Exact top-quark mass dependence in hadronic Higgs production

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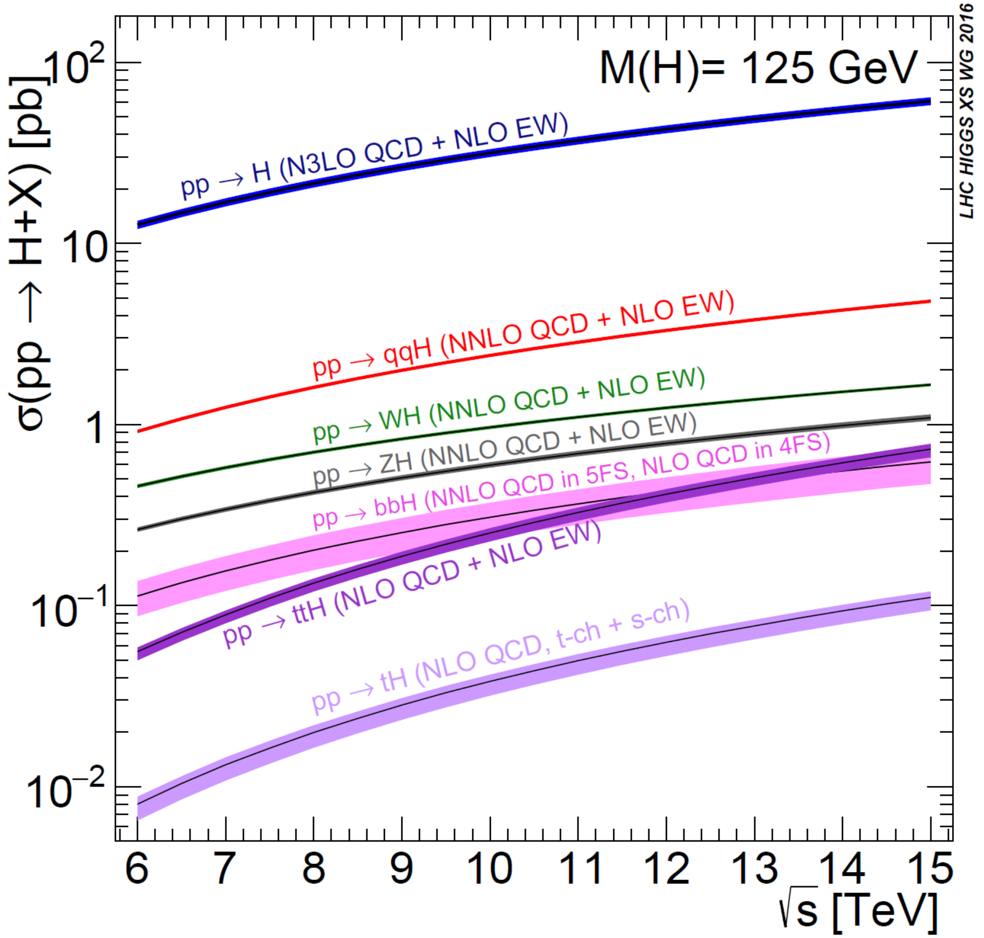
Motivation

- Gluon fusion is the predominant Higgs-boson production mode at the LHC
- Higgs-boson plays unique role in the SM:
  - Only scalar particle
  - Only particle with Yukawa interactions to fermions



Handbook of LHC Higgs cross sections:
4. Deciphering the nature of the Higgs sector
Report of the LHC Higgs Cross Section Working Group `16

