Quark Mass Effects in Higgs Production

Marco Niggetiedt

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

based on

PRL 132 (2024) 211902
[arXiv:2407.12413]

High Precision for
Hard Processes 2024

MAX-PLANCK-INSTITUT
FÜR PHYSIK

Turin
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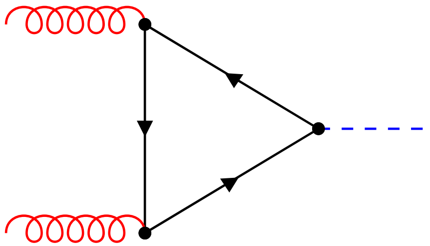
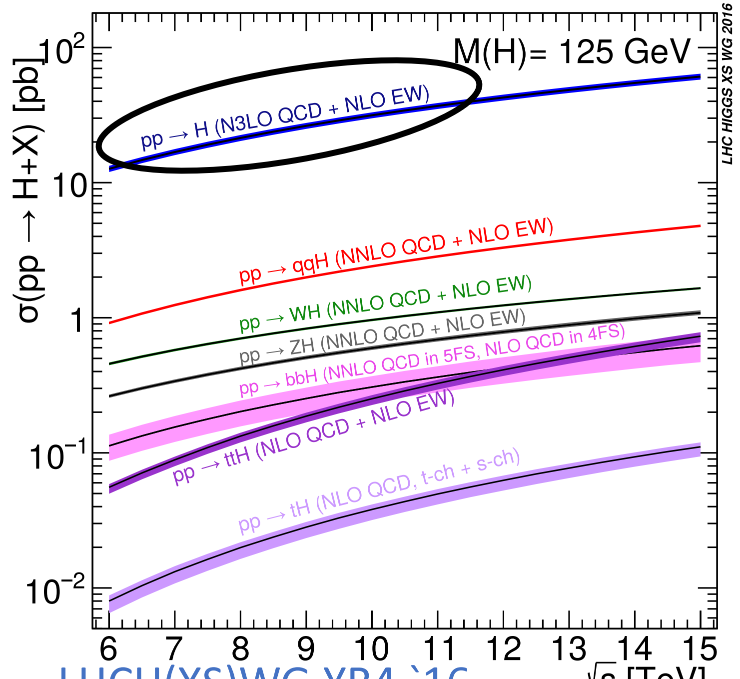
Gluon fusion

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

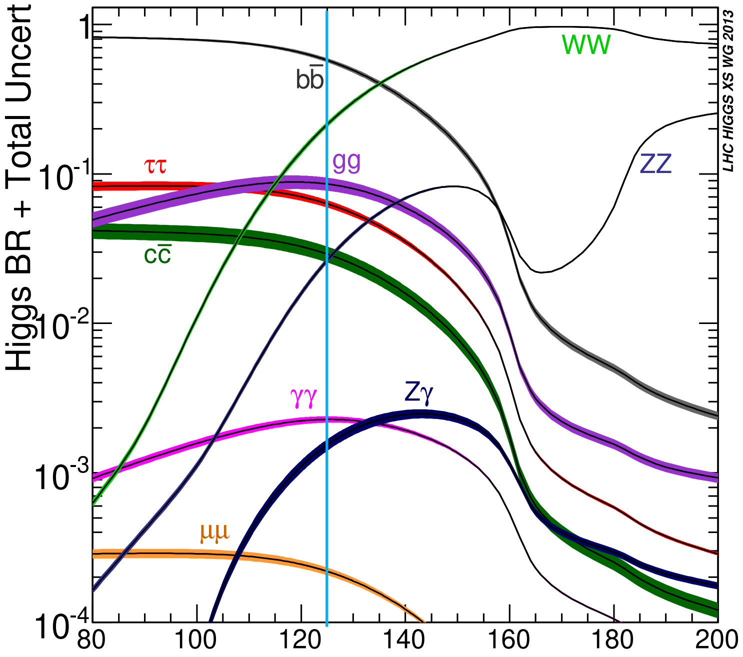


- Higgs boson plays unique role in the SM:
  - Only scalar particle
  - Only particle with Yukawa interactions to fermions
- Predictions for gluon fusion cross section directly impact extraction of Higgs couplings from experimental measurements
- Reducing theory uncertainty is crucial for facilitating 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:

$$\begin{aligned}
48.58\,\mathrm{pb} = \quad & 16.00\,\mathrm{pb} && (+32.9\%) && (\mathrm{LO,\ rEFT}) \\
& +20.84\,\mathrm{pb} && (+42.9\%) && (\mathrm{NLO,\ rEFT}) \\
& -\ \ 2.05\,\mathrm{pb} && (-4.2\%) && ((t,b,c),\ \mathrm{exact\ NLO}) \\
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\end{aligned}$$

LHCH(XS)WG YR4 `16

Anastasiou, Duhr, Dulat, et al. `16

- Sources of uncertainty:

$\delta(\text{scale})$	$\delta(\text{trunc})$	$\delta(\text{PDF-TH})$	$\delta(\text{EW})$	$\delta(t,b,c)$	$\delta(1/m_t)$
$+0.10$ 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 $\mathcal{O}(1\%)$

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Mistlberger `18

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Anastasiou, del Duca, Furlan, et al. `19
Becchetti, Bonciani, Del Duca, et al. `21

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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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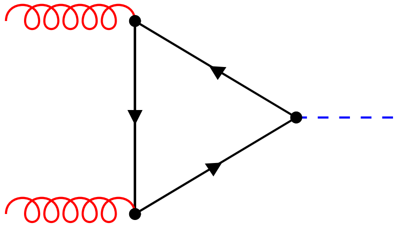
Order by order in perturbation theory

- LO contribution exactly known for almost 50 years



Georgi, Glashow, Machacek, et al. `78

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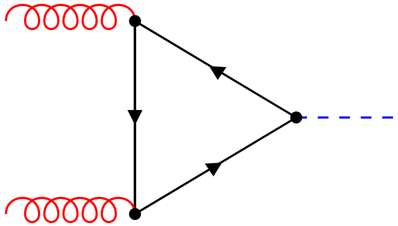

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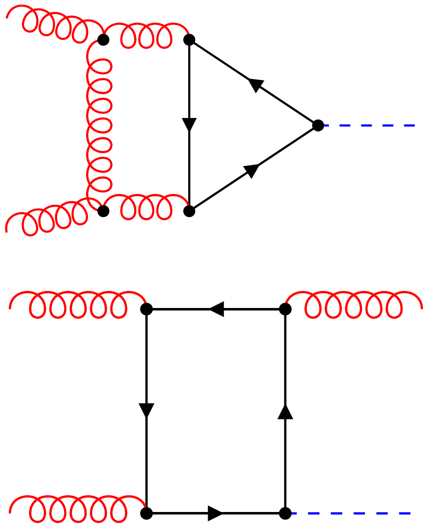
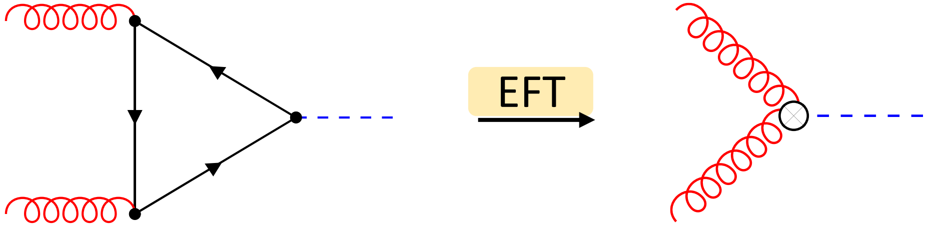
- NLO contribution exactly known for arbitrary quark masses running in the loop   Graudenz, Spira, Zerwas `93



Inclusive cross section in (r)EFT

- LO contribution exactly known for almost 50 years



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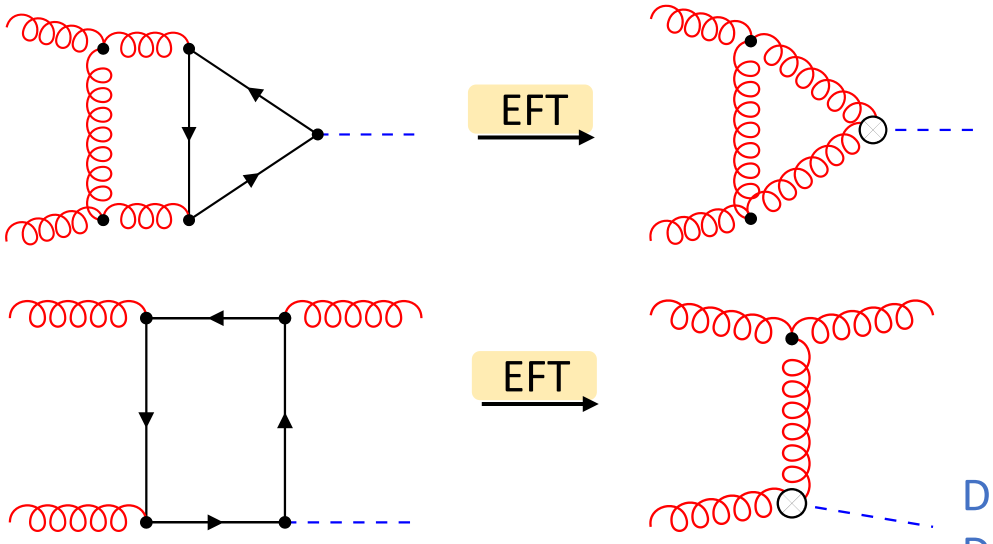


