Monte Carlo Modelling of HH

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HH workshop

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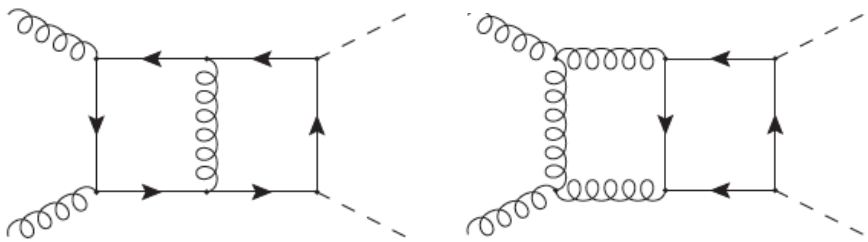
HH at NLO with exact top mass dependence

HH@NLO: Full top mass dependence

Borowka et al 1604.06447 and 1608.04798

NLO computation for gluon fusion with the exact top mass dependence complete



2-loop amplitudes computed with

GOSAM-2L $\Rightarrow$ REDUZE $\Rightarrow$ SECDEC 3

Numerical evaluation of integrals

$\sqrt{s}$	LO	B-i. NLO HEFT	NLO FT$_{approx}$	NLO
14 TeV	$19.85^{+27.6\%}_{-20.5\%}$	$38.32^{+18.1\%}_{-14.9\%}$	$34.26^{+14.7\%}_{-13.2\%}$	$32.91^{+13.6\%}_{-12.6\%}$

See also Stephen's talk

-14%

-4%

HH@NLO+PS: prerequisites

2D grid: s,t $\Rightarrow$ x, c_θ for a uniform distribution

$$x = f(\beta(\hat{s})), \quad \text{with} \quad \beta = \left(1 - \frac{4m_h^2}{\hat{s}}\right)^{\frac{1}{2}}$$

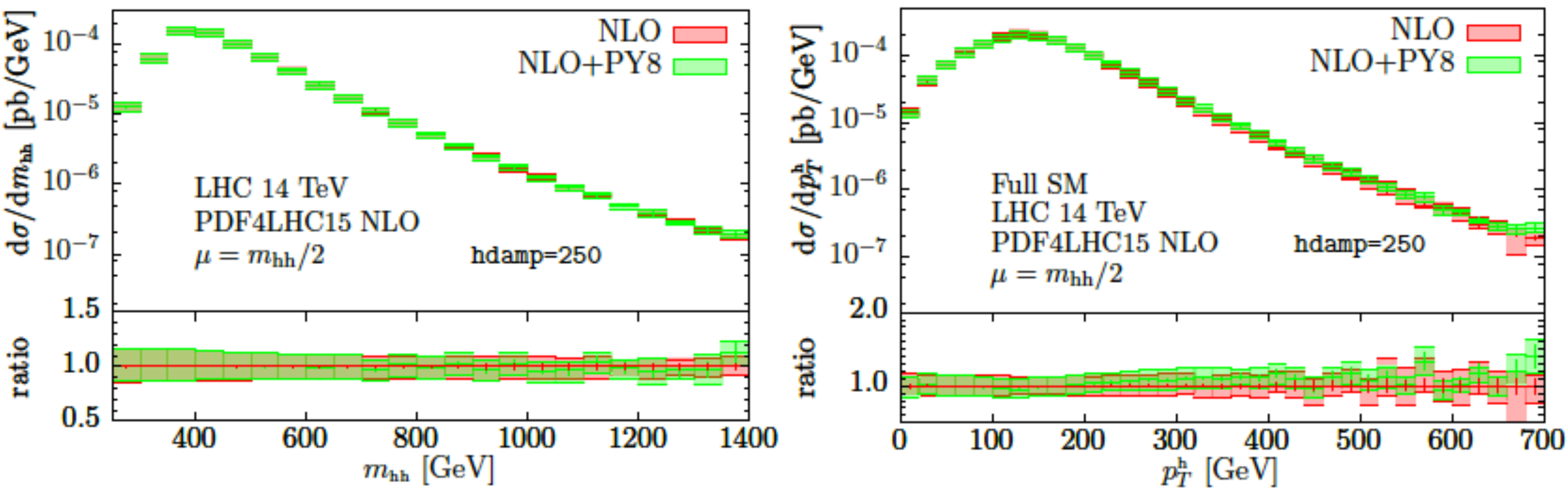
$$c_\theta = |\cos\theta| = \left|\frac{\hat{s} + 2\hat{t} - 2m_h^2}{\hat{s}\beta(\hat{s})}\right|,$$

Use of grid necessary to ensure reasonable running times

- Finite pieces of the virtual corrections obtained in the FKS convention as needed in the Powheg and MG5_aMC@NLO frameworks
- One-loop amplitudes for born and real kinematics:
  - Powheg: Implementation based on GoSam
  - MG5_aMC@NLO: MadLoop

- Both implementations allow comparisons to previous approximations: Born-improved and FTapprox

