Beyond the benchmarks: off-shell Higgs production

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https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGOFFSHELL

with slides kindly contributed by
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Ultimate Precision at Hadron Colliders Workshop

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Thanks to Stefan Höche for the slides template.

Overview

- Introduction
- Progress on SM corrections:
- $pp\,(\to H) \to ZZ$ production @ nNNLO QCD
- $gg\,(\to H) \to ZZ$ interference @ 2-loops with approx. m_t dependence
- $gg \to ZZ$ production @ 2 loops with full top mass dependence
- Going beyond BSM benchmarks @ LO:
- High-mass 1HSM interference effects beyond LO
- Progress on off-shell and interference EFT studies
- Off-shell and interference effects in SMEFT
- Universal EFT (oblique Higgs parameter)
- Higgs couplings without the Higgs
- Theoretical and experimental issues/questions
- Conclusions

High mass Higgs → WW search at CMS with 2016 data

PAS-HIG-17-033

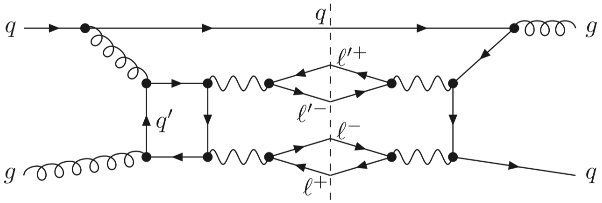
- High mass Higgs → WW search with 2016 data
- Combination of semi and fully-leptonic final states
- No significant excess observed
- SM-like limits based on YR4 ggF and VBF σ values
- 2HDM limits (with $\cos(\beta - \alpha) = 0.1$)
- Several MSSM benchmark scenario limits

Vector boson pair production at the LHC

- At the end of LHC run II:
  - $\rightarrow$ No evidence of New Physics is found
  - $\rightarrow$ Higgs couplings are found consistent with the SM
- Vector boson pair production is crucial because it is:
  - $\rightarrow$ Irreducible background to Higgs studies
  - $\rightarrow$ Useful for investigating signal-background interference effect and the Higgs boson width
  - $\rightarrow$ Background to BSM searches
  - $\rightarrow$ Sensitive to anomalous triple gauge couplings (aTGCs)
- Precise control of SM predictions is needed, especially in the tails of the distributions
  - $\rightarrow$ Higher order calculations are demanded

pp $\rightarrow$ ZZ $\rightarrow$ 4l at NNLO

- NNLO contributions increase the NLO results by $\sim$15%
- Gluon-fusion takes up about 60% of NNLO corrections
- NLO corrections to the gg channel are expected to be quantitatively relevant!
- Current experimental analyses: $\mathrm{NLO_{gg}}$ and $\mathrm{NNLO_{q\bar{q}}}$ are treated as independent contributions
  - $\rightarrow$ Not independent at NNLO



pp $\to$ ZZ $\to e^+e^-\mu^+\mu^-$ at nNNLO

Grazzini, Kallweit, Wiesemann, Yook (2018)

$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
	σ [fb]		$\sigma/\sigma_{\mathrm{NLO}} - 1$	
LO	$8.1881(8)^{+2.4\%}_{-3.2\%}$	$13.933(1)^{+5.5\%}_{-6.4\%}$	-27.5%	-29.8%
NLO	$11.2958(4)^{+2.5\%}_{-2.0\%}$	$19.8454(7)^{+2.5\%}_{-2.1\%}$	0%	0%
$q\bar{q}$NNLO	$12.09(2)^{+1.1\%}_{-1.1\%}$	$21.54(2)^{+1.1\%}_{-1.2\%}$	$+7.0\%$	$+8.6\%$
	σ [fb]		$\sigma/\sigma_{\mathrm{ggLO}} - 1$	
ggLO	$0.79355(6)^{+28.2\%}_{-20.9\%}$	$2.0052(1)^{+23.5\%}_{-17.9\%}$	0%	0%
$gg\mathrm{NLO}_{gg}$	$1.4787(4)^{+15.9\%}_{-13.1\%}$	$3.626(1)^{+15.2\%}_{-12.7\%}$	$+86.3\%$	$+80.8\%$
ggNLO	$1.3892(4)^{+15.4\%}_{-13.6\%}$	$3.425(1)^{+13.9\%}_{-12.0\%}$	$+75.1\%$	$+70.8\%$
	σ [fb]		$\sigma/\sigma_{\mathrm{NLO}} - 1$	
NNLO	$12.88(2)^{+2.8\%}_{-2.2\%}$	$23.55(2)^{+3.0\%}_{-2.6\%}$	$+14.0\%$	$+18.7\%$
nNNLO	$13.48(2)^{+2.6\%}_{-2.3\%}$	$24.97(2)^{+2.9\%}_{-2.7\%}$	$+19.3\%$	$+25.8\%$

- ggNLO makes up 10% of the total rate at 8 TeV and 14% at 13 TeV
- $\mathrm{ggNLO}_{\mathrm{gg}}$ increases ggLO contribution by 86% at 8 TeV and 81% at 13 TeV
- Including the qg channel lowers the ggNLO cross section by 6% at both 8 and 13 TeV
- NLO corrections to gg channel increase the NNLO prediction by 5% at 8 TeV and 6% at 13 TeV

The MATRIX framework M. Grazzini, S. Kallweit and M. Wiesemann (2017)

MUNICH
S. Kallweit

NNLO (+NNLL)

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Version: 1.0.0                            Nov 2017
Reference: arXiv:1711.06631

