HH: Top-quark Mass Dependence @ NLO

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Borowka, Greiner, Heinrich, Kerner, Schlenk, Schubert, Zirke

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arXiv:1608.04798 [hep-ph] (Submitted to JHEP)
Phys. Rev. Lett. 117 (2016) 012001, Erratum 079901

higgstools

Total Cross Section @ 14 TeV

	$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}$ (fb)	$\sigma_{\rm NNLO}$ (fb)
HEFT	$17.07^{+30.9\%}_{-22.2\%}$	$31.93^{+17.6\%}_{-15.2\%}$	$37.52^{+5.2\%}_{-7.6\%}$
B.I. HEFT	$19.85^{+27.6\%}_{-20.5\%}$	$38.32^{+18.1\%}_{-14.9\%}$	$43.63^{+5.2\%}_{-7.6\%}*$
FTapprox	$19.85^{+27.6\%}_{-20.5\%}$	$34.26^{+14.7\%}_{-13.2\%}$	–
Full Theory	$19.85^{+27.6\%}_{-20.5\%}$	$32.91^{+13.6\%}_{-12.6\%}$	–
N.I. HEFT	–	$32.91^{+13.6\%}_{-12.6\%}$	$38.67^{+5.2\%}_{-7.6\%}*$

PDF4LHC15_nlo_30_pdfas

$m_H = 125$ GeV

$m_T = 173$ GeV

Uncertainty:

$\mu_R = \mu_F = \frac{m_{HH}}{2}$

$\mu \in \left[\frac{\mu_0}{2}, 2\mu_0\right]$ (7 – point)

* re-weighted on total cross-section level

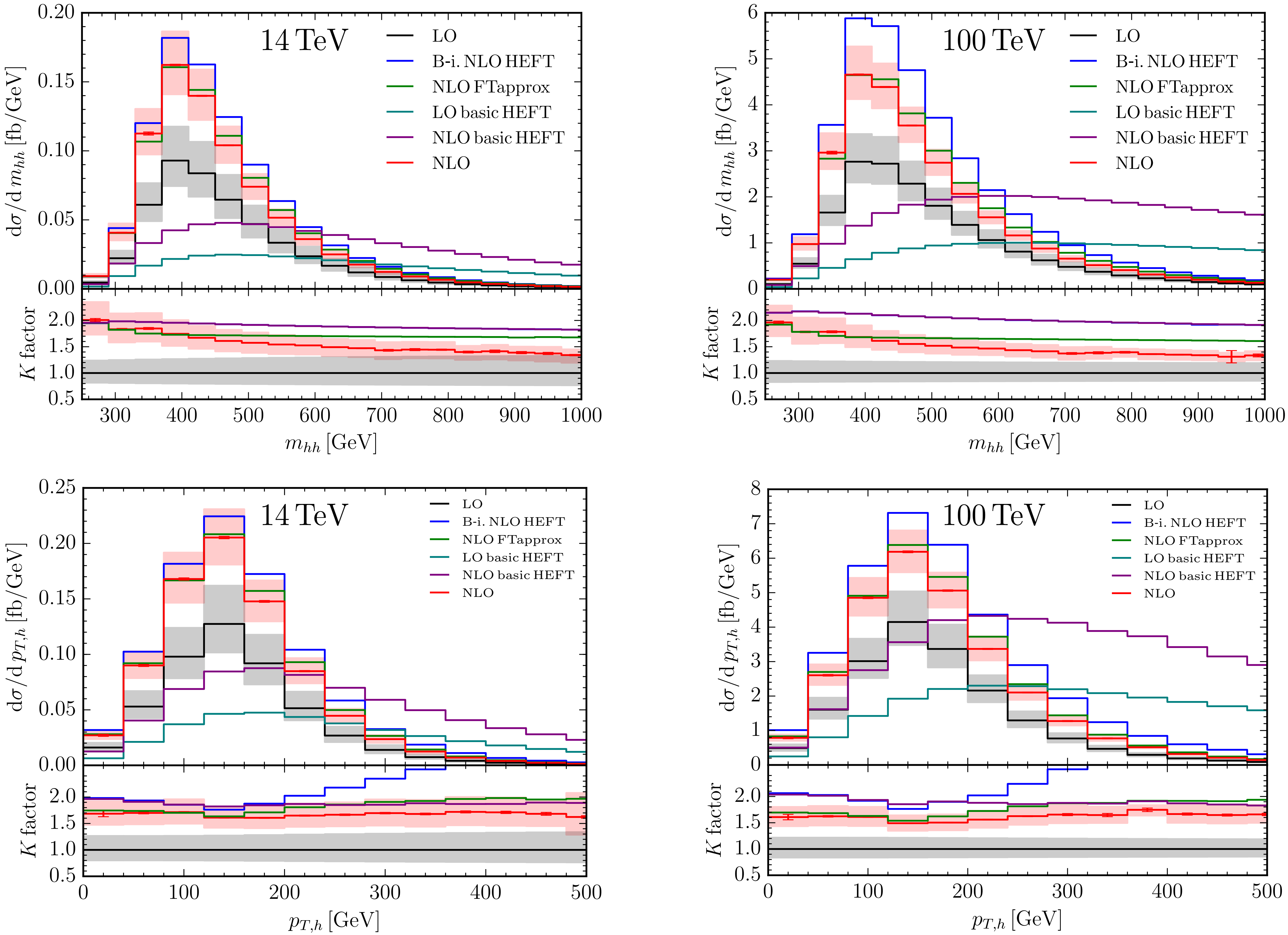
de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16;
Maltoni, Vryonidou, Zaro 14 (recalculated by us); Borowka, Greiner, Heinrich, Kerner, Schlenk, Schubert, Zirke 16;
Dawson, Dittmaier, Spira 98 (recalculated by us); Glover, van der Bij 88 (recalculated by us)

Comparison to Full Theory

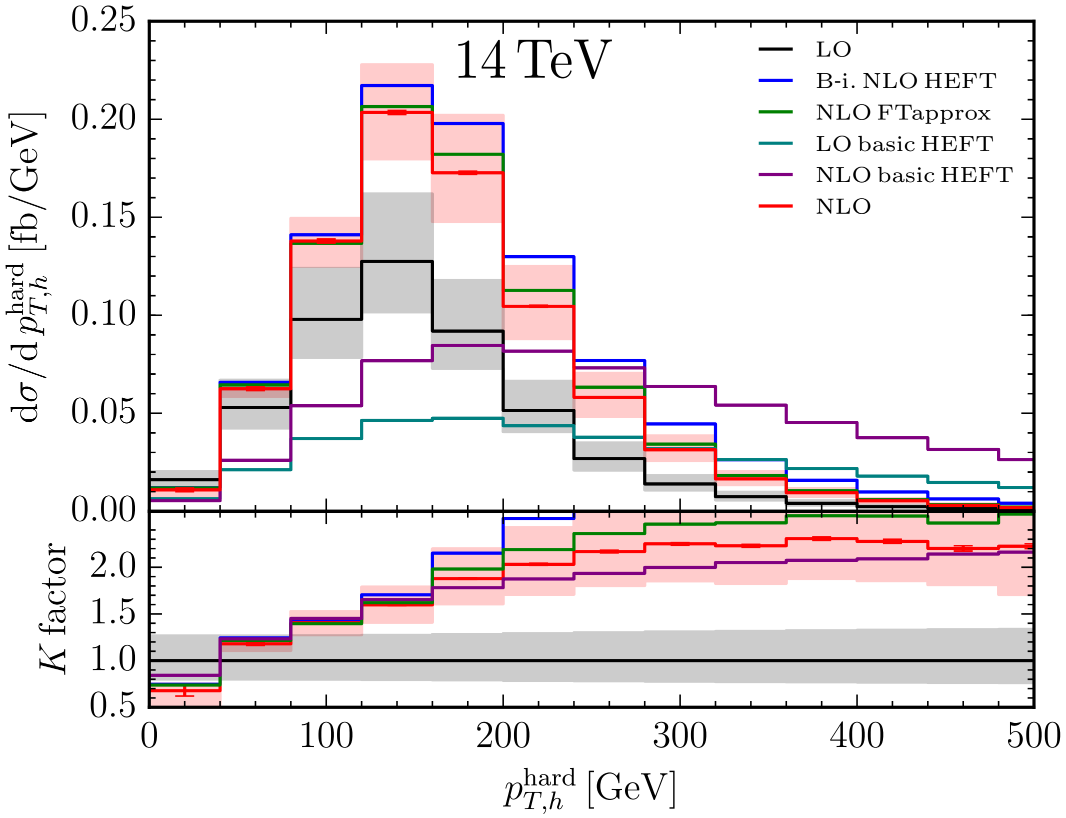
	$\Delta\sigma^{\rm Full}_{\rm LO}$	$\Delta\sigma^{\rm Full}_{\rm NLO}$
HEFT	-14%	-3.0%
B.I. HEFT	0%	$+16\%$
FTapprox	0%	$+4.1\%$

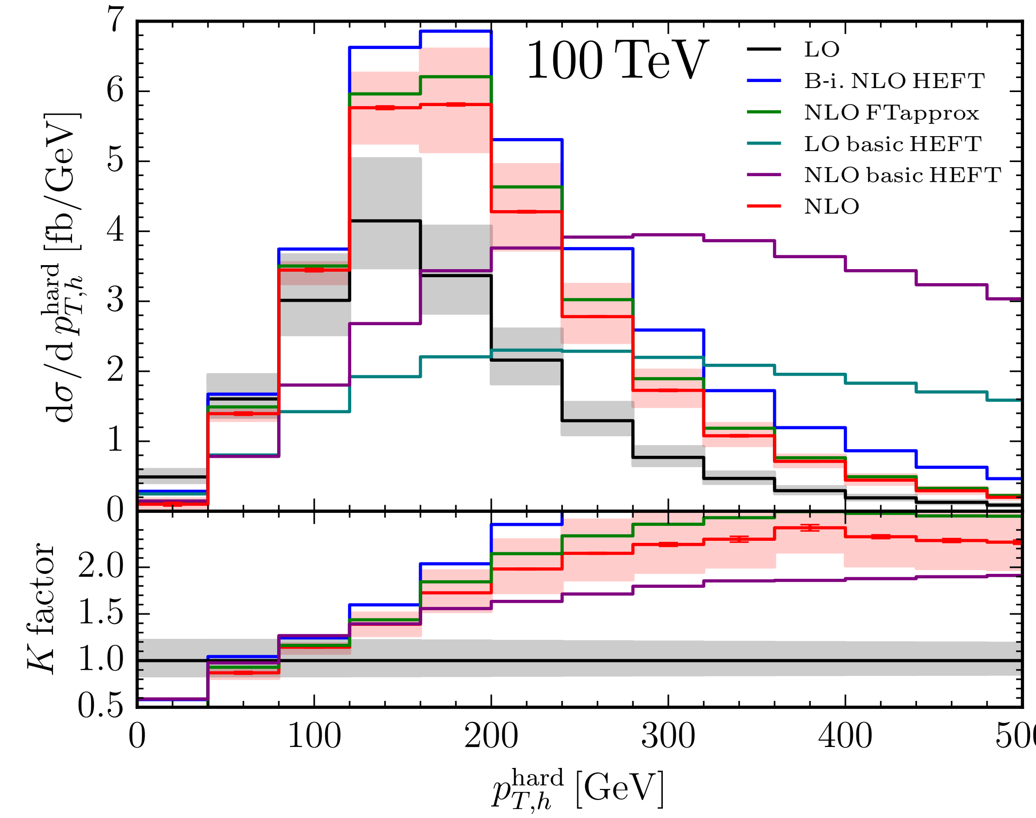
Can do a similar exercise @ 100 TeV, differences typically larger

