Collider Physics at the Precision Frontier:

The Higgs sector under scrutiny

Gudrun Heinrich
Institute for Theoretical Physics,
Karlsruhe Institute of Technology

Particle Physics Seminar
Universität Wien
April 5, 2022
Motivation

The Standard Model of Particle Physics is unlikely to be the end of the story

New physics at the Large Hadron Collider? Scientists are excited, but it’s too soon to be sure

LHCb (CERN)

How we found hints of new particles or forces of nature – and why it could change physics

muon anomalous magnetic moment measurement (Fermilab)
Motivation

New physics at the Large Hadron Collider? Scientists are excited, but it’s too soon to be sure
Current high energy frontier
Current high energy frontier

- at current energy frontier, no hints of new physics

Overview of CMS cross section results
Current high energy frontier

• at current energy frontier, no hints of new physics

however, this is a question of precision
The need for precise predictions

large spread in theory predictions based on different parton distribution functions
EFT parametrisation of new physics effects

CMS $t\bar{t}(l+jets)$, 13 TeV

top quark pairs at large invariant mass

best fit includes anomalous couplings

J. Ellis, Madigan, Mimasu, Sanz, You
2012.02779
Higgs couplings

Run I

\[ \lambda_1 \text{ or } (g/(2\nu))^{1/2} \]

\[ 19.7 \text{ fb}^{-1} (8 \text{ TeV}) + 5.1 \text{ fb}^{-1} (7 \text{ TeV}) \]

\[ 10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 1 \]

Particle mass (GeV)

CMS

- 68% CL
- 95% CL
- SM Higgs

(M, \varepsilon) fit
- 68% CL
- 95% CL

Gudrun Heinrich
Higgs couplings

Run I

\[ \lambda_1 \text{ or } (g/(2\pi)^2)^{1/2} \]

CMS

19.7 fb\(^{-1}\) (8 TeV) + 5.1 fb\(^{-1}\) (7 TeV)

Higgs coupling parameter

CMS Preliminary

\[ m_H = 125.38 \text{ GeV} \]

enormous experimental progress
High-Luminosity LHC

LHC / HL-LHC Plan

Run 1 | Run 2 | Run 3 | HL-LHC
---|---|---|---
LS1 | 7 TeV | 13 TeV | 13 - 14 TeV | 14 TeV
experiment beam pipes | nominal Lumi | 2 x nominal Lumi | LHC-LHC Installation | 5 to 7.5 x nominal Lumi
30 fb⁻¹ | 190 fb⁻¹ | 350 fb⁻¹

HL-LHC TECHNICAL EQUIPMENT:
- DESIGN STUDY
- PROTOTYPES
- CONSTRUCTION
- INSTALLATION & COMM.
- PHYSICS

HL-LHC CIVIL ENGINEERING:
- DEFINITION
- EXCAVATION
- BUILDINGS

rate \( R = L \cdot \sigma(s) \)
Low-luminosity LHC
Higgs production at HL-LHC: expected precision

ATLAS and CMS

HL-LHC Projection

σ_{ggH}
σ_{VBF}
σ_{WH}
σ_{ZH}
σ_{tth}

3000 fb^{-1}

HL-HE CERN Yellow Report, 1902.00134
Higgs production at HL-LHC: expected precision
Science (no) fiction?
Possible scenarios of future colliders

- **Japan**
  - 4 years: 20km tunnel, ILC: 250 GeV (2 ab⁻¹)
  - 9 years: 31km tunnel, 500 GeV (4 ab⁻¹)
  - 10 years: 40 km tunnel, 1 TeV (≥ 4.5 ab⁻¹)

- **China**
  - 8 years: 100km tunnel, CePC: 90/160/240 GeV (16/2.6/5.6 ab⁻¹)
  - 10 years: SppC aim similar to FCC-hh

- **CERN**
  - 8 years: 100km tunnel, FCC-ee: 90/160/250 GeV (150/10/5 ab⁻¹)
  - 15 years: FCC hh: 100 TeV (20-30 ab⁻¹)

