Karlsruhe Institute of Technology

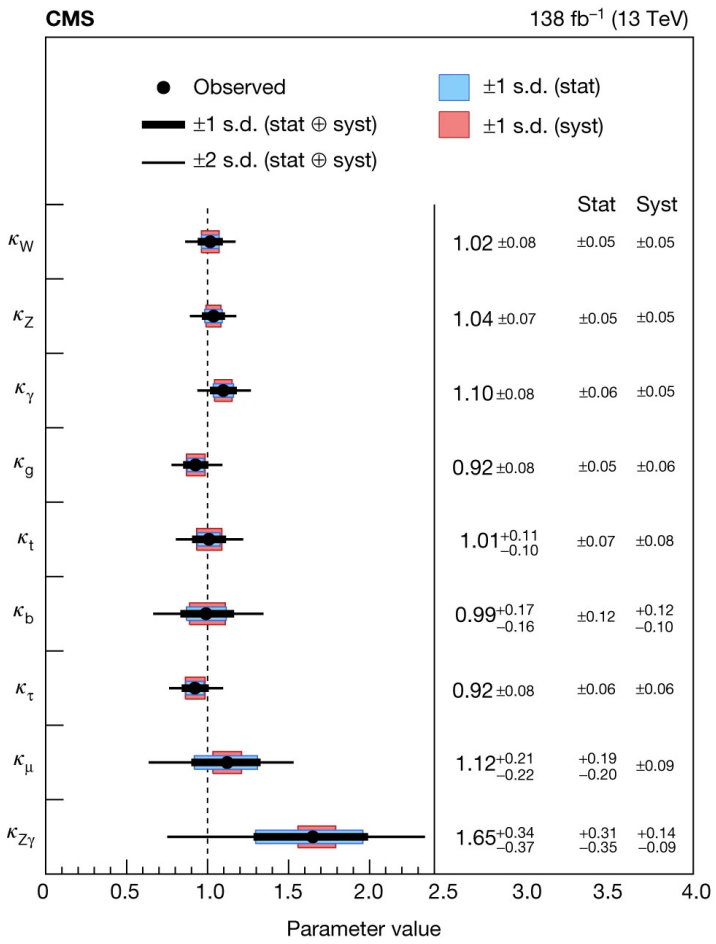
Institute for Theoretical Particle Physics

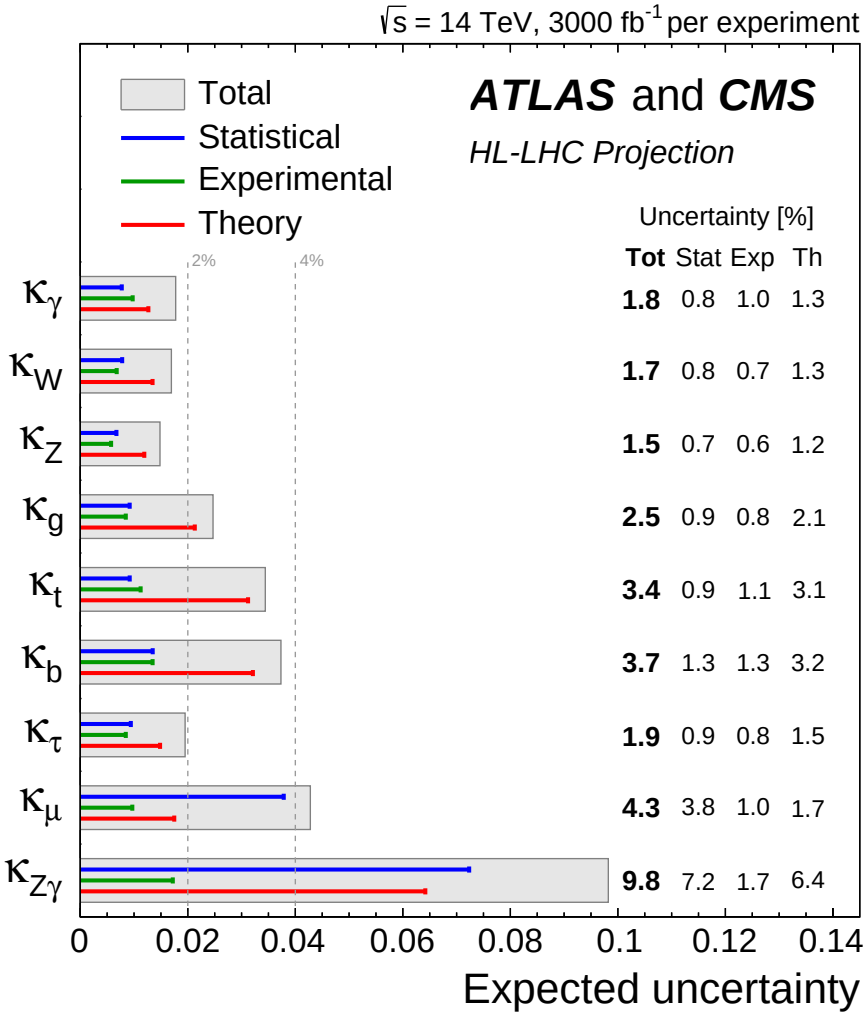
Precision Higgs Calculations

Matthias Steinhauser | QCD@LHC 2023, Durham, UK, Sep. 4-8, 2023

TTP KARLSRUHE

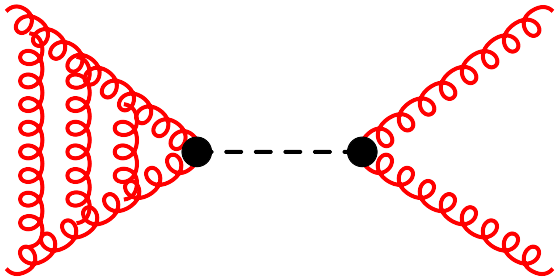
Higgs couplings



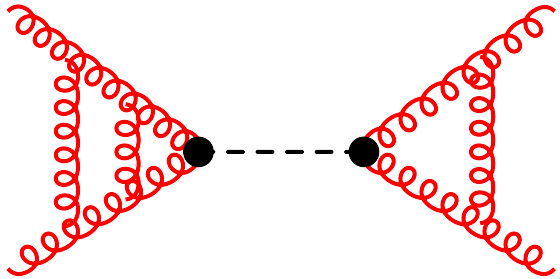


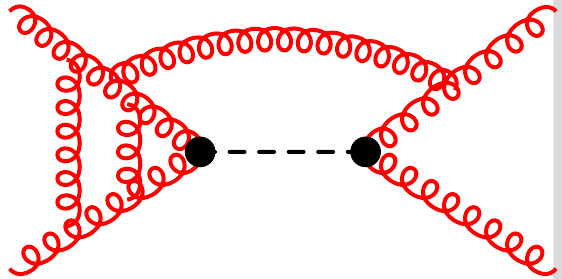
$gg \to H$

Higgs production to N^{3}LO

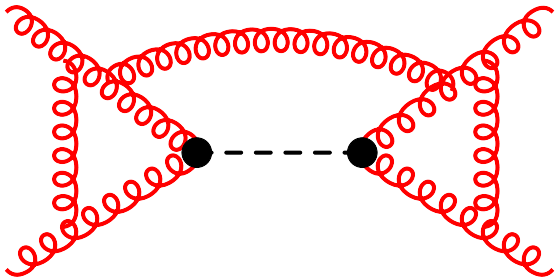


[Baikov,Chetyrkin,Smirnov,Smirnov, Steinhauser'09], [Gehrmann,Glover,Huber,Ikizlerli, Studerus'10]; [Lee,Smirnov'10]

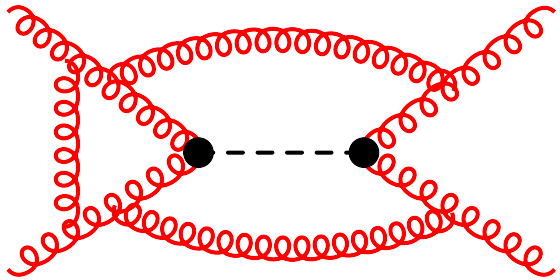




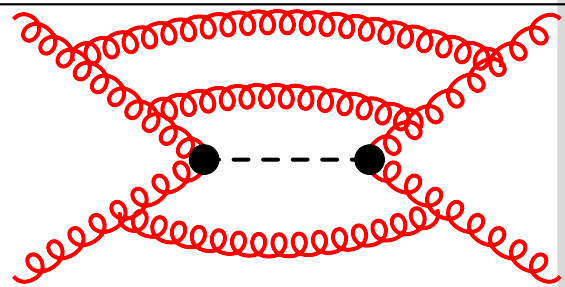
[Duhr,Gehrmann'13], [Li,Zhu'13], [Dulat,Mistlberger'14], [Duhr,Gehrmann,Jaquier'14]



[Anastasiou,Duhr,Dulat,Herzog, Mistlberger'13], [Kilgore'13]

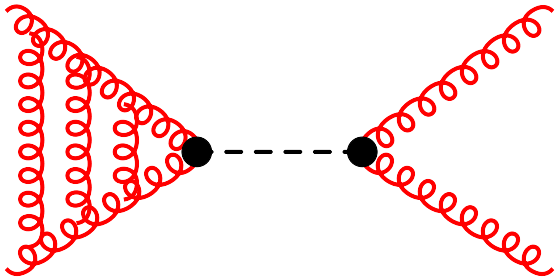


[Anastasiou,Duhr,Dulat,Furlan,Gehrmann, Herzog,Mistlberger'14], [Li,von Manteuffel,Schabinger,Zhu'14]