Munich -- the MUlti-chaNnel Integrator at swiss (CH) precision --
Automates qT-subtraction and Resummation to Integrate X-sections
```

q_T Subtraction
S. Catani and M. Grazzini (2007)

OpenLoops
F. Cascioli, J. Lindert, P. Maierhöfer and S. Pozzorini (2014)

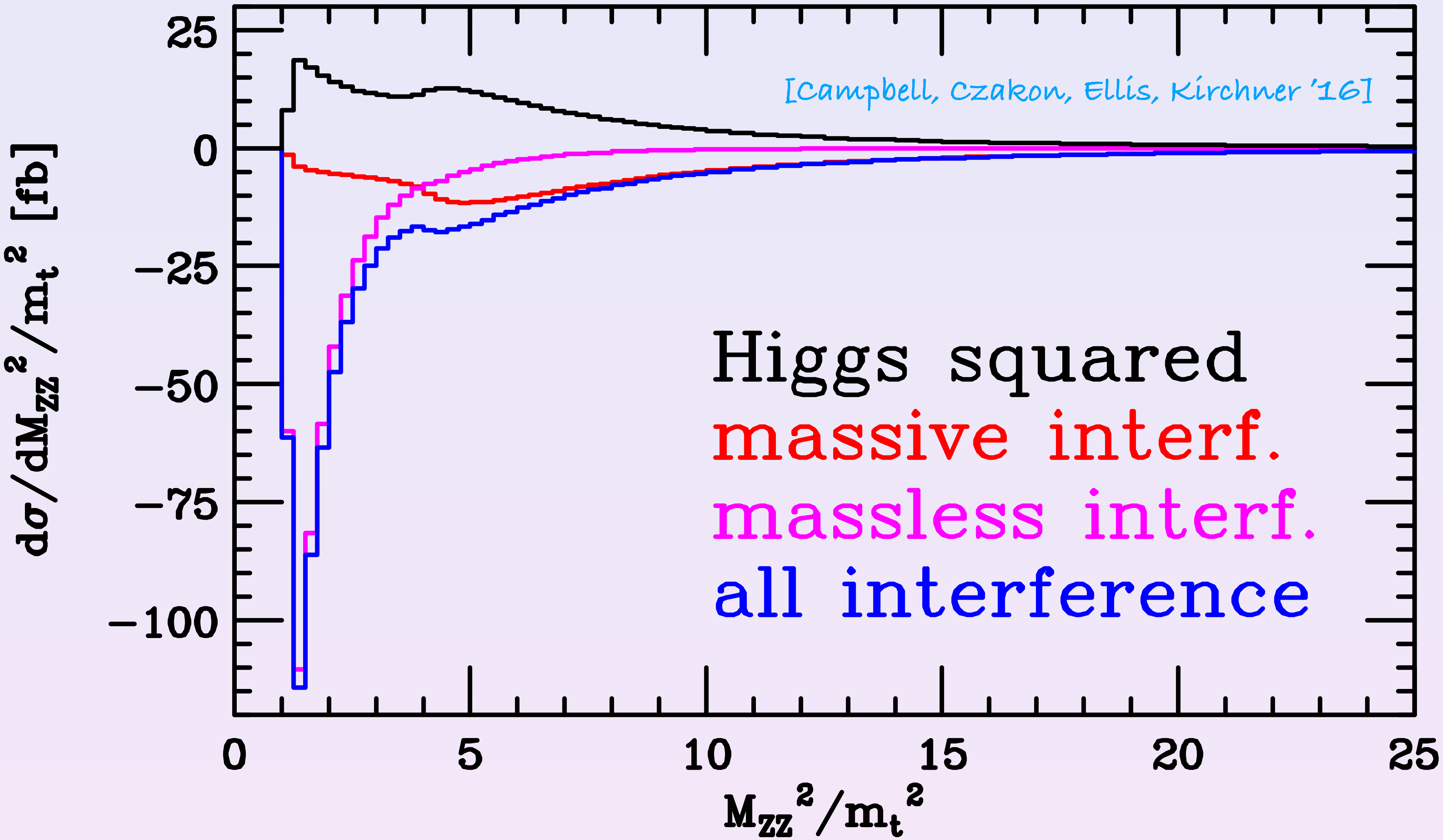
COLLIER
A. Denner, S. Dittmaier and L. Hofer (2016)

VVAMP T. Gehrmann, A. von Manteuffel, L. Tancredi (2015)

GiNaC C. Bauer, A. Frink and R. Kreckel (2002)

TDHPL T. Gehrmann and E. Remiddi

Importance of top loops



Top loops especially important in part of phase space where LME can't be applied.

Gluon fusion processes at higher orders

Computation of 2 -> 2 multi-scale processes at two-loop order difficult

Bottleneck: virtual corrections, dependence on several scales

Well-established method:

Asymptotic expansion in large top mass (LME)

$$\frac{1}{(p+q)^2-m^2} \approx \frac{1}{p^2-m^2}\left(1-\frac{2p\cdot q+q^2}{p^2-m^2}+...\right)$$

simplifies integrals dramatically

p loop momentum, q external momentum

At LO: Taylor expansion in $\frac{1}{m_t^2}$

At NLO: Taylor expansion in $\frac{1}{m_t^2}$ + log terms from IR divergent diagrams

Our idea

- Construct an approximation that works in (nearly) whole phase space based on simpler expansion

Based on LME and expansion around non-relativistic top threshold (THR) combined by Padé approximants

- Demonstrate method on a process that is known in full mass dependence

HH as it carries full complexity of 2 -> 2 [RG, Maier, Rauh '17]

- Apply to other cases

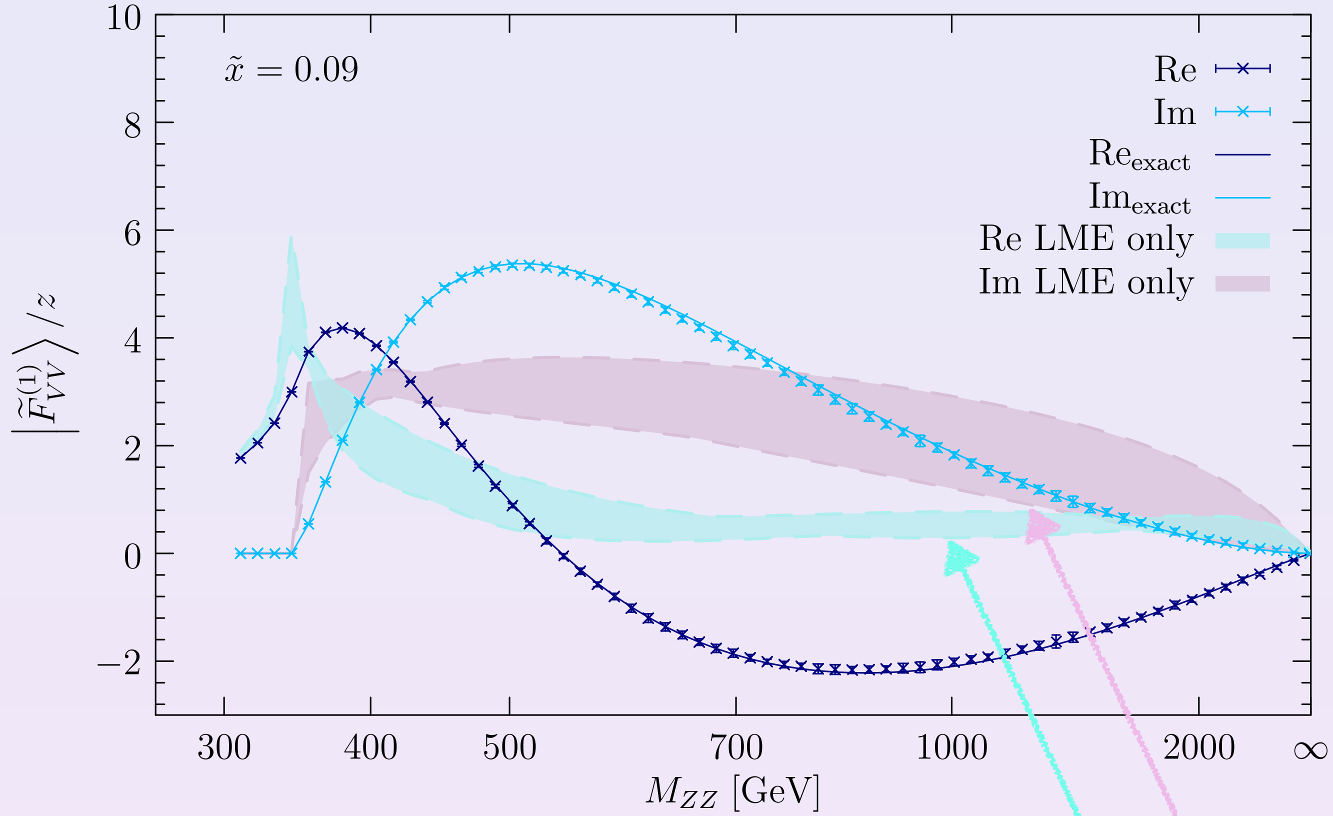
ZZ [RG, Maier, Rauh '19]

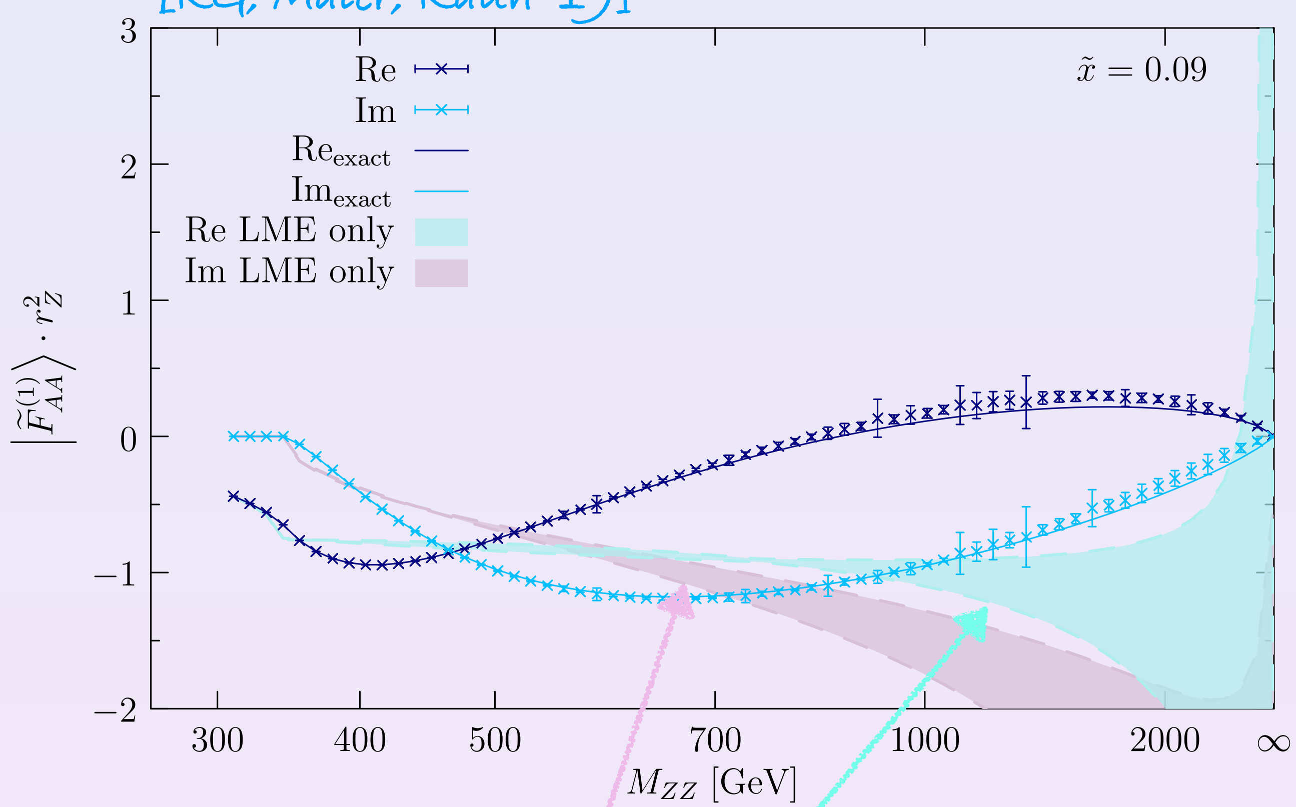
- Apply to higher loop orders

off-shell single Higgs production [Davies, RG, Maier, Rauh, Steinhauser '19]

$$\tilde{x} = \frac{p_T^2 + m_Z^2}{m_{ZZ}^2} \qquad z = \frac{M_{ZZ}^2}{4m_t^2} \qquad r_Z = \frac{M_Z^2}{M_{ZZ}^2}$$

[RG, Maier, Rauh '19]

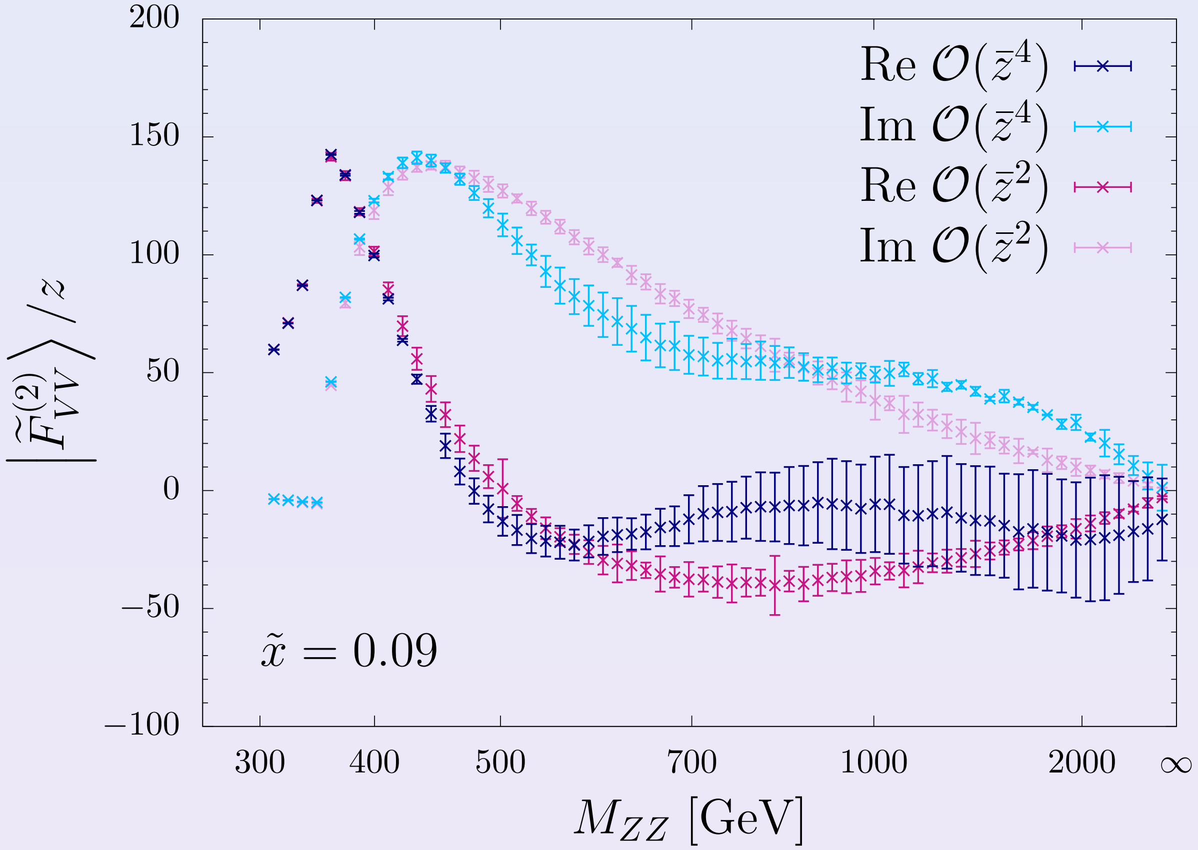


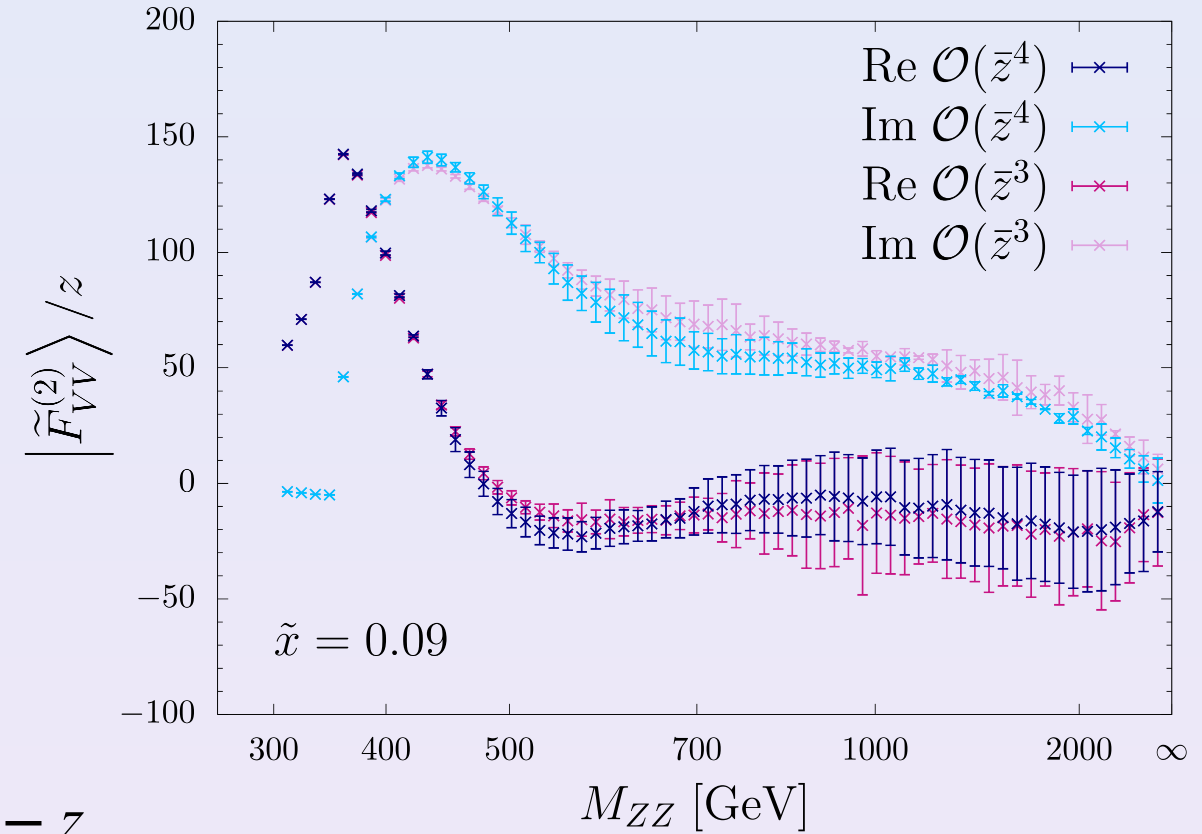


