Monte Carlo Modelling of HH

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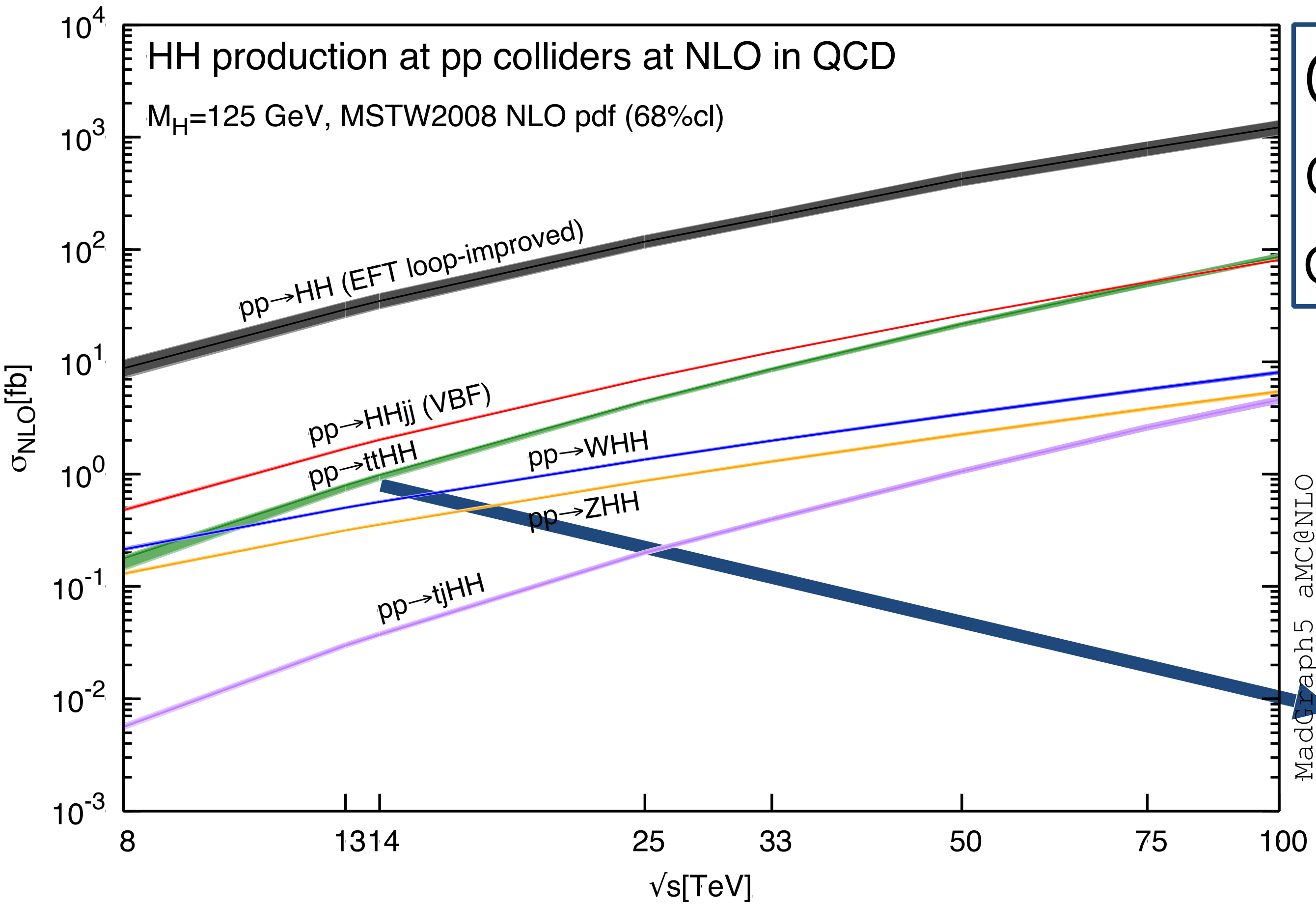
HH workshop

Fermilab

05/09/18

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

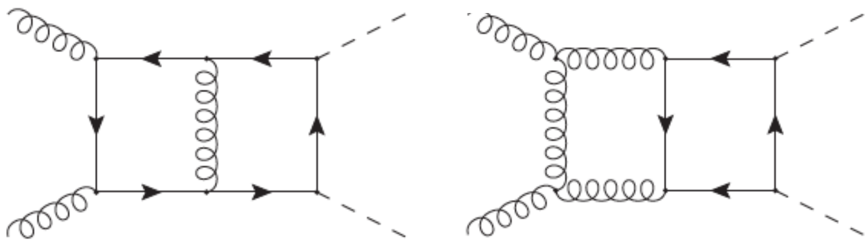
See also Baglio et al. arxiv:1212.5581 for a survey of all channels

Tree-level processes available at NLO+PS through public MC codes

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



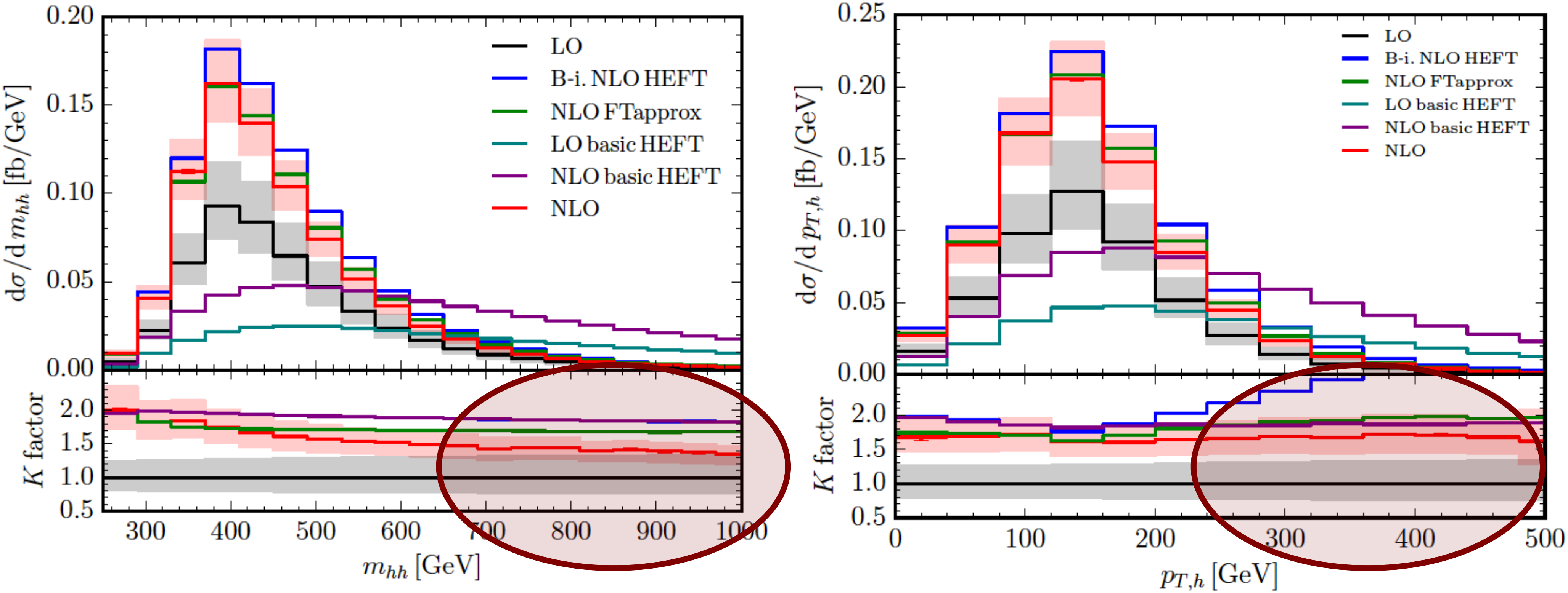
2-loop amplitudes computed with
GOSAM-2L → REDUZE → SECDEC 3
Numerical evaluation of integrals

$\sqrt{s}$	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%

See more in Javier's talk for further progress

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 $\Rightarrow$ x, c_θ for a uniform distribution