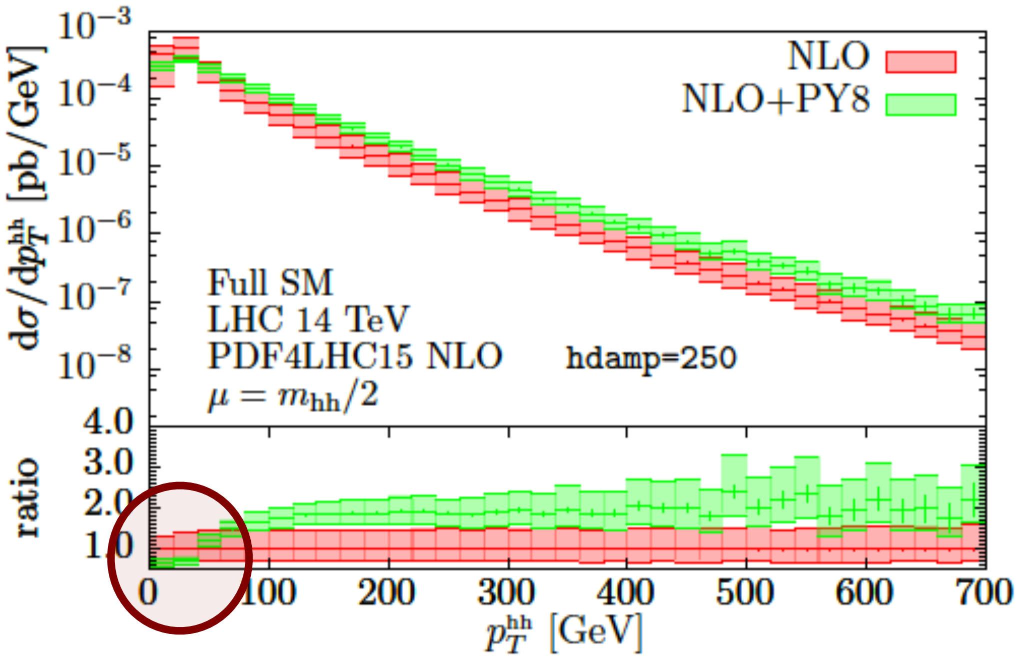
HH@NLO+PS: Results

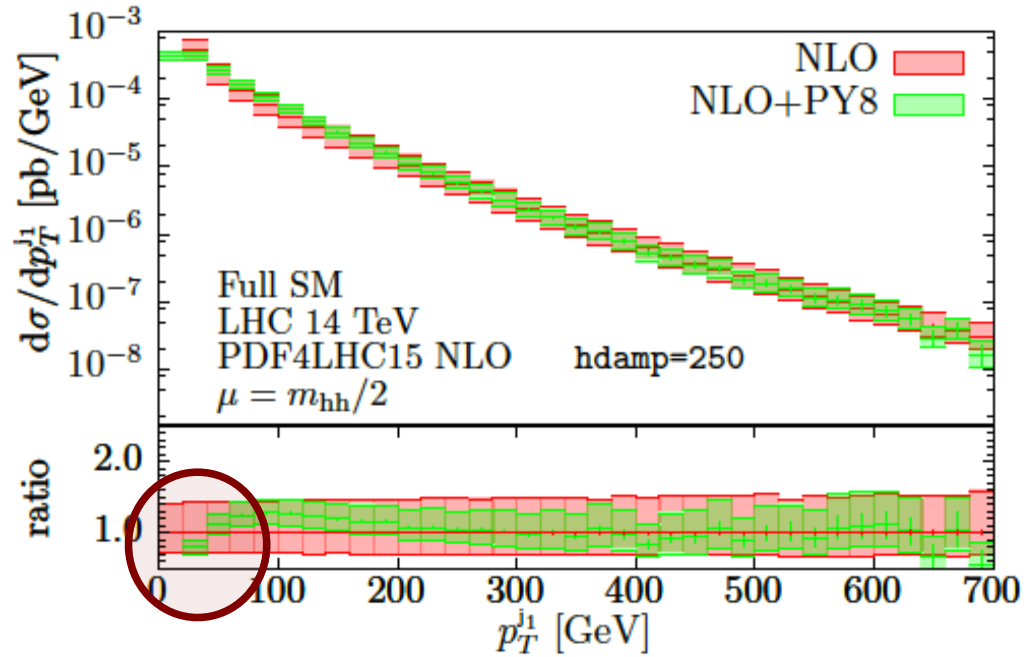


Insensitive to the PS, serve as validation

Heinrich, Jones, Kerner, Luisoni, EV arXiv:1703.09252

HH@NLO+PS:Results

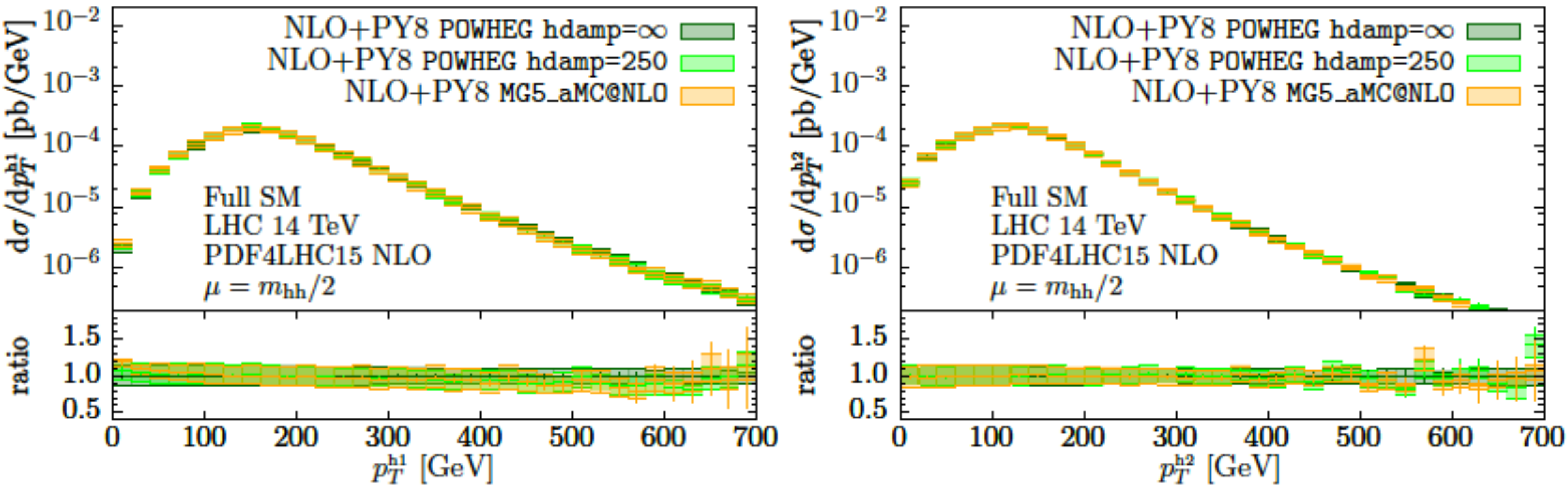




Parton shower needed to provide reliable predictions at low HH and jet p_T, where the fixed-order predictions diverge

Heinrich, Jones, Kerner, Luisoni, EV arXiv:1703.09252

Comparison between POWHEG and MG5_aMC

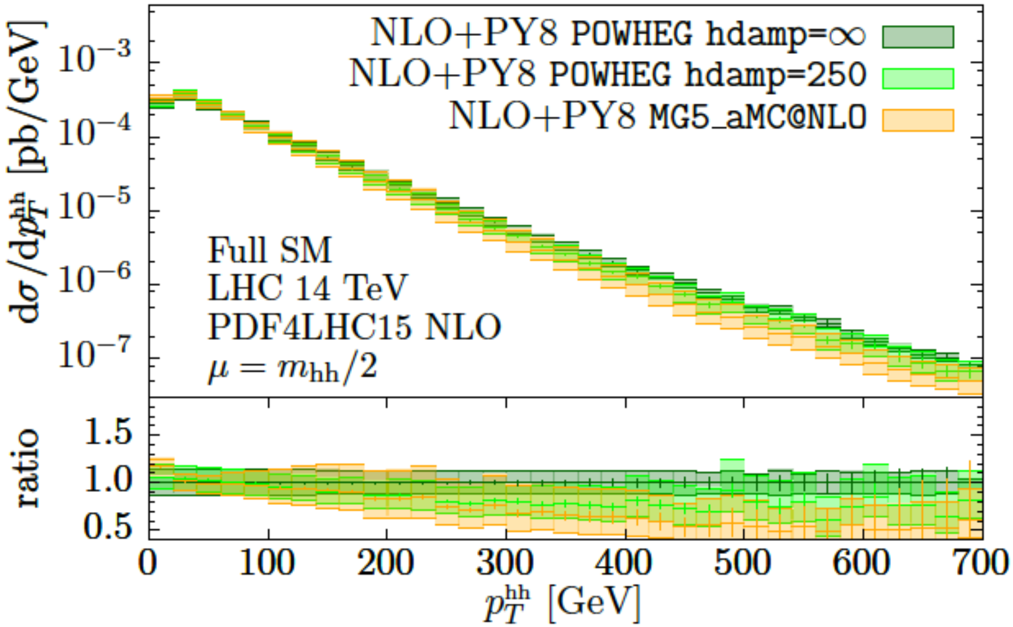


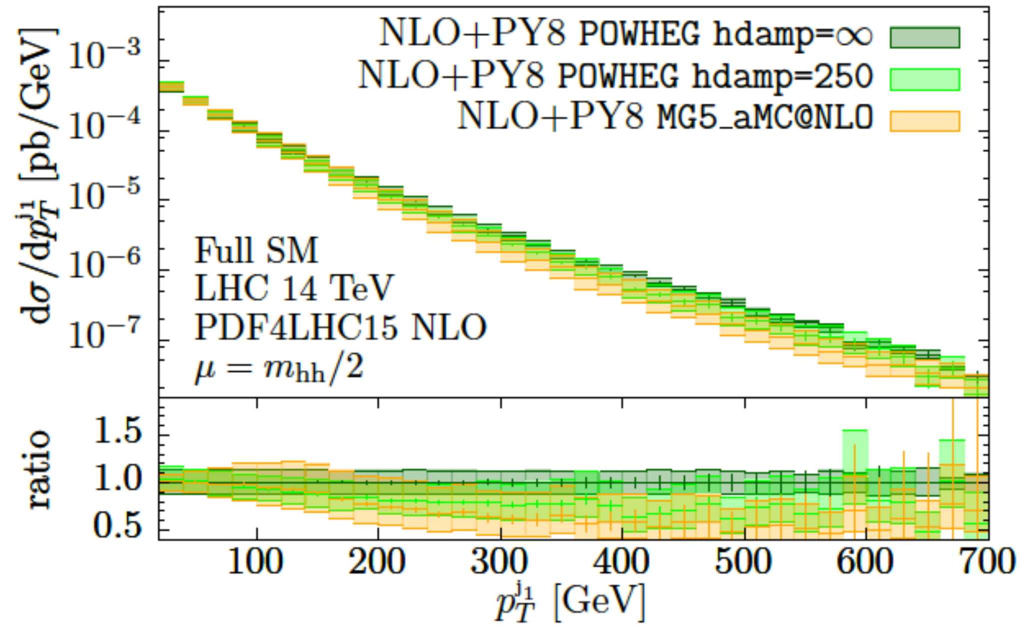
Same parton shower differences due to matching