Padé approximants as constructed from LME by

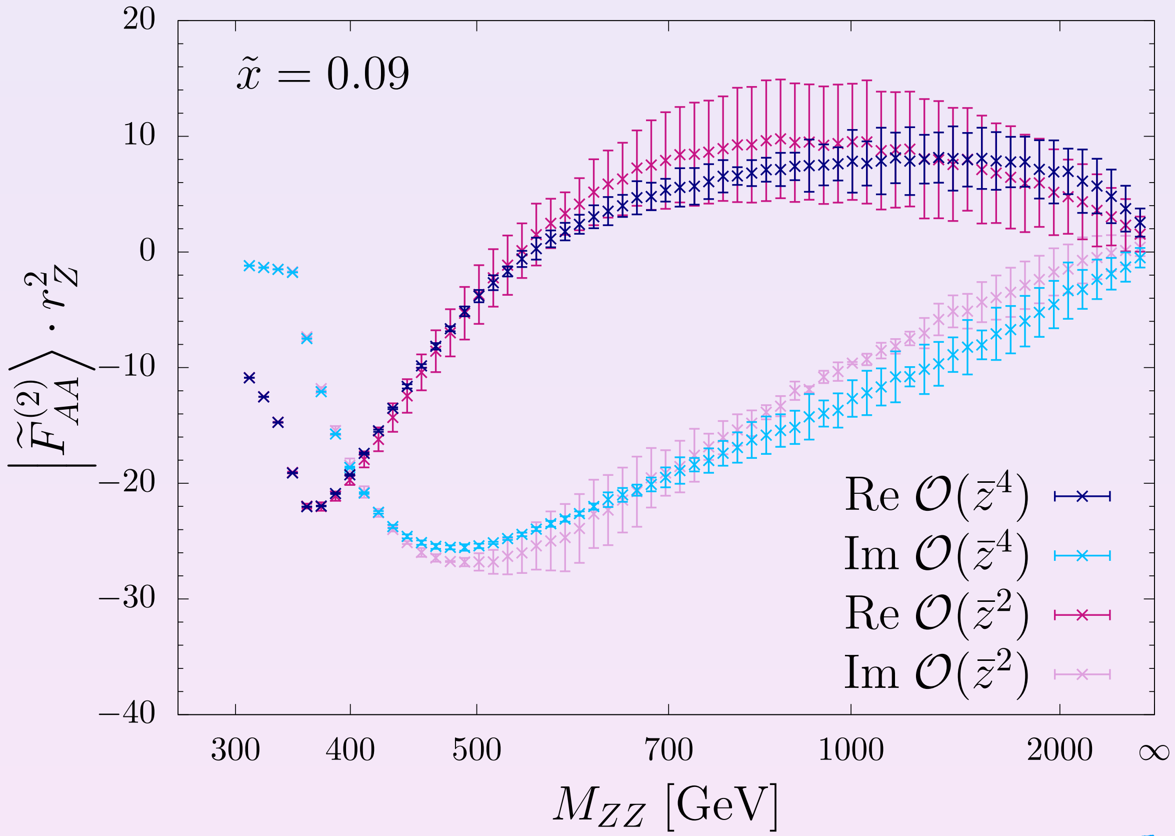
[Campbell, Czakon, Ellis, Kirchner '16]

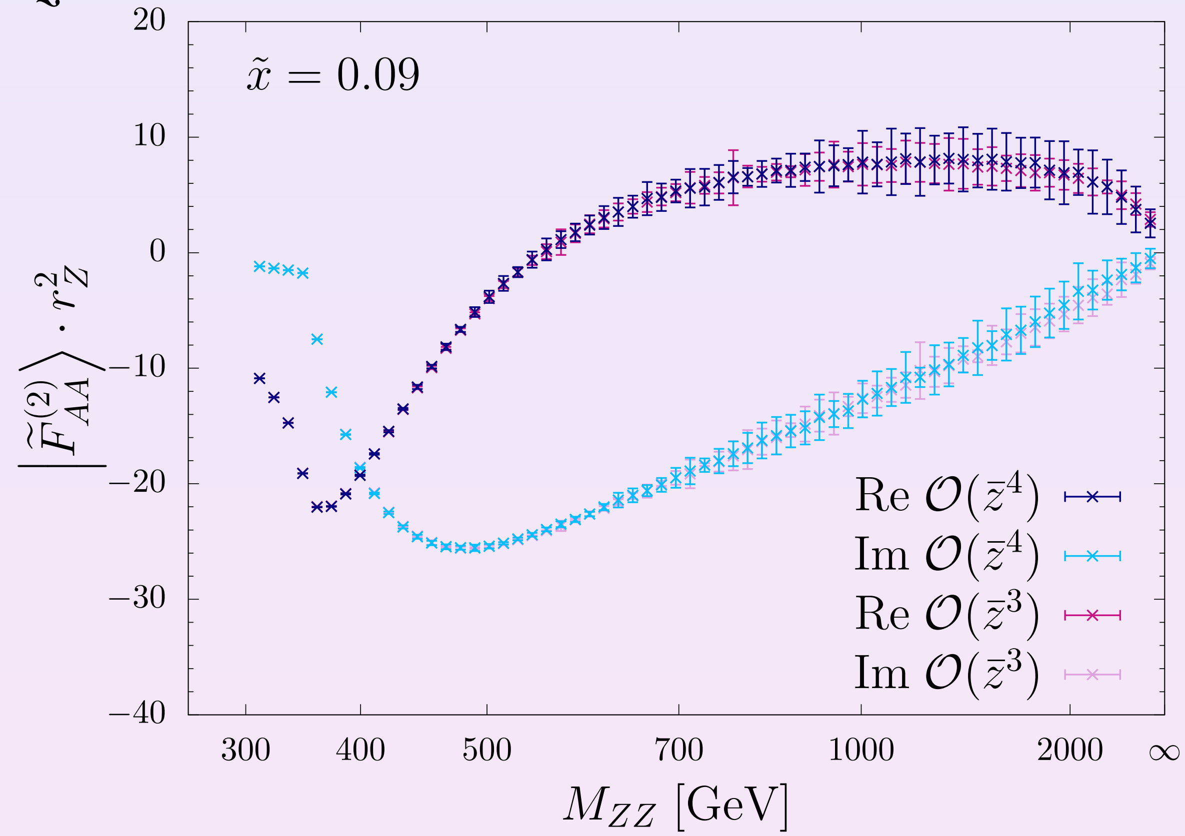
Convergence at NLO





$\bar{z} = 1 - z$





[RG, Maier, Rauh '19]

Bakul Agarwal, Andreas von Manteuffel (work in progress)

$gg \to ZZ$ at 2-loops with full top mass dependence

- Construct the amplitude and decompose into sum of all possible Lorentz structures and their 'form factors'

$$\mathcal{A}^{\mu\nu\rho\lambda} = \sum p_i^{\mu}\, p_j^{\nu}\, p_k^{\rho}\, p_l^{\lambda}\, A_{ijkl} + ..$$

- Solve linear system of equations to relate the 'form factors' to the original Feynman integral

- Use **Integration By Parts** identities to reduce the number of integrals to a basis set

- Rotate the basis integrals to a set of **finite integrals** ⇒ Much better behaved numerically

- **Evaluate** the finite integrals **numerically** using 'sector decomposition' (plus any needed improvements)

COMPARISON

Conventional IBP reduction

- Setup : None
- Reduction :
  - ~1 yr of CPU time for family A, up to tensor rank 3 (tensor rank 4 needed)
  - Terabytes of disk space
  - Need special file system on the High Performance Computing Cluster at MSU due to file corruptions

New Syzygy based IBP reduction

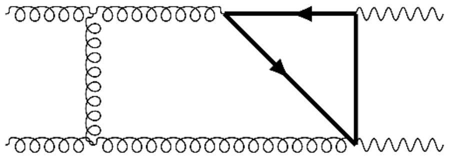
New

- Setup : Generation of syzygies (Can be **parallelised**)
  - ~ 30 hrs CPU time (single core) for family A, B
  - ~ 50 hrs CPU time (single core) for family C, D
- Reduction :
  - ~ 120 hrs CPU time for family A, B
  - ~ 50 weeks of CPU time for family C
  - ~ 15 weeks of CPU time for family D
  - ➢ This is heavily parallelised

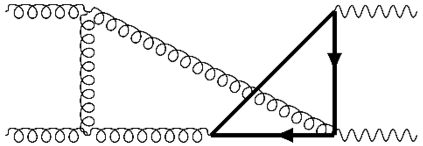
FINITE INTEGRALS

- Advantages:
  - Can write a custom integrator to evaluate such integrals much faster than available public codes : Initial tests suggest huge potential
  - Use integrals already appearing in the amplitude, often even as master integrals