Dawson`91
Djouadi, Spira, Zerwas `91

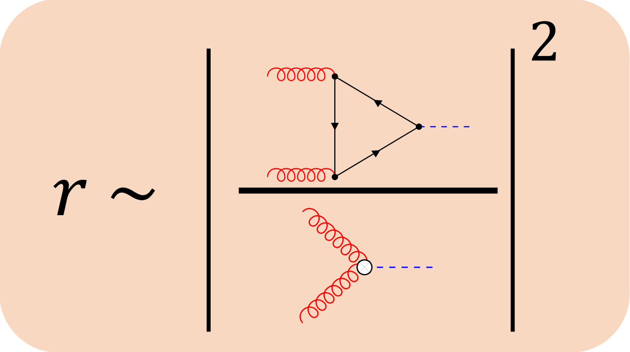
$$\mathcal{L}_{\mathrm{SM}}$$

$$\Big\downarrow \; m_t \to \infty$$

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

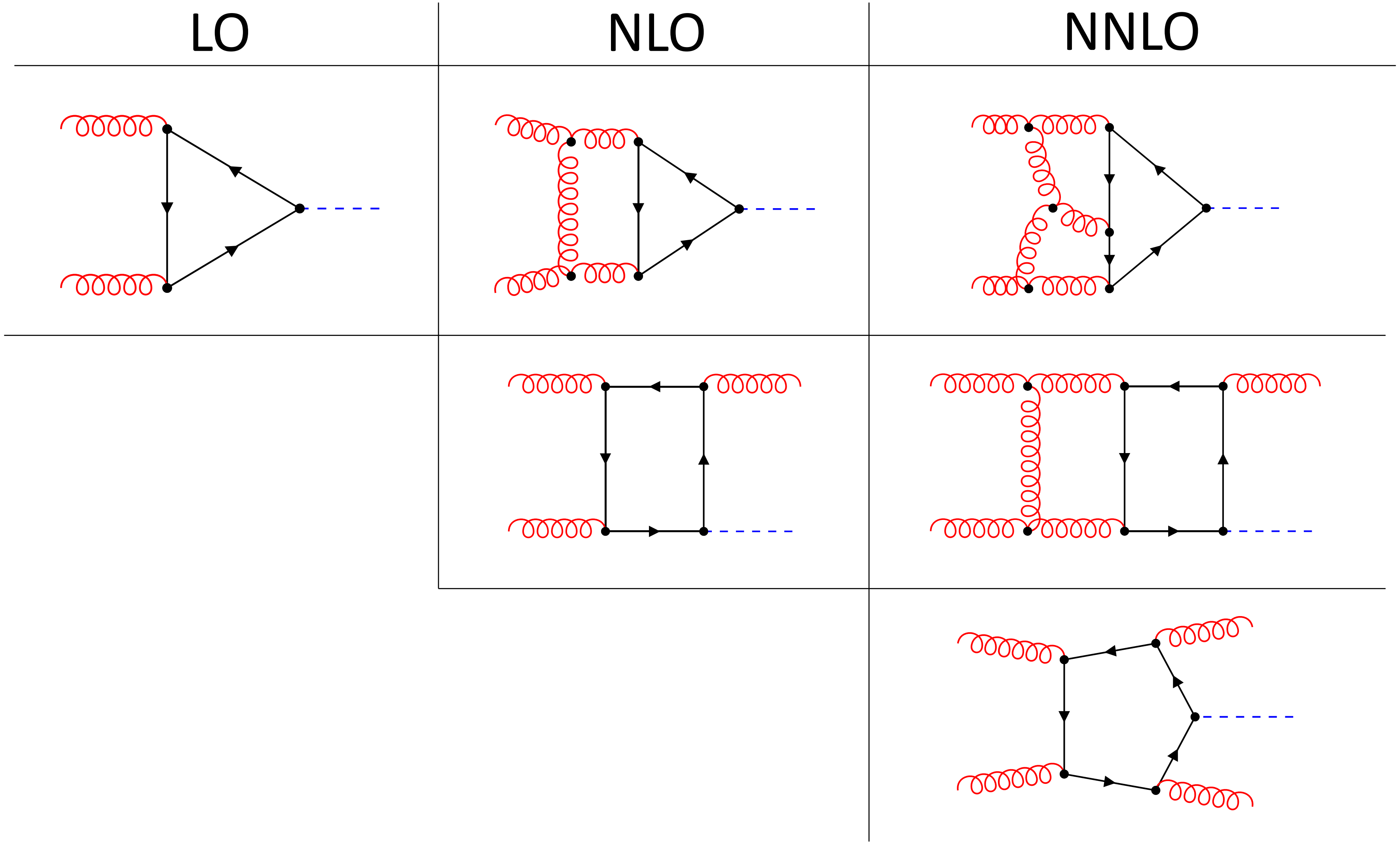
Chetyrkin, Kniehl, Steinhauser `98
Schröder, Steinhauser `06
Chetyrkin, Kühn, Sturm `06

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



Computation

Ingredients for the NNLO calculation



LO

NLO

NNLO

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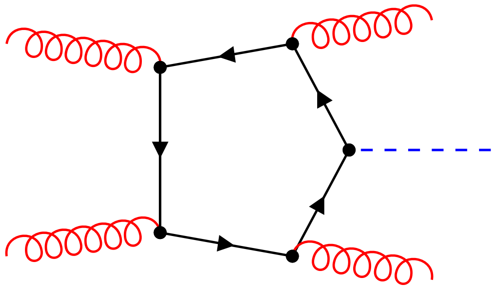
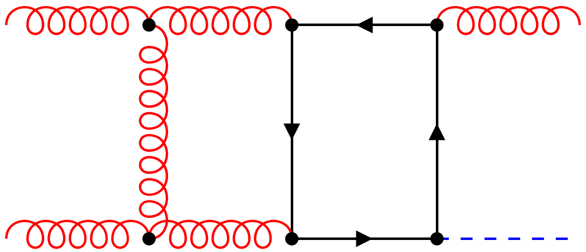


Analytic formulae available: Del Duca, Kilgore, Oleari, et al. `01
More compact expressions and implemented in **MCFM**:
Budge, Campbell, De Laurentis, et al. `20
Evaluate scalar integrals with **QCDLoop** library: Carrazza, Ellis, Zanderighi `16

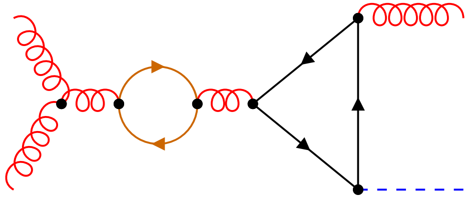


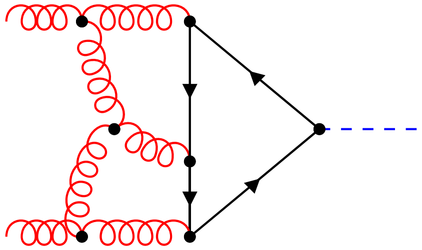
For one massive flavor:

- solve integrals numerically
- construct regular grids of IR-regulated amplitudes
- interpolate for efficient evaluation

For two massive flavors:

- all contributions factorize
  into products of one-loop integrals



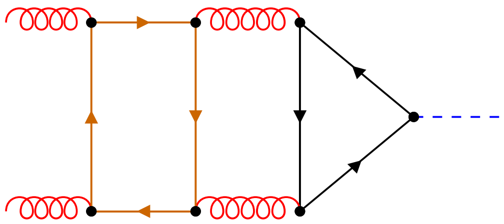


For one massive flavor: Czakon, MN `20

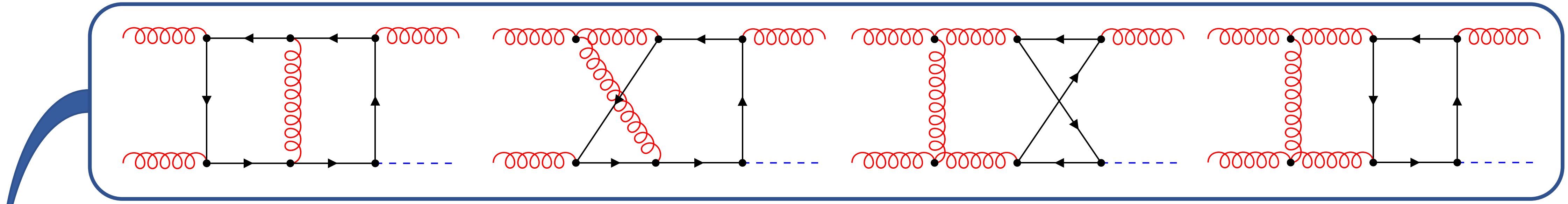
- asymptotic expansions in kinematic limits
- numerical samples in full parameter space

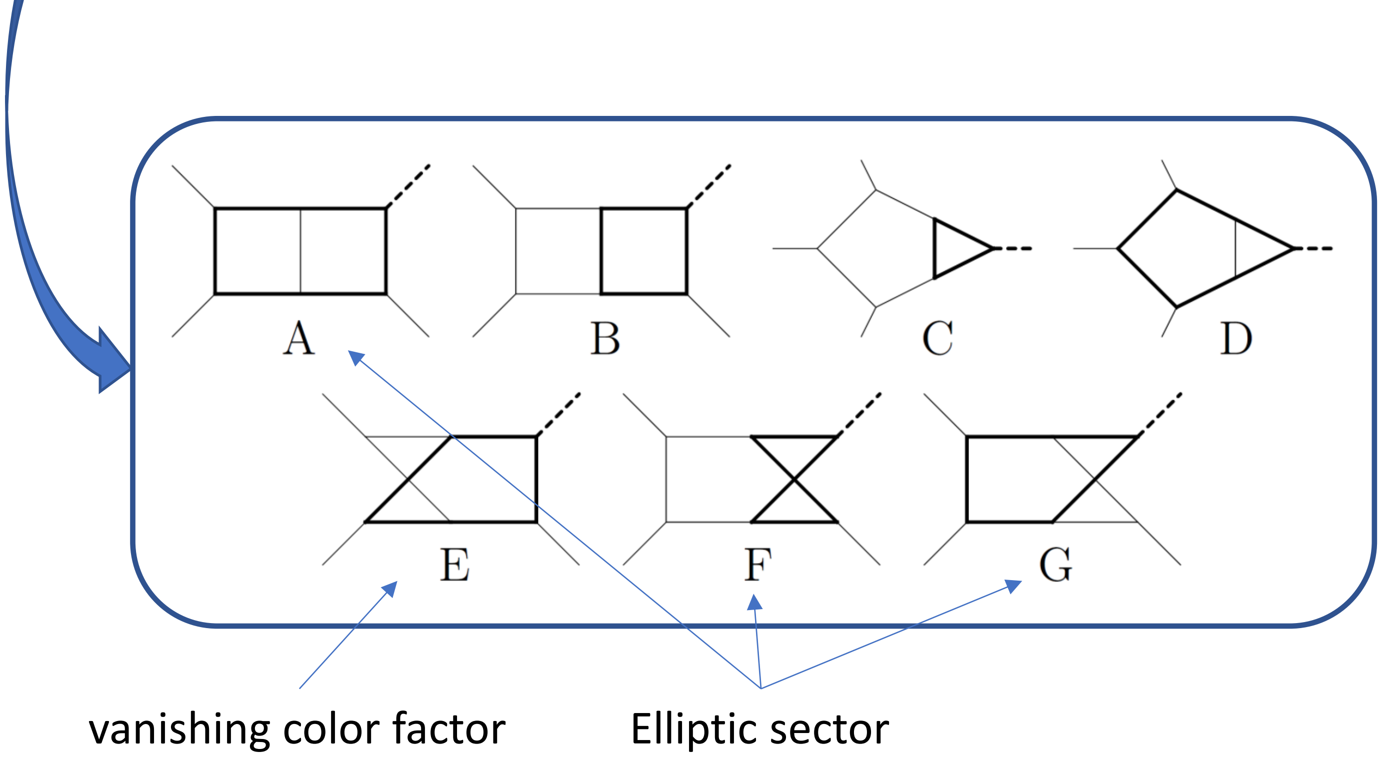
For two massive flavors: MN, Usovitsch `23

- deep large/small mass expansions
- numerical sampling with **AMFlow**: Liu, Ma `22



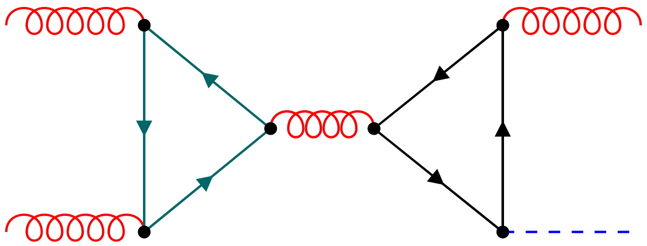
Real-virtual corrections





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:



Also see H+jet calculation: Bonciani, Del Duca, Frellesvig, et al. `22

Real-virtual corrections

- 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

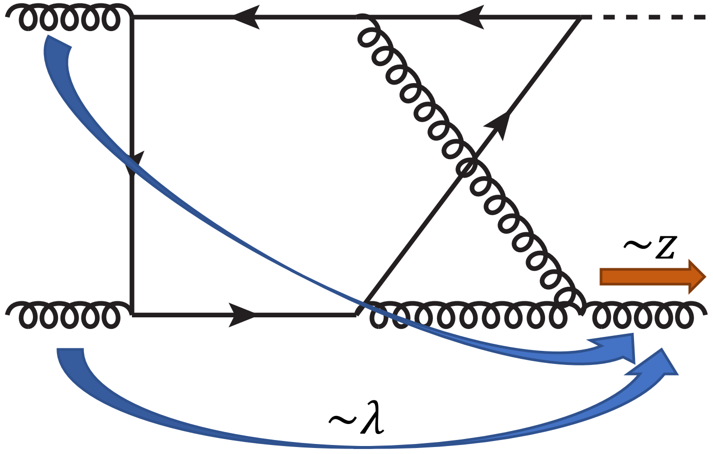
$\hat{t}/\hat{s} = z\,\lambda$

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

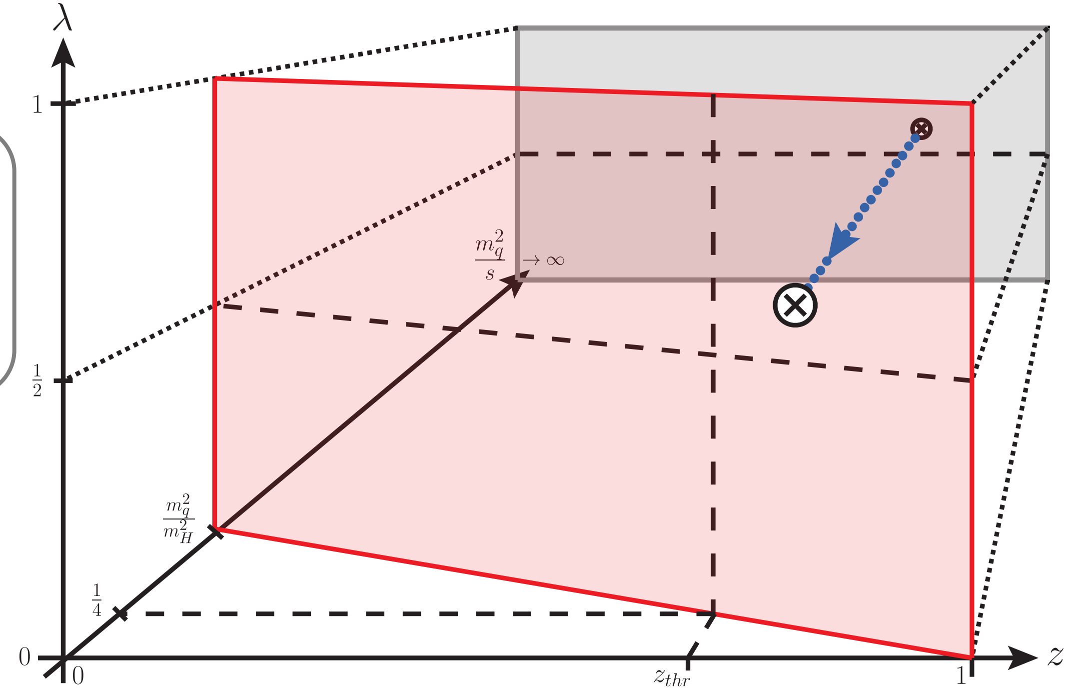
⟷

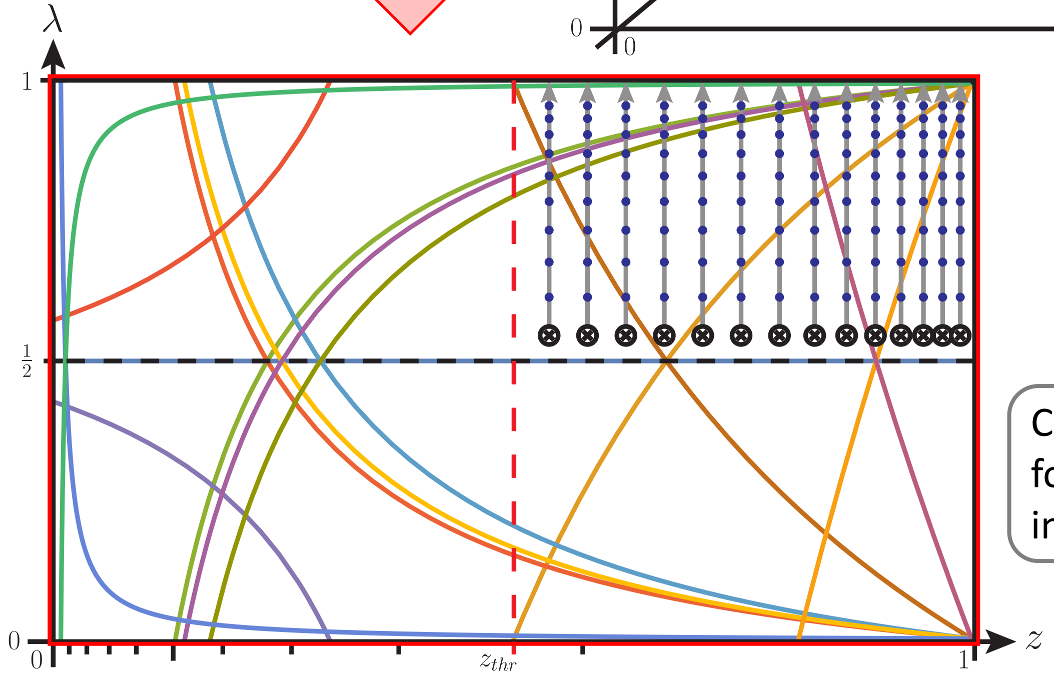
$z = 1-m_H^2/\hat{s}$

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



- ➢ 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

Regulated amplitudes for real-virtual corrections

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

λ = $\hat{t}/(\hat{t}+\hat{u})$

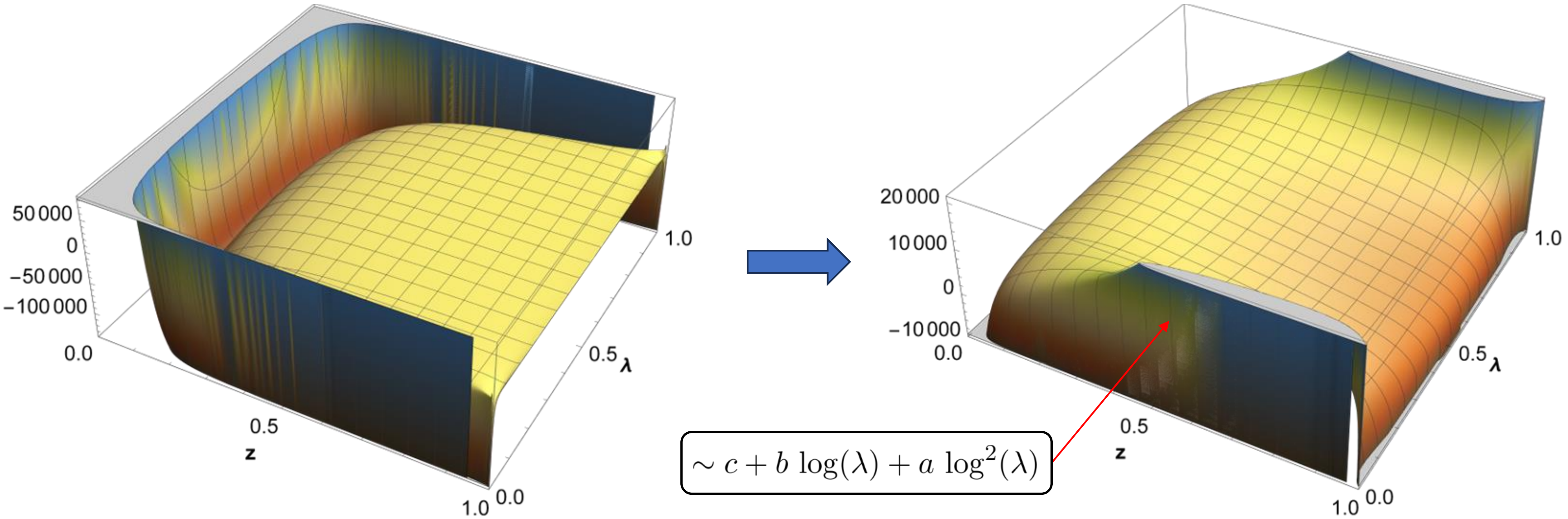
m_q^2/m_H^2 = const

Regulate IR divergences of exact amplitudes:

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

r ≈ 1.065 (top quarks)
r ≈ -0.129 (t×b interference)

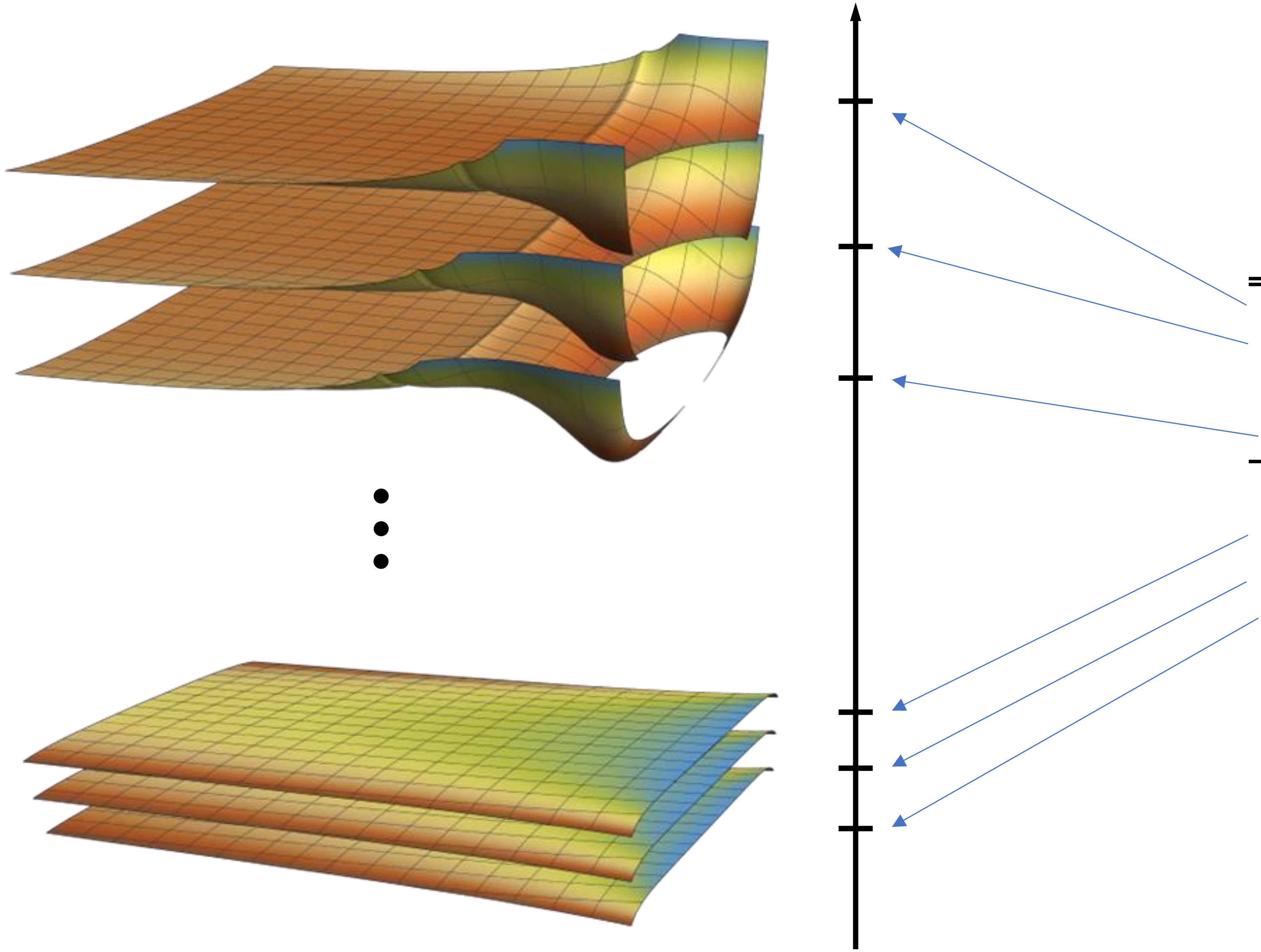
- $\mathcal{O}(10^6)$ numerical samples on regular grids
- regulated amplitudes suitable for interpolation



