OffShell Theory Status

Nikolas Kauer, Raoul Röntsch

16th Workshop of LHC Higgs Cross Section Working Group

16 October 2019

Introduction

- Focus on processes with sizeable contribution from offshell Higgs.

- E.g: $gg \rightarrow H \rightarrow VV$:

  10% of events above the $2m_V$ threshold.

  [Kauer, Passarino '12]

- Allows the exploration of the Higgs properties in a new kinematic regime:
  - Width   [Caola, Melnikov '13]
 - Couplings
  - Unitarization properties
  - ...

Ongoing Work

- Higher-order corrections:
  - Finite top mass effects at NLO.
  - Quark-gluon channel at NLO.
  - NLO+PS?
  - EW corrections?

- Interpretations:
  - Model dependence of Higgs width/couplings.
  - New directions.

Higher Order Corrections

Offshell Theory Status

Top mass dependence at NLO

- Offshell regime requires:
  - Full top quark mass dependence for amplitudes;
  - Interference between signal and background
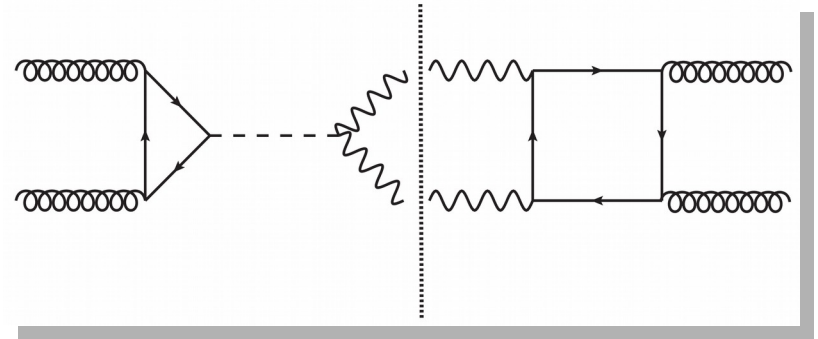
- At NLO, need two loop $gg \to VV$ with mass dependence: <u>very challenging and still not known!</u>
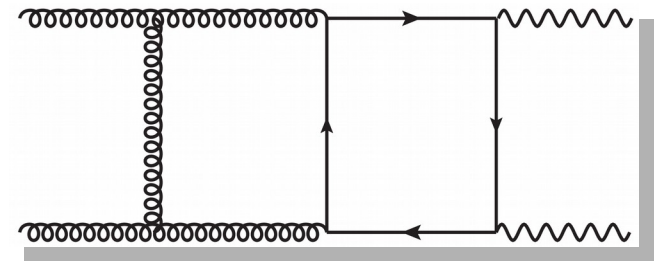

- Approximations:
  - Expansion in $1/m_t$ – valid in $m_H < m_{VV} < 2m_t$.

    [Campbell *et al.* '16; Caola *et al.* '16]

    → NLO corrections ~ 50%-80%
  - Expansion in $1/m_t$ + Padé Approximation. [Campbell *et al.* '15]

Top mass dependence at NLO

Recent progress:

- Expansion in *1/m_t* + Threshold expansion + Padé Approximation:

[Gröber, Maier, Rauh 1908.04061]

  – Inclusion of threshold expansion provides new analytic information -- improves Padé approximation.

  – Method tested for 2-loop corrections to $gg \to HH$ against full results from [Borowka *et al.* '16].

  – Method works well for one-loop $gg \to VV$.