- **Future collider plans**
  - 2020: HL-LHC: 13 TeV (3-4 ab⁻¹)
  - 2030: LHeC: 1.2 TeV (0.25-1 ab⁻¹)
  - 2040: CLIC: 380 GeV (1.5 ab⁻¹)
  - 2050: 1.5 TeV (2.5 ab⁻¹)
  - 2060: 3 TeV (5 ab⁻¹)

**Ursula Bassler,**
**European Strategy Meeting**
**Granada, May 2019**
Higgs couplings at future colliders

Higgs@FC WG
Kappa-3, 2019

Future colliders combined with HL-LHC
Uncertainty values on $\Delta S$ in %.
Limits on $Br(%)$ at 95% CL.
Higgs-boson self coupling

**Collider Physics at the Precision Frontier**

Gudrun Heinrich

*European Strategy Physics Briefing Book 1910.11775*
How to increase the precision of the predictions?

- parton shower
- hadronisation
- parton distribution functions (PDFs)
- underlying event
- fixed order calculations (production and decay)
  - reduce scale uncertainties $\mu_R, \mu_F$-dependence
  - reduce parametric uncertainties (couplings, masses)
  - resummation
  - reduce uncertainties in particular kinematic regions
Perturbation theory

\[
\sigma = \alpha_s^k \left( \sigma^{LO} + \alpha_s \sigma^{NLO} + \alpha_s^2 \sigma^{NNLO} + \ldots \right)
\]

\[
\alpha_s(M_Z) \approx 0.118 \quad \mathcal{O}(10\%) \quad \mathcal{O}(1\%)
\]

electroweak corrections: \( \alpha/\alpha_s \approx 0.1 \Rightarrow \) smaller, but beware of large terms like \( \log \left( \frac{M_Z^2}{\hat{s}} \right) \)

scale dependence: due to truncation of perturbative series \( \rightarrow \) measure of missing higher orders

\[
\sigma = \alpha_s^k (\mu_r) \left( \sigma^{LO}(\mu_f) + \alpha_s(\mu_r) \sigma^{NLO}(\mu_r, \mu_f) + \alpha_s^2(\mu_r) \sigma^{NNLO}(\mu_r, \mu_f) + \ldots \right)
\]

renormalisation scale \( \uparrow \) factorisation scale
Higher orders in perturbation theory

example pp to 2 jets: subprocess contributing at parton level: \( gg \to gg \)

LO

NLO virtual

NLO real

+ permutations (4 diagrams)

+ \ldots \ (60 loop diagrams)

+ \ldots \ (25 diagrams)
Higher orders in perturbation theory

example NNLO:

- double real
- 1-loop virtual
- 2-loop virtual

 implicit IR poles
explicit and implicit poles
explicit poles $1/\epsilon^{2L}$ ($D = 4 - 2\epsilon$)

bottlenecks:

- IR subtraction
- (multi)-loop integrals
Higher orders in perturbation theory

example NNLO:

- Double real
- 1-loop virtual
- 2-loop virtual

- Implicit IR poles (phase space integration)
- Explicit and implicit poles
- Explicit poles $1/\epsilon^{2L}$ ($D = 4 - 2\epsilon$)

bottlenecks:

- IR subtraction
- (multi)-loop integrals

current frontiers:

- NNLO automation
- N3LO coloured
- 2 loops, 4 legs with several mass scales
- 2 loops, 5 legs
- more than 2 loops
Highlights

- Colour singlet final state particles (H, Z, W)
- Going more and more differential

Bernhard Mistlberger, Amplitudes 2021

Slide inspired by G. Salam / L. Cieri...