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

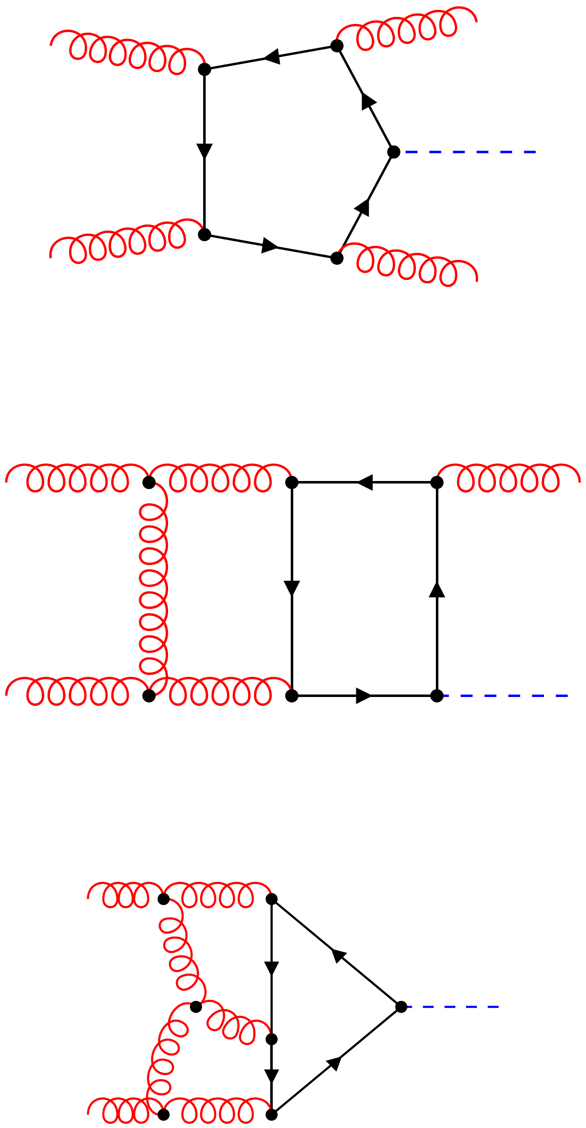
Interpolation to arbitrary quark masses

Repeat calculation of amplitudes for different fixed mass ratios:



Grid Mass	Value [GeV]	Ratio $m_{b,t}^2/m_H^2$
$\overline{m}_t(m_H/4)$	188.2	$213/94 \approx 2.27$
$\overline{m}_t(m_H/2)$	176.2	$149/75 \approx 1.99$
m_t	172.4	$23/12 \approx 1.92$
$\overline{m}_t(m_H)$	166.1	$136/77 \approx 1.77$
m_b	4.78	$1/684 \approx 1.46 \times 10^{-3}$
$\overline{m}_b(m_H/4)$	3.170	$1/1557 \approx 6.42 \times 10^{-4}$
$\overline{m}_b(m_H/2)$	2.961	$1/1782 \approx 5.61 \times 10^{-4}$
$\overline{m}_b(m_H)$	2.789	$1/2011 \approx 4.97 \times 10^{-4}$
$\overline{m}_b^{\text{min}}$	1.67	$1/5602 \approx 1.79 \times 10^{-4}$

Ingredients for the NNLO calculation



Analytic formulae available: Del Duca, Kilgore, Oleari, et al. `01
More compact expressions and implemented in **MCFM**:
Budge, Campbell, De Laurentis, et al. `20

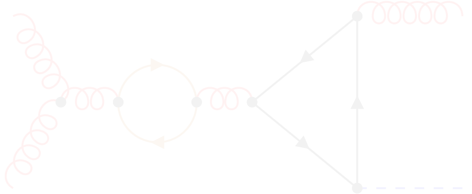
Evaluate scalar integrals with **QCDLoop** library: Carrazza, Ellis, Zanderighi `16

For one massive flavor:

- solve integrals numerically
- construct regular grids of IR-regulated amplitudes
- interpolate for efficient evaluation

For two massive flavors:

- all contributions factorize
  into products of one-loop integrals

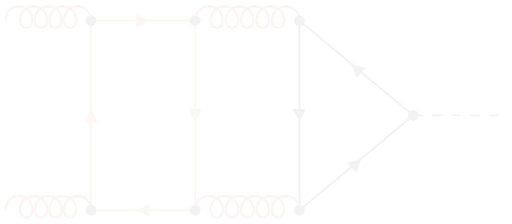


For one massive flavor: Czakon, MN `20

- asymptotic expansions in kinematic limits
- numerical samples in full parameter space

For two massive flavors: MN, Usovitsch `23

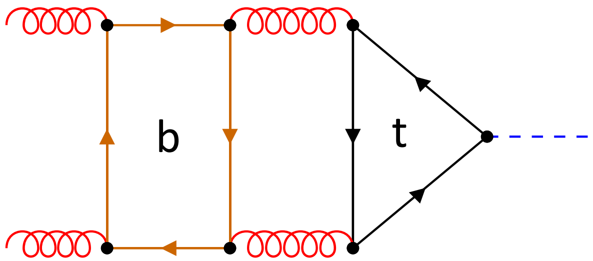
- deep large/small mass expansions
- numerical sampling with **AMFlow**: Liu, Ma `22

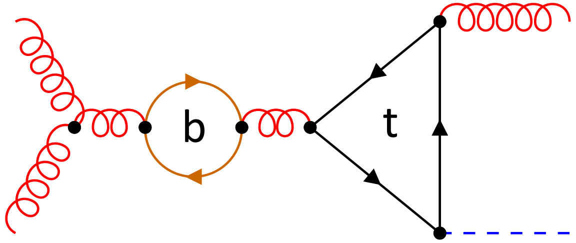


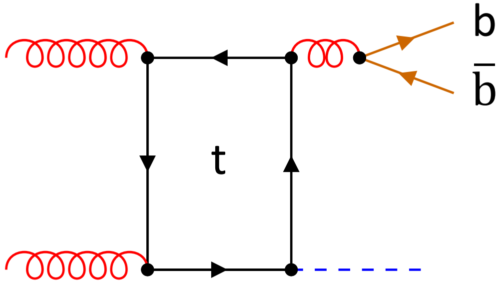
Phase-space integration
with sector-improved residue
subtraction scheme
(**Stripper** Czakon `10)

4-flavor scheme ↔ 5-flavor scheme

$\log(m_b^2)$-divergences in *virtual corrections* must cancel against divergences due to massive b-quark splittings in *real radiation*







Obtain double-real amplitudes with **Recola**: Actis, Denner, Hofer, et al. `16

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 the b-quark

Results

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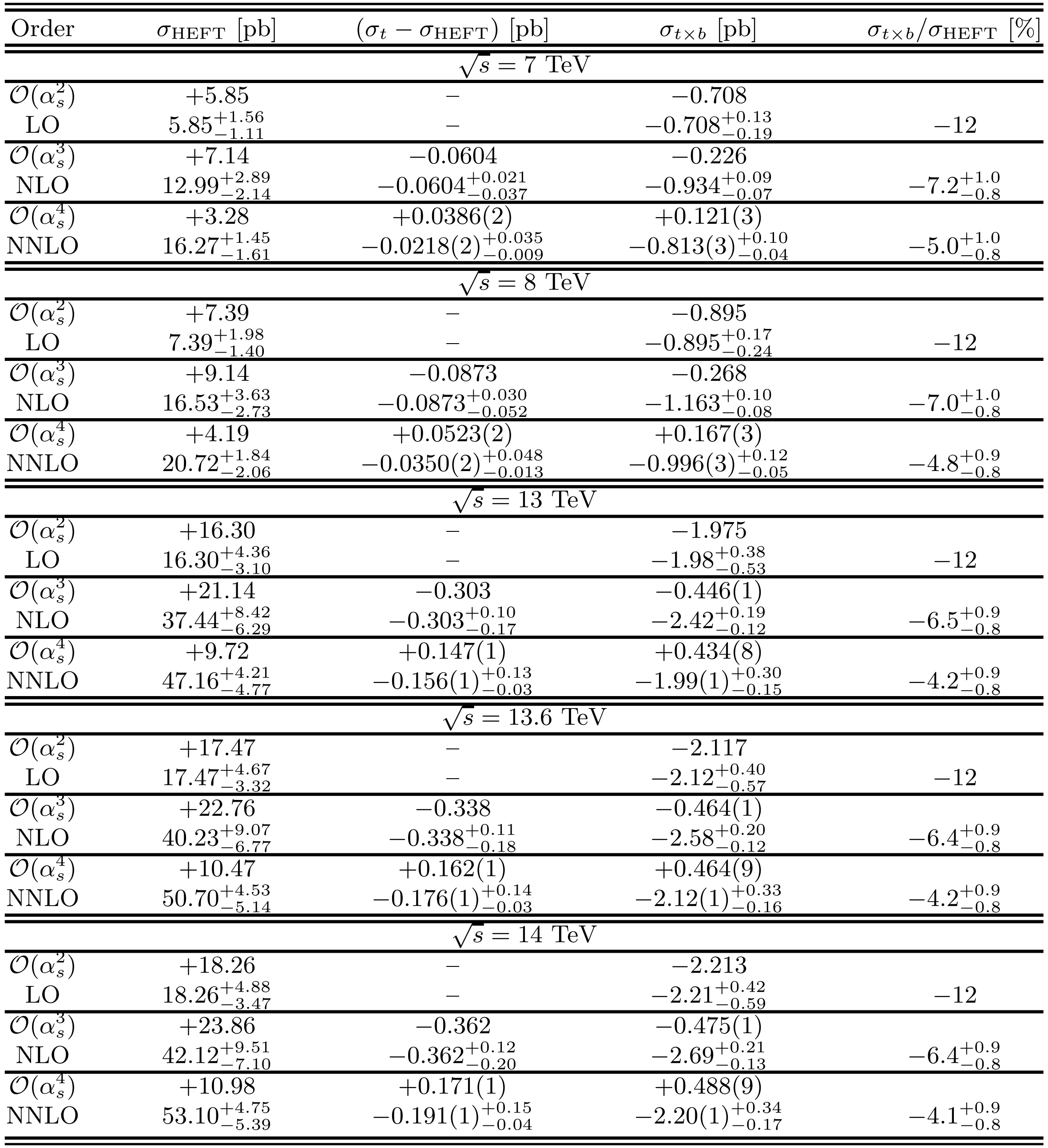