[Anastasiou,Duhr,Dulat,Mistlberger'13]

Higgs production to N^{3}LO



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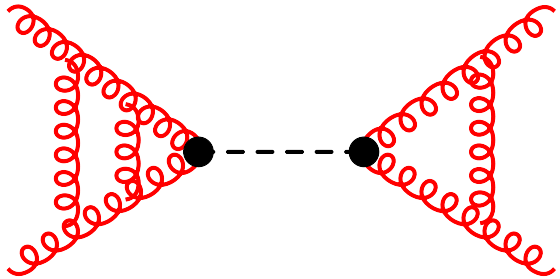
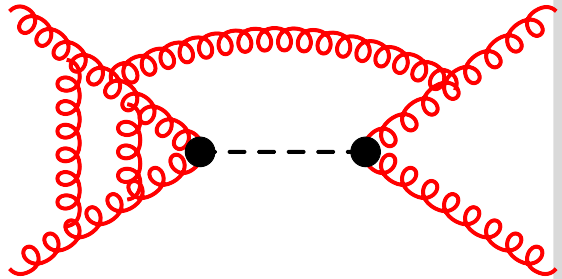


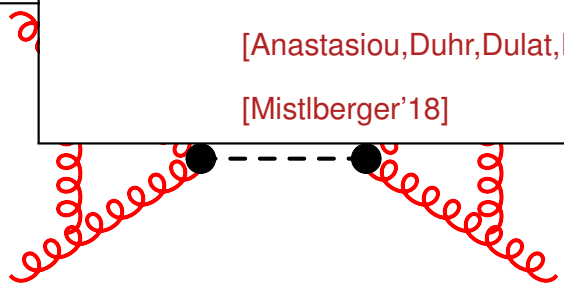


[Duhr,Gehrmann'13], [Li,Zhu'13], [Dulat,Mistlberger'14],]

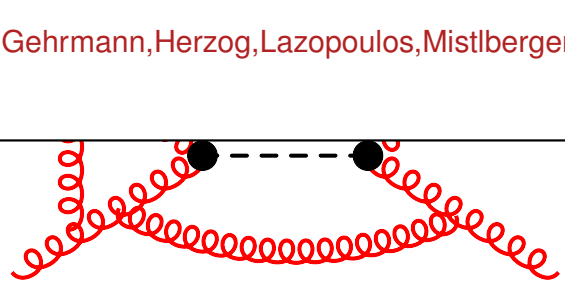
N^{3}LO: [Anastasiou,Duhr,Dulat,Herzog,Mistlberger'15]

[Anastasiou,Duhr,Dulat,Furlan,Gehrmann,Herzog,Lazopoulos,Mistlberger'16]

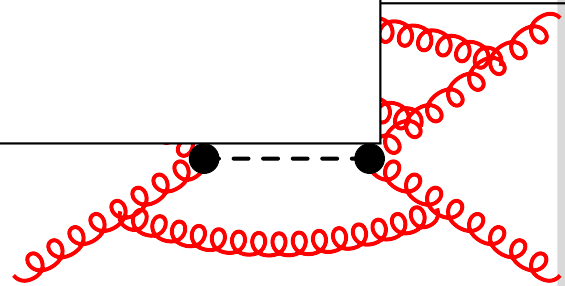
[Mistlberger'18]



[Anastasiou,Duhr,Dulat,Herzog, Mistlberger'13], [Kilgore'13]

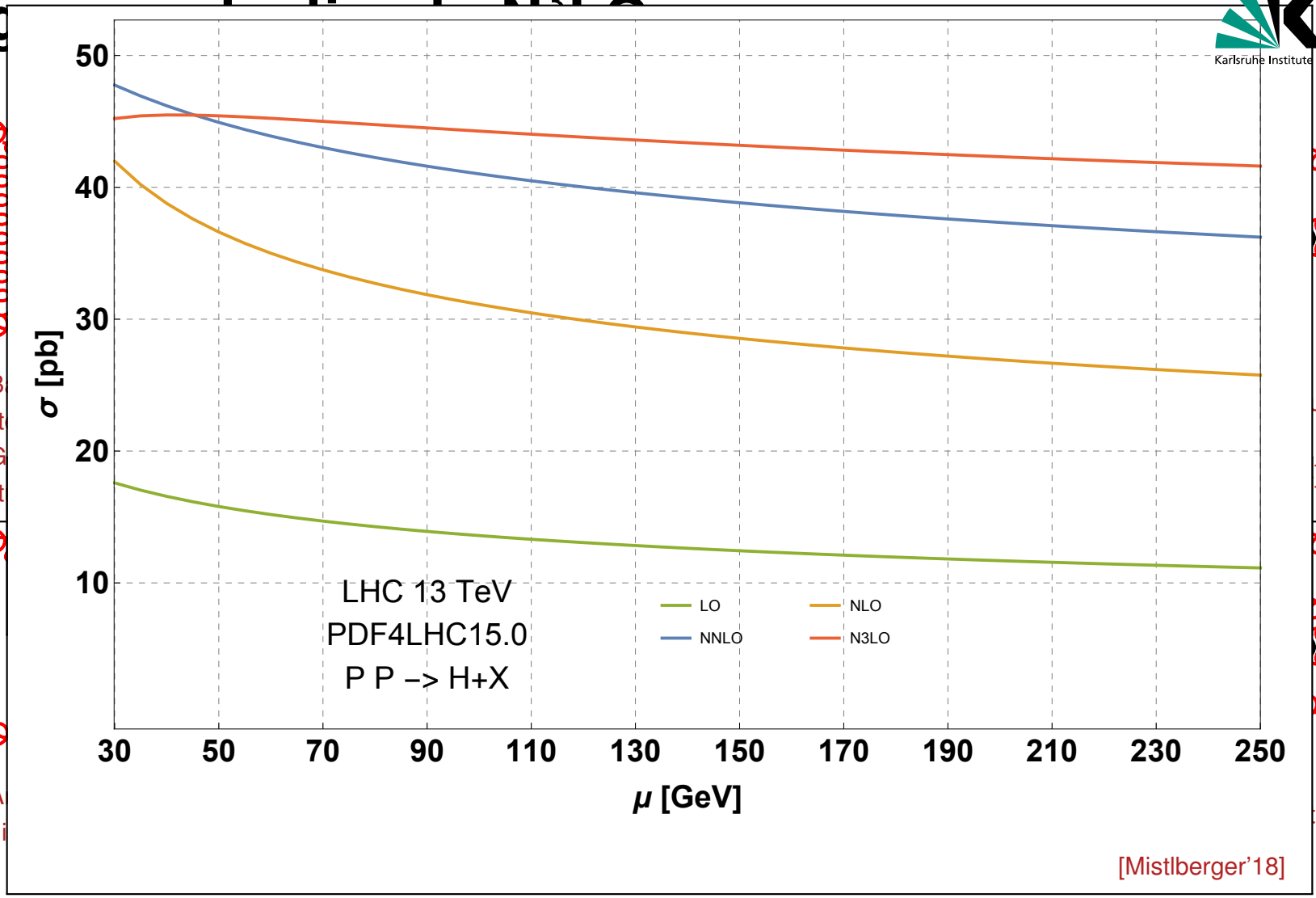


[Anastasiou,Duhr,Dulat,Furlan,Gehrmann, Herzog,Mistlberger'14], [Li,von Manteuffel,Schabinger,Zhu'14]



[Anastasiou,Duhr,Dulat,Mistlberger'13]

Hig



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Remaining uncertainties

[Anastasioua,Duhr,Dulat,Furlan,Gehrmann,Herzog,Lazopoulos,Mistlberger'16]

δ(scale)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$+0.21\%$ -2.37%	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

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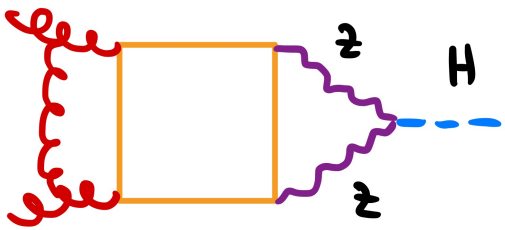

[Anastasiou,Boughezal,Petriello'09; Bonetti,Melnikov,Tancredi'16'18; Hirschi et al.'19; Anastasiou et al. '18; Bonetti et al.'20;. . . ;

Becchetti,Bonciani,Del Duca,Hirschi,Moriello,Schweitzer'20]

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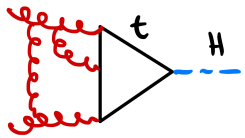
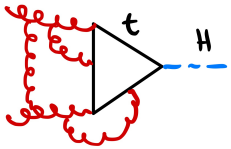
$\delta(1/m_t)$: finite m_t terms at NNLO 

[Czakon,Harlander,Klappert,Niggetiedt'21]

massive 3-loop form factor:

[Davies,Gröber,Maier,Rauh,Steinhauser'19; Harlander,Prausa,Usovitsch'19; Cakon,Niggetiedt'20]