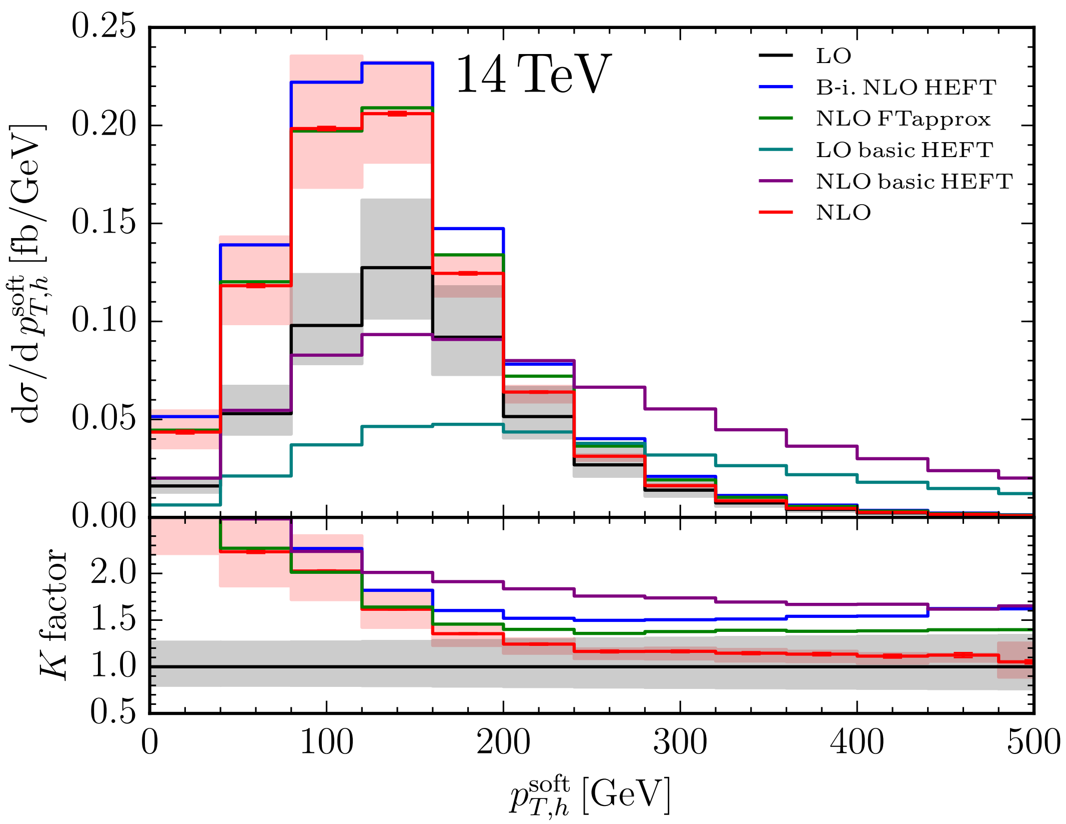
MHH & PT

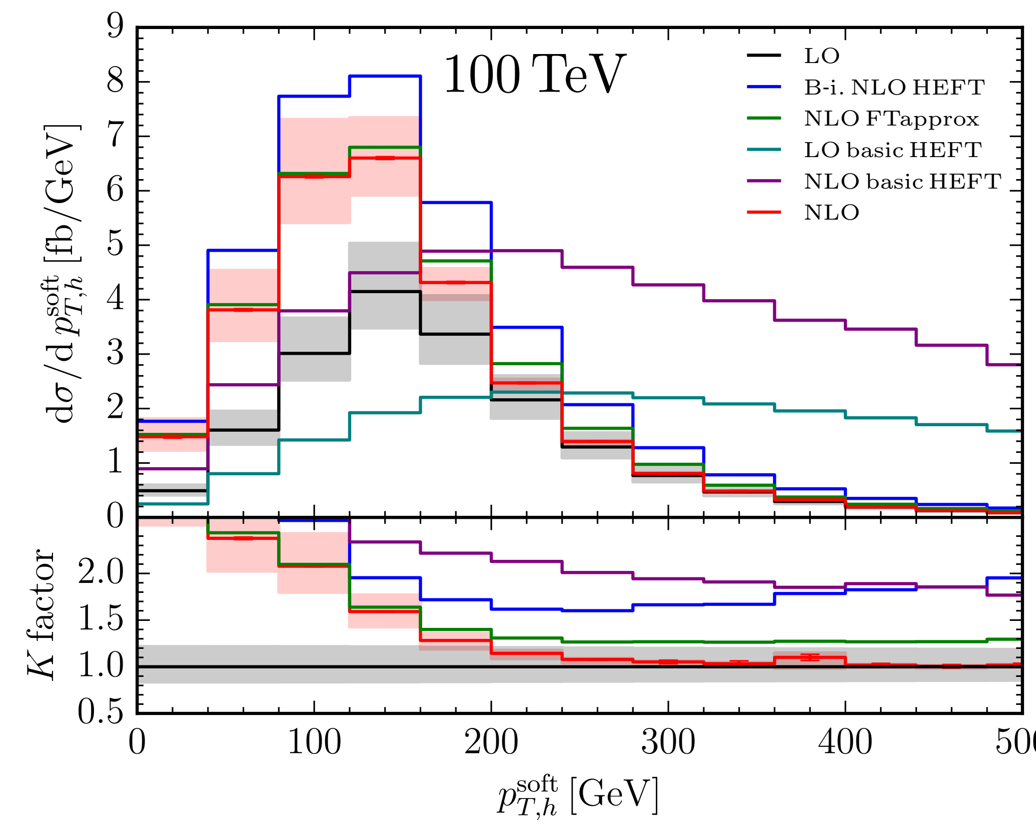

14 TeV
100 TeV
LO
B-i. NLO HEFT
NLO FTapprox
LO basic HEFT
NLO basic HEFT
NLO
dσ/d m_{hh} [fb/GeV]
K factor
m_{hh} [GeV]
dσ/d $p_{T,h}$ [fb/GeV]
$p_{T,h}$ [GeV]