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		$\sqrt{s} = 7$ TeV		
$\mathcal{O}(\alpha_s^2)$	$+5.85$	–	-0.708	
LO	$5.85^{+1.56}_{-1.11}$	–	$-0.708^{+0.13}_{-0.19}$	-12
$\mathcal{O}(\alpha_s^3)$	$+7.14$	-0.0604	-0.226	
NLO	$12.99^{+2.89}_{-2.14}$	$-0.0604^{+0.021}_{-0.037}$	$-0.934^{+0.09}_{-0.07}$	$-7.2^{+1.0}_{-0.8}$
$\mathcal{O}(\alpha_s^4)$	$+3.28$	$+0.0386(2)$	$+0.121(3)$	
NNLO	$16.27^{+1.45}_{-1.61}$	$-0.0218(2)^{+0.035}_{-0.009}$	$-0.813(3)^{+0.10}_{-0.04}$	$-5.0^{+1.0}_{-0.8}$
		$\sqrt{s} = 8$ 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
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		$\sqrt{s} = 13.6$ TeV		
$\mathcal{O}(\alpha_s^2)$	$+17.47$	–	-2.117	
LO	$17.47^{+4.67}_{-3.32}$	–	$-2.12^{+0.40}_{-0.57}$	-12
$\mathcal{O}(\alpha_s^3)$	$+22.76$	-0.338	$-0.464(1)$	
NLO	$40.23^{+9.07}_{-6.77}$	$-0.338^{+0.11}_{-0.18}$	$-2.58^{+0.20}_{-0.12}$	$-6.4^{+0.9}_{-0.8}$
$\mathcal{O}(\alpha_s^4)$	$+10.47$	$+0.162(1)$	$+0.464(9)$	
NNLO	$50.70^{+4.53}_{-5.14}$	$-0.176(1)^{+0.14}_{-0.03}$	$-2.12(1)^{+0.33}_{-0.16}$	$-4.2^{+0.9}_{-0.8}$
		$\sqrt{s} = 14$ TeV		
$\mathcal{O}(\alpha_s^2)$	$+18.26$	–	-2.213	
LO	$18.26^{+4.88}_{-3.47}$	–	$-2.21^{+0.42}_{-0.59}$	-12
$\mathcal{O}(\alpha_s^3)$	$+23.86$	-0.362	$-0.475(1)$	
NLO	$42.12^{+9.51}_{-7.10}$	$-0.362^{+0.12}_{-0.20}$	$-2.69^{+0.21}_{-0.13}$	$-6.4^{+0.9}_{-0.8}$
$\mathcal{O}(\alpha_s^4)$	$+10.98$	$+0.171(1)$	$+0.488(9)$	
NNLO	$53.10^{+4.75}_{-5.39}$	$-0.191(1)^{+0.15}_{-0.04}$	$-2.20(1)^{+0.34}_{-0.17}$	$-4.1^{+0.9}_{-0.8}$

Czakon, Eschment, MN, Poncelet, Schellenberger `23

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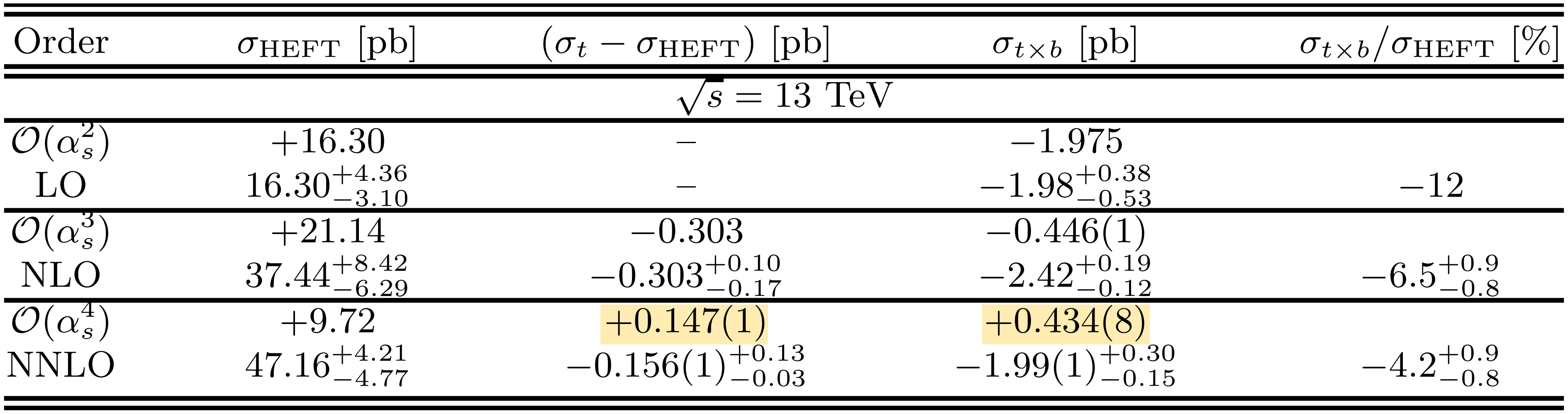

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➢ Interference effects much larger than pure top mass effect

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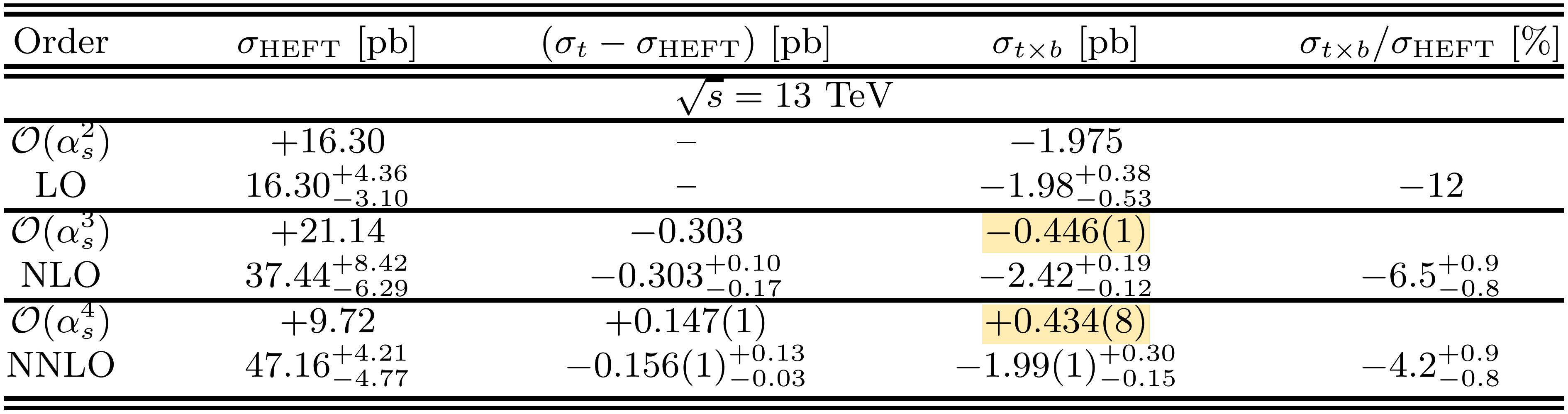

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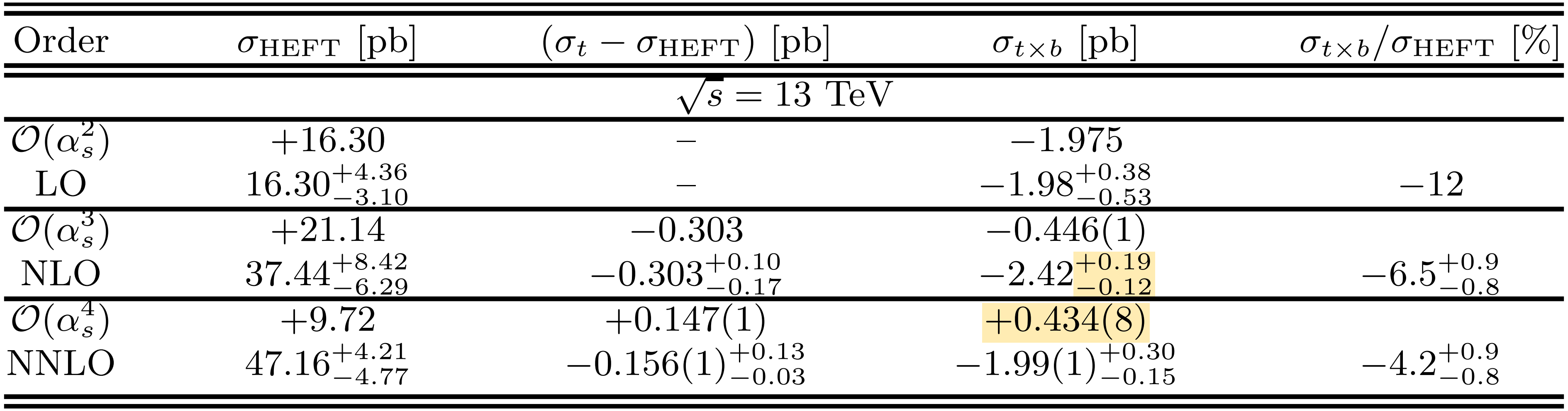

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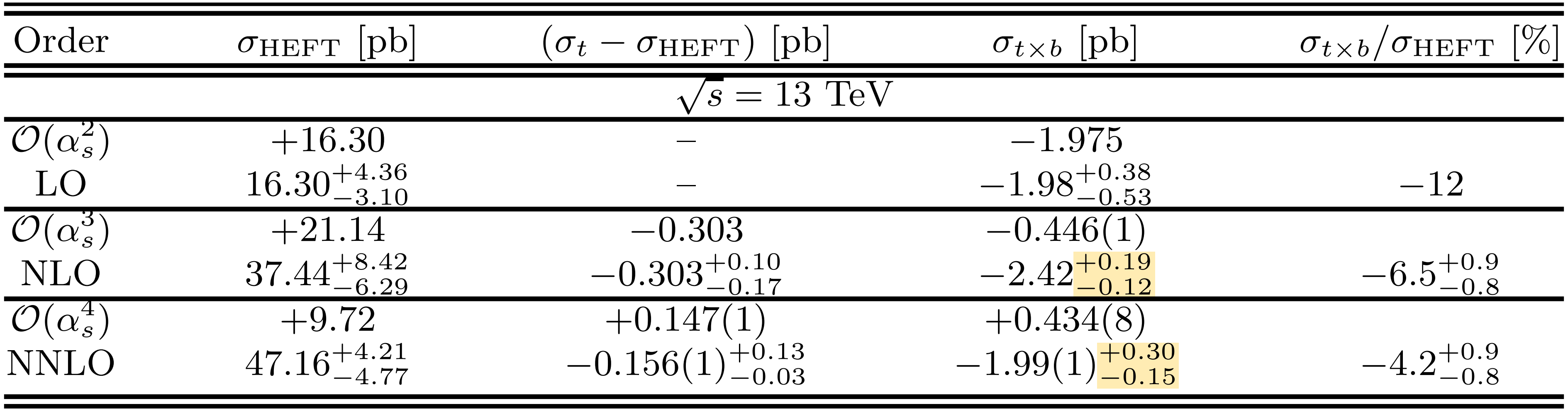

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NNLO	$47.16^{+4.21}_{-4.77}$	$-0.156(1)^{+0.13}_{-0.03}$	$-1.99(1)^{+0.30}_{-0.15}$	$-4.2^{+0.9}_{-0.8}$

