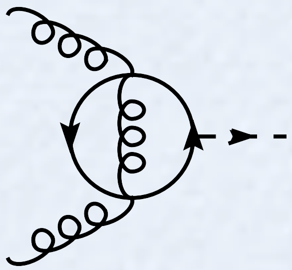
- Evaluate the master integrals

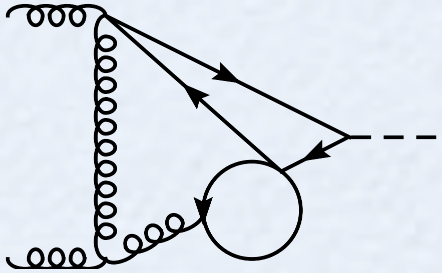
  ➡ much more difficult than in the SM (many mass scales)

  ➡ impossible with traditional analytic methods

Scalar QCD

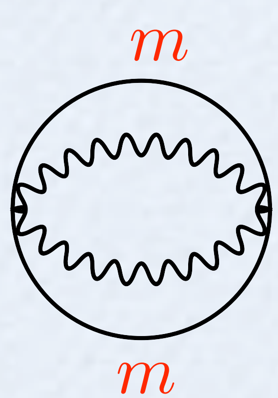
- part of supersymmetric models or other extensions of the SM
- first new result with our techniques
- not very different from the SM calculation, if only one heavy squark
- new vertices:



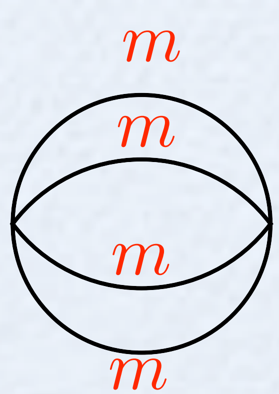


ONE-SCALE MASTER INTEGRALS

- same as for the SM (MATAD, Steinhauser)



$$(m^2)^{2-3\epsilon}\frac{\Gamma^2(1-\epsilon)\Gamma(\epsilon)\Gamma^2(-1+2\epsilon)\Gamma(-2+3\epsilon)}{\Gamma(2-\epsilon)\Gamma(-2+4\epsilon)}$$



non-trivial check of our numerical methods

$$(m^2)^{2-3\epsilon}\Gamma(1+\epsilon)^3\left(\frac{2}{\epsilon^3}+\frac{23}{3\epsilon^2}+\frac{35}{2\epsilon}+\frac{275}{12}\right)$$

Scalar QCD

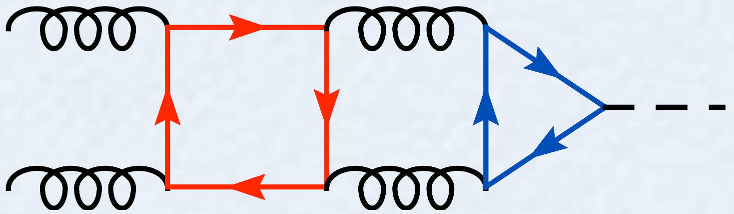
- Bare NNLO Wilson coefficient for scalar QCD (new!!):

$$
\begin{aligned}
C &= C_0 \left\{ 1 + \frac{\alpha_s}{\pi}\mathcal{N}\left[\frac{7}{2} - \frac{\pi}{\alpha_s}\frac{\lambda}{4\pi^2}\frac{2}{3}\right] \right. \\
&\quad + \left(\frac{\alpha_s}{\pi}\mathcal{N}\right)^2 \left[\left(\frac{5}{72} - \frac{13}{48\epsilon}\right) n_l + \frac{3}{128\epsilon^2} + \frac{5215}{768\epsilon} + \left(\frac{\pi^2}{256} - \frac{19967}{4608}\right) \right. \\
&\quad \left. \left. - \frac{\pi}{\alpha_s}\frac{\lambda}{4\pi^2}\left(\frac{1}{\epsilon} + \frac{191}{32}\right) - \left(\frac{\pi}{\alpha_s}\frac{\lambda}{4\pi^2}\right)^2 \left(\frac{7}{24\epsilon} + \frac{11}{48}\right) \right] \right\}
\end{aligned}
$$

$$
C_0 = \frac{\alpha_s}{24\pi v}\left(\frac{4\pi}{m_s^2}\right)^{\epsilon}\Gamma(1+\epsilon) \quad , \quad \mathcal{N} = e^{-\epsilon\gamma_E}\left(\frac{4\pi}{m_s^2}\right)^{\epsilon}
$$