  - Avoid computing reductions beyond those required for the amplitude

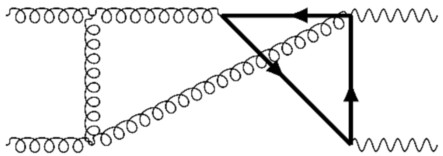
- Have a working code already; working on a more efficient implementation



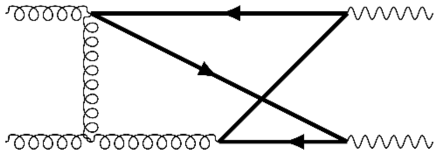
$* (-s)$



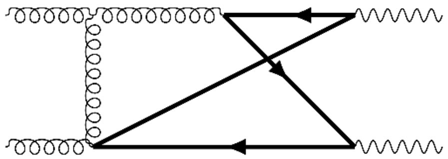
$* (s)$



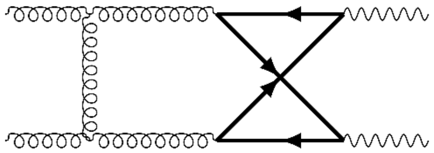
$* (s)$



$* (mz^2 - s - t)$

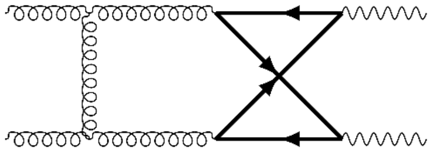


$* (mz^2 - t)$



$* s * (-mz^2 + s + t)$

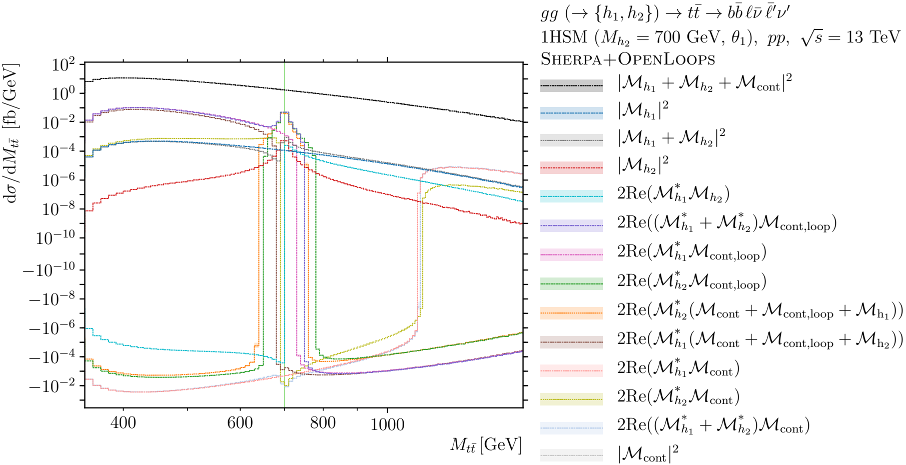
$(k_2)^2 - m_t^2$



$* (-s)$

High-mass signal-background interference with background corrections

NK, Lind, Maierhofer, Song (2019)



SMEFT basics

New Interactions of SM particles

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

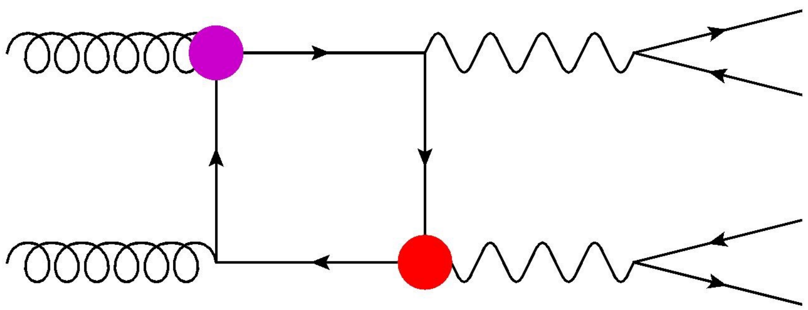
Buchmuller, Wyler Nucl.Phys. B268 (1986) 621-653

Grzadkowski et al arXiv:1008.4884

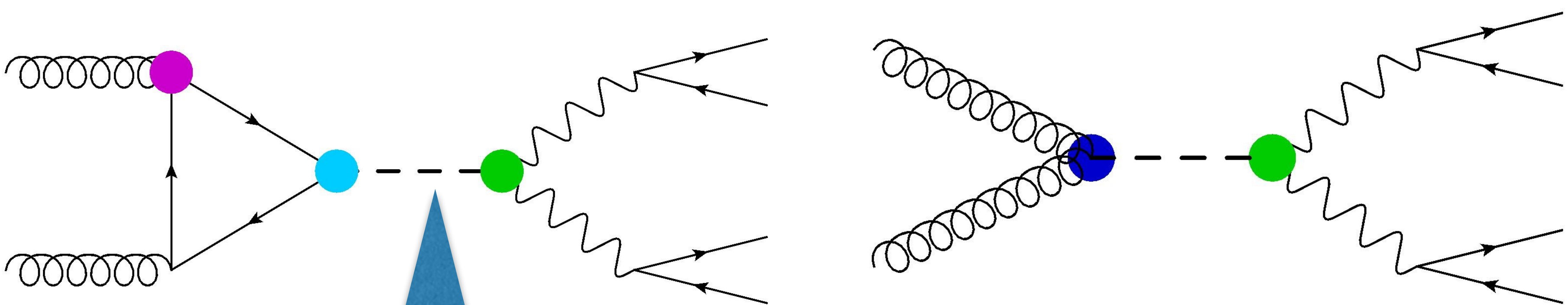
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu \varphi\right)^\star \left(\varphi^\dagger D_\mu \varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde W B}$	$\varphi^\dagger \tau^I \varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		

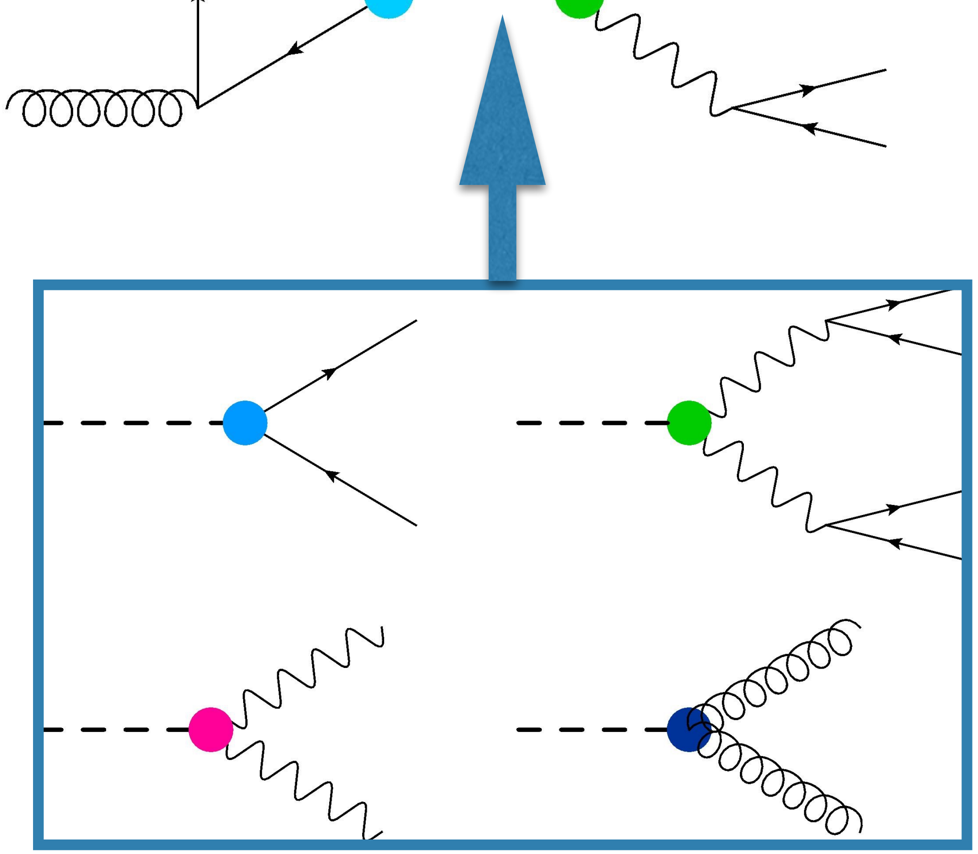
Off-shell production in the SMEFT



The background

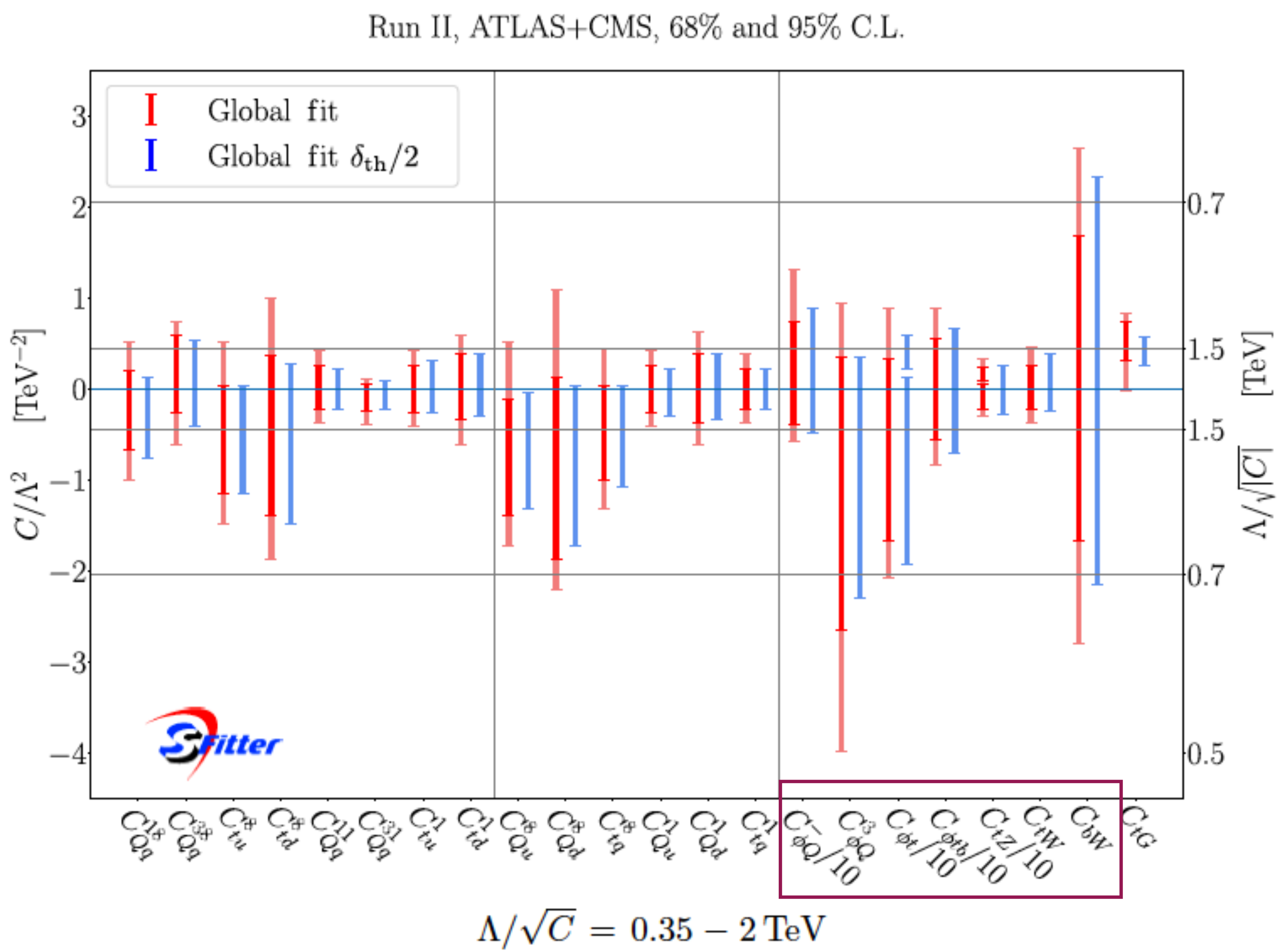


The signal



The Higgs width

The constraints on top operators



Brivio, Bruggisser, Maltoni, Moutafis, Plehn, EV, Westhoff, Zhang arXiv:1910.03606

SMEFT in Monte Carlo

Monte Carlo implementation based on:

- Warsaw basis
- Degrees of freedom for top operators as in arXiv:1802.07237 (LHCTopWG)

Current status:

- 73 degrees of freedom (top, Higgs, gauge):
  - CP-conserving
  - Flavour assumption: $U(2)_Q \times U(2)_u \times U(3)_d \times U(3)_L \times U(3)_e$
- 0/2F@NLO operators validated (with previous partial NLO implementations) → **http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO**
- 4F@NLO operators validation: on-going

Future plans