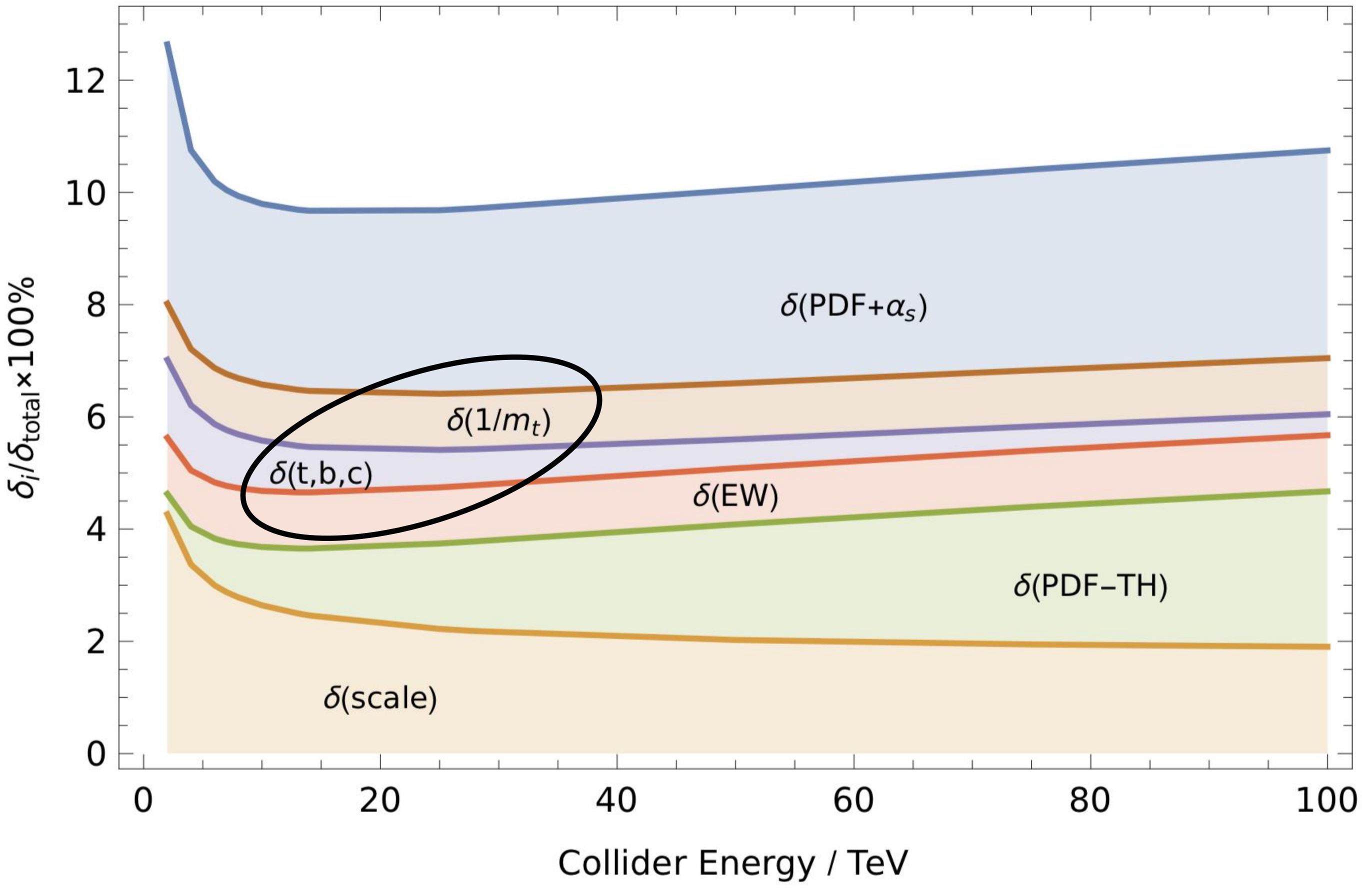
LHC @13 TeV

$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\,(\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\,(\textbf{PDF}+\alpha_s)\,.$$

Theory uncertainties

- δ(scale) and δ(PDF-TH) due to missing higher-order terms in $\hat{\sigma}$ and PDFs Anastasiou, et al. `15
- δ(trunc) has been removed Mistlberger `18
- δ(EW) was addressed recently
  Bonetti, Melnikov, Tancredi `18
  Anastasiou, del Duca, et al. `19
  Becchetti, Bonciani, et al. `21
- δ(t,b,c) and $\delta(1/m_t)$ related to quark mass effects

Higgs Physics at the HL-LHC and HE-LHC
Report from Working Group 2 on the Physics of the HL-LHC, and Perspectives at the HE-LHC `19



δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
+0.10 pb −1.15 pb	±0.18 pb	±0.56 pb	±0.49 pb	±0.40 pb	±0.49 pb
+0.21% −2.37%	±0.37%	±1.16%	±1%	±0.83%	±1%

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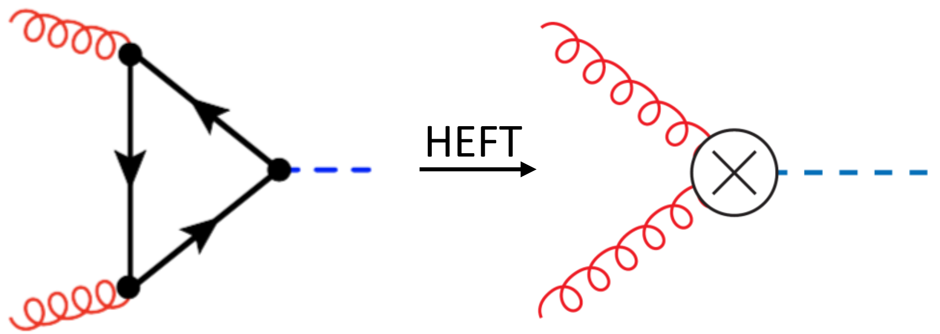
Contributions to σ_{tot}

$48.58\,\text{pb} =$	$16.00\,\text{pb}$	$(+32.9\%)$	(LO, rEFT)
	$+\,20.84\,\text{pb}$	$(+42.9\%)$	(NLO, rEFT)
	$-\;2.05\,\text{pb}$	(-4.2%)	$((t,b,c)$, exact NLO)
	$+\;9.56\,\text{pb}$	$(+19.7\%)$	(NNLO, rEFT)
	$+\;0.34\,\text{pb}$	$(+0.7\%)$	(NNLO, $1/m_t$)
	$+\;2.40\,\text{pb}$	$(+4.9\%)$	(EW, QCD-EW)
	$+\;1.49\,\text{pb}$	$(+3.1\%)$	(N^3LO, rEFT)



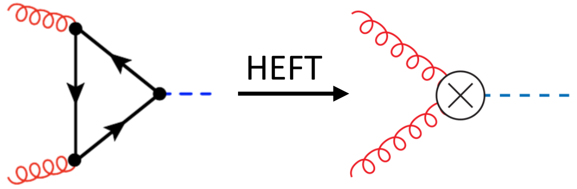
"Born-improved" total cross section:

$$\sigma^{\text{HO}}_{\text{HEFT}} = \left(\frac{\sigma^{\text{HO}}}{\sigma^{\text{LO}}}\right)_{M_t\to\infty} \sigma^{\text{LO}}$$

- Gluon-fusion is induced by quark loops
  - NLO result available for arbitrary quark masses Graudenz, Spira, Zerwas `93
  - Radiative corrections beyond NLO restricted to top-loop induced terms Anastasiou, Melnikov `02 Harlander, Kilgore `02 Ravindran, Smith, van Neerven `03
- Dominant effect of top-loop induced terms can be accounted for in HEFT approximation

HEFT

- Introduce effective Higgs-gluon vertex
  - → reduce number of loops by one
  - → reduce number of scales by one



- Very good agreement with exact result at NLO

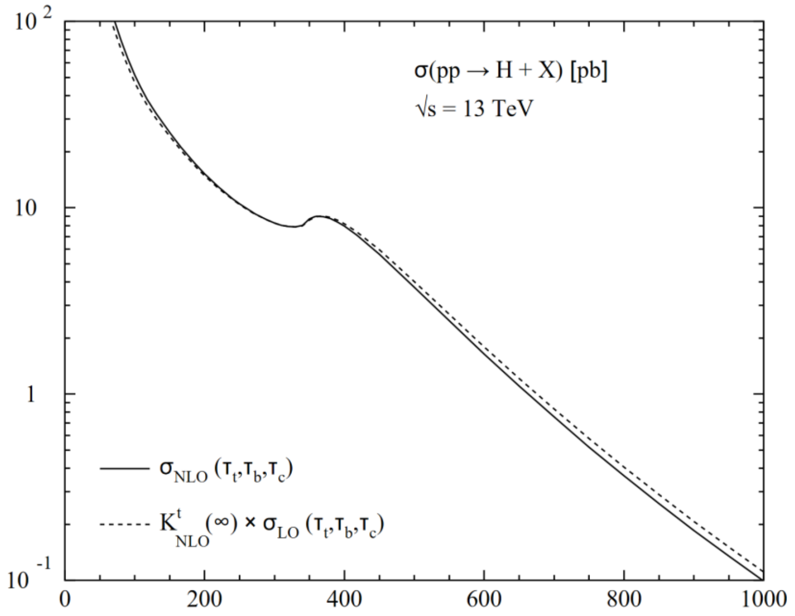
→ Remarkable, because

  - M_t being the largest scale is invalid over large range of $\sqrt{\hat{s}}$
  - $M_t \to \infty$ is applied to more than 50% of total cross section
  - HEFT fails to capture top-mass effects for partonic quark channels

