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Collaborative Research Center TRR 257

Particle Physics Phenomenology after the Higgs Discovery

Precision Higgs Physics & EFTs

29.9.2025

Questions

- What are (current and future) important topics in precision Higgs physics?
- What has been achieved in the CRC for this research area?
- Which synergies have been exploited?
- What was the overall impact of the CRC in precision Higgs physics?
- What are the perspectives in this research area beyond 2026?

A central paragraph from the last proposal

The Collaborative Research Center was created as a response to the paradigm shift towards **precision physics** as the driving force for **indirect searches** of New Physics.

Its main long-term research goal is the development of a comprehensive framework to search for, discover and explore physics beyond the Standard Model in a situation where the comparison of precise theoretical predictions with equally precise data plays an ever increasing role.

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NB: This also includes understanding SM physics better

Major topics in (precision) Higgs physics

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- Higgs boson couplings (in particular to 2nd generation fermions)
- rare decays (e.g. H -> Z gamma, or search for flavour violating decays)
- Higgs boson self-coupling(s)
- (longitudinal) vector boson scattering
- Higgs boson width
- CP properties (small admixtures of CP odd)
- The Higgs boson as a portal to new physics

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“The Higgs boson is a fantastic laboratory for new physics searches. The journey is only just beginning”

CERN Courier

(Not an) outline

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- Higgs boson production in gluon fusion (A1a)
- Higgs + jet production (A1b)
- Higgs + Z production in gluon fusion (A1b)
- Higgs boson pair production (A1b, A2b, A3bSM)
- ttH production (B1b, B2c)

Les Houches precision wishlist (Higgs)

Huss, Huston, Jones, Pellen, Röntsch 2504.06689

process	known	desired
$pp \to H$	$\mathrm{N^3LO_{HTL}}$ $\mathrm{NNLO_{QCD}^{(t,t\times b)}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}^{(HTL)}}$ $\mathrm{NLO_{QCD}}$	$\mathrm{N^4LO_{HTL}}$ (incl.)
$pp \to H+j$	$\mathrm{NNLO_{HTL}}$ $\mathrm{NLO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$	$\mathrm{NNLO_{HTL}\otimes NLO_{QCD}+NLO_{EW}}$ $\mathrm{N^3LO_{HTL}}$ $\mathrm{NNLO_{QCD}}$
$pp \to H+2j$	$\mathrm{NLO_{HTL}\otimes LO_{QCD}}$ $\mathrm{N^3LO_{QCD}^{(VBF^*)}}$ (incl.) $\mathrm{NNLO_{QCD}^{(VBF^*)}}$ $\mathrm{NLO_{EW}^{(VBF)}}$	$\mathrm{NNLO_{HTL}\otimes NLO_{QCD}+NLO_{EW}}$ $\mathrm{N^3LO_{QCD}^{(VBF^*)}}$ $\mathrm{NNLO_{QCD}^{(VBF)}}$ $\mathrm{NLO_{QCD}}$
$pp \to H+3j$	$\mathrm{NLO_{HTL}}$ $\mathrm{NLO_{QCD}^{(VBF)}}$	$\mathrm{NLO_{QCD}+NLO_{EW}}$ $\mathrm{NNLO_{QCD}^{(VBF^*)}}$
$pp \to VH$	$\mathrm{N^3LO_{QCD}}$ (incl.)$+\mathrm{NLO_{EW}}$ $\mathrm{NLO_{gg\to HZ}^{(t,b)}}$	$\mathrm{N^3LO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$
$pp \to VH+j$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD}+NLO_{EW}}$	

$pp \to HH$	$\mathrm{N^3LO_{HTL}\otimes NLO_{QCD}}$ $\mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
$pp \to HH+2j$	$\mathrm{N^3LO_{QCD}^{(VBF^*)}}$ (incl.) $\mathrm{NNLO_{QCD}^{(VBF^*)}}$ $\mathrm{NLO_{EW}^{(VBF)}}$	$\mathrm{NLO_{QCD}}$
$pp \to HHH$	$\mathrm{NNLO_{HTL}}$	$\mathrm{NLO_{QCD}}$
$pp \to H+t\bar{t}$	$\mathrm{NLO_{QCD}+NLO_{EW}}$ $\mathrm{NNLO_{QCD}}$ (approx.)	$\mathrm{NNLO_{QCD}}$
$pp \to H+t/\bar{t}$	$\mathrm{NLO_{QCD}+NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$

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— SM
— SM ⊗ EFT
— in progress
} CRC involvement

process	known	desired
$pp \to H$	$\mathrm{N^3LO_{HTL}}$ $\mathrm{NNLO_{QCD}^{(t,t\times b)}}$ A1a $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}^{(HTL)}}$ $\mathrm{NLO_{QCD}}$	$\mathrm{N^4LO_{HTL}}$ (incl.) B2a
$pp \to H+j$	$\mathrm{NNLO_{HTL}}$ A1b $\mathrm{NLO_{QCD}}$ +EFT $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$	$\mathrm{NNLO_{HTL}\otimes NLO_{QCD}+NLO_{EW}}$ $\mathrm{N^3LO_{HTL}}$ B1a $\mathrm{NNLO_{QCD}}$
$pp \to H+2j$	$\mathrm{NLO_{HTL}\otimes LO_{QCD}}$ $\mathrm{N^3LO_{QCD}^{(VBF^*)}}$ (incl.) $\mathrm{NNLO_{QCD}^{(VBF^*)}}$ A1c $\mathrm{NLO_{EW}^{(VBF)}}$	$\mathrm{NNLO_{HTL}\otimes NLO_{QCD}+NLO_{EW}}$ $\mathrm{N^3LO_{QCD}^{(VBF^*)}}$ $\mathrm{NNLO_{QCD}^{(VBF)}}$ A1c $\mathrm{NLO_{QCD}}$ A1b
$pp \to H+3j$	$\mathrm{NLO_{HTL}}$ $\mathrm{NLO_{QCD}^{(VBF)}}$	$\mathrm{NLO_{QCD}+NLO_{EW}}$ $\mathrm{NNLO_{QCD}^{(VBF^*)}}$
$pp \to VH$	A1b $\mathrm{N^3LO_{QCD}}$ (incl.) $+\mathrm{NLO_{EW}}$ $\mathrm{NLO_{gg\to HZ}^{(t,b)}}$ A1b	$\mathrm{N^3LO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$
$pp \to VH+j$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD}+NLO_{EW}}$	

$pp \to HH$	A1b, A3b $\mathrm{N^3LO_{HTL}\otimes NLO_{QCD}}$ A1b $\mathrm{NLO_{EW}}$ NLO QCD +EFT	$\mathrm{NNLO_{QCD}}$ A1b
$pp \to HH+2j$	$\mathrm{N^3LO_{QCD}^{(VBF^*)}}$ (incl.) $\mathrm{NNLO_{QCD}^{(VBF^*)}}$ $\mathrm{NLO_{EW}^{(VBF)}}$ NLO VBF QCD+EFT A2b	$\mathrm{NLO_{QCD}}$
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$pp \to H+t/\bar{t}$	$\mathrm{NLO_{QCD}+NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$

Higgs boson production in gluon fusion

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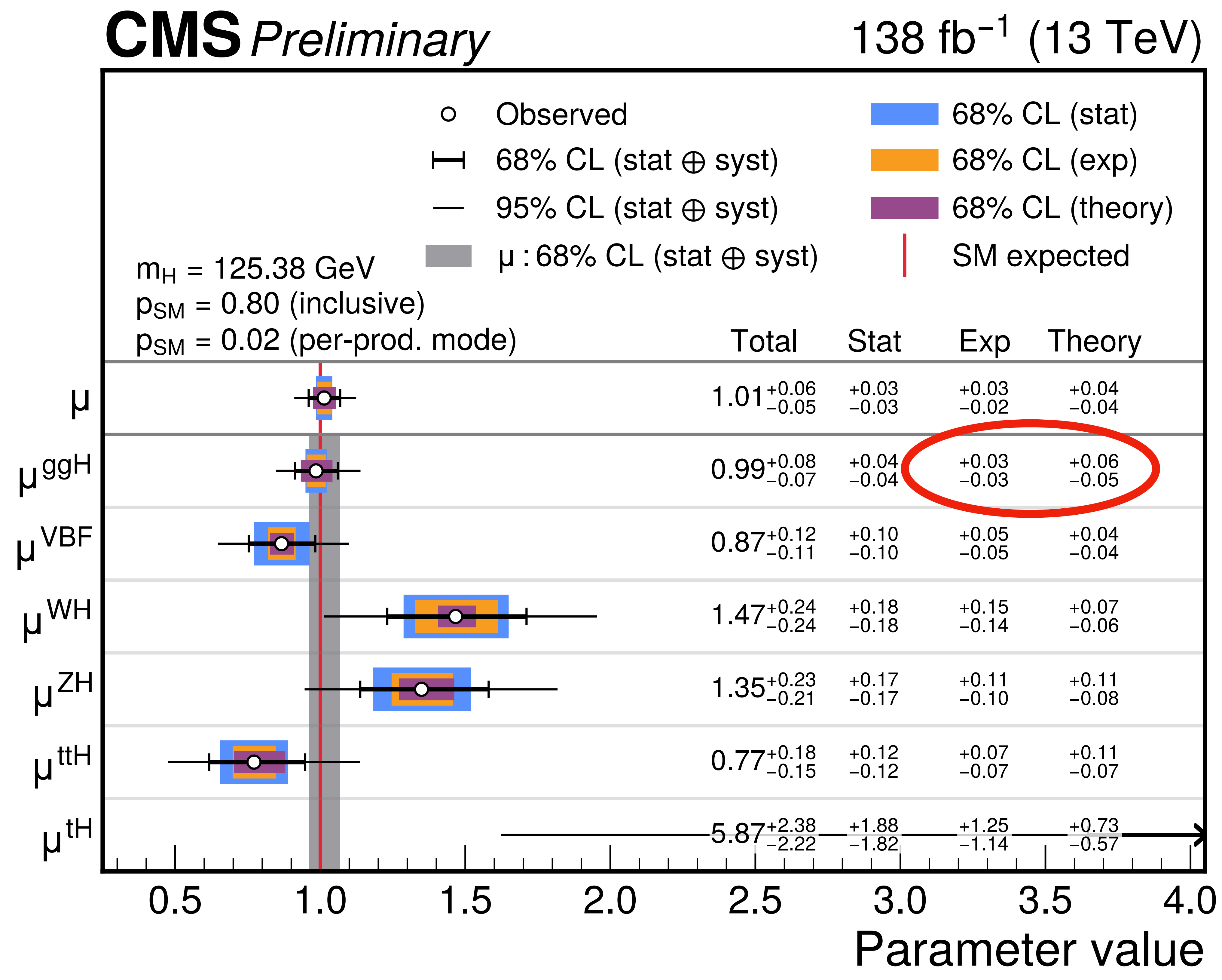
main Higgs production channels,
signal strengths:



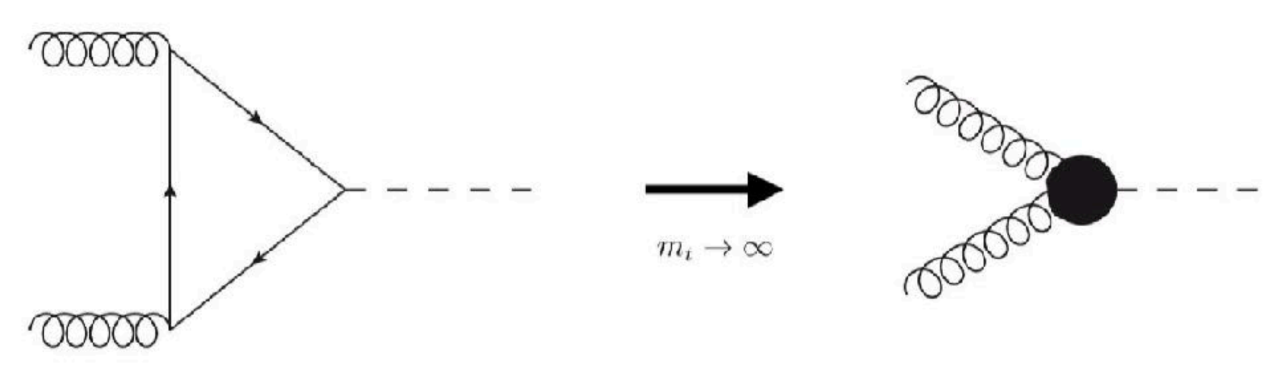
https://cds.cern.ch/record/2929999

Higgs boson production in gluon fusion (ggF):

theory uncertainties exceed experimental uncertainties

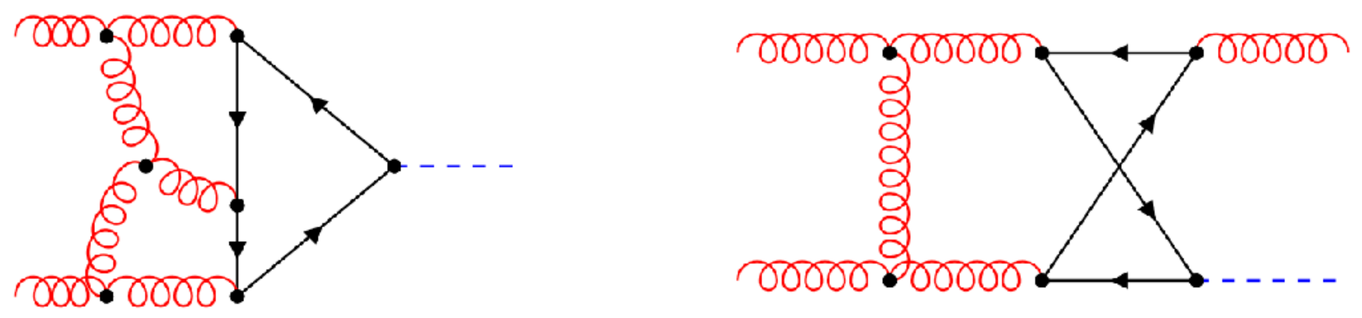
theory calculation used: $\mathrm{N3LO}_{(m_t \to \infty)}$ +NLO EW

Yellow Report 4 (2016), Mistlberger et al. 2018



heavy top limit (HTL)

full NNLO requires calculation of diagrams such as



Czakon, Harlander, Klappert, Niggetiedt '21

Higgs production in gluon fusion

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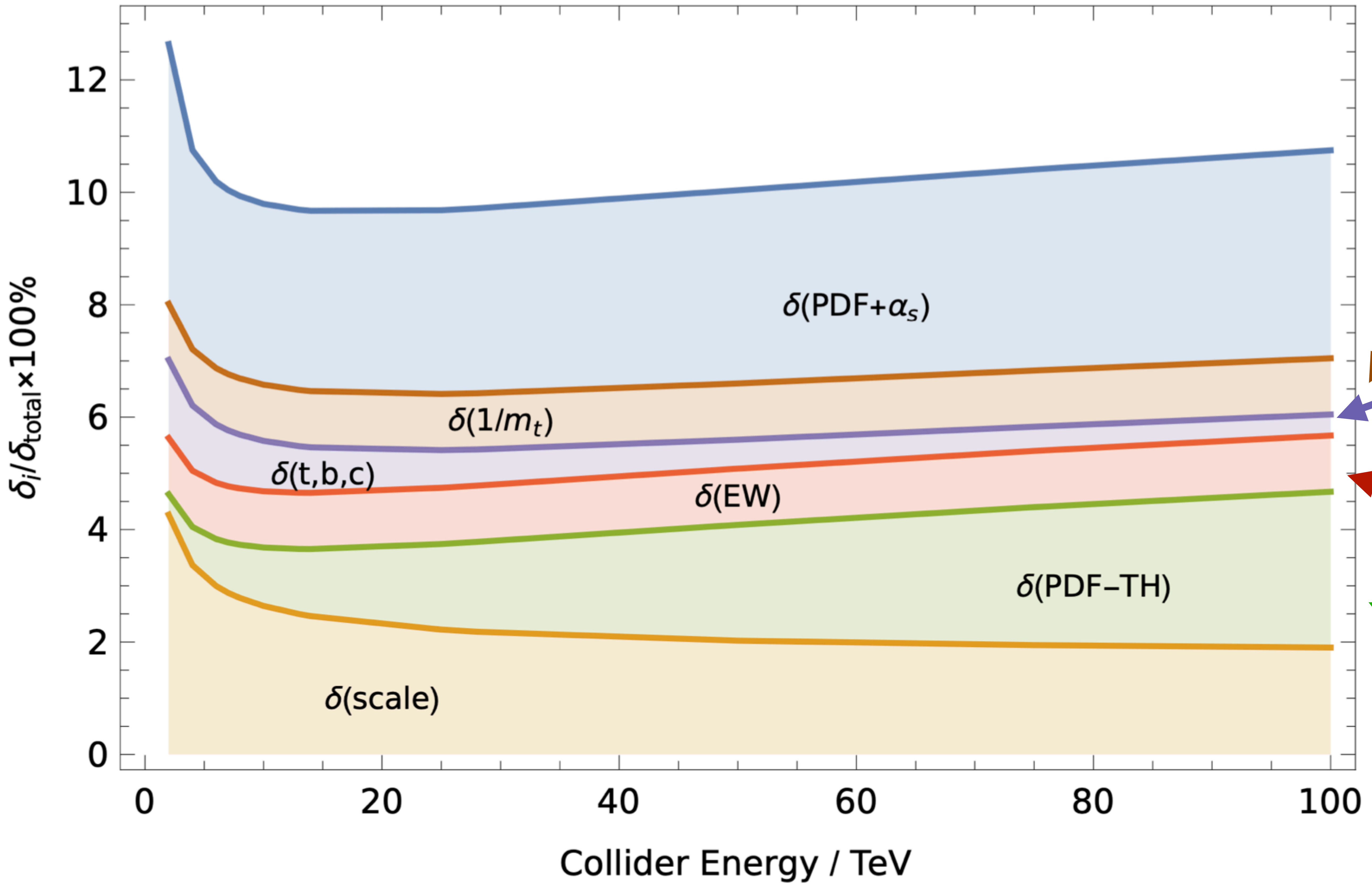
uncertainty budget 2018 Dulat, Lazopoulos, Mistlberger ’18



basically removed (NNLO with full top mass)

