Higgs pair production at the LHC at NLO+PS

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Nikhef

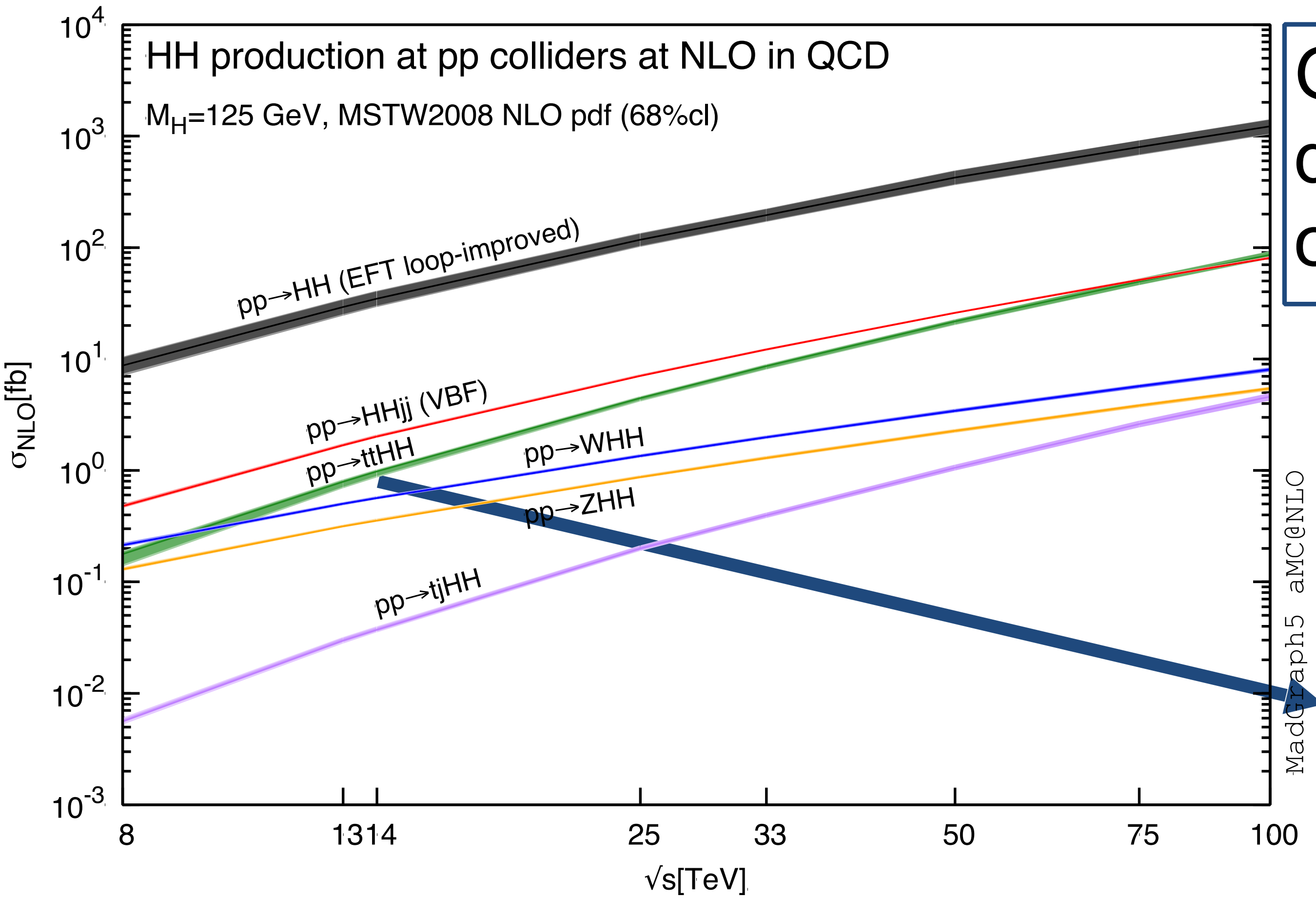
based on G. Heinrich, S.P. Jones, M. Kerner, G. Luisoni, EV
arXiv:1703.09252
accepted in JHEP

LHCHXSWG meeting

CERN

13/07/17

HH: the cross-sections



Gluon gluon fusion dominates
σ~40fb at 14TeV

VBF and ttHH potentially interesting e.g. ttHH arxiv:1409.8074, VBF: 1506.08008,1611.03860

Frederix et al. arxiv:1401.7340

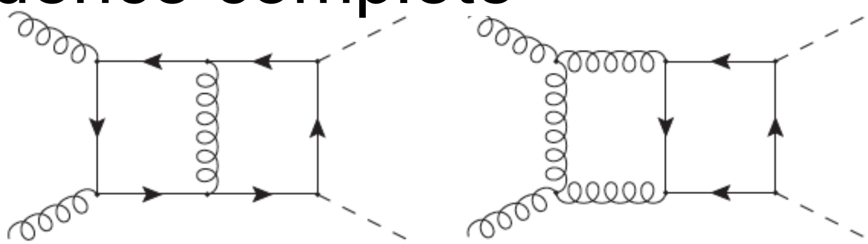
See also Baglio et al. arxiv:1212.5581 for a survey of all channels