- DY fiducial [Chen, Gehrmann, Glover et al. 22]
- DY-Rapidity [Chen, Gehrmann, Glover, et al.]
- Fiducial DY [Camarda, Cieri, Ferrera, 21]
- Fully differential Higgs -> 2Photons [Chen, BM, et al. 21]
- Fiducial Higgs and DY [Billis, Tackmann, et al., 21]
- Drell-Yan [Dulat, Duhr, BM, 20]
- ggF->HH [Chen, Li, Shao, Wang]
- bb->H [Dulat, Duhr, BM, 19]
- Higgs (Y approx.) [Dulat, BM, Pelloni, 18]
- HH (VBF) [Dreyer, Karlberg, 18]
- Higgs VBF [Dreyer, Karlberg, 16]
- Higgs Diff. Threshold App. [Dulat, BM, A. Pelloni, 17]
- Higgs, [BM, 18]
- Higgs Diff. qT [Cieri, Chen, Gehrmann, Glover, Huss, 18]
- Higgs Threshold Exp. [Anastasiou, Duhr, Dulat, Herzog, BM, 15]
- Higgs Jet Veto [Banfi, et al. 15]
Collider Physics at the Precision Frontier

Gudrun Heinrich

**ggH@N3LO fiducial**

*Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni, 2102.07607*

*Billis, Dehnadi, Ebert, Michel, Tackmann, 2102.08039*
Loop integrals: status 2-loop 5-point

**massless:**

\[ pp \rightarrow \gamma\gamma\gamma \]
Abreu, Page, Pascual, Sotnikov ’20 (leading color amplitudes)
Chawdry, Czakon, Mitov, Poncelet ’20 (leading color, full xs)
Kallweit, Sotnikov, Wiesemann ’20 (leading color, full xs)

\[ pp \rightarrow \gamma\gamma j \]
Chawdry, Czakon, Mitov, Poncelet ’21 (leading color, full xs)
Agarwal, Buccioni, Manteuffel, Tancredi ’21 (full color, amplitudes)

\[ gg \rightarrow \gamma\gamma g \]
Badger, Brønnum-Hansen, Chicherin, Gehrmann, Hartanto ’21 (amp)
Badger, Gehrmann, Marcoli, Moodie ’21 (full xs)

\[ pp \rightarrow j j j \]
Abreu, Febres Cordero, Ita, Page, Sotnikov ’21 (leading color amp)
Czakon, Mitov, Poncelet ’21 (full xs)
Loop integrals: status 2-loop 5-point

massless:

\[ pp \rightarrow \gamma\gamma\gamma \]
Abreu, Page, Pascual, Sotnikov ’20 (leading color amplitudes)
Chawdry, Czakon, Mitov, Poncelet ’20 (leading color, full xs)
Kallweit, Sotnikov, Wiesemann ’20 (leading color, full xs)

\[ pp \rightarrow \gamma\gamma j \]
Chawdry, Czakon, Mitov, Poncelet ’21 (leading color, full xs)
Agarwal, Buccioni, Manteuffel, Tancredi ’21 (full color, amplitudes)

\[ gg \rightarrow \gamma\gamma g \]
Badger, Brønnum-Hansen, Chicherin, Gehrmann, Hartanto ’21 (amp)
Badger, Gehrmann, Marcoli, Moodie ’21 (full xs)

\[ pp \rightarrow jjj \]
Abreu, Febres Cordero, Ita, Page, Sotnikov ’21 (leading color amp)
Czakon, Mitov, Poncelet ’21 (full xs)

important tool: pentagon functions in C++
Chicherin, Sotnikov ’21
3-jet production at NNLO

3-jet/2-jet ratio

Czakon, Mitov, Poncelet '21

$R_{3/2}$, Scale: $\mu_0 = \hat{H}_T$, LHC 13 TeV

$p_T(j_1)$ [GeV]

ratio to NLO

LO
NLO
NNLO
2-loop 5-point (one off-shell leg)

\[ p^2 \neq 0 \]

Abreu, Ita, Moriello, Page, Tschernow ’20 (planar)
Canko, Papadopoulos, Syrrakos ’21 (planar, analytic)

W + 4 partons

Badger, Brønnum-Hansen, Hartanto, Peraro ’19 (planar, num. unitarity)
Abreu, Febres Cordero, Ita, Klinkert, Page, Sotnikov ’21 (leading color)

\[ u\bar{d} \rightarrow W^+ b\bar{b} \]

