Susy QCD corrections in Higgs boson production via gluon fusion

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Outline

NLO SUSY-QCD corrections to $gg \to h$ (in progress. . .)

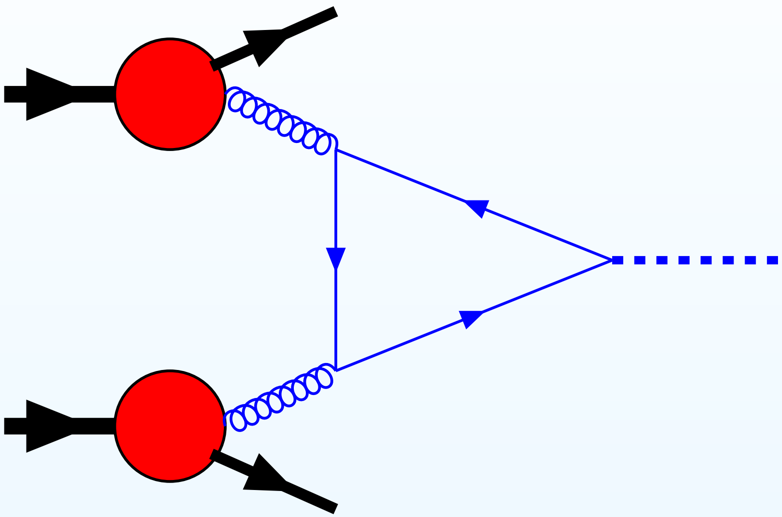
in collaboration with Stefan Beerli, Stefan Bucherer, Alejandro Daleo and Zoltan Kunszt

- introduction
- quark and scalar-quark two-loop amplitudes
- diagrams with gluinos and squarks (the method only - no results)
- summary

NNLO QCD corrections for $gg \to h \to W^+W^- \to l^+l^-\nu\nu$ (full calculation with all experimental cuts at the parton level)

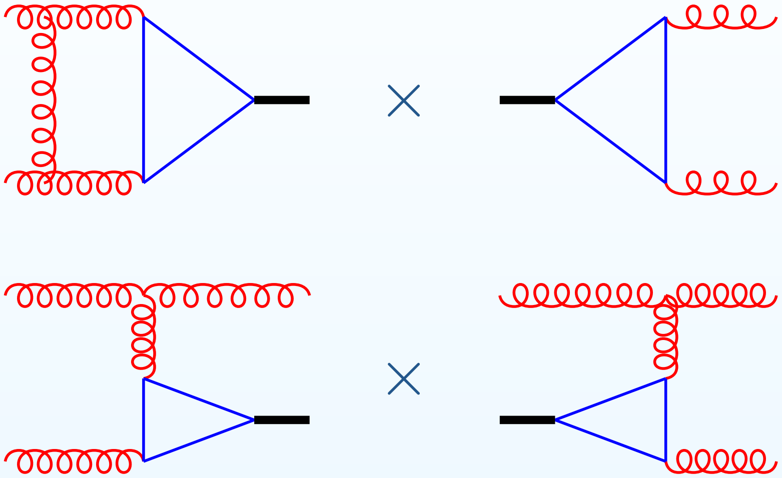
in collaboration with Günther Dissertori and Fabian Stöckli

The gluon-gluon fusion channel in the Standard Model



- Higgs boson couples to gluons at the one-loop level, through (heavy) quarks
- Recall the large gluon density at $x \sim 10^{-4} - 10^{-2}, Q \sim 100\mathrm{GeV}$
- Large Born cross-section at the LHC ($\sim \mathcal{O}(20)pb$)
- But not precise - scale uncertainty $\sim 40\%$

