Top-Bottom Interference Contribution to Fully-Inclusive Higgs Production

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

based on

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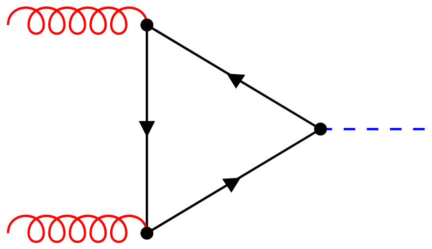
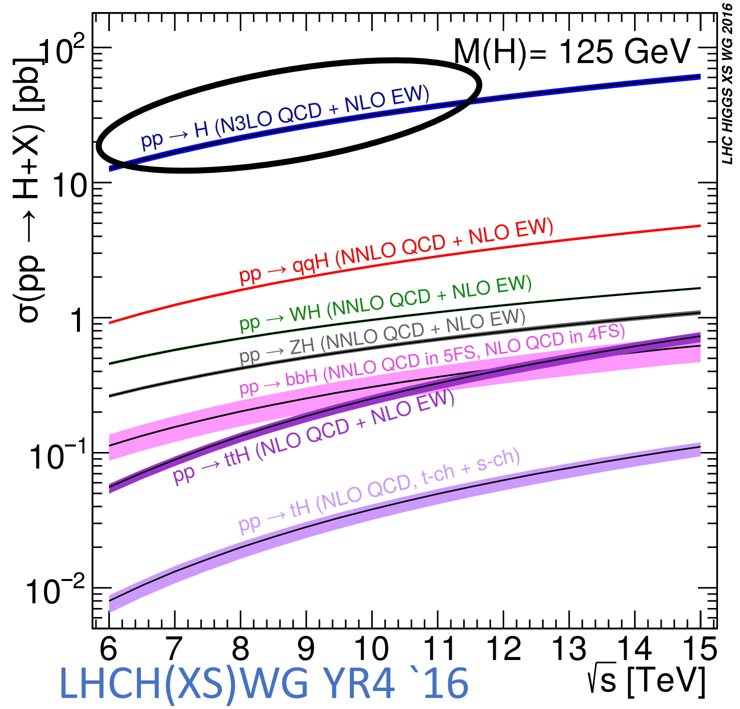
Gluon fusion

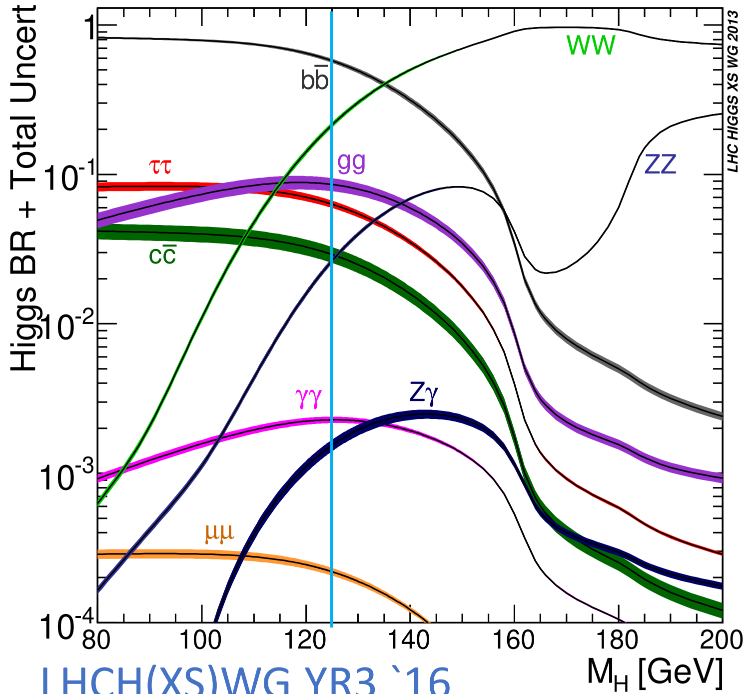
- Gluon fusion is the predominant Higgs boson production mode at the LHC
  - loop induced process



- 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:

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

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

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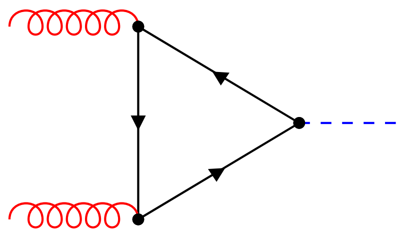
Order by order in perturbation theory

- LO contribution exactly known for almost 50 years



Georgi, Glashow, Machacek, et al. `78

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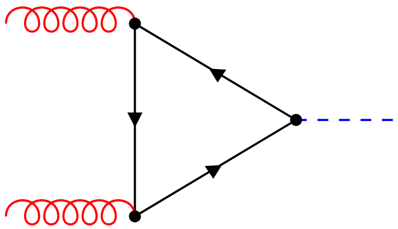

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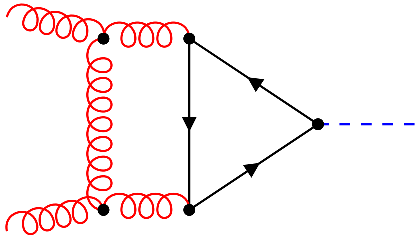
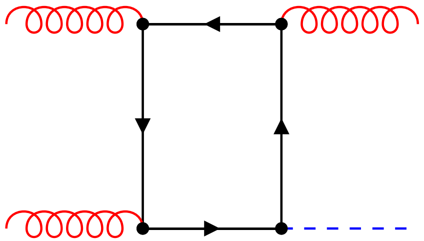
- NLO contribution exactly known for arbitrary quark masses running in the loop Graudenz, Spira, Zerwas `93





Inclusive cross section in (r)EFT

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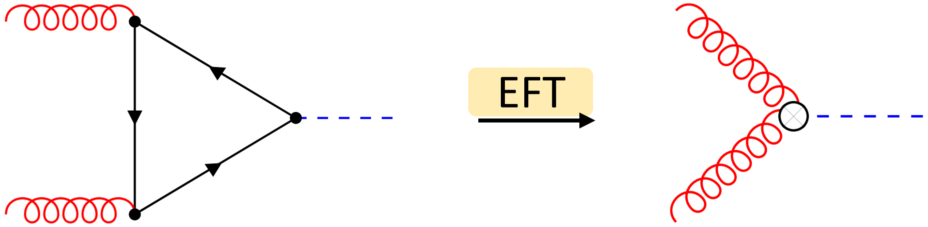

