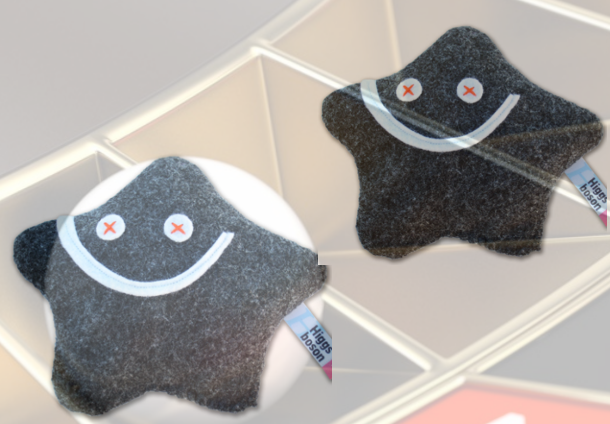
MonteCarlos for HH production
in the SM

Marco Zaro

LPTHE - UPMC

HPPC2015 Workshop @ Mainz



Definition

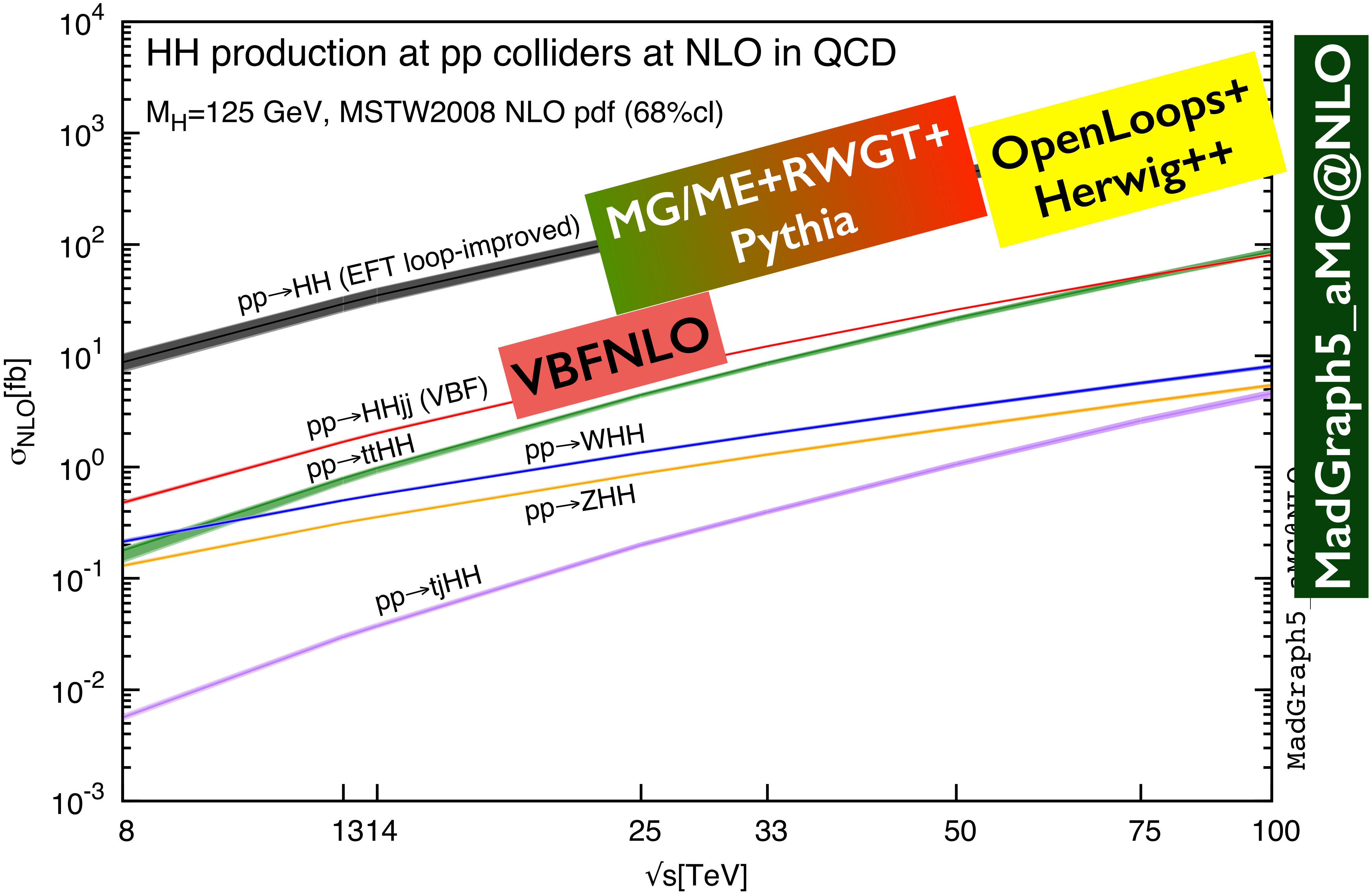
- MonteCarlo: a (public) tool that provides differential distributions for any observable or unweighted events, beyond LO/lowest-multiplicity

Beyond total rates

- More than total rates needed for realistic pheno studies
  - Selection/acceptance cuts are imposed on particles in the final state
  - One may want to look to specific differential distributions
- Accurate (i.e. including QCD effects beyond LO) and realistic (i.e. matched with PS) fully differential predictions are necessary!

What is on the market?

Production channels:



ggHH tot xsec also known at NNLO (in the EFT) (de Florian, Mazzitelli, arXiv:1309.6594)

HH-VBF tot xsec also known at NNLO (Liu-Sheng, Ren-You, Wen-Gan, Lei, Wei-Hua, Xiao-Zhou, arXiv:1401.7754)

VHH tot xsec also known at NNLO (Baglio, Djouadi, Grober, Muhlleitner, Quevillon, Spira, arXiv:1212:5581)

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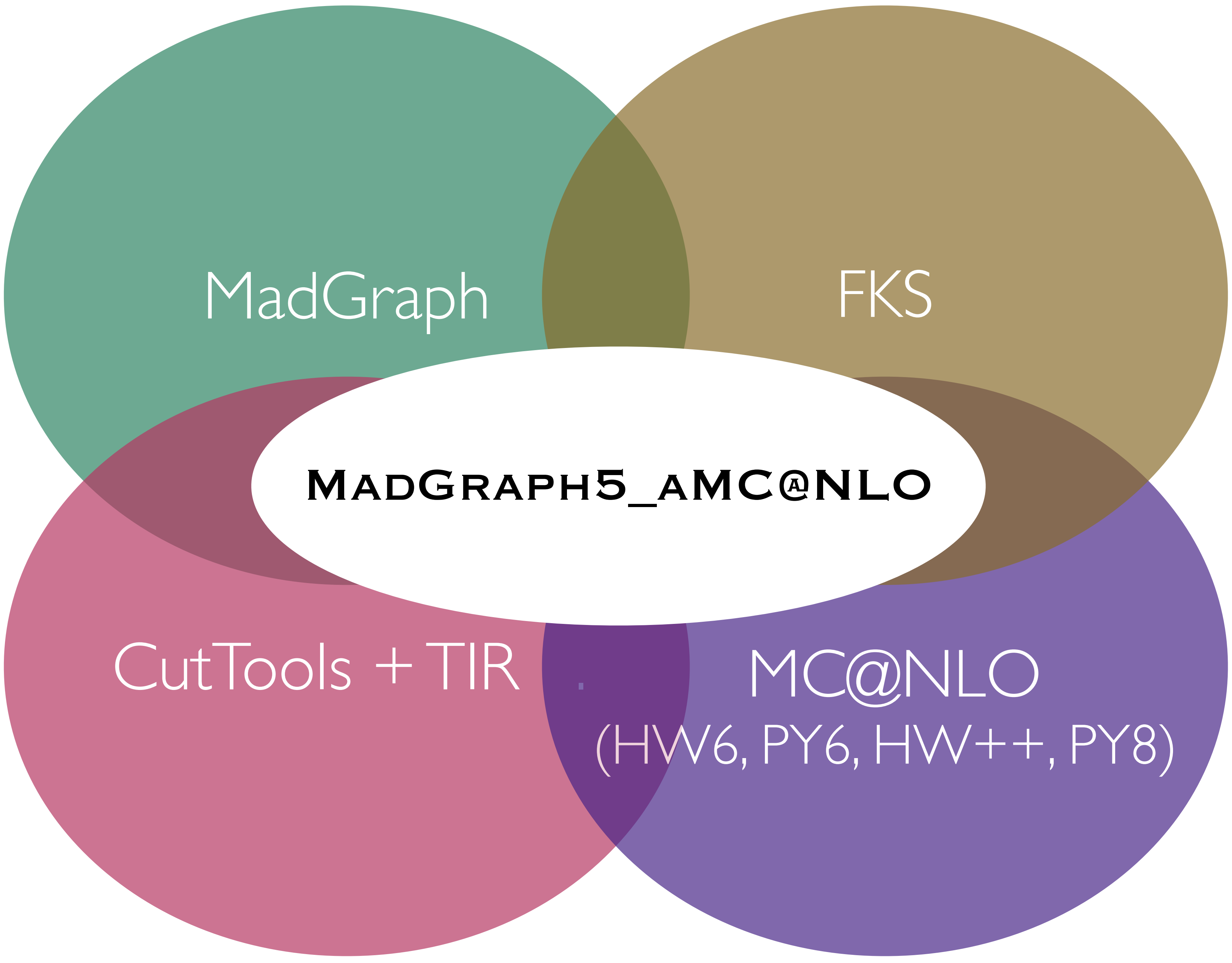
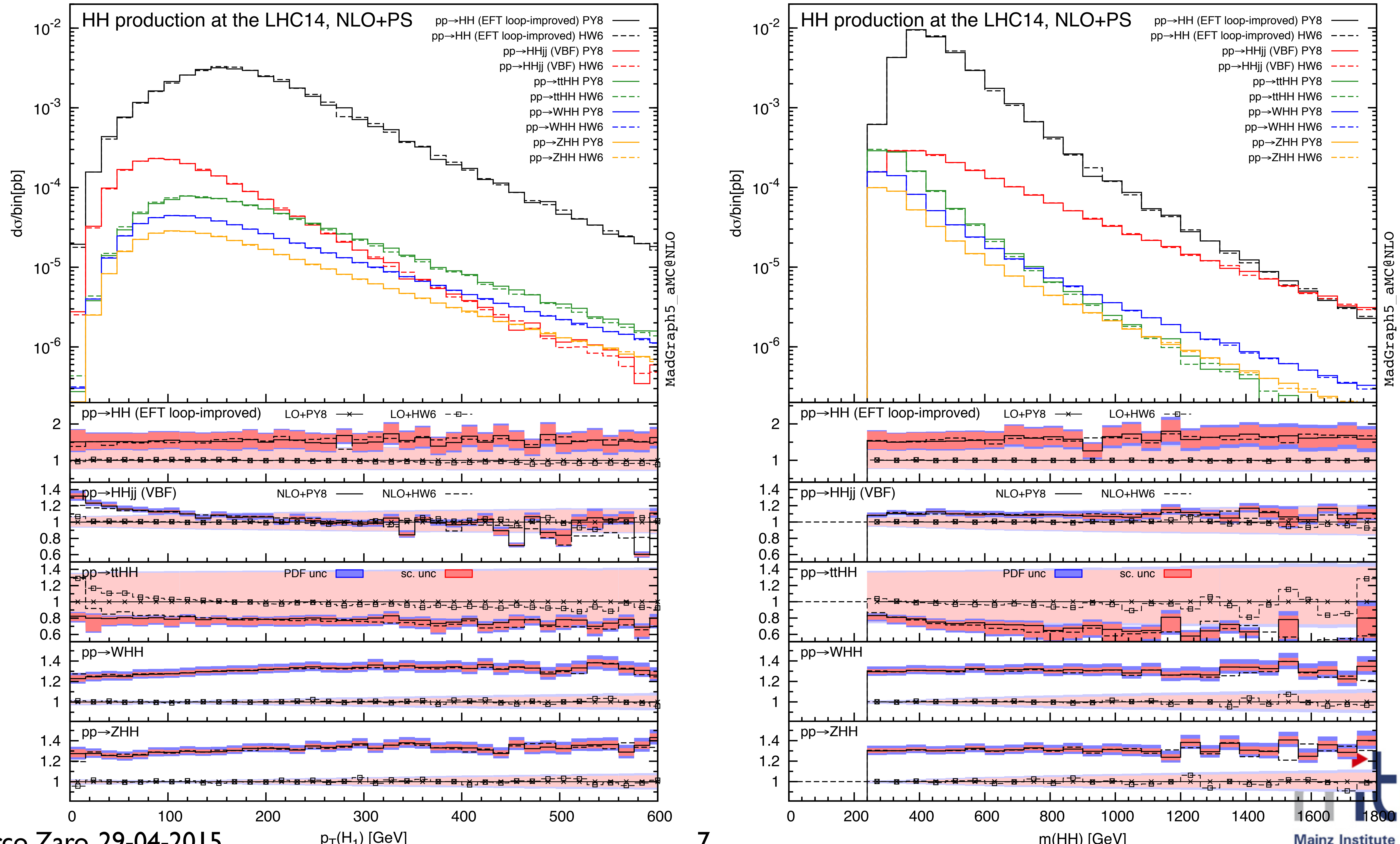
MadGraph5_aMC@NLO

