HH production: NLO+PS and top-quark mass effects in gluon fusion

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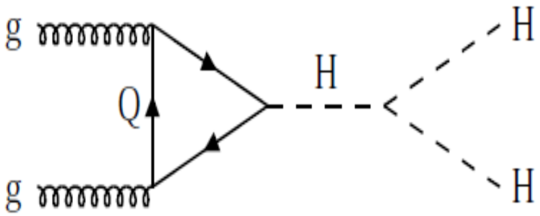
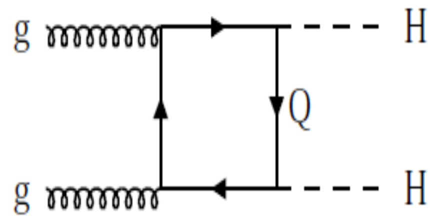
Phys.Lett. B732 (2014) 142-149 and JHEP 1411 (2014) 079

HPPC2015
Mainz
29/4/15

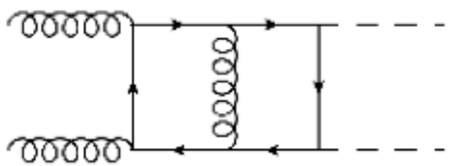
HH in gluon-gluon fusion





Biggest cross section
Only loop induced channel

- Exact NLO computation requires:
  - Real emissions: HHj one loop (doable) ✔
  - Virtual corrections: Include 2-loop amplitudes ✗



Not available (yet)

Use a low energy theory

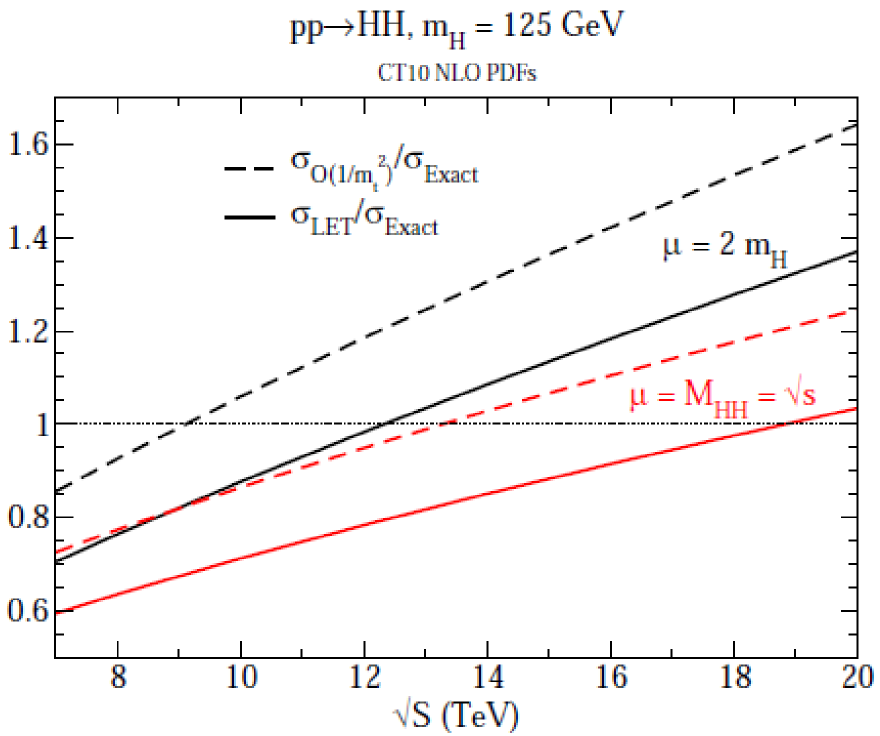
Effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \frac{1}{4}\frac{\alpha_s}{3\pi} G^a_{\mu\nu} G^{a\,\mu\nu} \log(1 + h/v)$$

$$\mathcal{L} \supset +\frac{1}{4}\frac{\alpha_s}{3\pi v} G^a_{\mu\nu} G^{a\,\mu\nu} h - \frac{1}{4}\frac{\alpha_s}{6\pi v^2} G^a_{\mu\nu} G^{a\,\mu\nu} h^2 \,.$$