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

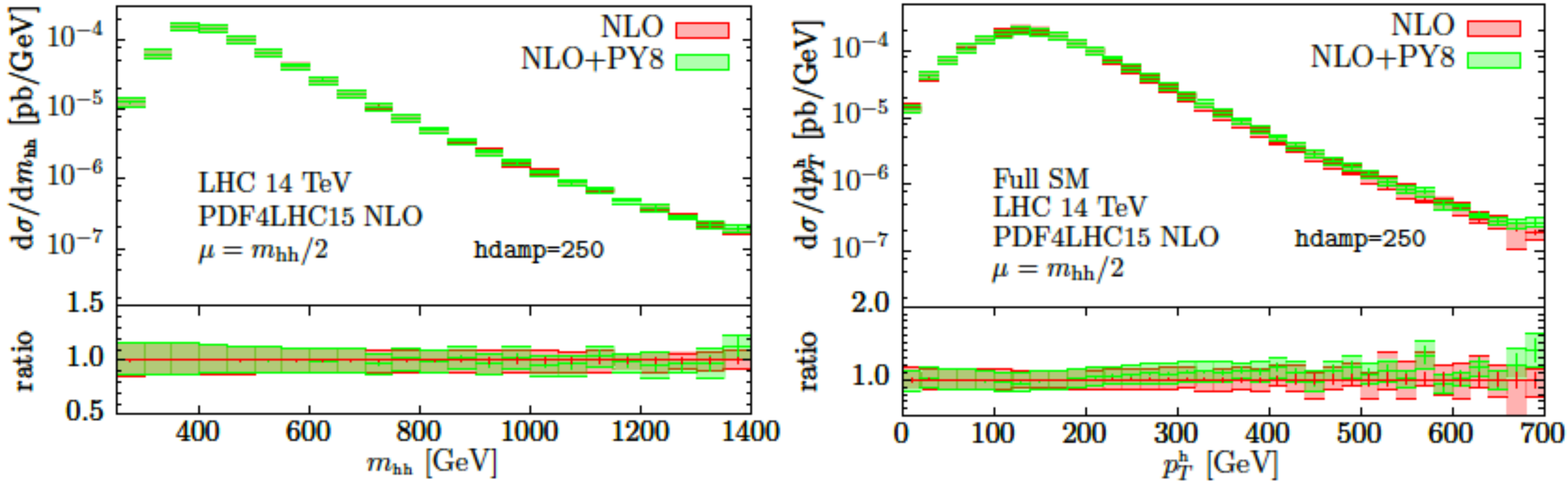
$$c_\theta = |\cos\theta| = \left|\frac{\hat{s} + 2\hat{t} - 2m_h^2}{\hat{s}\beta(\hat{s})}\right|,$$

Use of grid necessary to ensure reasonable running times

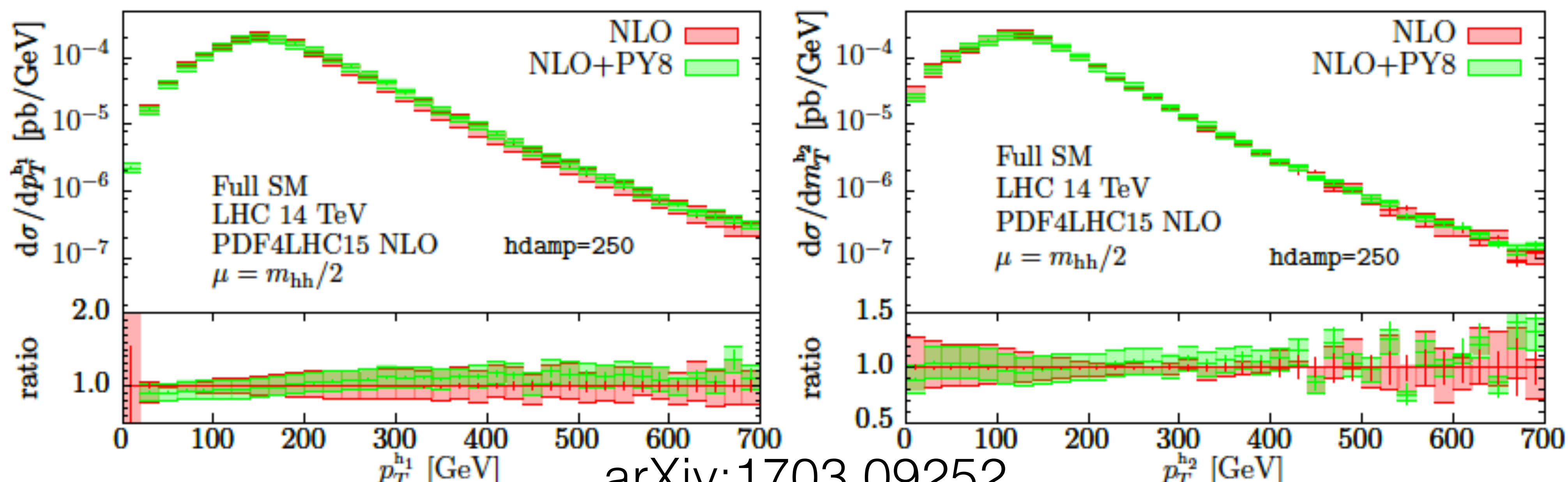
- Finite pieces of the virtual corrections obtained in the FKS convention as needed in the Powheg and MG5_aMC@NLO frameworks
- One-loop amplitudes for born and real kinematics:
  - Powheg: Implementation based on GoSam
  - MG5_aMC@NLO: MadLoop