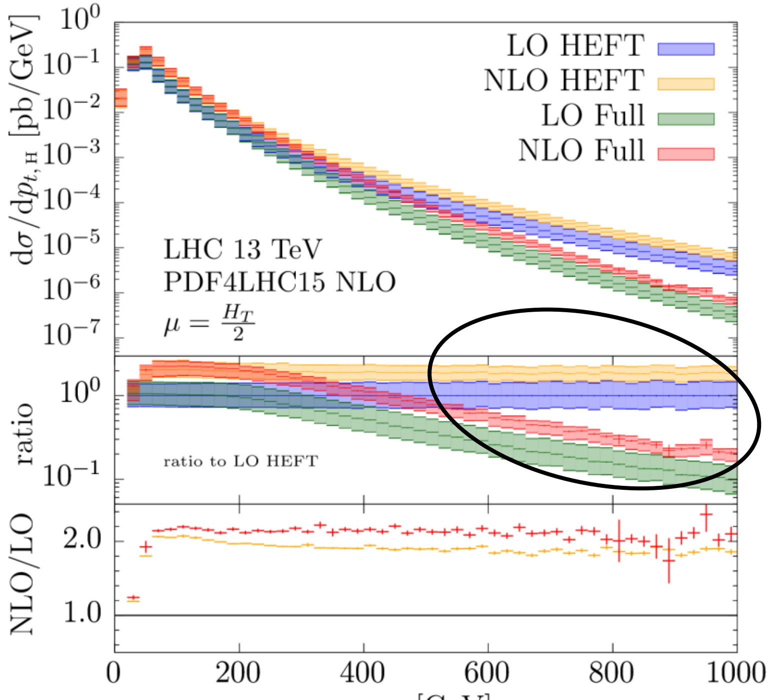
- Qualitative explanation:
  - Suppression of large-$\hat{s}$ region by PDFs
  - Dominance of the soft region

- Only estimate of top-mass effects beyond HEFT at NNLO based on combination of $1/M_t$-expansion with leading terms in large-$\hat{s}$ limit

  → Eliminate this uncertainty with exact calculation of top-quark mass effects



Spira `16



Jones, Kerner, Luisoni `18

Ingredients

- 3-loop virtual corrections (✓)

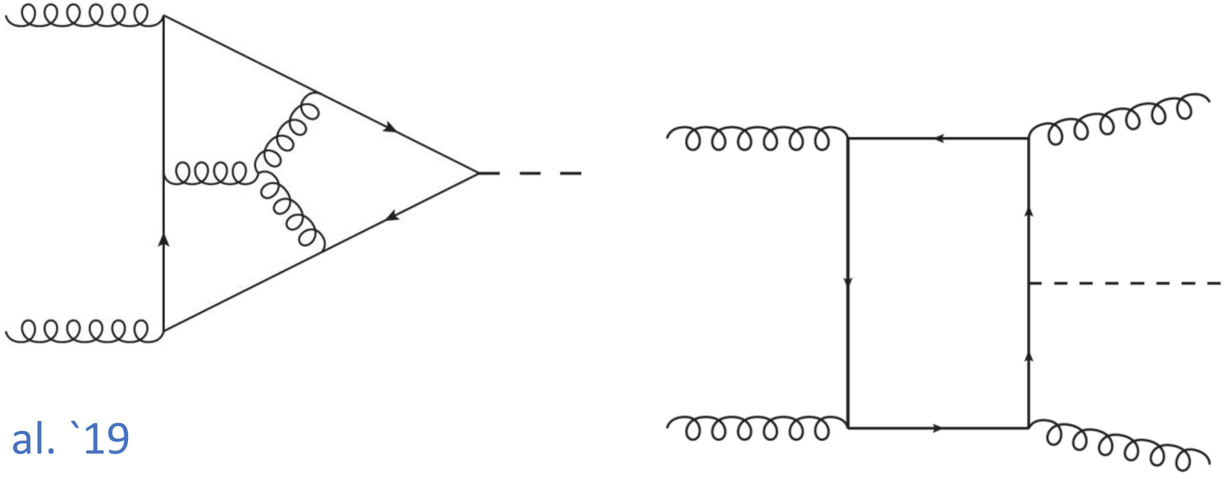
  → Davies, Gröber, et al. `19
  Czakon, MN `20

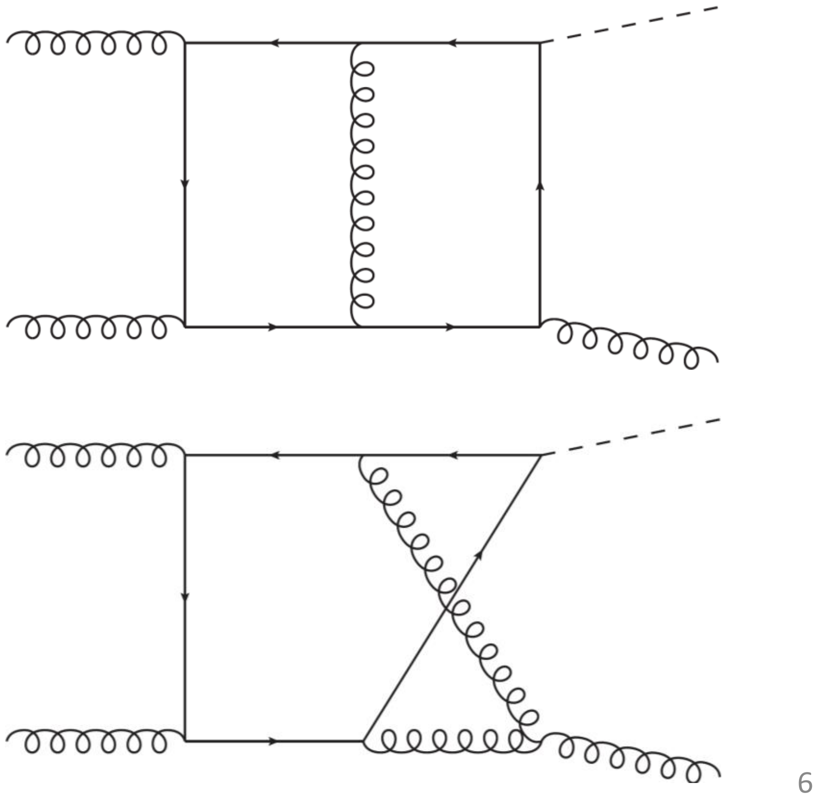
- Double-real corrections (✓)

