Top-Bottom Interference Contribution to Fully-Inclusive Higgs Production

Marco Niggetiedt

with M. Czakon, F. Eschment, R. Poncelet, T. Schellenberger and J. Usovitsch

based on

JHEP 02 (2024) 087
[arXiv:2312.09896]

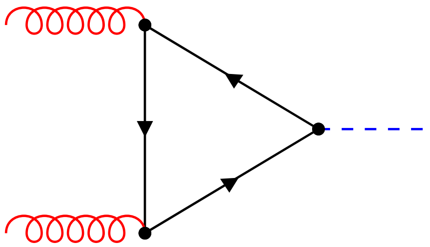
2nd Workshop on Tools for High Precision LHC Simulations

MAX-PLANCK-INSTITUT FÜR PHYSIK

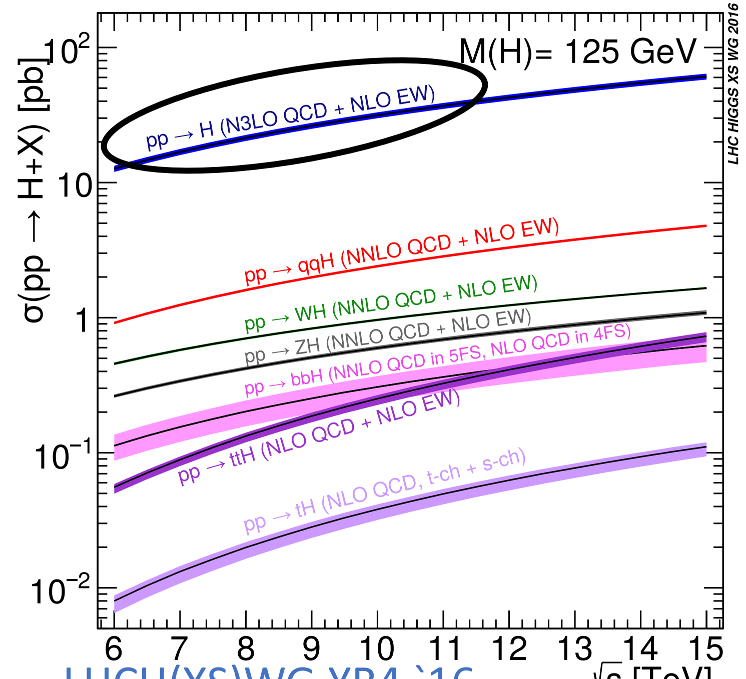
Castle Ringberg
May 10th 2024

Gluon fusion

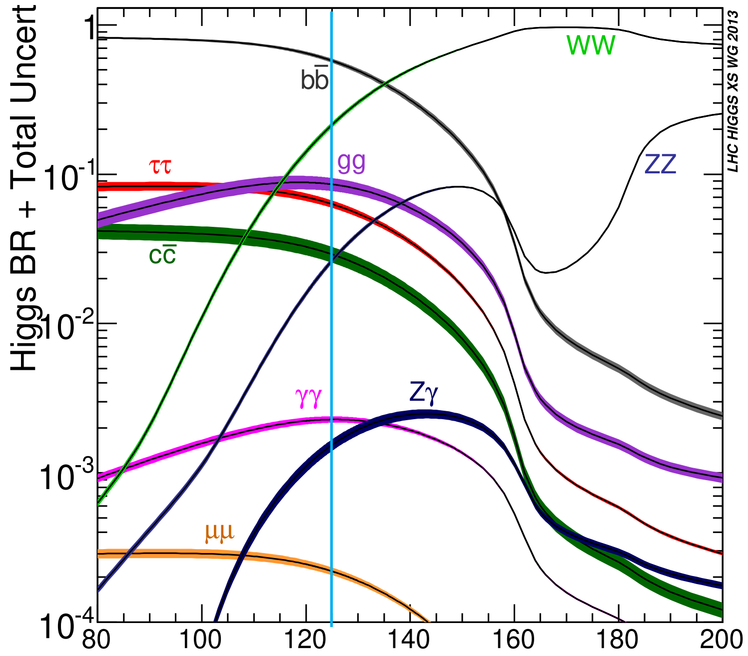
- Gluon fusion is the predominant Higgs boson production mode at the LHC
  - loop induced process



- Higgs boson plays unique role in the SM:
  - Only scalar particle
  - Only particle with Yukawa interactions to fermions
- Predictions for gluon fusion cross section directly impact extraction of Higgs couplings from experimental measurements
- Reducing theory uncertainty is crucial for facilitating high precision measurements of Higgs couplings at the LHC
- High luminosity LHC projections anticipate uncertainty $\mathcal{O}(2\%)$ and theory uncertainty to be halved WG2 Report `19



LHCH(XS)WG YR4 `16



LHCH(XS)WG YR3 `16

Inclusive gluon fusion cross section (YR4 `16)

- Inclusive gluon fusion cross section according to LHCH(XS)WG YR4 `16 at the LHC at 13 TeV:

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

LHCH(XS)WG YR4 `16
Anastasiou, Duhr, Dulat, et al. `16

- Sources of uncertainty:

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%	$\pm0.37\%$	$\pm1.16\%$	$\pm1\%$	$\pm0.83\%$	$\pm1\%$

← All sources $\mathcal{O}(1\%)$

Inclusive gluon fusion cross section (YR4 `16)

- Inclusive gluon fusion cross section according to LHCH(XS)WG YR4 `16 at the LHC at 13 TeV:

Mistlberger `18

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

LHCH(XS)WG YR4 `16
Anastasiou, Duhr, Dulat, et al. `16

- Sources of uncertainty:

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%	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

All sources $\mathcal{O}(1\%)$

Inclusive gluon fusion cross section (YR4 `16)

- Inclusive gluon fusion cross section according to LHCH(XS)WG YR4 `16 at the LHC at 13 TeV:

$48.58\,\text{pb} =$	$16.00\,\text{pb}$	$(+32.9\%)$	(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)

Mistlberger `18

Bonetti, Melnikov, Tancredi `18
Anastasiou, del Duca, Furlan, et al. `19
Becchetti, Bonciani, Del Duca, et al. `21

LHCH(XS)WG YR4 `16
Anastasiou, Duhr, Dulat, et al. `16

- Sources of uncertainty:

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%	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

← All sources $\mathcal{O}(1\%)$

Inclusive gluon fusion cross section (YR4 `16)

- Inclusive gluon fusion cross section according to LHCH(XS)WG YR4 `16 at the LHC at 13 TeV:

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

Mistlberger `18

Bonetti, Melnikov, Tancredi `18
Anastasiou, del Duca, Furlan, et al. `19
Becchetti, Bonciani, Del Duca, et al. `21

Czakon, Harlander, Klappert, et al. `21

LHCH(XS)WG YR4 `16
Anastasiou, Duhr, Dulat, et al. `16

- Sources of uncertainty:

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%

← All sources $\mathcal{O}(1\%)$

Inclusive gluon fusion cross section (YR4 `16)

- Inclusive gluon fusion cross section according to LHCH(XS)WG YR4 `16 at the LHC at 13 TeV:

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

Mistlberger `18

Bonetti, Melnikov, Tancredi `18
Anastasiou, del Duca, Furlan, et al. `19
Becchetti, Bonciani, Del Duca, et al. `21

Czakon, Harlander, Klappert, et al. `21

Das, Moch, Vogt `20

LHCH(XS)WG YR4 `16
Anastasiou, Duhr, Dulat, et al. `16

- Sources of uncertainty:

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%	$\pm0.37\%$	$\pm1.16\%$	$\pm1\%$	$\pm0.83\%$	$\pm1\%$

All sources $\mathcal{O}(1\%)$

Inclusive gluon fusion cross section (YR4 `16)

- Inclusive gluon fusion cross section according to LHCH(XS)WG YR4 `16 at the LHC at 13 TeV:

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

LHCH(XS)WG YR4 `16
Anastasiou, Duhr, Dulat, et al. `16

Mistlberger `18

Bonetti, Melnikov, Tancredi `18
Anastasiou, del Duca, Furlan, et al. `19
Becchetti, Bonciani, Del Duca, et al. `21

Czakon, Harlander, Klappert, et al. `21

Das, Moch, Vogt `20

Moch, Ruijl, Ueda, et al. `21
McGowan, Cridge, Harland-Lang et al. `22
Falcioni, Herzog, Moch, et al. `23/`24
NNPDF Collaboration `24

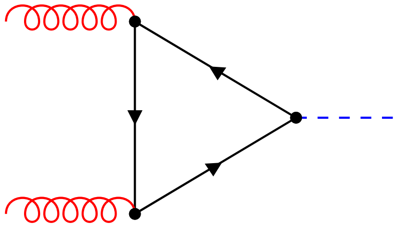
- Sources of uncertainty:

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

← All sources $\mathcal{O}(1\%)$

Order by order in perturbation theory

- LO contribution exactly known for almost 50 years

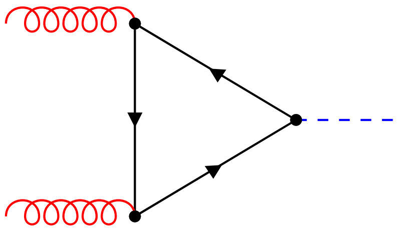


Georgi, Glashow, Machacek, et al. `78

$48.58\,\text{pb} =$	$16.00\,\text{pb}$	$(+32.9\%)$	(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)

Order by order in perturbation theory

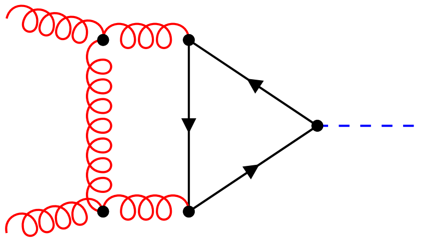
- LO contribution exactly known for almost 50 years

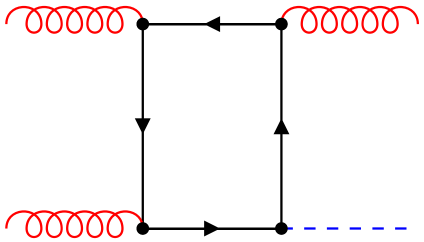


Georgi, Glashow, Machacek, et al. `78

$48.58\,\text{pb} =$	$16.00\,\text{pb}$	$(+32.9\%)$	(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)

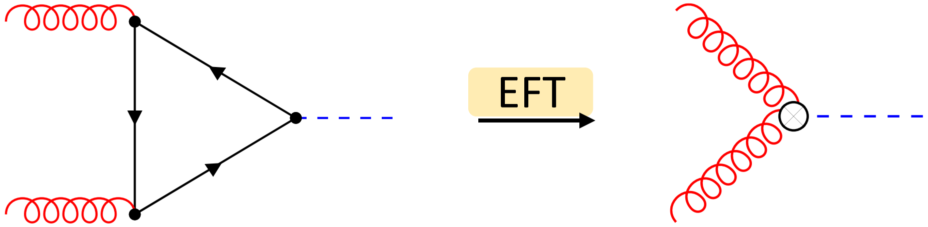
- NLO contribution exactly known for arbitrary quark masses running in the loop   Graudenz, Spira, Zerwas `93





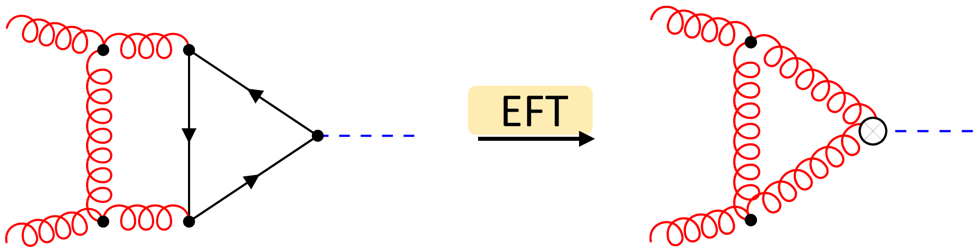
Inclusive cross section in (r)EFT

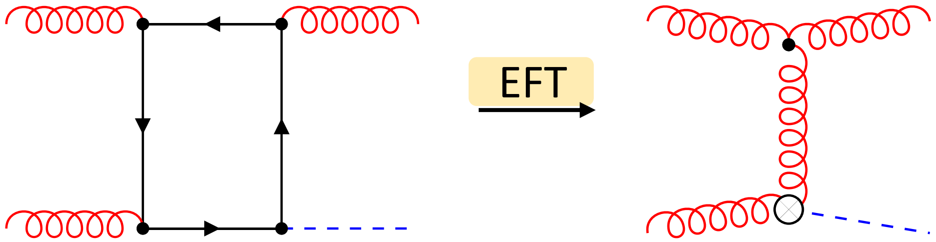
- LO contribution exactly known for almost 50 years



Georgi, Glashow, Machacek, et al. \`78

- NLO contribution exactly known for arbitrary quark masses running in the loop   Graudenz, Spira, Zerwas \`93





Dawson\`91
Djouadi, Spira, Zerwas \`91

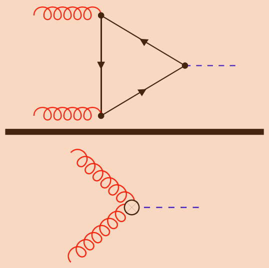
$$\mathcal{L}_{\mathrm{SM}}$$

$\downarrow$ $m_t \to \infty$

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM},5} - \frac{1}{4} C\, H\, G^a_{\mu\nu} G^{\mu\nu}_a$$

Chetyrkin, Kniehl, Steinhauser \`98
Schröder, Steinhauser \`06
Chetyrkin, Kühn, Sturm \`06

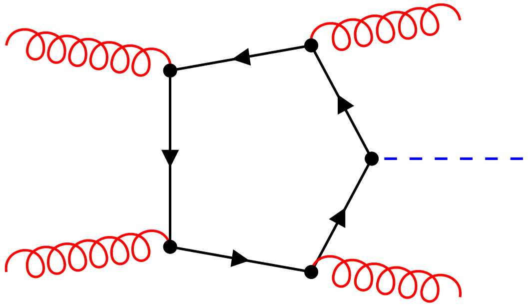
$$\sigma^{\mathrm{HO}}_{\mathrm{HEFT}} = \left(\frac{\sigma^{\mathrm{HO}}}{\sigma^{\mathrm{LO}}}\right)_{M_t \to \infty} \sigma^{\mathrm{LO}}$$

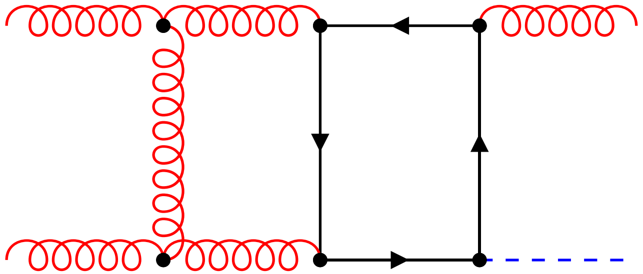
$r \sim \Big|$  $\Big|^2$

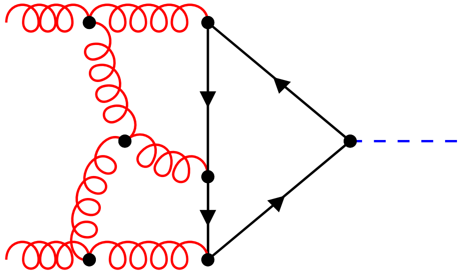
Computation

Ingredients for exact quark mass effects at NNLO

- Beyond NLO:



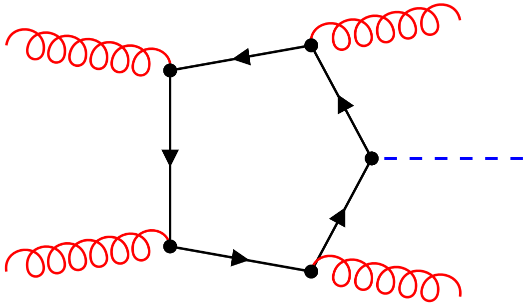




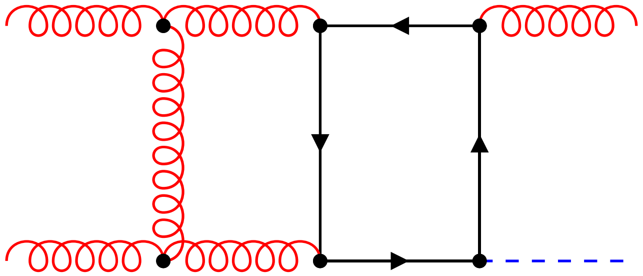
Analytically: Del Duca, Kilgore, Oleari, et al. `01
OpenLoops 2: Buccioni, Lang, Lindert, et al. `19
Analytically (more compact and
implemented in MCFM): Budge, Campbell, De Laurentis, et al. `20