First order QCD radiative corrections



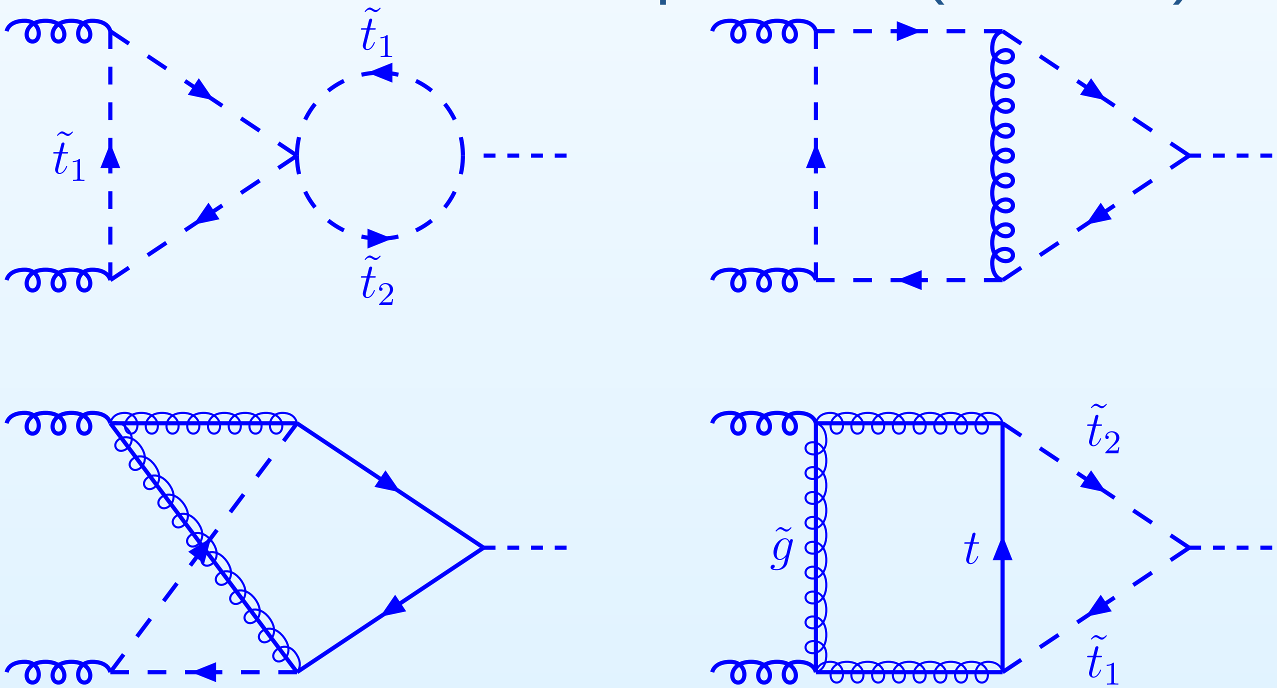
- a two-loop calculation, Spira, Djouadi, Graudenz, Zerwas
- large scale uncertainty $\sim 25\%$
- a very big correction $(\sim 70\%)$ Dawson; Spira et. al.

Gluon fusion: sensitive to BSM physics

- Anything that couples to gluons and the Higgs boson can circulate inside the production loop!
- There is a lot of room in the model building world to change the cross-section significantly
- For example, an additional quark in a Left-Right symmetric Randall-Sundrum model could alter the Higgs cross-section from -50% to $+400\%$ without any conflict with electroweak precision data. Djouadi, Moreau
- The interpretation of the nature of the Higgs boson will also rely on the magnitude of the cross-section in various BSM models.

Two-loop corrections in BSM

- The LO cross-section is uncertain in the SM. It is the same (or worse) uncertain in BSM. Can we compute the NLO cross-section scanning a multitude of models?
- For the MSSM only, we need two loop three point diagrams with up to four different internal particles (masses)



Effective theory approach

- Heavy Quark Effective Theory is very succesful for the SM Higgs boson. It will be successful in many other scenaria too. Still a formidable computation!
- NLO Wilson coefficient for heavy quarks+squarks+gluinos is known Harlander, Steinhauser
- It should be a very good approximation for a light MSSM Higgs boson
- ET hierarchies are not always satisfied. E.g. heavy Higgs boson? Other BSM than MSSM?

