Exact top-quark mass dependence in hadronic Higgs production
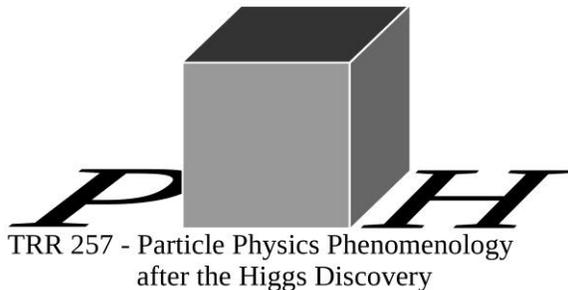
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in collaboration with M. Czakon, R.V. Harlander and J. Klappert

Institute for Theoretical Particle Physics and Cosmology

RWTH Aachen University

Based on arXiv:2105.04436

TRR 257 - Particle Physics Phenomenology
after the Higgs Discovery

Institute for
Theoretical
Particle Physics
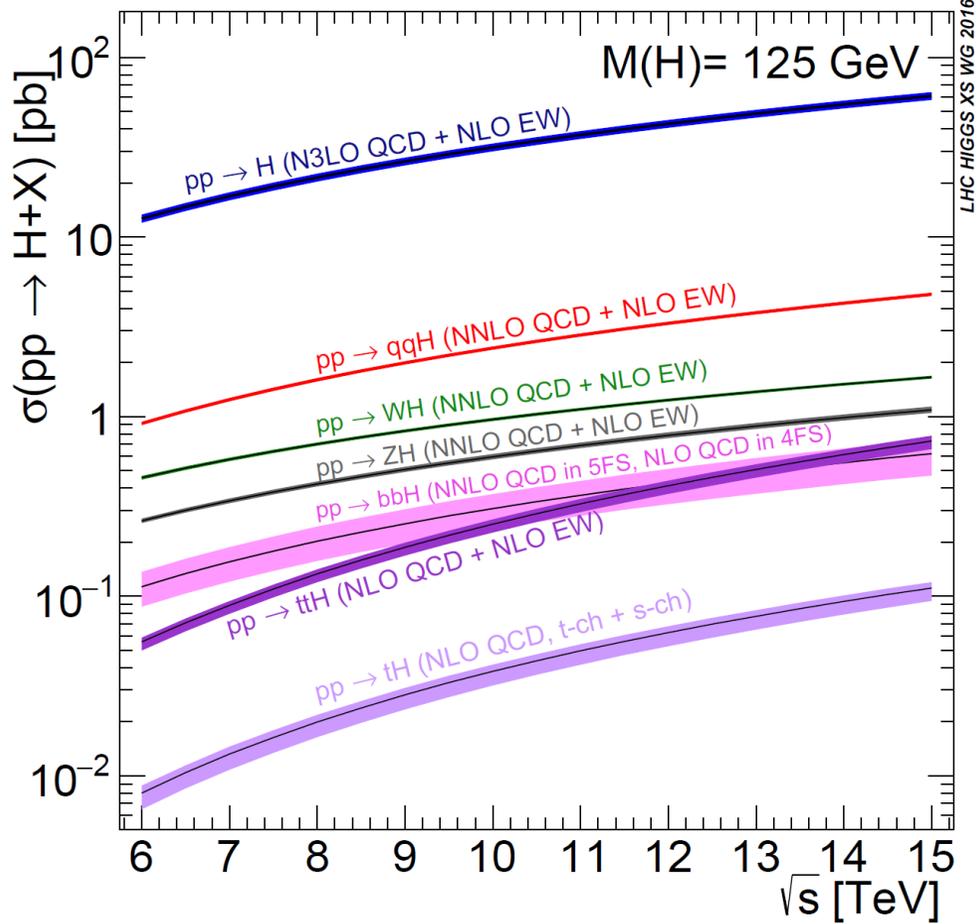and Cosmology

