Higgs 2020

29 October 2020

Theory Predictions:
HH and Combinations with Single Higgs

Stephen Jones

The Higgs self-coupling

Standard Model Higgs Lagrangian:

$$\mathcal{L} \supset -V(\phi), \quad V(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$$

EW symmetry breaking

$$V(H) = \frac{1}{2}m_H^2 H^2 + \boxed{\lambda v H^3} + \frac{\lambda}{4}H^4,$$

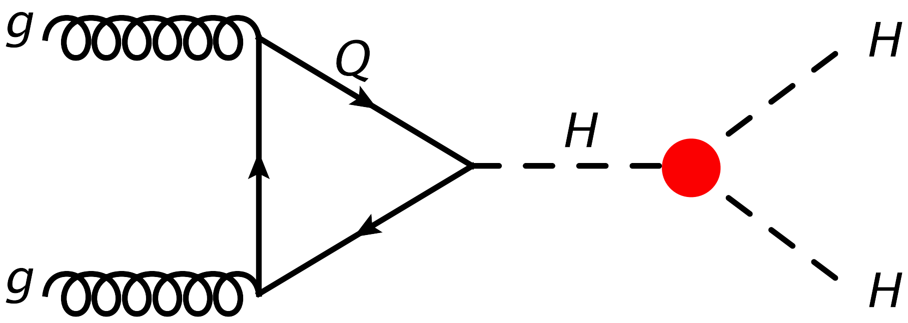
$$\mu^2 = \lambda v^2$$

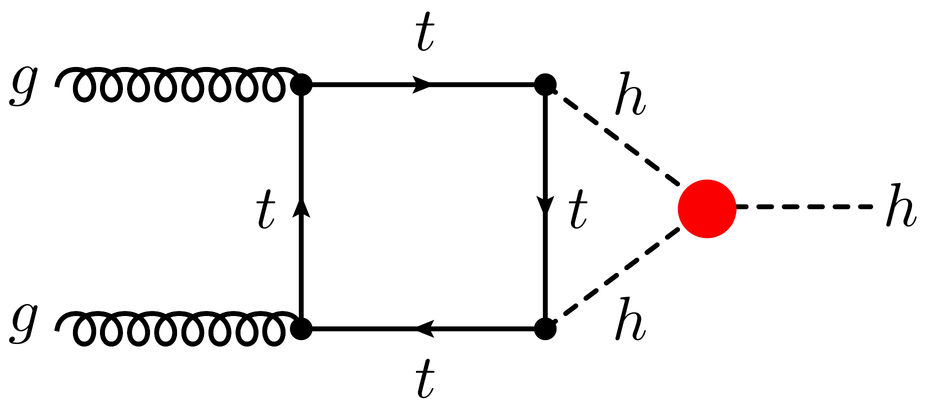
$$m_H^2 = 2\lambda v^2$$

SM: self-couplings determined by m_H, v

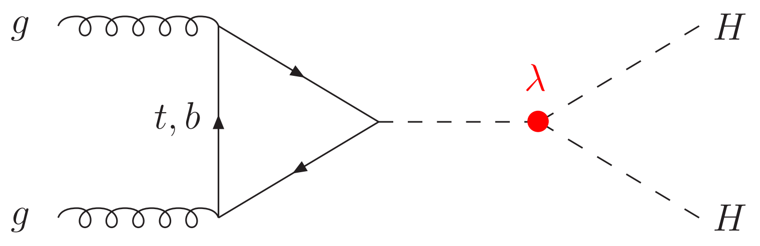
TH: coupling known in SM

EXP: need to find and measure processes involving Higgs self couplings

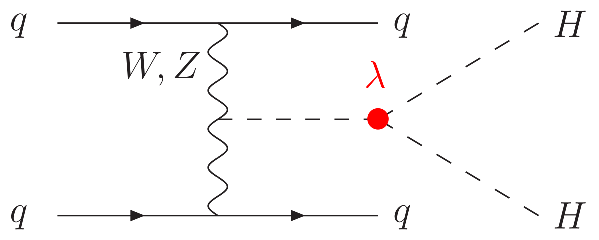




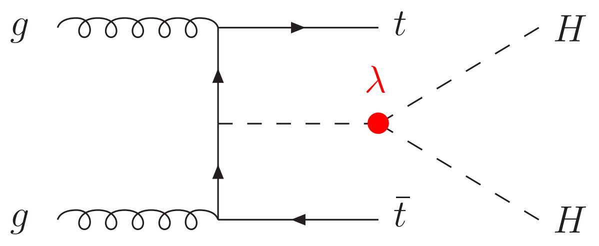
HH Production Channels at the LHC



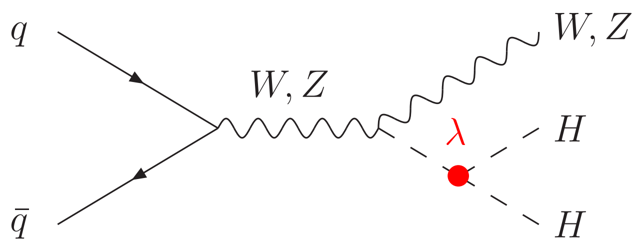
Gluon Fusion



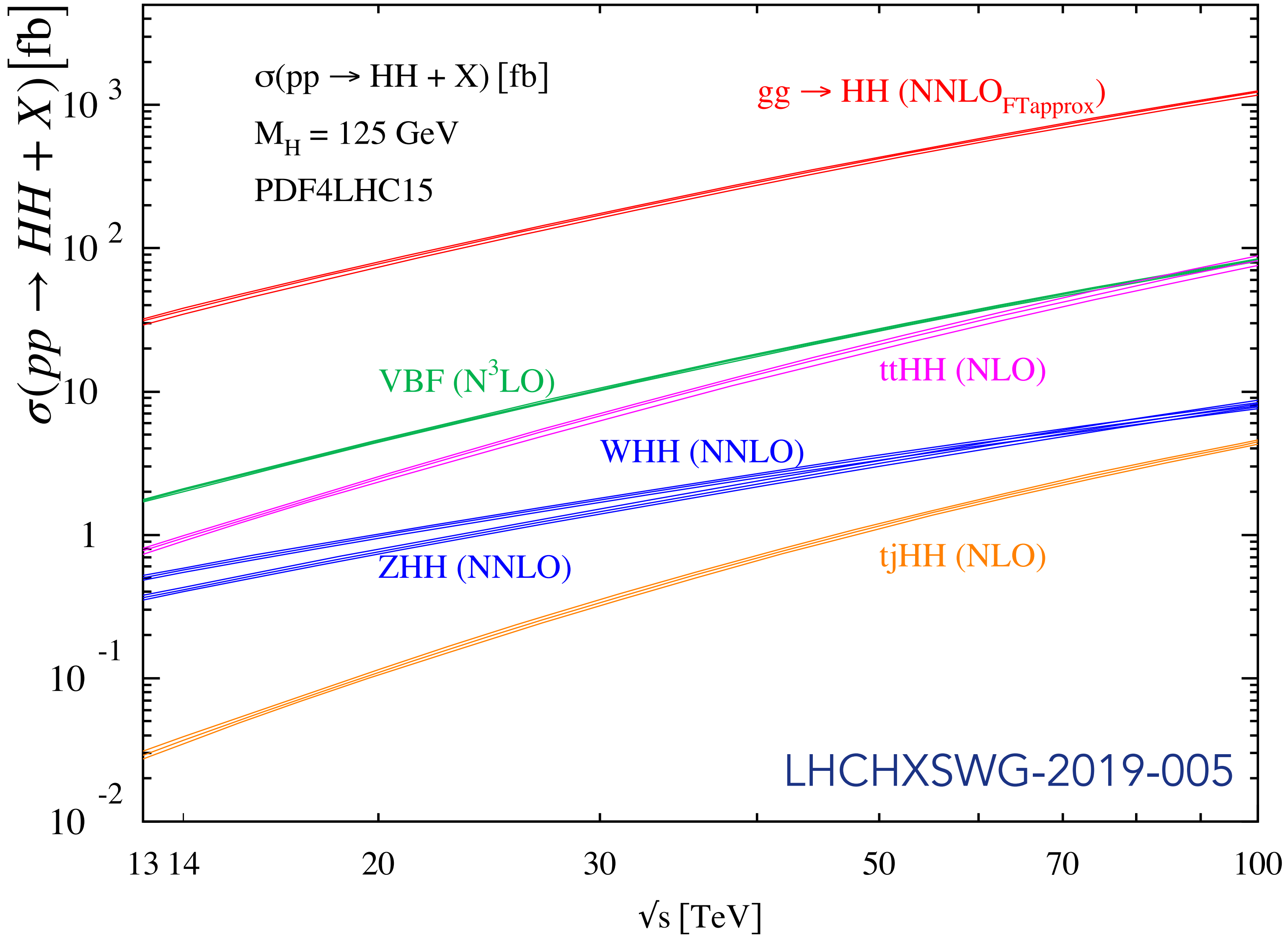
Vector Boson Fusion



Associated Production ($t\bar{t}$)



Associated Production (W,Z)