New techniques for analytic two-loop computations

- Automated reduction to master integrals

  Gehrmann, Remiddi; Laporta; CA, Lazopoulos

- Differential Equations Kotikov; Gehrmann, Remiddi
- Mellin-Barnes method

  Smirnov; Tausk

Two-loop diagrams with one quark or squark

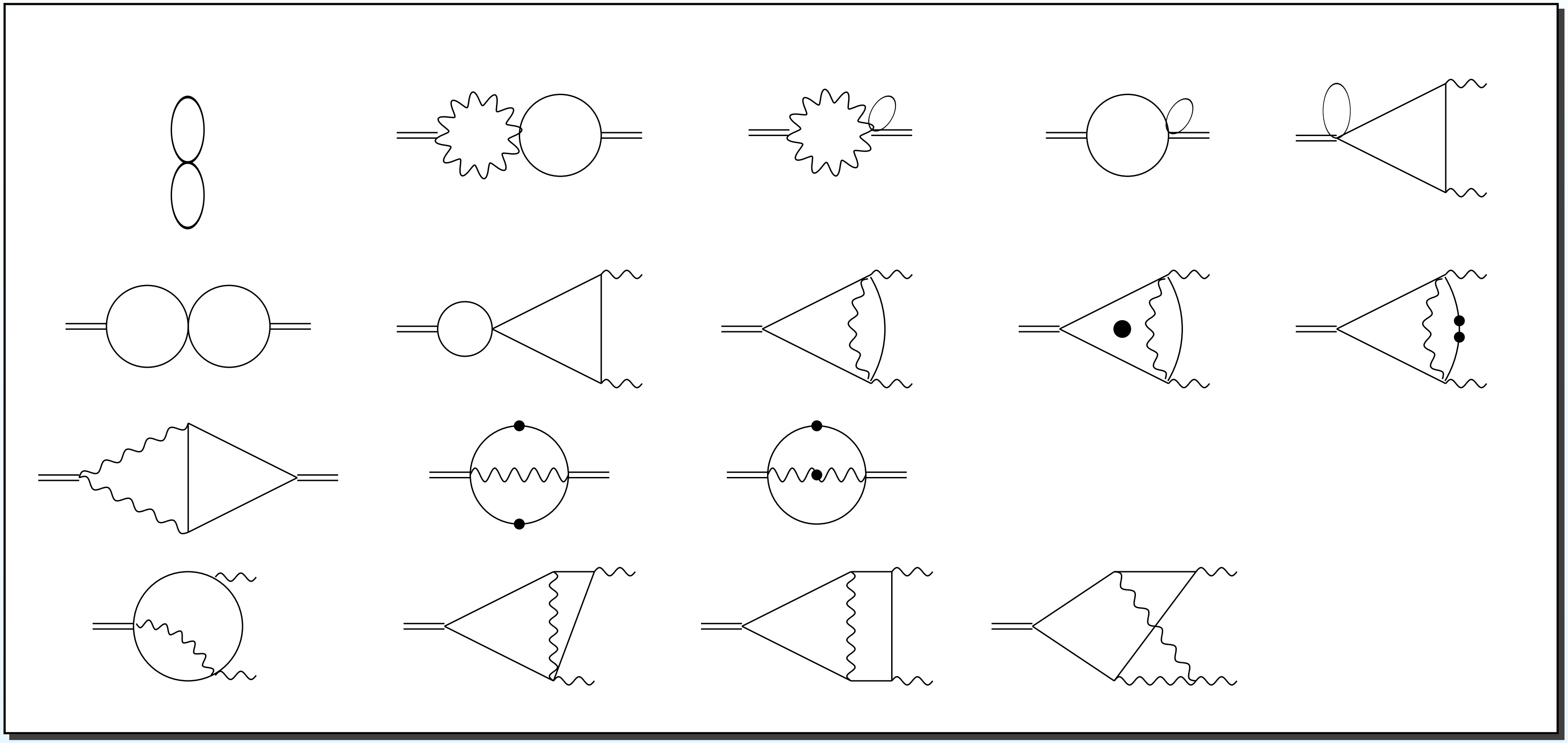
Complete analytic calculation

- reduced to linear combinations of master integrals using Laporta's algorithm
- complete set of master integrals computed with the method of differential equations (most were already known in the literature)
- analytic continuation of the master integrals above threshold

Contributions mediated by a heavy quark agree with the results of Spira *et al.* in the analytic form derived by Harlander and Kant
First results for the scalar quark contributions, simultaneous with

Aglietti *et al.* and Mühlleitner and Spira

Master Integrals



All computed in terms of logs and polylogs or equivalent functions

valid in all kinematic regions.