m_{hh}, p_T^H, p_T^{H1}, p_T^{H2} largely insensitive to the matching

Heinrich, Jones, Kerner, Luisoni, EV arXiv:1703.09252

Comparison between Powheg and MG5_aMC



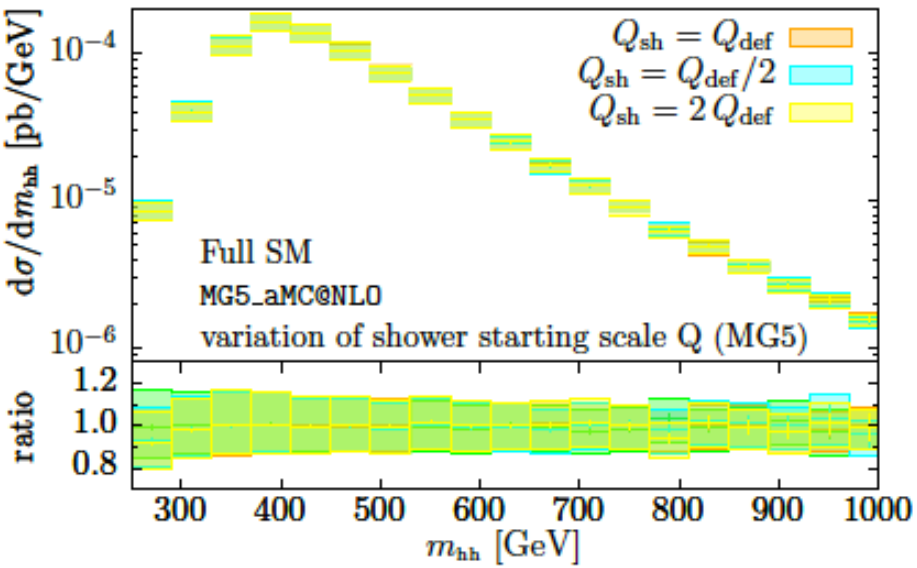


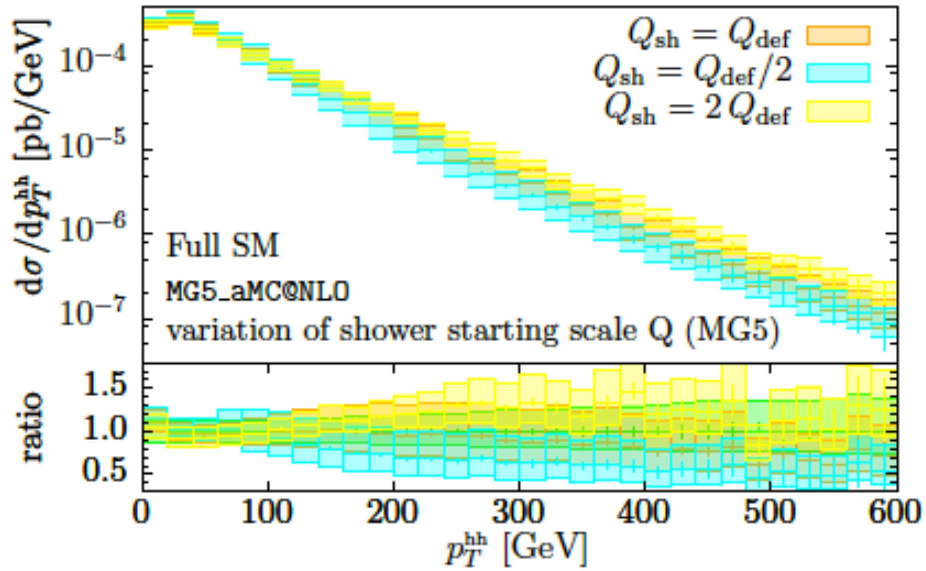
- hdamp limits the amount of exponentiated radiation in Powheg

$$R_{\mathrm{sing}} = R \times F\,, \qquad R_{\mathrm{reg}} = R \times (1-F) \qquad F = \frac{h^2}{(p_T^{\mathrm{hh}})^2 + h^2}$$

- Reducing hdamp gives softer distributions in Powheg
- Default MG5_aMC@NLO gives relatively soft distributions

Shower parameters: shower scale in MG5





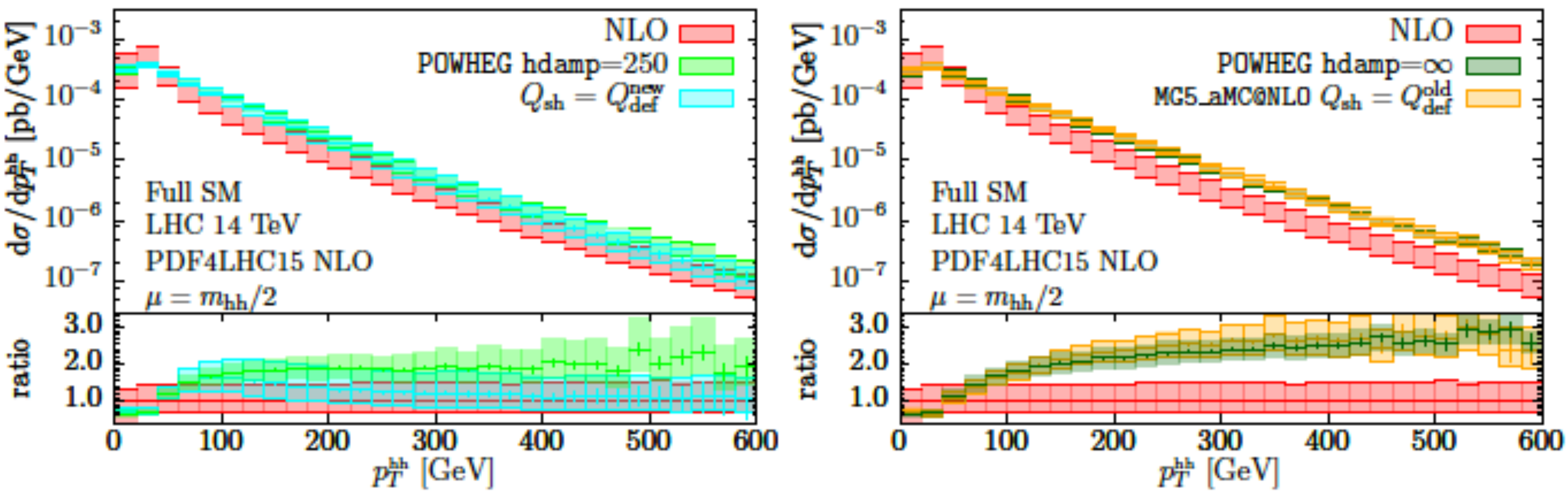
Default shower scale in MC@NLO (since 2.5.3): picked in the interval

$$\texttt{shower\_scale\_factor} \times [0.1\, H_T/2, H_T/2]$$

can be set in the run_card

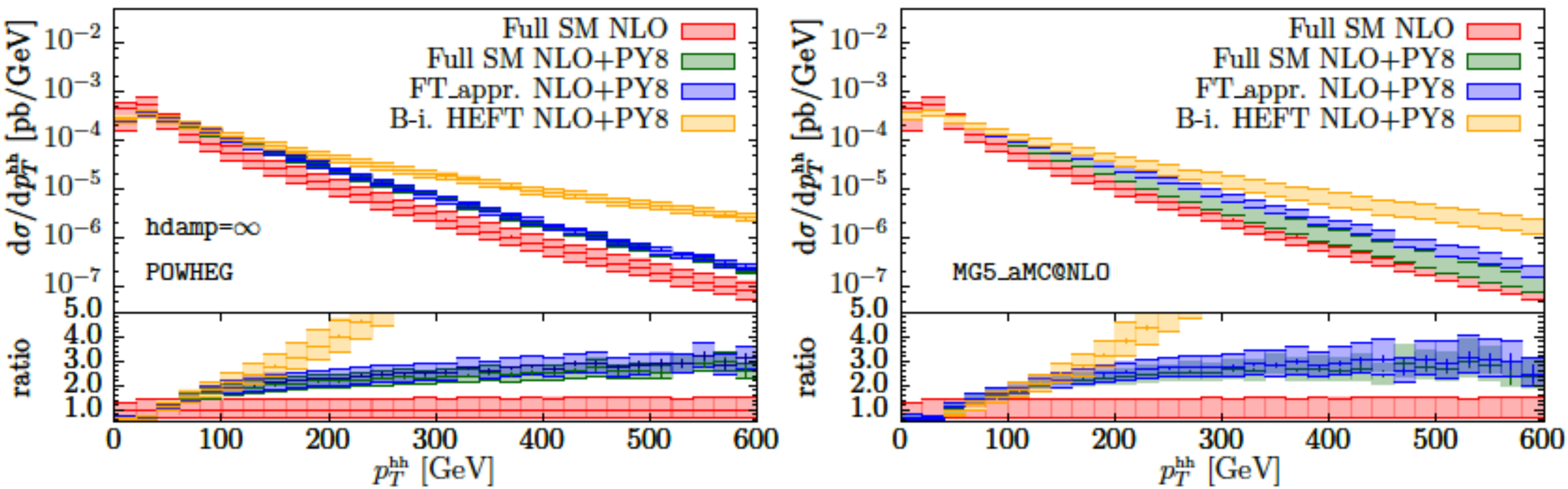
Impact of reducing the shower scale: Softer p_T^{HH} distributions