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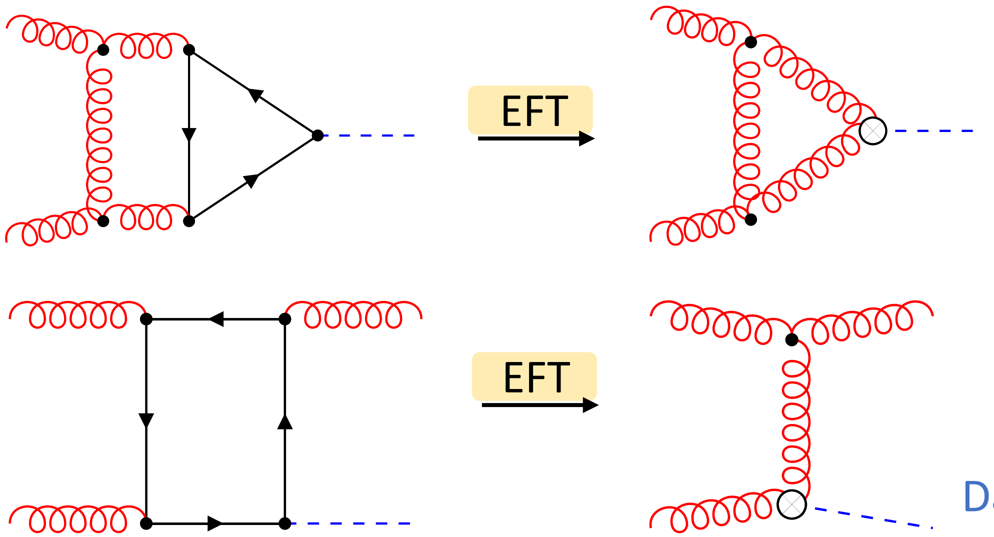


Dawson`91
Djouadi, Spira, Zerwas `91

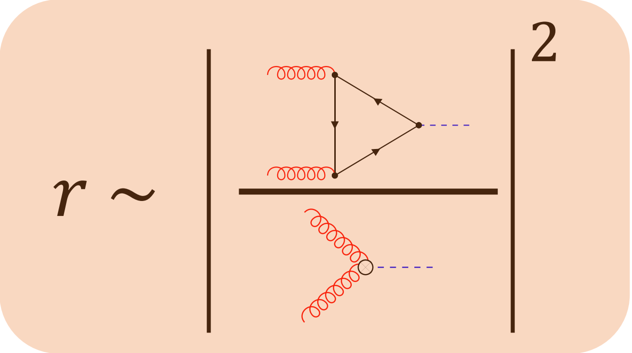
$$\mathcal{L}_{\rm SM}$$

$$m_t \to \infty$$

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

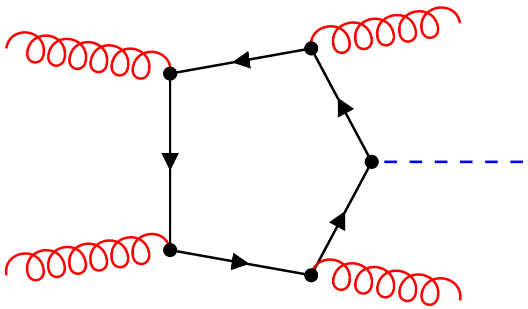
Chetyrkin, Kniehl, Steinhauser `98
Schröder, Steinhauser `06
Chetyrkin, Kühn, Sturm `06

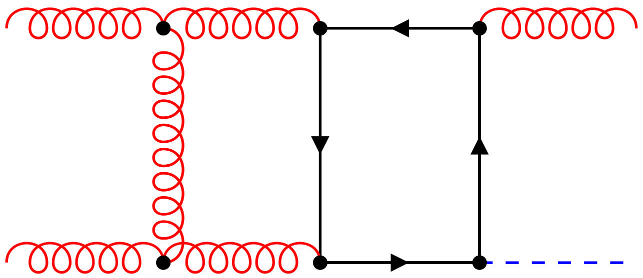
$$\sigma^{\rm HO}_{\rm HEFT} = \left(\frac{\sigma^{\rm HO}}{\sigma^{\rm LO}}\right)_{M_t \to \infty} \sigma^{\rm LO}$$

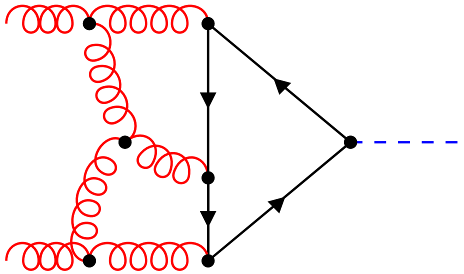


Computation

Ingredients for exact quark mass effects at NNLO







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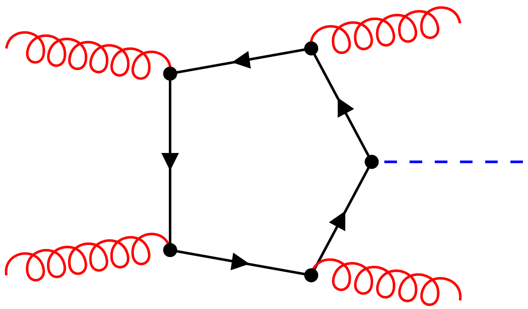

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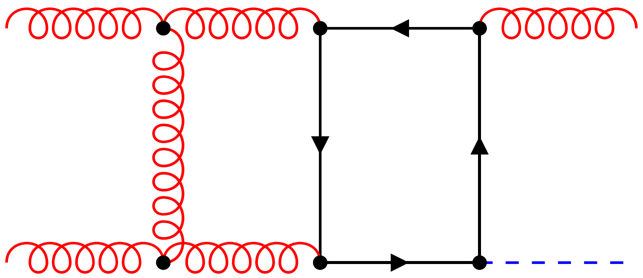