  → del Duca, Kilgore, et al. `01

- 2-loop real-virtual corrections:
  - 4 scales (m_q^2, s, t, u or m_H^2)
    + dimension $\mathrm{d} = 4 - 2\varepsilon$
  - 282 diagrams for gg→Hg
  - 49 diagrams for $q\bar{q}$ →Hg

→ Master integrals have been computed
Frellesvig, Hidding, et al. `19

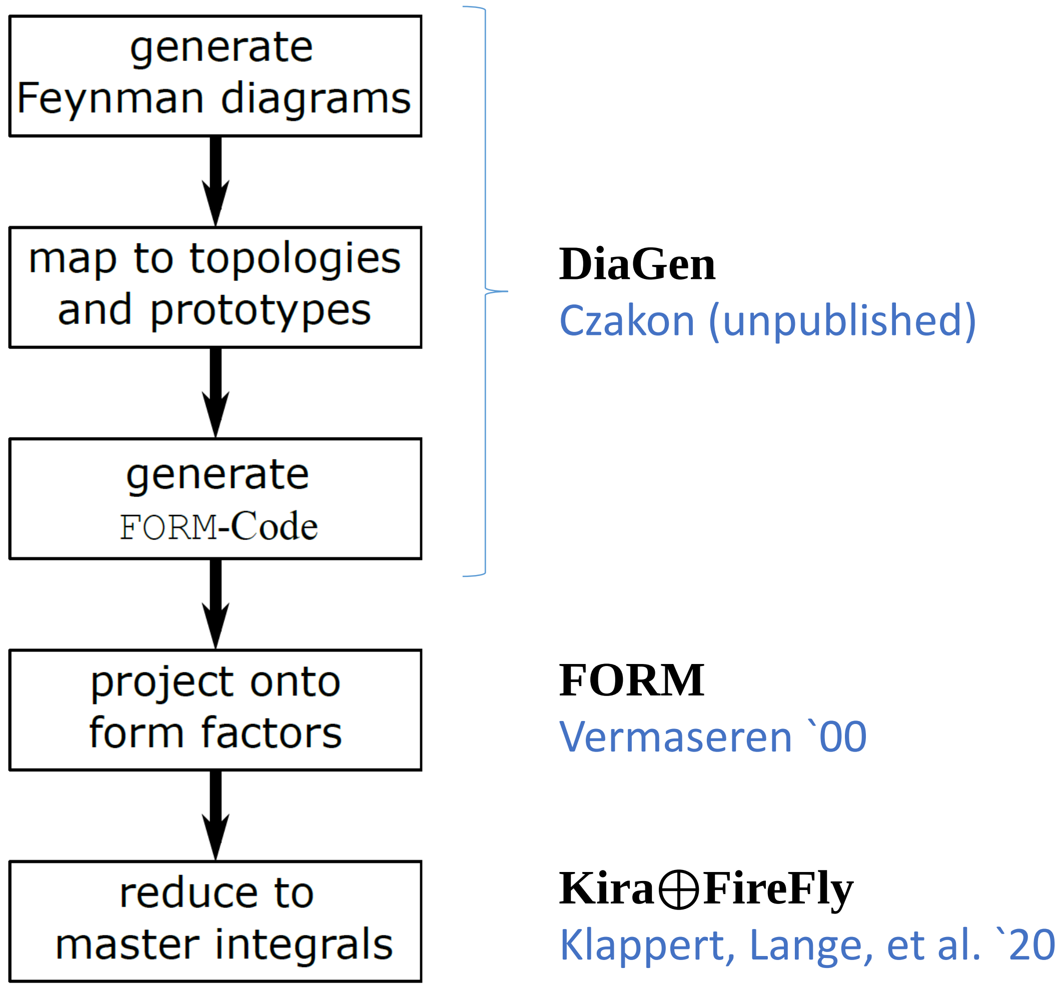




Workflow of the computation

- Get rid of tensor/colour structure to end up with a linear combination of scalar integrals with rational function coefficients in front

- Reduce the scalar integrals to a linearly independent set of master integrals (MI) (447 master integrals for gg→Hg)
- Reduction is highly non-trivial since rational coefficients depend on 5 variables!
  → Exploit finite fields to reconstruct symbolic coefficients from numerical probes of the system of equations



Details of the reduction

- Run reduction once with symbolic d and m_q^2, kinematics are set to rational numbers

  → arrive at the default basis of dotted masters

- Perform an automatized (heuristic) search for a basis, which minimizes the size of differential equations in m_q^2 by shifting the dots

- Reduce with full symbolic dependence to this set of master integrals

- Additionally, shift dimension of (almost) all masters with seven propagators from $\mathrm{d} = 4 - 2\varepsilon$ to $\mathrm{d} = 6 - 2\varepsilon$

→ New basis guarantees faster reduction
→ Better numerical stability

Computing the MI

- Refrain from computing the MI analytically
- Two popular methods for calculating MI numerically:
  - Sector decomposition
  - Via differential equations
- Take the derivative of the MI with respect to the kinematic invariants and reduce the result to obtain a system of differential equations
- Provide boundary conditions in the limit $m_q^2 \to \infty$ and let the system evolve

