Accurate predictions for Higgs pair production at the LHC

R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, P. Torrielli, E. Vryonidou, MZ
arXiv: 1401.7340, PLB

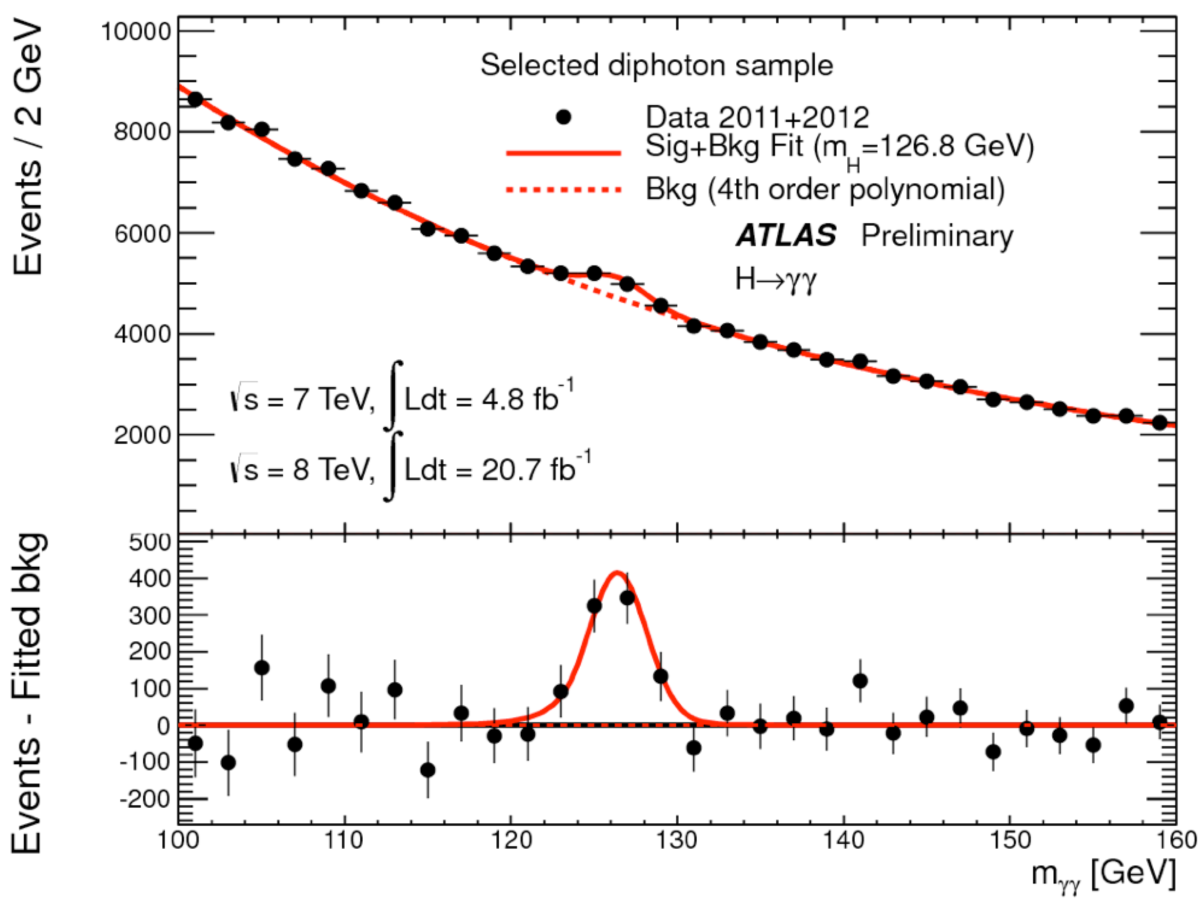
Marco Zaro, LPTHE - UPMC Paris VI

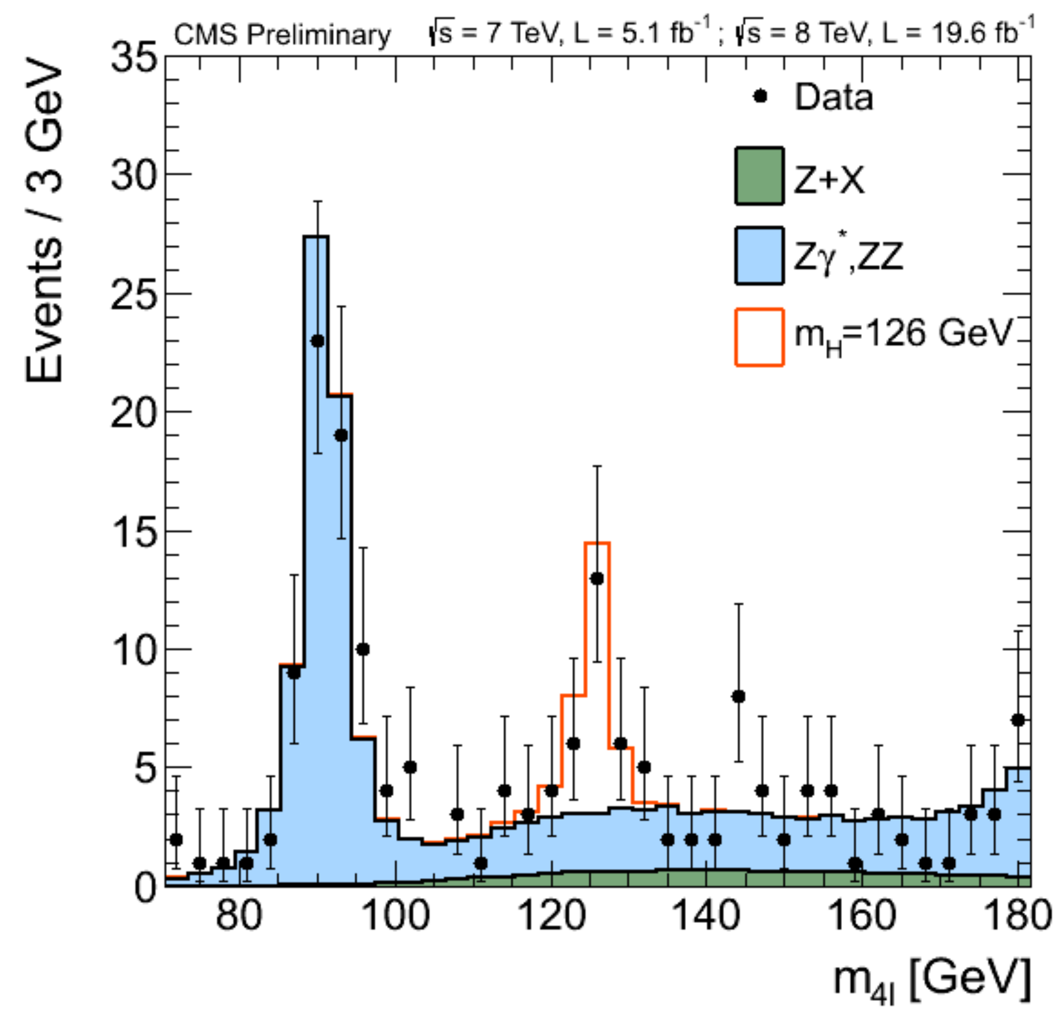
HiggsHunting 2014, Orsay

July 22, 2014

LHCPhenoNet

A new 125 GeV resonance has been found (long time ago…)





Is it THE Higgs boson *as expected in the SM?*

NAME

Higgs boson

DATE OF BIRTH

Jul 4th 2012 (presumed)

SPIN 0

CP even

FERMIONIC COUPLING

m_f/v

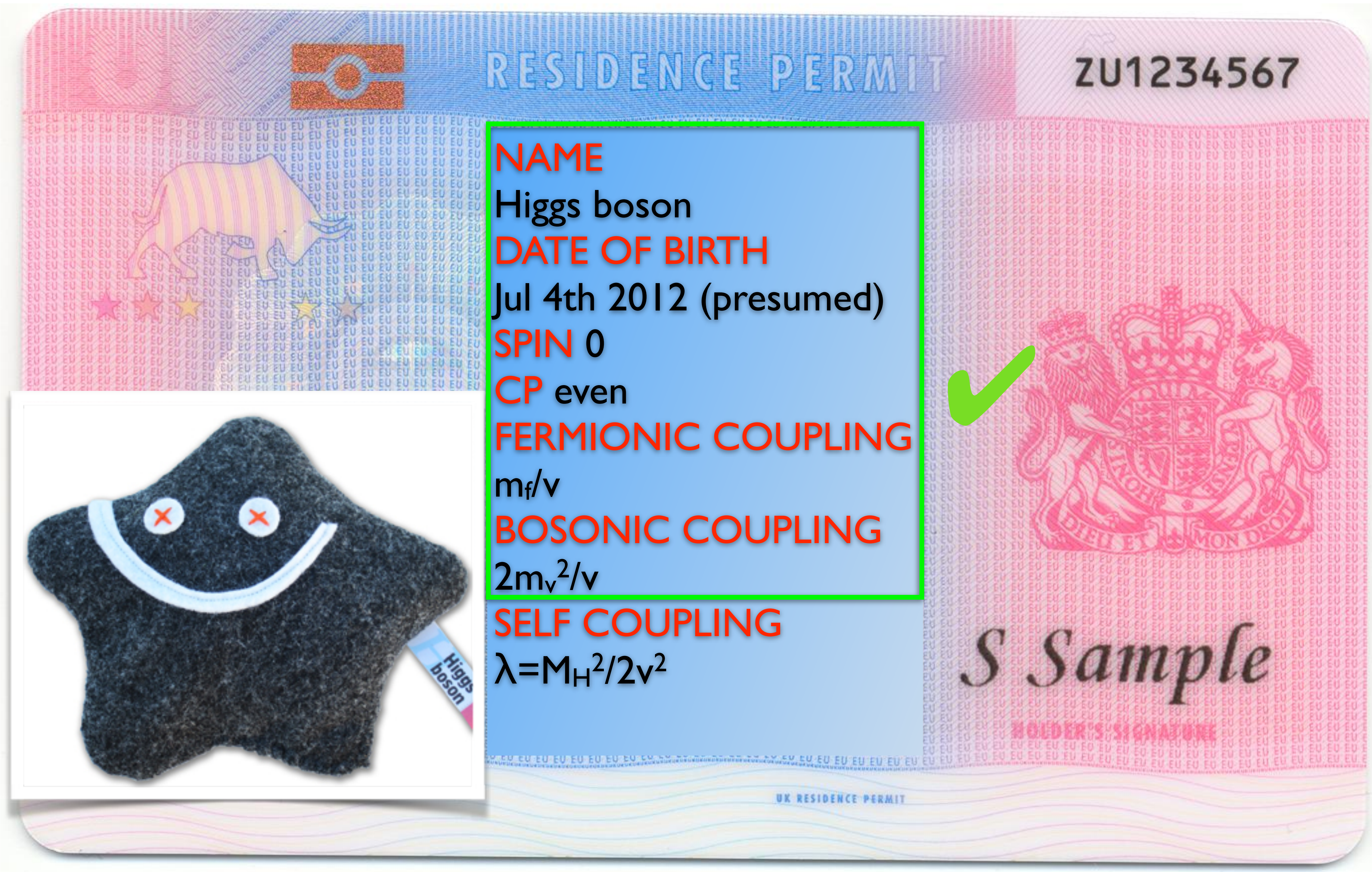
BOSONIC COUPLING

$2m_V^2/v$

SELF COUPLING

$\lambda=M_H^2/2v^2$

Many properties have been measured…



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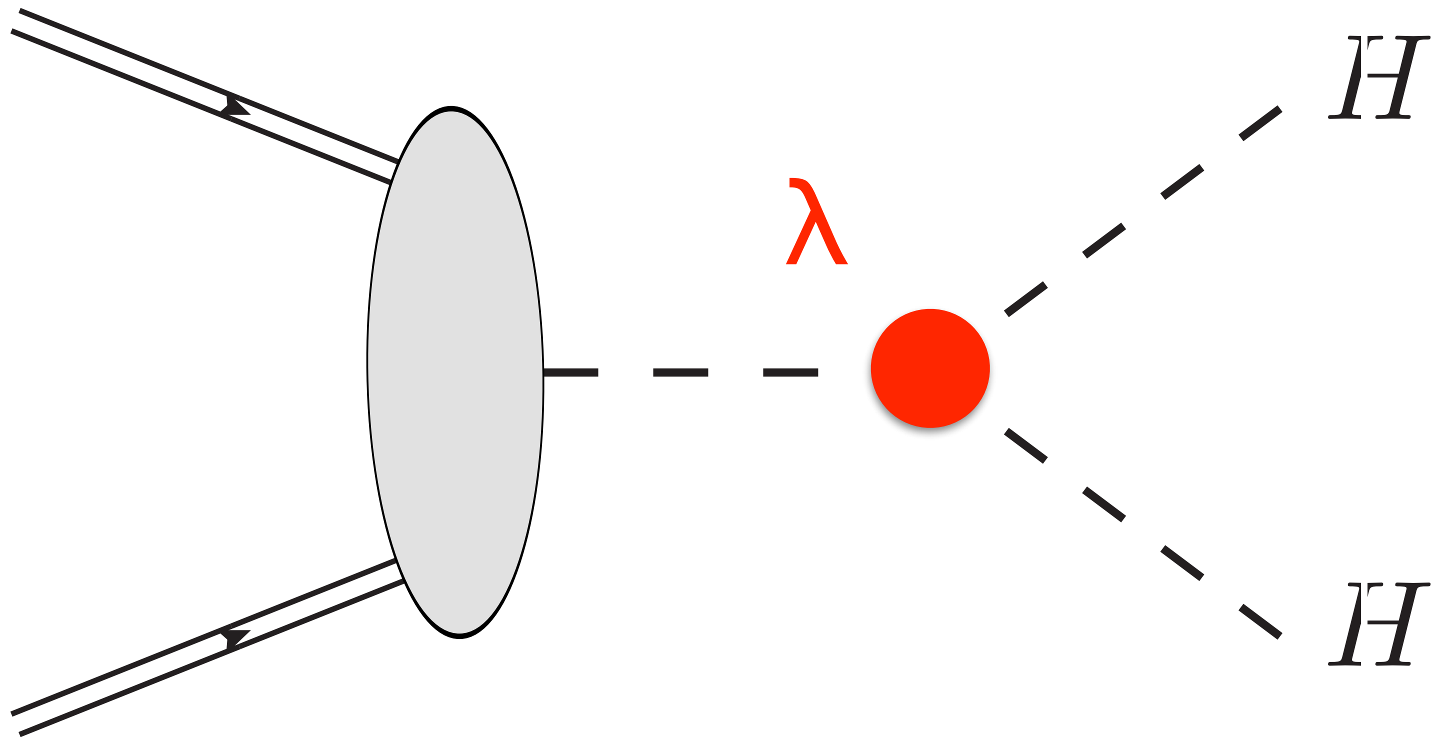
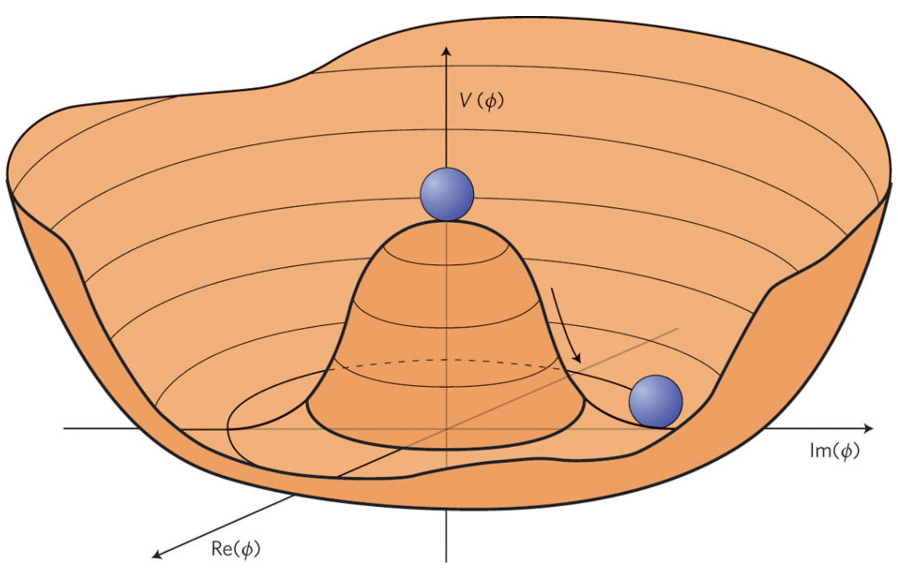