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

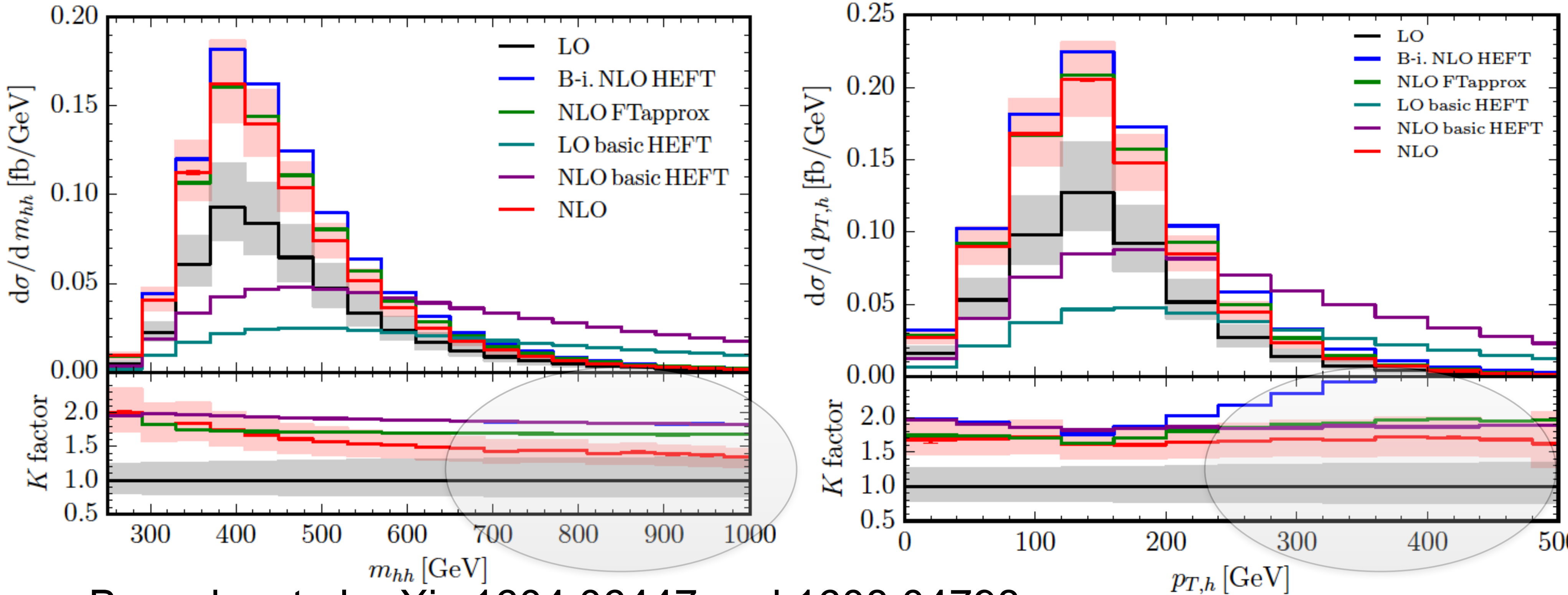
GOSAM-2L → REDUZE → SECDEC 3

Numerical evaluation of integrals

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

-14% -4%

Differential distributions at NLO



Borowka et al arXiv:1604.06447 and 1608.04798

- Exact NLO result softer than all other approximations in high m_{hh} region (up to ~20% difference)
- FT_{approx} in MG5_aMC good for high p_T (boosted searches)

HH@NLO+PS: prerequisites

2D grid: s,t ⇒ x, c_θ for a uniform distribution

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

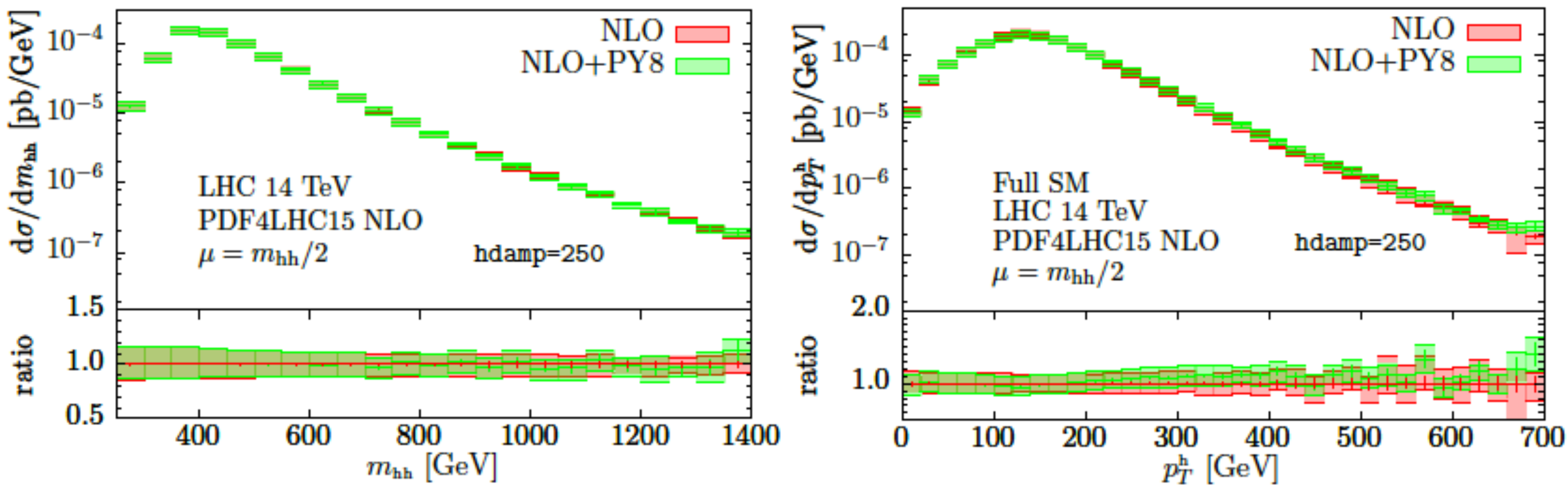
$$c_\theta = |\cos\theta| = \left|\frac{\hat{s} + 2\hat{t} - 2m_h^2}{\hat{s}\beta(\hat{s})}\right|,$$

Use of grid necessary to ensure reasonable running times

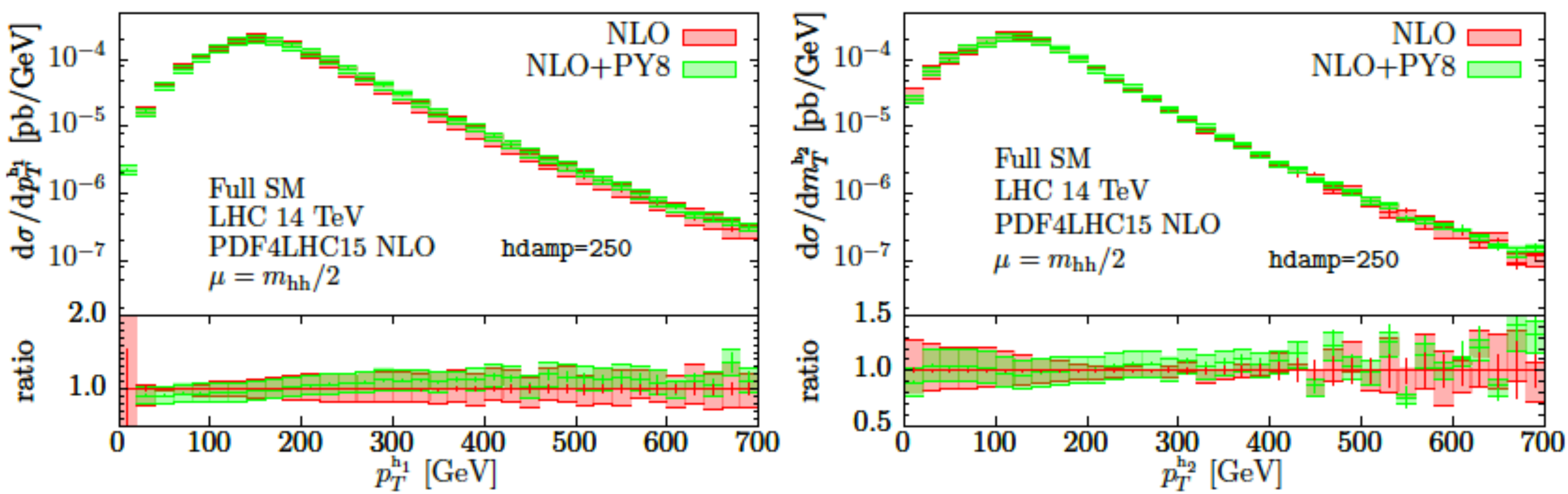
- Finite pieces of the virtual corrections obtained in the FKS convention as needed in the Powheg and MG5_aMC@NLO frameworks
- One-loop amplitudes for born and real kinematics:
  - Powheg: Implementation based on GoSam
  - MG5_aMC@NLO: MadLoop