J. Alwall, R. Frederix, S. Frixione, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, V. Hirschi, MZ

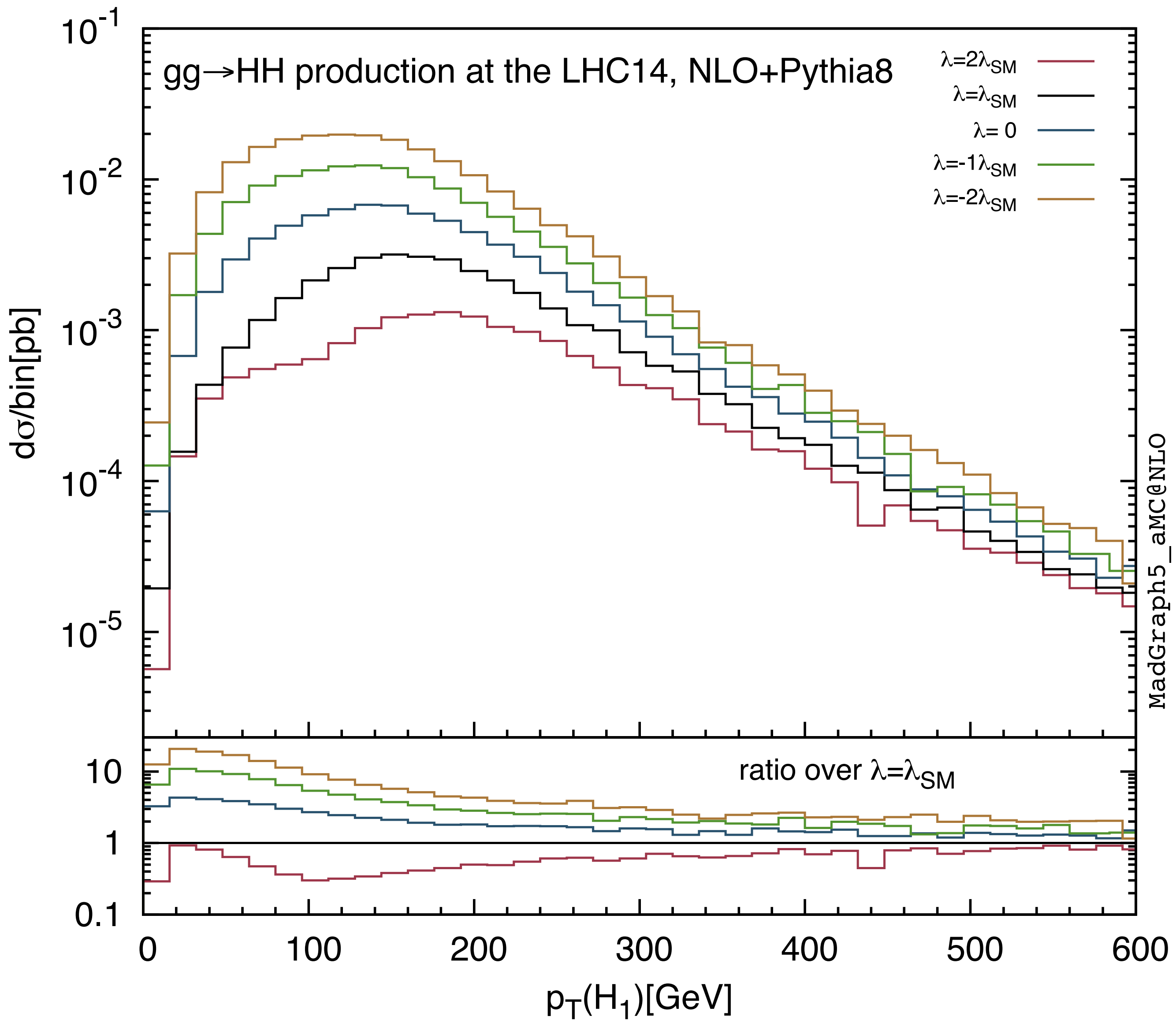
arXiv:1405.0301

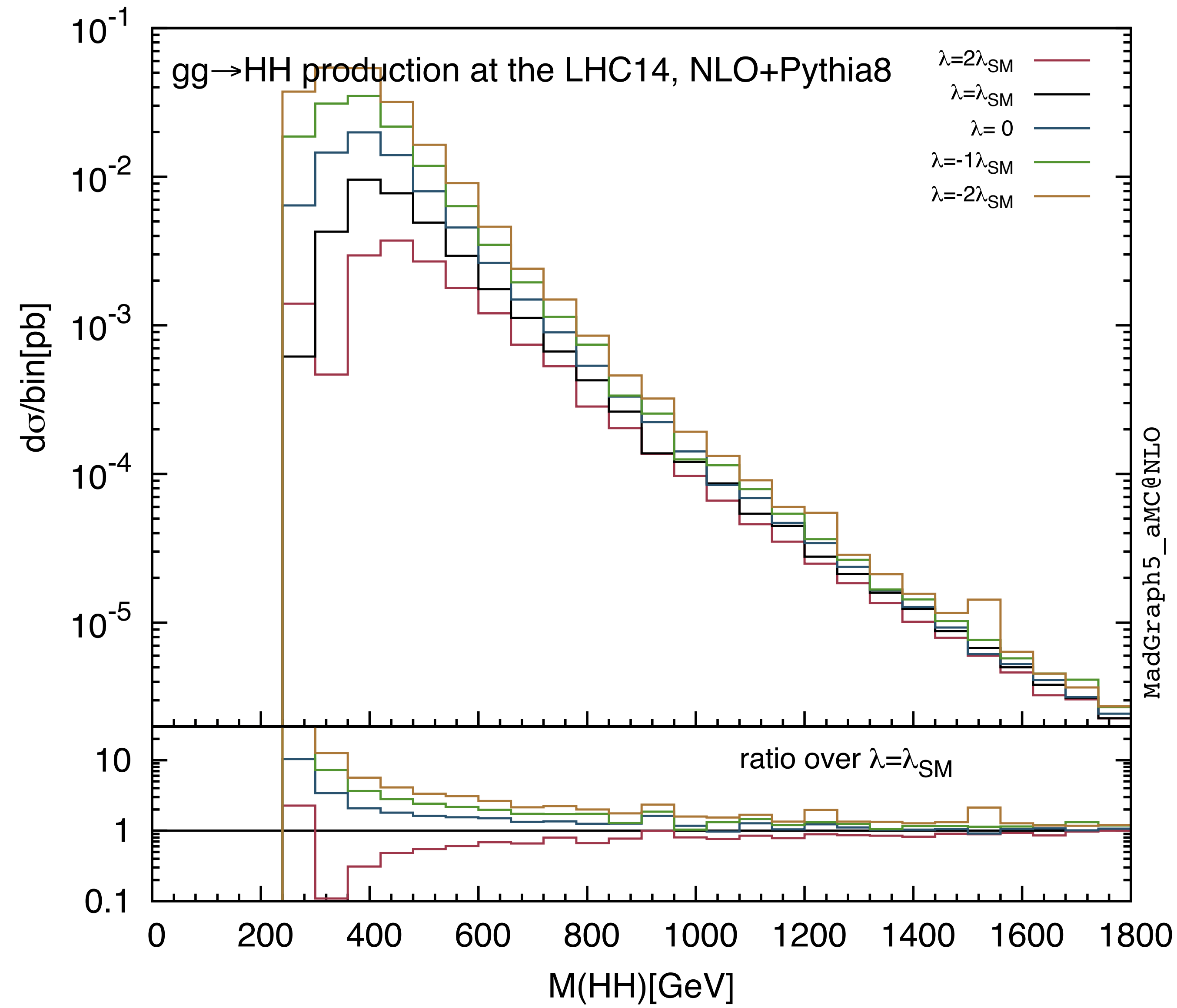


HH differential observables