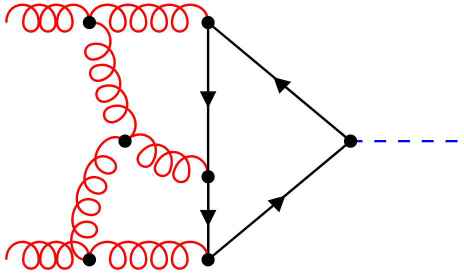
Ingredients for exact quark mass effects at NNLO

- Beyond NLO:



Analytically: Del Duca, Kilgore, Oleari, et al. `01
OpenLoops 2: Buccioni, Lang, Lindert, et al. `19
Analytically (more compact and
implemented in MCFM): Budge, Campbell, De Laurentis, et al. `20

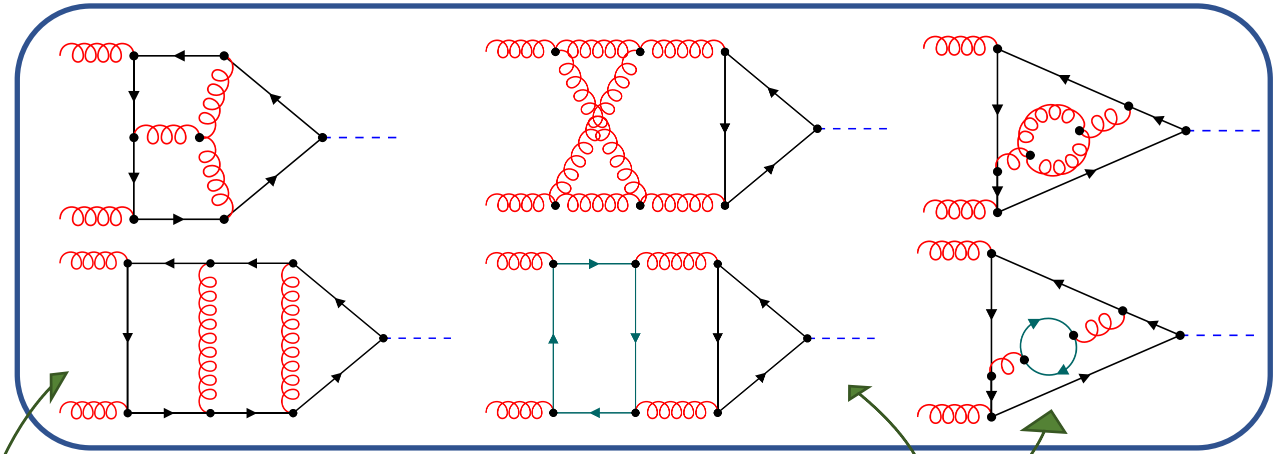




Double-virtual corrections

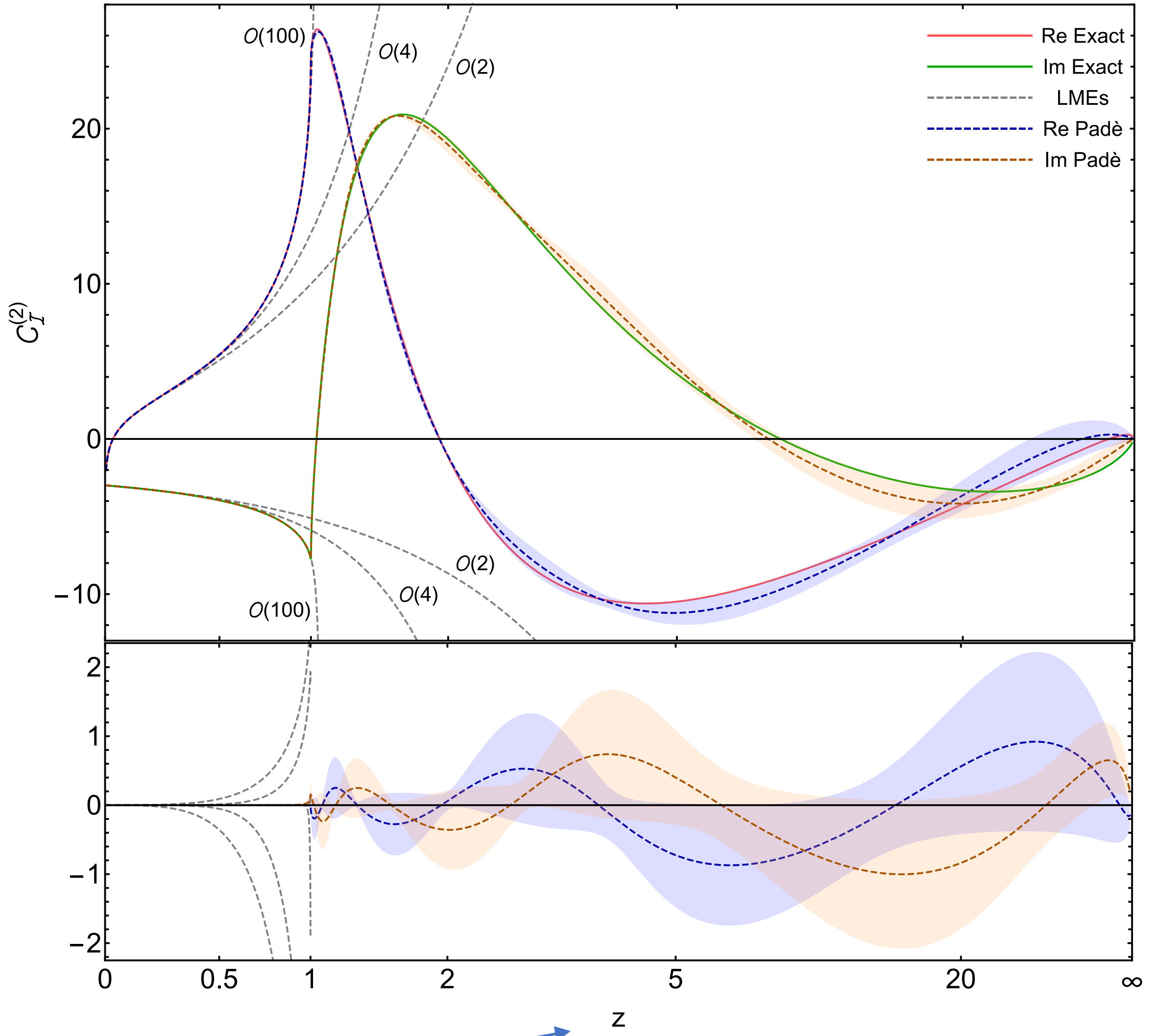
Double-virtual corrections

One massive flavor



Light-fermion contribution (analytically):
Harlander, Prausa, Usovitsch `19
Leading color contribution (analytically):
Prausa, Usovitsch `20

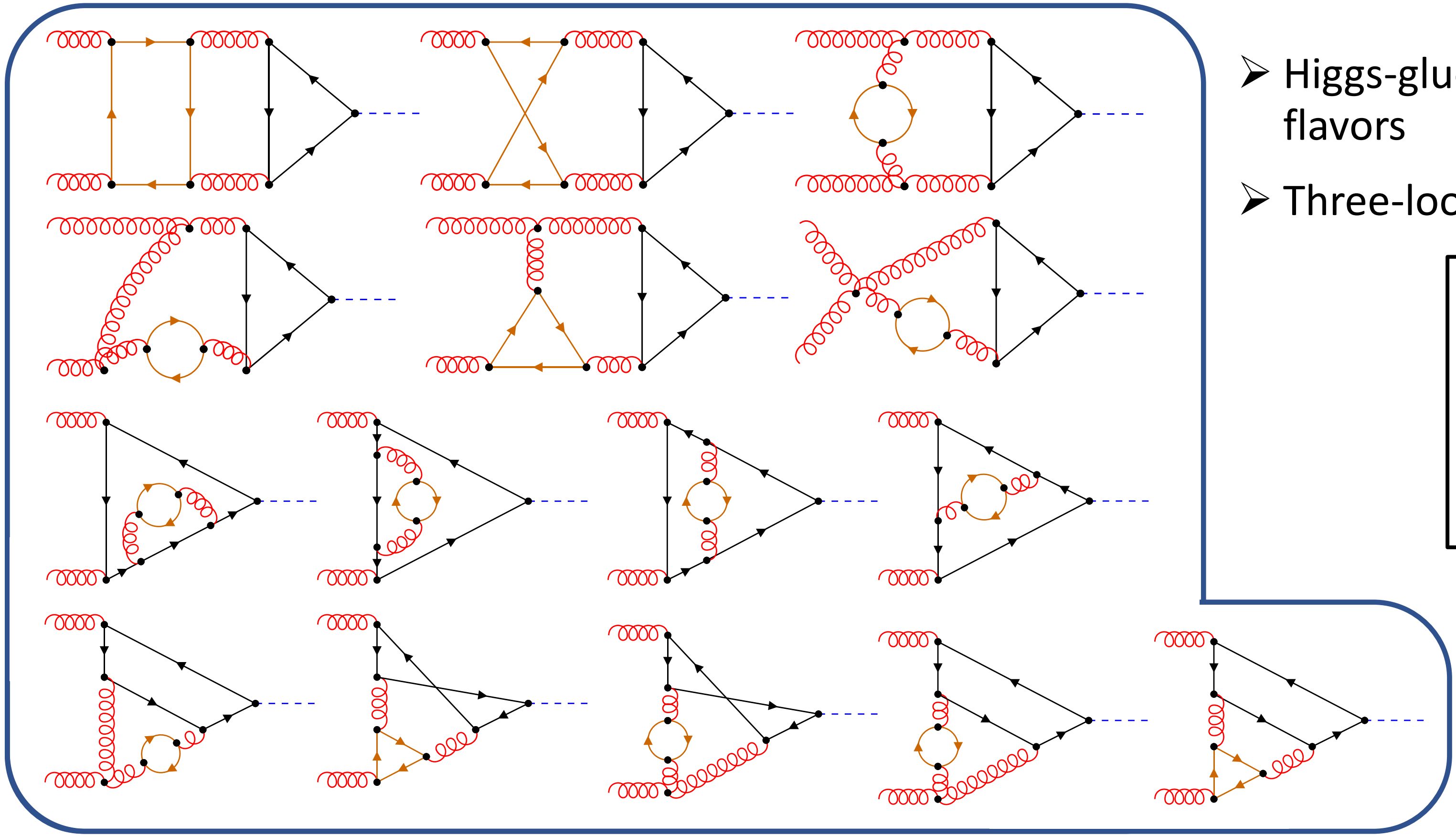
Padé approximation: Davies, Gröber, Maier et al. `19
Numerically exact: Czakon, MN `20



$z = m_H^2/4m_q^2$

Double-virtual corrections

Two massive flavors



- Higgs-gluon form factor in QCD with $n_f = n_t + n_b + n_l$ flavors
- Three-loop coefficient:

$$C^{(2)} = n_t\, C_t^{(2)} + n_t^2\, C_{tt}^{(2)} + n_t n_l\, C_{tl}^{(2)} + n_b\, C_b^{(2)} + n_b^2\, C_{bb}^{(2)} + n_b n_l\, C_{bl}^{(2)} + n_t n_b \left(C_{tb}^{(2)} + C_{bt}^{(2)} \right)$$

✓

Czakon, MN \`20

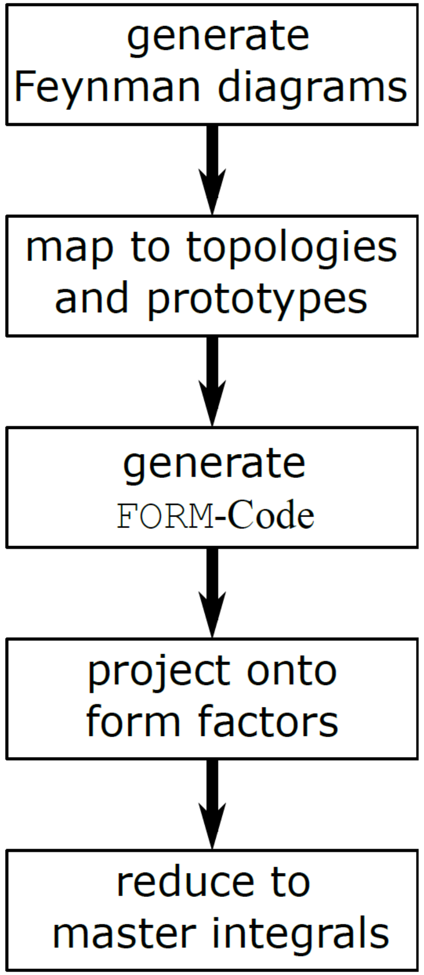
MN, Usovitsch \`23

Note: $\frac{m_H^2}{m_t^2} \approx 0.5$ and $\frac{m_b^2}{m_H^2} \approx 0.0015$

- Solution strategy:
  - Compute expansions for $m_b^2 \ll m_H^2 \ll m_t^2$
  - Sample remaining parameter space numerically

Workflow of the Computation

$x = m_t^2/m_H^2$
$y = m_b^2/m_H^2$

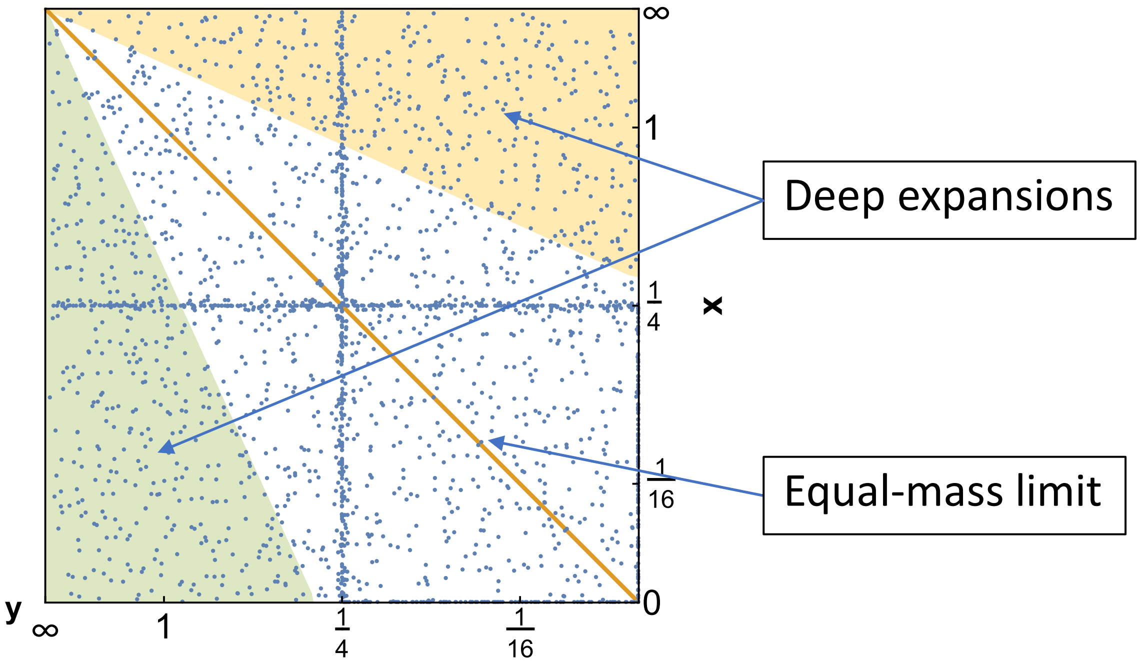


DiaGen
Czakon (private)

FORM
Vermaseren `00

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

- Variables: x, y
- Differential operators in $\{x, y\}$ can be expressed in terms of derivatives with respect to $\{m_t^2, m_b^2\}$ — Kotikov `91, Gehrmann, Remiddi `00
- Exploit symmetry: $C_{tb}^{(2)}(x,y) = C_{bt}^{(2)}(y,x)$
- Solve ~300 MIs numerically using **AMFlow** — Liu, Ma `22