Czakon, Harlander, Klappert, Niggetiedt ‘21

t-b interference at NNLO

Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger ’23, ‘24

reduced to 0.6%

Bechetti et al ’20, ’21, Bonetti et al ’18, ’20, ‘22

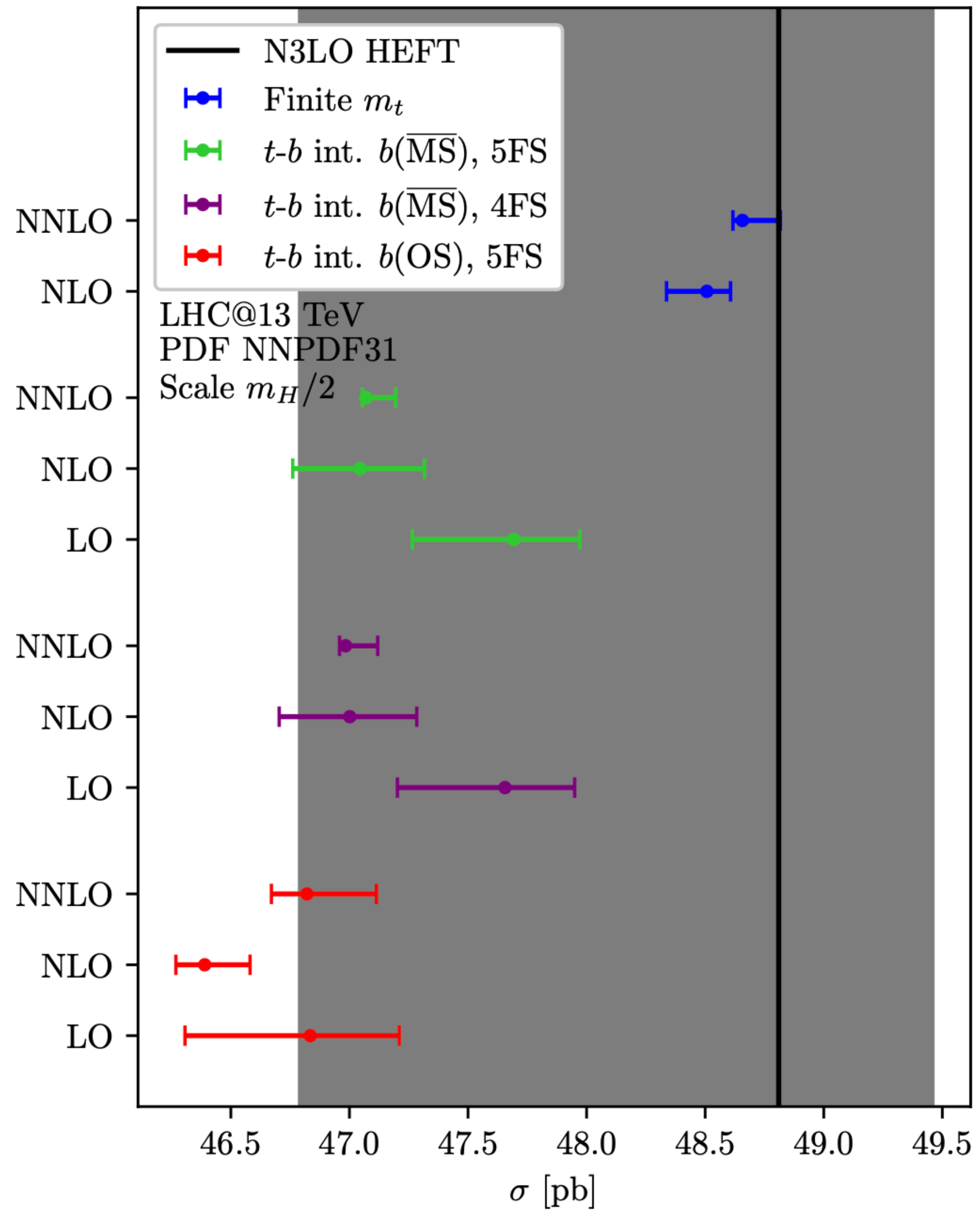
mismatch between PDF (NNLO) and ME (N3LO)
towards N3LO PDFs:

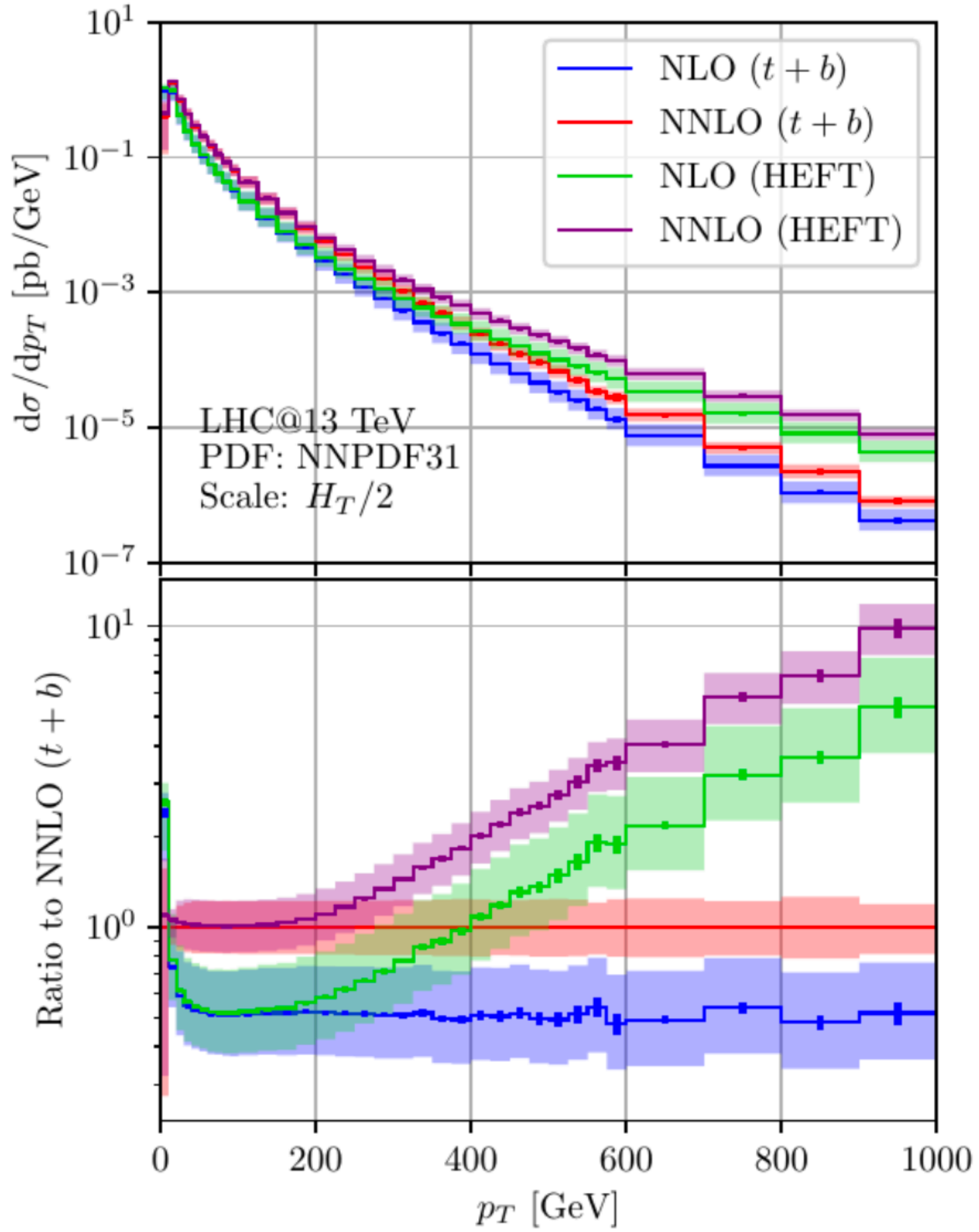
N4LO soft-virtual approx. Das, Moch, Vogt ’20; resummation Bell, Das et al. ’23, ’24

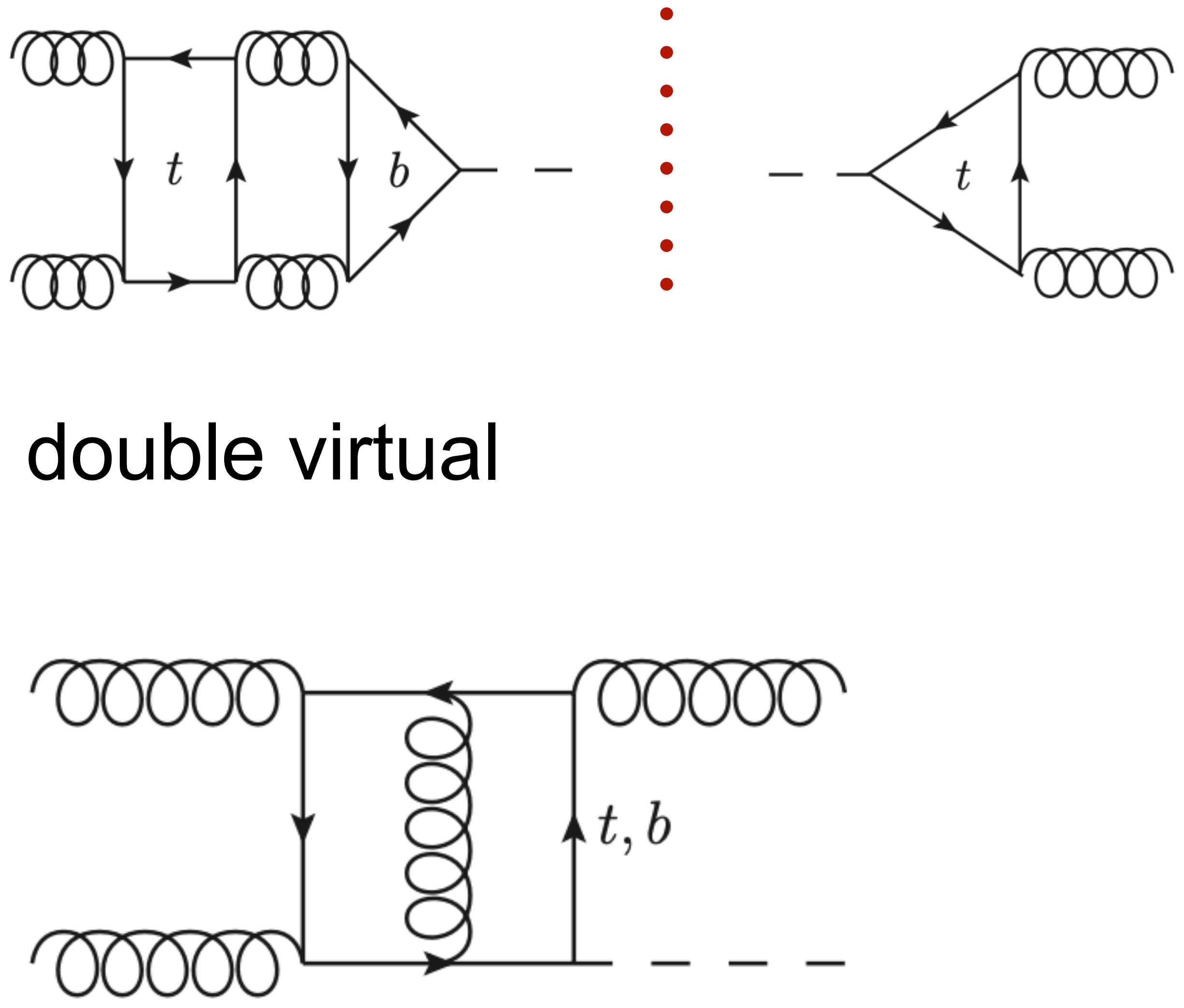
4-loop form factor Lee, Manteuffel, Schabinger, Smirnov, Smirnov Steinhauser ’22,’23

ggH: top-bottom interference at NNLO

Czakon, Eschment, Niggtiedt, Poncelet, Schellenberger ’23, ‘24







double virtual

real-virtual

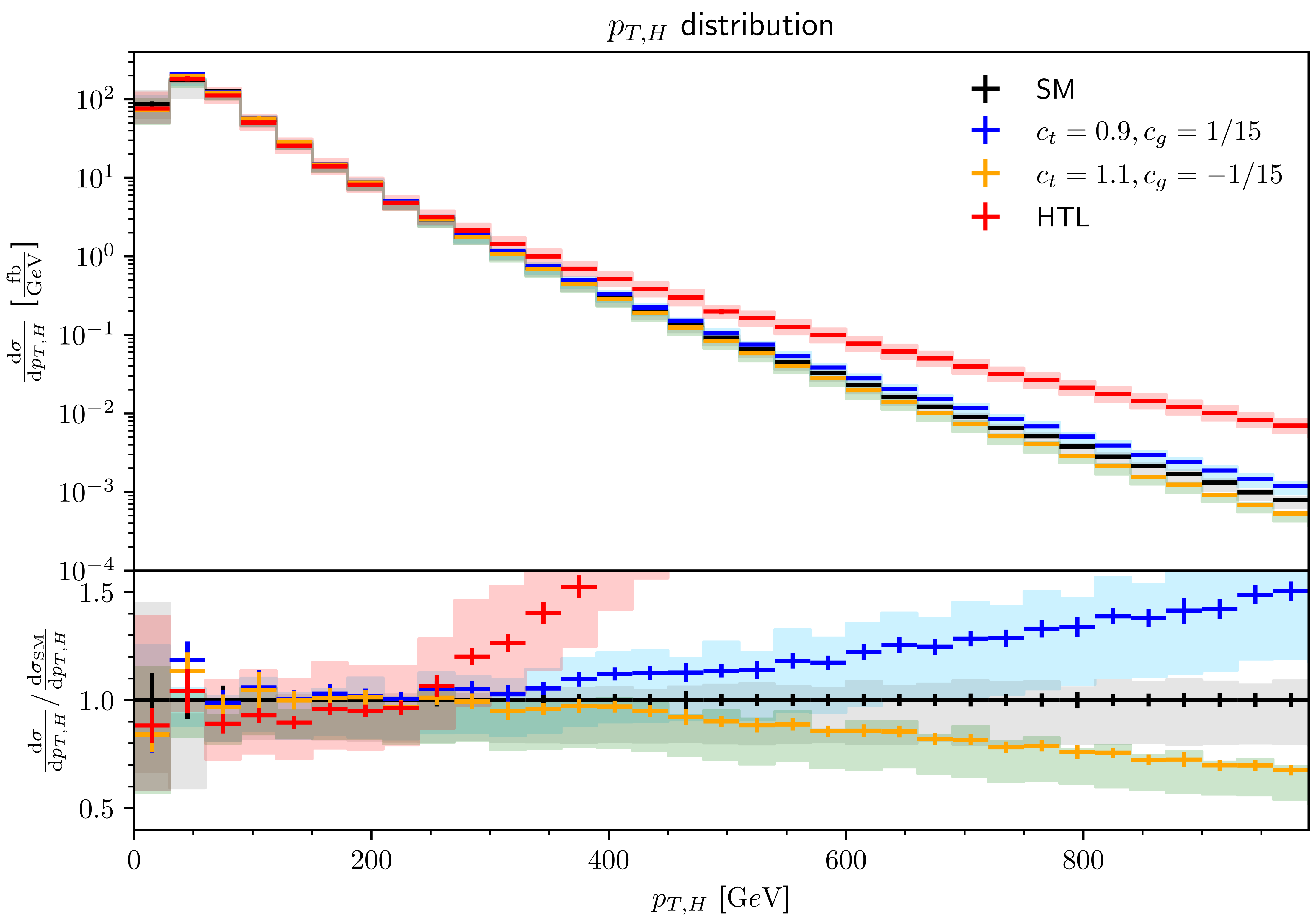
$$\sigma_{ggH} = 48.81(1)^{+0.65}_{-2.02}(\mathrm{N^3LO\ HEFT}) - 0.16^{+0.13}_{-0.03}(\mathrm{NNLO}\ t) - 1.74(2)^{+0.13}_{-0.03}(\mathrm{NNLO}\ t \times b)\ \mathrm{pb}.$$