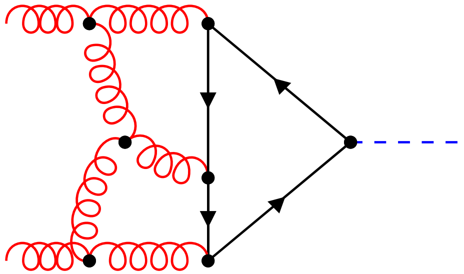

Double-virtual corrections

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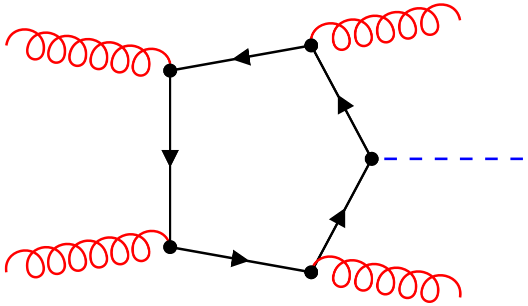

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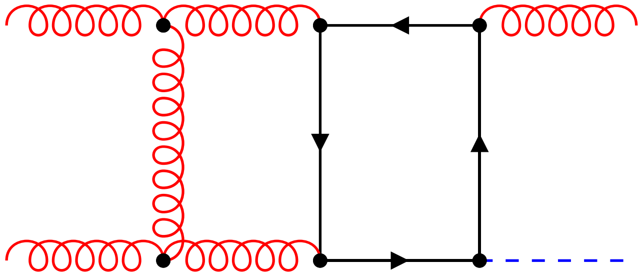

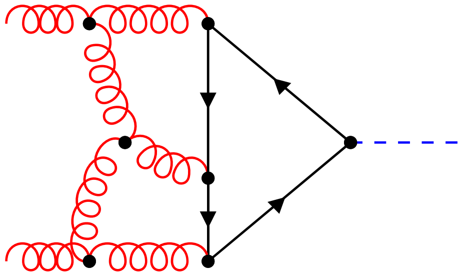

Double-virtual corrections
Czakon, MN `20
MN, Usovitsch `23

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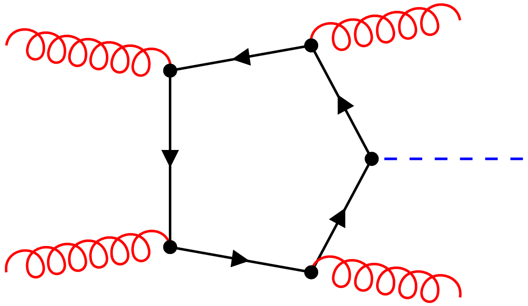

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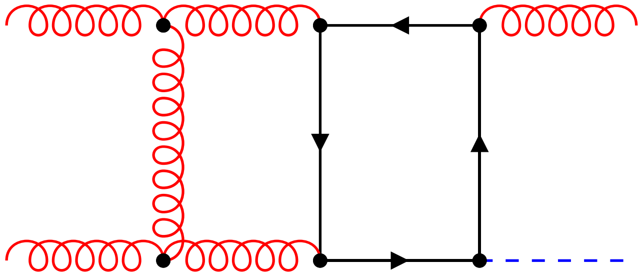

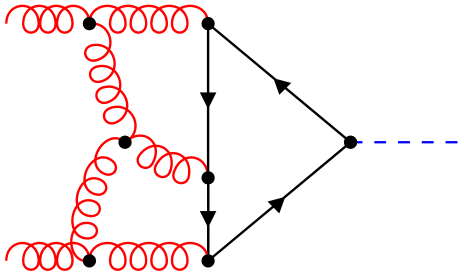

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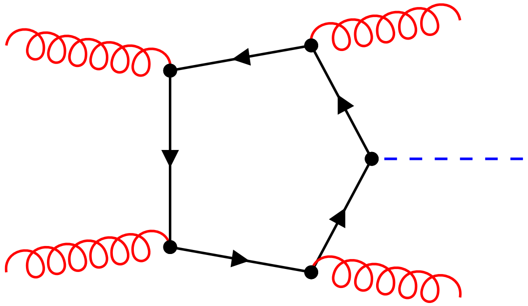

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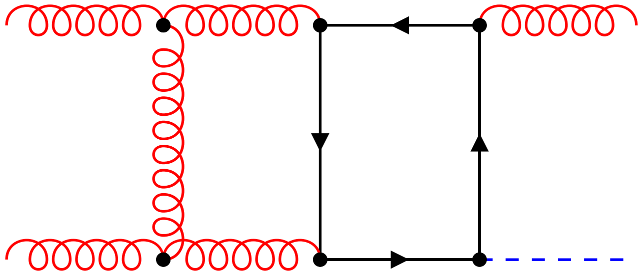

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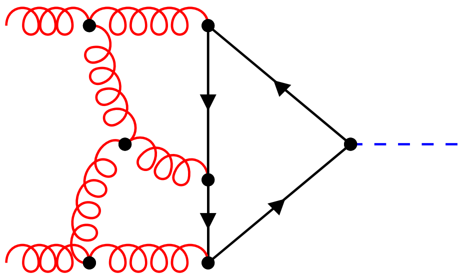