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

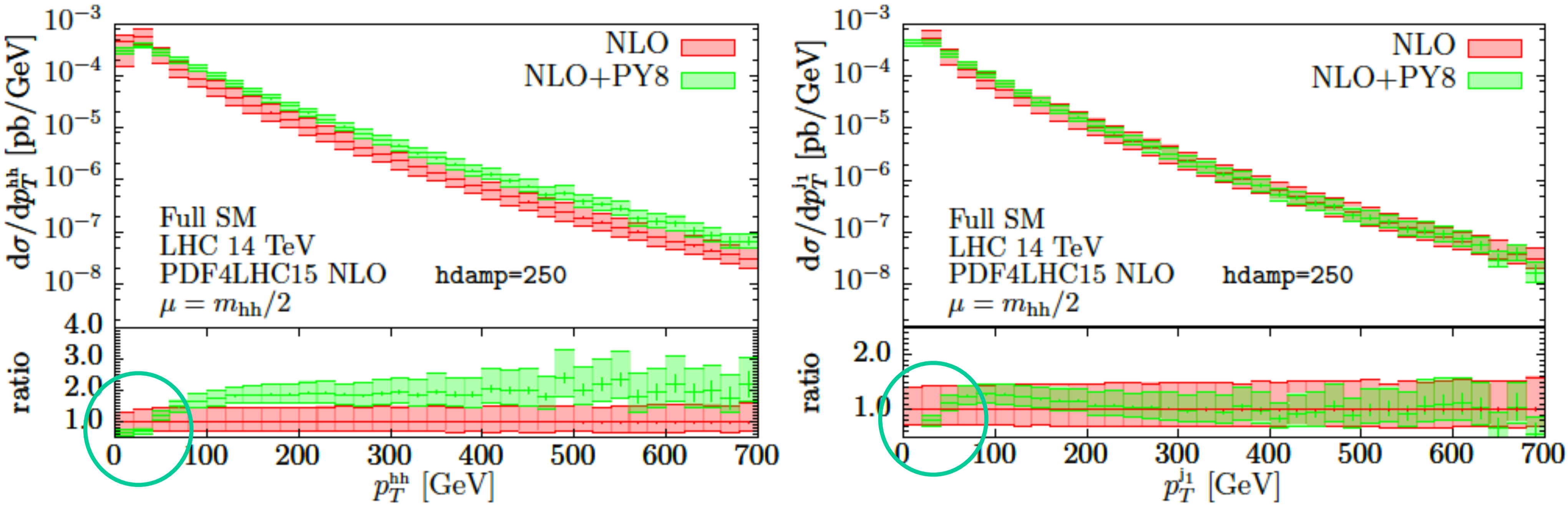
HH@NLO+PS: Results



Insensitive to the PS, serve as validation

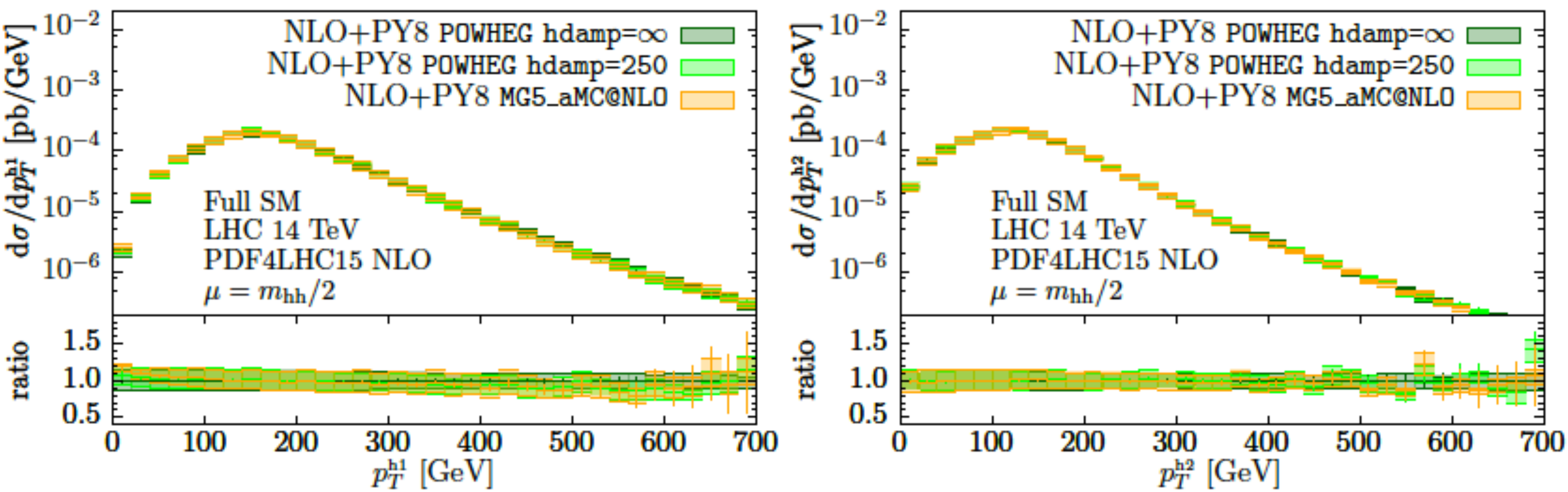


HH@NLO+PS:Results



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

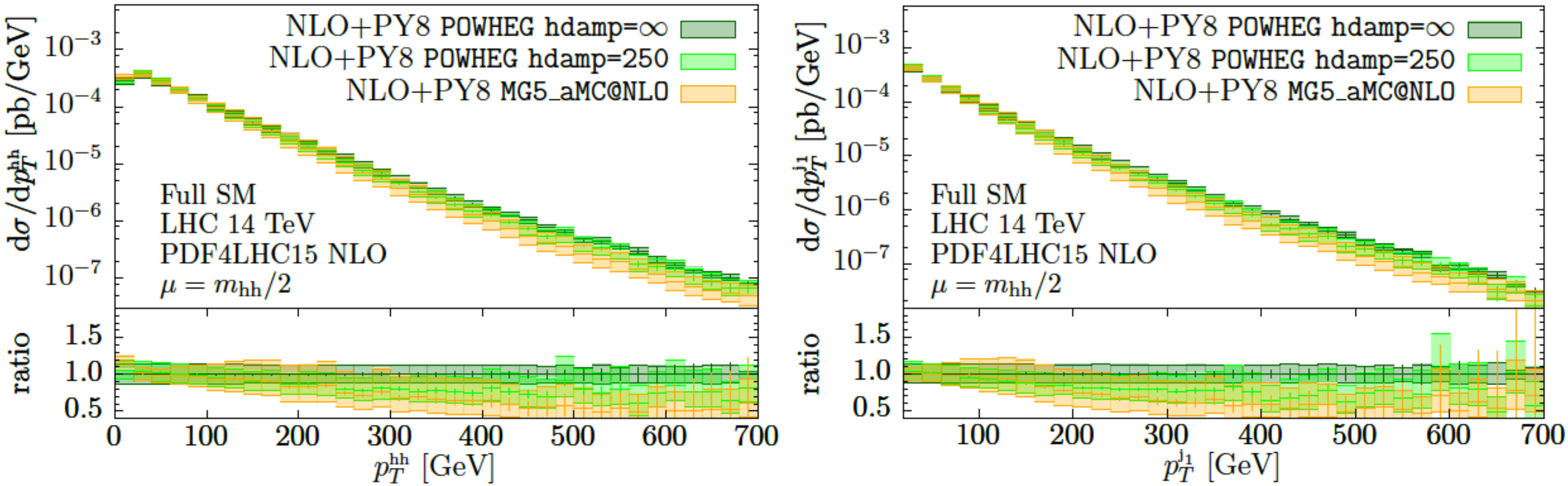
Comparison between Powheg and MG5_aMC



Same parton shower → differences due to matching

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