Squark contributions at two loops

$$\frac{4\,x\,C_F}{(1-x)^2}\Bigg\{5+\frac{3\,x^2}{(1-x)\,(1+x)}\,H(0,x)-3\,H(1,x)+\frac{4\,x\,\zeta_2}{(1-x)^2}\,H(0,x)+\frac{8\,x\,(1+x^2)\,\zeta_2}{(1-x)^3\,(1+x)}\,H(0,0,x)+\frac{36\,x\,(1+x^2)\,\zeta_2^2}{5\,(1-x)^3\,(1+x)}+\frac{12\,x\,\zeta_3}{(1-x)^2}$$
$$+\frac{16\,x\,(1+x^2)\,\zeta_3}{(1-x)^3\,(1+x)}\,H(0,x)-\frac{3\,x\,(1+5\,x)}{(1-x)^2\,(1+x)}\,H(0,0,x)+\frac{6\,x}{(1-x)\,(1+x)}\,H(0,1,x)+\frac{6\,x}{(1-x)\,(1+x)}\,H(1,0,x)$$
$$+\frac{16\,x}{(1-x)^2}\,H(0,-1,0,x)-\frac{x\,(-13+7\,x)}{(1-x)^3}\,H(0,0,0,x)+\frac{12\,x}{(1-x)^2}\,H(0,0,1,x)+\frac{8\,x}{(1-x)^2}\,H(0,1,0,x)$$
$$+\frac{16\,x}{(1-x)^2}\,H(1,0,0,x)-\frac{16\,x\,(1+x^2)}{(1-x)^3\,(1+x)}\,H(0,-1,0,0,x)+\frac{32\,x\,(1+x^2)}{(1-x)^3\,(1+x)}\,H(0,0,-1,0,x)$$
$$+\frac{2\,x\,(1+x^2)}{(1-x)^3\,(1+x)}\,H(0,0,0,0,x)-\frac{8\,x\,(1+x^2)}{(1-x)^3\,(1+x)}\,H(0,0,1,0,x)+\frac{28\,x\,(1+x^2)}{(1-x)^3\,(1+x)}\,H(0,1,0,0,x)\Bigg\}$$
$$\frac{4\,x\,C_A}{(1-x)^2}\Bigg\{3-\frac{32\,x\,\zeta_2^2}{5\,(1-x)^2}-\frac{16\,x\,\zeta_3}{(1-x)^2}-\frac{12\,x\,\zeta_3}{(1-x)^2}\,H(0,x)-\frac{24\,x\,\zeta_3}{(1-x)^2}\,H(1,x)-\frac{2\,x}{(1-x)^2}\,H(0,0,x)+\frac{2\,(1-7\,x)\,x}{(1-x)^3}\,H(0,0,0,x)$$
$$+\frac{16\,x}{(1-x)^2}\,H(1,0,0,x)-\frac{4\,x\,\zeta_2}{(1-x)^2}\,H(0,0,x)-\frac{8\,x\,\zeta_2}{(1-x)^2}\,H(1,0,x)-\frac{8\,x}{(1-x)^2}\,H(0,0,-1,0,x)-\frac{2\,x}{(1-x)^2}\,H(0,0,0,0,x)$$
$$-\frac{16\,x}{(1-x)^2}\,H(1,0,-1,0,x)+\frac{8\,x}{(1-x)^2}\,H(1,0,0,0,x)\Bigg\}$$

Many massive particle in the loops

- Analytic computations are not easy any more!
  Mass-thresholds and singualrities in $D = 4$ dimensions.
- Could be attacked numerically; e.g. methods of Passarino and Uccirati or Spira et al.
- These methods operate on a case by case basis and may be limited in applications.
- Do we have an algorithm which can treat generic mutli-loop integrals with infrared, ultraviolet, and all types of threshold singularities?