Badger, Hartanto, Zoia ’21 (planar, analytic)

\[ pp \rightarrow b\bar{b}H \]

Badger, Hartanto, Krys, Zoia ’21 (leading colour)

non-planar:

Abreu, Ita, Page, Tschernov ’21
Liu, Ma ’21
**3-loop 4-point**

\[ pp \rightarrow \gamma \gamma \]  
Caola, Manteuffel, Tancredi '20

\[ q\bar{q} \rightarrow q\bar{q} \]  
Caola, Chakraborti, Gambuti, Manteuffel, Tancredi '21

**4-loop 3-point**

\[ H \rightarrow \gamma \gamma \]  
Davies, Herren '21 (large mt-expansion)

Form factors, e.g. \[ \gamma^* \rightarrow q\bar{q} \]  
Agarwal, Manteuffel, Panzer, Schabinger '21

Lee, Manteuffel, Schabinger, Smirnov^2 '21, ...

**3-loop 3-point with massive propagators**

\[ gg \rightarrow H \]  
Czakon, Harlander, Klappert, Niggetiedt '21 (full cross section)

semi-numerically
2-loop 4-point with massive propagators numerically:

\[ pp \rightarrow t\bar{t} \quad \text{Czakon, Mitov '13} \]
\[ pp \rightarrow HH \quad \text{Borrowka, Greiner, GH, Jones, Kerner, Schlenk, Schubert, Zirke '16} \]
\[ pp \rightarrow Hj \quad \text{Jones, Kerner, Luisoni '18} \]
\[ pp \rightarrow W^+W^- \quad \text{Brønnum-Hansen, Wang '20} \]
\[ pp \rightarrow HZ \quad \text{Chen, GH, Jones, Kerner, Klappert, Schlenk '20} \]
\[ pp \rightarrow ZZ \quad \text{Agarwal, Jones, Manteuffel '20} \]
2-loop 4-point with massive propagators

**analytically:** \( H + j \) full set of master integrals

Frellesvig et al. '19

mixed QCD-EW corrections to Higgs production

Bechetti et al. ‘20

mixed QCD-EW corrections to Drell-Yan

Heller, von Manteuffel et al. ’19, ‘20
Bonciani et al. ‘21
Buccioni, Caola, Chawdhry et al. ‘22

2-loop 4-fermion scattering in QED

- Bonciani et al. ‘21
- Banerjee et al. ’20, ‘21
## Pro’s and con’s analytic/numerical

<table>
<thead>
<tr>
<th></th>
<th>analytic</th>
<th>numerical</th>
</tr>
</thead>
<tbody>
<tr>
<td>pole cancellation</td>
<td>exact</td>
<td>with numerical uncertainty</td>
</tr>
<tr>
<td>fast evaluation</td>
<td>mostly</td>
<td>depends</td>
</tr>
<tr>
<td>control of integrable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>singularities</td>
<td>analytic continuation</td>
<td>less straightforward</td>
</tr>
<tr>
<td>extension to more</td>
<td></td>
<td></td>
</tr>
<tr>
<td>scales/loops</td>
<td>difficult</td>
<td>promising</td>
</tr>
<tr>
<td>automation</td>
<td>difficult</td>
<td>less difficult</td>
</tr>
</tbody>
</table>
## Pro’s and con’s analytic/numerical