Comparison between Powheg and MG5_aMC



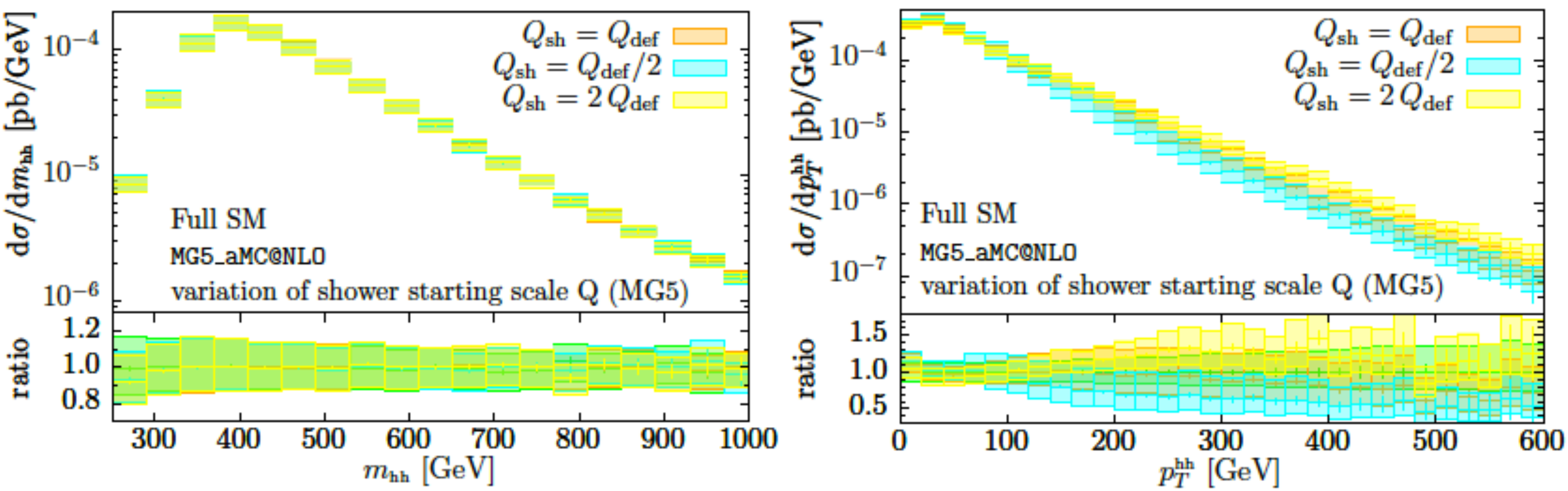
- hdamp limits the amount of exponentiated radiation in Powheg

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

$$R_{\rm reg} = R \times (1 - F)$$

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

Shower parameters: shower scale in MG5



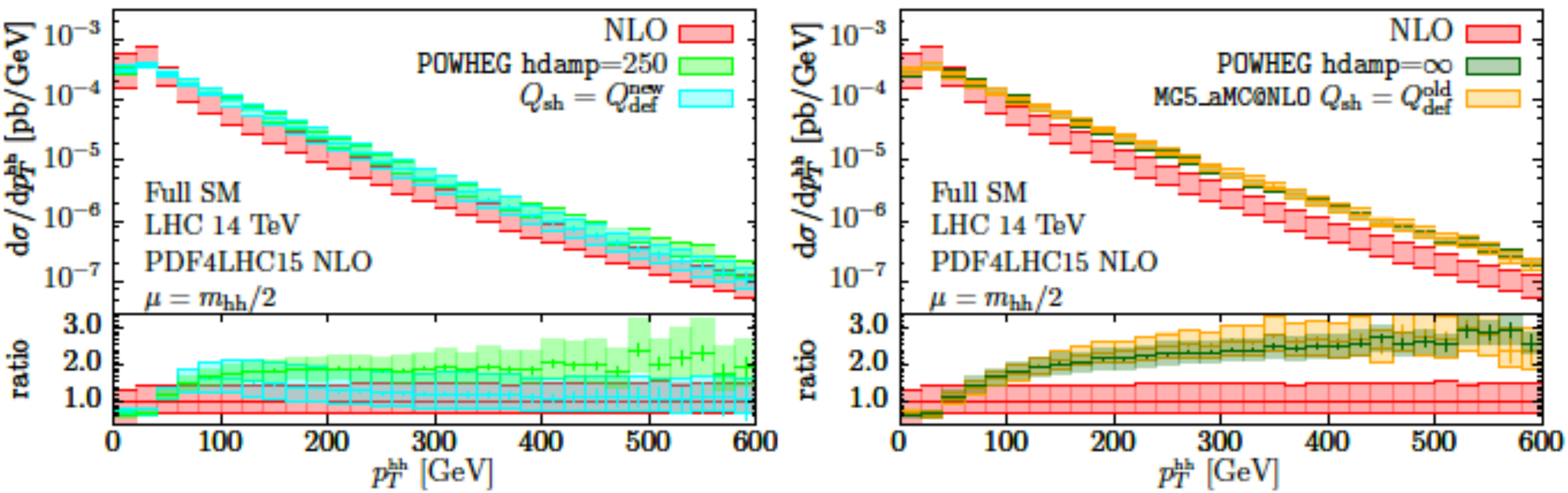
Default shower scale in MC@NLO (since 2.5.3): picked in the interval