4-loop form factor 

available for $m_H \ll m_t$ [Davies,Herren,Steinhauser'19]

(3 expansion terms; fast convergence)

1st step at N^{3}LO beyond the $m_t \to \infty$ limit

Remaining uncertainties

[Anastasioua,Duhr,Dulat,Furlan,Gehrmann,Herzog,Lazopoulos,Mistlberger'16]

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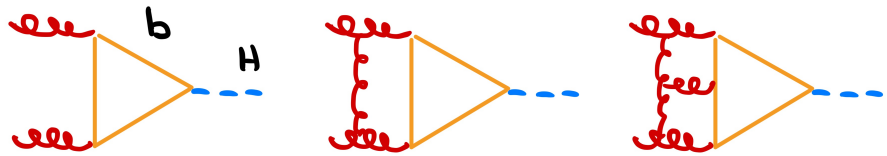
$\delta(t,b,c)$: finite m_b effects in $t-b$ interference



effective expansion parameter: $\alpha_s \log^2 \frac{m_H^2}{m_b^2} \sim 4$

[Melnikov,Penin'16; Liu,Penin'17; ... Caoloa et al.'18; ... ; Anastasiou,Penin'20; Liu,Neubert,Schnubel,Wang'22]

all-order sub-leading logarithmic approximation: $\alpha_s^n \log^{2n-1}(m_H^2/m_b^2)$

➪ estimate of the bottom quark mediated contribution beyond NLO:

$$-0.34\ldots + 0.08 \text{ pb}$$

➪ factor 2 reduction [Anastasiou,Penin'20]

Remaining uncertainties

[Anastasioua,Duhr,Dulat,Furlan,Gehrmann,Herzog,Lazopoulos,Mistlberger'16]

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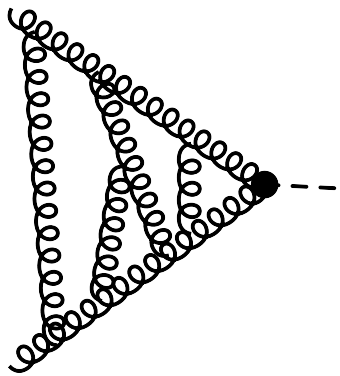
- N^{4}LO ? ➪ 1st steps
- 4-loop *Hgg* form factor

  [Lee,von Manteuffel,Schabinger,Smirnov,Smirnov,Steinhauser'22]
- soft-virtual approximation: [Das,Moch,Vogt'20]



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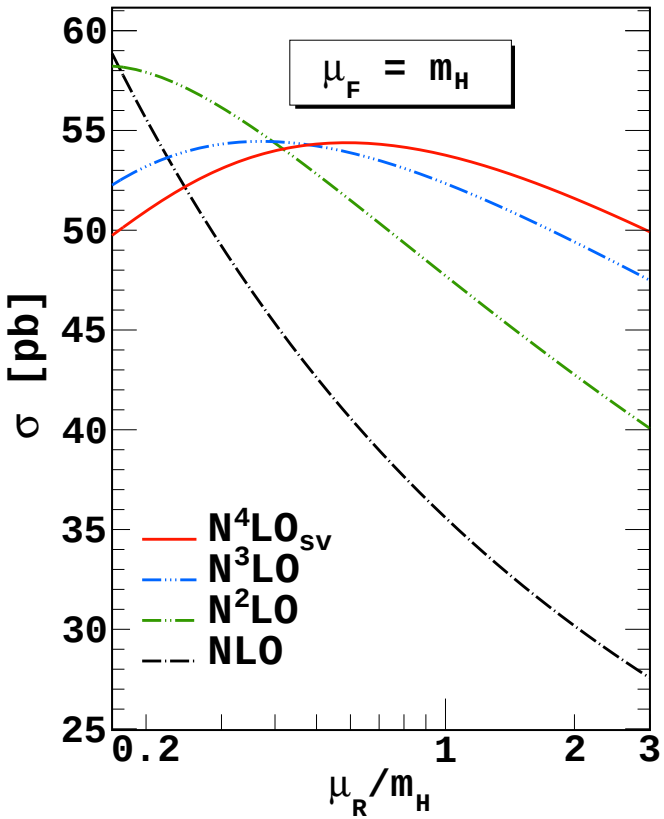
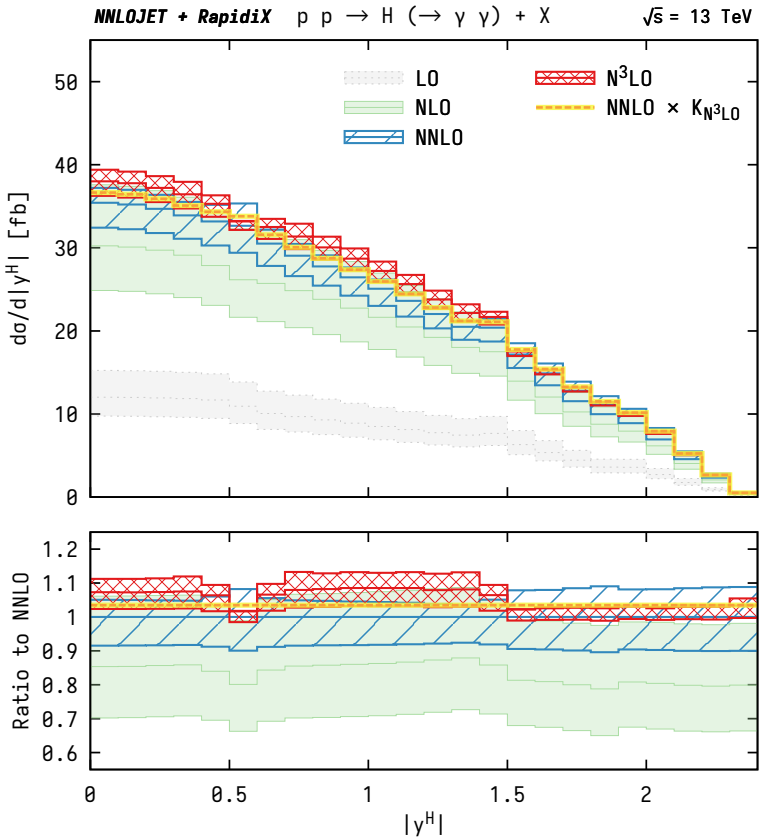
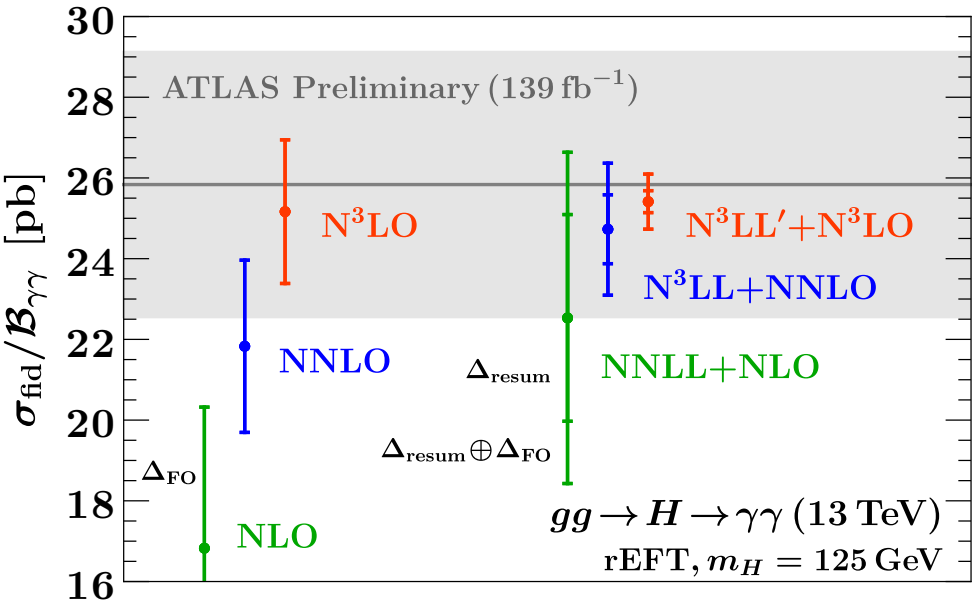


Differential Higgs production at N^{3}LO

- [Cieri,Chen,Gehrmann,Glover,Huss'18; Dulat,Mistlberger,Pelloni'19]: Higgs rapidity
- [Chen,Gehrmann,Glover,Huss,Mistlberger,Pelloni'21]: fully differential, fiducial cuts
- [Billis,Dehnadi,Ebert,Michel,Tackmann'21]: p_T distribution, fiducial cuts, resummation of $\log p_T/m_H$ terms