<table>
<thead>
<tr>
<th></th>
<th>analytic</th>
<th>numerical</th>
</tr>
</thead>
<tbody>
<tr>
<td>pole cancellation</td>
<td>exact</td>
<td>with numerical uncertainty</td>
</tr>
<tr>
<td>fast evaluation</td>
<td>mostly</td>
<td>depends</td>
</tr>
<tr>
<td>control of integrable</td>
<td>analytic continuation</td>
<td>less straightforward</td>
</tr>
<tr>
<td>singularities</td>
<td>difficult</td>
<td>promising</td>
</tr>
<tr>
<td>extension to more scales/loops</td>
<td>difficult</td>
<td>promising</td>
</tr>
<tr>
<td>automation</td>
<td>difficult</td>
<td>less difficult</td>
</tr>
<tr>
<td></td>
<td>Analytic</td>
<td>Numerical</td>
</tr>
<tr>
<td>------------------------</td>
<td>---------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>Pole cancellation</td>
<td>Exact</td>
<td>With numerical uncertainty</td>
</tr>
<tr>
<td>Fast evaluation</td>
<td>Mostly</td>
<td>Depends</td>
</tr>
<tr>
<td>Control of integrable</td>
<td>Analytic continuation</td>
<td>Less straightforward</td>
</tr>
<tr>
<td>Singularities</td>
<td>Difficult</td>
<td>Promising</td>
</tr>
<tr>
<td>Extension to more</td>
<td>Difficult</td>
<td>Less difficult</td>
</tr>
<tr>
<td>Scales/loops</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Automation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pro’s and con’s analytic/numerical

- Pole cancellation: Exact (analytic) vs. Uncertainty (numerical)
- Fast evaluation: Mostly (analytic) vs. Depends (numerical)
- Control of integrable singularities: Analytic continuation (analytic) vs. Less straightforward (numerical)
- Extension to more scales/loops: Difficult (analytic) vs. Promising (numerical)
- Automation: Difficult (analytic) vs. Less difficult (numerical)

Often a combination can be beneficial, e.g., high energy limit analytically, Davies et al. 1907.06408
The Next Challenges

- scale uncertainties: how well do they estimate missing higher orders?
  - depends on choice of central scales, modes of variation, contributing partonic channels, ...

- electroweak corrections, mixed QCD-EW

- PDFs

- quark mass-related uncertainties: neglected masses, different renormalisation schemes

- need for resummation in certain kinematic regions

- parton shower uncertainties

- Effective Field Theories: truncation uncertainties, validity range
Scale uncertainties: Higgs production in gluon fusion

B. Mistlberger ’18
Scale uncertainties: Drell-Yan (W-production)
Scale uncertainties: Drell-Yan (W-production)

NNLO $\mu_F$-scale uncertainty bands do not properly reflect the uncertainty
Mass effects, parton shower uncertainties

WH production at NNLO + decay $H \rightarrow b\bar{b}$ with massive b-quarks

Behring, Bizon, Caola, Melnikov, Röntsch 2003.08321

significant differences between massive and massless case and NNLO vs NLO+PS
Exploring the Higgs potential through Higgs boson pair production in gluon fusion

\[ \mathcal{L} \supset -m_t \left( c_t \frac{h}{\sqrt{v}} + c_{tt} \frac{h^2}{v^2} \right) \bar{t} t - c_{hhh} \frac{m_h^2}{2v} h^3 + \frac{\alpha_s}{8\pi} \left( c_{ggh} \frac{h}{\sqrt{v}} + c_{gghh} \frac{h^2}{v^2} \right) G_{\mu\nu}^a G^{a,\mu\nu} \]

description of unknown interactions at high energies through Effective Field Theory

Standard Model: \( c_{tt} = 0, c_{ggh} = 0, c_{gghh} = 0 \)
Higher order corrections: SM

N3LO:  
Chen, Li, Shao, Wang ’19  
(HTL with top mass effects)

NNLO:  
De Florian, Mazzitelli ’13  
Grigo, Melnikov, Steinhauser ’14

NNLO_{F T \text{approx}}:  
Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli ’18

inclusion of top quark mass dependence except in virtual $\mathcal{O}(\alpha_s^3)$

NLO full $m_t$:  
Borowka, Greiner, GH, Jones, Kerner, Schlenk et al. ’16  
Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher ’18  
Davies, GH, Jones, Kerner, Mishima, Steinhauser, Wellmann ’19

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

Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira ’18, ’20
Higher order corrections: SM

N3LO: Chen, Li, Shao, Wang ’19
(HTL with top mass effects)