- ➢ 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
- ➢ Similar effects for different top quark mass ($m_t \approx 170.979$ GeV)

Czakon, Eschment, MN,
Poncelet, Schellenberger `23

Total cross section: 5-flavor scheme

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
- central scale: $\mu_R = \mu_F = m_H/2$ (7-point scale variation)
- $m_H = 125$ GeV $\Rightarrow m_t \approx 173.055$ GeV and $m_b \approx 4.779$ GeV (OS-scheme, but Y_b in $\overline{\text{MS}}$ with $\overline{m}_b(\overline{m}_b) \approx 4.18$ GeV)
- previous estimate: $-2.18^{+0.20}_{-0.20}$ pb Anastasiou, Penin `20

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

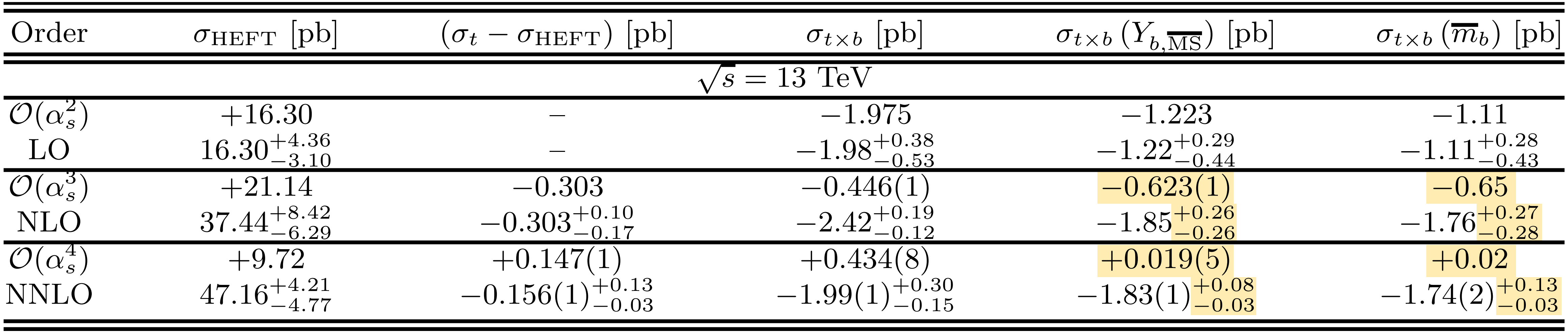
- ➢ Interference effects much larger than pure top mass effect
- ➢ Interference effect at NNLO cancels against NLO
- ➢ Interference effect at NNLO larger than NLO scale variation (similar in HEFT but less severe)
- ➢ Interference NNLO scale variation increases compared to NLO
- ➢ Similar effects for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

Czakon, Eschment, MN,
Poncelet, Schellenberger `23

Total cross section: 5-flavor scheme

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
- central scale: $\mu_R = \mu_F = m_H/2$ (7-point scale variation)
- m_H = 125 GeV ⇒ $m_t \approx$ 173.055 GeV (OS-scheme) and m_b in $\overline{\rm MS}$-scheme with $\overline{m}_b(\overline{m}_b) \approx$ 4.18 GeV
- previous estimate: $-2.18^{+0.20}_{-0.20}$ pb Anastasiou, Penin `20



Order	$\sigma_{\rm HEFT}$ [pb]	$(\sigma_t - \sigma_{\rm HEFT})$ [pb]	$\sigma_{t\times b}$ [pb]	$\sigma_{t\times b}\,(Y_{b,\overline{\rm MS}})$ [pb]	$\sigma_{t\times b}\,(\overline{m}_b)$ [pb]
$\sqrt{s} = 13$ TeV					
$\mathcal{O}(\alpha_s^2)$	$+16.30$	–	-1.975	-1.223	-1.11
LO	$16.30^{+4.36}_{-3.10}$	–	$-1.98^{+0.38}_{-0.53}$	$-1.22^{+0.29}_{-0.44}$	$-1.11^{+0.28}_{-0.43}$
$\mathcal{O}(\alpha_s^3)$	$+21.14$	-0.303	$-0.446(1)$	$-0.623(1)$	-0.65
NLO	$37.44^{+8.42}_{-6.29}$	$-0.303^{+0.10}_{-0.17}$	$-2.42^{+0.19}_{-0.12}$	$-1.85^{+0.26}_{-0.26}$	$-1.76^{+0.27}_{-0.28}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+0.147(1)$	$+0.434(8)$	$+0.019(5)$	$+0.02$
NNLO	$47.16^{+4.21}_{-4.77}$	$-0.156(1)^{+0.13}_{-0.03}$	$-1.99(1)^{+0.30}_{-0.15}$	$-1.83(1)^{+0.08}_{-0.03}$	$-1.74(2)^{+0.13}_{-0.03}$

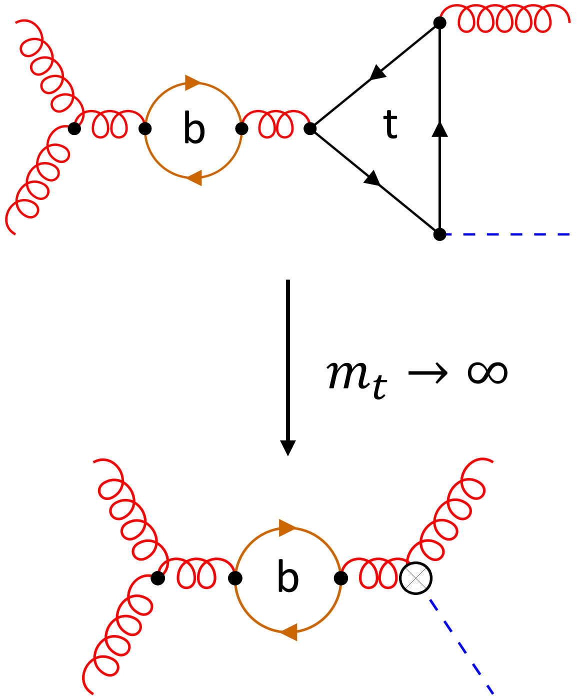
- ➢ Interference effects much larger than pure top mass effect
- ➢ Interference effect at NNLO cancels against NLO
- ➢ Interference effect at NNLO larger than NLO scale variation (similar in HEFT but less severe)
- ➢ Interference NNLO scale variation increases compared to NLO
- ➢ Similar effects for 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 $\overline{\rm MS}$-scheme

Czakon, Eschment, MN,
Poncelet, Schellenberger `24

What happens in 4-flavor scheme?

- Validate the cancellation of logarithmic mass divergences in HEFT (rescaling as in 5FS)
- Effects beyond missing b-quark PDF contribution appear for the first time at NNLO
- PDF set: **NNPDF31_nnlo_as_0118_nf_4**

Order	σ_{HEFT} [pb]				
	$\sqrt{s} = 13$ TeV				
	5FS	4FS $m_b = 0.01$ GeV	4FS $m_b = 0.1$ GeV	4FS $m_b = 4.78$ GeV	4FS $\overline{m}_b(\overline{m}_b) = 4.18$ GeV
$\mathcal{O}(\alpha_s^2)$	$+16.30$	$+16.27$	$+16.27$	$+16.27$	16.27
LO	$16.30^{+4.36}_{-3.10}$	$16.27^{+4.63}_{-3.22}$	$16.27^{+4.63}_{-3.22}$	$16.27^{+4.63}_{-3.22}$	$16.27^{+4.63}_{-3.22}$
$\mathcal{O}(\alpha_s^3)$	$+21.14$	$+20.08(3)$	$+20.08(3)$	$+20.08(3)$	$+20.08(3)$
NLO	$37.44^{+8.42}_{-6.29}$	$36.35(3)^{+8.57}_{-6.32}$	$36.35(3)^{+8.57}_{-6.32}$	$36.35(3)^{+8.57}_{-6.32}$	$36.35(3)^{+8.57}_{-6.32}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+10.8(4)$	$+11.1(4)$	$+9.5(2)$	$+9.6(2)$
NNLO	$47.16^{+4.21}_{-4.77}$	$47.2(4)^{+5.4}_{-5.4}$	$47.5(4)^{+5.4}_{-5.5}$	$45.9(2)^{+4.3}_{-4.9}$	$46.0(2)^{+4.4}_{-5.0}$

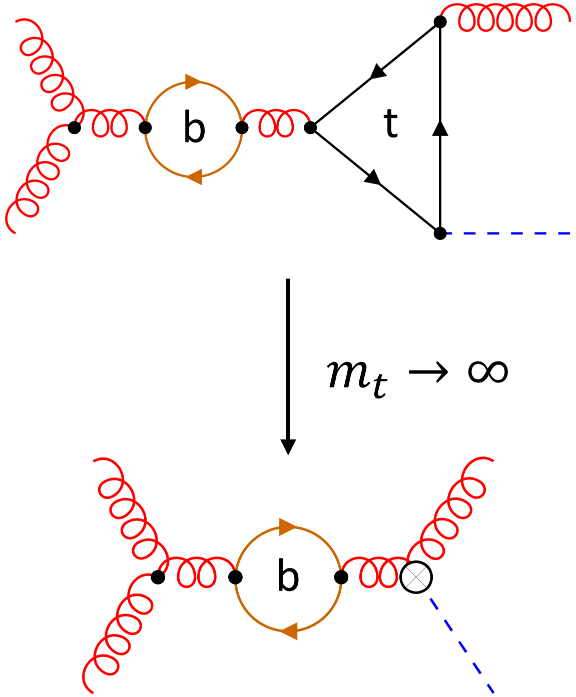


Czakon, Eschment, MN,
Poncelet, Schellenberger `24

What happens in 4-flavor scheme?

- Validate the cancellation of logarithmic mass divergences in HEFT (rescaling as in 5FS)
- Effects beyond missing b-quark PDF contribution appear for the first time at NNLO
- PDF set: **NNPDF31_nnlo_as_0118_nf_4**

Order	σ_{HEFT} [pb]				
	$\sqrt{s} = 13$ TeV				
	5FS	4FS $m_b = 0.01$ GeV	4FS $m_b = 0.1$ GeV	4FS $m_b = 4.78$ GeV	4FS $\overline{m}_b(\overline{m}_b) = 4.18$ GeV
$\mathcal{O}(\alpha_s^2)$	$+16.30$	$+16.27$	$+16.27$	$+16.27$	16.27
LO	$16.30^{+4.36}_{-3.10}$	$16.27^{+4.63}_{-3.22}$	$16.27^{+4.63}_{-3.22}$	$16.27^{+4.63}_{-3.22}$	$16.27^{+4.63}_{-3.22}$
$\mathcal{O}(\alpha_s^3)$	$+21.14$	$+20.08(3)$	$+20.08(3)$	$+20.08(3)$	$+20.08(3)$
NLO	$37.44^{+8.42}_{-6.29}$	$36.35(3)^{+8.57}_{-6.32}$	$36.35(3)^{+8.57}_{-6.32}$	$36.35(3)^{+8.57}_{-6.32}$	$36.35(3)^{+8.57}_{-6.32}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+10.8(4)$	$+11.1(4)$	$+9.5(2)$	$+9.6(2)$
NNLO	$47.16^{+4.21}_{-4.77}$	$47.2(4)^{+5.4}_{-5.4}$	$47.5(4)^{+5.4}_{-5.5}$	$45.9(2)^{+4.3}_{-4.9}$	$46.0(2)^{+4.4}_{-5.0}$



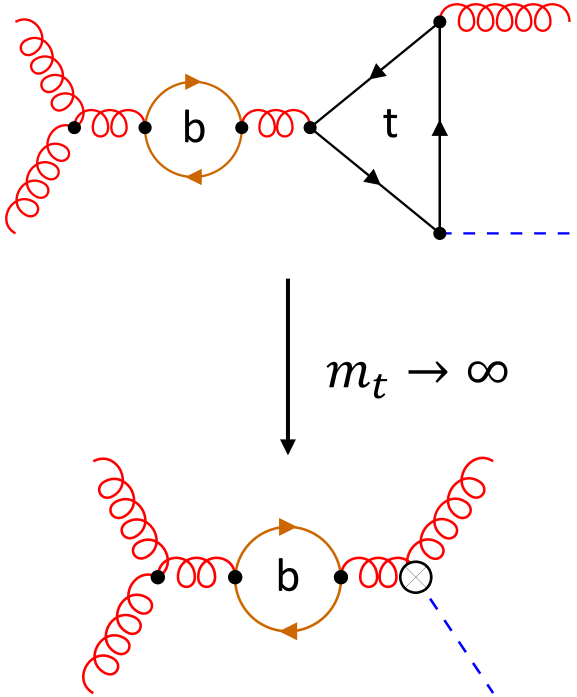
➢ NNLO corrections approach constant value in the limit $m_b^2 \to 0$
Central value seems to converge to 5FS

Czakon, Eschment, MN,
Poncelet, Schellenberger `24

What happens in 4-flavor scheme?