The Higgs self-coupling

The Higgs self-coupling

- The only parameter of the Higgs boson Lagrangian which cannot be measured in single Higgs production is its self-coupling λ
- λ drives the Higgs potential shape: $V(\phi)=\mu^2\phi^2/2+\lambda\phi^4/4$
  - In the SM: $M_H^2=2\lambda v^2=-2\mu^2$



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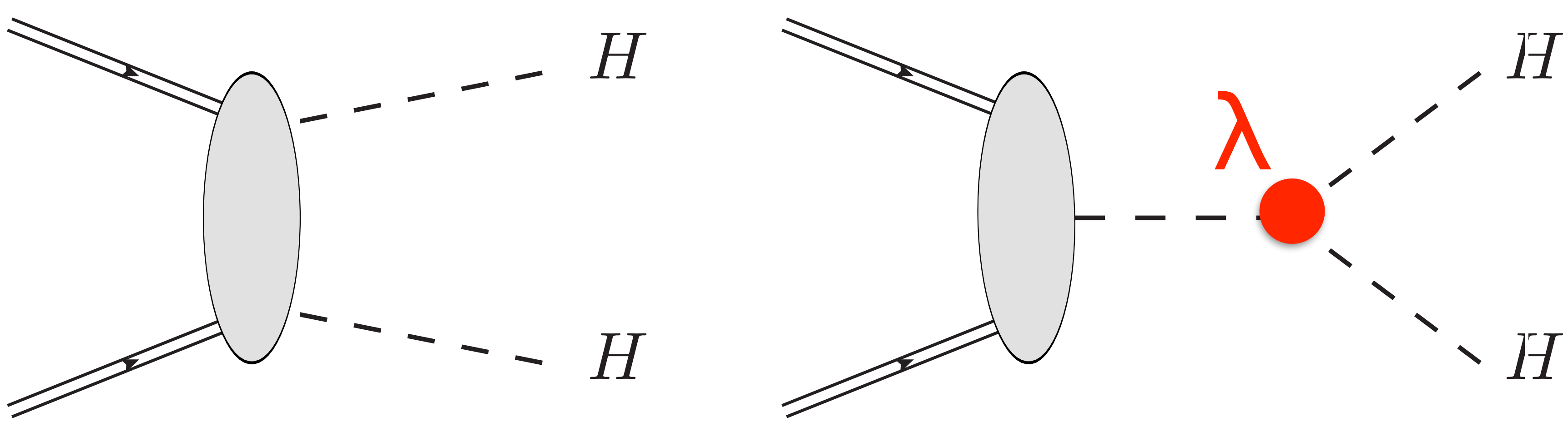
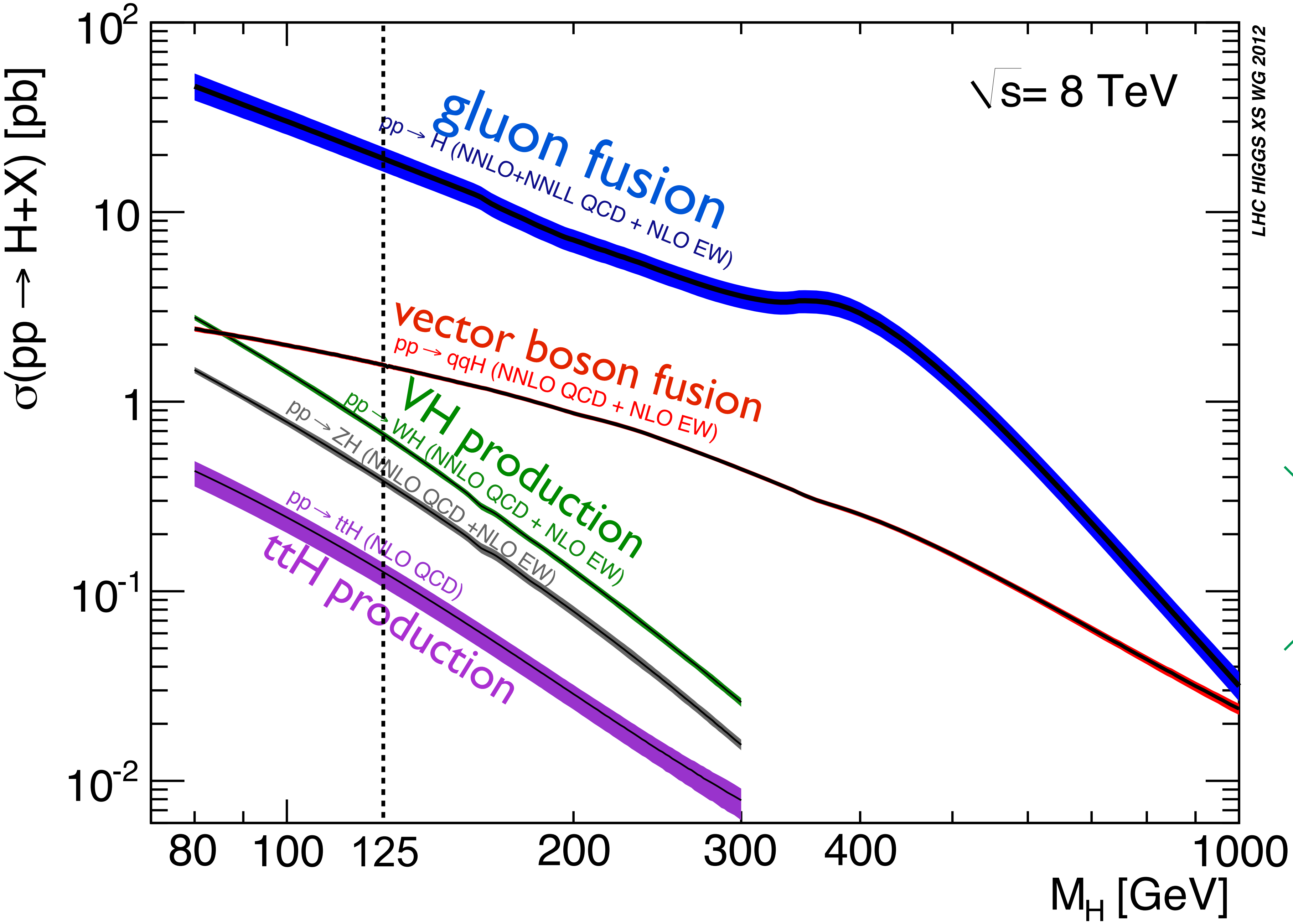
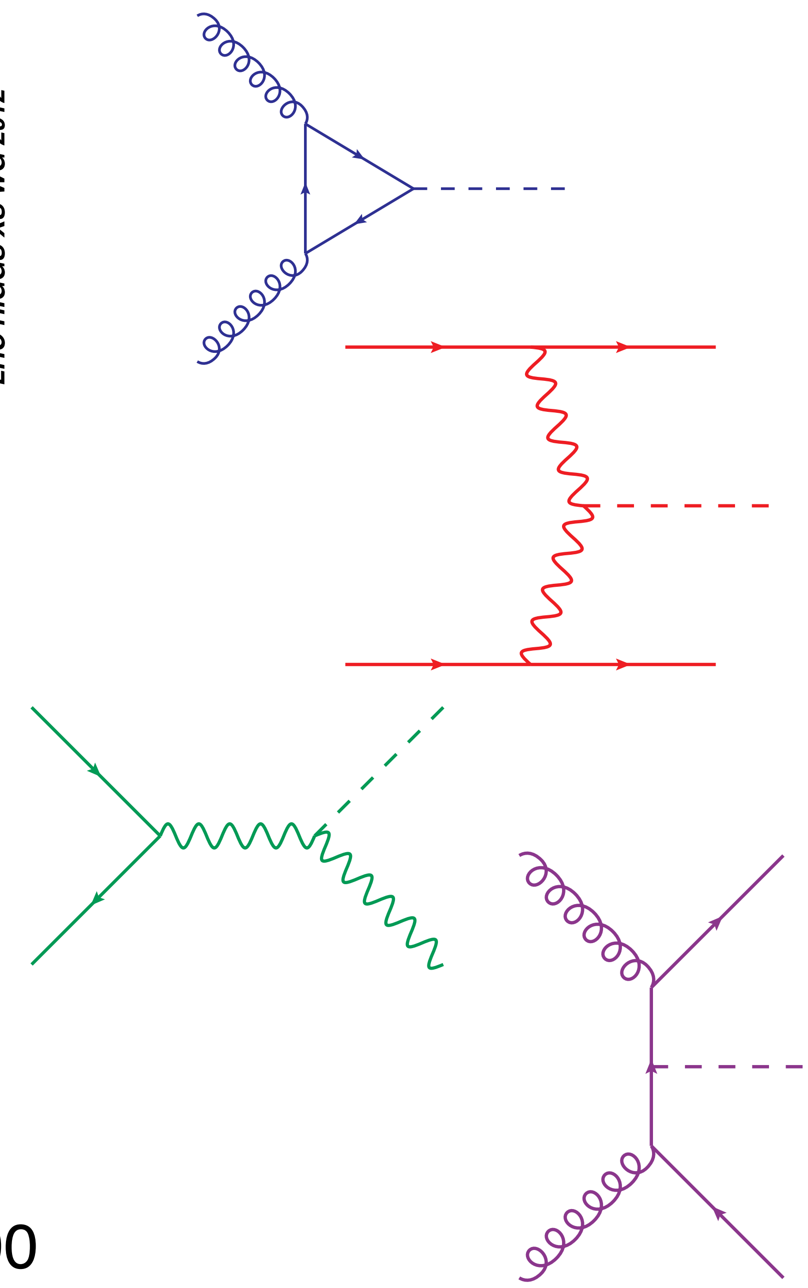
  - In the SM: $M_H^2=2\lambda v^2=-2\mu^2$
- To measure lambda one has to look at double Higgs production