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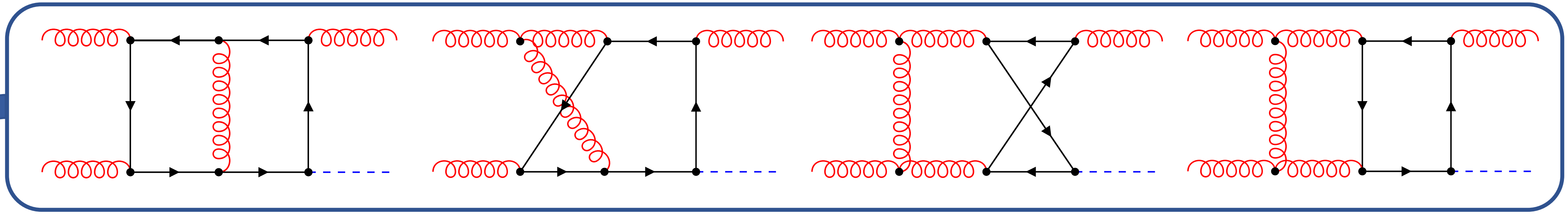
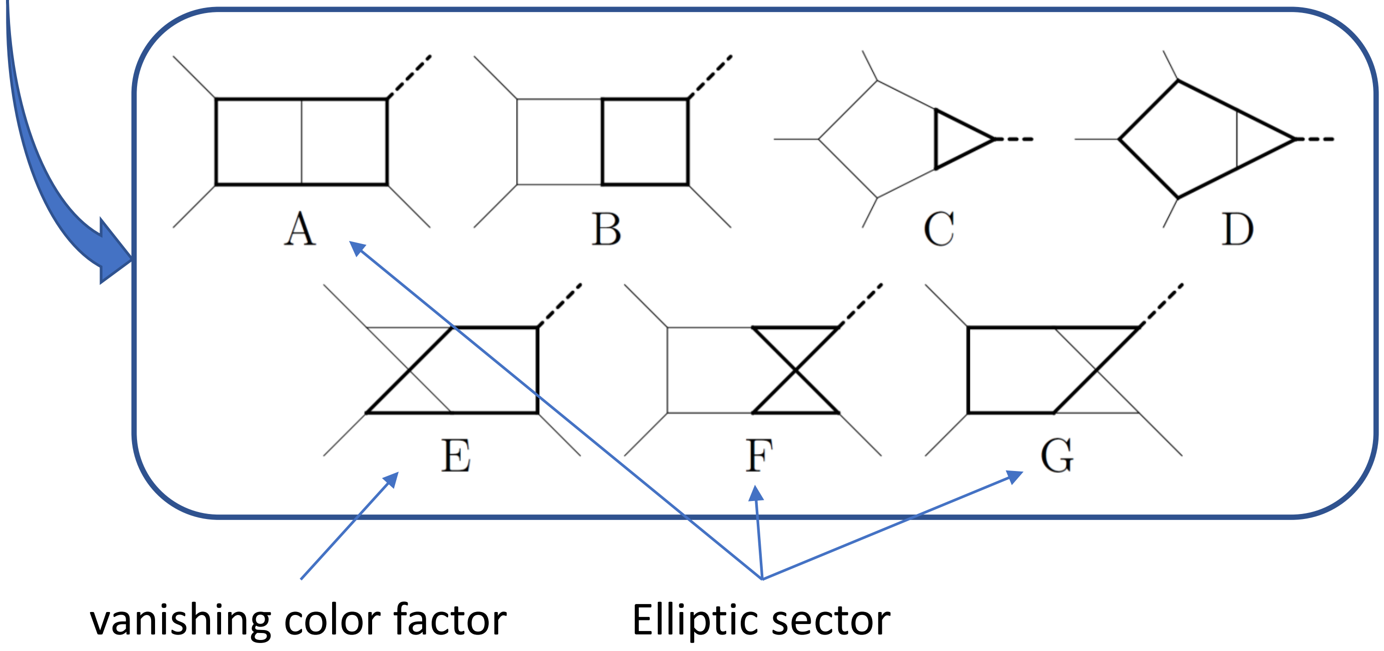
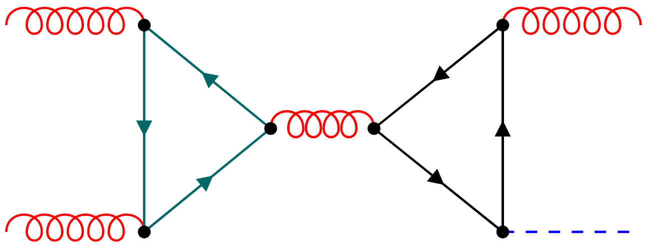




A,B,C,D: Bonciani, Del Duca, Frellesvig, et al. `16
F: Bonciani, Del Duca, Frellesvig, et al. `19
G: Frellesvig, Hidding, Maestri, et al. `19

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 <u>fix ratio</u> 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:

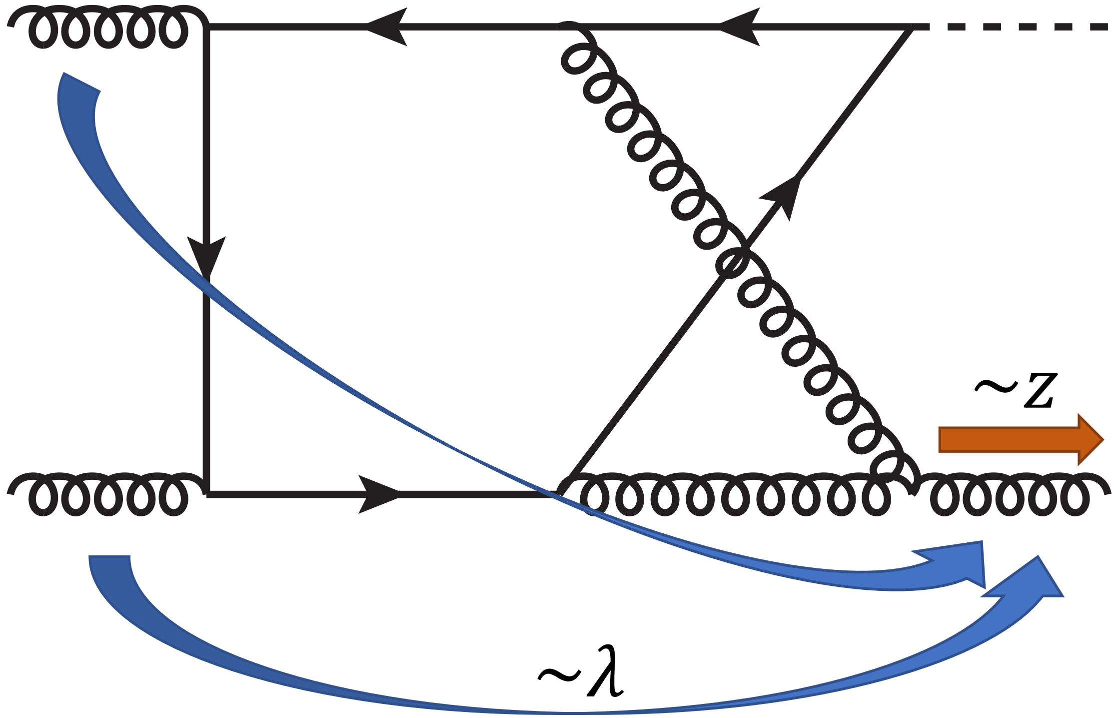
- $\lambda \in (0,1)$
- $z \in (0,1)$

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

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

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

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

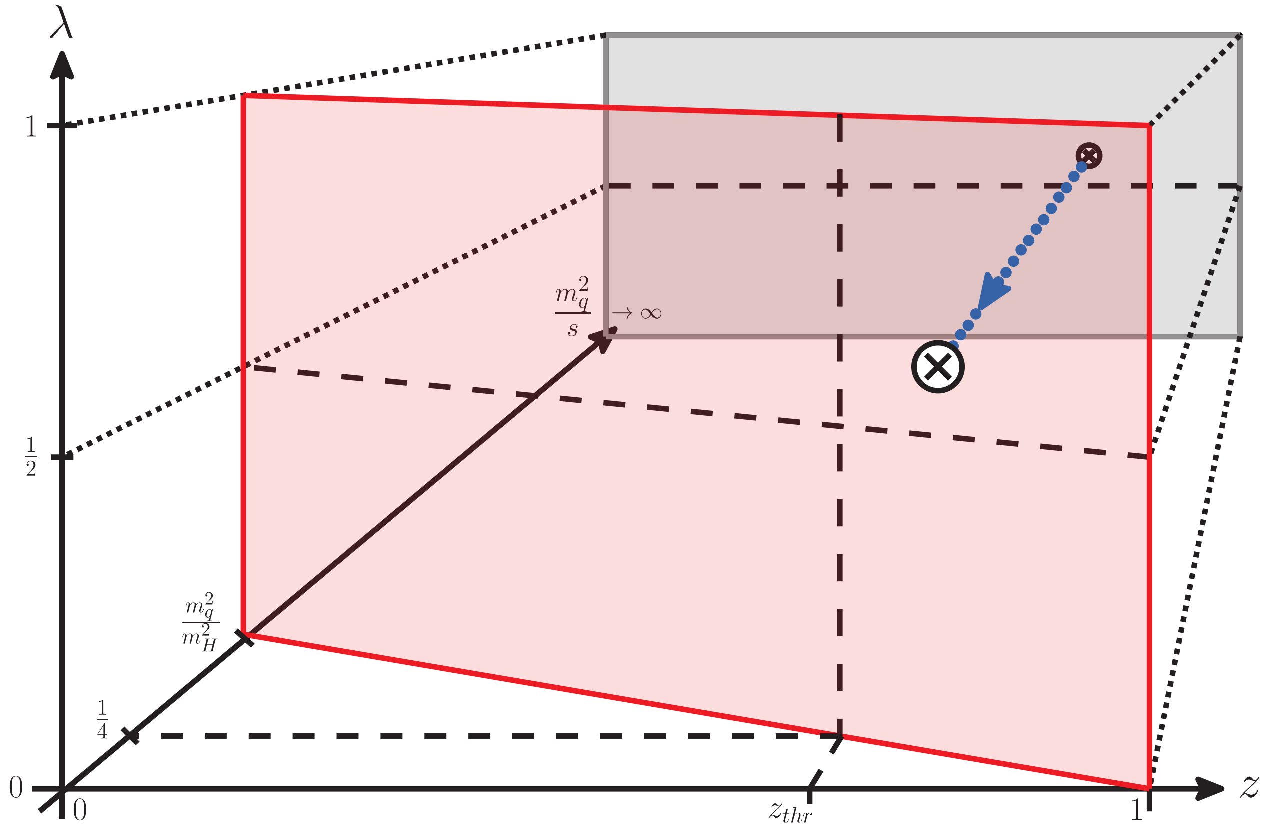


Numerical evolutions

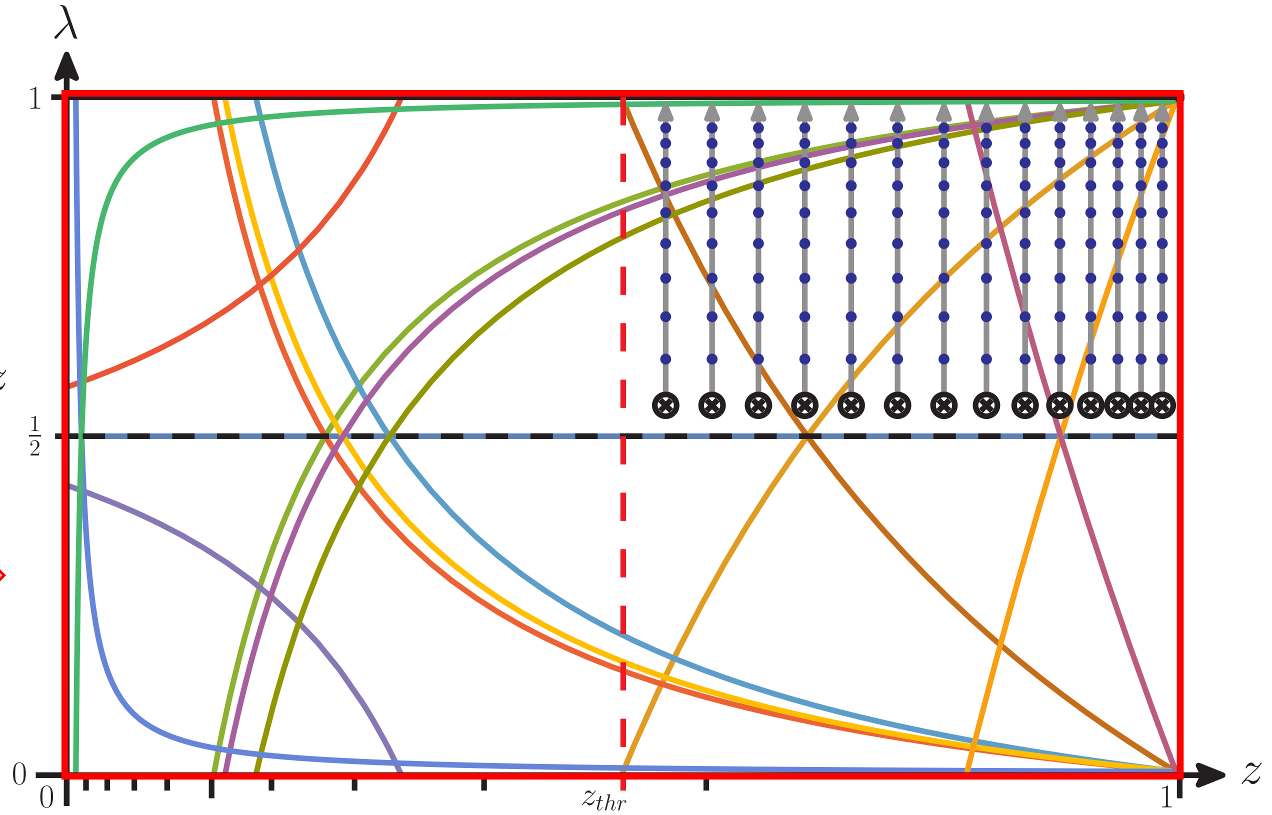
$z = 1\text{-}m_H^2/\hat{s}$

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

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



- Initial condition given in the limit $m_q^2 \to \infty$
- Transport boundary from $m_q^2 \to \infty$ to physical plane