Deep asymptotic expansions

$x = m_t^2/m_H^2$
$y = m_b^2/m_H^2$

- Employ differential equations for MIs:

$$\frac{\mathrm{d}M_i(x,y,\epsilon)}{\mathrm{d}x} = A_{ij}(x,y,\epsilon)\, M_j(x,y,\epsilon) \quad \Longleftarrow \quad M_i(x,y,\epsilon) = \sum_{l=0}^{\overline{n}_i - \underline{n}_i} \epsilon^{\underline{n}_i + l}\, I_{\underline{k}_i + l}(x,y)$$

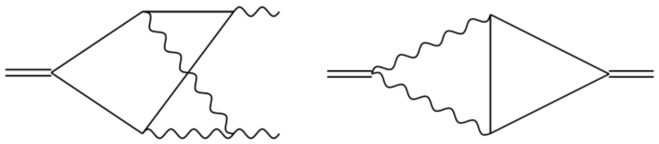
$$\frac{\mathrm{d}I_k(x,y)}{\mathrm{d}x} = B_{kl}(x,y)\, I_l(x,y)$$

- Solution ansatz for $x \to \infty$:

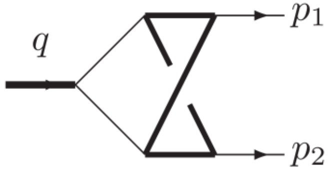
$$I_k(x,y) = \sum_{l=\underline{l}_k}^{\infty} \sum_{m=0}^{\overline{m}_k} c_{klm}(y) \frac{\log^m(x)}{x^l}$$

rational functions multiplying boundary condition

$$\{1,\, i\pi,\, \pi^2,\, \zeta_3,\, \log(y),\, \mathrm{HPL}(\ldots,y),\, \mathrm{elliptic}\}$$



Anastasiou, Beerli, Bucherer `06



von Manteuffel, Tancredi `17

Deep asymptotic expansions

$x = m_t^2 / m_H^2$
$y = m_b^2 / m_H^2$

- Employ differential equations for MIs:

$$\frac{\mathrm{d}M_i(x,y,\epsilon)}{\mathrm{d}x} = A_{ij}(x,y,\epsilon)\, M_j(x,y,\epsilon) \quad \Longleftarrow \quad M_i(x,y,\epsilon) = \sum_{l=0}^{\overline{n}_i - \underline{n}_i} \epsilon^{\underline{n}_i + l}\, I_{\underline{k}_i + l}(x,y)$$

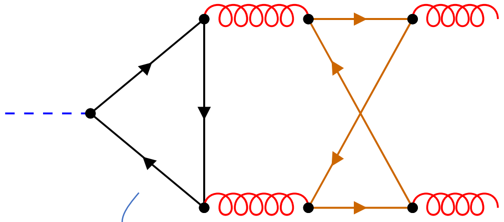
$$\frac{\mathrm{d}I_k(x,y)}{\mathrm{d}x} = B_{kl}(x,y)\, I_l(x,y)$$

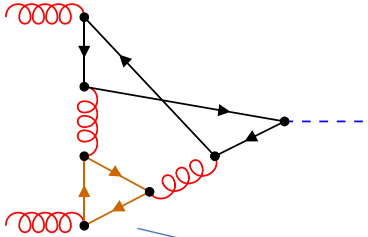
- Solution ansatz for $x \to \infty$:

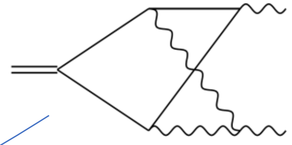
$$I_k(x,y) = \sum_{l=\underline{l}_k}^{\infty} \sum_{m=0}^{\overline{m}_k} c_{klm}(y) \frac{\log^m(x)}{x^l}$$

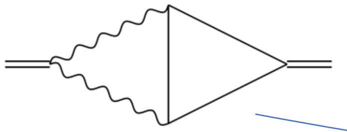
rational functions multiplying boundary condition

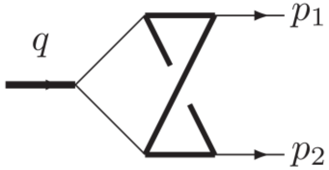
$$\{1,\ i\pi,\ \pi^2,\ \zeta_3,\ \log(y),\ \mathrm{HPL}(\ldots,y),\ \mathrm{elliptic}\}$$











Anastasiou, Beerli, Bucherer `06

von Manteuffel, Tancredi `17

Deep asymptotic expansions

$x = m_t^2/m_H^2$
$y = m_b^2/m_H^2$

- Employ differential equations for MIs:

$$\frac{\mathrm{d}M_i(x,y,\epsilon)}{\mathrm{d}x} = A_{ij}(x,y,\epsilon)\,M_j(x,y,\epsilon) \quad \Longleftarrow \quad M_i(x,y,\epsilon) = \sum_{l=0}^{\overline{n}_i-\underline{n}_i} \epsilon^{\underline{n}_i+l}\, I_{\underline{k}_i+l}(x,y)$$

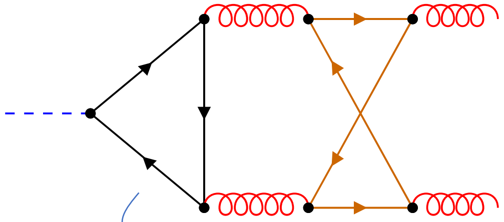
$$\frac{\mathrm{d}I_k(x,y)}{\mathrm{d}x} = B_{kl}(x,y)\,I_l(x,y)$$

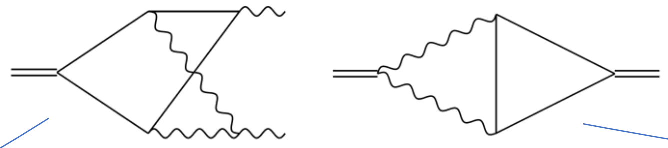
- Solution ansatz for $x \to \infty$:

$$I_k(x,y) = \sum_{l=\underline{l}_k}^{\infty} \sum_{m=0}^{\overline{m}_k} c_{klm}(y)\,\frac{\log^m(x)}{x^l}$$

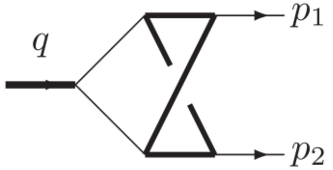
rational functions multiplying boundary condition

$$\{1,\ i\pi,\ \pi^2,\ \zeta_3,\ \log(y),\ \mathrm{HPL}(\ldots,y),\ \text{elliptic}\}$$





Anastasiou, Beerli, Bucherer `06

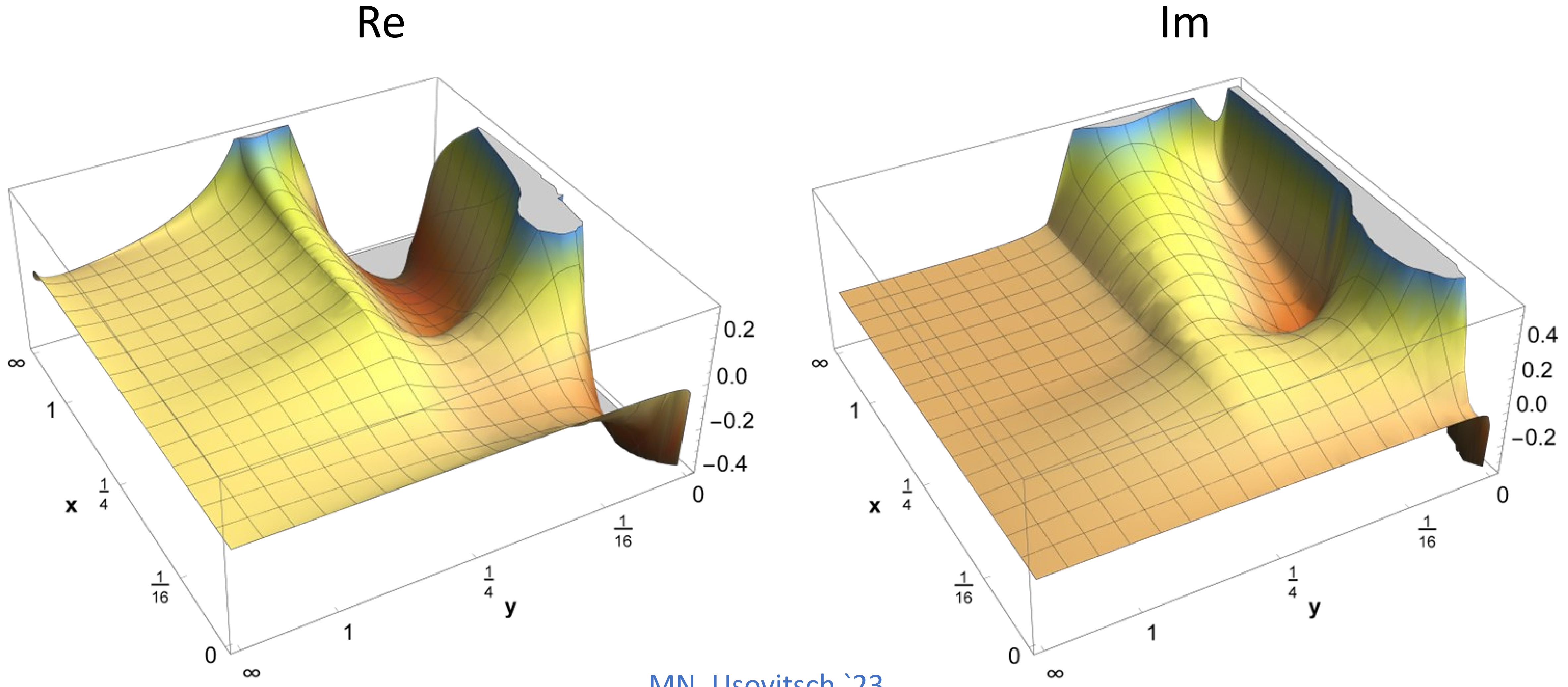


von Manteuffel, Tancredi `17

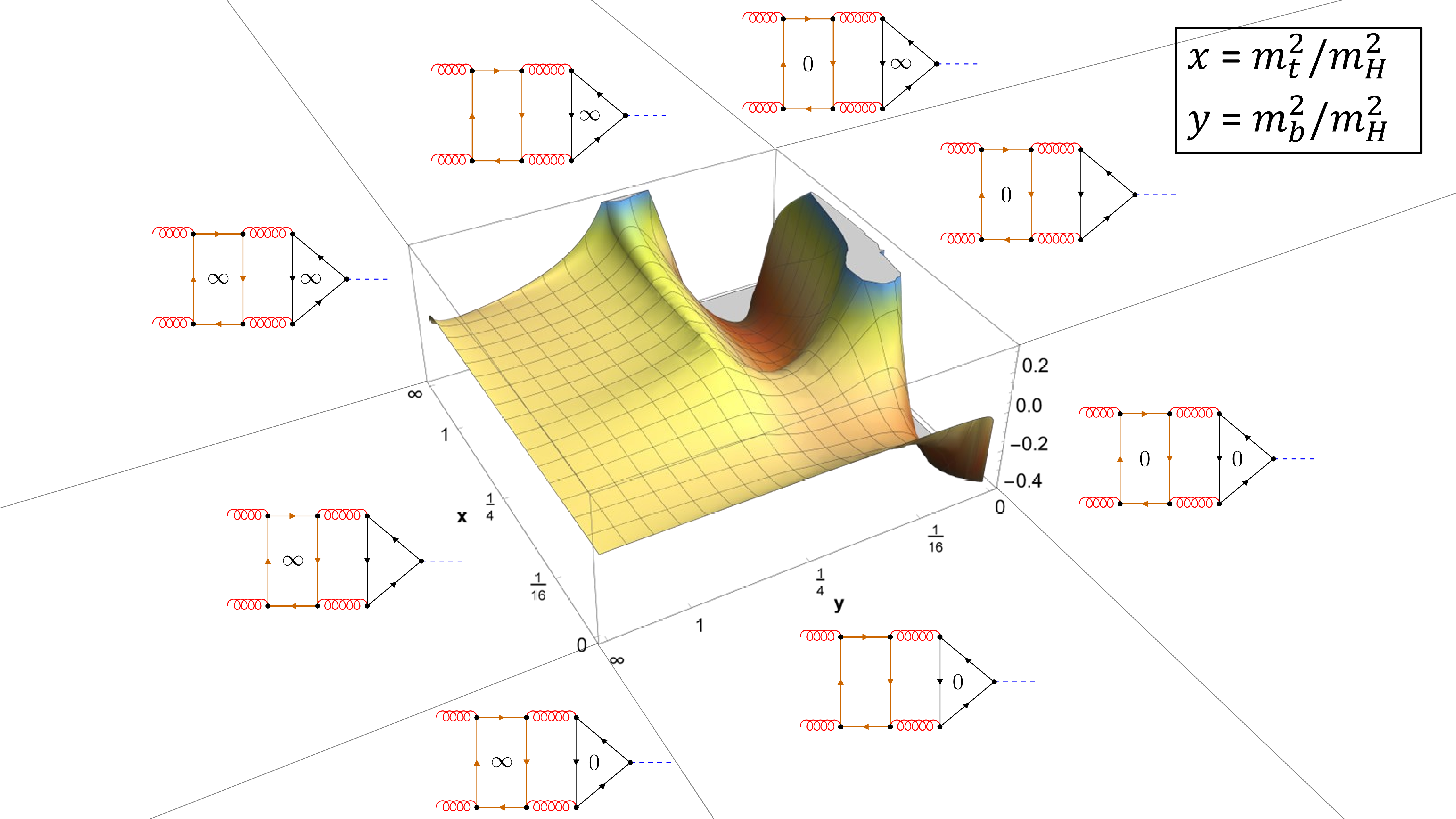
➢ More efficient: Sample expansion coefficients for <u>different values of y</u> and reconstruct exact form at the <u>amplitude level</u>