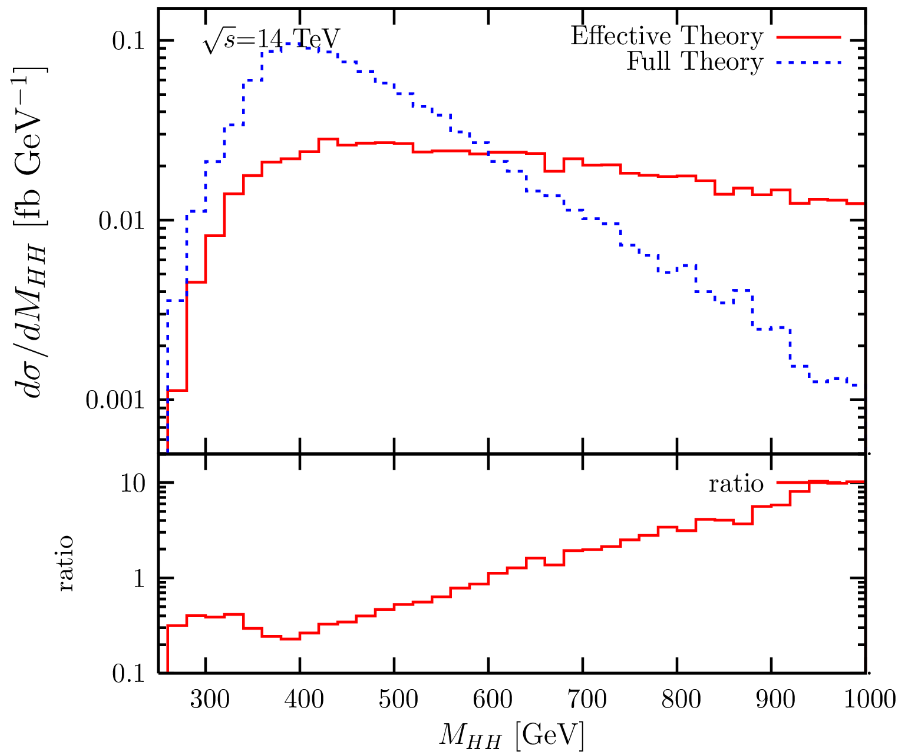
HEFT approach in HH production

How well does the HEFT work for HH at LO?



Dawson, Furlan, Lewis 1206.6663

10-20% difference for the total cross section



MadGraph5_aMC@NLO

HEFT fails to reproduce the differential distributions, also for additional jets

Mass effects are important and need to be included

NLO approximations for HH: A step further

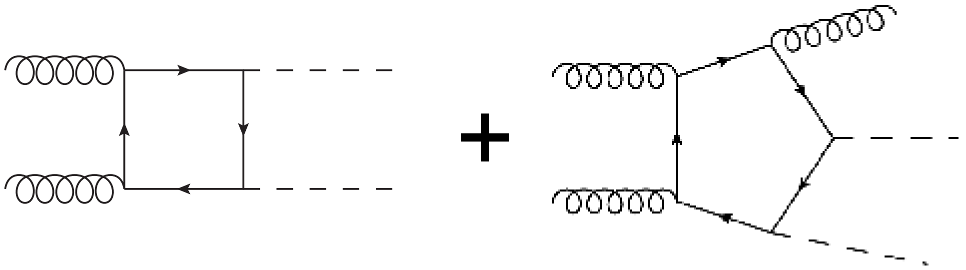
Going beyond the Hpair approximation

Using all available information:

1) Exact real emission matrix elements
2) Virtual corrections in the HEFT-rescaled by the exact born

Within the MG5_aMC@NLO framework:

- HEFT UFO model allows us to generate events at NLO
- MadLoop can perform the computation of the one-loop matrix elements: born and real-emission