4TH GENERATION

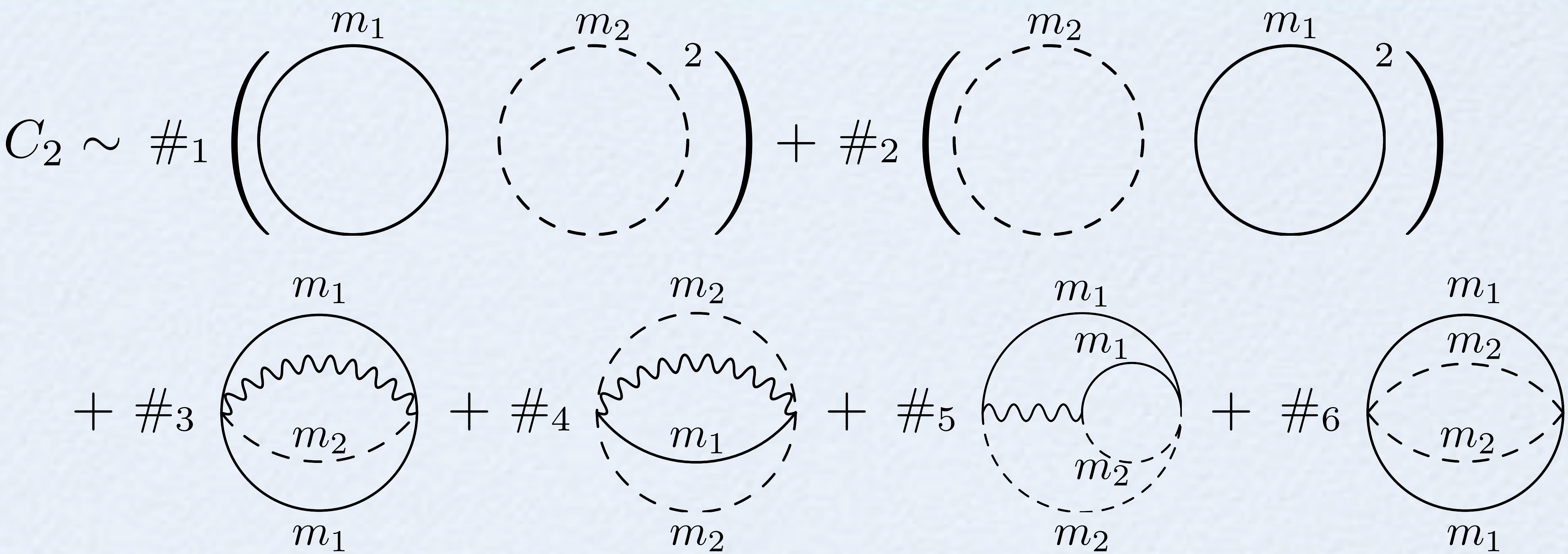
- the two mass scales appear together at NNLO for the first time:



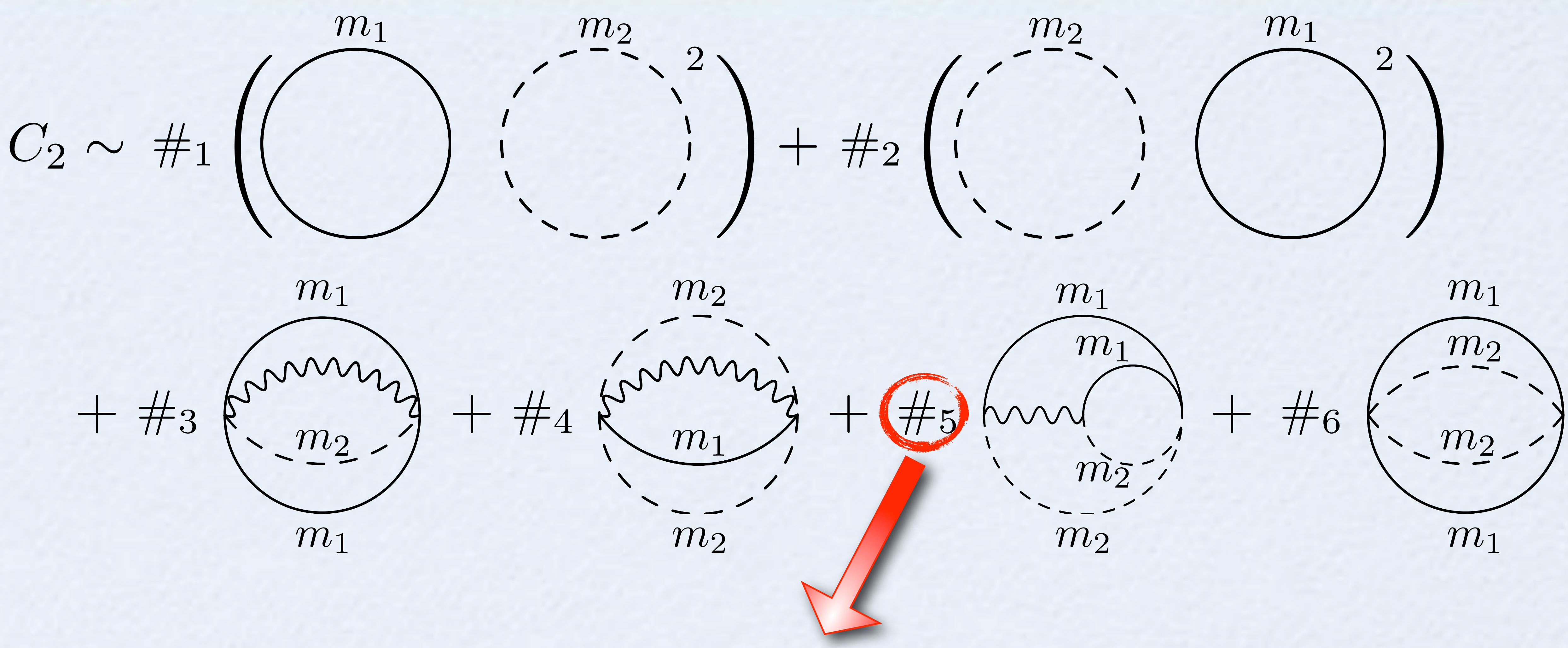
+ other 115

  - can use the same routines as for the previous calculation
  - master integrals now contain up to two, different, massive propagators