Finite remainder of $C_{tb}^{(2)}$

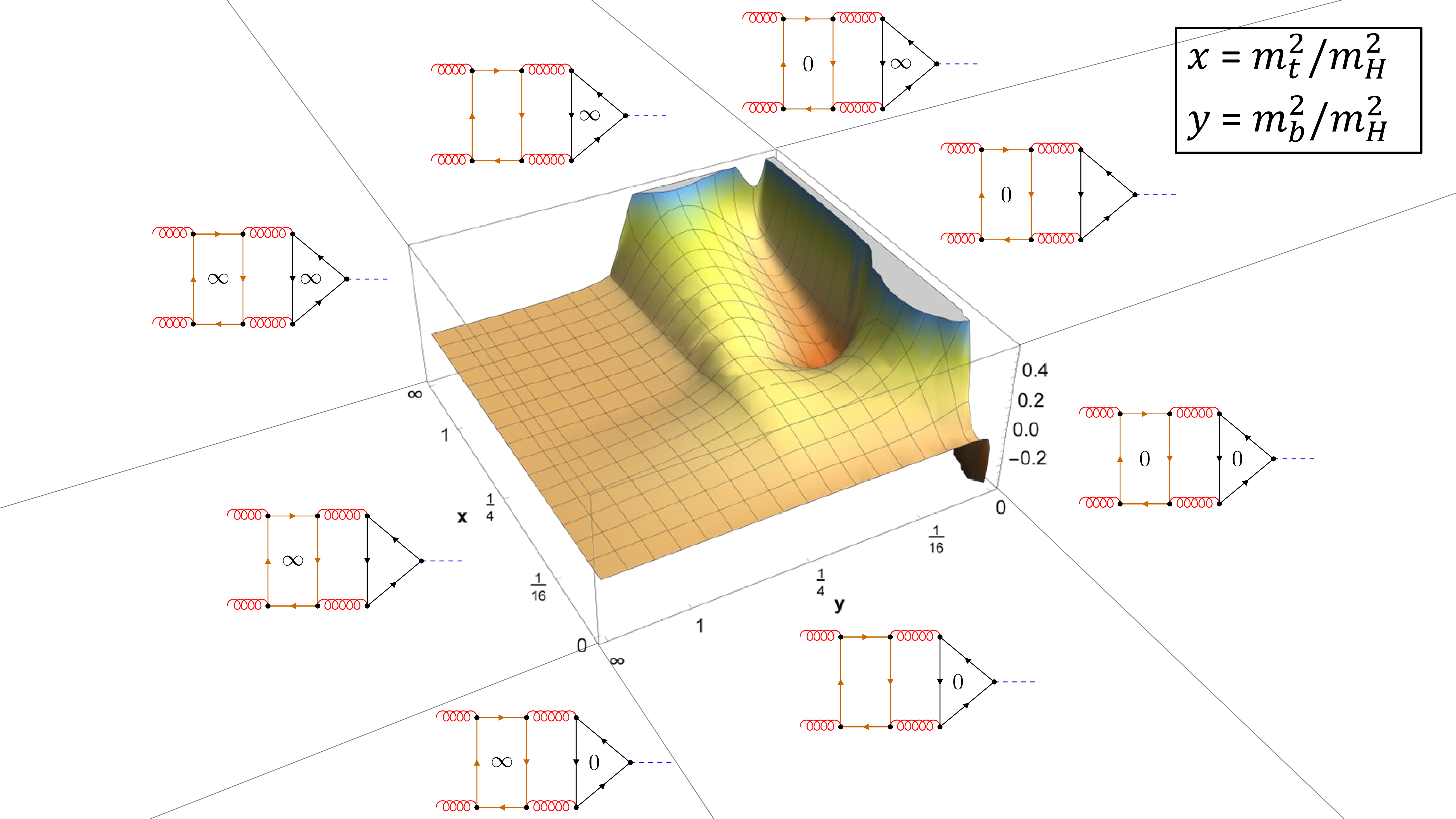
$x = m_t^2/m_H^2$
$y = m_b^2/m_H^2$



MN, Usovitsch `23



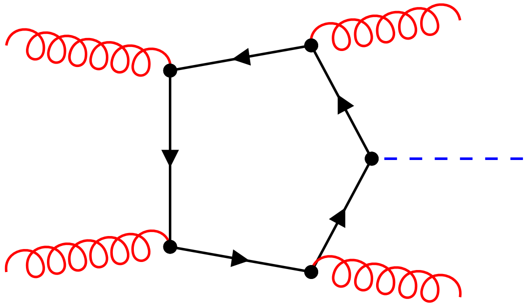
$x = m_t^2/m_H^2$
$y = m_b^2/m_H^2$
0.2
0.0
−0.2
−0.4
x
∞
1
$\frac{1}{4}$
$\frac{1}{16}$
0
y
∞
1
$\frac{1}{4}$
$\frac{1}{16}$
0
∞
0



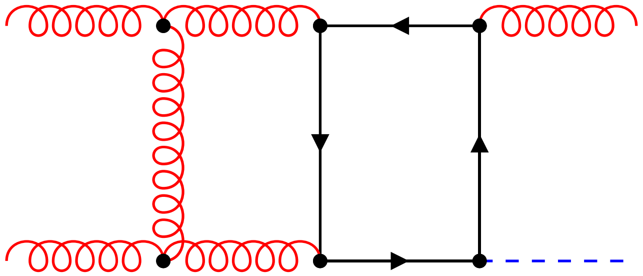
$x = m_t^2/m_H^2$
$y = m_b^2/m_H^2$
x
y
0
$\frac{1}{16}$
$\frac{1}{4}$
1
∞
0.4
0.2
0.0
−0.2

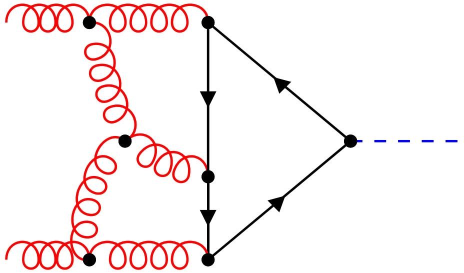
Ingredients for exact quark mass effects at NNLO

- Beyond NLO:



Analytically: Del Duca, Kilgore, Oleari, et al. \`01
OpenLoops 2: Buccioni, Lang, Lindert, et al. \`19
Analytically (more compact and implemented in MCFM): Budge, Campbell, De Laurentis, et al. \`20

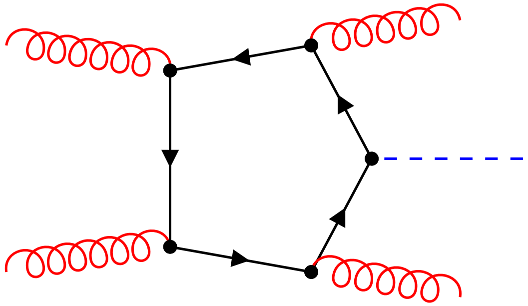




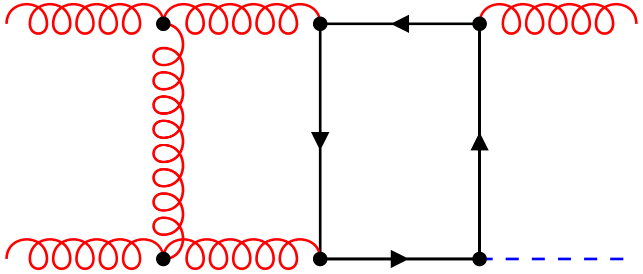
Double-virtual corrections ✓

Ingredients for exact quark mass effects at NNLO

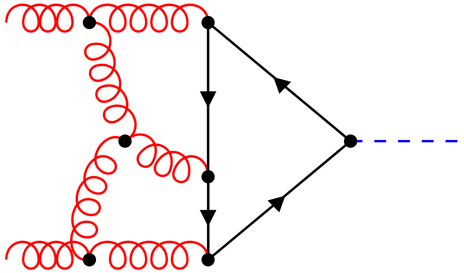
- Beyond NLO:



Analytically: Del Duca, Kilgore, Oleari, et al. `01
OpenLoops 2: Buccioni, Lang, Lindert, et al. `19
Analytically (more compact and implemented in MCFM): Budge, Campbell, De Laurentis, et al. `20

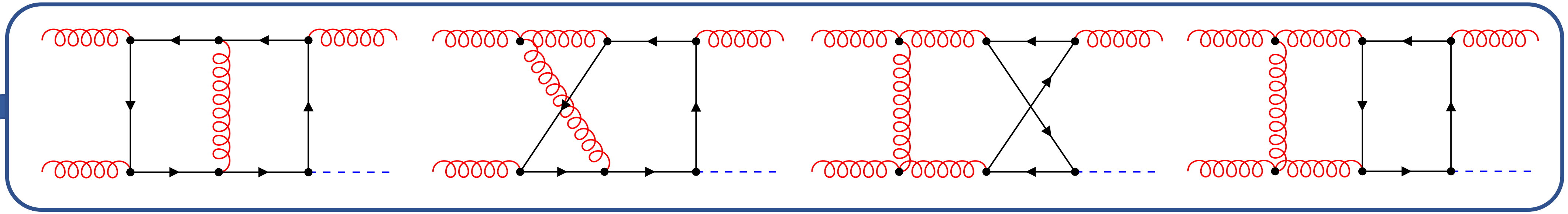


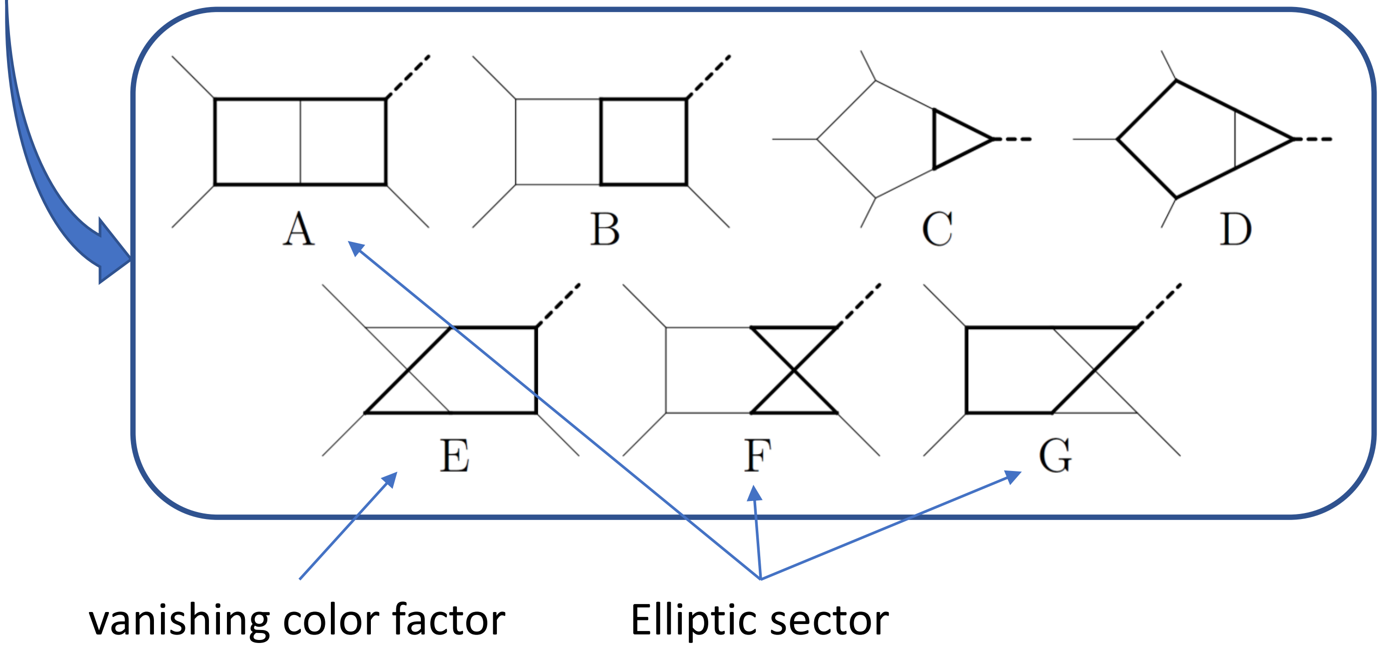
Real-virtual corrections



Double-virtual corrections ✓

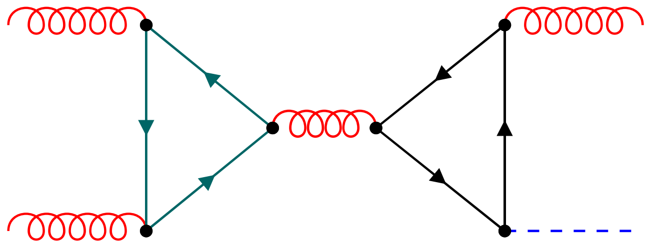
Real-virtual corrections





A,B,C,D: Bonciani, Del Duca, Frellesvig, et al. `16
F: Bonciani, Del Duca, Frellesvig, et al. `19
G: Frellesvig, Hidding, Maestri, et al. `19

Contributions with two closed fermion chains are always factorizable:



Parametrization

- Variables: $\hat{s}$, $\hat{t}$, $\hat{u}$, m_H^2, m_q^2
- Introduce dimensionless variables and fix ratio m_q^2/m_H^2
  - ➢ z parametrizes soft limit
  - ➢ λ parametrizes collinear limit

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

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

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

$m_b^2/m_H^2 = 1/684$

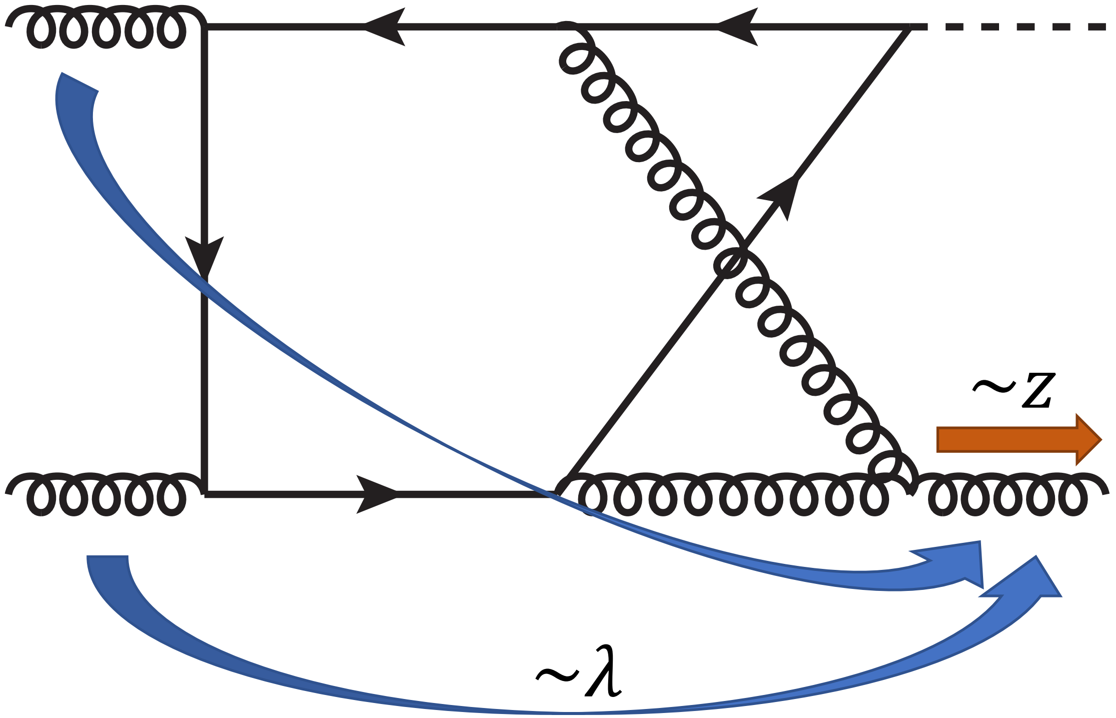
Range of parameters:
- $\lambda \in (0,1)$
- $z \in (0,1)$

$\hat{t}/\hat{s} = z\,\lambda$

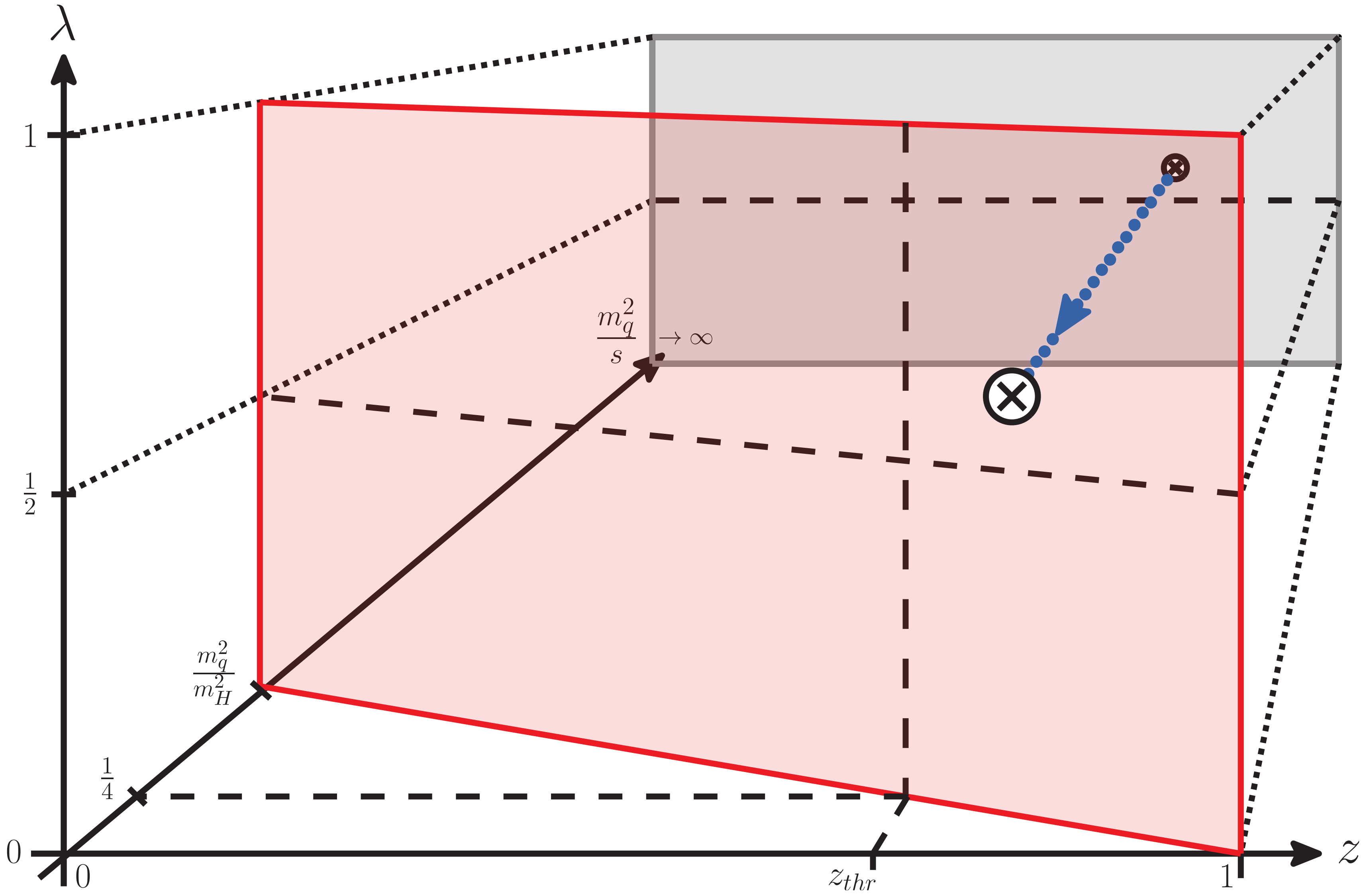
$\hat{u}/\hat{s} = z\,(1\text{-}\lambda)$