- Full NLO model release (4F@NLO)
- Other flavour assumptions
- CP-violating effects

Work in progress with: C. Degrande, G. Durieux, F. Maltoni, K. Mimasu, C. Zhang

Oblique Higgs parameter

[Englert, Giudice, Greljo, Mccullough]
1903.07725

- How does the Higgs boson propagate? (*)

- What is the analogue of **W,Y** in Higgs physics?
  W, Y: EW oblique corrections (extending S, T)

$$\mathcal{L}_{\hat{H}} = \frac{\hat{H}}{m_h^2} |\Box H|^2$$

- ***$\hat{H}$: the hallmark of off-shell Higgs physics***

(*) Framed within a general EFT context the answer to this question is unphysical and basis-dependent. However there is a broad class of microscopic theories (called Universal theories) which single out a specific EFT basis in which this question not only becomes well-defined, but also plays a key role in mapping out the boundaries of the UV.

Universal EFT

- A very broad class of UV theories singles out a particular set of EFT operators at the matching scale
- **There exist a field basis** in which all leading-order effects are captured by dim-6 operators built **from SM bosonic fields only**
- How?

  - NP interacts primarily with the SM bosons, or

  - NP couples to the conserved currents

Universal EFT

$$\Box H = J_H$$

Field redefinitions by equation of motion

'Boson-only' basis

$$|\Box H|^2$$

'Conventional' basis

$$|J_H|^2$$

$$J_H = \mu^2 H - 2\lambda |H|^2 H - \bar{q} i \sigma_2 Y_u^\dagger u - \bar{d} Y_d q - \bar{e} Y_e \ell$$

- 'Boson-only' basis (Universal basis) more clearly matches with the UV properties of a Universal theory
- 'Conventional' basis easier for calculations
- Universal basis is not closed under RG evolution [Wells, Zhang] 1512.03056
- By definition, universal theories satisfy minimal flavor violation (MFV)

Physical effects of Higgs-only operators

'Higgs-only'

$[g_*^0]$	$[g_*^2]$	$[g_*^4]$
$\mathcal{O}_\Box = \frac{c_\Box}{M^2} \lvert \Box H \rvert^2$	$\mathcal{O}_H = \frac{c_H}{2M^2} \left(\partial^\mu \lvert H \rvert^2\right)^2$	$\mathcal{O}_6 = \frac{c_6}{M^2} \lvert H \rvert^6$