RWTH AACHEN UNIVERSITY

Young Scientists Forum
Aachen (virtual), May 28th 2021

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
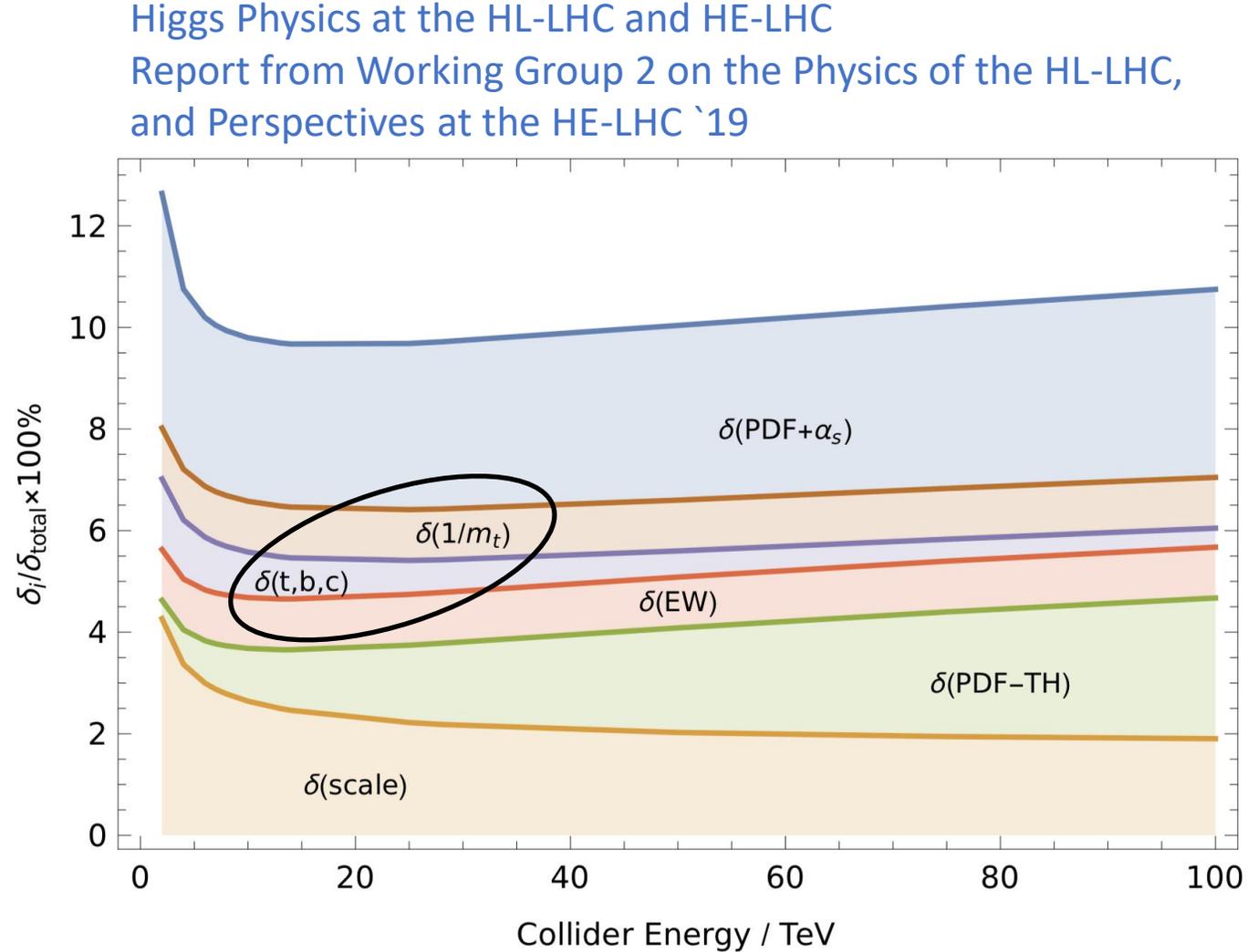Report of the LHC Higgs Cross Section Working Group `16

LHC @ 13 TeV

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

Theory uncertainties

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) 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

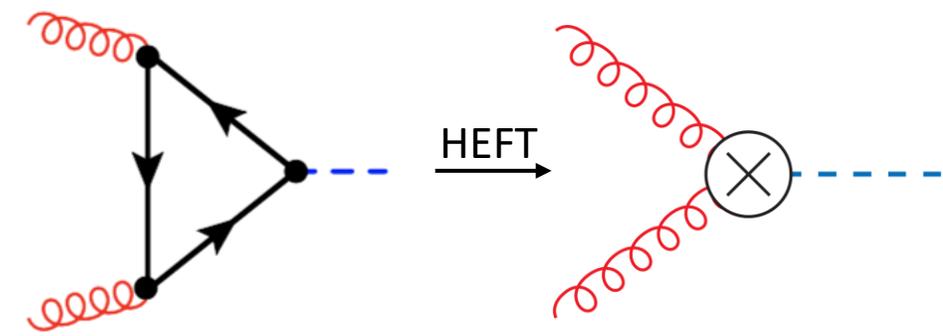| δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t, b, c)$	$\delta(1/m_t)$
$+0.10$ pb -1.15 pb	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$+0.21\%$ -2.37%	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

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

Contributions to σ_{tot}

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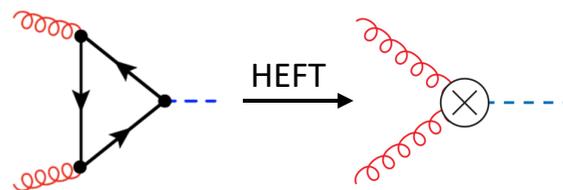& +\;\;1.49\,\text{pb} & (+3.1\%) & (\text{N}^3\text{LO, rEFT})
\end{array}
$$

"Born-improved" total cross section:

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

- 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

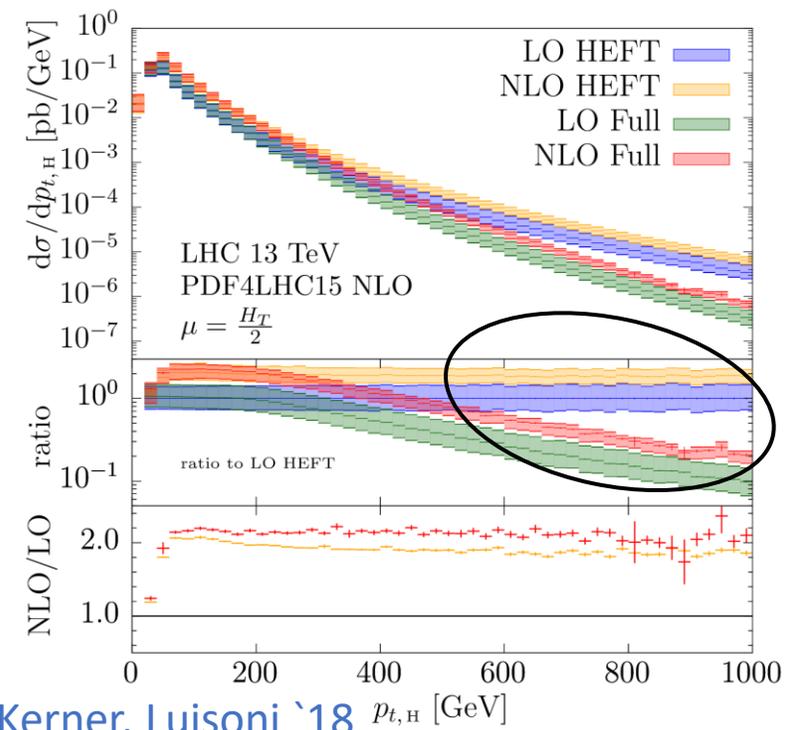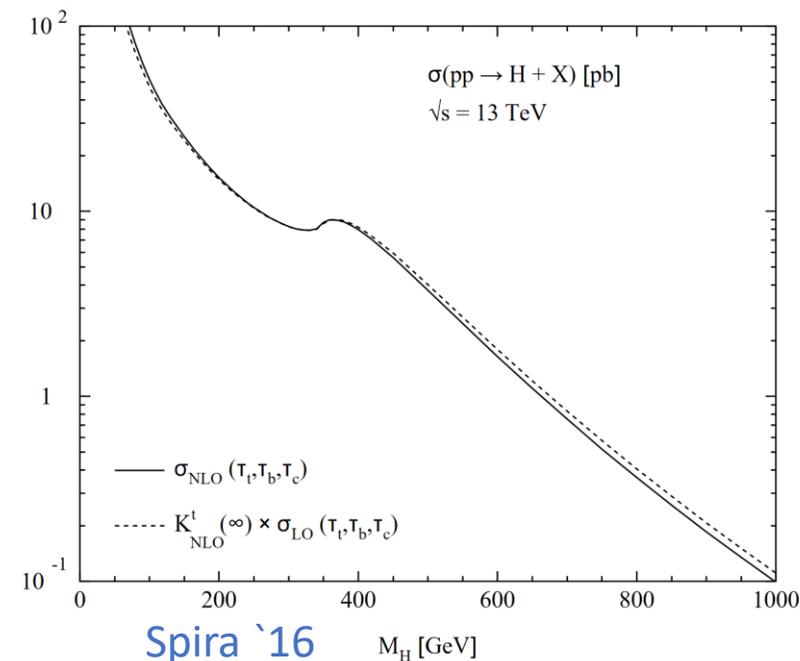- Very good agreement with exact result at NLO
  → <u>Remarkable</u>, because
  - M_t being the largest scale is invalid over large range of $\sqrt{s}$
  - $M_t \to \infty$ is applied to more than 50% of total cross section
  - HEFT fails to capture top-mass effects for partonic quark channels

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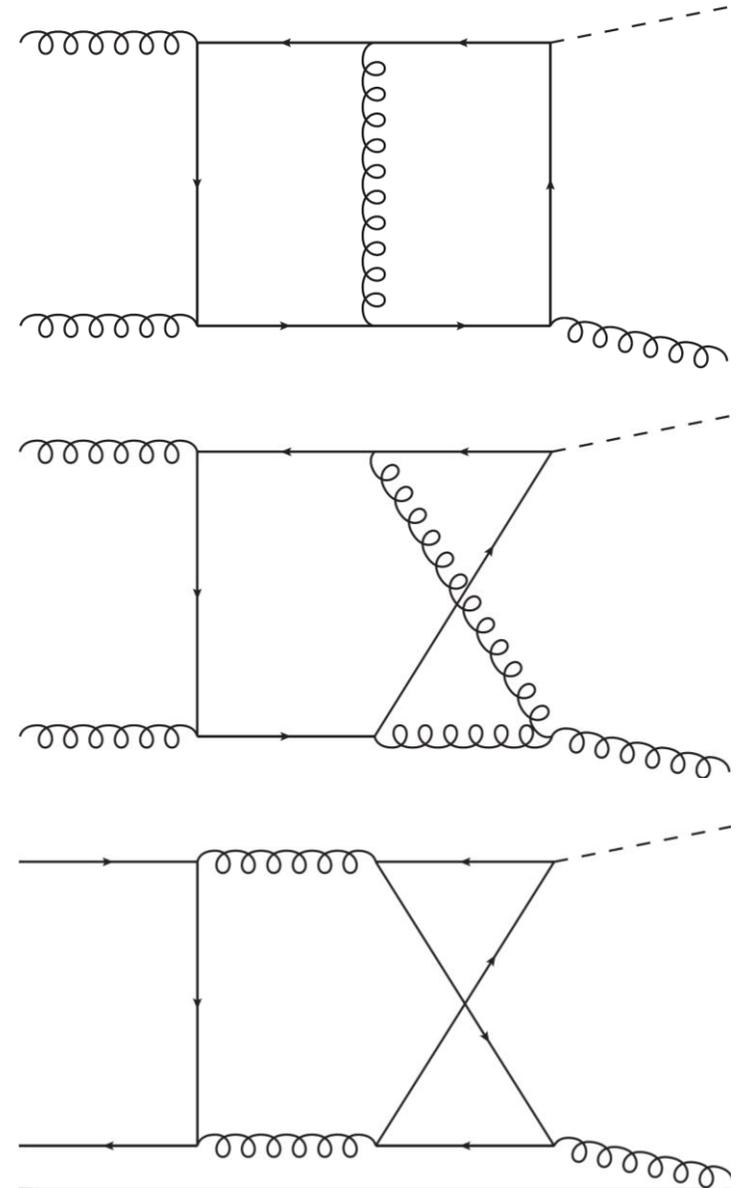 - Dominance of the soft region