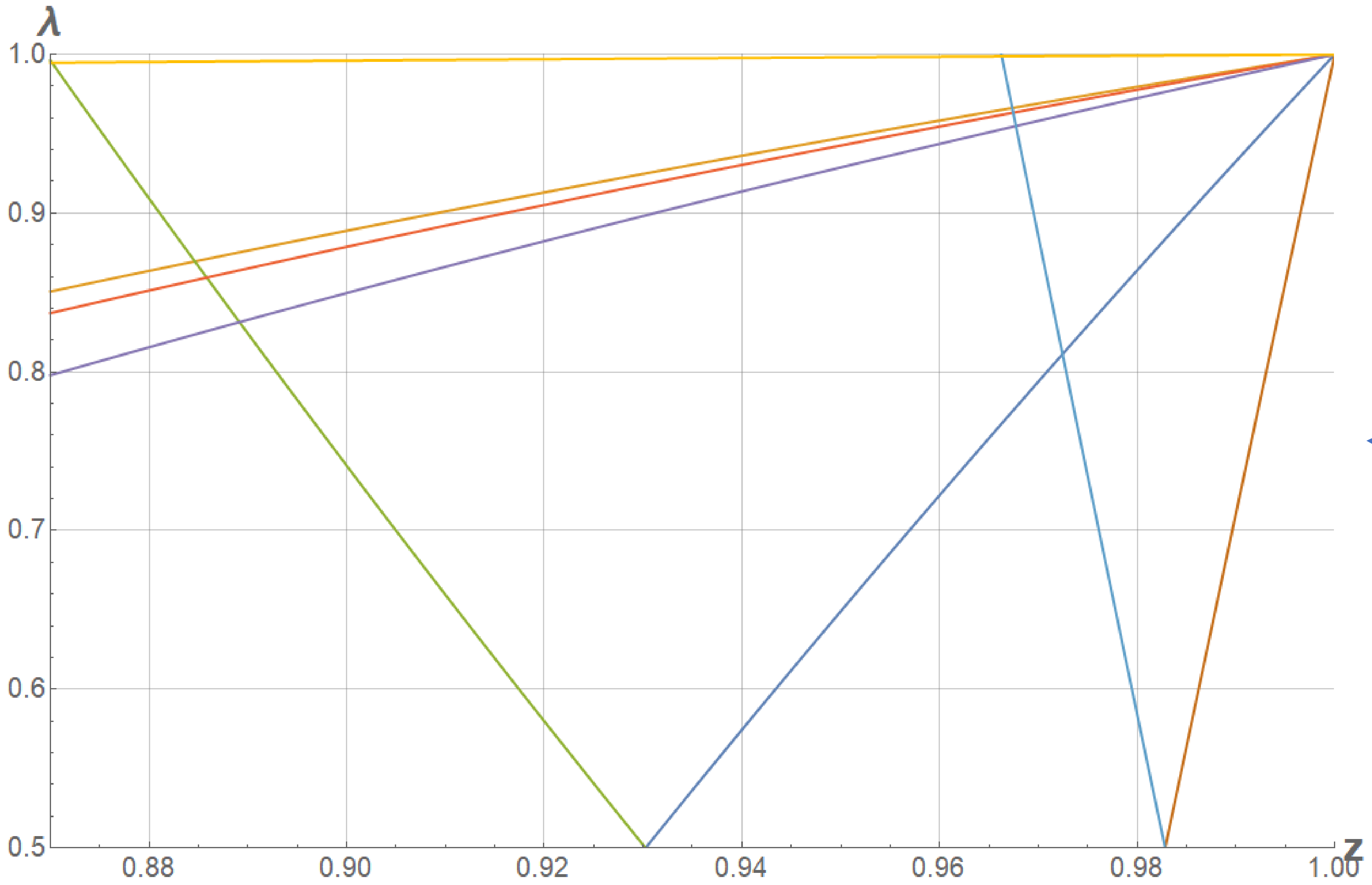
Details of the computation

$z = 1 - m_H^2/\hat{s}$

$\lambda = \hat{t}/(\hat{t}+\hat{u})$

$m_t^2/m_H^2 = 23/12$

Above top-quark threshold



Range of parameters:

- $\lambda \in (0,1)$
- $z \in (0,1)$

Poles of differential equations in λ

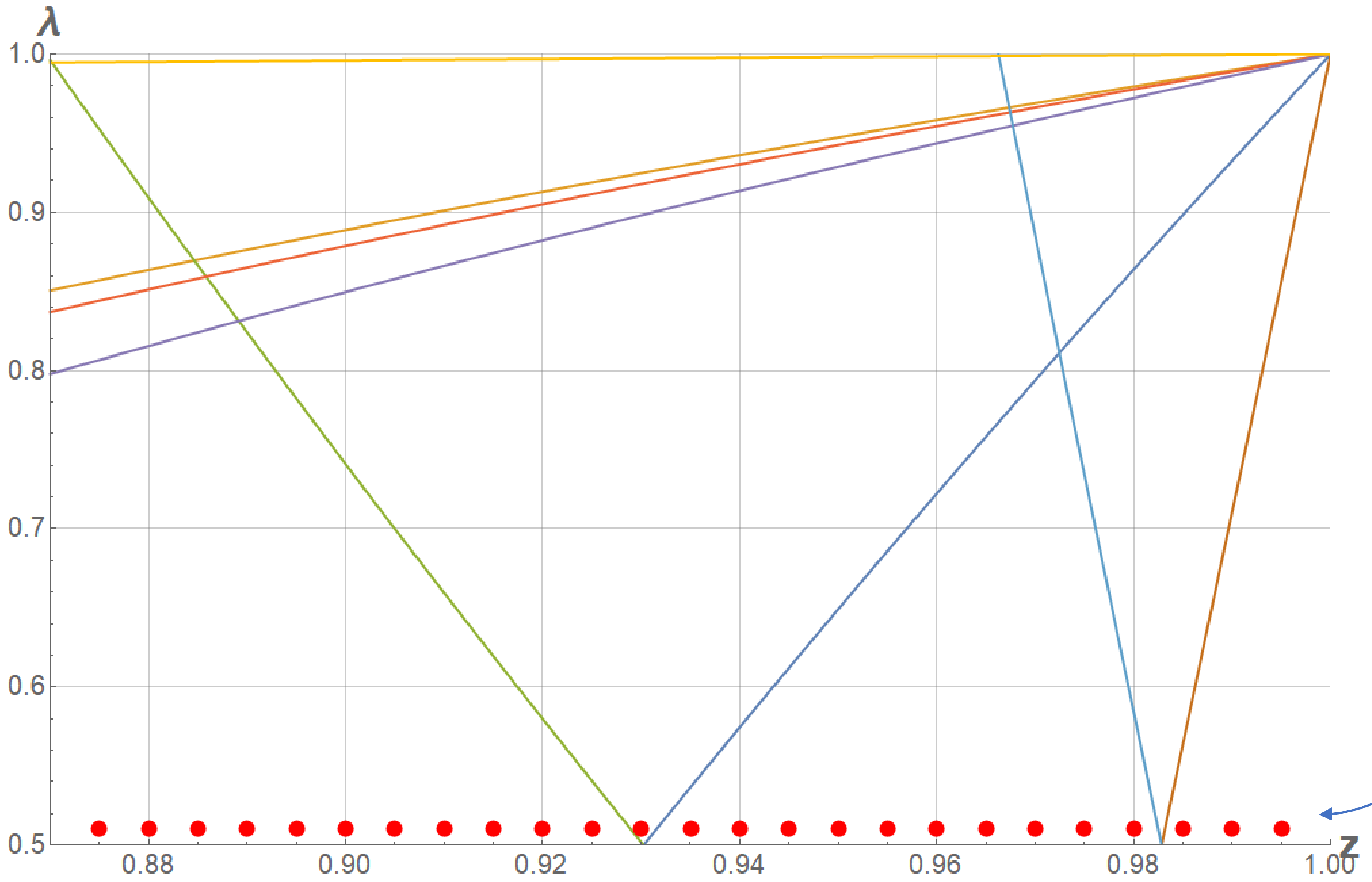
Details of the computation

$z = 1\text{-}m_H^2/\hat{s}$

$\lambda = \hat{t}/(\hat{t}+\hat{u})$

$m_t^2/m_H^2 = 23/12$

Above top-quark threshold



Integrate differential equations in m_q^2 from boundaries at $m_q^2 \to \infty$ to top-quark mass

Boundaries for numerical integration

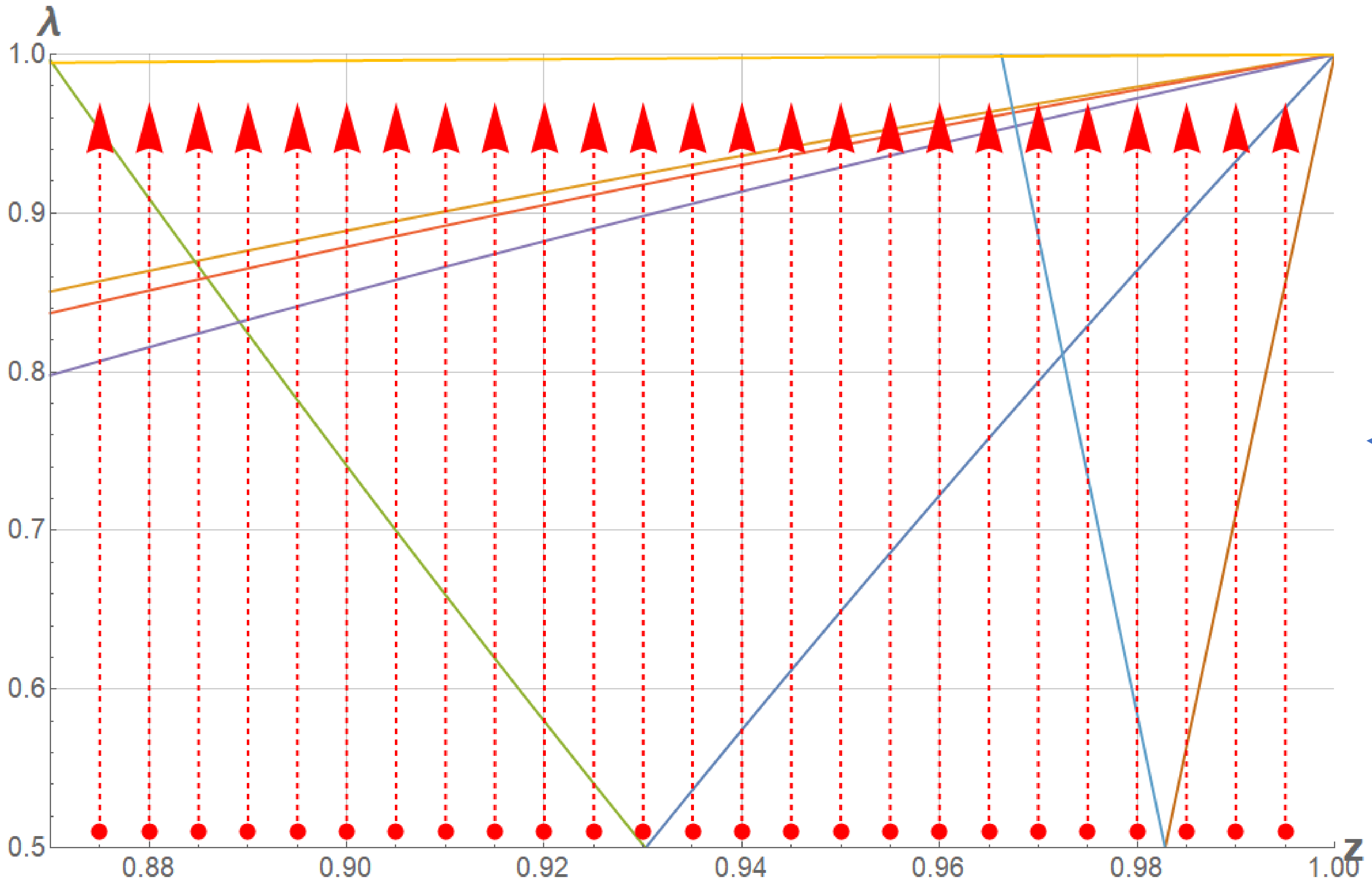
Details of the computation

$z = 1 - m_H^2/\hat{s}$

$\lambda = \hat{t}/(\hat{t}+\hat{u})$

$m_t^2/m_H^2 = 23/12$

Above top-quark threshold



Integrate differential equations in λ to the edge at $\lambda \sim 1$

Collect numerical samples for MI along straight integration contours

Details of the computation

- Problem is symmetric with respect to λ = 1/2

  → reflect numerical samples to cover entire region above top-quark threshold

- Below threshold:
  - Construct large-mass expansion up to order $(1/m_q^2)^{40}$ with full symbolic dependence
  - Method to obtain expansion coefficients inspired by interpolation techniques