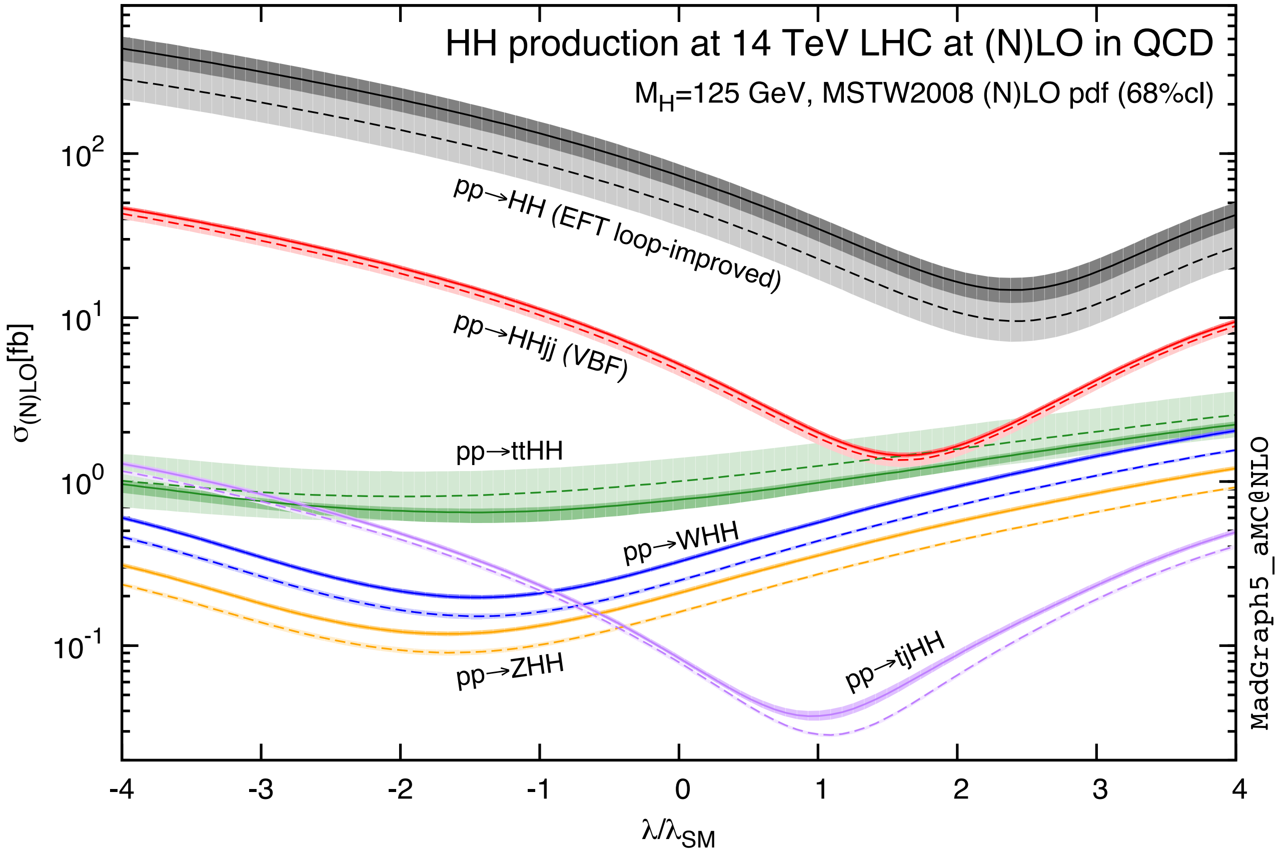


Production channels similar to H

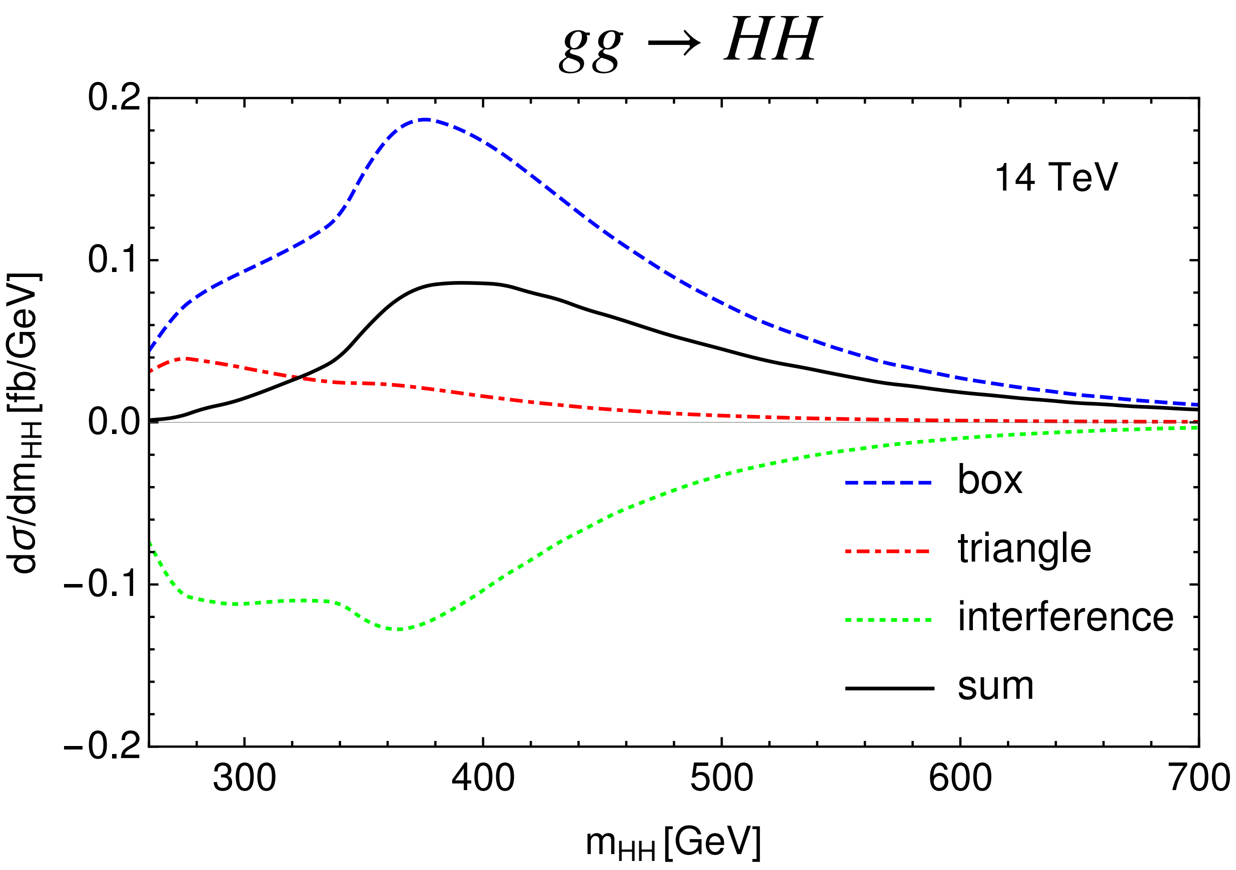
A very important difference:

$$\sigma(pp \to HH) \sim \frac{\sigma(pp \to H)}{1000}$$

HH Self Coupling Dependence



Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torrielli, Vryonidou, M. Zaro 14



LHCHXSWG-2019-005

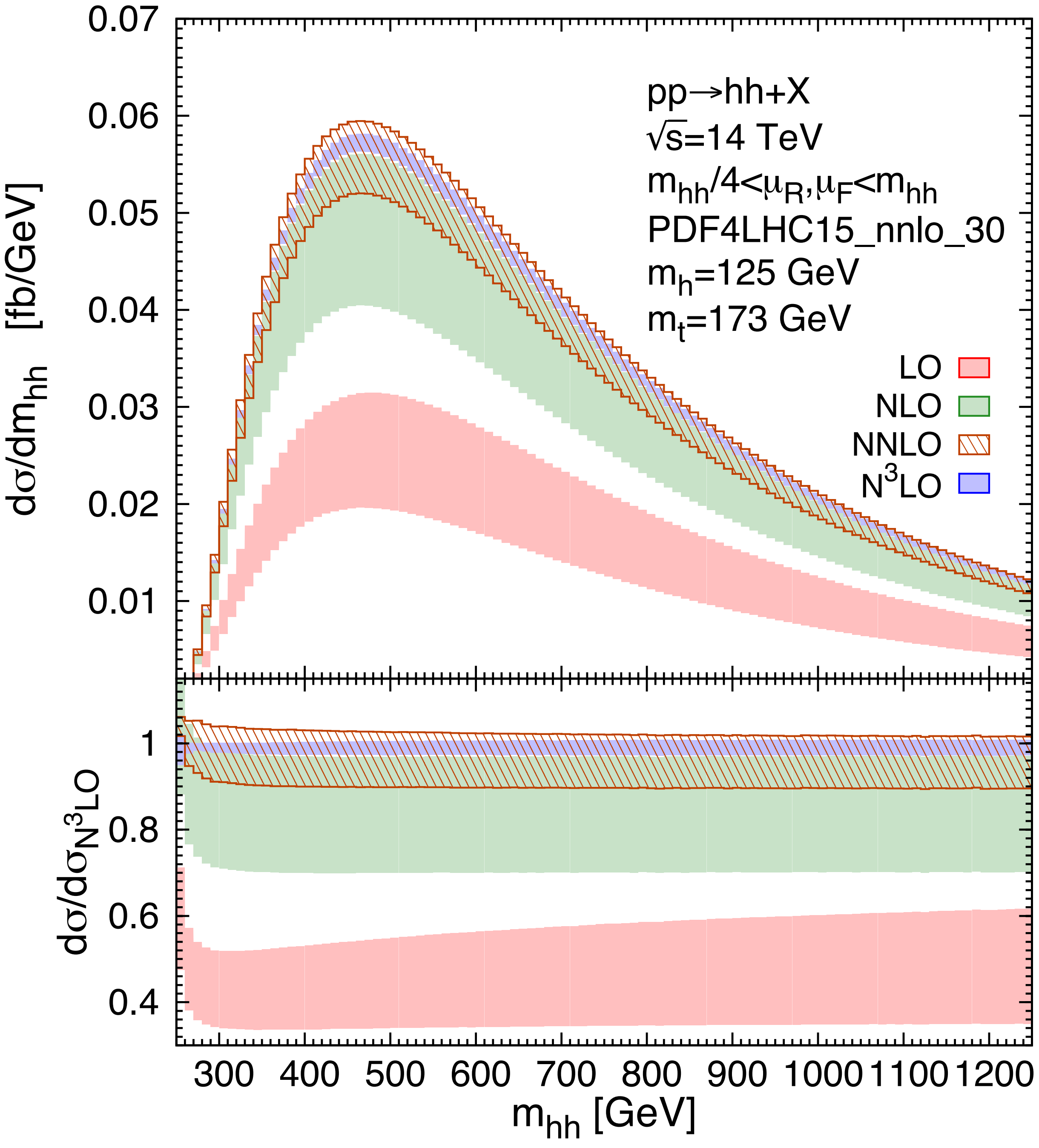
Theory uncertainties on cross section translate into uncertainties on the self-coupling extraction:

For $gg \rightarrow HH$ close to SM λ_{hhh} we observe $\dfrac{\Delta\sigma}{\sigma} \sim -\dfrac{\Delta\lambda}{\lambda}$

Differential measurements provide additional information and break degeneracies present at total cross-section level

HH Gluon Fusion: N^{3}LO HTL

N^{3}LO results for Gluon fusion in the $m_T \to \infty$ were recently obtained



Chen, Li, Shao, Wang 19

order \ $\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
LO	$13.80^{+31\%}_{-22\%}$	$17.06^{+31\%}_{-22\%}$	$98.22^{+26\%}_{-19\%}$	$2015^{+19\%}_{-15\%}$
NLO	$25.81^{+18\%}_{-15\%}$	$31.89^{+18\%}_{-15\%}$	$183.0^{+16\%}_{-14\%}$	$3724^{+13\%}_{-11\%}$
NNLO	$30.41^{+5.3\%}_{-7.8\%}$	$37.55^{+5.2\%}_{-7.6\%}$	$214.2^{+4.8\%}_{-6.7\%}$	$4322^{+4.2\%}_{-5.3\%}$
N^{3}LO	$31.31^{+0.66\%}_{-2.8\%}$	$38.65^{+0.65\%}_{-2.7\%}$	$220.2^{+0.53\%}_{-2.4\%}$	$4438^{+0.51\%}_{-1.8\%}$

Very mild scale dependence

Take $\hat{\sigma}^a$ part of result from known single Higgs calculation

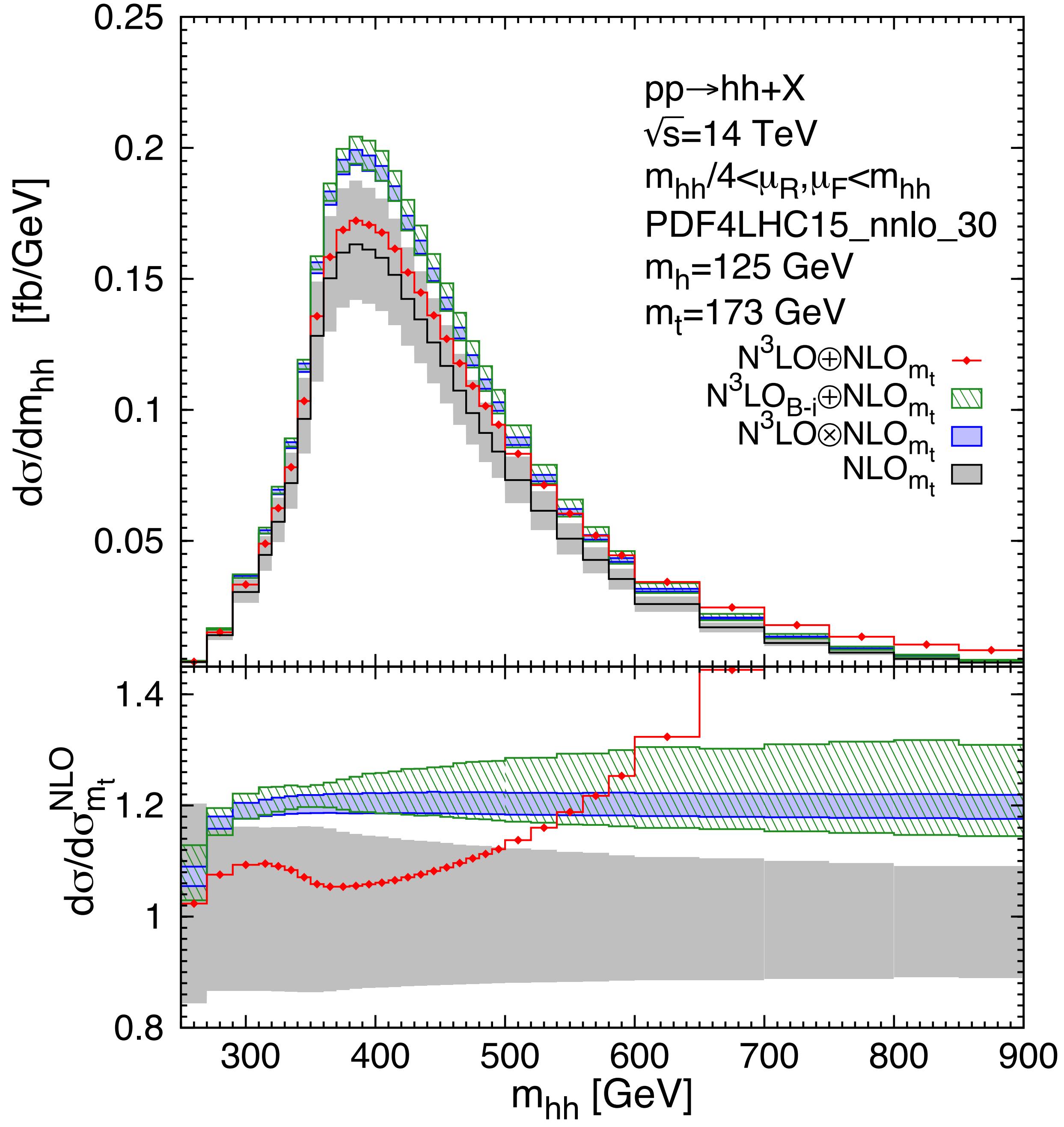
Anastasiou, Duhr, Dulat, Herzog, Mistlberger 15; Dulat, Lazopoulos, Mistlberger 18

2-loop box piece of $\hat{\sigma}^b$ first computed earlier

Banerjee, Borowka, Dhani, Gehrmann, Ravindran 18

HH Gluon Fusion: N^3LO HTL + NLO SM

Top quark mass effects (known up to NLO) have also been included



Chen, Li, Shao, Wang 19

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
NLO_{m_t}	$27.56^{+14\%}_{-13\%}$	$32.64^{+14\%}_{-12\%}$	$126.2^{+12\%}_{-10\%}$	$1119^{+13\%}_{-13\%}$
$\mathrm{NNLO}\oplus\mathrm{NLO}_{m_t}$	$32.16^{+5.9\%}_{-5.9\%}$	$38.29^{+5.6\%}_{-5.5\%}$	$157.3^{+3.0\%}_{-4.7\%}$	$1717^{+5.8\%}_{-12\%}$
$\mathrm{NNLO}_{\mathrm{B-i}}\oplus\mathrm{NLO}_{m_t}$	$33.08^{+5.0\%}_{-4.9\%}$	$39.16^{+4.9\%}_{-5.0\%}$	$150.8^{+4.6\%}_{-5.7\%}$	$1330^{+4.0\%}_{-7.2\%}$
$\mathrm{NNLO}\otimes\mathrm{NLO}_{m_t}$	$32.47^{+5.3\%}_{-7.8\%}$	$38.42^{+5.2\%}_{-7.6\%}$	$147.6^{+4.8\%}_{-6.7\%}$	$1298^{+4.2\%}_{-5.3\%}$
$\mathrm{N^3LO}\oplus\mathrm{NLO}_{m_t}$	$33.06^{+2.1\%}_{-2.9\%}$	$39.40^{+1.7\%}_{-2.8\%}$	$163.3^{+4.0\%}_{-8.3\%}$	$1833^{+14\%}_{-20\%}$
$\mathrm{N^3LO}_{\mathrm{B-i}}\oplus\mathrm{NLO}_{m_t}$	$34.17^{+1.9\%}_{-4.6\%}$	$40.44^{+1.9\%}_{-4.7\%}$	$155.5^{+2.3\%}_{-5.0\%}$	$1372^{+2.8\%}_{-5.0\%}$
$\mathrm{N^3LO}\otimes\mathrm{NLO}_{m_t}$	$33.43^{+0.66\%}_{-2.8\%}$	$39.56^{+0.64\%}_{-2.7\%}$	$151.7^{+0.53\%}_{-2.4\%}$	$1333^{+0.51\%}_{-1.8\%}$

Very mild scale dependence persists also after including top mass effects up to NLO

Results agree with $\mathrm{NNLO}_{\mathrm{FTapprox}}$ result (which retains m_T effects in real radiation) but with reduced scale uncertainty