A reweighting approach for HH

- NLO HEFT event generation: MC@NLO method

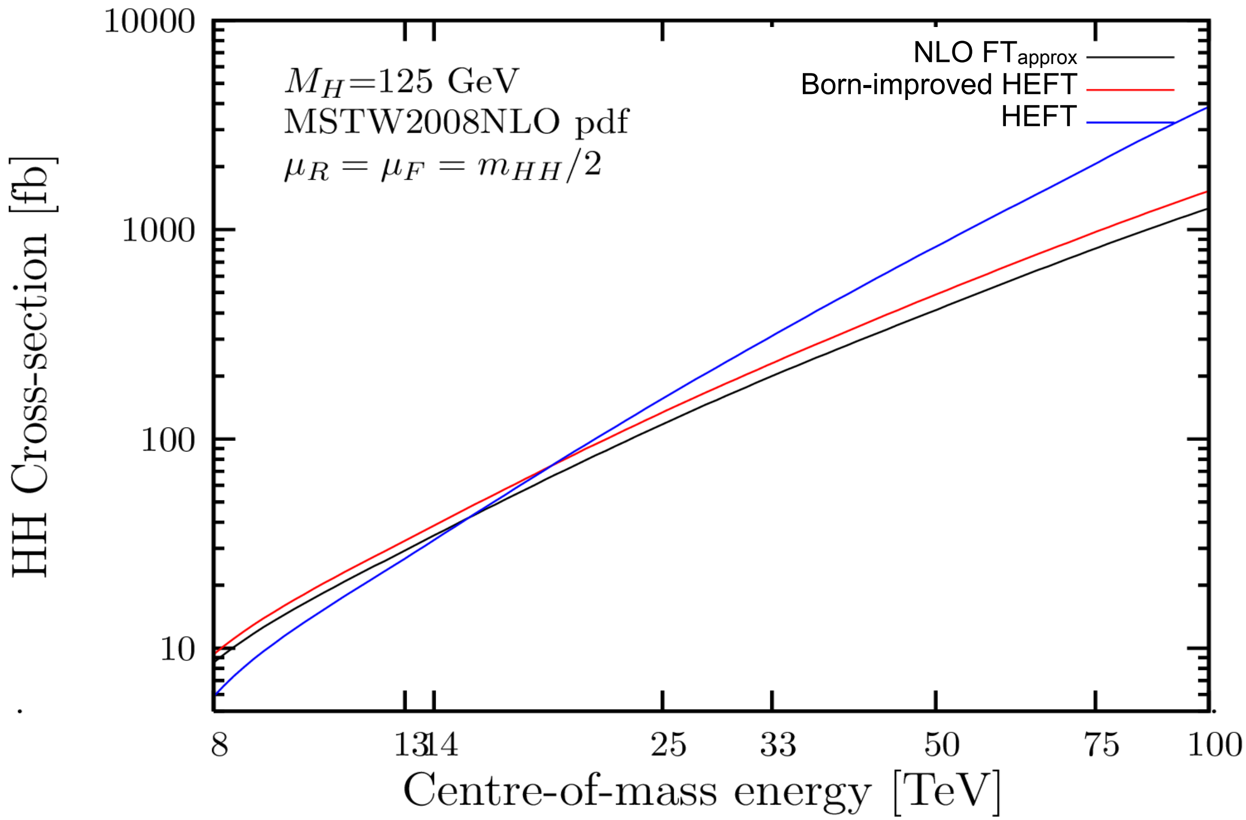
$$d\sigma^{(\mathbb{H})} = d\phi_{n+1}\left(\mathcal{R} - \mathcal{C}_{MC}\right) ,$$
$$d\sigma^{(\mathbb{S})} = d\phi_{n+1}\left[\left(\mathcal{B} + \mathcal{V} + \mathcal{C}^{int}\right)\frac{d\phi_n}{d\phi_{n+1}} + \left(\mathcal{C}_{MC} - \mathcal{C}\right)\right]$$

- Different weights stored internally: virtual, real and counter terms
- Reweight on an event-by-event basis using the results of the exact loop matrix elements. Schematically:

$$\mathcal{B}, \mathcal{V}, \mathcal{C}^{(int)}, \mathcal{C}_{MC} \quad \times \quad \mathcal{B}_{FT}/\mathcal{B}_{HEFT}$$
$$\mathcal{R} \quad \times \quad \mathcal{R}_{FT}/\mathcal{R}_{HEFT}$$

- Fully differential reweighting
- Setup allows implementation of a Born (Hpair-type) reweighting if all weights are reweighted by $\mathcal{B}_{FT}/\mathcal{B}_{HEFT}$

Results: Total cross section for HH



Comparing:

- NLO FT$_{approx}$ (exact real-approximate virtuals)
- Born-improved HEFT
- NLO HEFT

- Reduction of the cross section by about 10% compared to the Born-improved results at 14 TeV