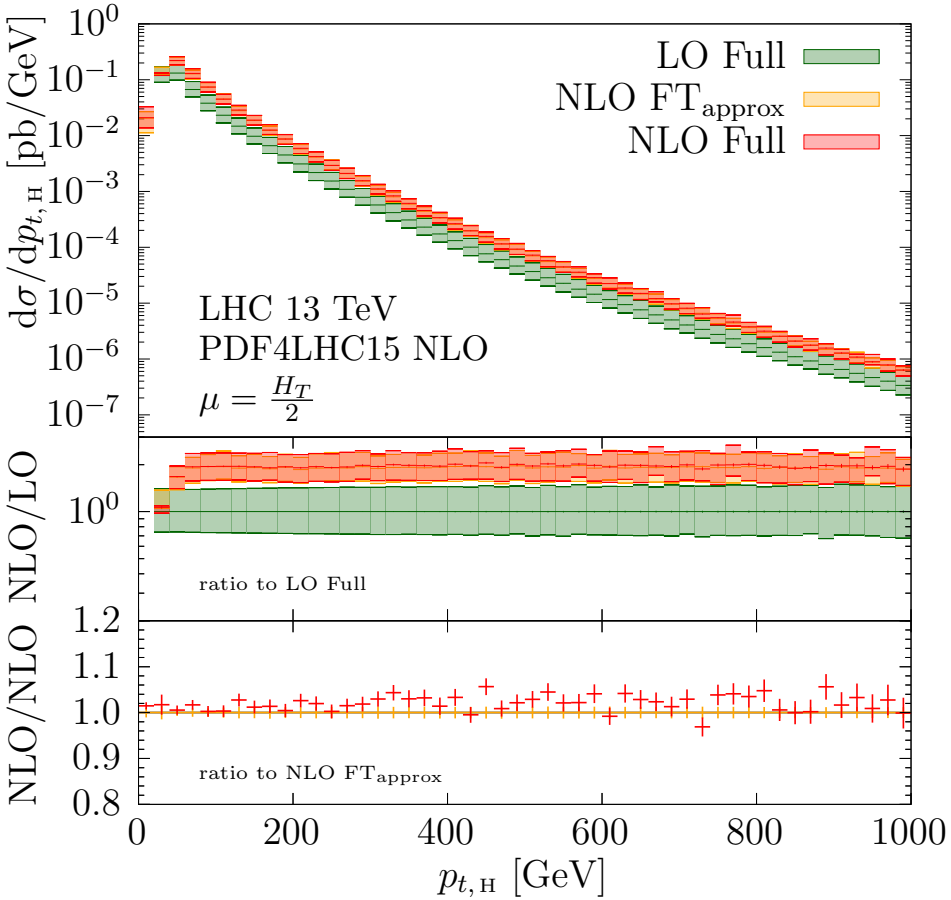


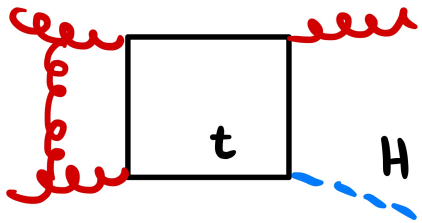


H + jet

$gg \to Hg$ at NLO

- small m_t expansion [Kudashkin,Lindert,Melnikov,Wever'18; Neumann'18]
- exact calculation [Jones,Kerner,Luisoni'18; Chen,Huss,Jones,Kerner,Lang,Lindert,Zhang'21]





- EW corrections $\sim \lambda$ [Gao,Shen,Wang,Yang,Zhou'23']
- full NLO EW correction in large-m_t expansion [Davies,Schönwald,Steinhauser,Zhang'23]

$gg \to Hg$ at NLO

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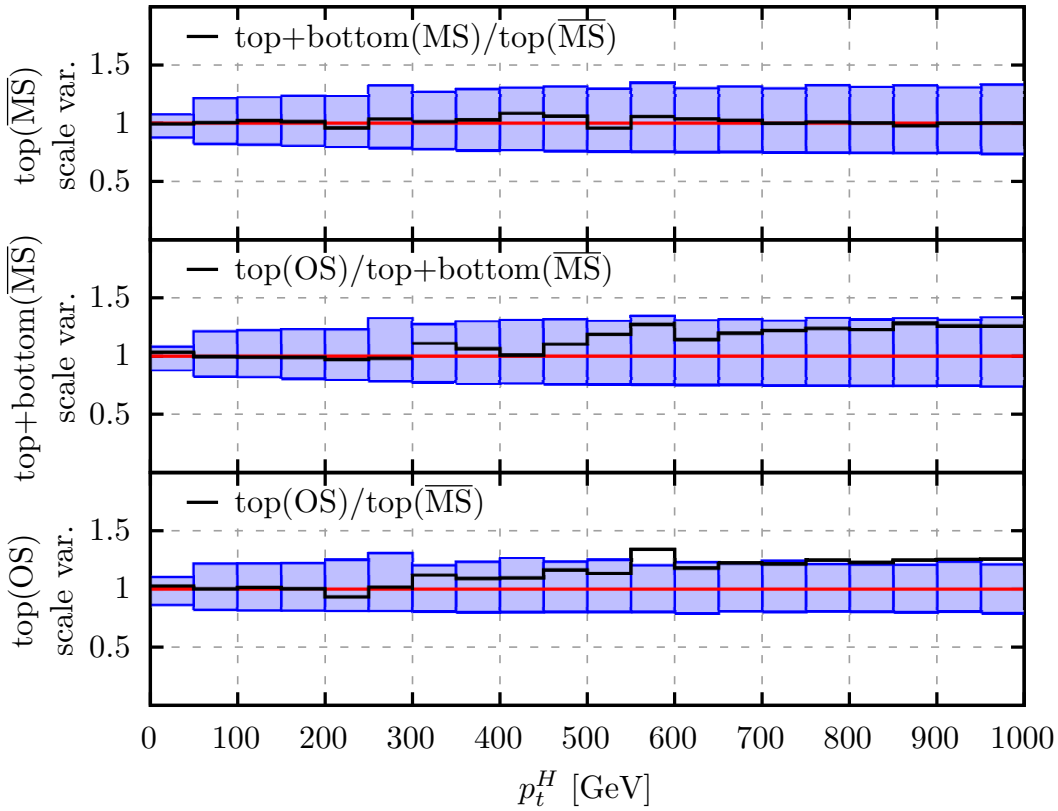
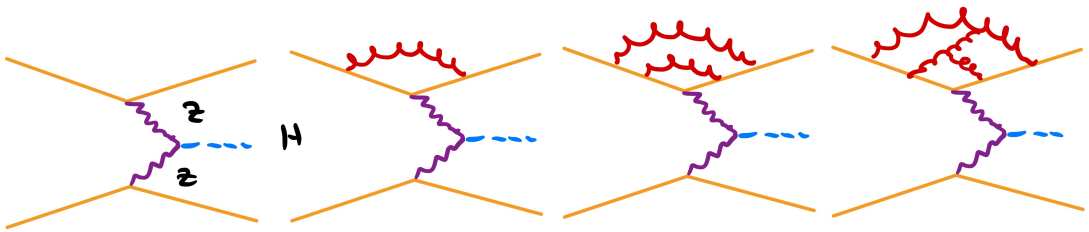
- exact calculation [Jones,Kerner,Luisoni'18; Chen,Huss,Jones,Kerner,Lang,Lindert,Zhang'21]
- m_t and m_b dependence; study of renormalization schemes

[Bonciani,Del Duca,Frellesvig,Hidding,Hirschi,Moriello,Salvatori,Somogyi,Tramontano'22]