PT Hard & PT Soft

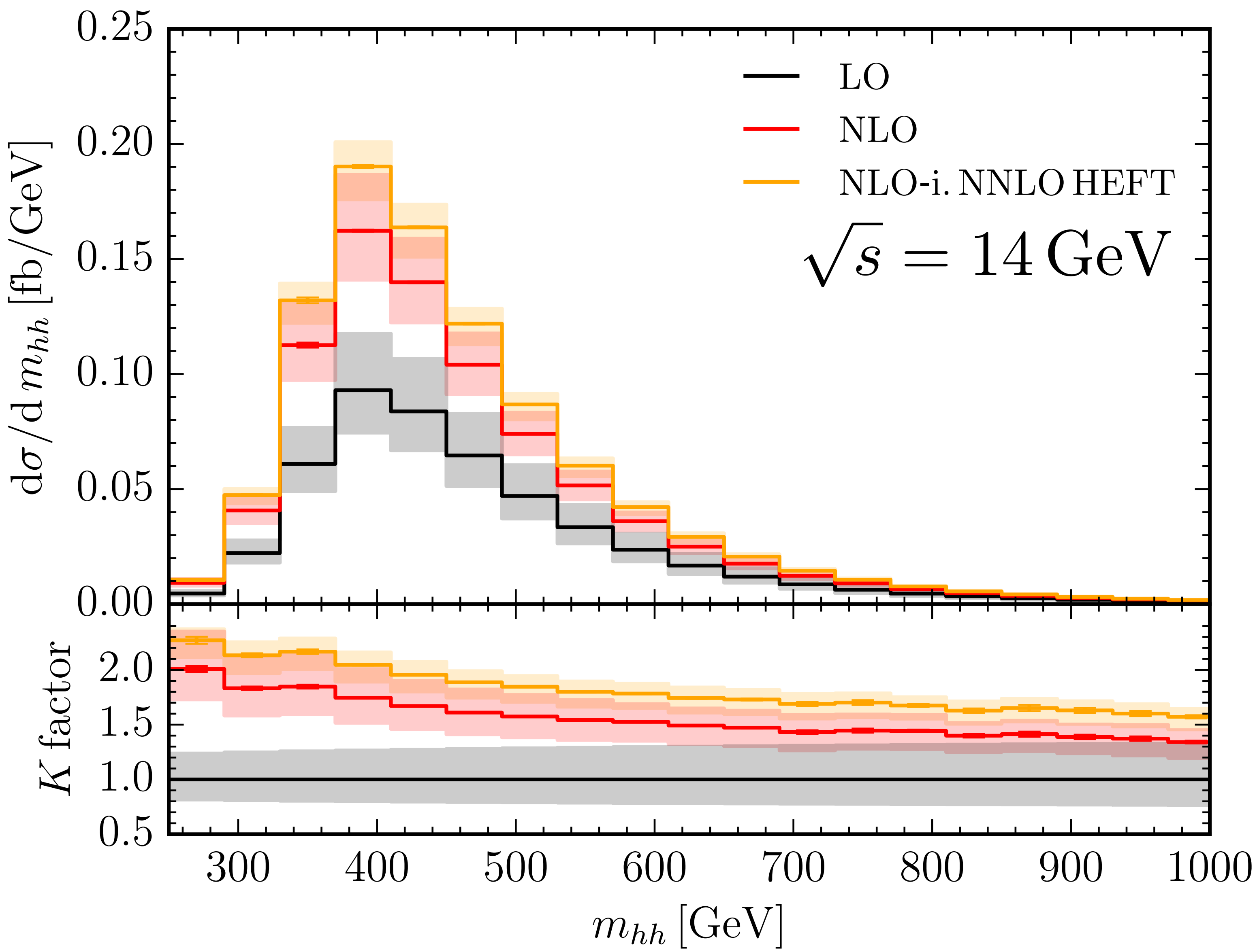








NLO Improved HEFT



First attempt to combine full NLO

Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16

+

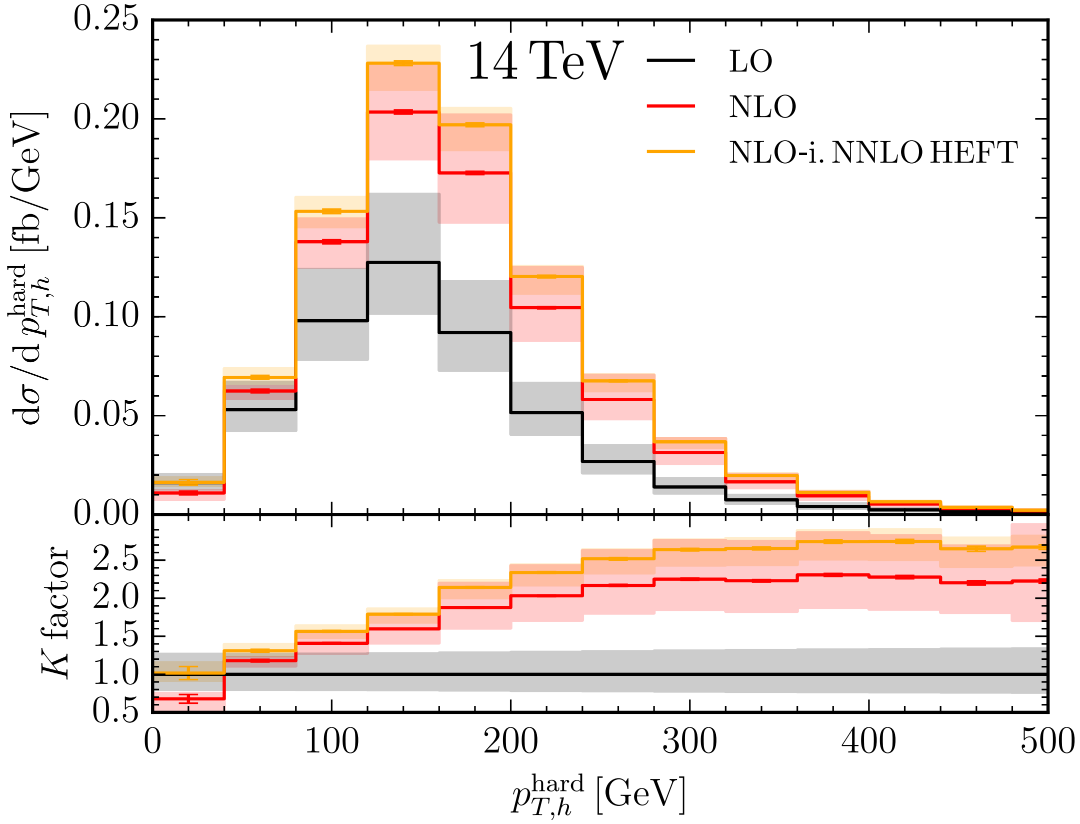
NNLO HEFT (Differential)

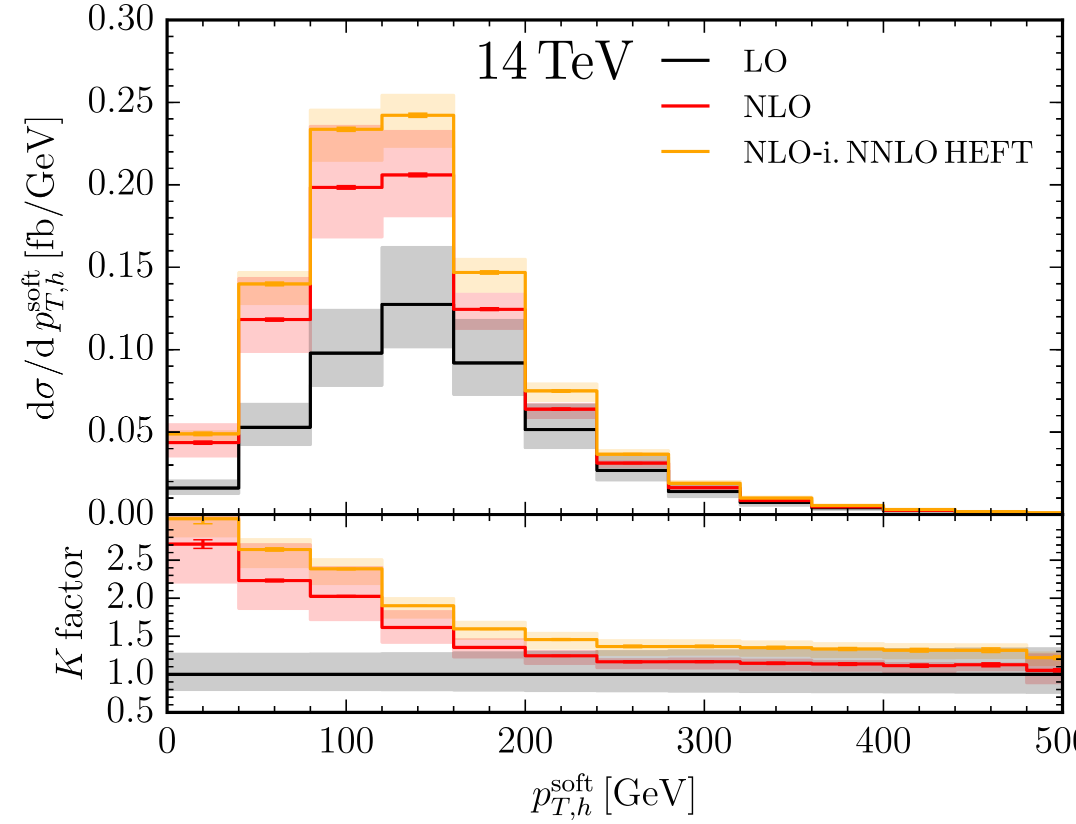
de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16

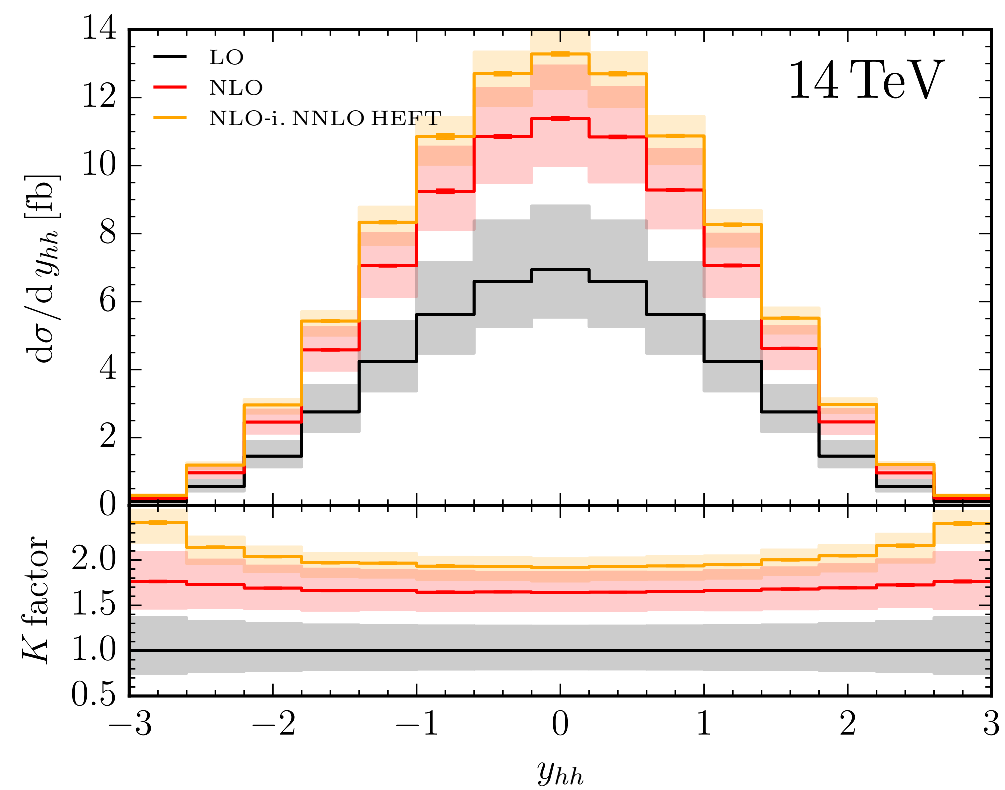
$$\frac{\mathrm{d}\sigma^{\mathrm{approx.}}}{\mathrm{d}m_{hh}} \equiv \frac{\mathrm{d}\sigma_{\mathrm{NLO}}}{\mathrm{d}m_{hh}} \times \frac{\mathrm{d}\sigma^{\mathrm{HEFT}}_{\mathrm{NNLO}}/\mathrm{d}m_{hh}}{\mathrm{d}\sigma^{\mathrm{HEFT}}_{\mathrm{NLO}}/\mathrm{d}m_{hh}}$$

Bin-by-bin rescaling of NLO by NNLO HEFT K-factor

NLO Improved HEFT







Open Questions/ Projects

How to communicate our result

1D Distributions (done), BHS nTuples (in progress), Grid (?)

Improve N.I. HEFT

Fully differential/improved re-weighting (agreed w/ Grazzini et al.)

Parton Shower

POWHEG (in progress w/ Luisoni, may need grid), Other MC (?)

EFT/MSSM/2HDM/…

EFT (?), MSSM & 2HDM (no concrete plans)

Result Cross-check & Refinement

Recalculation by other groups (in progress?)

Recalculate with top-quark width and $m_T \neq 173\,\mathrm{GeV}$, $m_H \neq 125\,\mathrm{GeV}$ (?)

Thank you for listening!

