Parton shower and finite top mass effects in HH production

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In collaboration with
Borowka, Greiner, Heinrich, Jones, Luisoni, Schlenk, Schubert, Vryonidou, Zirke

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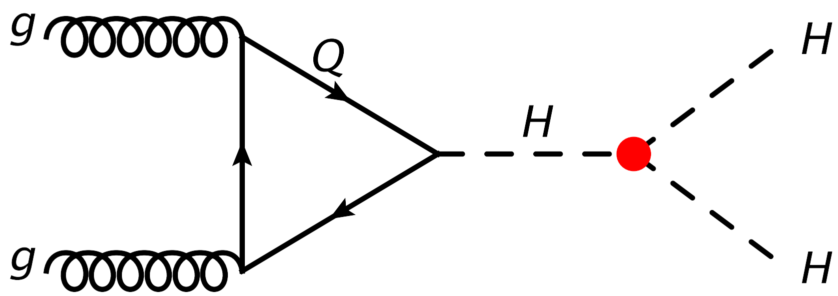
PRL 117 (2016) 012001, Erratum 079901 [1604.06447]

Motivation

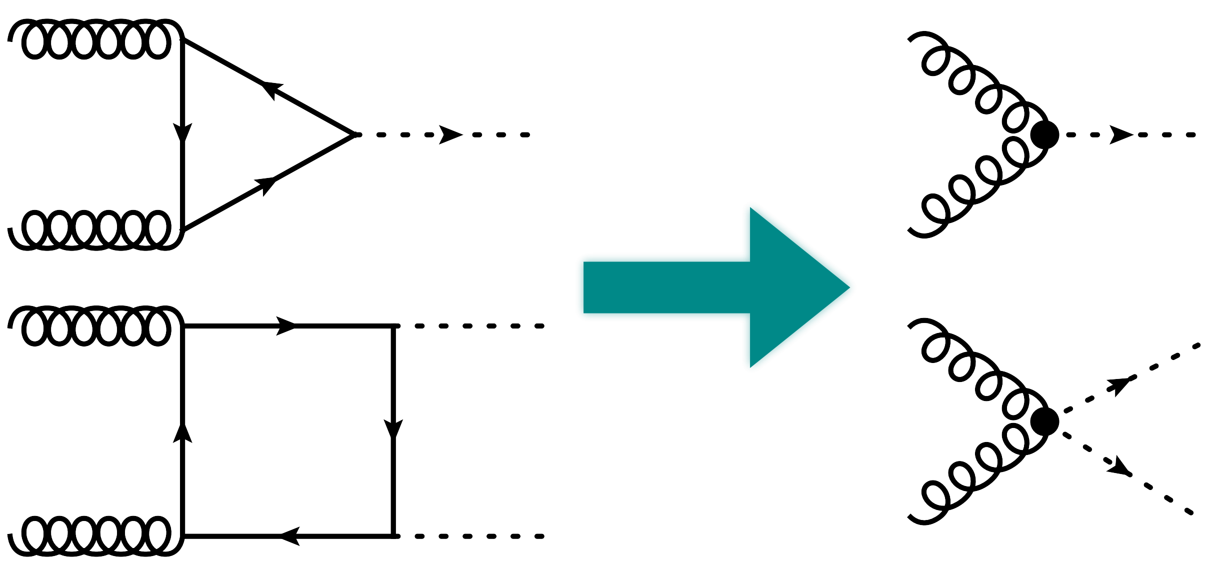
Dominant production mechanism for HH production is gluon fusion



Sensitive to HHH coupling

Test of Higgs potential & EW symmetry breaking

Most calculations are done in $m_t \to \infty$ limit (Higgs EFT)



HEFT valid for $\sqrt{s} \ll 2\, m_T$

Higgs pair production:

$$2\, m_H < \sqrt{s}$$

full top quark mass dependence required for accurate predictions

gg→HH calculations

1. LO, including full m_T dependence
   Glover, van der Bij `88

2. NLO, (Born-improved) HEFT **K ≈ 2**
   Dawson, Dittmaier, Spira `98
   - including full m_T dependence in real radiation (FT approx.) **-10%**
     Maltoni, Vryonidou, Zaro `14
   - including $1/m_T$ expansion **±10%**
     Grigo, Hoff, Melnikov, Steinhauser `13;
     Grigo, Hoff, Steinhauser `15
     Degrassi, Giardino, Gröber `16

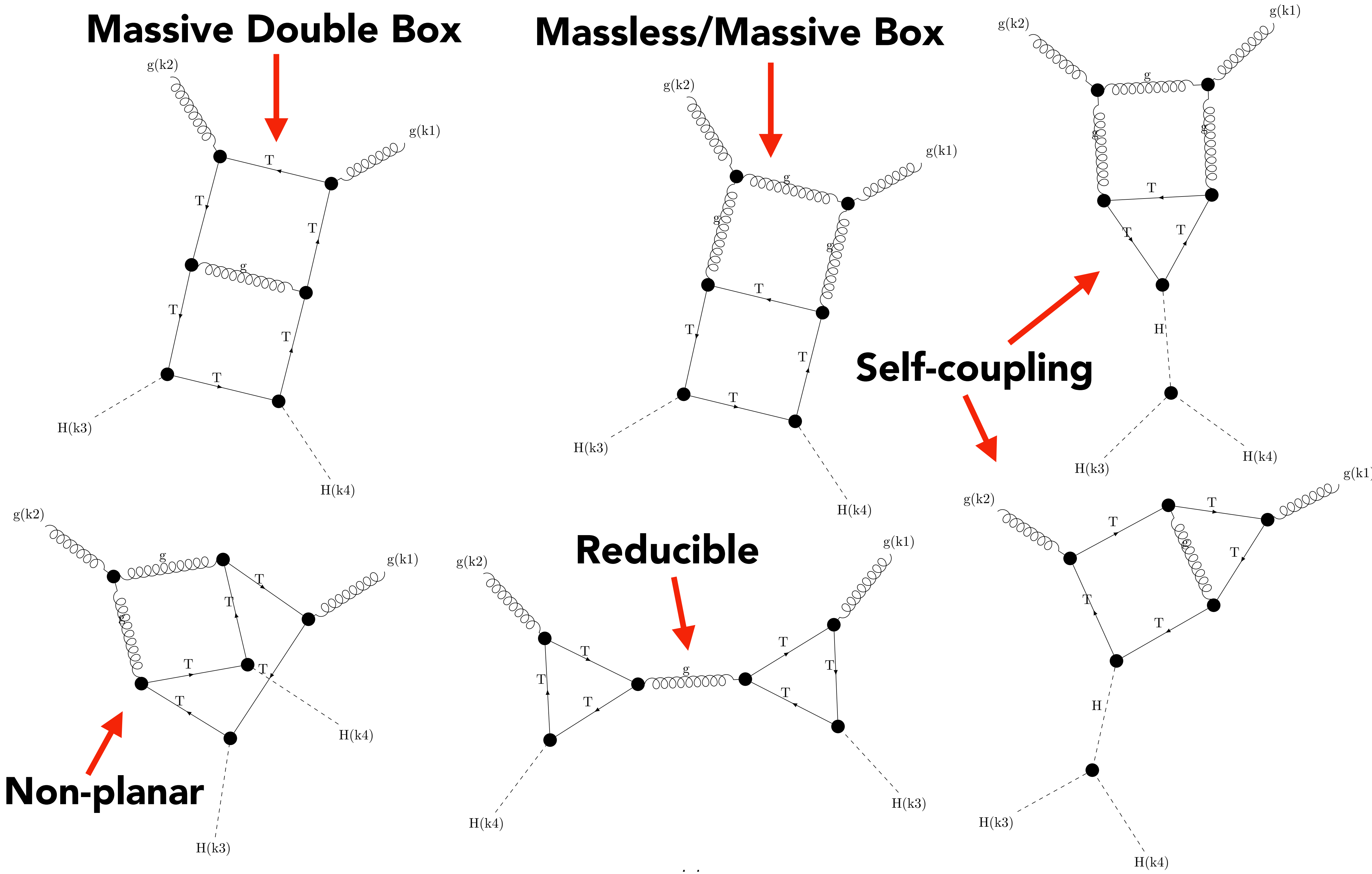
3. NLO, including full m_T dependence
   Borowka, Greiner, Heinrich, Jones, MK,
   Schlenk, Schubert, Zirke `16
   - NLO matched to parton shower
     Heinrich, Jones, Luisoni, MK, Vryonidou `17

   this talk

   - transverse momentum NLL+NLO
     Ferrera, Pires `16

4. NNLO (HEFT) **+20%**
   de Florian, Mazzitelli `13
   - including all matching coefficients
     Grigo, Melnikov, Steinhauser `14
   - including $1/m_T$ expansion
     Grigo, Hoff, Steinhauser `15
   - NNLL soft gluon resummation
     Shao, Li, Li, Wang `13
   - NNLL + NNLO matching
     de Florian, Mazzitelli `15
   - fully differential
     de Florian, Grazzini, Hanga, Kallweit,
     Lindert, Maierhöfer, Mazzitelli, Rathlev `16

Two Loop Diagrams



most complicated integrals not known analytically
→ numeric calculation required

NLO Calculation

1. Reduction to master integrals using Reduze von Manteuffel, Studerus`12
   - full reduction achieved only for planar integrals (non-planar integrals evaluated directly)
   - use finite basis von Manteuffel, Panzer, Schabinger `15

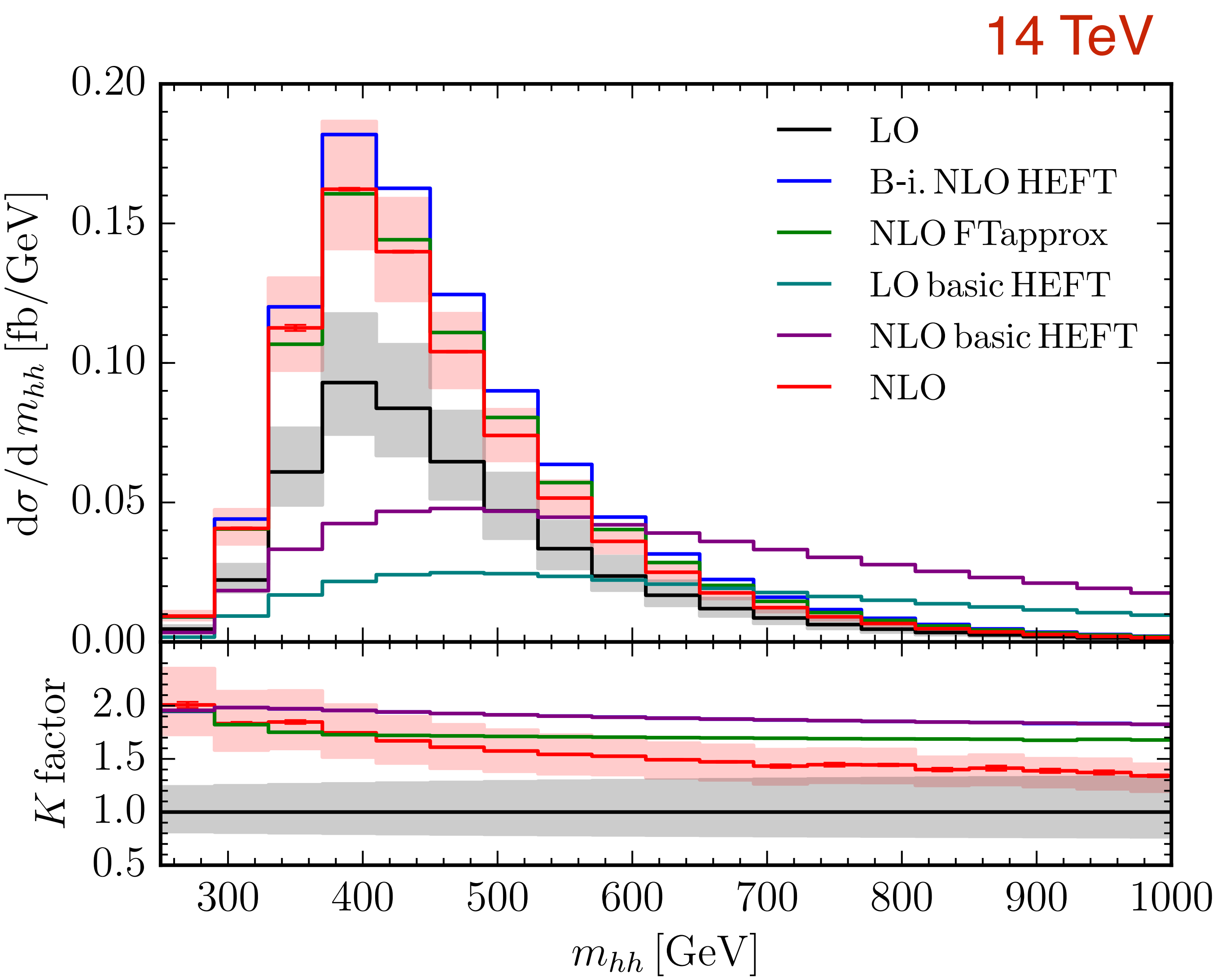
2. Numerical evaluation of 2-loop integrals using SecDec Borowka, Heinrich, Jahn, Jones, MK, Schlenk, Zirke
   - using Quasi-Monte-Carlo integration with $\mathcal{O}(n^{-1})$ scaling
     Li, Wang, Yan, Zhao `15; Review: Dick, Kuo, Sloan
   - dynamically set number of sampling points for each integral
   - parallelization on gpu