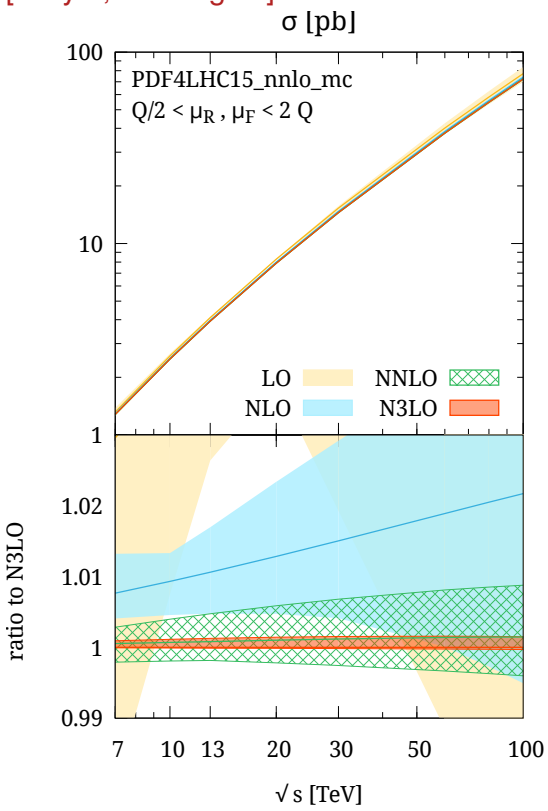


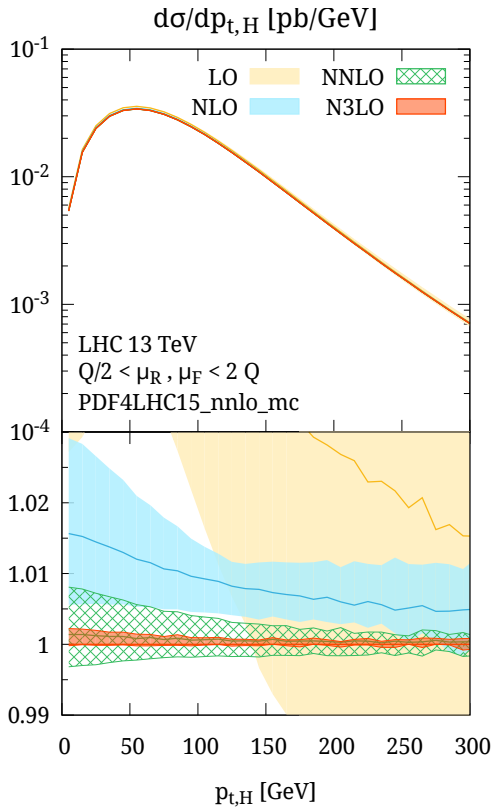
VBF

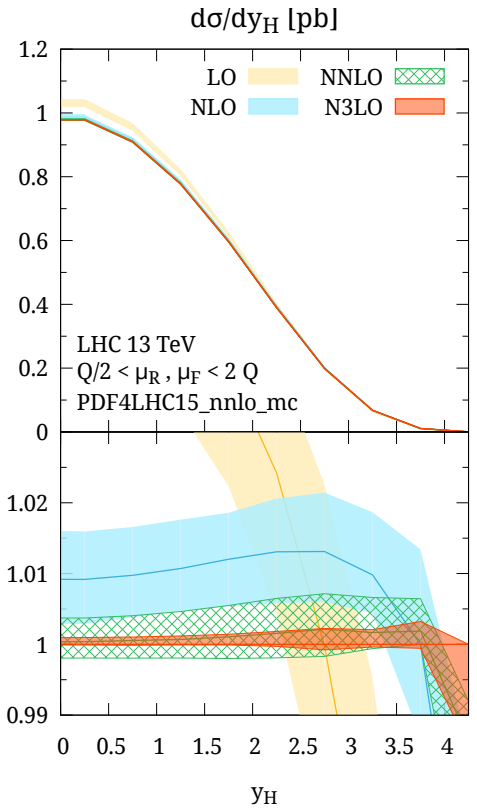
Factorizable



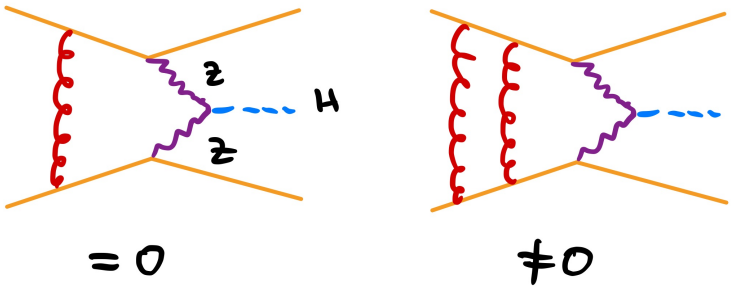
[Dreyer,Karlberg'16]







Non-factorizable

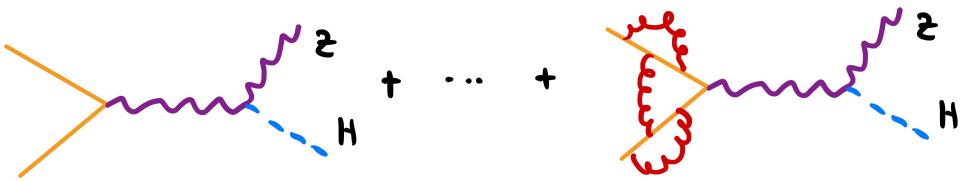


- $1/N_c^2$ suppressed
- but: π^2 enhancement [Liu,Melnikov,Penin'19] (see also [Dreyer,Karlberg,Tencredi'22])
- [Asteriadis,Brønnum-Hansen,Melnikov'23]: real-virtual and double-real non-factorizable contribution
- [Long,Melnikov,Quarroz'23]: leading power correction to the eikonal limit

➪ talk by Christian Brønnum-Hansen

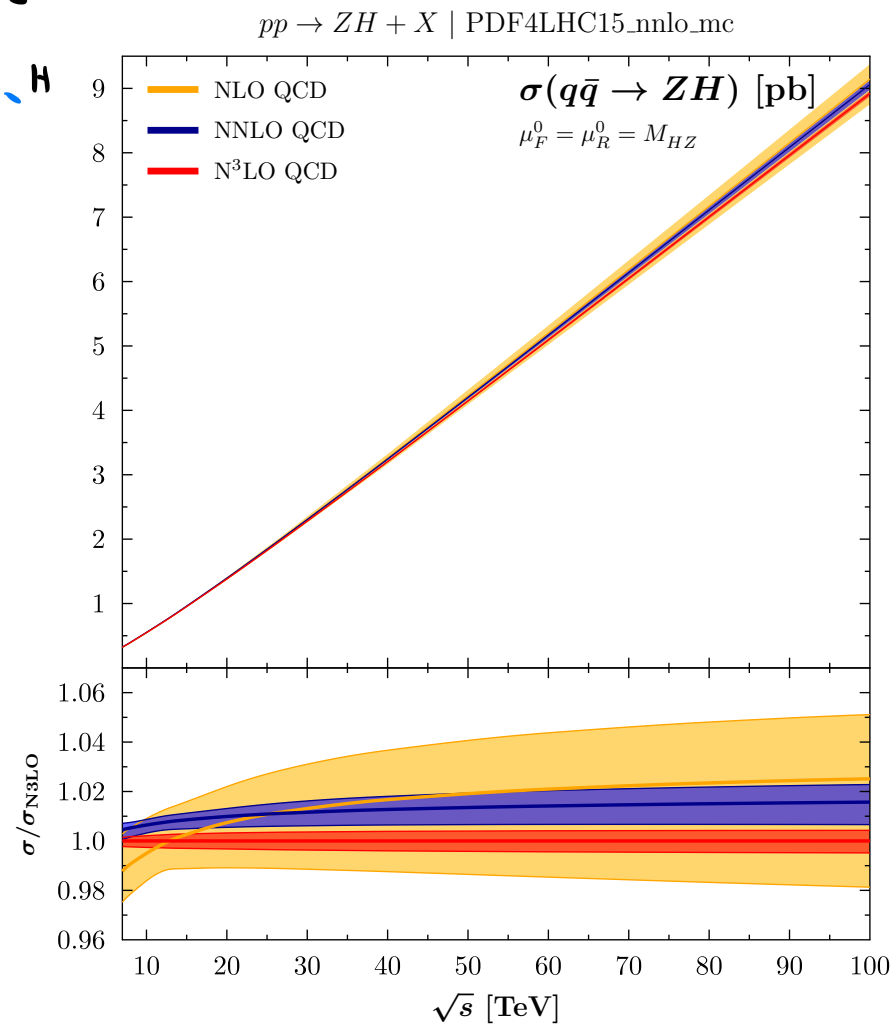
$H + \mathrm{V}$

$q\bar{q}$ channel to N^{3}LO

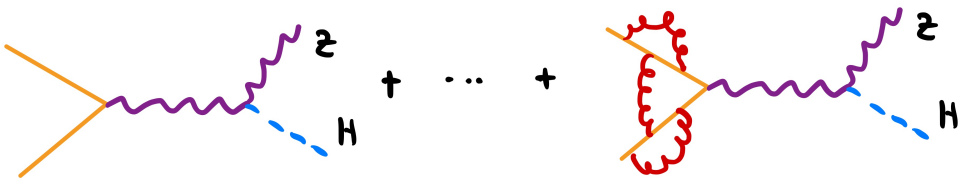


- Inclusive N^{3}LO

  [Baglio,Duhr,Mistlberger'22]



$q\bar{q}$ channel to N^{3}LO



- Inclusive N^{3}LO

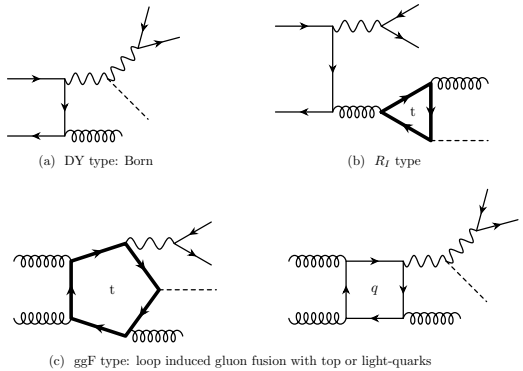
  [Baglio,Duhr,Mistlberger'22]