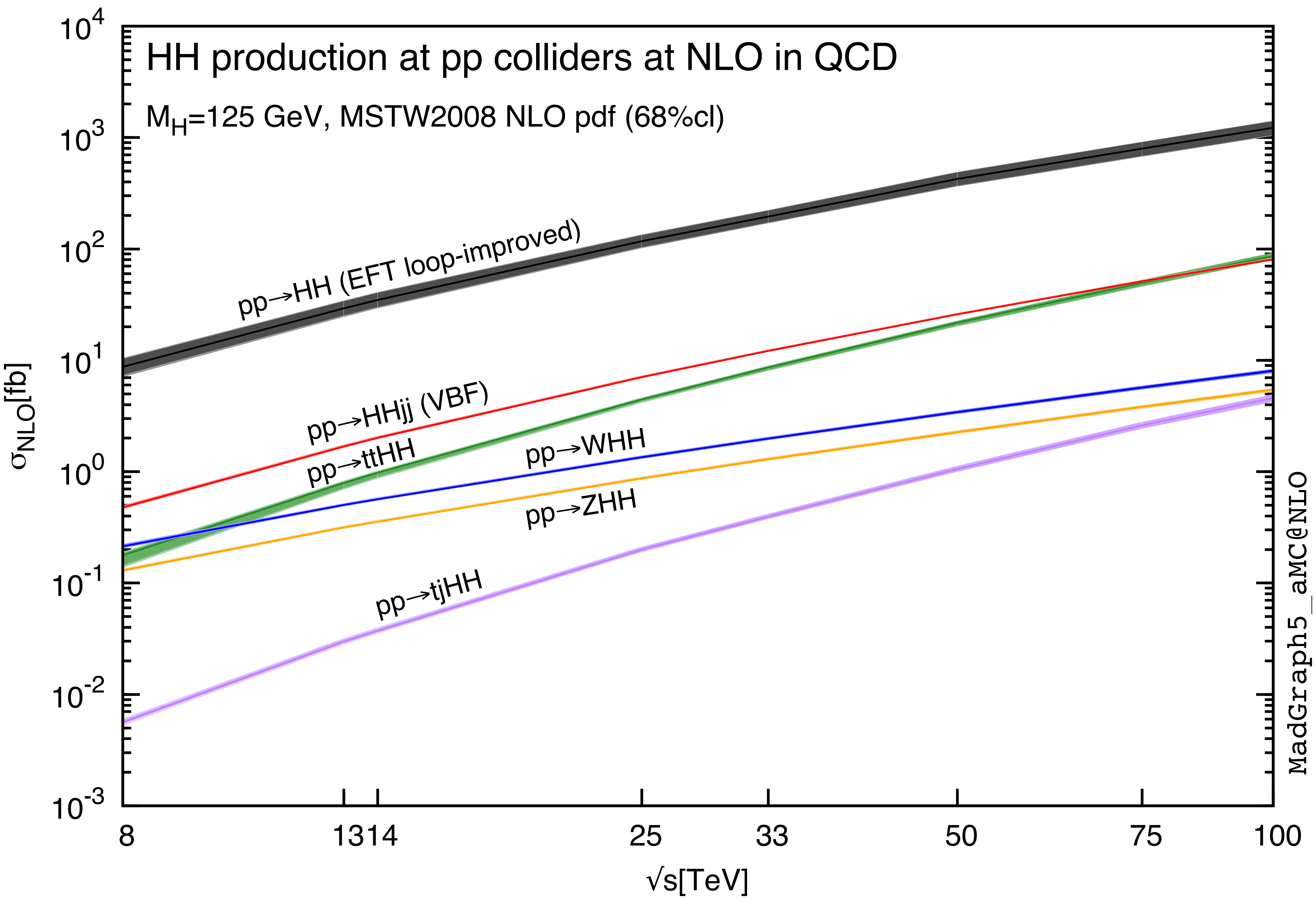


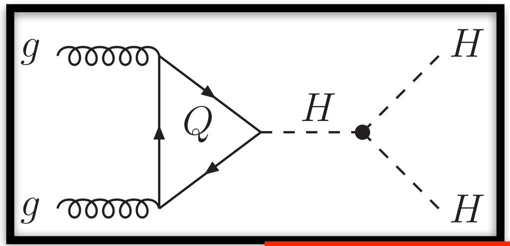
Single Higgs production channels

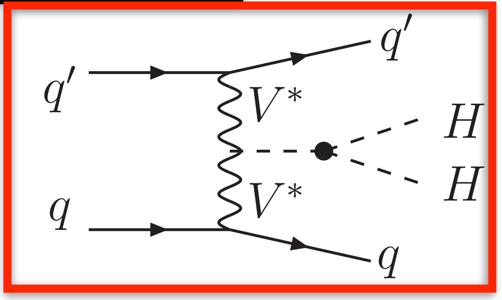


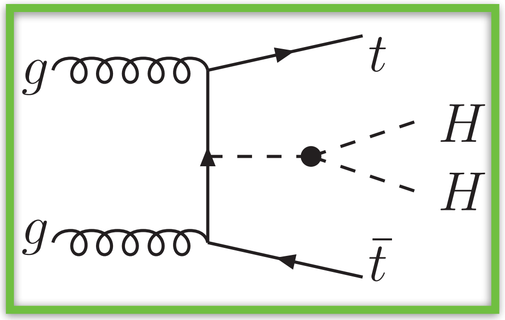


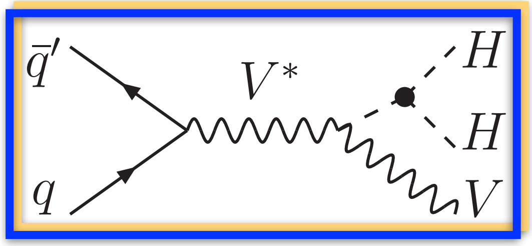
Double Higgs production channels









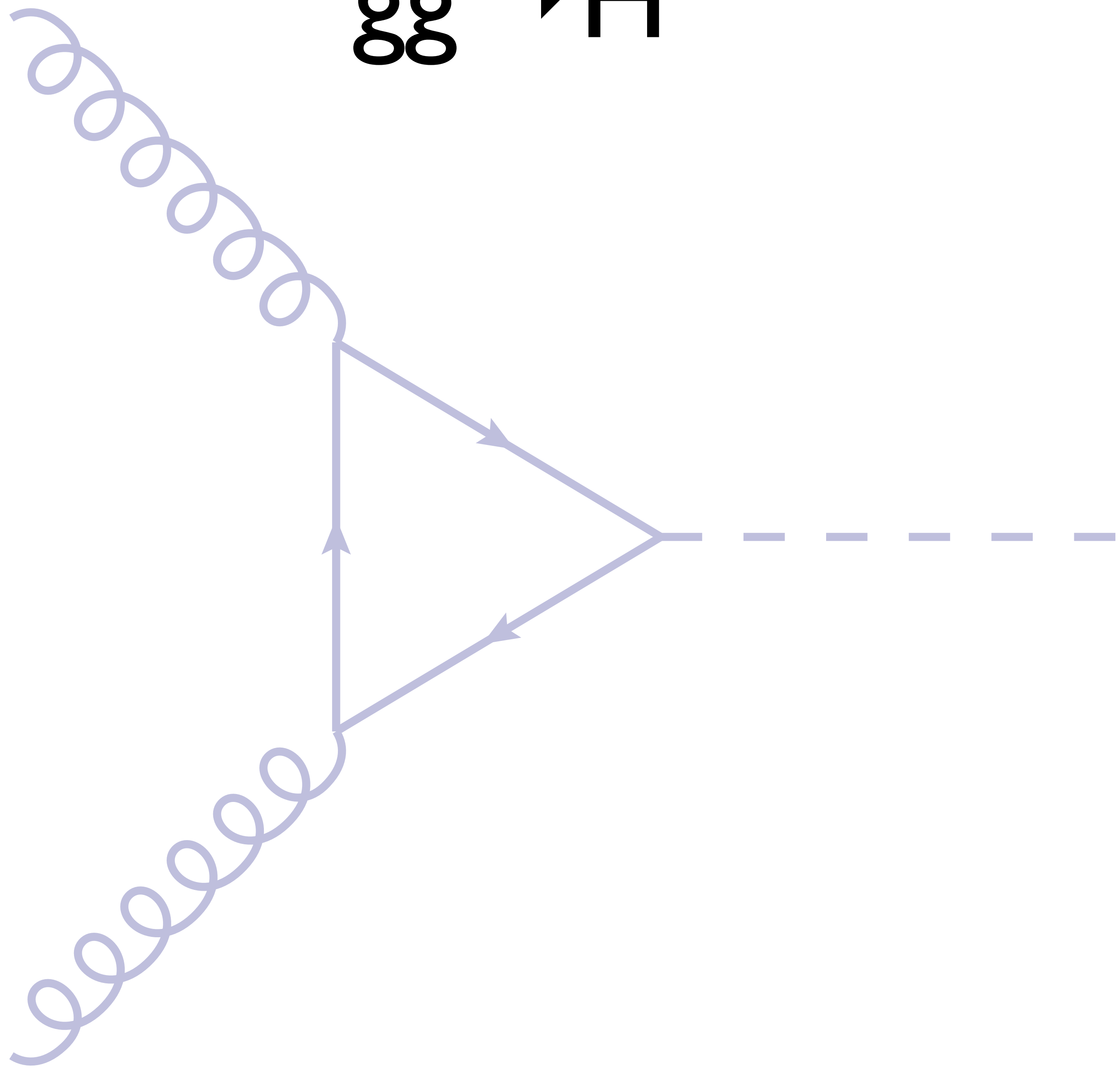


ggHH also known at NNLO (in the EFT) (de Florian, Mazzitelli, arXiv:1309.6594)

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

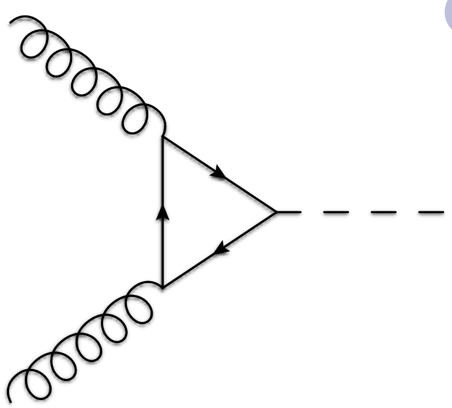
VHH also known at NNLO (Baglio, Djouadi, Grober, Muhlleitner, Quevillon, Spira, arXiv:1212:5581)

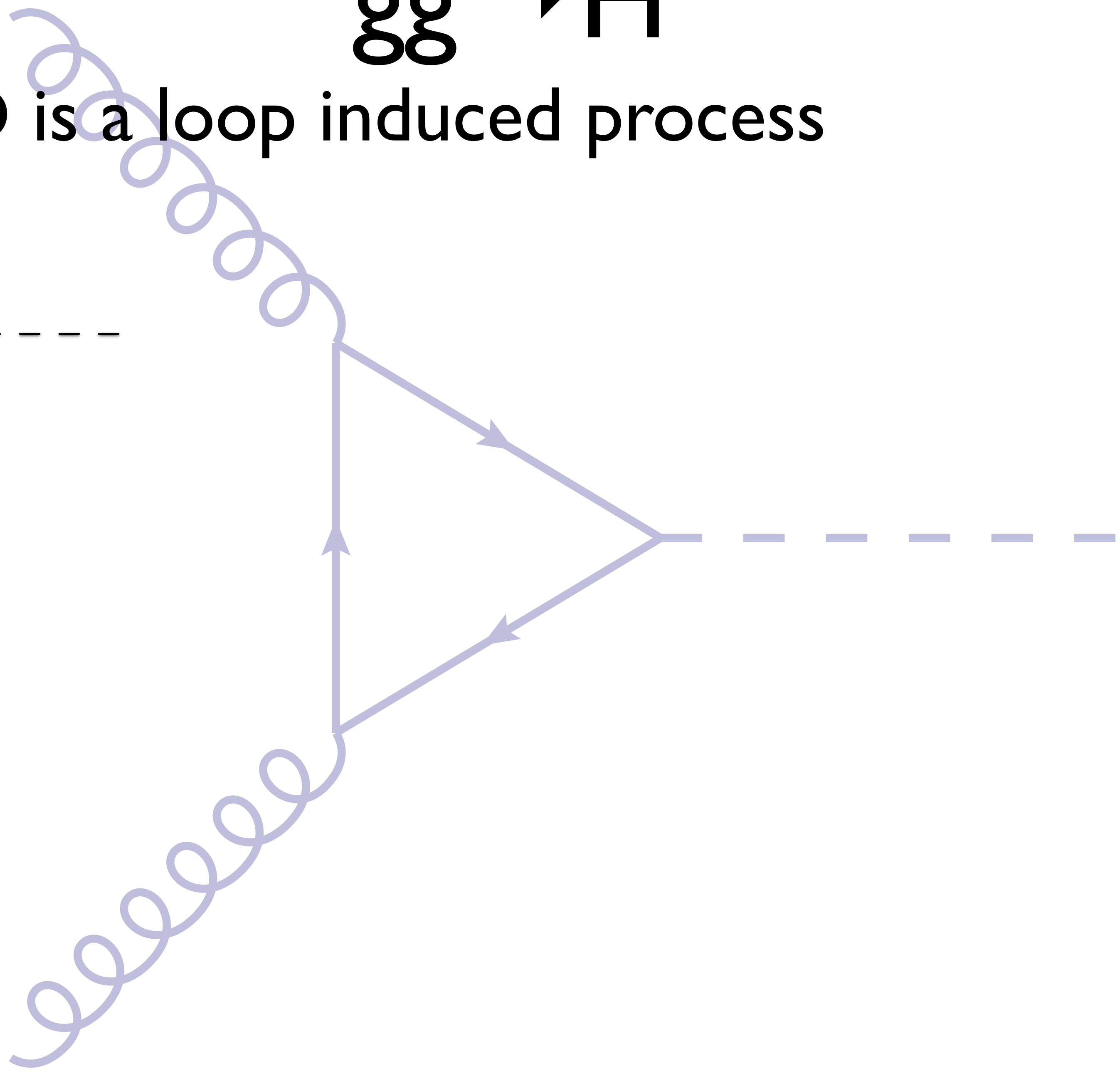
The tricky case:
gg→H



The tricky case: gg→H

- ggH at the LO is a loop induced process





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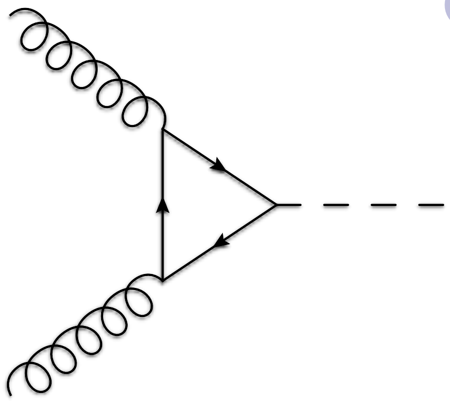
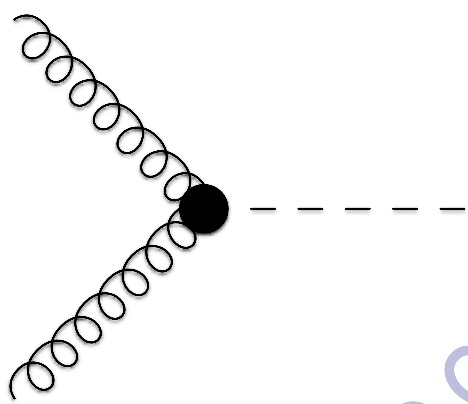


- Use an effective theory in the limit $m_t \to \infty$



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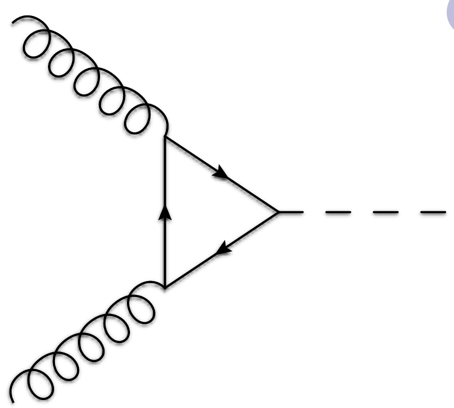

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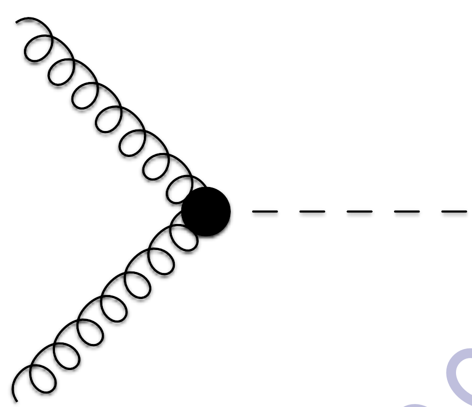

- Does it work?

The tricky case: gg→H

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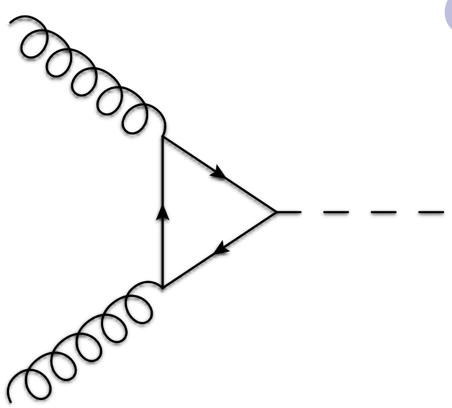

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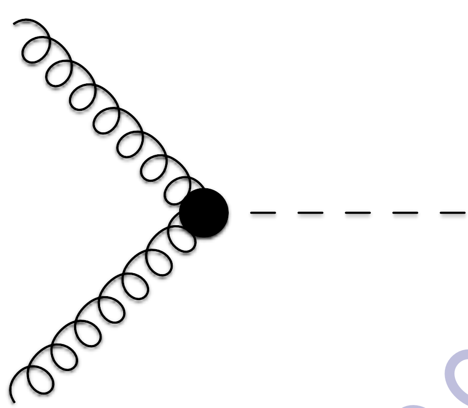

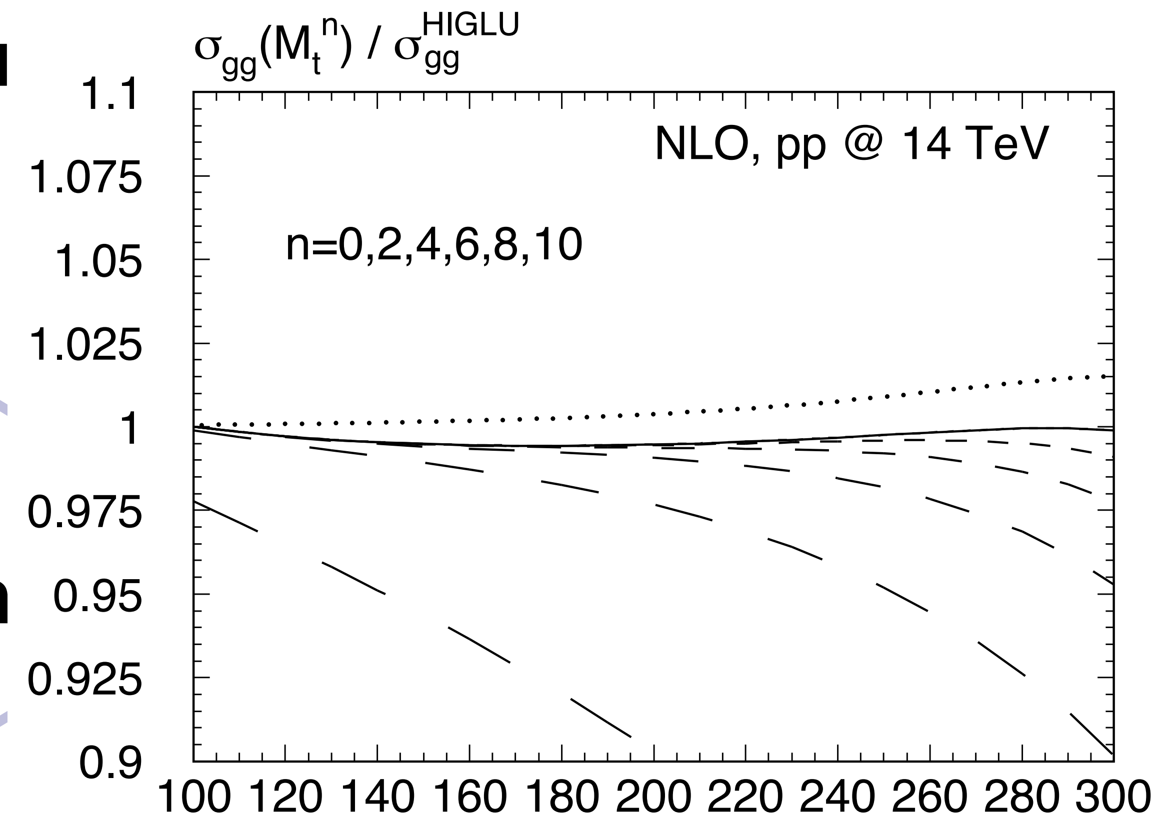

R. Harlander, K. Ozeren, arXiv:0909.3420

- Does it work?
  - For the cross-section it does quite well (if $m_h < m_t$)