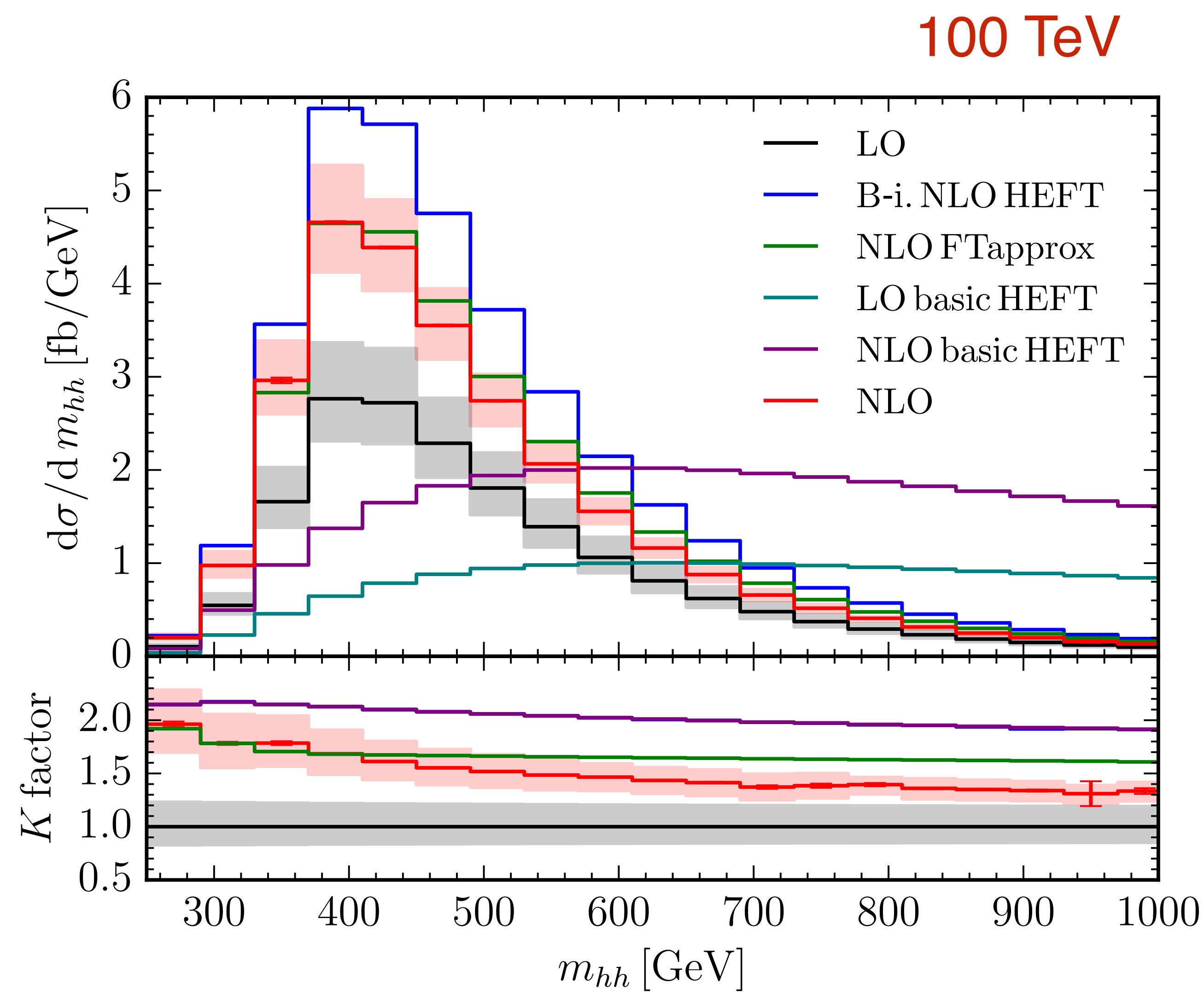
3. Use unweighted events (based on LO) for phase space integration of virtuals

4. Real radiation amplitudes using GoSam
   Cullen, van Deurzen, Greiner, Heinrich, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Schlenk, von Soden-Fraunhofen, Tramontano

5. Dipole subtraction Catani Seymour
   to deal with IR singularities

NLO Results — Invariant Mass

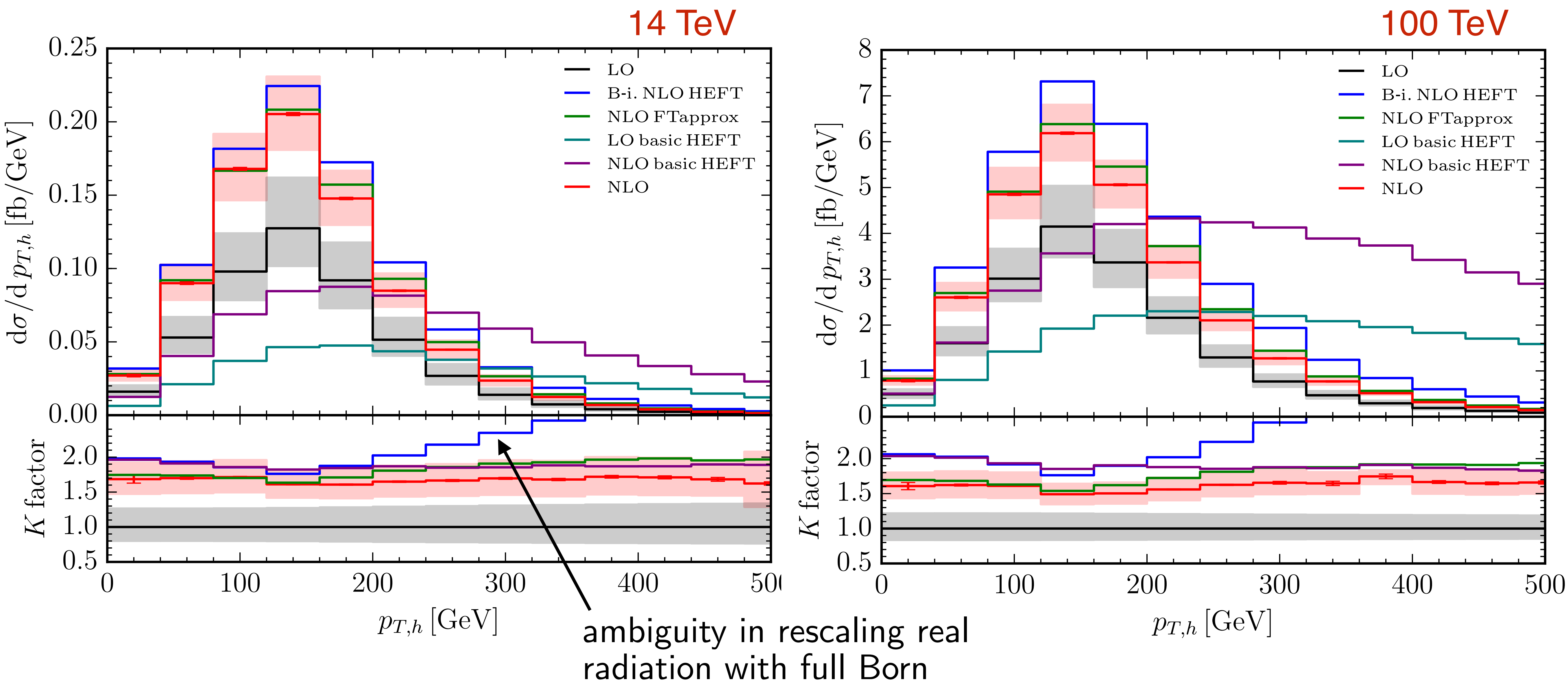




- basic HEFT leads to wrong shape
- B.I. HEFT overestimates by 16% / 30%
- FT approx closer to full result
  (difference increasing with m_{hh})

	14 TeV	100 TeV
LO	$19.85^{+27.6\%}_{-20.5\%}$	$731.3^{+20.9\%}_{-15.9\%}$
B.i. HEFT	$38.32^{+18.1\%}_{-14.9\%}$	$1511^{+16.0\%}_{-13.0\%}$
FT approx	$34.26^{+14.7\%}_{-13.2\%}$	$1220^{+11.9\%}_{-10.7\%}$
NLO full	$32.91^{+13.6\%}_{-12.6\%}$	$1149^{+10.8\%}_{-10.0\%}$

NLO Results — Higgs Momentum



- basic HEFT leads to wrong shape
- B.I. HEFT overestimates by 16% / 30%
- FT approx closer to full result (difference increasing with $p_{T,h}$)

top mass effects important, in particular at $\sqrt{s} = 100\,\mathrm{TeV}$

Parton Shower Interface

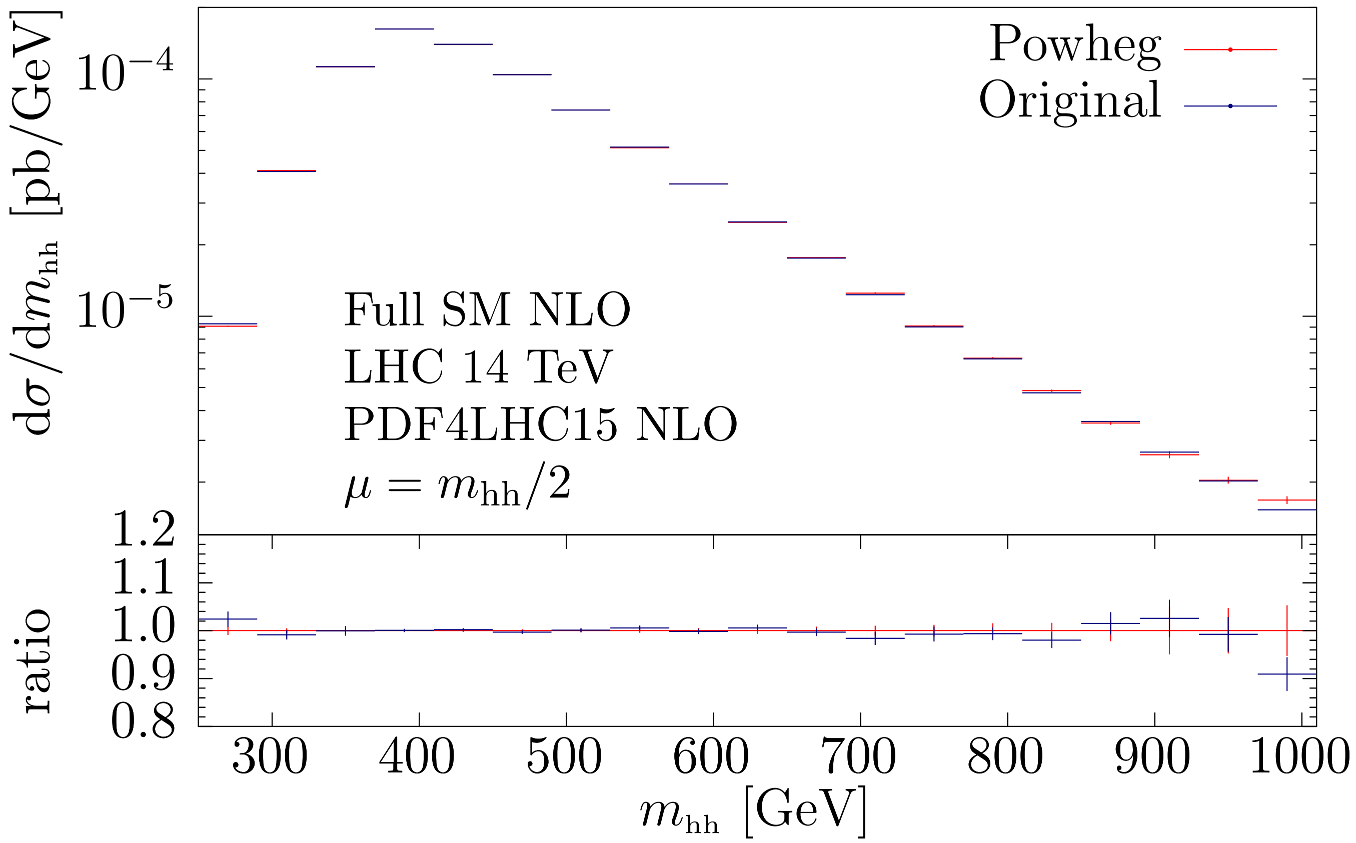
2-loop amplitude too slow (median 2h on gpu) for direct interface to PS
→ construct grid for interpolation of virtual amplitude (3741 2-loop results used)