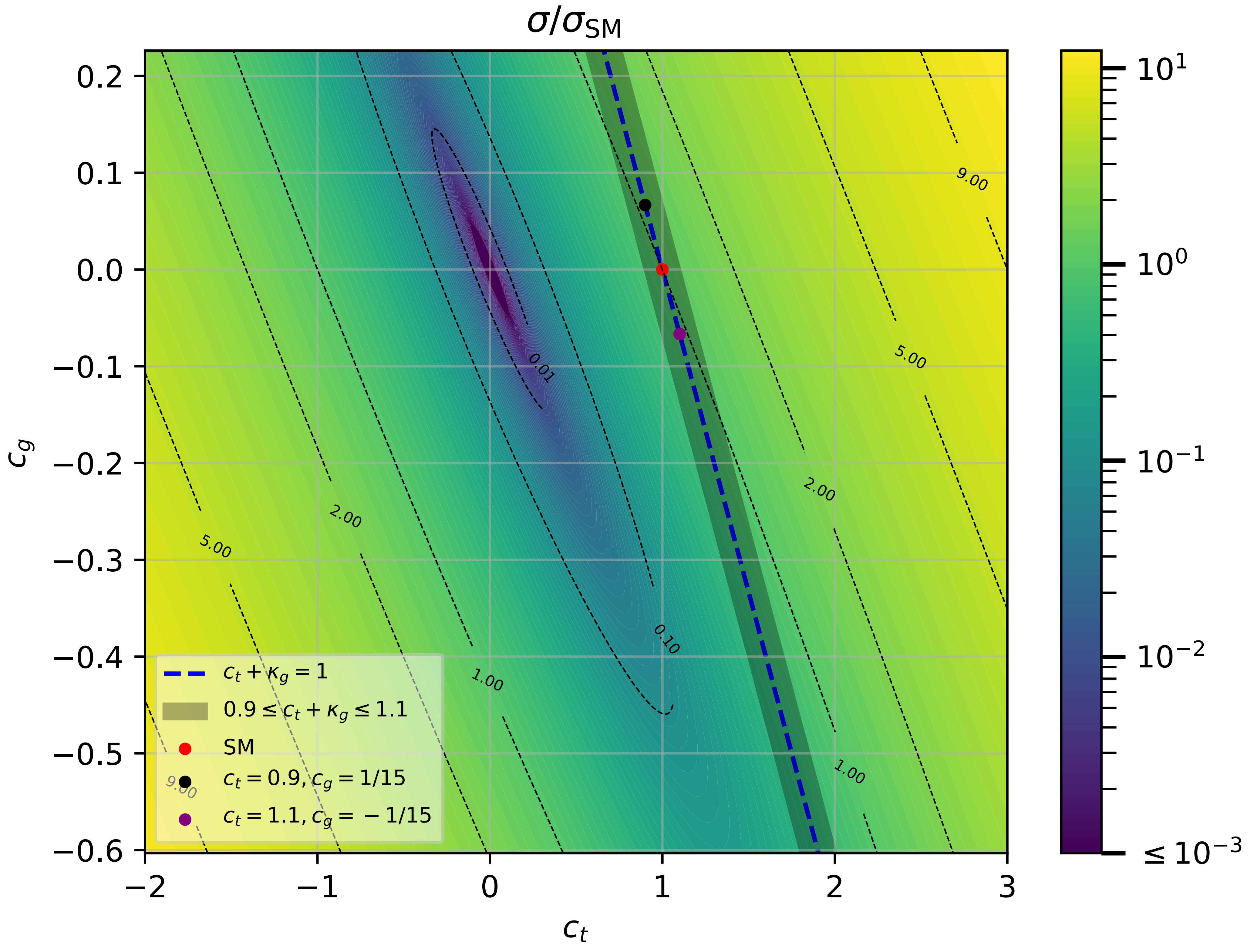
Tom Schellenberger,
Young Scientists Meeting 2024

Higgs + Jet at NLO QDC with anomalous couplings

Campillo, GH, Kerner, Kunz 2409.05728 (based on SM NLO calculation of Jones, Kerner, Luisoni '18)

NLO QCD with full top mass including anomalous couplings





effects of c_t, c_g exceed scale uncertainties at large pT,H **inclusion of subleading operators in progress**

Higgs + Z production in gluon fusion

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ggZH @ NLO QCD

http://arxiv.org/abs/2204.05225 Chen, Davies, GH, Jones, Kerner, Mishima, Schlenk, Steinhauser

- combination of numerical approach (pySecDec) with high energy expansion
- allowed study of top quark mass renormalisation scheme dependence

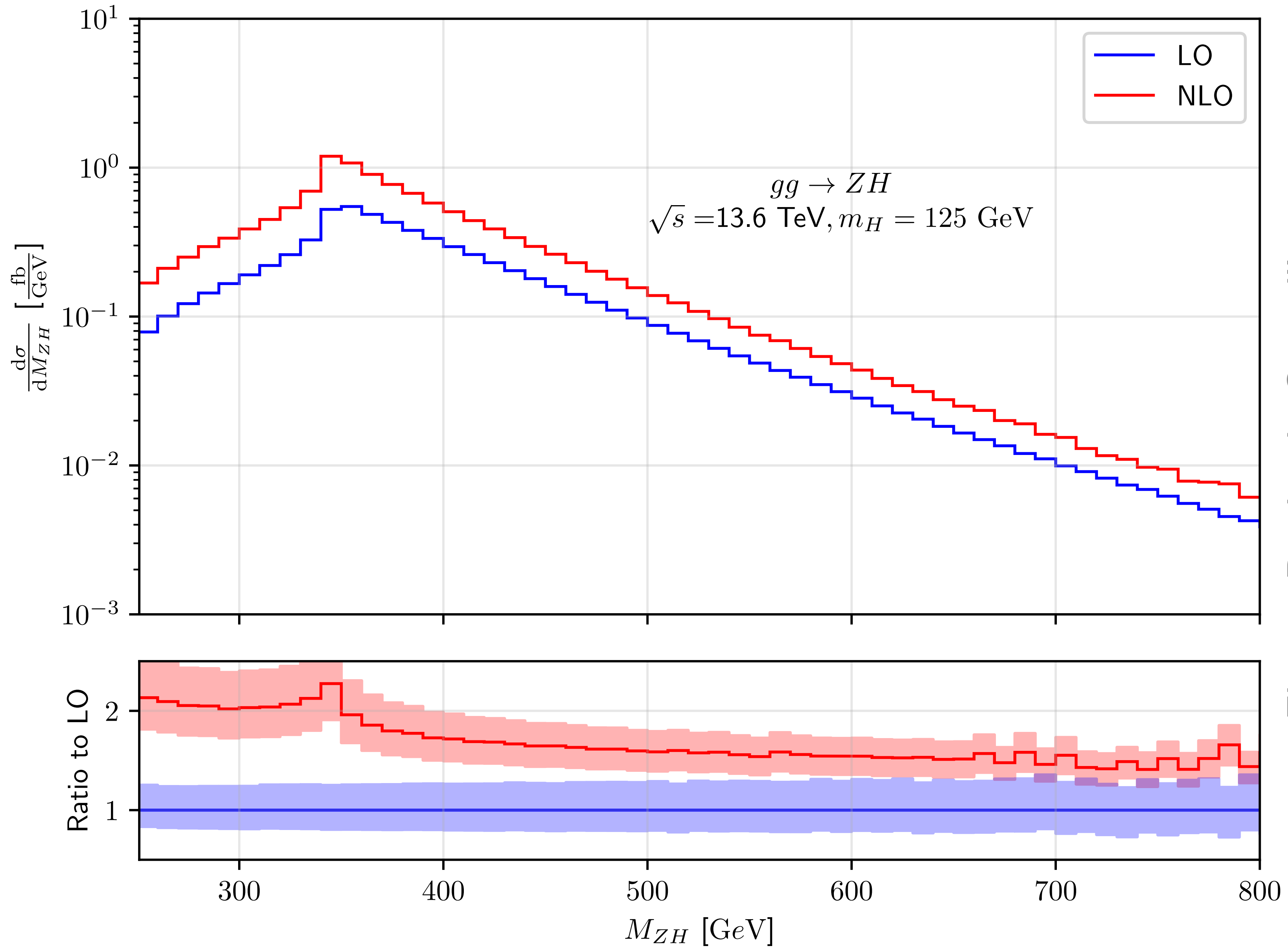

Figure: Benjamin Campillo

contribution to Report 5

http://arxiv.org/abs/2508.09905

Campillo Aveleira, Davies, GH, Gröber, Jones, Kerner, Steinhauser, Vitti et al.

- combination of expansions in forward and high-energy limits

http://arxiv.org/abs/2509.07072

Davies, Grau, Schönwald, Steinhauser, Stremmer, Vitti → coverage of basically whole phase space

will be included in Powheg code ggxy

fast evaluation

Higgs boson pair production

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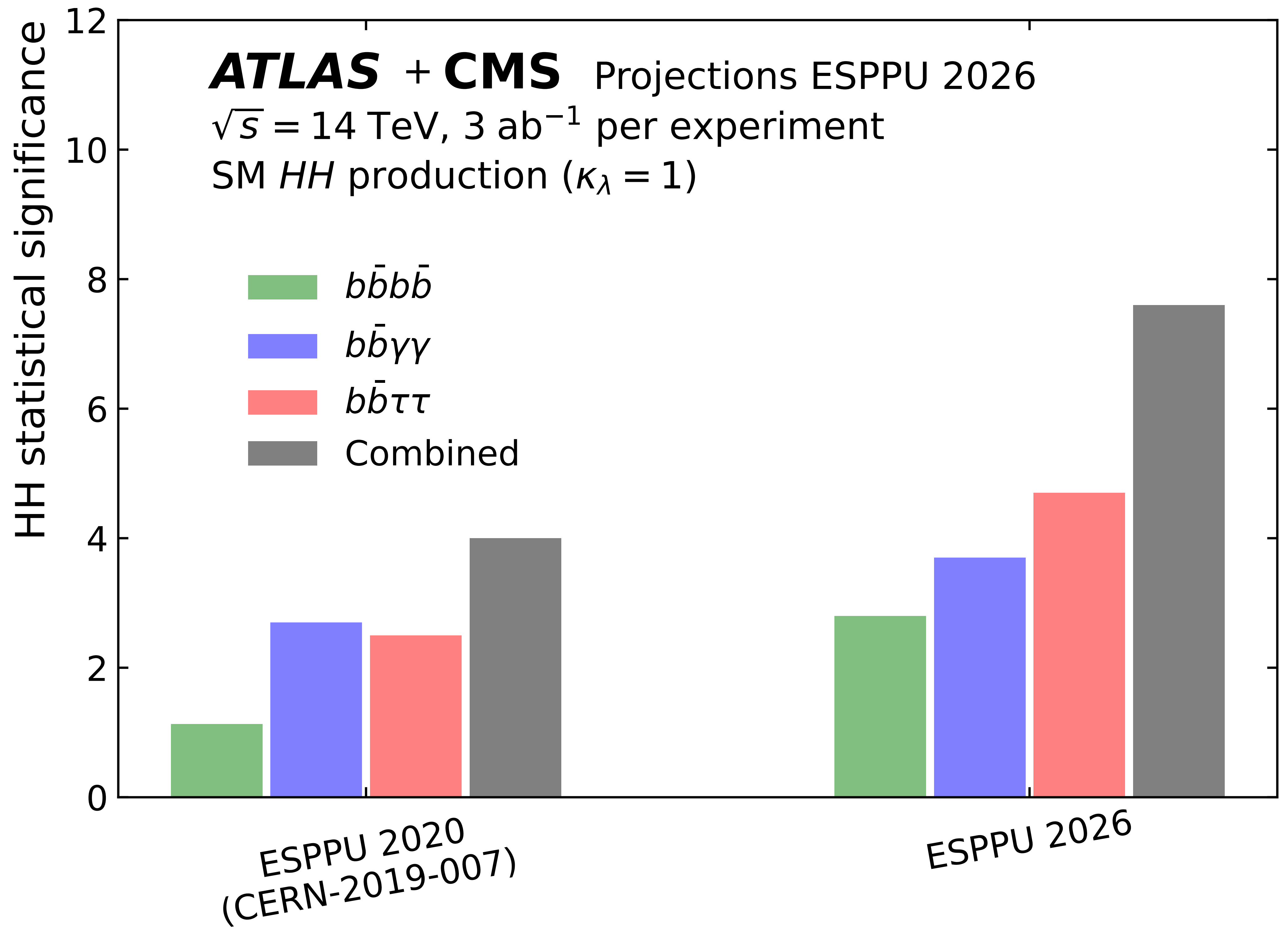


CMS-HIG-25-002 ; ATL-PHYS-PUB-2025-018

Highlights of the HL-LHC physics projections by ATLAS and CMS

Input submitted to the European Strategy for Particle Physics Update 2026

- anticipates discovery of HH production
- expected precision on trilinear coupling

$$\kappa_\lambda \lesssim 30\%$$

if κ_λ different from SM value: **new physics**

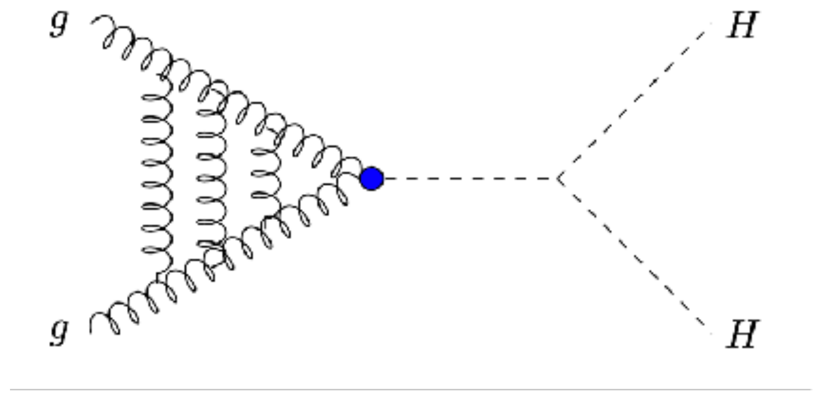
precise theory predictions very important !

both for SM and BSM

not covered in this talk: A3a, BSM-A3b

Higgs boson pair production: theory status

- highest perturbative order in heavy top limit:



N3LO(HTL)+N3LL   Ajjath, Shao '22   scale uncertainties $\mathcal{O}(1\%)$

N3LO(HTL):   Chen, Li, Shao, Wang '19 (HTL with NLO top mass effects)   scale uncertainties $\mathcal{O}(3\%)$

- top mass dependence everywhere except in virtual $\mathcal{O}(\alpha_s^3)$

NNLO(FTapprox)   Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli '18   scale uncertainties $\mathcal{O}(5\%)$

- NLO full m_t dependence   scale uncertainties $\mathcal{O}(15\%)$

Borowka, Greiner, GH, Jones, Kerner, Schlenk et al. '16

Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher '18

Davies, GH, Jones, Kerner, Mishima, Steinhauser, Wellmann '19

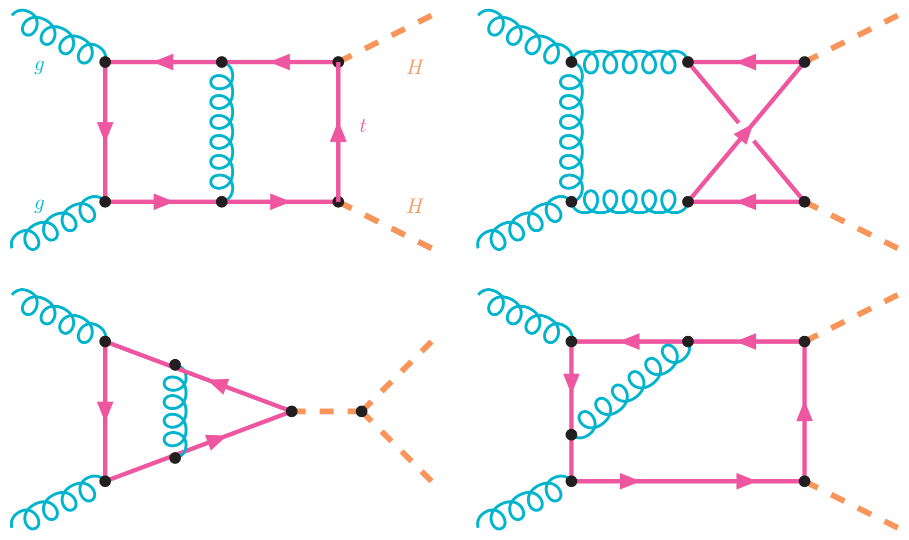


image: S. Jones

Higgs boson pair production: theory status

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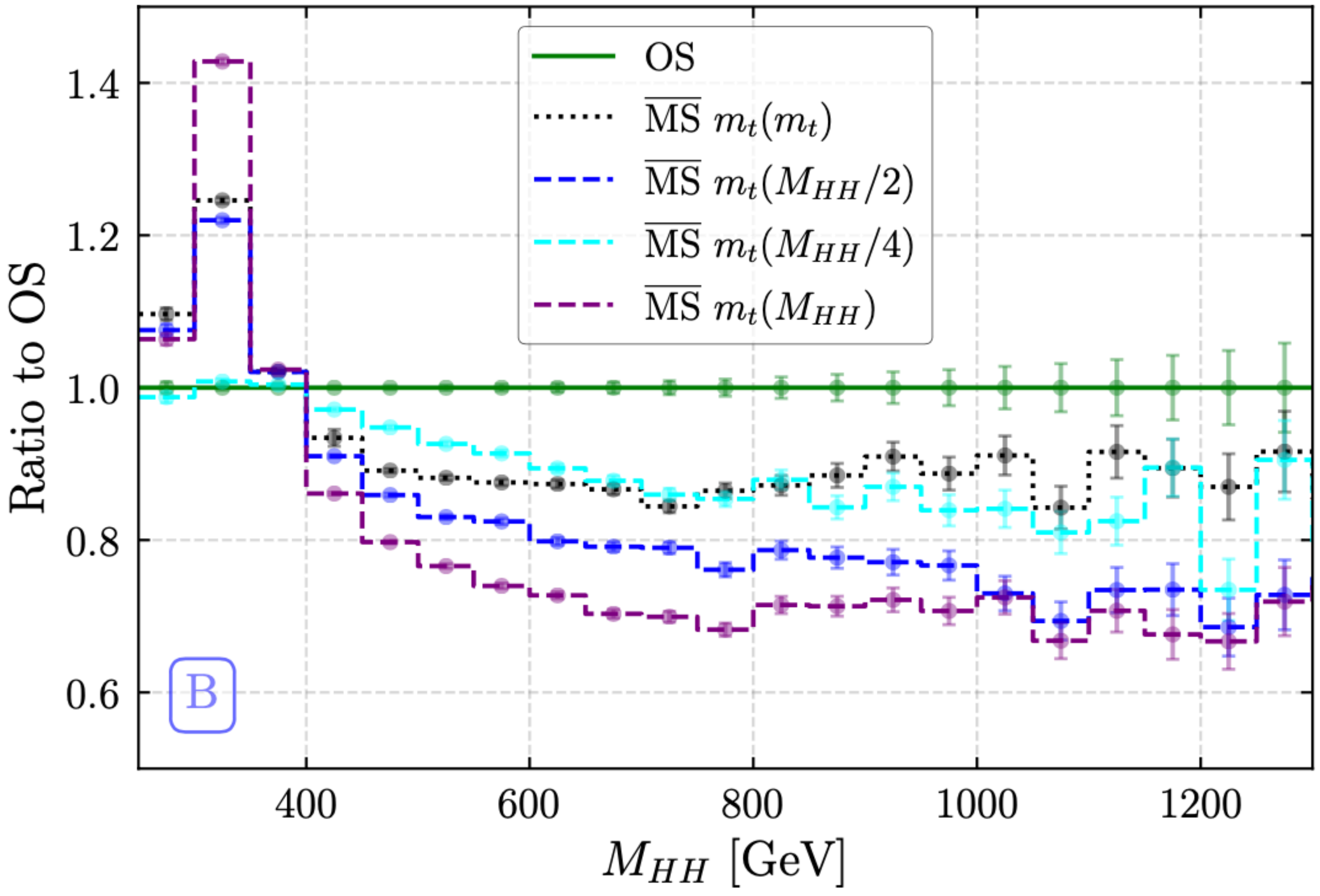
What about other uncertainties?