Grazzini, Heinrich, SJ, Kallweit, Kerner, Lindert, Mazzitelli 18; (+NNLL) de Florian, Mazzitelli 18;

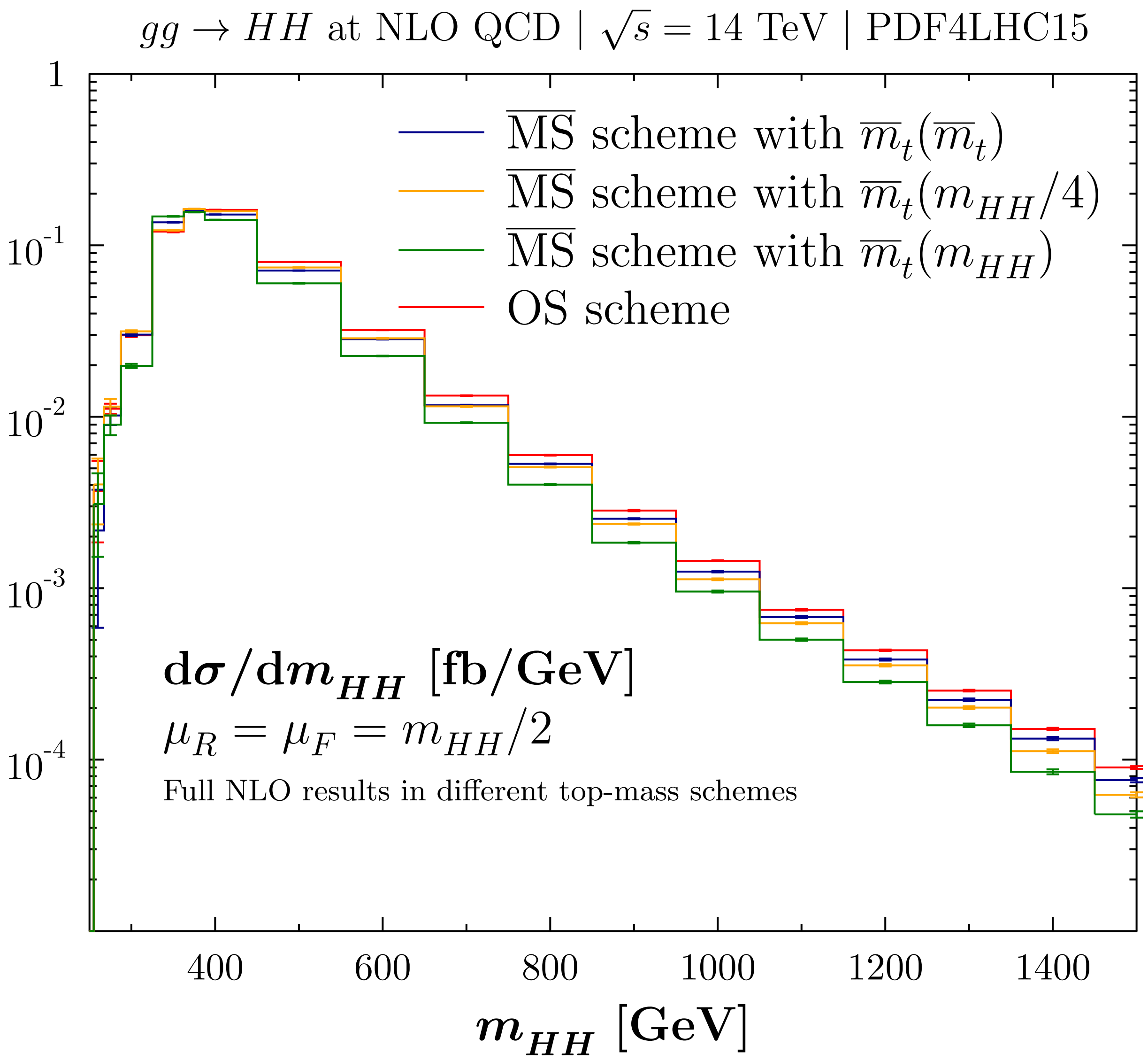
HH Gluon Fusion: Mass Scheme Uncertainties

With such a tiny scale uncertainty, other sources of uncertainty become relevant

HH@NLO: m_T in the OS and $\overline{\mathrm{MS}}$ scheme

Baglio, Campanario, Glaus, Mühlleitner, (+Ronca), Spira, Streicher 18, (20)

See talk of Seraina Glaus on Tue



Top quark mass scheme unc:

$$\frac{d\sigma(gg \to HH)}{dQ}\bigg|_{Q=300\text{ GeV}} = 0.0312(5)^{+9\%}_{-23\%}\ \text{fb/GeV},$$

$$\frac{d\sigma(gg \to HH)}{dQ}\bigg|_{Q=400\text{ GeV}} = 0.1609(4)^{+7\%}_{-7\%}\ \text{fb/GeV},$$

$$\frac{d\sigma(gg \to HH)}{dQ}\bigg|_{Q=600\text{ GeV}} = 0.03204(9)^{+0\%}_{-26\%}\ \text{fb/GeV},$$

$$\frac{d\sigma(gg \to HH)}{dQ}\bigg|_{Q=1200\text{ GeV}} = 0.000435(4)^{+0\%}_{-30\%}\ \text{fb/GeV},$$

Large uncertainty obtained comparing OS scheme with $\overline{\mathrm{MS}}$ scheme at scale m_{HH}

Such mass scheme uncertainties will show up in other processes (e.g. HJ, ZH)

Jones, Spira (Les Houches 19)

See talks of Daniel de Florian on Mon & Jonas Lindert on Tue

HH Gluon Fusion: Mass Scheme Uncertainties (II)

Combination of scale (μ_R, μ_F) and top mass scheme (OS / $\overline{\mathrm{MS}}$) studied very recently
Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 20

If we wish to take the **envelope** of the predictions as the uncertainty, then the two uncertainties should be added **linearly** (validated at NLO)

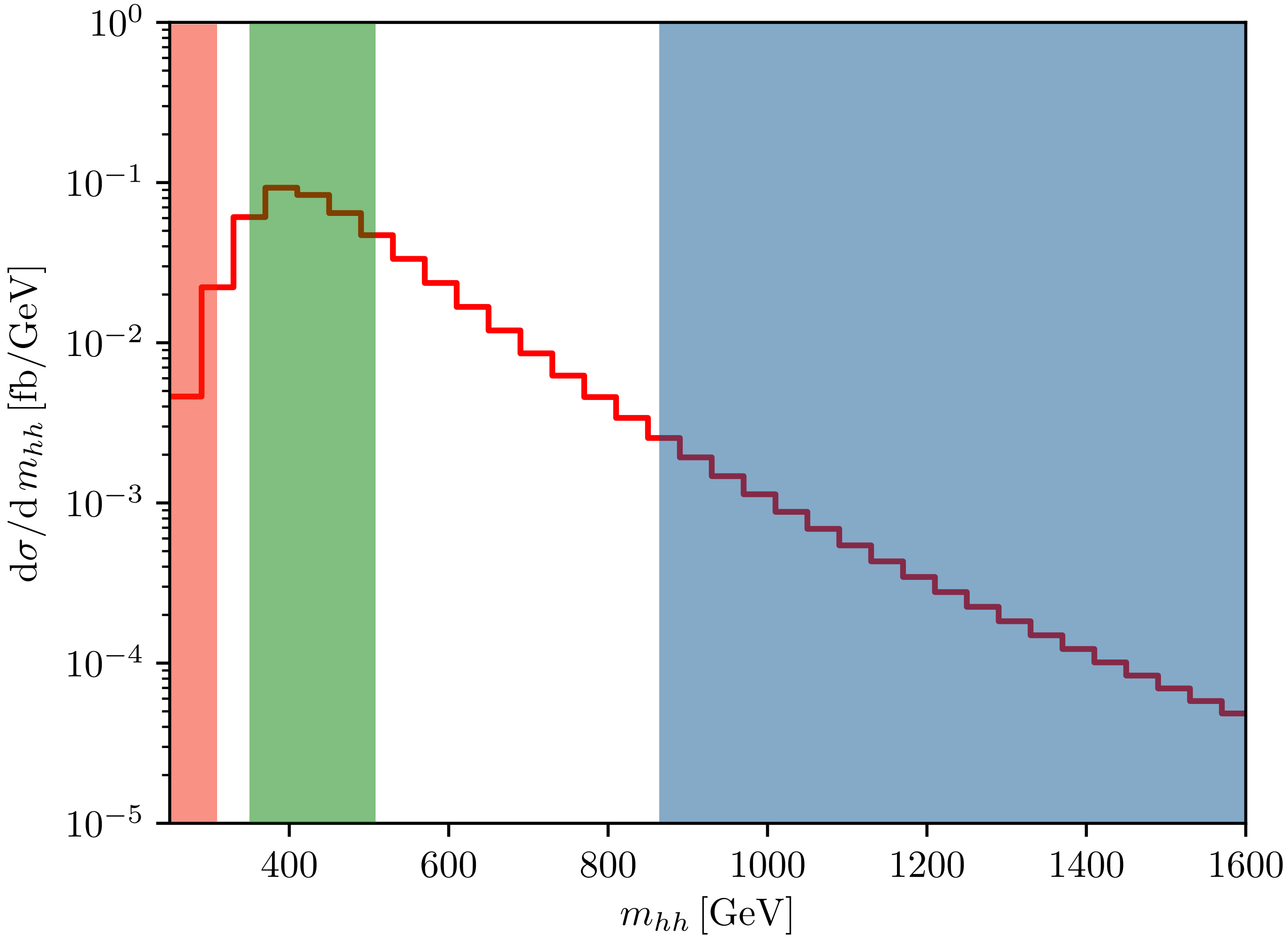
Above authors advocate use of $\mathrm{NNLO}_{\mathrm{FTapprox}}$ with (NLO) mass scheme errors added