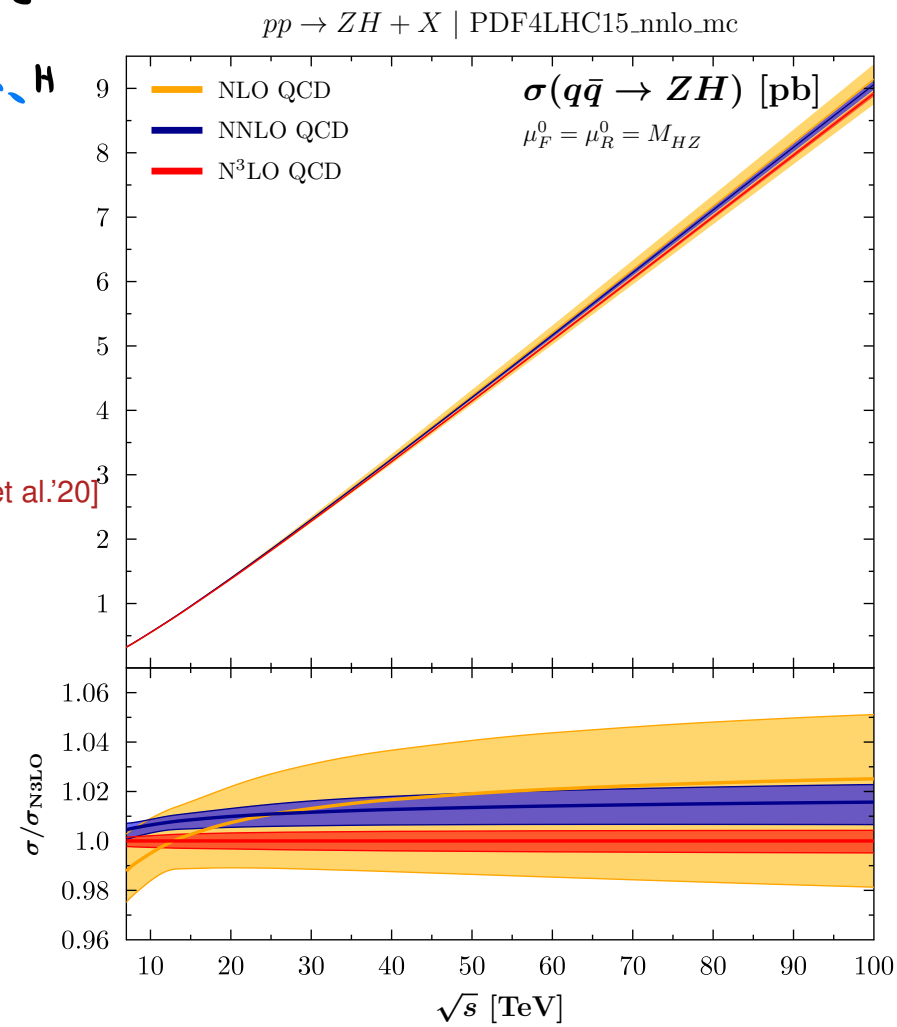
- NNLO QCD + *H* decays

  [Ferrera et al'17; Caola et al.'17; Gauld et al. '19; Behring et al.'20]

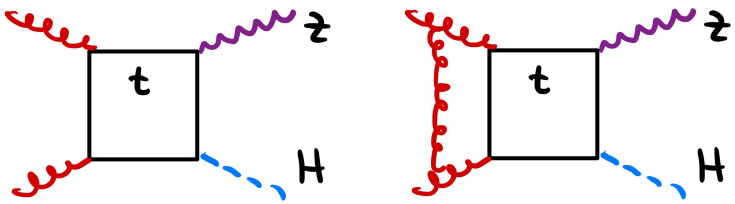
- *VH* + jet to α_s^3

  [Gauld,Gehrmann-De Ridder,Glover,Huss,Majer'21]





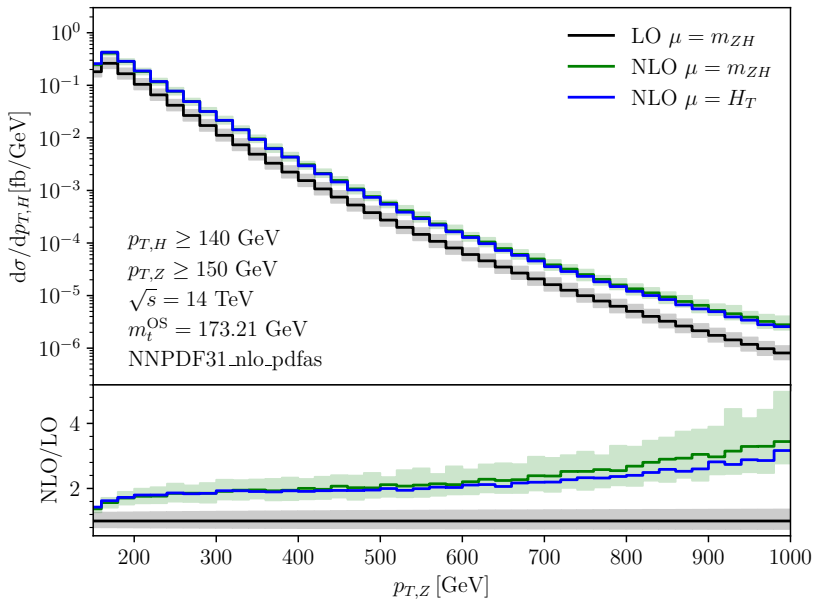
$gg \to ZH$

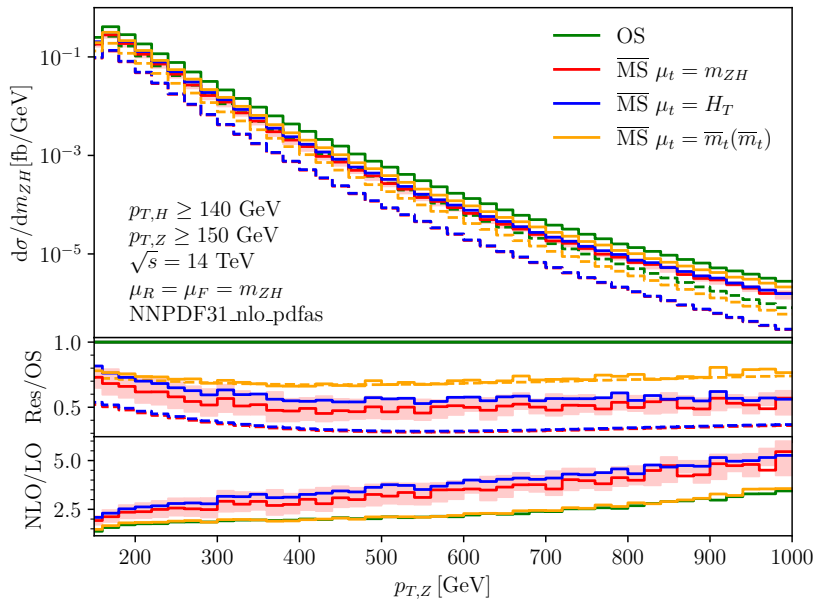


- [Davies,Mishima,Steinhauser'20]: high-energy expansion ($s, t \gg m_t^2 \gg m_Z^2, m_H^2$)
- [Bellafronte,Degrassi,Giardino,Gröber,Vitti'22]: small p_T expansion
- [Chen,Heinrich,Jones,Kerner,Klappert,Schlenk'20] numerical calculation (s, t, m_t, m_Z, m_H)
- [Wang,Xu,Xu,Yang'21]: expansion in m_Z and m_H; analytic and numeric methods for the remaining integrals
- [Chen,Davies,Heinrich,Jones,Kerner,Mishima,Schlenk,Steinhauser'22]:
  numerical calculation for $p_T < 150$ GeV
  $\otimes$ high-energy expansion for $p_T > 150$ GeV
  ➪ avoid costly numerical evaluation in large parts of phase space
- [Degrassi,Gröber,Vitti,Zhao'22]: small $p_T \otimes$ high-energy expansion

$gg \to ZH$

[Chen,Davies,Heinrich,Jones,Kerner,Mishima,Schlenk,Steinhauser'22]

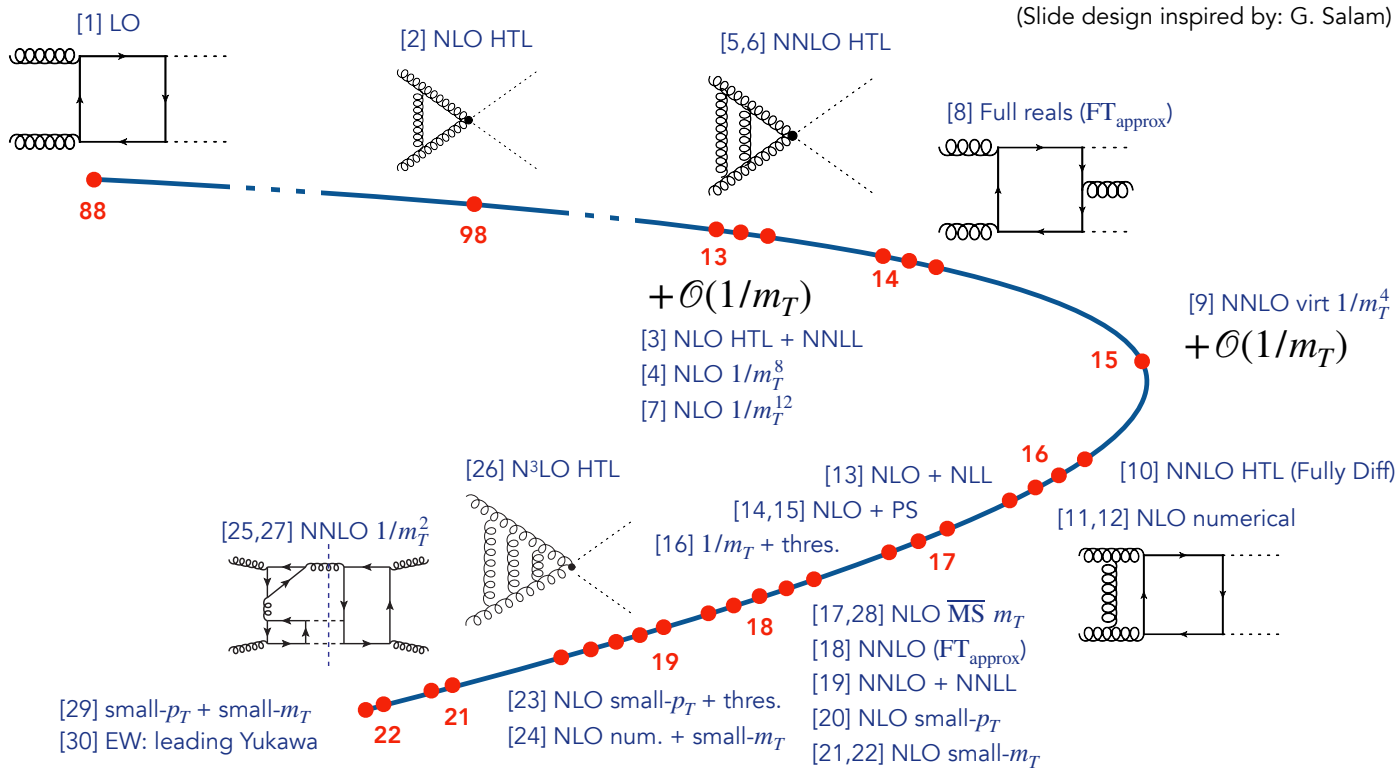




- large K factors (slightly tamed by cuts on soft Z or H)
- large m_t renormalization scheme dependence