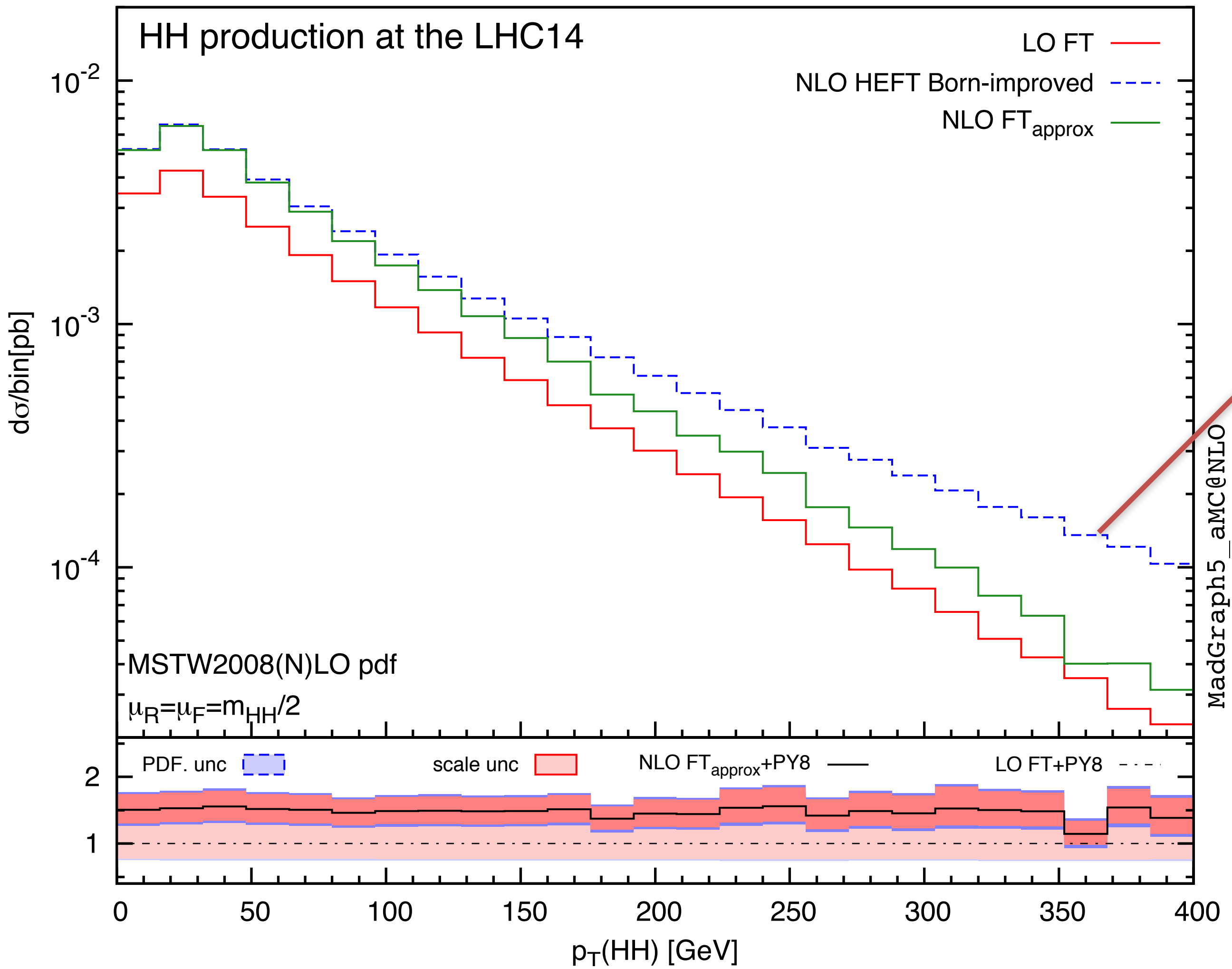
Results at 14 TeV [fb]

LO	FT, $\Gamma_t = 0$ GeV	$23.2^{+32.3+2.0\%}_{-22.9-2.3\%}$
	FT, $\Gamma_t = 1.5$ GeV	$22.7^{+32.3+2.0\%}_{-22.9-2.3\%}$
NLO	HEFT	$32.9^{+18.1+2.9\%}_{-15.5-3.7\%}$
	HEFT Born-improved	$38.5^{+18.4+2.0\%}_{-15.1-2.4\%}$
	FT$_{approx}$ (virtuals: Born-rescaled HEFT)	$34.3^{+15.0+1.5\%}_{-13.4-2.4\%}$