- top mass scheme uncertainties → next slide
- electroweak (EW) corrections → next-to-next slide
- uncertainties related to Higgs boson decay: large NLO corrections observed in $HH \to b\bar{b}\gamma\gamma$ tamed by parton shower
  Braun, Fontes, GH 2509.13304
- in combination with SMEFT: truncation uncertainties, running Wilson coefficients, which EFT?
- in combination with BSM models: resonant heavy Higgs decays, relation to Early Universe, Baryogenesis, …

all topics are addressed within the CRC !

top mass renormalisation scheme uncertainties



Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira '18, '20 ;
Bagnaschi, Degrassi, Gröber '23

top mass scheme uncertainty:
pole mass versus $\overline{\text{MS}}$ mass

currently largest uncertainty in Higgs boson pair production

recently:

reduction of uncertainty on virtual part of NLO amplitude to about 4-7% at large mHH thanks to resummation of leading power mass-logarithms in the high energy limit

Jaskiewicz, Jones, Szafron, Ulrich, 2501.00587

full NNLO expected to reduce this uncertainty substantially

Higgs boson pair production: towards NNLO QCD

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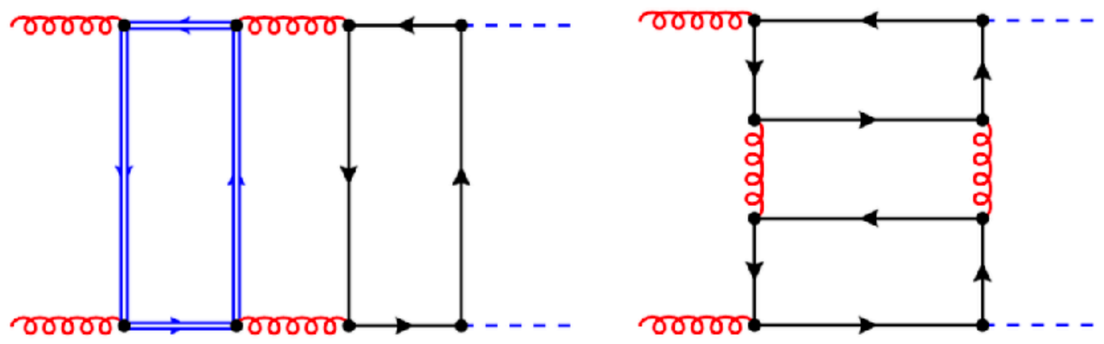
- complete light-fermion contribution of 3-loop virtual corrections

  Davies, Schönwald, Steinhauser   2307.04796



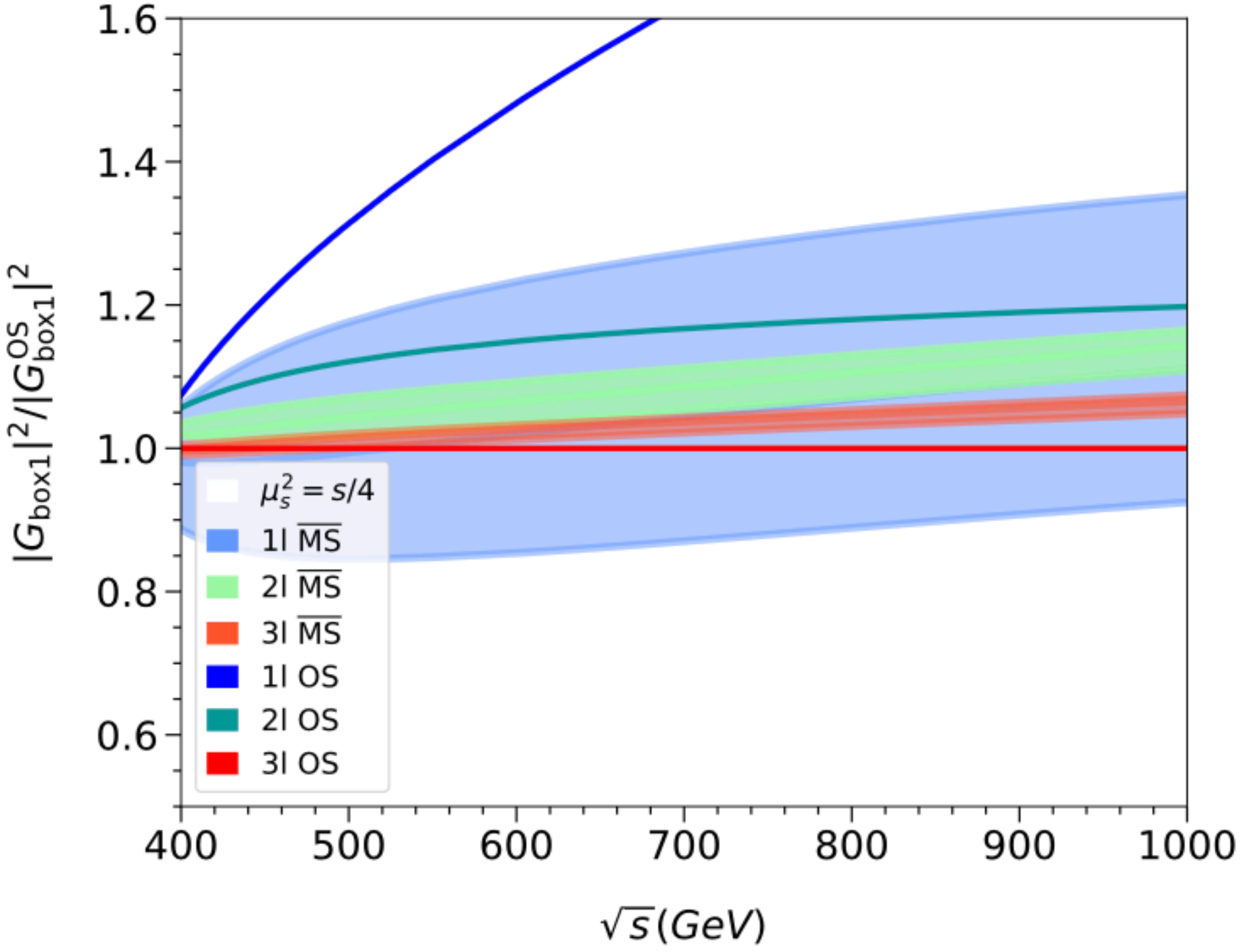
- reducible 3-loop corrections

  Davies, Schönwald, Steinhauser, Vitti   2405.20372

- large-Nc virtual corrections in the forward limit

  Davies, Schönwald, Steinhauser 2503.17449

  -> glimpse on **NNLO** analysis of the top quark mass renormalisation scheme dependence



NLO electroweak corrections to ggHH

full NLO EW: Bi, Huang, Huang, Ma, Yu ’23 → reduction of total cross section by 4%

NLO electroweak corrections to ggHH

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leading 2-loop Yukakwa corrections

Davies, Mishima, Schönwald, Steinhauser, Zhang ’22

complete EW corrections in the large-mt expansion

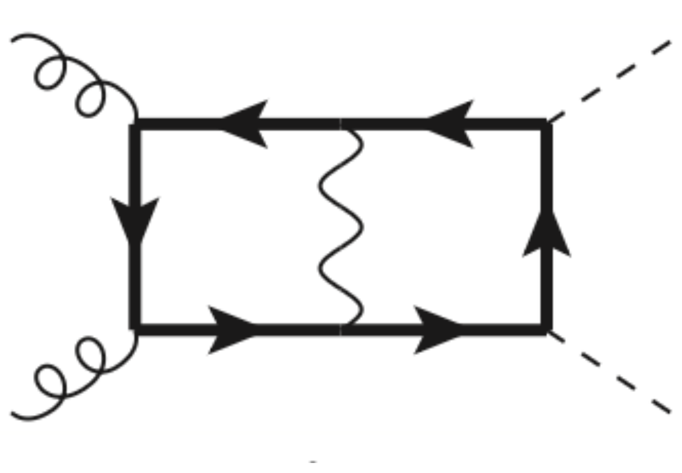
Davies, Schönwald, Steinhauser, Zhang ’23

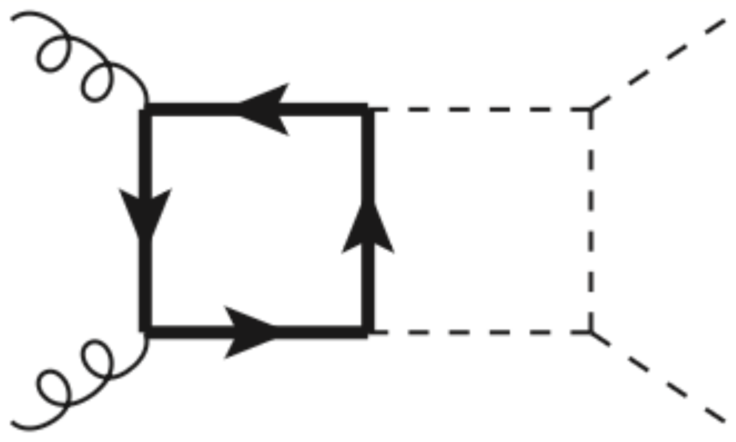
exact analytic expressions for 1PI contributions

Davies, Schönwald, Steinhauser, Zhang ’24

Yukawa and self-coupling contributions in high energy expansion

Davies, Schönwald, Steinhauser, Zhang ’25





Yukawa-type corrections in (partial) HTL

Mühlleitner, Schlenk, Spira ’22

full NLO EW corrections under construction

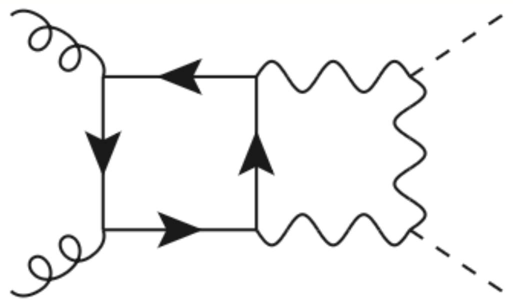
Bhattacharya, Campanario, Carlotti, Chang, Mazzitelli, Mühlleitner, Ronca, Spira

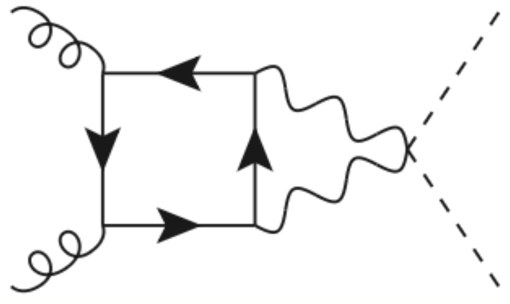
Yukawa- and Higgs self-coupling type corrections:

GH, Jones, Kerner, Stone, Vestner ‘24

2-loop light-quark EW corrections

Bonetti, Rendler, Torres-Bobadilla 2503.16620





figures: Marco Bonetti

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synergies:
comparison of preliminary results

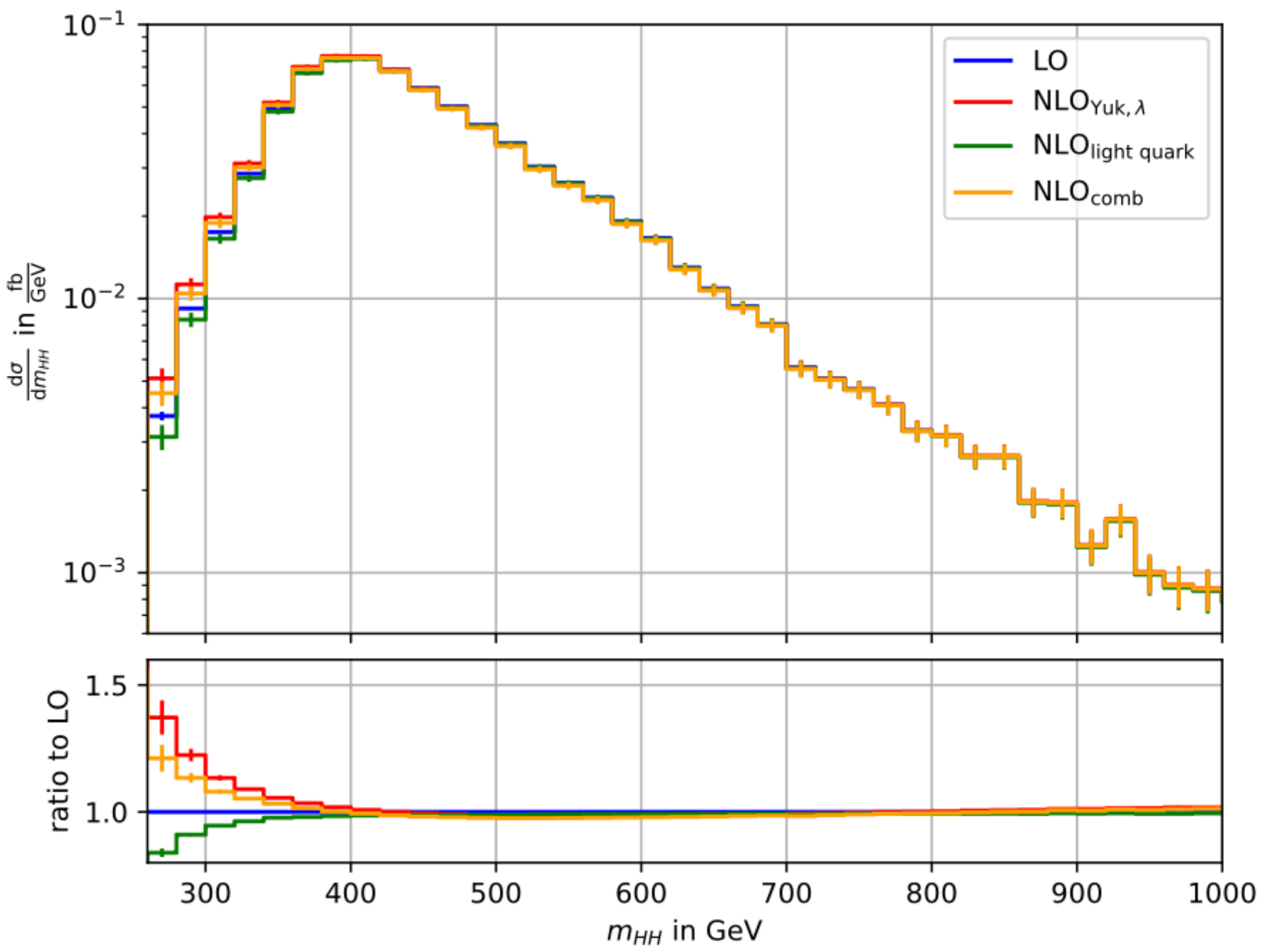
Yukawa- and Higgs self-coupling type corrections:
GH, Jones, Kerner, Stone, Vestner ‘24

2-loop light-quark EW corrections
Bonetti, Rendler, Torres-Bobadilla 2503.16620

figures: Marco Bonetti

Higgs boson pair production: towards NLO EW

light-quark and Yukawa $+\lambda$-corrections combined:

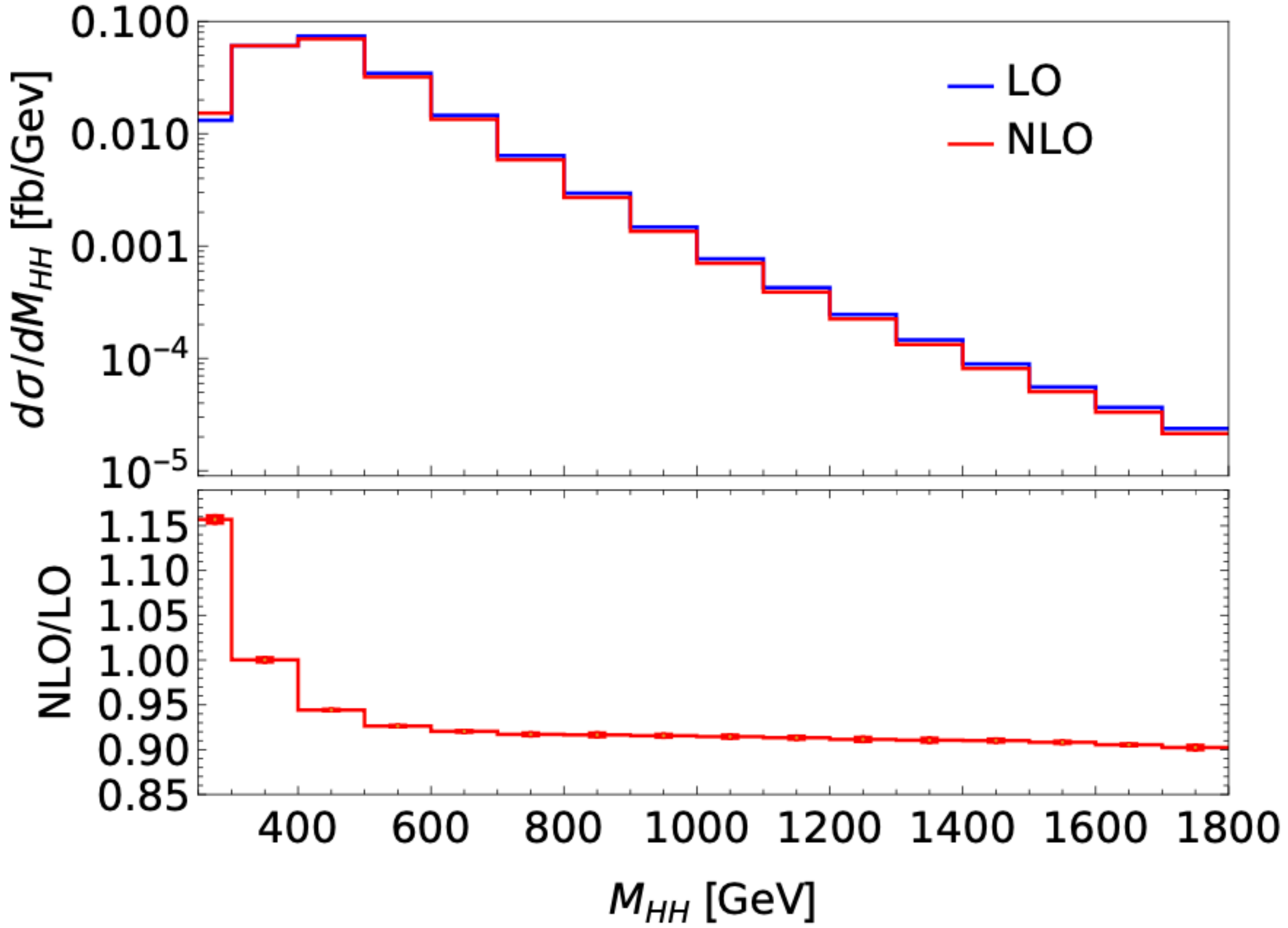


GH, Jones, Kerner, Stone, Vestner ‘24

Bonetti, Rendler, Torres-Bobadilla ’25

full EW corrections

(Bi, Huang, et al. 2023)



Public codes for HH production at NLO

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Powheg+GoSam + matching to parton showers in

https://gitlab.com/POWHEG-BOX/V2

HEFT: ggHH code GH, Jones, Kerner, Scyboz, 2006.16877

5 leading operators in HEFT, couplings $c_{hhh}, c_t, c_{tt}, c_{ggh}, c_{gghh}$

SMEFT: ggHH_SMEFT GH, J. Lang, L. Scyboz, 2204.13045

4 leading operators, different truncation options

+ 6 subleading operators (chromo, 4-top) GH, J. Lang, 2311.15004

+ running Wilson coefficients GH, J. Lang, 2409.19578

fast code for SM:

ggxy Joshua Davies, Kay Schoenwald, Matthias Steinhauser, Daniel Stremmer 2506.04323

https://gitlab.com/POWHEG-BOX/V2/User-Processes/ggxy_ggHH

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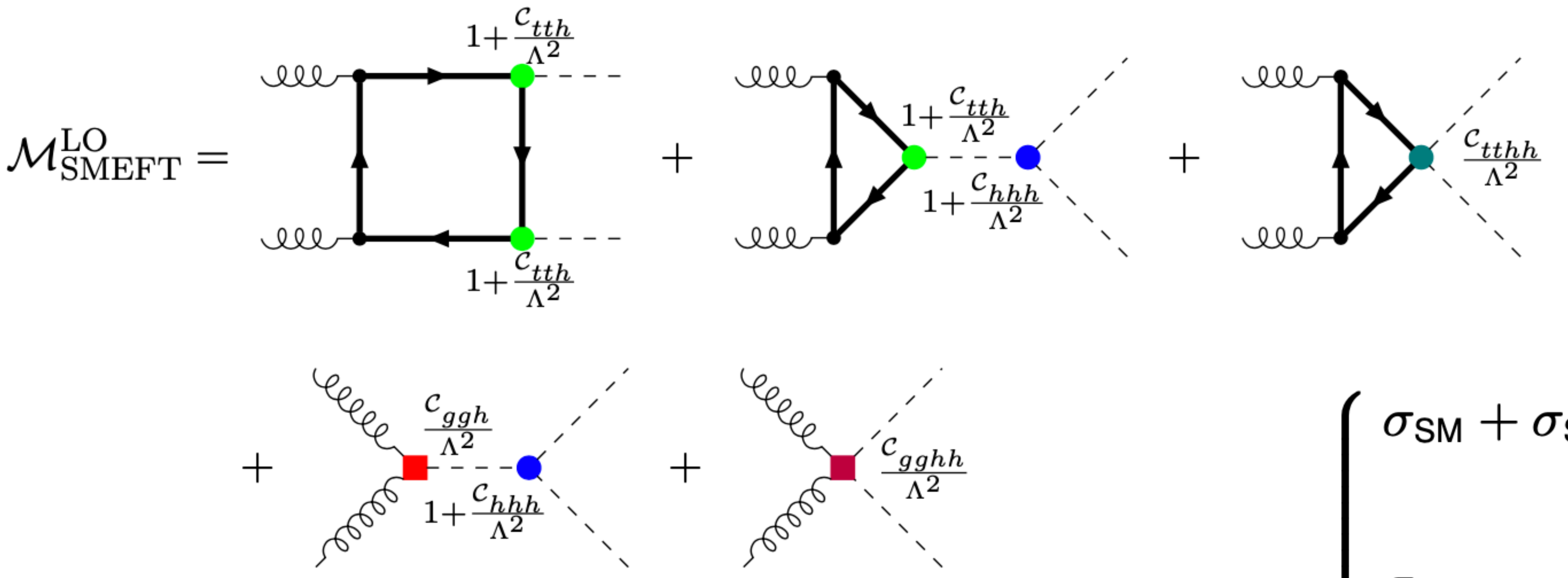
used by ATLAS and CMS

fast code for SM:

ggxy Joshua Davies, Kay Schoenwald, Matthias Steinhauser, Daniel Stremmer 2506.04323

https://gitlab.com/POWHEG-BOX/V2/User-Processes/ggxy_ggHH

SMEFT truncation



$$\boxed{\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{\mathrm{dim6}} + \mathcal{O}(\frac{1}{\Lambda^3})}$$

available in ggHH_SMEFT code:

options SMEFTtruncation 0,1,2,3

$$\sigma \simeq \begin{cases} \sigma_{\mathrm{SM}} + \sigma_{\mathrm{SM}\times\mathrm{dim6}} & \text{“linear”} \quad \text{(a)} \\ \sigma_{(\mathrm{SM}+\mathrm{dim6})\times(\mathrm{SM}+\mathrm{dim6})} & \text{“quadratic”} \quad \text{(b)} \\ \sigma_{(\mathrm{SM}+\mathrm{dim6})\times(\mathrm{SM}+\mathrm{dim6})} + \sigma_{\mathrm{SM}\times\mathrm{dim6}^2} & \text{(c)} \\ & \text{double insertions} \\ \sigma_{\left(\mathrm{SM}+\mathrm{dim6}+\mathrm{dim6}^2\right)\times\left(\mathrm{SM}+\mathrm{dim6}+\mathrm{dim6}^2\right)} & \text{(d)} \end{cases}$$

HEFT situation (up to treatment of α_s)

Running Wilson coefficients

new in the ggHH_SMEFT code [GH, Jannis Lang, 2409.19578]

$$\mu \frac{\partial \mathcal{C}_i}{\partial \mu} = \frac{\gamma_{\mathcal{C}_i}^{\mathcal{C}_j}}{16\pi^2} \mathcal{C}_j \quad , \quad \gamma_{\mathcal{C}_i}^{\mathcal{C}_j}$$: anomalous dimension

see also
Maltoni, Ventura, Vryonidou 2406.06670
Di Noi, Gröber 2312.11327, 2507.10295
Di Noi, Gröber, Mandal 2408.03252
Haisch 2503.06249
Aoude et al. 2212.05067
Battaglia, Grazzini, Spira, Wiesemann 2109.02987
Deutschmann, Duhr, Maltoni, Vryonidou 1708.00460
Maltoni, Vryonidou, Zhang 1607.05330
Jenkins, Manohar, Trott ‘13

new options for users:

WCscaledependence:

0: no running, $\mu_{\mathrm{EFT}} = \mu_R$

1: $\mu_{\mathrm{EFT}} = \mu_0 \cdot \mathtt{EFTscfact}$, μ_0 fixed by the user

2: $\mu_{\mathrm{EFT}} = m_{hh}/2 \cdot \mathtt{EFTscfact}$

EFTscfact: variation factor

inputscaleEFT: scale μ_0 where the running starts

Running Wilson coefficients: example C_{tG}

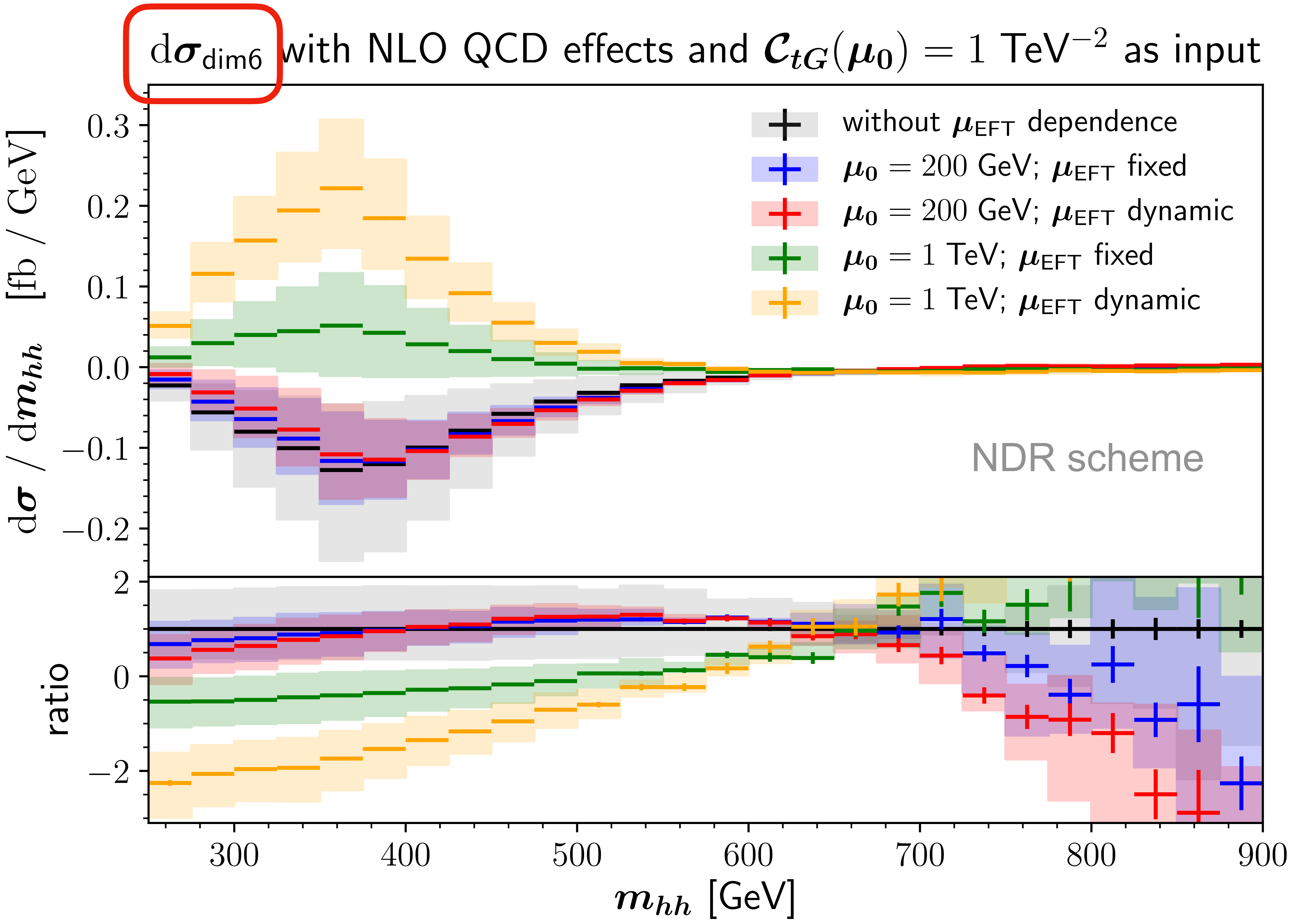


figure: Jannis Lang

$$\mathrm{d}\sigma = \underbrace{\underbrace{\mathrm{d}\sigma_{\mathrm{SM}} + \boxed{\mathrm{d}\sigma_{\mathrm{dim6}}}}_{(a)} + \mathrm{d}\sigma_{\mathrm{dim6}\times\mathrm{dim6}}}_{(b)}$$

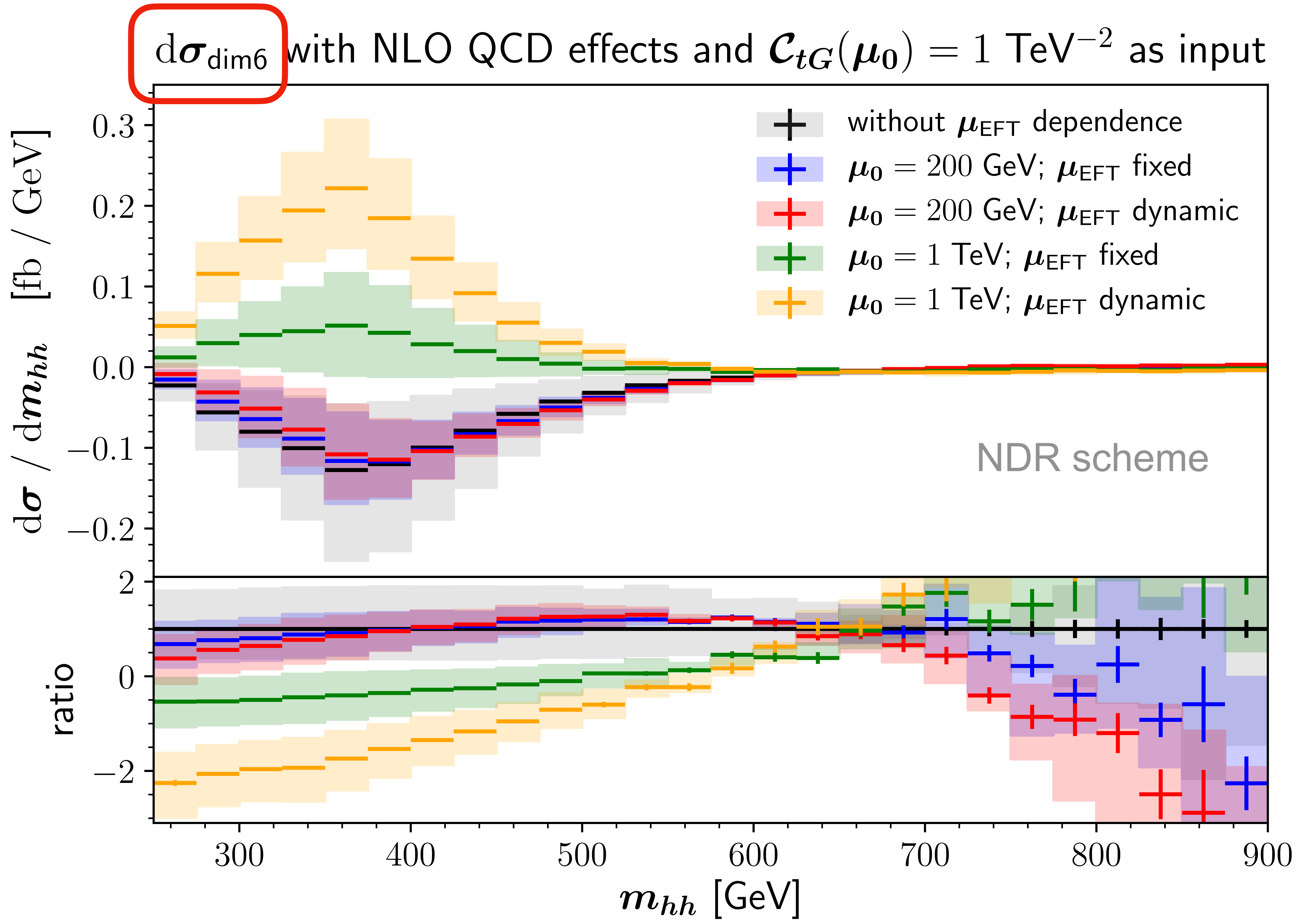
$$\mathrm{d}\sigma_{\mathrm{dim6}} := \sum_i \mathcal{C}_i(\mu_{\mathrm{EFT}})\mathrm{d}\sigma_i\left(\mu_R, \mu_F, \mu_{\mathrm{EFT}}\right)$$

dim6-interference contribution:

sign change for large μ_0

$\longrightarrow$ large dependence on choice of $\mu_0, \mu_{\mathrm{EFT}}$

Running Wilson coefficients: example C_{tG}



$$d\sigma = \underbrace{\underbrace{d\sigma_{\text{SM}} + \boxed{d\sigma_{\text{dim6}}}}_{(a)} + d\sigma_{\text{dim6}\times\text{dim6}}}_{(b)}$$

$$d\sigma_{\text{dim6}} := \sum_i \mathcal{C}_i(\mu_{\text{EFT}})\,d\sigma_i\,(\mu_R, \mu_F, \mu_{\text{EFT}})$$

dim6-interference contribution:

sign change for large μ_0

→ large dependence on choice of μ_0, μ_{EFT}

still a lot to explore combining precision Higgs physics and EFTs !