Backup

YR4 Numbers

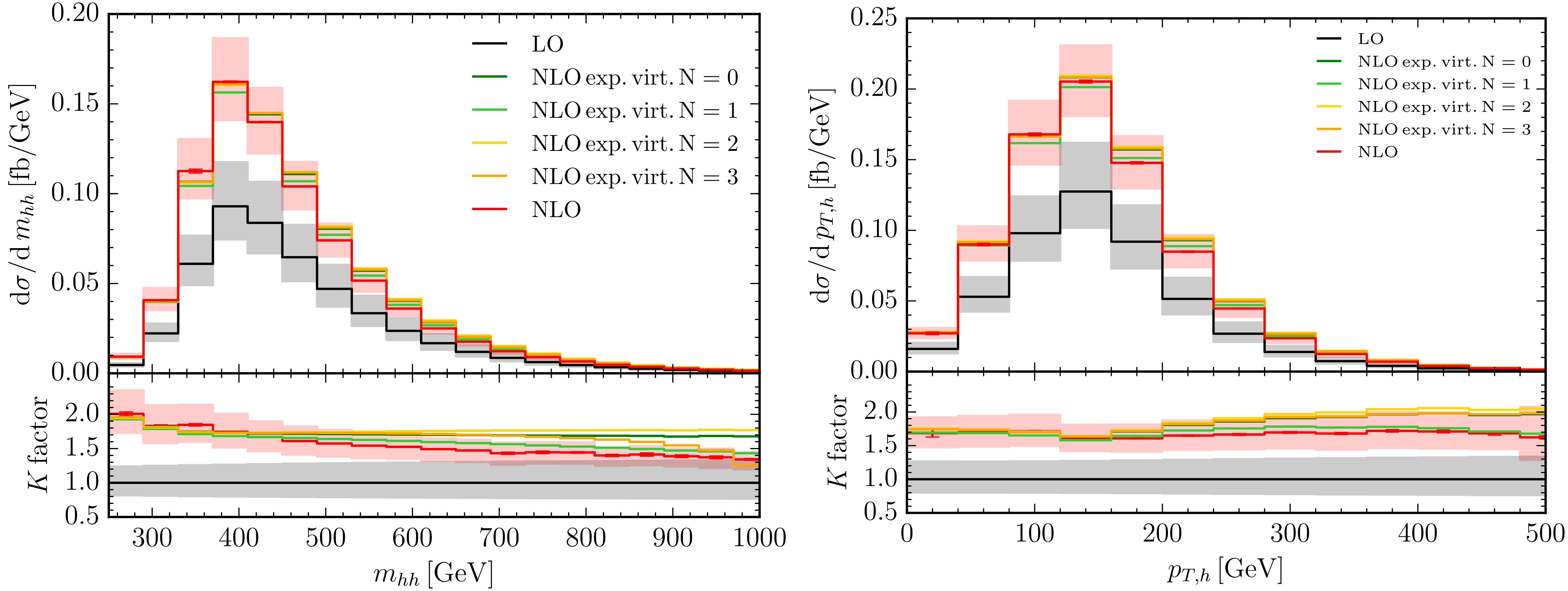
YR4 Prescription:

$$\sigma(gg \to hh)^{exact}_{NLO} = \sigma(gg \to hh)^{HEFT}_{NLO}(1+\delta_t)$$

$$\sigma'_{NNLL} = \sigma_{NNLL} + \delta_t \sigma^{HEFT}_{NLO}$$

$\sqrt{s}$	σ'_{NNLL} (fb)	Scale Unc. (%)	PDF Unc. (%)	α_S Unc. (%)
7 TeV	7.078	$+4.0-5.7$	± 3.4	± 2.8
8 TeV	10.16	$+4.1-5.7$	± 3.1	± 2.6
13 TeV	33.53	$+4.3-6.0$	± 2.1	± 2.3
14 TeV	39.64	$+4.4-6.0$	± 2.1	± 2.2

Expansion in Top-quark Mass



(Zirke) Virtuals: asymptotic expansion in $1/m_T^2$ (`q2e/exp`+ `Reduze` + `matad`)

Harlander, Seidensticker, Steinhauser 97,99; von Manteuffel, Studerus 12; Steinhauser 00

Grigo, Hoff, Melnikov, Steinhauser 13; Grigo, Hoff 14;
Grigo, Hoff, Steinhauser 15

Low m_{hh} **:** Expansion seems ok in first bin $\sqrt{\hat{s}} < 2m_T$

Total XS: $\mathcal{O}(5\%)$ differences between first few terms of expansion

Top-quark Width Effects

Total XS @ LO: reduced by 2% by including top-quark width

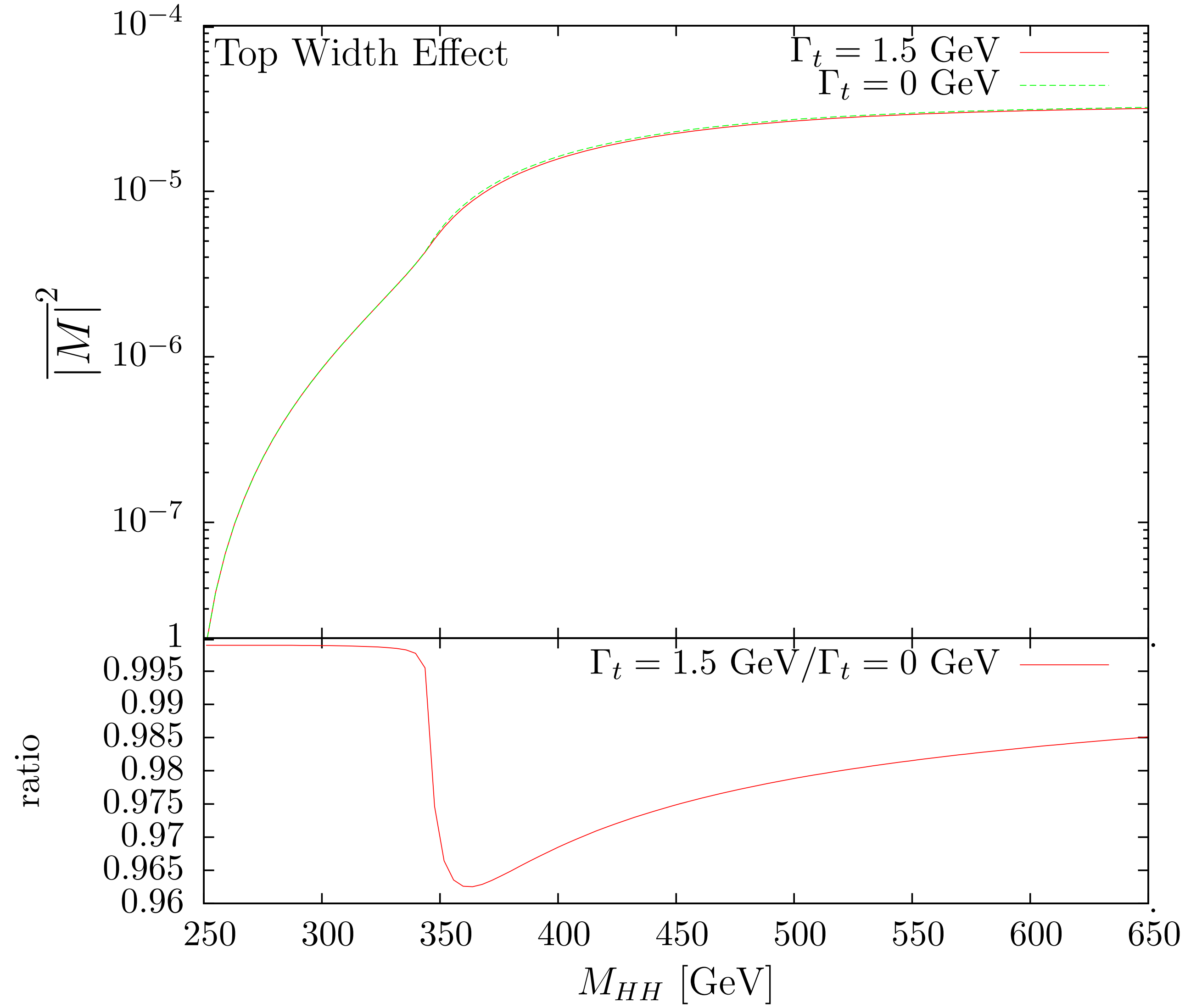


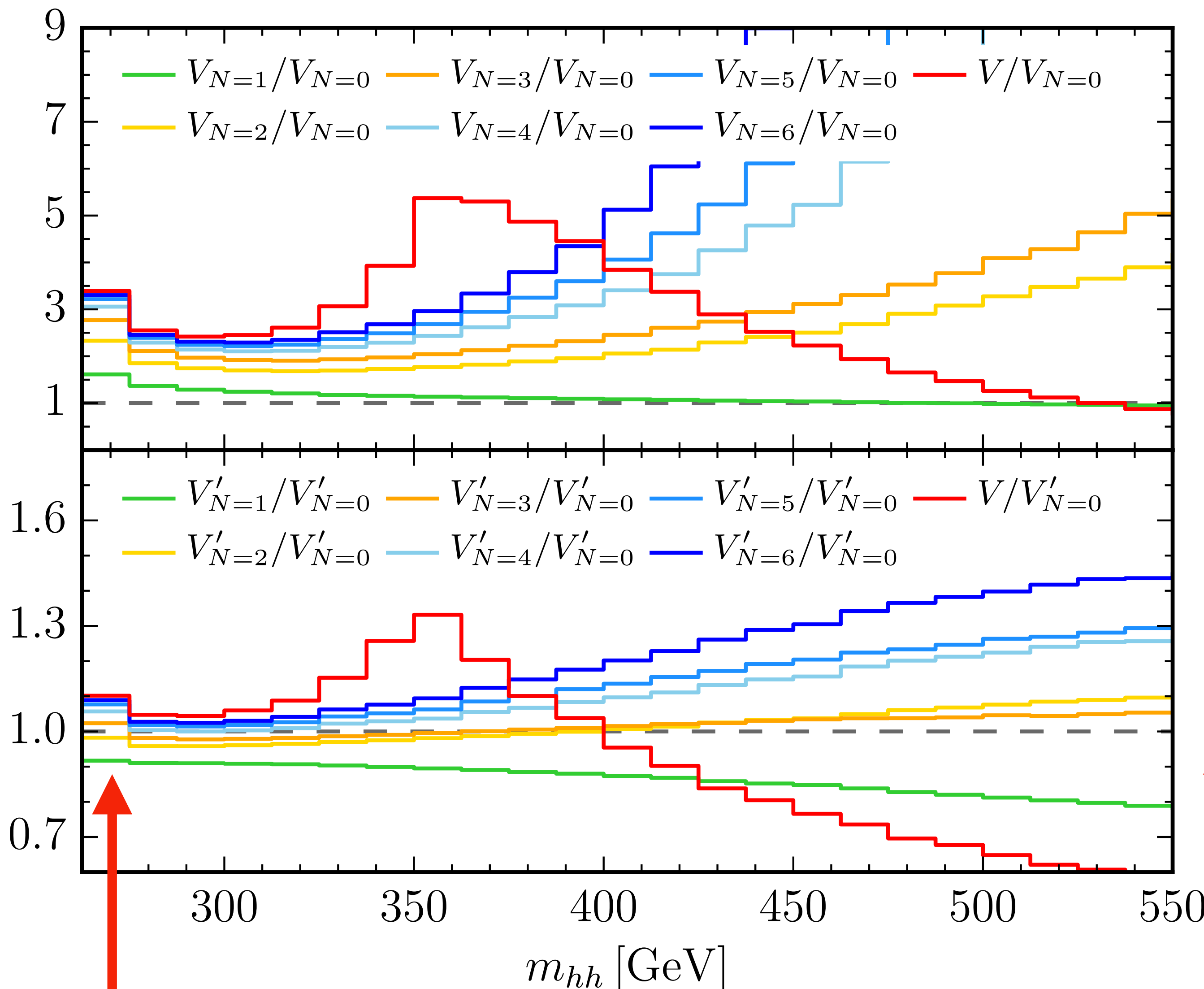
Figure 3: Top width effect on the one-loop (Born) matrix element squared for $gg \to HH$. The results for $\Gamma_t = 0$ and 1.5 GeV are shown along with the corresponding ratio.