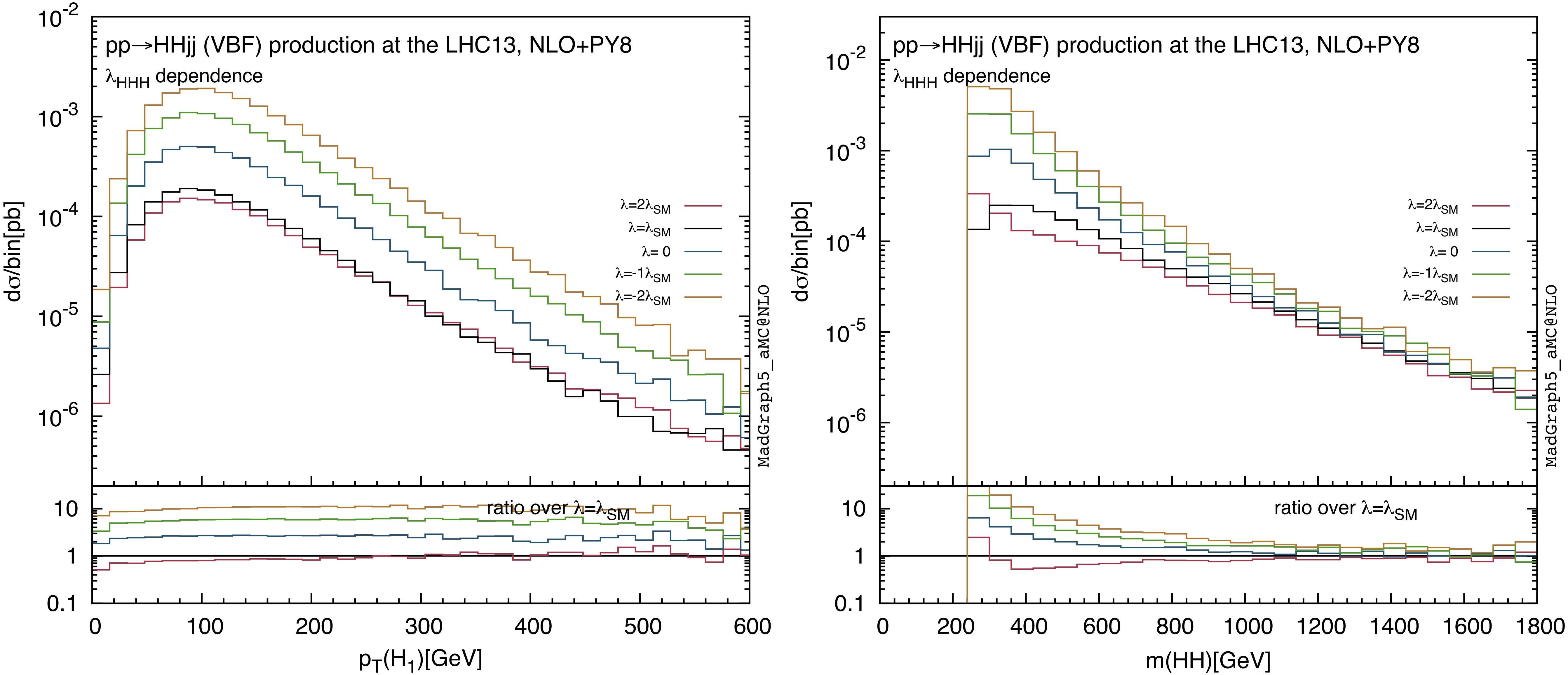


λ_{HHH} dependence in gg→HH

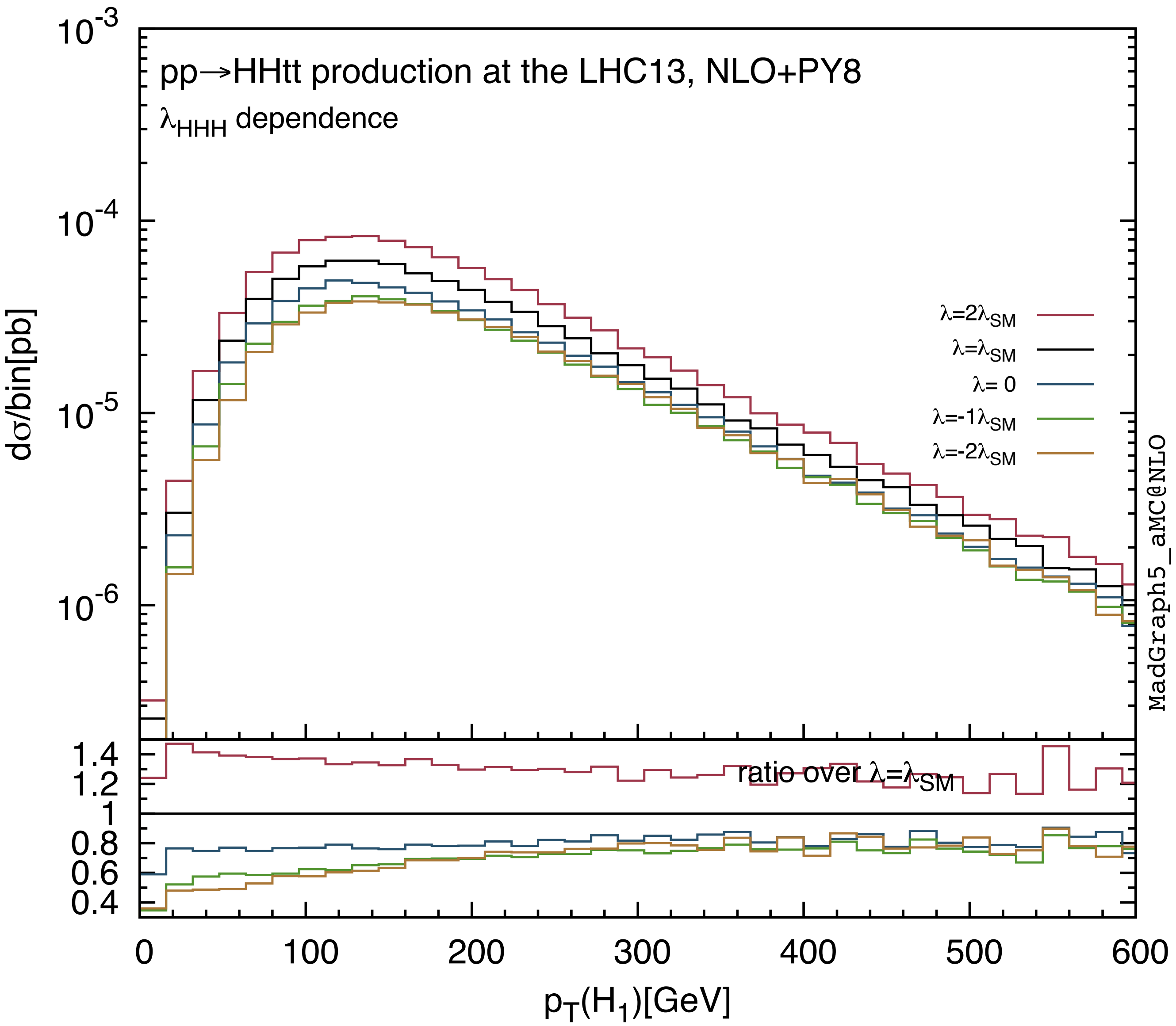


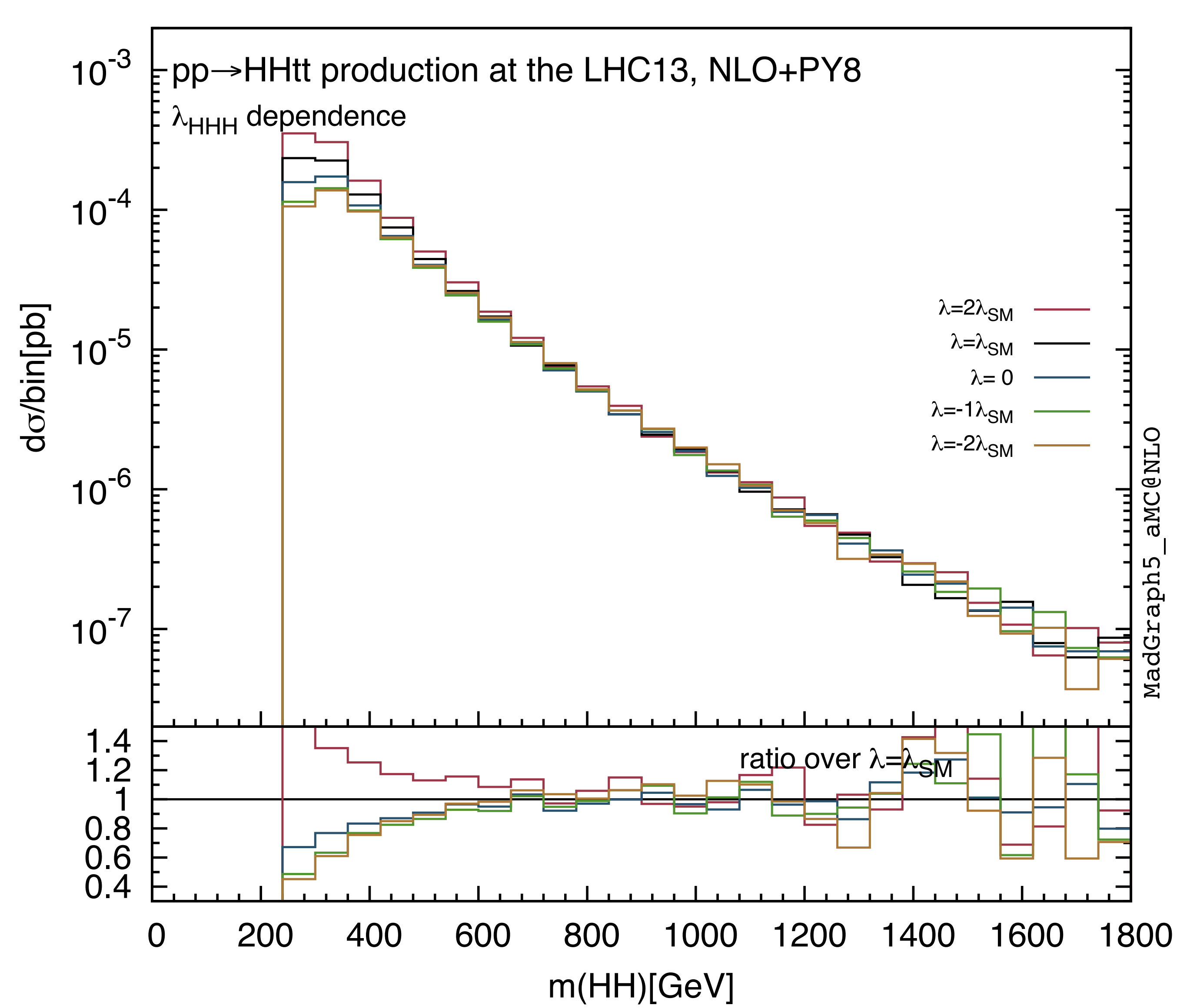


λ_{HHH} dependence in VBF

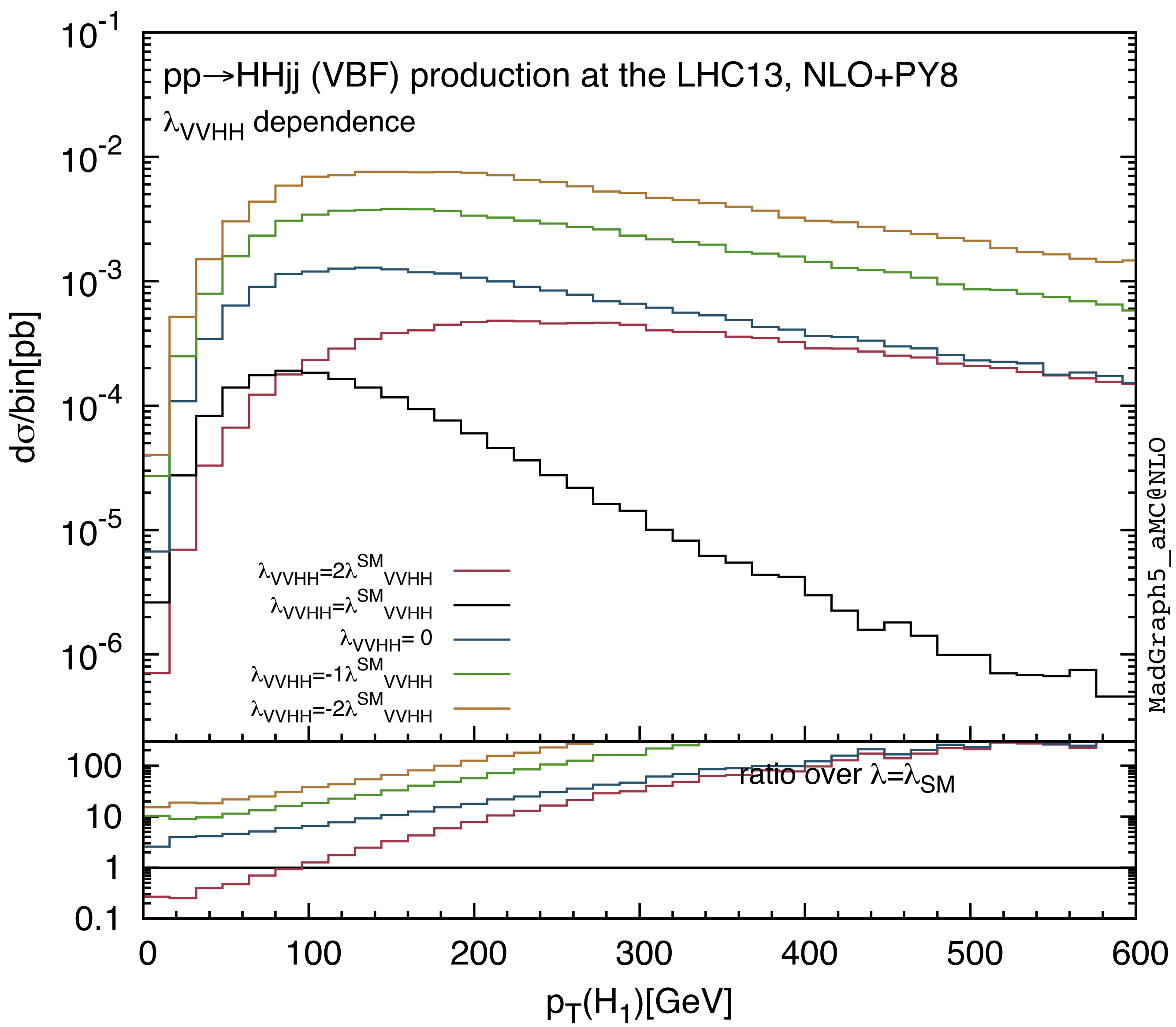