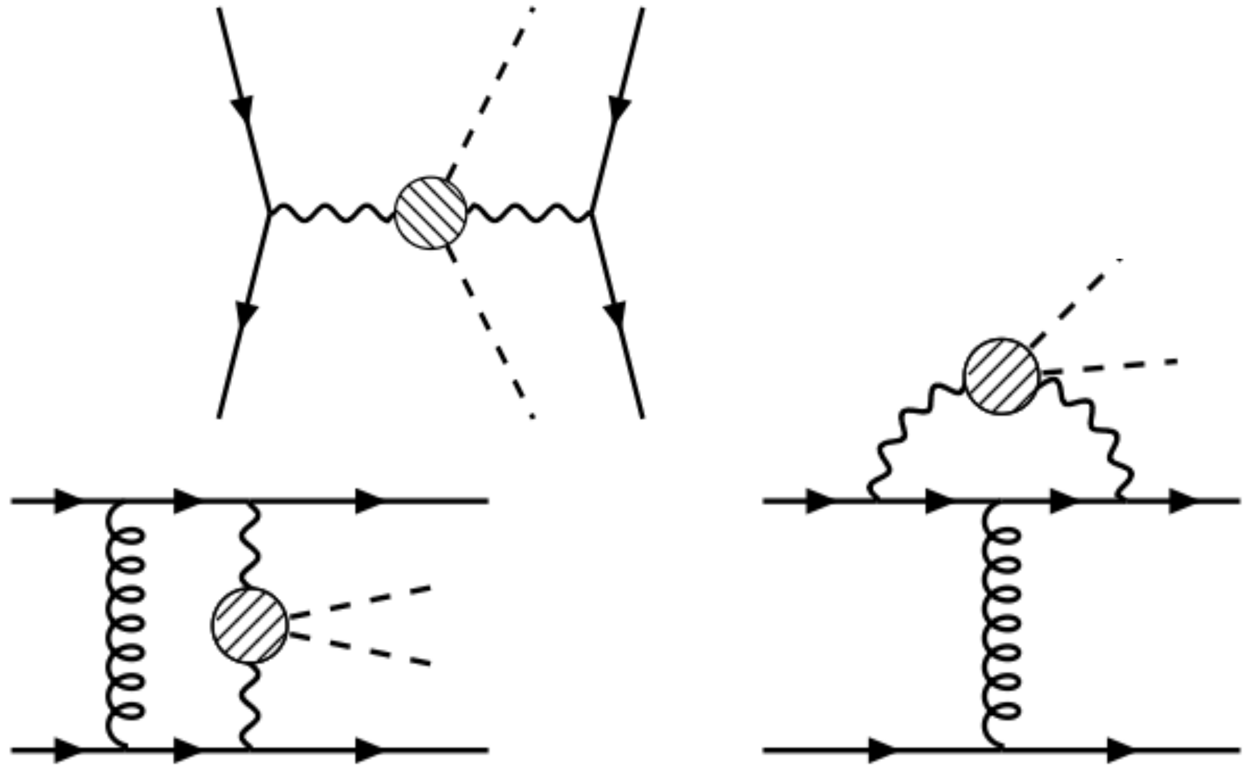
→ **new synergies through Anke Biekötter's group**

Higgs pair production in Vector Boson Fusion + HEFT

full NLO QCD corrections (GoSam+Whizard) + leading HEFT operators

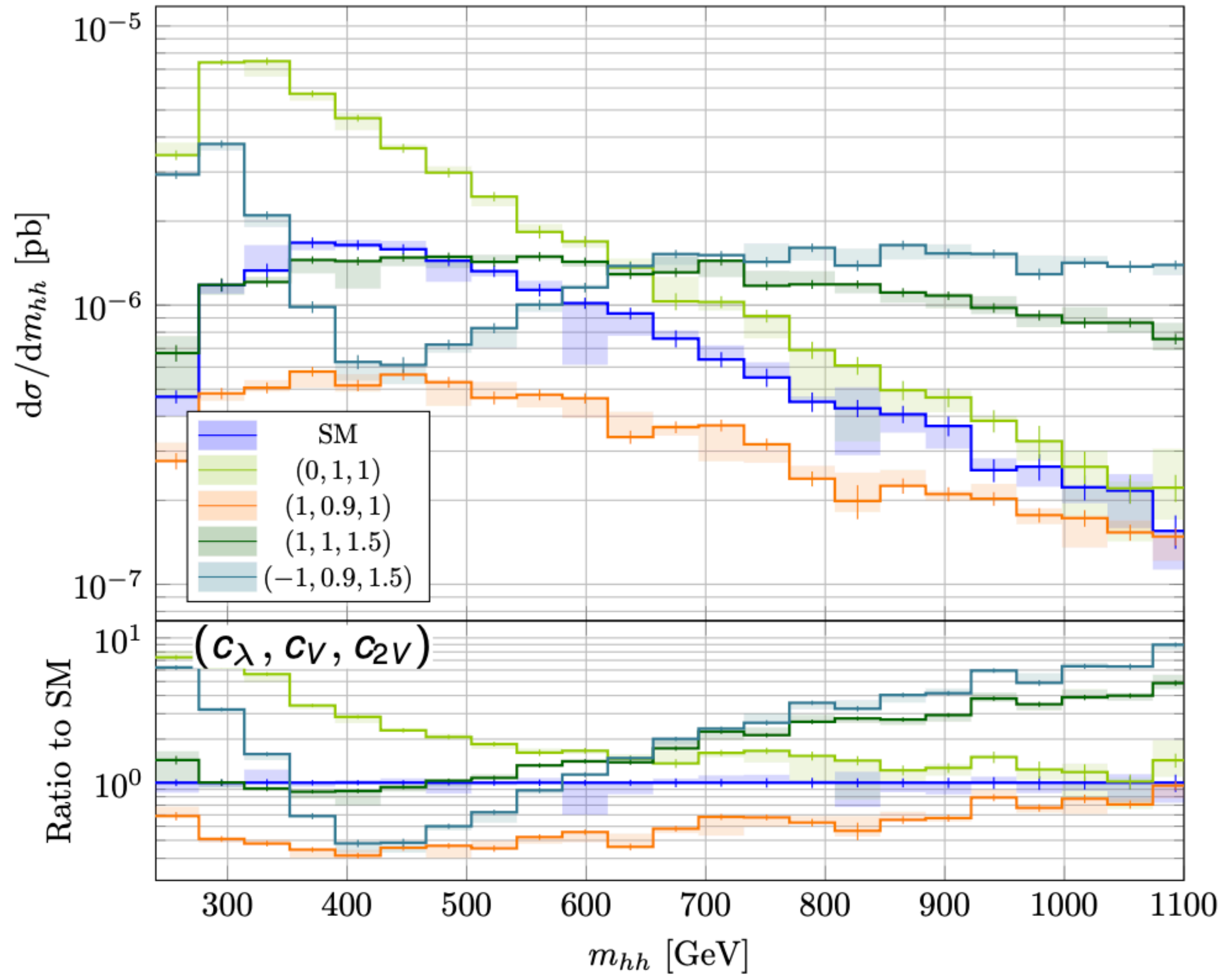
Jens Braun, Pia Bredt, GH, Marius Höfer 2502.09132

$$\mathcal{L}_{\text{eff}} \supset \left(2c_V \frac{h}{v} + c_{2V}\frac{h^2}{v^2}\right)\left(m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right) + c_\lambda \frac{m_h^2}{2v} h^3$$



examples of diagrams we included beyond VBF approx.

- calculation **not** limited to structure function approximation
- constraints on trilinear Higgs coupling complementary to gluon fusion
- access to HHV and HHVV couplings
- EFT operators can lead to pronounced shape changes



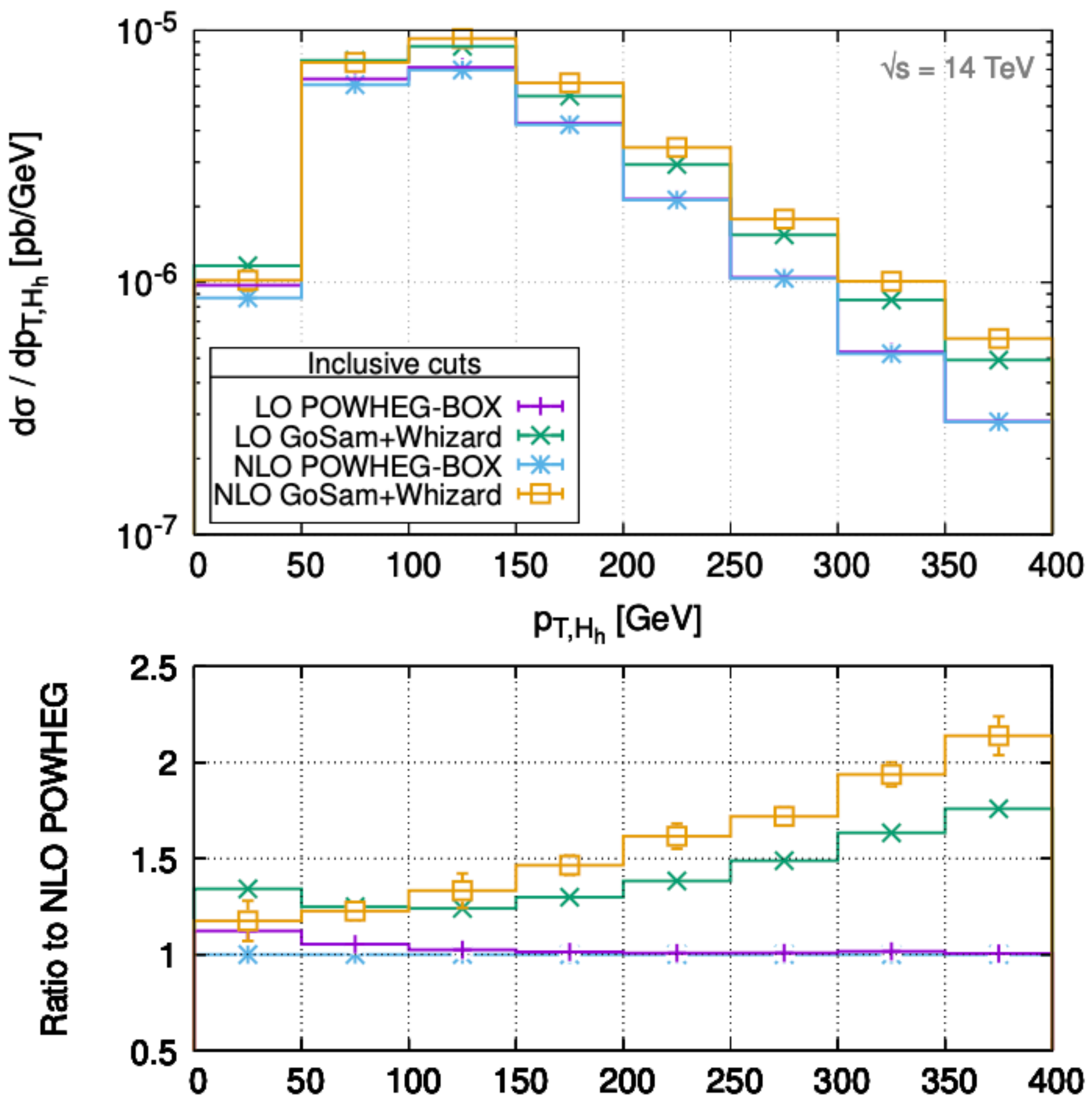
Higgs boson pair production in Vector Boson Fusion + HEFT

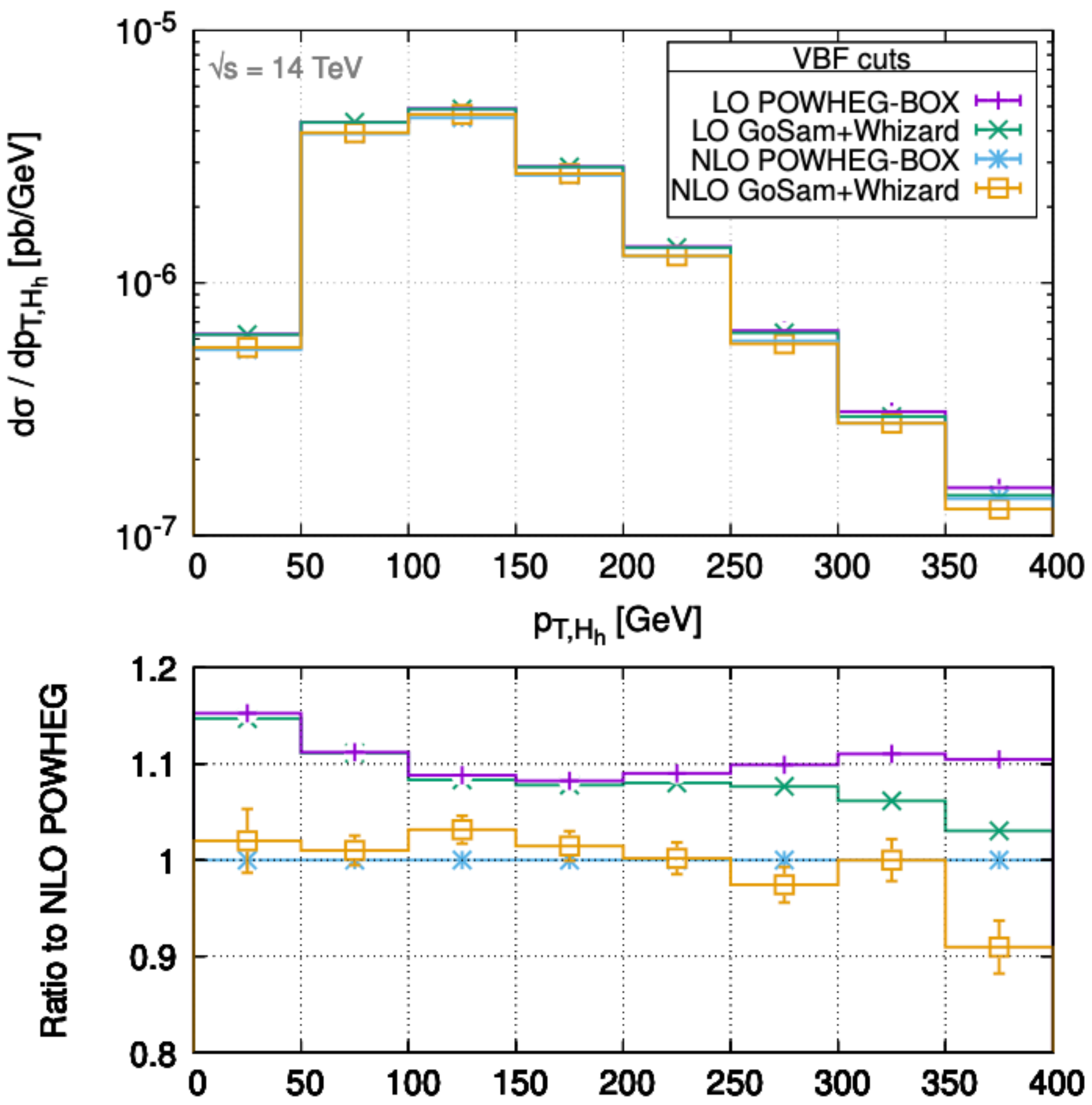
Karlsruhe Institute of Technology

contribution to Report 5 Braun, Bredt, GH, Höfer, Jäger, Karlberg, Reinhardt

detailed comparison to the VBF approximation of Jäger et al. (Powheg)

left:
inclusive setup





right:
VBF cuts

$$m_{jj}^{\text{tag}} > 600\ \text{GeV}\,,$$

$$\Delta\eta_{jj}^{\text{tag}} = |\eta_{j_1}^{\text{tag}} - \eta_{j_2}^{\text{tag}}| > 4.5\,.$$