Scale (μ_R, μ_F)		**NLO Mass Scheme Unc.**		**Proposed Combination**
$\kappa_\lambda = -10: \quad \sigma_{tot} = 1680^{+3.0\%}_{-7.7\%}$ fb,		$\kappa_\lambda = -10: \quad \sigma_{tot} = 1438(1)^{+10\%}_{-6\%}$ fb,		$\kappa_\lambda = -10: \quad \sigma_{tot} = 1680^{+13\%}_{-14\%}$ fb,
$\kappa_\lambda = -5: \quad \sigma_{tot} = 598.9^{+2.7\%}_{-7.5\%}$ fb,		$\kappa_\lambda = -5: \quad \sigma_{tot} = 512.8(3)^{+10\%}_{-7\%}$ fb,		$\kappa_\lambda = -5: \quad \sigma_{tot} = 598.9^{+13\%}_{-15\%}$ fb,
$\kappa_\lambda = -1: \quad \sigma_{tot} = 131.9^{+2.5\%}_{-6.7\%}$ fb,		$\kappa_\lambda = -1: \quad \sigma_{tot} = 113.66(7)^{+8\%}_{-9\%}$ fb,		$\kappa_\lambda = -1: \quad \sigma_{tot} = 131.9^{+11\%}_{-16\%}$ fb,
$\kappa_\lambda = 0: \quad \sigma_{tot} = 70.38^{+2.4\%}_{-6.1\%}$ fb,		$\kappa_\lambda = 0: \quad \sigma_{tot} = 61.22(6)^{+6\%}_{-12\%}$ fb,		$\kappa_\lambda = 0: \quad \sigma_{tot} = 70.38^{+8\%}_{-18\%}$ fb,
$\kappa_\lambda = 1: \quad \sigma_{tot} = 31.05^{+2.2\%}_{-5.0\%}$ fb,	**+**	$\kappa_\lambda = 1: \quad \sigma_{tot} = 27.73(7)^{+4\%}_{-18\%}$ fb,	**=**	$\kappa_\lambda = 1: \quad \sigma_{tot} = 31.05^{+6\%}_{-23\%}$ fb,
$\kappa_\lambda = 2: \quad \sigma_{tot} = 13.81^{+2.1\%}_{-4.9\%}$ fb,		$\kappa_\lambda = 2: \quad \sigma_{tot} = 13.2(1)^{+1\%}_{-23\%}$ fb,		$\kappa_\lambda = 2: \quad \sigma_{tot} = 13.81^{+3\%}_{-28\%}$ fb,
$\kappa_\lambda = 2.4: \quad \sigma_{tot} = 13.10^{+2.3\%}_{-5.1\%}$ fb,		$\kappa_\lambda = 2.4: \quad \sigma_{tot} = 12.7(1)^{+4\%}_{-22\%}$ fb,		$\kappa_\lambda = 2.4: \quad \sigma_{tot} = 13.10^{+6\%}_{-27\%}$ fb,
$\kappa_\lambda = 3: \quad \sigma_{tot} = 18.67^{+2.7\%}_{-7.3\%}$ fb,		$\kappa_\lambda = 3: \quad \sigma_{tot} = 17.6(1)^{+9\%}_{-15\%}$ fb,		$\kappa_\lambda = 3: \quad \sigma_{tot} = 18.67^{+12\%}_{-22\%}$ fb,
$\kappa_\lambda = 5: \quad \sigma_{tot} = 94.82^{+4.9\%}_{-8.8\%}$ fb,		$\kappa_\lambda = 5: \quad \sigma_{tot} = 83.2(3)^{+13\%}_{-4\%}$ fb,		$\kappa_\lambda = 5: \quad \sigma_{tot} = 94.82^{+18\%}_{-13\%}$ fb,
$\kappa_\lambda = 10: \quad \sigma_{tot} = 672.2^{+4.2\%}_{-8.5\%}$ fb		$\kappa_\lambda = 10: \quad \sigma_{tot} = 579(1)^{+12\%}_{-4\%}$ fb		$\kappa_\lambda = 10: \quad \sigma_{tot} = 672.2^{+16\%}_{-13\%}$ fb

See talk of Seraina Glaus on Tue

Mass Uncertainties: Where do we go from here?

1) Just keep calculating, but NNLO with full m_T is very challenging



Low invariant mass:
expand in $1/m_T^2$
known to NNLO
Grigo, Hoff, Steinhauser 15;

Around Peak:
threshold expansion
Gröber, Maier, Rauh 17

High energy:
small-m_T expansion
known at NLO
Davies, Mishima, Steinhauser, Wellmann 18, 19

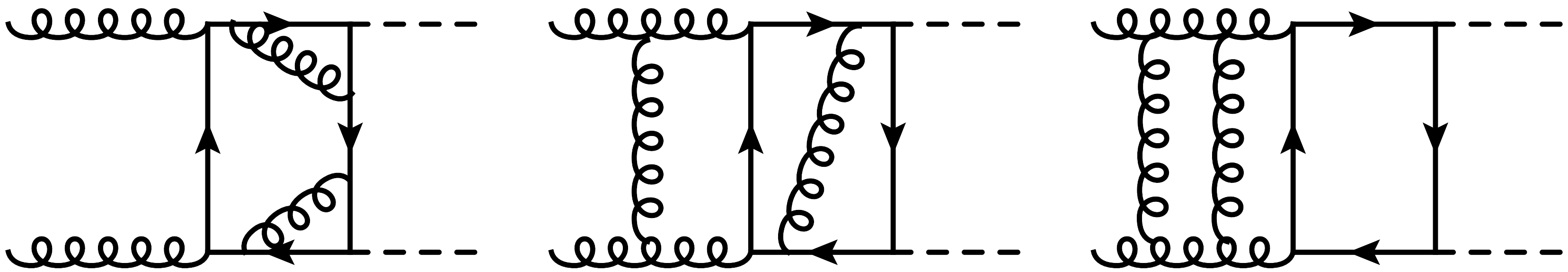
See also: Davies, Steinhauser 19; Davies, Herren, Mishima, Steinhauser 19; Davies, Gröber, Maier, Rauh, Steinhauser 19; Giardino, Gröber 18;

2) Understand structure of mass logarithms Liu, Penin 17, 18

3) Choose preferred scales/schemes? (Threshold: OS, HE: $\overline{\mathrm{MS}}$?)

Expansions beyond NLO

NNLO Virtual:



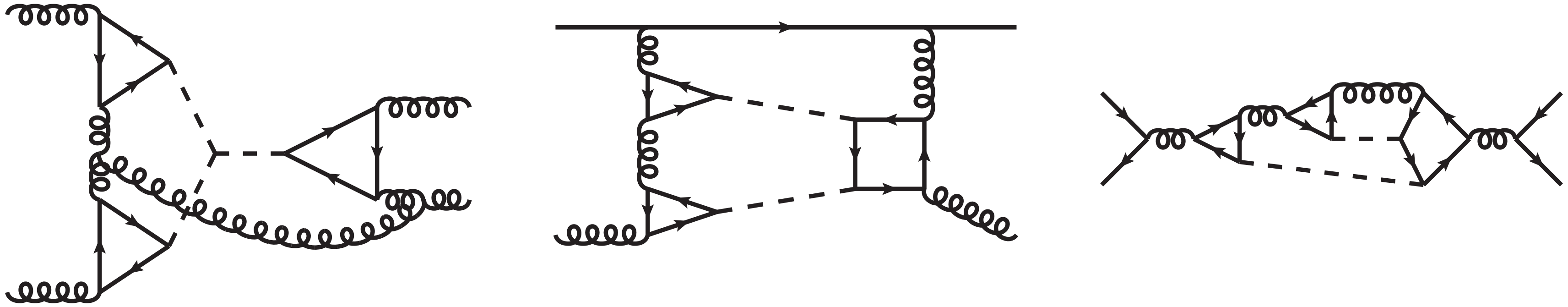
Computed 3-loop virtual piece in large-m_T expansion:

Boxes up to $1/m_T^8$

Triangles up to $1/m_T^{14}$

Davies, Steinhauser 19

NNLO Real-Virtual (Partial):

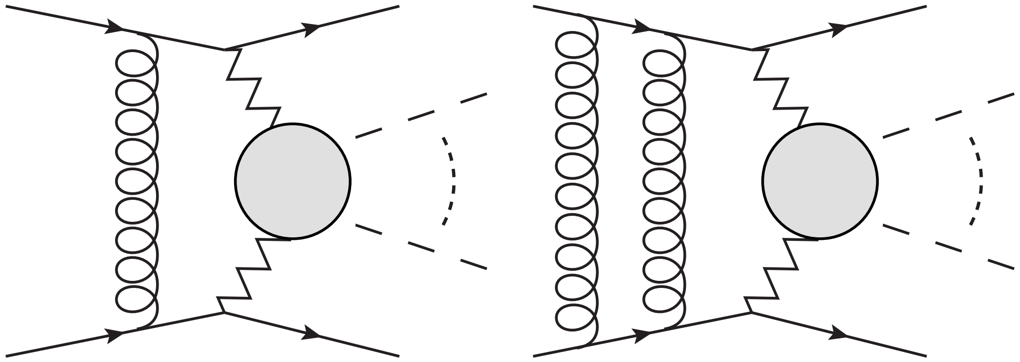


Davies, Herren,
Mishima, Steinhauser 19

5-loop forward scattering amplitudes

Calculation restricted to diagrams with 3 closed top quark loops (n_h^3)