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

HH@NLO+PS: Results

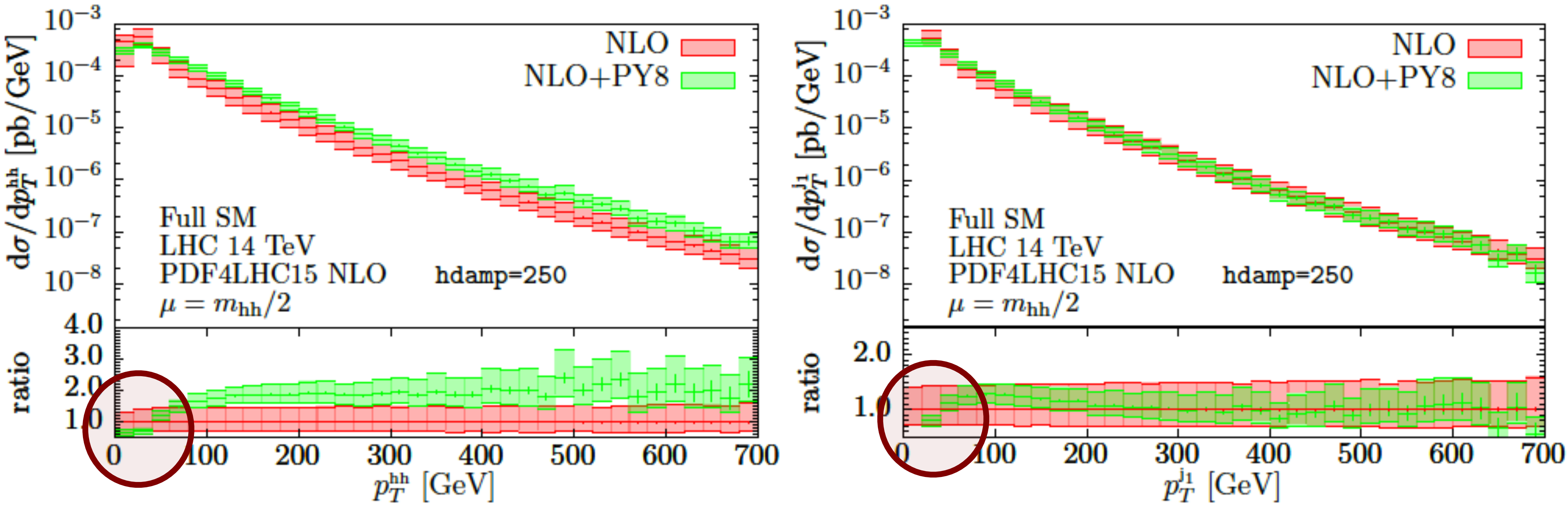


Insensitive to the PS, serve as validation



arXiv:1703.09252

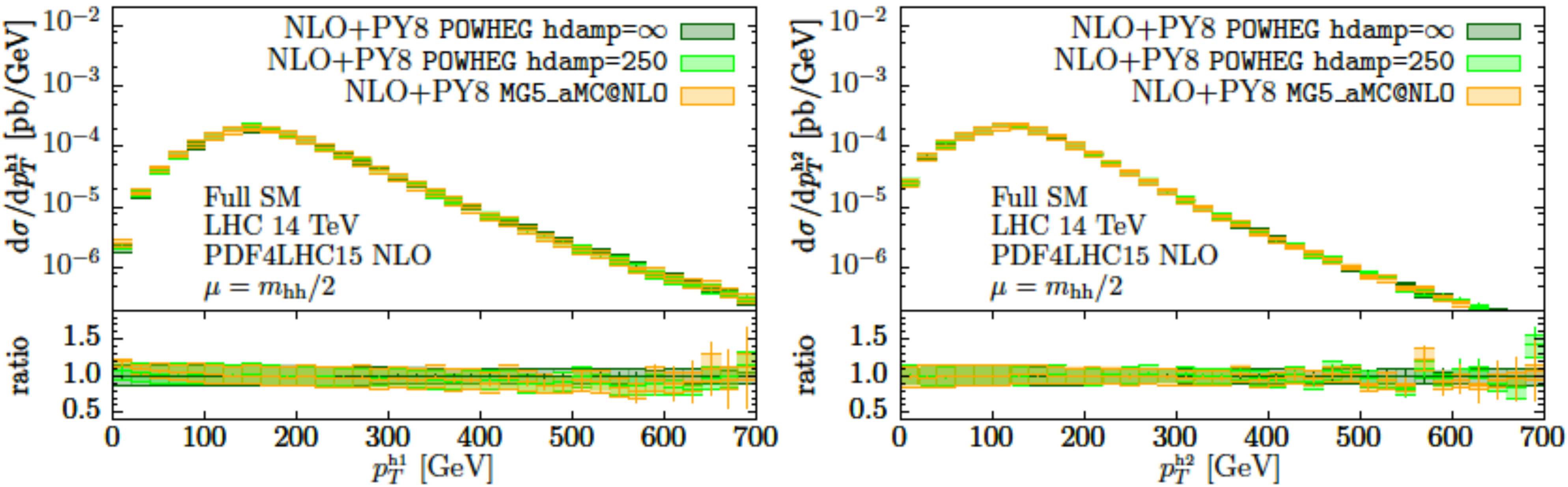
HH@NLO+PS:Results



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

arXiv:1703.09252

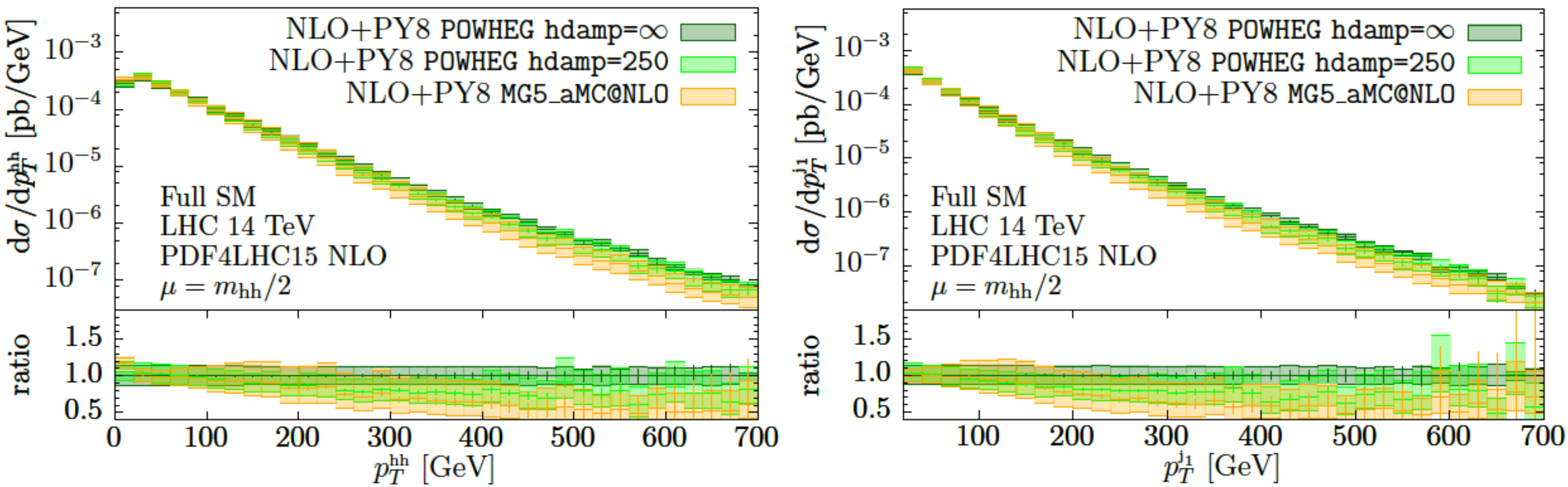
Comparison between Powheg and MG5_aMC



Same parton shower → differences due to matching

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

Comparison between Powheg and MG5_aMC

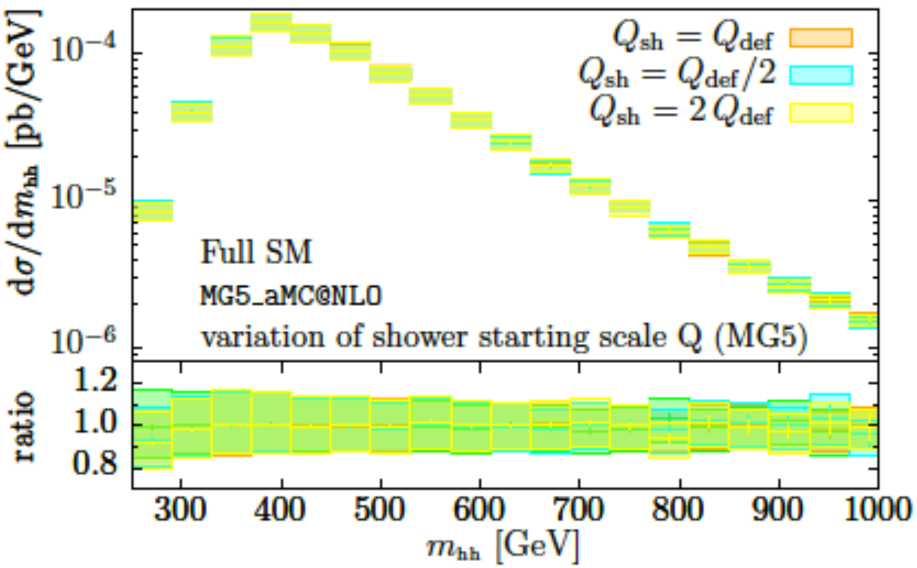


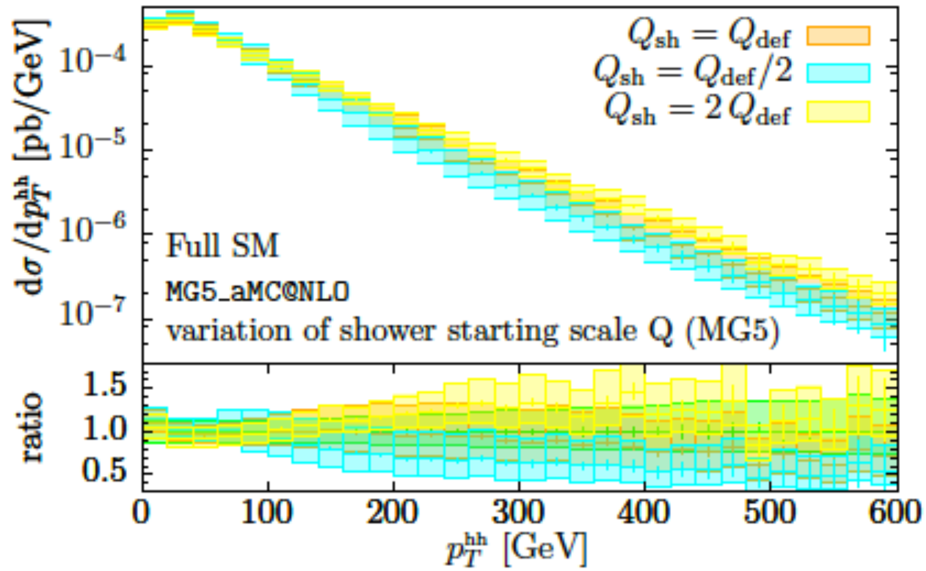
- hdamp limits the amount of exponentiated radiation in Powheg