Maltoni, Vryonidou, Zaro 14

Comparison to Expansion

Can compare just virtual ME to expansion:

$$d\hat{\sigma}_N = \sum_{\rho=0}^{N} d\hat{\sigma}^{(\rho)} \left(\frac{\Lambda}{m_t}\right)^{2\rho} \qquad \Lambda \in \left\{\sqrt{\hat{s}}, \sqrt{\hat{t}}, \sqrt{\hat{u}}, m_h\right\}$$



$$V_N = \left(d\hat{\sigma}_N^V + d\hat{\sigma}_N^{LO} \otimes \mathbf{I}\right)$$

$$V'_N = V_N \frac{d\hat{\sigma}^{LO}}{d\hat{\sigma}_N^{LO}}$$

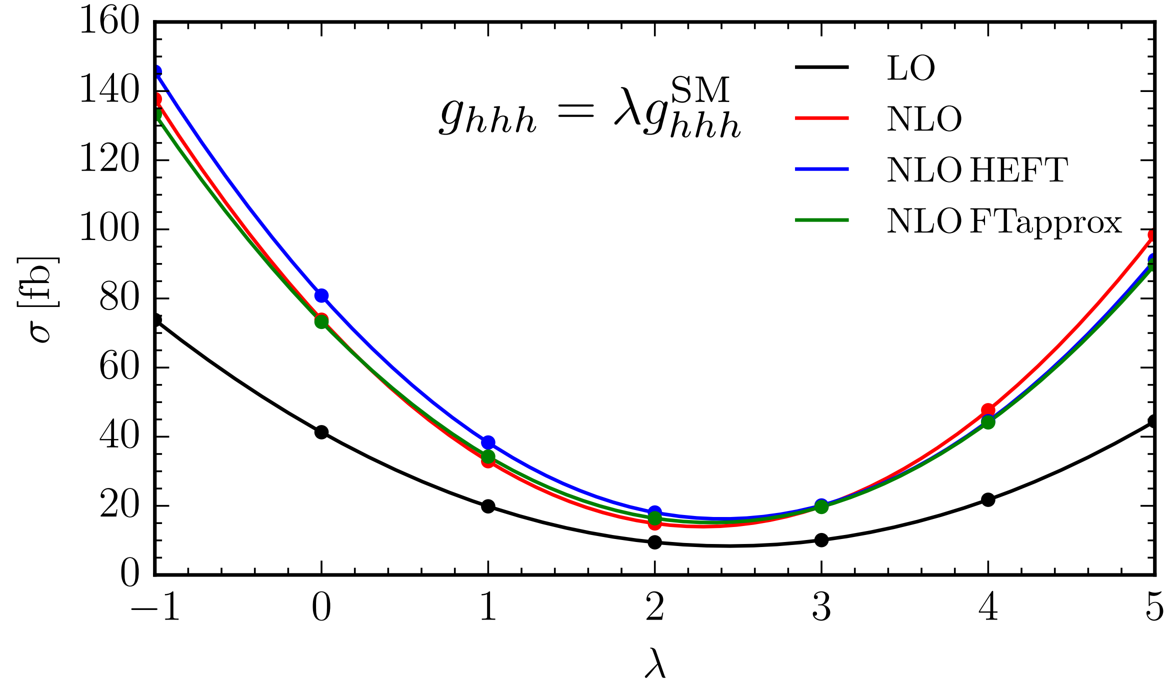
Rescaled better but does not describe full above threshold

Expansion converges on full $\sqrt{\hat{s}} < 2m_T$

$V_{N\geq 4}$ thanks to J. Hoff

Grigo, Hoff, Steinhauser 15

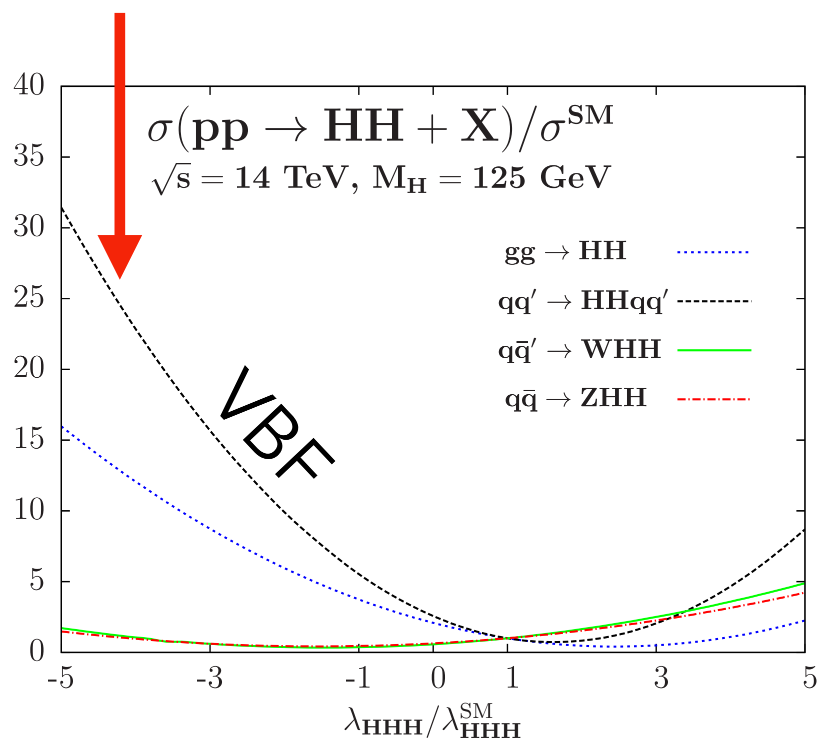
Triple-Higgs Coupling Sensitivity



SM: Destructive interference between g_{hhh} and y_T^2 contrib.

Distributions: can help to distinguish between λ values

VBF: More sensitive (but small XS)



Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, Spira 12

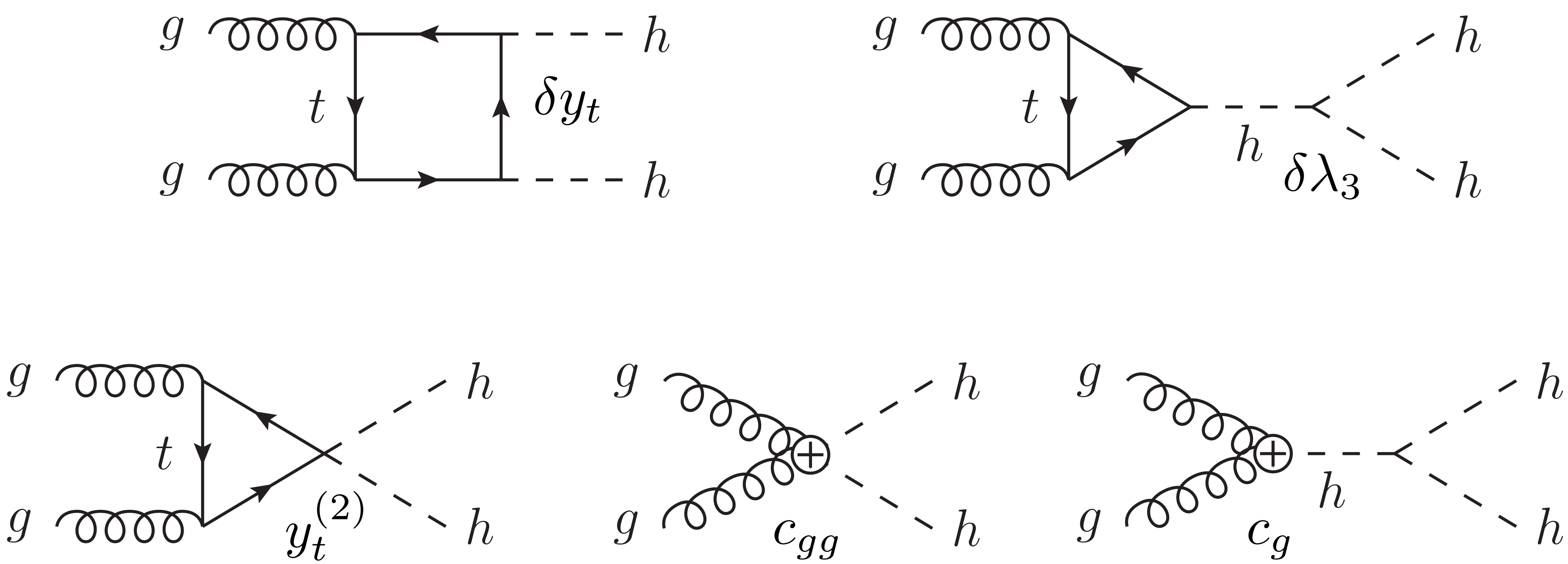
Can increase sensitivity to HH:

- $p_{T,jet}^{min}$ cut
- $\sigma(gg \to HH)/\sigma(gg \to H)$
- Multivariate $b\bar{b}b\bar{b}$

Barr, Dolan, Englert, Ferreira de Lima, Spannowsky 15; Mangano et al. 16; Goertz, Papaefstathiou, Yang, Zurita 13; Behr, Bortoletto, Frost, Hartland, Issever, Rojo 15