- Validate the cancellation of logarithmic mass divergences in HEFT (rescaling as in 5FS)
- Effects beyond missing b-quark PDF contribution appear for the first time at NNLO
- PDF set: **NNPDF31_nnlo_as_0118_nf_4**

Order	σ_{HEFT} [pb]				
	$\sqrt{s} = 13$ TeV				
	5FS	4FS $m_b = 0.01$ GeV	4FS $m_b = 0.1$ GeV	4FS $m_b = 4.78$ GeV	4FS $\overline{m}_b(\overline{m}_b) = 4.18$ GeV
$\mathcal{O}(\alpha_s^2)$	$+16.30$	$+16.27$	$+16.27$	$+16.27$	16.27
LO	$16.30^{+4.36}_{-3.10}$	$16.27^{+4.63}_{-3.22}$	$16.27^{+4.63}_{-3.22}$	$16.27^{+4.63}_{-3.22}$	$16.27^{+4.63}_{-3.22}$
$\mathcal{O}(\alpha_s^3)$	$+21.14$	$+20.08(3)$	$+20.08(3)$	$+20.08(3)$	$+20.08(3)$
NLO	$37.44^{+8.42}_{-6.29}$	$36.35(3)^{+8.57}_{-6.32}$	$36.35(3)^{+8.57}_{-6.32}$	$36.35(3)^{+8.57}_{-6.32}$	$36.35(3)^{+8.57}_{-6.32}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+10.8(4)$	$+11.1(4)$	$+9.5(2)$	$+9.6(2)$
NNLO	$47.16^{+4.21}_{-4.77}$	$47.2(4)^{+5.4}_{-5.4}$	$47.5(4)^{+5.4}_{-5.5}$	$45.9(2)^{+4.3}_{-4.9}$	$46.0(2)^{+4.4}_{-5.0}$



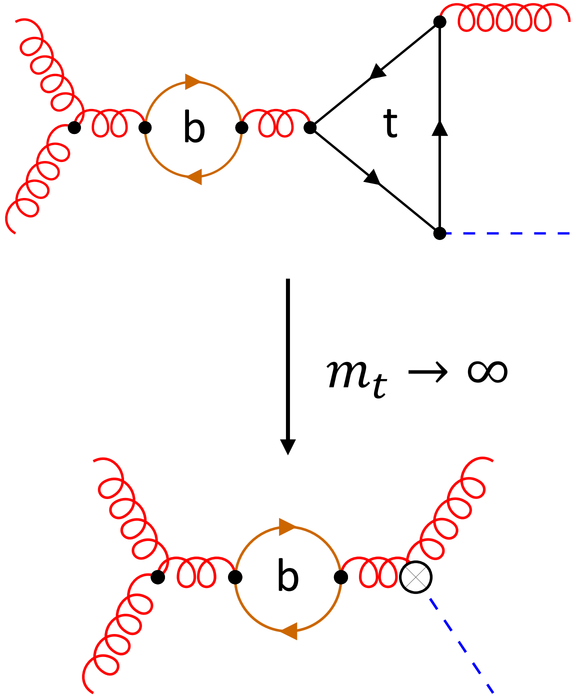
- ➢ NNLO corrections approach constant value in the limit $m_b^2 \to 0$
  Central value seems to converge to 5FS
- ➢ Total cross section insensitive with respect to renormalization scheme for m_b
  $\hookrightarrow$ m_b only present in the loop

Czakon, Eschment, MN,
Poncelet, Schellenberger `24

What happens in 4-flavor scheme?

- Validate the cancellation of logarithmic mass divergences in HEFT (rescaling as in 5FS)
- Effects beyond missing b-quark PDF contribution appear for the first time at NNLO
- PDF set: **NNPDF31_nnlo_as_0118_nf_4**

Order	σ_{HEFT} [pb]				
	$\sqrt{s} = 13$ TeV				
	5FS	4FS	4FS	4FS	4FS
		$m_b = 0.01$ GeV	$m_b = 0.1$ GeV	$m_b = 4.78$ GeV	$\overline{m}_b(\overline{m}_b) = 4.18$ GeV
$\mathcal{O}(\alpha_s^2)$	$+16.30$	$+16.27$	$+16.27$	$+16.27$	16.27
LO	$16.30^{+4.36}_{-3.10}$	$16.27^{+4.63}_{-3.22}$	$16.27^{+4.63}_{-3.22}$	$16.27^{+4.63}_{-3.22}$	$16.27^{+4.63}_{-3.22}$
$\mathcal{O}(\alpha_s^3)$	$+21.14$	$+20.08(3)$	$+20.08(3)$	$+20.08(3)$	$+20.08(3)$
NLO	$37.44^{+8.42}_{-6.29}$	$36.35(3)^{+8.57}_{-6.32}$	$36.35(3)^{+8.57}_{-6.32}$	$36.35(3)^{+8.57}_{-6.32}$	$36.35(3)^{+8.57}_{-6.32}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+10.8(4)$	$+11.1(4)$	$+9.5(2)$	$+9.6(2)$
NNLO	$47.16^{+4.21}_{-4.77}$	$47.2(4)^{+5.4}_{-5.4}$	$47.5(4)^{+5.4}_{-5.5}$	$45.9(2)^{+4.3}_{-4.9}$	$46.0(2)^{+4.4}_{-5.0}$



- ➢ NNLO corrections approach constant value in the limit $m_b^2 \to 0$
  Central value seems to converge to 5FS
- ➢ Total cross section insensitive with respect to renormalization scheme for m_b
  $\hookrightarrow$ m_b only present in the loop
- ➢ 2% shift in agreement with previous estimate: Pietrulewicz, Stahlhofen `23

Czakon, Eschment, MN,
Poncelet, Schellenberger `24

What about top quark mass effects?

- Finite top quark mass effects beyond HEFT: 5FS ↔ 4FS

Order	σ_{HEFT} [pb]	
	$\sqrt{s} = 13$ TeV	
	5FS	4FS
		$\overline{m}_b(\overline{m}_b) = 4.18$ GeV
$\mathcal{O}(\alpha_s^2)$	$+16.30$	16.27
LO	$16.30^{+4.36}_{-3.10}$	$16.27^{+4.63}_{-3.22}$
$\mathcal{O}(\alpha_s^3)$	$+21.14$	$+20.08(3)$
NLO	$37.44^{+8.42}_{-6.29}$	$36.35(3)^{+8.57}_{-6.32}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+9.6(2)$
NNLO	$47.16^{+4.21}_{-4.77}$	$46.0(2)^{+4.4}_{-5.0}$

Order	$(\sigma_t - \sigma_{\text{HEFT}})$ [pb]	
	$\sqrt{s} = 13$ TeV	
	5FS	4FS
	$m_t = 173.06$ GeV	$m_t = 173.06$ GeV
		$\overline{m}_b(\overline{m}_b) = 4.18$ GeV
LO	-	-
$\mathcal{O}(\alpha_s^3)$	-0.30	-0.27
NLO	$-0.30^{+0.10}_{-0.17}$	$-0.27^{+0.09}_{-0.16}$
$\mathcal{O}(\alpha_s^4)$	$+0.14$	$+0.12$
NNLO	$-0.16^{+0.13}_{-0.03}$	$-0.15^{+0.10}_{-0.02}$

Czakon, Eschment, MN,
Poncelet, Schellenberger `24

What about top quark mass effects?

- Finite top quark mass effects beyond HEFT: 5FS ↔ 4FS

Order	σ_{HEFT} [pb]	
	$\sqrt{s} = 13$ TeV	
	5FS	4FS
		$\overline{m}_b(\overline{m}_b) = 4.18$ GeV
$\mathcal{O}(\alpha_s^2)$	$+16.30$	16.27
LO	$16.30^{+4.36}_{-3.10}$	$16.27^{+4.63}_{-3.22}$
$\mathcal{O}(\alpha_s^3)$	$+21.14$	$+20.08(3)$
NLO	$37.44^{+8.42}_{-6.29}$	$36.35(3)^{+8.57}_{-6.32}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+9.6(2)$
NNLO	$47.16^{+4.21}_{-4.77}$	$46.0(2)^{+4.4}_{-5.0}$

Order	$(\sigma_t - \sigma_{\text{HEFT}})$ [pb]	
	$\sqrt{s} = 13$ TeV	
	5FS	4FS
	$m_t = 173.06$ GeV	$m_t = 173.06$ GeV
		$\overline{m}_b(\overline{m}_b) = 4.18$ GeV
LO	-	-
$\mathcal{O}(\alpha_s^3)$	-0.30	-0.27
NLO	$-0.30^{+0.10}_{-0.17}$	$-0.27^{+0.09}_{-0.16}$
$\mathcal{O}(\alpha_s^4)$	$+0.14$	$+0.12$
NNLO	$-0.16^{+0.13}_{-0.03}$	$-0.15^{+0.10}_{-0.02}$

- ➢ Small power-suppressed effect: -0.01 pb
- ➢ 2% shift in HEFT

Czakon, Eschment, MN,
Poncelet, Schellenberger `24

What about top quark mass effects?