HH

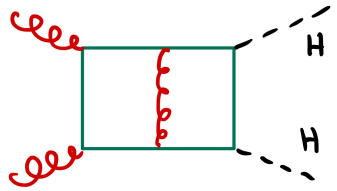
HH: Theory History



[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16; [13] Ferrera, Pires 16; [14] Heinrich, SPJ, Kerner, Luisoni, Vryonidou 17; [15] SPJ, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, SPJ, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Degrassi, Giardino, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, SPJ, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19, 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafronte, Degrassi, Giardino, Gröber, Vitti 22; [30] Davies, Mishima, Schönwald, Steinhauser, Zhang 22;

[slide from Stephen Jones]

Exact NLO



- scales: s, t, m_t, m_H
- Purely numerical calculations

  [Borowka,Greiner,Heinrich,Jones,Kerner,Schlenk,Schubert,Zirke'16;

  Borowka,Greiner,Heinrich,Jones,Kerner,Schlenk,Zirke'16;

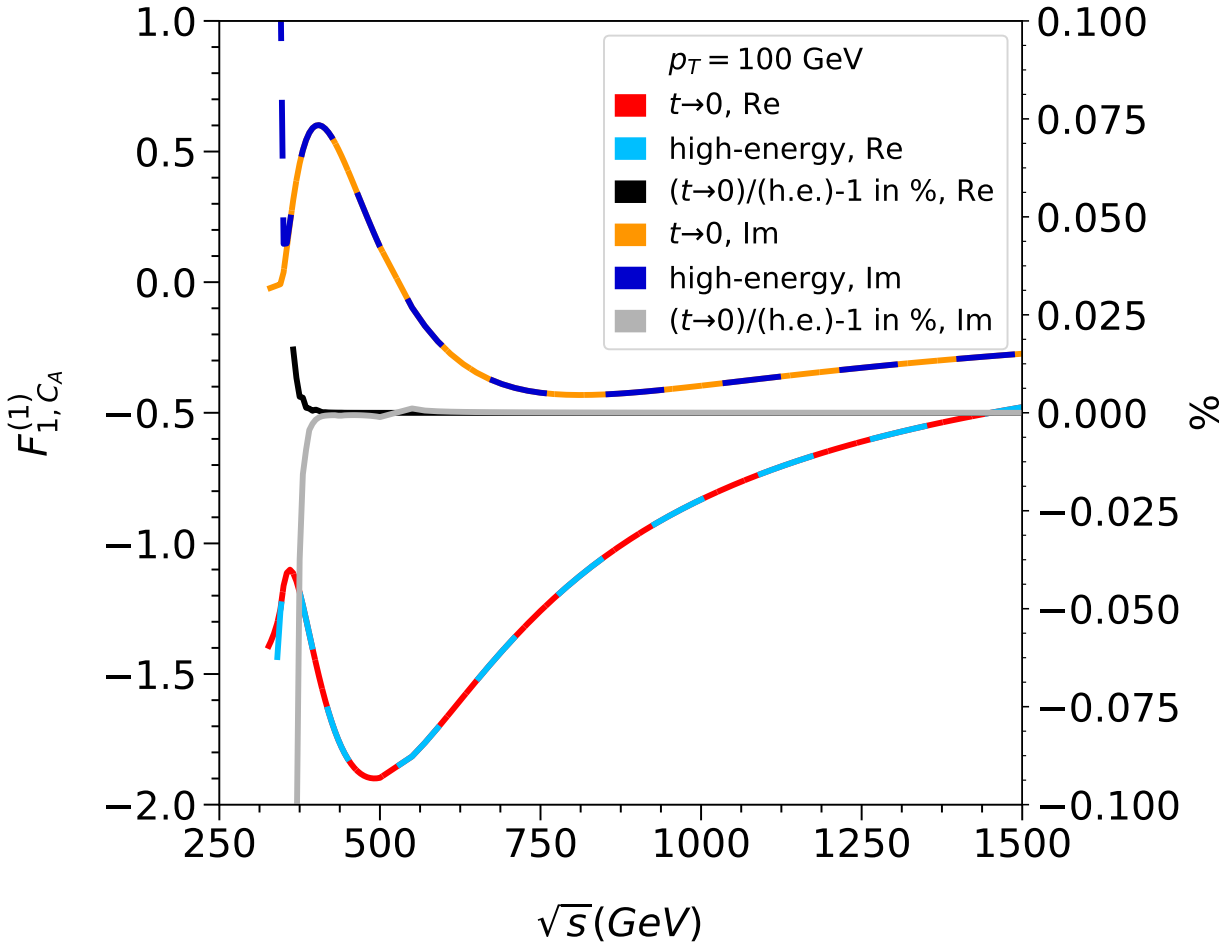
  Baglio,Campanario,Glaus,Mühlleitner,Spira,Streicher'18]
- Combination of analytic high-energy and numerical calculation (needed for smaller phase-space)

  [Davies,Heinrich,Jones,Kerner,Mishima,Steinhauser,Wellmann'19]
- Combination of low-order high-energy and "p_T expansion"

  [Bellafronte,Degrassi,Giardino,Gröber,Vitti'22]
- Combination of high-order high-energy and "t expansion"

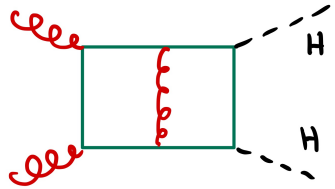
  [Davies,Mishima,Steinhauser'23]

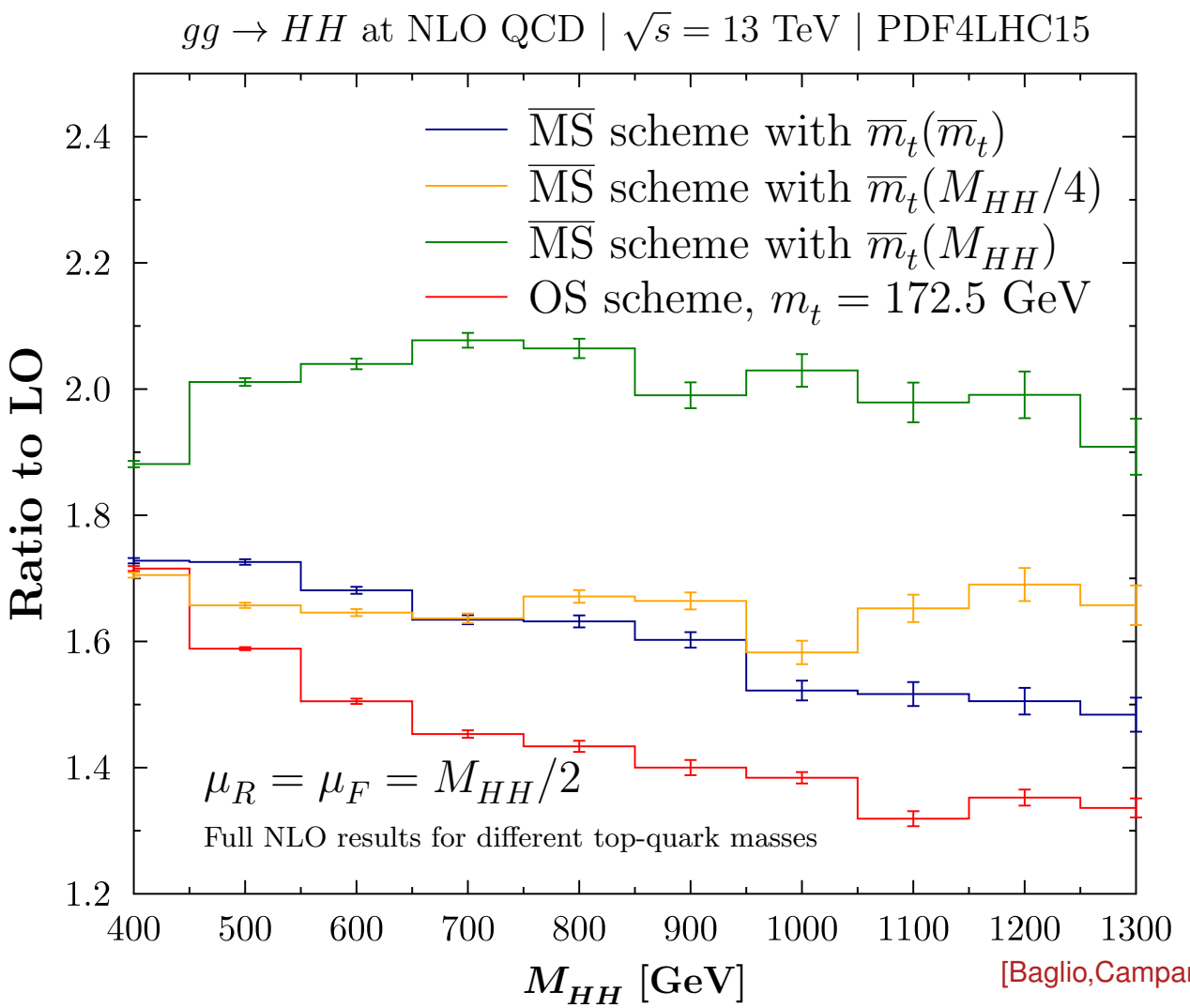
Combination of high-order high-energy and "t expansion"