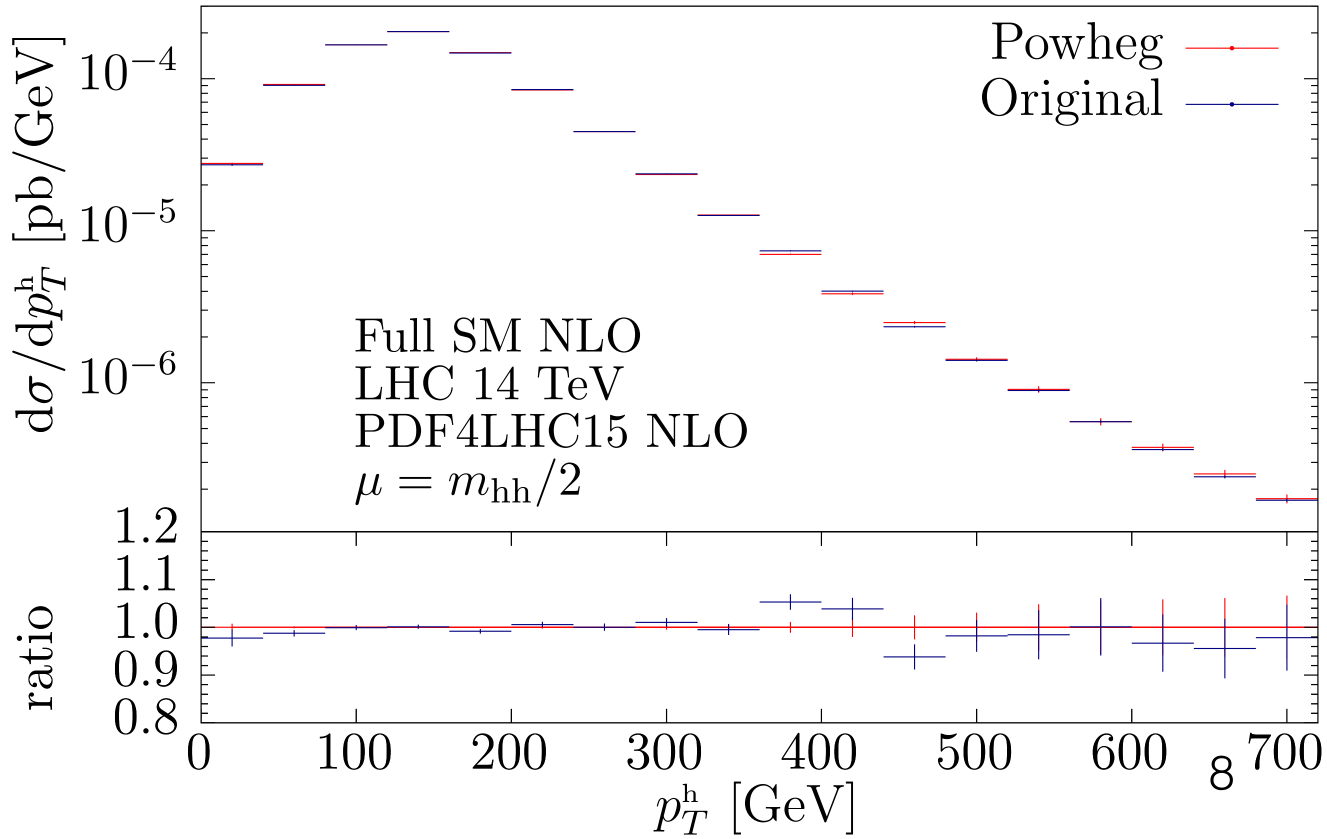
input parameters ($\hat{s}$, $\hat{t}$) transformed to

$$x = f(\beta(\hat{s})), \quad c_\theta = |\cos\theta| = \left|\frac{\hat{s} + 2\hat{t} - 2m_H^2}{\hat{s}\beta(\hat{s})}\right|, \quad \beta = \left(1 - \frac{4m_H^2}{\hat{s}}\right)^{\frac{1}{2}}$$

→ nearly uniform distribution of phase space points in $(x, c_\theta) \in [0,1]^2$ if $f(\beta)$ chosen according to cumulative distribution of points in original calculation

Grid validation:





LHE Events in HEFT & comparison with NNLO

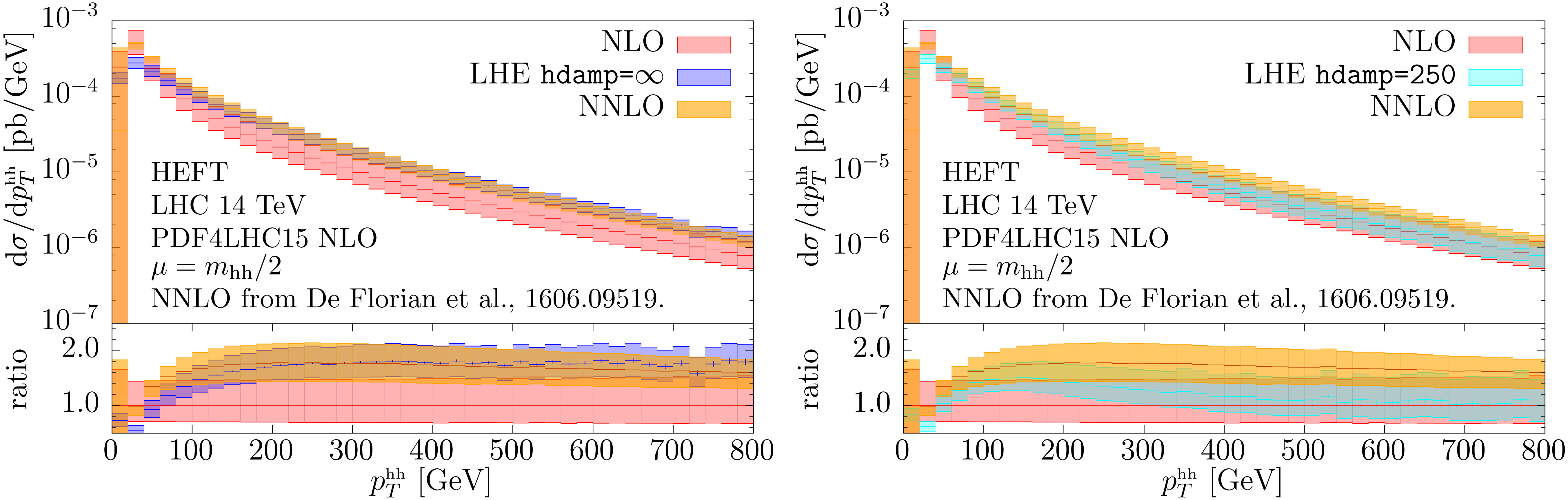
Les Houches Event Level:

Sudakov factor included, but no parton shower

Powheg allows to split real radiation into (exponentiated) singular and regular part

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

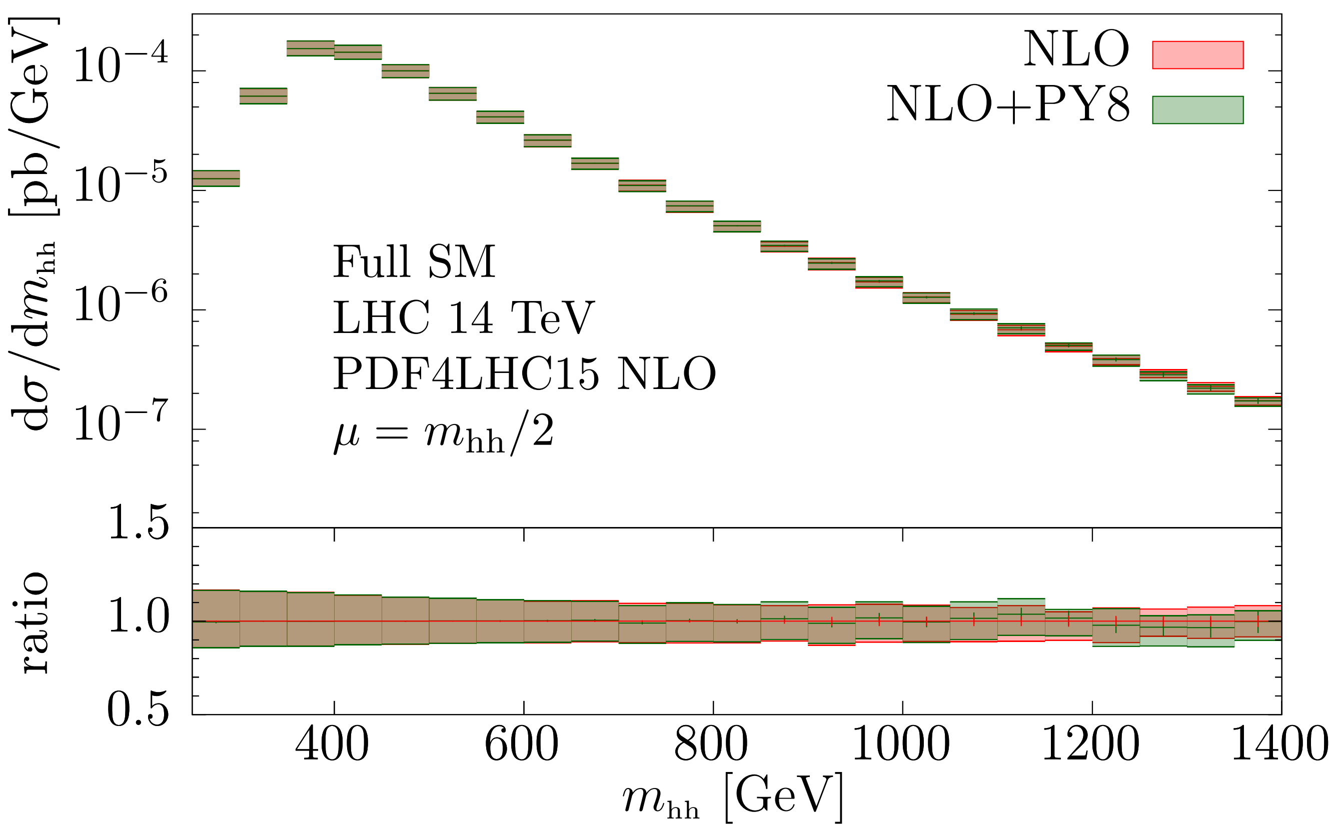
with $F = \dfrac{h^2}{(p_T^{\text{hh}})^2 + h^2}$

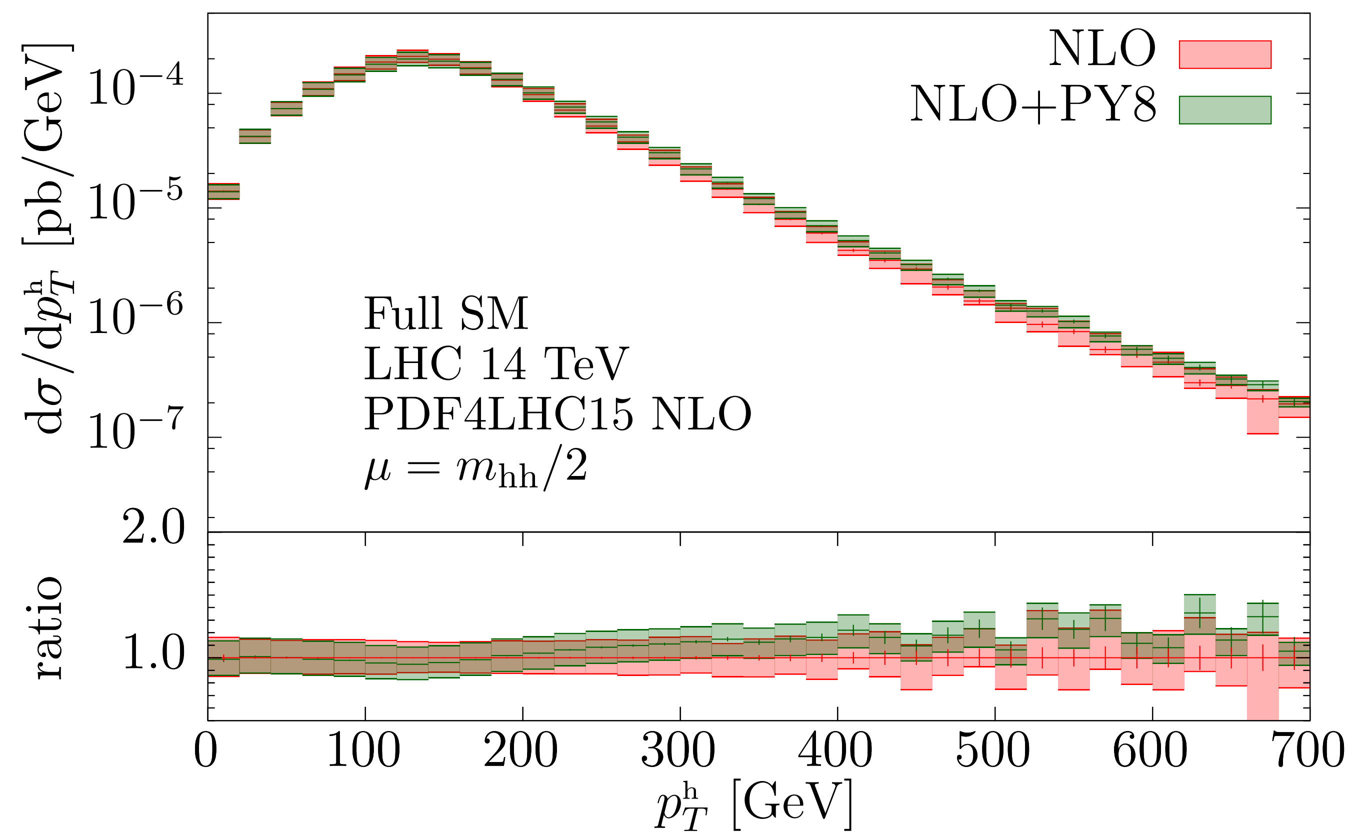


- $h = \infty$: LHE level results close to NNLO
- $h = 250$: LHE level approaches NLO in tail of p_T^{hh} distribution