(*) custodial symmetry

$$\mathcal{O}_R = \frac{c_R}{M^2} \lvert H \rvert^2 \lvert D^\mu H \rvert^2$$

In conclusion, the 'Higgs-only' basis is described by 4 independent Wilson coefficients ($c_\Box, c_H, c_R, c_6$) and leads to 3 physical observables in Higgs couplings: universal modifications of $h \to VV$ and $h \to \bar{f}f$, and the Higgs trilinear vertex. Therefore, even in this restrictive class of EFT, it is not possible to unambiguously determine $\hat{H}$ by combining on-shell Higgs coupling measurements and a measurement of the trilinear coupling.

- Off-shell measurements **required** to close the Higgs-only set

goldstones = longitudinals

$$|H|^2 \sim (v+h)^2 + \vec{\phi}^2$$

ops that modify HC will induce processes with longitudinal vectors

HC: $|H|^2 \mathcal{O}_{\text{SM}} \supset vh\mathcal{O}_{\text{SM}}$

HwH: $|H|^2 \mathcal{O}_{\text{SM}} \supset \vec{\phi}^2 \mathcal{O}_{\text{SM}}$

Henning, Lombardo, Riembau, Riva (2018/19)

Example: $|H|^6$

$$|H|^6 \supset v^3 h^3$$ ← trilinear

$$|H|^6 \supset vh\phi^4 + \phi^6$$

$V_L V_L \to V_L V_L V_L V_L$ (from ϕ^6)

$V_L V_L \to V_L V_L h$ (from $vh\phi^4$)

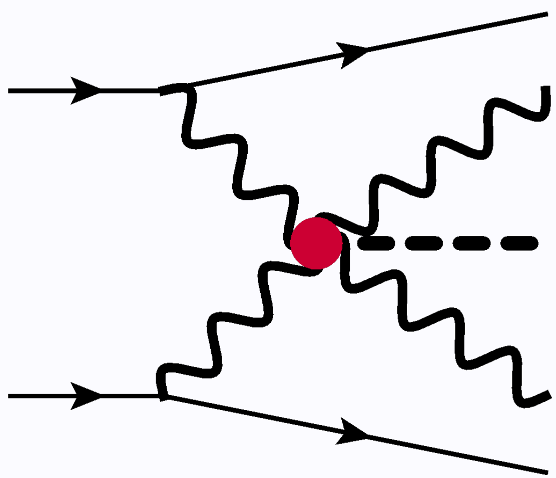
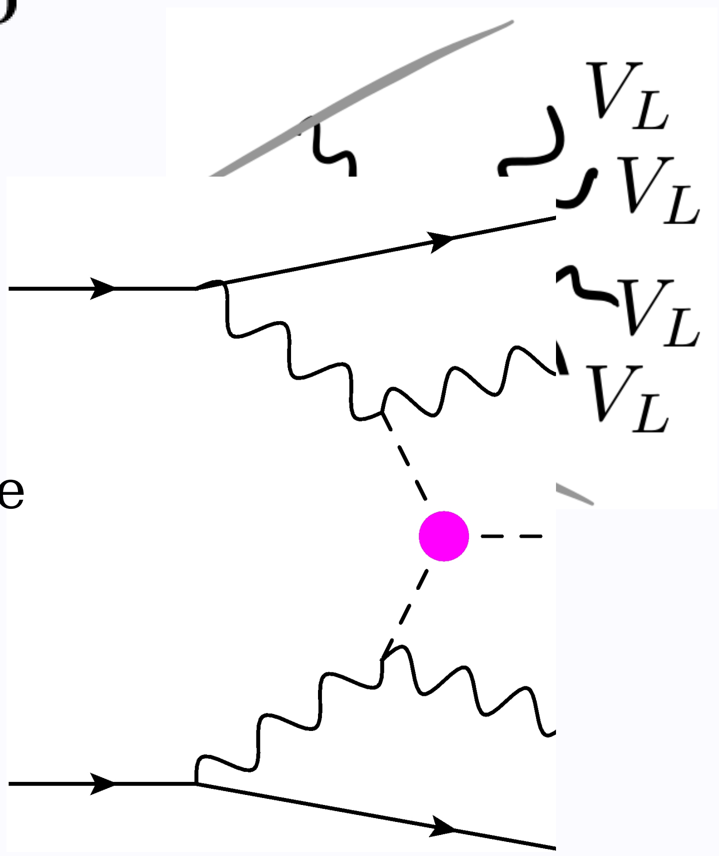
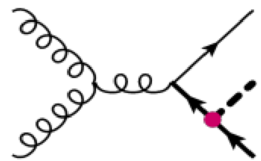
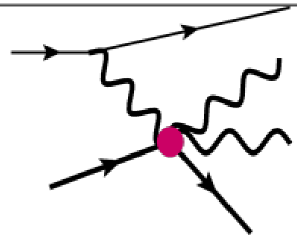
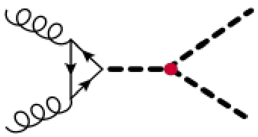
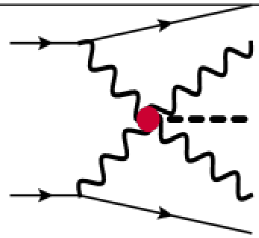
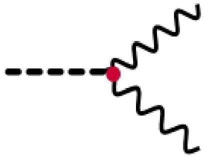
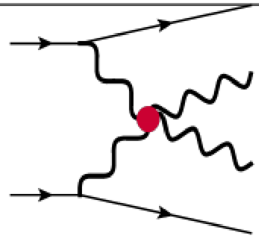
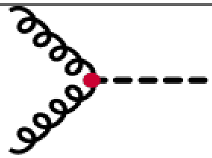
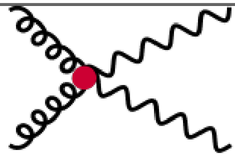


diagram in unitary gauge →

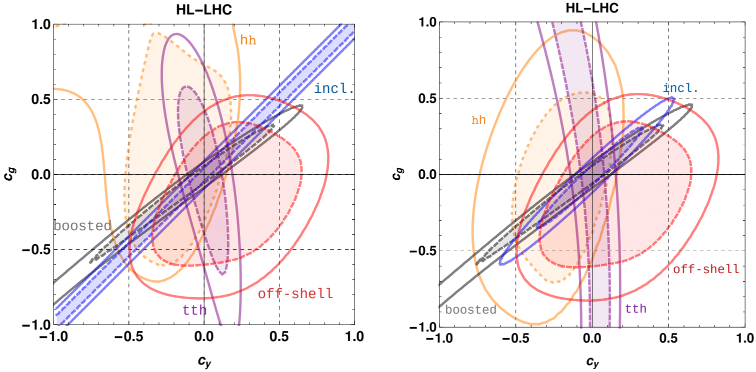


Processes considered

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

Results of combination for HL -LHC

Azatov, Grojean, Paul, Salvioni (2016/18)



no $h\gamma\gamma$ operator

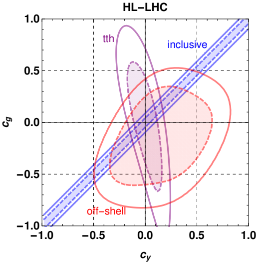