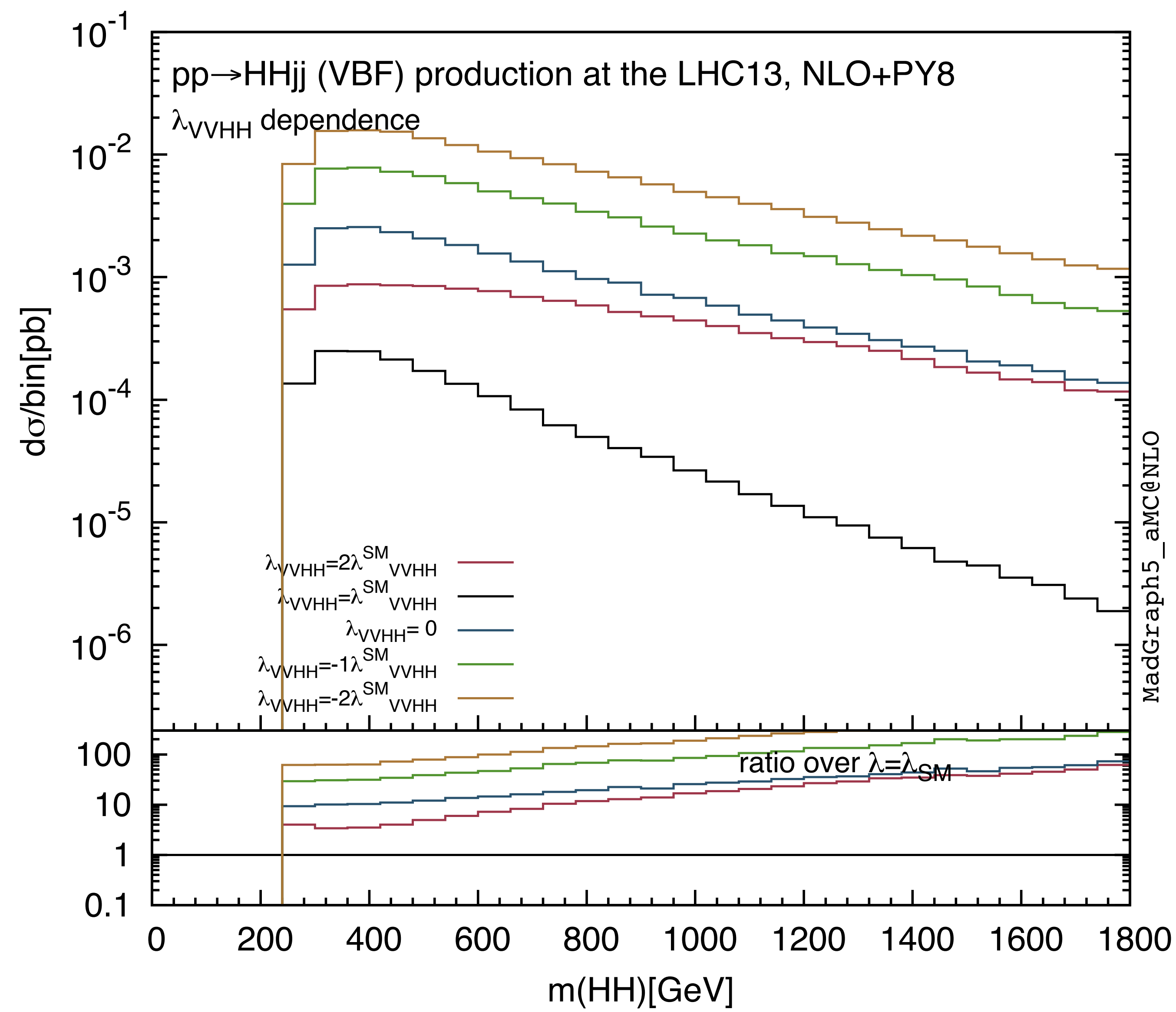
λ_{HHH} dependence in $t\bar{t}HH$





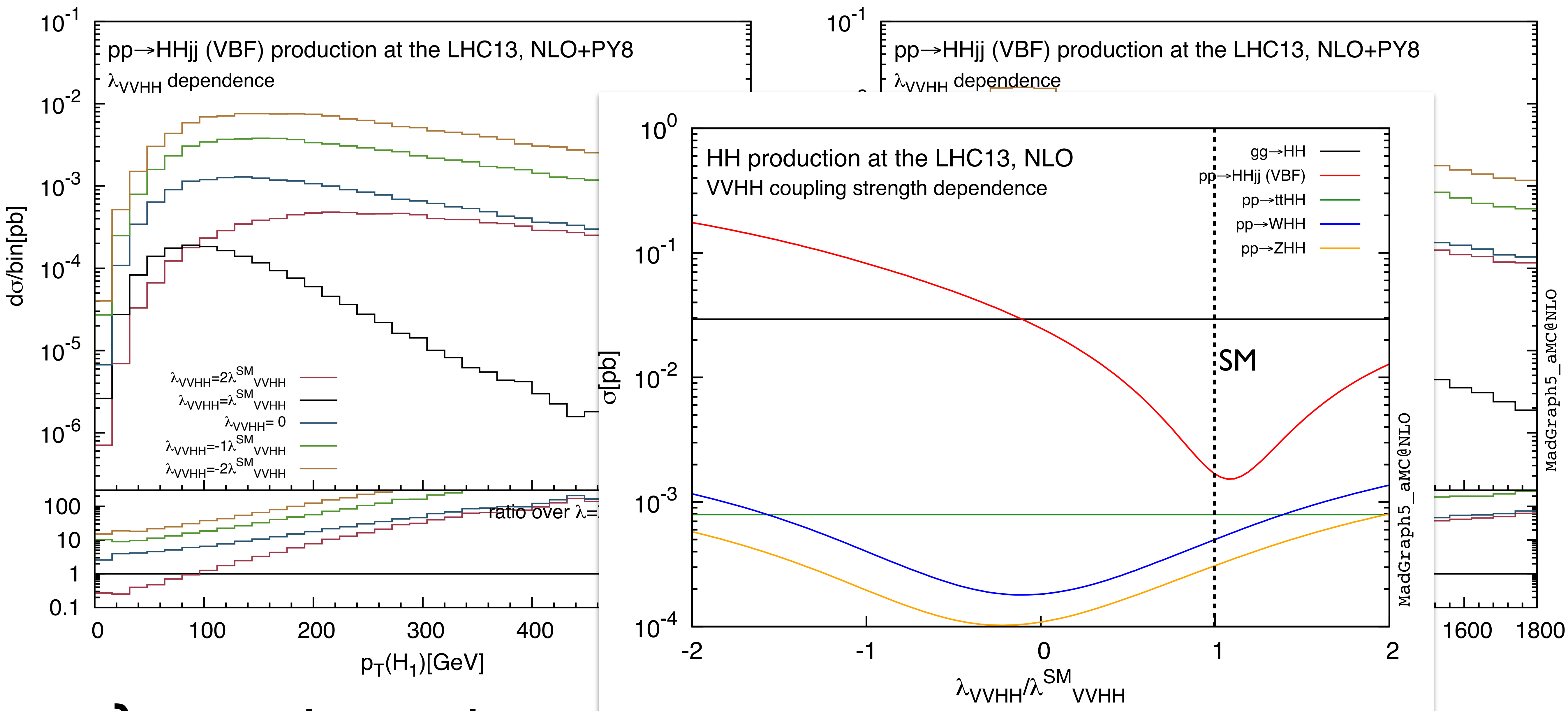
λ_{VVHH} dependence in VBF





- λ_{VVHH} changed in a custodial way (same scaling factor for W and Z)