VBF HH: Non-factorisable contribution

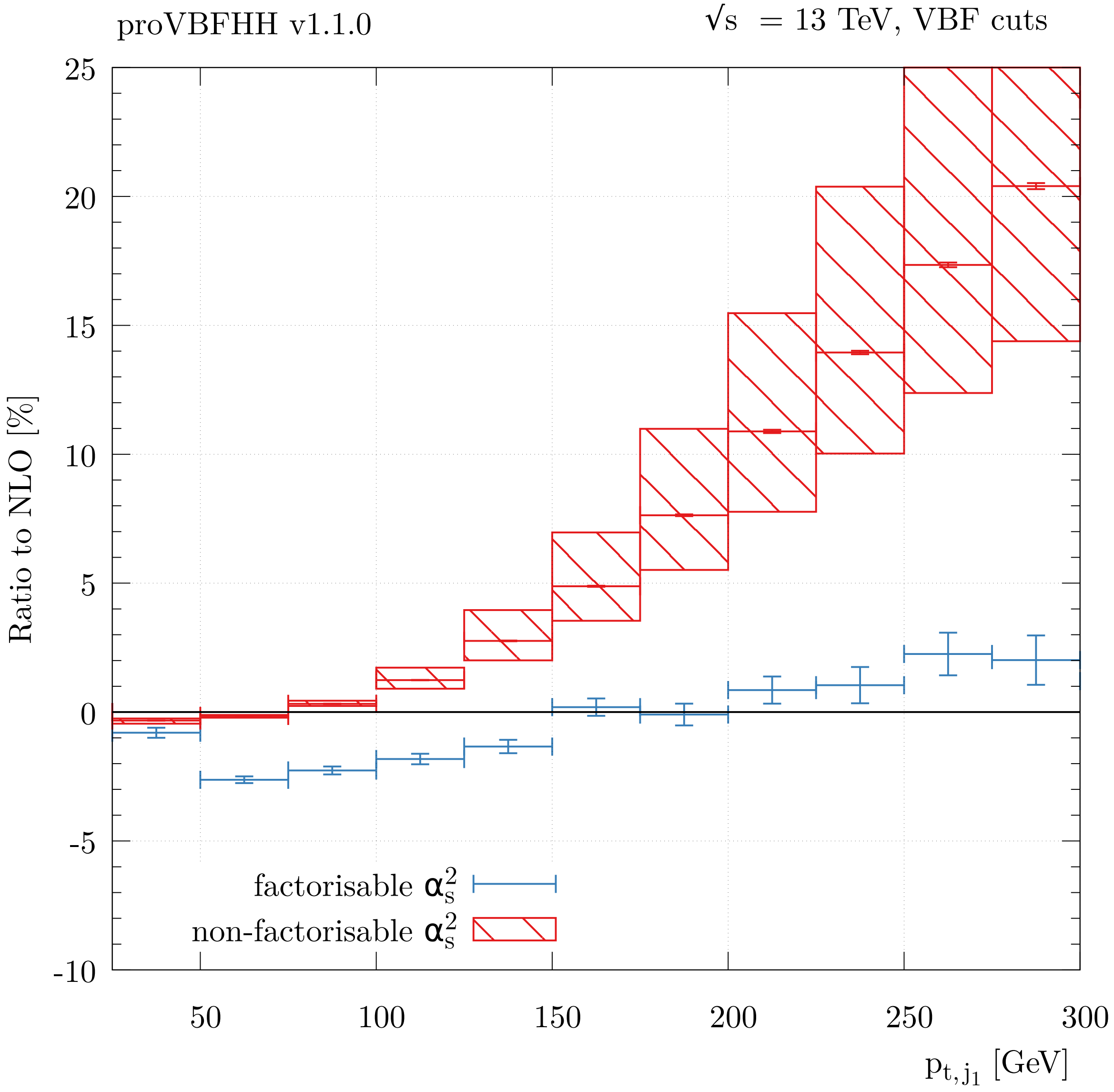


VBF Approximation/structure function approach: neglect the (colour suppressed) exchange of particles between the quark lines

Non-factorisable contributions recently studied using the eikonal approximation
Liu, Melnikov, Penin 19
Dreyer, Karlberg, Tancredi 20

Delicate cancellations between ``box" and ``triangle" (λ_3) diagrams spoiled, giving rise to a large corrections

$$\mathrm{d}\sigma^{\mathrm{NNLO}}_{HH,\mathrm{nf}} \sim \tilde{\alpha}_s^2 \left[\left(1 - \frac{\pi^2}{3}\right) \left(\mathrm{d}\sigma^{\mathrm{LO}}_{TT} + \mathrm{d}\sigma^{\mathrm{LO}}_{TB}\right) + \left(\frac{5}{4} - \frac{\pi^2}{3}\right) \mathrm{d}\sigma^{\mathrm{LO}}_{BB} \right].$$



Note: (As pointed out by authors) Eikonal approximation not trustworthy for too high $p_{t,j}$