- Collect numerical samples for MIs along straight contours in λ for different values of z

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

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

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

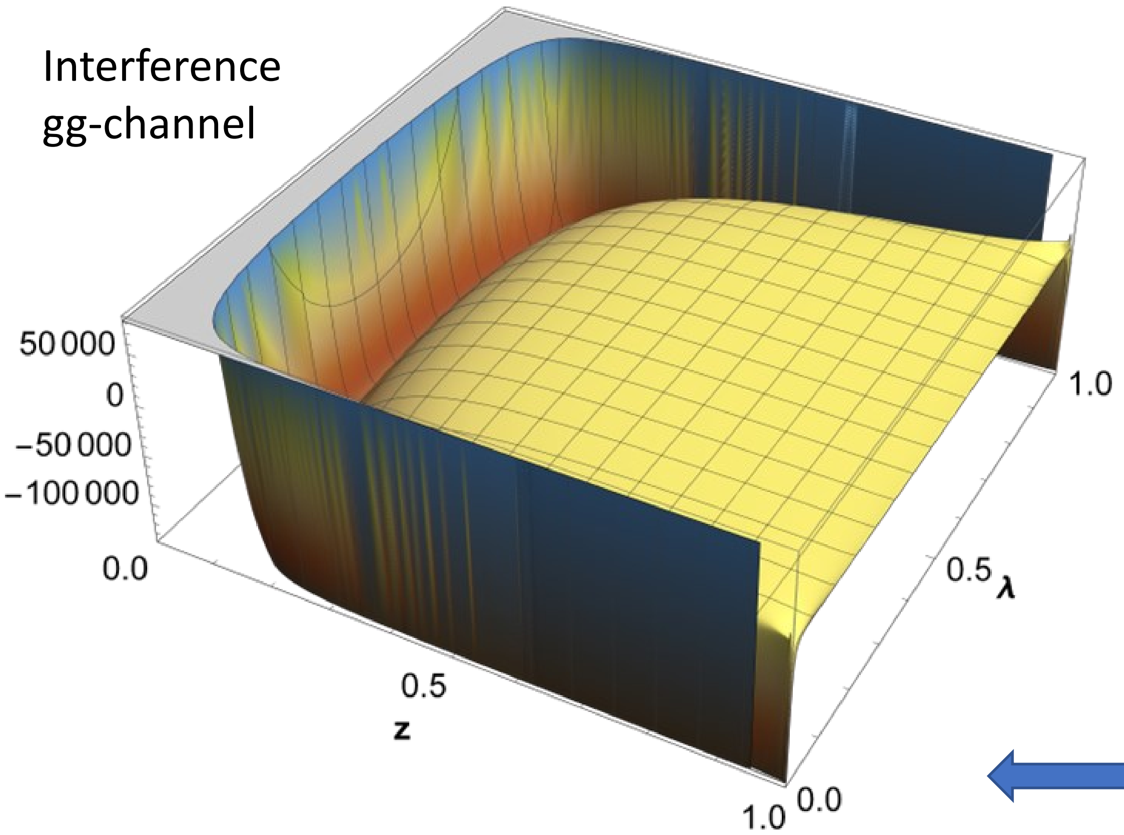
$$\mathcal{M}_{++-} = \frac{1}{\sqrt{2}} \frac{[12]^3}{[13][23]} \frac{s_{23}}{s_{12}}\left(F_1 + \frac{s_{13}}{2}F_4\right) \qquad \mathcal{M}_{--+} = \mathcal{M}_{++-}\Big|_{\langle ij\rangle \leftrightarrow [ji]}$$

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

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

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

Interference gg-channel



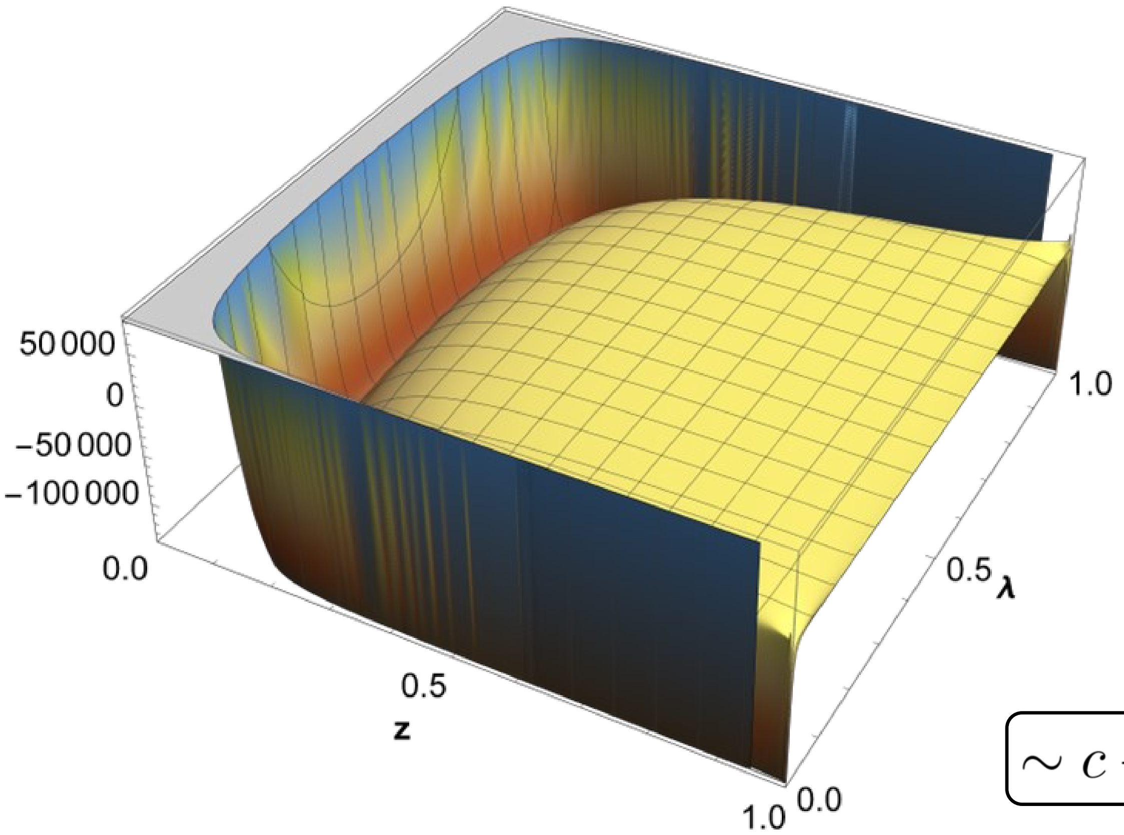
Subtraction of IR divergences for **gg → gH**