Shower parameters in MG5_aMC and Powheg



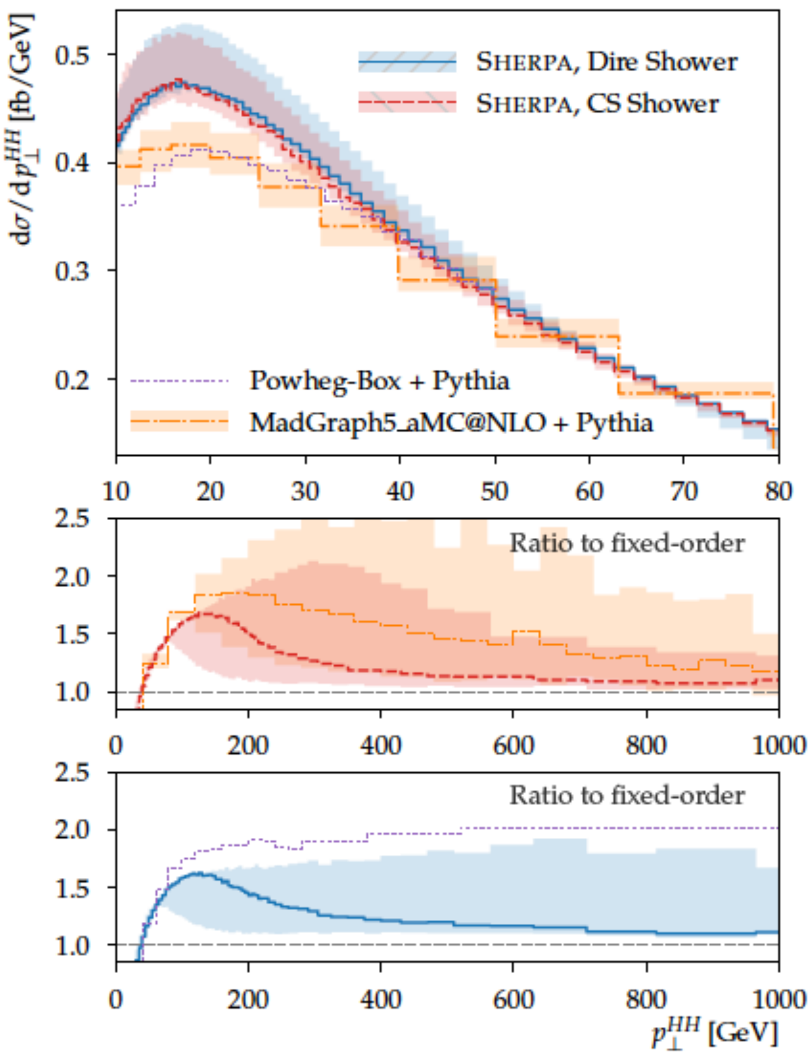
- Previous shower scale used in MG5_aMC: $[0.1\sqrt{\hat{s}}, \sqrt{\hat{s}}]$ gives significantly harder distributions close to hdamp=infinity
- New default scale approaches the fixed-order result much faster: a more natural choice
- Similarly hdamp=250 gives softer results, closer to the FO

Comparison with previous approximations

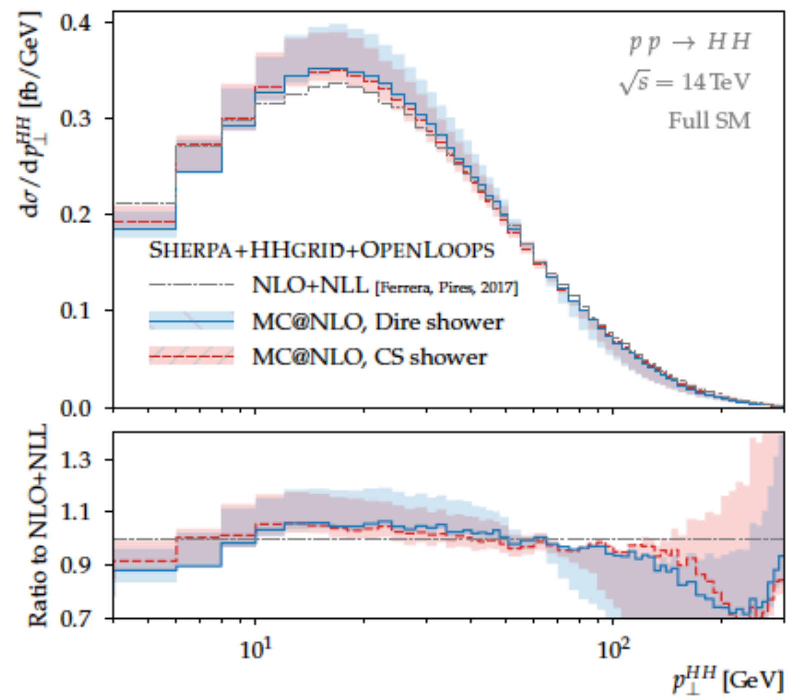


- Born-improved predictions much harder than exact computation
- FT_approx giving a good description of the high pT regions also in the NLO+PS predictions: exact real matrix element

More on NLO+PS: Stephen's talk



Comparison between shower algorithms



Comparison with resummation

- Small shower uncertainties
- Larger matching uncertainties
- Good agreement with resummation

Jones and Kuttimalai arXiv:1711.03319

Monte Carlo tools for SMEFT

SMEFT

New Interactions of SM particles

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

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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		

SMEFT assumptions

- No light new physics ($E<\Lambda$)
- Expansion in $1/\Lambda^2$: dimension-6 effects are expected to be dominant over dimension-8 effects etc
- Respects the symmetries of the SM: Higgs is an SU(2) doublet (c.f. EWchL where H is a singlet)

Which operators enter in HH?

Constraints

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q}t)\, \tilde{\phi}\,,$$

Inclusive H, Higgs plus jets, ttH

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$$

Inclusive H, Higgs plus jets, ttH

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}$$

tt, ttH, ttV….

$$O_6 = -\lambda(\phi^\dagger \phi)^3$$

HH (single Higgs@NLO)

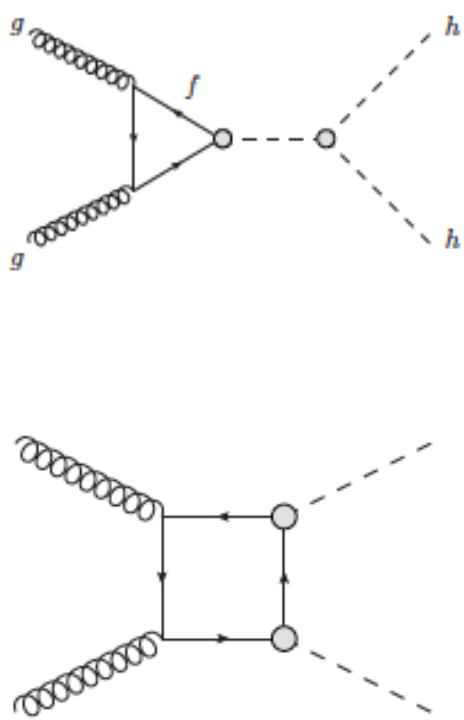
$$O_H = \frac{1}{2}(\partial_\mu(\phi^\dagger \phi))^2$$