HH VBF: NNLO QCD + NLO EW

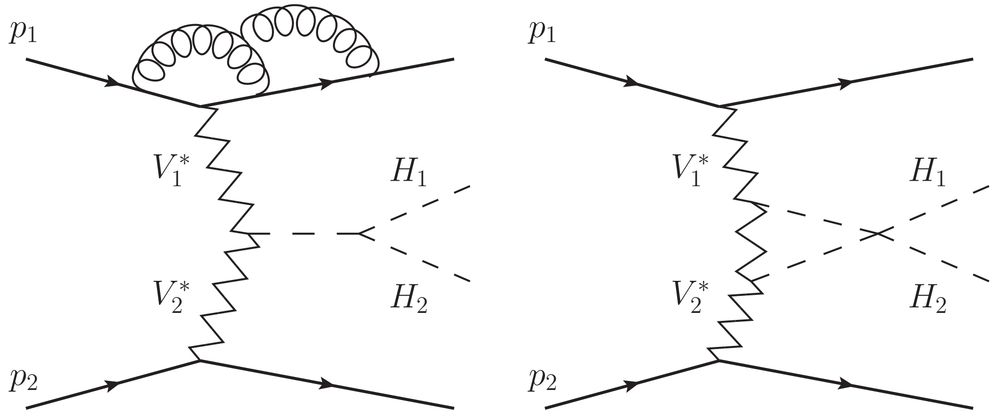
Inclusive known to N^3LO QCD

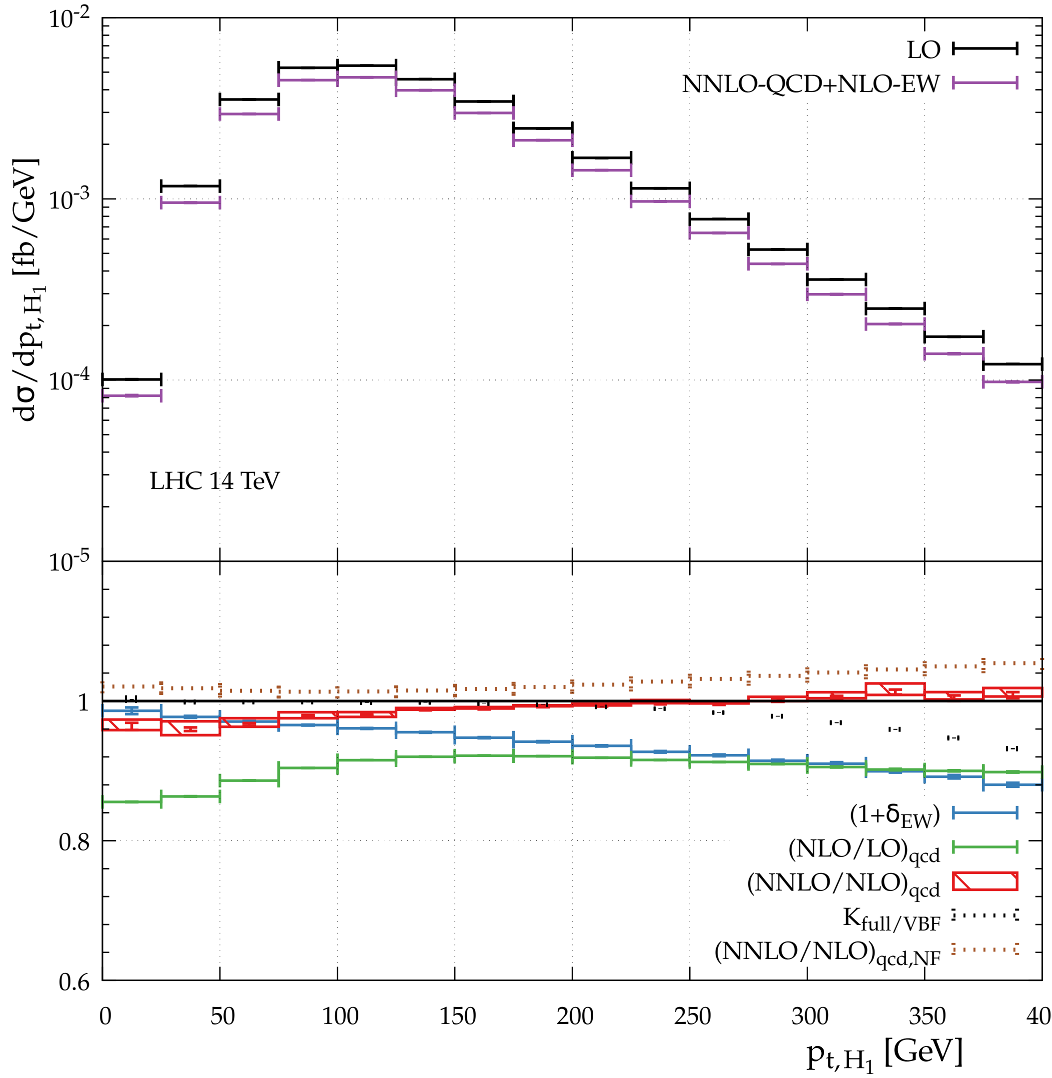
Dreyer, Karlberg 18

New state of the art for differential predictions

NNLO QCD Dreyer, Karlberg 18

+ NLO EW Dreyer, Karlberg, Lang, Pellen 20





$\sigma^{\text{full}}_{\text{LO}}$	$\delta^{\text{full}}_{\text{NLO QCD}}$	$\delta^{\text{VBF}}_{\text{NNLO QCD}}$	$\delta^{\text{full}}_{\text{NLO EW}}$	$\sigma_{\text{NNLO QCD}\times\text{NLO EW}}$	$\delta^{\text{NF}}_{\text{NNLO QCD}}$ [fb]
$0.78444(9)^{+0.0825}_{-0.0694}$	$-0.07110(13)$	$-0.0115(5)$	$-0.0476(2)$	$0.6684(5)^{+0.002}_{-0.0004}$	$0.01237(2)$
${}^{+10.5\%}_{-8.8\%}$	-9.1%	-1.5%	-6.1%	$-14.8\%^{+0.3\%}_{-0.06\%}$	$+1.7\%$

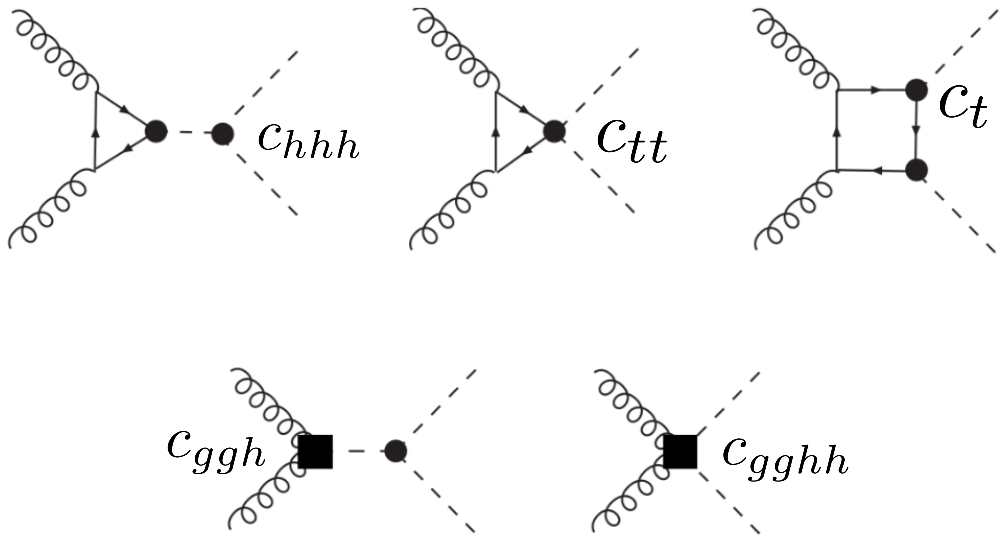
EW corrections similar in size to NLO QCD corrections and to those in single Higgs case

Non-factorisable contribution similar to NNLO QCD factorisable contribution but with opposite sign

All corrections available in public code: **proVBFHH v1.1.0**

HH Gluon Fusion: EFT Results

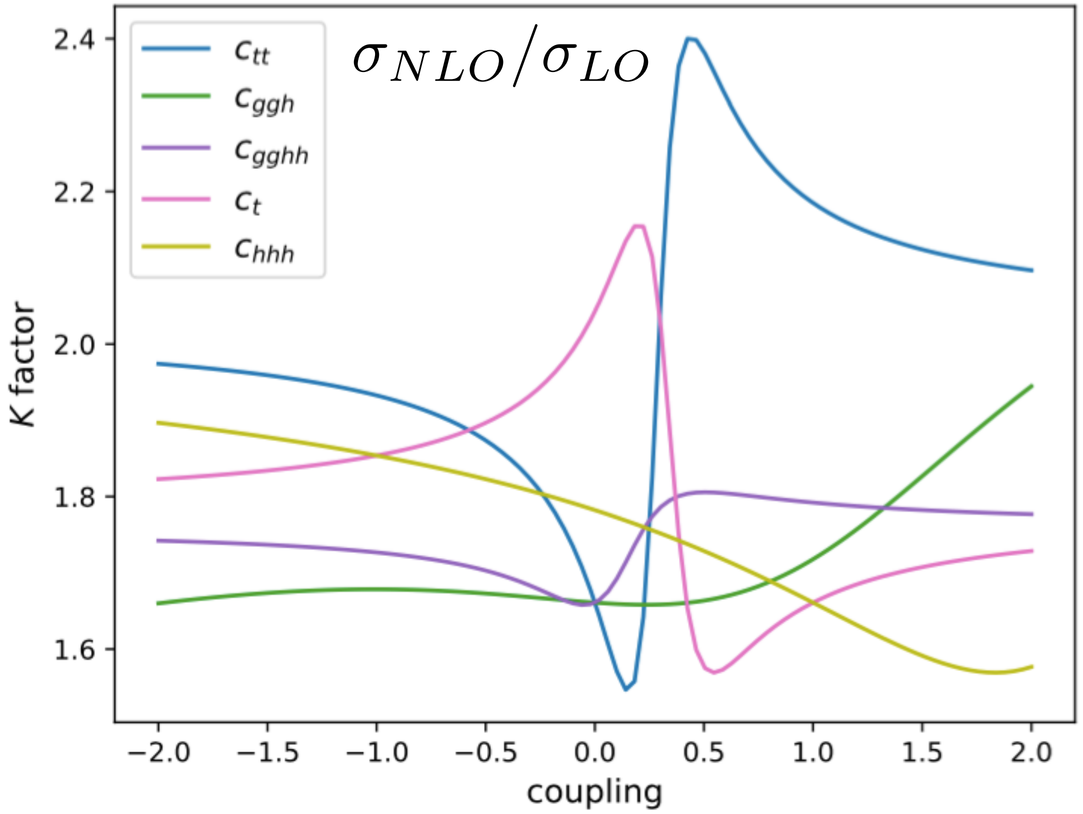
Just varying λ: one ``direction'' in EFT parameter space
Parametrise **non-resonant** new physics with EFT:



NLO QCD corrections with full top-quark mass dependence known (non-linear EFT framework)

Buchalla, Capozi, Celis, Heinrich, Scyboz 18

- Results for 12 BSM ``clusters''/benchmarks
- Coefficients for reconstructing $\sigma_{\text{tot}}, m_{hh}$ for arbitrary values of the couplings
- K-factors show significant dependence on the couplings



See also:

(B.I. NLO HTL) Gröber, Mühlleitner, Spira, Streicher 15;
(B.I. NNLO HTL) de Florian, Fabre, Mazzitelli 17;
Dall'Osso, Dorigo, Gottardo, Oliveira, Tosi, Goertz 15; Carvalho, Manzano, Dorigo, Gouzevich 16;