  - Sufficient to cover region below top-quark threshold

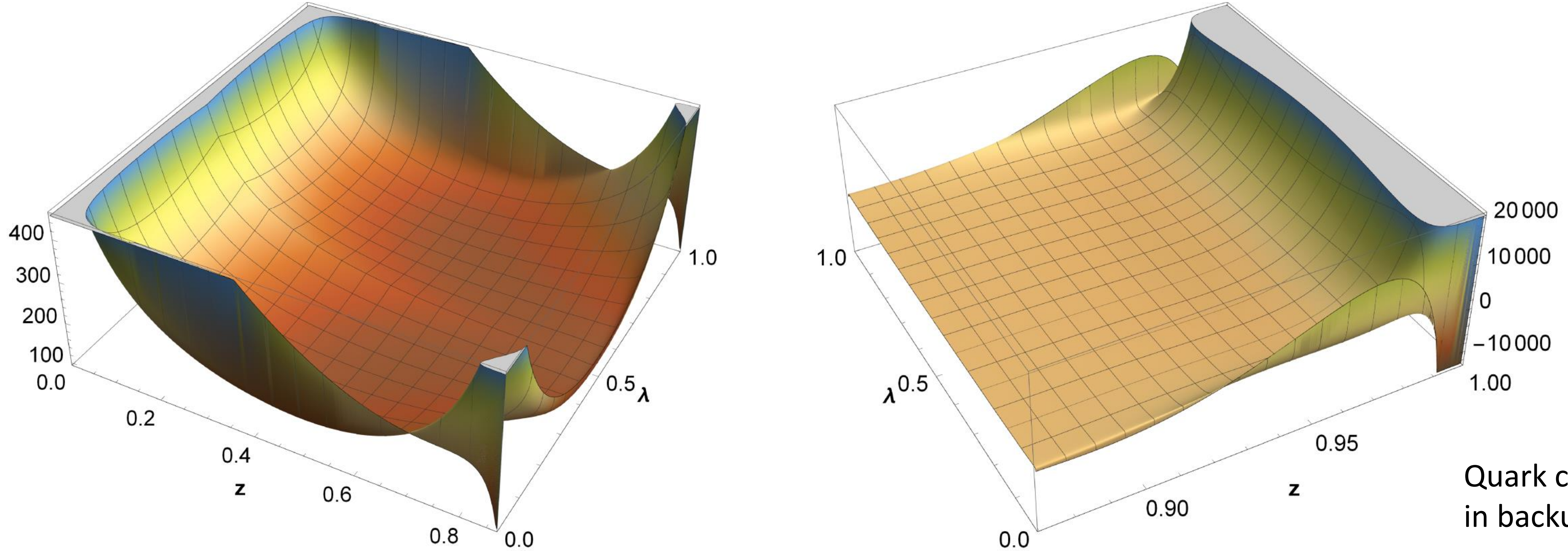
Subtraction for gg → gH

$z = 1 - m_H^2/\hat{s}$
$\lambda = \hat{t}/(\hat{t}+\hat{u})$
$m_t^2/m_H^2 = 23/12$

- Directly evaluate difference between HEFT and the exact result:

$$\langle M^{(1)}_{\text{exact}}|M^{(2)}_{\text{exact}}\rangle|_{\text{regulated}} \equiv \langle M^{(1)}_{\text{exact}}|M^{(2)}_{\text{exact}}\rangle - \left[\langle M^{(1)}_{\text{HEFT}}|M^{(2)}_{\text{HEFT}}\rangle + \frac{8\pi\alpha_s}{\hat{t}}\left\langle P^{(0)}_{gg}\left(\frac{\hat{s}}{\hat{s}+\hat{u}}\right)\right\rangle\langle F^{(1)}|(F^{(2)}_{\text{exact}} - F^{(2)}_{\text{HEFT}})\rangle\right]$$

- Real part of the regulated quantity at $\mu_R = m_H/2$:



Quark channels in backup →

- Integrate in λ and convolute with PDFs to obtain contribution to σ_{tot}
- Subtraction term and other contributions are computed with Monte Carlo methods using **Stripper** Czakon (unpublished)

Results

- Effects of a finite top-quark mass on the total hadronic Higgs-boson production cross section for the LHC
  - PDF set: NNPDF31_nnlo_as_0118
  - $\mu_R = \mu_F = m_H/2$
  - $M_H = 125$ GeV $\Rightarrow M_t \approx 173.055$ GeV