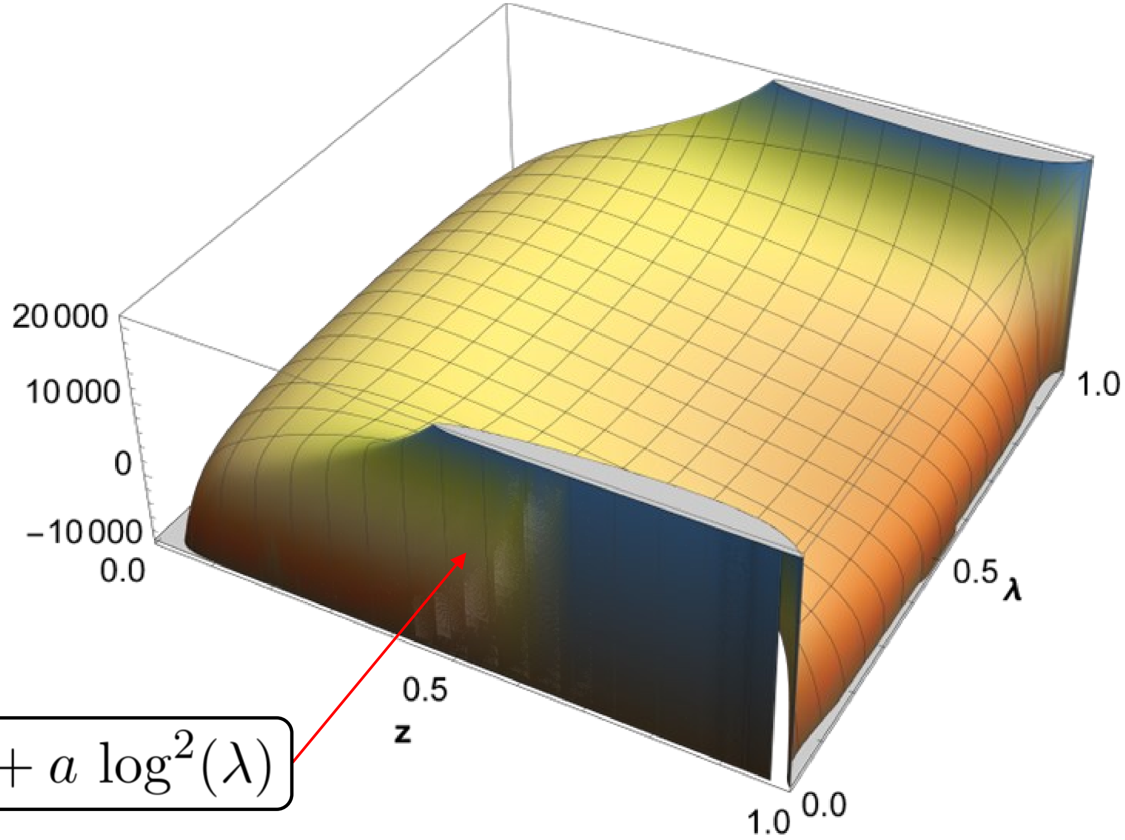
$z = 1 - m_H^2/\hat{s}$
$\lambda = \hat{t}/(\hat{t}+\hat{u})$

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

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

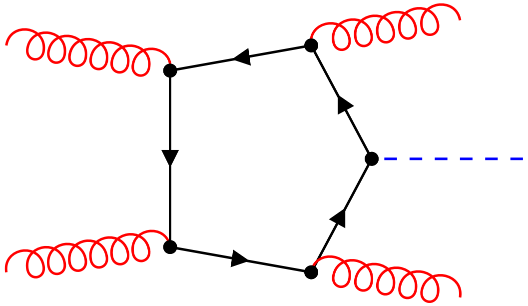
- From unregulated to regulated quantity at $\mu_R = m_H/2$:



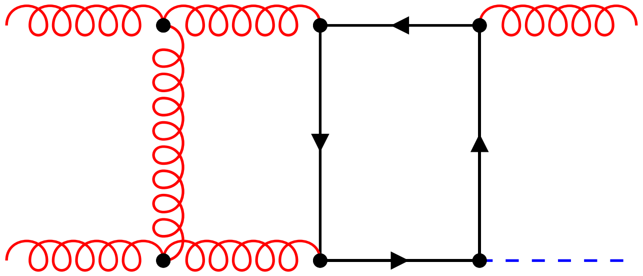


$$\sim c + b\,\log(\lambda) + a\,\log^2(\lambda)$$

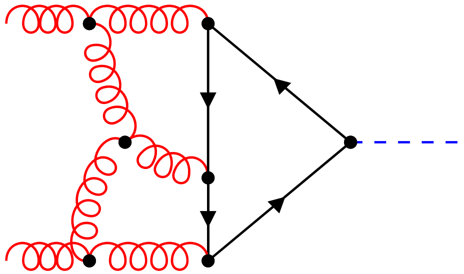
Ingredients for exact quark mass effects at NNLO