NNLO: De Florian, Mazzitelli ’13
Grigo, Melnikov, Steinhauser ’14

NNLO_F^\text{approx}
Grazzini, Kallweit, GH, Jones,
Kerner, Lindert, Mazzitelli ‘18

inclusion of top quark mass dependence except in virtual \( O(\alpha_s^3) \)

NLO full \( m_t \)
Borowka, Greiner, GH, Jones, Kerner, Schlenk et al. ‘16
Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher ’18
Davies, GH, Jones, Kerner, Mishima, Steinhauser, Wellmann ‘19

top quark mass scheme uncertainties: pole mass versus \( \bar{\text{MS}} \) mass
Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira ’18, ’20

scale uncertainties \( O(3\%) \)

heavy top limit (HTL)
Higher order corrections: SM

N3LO: Chen, Li, Shao, Wang '19
(HTL with top mass effects)

NNLO: De Florian, Mazzitelli '13
Grigo, Melnikov, Steinhauser '14

NNLO\_F\_T\_approx Grazzini, Kallweit, GH, Jones,
Kerner, Lindert, Mazzitelli '18

inclusion of top quark mass dependence except in virtual \( \mathcal{O}(\alpha_s^3) \)

NLO full \( m_t \)
Borowka, Greiner, GH, Jones, Kerner, Schlenk et al. '16
Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher '18
Davies, GH, Jones, Kerner, Mishima, Steinhauser, Wellmann '19

top quark mass scheme uncertainties: pole mass versus \( \overline{\text{MS}} \) mass
Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira '18, '20
Higher order corrections: SM

**N3LO:** Chen, Li, Shao, Wang '19
(HTL with top mass effects)

**NNLO:** De Florian, Mazzitelli '13
Grigo, Melnikov, Steinhauser '14

**NNLO\textsubscript{FTapprox}**
Grazzini, Kallweit, GH, Jones,
Kerner, Lindert, Mazzitelli '18

inclusion of top quark mass dependence except in virtual \( \mathcal{O}(\alpha_s^3) \)

**NLO full** \( m_t \)
Borowka, Greiner, GH, Jones, Kerner, Schlenk et al. '16
Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher '18
Davies, GH, Jones, Kerner, Mishima, Steinhauser, Wellmann '19

top quark mass scheme uncertainties:
poles mass versus MS mass
Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira '18, '20

scale uncertainties \( \mathcal{O}(3\%) \)

residual missing top mass effects estimated to \( \mathcal{O}(5\%) \)

uncertainty due to top mass scheme \( \mathcal{O}(20\%) \)

heavy top limit (HTL)
Top quark mass renormalisation scheme uncertainties

\[
\overline{m}_t(m_t) = \frac{m_t}{1 + \frac{4}{3} \frac{\alpha_s(m_t)}{\pi} + K_2 \left( \frac{\alpha_s(m_t)}{\pi} \right)^2 + K_3 \left( \frac{\alpha_s(m_t)}{\pi} \right)^3} + \ldots
\]

relation between pole mass and \( \overline{\text{MS}} \) mass

Baglio, Campanario, Glaus Mühlleitner, Ronca, Spira 2003.03227, 2008.11626

also present in other heavy quark loop induced processes

\( gg \to HH \) at NLO QCD | \( \sqrt{s} = 13 \) TeV | PDF4LHC15

Ratio to LO

\( \mu_R = \mu_F = \frac{M_{HH}}{2} \)

Full NLO results for different top-quark masses

\( M_{HH} \) [GeV]
Effective Field Theory expansion schemes

SMEFT (Standard Model Effective Field Theory):

\[ \mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{\text{dim6}} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right) \]

canonical dimension counting

HEFT (Higgs Effective Field Theory):

\[ \mathcal{L}_{\text{HEFT}} = \mathcal{L}_0 + \sum_{L=1}^{\infty} \sum_i \left(\frac{1}{16\pi^2}\right)^L c_i^{(L)} \mathcal{O}_i^{(L)} \]

counting of loop orders, expansion parameter: \( f^2/\Lambda^2 \approx 1/(16\pi^2) \)
(similar to chiral perturbation theory)

new physics scale \( \Lambda \)
characteristic scale of Goldstone bosons
EW scale \( v \sim 246 \text{ GeV} \)
Lagrangians relevant for HH production