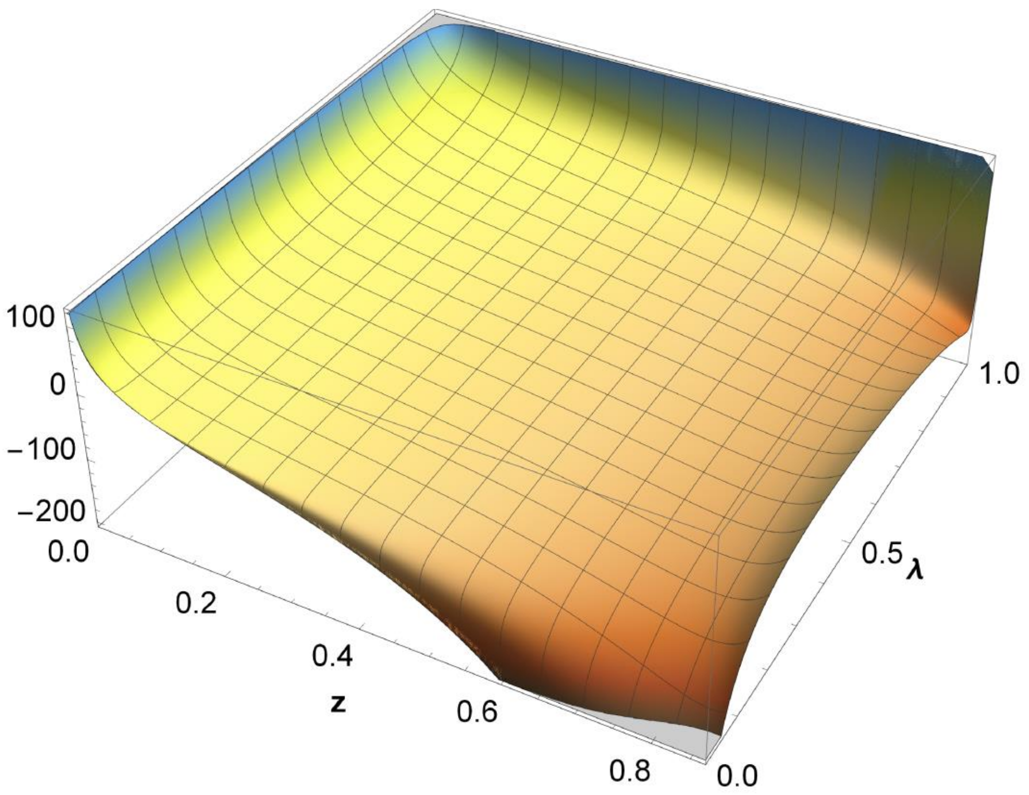
channel	$\sigma^{\text{NNLO}}_{\text{HEFT}}$ [pb] $\mathcal{O}(\alpha_s^2)+\mathcal{O}(\alpha_s^3)+\mathcal{O}(\alpha_s^4)$	$(\sigma^{\text{NNLO}}_{\text{exact}} - \sigma^{\text{NNLO}}_{\text{HEFT}})$ [pb] $\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^4)$	$(\sigma^{\text{NNLO}}_{\text{exact}}/\sigma^{\text{NNLO}}_{\text{HEFT}} - 1)$ [%]
$\sqrt{s} = 8$ TeV				
gg	$7.39 + 8.58 + 3.88$	$+0.0353$	$+0.0879 \pm 0.0005$	$+0.62$
qg	$0.55 + 0.26$	-0.1397	-0.0021 ± 0.0005	-18
$q\bar{q}$	$0.01 + 0.04$	$+0.0171$	-0.0191 ± 0.0002	-4
total	$7.39 + 9.15 + 4.18$	-0.0873	$+0.0667 \pm 0.0007$	-0.10
$\sqrt{s} = 13$ TeV				
gg	$16.30 + 19.64 + 8.76$	$+0.0345$	$+0.2431 \pm 0.0020$	$+0.62$
qg	$1.49 + 0.84$	-0.3696	-0.0115 ± 0.0010	-16
$q\bar{q}$	$0.02 + 0.10$	$+0.0322$	-0.0501 ± 0.0006	-15
total	$16.30 + 21.15 + 9.79$	-0.3029	$+0.1815 \pm 0.0023$	-0.26

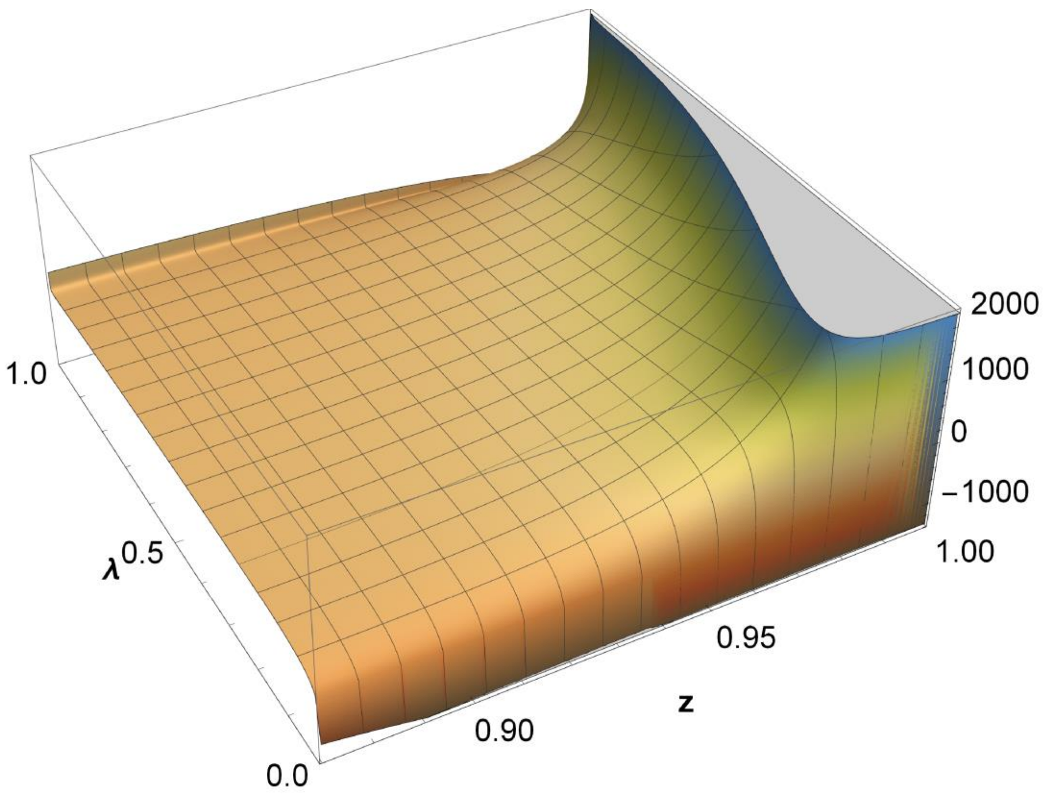
Conclusions

- The hadronic Higgs production cross section including the full top-quark mass dependence was computed
- Slight decrease relative to the result in HEFT
  - -0.26% at 13 TeV
  - -0.10% at 8 TeV
- The result confirms and eliminates the uncertainty estimate from the lack of knowledge of the exact top-quark mass effects
- Same techniques can be applied to compute bottom-quark mass effects

Backup

$qg \to \mathrm{qH}$





$q\bar{q} \rightarrow \mathrm{gH}$