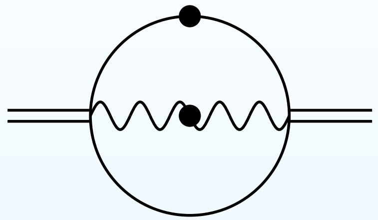
Automated numerical methods

Two general and fully automated methods to deal with multiloop integrals in a numerical way

- sector decomposition — Binoth, Heinrich
  - extended to fully differential NNLO cross section calculations — CA, Melnikov, Petriello
  - not possible to handle thresholds automatically
- numerical integration of Mellin-Barnes representations — CA, Daleo; Czakon
  - works fine both in Euclidean and physical regions
  - has problems in most loop integrals with internal masses
  - most probably cannot deal with thresholds

None of these two can do $gg \to h$ at two loops

Loop Singularities



$$\sim \int dxdy \frac{\cdots}{x^{1+\epsilon}\left(M_t^2(x+y) - M_h^2 xy - i\delta\right)^{1+\epsilon}}$$

- (Overlapping) singularities at the edges of the integration region. Regulated by ϵ

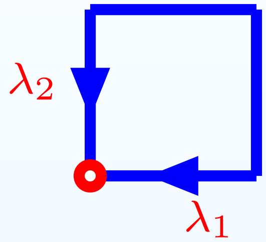
$$x = y = 0$$

- Threshold singularities $\rightsquigarrow i\pi$ terms

$$M_t^2(x+y) = M_h^2 xy$$

Overlapping singularities can be factorized

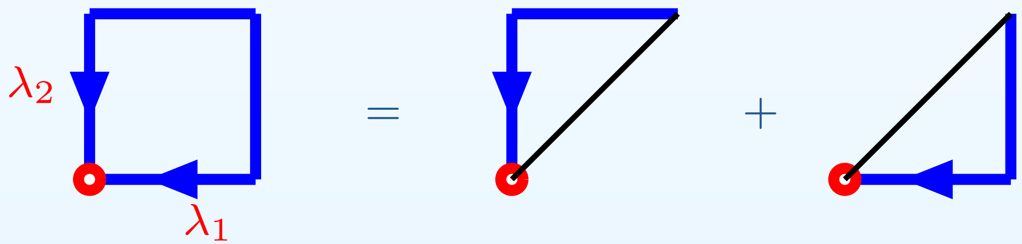
- Singularity when two (or more) variables reach the same corner



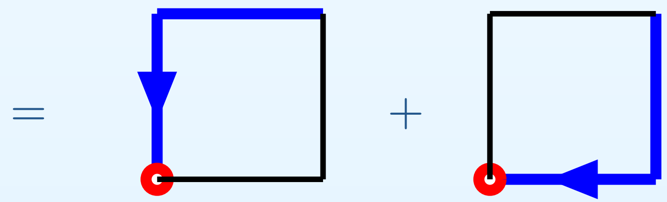
$$: \quad \frac{\lambda_1^\epsilon \lambda_2^\epsilon}{(\lambda_1 + \lambda_2)^2} f(\lambda_1, \lambda_2)$$

- Split into sectors

Binoth, Heinrich; Denner, Roth; Hepp

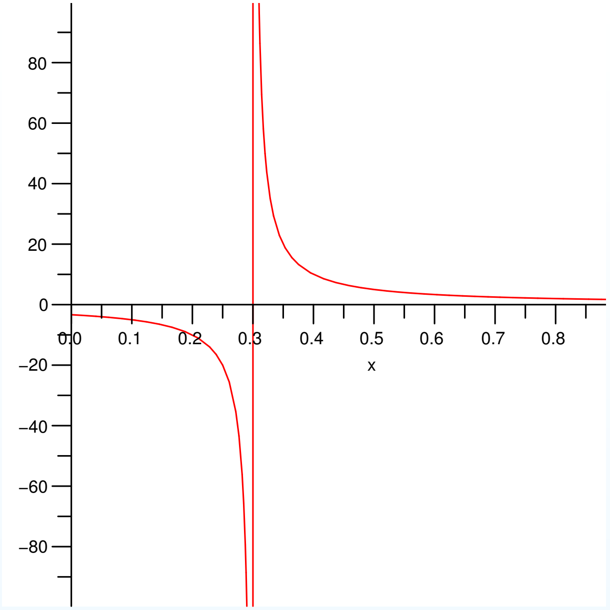


- map each sector to $[0, 1]$



$$= \int_0^1 d\lambda_1 d\lambda_2 \frac{1}{\lambda_1^{-1+\epsilon}} \frac{f(\lambda_1, \lambda_2 \lambda_1)}{(1+\lambda_2)^2} + \int_0^1 d\lambda_1 d\lambda_2 \frac{1}{\lambda_2^{-1+\epsilon}} \frac{f(\lambda_1 \lambda_2, \lambda_2)}{(1+\lambda_1)^2}$$