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

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



Evolution of differential equations



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

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

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

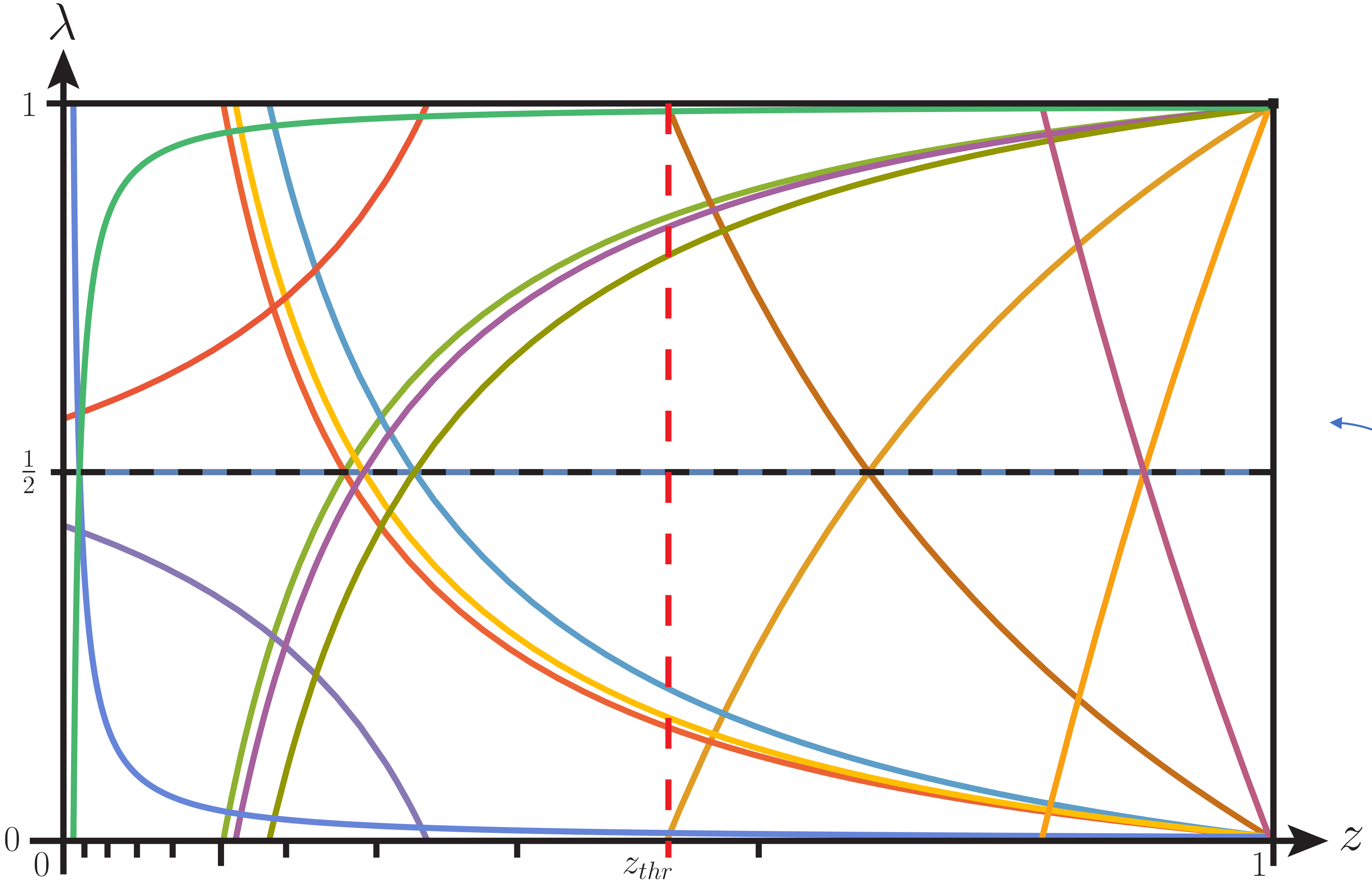
Range of parameters:

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

$z_{thr} = 1 - \frac{m_H^2}{4m_q^2}$

For $m_t^2/m_H^2 = 23/12$:
$z_{thr} = 20/23 \approx 0.87$

Evolution in the (z,λ)-plane



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

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

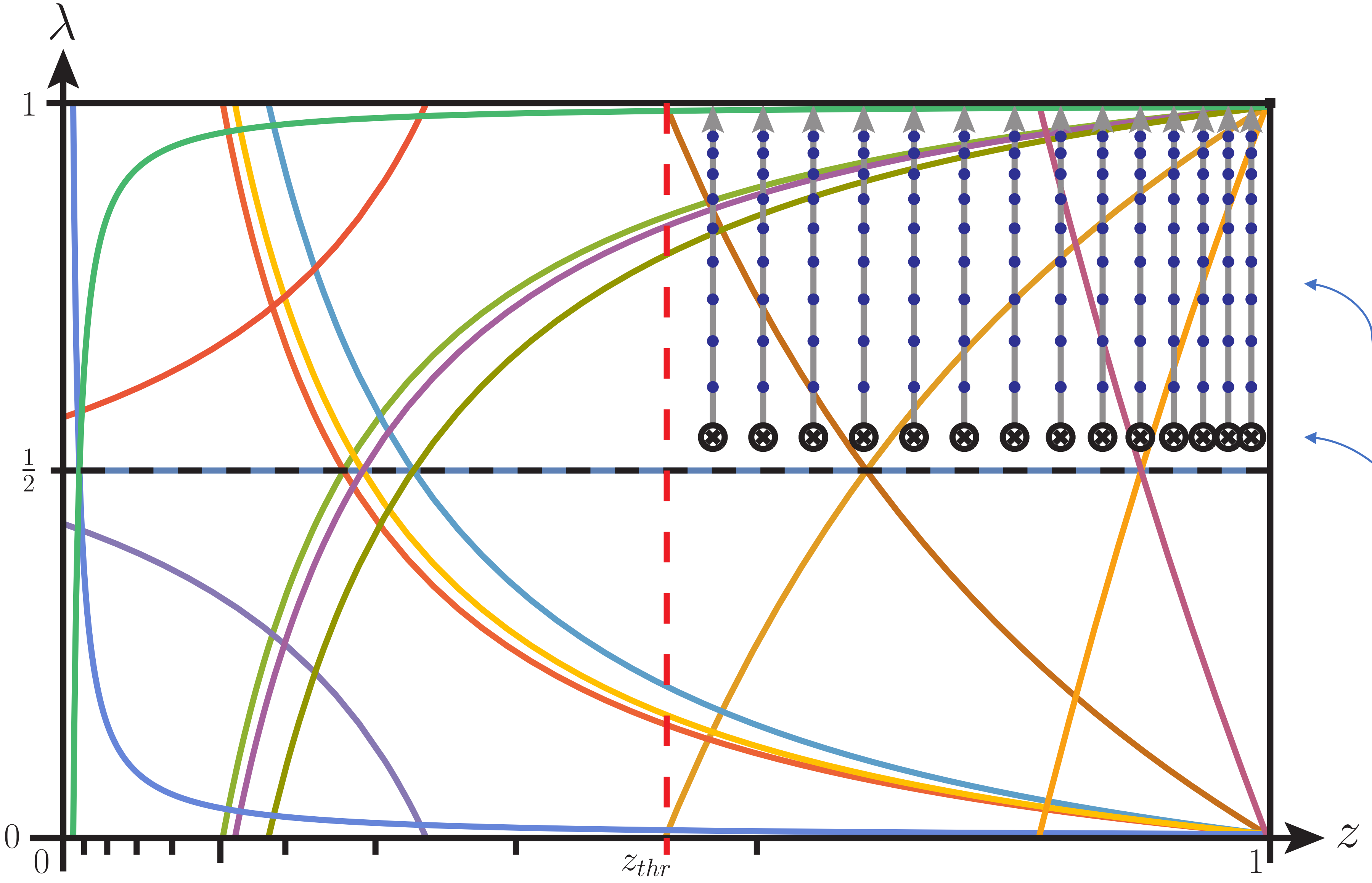
$m_t^2/m_H^2 = 23/12$

Range of parameters:

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

Poles of differential equations in λ

Evolution in the (z,λ)-plane



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

λ = $\hat{t}/(\hat{t}+\hat{u})$

m_t^2/m_H^2 = 23/12

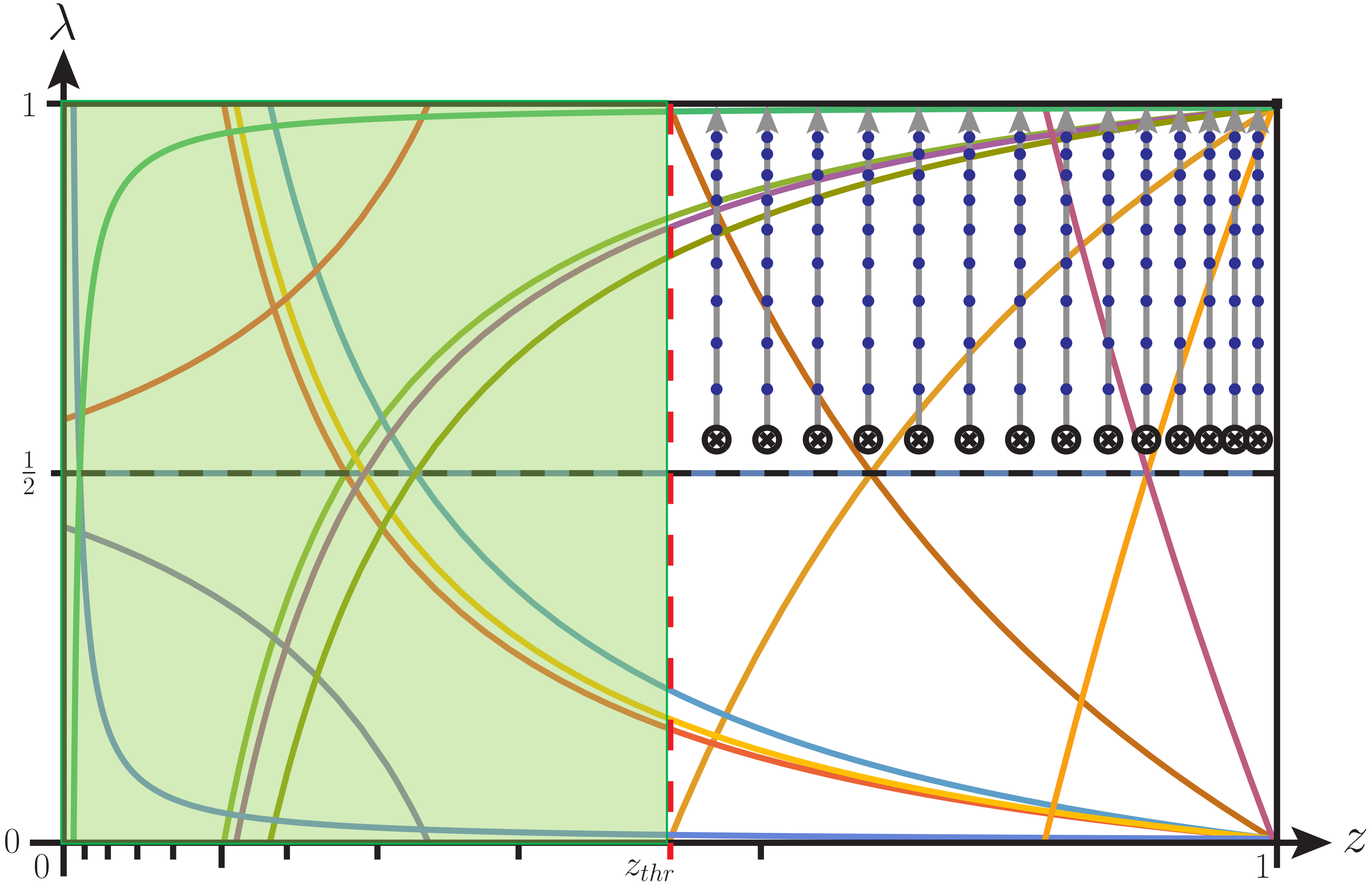
Range of parameters:

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

Collect numerical samples for MI along straight integration contours

Boundaries from numerical integration in the mass

Evolution in the (z,λ)-plane



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

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

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

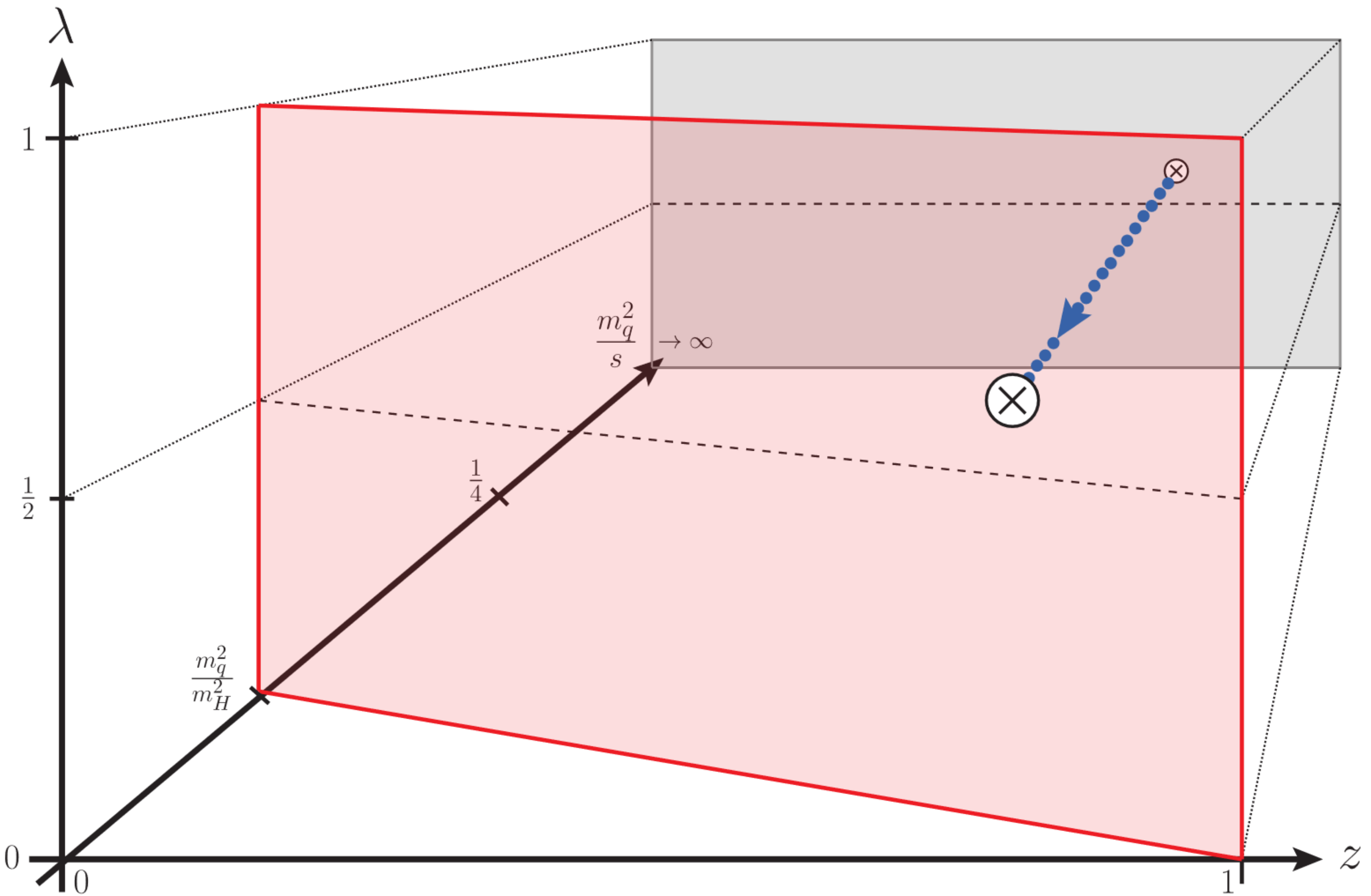
Range of parameters:

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

Region below threshold covered by LME

LME $\mathcal{O}((1/m_q^2)^{40})$

Evolution of differential equations



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

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

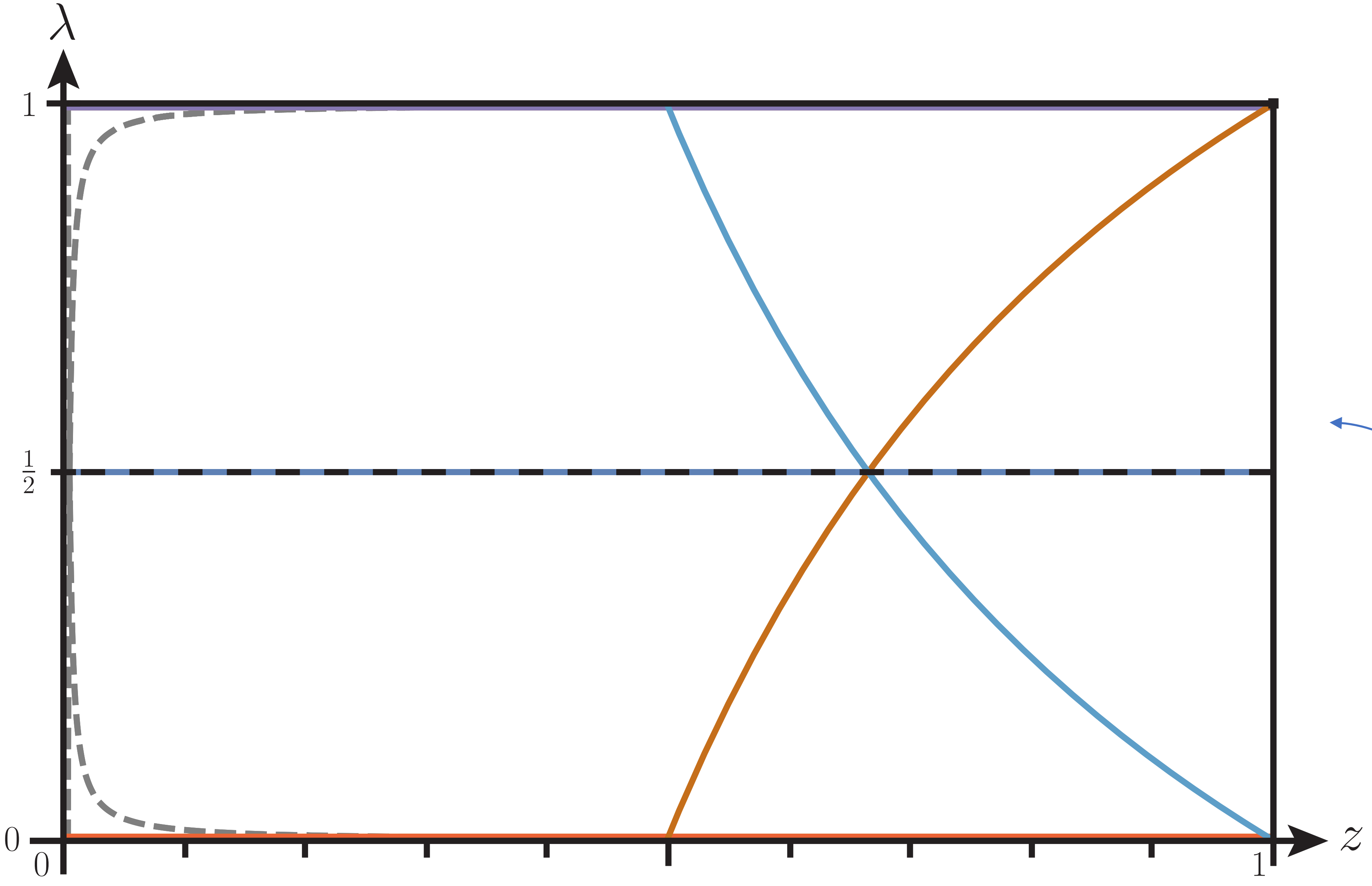
m_b^2/m_H^2 = 1/684

Range of parameters:

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

$z_{thr} = 1 - \frac{m_H^2}{4m_q^2} < 0$

Evolution in the (z,λ)-plane



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

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

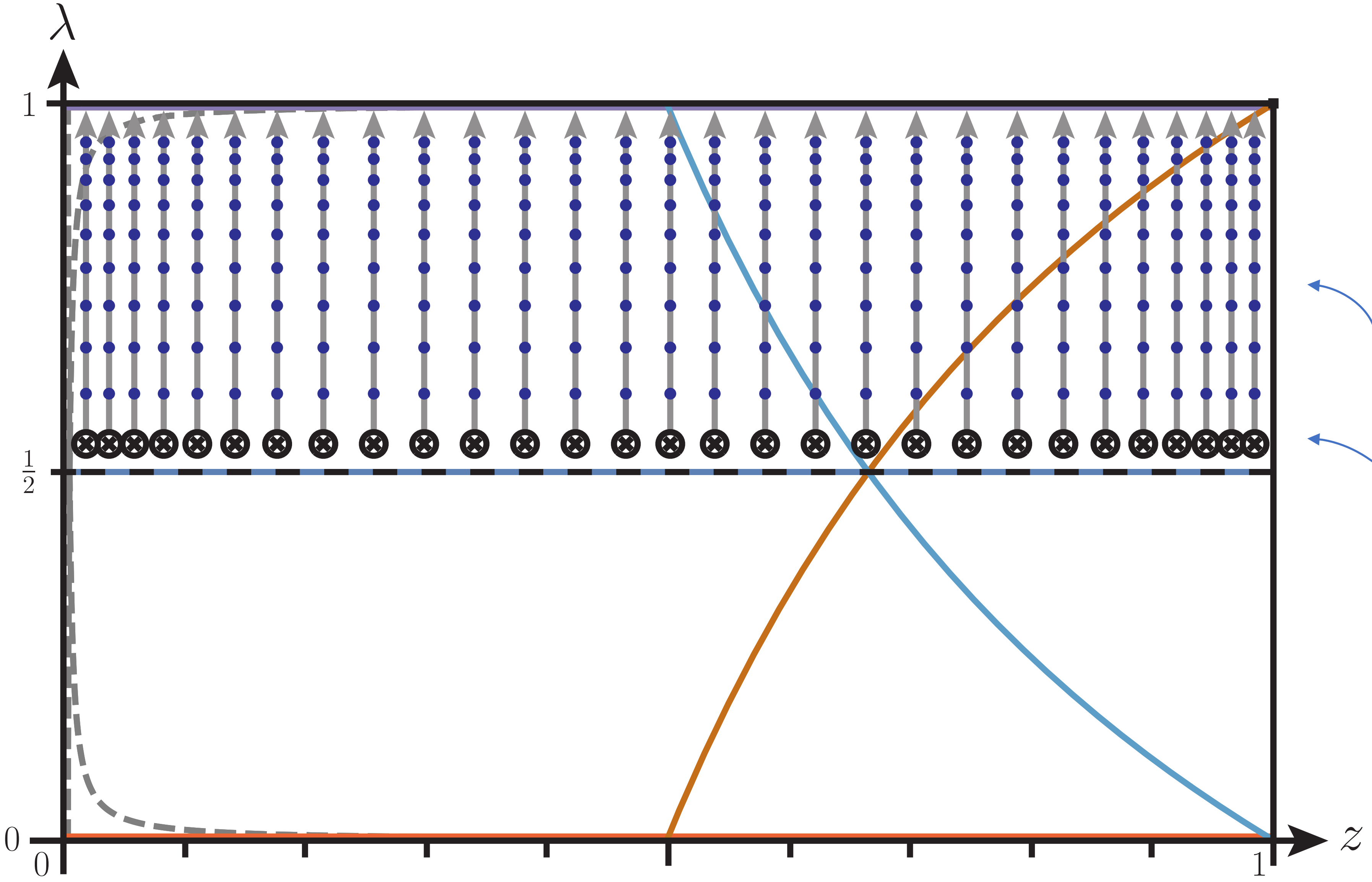
$m_b^2/m_H^2 = 1/684$

Range of parameters:

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

Poles of differential equations in λ

Evolution in the (z,λ)-plane



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

λ = $\hat{t}/(\hat{t}+\hat{u})$

m_b^2/m_H^2 = 1/684

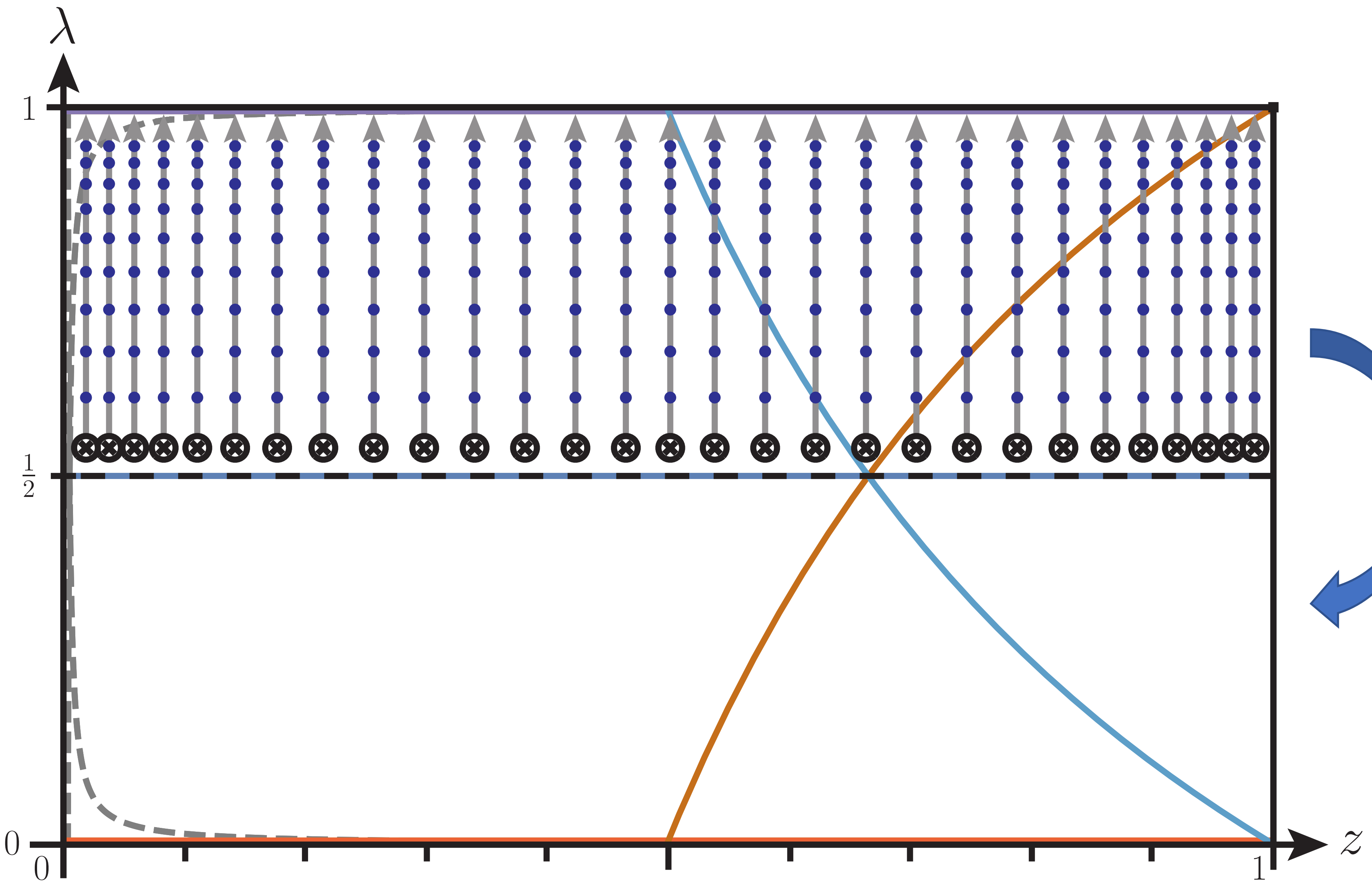
Range of parameters:

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

Collect numerical samples for MI along straight integration contours

Boundaries from numerical integration in the mass

Evolution in the (z,λ)-plane



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

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

$m_b^2/m_H^2 = 1/684$

Range of parameters:

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

Exploit symmetry of the problem at the amplitude level!

Construction of amplitudes

- Collected 2×10^6 numerical samples for MIs at m_t^2/m_H^2 by evaluation of the LME and numerical evolution above threshold
- Collected 1×10^6 numerical samples for MIs at m_b^2/m_H^2 via numerical evolution in the entire phase space

Insert into form factors and construct helicity amplitudes

$$\mathcal{M}_{+++} = \frac{1}{\sqrt{2}} \frac{s_{12}s_{23}}{\langle 12\rangle\langle 23\rangle\langle 31\rangle}\left(F_1 + \frac{s_{13}}{s_{23}}F_2 + \frac{s_{13}}{s_{12}}F_3 + \frac{s_{13}}{2}F_4\right)$$

$$\mathcal{M}_{---} = \mathcal{M}_{+++}\Big|_{\langle ij\rangle\leftrightarrow[ji]} = -\frac{1}{\sqrt{2}} \frac{s_{12}s_{23}}{[12][23][31]}\left(F_1 + \frac{s_{13}}{s_{23}}F_2 + \frac{s_{13}}{s_{12}}F_3 + \frac{s_{13}}{2}F_4\right)$$