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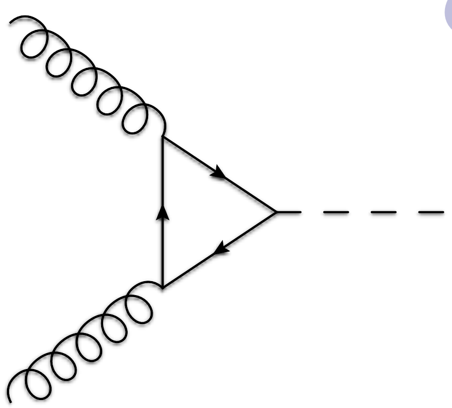

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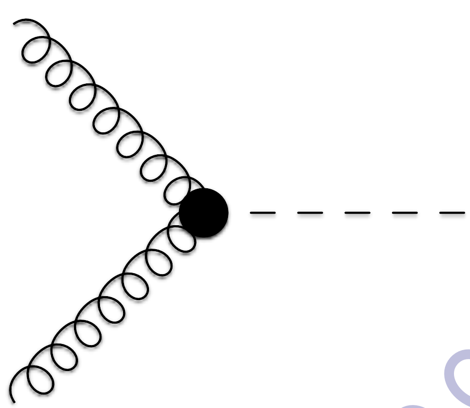

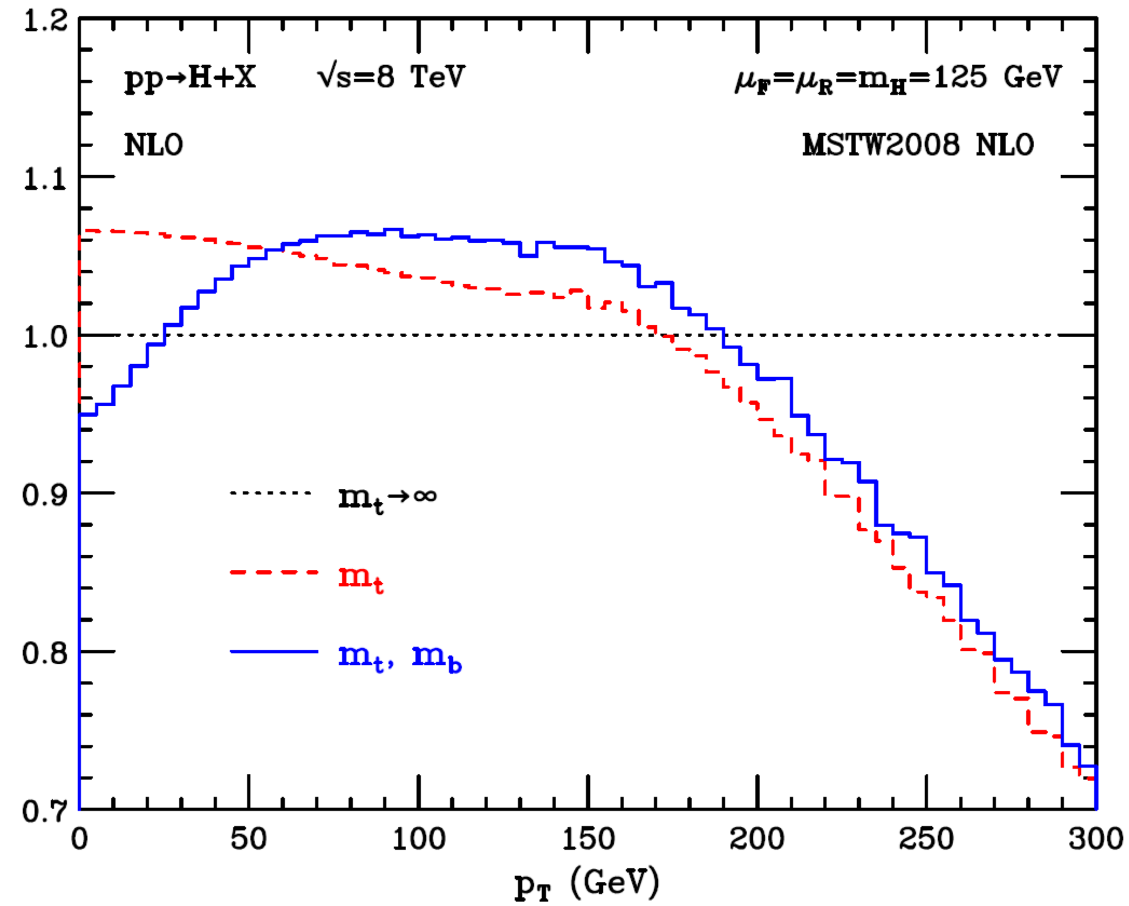

- Does it work?
  - For the cross-section it does quite well (if $m_h < m_t$)
  - Be careful for differential distributions (e.g Higgs p_T)

The trickier case: $gg \to HH$

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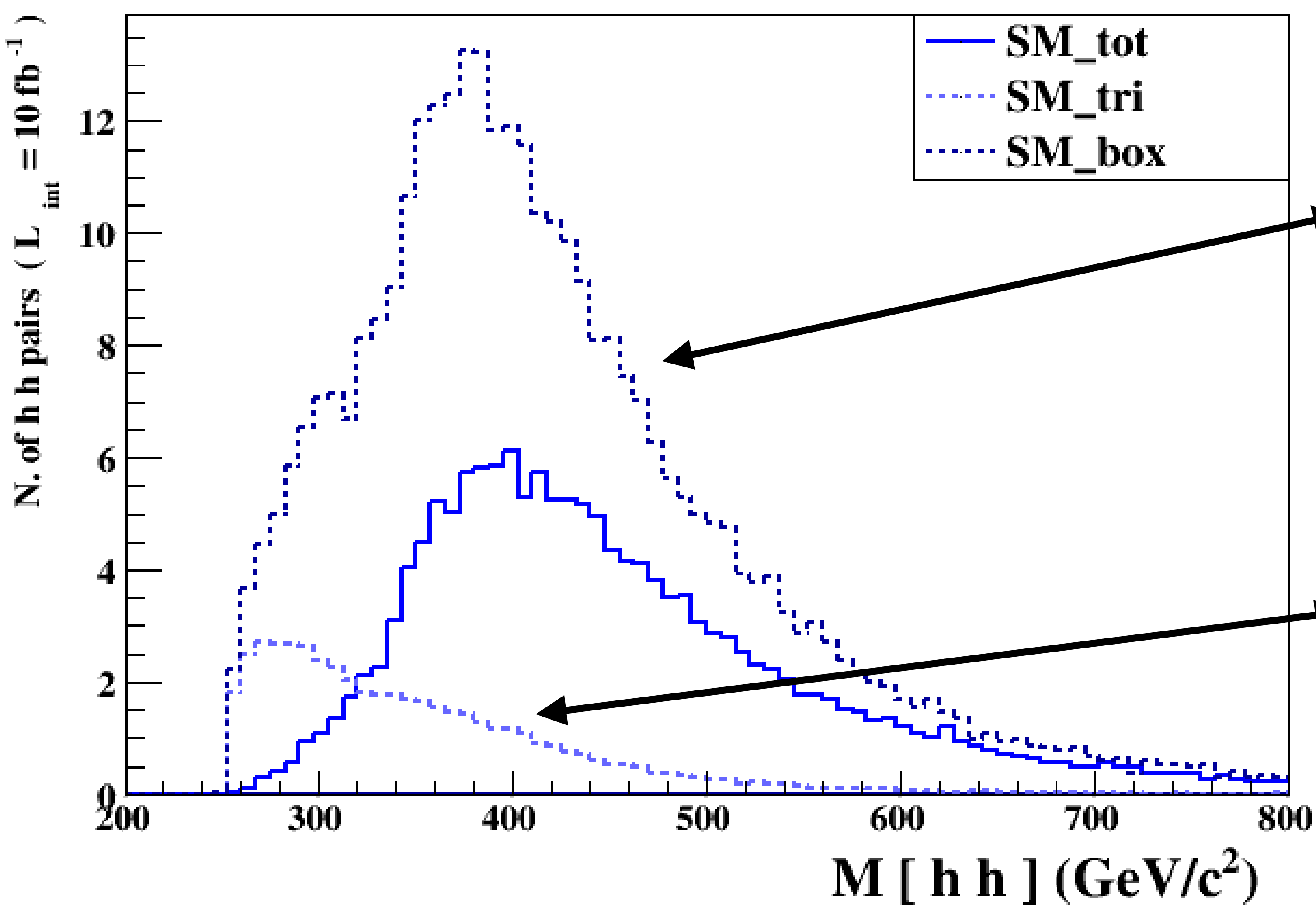
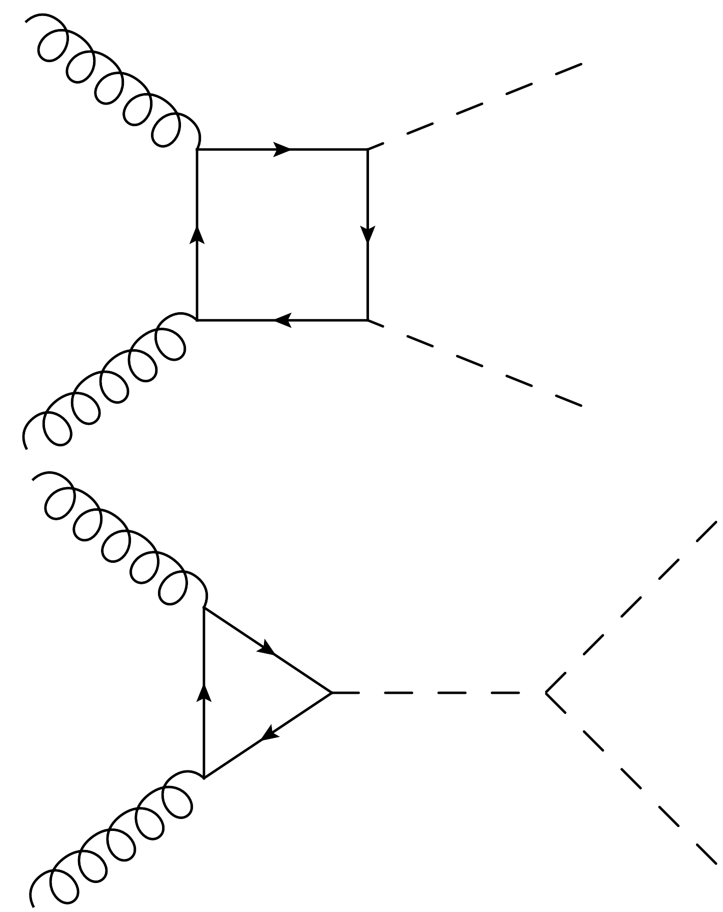
- gg→HH at the LO is a loop induced process too!
  - Triangle and box diagrams interfere destructively





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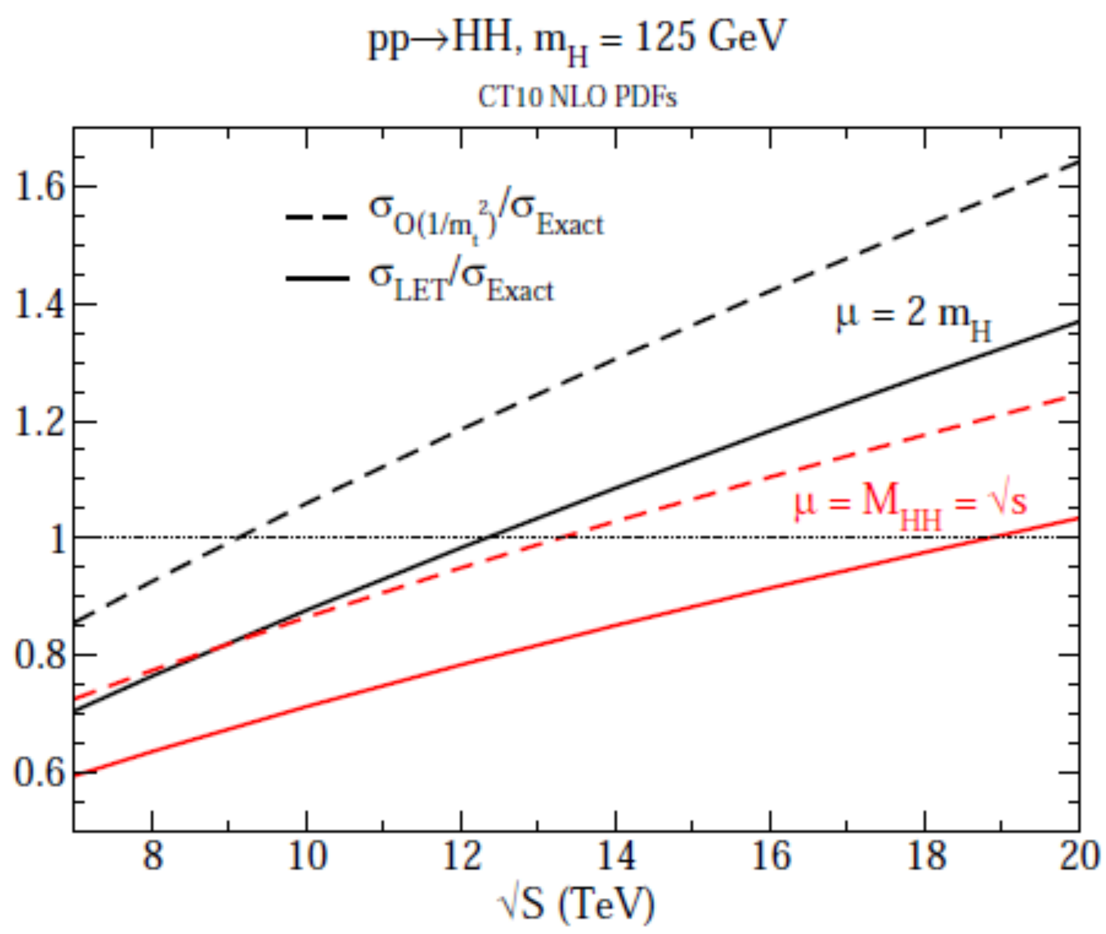
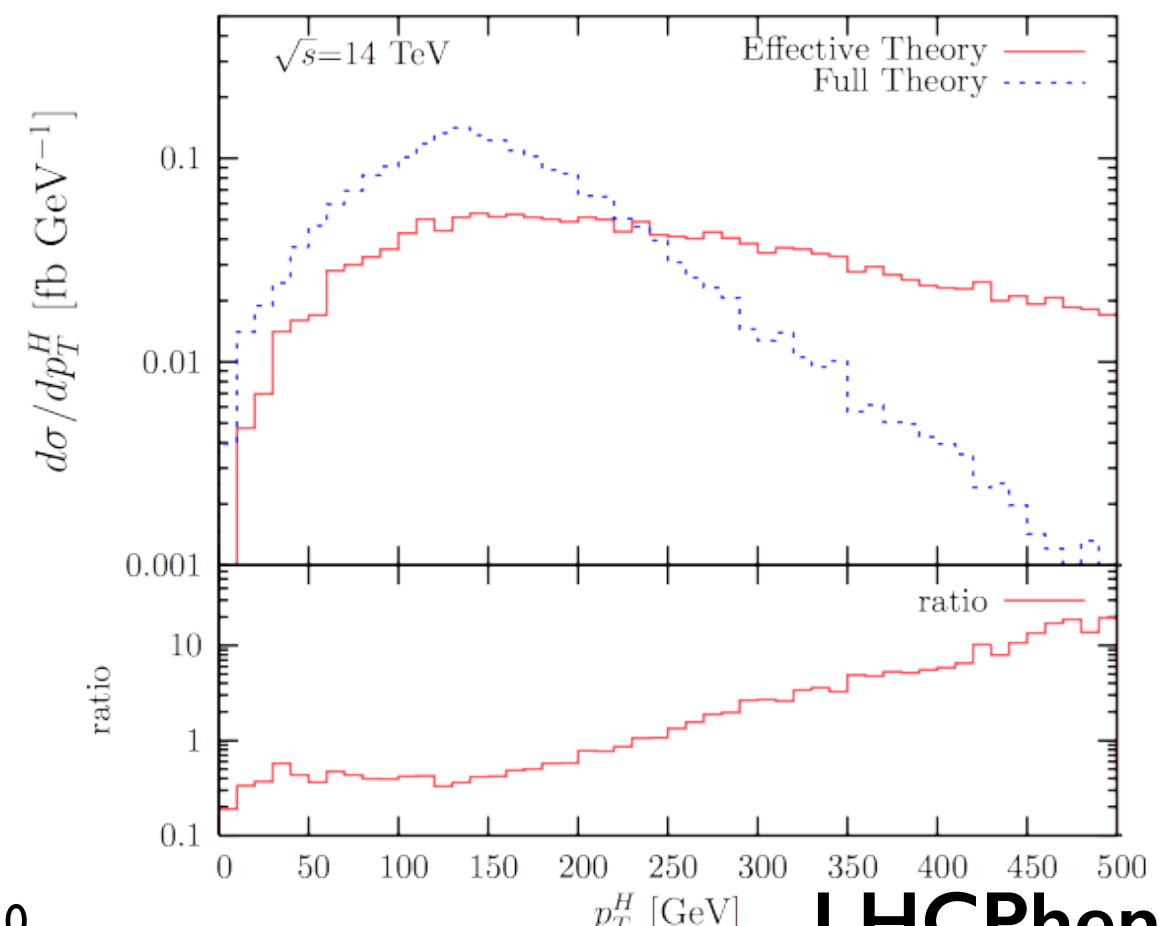
- Unlike the single-Higgs case, EFT ($m_t \to \infty$) does not work well