All Higgs couplings H decays, VH, VBF…

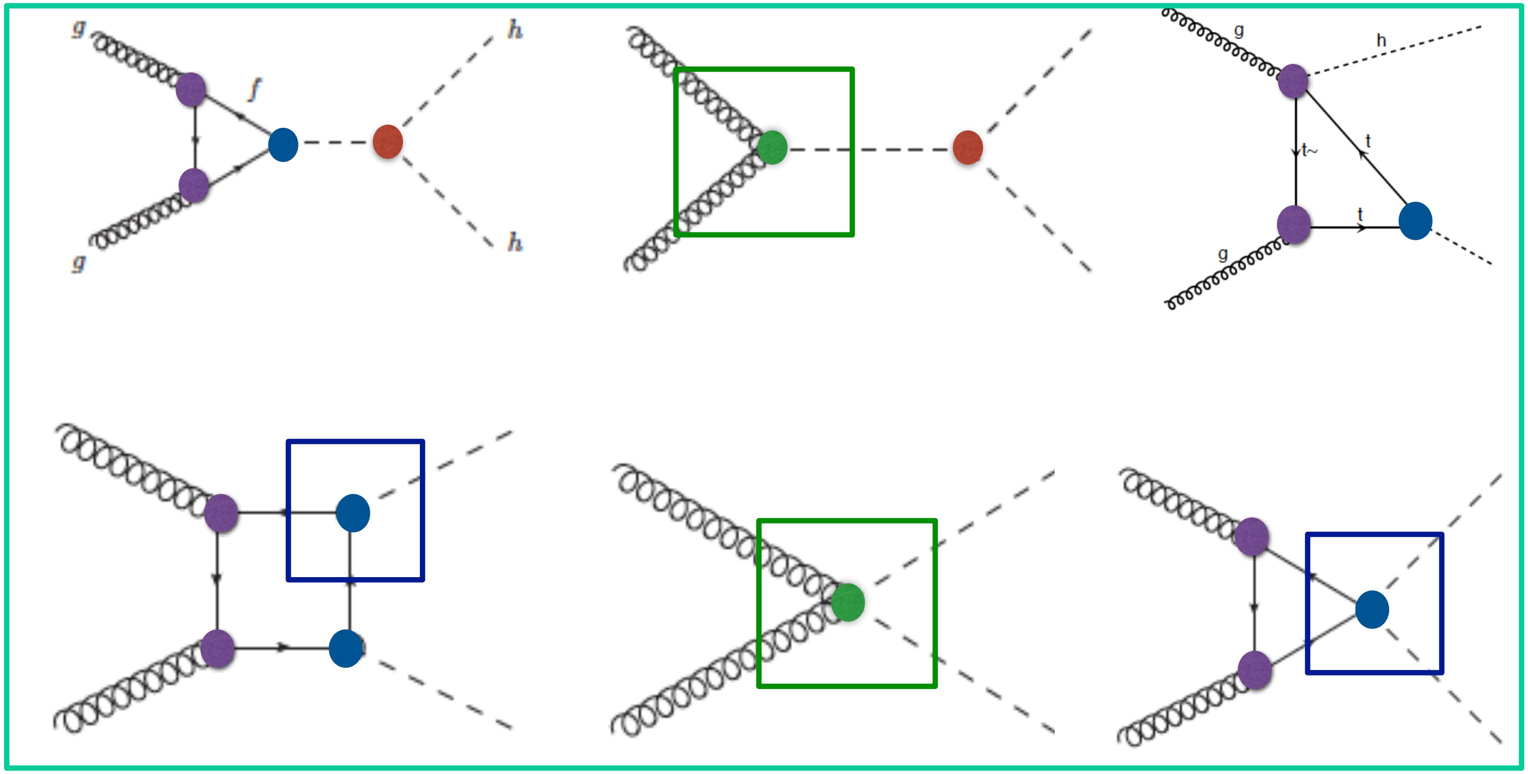
All but one operator will receive constraints from another processes (at LO)