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

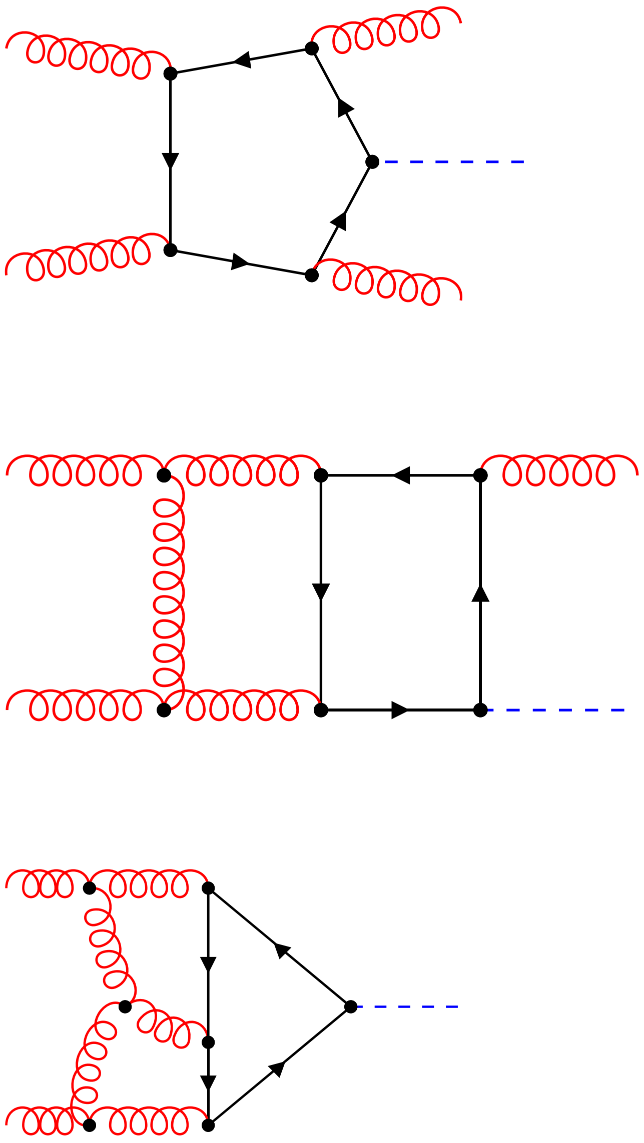


Real-virtual corrections ✓



Double-virtual corrections ✓
Czakon, MN `20
MN, Usovitsch `23

Ingredients for exact quark mass effects at NNLO



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Analytically (more compact and implemented in MCFM): Budge, Campbell, De Laurentis, et al. `20

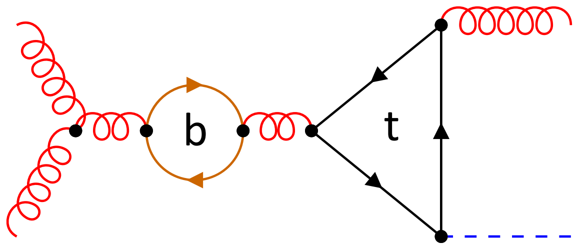
Phase-space integration with sector-improved residue subtraction scheme (**Stripper** Czakon `10)

Double-virtual corrections
Czakon, MN `20
MN, Usovitsch `23

Results

Note on the flavor scheme

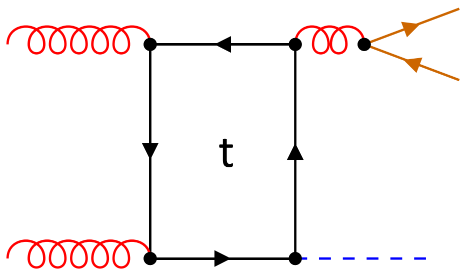
- Subsets of diagrams in real-virtual and double virtual contribution give rise logarithmic mass divergences



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

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
  - μ_R = μ_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	σ_{HEFT} [pb]	$(\sigma_t - \sigma_{\text{HEFT}})$ [pb]	$\sigma_{t\times b}$ [pb]	$\sigma_{t\times b}/\sigma_{\text{HEFT}}$ [%]
		$\sqrt{s} = 8$ 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
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  - $\mu_R = \mu_F = m_H/2$ (central scale)
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Czakon, Eschment, MN, Poncelet, Schellenberger `23

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➢ Interference effects much larger than pure top mass effect

Czakon, Eschment, MN, Poncelet, Schellenberger `23

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Czakon, Eschment, MN, Poncelet, Schellenberger `23

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- ➢ 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)

Results

- Effects of interference of top- and bottom-quark amplitudes on Higgs production in gluon-fusion at the LHC
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  - $\mu_R = \mu_F = m_H/2$ (central scale)
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- ➢ Interference effect at NNLO larger than NLO scale variation (similar in HEFT but less severe)
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Results

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  - PDF set: **NNPDF31_nnlo_as_0118** NNPDF Collaboration `17
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- ➢ 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)

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 (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
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- ➢ 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)
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  - 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	$47.16^{+4.21}_{-4.77}$	$-0.156(1)^{+0.13}_{-0.03}$	$-1.99(1)^{+0.30}_{-0.15}$	$-1.83(1)^{+0.08}_{-0.03}$	$-1.74(2)^{+0.13}_{-0.01}$

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 ($m_t \approx$ 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

  ⟵ $\mathcal{O}(1\%)$ effect
- 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
  - Bonciani, Del Duca, Frellesvig, et al. `22

- Next steps:
  - Complete calculation with quark masses renormalized in $\overline{MS}$-scheme
  - Consistent treatment of massive quarks in 4-flavor scheme
  - Top-charm interference contribution

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preliminary

Order	$\sigma_{t\times b}$ [pb]	
	$\sqrt{s} = 13$ TeV	
	5FS	4FS
$\mathcal{O}(\alpha_s^2)$	-1.975	-1.971
LO	$-1.98^{+0.37}_{-0.53}$	$-1.97^{+0.39}_{-0.56}$
$\mathcal{O}(\alpha_s^3)$	$-0.447(4)$	$-0.455(4)$
NLO	$-2.42^{+0.19}_{-0.12}$	$-2.43^{+0.21}_{-0.13}$
$\mathcal{O}(\alpha_s^4)$	$+0.434(8)$	$+0.389(11)$
NNLO	$-1.99(1)^{+0.30}_{-0.15}$	$-2.04(1)^{+0.29}_{-0.14}$