- 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 $d = 4 - 2\varepsilon$
  - 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

generate Feynman diagrams

↓

map to topologies and prototypes

↓

generate FORM-Code

DiaGen
Czakon (unpublished)

↓

project onto form factors

FORM
Vermaseren `00

↓

reduce to master integrals

Kira⊕FireFly
Klappert, Lange, et al. `20

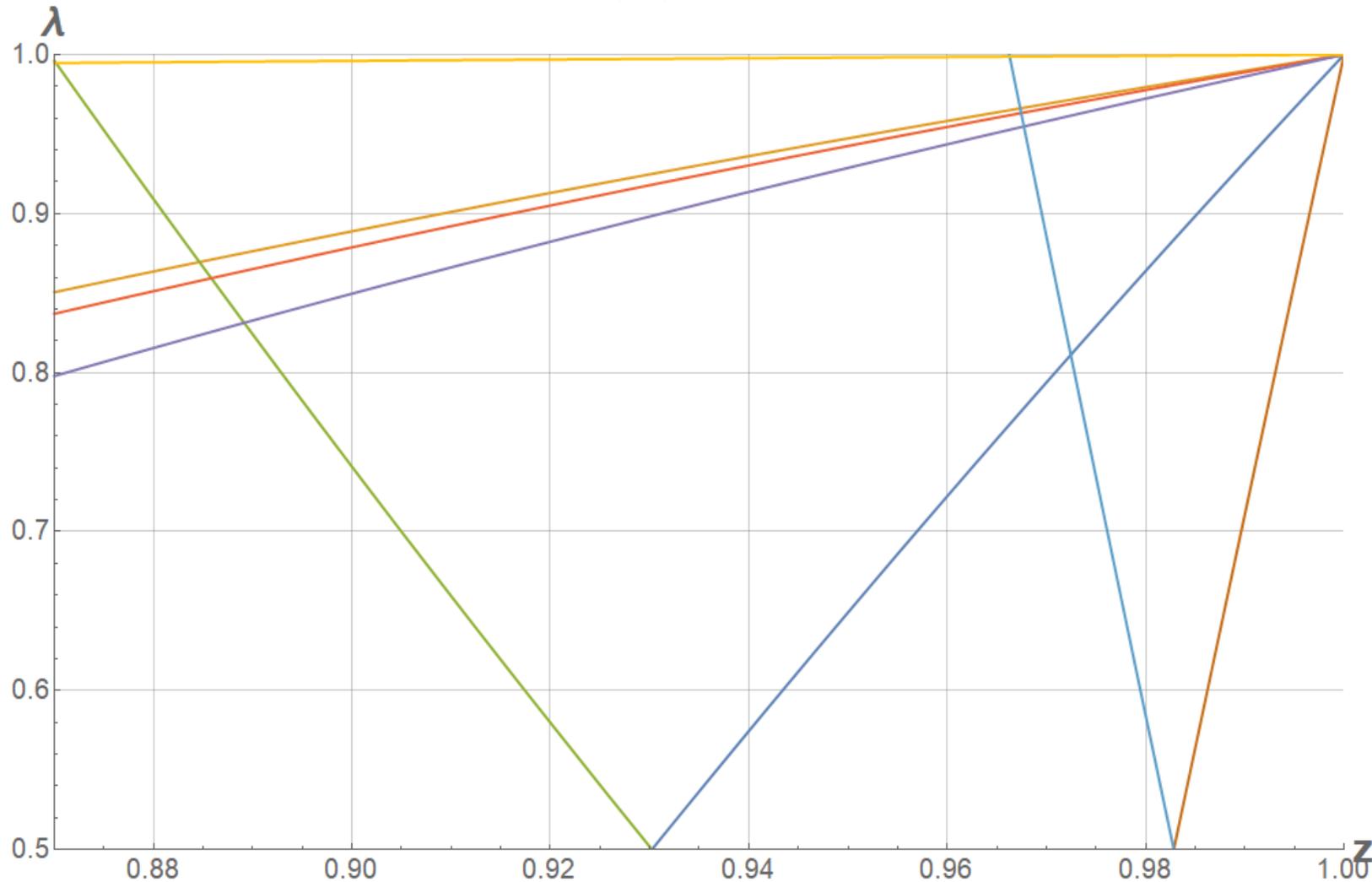# Details of the reduction

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

  → arrive at the default basis of <u>dotted masters</u>

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

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

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

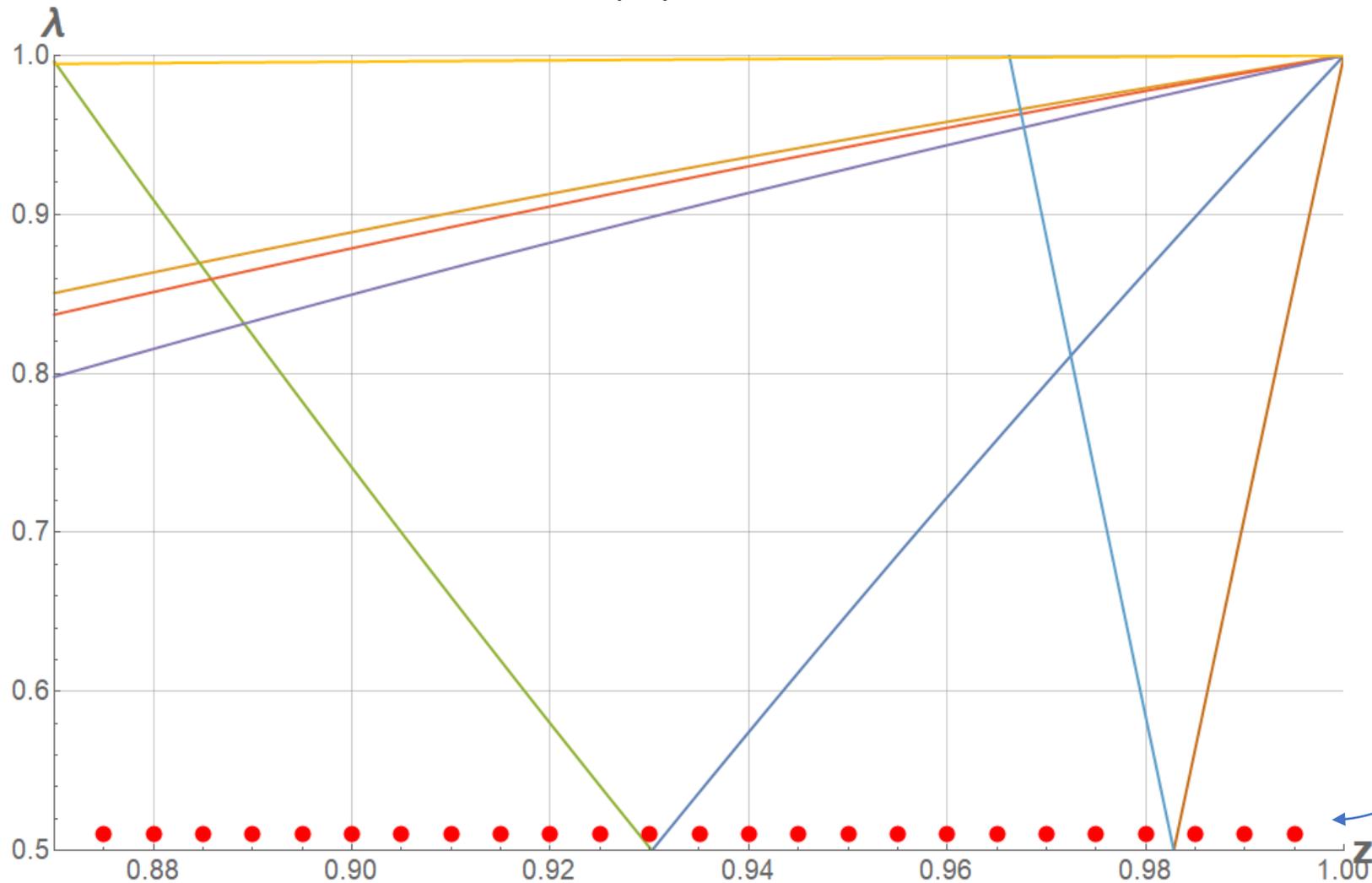Range of parameters:
- $\lambda \in (0,1)$
- $z \in (0,1)$