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

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

Shower parameters: shower scale in MG5





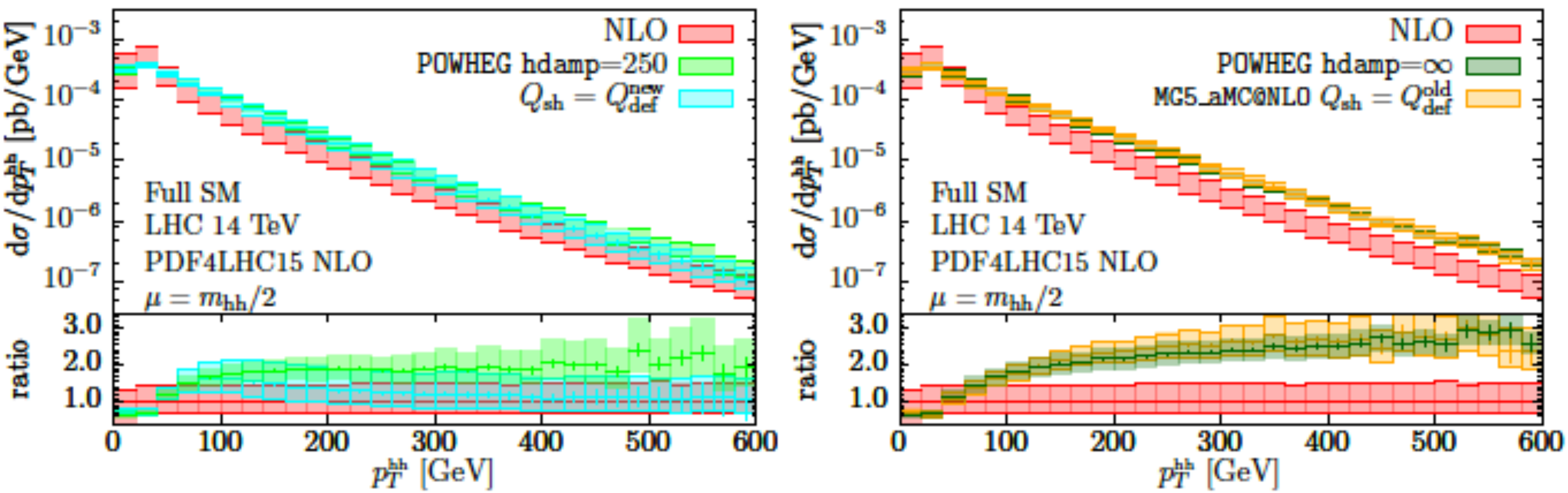
Default shower scale in MC@NLO (since 2.5.3): picked in the interval

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

can be set in the run_card

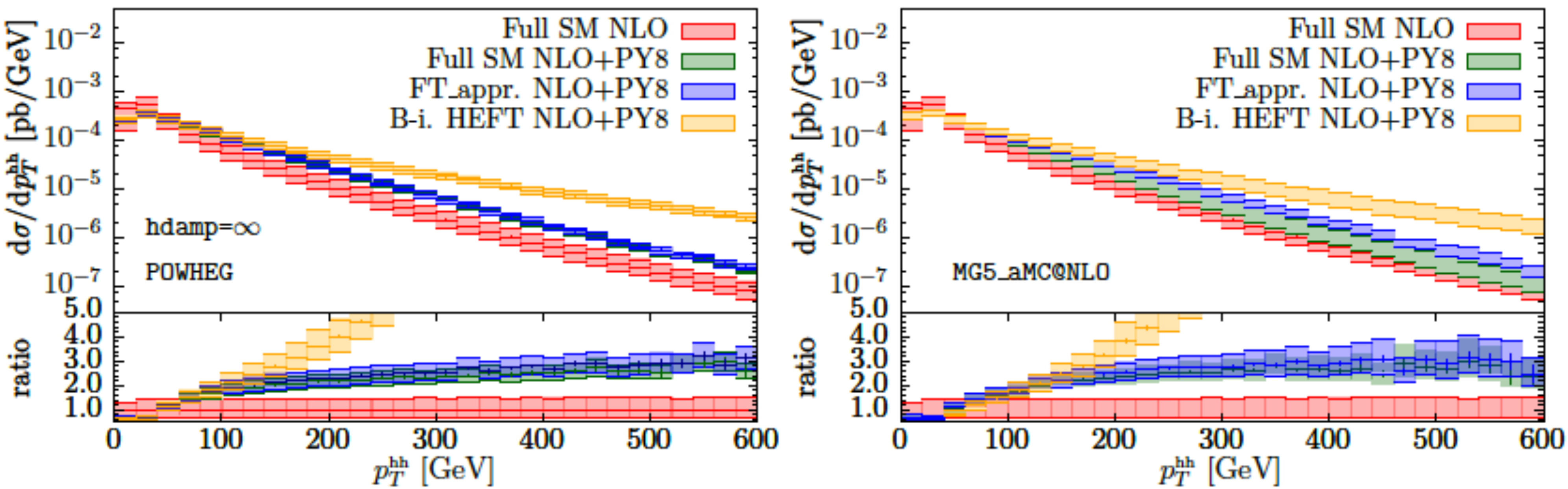
Impact of reducing the shower scale: Softer p_T^{HH} distributions

Shower parameters in MG5_aMC and Powheg



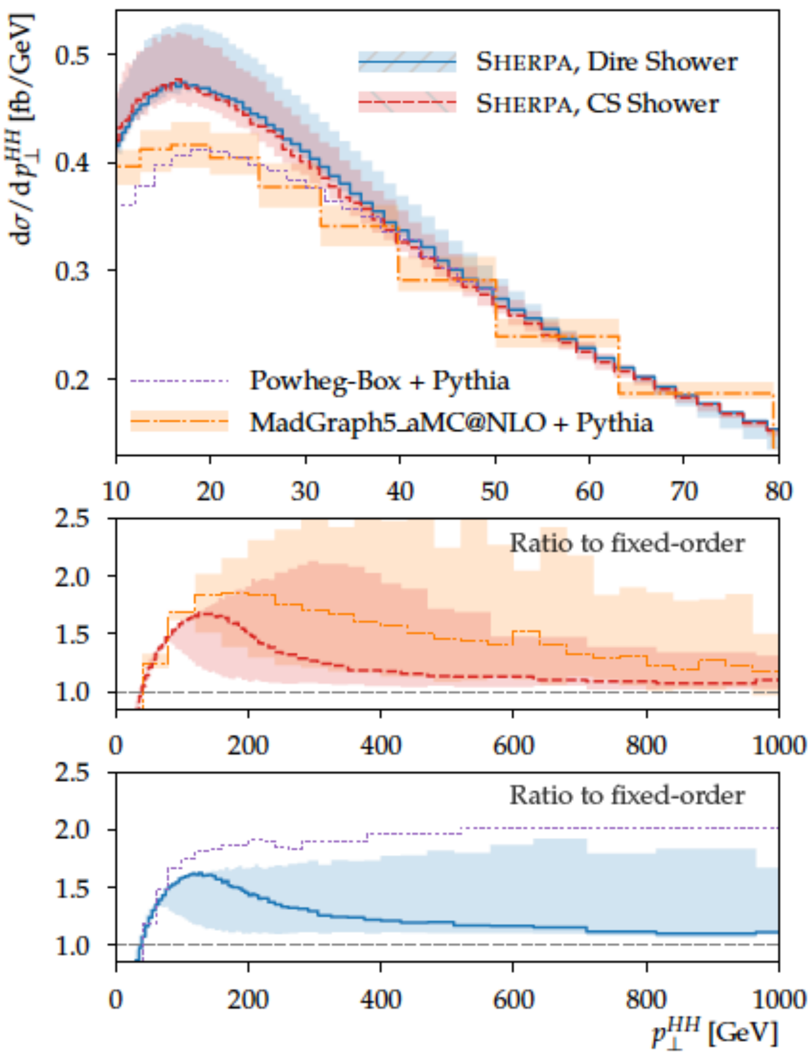
- Previous shower scale used in MG5_aMC: $[0.1\sqrt{\hat{s}}, \sqrt{\hat{s}}]$ gives significantly harder distributions close to hdamp=infinity
- New default scale approaches the fixed-order result much faster: a more natural choice
- Similarly hdamp=250 gives softer results, closer to the FO