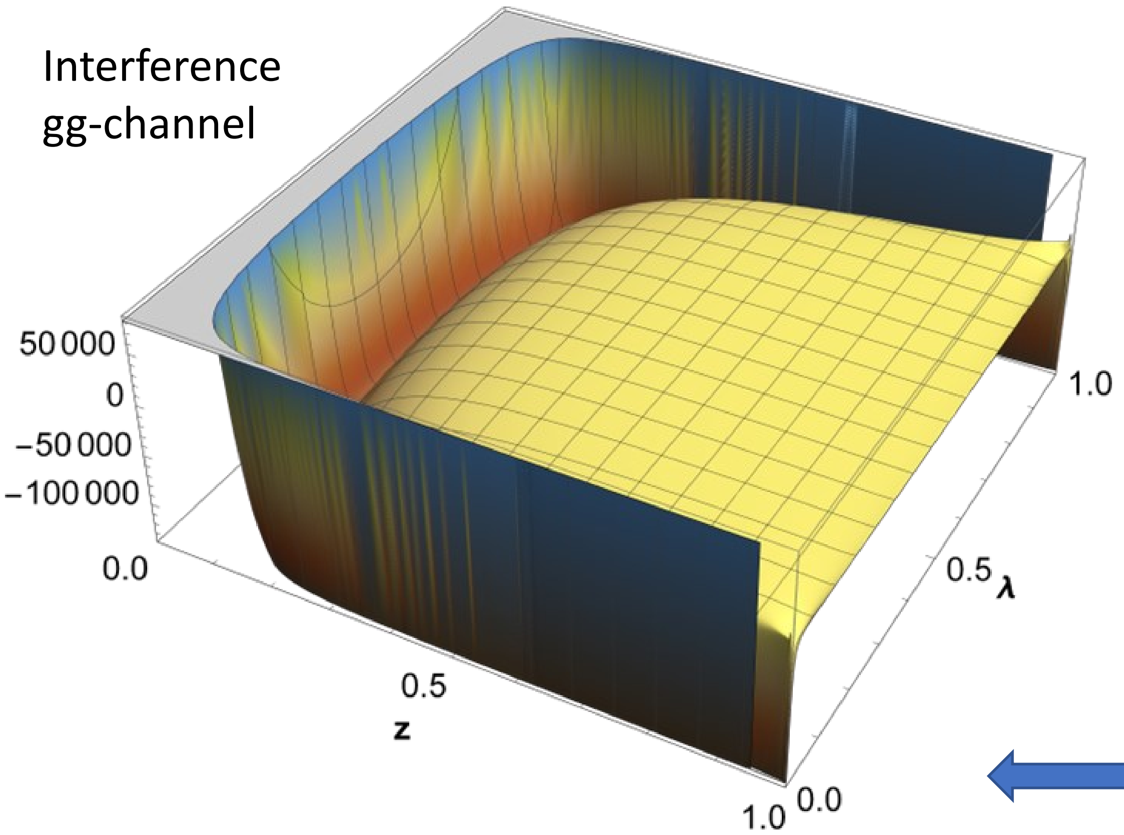
$$\mathcal{M}_{++-} = \frac{1}{\sqrt{2}} \frac{[12]^3}{[13][23]} \frac{s_{23}}{s_{12}}\left(F_1 + \frac{s_{13}}{2}F_4\right) \qquad \mathcal{M}_{--+} = \mathcal{M}_{++-}\Big|_{\langle ij\rangle\leftrightarrow[ji]}$$

$$\mathcal{M}_{+-+} = \frac{1}{\sqrt{2}} \frac{[13]^3}{[12][23]} \frac{s_{12}}{s_{13}}\left(F_2 + \frac{s_{23}}{2}F_4\right) \qquad \mathcal{M}_{-+-} = \mathcal{M}_{+-+}\Big|_{\langle ij\rangle\leftrightarrow[ji]}$$

$$\mathcal{M}_{-++} = \frac{1}{\sqrt{2}} \frac{[23]^3}{[12][13]} \frac{s_{13}}{s_{23}}\left(F_3 + \frac{s_{12}}{2}F_4\right) \qquad \mathcal{M}_{+--} = \mathcal{M}_{-++}\Big|_{\langle ij\rangle\leftrightarrow[ji]}$$

$$|\mathcal{M}|^2 = \sum_{h\in Hel.} |\mathcal{M}_h|^2$$

Interference gg-channel



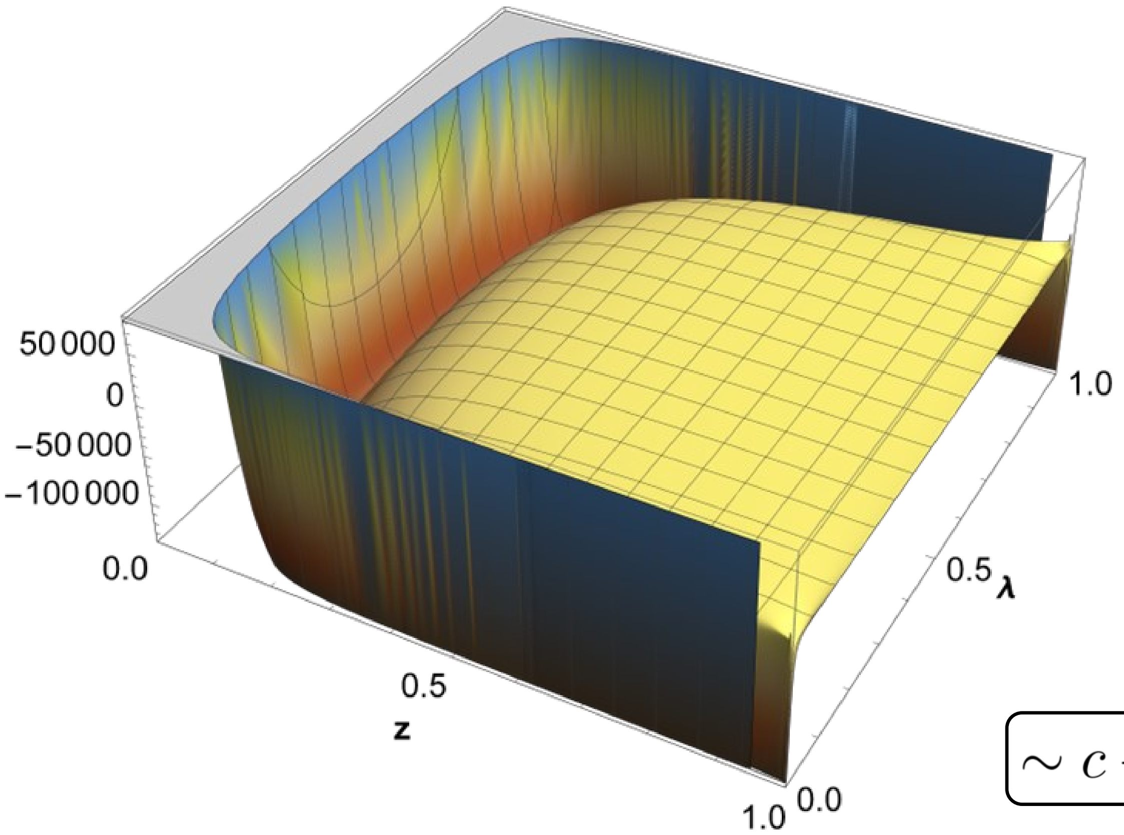
Subtraction of IR divergences for gg → gH

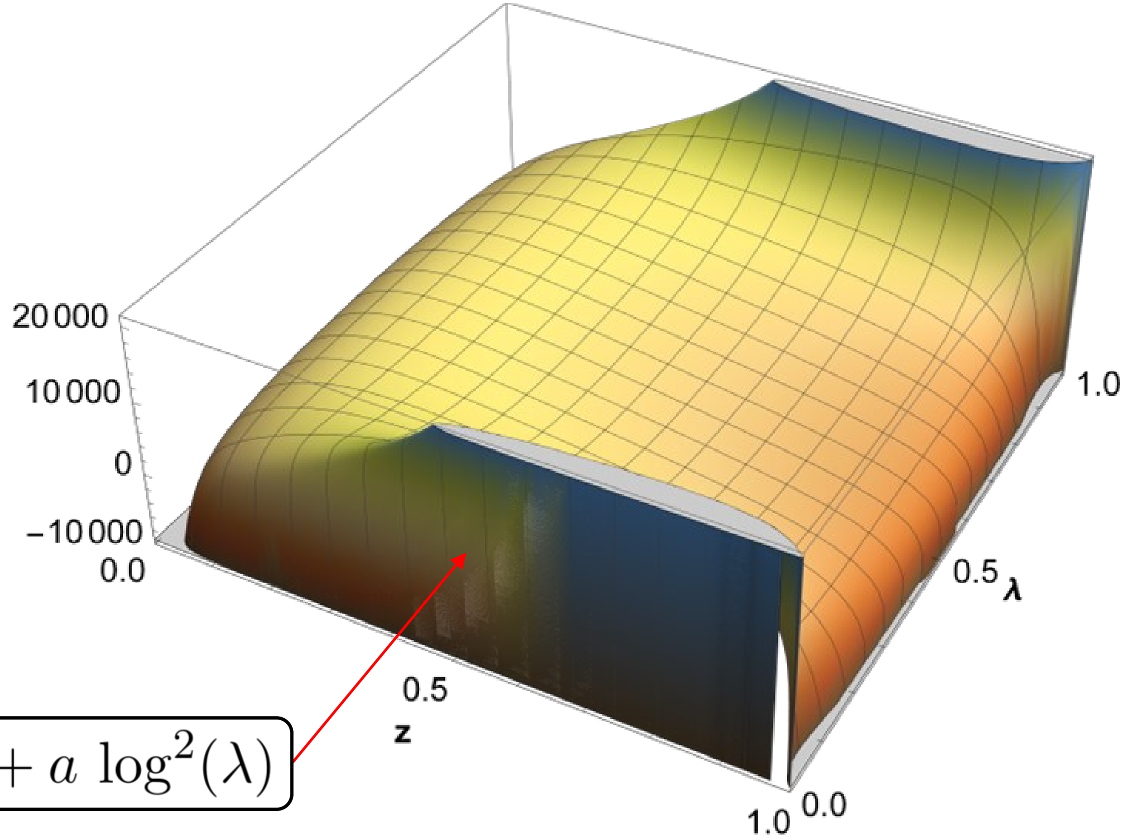
$z = 1 - m_H^2/\hat{s}$
$\lambda = \hat{t}/(\hat{t}+\hat{u})$

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

- From unregulated to regulated quantity at $\mu_R = m_H/2$:

$$r = \frac{\sigma^{\text{LO}}_{t\times b}}{\sigma^{\text{LO}}_{\text{HTL}}} \approx -0.129$$

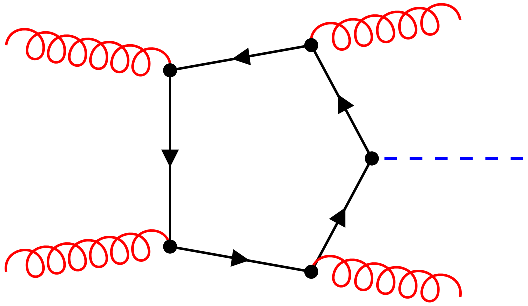




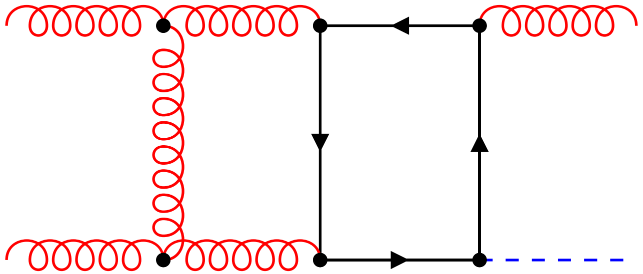
$\sim c + b\,\log(\lambda) + a\,\log^2(\lambda)$

Ingredients for exact quark mass effects at NNLO

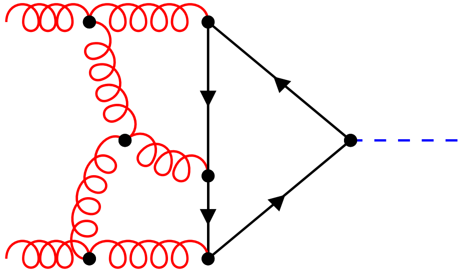
- Beyond NLO:



Analytically: Del Duca, Kilgore, Oleari, et al. `01
OpenLoops 2: Buccioni, Lang, Lindert, et al. `19
Analytically (more compact and implemented in MCFM): Budge, Campbell, De Laurentis, et al. `20



Real-virtual corrections ✓



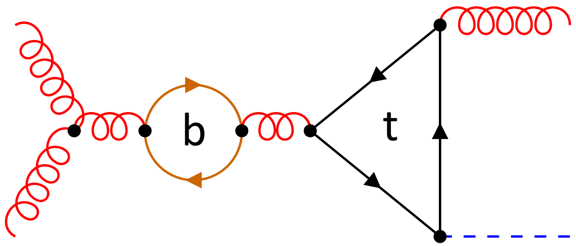
Double-virtual corrections ✓

Phase space integration individual contributions performed using **Stripper** framework Czakon `10

Results

Note on the flavor scheme

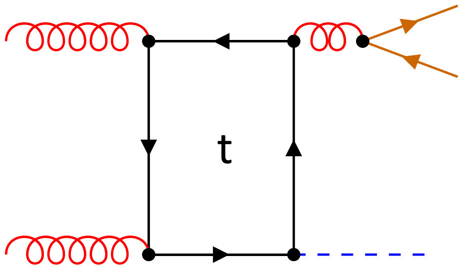
- Subsets of diagrams in real-virtual and double virtual contribution give rise logarithmic mass divergences



$$\xrightarrow{m_b^2 \to 0} \log(m_b^2)$$

4-flavor scheme

- Consistent treatment of massive t- and b-quarks
- Exclude b-quark from initial state
- Include massive b-quark splittings in final state



5-flavor scheme

- Treat b-quark as massless particle
- Massive b-quark only present in loops directly attached to the Higgs-boson
- Corresponds to theory with a replica b-quark carrying the mass of a heavy b-quark

Results

- Effects of interference of top- and bottom-quark amplitudes on Higgs production in gluon-fusion at the LHC
  - PDF set: **NNPDF31_nnlo_as_0118** NNPDF Collaboration `17
  - $\mu_R = \mu_F = m_H/2$ (central scale)
  - m_H = 125 GeV ⇒ $m_t \approx$ 173.055 GeV and $m_b \approx$ 4.779 GeV (*both* in OS-scheme)
  - HEFT values obtained with **SusHi** Harlander, Liebler, Mantler `16

Czakon, Eschment, MN, Poncelet, Schellenberger `23

Order	$\sigma_{\rm HEFT}$ [pb]	$(\sigma_t - \sigma_{\rm HEFT})$ [pb]	$\sigma_{t\times b}$ [pb]	$\sigma_{t\times b}/\sigma_{\rm HEFT}$ [%]
$\sqrt{s} = 8$ TeV				
$\mathcal{O}(\alpha_s^2)$	$+7.39$	–	-0.895	
LO	$7.39^{+1.98}_{-1.40}$	–	$-0.895^{+0.17}_{-0.24}$	-12
$\mathcal{O}(\alpha_s^3)$	$+9.14$	-0.0873	-0.268	
NLO	$16.53^{+3.63}_{-2.73}$	$-0.0873^{+0.030}_{-0.052}$	$-1.163^{+0.10}_{-0.08}$	$-7.0^{+1.0}_{-0.8}$
$\mathcal{O}(\alpha_s^4)$	$+4.19$	$+0.0523(2)$	$+0.167(3)$	
NNLO	$20.72^{+1.84}_{-2.06}$	$-0.0350(2)^{+0.048}_{-0.013}$	$-0.996(3)^{+0.12}_{-0.05}$	$-4.8^{+0.9}_{-0.8}$
$\sqrt{s} = 13$ TeV				
$\mathcal{O}(\alpha_s^2)$	$+16.30$	–	-1.975	
LO	$16.30^{+4.36}_{-3.10}$	–	$-1.98^{+0.38}_{-0.53}$	-12
$\mathcal{O}(\alpha_s^3)$	$+21.14$	-0.303	$-0.446(1)$	
NLO	$37.44^{+8.42}_{-6.29}$	$-0.303^{+0.10}_{-0.17}$	$-2.42^{+0.19}_{-0.12}$	$-6.5^{+0.9}_{-0.8}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+0.147(1)$	$+0.434(8)$	
NNLO	$47.16^{+4.21}_{-4.77}$	$-0.156(1)^{+0.13}_{-0.03}$	$-1.99(1)^{+0.30}_{-0.15}$	$-4.2^{+0.9}_{-0.8}$

Results

- Effects of interference of top- and bottom-quark amplitudes on Higgs production in gluon-fusion at the LHC
  - PDF set: **NNPDF31_nnlo_as_0118** NNPDF Collaboration `17
  - μ_R = μ_F = $m_H/2$ (central scale)
  - m_H = 125 GeV ⇒ m_t ≈ 173.055 GeV and m_b ≈ 4.779 GeV (*both* in OS-scheme)
  - HEFT values obtained with **SusHi** Harlander, Liebler, Mantler `16