Threshold singularities



- Singular inside the integration region; not the edges

$$I = \int_0^1 dx \frac{1}{x - a - i0},$$

- Regulator $i0$ is not good enough for a numerical evaluation.
- Choose a different contour $C : z = x - i\lambda x(1 - x)$

$$\begin{aligned} I &= \int_C dz \frac{1}{z - a} = \int_0^1 dx \frac{\partial z}{\partial x} \frac{1}{z - a} \\ &= \int_0^1 dx \left[1 + i\lambda \left(1 - \frac{x}{2}\right)\right] \frac{1}{x - a - i\lambda x(1 - x)} \end{aligned}$$

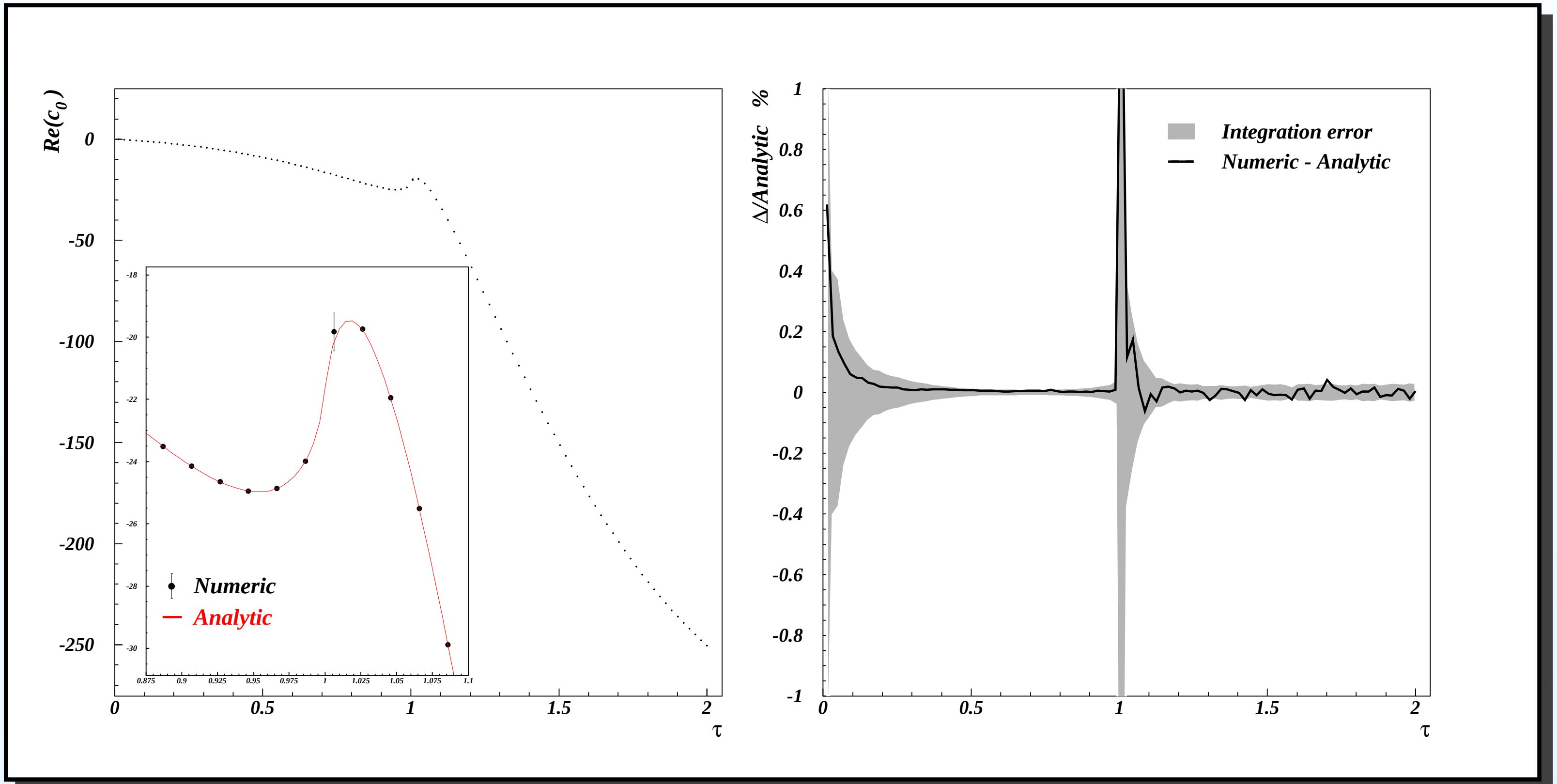
- Suitable for numerical integration!