double Higgs from 1502.00539; H+j from 1405.4295, inclusive and tth from ATL-PHYS-PUB-2013-014

Fit with only O_y and O_g operators

Azatov et al.

The degeneracy becomes even worse if we add the following operator to the lagrangian

$$\mathcal{L}_6 = c_y \frac{y_t |H|^2}{v^2} \bar{Q}_L \widetilde{H} t_R + \text{h.c.} + \frac{c_g g_s^2}{48\pi^2 v^2} |H|^2 G_{\mu\nu} G^{\mu\nu} + \frac{c_g g'^2}{18\pi^2 v^2} |H|^2 B_{\mu\nu} B^{\mu\nu}$$



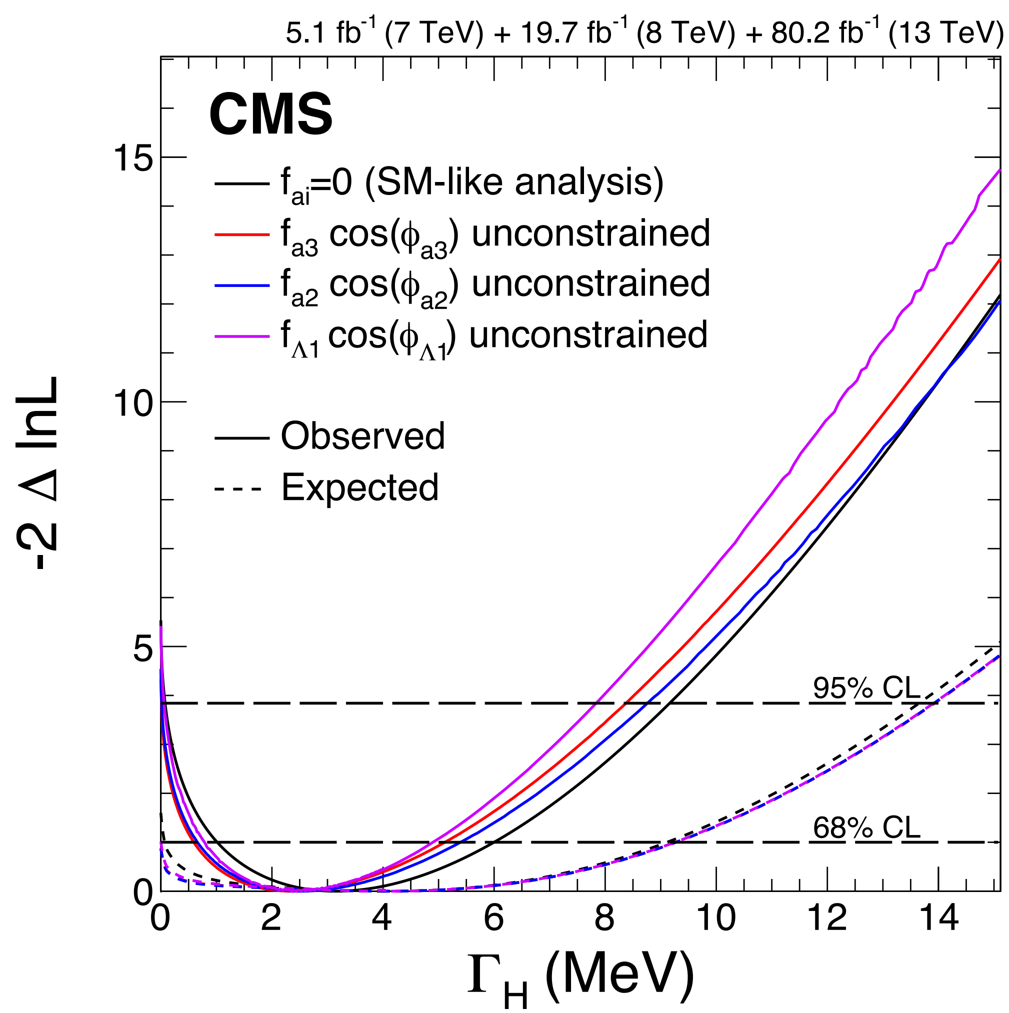
Modification of the Higgs interactions to gluons and to photons are controlled by $c_y - c_g$

(3) anomalous HVV couplings (EFT)

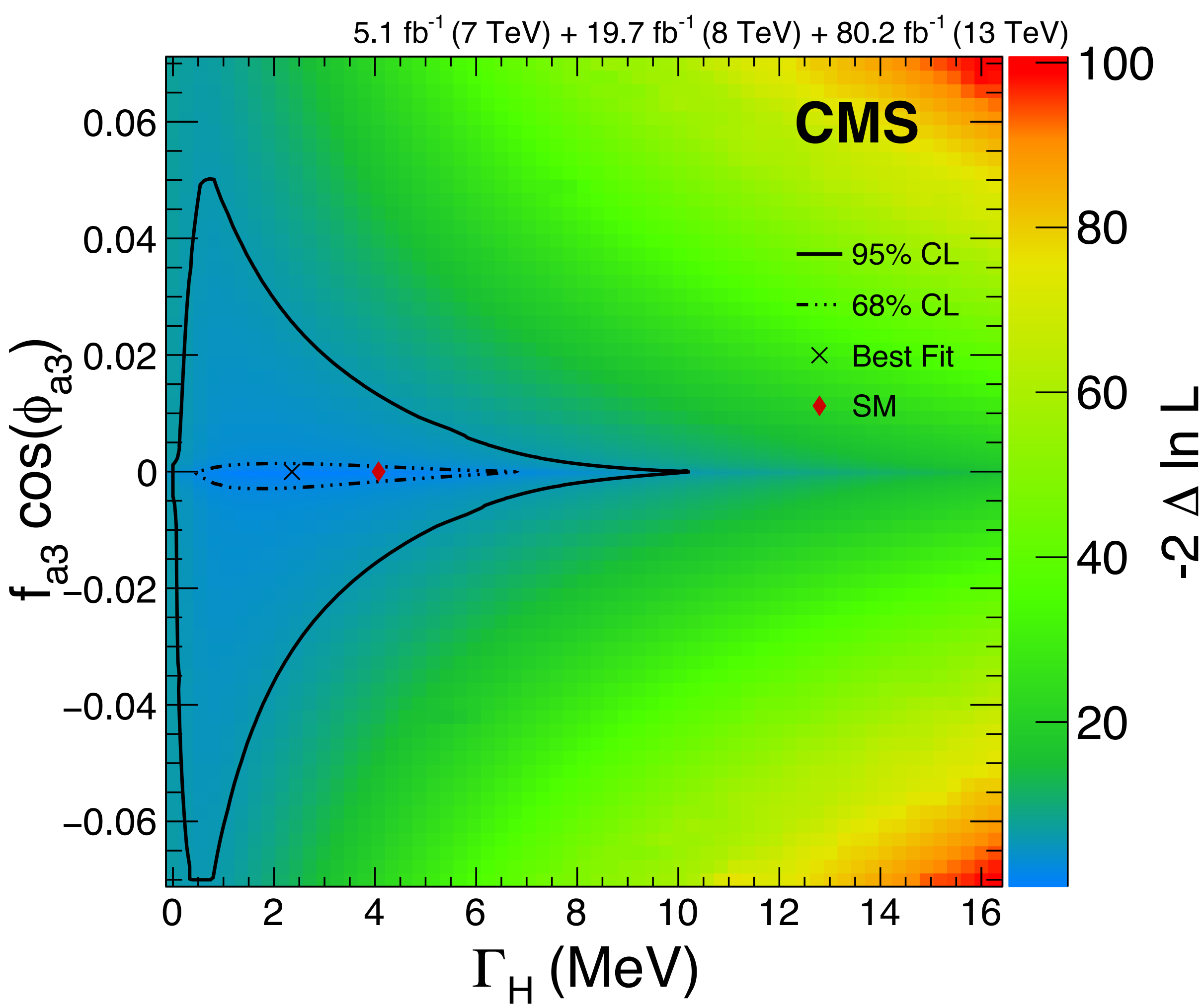
- tested anomalous HVV couplings (production and decay)

$$\frac{d\,\sigma_{gg\to H\to ZZ}}{d\,m_{ZZ}^2} \sim \frac{g_{\mathrm{ggH}}^2 g_{\mathrm{HZZ}}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H{}^2}$$

(1) not much effect on Γ_H



(2) constrain couplings given Γ_H or profile Γ_H



Count the number of EFT parameters in the Higgs basis

- Higgs HVV basis is ideal for off-shell studies
  - — does not mix physical states Z,γ,W to non-physical B,W^0,W
  - — off-shell effect is interplay of Z* (or W*) vs H*
  - — it is always possible to rotate the basis in the end
- Reduce to 4 HVV and 2 Hgg EFT couplings

  on CMS also set $g_i^{WW} = g_i^{ZZ}$ ($\Leftrightarrow c_w = 1$ in EFT relationship)

$$
\begin{aligned}
g_1^{WW} &= g_1^{ZZ}, \\
g_2^{WW} &= c_w^2 g_2^{ZZ} + s_w^2 g_2^{\gamma\gamma} + 2 s_w c_w g_2^{Z\gamma}, \\
g_4^{WW} &= c_w^2 g_4^{ZZ} + s_w^2 g_4^{\gamma\gamma} + 2 s_w c_w g_4^{Z\gamma}, \\
\frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}(c_w^2 - s_w^2) &= \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2}, + 2 s_w^2 \frac{g_2^{\gamma\gamma} - g_2^{ZZ}}{M_Z^2} + 2\frac{s_w}{c_w}(c_w^2 - s_w^2)\frac{g_2^{Z\gamma}}{M_Z^2}, \\
\frac{\kappa_2^{Z\gamma}}{(\Lambda_1^{Z\gamma})^2}(c_w^2 - s_w^2) &= 2 s_w c_w \left(\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + \frac{g_2^{\gamma\gamma} - g_2^{ZZ}}{M_Z^2} \right) + 2(c_w^2 - s_w^2)\frac{g_2^{Z\gamma}}{M_Z^2}.