BSM EFT

Parametrise **non-resonant** new physics with EFT (5 parameters):



Azatov, Contino, Panico, Son 15;
(Cluster analysis) Dall'Osso, Dorigo, Gottardo, Oliveira, Tosi, Goertz 15;
\+ Carvalho, Manzano, Dorigo, Gouzevich 16;
(B.I. HEFT) Gröber, Mühlleitner, Spira, Streicher 15;

← 12 representative ``clusters''

Just varying λ: one ``direction'' in EFT parameter space

Resonant Production

YR4 details two benchmark scenarios for initial study

Higgs Singlet Model

$$\Phi^T = (\phi^+, \tilde{\phi}_0 = \frac{\phi_0 + v}{\sqrt{s}})$$

$$S = \frac{s + \langle S \rangle}{\sqrt{2}}$$

$$V = -m^2 \Phi^\dagger \Phi - \mu^2 S^2 + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 S^4 + \lambda_3 \Phi^\dagger \Phi S^2$$

Large $\mathcal{O}(20 - 30\%)$ $H \to hh$

Cross-section can be enhanced by up to 10-20x

2 Higgs Doublet Model (2HDM)

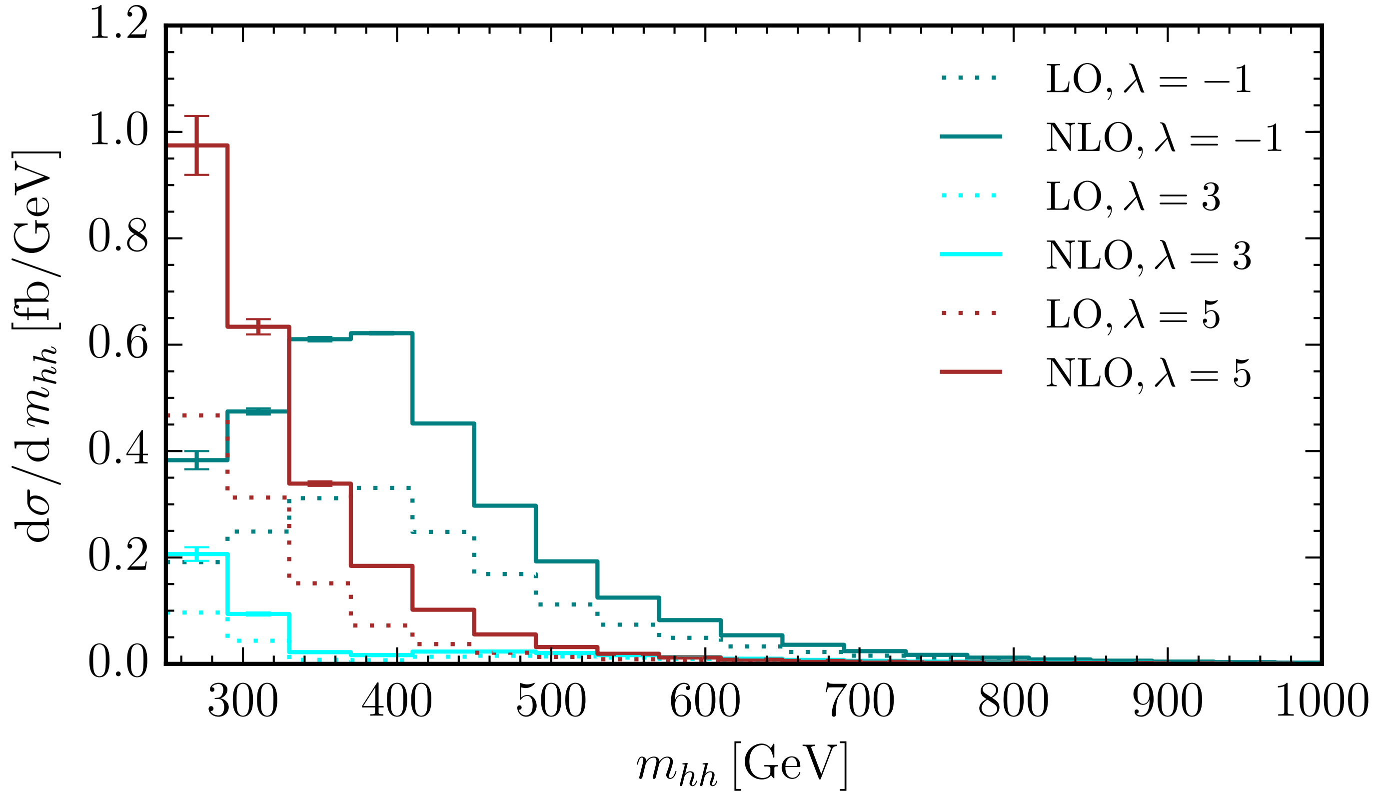
2 neutral scalars → h^0, H^0, A, H^+, H^- ← 2 charged Higgs

↑ Pseudoscalar

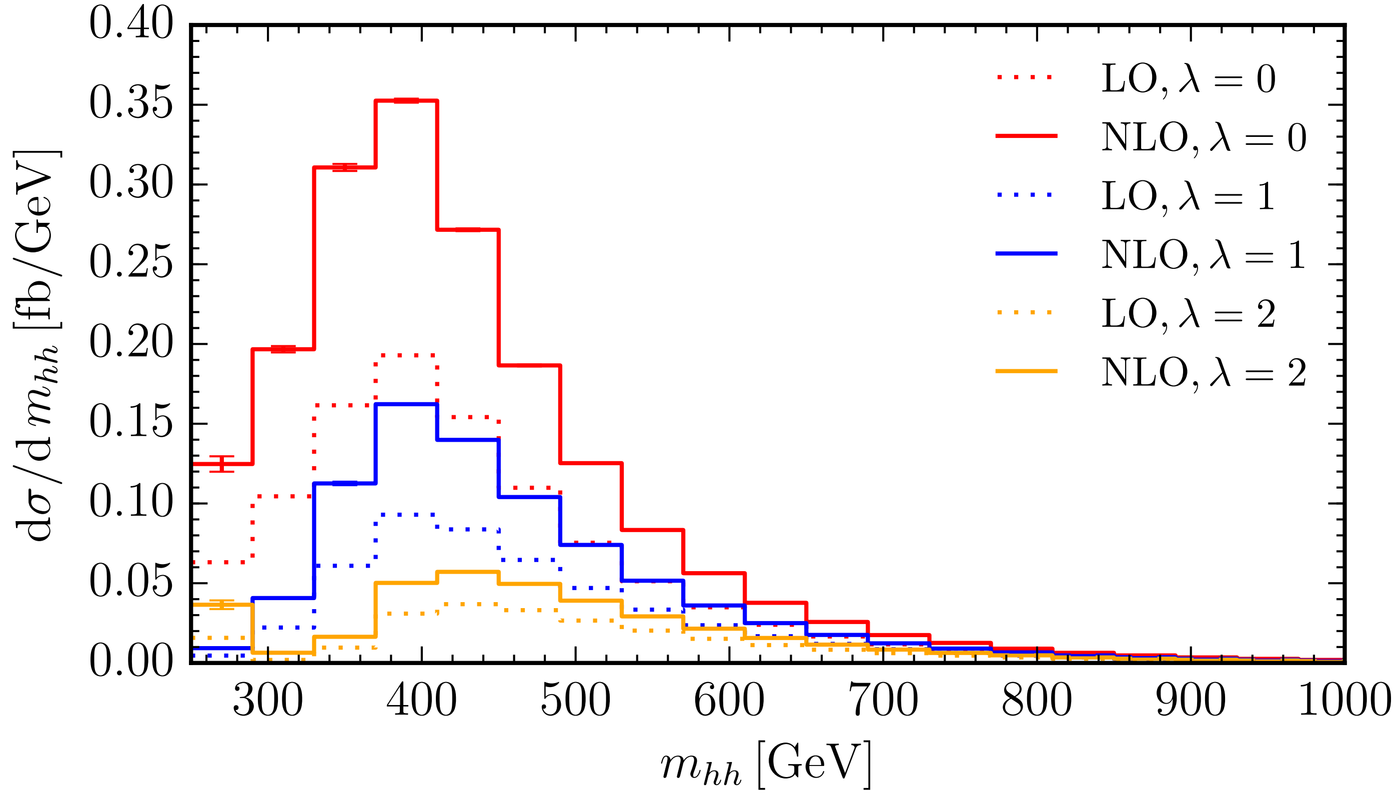
Behaviour strongly depends on the scenario