Order	σ_{HEFT} [pb]	$(\sigma_t - \sigma_{\mathrm{HEFT}})$ [pb]	$\sigma_{t\times b}$ [pb]	$\sigma_{t\times b}/\sigma_{\mathrm{HEFT}}$ [%]
		$\sqrt{s} = 13$ TeV		
$\mathcal{O}(\alpha_s^2)$	$+16.30$	–	-1.975	
LO	$16.30^{+4.36}_{-3.10}$	–	$-1.98^{+0.38}_{-0.53}$	-12
$\mathcal{O}(\alpha_s^3)$	$+21.14$	-0.303	$-0.446(1)$	
NLO	$37.44^{+8.42}_{-6.29}$	$-0.303^{+0.10}_{-0.17}$	$-2.42^{+0.19}_{-0.12}$	$-6.5^{+0.9}_{-0.8}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+0.147(1)$	$+0.434(8)$	
NNLO	$47.16^{+4.21}_{-4.77}$	$-0.156(1)^{+0.13}_{-0.03}$	$-1.99(1)^{+0.30}_{-0.15}$	$-4.2^{+0.9}_{-0.8}$

Czakon, Eschment, MN, Poncelet, Schellenberger `23

Results

- Effects of interference of top- and bottom-quark amplitudes on Higgs production in gluon-fusion at the LHC
  - PDF set: **NNPDF31_nnlo_as_0118** NNPDF Collaboration `17
  - μ_R = μ_F = $m_H/2$ (central scale)
  - m_H = 125 GeV ⇒ m_t ≈ 173.055 GeV and m_b ≈ 4.779 GeV (*both* in OS-scheme)
  - HEFT values obtained with **SusHi** Harlander, Liebler, Mantler `16

Order	σ_{HEFT} [pb]	$(\sigma_t - \sigma_{\text{HEFT}})$ [pb]	$\sigma_{t\times b}$ [pb]	$\sigma_{t\times b}/\sigma_{\text{HEFT}}$ [%]
		$\sqrt{s} = 13$ TeV		
$\mathcal{O}(\alpha_s^2)$	$+16.30$	–	-1.975	
LO	$16.30^{+4.36}_{-3.10}$	–	$-1.98^{+0.38}_{-0.53}$	-12
$\mathcal{O}(\alpha_s^3)$	$+21.14$	-0.303	$-0.446(1)$	
NLO	$37.44^{+8.42}_{-6.29}$	$-0.303^{+0.10}_{-0.17}$	$-2.42^{+0.19}_{-0.12}$	$-6.5^{+0.9}_{-0.8}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+0.147(1)$	$+0.434(8)$	
NNLO	$47.16^{+4.21}_{-4.77}$	$-0.156(1)^{+0.13}_{-0.03}$	$-1.99(1)^{+0.30}_{-0.15}$	$-4.2^{+0.9}_{-0.8}$

➢ Interference effects much larger than pure top mass effect

Czakon, Eschment, MN, Poncelet, Schellenberger `23

Results

- Effects of interference of top- and bottom-quark amplitudes on Higgs production in gluon-fusion at the LHC
  - PDF set: **NNPDF31_nnlo_as_0118** NNPDF Collaboration `17
  - $\mu_R = \mu_F = m_H/2$ (central scale)
  - m_H = 125 GeV ⇒ $m_t \approx$ 173.055 GeV and $m_b \approx$ 4.779 GeV (*both* in OS-scheme)
  - HEFT values obtained with **SusHi** Harlander, Liebler, Mantler `16

Order	σ_{HEFT} [pb]	$(\sigma_t - \sigma_{\mathrm{HEFT}})$ [pb]	$\sigma_{t\times b}$ [pb]	$\sigma_{t\times b}/\sigma_{\mathrm{HEFT}}$ [%]
		$\sqrt{s} = 13$ TeV		
$\mathcal{O}(\alpha_s^2)$	$+16.30$	–	-1.975	
LO	$16.30^{+4.36}_{-3.10}$	–	$-1.98^{+0.38}_{-0.53}$	-12
$\mathcal{O}(\alpha_s^3)$	$+21.14$	-0.303	$-0.446(1)$	
NLO	$37.44^{+8.42}_{-6.29}$	$-0.303^{+0.10}_{-0.17}$	$-2.42^{+0.19}_{-0.12}$	$-6.5^{+0.9}_{-0.8}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+0.147(1)$	$+0.434(8)$	
NNLO	$47.16^{+4.21}_{-4.77}$	$-0.156(1)^{+0.13}_{-0.03}$	$-1.99(1)^{+0.30}_{-0.15}$	$-4.2^{+0.9}_{-0.8}$

- ➢ Interference effects much larger than pure top mass effect
- ➢ Interference effect at NNLO cancels against NLO

Czakon, Eschment, MN, Poncelet, Schellenberger `23

Results

- Effects of interference of top- and bottom-quark amplitudes on Higgs production in gluon-fusion at the LHC
  - PDF set: **NNPDF31_nnlo_as_0118** NNPDF Collaboration `17
  - μ_R = μ_F = $m_H/2$ (central scale)
  - m_H = 125 GeV ⇒ m_t ≈ 173.055 GeV and m_b ≈ 4.779 GeV (*both* in OS-scheme)
  - HEFT values obtained with **SusHi** Harlander, Liebler, Mantler `16

Order	σ_{HEFT} [pb]	$(\sigma_t - \sigma_{\text{HEFT}})$ [pb]	$\sigma_{t\times b}$ [pb]	$\sigma_{t\times b}/\sigma_{\text{HEFT}}$ [%]
		$\sqrt{s} = 13$ TeV		
$\mathcal{O}(\alpha_s^2)$	$+16.30$	–	-1.975	
LO	$16.30^{+4.36}_{-3.10}$	–	$-1.98^{+0.38}_{-0.53}$	-12
$\mathcal{O}(\alpha_s^3)$	$+21.14$	-0.303	$-0.446(1)$	
NLO	$37.44^{+8.42}_{-6.29}$	$-0.303^{+0.10}_{-0.17}$	$-2.42^{+0.19}_{-0.12}$	$-6.5^{+0.9}_{-0.8}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+0.147(1)$	$+0.434(8)$	
NNLO	$47.16^{+4.21}_{-4.77}$	$-0.156(1)^{+0.13}_{-0.03}$	$-1.99(1)^{+0.30}_{-0.15}$	$-4.2^{+0.9}_{-0.8}$

- ➢ Interference effects much larger than pure top mass effect
- ➢ Interference effect at NNLO cancels against NLO
- ➢ Interference effect at NNLO larger than NLO scale variation (similar in HEFT but less severe)

Czakon, Eschment, MN, Poncelet, Schellenberger `23

Results

- Effects of interference of top- and bottom-quark amplitudes on Higgs production in gluon-fusion at the LHC
  - PDF set: **NNPDF31_nnlo_as_0118** NNPDF Collaboration `17
  - $\mu_R = \mu_F = m_H/2$ (central scale)
  - m_H = 125 GeV ⇒ $m_t \approx$ 173.055 GeV and $m_b \approx$ 4.779 GeV (*both* in OS-scheme)
  - HEFT values obtained with **SusHi** Harlander, Liebler, Mantler `16

Order	σ_{HEFT} [pb]	$(\sigma_t - \sigma_{\mathrm{HEFT}})$ [pb]	$\sigma_{t\times b}$ [pb]	$\sigma_{t\times b}/\sigma_{\mathrm{HEFT}}$ [%]
		$\sqrt{s} = 13$ TeV		
$\mathcal{O}(\alpha_s^2)$	$+16.30$	–	-1.975	
LO	$16.30^{+4.36}_{-3.10}$	–	$-1.98^{+0.38}_{-0.53}$	-12
$\mathcal{O}(\alpha_s^3)$	$+21.14$	-0.303	$-0.446(1)$	
NLO	$37.44^{+8.42}_{-6.29}$	$-0.303^{+0.10}_{-0.17}$	$-2.42^{+0.19}_{-0.12}$	$-6.5^{+0.9}_{-0.8}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+0.147(1)$	$+0.434(8)$	
NNLO	$47.16^{+4.21}_{-4.77}$	$-0.156(1)^{+0.13}_{-0.03}$	$-1.99(1)^{+0.30}_{-0.15}$	$-4.2^{+0.9}_{-0.8}$

- ➢ Interference effects much larger than pure top mass effect
- ➢ Interference effect at NNLO cancels against NLO
- ➢ Interference effect at NNLO larger than NLO scale variation (similar in HEFT but less severe)
- ➢ Interference NNLO scale variation increases compared to NLO

Czakon, Eschment, MN, Poncelet, Schellenberger `23

Results

- Effects of interference of top- and bottom-quark amplitudes on Higgs production in gluon-fusion at the LHC
  - PDF set: **NNPDF31_nnlo_as_0118** NNPDF Collaboration `17
  - μ_R = μ_F = $m_H/2$ (central scale)
  - m_H = 125 GeV ⇒ m_t ≈ 173.055 GeV and m_b ≈ 4.779 GeV (*both* in OS-scheme)
  - HEFT values obtained with **SusHi** Harlander, Liebler, Mantler `16

Order	σ_{HEFT} [pb]	$(\sigma_t - \sigma_{\text{HEFT}})$ [pb]	$\sigma_{t\times b}$ [pb]	$\sigma_{t\times b}/\sigma_{\text{HEFT}}$ [%]
		$\sqrt{s} = 13$ TeV		
$\mathcal{O}(\alpha_s^2)$	$+16.30$	–	-1.975	
LO	$16.30^{+4.36}_{-3.10}$	–	$-1.98^{+0.38}_{-0.53}$	-12
$\mathcal{O}(\alpha_s^3)$	$+21.14$	-0.303	$-0.446(1)$	
NLO	$37.44^{+8.42}_{-6.29}$	$-0.303^{+0.10}_{-0.17}$	$-2.42^{+0.19}_{-0.12}$	$-6.5^{+0.9}_{-0.8}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+0.147(1)$	$+0.434(8)$	
NNLO	$47.16^{+4.21}_{-4.77}$	$-0.156(1)^{+0.13}_{-0.03}$	$-1.99(1)^{+0.30}_{-0.15}$	$-4.2^{+0.9}_{-0.8}$

Czakon, Eschment, MN, Poncelet, Schellenberger `23

- ➢ Interference effects much larger than pure top mass effect
- ➢ Interference effect at NNLO cancels against NLO
- ➢ Interference effect at NNLO larger than NLO scale variation (similar in HEFT but less severe)
- ➢ Interference NNLO scale variation increases compared to NLO
- ➢ Similar effects for different top quark mass (m_t ≈ 170.979 GeV)

Results

- Effects of interference of top- and bottom-quark amplitudes on Higgs production in gluon-fusion at the LHC
  - PDF set: **NNPDF31_nnlo_as_0118** NNPDF Collaboration `17
  - $\mu_R = \mu_F = m_H/2$ (central scale)
  - m_H = 125 GeV $\Rightarrow m_t \approx$ 173.055 GeV and $m_b \approx$ 4.779 GeV (OS-scheme, but Y_b in $\overline{MS}$ with $\overline{m}_b(\overline{m}_b) \approx$ 4.18 GeV)
  - HEFT values obtained with **SusHi** Harlander, Liebler, Mantler `16

Order	σ_{HEFT} [pb]	$(\sigma_t - \sigma_{\text{HEFT}})$ [pb]	$\sigma_{t\times b}$ [pb]	$\sigma_{t\times b}\,(Y_{b,\overline{\text{MS}}})$ [pb]
		$\sqrt{s} = 13$ TeV		
$\mathcal{O}(\alpha_s^2)$	$+16.30$	–	-1.975	-1.223
LO	$16.30^{+4.36}_{-3.10}$	–	$-1.98^{+0.38}_{-0.53}$	$-1.22^{+0.29}_{-0.44}$
$\mathcal{O}(\alpha_s^3)$	$+21.14$	-0.303	$-0.446(1)$	$-0.623(1)$
NLO	$37.44^{+8.42}_{-6.29}$	$-0.303^{+0.10}_{-0.17}$	$-2.42^{+0.19}_{-0.12}$	$-1.85^{+0.26}_{-0.26}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+0.147(1)$	$+0.434(8)$	$+0.019(5)$
NNLO	$47.16^{+4.21}_{-4.77}$	$-0.156(1)^{+0.13}_{-0.03}$	$-1.99(1)^{+0.30}_{-0.15}$	$-1.83(1)^{+0.08}_{-0.03}$

Czakon, Eschment, MN, Poncelet, Schellenberger `23

- ➢ Interference effects much larger than pure top mass effect
- ➢ Interference effect at NNLO cancels against NLO
- ➢ Interference effect at NNLO larger than NLO scale variation (similar in HEFT but less severe)
- ➢ Interference NNLO scale variation increases compared to NLO
- ➢ Similar effects for different top quark mass ($m_t \approx$ 170.979 GeV)
- ➢ Improved convergence in mixed renormalization scheme compared to OS-scheme

Results

- Effects of interference of top- and bottom-quark amplitudes on Higgs production in gluon-fusion at the LHC
  - PDF set: **NNPDF31_nnlo_as_0118** NNPDF Collaboration `17
  - μ_R = μ_F = $m_H/2$ (central scale)
  - m_H = 125 GeV ⇒ m_t ≈ 173.055 GeV (OS-scheme) and m_b in $\overline{MS}$-scheme with $\overline{m}_b(\overline{m}_b)$ ≈ 4.18 GeV
  - HEFT values obtained with **SusHi** Harlander, Liebler, Mantler `16

Order	σ_{HEFT} [pb]	$(\sigma_t - \sigma_{\text{HEFT}})$ [pb]	$\sigma_{t\times b}$ [pb]	$\sigma_{t\times b}\,(Y_{b,\overline{\text{MS}}})$ [pb]	$\sigma_{t\times b}\,(\overline{m}_b)$ [pb]
			$\sqrt{s} = 13$ TeV		
$\mathcal{O}(\alpha_s^2)$	$+16.30$	–	-1.975	-1.223	-1.118
LO	$16.30^{+4.36}_{-3.10}$	–	$-1.98^{+0.38}_{-0.53}$	$-1.22^{+0.29}_{-0.44}$	$-1.118^{+0.28}_{-0.43}$
$\mathcal{O}(\alpha_s^3)$	$+21.14$	-0.303	$-0.446(1)$	$-0.623(1)$	-0.647
NLO	$37.44^{+8.42}_{-6.29}$	$-0.303^{+0.10}_{-0.17}$	$-2.42^{+0.19}_{-0.12}$	$-1.85^{+0.26}_{-0.26}$	$-1.76^{+0.27}_{-0.28}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+0.147(1)$	$+0.434(8)$	$+0.019(5)$	$+0.02(1)$
NNLO	$47.16^{+4.21}_{-4.77}$	$-0.156(1)^{+0.13}_{-0.03}$	$-1.99(1)^{+0.30}_{-0.15}$	$-1.83(1)^{+0.08}_{-0.03}$	$-1.74(2)^{+0.13}_{-0.01}$

Czakon, Eschment, MN, Poncelet, Schellenberger `23 (preliminary)

- ➢ Interference effects much larger than pure top mass effect
- ➢ Interference effect at NNLO cancels against NLO
- ➢ Interference effect at NNLO larger than NLO scale variation (similar in HEFT but less severe)
- ➢ Interference NNLO scale variation increases compared to NLO
- ➢ Similar effects for different top quark mass (m_t ≈ 170.979 GeV)
- ➢ Improved convergence in mixed renormalization scheme compared to OS-scheme
- ➢ Similar pattern of corrections for m_b in $\overline{MS}$-scheme

Summary and outlook

- The top-bottom interference contribution to the total Higgs production cross section was computed with *both* quarks renormalized in the OS-scheme
  - $\mathcal{O}(\alpha_s^4)$ correction at 8 TeV: +0.167 pb
  - $\mathcal{O}(\alpha_s^4)$ correction at 13 TeV: +0.434 pb
- NNLO correction at 13 TeV: $-1.99(1)^{+0.30}_{-0.15}$ pb compatible with previous estimate $-2.18^{+0.20}_{-0.20}$ pb Anastasiou, Penin `20
- Top-quark and interference contribution not sensitive to small variations of the top-quark mass
- Interference shows signs of poor perturbative convergence
  - Better convergence in $\overline{MS}$-scheme for the bottom-quark mass or Yukawa coupling only

- Cross checks: at the differential level
  - Jones, Kerner, Luisoni `18
  - Caola, Lindert, Melnikov, et al. `18

- Next steps:
  - Complete calculation with quark masses renormalized in $\overline{MS}$-scheme (compare e.g. Bonciani, Del Duca, Frellesvig, et al. `22)
  - Consistent treatment of massive quarks in 4-flavor scheme
  - Top-charm interference contribution