Comparison with previous approximations

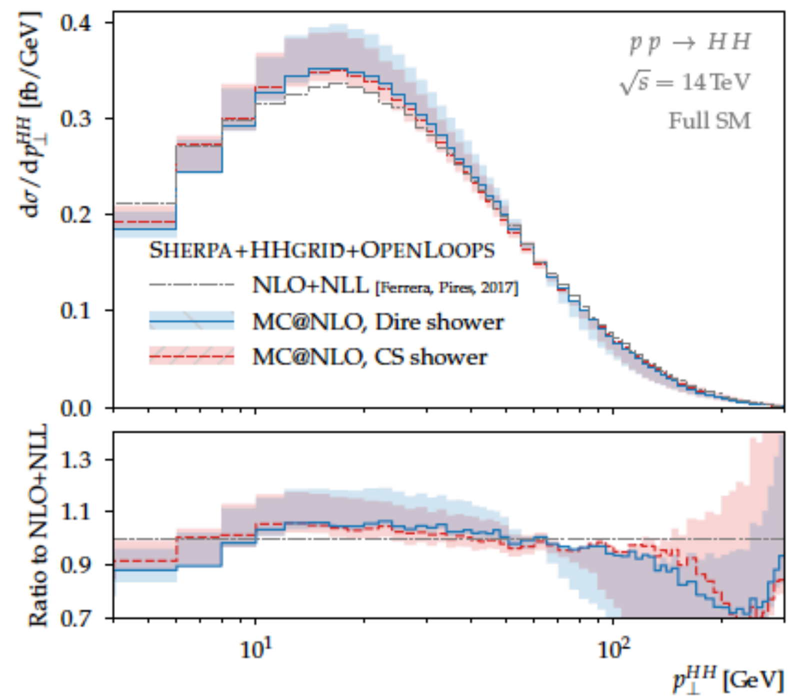


- Born-improved predictions much harder than exact computation
- FT_approx giving a good description of the high pT regions also in the NLO+PS predictions: exact real matrix element