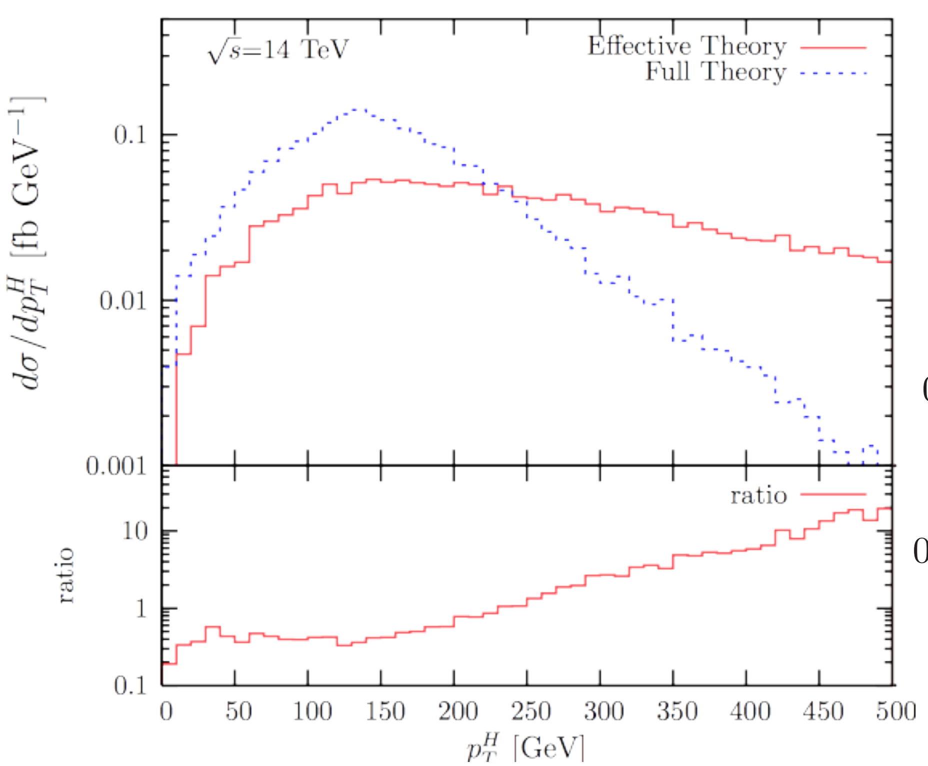
λ_{VVHH} dependence in VBF



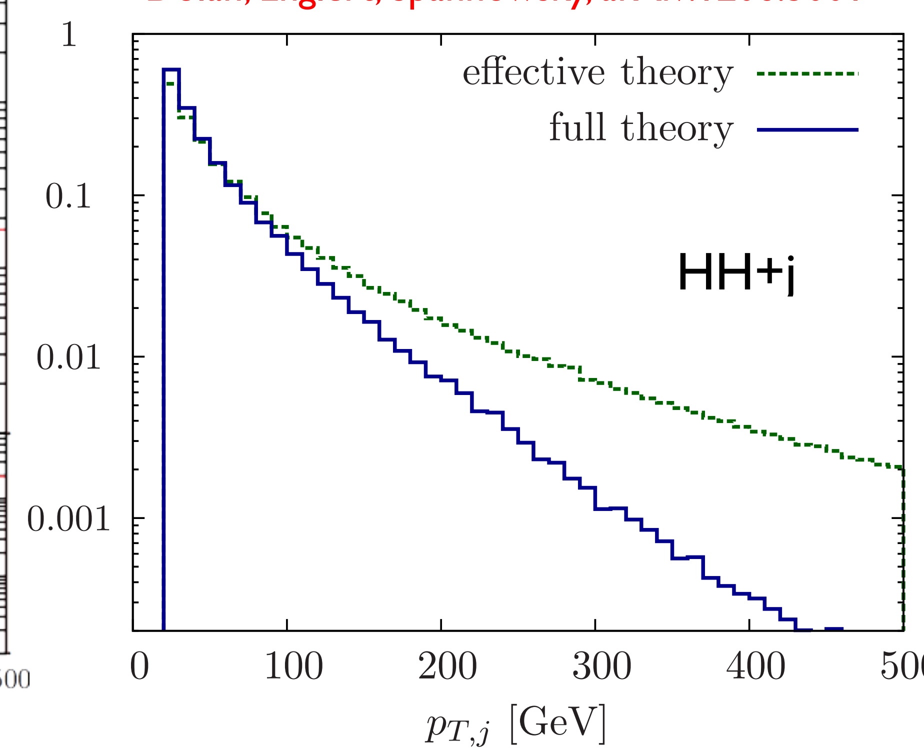
- λ_{VVHH} changed in a custodial way (same scaling factor for W and Z)

HH in MadGraph5_aMC@NLO

- All sub-leading HH production modes can be simulated automatically in MadGraph5_aMC@NLO at NLO+PS
- gg→HH needs special care:
  - The top-quark effective theory breaks down for HH production



Dolan, Englert, Spannowsky, arXiv:1206.5001



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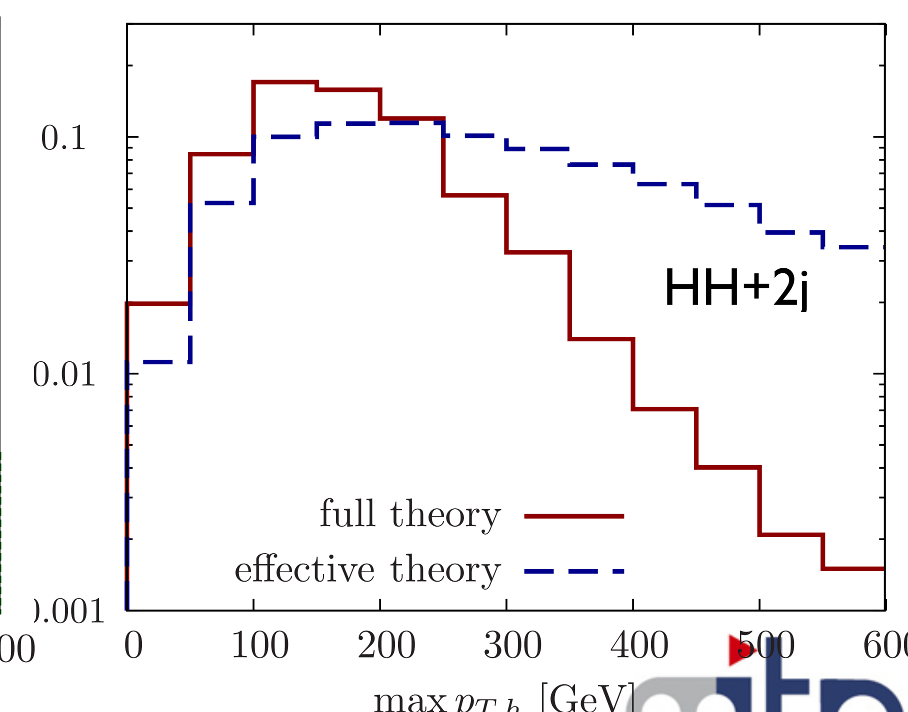

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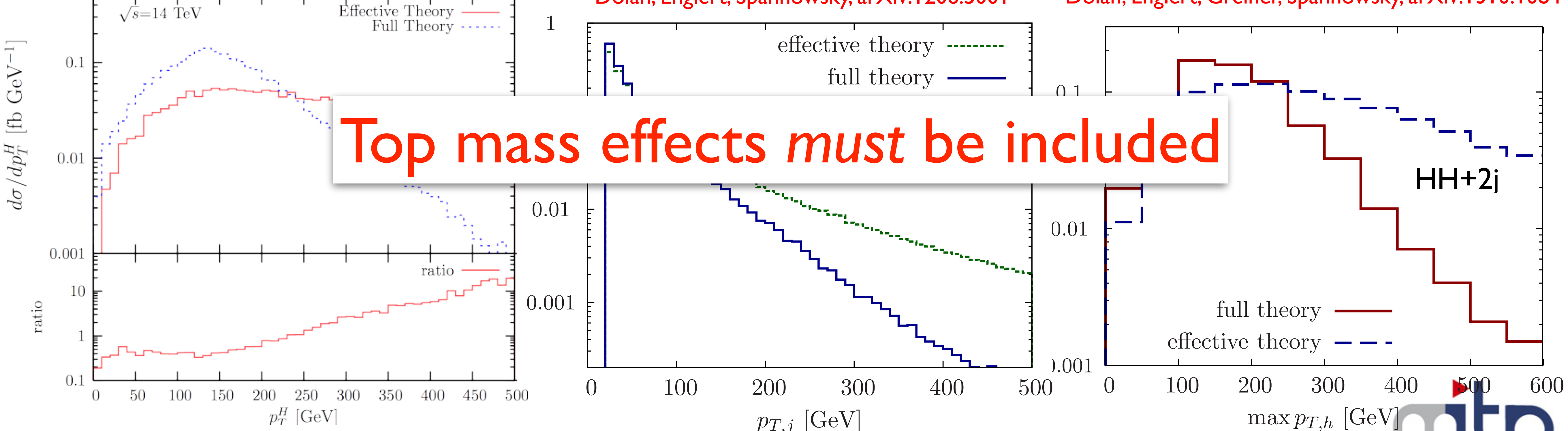


Top mass effects *must* be included

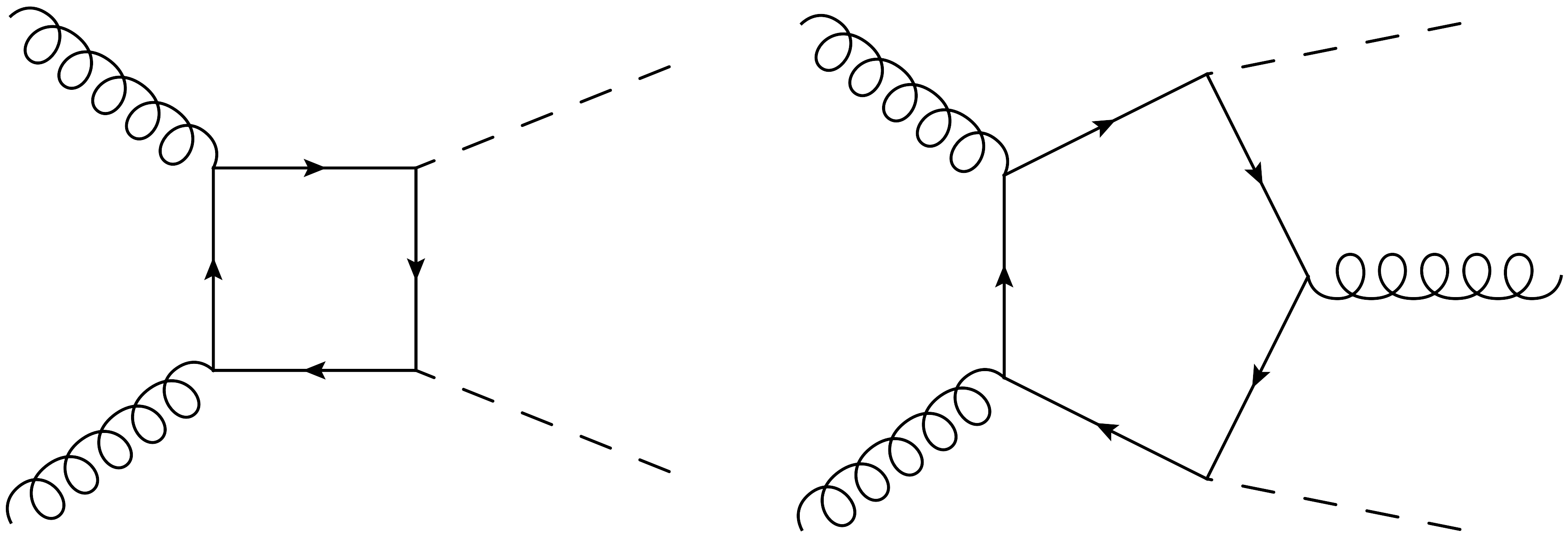
Inclusion of top mass effects

(see also afternoon talks)