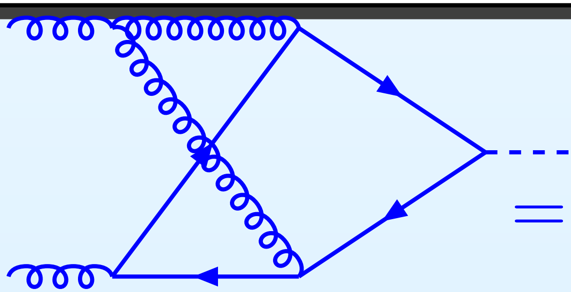
General multi-loop integration method

- Merge the sector decomposition algorithm with an algorithm proposed by Nagy and Soper to deform the contour automatically for Feynman parameters
- Very general method introduced by two groups:
  - Lazopoulos, Melnikov, Petriello to compute $pp \to ZZZ$ at NLO
  - CA, Beerli, Daleo for the two-loop SUSY QCD amplitude, re-computing numerically all diagrams with (initially) only quarks or one squark.

SUSY QCD corrections to $gg \to h$

whole amplitude, including gluinos and squark-mixing, with similar precision





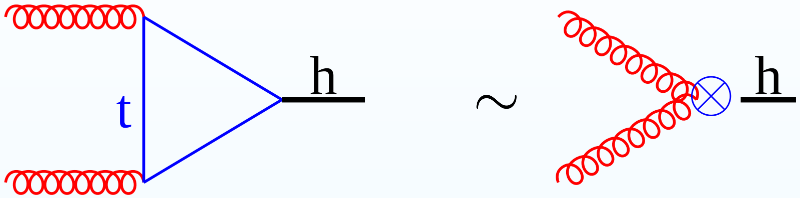
$$= \mathcal{C}\left(\frac{c_1}{\epsilon} + c_0\right)$$

Status of the calculation

- Have computed all two-loop diagrams with quarks, squarks (and squark-mixing), gluinos.
- Renormalization + checked the infrared poles
- Performed a consistency check with our separate analytic calculation in the $m_h \to 0$ limit.
- We are checking against the computation of the Wilson coefficient of Harlander and Steinhauser
- Re-computed the real radiation $gg \to hg, \ldots$ amplitudes
- Finishing checks on the two-loop amplitude
- Writing the NLO Monte-Carlo program. Results soon (sorry!)