- Finite top quark mass effects beyond HEFT: 5FS ↔ 4FS
- Mass renormalization scheme difference

Order	σ_{HEFT} [pb]	
	$\sqrt{s} = 13$ TeV	
	5FS	4FS
		$\overline{m}_b(\overline{m}_b) = 4.18$ GeV
$\mathcal{O}(\alpha_s^2)$	$+16.30$	16.27
LO	$16.30^{+4.36}_{-3.10}$	$16.27^{+4.63}_{-3.22}$
$\mathcal{O}(\alpha_s^3)$	$+21.14$	$+20.08(3)$
NLO	$37.44^{+8.42}_{-6.29}$	$36.35(3)^{+8.57}_{-6.32}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+9.6(2)$
NNLO	$47.16^{+4.21}_{-4.77}$	$46.0(2)^{+4.4}_{-5.0}$

Order	$(\sigma_t - \sigma_{\mathrm{HEFT}})$ [pb]	
	$\sqrt{s} = 13$ TeV	
	5FS	4FS
	$m_t = 173.06$ GeV	$m_t = 173.06$ GeV
		$\overline{m}_b(\overline{m}_b) = 4.18$ GeV
LO	-	-
$\mathcal{O}(\alpha_s^3)$	-0.30	-0.27
NLO	$-0.30^{+0.10}_{-0.17}$	$-0.27^{+0.09}_{-0.16}$
$\mathcal{O}(\alpha_s^4)$	$+0.14$	$+0.12$
NNLO	$-0.16^{+0.13}_{-0.03}$	$-0.15^{+0.10}_{-0.02}$

Order	$(\sigma_t^{\overline{\mathrm{MS}}} - \sigma_t^{\mathrm{OS}})$ [pb]
	$\sqrt{s} = 13$ TeV
$\mathcal{O}(\alpha_s^2)$	-0.04
LO	$-0.04^{+0.12}_{-0.17}$
$\mathcal{O}(\alpha_s^3)$	$+0.02$
NLO	$-0.02^{+0.14}_{-0.30}$
$\mathcal{O}(\alpha_s^4)$	$+0.01$
NNLO	$-0.01^{+0.12}_{-0.24}$

- ➢ Small power-suppressed effect: −0.01 pb
- ➢ 2% shift in HEFT

Czakon, Eschment, MN,
Poncelet, Schellenberger `24

What about top quark mass effects?

- Finite top quark mass effects beyond HEFT: 5FS ↔ 4FS
- Mass renormalization scheme difference

Order	σ_{HEFT} [pb]	
	$\sqrt{s} = 13$ TeV	
	5FS	4FS
		$\overline{m}_b(\overline{m}_b) = 4.18$ GeV
$\mathcal{O}(\alpha_s^2)$	$+16.30$	16.27
LO	$16.30^{+4.36}_{-3.10}$	$16.27^{+4.63}_{-3.22}$
$\mathcal{O}(\alpha_s^3)$	$+21.14$	$+20.08(3)$
NLO	$37.44^{+8.42}_{-6.29}$	$36.35(3)^{+8.57}_{-6.32}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+9.6(2)$
NNLO	$47.16^{+4.21}_{-4.77}$	$46.0(2)^{+4.4}_{-5.0}$

Order	$(\sigma_t - \sigma_{\text{HEFT}})$ [pb]	
	$\sqrt{s} = 13$ TeV	
	5FS	4FS
	$m_t = 173.06$ GeV	$m_t = 173.06$ GeV
		$\overline{m}_b(\overline{m}_b) = 4.18$ GeV
LO	-	-
$\mathcal{O}(\alpha_s^3)$	-0.30	-0.27
NLO	$-0.30^{+0.10}_{-0.17}$	$-0.27^{+0.09}_{-0.16}$
$\mathcal{O}(\alpha_s^4)$	$+0.14$	$+0.12$
NNLO	$-0.16^{+0.13}_{-0.03}$	$-0.15^{+0.10}_{-0.02}$

Order	$(\sigma_t^{\overline{\text{MS}}} - \sigma_t^{\text{OS}})$ [pb]
	$\sqrt{s} = 13$ TeV
$\mathcal{O}(\alpha_s^2)$	-0.04
LO	$-0.04^{+0.12}_{-0.17}$
$\mathcal{O}(\alpha_s^3)$	$+0.02$
NLO	$-0.02^{+0.14}_{-0.30}$
$\mathcal{O}(\alpha_s^4)$	$+0.01$
NNLO	$-0.01^{+0.12}_{-0.24}$

- ➢ Small power-suppressed effect: −0.01 pb
- ➢ 2% shift in HEFT
- ➢ No scheme dependence at the central scale

Czakon, Eschment, MN,
Poncelet, Schellenberger `24

What about top quark mass effects?

- Finite top quark mass effects beyond HEFT: 5FS ↔ 4FS
- Mass renormalization scheme difference

Order	σ_{HEFT} [pb]	
	$\sqrt{s} = 13$ TeV	
	5FS	4FS
		$\overline{m}_b(\overline{m}_b) = 4.18$ GeV
$\mathcal{O}(\alpha_s^2)$	$+16.30$	16.27
LO	$16.30^{+4.36}_{-3.10}$	$16.27^{+4.63}_{-3.22}$
$\mathcal{O}(\alpha_s^3)$	$+21.14$	$+20.08(3)$
NLO	$37.44^{+8.42}_{-6.29}$	$36.35(3)^{+8.57}_{-6.32}$
$\mathcal{O}(\alpha_s^4)$	$+9.72$	$+9.6(2)$
NNLO	$47.16^{+4.21}_{-4.77}$	$46.0(2)^{+4.4}_{-5.0}$

Order	$(\sigma_t - \sigma_{\text{HEFT}})$ [pb]	
	$\sqrt{s} = 13$ TeV	
	5FS	4FS
	$m_t = 173.06$ GeV	$m_t = 173.06$ GeV
		$\overline{m}_b(\overline{m}_b) = 4.18$ GeV
LO	-	-
$\mathcal{O}(\alpha_s^3)$	-0.30	-0.27
NLO	$-0.30^{+0.10}_{-0.17}$	$-0.27^{+0.09}_{-0.16}$
$\mathcal{O}(\alpha_s^4)$	$+0.14$	$+0.12$
NNLO	$-0.16^{+0.13}_{-0.03}$	$-0.15^{+0.10}_{-0.02}$

Order	$(\sigma_t^{\overline{\text{MS}}} - \sigma_t^{\text{OS}})$ [pb]
	$\sqrt{s} = 13$ TeV
$\mathcal{O}(\alpha_s^2)$	-0.04
LO	$-0.04^{+0.12}_{-0.17}$
$\mathcal{O}(\alpha_s^3)$	$+0.02$
NLO	$-0.02^{+0.14}_{-0.30}$
$\mathcal{O}(\alpha_s^4)$	$+0.01$
NNLO	$-0.01^{+0.12}_{-0.24}$

- ➢ Small power-suppressed effect: −0.01 pb
- ➢ 2% shift in HEFT
- ➢ No scheme dependence at the central scale
- ➢ Use of 5FS and OS-scheme for finite top quark mass effects justified

Czakon, Eschment, MN,
Poncelet, Schellenberger `24

Overview: top-bottom interference effects

- Top-bottom interference contribution in different setups
- PDF set: **NNPDF31_nnlo_as_0118**
- previous estimate: $-2.18^{+0.20}_{-0.20}$ pb Anastasiou, Penin `20

Order	$\sigma_{t\times b}$ [pb]			
	$\sqrt{s} = 13$ TeV			
	5FS	5FS	5FS	4FS
	$m_t = 173.06$ GeV	$m_t = 173.06$ GeV	$m_t(m_t) = 162.7$ GeV	$m_t = 173.06$ GeV
	$\overline{m}_b(\overline{m}_b) = 4.18$ GeV	$m_b = 4.78$ GeV	$\overline{m}_b(\overline{m}_b) = 4.18$ GeV	$\overline{m}_b(\overline{m}_b) = 4.18$ GeV
$\mathcal{O}(\alpha_s^2)$	-1.11	-1.98	-1.12	-1.15
LO	$-1.11^{+0.28}_{-0.43}$	$-1.98^{+0.38}_{-0.53}$	$-1.12^{+0.28}_{-0.42}$	$-1.15^{+0.29}_{-0.45}$
$\mathcal{O}(\alpha_s^3)$	-0.65	-0.44	-0.64	-0.66
NLO	$-1.76^{+0.27}_{-0.28}$	$-2.42^{+0.19}_{-0.12}$	$-1.76^{+0.27}_{-0.28}$	$-1.81^{+0.28}_{-0.30}$
$\mathcal{O}(\alpha_s^4)$	$+0.02$	$+0.43$	-0.02	-0.02
NNLO	$-1.74(2)^{+0.13}_{-0.03}$	$-1.99(2)^{+0.29}_{-0.15}$	$-1.78(1)^{+0.15}_{-0.03}$	$-1.83(2)^{+0.14}_{-0.03}$

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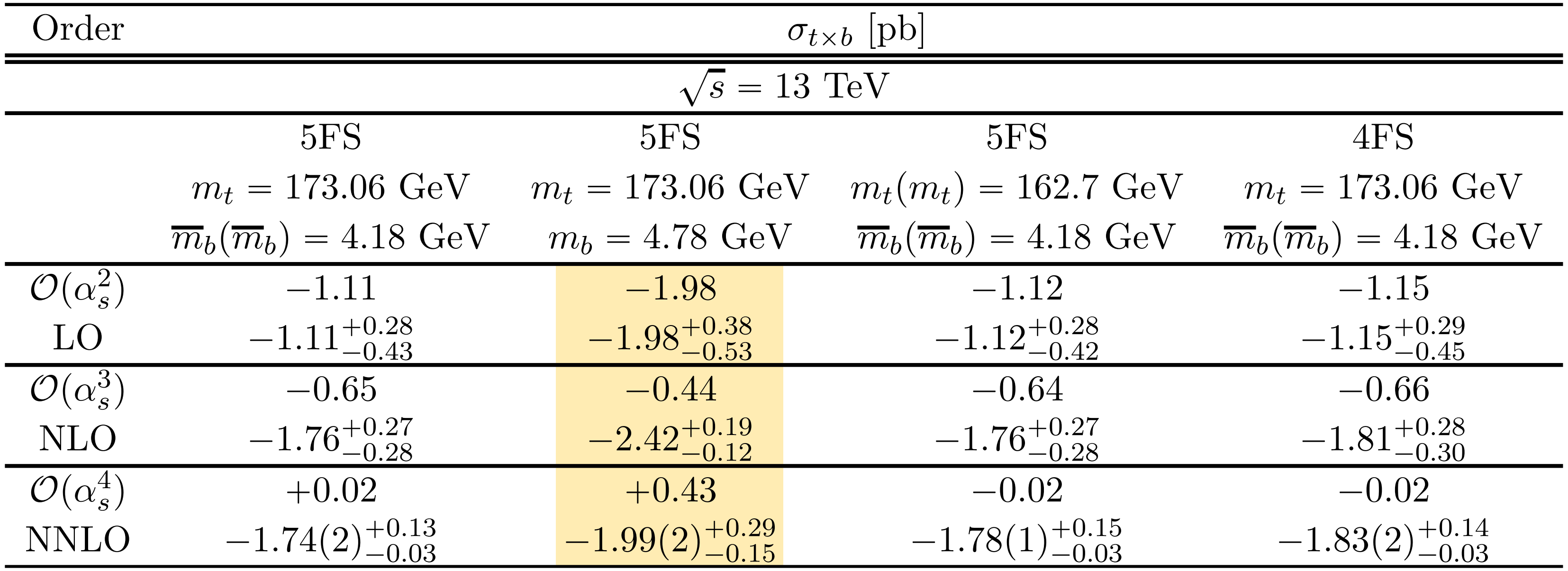

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Summary

- A thorough analysis of the impact of finite top- and bottom-quark masses on the total Higgs production cross section has been performed
    - different flavor schemes
    - different mass renormalization schemes

- Top-quark and interference contribution not sensitive to small variations of the top-quark mass
- 5FS and 4FS agree within scale uncertainties
- Renormalization scheme dependence
    - no scheme dependence for the top-quark mass
    - interference shows signs of poor perturbative convergence
    - better convergence in $\overline{\mathrm{MS}}$-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