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

can be set in the run_card

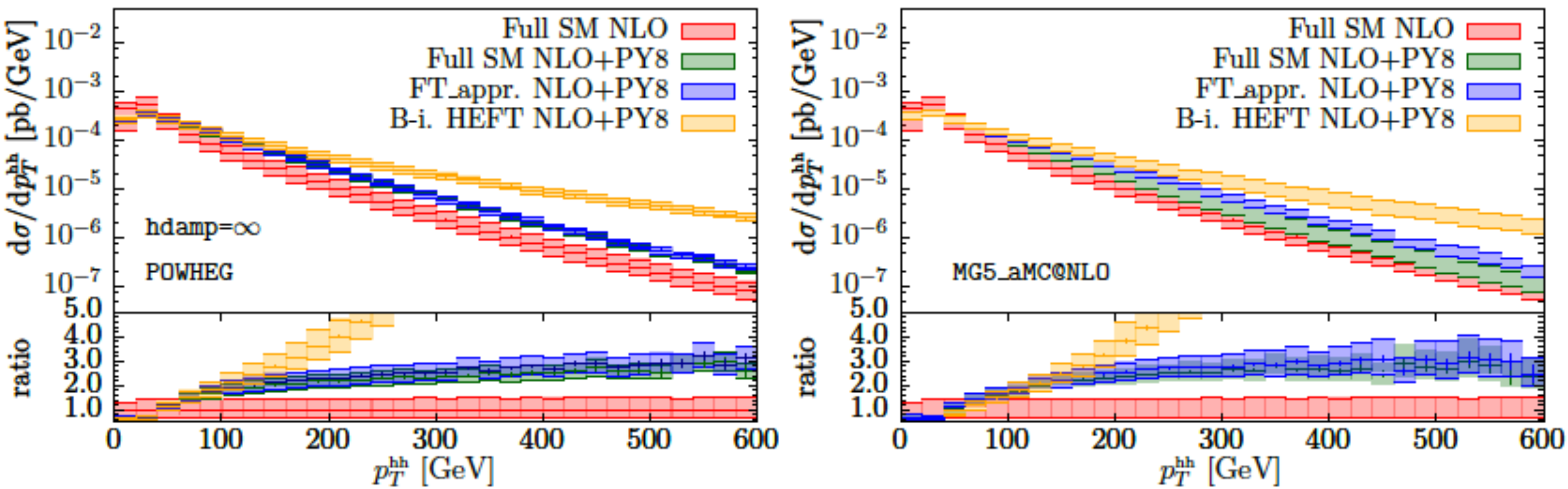
Impact of reducing the shower scale: Softer p_T^{HH} distributions

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



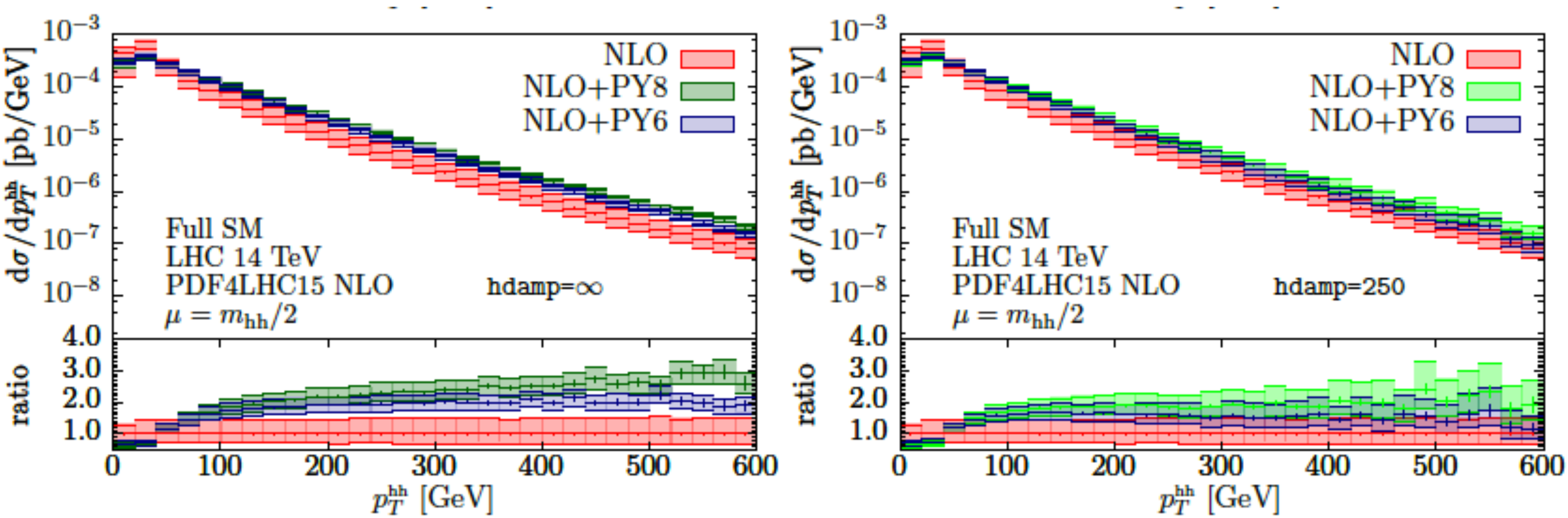
- Born-improved predictions much harder than exact computation
- FT_approx giving a good description of the high pT regions also in the NLO+PS predictions: exact real matrix element

Summary and conclusions

- HH gluon-fusion cross section now 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