2%: Use of Complex-Mass-Scheme Finite top width

10% : Exact real emission amplitudes

Differential distributions for the LHC



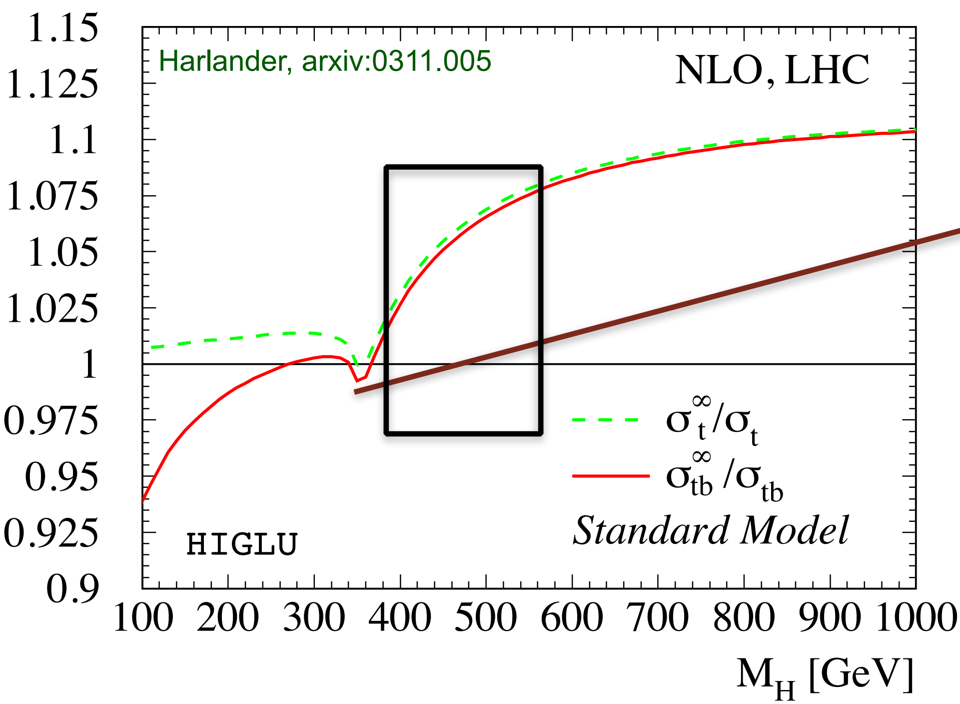
Including the exact matrix elements has a bigger effect in the region of hard parton emission: tail of pT(HH) distribution
Exact matrix elements give a better description

Are our results robust?

One might argue that we are spoiling possible cancellations by including the exact top mass dependence in the real corrections but not in the virtual corrections…

Let's look at single Higgs production: Comparison of

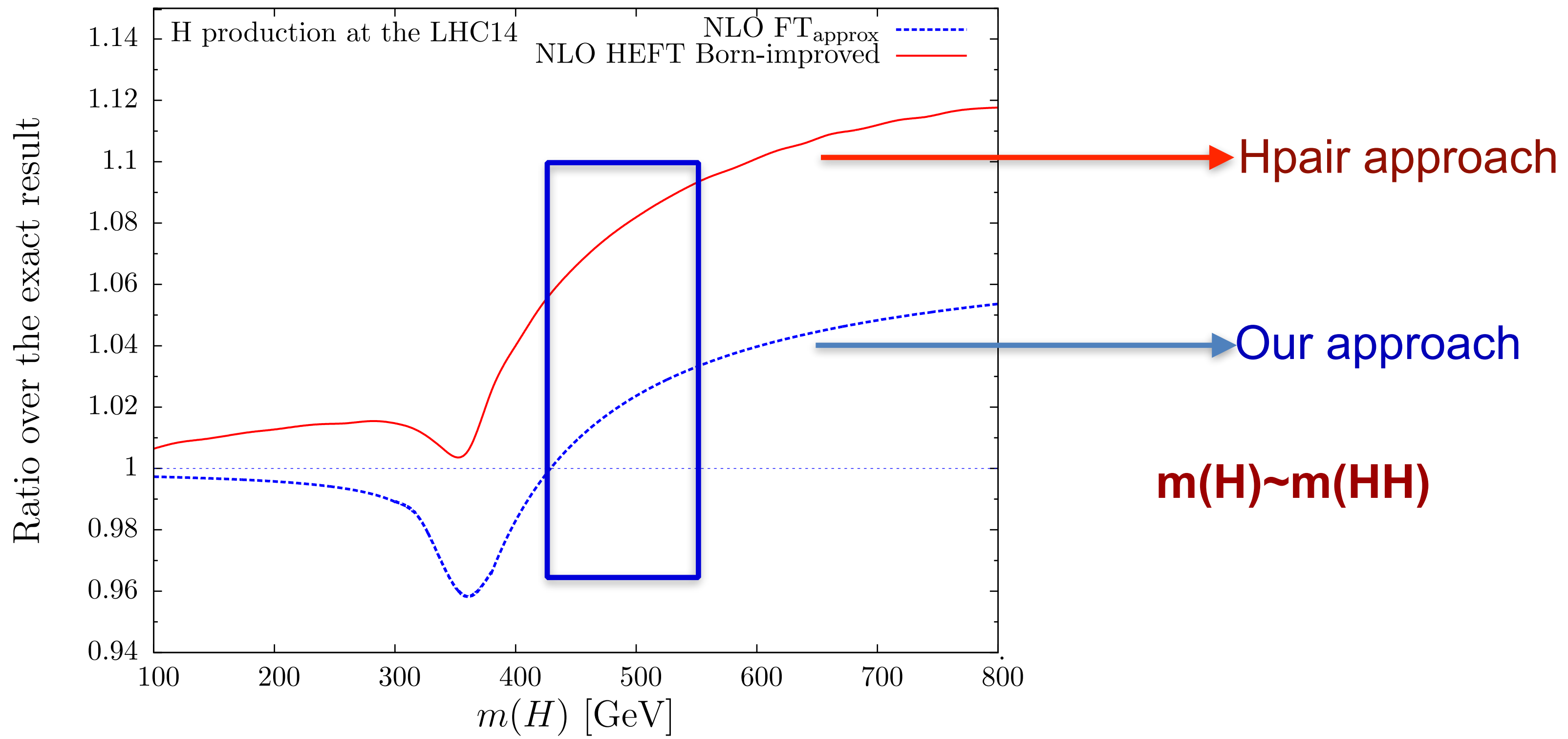
- Born-rescaled HEFT results $\sigma^{NLO}_{HEFT} \times \sigma^{LO}_{FT}/\sigma^{LO}_{HEFT}$
- Available exact results