Results including Parton Shower

Powheg + Pythia8





no effect on invariant mass

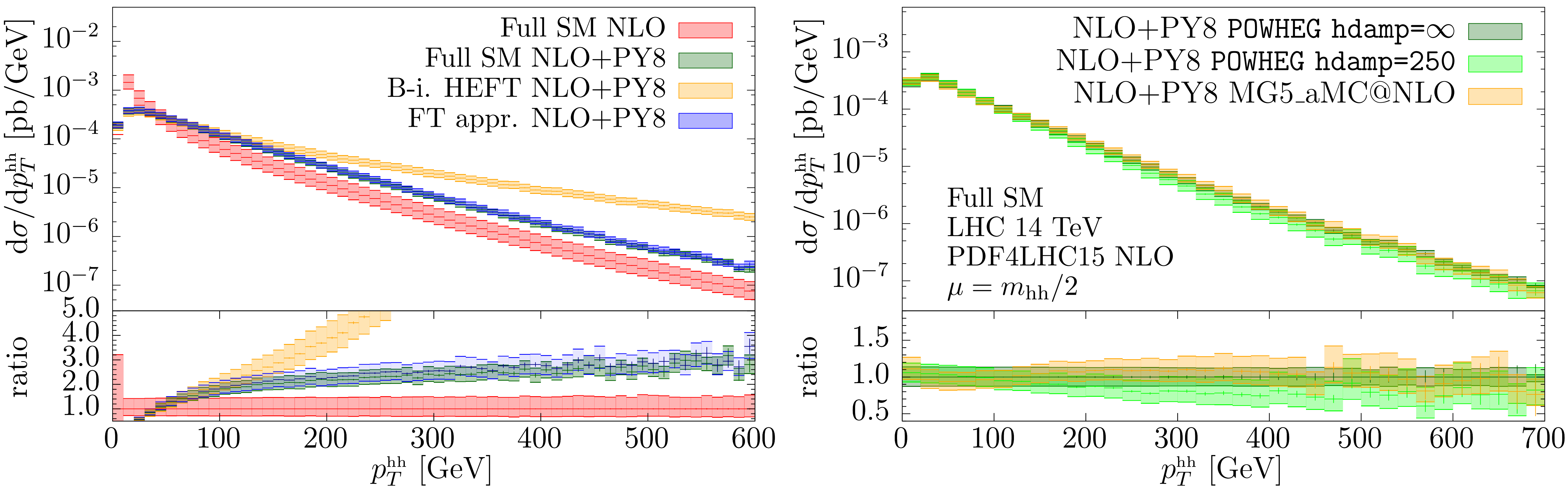
parton shower enhances tails of p_T distributions

only small parton shower effects on NLO accurate observables

Results including Parton Shower

Parton shower effects large for observables sensitive to real radiation, e.g. p_T^{hh}

Powheg MadGraph5_aMC@NLO

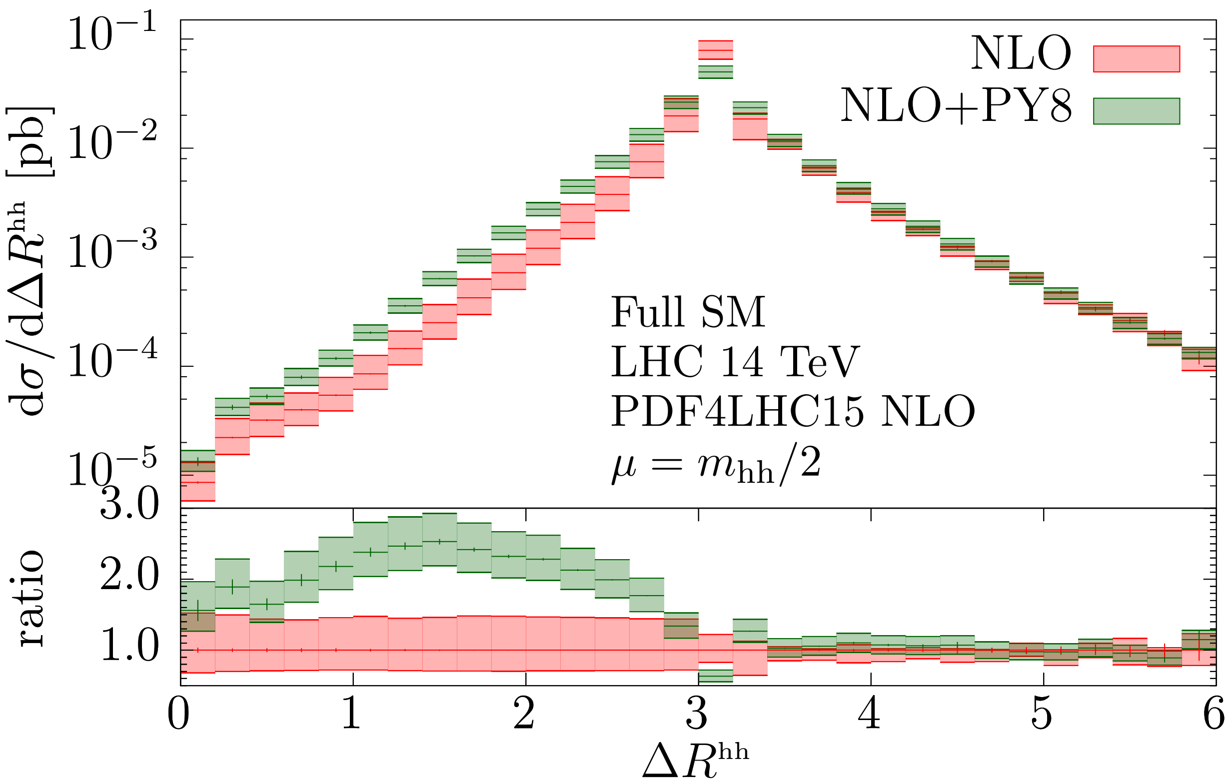


- parton shower enhances tail p_T^{hh} distribution by factor of ~2
- difference of matching schemes of ~20%
- small difference between full NLO and FT approx. result

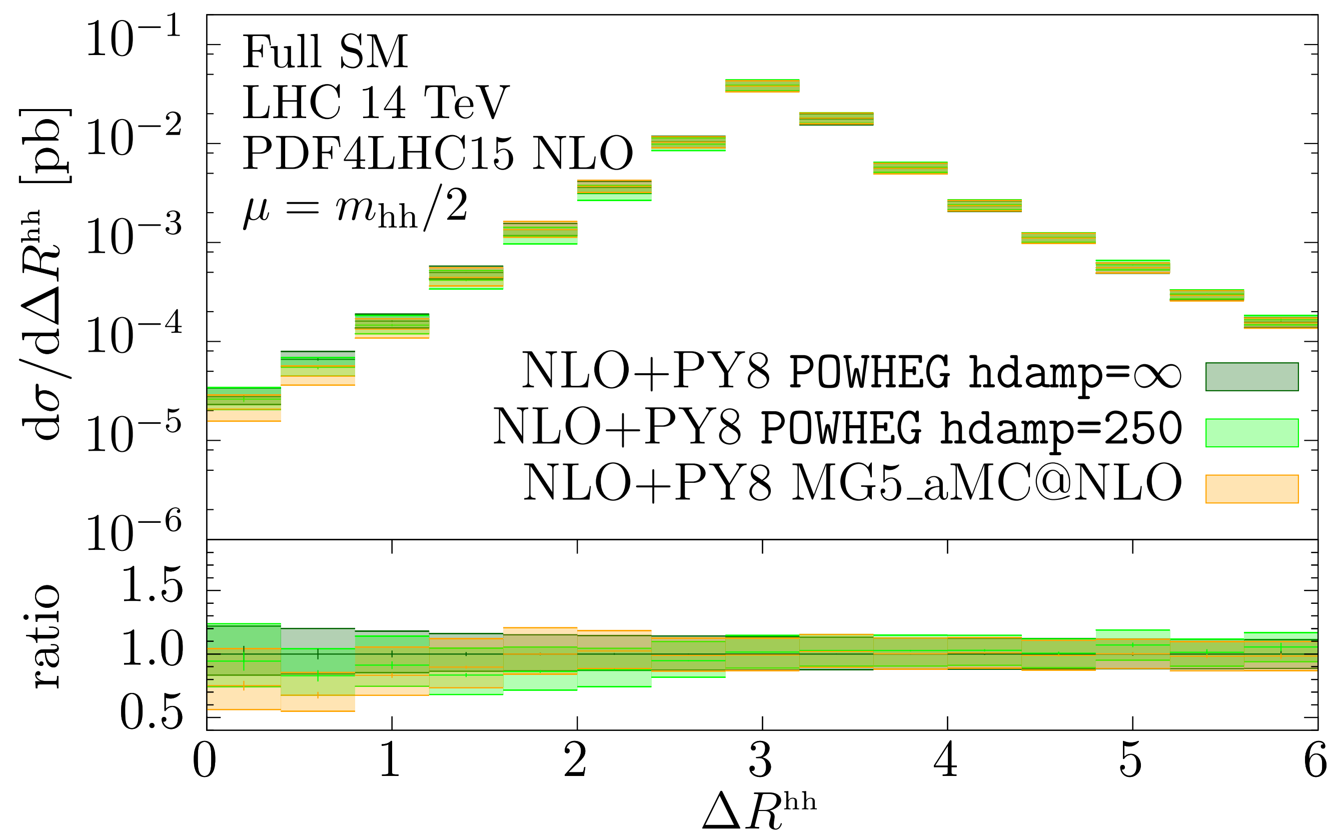
Results including Parton Shower

Parton shower effects large for observables sensitive to real radiation, e.g. ΔR^{hh}

Powheg



MadGraph5_aMC@NLO



$\Delta R^{hh} < \pi$

- filled by real radiation only LO accurate
- parton shower corrections up to factor of ~2.5
- differences due to matching method visible

$\Delta R^{hh} > \pi$

- NLO accurate
- small dependence on parton shower / matching

Summary & Outlook

Higgs pair production at NLO

- retaining full m_t dependence
- numeric evaluation of 2-loop amplitudes
- reduces cross section by 14% compared to Born-improved HEFT
- corrections not uniform over phase space

Matching to Parton Showers

- up to ~20% differences for NLO accurate observables
  only small dependence on matching method
- effects can be large for LO accurate observables

Outlook

- comparison with Herwig and Sherpa parton shower
- combination of NLO in full theory with NNLO HEFT

Backup

Two Loop Amplitude

- tensor structure Glover, van der Bij `88

$$\mathcal{M} = \epsilon_\mu(p_1,n_1)\epsilon_\nu(p_2,n_2)\,\mathcal{M}^{\mu\nu}$$

$$\mathcal{M}^{\mu\nu} = A_1(s,t,m_H^2,m_t^2,D)\,T_1^{\mu\nu} + A_2(s,t,m_H^2,m_t^2,D)\,T_2^{\mu\nu}$$

with

$$T_1^{\mu\nu} = g^{\mu\nu} - \frac{p_1^\nu\,p_2^\mu}{p_1\cdot p_2}$$

$$T_2^{\mu\nu} = g^{\mu\nu} + \frac{1}{p_T^2\,(p_1\cdot p_2)}\left\{m_H^2 p_1^\nu\,p_2^\mu - 2\,(p_1\cdot p_3)\,p_3^\nu\,p_2^\mu - 2\,(p_2\cdot p_3)\,p_3^\nu\,p_1^\mu + 2\,(p_1\cdot p_2)\,p_3^\nu\,p_3^\mu\right\}$$

$$\mathcal{M}^{++} = \mathcal{M}^{--} = -A_1$$
$$\mathcal{M}^{+-} = \mathcal{M}^{-+} = -A_2$$

triangle diagrams gg→H→HH only contribute to A_1

- projectors

construct $P_i^{\mu\nu} = \sum_j c_{ij} T_j^{\mu\nu}$ such that

$$P_1^{\mu\nu}\mathcal{M}_{\mu\nu} = A_1(s,t,m_H^2,m_t^2,D)$$
$$P_2^{\mu\nu}\mathcal{M}_{\mu\nu} = A_2(s,t,m_H^2,m_t^2,D)$$