  – **NEW**: two-loop $gg \to VV$ form factors
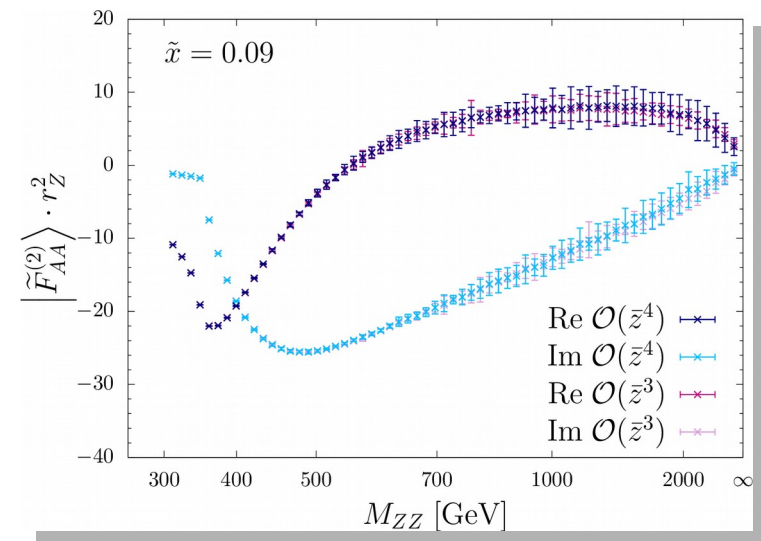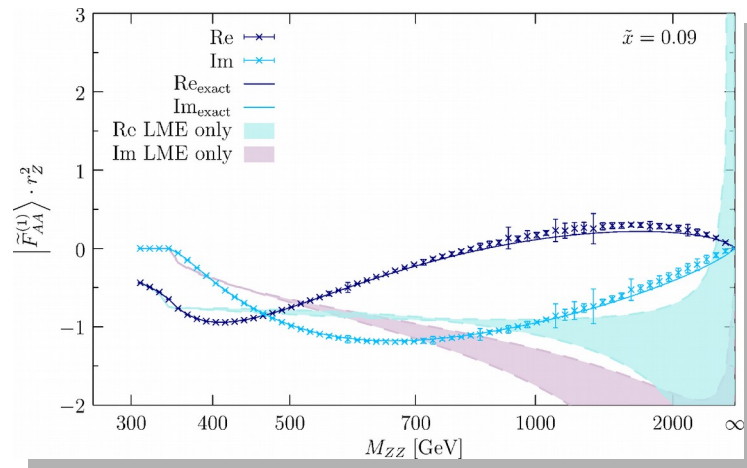
Progress towards full two-loop amplitude

A. von Manteuffel and B. Agarwal, work in progress

$gg \to ZZ$ at 2-loops

- 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** $\Rightarrow$ Much better behaved numerically

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

[Talk by B. Agarwal, May 2019]

Quark-Gluon Effects

- Quark-gluon channel for loop diagrams opens up at NLO.
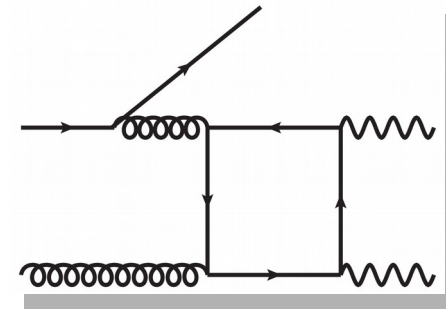
- Effects on interference included by [Campbell *et al.* '16].

- Included in background $gg \rightarrow VV$ (massless loops) [Grazzini, Kallweit, Wiesemann, Yook, 1811.09593] [Talk by J.Y. Yook, May 2019]

- Interference between loop-induced corrections and corrections to tree-level processes.

  - **Numerical impact?**

  - **Impact on scale variation?**

Interpretations
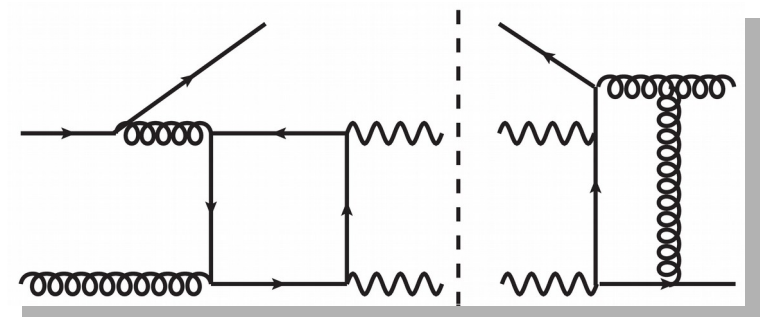
Offshell Theory Status

Higgs Width and Offshell Couplings

- E.g. width extraction from comparison of offshell and onshell production model dependent.

- How can we best exploit the offshell data?

- Simultaneously constrain widths and BSM couplings [Ulascan's talk]:

$$A(H \rightarrow VV) \propto \left[a_1^{VV} - \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_1^2}{\left(\Lambda_1^{VV}\right)^2} - \frac{\kappa_3^{VV} (q_1 + q_2)^2}{\left(\Lambda_Q^{VV}\right)^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^*$$