**SMEFT:**

\[
\Delta \mathcal{L}_{\text{Warsaw}} = \frac{C_{H,\Box}}{\Lambda^2} (\phi^\dagger \phi) (\phi^\dagger \phi) + \frac{C_{HD}}{\Lambda^2} (\phi^\dagger D_\mu \phi)^* (\phi^\dagger D^\mu \phi) + \frac{C_H}{\Lambda^2} (\phi^\dagger \phi)^3 \\
+ \left( \frac{C_{uH}}{\Lambda^2} \phi^\dagger \phi q_L \phi^c t_R + h.c. \right) + \frac{C_{HG}}{\Lambda^2} \phi^\dagger \phi G^a_{\mu\nu} G^{\mu\nu, a} \\
\text{(Warsaw basis)}
\]

Grzadkowski et al. 1008.4884

**HEFT:**

\[
\mathcal{L} \supset -m_t \left( c_t \frac{h}{v} + c_{tt} \frac{h^2}{v^2} \right) \bar{t} t - c_{hhh} \frac{m_h^2}{2v} h^3 + \frac{\alpha_s}{8\pi} \left( c_{ggh} \frac{h}{v} + c_{gghh} \frac{h^2}{v^2} \right) G^a_{\mu\nu} G^{a,\mu\nu}
\]

Buchalla et al. '13, '18
Lagrangians relevant for HH production

coupling relations at Lagrangian level:

<table>
<thead>
<tr>
<th>HEFT</th>
<th>Warsaw</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{hhh}$</td>
<td>$1 - 2 \frac{v^2}{\Lambda^2} \frac{v^2}{m_h^2} C_H + 3 \frac{v^2}{\Lambda^2} C_{H,\text{kin}}$</td>
</tr>
<tr>
<td>$c_t$</td>
<td>$1 + \frac{v^2}{\Lambda^2} C_{H,\text{kin}} - \frac{v^2}{\Lambda^2} \frac{v}{\sqrt{2}m_t} C_{uH}$</td>
</tr>
<tr>
<td>$c_{tt}$</td>
<td>$-\frac{v^2}{\Lambda^2} \frac{3v}{2\sqrt{2}m_t} C_{uH} + \frac{v^2}{\Lambda^2} C_{H,\text{kin}}$</td>
</tr>
<tr>
<td>$C_{ggh}$</td>
<td>$\frac{v^2}{\Lambda^2} \frac{8\pi}{\alpha_s} C_{HG}$</td>
</tr>
<tr>
<td>$C_{gghh}$</td>
<td>$\frac{v^2}{\Lambda^2} \frac{4\pi}{\alpha_s} C_{HG}$</td>
</tr>
</tbody>
</table>

$$C_{H,\text{kin}} = C_{H,\Box} - \frac{1}{4} C_{HD}$$
SMEFT double operator insertions

\[ \mathcal{M} = 1 + \frac{C_t'}{\Lambda^2} + 1 + \frac{C_t'}{\Lambda^2} + \frac{C_{ggg}'}{\Lambda^2} + \frac{C_{hhh}'}{\Lambda^2} + \ldots \]

\[ = \mathcal{M}_{SM} + \mathcal{M}_{\text{dim6}} + \mathcal{M}_{\text{dim6}^2} \]

terms \( \sim 1/\Lambda^4 \) same order as dim 8 operators (which are not included)
SMEFT at amplitude squared level

4 possibilities:

\[
\sigma \sim \begin{cases} 
\sigma_{\text{SM}} + \sigma_{\text{SM} \times \text{dim6}} & (a) \\
\sigma_{(\text{SM}+\text{dim6}) \times (\text{SM}+\text{dim6})} & (b) \\
\sigma_{(\text{SM}+\text{dim6}) \times (\text{SM}+\text{dim6})} + \sigma_{\text{SM} \times \text{dim6}^2} & (c) \\
\sigma_{(\text{SM}+\text{dim6}+\text{dim6}^2) \times (\text{SM}+\text{dim6}+\text{dim6}^2)} & (d)
\end{cases}
\]