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- $gg \to HH$ at the LO is a loop induced process too!
  - Triangle and box diagrams interfere destructively
- Unlike the single-Higgs case, EFT ($m_t \to \infty$) does not work well
  - Need to consistently take into account loop effects
    - Include the exact one-loop matrix elements

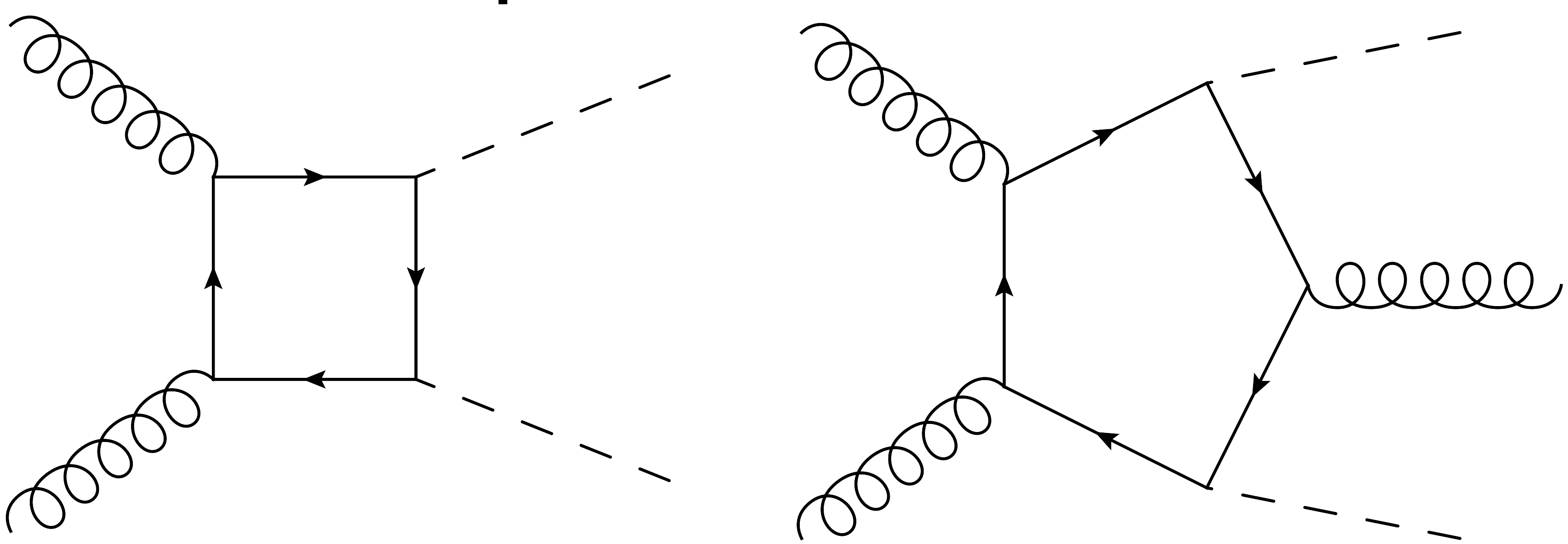
gg→HH @NLO with MadGraph5_aMC@NLO

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

gg→HH @NLO
with MadGraph5_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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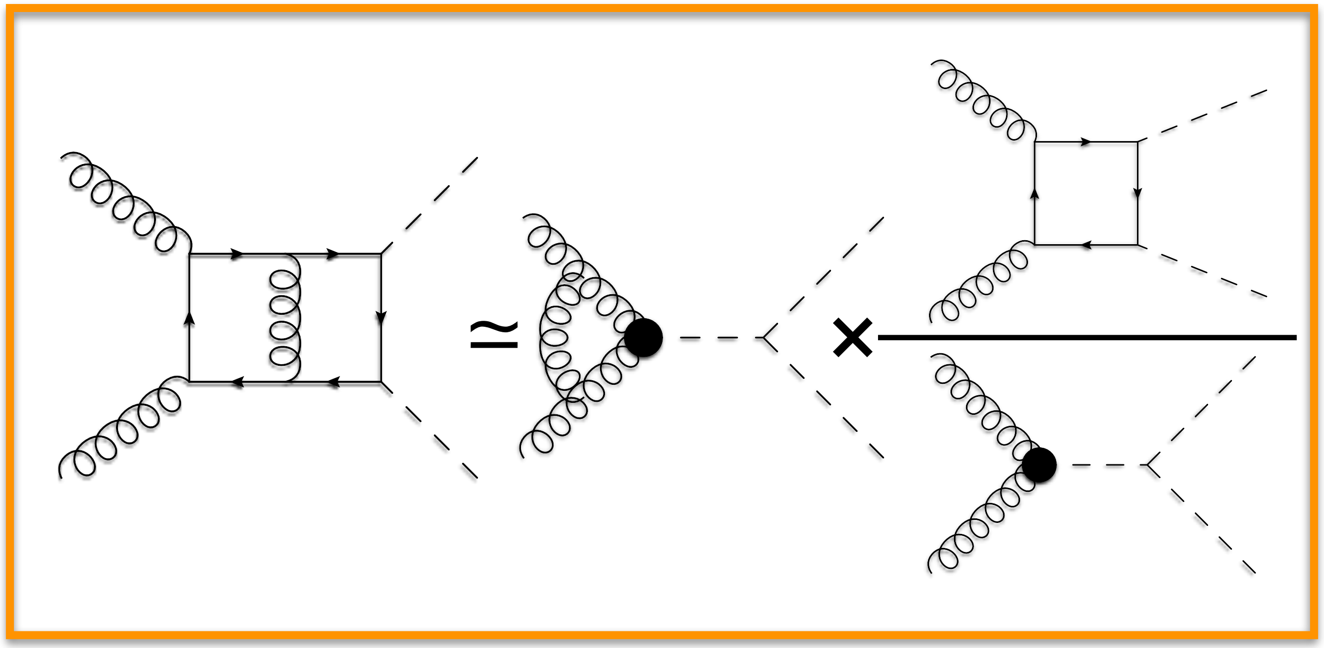
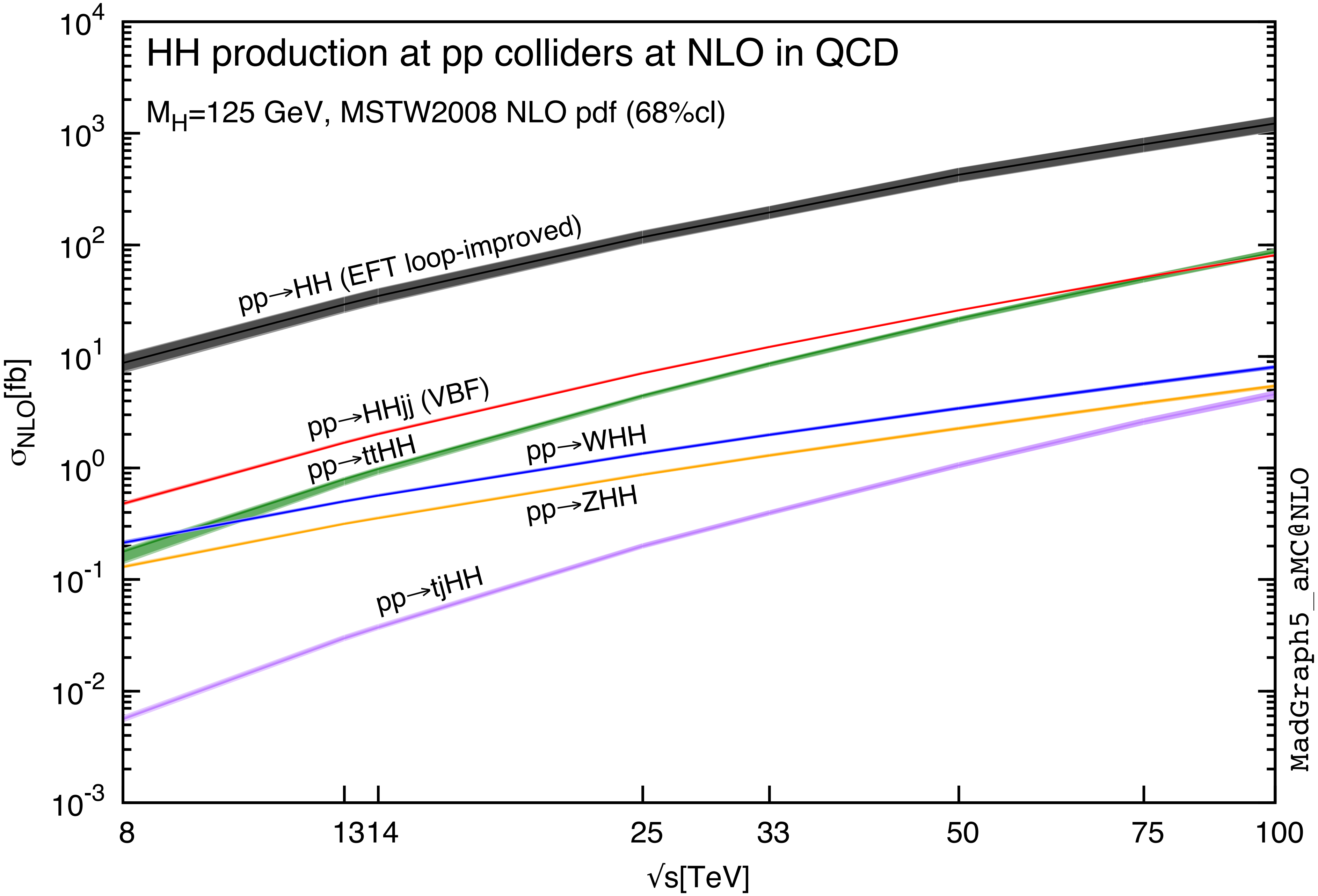
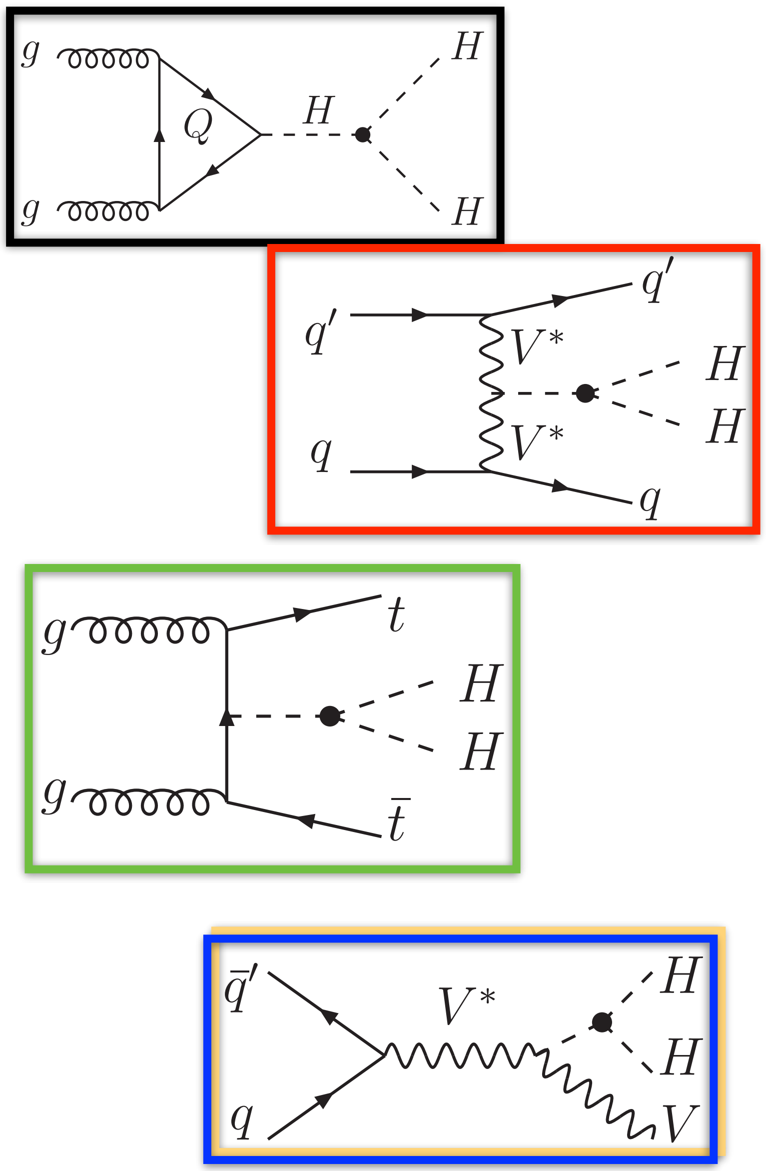
- Include exact one-loop born and real emission ME
- Two-loop virtual ME is currently unknown
  - Approximate with the born-rescaled EFT