$$+ a_2^{VV} f_{\mu\nu}^{*(1)} f*(2)\mu\nu + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}*(2)\mu\nu$$
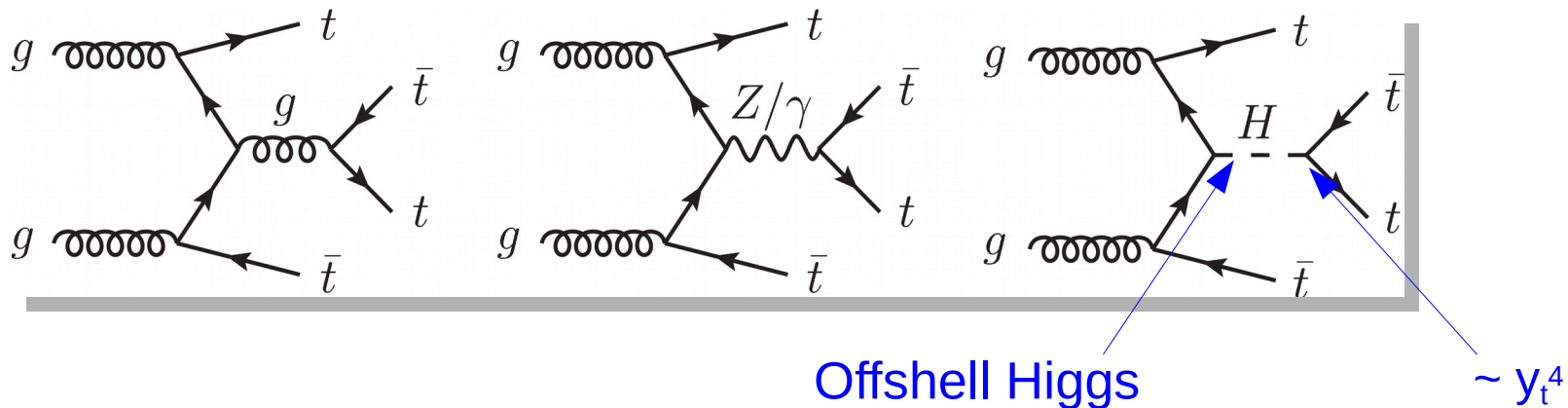
[Anderson *et al.* '13]

- Other ideas?

New Directions (I)

Top Yukawa and width constraints in $t\bar{t}t\bar{t}$ production

[Cao, Chen, Liu '16; Cao, Chen, Liu, Zhang, Zhang, 1901.04567]

Offshell Higgs   ~ y_t^4

- Combination with e.g. GF and $t\bar{t}H$ production ⟹ constrain top Yukawa, CP mixing of Higgs, Higgs width...

- See Ulascan's talk.

New Directions (II)

- Higgs interference effects on heavy Higgs states

  [Kauer, Lind, Maierhöfer, Song, 1905.03296] [Talk by N. Kauer, May 2019]

  – Large loop interference effects for gg $(\to h_1, h_2)$ $\to$ WW.

  – Large tree and larger loop interference effects in gg $(\to h_1, h_2)$ $\to$ $t\bar{t}$.

  – "Higgs interference is a constituent part of BSM signal."

- "Higgs without Higgs": look at Higgs couplings through high energy processes with longitudinal vector bosons.

  [Henning, Lombardo, Riembau, Riva, 1812.09299]

  [Talk by B. Henning, May 2019]
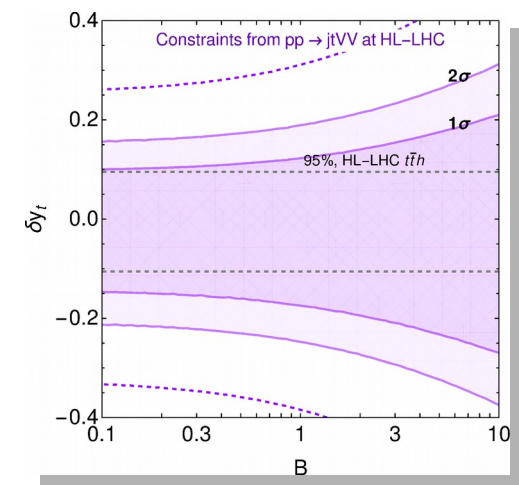
Summary

- Progress on top mass dependence for NLO calculations:
  - Use of $1/m_t$ + threshold expansion + Pade approximation.
  - Progress towards full two-amplitudes with top mass dependence.

- Quark-gluon effects now known for $gg \rightarrow VV$ background.
  - Impact on scale dependence? Other qg channels?

- Still no NLO+PS results for offshell $gg(\rightarrow H) \rightarrow VV.$

- New possibilities beyond $gg (\rightarrow H) \rightarrow VV$, e.g. $t\bar{t}t\bar{t}$.

THANK YOU FOR YOUR ATTENTION