Michael Spira: "Below and at the $2m_t$ threshold a cancellation is happening between the top mass effects in the real and virtual corrections and the Born-rescaled HEFT result is very close to the exact one"

The single Higgs case

Same procedure applied to single Higgs production for different Higgs masses: Comparison to the exact result:



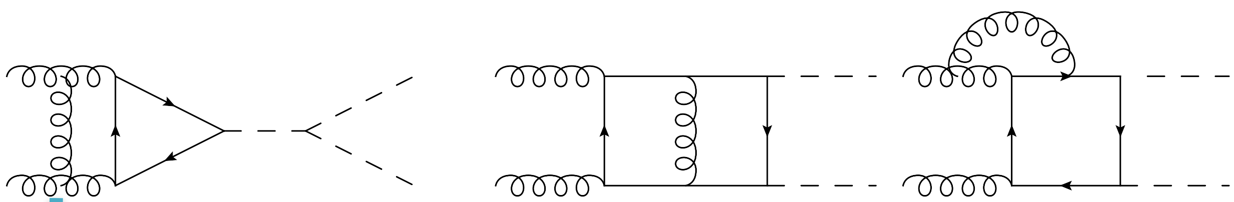
m(H)~m(HH)

The bulk of the HH cross section lies well above the $2m_t$ threshold

In this region the Born-rescaled results overestimate the exact result for single Higgs: 7-8% at 500 GeV

Approximate virtual corrections

Varying the virtual corrections for HH



- Part (triangle) of the virtual corrections is known from single Higgs NLO corrections
- Corrections known as a function of the Higgs and top masses

Assume these corrections factorise in the same way for the box and triangle i.e.

$$\sigma_{virt}^{HH} = \frac{\sigma_{virt}^{H}}{\sigma_{Born}^{H}} \times \sigma_{Born}^{HH}$$

NLO results at 14 TeV [fb]

$\mathrm{FT}_{\mathrm{approx}}$ (virtuals: Born-rescaled HEFT)	$34.3^{+15.0+1.5\%}_{-13.4-2.4\%}$
$\mathrm{FT}'_{\mathrm{approx}}$ (virtuals: estimated from single Higgs in FT)	$35.0^{+15.7+2.0\%}_{-13.7-2.4\%}$

→ 2% effect

Conclusion: Results are stable under the variation of estimates for the (unknown) finite part of the virtual corrections

Summary-Outlook

- New Monte Carlo implementation of the gluon fusion process at approximate NLO, provided within MG5_aMC@NLO
- Results are obtained by employing the exact matrix elements for the real emission amplitudes and Born-rescaled HEFT virtual corrections
- Provides a better description of the high p_T kinematics and a total cross section different by -10% from the Born-rescaled result

- **Comparison to other NLO approximations (Jonathan's talk)**

⇒ **Associated uncertainty due to missing top mass effects ~10%**

Thanks for your attention...