4th Generation

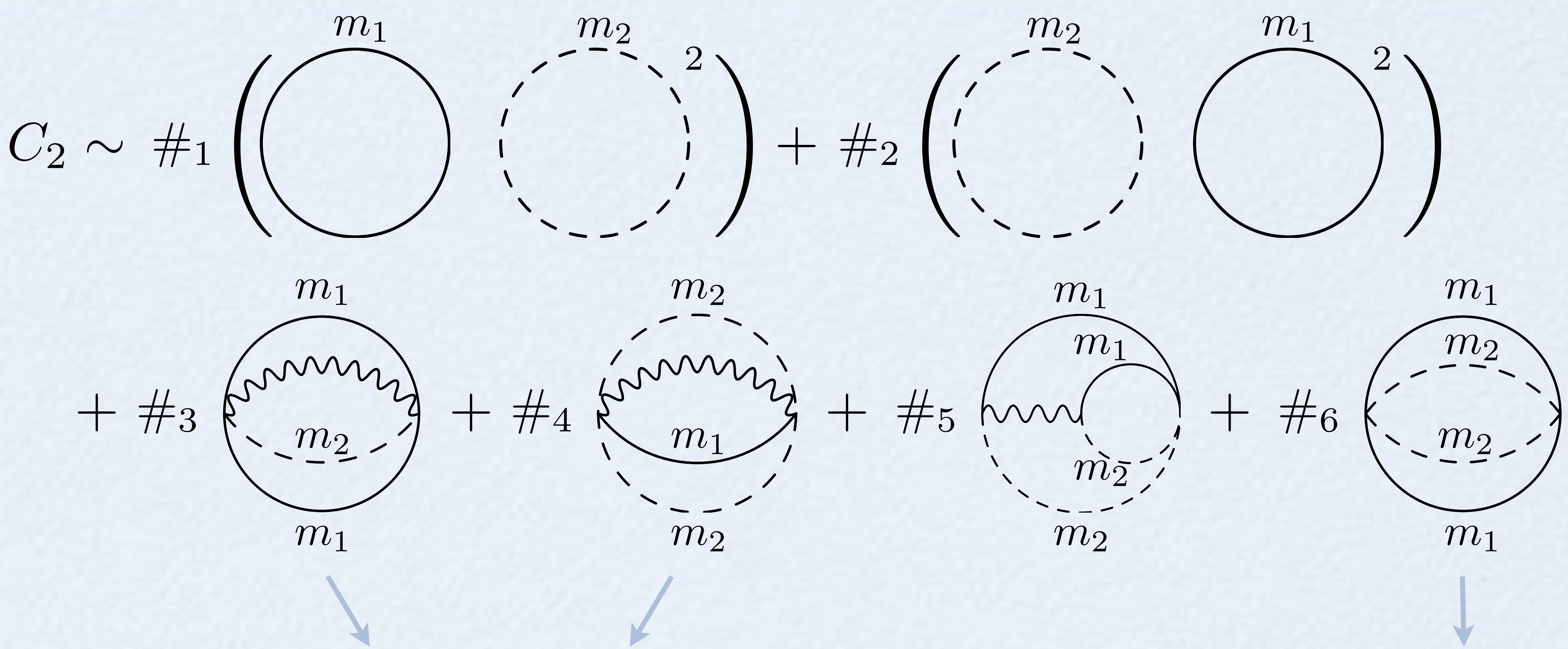


4TH GENERATION



$$\frac{g_s^6 m_H^2 (m_1^2 - m_2^2)}{512 m_1^6 m_2^6 v}\left[\frac{(m_1^2-m_2^2)^2\left(19m_1^4+24m_1^2m_2^2+19m_2^4\right)}{\epsilon} - \frac{1371m_1^8+2096m_1^6m_2^2+1442m_1^4m_2^4+2384m_1^2m_2^6+3m_2^8}{36}\right]$$