SMEFT in HH

SM



SMEFT



Loop-level

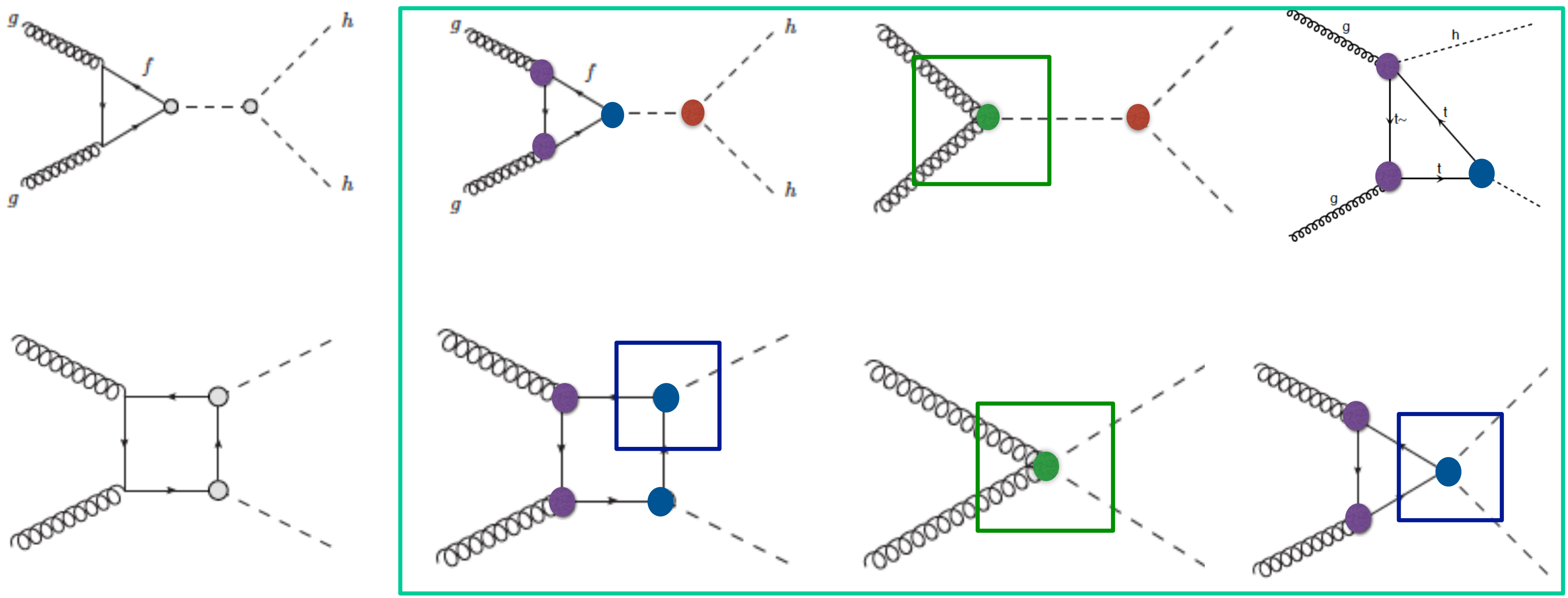
Loop-level

Tree-level

Loop-level

SMEFT in HH

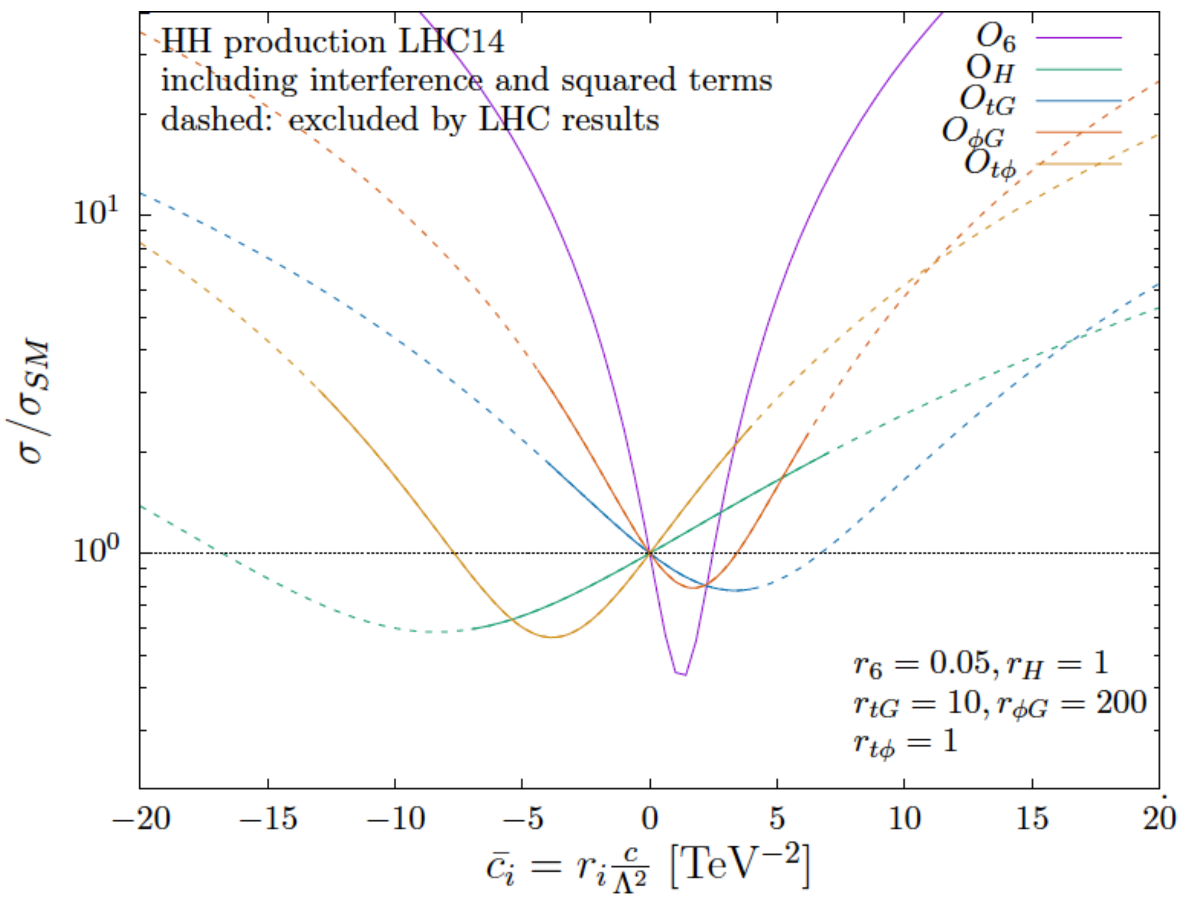
SM SMEFT

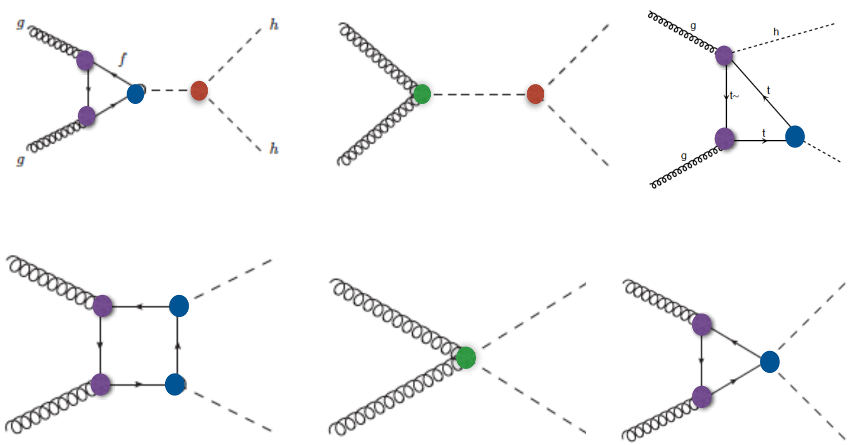


Loop-level Loop-level Tree-level Loop-level

c.f. in EWchL (Buchalla et al arXiv:1806.05162) c_{gghh}-c_{ggh} and c_t-c_{tt} are independent, with c_{gghh}, c_{tt} and c_{hhh} to be determined by HH

How to extract λ_{HHH} from HH: EFT





Other couplings enter in the same process:
top Yukawa, ggh(h) coupling, top-gluon interaction

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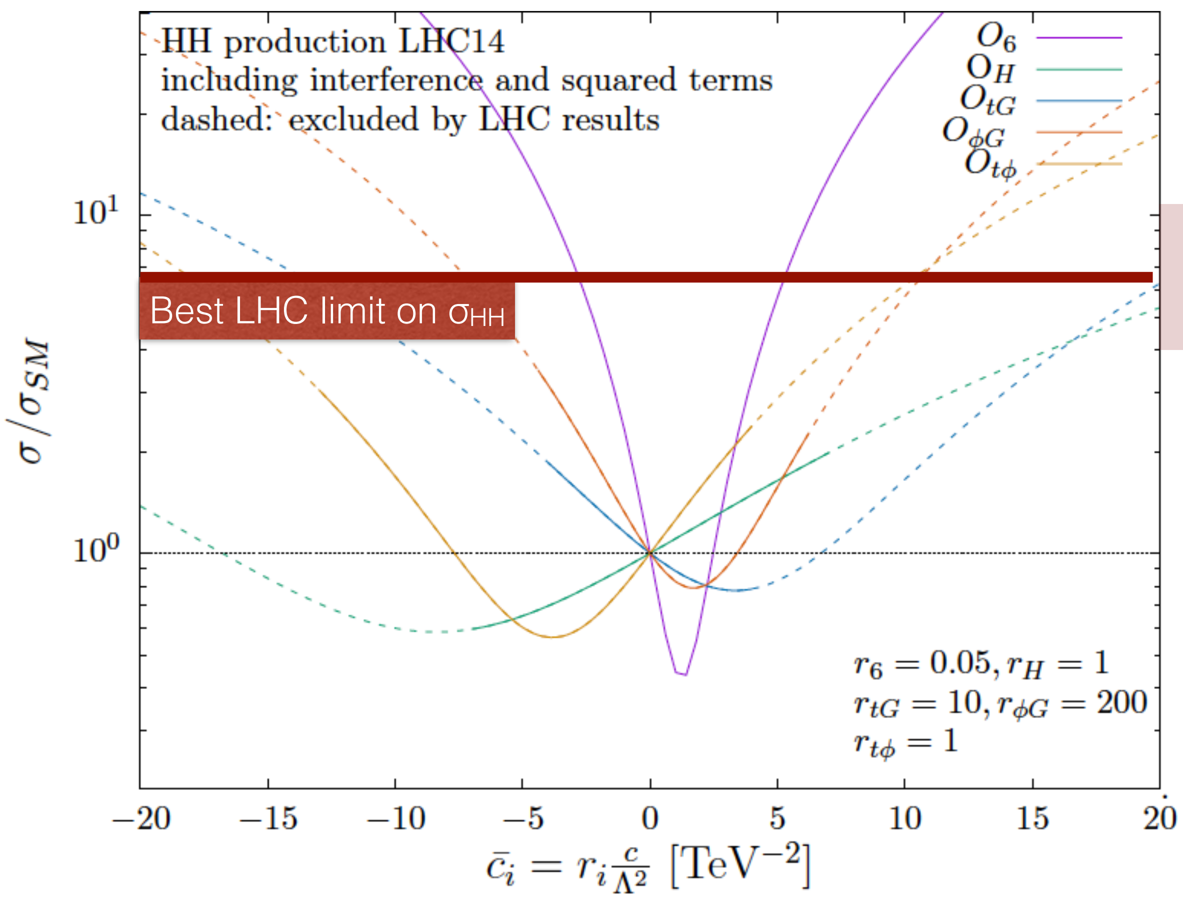

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi}\,,$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$$