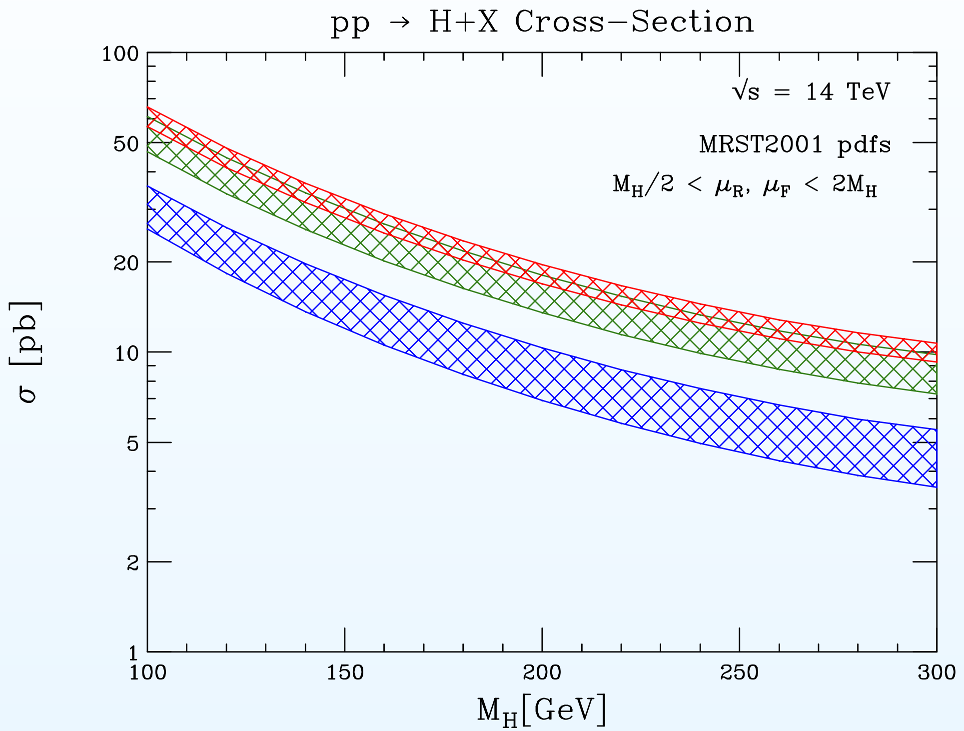
NNLO computation for SM $gg \to H \to WW \to l^+l^-\nu\nu$

Heavy top-quark approximation



- A very good approximation for a light Higgs boson
- Simplifies QCD corrections at NNLO ($3 \rightarrow 2$ loops).
- NNLO effective theory   Chetyrkin, Kniehl, Steinhauser

Higgs boson total cross-section through NNLO



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

- Slowly converging perturbative series: large NLO (70%) and smaller NNLO (30%) corrections,
- Scale variation ($\sim 15\%$ at NNLO)

Effect of experimental cuts

- NNLO for fully differential cross-sections are not trivial
- $pp \to h$, $pp \to h \to \gamma\gamma$: First such computations for a hadron collider process
  CA, Melnikov, Petriello
- Extended the NNLO calculation to $pp \to htoWW \to ll\nu\nu$
  CA, Dissertori,Stöckli
- For $m_h \sim 160 - 180\mathrm{GeV}$ almost exclusive decay to Ws.
- No narrow peak reconstruction; large backgrounds from top and W pairs.
- Aggressive cuts (jet-veto,large missing energy, small lepton angle, restricted lepton p_t) to isolate a signal.
- What is the cross-section after cuts?

Accepted cross-section

- Loose preselection cuts

$\sigma(\text{fb})$	LO	NLO	NNLO
$\mu = \frac{m_h}{2}$	71.63 ± 0.07	126.95 ± 0.13	140.73 ± 0.45

$M_{ll} < 80\text{GeV},\ p_t^l > 20\text{GeV},\ |\eta^l| < 2,\ \Delta\phi < 135°,;E_t^{miss} > 20\text{GeV}$

- Signal selection cuts

$\sigma(\text{fb})$	LO	NLO	NNLO
$\mu = \frac{m_h}{2}$	21.002 ± 0.021	22.47 ± 0.11	18.45 ± 0.54
$\mu = 2m_h$	14.529 ± 0.014	19.50 ± 0.10	19.01 ± 0.27

$12\text{GeV} < M_{ll} < 40\text{GeV},\ p_t^l > 25\text{GeV},\ 30\text{GeV} < p_t^{l,max} < 55\text{GeV},\ |\eta^l| < 2,\ \Delta\phi < 45°,;E_t^{miss} > 50\text{GeV},;\text{isolation},\ p_t^{\text{jet}} < 25\text{GeV}$

Conclusions

- Two-loop amplitude for $gg \to h$ in SUSY QCD:
  - Complete analytic and numerical calculation of single quark and squark loops
  - Last checks on the full amplitude including gluino and mixed squark diagrams
- NLO Monte-Carlo is also under completion
- A new numerical method for computing multi-loop divergent integrals with thresholds automatically
- Brief report on the NNLO cross-section for the SM $pp \to H \to WW \to ll\nu\nu$ at the LHC. Dramatic change of K-factors with cuts!