More on NLO+PS



Comparison between shower algorithms

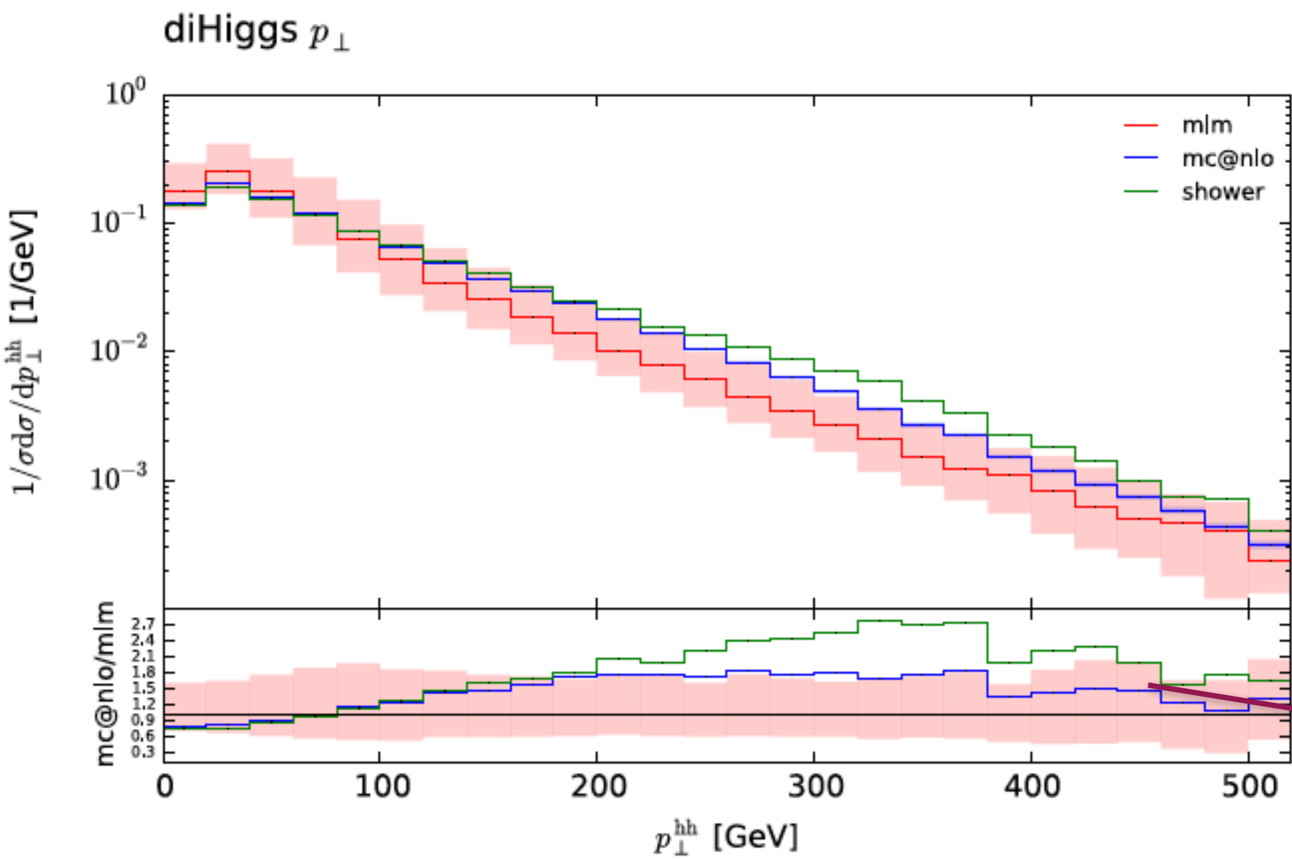


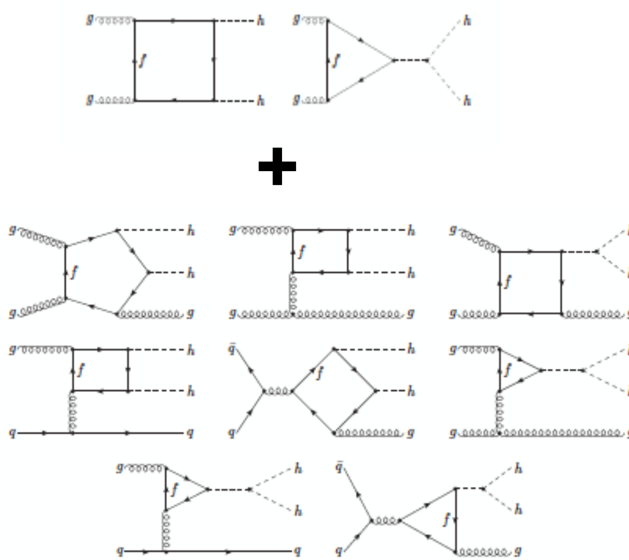
Comparison with resummation

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

Jones and Kuttimalai arXiv:1711.03319

Merging and matching





better description at high-pt

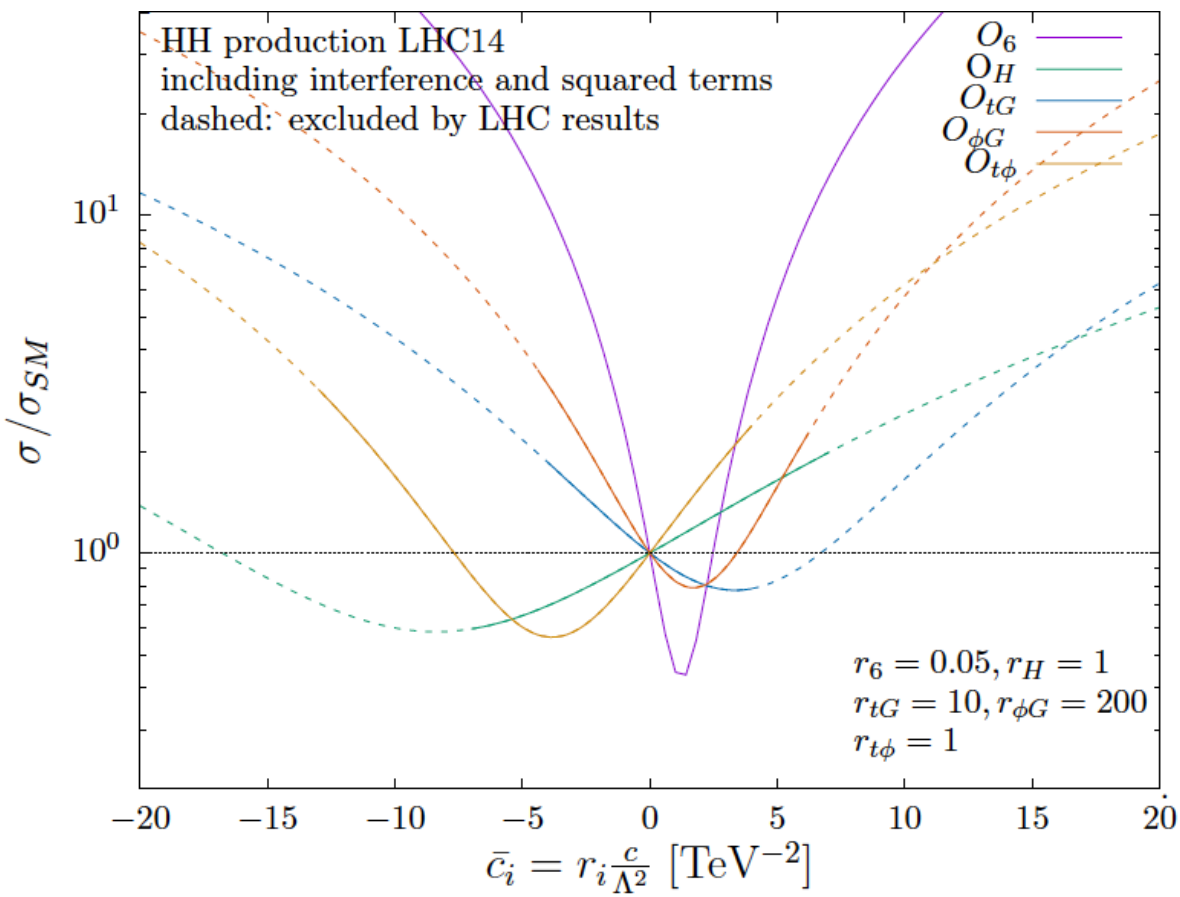
Maierhöfer, Papaefstathiou, arXiv:1401.0007
and comparison in YR4

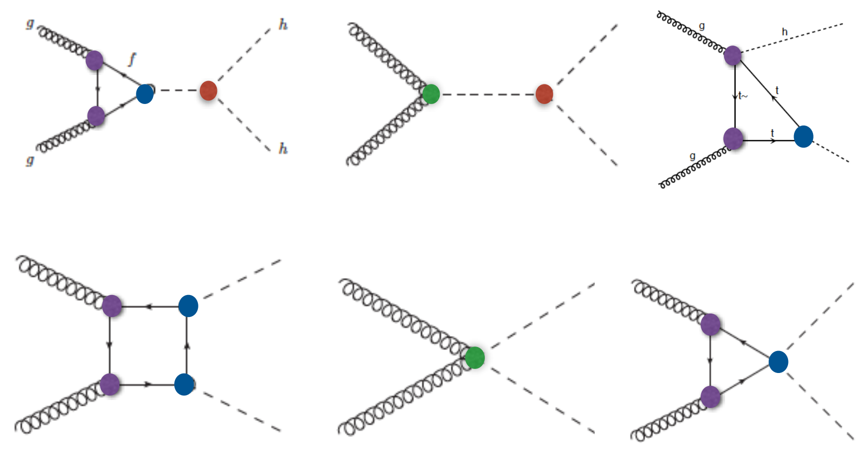
MLM, CKKW merging
Available in Herwig and MG5 (better solution than LO+PS)

Monte Carlo tools for BSM in HH

- EFT
- Resonances

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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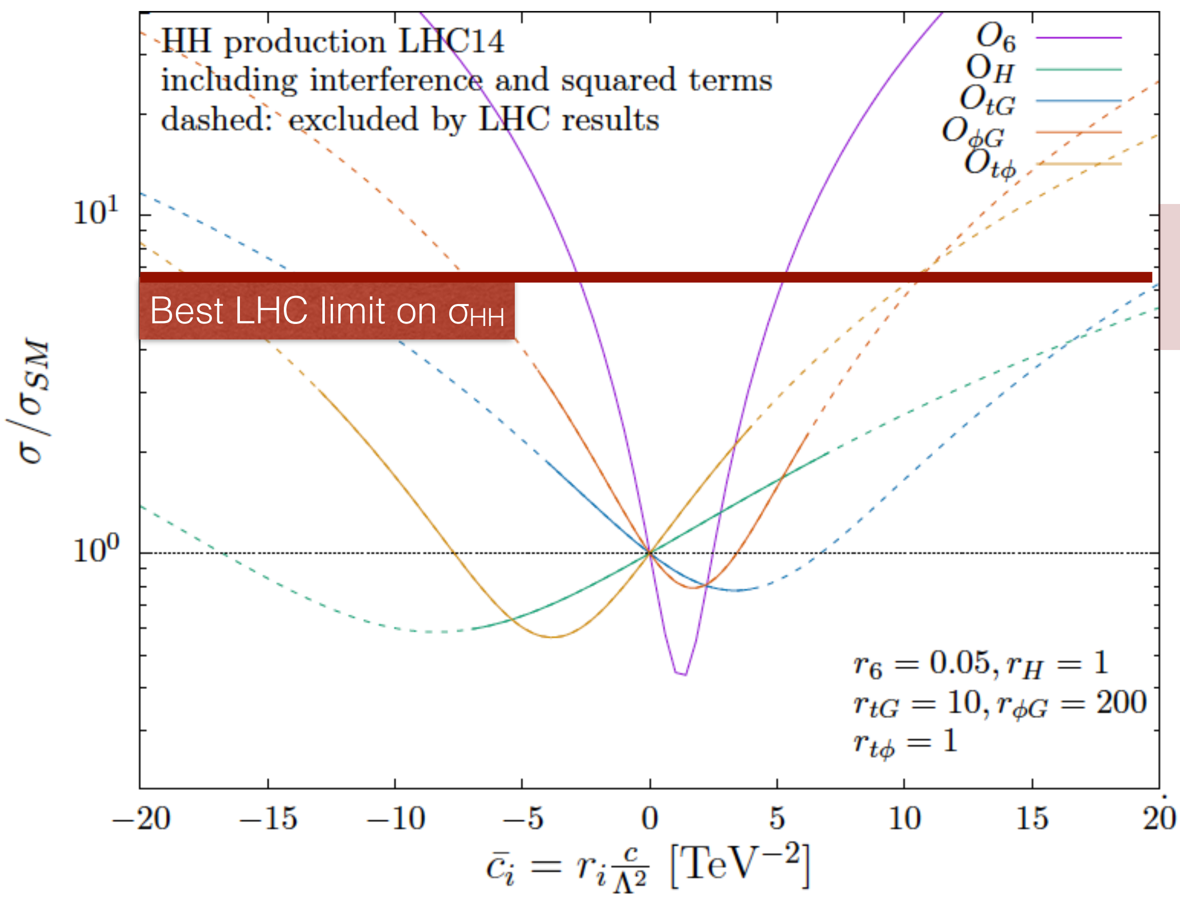

$$O_{t\phi} = y_t^3 \left(\phi^\dagger\phi\right) \left(\bar{Q}t\right) \tilde{\phi} \,,$$

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

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

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

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

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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