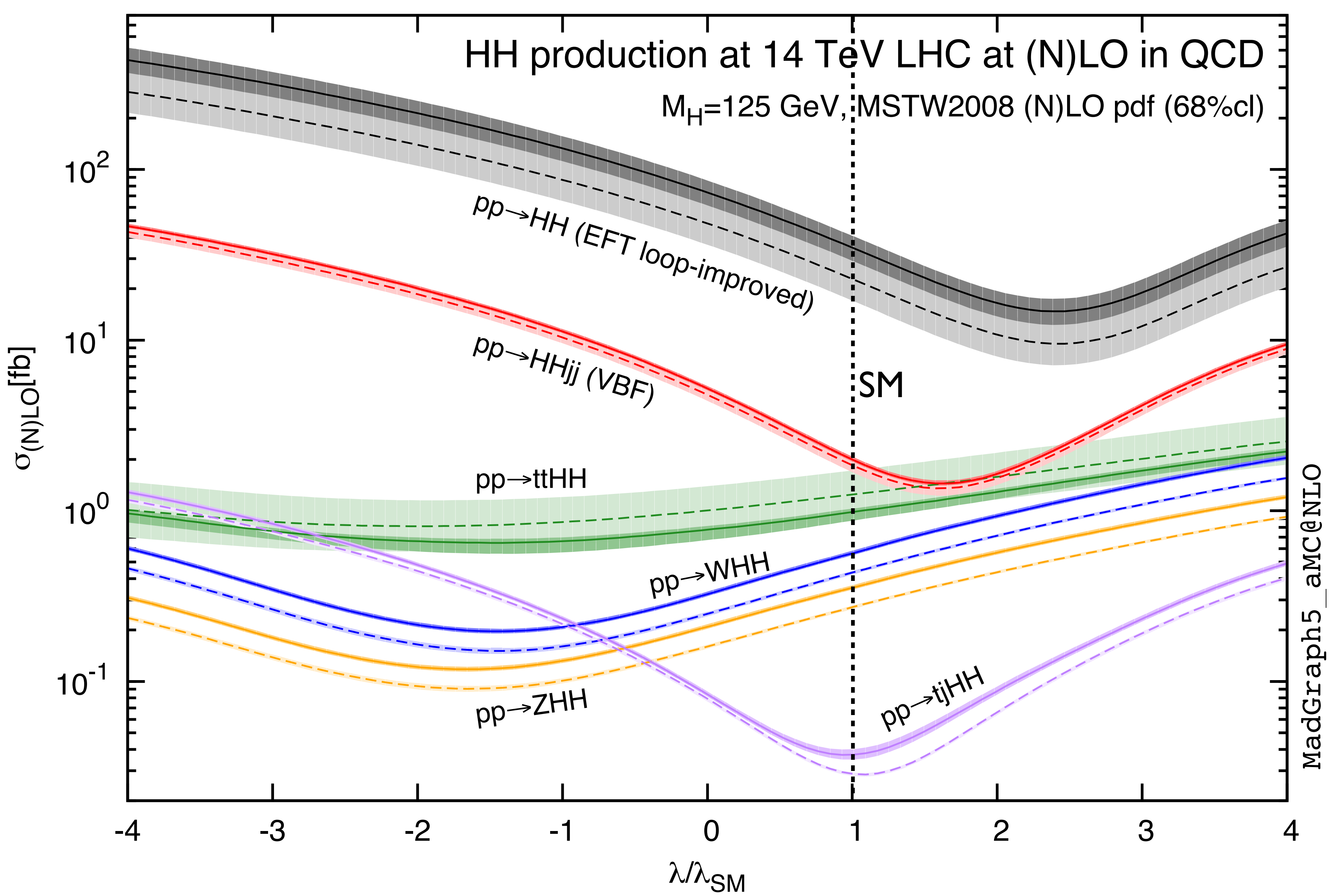
Results

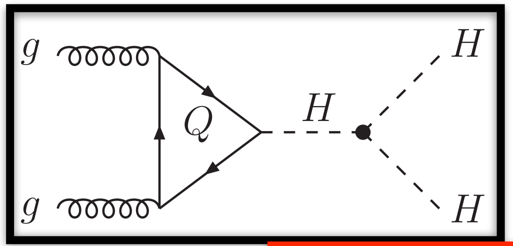
Total cross-section

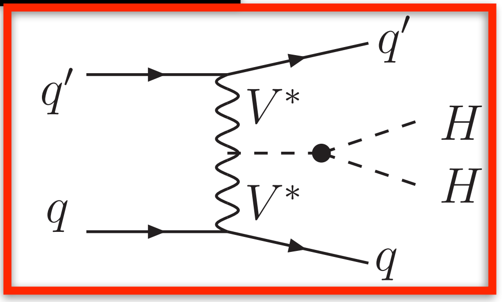


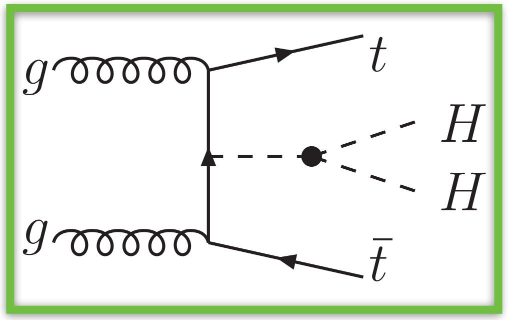


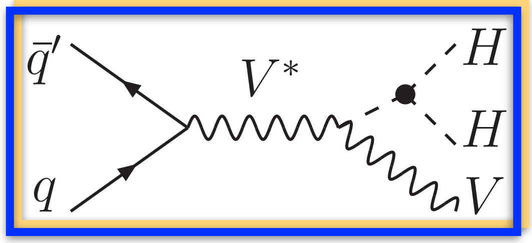
Lambda dependence



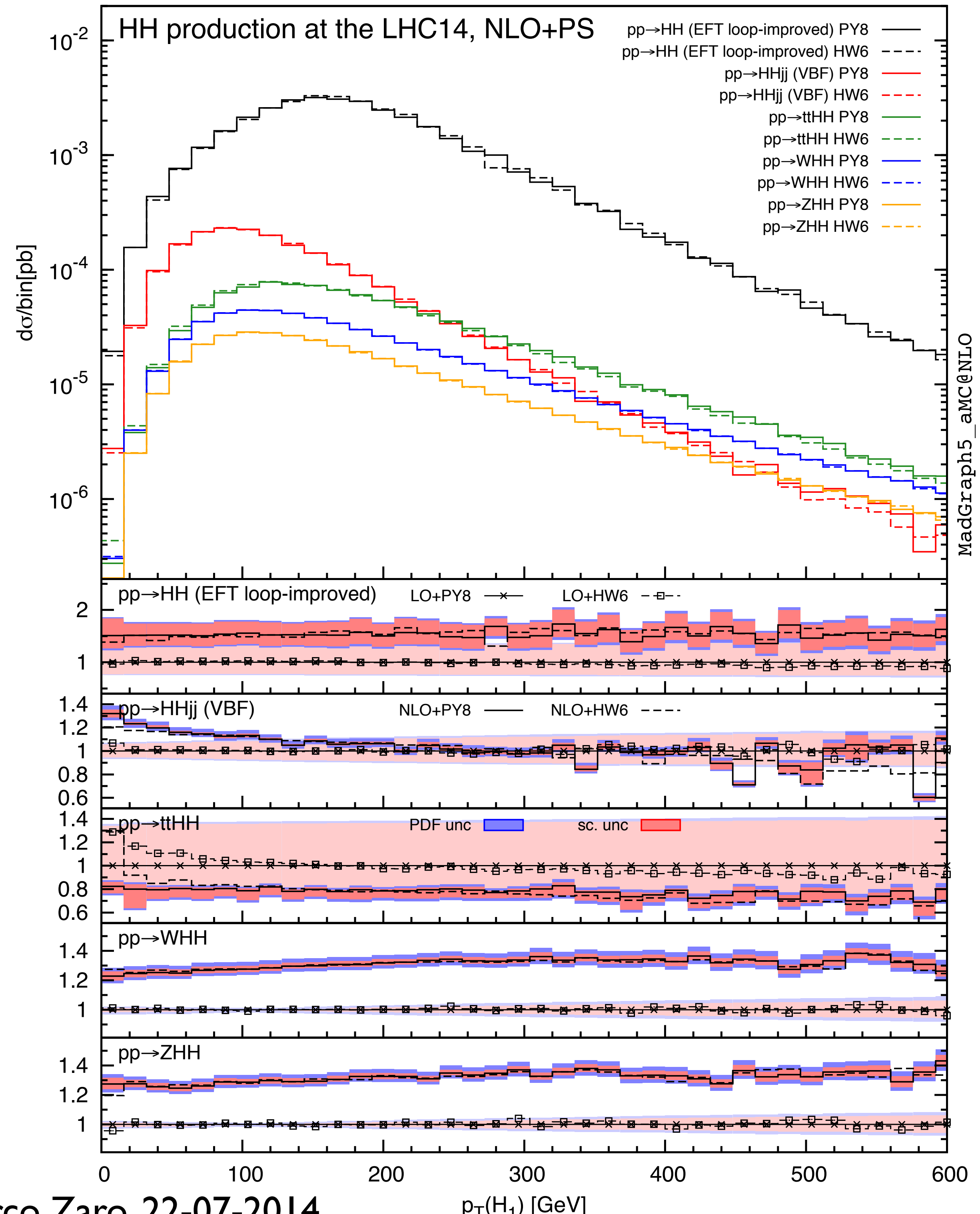


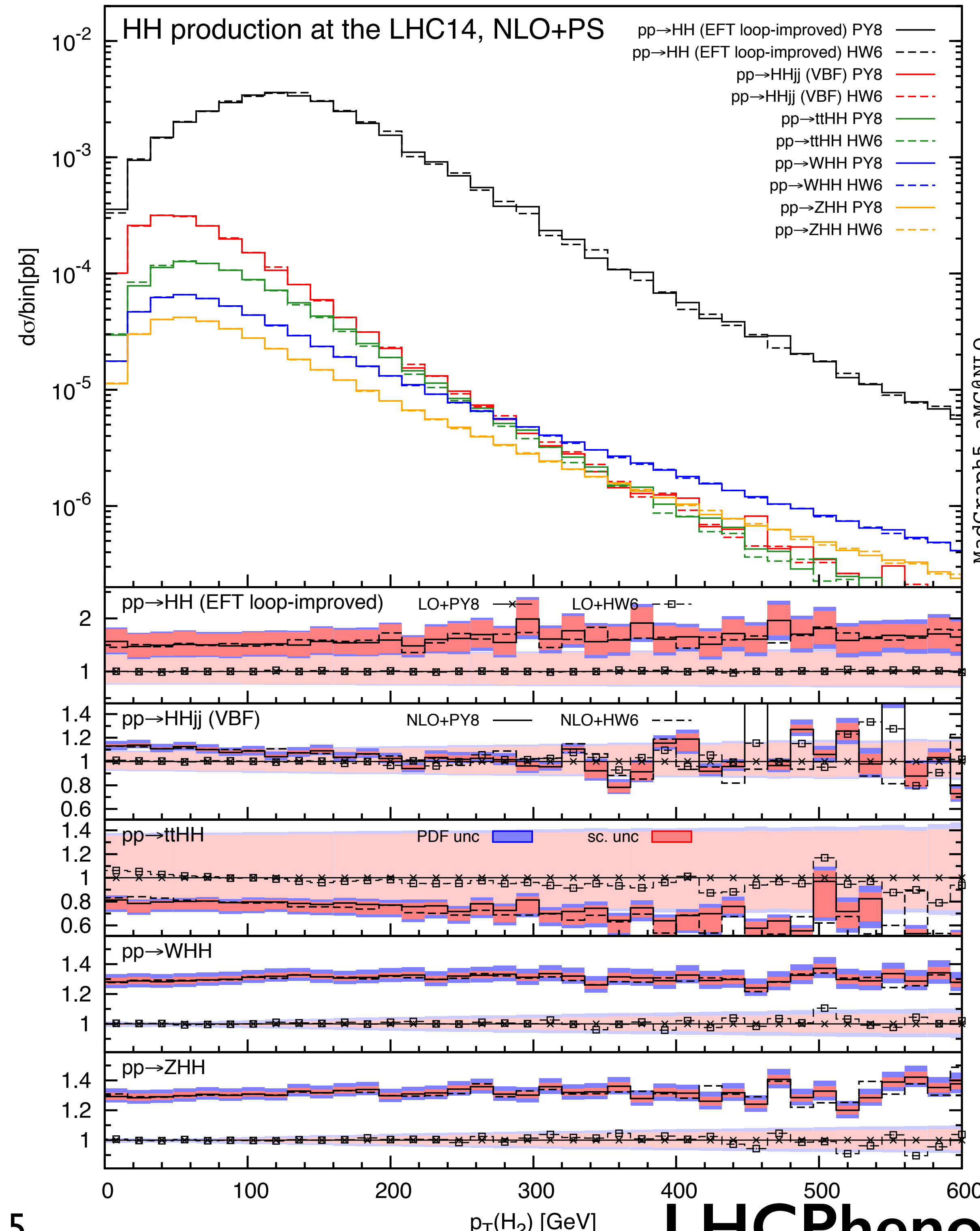






HH differential observables
(for the first time at NLO + PS)





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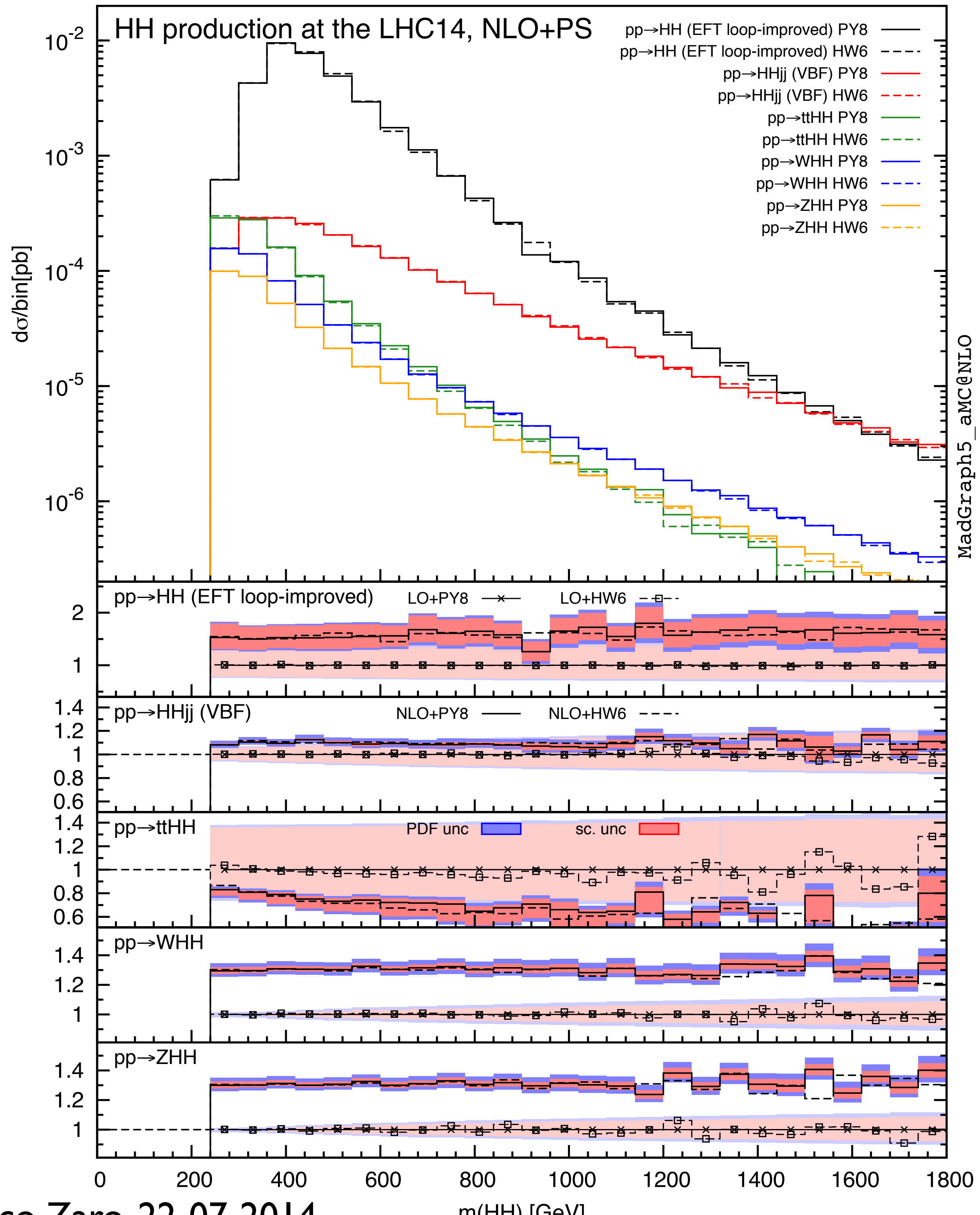