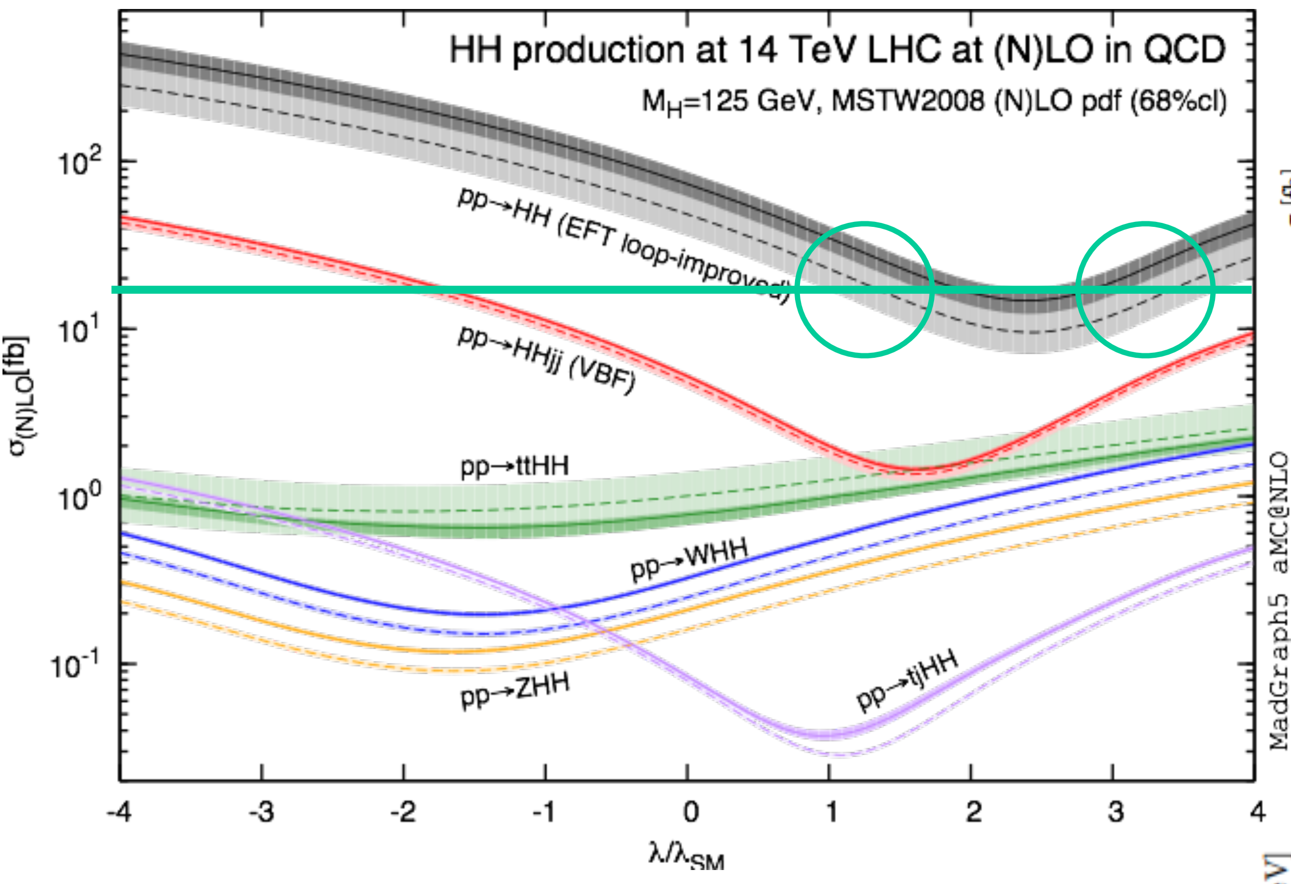
BACKUP slides

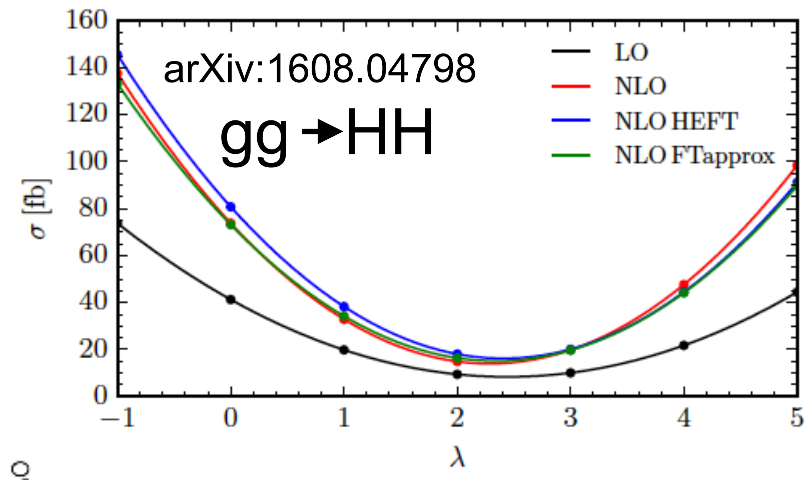
Comparison between PY6 and PY8



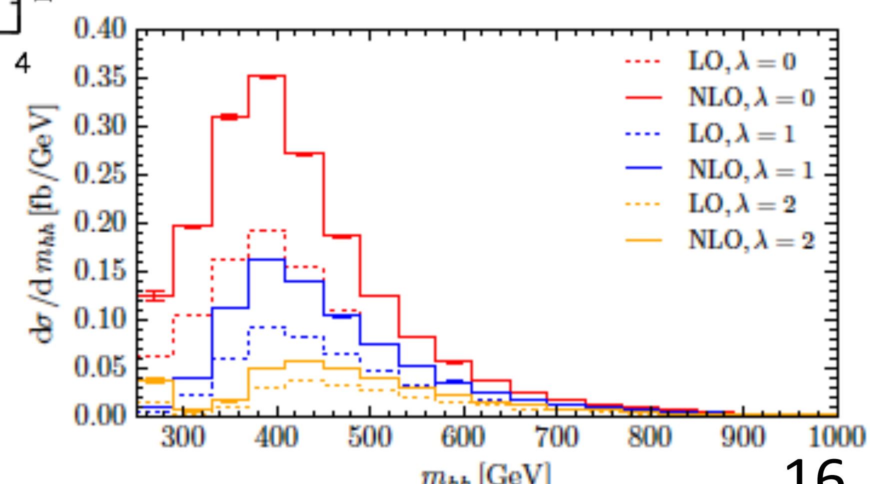
Pythia6 giving softer distributions than Pythia8