Hespel, López-Val, Vryonidou 14

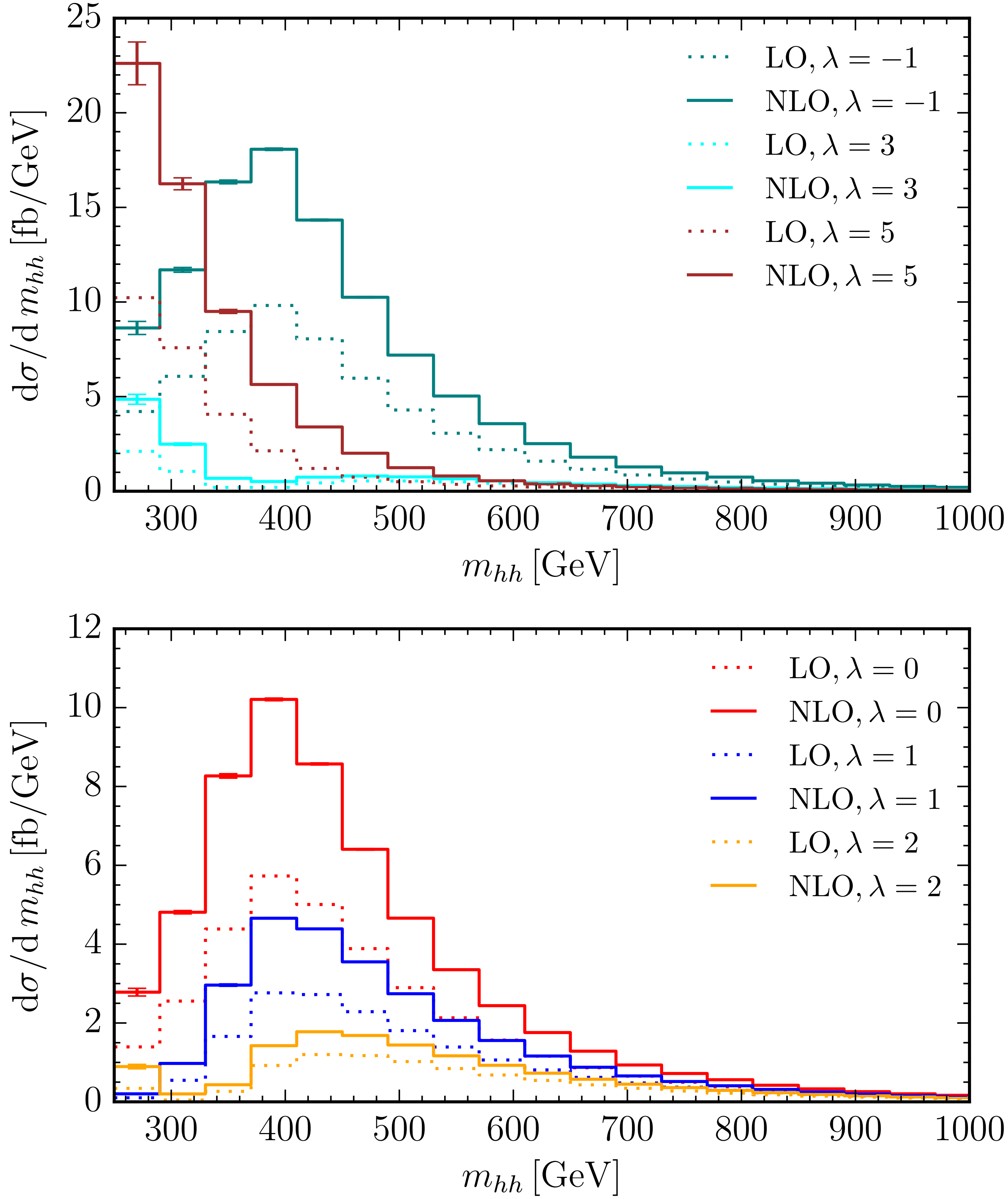
Lambda Variation



$\sqrt{s} = 14\,\text{TeV}$



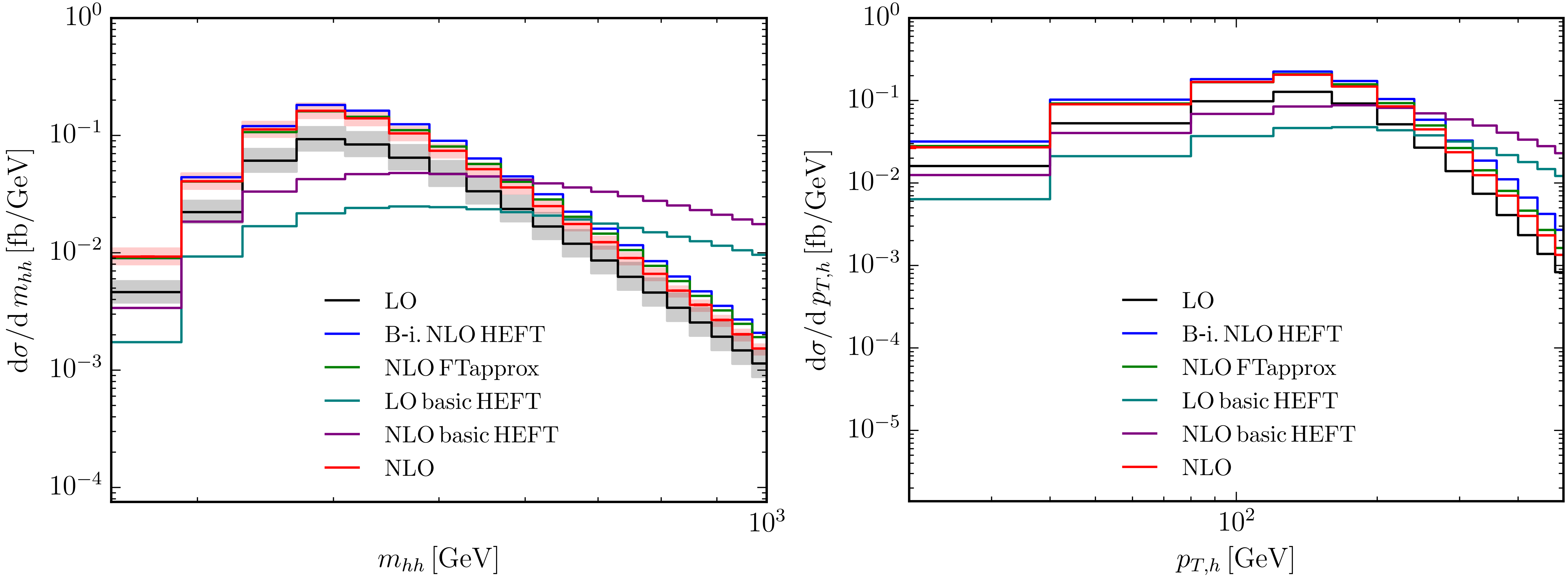
Lambda Variation



$\sqrt{s} = 100\,\mathrm{TeV}$

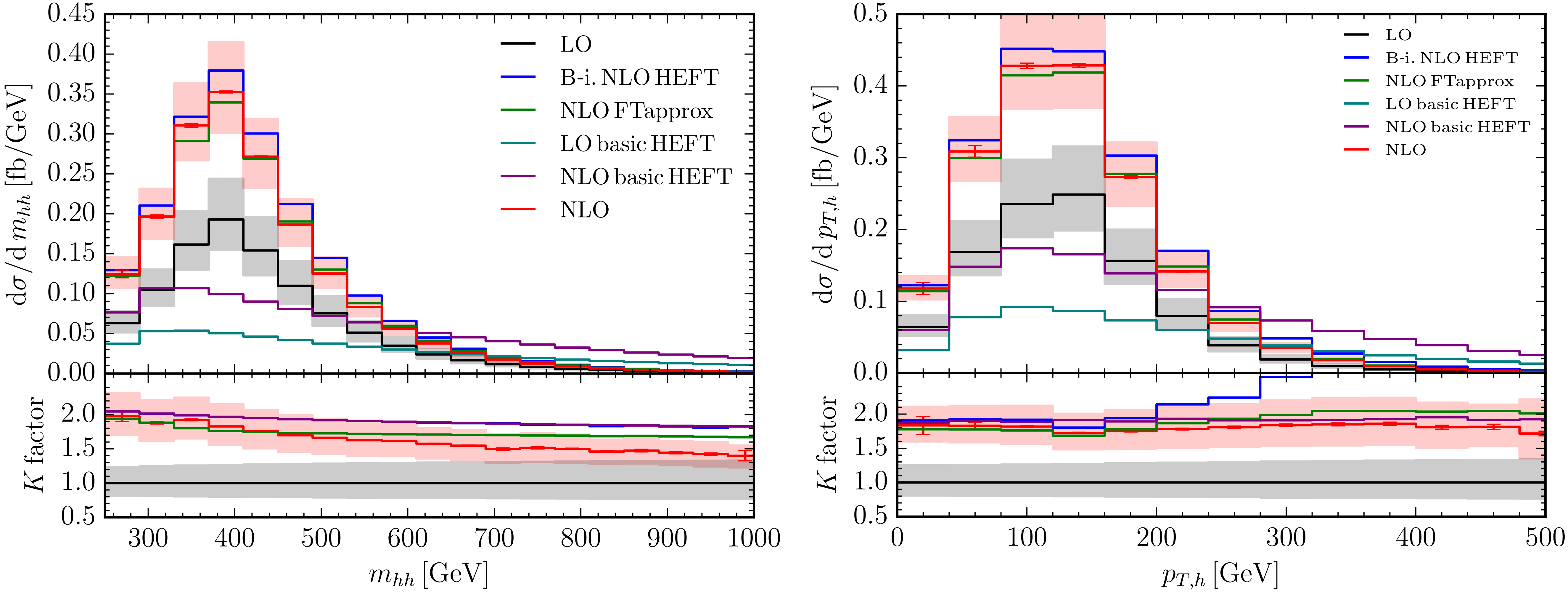
Scaling

$\sqrt{s} = 14\,\text{TeV}$



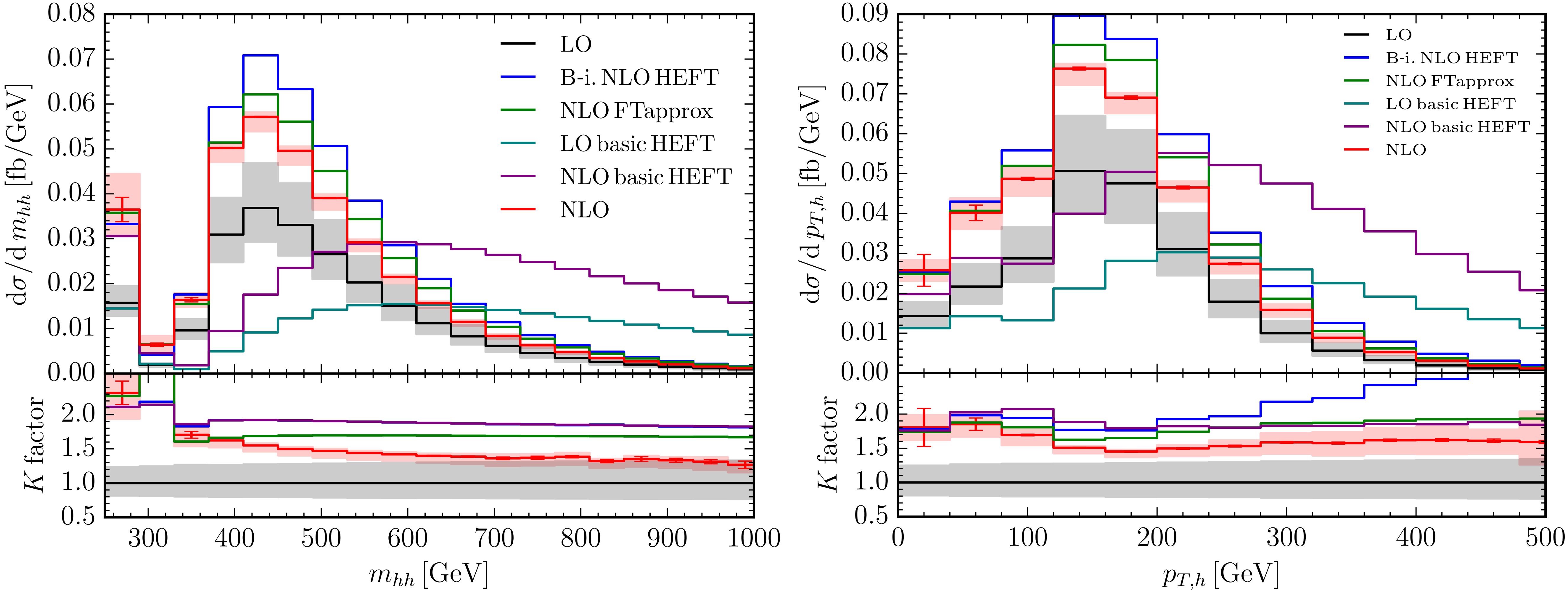
Lambda 0 x SM

$\sqrt{s} = 14\,\mathrm{TeV}$



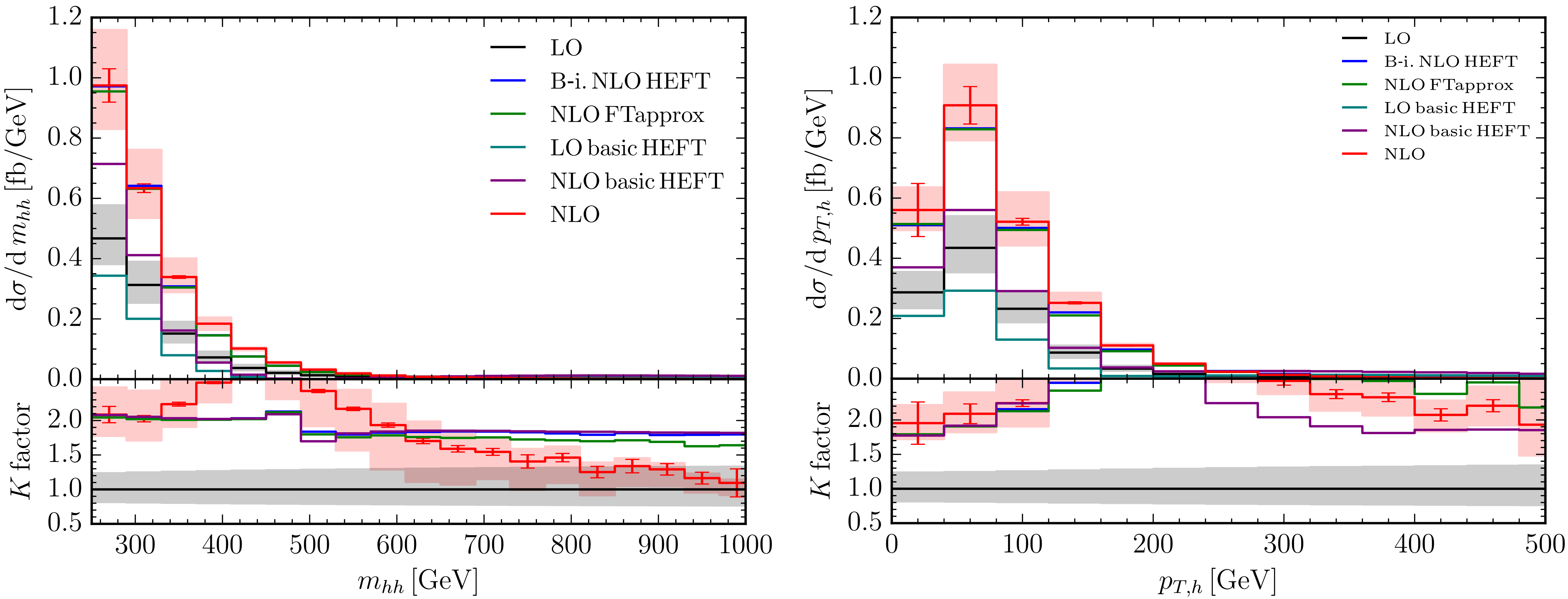
Lambda 2 x SM

$\sqrt{s} = 14\,\mathrm{TeV}$



Lambda 5 x SM

$\sqrt{s} = 14\,\text{TeV}$



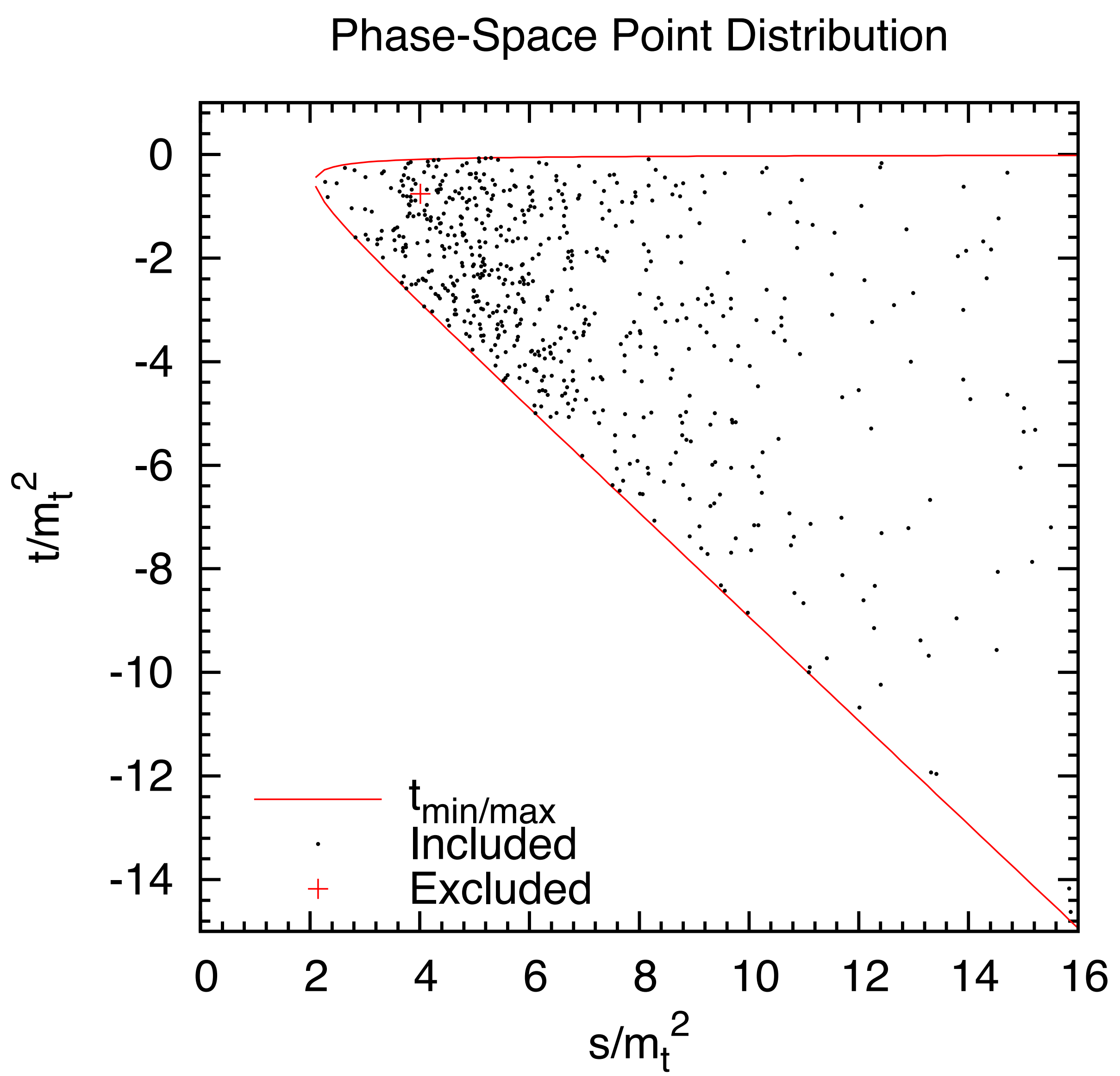
Phase-space Sampling

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 665 Events, compute at NLO



Median GPU time per PS point: 2 hours

Total compute time used: 4680 GPU Hours

Wall time: **6 days**

Current Experimental Limits

Decay Ch.	B.R.	95% Excl.	Analysis $\left(\left[fb^{-1}\right], \sqrt{s}\ [\text{TeV}]\right)$
$b\bar{b}b\bar{b}$	33%	$< 29 \cdot \sigma_{\text{SM}}$	ATLAS-CONF-2016-017 (3.2,13)
			ATLAS-CONF-2016-049 (13.3,13)
$b\bar{b}WW$	25%	–	–
$b\bar{b}\tau\tau$	7.3%	$< 200 \cdot \sigma_{\text{SM}}$	CMS PAS HIG-16-012 (2.7,13)
			CMS PAS HIG-16-028 (12.9,13)
			CMS PAS HIG-15-013 (18.3,8)
$b\bar{b}ZZ$	3.0%	–	–