\end{aligned}
$$

do not consider in off-shell

Some questions to discuss in this forum

- How to explore (hep-ex → hep-ph) off-shell region?
  - — present as Γ_H
  - — present as off-shell signal strength μ, or σ
  - — present as some STXS-like signal strengths
  - — present as modification of (EFT) H couplings
  - — present as modification of (EFT) EW parameters
  - — present as search for new resonance(s)
  - — present as search for some other (exotic) model
  - — present as differential distribution
  - — present as in other ways …
- May become very complex, but we also should be practical:
  - — in hep-ex, we like to have a path to explore the data
  - — at present, we are not limited in having paths
  - — each option has pros and cons…

My conclusions

- Precision: impressive progress to 2-loop with ∼/full m_t dependence, calculations/tools for $pp \to ZZ$ @ NNLO+ becoming available, *WW* next
- Beyond specific models/benchmarks:
  Two frameworks/paradigms to study high-mass New Physics: κ or EFT
- Tools available, SMEFT@NLO MC implement. compl./being validated
  need to coordinate tools development with experiments for max. effect
- Theory ↔ Experiment: most suitable EFT bases? Accord(s)?
- Finding limits for some EFT operators/κ's using some processes/signatures with certain c_i assumptions is an excellent start, but not the end
- TH, Pheno and Exp need to work together: Theoretical aspects and how to test them experimentally needs to be discussed comprehensively and jointly to fully exploit the LHC (facilitated by working groups)
- Within experiments: official support at high level is desirable
- **Producing more/better limits is not the ultimate goal**
- **(Higgs) NP characterisation is our task – or to rule it out**
- EFT validity: need to exclude light new degrees of freedom
- Theoretical work on realisations of SM deviations continues to be important