MLM merging

Li, Yan, Zhao, arXiv:1312.3830

Maierhofer, Papaefstathiou, arXiv:1401.0007



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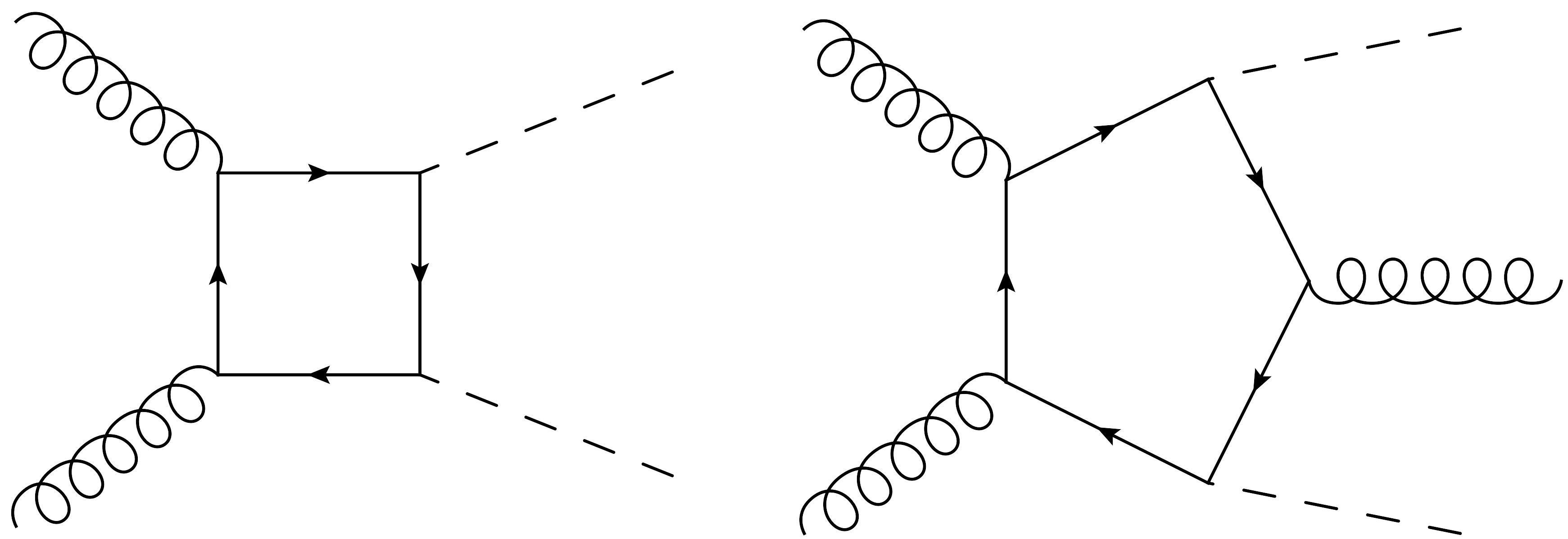
- Include exact one-loop born and real-emission ME



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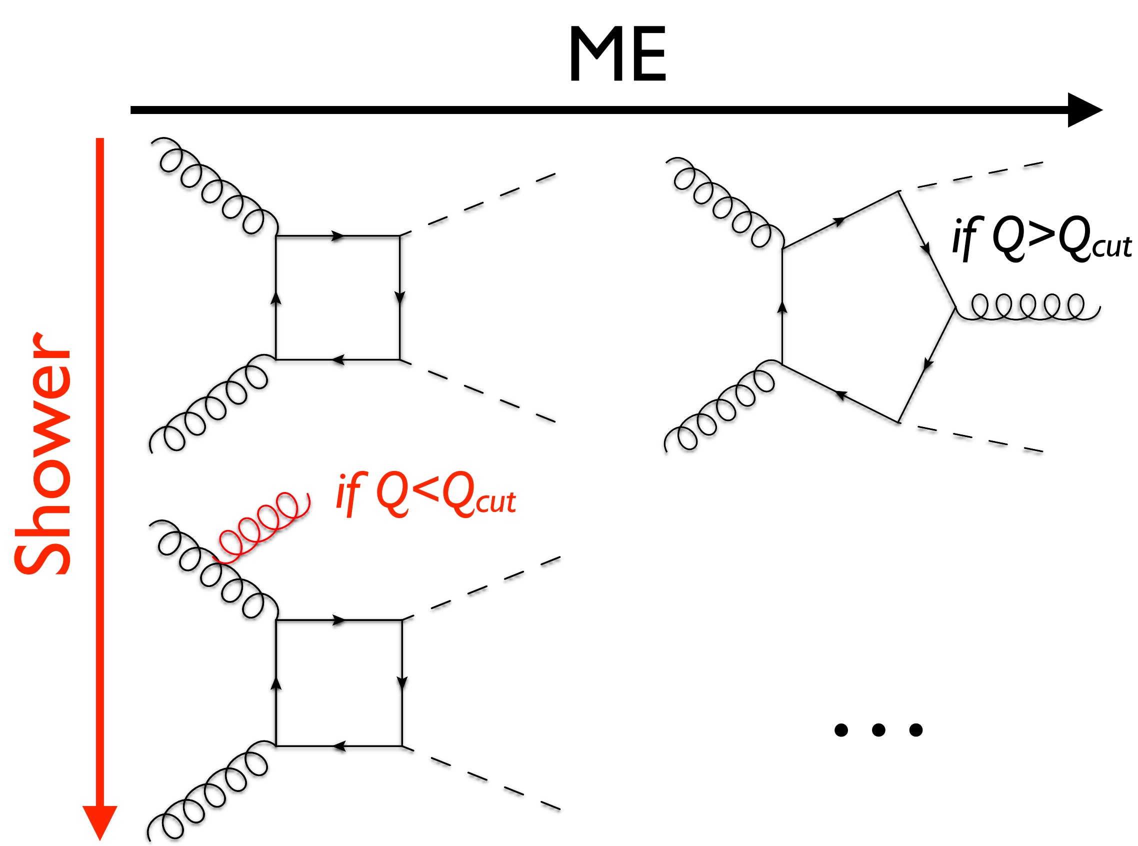
- Include exact one-loop born and real-emission ME
- Use a merging scale (arbitrary) to separate soft and hard emissions (shower vs ME driven)



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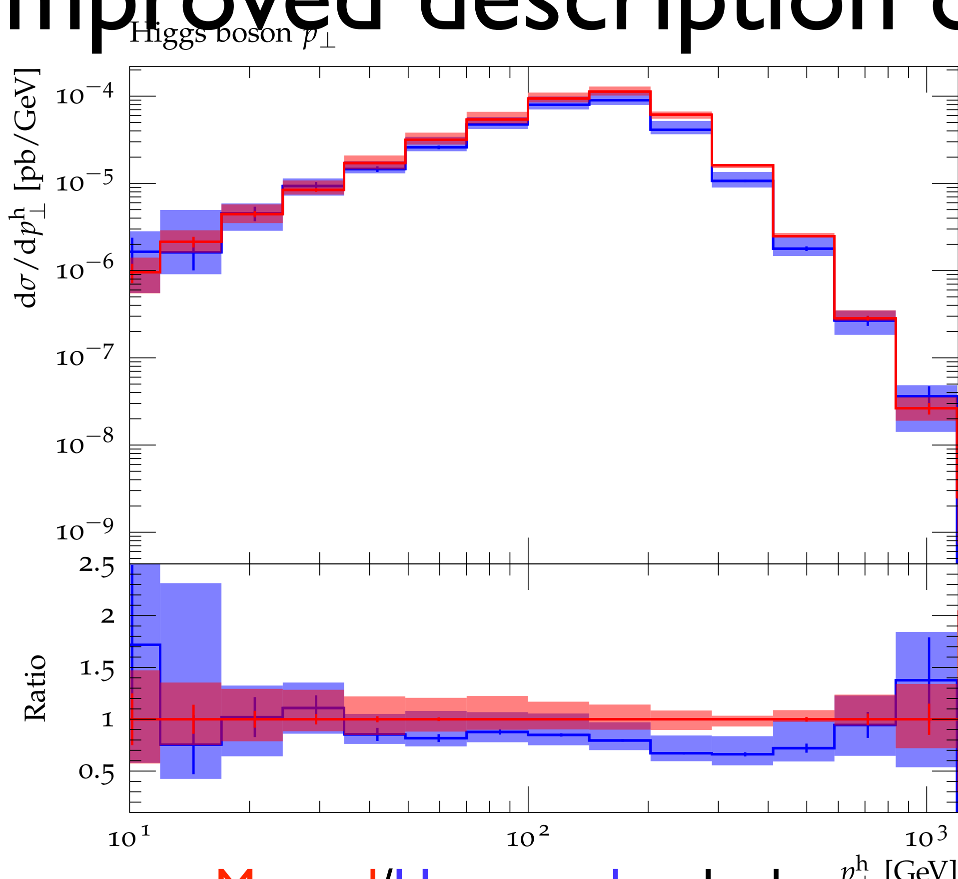
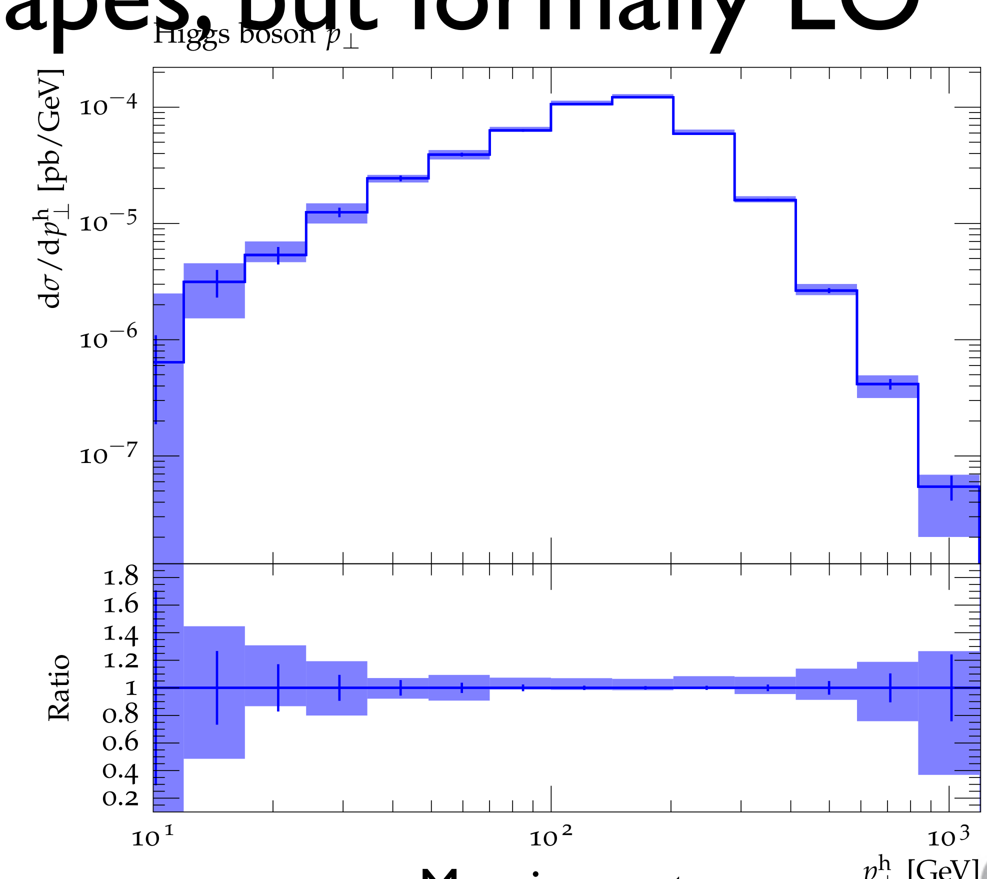
- Include exact one-loop born and real-emission ME
- Use a merging scale (arbitrary) to separate soft and hard emissions (shower vs ME driven)
  - Improved description of shapes, but formally LO



Merged/Unmerged scale dep.