large impact of
non-VBF type diagrams

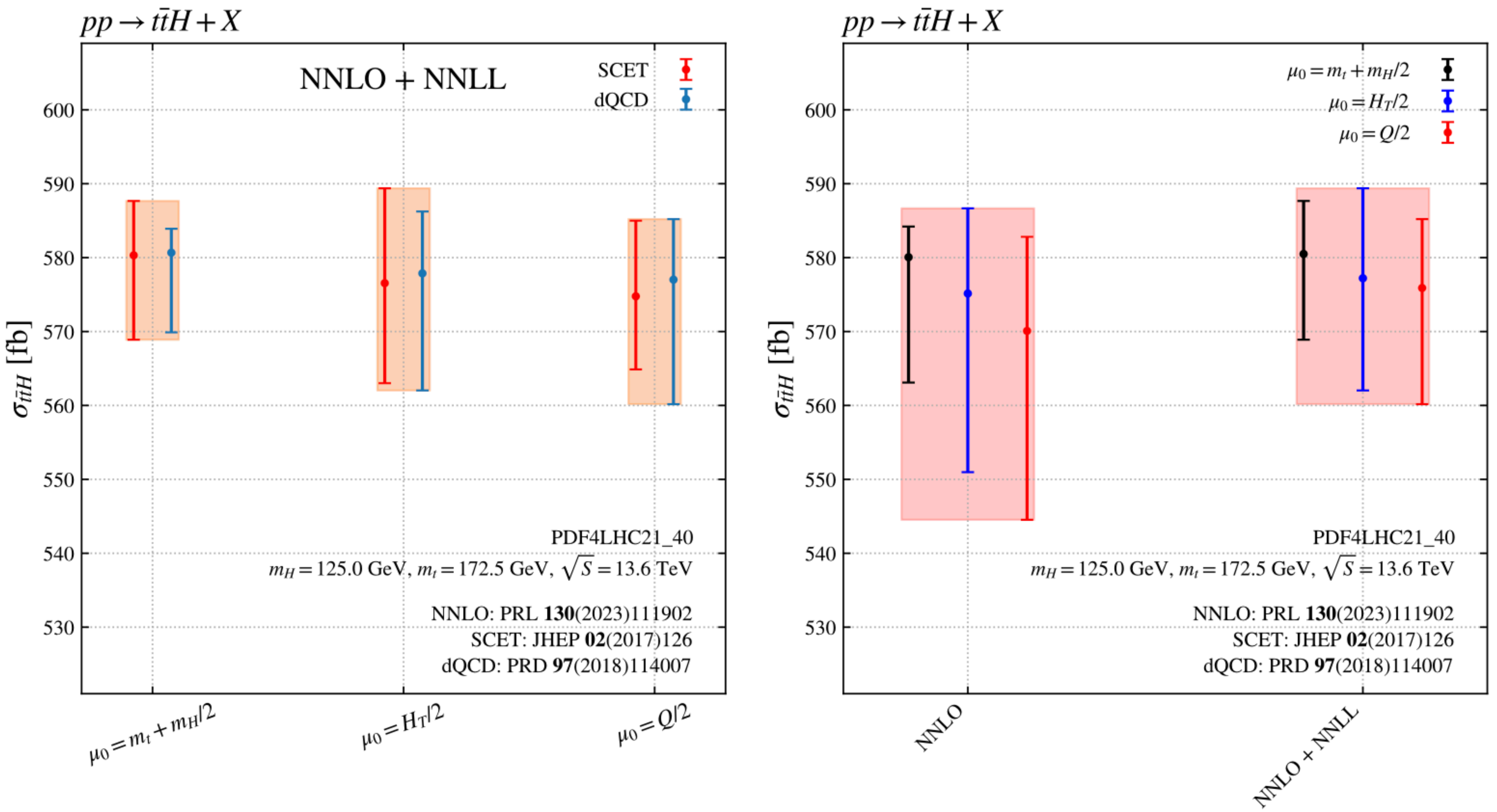
ttH production

State-of-the-art cross sections for $t\bar{t}H$: NNLO predictions matched with NNLL resummation and EW corrections

Roger Balsach[1] Alessandro Broggio[2] Simone Devoto[3] Andrea Ferroglia[4] Rikkert Frederix[5] Massimiliano Grazzini[6] Stefan Kallweit[6] Anna Kulesza[1] Javier Mazzitelli[7] Leszek Motyka[8] Davide Pagani[9] Benjamin D. Pecjak[10] Chiara Savoini[11] Tomasz Stebel[8] Malgorzata Worek[12] Marco Zaro[13]

https://arxiv.org/abs/2503.15043

contribution to CERN Report 5



ttH NLO QCD + SMEFT: (B2c)

in progress …

One-loop calculations in Effective Field Theories with GoSam-3.0 2507.23549

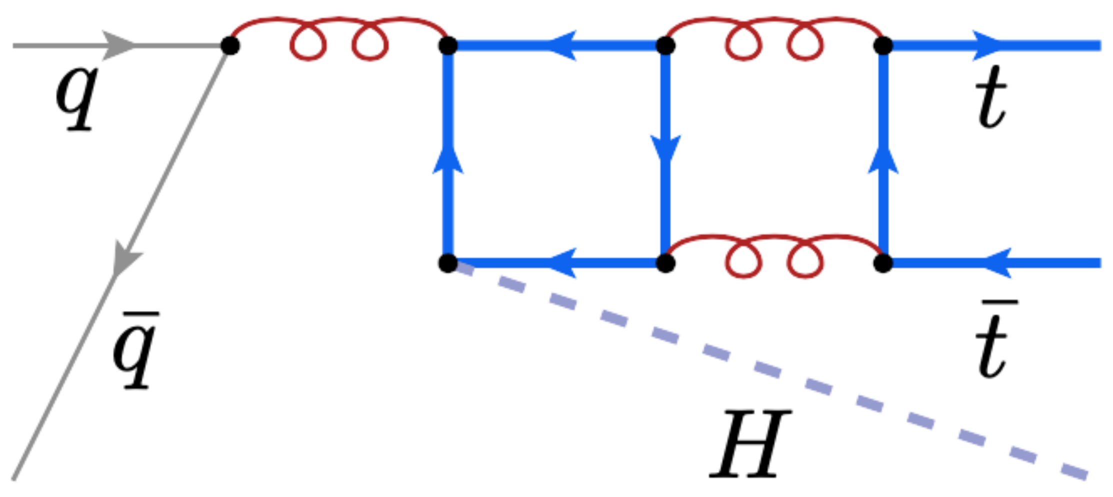
Jens Braun, Benjamin Campillo, GH, Marius Höfer, Stephen P. Jones, Matthias Kerner, Jannis Lang, Vitaly Magerya

PhD Thesis of Jonathan Hermann (RWTH) *Signal and background modeling in BSM studies in the top-quark sector at the LHC*

Master Thesis of Marijn van Geest (KIT) *Anomalous Couplings within Standard Model Effective Field Theory in ttH Production at NLO QCD*

2-loop pentagon amplitudes

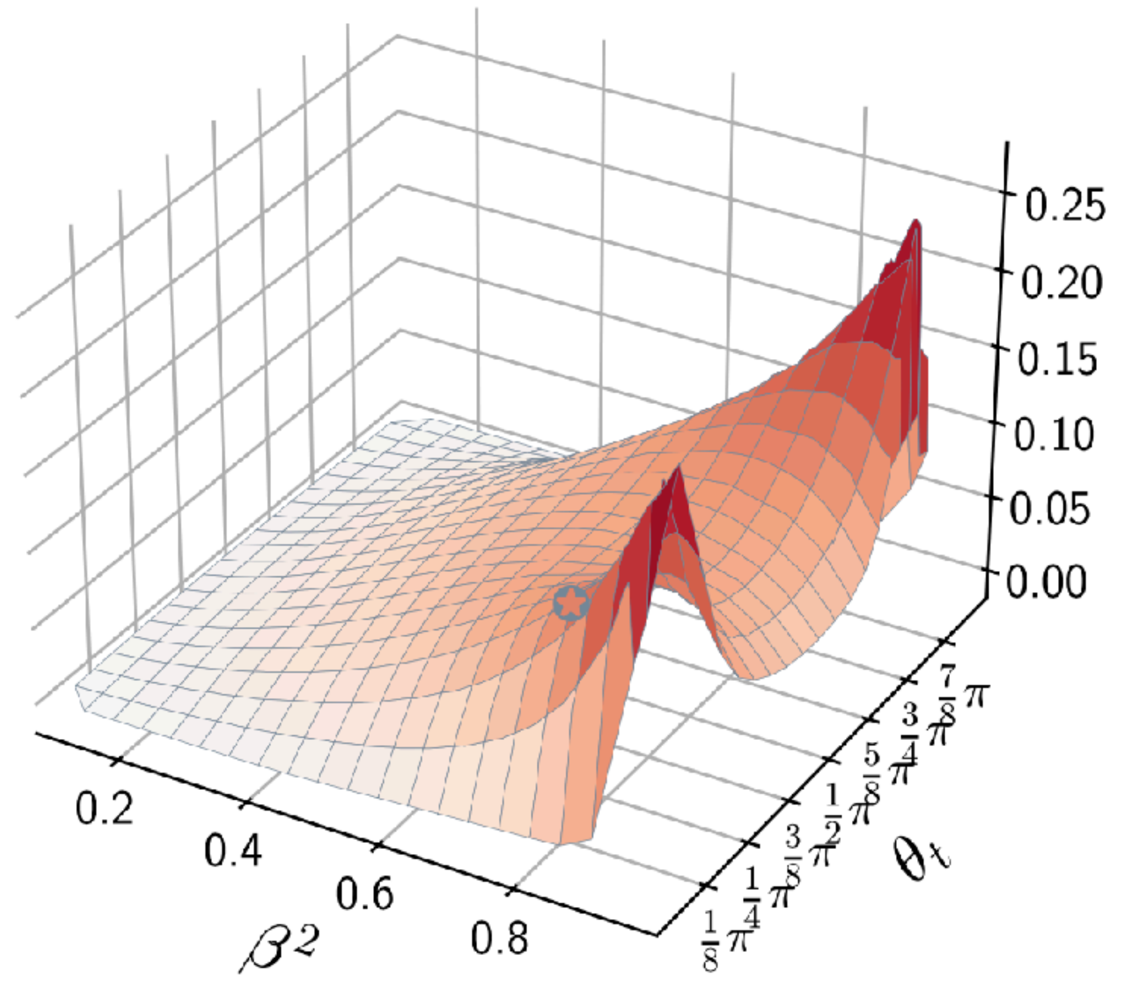
2-loop 5-point amplitudes: 5 kinematic scales, for ttH in addition 2 masses



ttH @2-loops partial results:

- t -> H fragmentation functions   Brancaccio, Czakon, Generet, Krämer, Mück, 2106.06516
- infrared pole coefficients   Chen, Ma, Wang, Yang, Ye, 2202.02913
- leading colour contributions to amplitudes with light-quark loops

  Febres Cordero, Figueiredo, Kraus, Page, Reina, 2312.08131
- 1-loop to order eps^2   Buccioni, Kreer, Liu, Tancredi, 2312.10013
- high-energy limit, numerically   Wang, Xia, Yang, Ye, 2402.00431

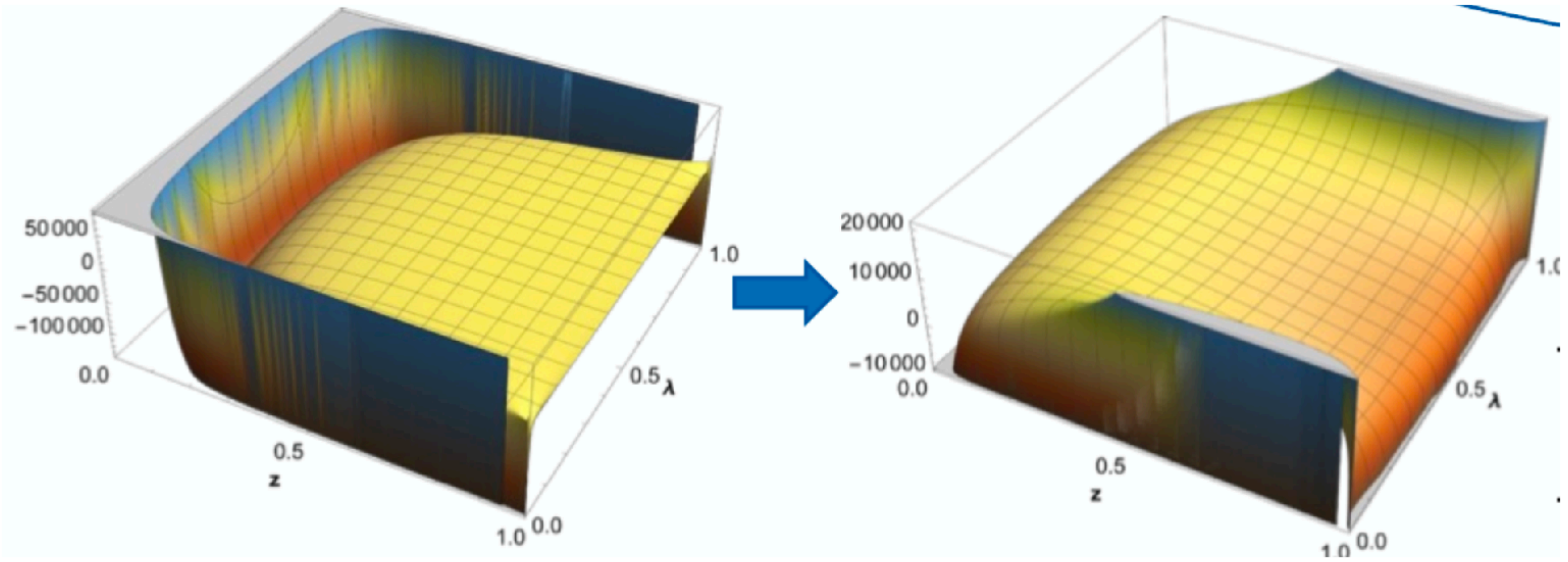


- Nf-part in quark channel, numerically

  Agarwal, GH, Jones, Kerner, Klein, Lang, Magerya, Olsson, 2402.03301 → research on amplitude interpolation

Multi-scale multi-loop amplitudes

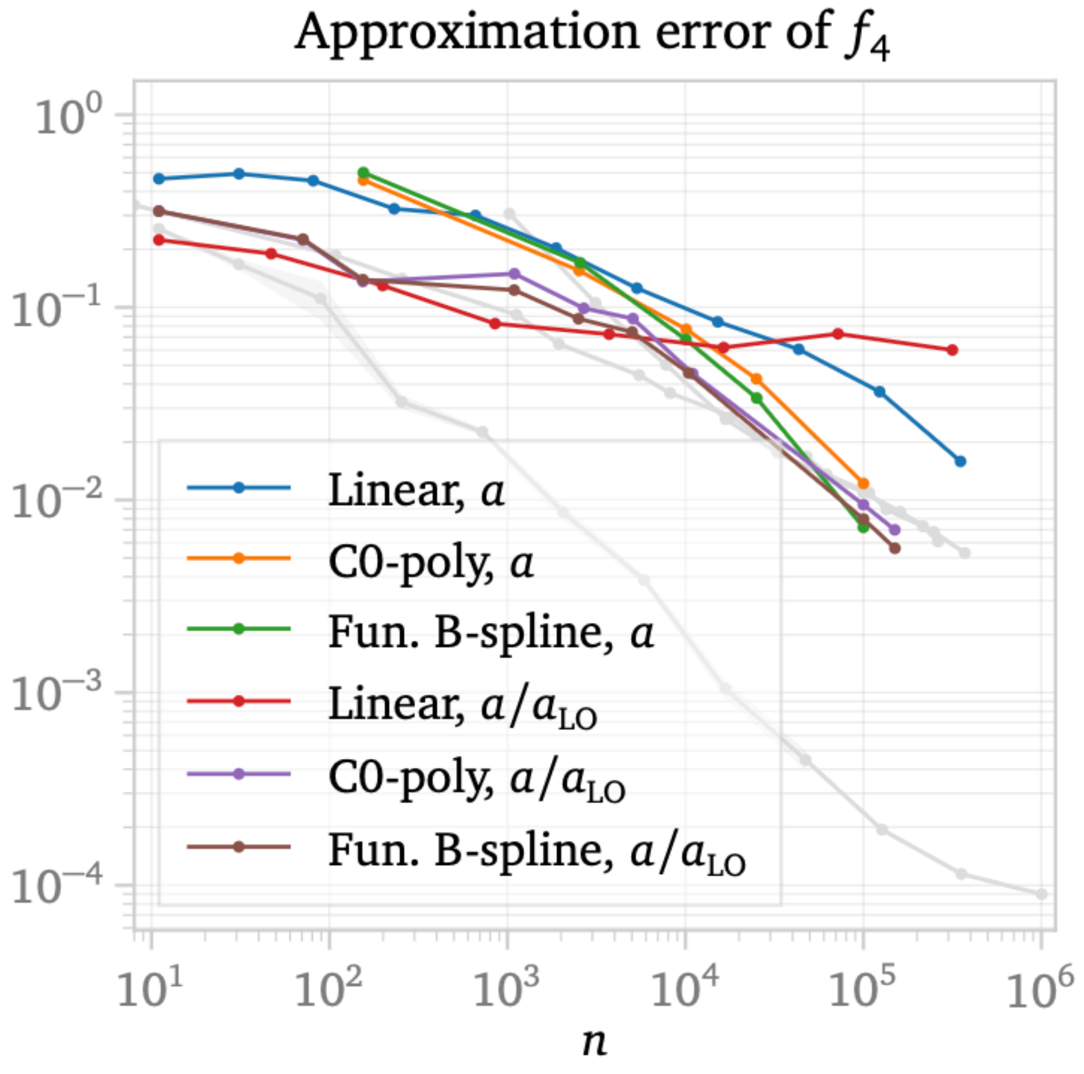
potential synergies: grid interpolation is done in Aachen, Karlsruhe and Heidelberg