(a): “linearised dim 6” (first order of expansion in $1/\Lambda^2$ at cross section level)

(b): “quadratic dim 6” (first order of expansion in $1/\Lambda^2$ at amplitude level)

(c): include all terms $O(1/\Lambda^4)$ coming from $\text{dim6}^2$ and double operator insertions

(d): would correspond to HEFT except for treatment of $\alpha_s$
Total HH cross section

flat directions very different in linear versus quadratic dim 6

figures: Jannis Lang
Higgs boson pair invariant mass spectrum

<table>
<thead>
<tr>
<th>benchmark</th>
<th>$C_{hh}$</th>
<th>$C_t$</th>
<th>$C_{tt}$</th>
<th>$C_{gg}$</th>
<th>$C_{gggh}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1*</td>
<td>3.94</td>
<td>0.94</td>
<td>$-\frac{1}{3}$</td>
<td>0.5</td>
<td>0.25*</td>
</tr>
<tr>
<td>6*</td>
<td>5.68</td>
<td>0.83</td>
<td>$\frac{1}{3}$</td>
<td>-0.5</td>
<td>-0.25*</td>
</tr>
</tbody>
</table>

Modified benchmark point 1 at NLO

$\Lambda = 1 \text{ TeV}$

$\Lambda = 2 \text{ TeV}$

$\Lambda = 4 \text{ TeV}$

Figures: Jannis Lang
Higgs boson pair invariant mass spectrum

significant differences, delicate interference patterns

parameter point valid in HEFT invalid in SMEFT

figures: Jannis Lang
Indirect signs of New Physics: precision is the key

Increasing the precision at the percent level has many facets:
missing higher orders (QCD/EW), parton shower uncertainties, PDFs,
heavy quark mass effects/scheme dependence, non-perturbative effects, …

Testable hypotheses of New Physics:
Concrete models -> model dependence
Effective field theories -> dependence on counting scheme, truncation, unitarity
Indirect signs of New Physics: precision is the key

Increasing the precision at the percent level has many facets:
missing higher orders (QCD/EW), parton shower uncertainties, PDFs,
heavy quark mass effects/scheme dependence, non-perturbative effects, …

Testable hypotheses of New Physics:
Concrete models -> model dependence
Effective field theories -> dependence on counting scheme, truncation, unitarity

joint efforts needed to work on all the different aspects!
bbH
Drell-Yan (NC)

Duhr, Dulat, Mistlberger
2001.07717
Highest perturbative orders (SM)

Chen, Li, Shao, Wang 1912.13001

Grazzini, Kallweit, GH, Jones, Kerner, Lindert, Mazzitelli 1803.02463
Counting schemes

HEFT (EWChL): “loop expansion”

based on chiral dimension $d_\chi = 2L + 2$  $L$: “Loop”

with $d_\chi(A_\mu, \varphi, h) = 0$, $d_\chi(\partial, \bar{\psi}\psi, g, y) = 1$

$\xi = v^2 / f^2$

expansion in canonical dimension $1/\Lambda^2$

SMEFT

figure: G.Buchalla
Factorisation

\[ d\sigma_{pp \rightarrow H+X} = \sum_{i,j} \int_0^1 dx_1 f_{i/p_a}(x_1, \alpha_s, \mu_f) \int_0^1 dx_2 f_{j/p_b}(x_2, \alpha_s, \mu_f) d\hat{\sigma}_{ij \rightarrow H+X}(x_1, x_2, \alpha_s, \mu_r, \mu_f) + \mathcal{O}\left(\frac{\Lambda}{Q}\right)^p \]

- Renormalisation scale
- Factorisation scale
- Parton distribution functions (PDFs)
- Partonic cross section
- Non-perturbative
- Perturbative