Amplitude Structure

rewrite loop integrals with r propagators and s inverse propagators as

$$I_{r,s}(s,t,m_h^2,m_t^2) = (M^2)^{-L\epsilon}(M^2)^{2L-r+s} I_{r,s}\left(\frac{s}{M^2},\frac{t}{M^2},\frac{m_h^2}{M^2},\frac{m_t^2}{M^2}\right)$$

arbitrary scale

and write renormalized form factors as

$$F^{\text{virt}} = aF^{(1)} + a^2(\frac{n_g}{2}\,\delta Z_A + \delta Z_a)F^{(1)} + a^2\delta m_t^2 F^{ct,(1)} + a^2 F^{(2)} + \mathcal{O}(a^3)$$

$$F^{(1)} = \left(\frac{\mu_R^2}{M^2}\right)^{\varepsilon}\left[b_0^{(1)} + b_1^{(1)}\varepsilon + b_2^{(1)}\varepsilon^2 + \mathcal{O}(\varepsilon^3)\right], \qquad \text{(1-loop)}$$

$$F^{ct,(1)} = \left(\frac{\mu_R^2}{M^2}\right)^{\varepsilon}\left[c_0^{(1)} + c_1^{(1)}\varepsilon + \mathcal{O}(\varepsilon^2)\right], \qquad \text{(mass counter-term)}$$

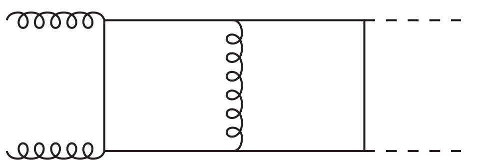
$$F^{(2)} = \left(\frac{\mu_R^2}{M^2}\right)^{2\varepsilon}\left[\frac{b_{-2}^{(2)}}{\varepsilon^2} + \frac{b_{-1}^{(2)}}{\varepsilon} + b_0^{(2)} + \mathcal{O}(\varepsilon)\right], \qquad \text{(2-loop)}$$

$\rightarrow$ scale variations do not require re-computation of $b_i^{(n)}$, $c_i^{(n)}$

Amplitude Evaluation — Example

$\sqrt{s} = 327.25\,\text{GeV},\ \sqrt{-t} = 170.05\,\text{GeV},\ M^2 = s/4$

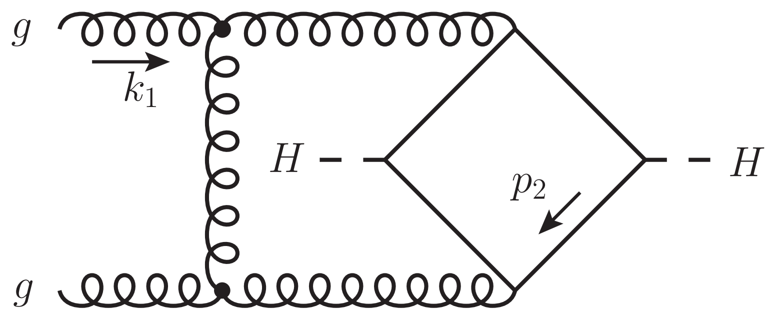
contributing integrals:



integral	value	error	time [s]
...			
F1_011111110_ord0	(0.484, 4.96e-05)	(4.40e-05, 4.23e-05)	11.8459
...			
N3_111111100_k1p2k2p2_ord0	(0.0929, -0.224)	(6.32e-05, 5.93e-05)	235.412
N3_111111100_1_ord0	(-0.0282, 0.179)	(8.01e-05, 9.18e-05)	265.896
N3_111111100_k1p2k1p2_ord0	(0.0245, 0.0888)	(5.06e-05, 5.31e-05)	282.794
N3_111111100_k1p2_ord0	(-0.00692, -0.108)	(3.05e-05, 3.05e-05)	433.342

≈ 700 integrals

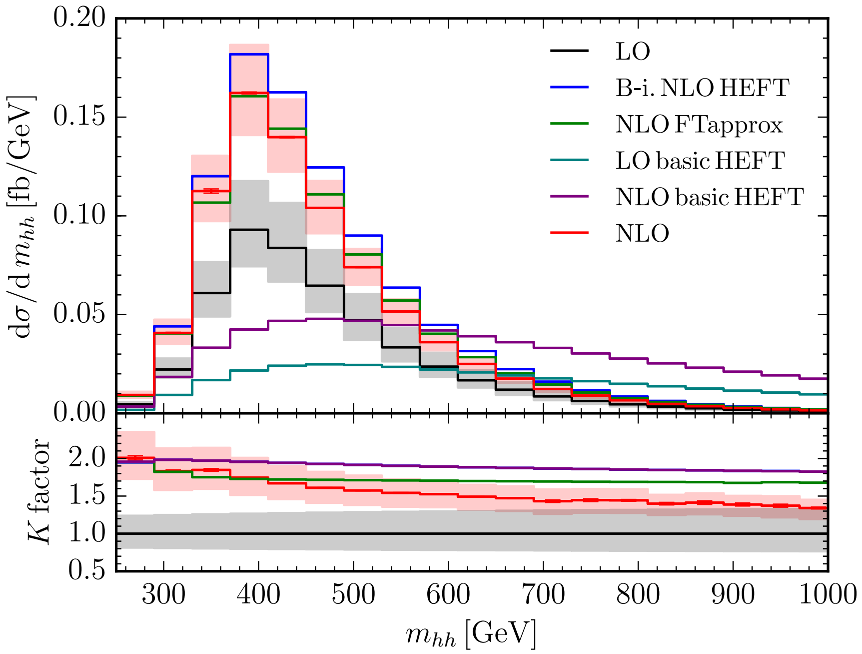
$$I(s,t,m_t^2,m_h^2) = -\left(\frac{\mu^2}{M^2}\right)^{2\varepsilon}\Gamma(3+2\epsilon)M^{-4}\left(\frac{A_{-2}}{\epsilon^2}+\frac{A_{-1}}{\epsilon^1}+A_0+\mathcal{O}(\epsilon)\right)$$



sector decomposition

sector	integral value	error	time [s]	#points
5	(-1.34e-03, 2.00e-07)	(2.38e-07, 2.69e-07)	0.255	1310420
6	(-1.58e-03, -9.23e-05)	(7.44e-07, 5.34e-07)	0.266	1310420
...				
41	(0.179, -0.856)	(1.10e-05, 1.22e-05)	29.484	79952820
42	(0.359, -1.308)	(1.40e-06, 1.58e-06)	80.24	211436900
44	(0.0752, -1.185)	(5.44e-07, 6.76e-07)	99.301	282904860

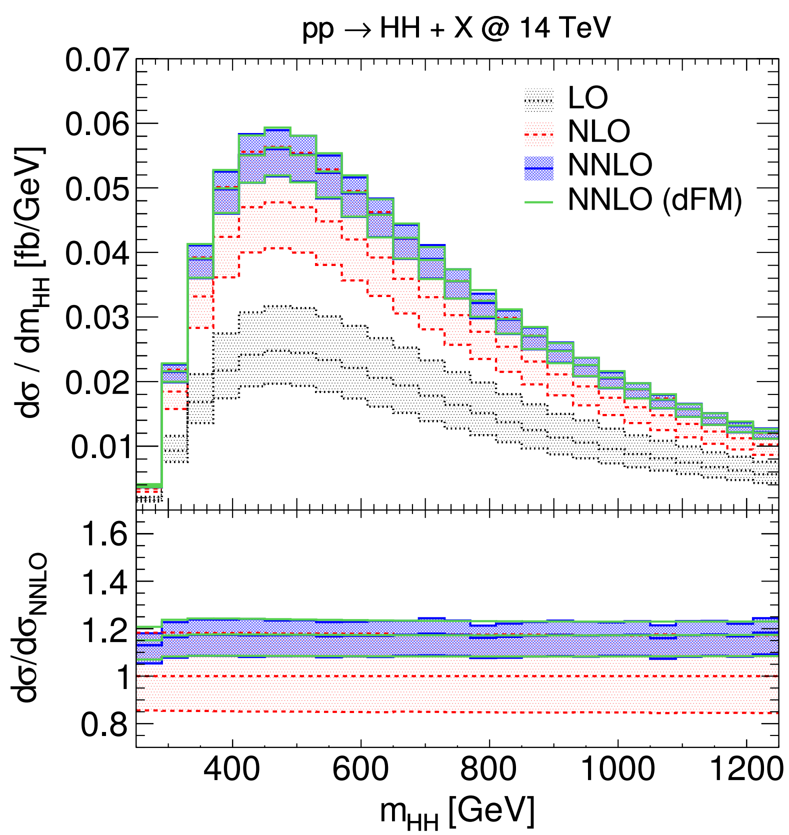
Results - Combination with $NNLO_{HEFT}$

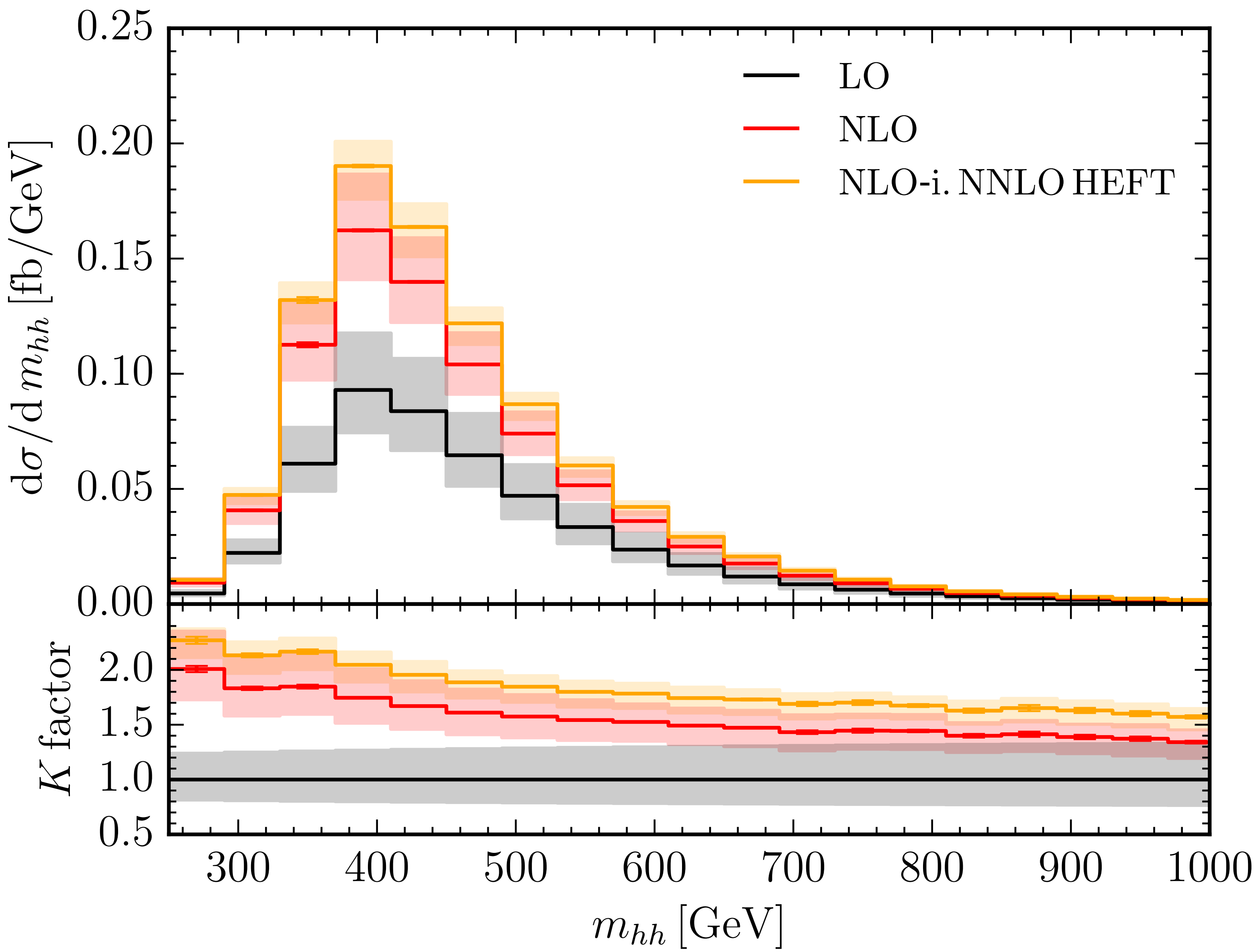


first attempt to combine NLO_{full} with $NNLO_{HEFT}$

NLO-improved NNLO HEFT:

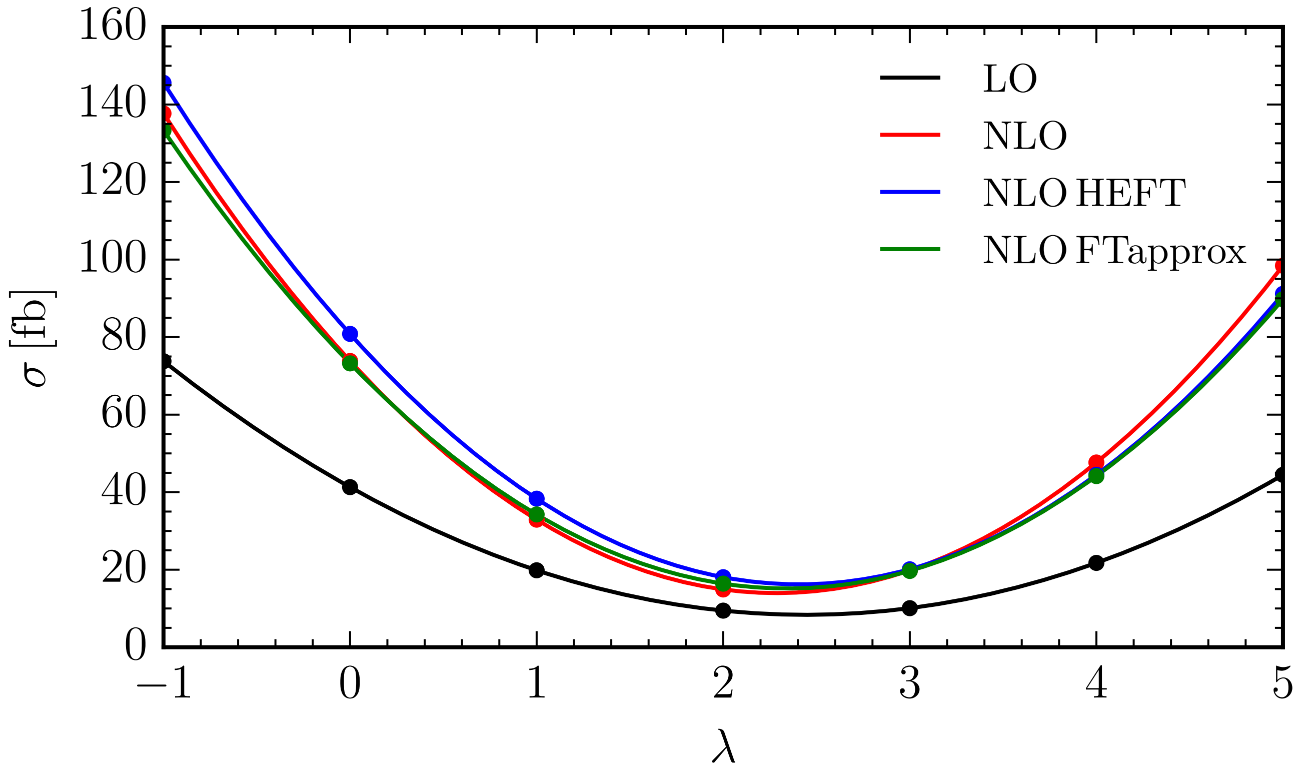
$$\frac{d\sigma_{\rm NLO}^{\rm full}}{dm_{hh}} \cdot \frac{d\sigma_{\rm NNLO}^{\rm HEFT}/dm_{hh}}{d\sigma_{\rm NLO}^{\rm HEFT}/dm_{hh}}$$

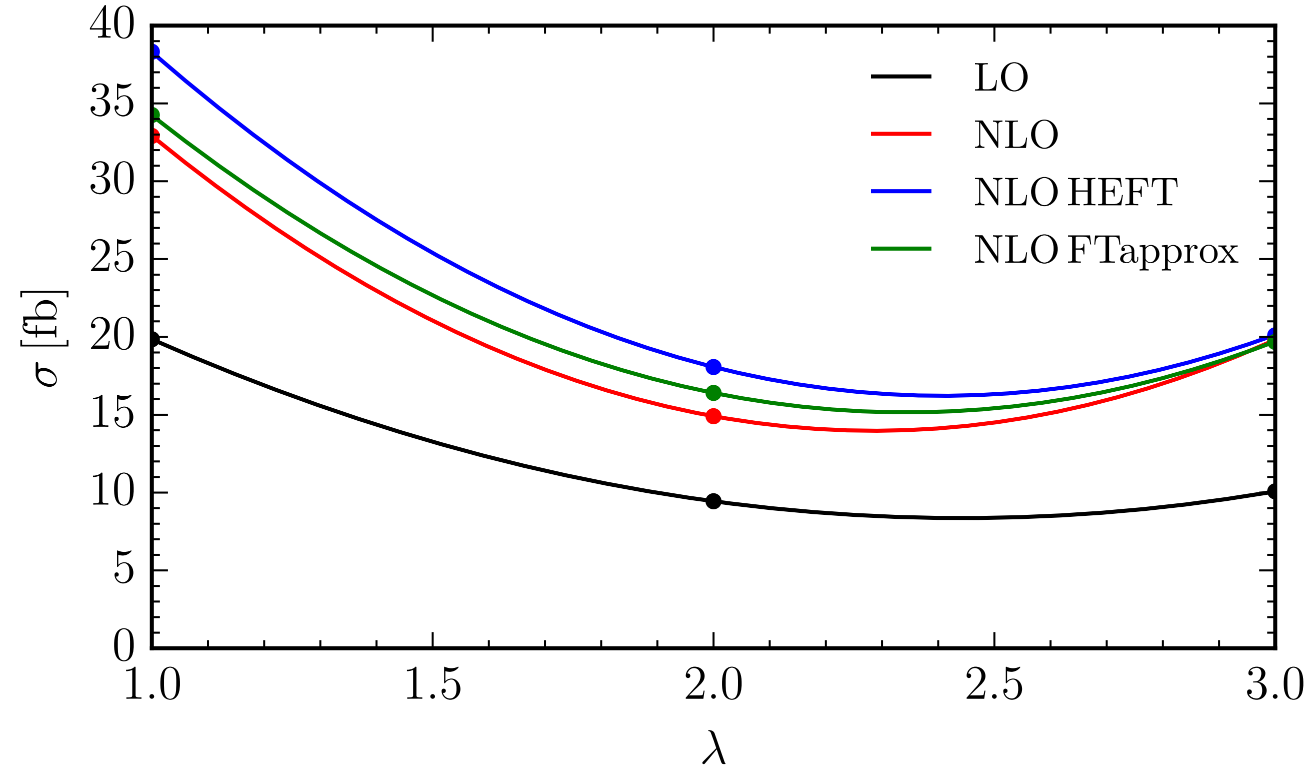




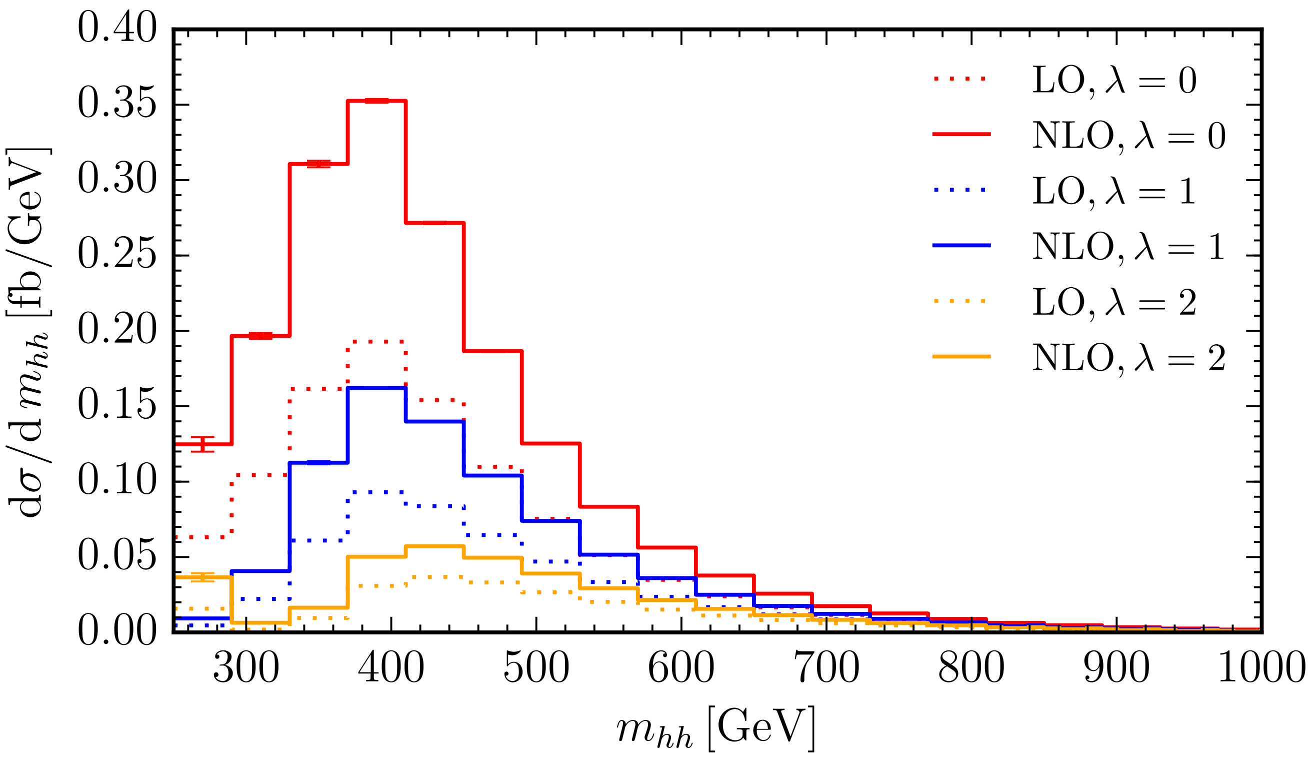
de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev `16