Poles of differential equations in λ

Details of the computation

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

Above top-quark threshold

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

Boundaries for numerical integration

10

Details of the computation

Above top-quark threshold

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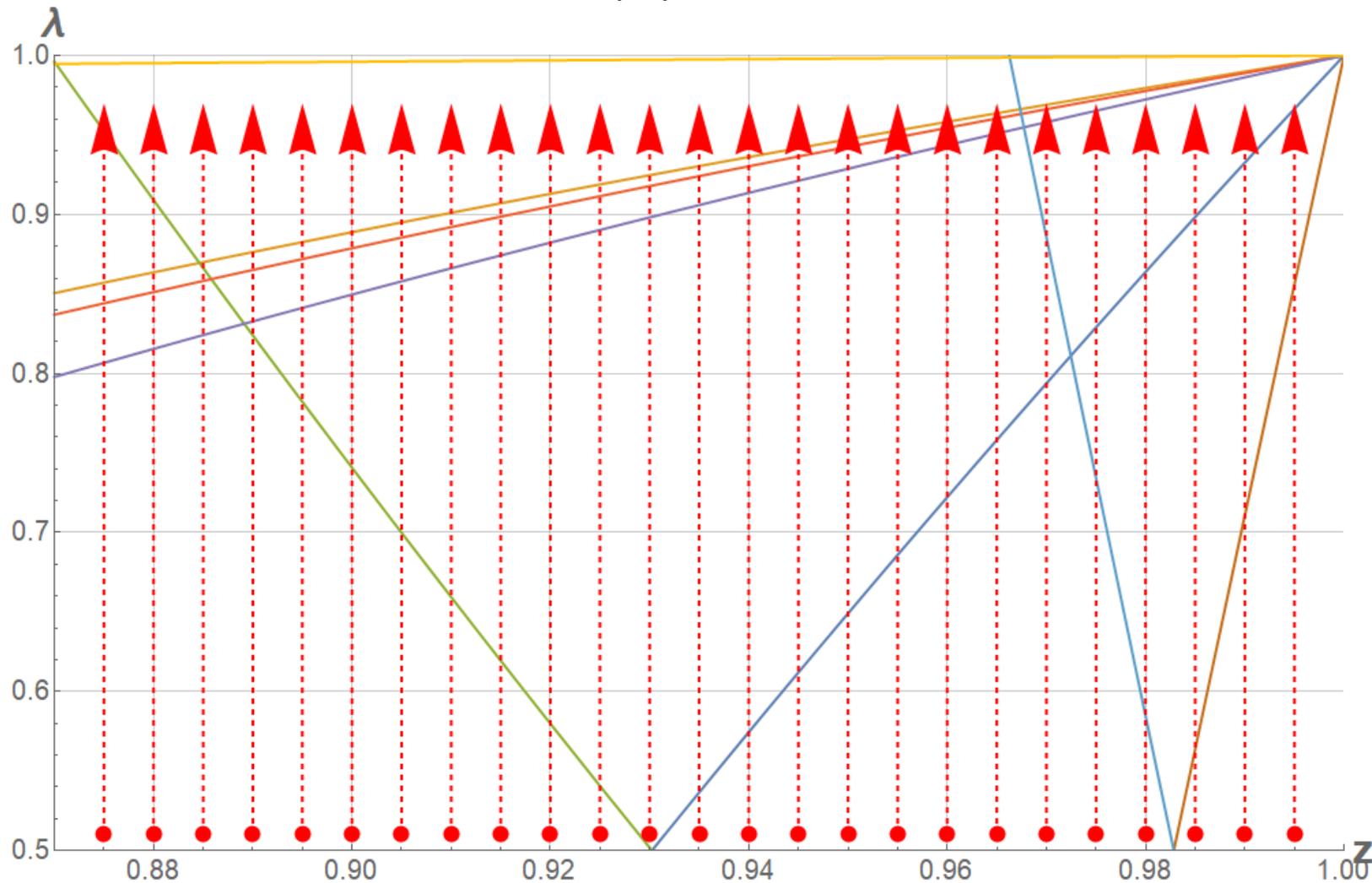$$m_t^2/m_H^2 = 23/12$$