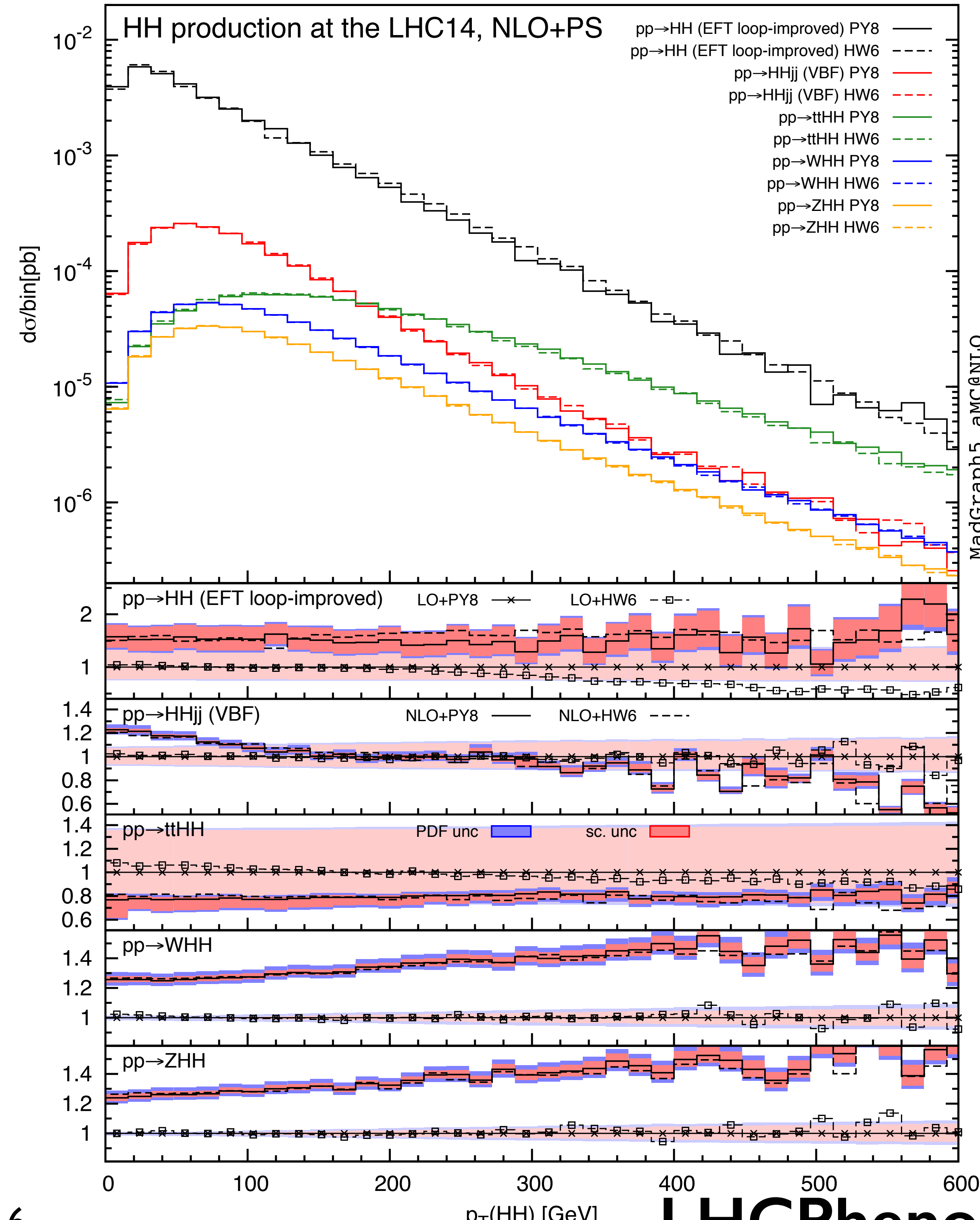

Conclusions

- Higgs pair production will be a key process to be looked at the next run of the LHC and at a FC
- It is the simplest class of processes which is sensitive to the Higgs boson self coupling λ
- Accurate predictions for the Higgs pair production mechanisms are needed
- All production mechanisms can be computed at NLO accuracy within the MadGraph5_aMC@NLO framework,
  - All automated, but $gg \to HH$
  - General approach to include loop-ME
- Fully differential predictions at NLO + PS are available for the first time for all production channels

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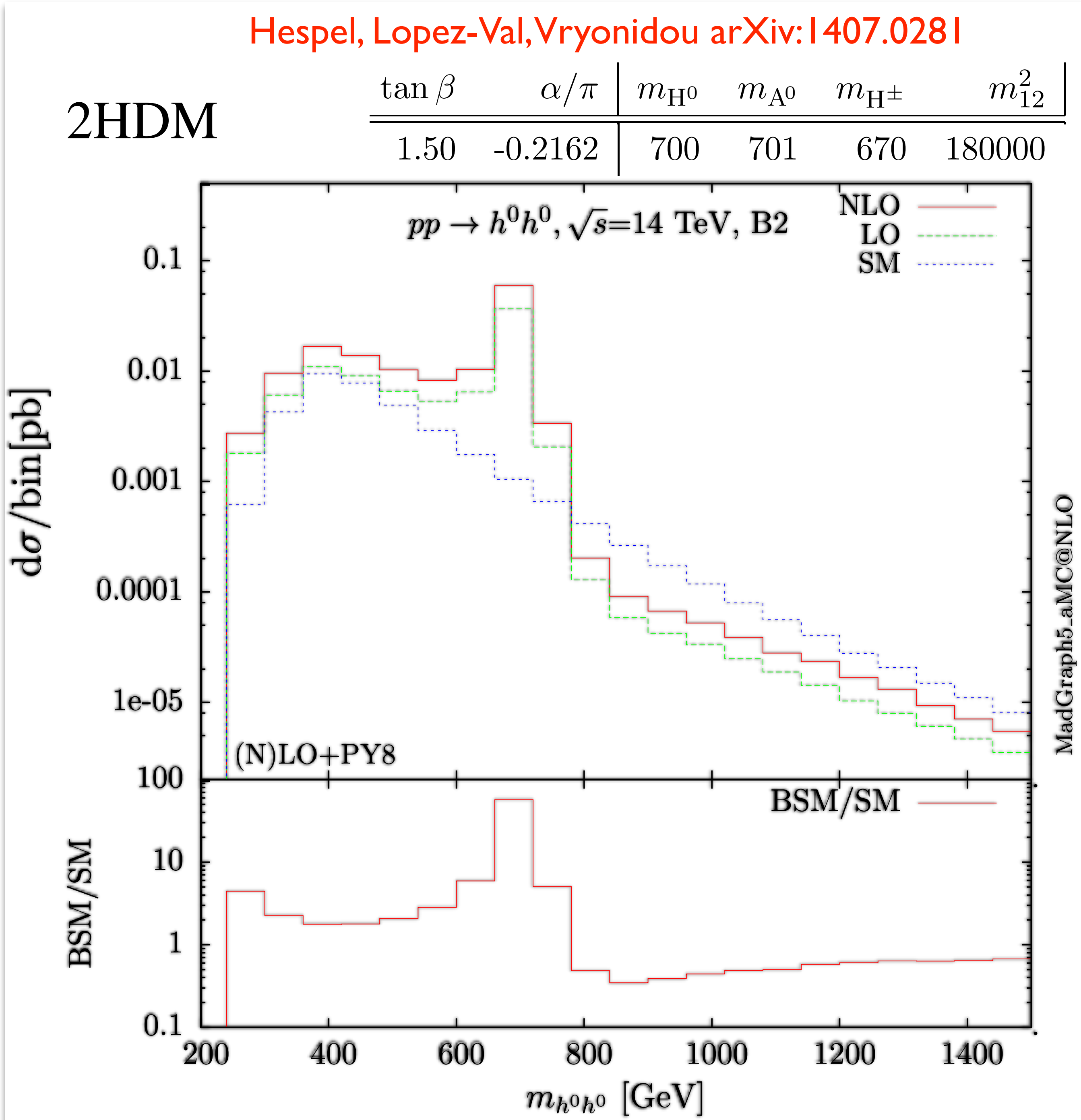

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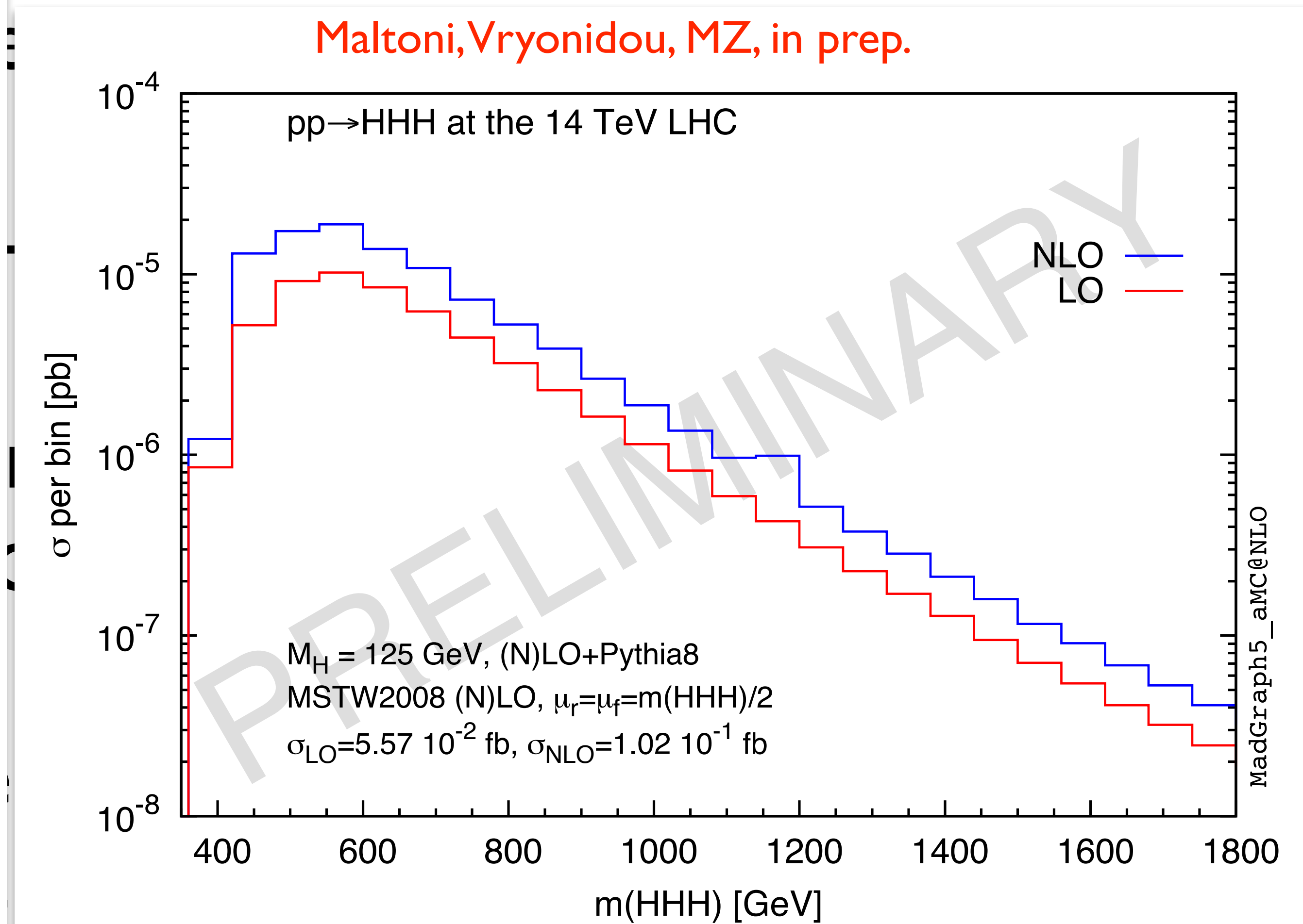
FC



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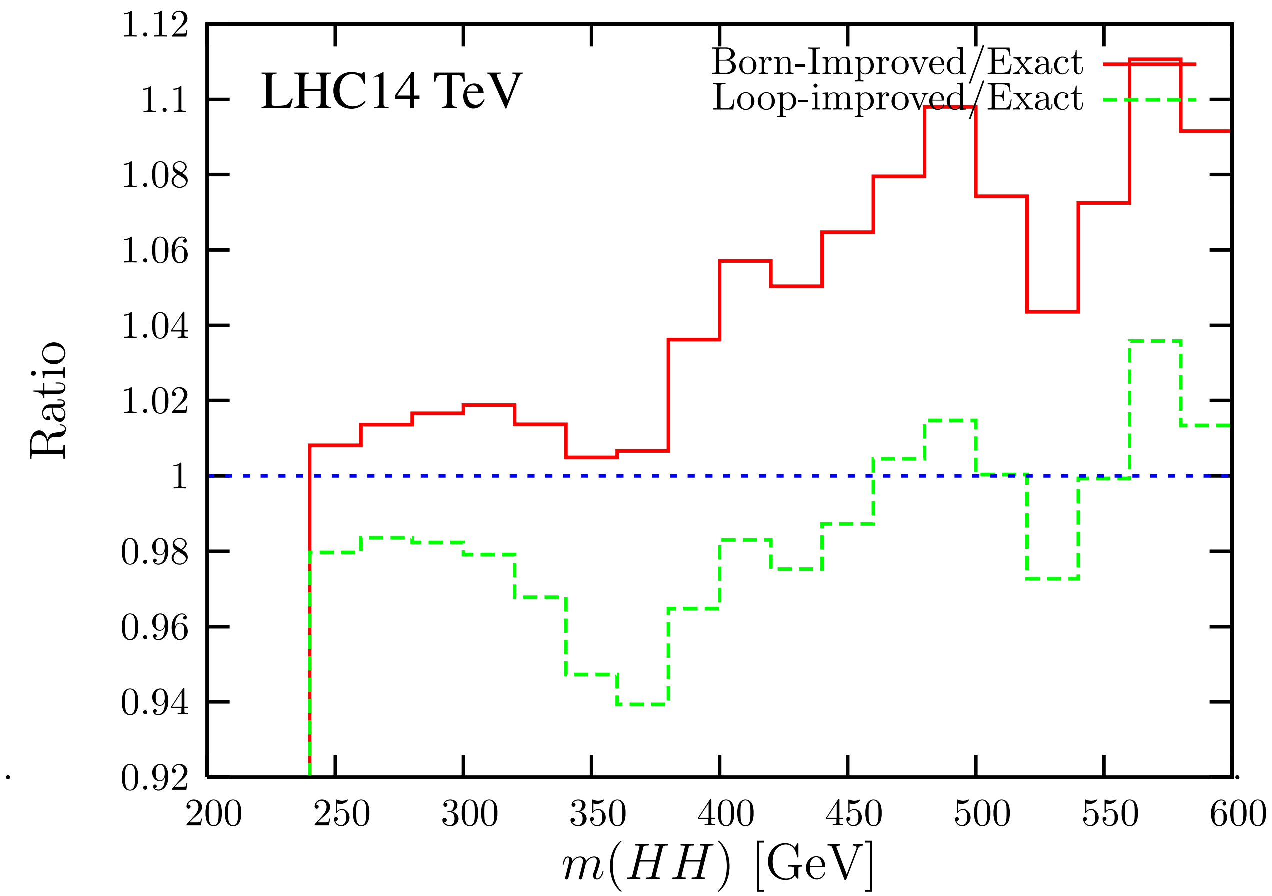
Backup slides

Different approximations for gg→HH

- Only consider terms ~λ
  - Reweight everything with the Born ME (as HPAIR) or with the Born and real ME



NLO: how to?