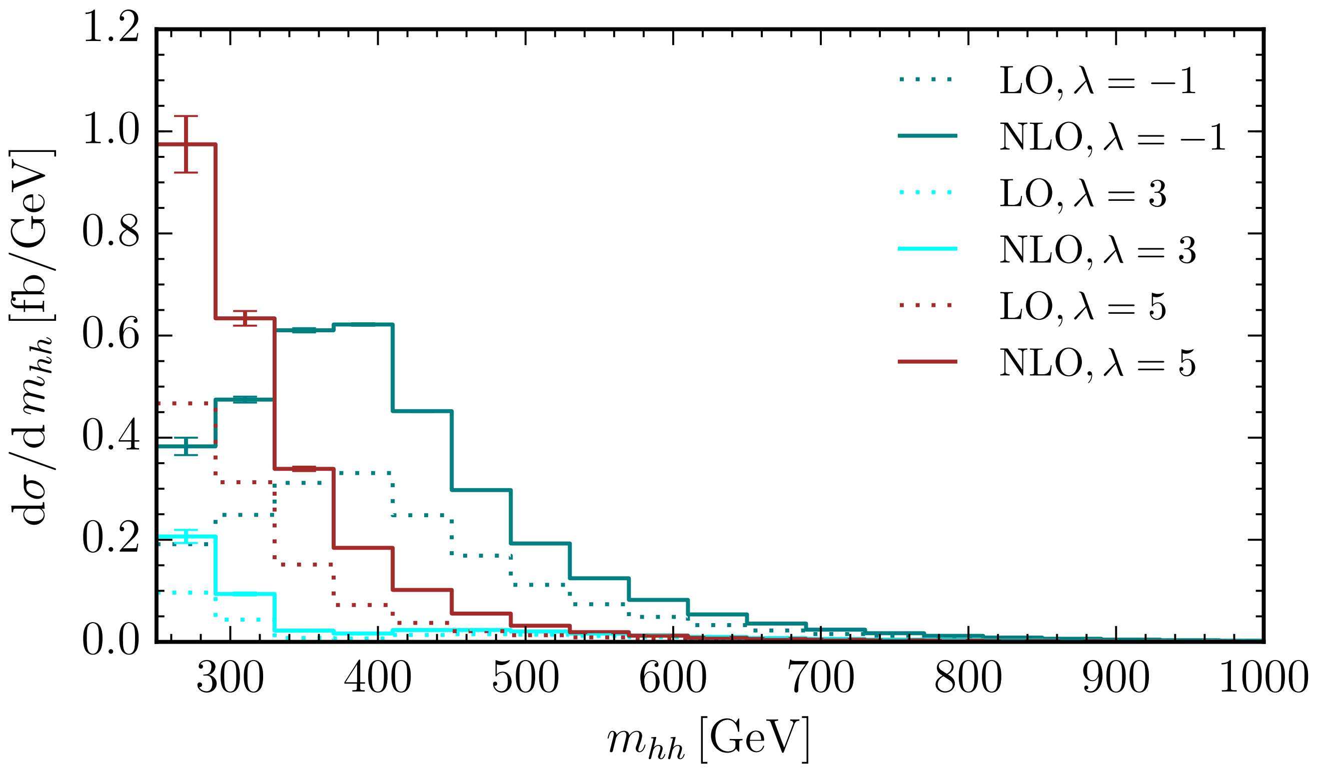
modified Higgs self-interactions





modified Higgs self-interactions





Calculation of σ^V

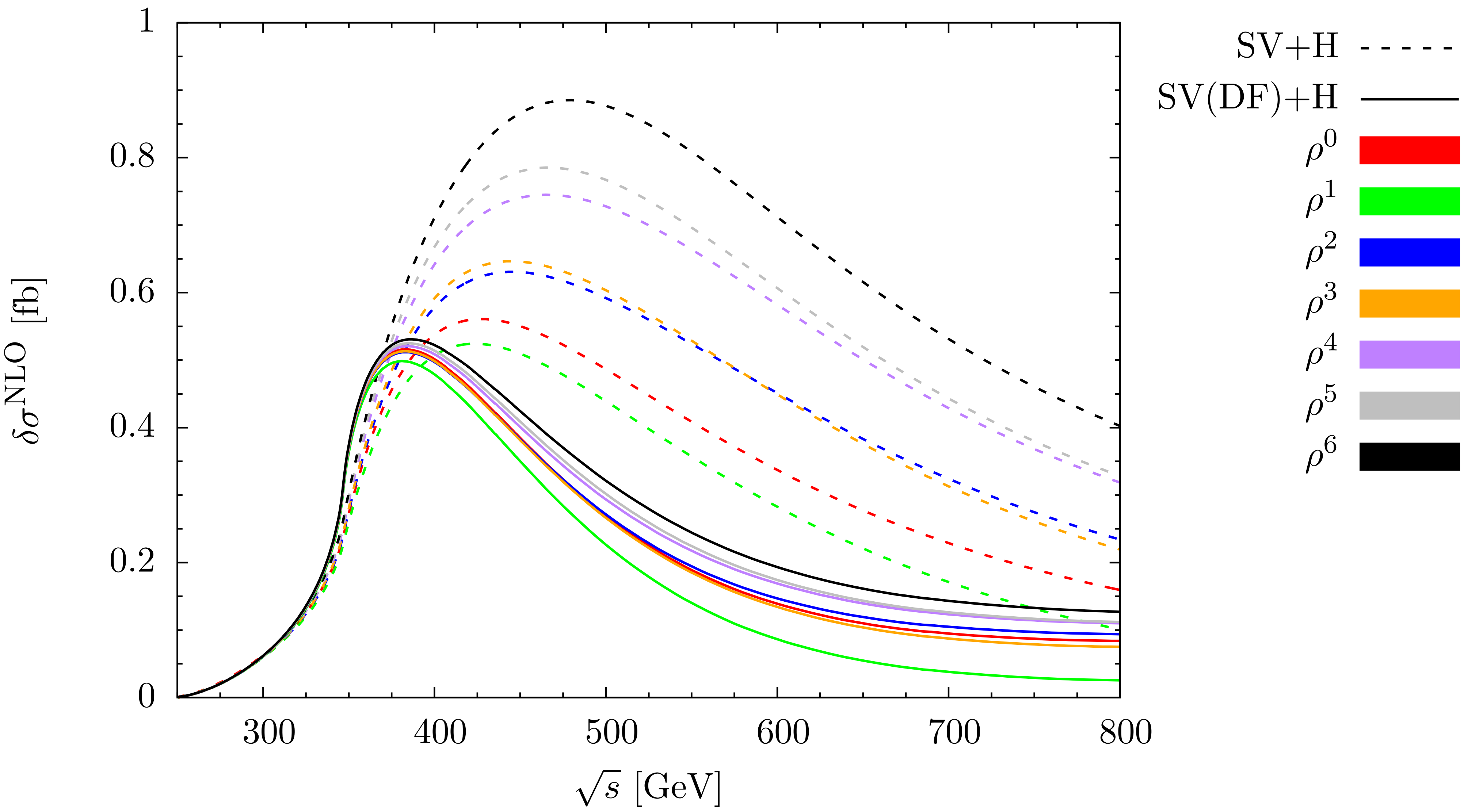
- Importance sampling:

LO calculation
↓
unweighted events
↓
sampling points virtual amplitude

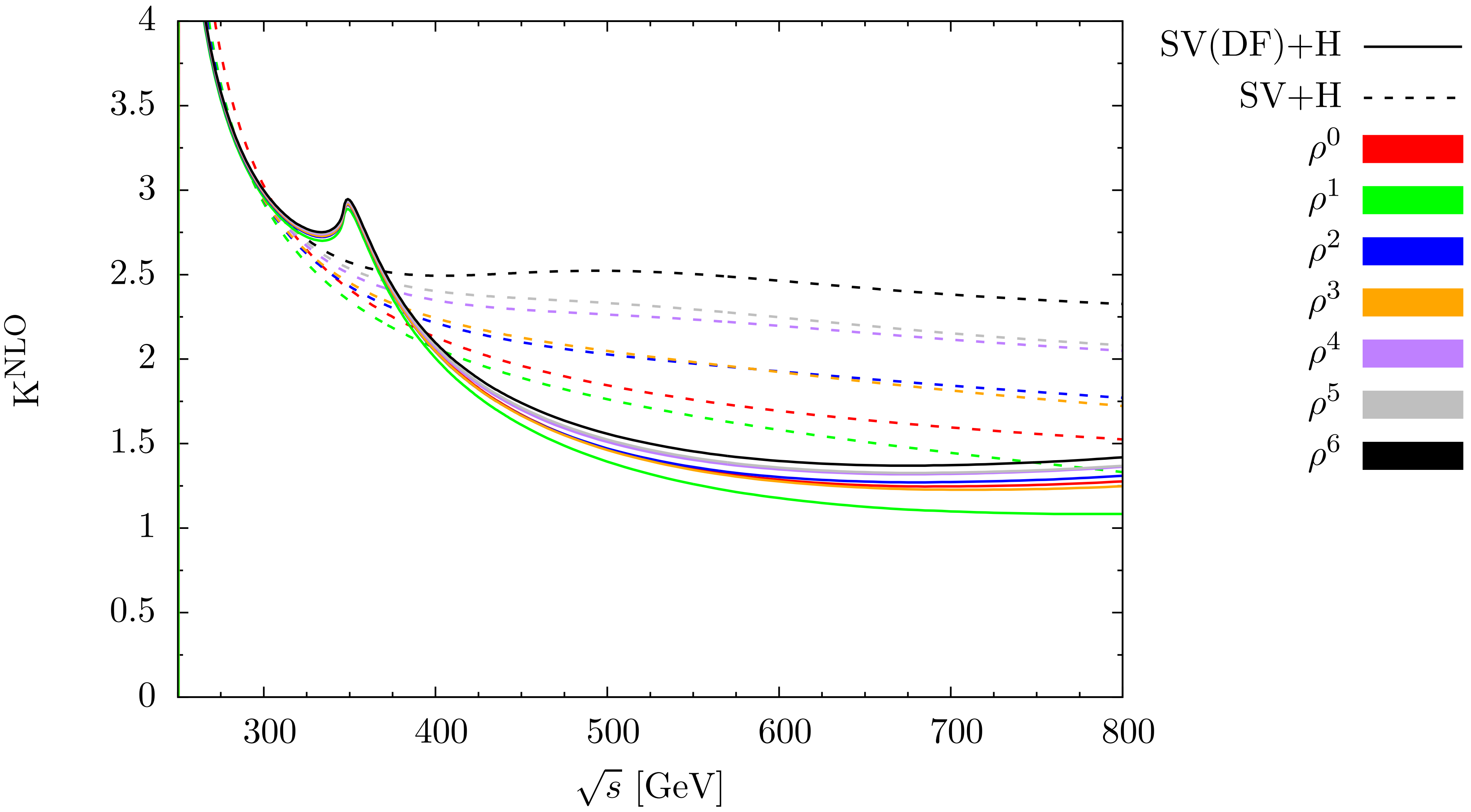
} σ^V with 2.5% accuracy using ~1000 phase-space points

- Accuracy goal:
  - 3% for form factor F_1
  - 5-20% for form factor F_2 (depending on F_2/F_1)