4TH GENERATION



Bytev, Kalmykov, Kniehl

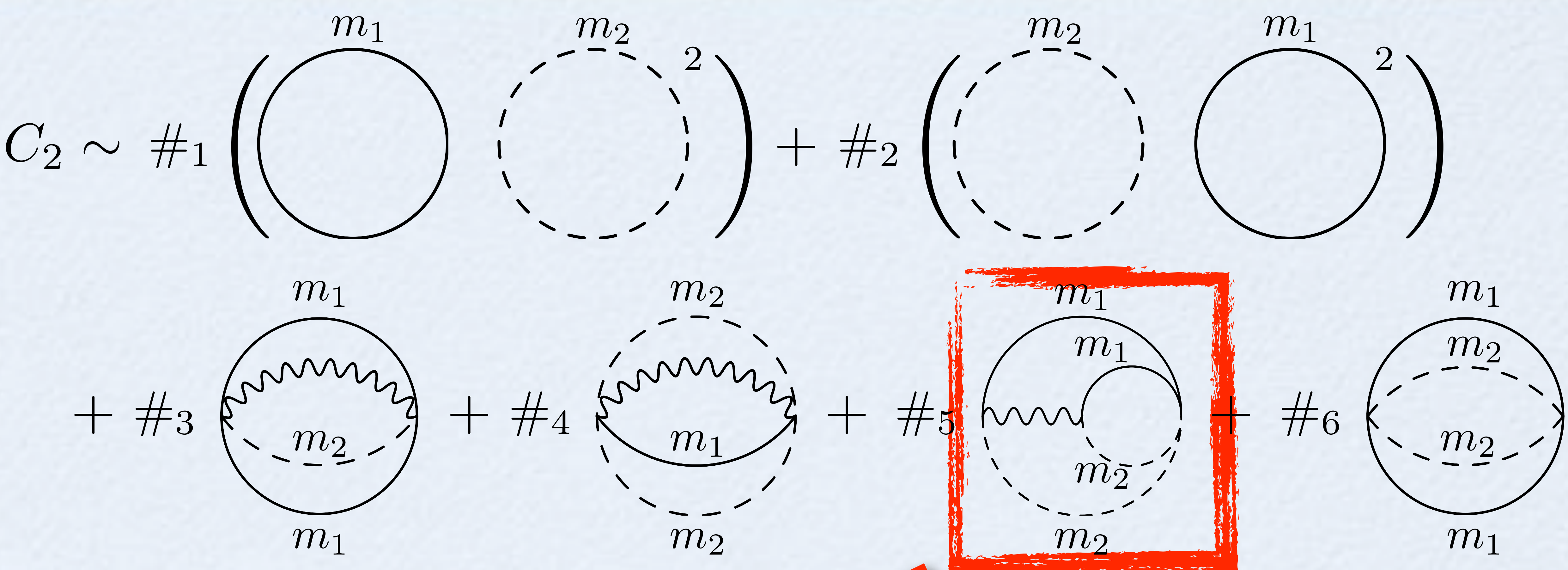
Bekavac, Grozin, Seidel, Smirnov

Sector decomposition

Hepp; Denner, Roth; Binoth, Heinrich; Anastasiou, Melnikov, Petriello; Anastasiou, Beerli, Daleo; Lazopoulos, Melnikov, Petriello

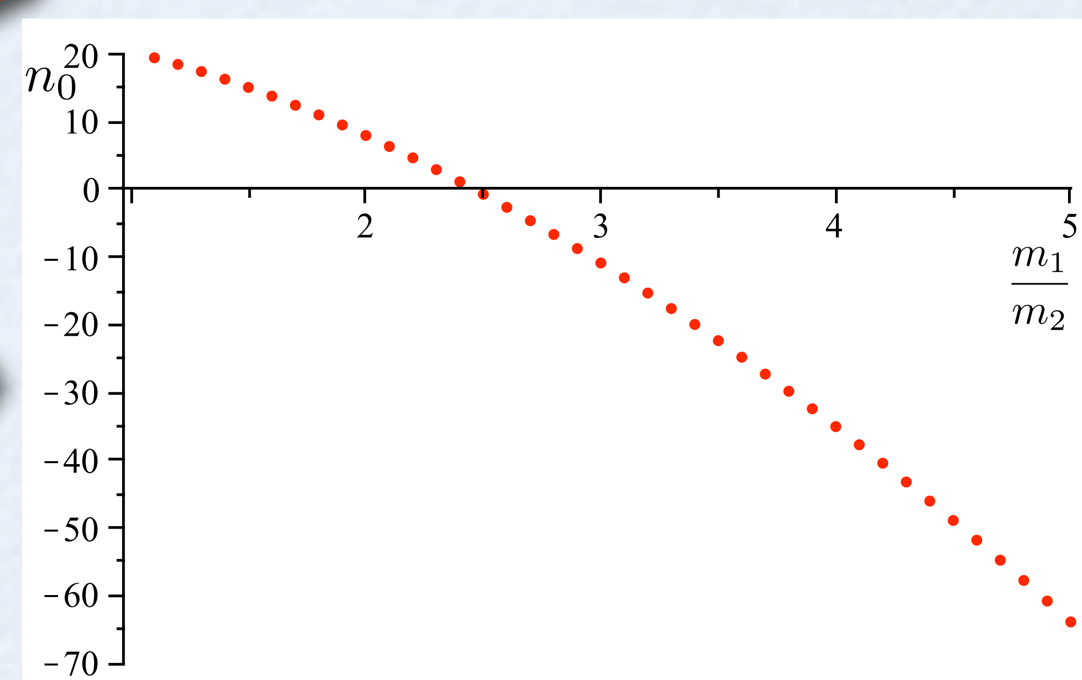
- method for calculating numerically divergent multi-dimensional integrals
- can be applied regardless of the number of mass scales
- own efficient implementation

4th Generation



$$\frac{n_3}{\epsilon^3} + \frac{n_2}{\epsilon^2} + \frac{n_1}{\epsilon} + n_0 + N_1 \epsilon$$

sector decomposition



Applications

- First NNLO matching calculation for scalar QCD and fourth SM generation
- .. to come:
  - composite Higgs models at NNLO
  - MSSM at NNLO
  - ... and whatever the LHC asks for!

Conclusions

- the Higgs boson is likely to come with some new physics
- many viable BSM theories exist, and many need to introduce new, coloured particles
- they can significantly affect the gluon-fusion cross section
- effective theory disentangles new physics from QCD
- we have automatised the matching procedure for BSM models through NNLO
- ready for high-precision predictions for Higgs boson cross-section

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watch this space!