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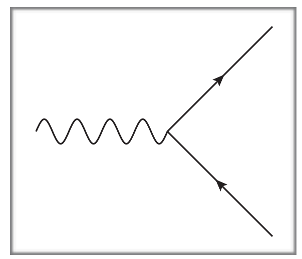
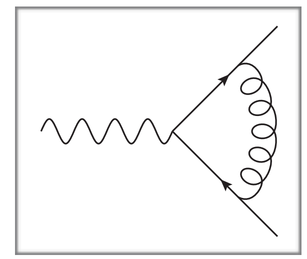
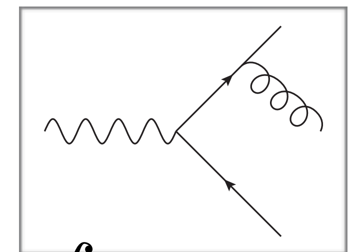
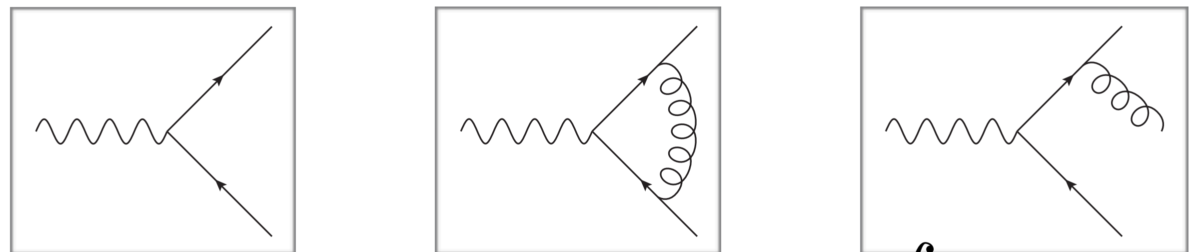
  

$$d\sigma^{n}_{NLO} \quad = \quad d\sigma^{n}_{LO} \quad + \quad d\sigma^{n}_{V} \quad + \int d\Phi_1 \; d\sigma^{n+1}_{R}$$

NLO: how to?



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  - Divergences cancel with those from virtuals (in D=4-2eps)
  - Need to cancel them before numerical integration (in D=4)

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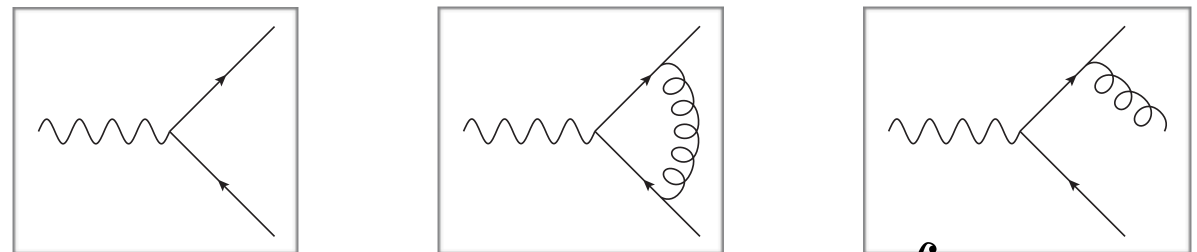

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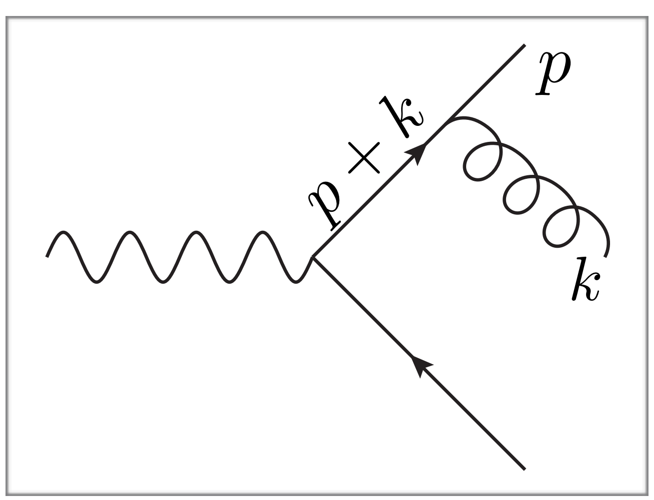
  - Need to cancel them before numerical integration (in D=4)
- Structure of divergences is universal:

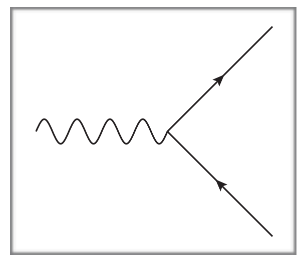


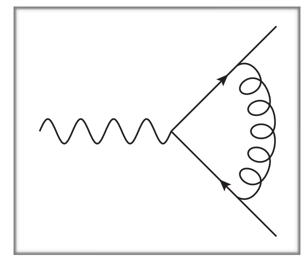
$$(p+k)^2 = 2E_pE_k(1-\cos\theta_{pk})$$

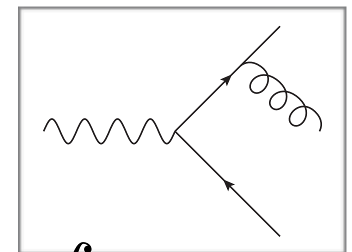
$$\lim_{p//k} |M_{n+1}|^2 \simeq |M_n|^2 \; P^{AP}(z)$$

$$\lim_{k\to 0} |M_{n+1}|^2 \simeq \sum_{ij} |M_n^{ij}|^2 \frac{p_ip_j}{p_ik \; p_jk}$$

NLO: how to?







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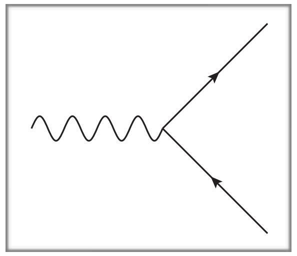
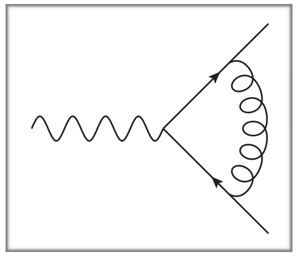
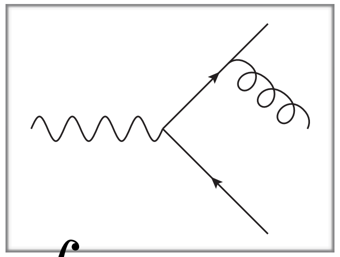
NLO: how to?

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$$d\sigma^n_{NLO} = d\sigma^n_{LO} + d\sigma^n_V - \int d\Phi_1 \, C + \int d\Phi_1 \, \left(C + d\sigma^{n+1}_R\right)$$

- Add local counterterms in the singular regions and subtract its integrated finite part (poles will cancels against the virtuals)
- The *n* and *n+1* body integral now are finite in 4 dimension
  - Can be integrated numerically

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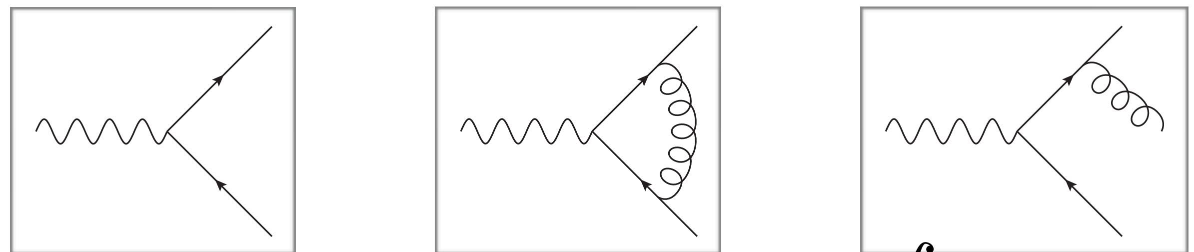

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How to do this in an efficient way?

The FKS subtraction

Frixione, Kunszt, Signer, arXiv:hep-ph/9512328

- Soft/collinear singularities arise in many PS regions
- Find parton pairs *i*, *j* that can give collinear singularities
- Split the phase space into regions with one collinear sing
  - Soft singularities are split into the collinear ones

$$|M|^2 = \sum_{ij} S_{ij} |M|^2 = \sum_{ij} |M|^2_{ij} \qquad \sum S_{ij} = 1$$

$$S_{ij} \to 1 \text{ if } k_i \cdot k_j \to 0 \qquad S_{ij} \to 0 \text{ if } k_{m \neq i} \cdot k_{n \neq j} \to 0$$

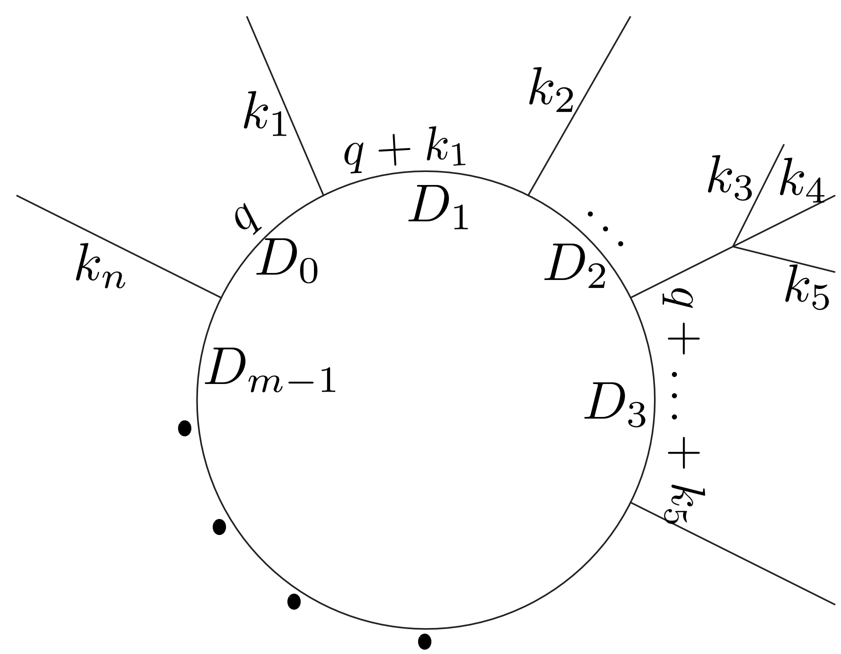
- Integrate them independently
  - Parallelize integration
  - Choose ad-hoc phase space parameterization
- Advantages:
  - # of contributions ~ n^2
  - Exploit symmetries: 3 contributions for `X Y > ng`

Loops: the OPP Method

Ossola, Papadopoulos, Pittau, arXiv:hep-ph/0609007 & arXiv:0711.3596

- Passarino & Veltman reduction:
  - Write the amplitude at the integral level as linear combination of 1-...-4-point scalar integrals

$$
\begin{aligned}
A(q) &= \sum_{i_0<i_1<i_2<i_3}^{m-1} d(i_0 i_1 i_2 i_3) D_0(i_0 i_1 i_2 i_3) \\
&+ \sum_{i_0<i_1<i_2}^{m-1} c(i_0 i_1 i_2) C_0(i_0 i_1 i_2) \\
&+ \sum_{i_0<i_1}^{m-1} b(i_0 i_1) B_0(i_0 i_1) \\
&+ \sum_{i_0}^{m-1} a(i_0) A_0(i_0) \\
&+ R
\end{aligned}
$$



  - Do this at the integrand level

Loops: the OPP Method

Ossola, Papadopoulos, Pittau, arXiv:hep-ph/0609007 & arXiv:0711.3596

$$A(\bar{q}) = \frac{N(q)}{\bar{D}_0\bar{D}_1\cdots\bar{D}_{m-1}}$$

$$\begin{aligned} N(q) = & \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d(i_0i_1i_2i_3) + \tilde{d}(q;i_0i_1i_2i_3)\right] \prod_{i\neq i_0,i_1,i_2,i_3}^{m-1} D_i \\ + & \sum_{i_0<i_1<i_2}^{m-1} \left[c(i_0i_1i_2) + \tilde{c}(q;i_0i_1i_2)\right] \prod_{i\neq i_0,i_1,i_2}^{m-1} D_i \\ + & \sum_{i_0<i_1}^{m-1} \left[b(i_0i_1) + \tilde{b}(q;i_0i_1)\right] \prod_{i\neq i_0,i_1}^{m-1} D_i \\ + & \sum_{i_0}^{m-1} \left[a(i_0) + \tilde{a}(q;i_0)\right] \prod_{i\neq i_0}^{m-1} D_i \\ + & \tilde{P}(q) \prod_{i}^{m-1} D_i \,. \end{aligned}$$

- Sample the numerator at complex values of the loop momenta in order to reconstruct the *a,b,c,d* coefficients and part of the rational terms (R1)
- Use CutTools: fed with the loop numerator outputs the coefficients of the scalar integrals and CC rational terms (R1)
- Add R2-rational terms/UV counterterms
  - Model dependent but process-independent

Loop ME evaluation: MadLoop

Hirschi et al. arXiv:1103.0621

- Load the NLO UFO model
- Generate Feynman diagrams to evaluate the loop ME
- Add R2/UV renormalisation counter terms
- Interface to CutTools or to tensor reduction programs (in progress)
- Check PS point stability (and switch to QP if needed)
- Improved with the OpenLoops method — Cascioli, Maierhofer, Pozzorini arXiv:1111.5206
- And much more (can be used as standalone or external OLP via the BLHA, handle loop-induced processes, …)

Matching in MC@NLO

- Use suitable counterterms to avoid double counting the emission from shower and ME, keeping the correct rate at order α_s:

$$\frac{d\sigma_{MC@NLO}}{dO} = \underbrace{\left(\mathcal{B} + \mathcal{V} + \int d\Phi_1 MC\right) d\Phi_n\, I^n_{MC}(O)}_{\text{S-events}} + \underbrace{(\mathcal{R} - MC)\, d\Phi_n\, d\Phi_1\, I^{n+1}_{MC}(O)}_{\text{H-events}}$$

- MC depends on the PSMC's Sudakov:

$$MC = \left| \frac{\partial\left(t^{MC}, z^{MC}, \phi\right)}{\partial \Phi_1} \right| \frac{1}{t^{MC}} \frac{\alpha_s}{2\pi} \frac{1}{2\pi} P\left(z^{MC}\right) \mathcal{B}$$

- Available for Herwig6, Pythia6 (virtuality-ordered), Herwig++, Pythia8 (in the new release)
- MC acts as local counterterm
- Some weights can be negative (unweighting up to sign)
  - Only affects statistics