Merging syst.

gg→HH @NLO: HPAIR

Dawson, Dittmaier, Spira, arXiv:hep-ph/9805244

$$d\sigma^n_{NLO} = d\sigma^n_{LO} + d\sigma^n_V + \int d\Phi_1 \, d\sigma^{n+1}_R$$

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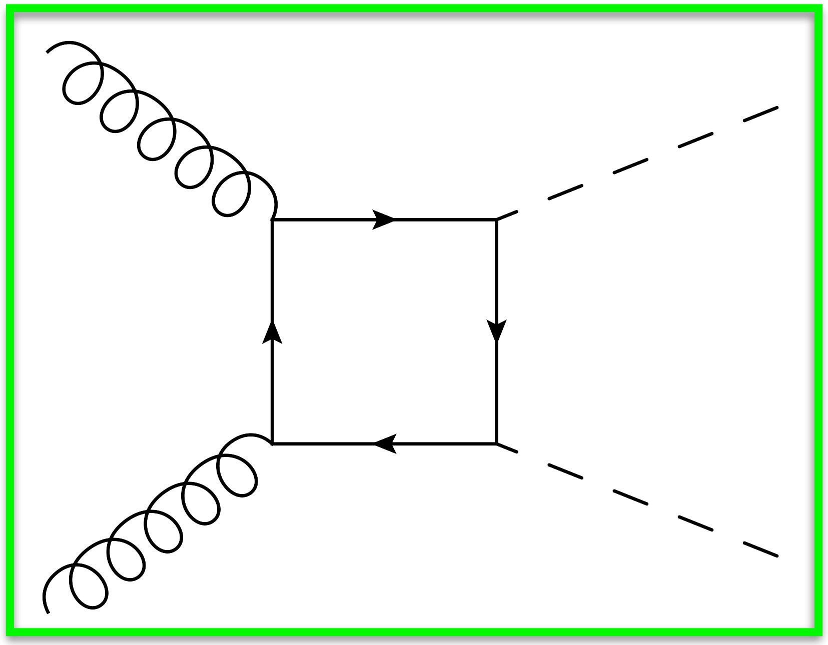
$$d\sigma^n_{NLO} = \boxed{d\sigma^n_{LO}} + d\sigma^n_V + \int d\Phi_1 \, d\sigma^{n+1}_R$$

- Include exact one-loop born matrix-element



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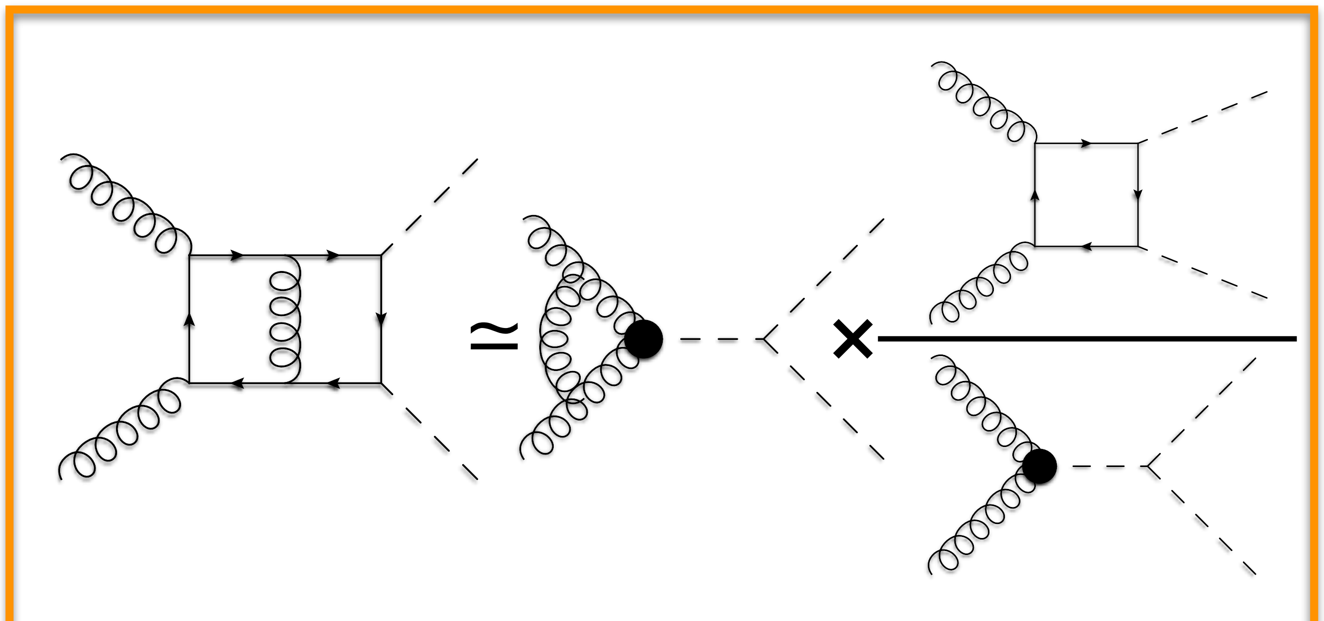
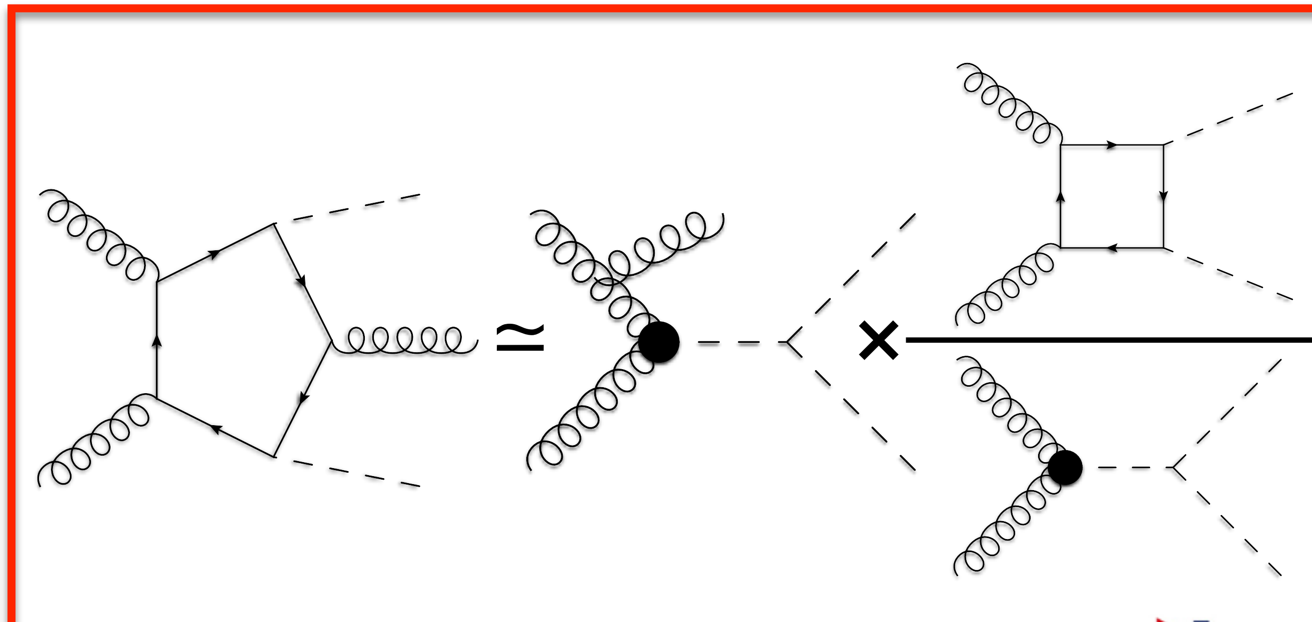
$$d\sigma^n_{NLO} = \boxed{d\sigma^n_{LO}} + \boxed{d\sigma^n_V} + \boxed{\int d\Phi_1 \, d\sigma^{n+1}_R}$$

- Include exact one-loop born matrix-element
- Approximate real and virtuals with the born-rescaled EFT





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$$d\sigma^{n}_{NLO} = \boxed{d\sigma^{n}_{LO}} + \boxed{d\sigma^{n}_{V}} + \boxed{\int d\Phi_1 \, d\sigma^{n+1}_{R}}$$

- Include exact one-loop born matrix-element
- Approximate real and virtuals with the born-rescaled EFT
- Only inclusive NLO cross-section

$$\begin{aligned}
\sigma_{\mathrm{LO}} &= \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \, \hat\sigma_{\mathrm{LO}}(Q^2 = \tau s), \\
\Delta\sigma_{\mathrm{virt}} &= \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \, \hat\sigma_{\mathrm{LO}}(Q^2 = \tau s) \; C, \\
\Delta\sigma_{gg} &= \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat\sigma_{\mathrm{LO}}(Q^2 = z\tau s) \left\{ -zP_{gg}(z) \log \frac{M^2}{\tau s} \right. \\
&\left. \quad - \frac{11}{2}(1-z)^3 + 6[1 + z^4 + (1-z)^4] \left(\frac{\log(1-z)}{1-z} \right)_+ \right\}
\end{aligned}$$

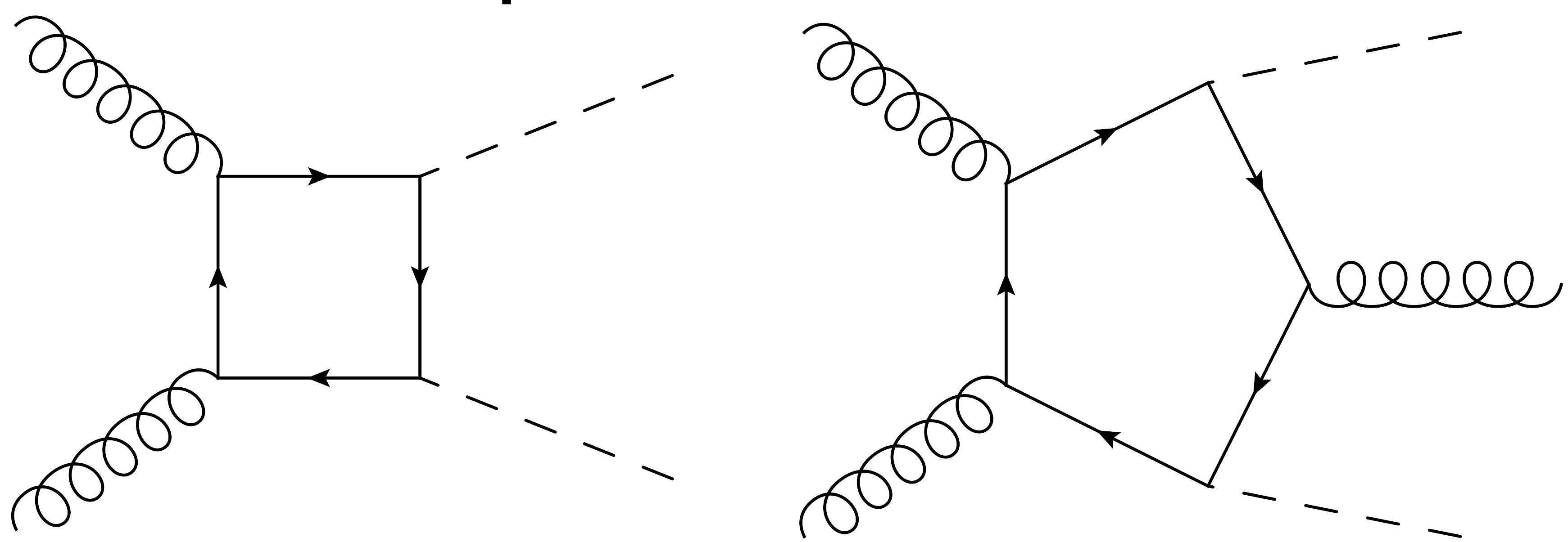
gg→HH @NLO with aMC@NLO

$$d\sigma^n_{NLO} \quad = \quad d\sigma^n_{LO} \quad + \quad d\sigma^n_V \quad + \int d\Phi_1 \, d\sigma_R^{n+1}$$

gg→HH @NLO with aMC@NLO

$$d\sigma^{n}_{NLO} = \boxed{d\sigma^{n}_{LO}} + d\sigma^{n}_{V} + \boxed{\int d\Phi_1 \, d\sigma^{n+1}_{R}}$$