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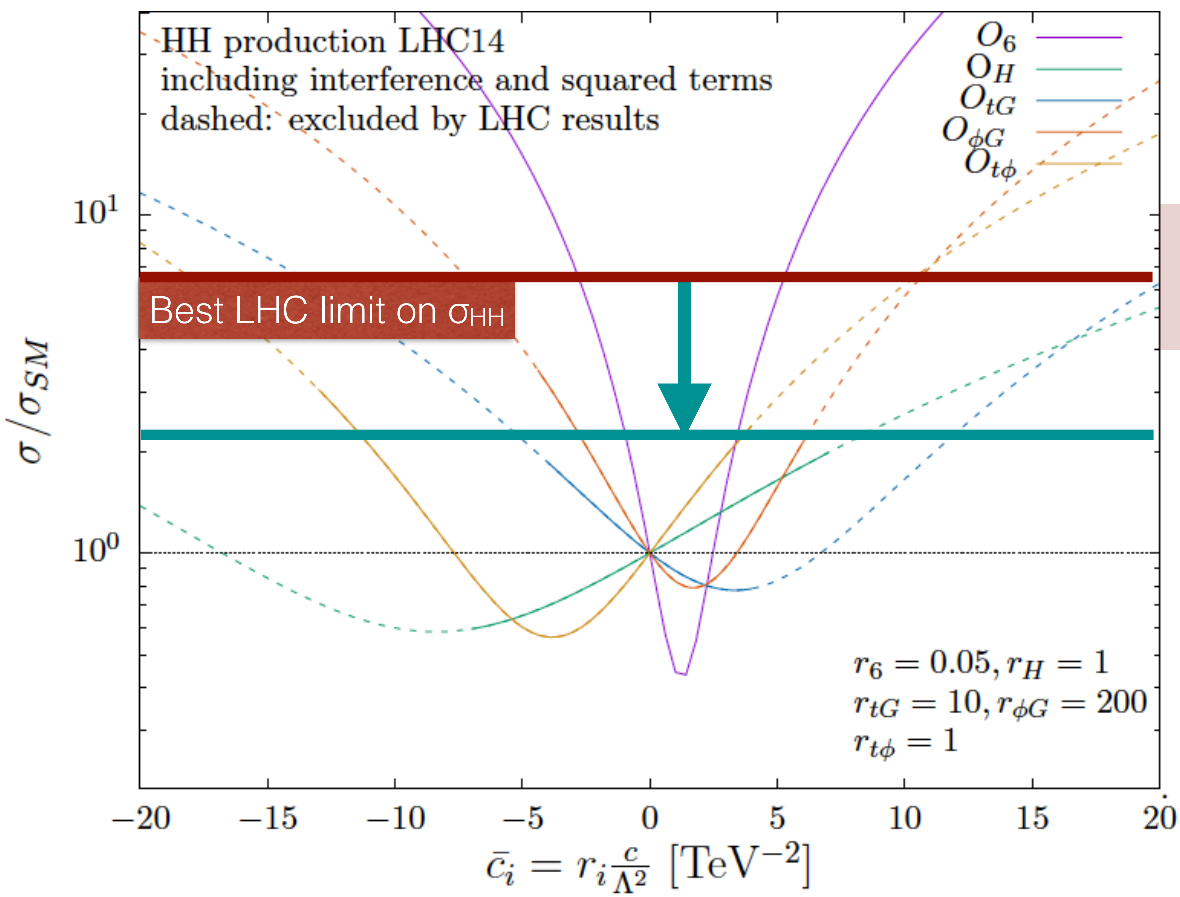

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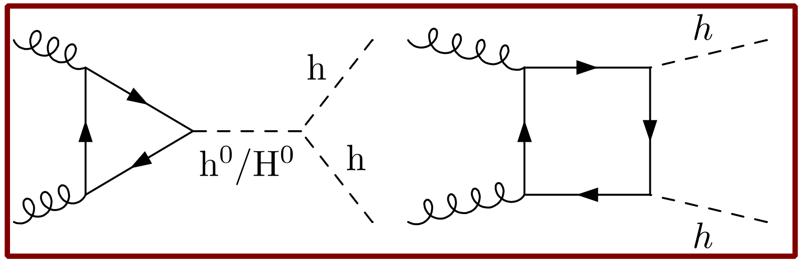
The future
Precise knowledge of other Wilson coefficients will be needed to bound λ as the bound gets closer to SM
Differential distributions will also be necessary

Resonant Higgs pair production:2HDM



Relevant couplings:

- Heavy quark Yukawas

$$g_{hxx} \equiv g_x^h = \left(1 + \Delta_x^h\right)\ g_x^{\rm SM}$$

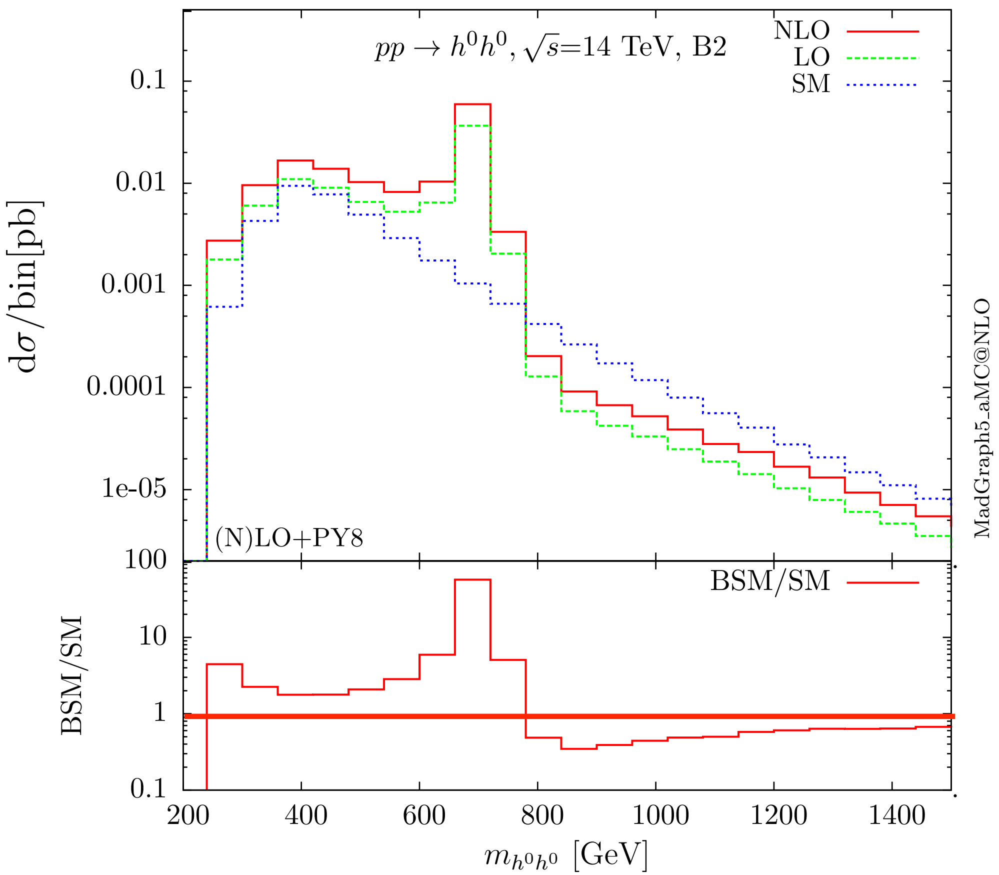
	Type I	Type II
$1+\Delta_t^{\rm h^0}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$
$1+\Delta_b^{\rm h^0}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
$1+\Delta_t^{\rm H^0}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$
$1+\Delta_b^{\rm H^0}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$

- Trilinear Higgs couplings

$$\lambda_{\rm h^0h^0h^0}: \quad -\frac{3}{\sin 2\beta}\left[\frac{4\cos(\alpha+\beta)\cos^2(\beta-\alpha)\, m_{12}^2}{\sin 2\beta} - m_{\rm h^0}^2\left(2\cos(\alpha+\beta) + \sin 2\alpha\, \sin(\beta-\alpha)\right)\right]$$

$$\lambda_{\rm h^0h^0H^0}: \quad \frac{\cos(\beta-\alpha)}{\sin 2\beta}\left[\sin 2\alpha\left(2m_{\rm h^0}^2 + m_{\rm H^0}^2\right) - \frac{2m_{12}^2}{\sin 2\beta}\left(3\sin 2\alpha - \sin 2\beta\right)\right]$$

Higgs pair production
Resonant 2HDM scenario: Heavy H



2HDM input: Type-II

	$\tan\beta$	α/π	m_{H^0}	m_{A^0}	$m_{H^\pm}$	m_{12}^2
B2	1.50	-0.2162	700	701	670	180000

- **Slightly reduced top Yukawa**
- **40% reduction of the hhh coupling**
- **Enhanced Hhh coupling**