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

Collect numerical samples for MI along straight integration contours
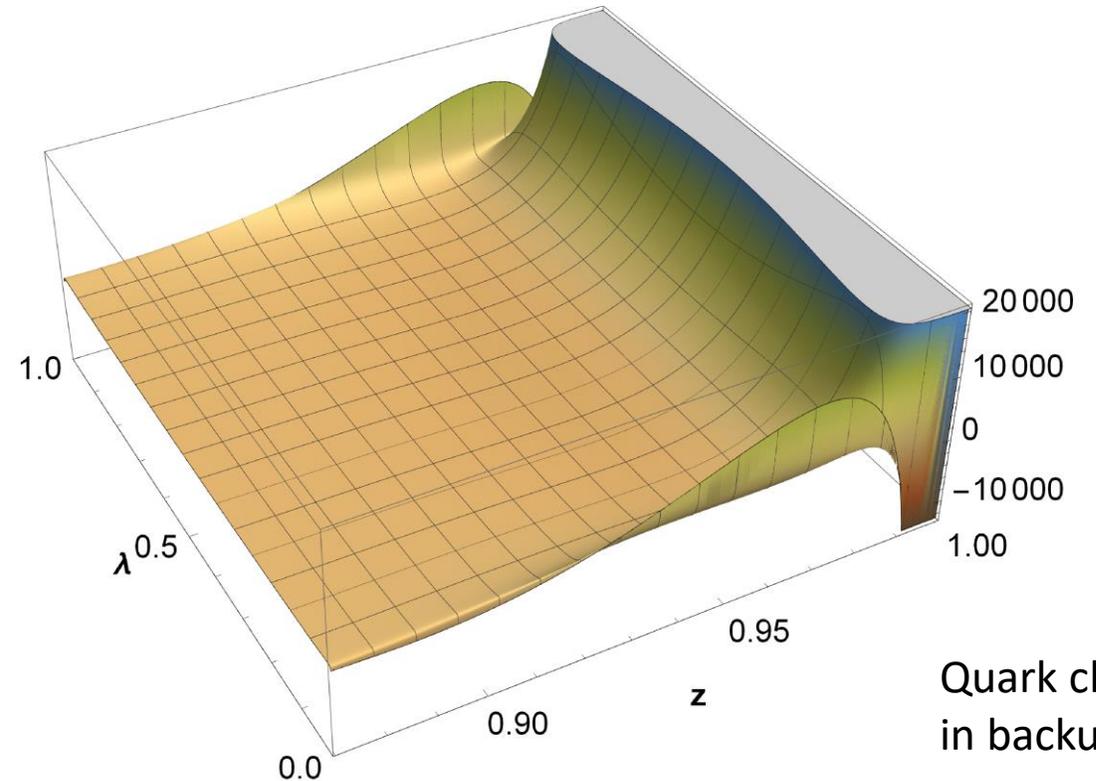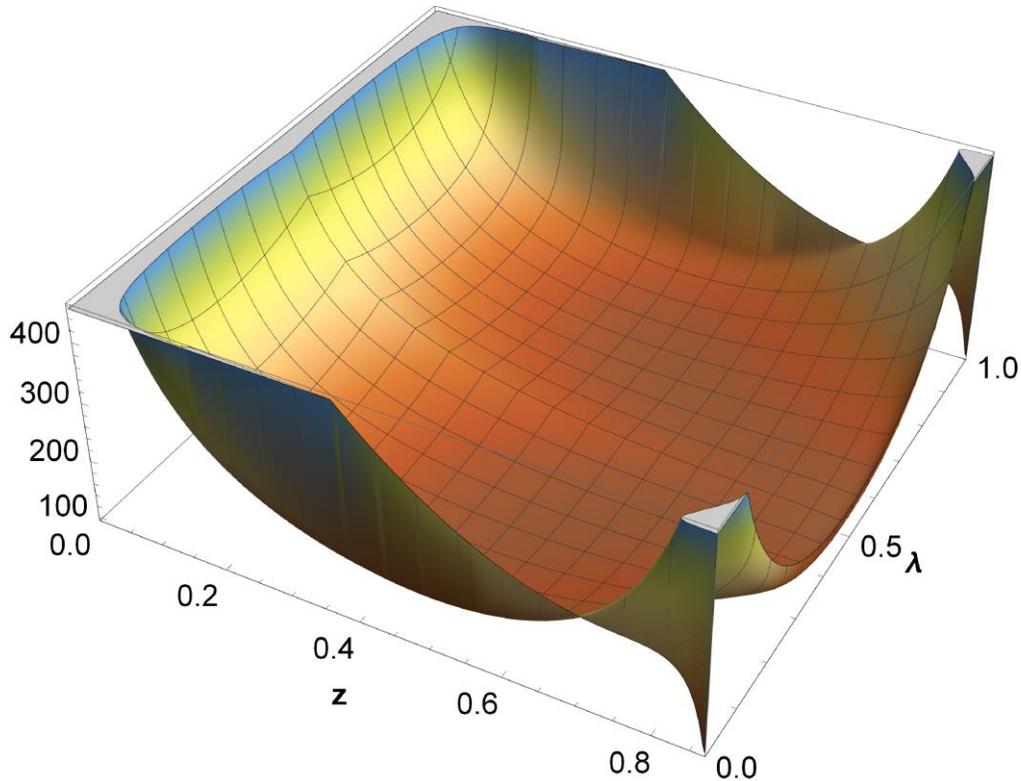
Details of the computation

- 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 **FireFly** Klappert, Lange `19

    - Sufficient to cover region below top-quark threshold

Subtraction for gg → gH

- Directly evaluate difference between HEFT and the exact result:

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

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

- 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) 12

Quark channels
in backup →

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
  - $\mu_R = \mu_F = m_H/2$
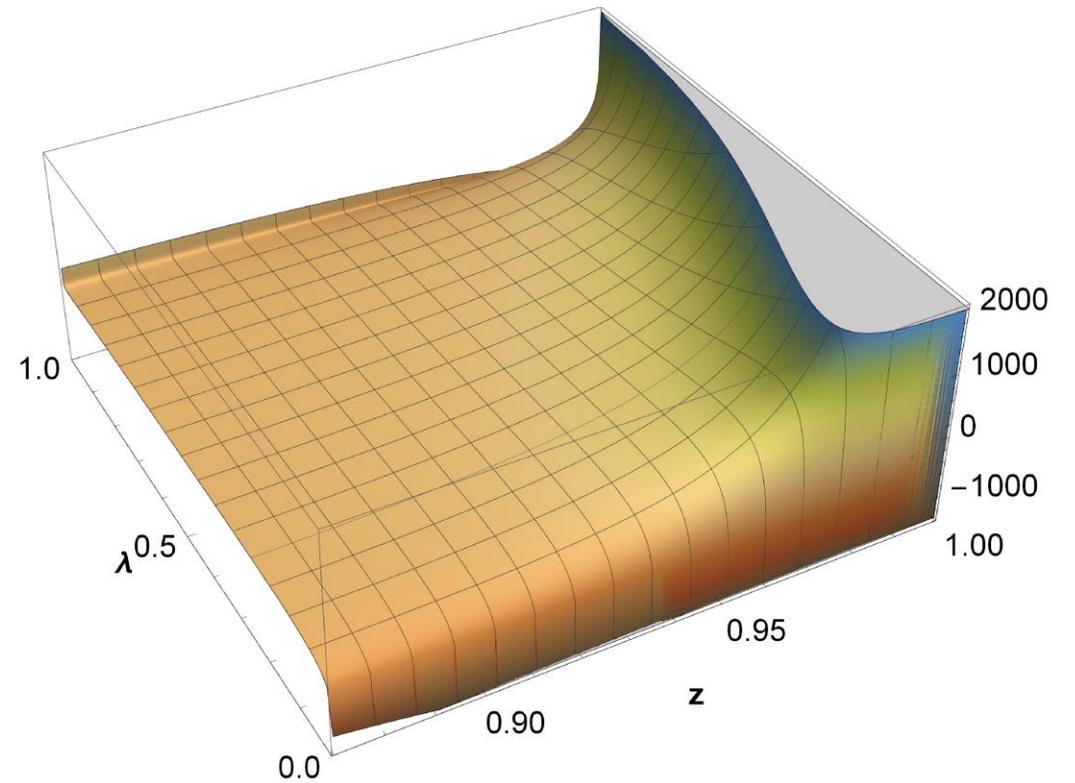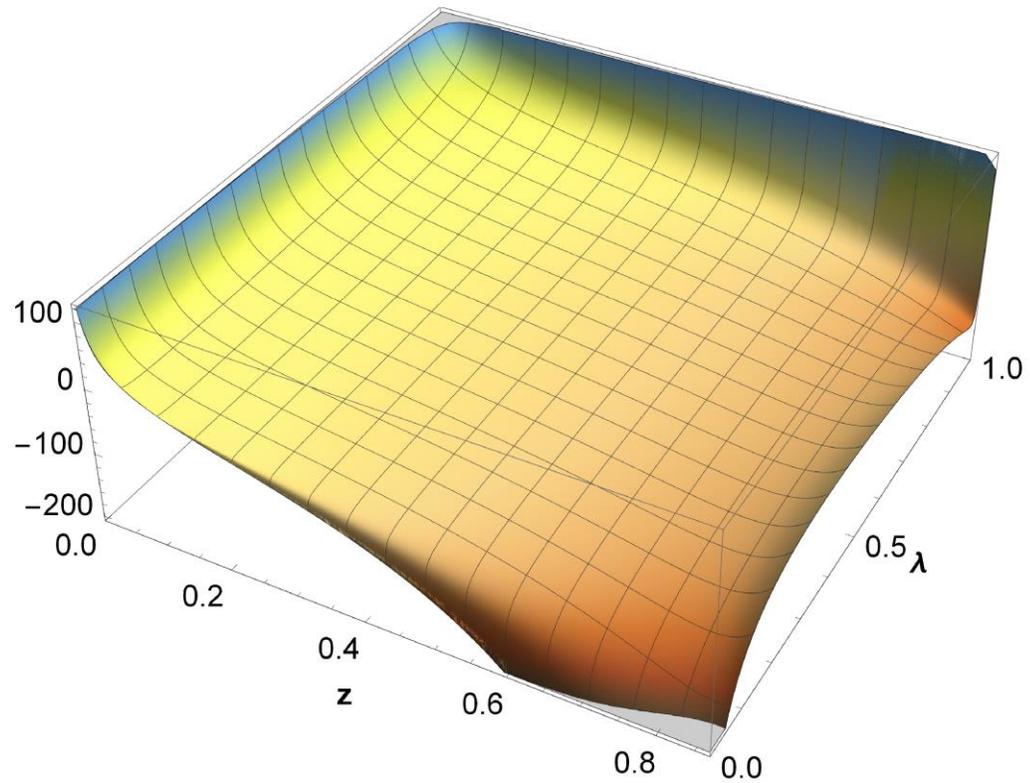 - $M_H = 125$ GeV $\Rightarrow M_t \approx 173.055$ GeV

channel	$\sigma_{\mathrm{HEFT}}^{\mathrm{NNLO}}$ [pb] $\mathcal{O}(\alpha_s^2) + \mathcal{O}(\alpha_s^3) + \mathcal{O}(\alpha_s^4)$	$(\sigma_{\mathrm{exact}}^{\mathrm{NNLO}} - \sigma_{\mathrm{HEFT}}^{\mathrm{NNLO}})$ [pb] $\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^4)$	$(\sigma_{\mathrm{exact}}^{\mathrm{NNLO}}/\sigma_{\mathrm{HEFT}}^{\mathrm{NNLO}} - 1)$ [%]
$\sqrt{s} = 8\,\mathrm{TeV}$				
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
qq	$0.01 + 0.04$	$+0.0171$	-0.0191 ± 0.0002	-4
total	$7.39 + 9.15 + 4.18$	-0.0873	$+0.0667 \pm 0.0007$	-0.10
$\sqrt{s} = 13\,\mathrm{TeV}$				
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
qq	$0.02 + 0.10$	$+0.0322$	-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

Backup

$qg \rightarrow qH$

$q\bar{q} \rightarrow gH$