[Davies,Mishima,Schönwald,Steinhauser'23]

Renormalization scheme dependence



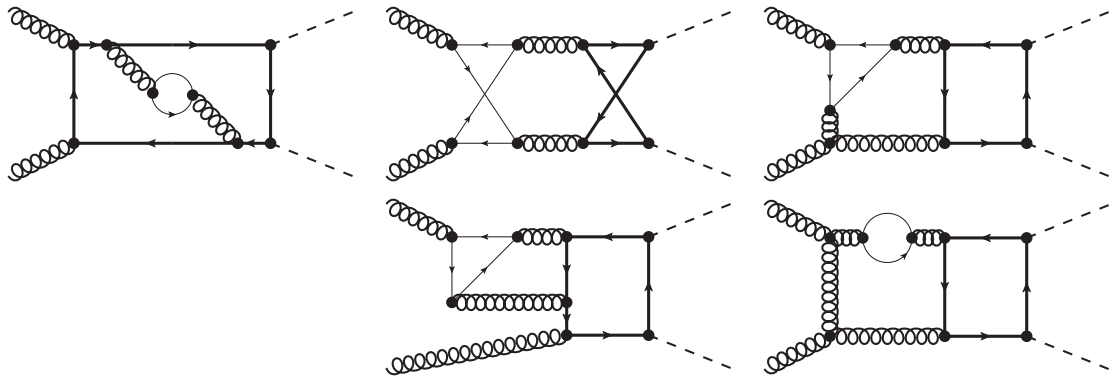


➪ NNLO needed !?

[Baglio,Campanario,Glaus,Mühlleitner,Ronca,Spira'20]

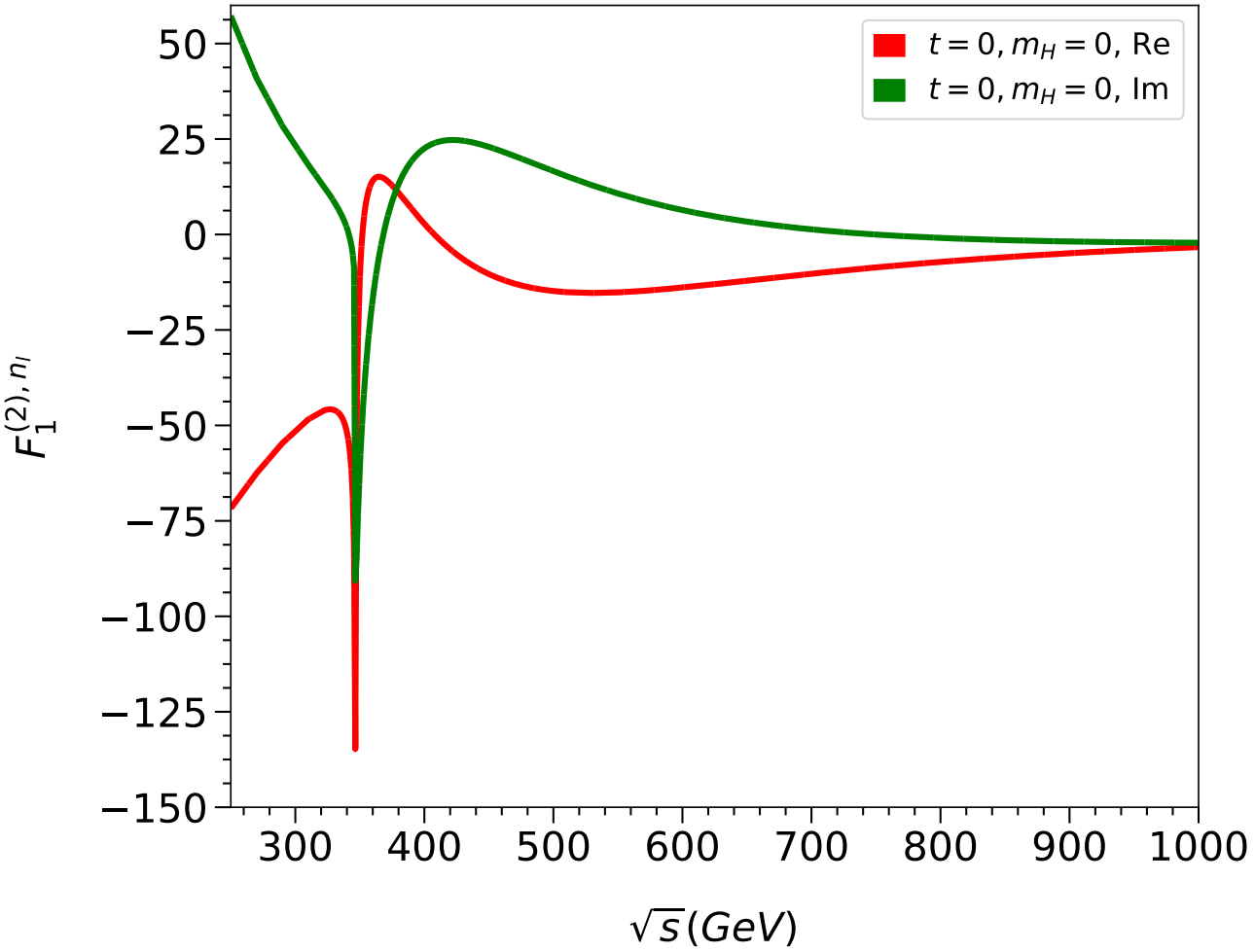
Can we go to 3 loops?

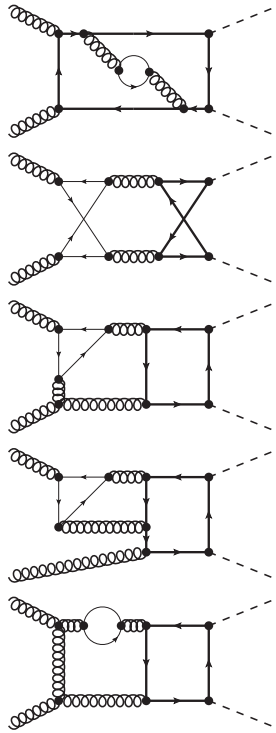
- promising: $t \to 0$ expansion
- fast convergence
- covers important region of phase space
- result would be useful for studying renormalization scheme dependence
- 1st step: fermionic corrections for $t = 0$, $m_H = 0$



3-loop n_l for $t = 0, m_H = 0$

[Davies,Schönwald,Steinhauser'23]





More H topics ...

- NNLO $t\bar{t}H$ production [Catani,Devoto,Grazzini,Kallweit,Mazzitelli,Savoini'23]

  ➪ talk by Simone Devoto
- VBF for HH: [Dreyer,Karlberg'18; Dreyer,Karlberg,Tancredi'20; Dreyer,Karlberg,Lang,Pellen'20]
- $pp \to H+ \geq 1$ jet, resummed $\log(s/p_T^2)$

  [Andersen,Hassan,Maier,Paltrinieri,Papaefstathiou,Smillie'22]
- m_b effects to p_{TH} spectrum [Pietrulewicz,Stahlhofen'23]
- q_T distribution of $q\bar{q} \to H$, $q = s, c, b$, to N^{3}LL$'$+aN^{3}LO

  [Cal,von Kuk,Lim,Tackmann'23]
- $gg \to H \to \gamma\gamma \otimes \gamma\gamma \leftarrow gg$ [Bargiela,Buccioni,Caola,Devoto,von Manteuffel,Tancredi'22]
- next-to-soft resummations [Ravindran,Sankar,Tiwari'22, ...]
- Complete NLO EW corrections to $gg \to HH$ for large m_t [Davies et al. 23]
- H decays
- Γ_H
- BSM, SMEFT, ...
- PDFs ➪ talk by Lucian Harland-Lang
- ...

Conclusions

- Many complicated calculations within a short time
- (Complete) NLO is default
  (Towards) NNLO where necessary
  Sometimes also N^3LO
- Many innovative tools for computing Feynman integrals
- Theory will be ready for HL-LHC