- Run time: (gpu time)
  - 80 min - 2 d (≙wall-clock limit)
  - median: 2h

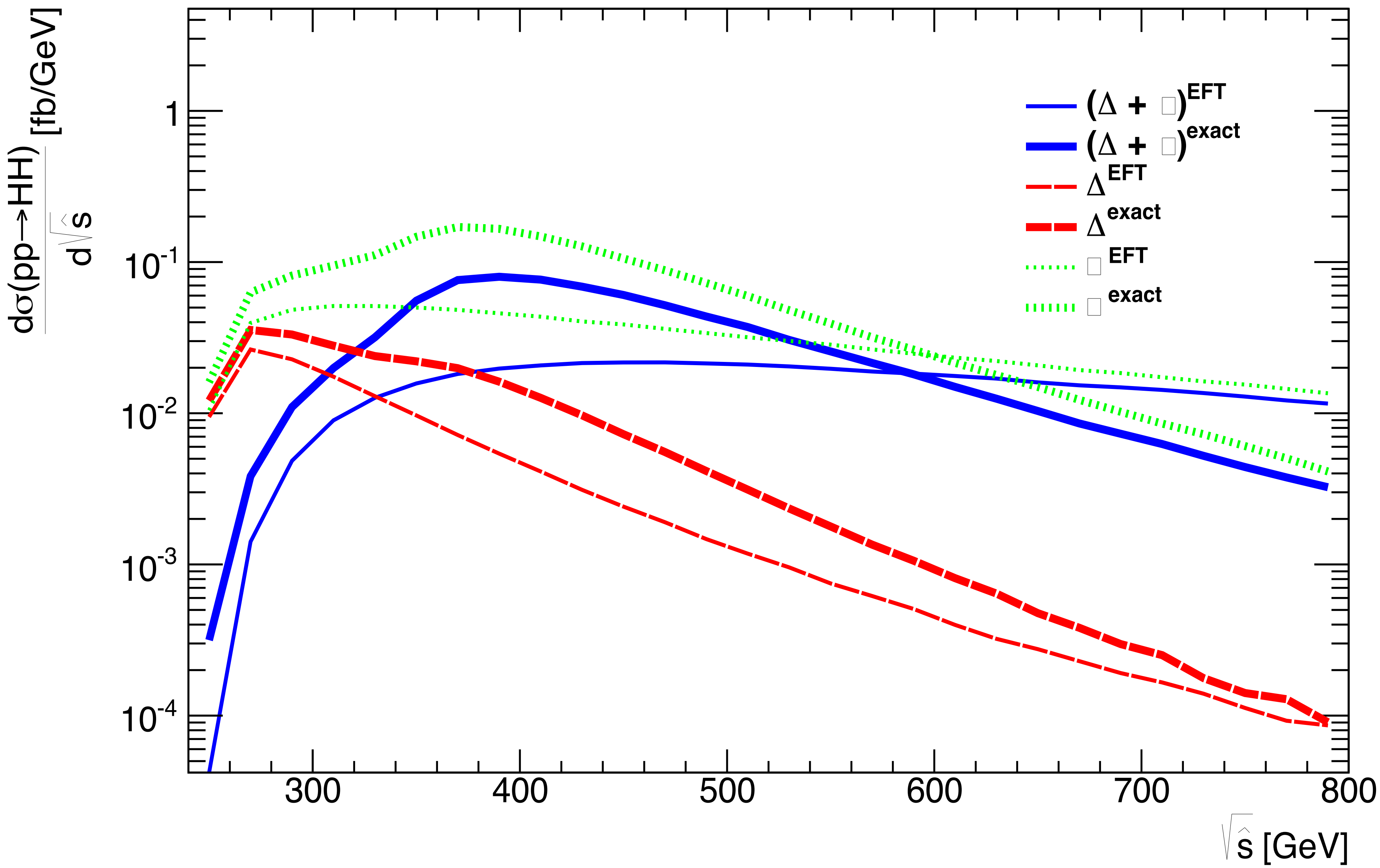


Grigo, Hoff, Steinhauser `15



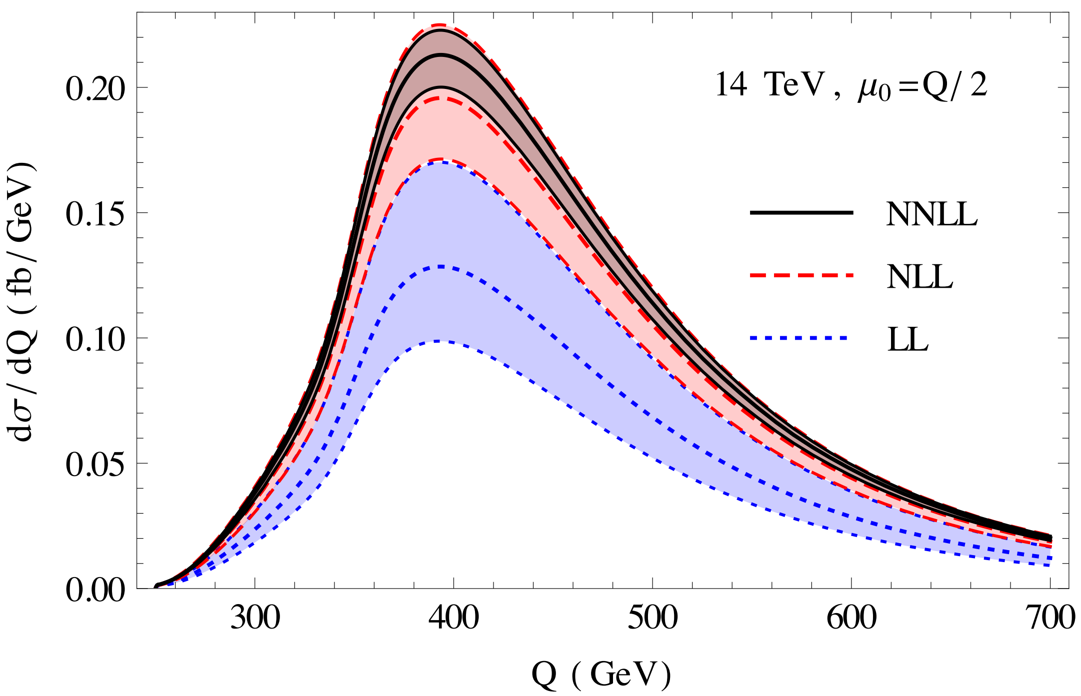
Grigo, Hoff, Steinhauser `15

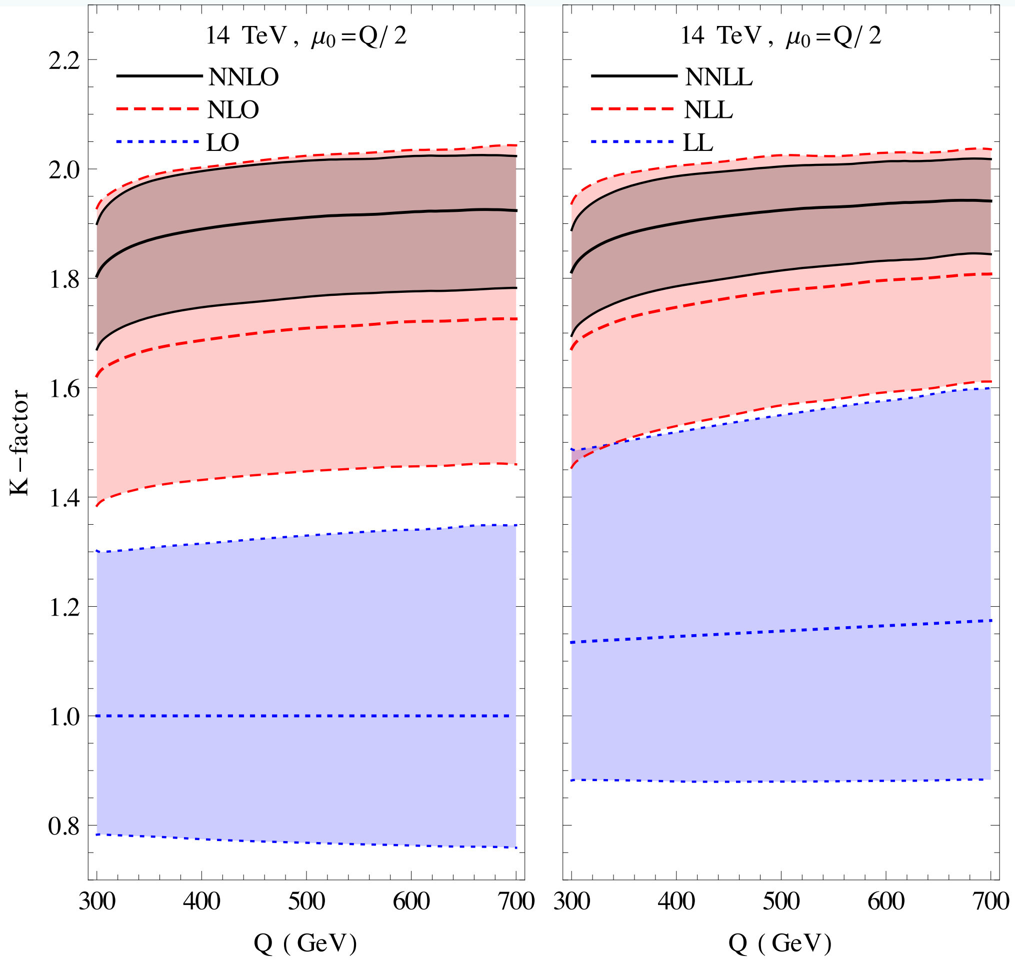
Differential Cross Section



Slawinska, van den Wollenberg, van Eijk, Bentvelsen `14

NNLO and NNLL results



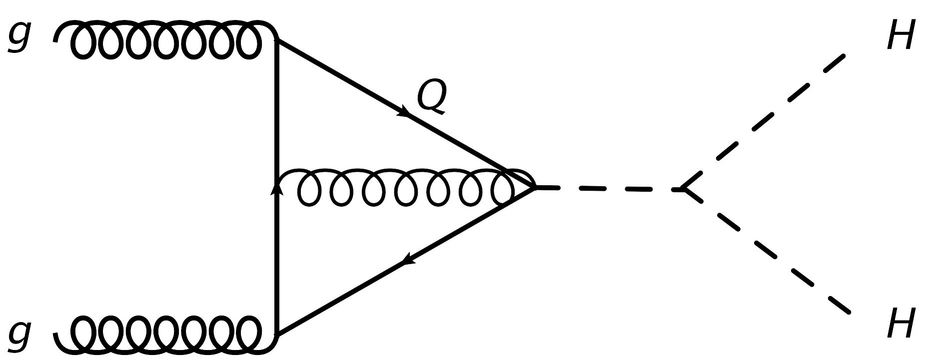


de Florian, Mazzitelli `15

$\mu_0 = Q$	NNLO (fb)	scale unc. (%)	NNLL (fb)	scale unc. (%)	PDF unc. (%)	PDF+α_S unc. (%)
8 TeV	9.92	$+9.3 - 10$	10.8	$+5.4 - 5.9$	$+5.6 - 6.0$	$+9.3 - 9.2$
13 TeV	34.3	$+8.3 - 8.9$	36.8	$+5.1 - 6.0$	$+4.0 - 4.3$	$+7.7 - 7.5$
14 TeV	40.9	$+8.2 - 8.8$	43.7	$+5.1 - 6.0$	$+3.8 - 4.0$	$+7.5 - 7.3$
33 TeV	247	$+7.1 - 7.4$	259	$+5.0 - 6.1$	$+2.2 - 2.8$	$+6.1 - 6.1$
100 TeV	1660	$+6.8 - 7.1$	1723	$+5.2 - 6.1$	$+2.1 - 3.0$	$+5.7 - 5.8$
$\mu_0 = Q/2$	NNLO (fb)	scale unc. (%)	NNLL (fb)	scale unc. (%)	PDF unc. (%)	PDF+α_S unc. (%)
8 TeV	10.8	$+5.7 - 8.5$	11.0	$+4.0 - 5.6$	$+5.8 - 6.1$	$+9.6 - 9.3$
13 TeV	37.2	$+5.5 - 7.6$	37.4	$+4.2 - 5.8$	$+4.1 - 4.3$	$+7.8 - 7.6$
14 TeV	44.2	$+5.5 - 7.6$	44.5	$+4.2 - 5.9$	$+3.9 - 4.1$	$+7.6 - 7.4$
33 TeV	264	$+5.3 - 6.6$	265	$+4.6 - 6.1$	$+2.4 - 2.7$	$+6.3 - 6.1$
100 TeV	1760	$+5.3 - 6.7$	1762	$+4.9 - 6.4$	$+2.2 - 3.1$	$+6.2 - 7.0$

Analytically known integrals

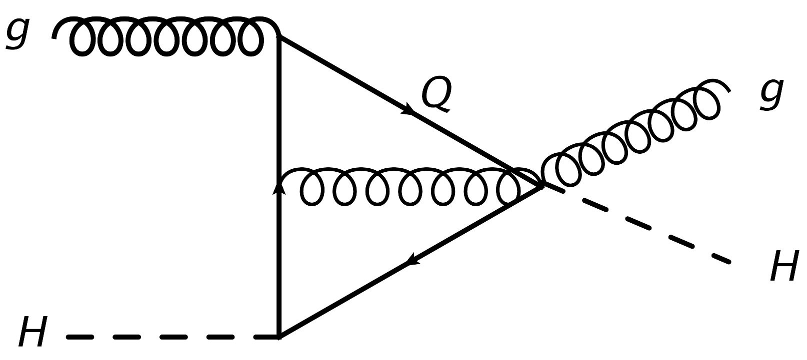
3-point, 1 off-shell leg



Spira, Djouadi et al. `93, `95
Bonciani, Mastrolia `03, `04
Anastasiou, Beerli et al. `06

$\rightarrow$HPLs

3-point, 2 off-shell leg



Gehrmann, Guns, Kara `15

$\rightarrow$ generalized HPLs, 12 letters

Amplitude Structure

Form factors are sums of rational functions multiplied by integrals that depend on ratios of the scales s, t, m_h^2, m_t^2 and the arbitrary scale M^2

$$
\begin{aligned}
F^{(L)} &= \sum_i \left[\left(\sum_j C_{i,j}^{(L)} \epsilon^j \right) \cdot \left(\sum_k I_{i,k}^{(L)} \epsilon^k \right) \right] \\
&= \quad \epsilon^{-2} \left[C_{1,-2}^{(L)} \cdot {\color{red} I_{1,0}^{(L)}} + C_{1,-1}^{(L)} \cdot I_{1,-1}^{(L)} + \ldots \right] \\
&\quad + \epsilon^{-1} \left[C_{1,-1}^{(L)} \cdot {\color{red} I_{1,0}^{(L)}} + \ldots \right] + \ldots
\end{aligned}
$$

compute only once

Additionally, all L-loop form factors are computed simultaneously without re-evaluating common integrals

Note: $gg \to HH$ is a loop induced process, real subtraction and mass factorisation contained in $\mathbf{I}, \mathbf{P}, \mathbf{K}$ operators (not discussed here)

Catani, Seymour 96

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Phase-Space Sampling

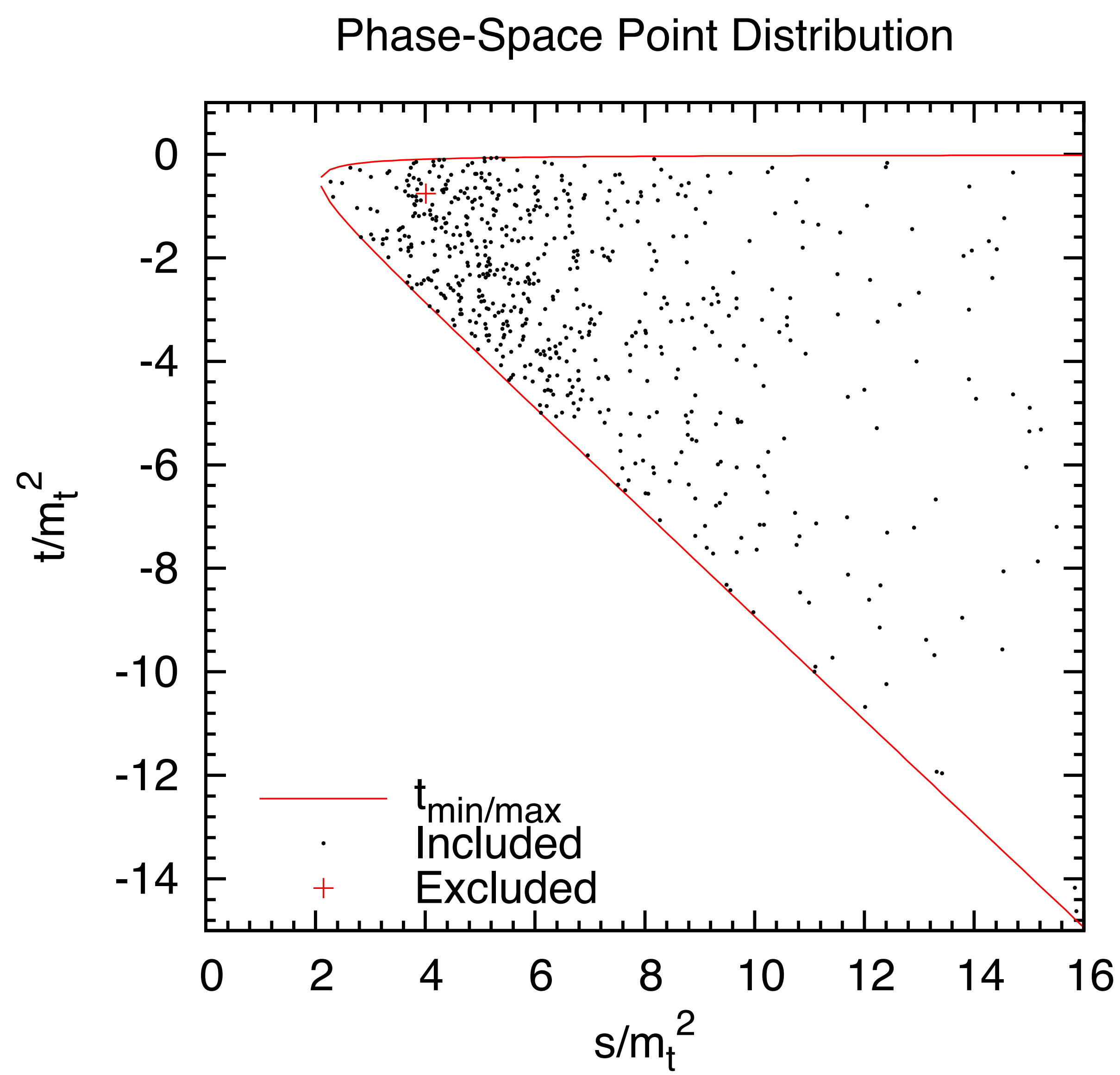
Phase-space implemented by hand
limited to 2-3 w/ 2 massive particles

Events for virtual:

1) VEGAS algorithm applied to LO matrix element $\mathcal{O}(100k)$ events computed

2) Using LO events unweighted events generated using accept/reject method $\mathcal{O}(30k)$ events remain

3) Randomly select 666 Events (woops), compute at NLO, exclude 1



Note: No grids used either for integrals or phase-space

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