$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}$$

$$O_6 = -\lambda (\phi^\dagger \phi)^3$$

$$O_H = \frac{1}{2} (\partial_\mu (\phi^\dagger \phi))^2$$

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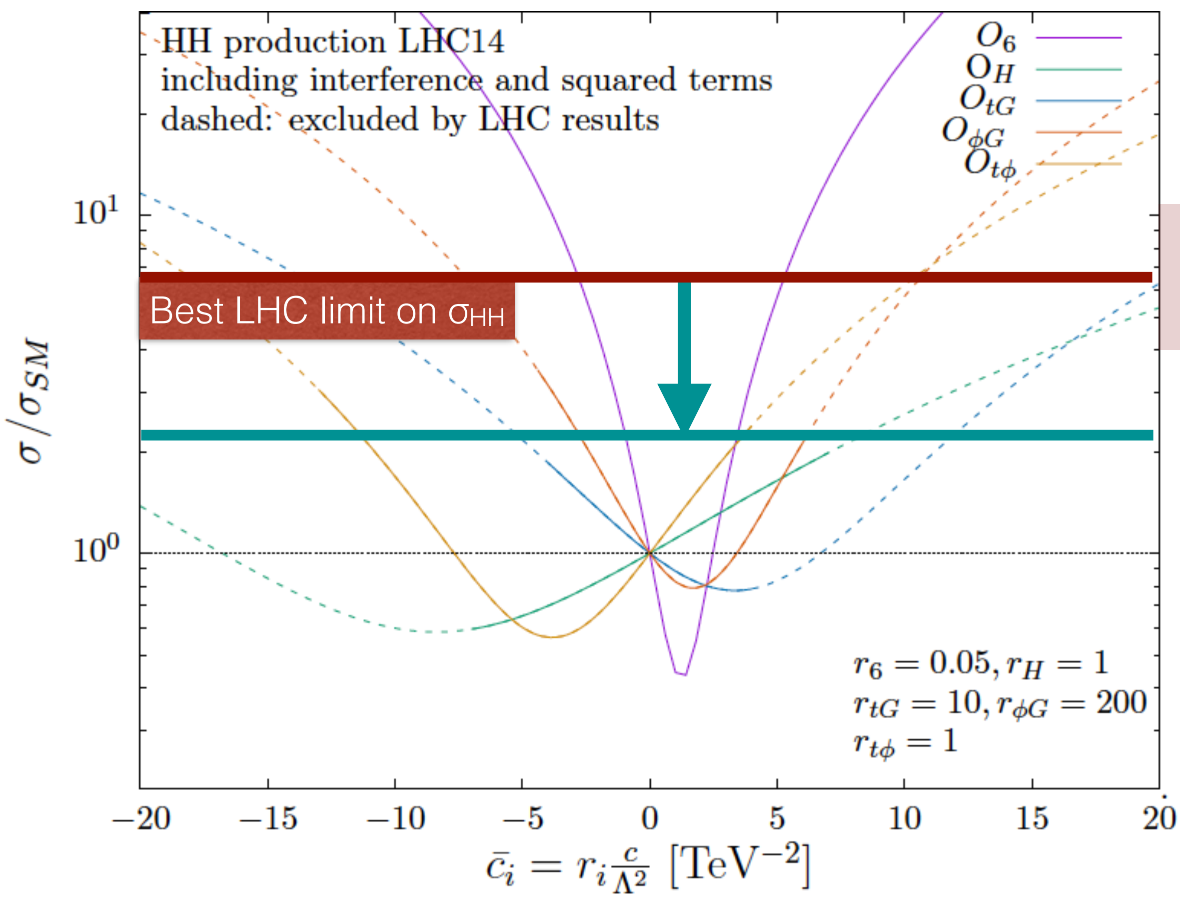
The present
Given the current constraints on σ(HH), σ(H) and the fresh ttH measurement, the Higgs self-coupling can be currently constrained "ignoring" other couplings

How to extract λ_{HHH} from HH: EFT



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The future
Precise knowledge of other Wilson coefficients will be needed to bound λ as the bound gets closer to SM
Differential distributions will also be necessary

SMEFT strategy

- Need for SMEFT global analysis including all relevant operators
- Ignoring operators (chromo) is against the model independent nature of the SMEFT
- Other operators (4/5) will receive constraints from other processes, which can and should be taken into account in a SMEFT analysis of HH

SMEFT in Monte Carlo

SMEFTsim: Full implementation of Warsaw basis
LO implementation as documented in Brivio, Jiang, Trott arXiv:1709.06492

SMEFT@NLO:
Needed to compute tree-level processes at NLO
Needed to compute loop-induced processes like Higgs pair production
Degrande, Durieux, Maltoni, Mimasu, EV, Zhang

Towards a complete implementation@NLO

Based on:

- Warsaw basis
- Degrees of freedom for top operators as in dim6top

Current status:

- 73 degrees of freedom (top, Higgs, gauge):
  - CP-conserving
  - Flavour assumption: $U(2)_Q \times U(2)_u \times U(3)_d \times U(3)_L \times U(3)_e$
- Successful validation at LO with dim6top (in turn validated with SMEFTsim)
- 0/2F@NLO operators validated (with previous partial NLO implementations) → **http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO**

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

Practical considerations

Comments on how to use this model for HH

- Full model contains 73 degrees of freedom with only 5 relevant for HH production → Use a restriction card when loading the model
- Squared coupling order constraints can be used to obtain the interference only and squared contributions
- Interference between tree level and loop diagrams can be obtained via reweighting
- Reweighting can be used:
  - Event samples with multiple weights corresponding to different coefficient values

Syntax examples

Process cards

```
import model SMEFTatNLO_U2_2_U3_3_cG_4F_LO_UFO-HHloop
generate g g > h h NP=0 QCD=0 QED=2 [QCD]
output gghh_sm
```

restriction card

SM

```
import model SMEFTatNLO_U2_2_U3_3_cG_4F_LO_UFO-HHloop
define p = 21 2 4 1 3 -2 -4 -1 -3 5 -5 # pass to 5 flavors
define j = p
generate g g > h h  NP=2 QCD=0 QED=2 NP^2==2 [QCD]
output gghh_loop_inter
```

interference

```
import model SMEFTatNLO_U2_2_U3_3_cG_4F_LO_UFO-HHloop
define p = 21 2 4 1 3 -2 -4 -1 -3 5 -5 # pass to 5 flavors
define j = p
generate g g > h h  NP=2 QCD=0 QED=2 NP^2==4 [QCD]
```

square

```
import model SMEFTatNLO_U2_2_U3_3_cG_4F_LO_UFO-HH
define p = 21 2 4 1 3 -2 -4 -1 -3 5 -5 # pass to 5 flavors
define j = p
generate g g > h h  NP=2 QCD=0 QED=2 NP^2==4
```