Dependence on the trilinear Higgs coupling





arXiv:1608.04798



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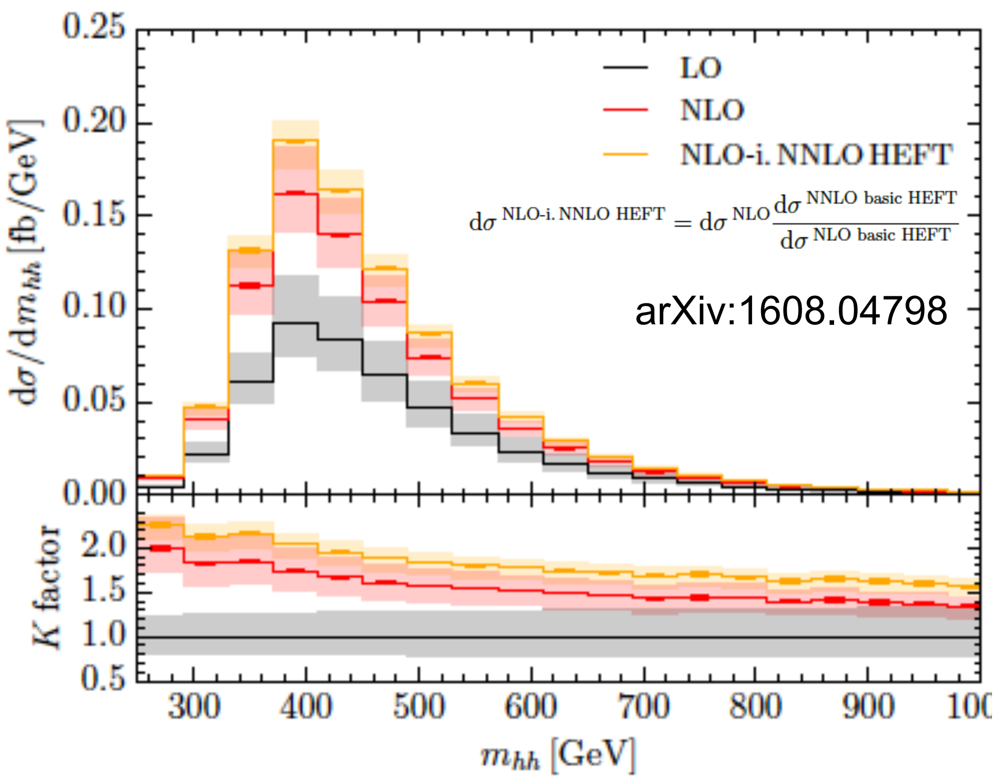
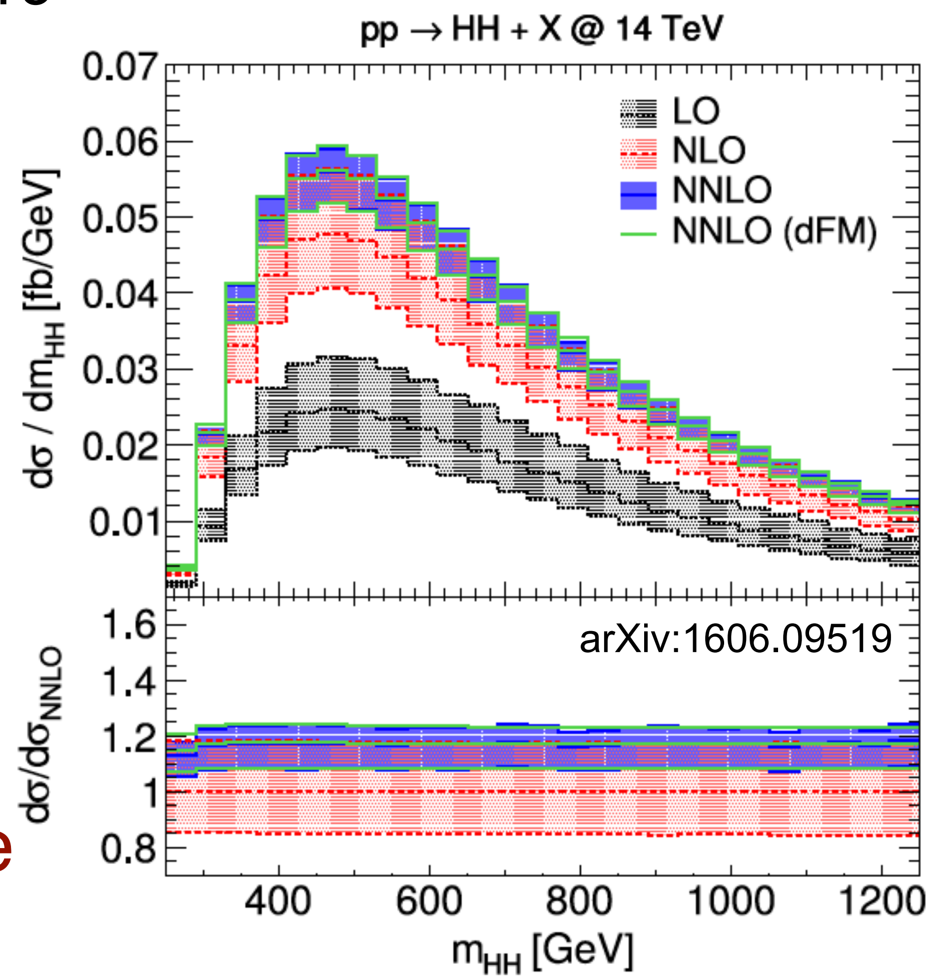
HH beyond NLO

- NNLO calculation in the EFT: De Florian, Mazzitelli (arXiv: 1305.5206,1309.6594)
- NNLO+NNLL resummation (arXiv:1505.07122)
- Differential distributions at NNLO with q_T subtraction: De Florian et al arXiv:1606.09519



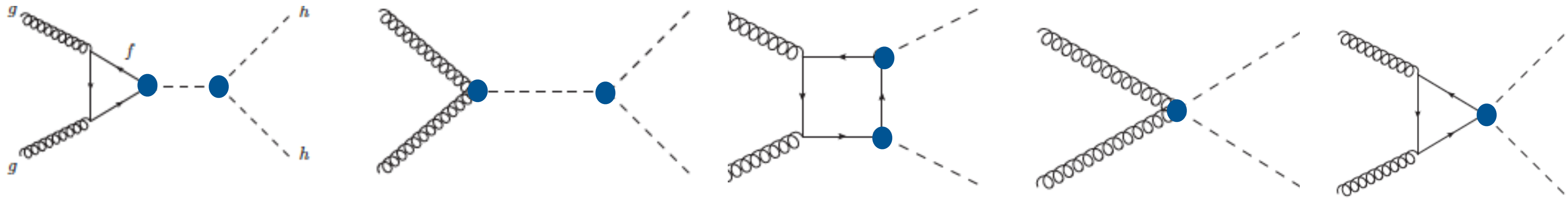


NNLO corrections increase the cross section by 20%

Non-resonant BSM: HH in the EFT

A general effective theory parametrisation (relevant for gg → hh) valid for a generic Higgs (non-linear Lagrangian):

$$\mathcal{L} \supset -m_t \bar{t}t \left(c_t \frac{h}{v} + c_{2t} \frac{h^2}{2v^2} \right) - c_3 \frac{m_h^2}{2v} h^3 + \frac{g_s^2}{4\pi^2} \left(c_g \frac{h}{v} + c_{2g} \frac{h^2}{2v^2} \right) G_{\mu\nu} G^{\mu\nu}$$



For an SU(2)$_L$ doublet Higgs (favoured by Higgs data and EWPT) :

Linear Lagrangian $\boxed{\mathcal{L}_{lin} = \mathcal{L}_{SM} + \Delta\mathcal{L}_6 + \Delta\mathcal{L}_8 + \ldots}$

$$\boxed{\Delta\mathcal{L}_6 \supset \frac{\bar{c}_H}{2v^2} [\partial_\mu (H^\dagger H)]^2 + \frac{\bar{c}_u}{v^2} y_u H^\dagger H \bar{q}_L H^c u_R - \frac{\bar{c}_6}{v^2} \frac{m_h^2}{2v^2} (H^\dagger H)^3 + \frac{\bar{c}_g}{m_w^2} g_s^2 H^\dagger H G_{\mu\nu} G^{\mu\nu}}$$