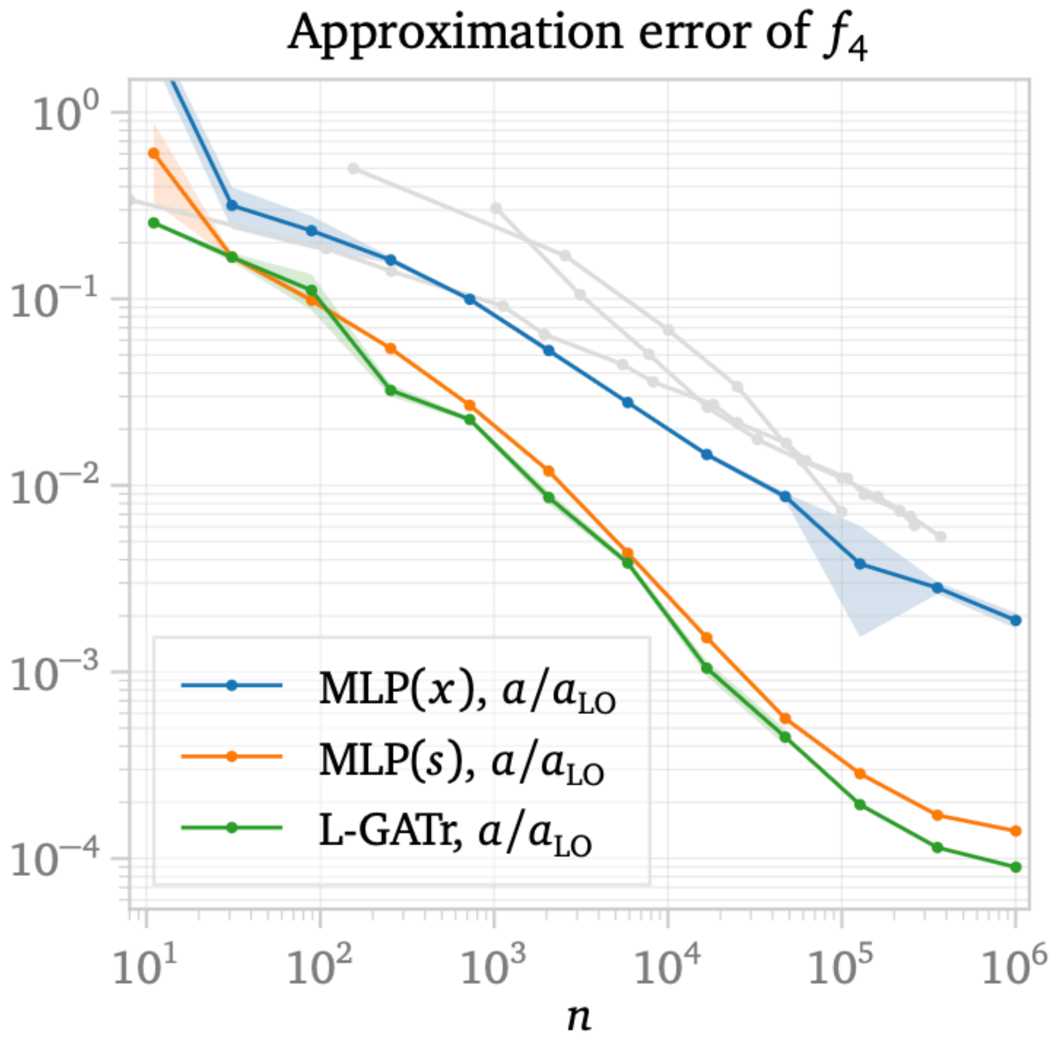


- Interpolate to any phace space point with cubic splines
- Add back subracted terms unsing analytical expressions

Czakon, Harlander, Klappert, Niggetiedt ‘21

Czakon, Eschment, Niggtiedt, Poncelet, Schellenberger ’23, ‘24





Breso, GH, Margerya, Olsson 2412.09534

test function f4: $gg \to t\bar{t}H$ at 1-loop

machine learning performs better than Chebychev polynomials, splines, sparse grids, …

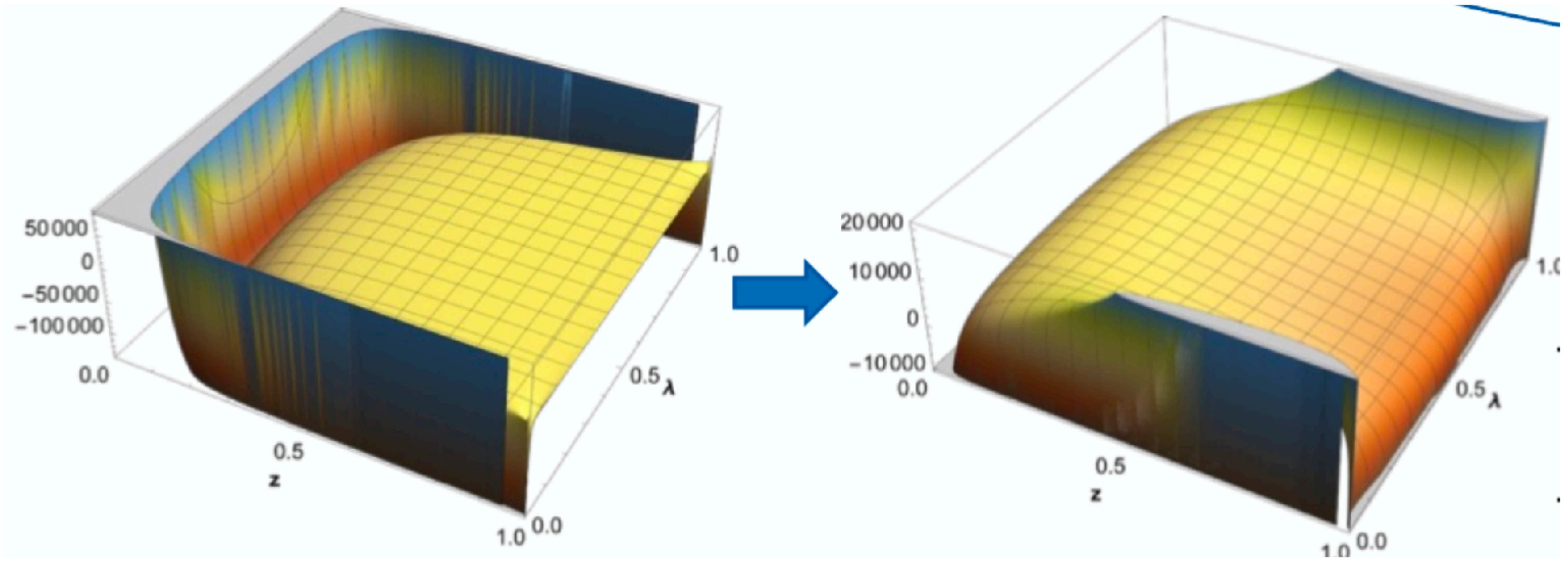
ongoing: learning amplitudes with uncertainties

Bahl, Braun, GH, Plehn, Revelli

Multi-scale multi-loop amplitudes

Karlsruhe Institute of Technology

potential synergies: grid interpolation is done in Aachen, Karlsruhe and Heidelberg



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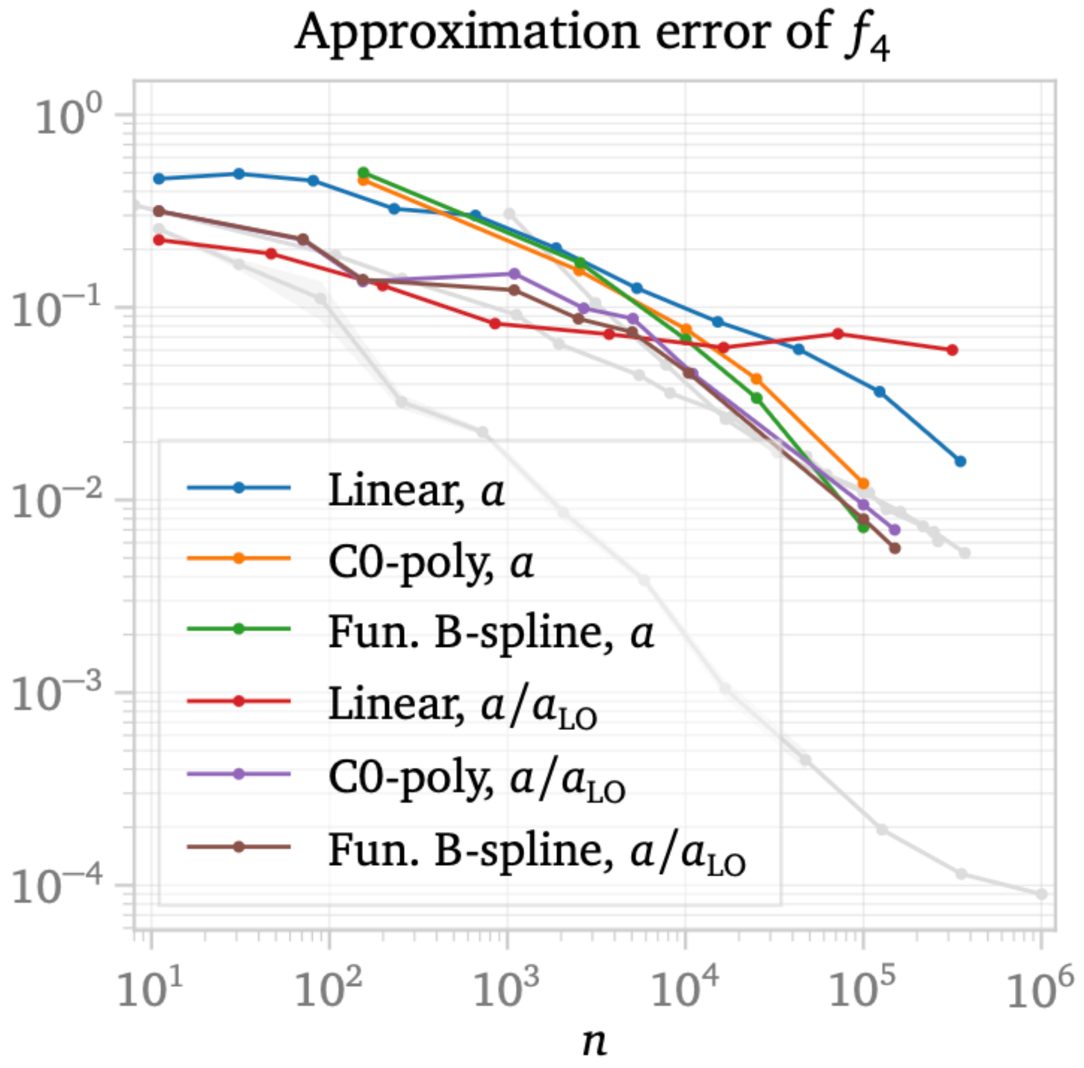

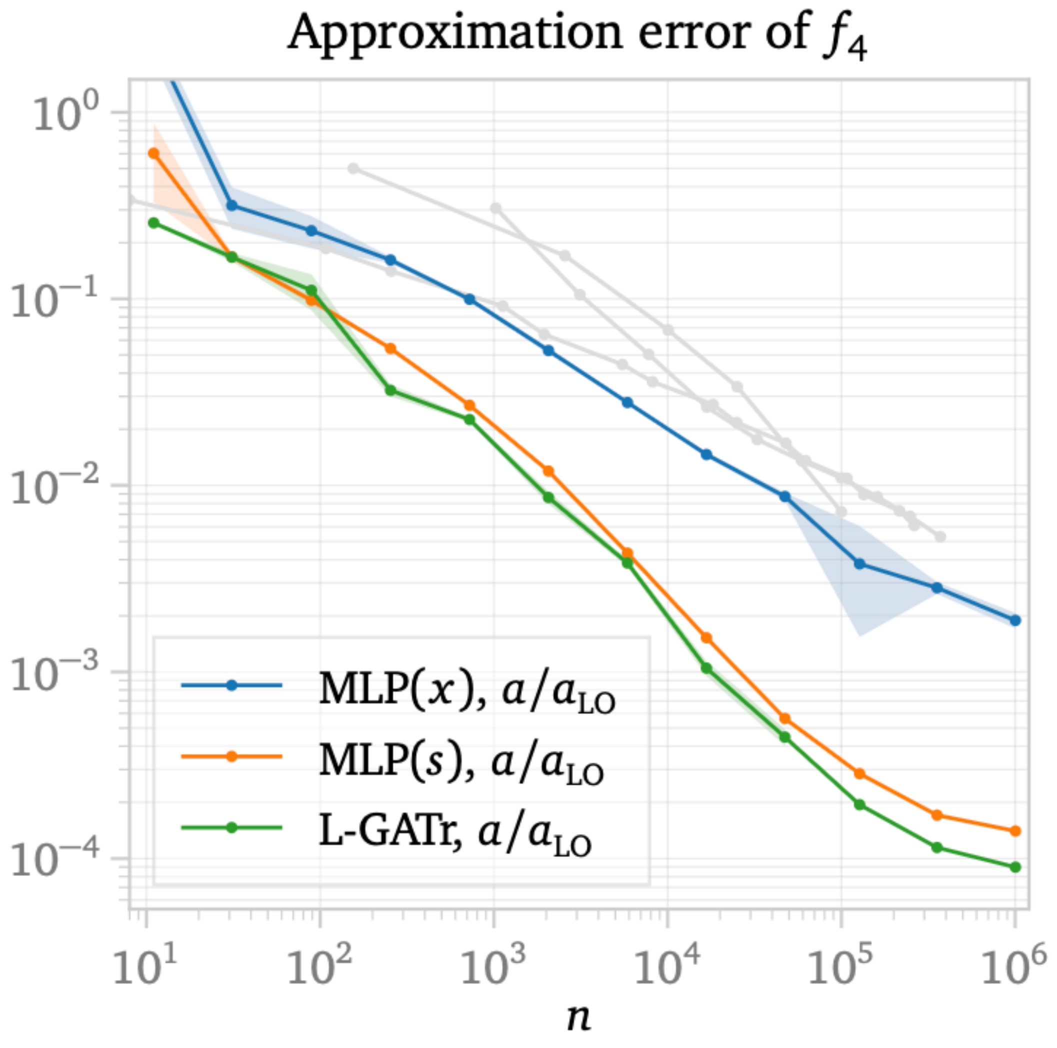

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ongoing: learning amplitudes with uncertainties

Bahl, Braun, GH, Plehn, Revelli

to be continued with more weight in FP3

Synergies

Hbb vertex at four loops and hard matching coefficients in SCET for various currents

#1

Amlan Chakraborty (Michigan State U. and IMSc, Chennai), Tobias Huber (Siegen U.), Roman N. Lee (Novosibirsk, IYF), Andreas von Manteuffel (Michigan State U.), Robert M. Schabinger (Michigan State U.) et al. (Apr 5, 2022) M. Steinhauser

Published in: *Phys.Rev.D* 106 (2022) 7, 074009 • e-Print: 2204.02422 [hep-ph]

ZH production in gluon fusion at NLO in QCD

Long Chen (RWTH Aachen U. and Shandong U.), Joshua Davies (Sussex U.), Gudrun Heinrich (KIT, Karlsruhe), Stephen P. Jones (Durham U., IPPP), Matthias Kerner (KIT, Karlsruhe and KIT, Karlsruhe, IKP) et al. (Apr 11, 2022) M. Steinhauser

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Two-loop amplitudes for $t\bar{t}H$ production: the quark-initiated N_f-part

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Published in: *JHEP* 05 (2024) 013, *JHEP* 06 (2024) 142 (erratum) • e-Print: 2402.03301 [hep-ph]

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ftint: Calculating gradient-flow integrals with pySecDec

Robert V. Harlander (RWTH Aachen U.), Theodoros Nellopoulos (RWTH Aachen U.), Anton Olsson (KIT, Karlsruhe, TP), Marius Wesle (Tubingen U., IAAT) (Jul 23, 2024)

Published in: *Comput.Phys.Commun.* 306 (2025) 109384 • e-Print: 2407.16529 [hep-ph]

Interpolating amplitudes

Víctor Bresó (U. Heidelberg, ITP), Gudrun Heinrich (KIT, Karlsruhe, TP), Vitaly Magerya (CERN), Anton Olsson (KIT, Karlsruhe, TP) (Dec 12, 2024)

e-Print: 2412.09534 [hep-ph]

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Published in: *JHEP* 07 (2025) 209 • e-Print: 2502.09132 [hep-ph]

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KIT - Siegen

Summary

- The CRC did have an impact in precision Higgs physics: cutting edge calculations, phenomenology and tools for experimental analyses
- Some synergies within the CRC have been exploited, more to come
- What are the perspectives in this research area beyond 2026?
  - Run 3 data will be collected until mid-2026 and will be analysed until 2030 (at least)
  - HL-LHC will start in 2030 and deliver data with unprecedented precision, may discover BSM if trilinear Higgs coupling is not SM-like
  - A future e+e- collider will require even higher precision, in particular EW corrections
  - -> precision calculations more important than ever
- (personal view) methods will change considerably in the next 10 years, let's be part of it!

Appendix

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Project-specific future plans

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- A1b: more precision Higgs physics combined with EFTs, also NLO EW-type operators, synergies with Anke Biekötter
- A2b: -> ML for amplitudes, applications to multi-scale 2-loop amplitudes (e.g. ttH), synergies with Anja Butter, Tilman Plehn
- B2c: continue, harvesting after tools development still to come