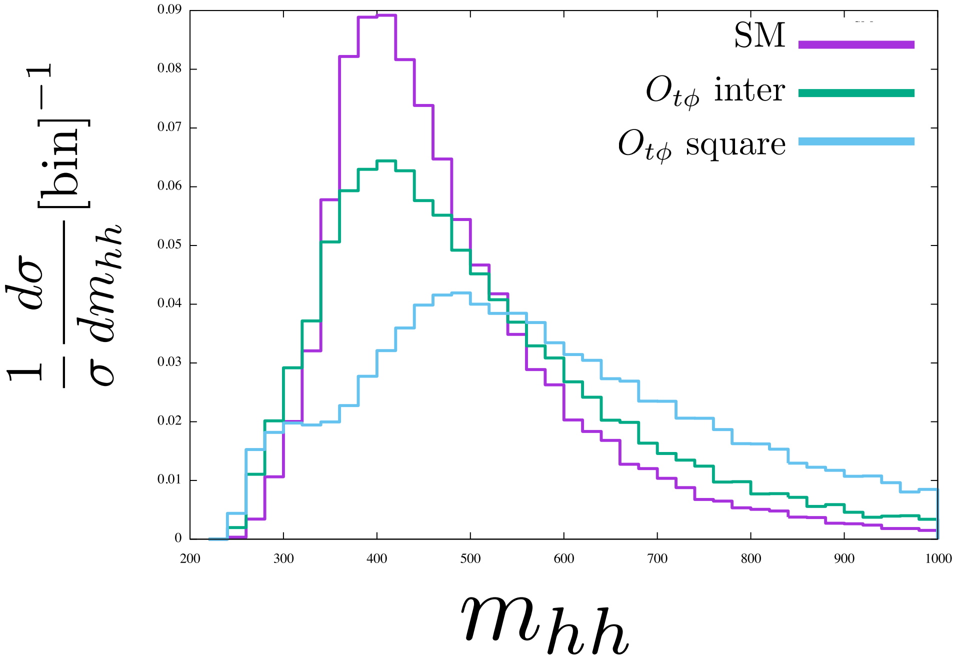
tree-level

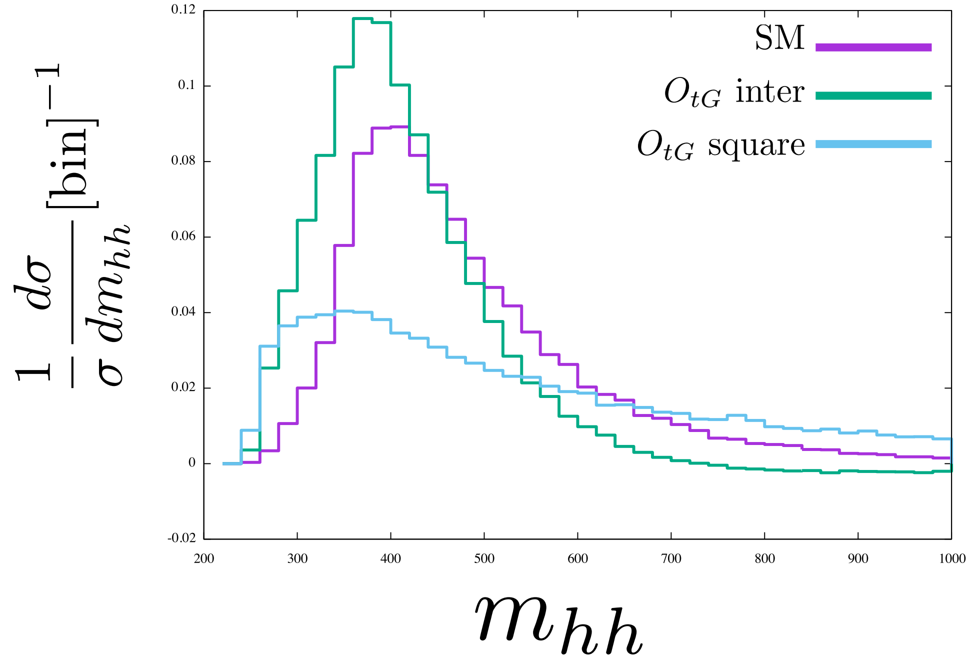
Reweight card

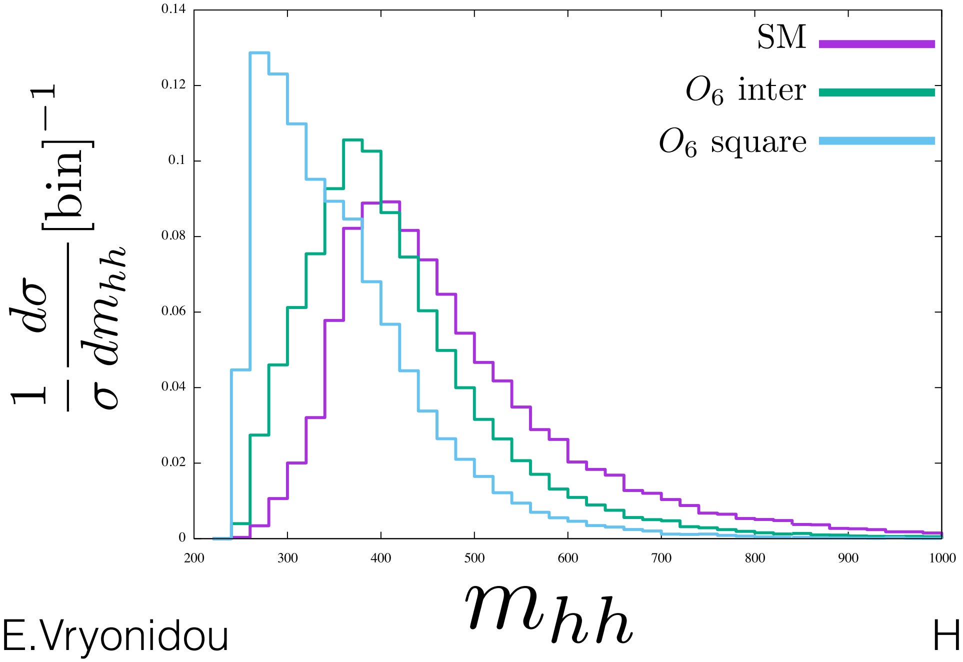
```
change model SMEFTatNLO_U2_2_U3_3_cG_4F_LO_UFO-HH
change process g g > h h  NP=2 QCD=0 QED=2 NP^2==2 [QCD]
change output 2.0
launch
```

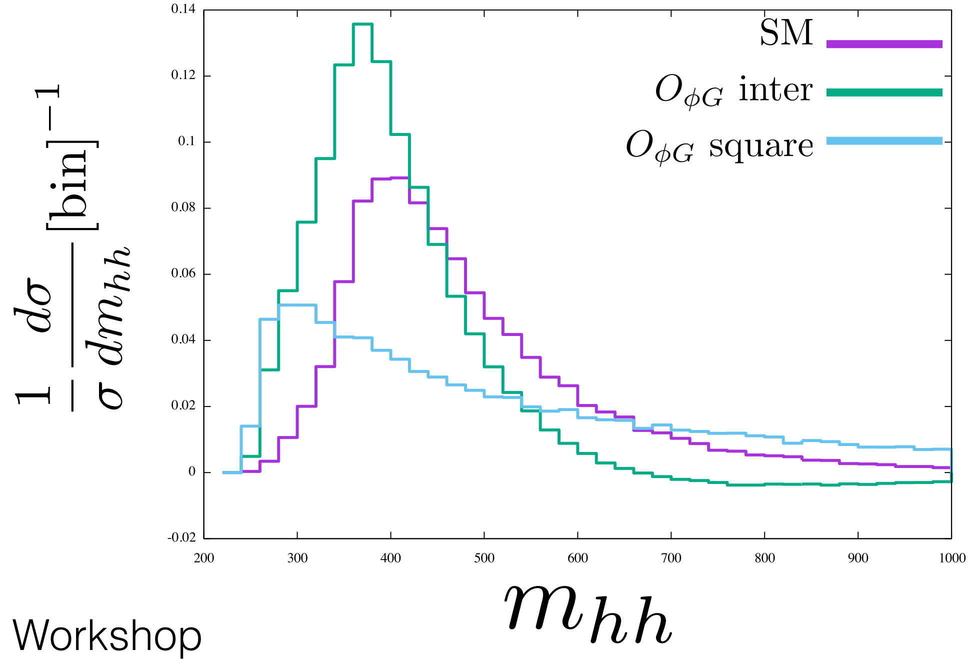
tree x loop

Results


SM
$O_{t\phi}$ inter
$O_{t\phi}$ square
$\frac{1}{\sigma}\frac{d\sigma}{dm_{hh}}[\mathrm{bin}]^{-1}$
m_{hh}


SM
O_{tG} inter
O_{tG} square
$\frac{1}{\sigma}\frac{d\sigma}{dm_{hh}}[\mathrm{bin}]^{-1}$
m_{hh}


SM
O_6 inter
O_6 square
$\frac{1}{\sigma}\frac{d\sigma}{dm_{hh}}[\mathrm{bin}]^{-1}$
m_{hh}


SM
$O_{\phi G}$ inter
$O_{\phi G}$ square
$\frac{1}{\sigma}\frac{d\sigma}{dm_{hh}}[\mathrm{bin}]^{-1}$
m_{hh}

Summary and conclusions

- SM HH gluon-fusion cross section known at NLO with the exact top mass dependence
- NLO+PS predictions including full mass effects
- Available implementations
  - POWHEG-BOX V2: User-Processes-V2/ggHH/
  - MG5_aMC@NLO (contact me)
- SMEFT Monte Carlo implementation at LO available:
  - All relevant operators in SMEFT: 5 operators for HH
  - Public UFO model can be found here:
- http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO
  - Squared syntax and reweighting in MG5_aMC facilitate sample generation for EFT analysis

Thanks for your attention