Goertz et al. arxiv:1410.3471
Contino et al. arXiv:1502.00539

The relevant terms

$$\mathcal{L} \supset -m_t \bar{t}t \left(c_t \frac{h}{v} + c_{2t} \frac{h^2}{2v^2} \right) - c_3 \frac{m_h^2}{2v} h^3 + \frac{g_s^2}{4\pi^2} \left(c_g \frac{h}{v} + c_{2g} \frac{h^2}{2v^2} \right) G_{\mu\nu} G^{\mu\nu}$$

5 parameters

$$\Delta\mathcal{L}_6 \supset \frac{\bar{c}_H}{2v^2} [\partial_\mu (H^\dagger H)]^2 + \frac{\bar{c}_u}{v^2} y_u H^\dagger H \bar{q}_L H^c u_R - \frac{\bar{c}_6}{v^2} \frac{m_h^2}{2v^2} (H^\dagger H)^3 + \frac{\bar{c}_g}{m_w^2} g_s^2 H^\dagger H G_{\mu\nu} G^{\mu\nu}$$

4 parameters

The connection:

$$\boxed{c_t = 1 - \frac{\bar{c}_H}{2} - \bar{c}_u \,, \quad c_{2t} = -\frac{1}{2} (\bar{c}_H + 3\bar{c}_u) \,, \quad c_3 = 1 - \frac{3}{2} \bar{c}_H + \bar{c}_6 \,, \quad c_g = c_{2g} = \bar{c}_g \left(\frac{4\pi}{\alpha_2} \right)}$$

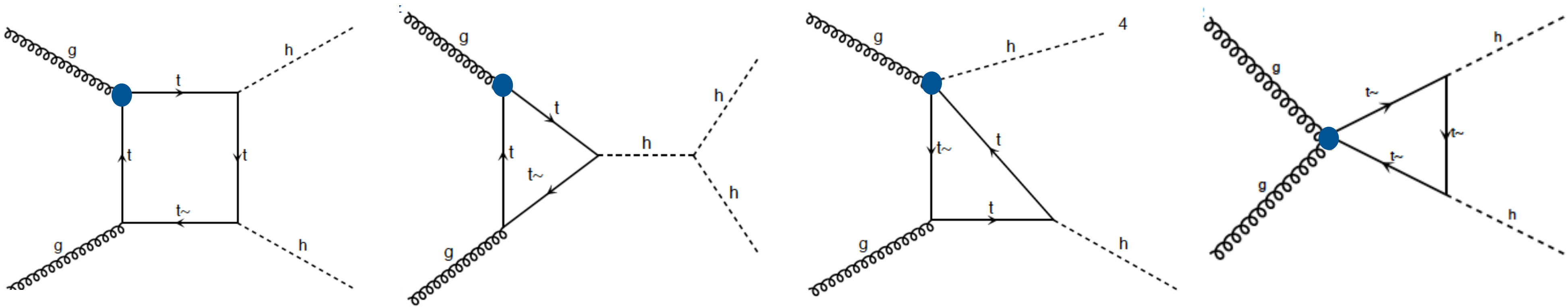
Note:Field redefinition
removes the Higgs derivative terms
see Giudice et al hep-ph/0703164

$$h \to h - \frac{c_H \xi}{2} \left(h + \frac{h^2}{v} + \frac{h^3}{3v^2} \right)$$

The missing dimension-6 part

Chromomagnetic operator is also contributing

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

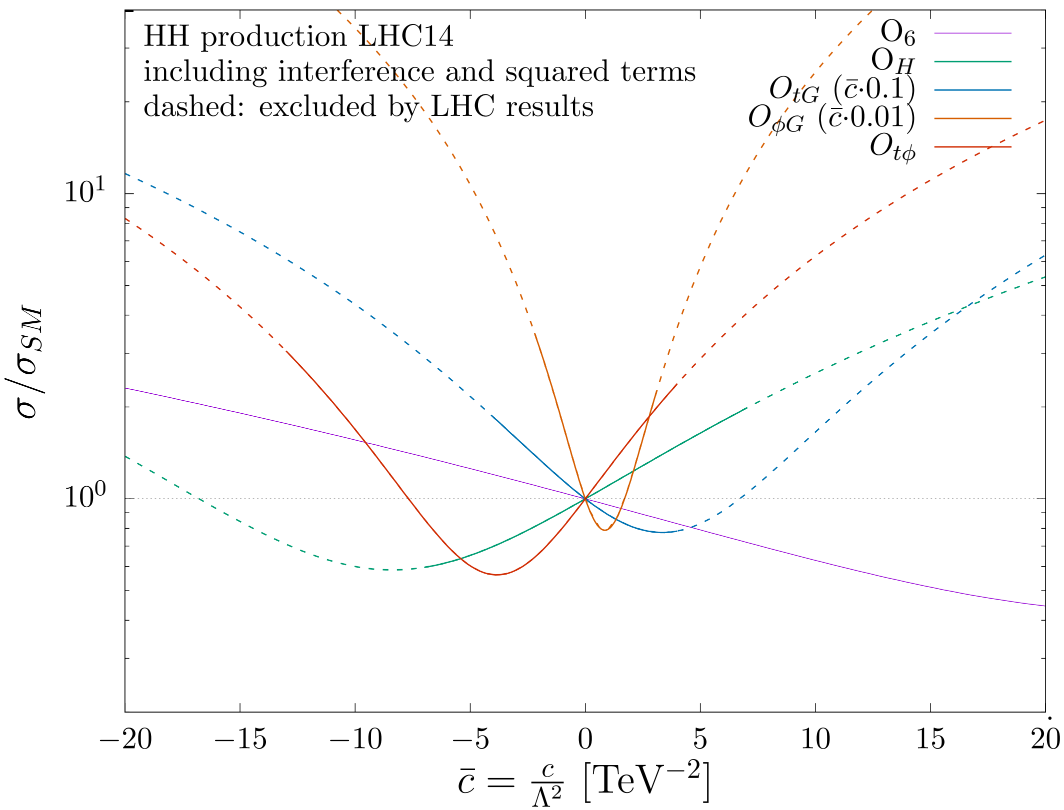


Needs to be taken into account in the context of a global EFT analysis for HH
Constraints from top pair production at NLO:

$C_{tg}=$ [-0.42,0.30] Zhang and Franzosi arxiv:1503.08841

How much does this operator contribute to HH?

How will the chromo affect the HH EFT analyses?



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

slightly different normalisation

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

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

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

$$\kappa_\lambda = 1 - c_H \frac{3v^2}{2\Lambda^2} + c_6 \frac{v^2}{\Lambda^2}$$

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

5 parameters

- Very mild dependence on c_6
- Precise knowledge of other Wilson coefficients needed to bound c6
- Differential distributions will also be necessary

Approximate constraints from single Higgs (e.g. Butter et al arxiv:1604.03105) and top pair production (Franzosi and Zhang arxiv:1503.08841)