$\sigma_{hh}\sim$ 4 times the SM prediction

Higgs pair production

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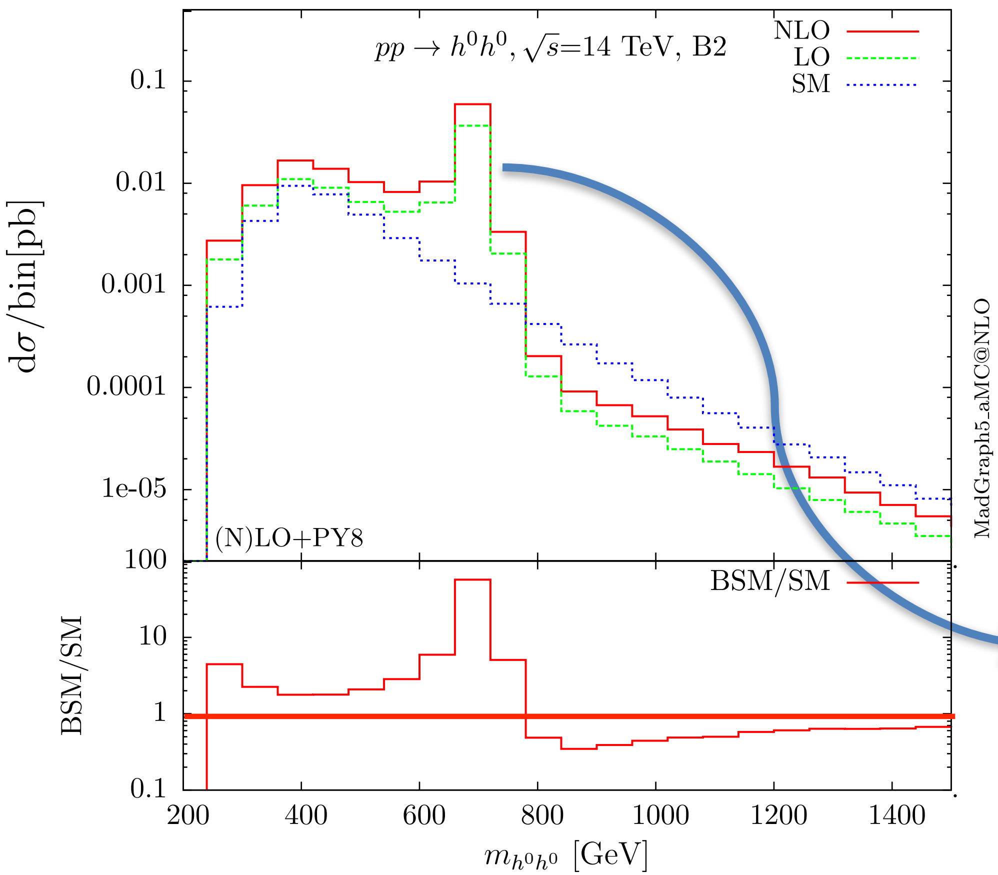

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- Distinctive resonance peak
- **Interference patterns before and after the peak, need to go beyond the NWA**

Higgs pair production
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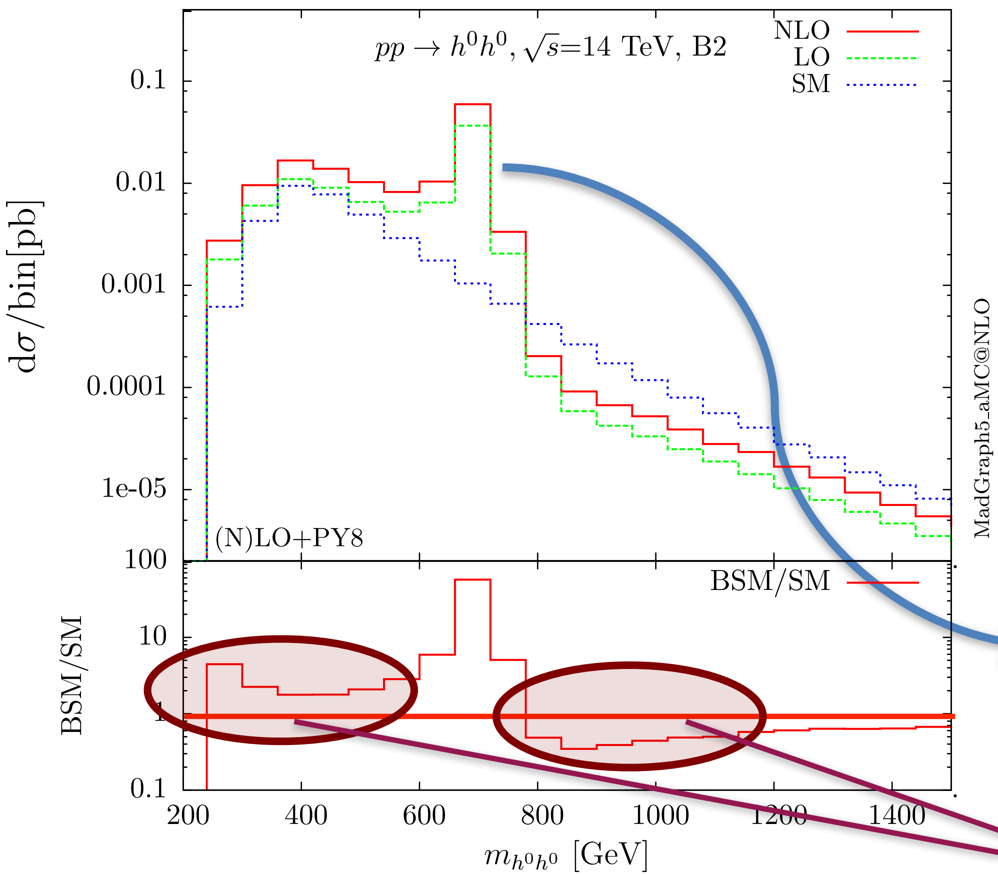

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Availability of tools: 2HDM

- 2HDM HH calculation using the NLO-ready 2HDM model: Degrande arXiv:1406.3030
- Model available in Feynrules database
- http://feynrules.irmp.ucl.ac.be/wiki/NLOModels
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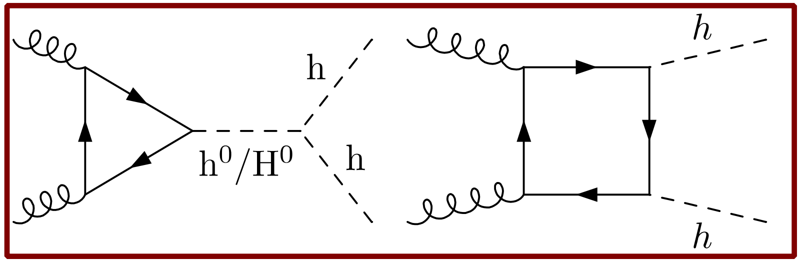
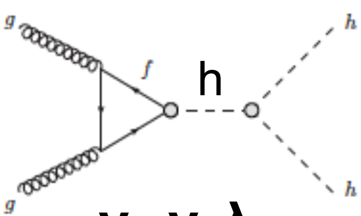
- Exact LO computation with the full top and bottom mass dependence
- MG5_aMC@NLO: loop-induced event generation
  - import model 2HDM_NLO
  - generate g g > h1 h1 [QCD]
  - output gghh
- This includes the SM-like diagrams + heavy Higgs diagrams + interference

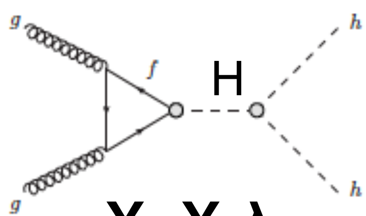


c.f. generate g g > h2 > h1 h1 [QCD] (signal only)

General comments on parameter space for models with extra scalars



y_b, y_t, λ_{hhh}



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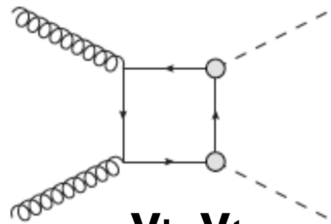

y_b, y_t

In models with extra scalars:

- Parameters of interest for HH:
  - Light and Heavy Higgs Yukawas
  - Trilinear Hhh coupling
  - Trilinear hhh coupling

Width is not a free parameter

For a pronounced resonance:

+ Enhanced Heavy Higgs top Yukawa

+ Large trilinear Hhh coupling

+ Relatively Low Mass Heavy Higgs

- Going beyond the NWA approximation needed as the sensitivity improves, reaching cross-sections larger by factors of a few above the SM prediction and for resonances with larger widths

Summary and conclusions

- 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)
- EFT implementation available
- 2HDM implementation (with interference) available


Thanks for your attention