- Include exact one-loop born and real emission ME



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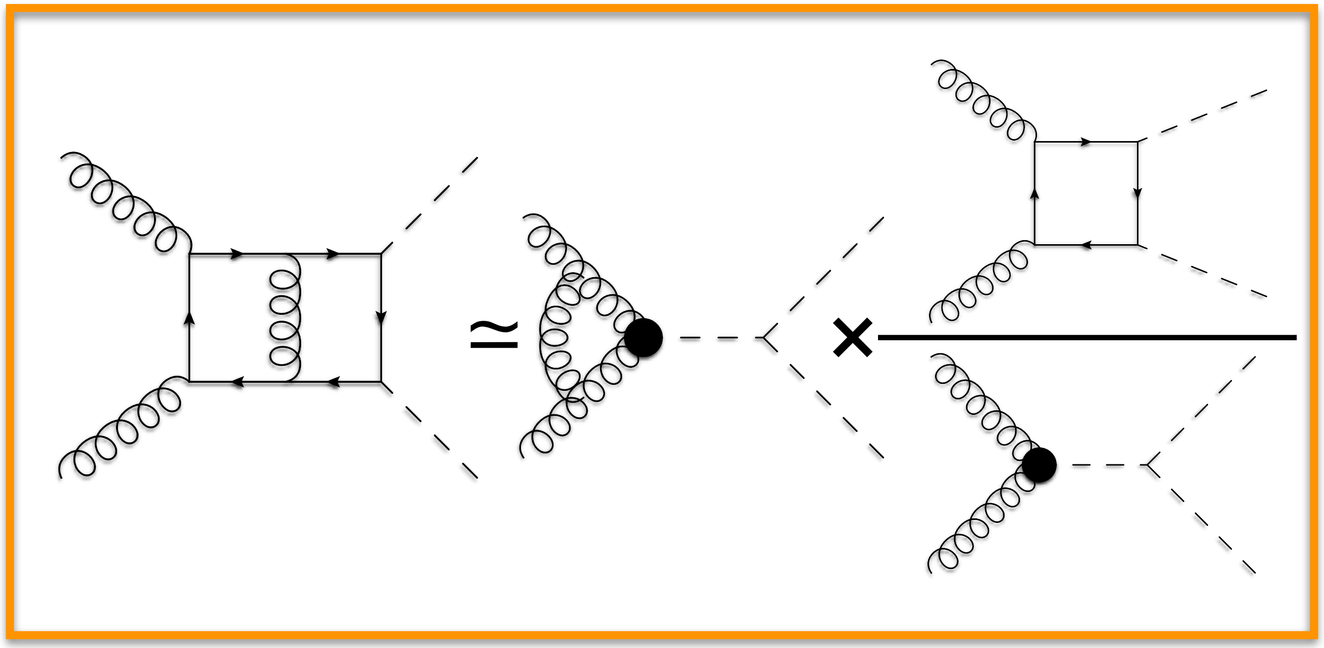
gg→HH @NLO with aMC@NLO

$$d\sigma^n_{NLO} = \boxed{d\sigma^n_{LO}} + \boxed{d\sigma^n_V} + \boxed{\int d\Phi_1 \, d\sigma^{n+1}_R}$$

- Include exact one-loop born and real emission ME
- Two-loop virtual ME is currently unknown
  - Approximate with the born-rescaled EFT



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- Include exact one-loop born and real emission ME
- Two-loop virtual ME is currently unknown
  - Approximate with the born-rescaled EFT
- In practice m_t effects included by reweighting (straightforward in the (a)MC@NLO formalism)

$$d\sigma^{(\mathbb{H})} = d\phi_{n+1}\left(\mathcal{R} - \mathcal{C}_{MC}\right),$$

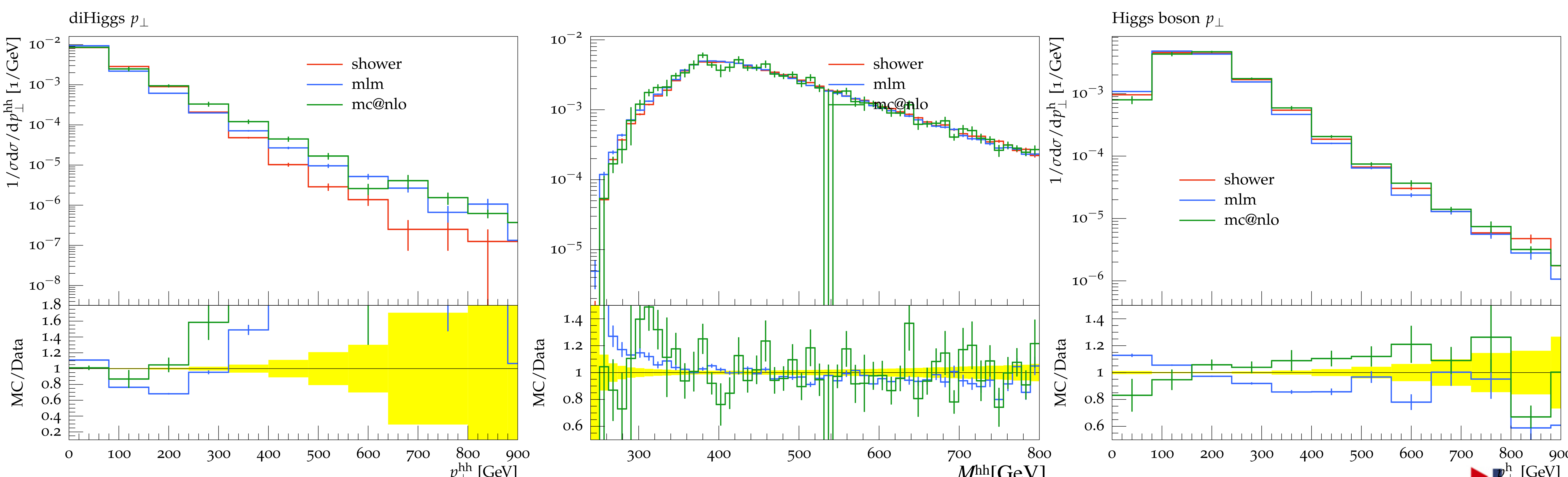
$$d\sigma^{(\mathbb{S})} = d\phi_{n+1}\left[\left(\mathcal{B} + \mathcal{V} + \mathcal{C}^{int}\right)\frac{d\phi_n}{d\phi_{n+1}} + \left(\mathcal{C}_{MC} - \mathcal{C}\right)\right]$$

reweigh with Born

reweigh with real

aMC@NLO vs merging

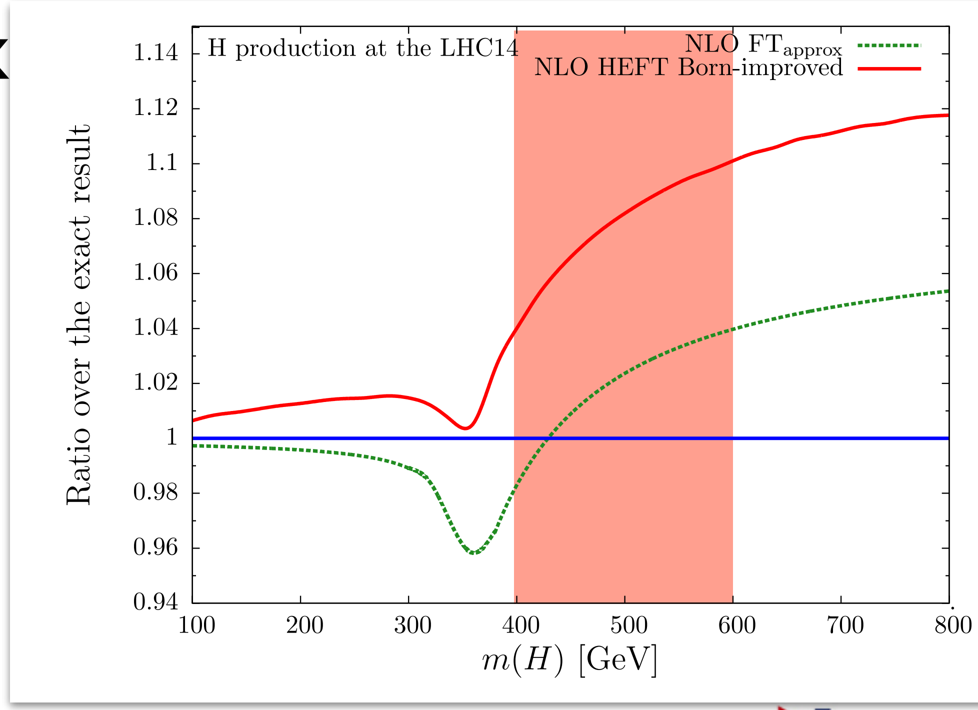
- Disclaimer: not tuned comparison
  - Different scales ($m_{HH}/2$ vs $\hat{s}$)
  - Same shower (Herwig++) but different shower scales



Plots by Andreas

Thoughts and open questions #1

- We can simulate quite precisely (NLO+PS) all production channels. Will we ever observe them all?
- gg→HH: inclusion of top mass effects is crucial for meaningful differential distributions. Still, *exact* NLO is missing
  - How good/bad is the aMC@NLO approximation?
    - Quite good (<5%) if there were no box
  - For loop-experts: how far is the exact double box?



Thoughts and open questions #2

- LO-merging: do we need HH+2j?
- Do we need (Can we compute) EW corrections for gg→HH?
  - Taking "inspiration" from gg→H (triangle vs $\sigma(m_H)$) may be misleading
  - $\sigma(m_H)$ has no Sudakov enhancement

Actis, Passarino, Sturm,Uccirati, 0803.1301 (gg→H)