$WW\tau\tau$	2.71%	–	–
$WWZZ$	1.13%	–	–
$b\bar{b}\gamma\gamma$	0.26%	$< 3.9pb$	ATLAS-CONF-2016-004 (3.2,13)
		$< 74 \cdot \sigma_{\text{SM}}$	CMS-HIG-13-032 (19.7,8)
$\gamma\gamma\gamma\gamma$	0.001%	–	–
$b\bar{b}VV(\to l\nu l\nu)$	1.23%	$400 \cdot \sigma_{\text{SM}}$	CMS PAS HIG-16-024 (2.3,13)
$\gamma\gamma WW^*(\to l\nu jj)$	–	$< 25pb$	ATLAS-CONF-2016-071 (13.3,13)
Comb Ch.	–	$< 70 \cdot \sigma_{\text{SM}}$	ATLAS arXiv:1509.04670v2 (20.3,8)

Future Experimental Prospects

HL-LHC (14 TeV)

ATLAS+CMS bbγγ + bbττ: Expected significance 1.9 sigma

CERN-LHCC-2015-10

ATLAS bbγγ: Signal significance 1.3 sigma ATL-PHYS-PUB-2014-019

ATLAS bbττ: Signal significance 0.6 sigma ATL-PHYS-PUB-2015-046

FCC (100 TeV)

This rate is expected to provide a clear signal in the $HH \to (b\bar{b})(\gamma\gamma)$ channel and to allow determination of λ_{3H} with an accuracy of $30-40\%$ with a luminosity of 3 ab^{-1}, and of $5-10\%$ with a luminosity of 30 ab^{-1} [497–499]. A rare decay channel which is potentially interesting is $HH \to (b\bar{b})(ZZ) \to (b\bar{b})(4l)$, with a few expected signal events against $\mathcal{O}(10)$ background events at 3 ab^{-1} [500].

arXiv:1607.01831