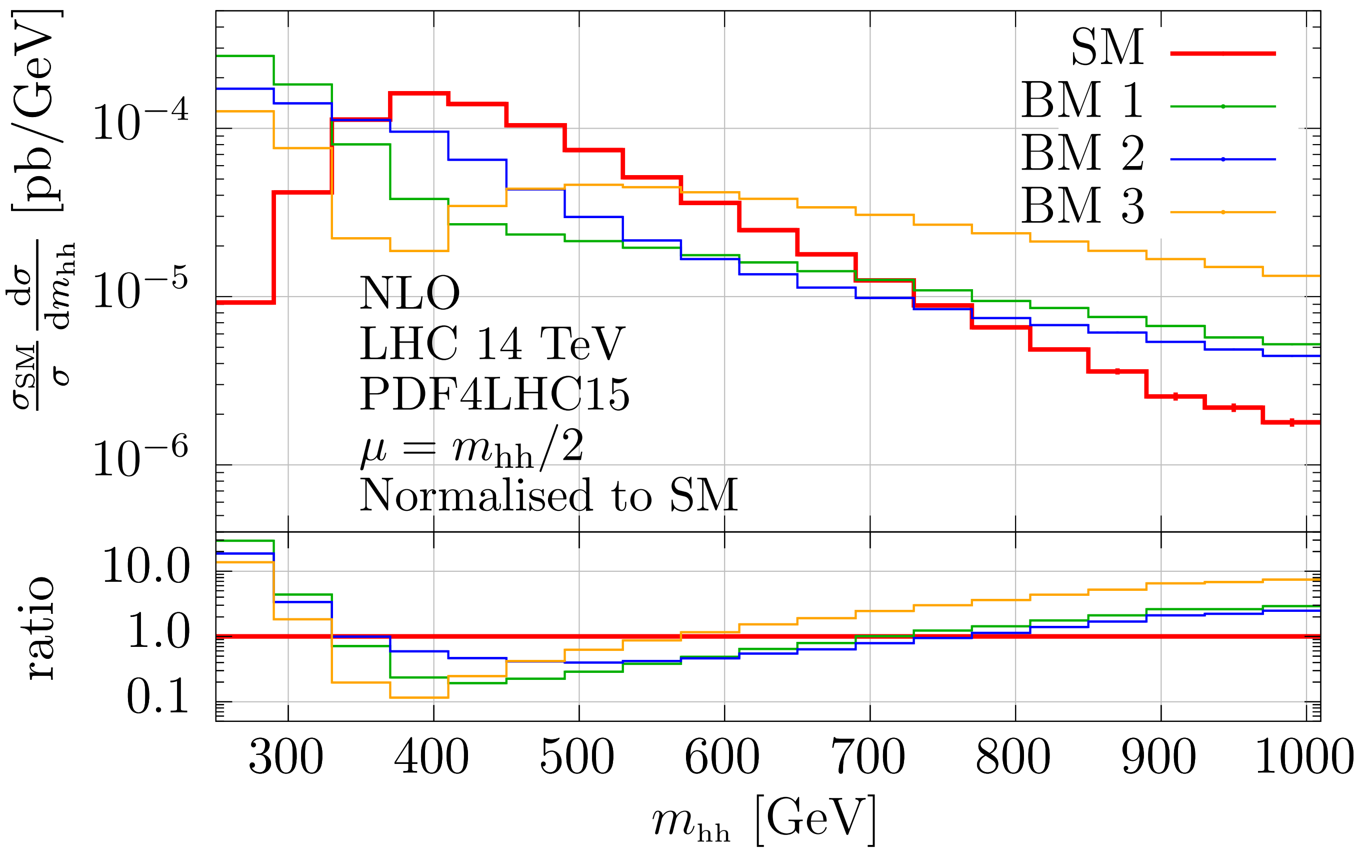
HH Gluon Fusion: EFT Results (II)

Results in non-linear EFT framework for $gg \to HH$ @ NLO (2-loop) with full m_T are now publicly available in POWHEG-BOX (See /User-Processes-V2/ggHH)

Heinrich, SJ, Kerner, Scyboz 20

$$
\begin{aligned}
|\mathcal{M}_{\mathrm{BSM}}|^2 = {} & a_1\, c_t^4 + a_2\, c_{tt}^2 + a_3\, c_t^2 c_{hhh}^2 + a_4\, c_{ggh}^2 c_{hhh}^2 + a_5\, c_{gghh}^2 + a_6\, c_{tt} c_t^2 + a_7\, c_t^3 c_{hhh} \\
& + a_8\, c_{tt} c_t\, c_{hhh} + a_9\, c_{tt} c_{ggh} c_{hhh} + a_{10}\, c_{tt} c_{gghh} + a_{11}\, c_t^2 c_{ggh} c_{hhh} + a_{12}\, c_t^2 c_{gghh} \\
& + a_{13}\, c_t c_{hhh}^2 c_{ggh} + a_{14}\, c_t c_{hhh} c_{gghh} + a_{15}\, c_{ggh} c_{hhh} c_{gghh} + a_{16}\, c_t^3 c_{ggh} \\
& + a_{17}\, c_t c_{tt} c_{ggh} + a_{18}\, c_t c_{ggh}^2 c_{hhh} + a_{19}\, c_t c_{ggh} c_{gghh} + a_{20}\, c_t^2 c_{ggh}^2 \\
& + a_{21}\, c_{tt} c_{ggh}^2 + a_{22}\, c_{ggh}^3 c_{hhh} + a_{23}\, c_{ggh}^2 c_{gghh}\,.
\end{aligned}
$$

Born-virtual interference term parametrised with 23 linearly independent sets of couplings, grids generated for each interference term, combined at run time



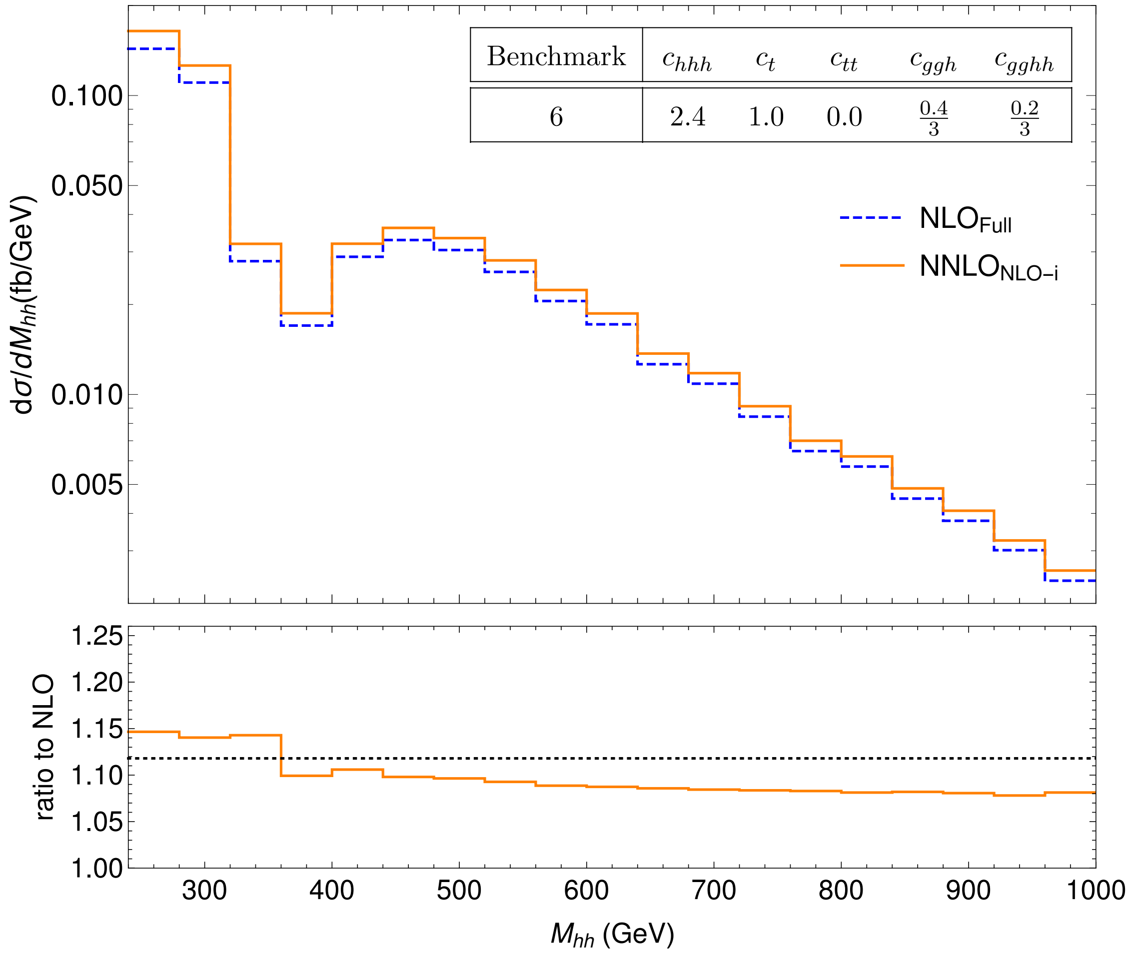
Allows user to specify EFT couplings in a completely flexible manner

Note: Chromo-magnetic operator not included here (suppressed depending on EFT counting)

HH Gluon Fusion: NNLO HTL + NLO SM with EFT

NNLO (Born-improved) HTL limit results known including dim-6 operators

de Florian, Fabre, Mazzitelli 17



de Florian, Fabre, Heinrich, Mazzitelli (Les Houches 19)

Can apply bin-by-bin reweighting to obtain NLO improved results including EFT effects

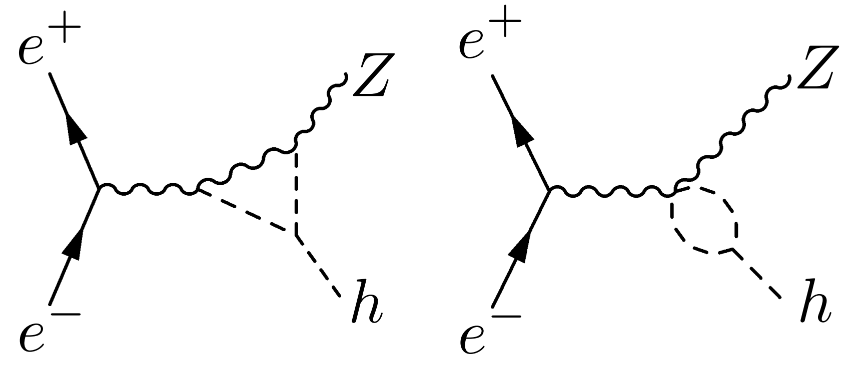
$$\Delta\sigma(\mathrm{NNLO_{NLO-i}}) = \Delta\sigma(\mathrm{NNLO_{B-i}}) \times \frac{\Delta\sigma(\mathrm{NLO_{Full}})}{\Delta\sigma(\mathrm{NLO_{B-i}})}$$

c_{hhh}	-1	0	1	2	2.4	3	5
σ [fb]	$131.9^{+2.5\%}_{-6.7\%}$	$70.38^{+2.4\%}_{-6.1\%}$	$31.05^{+2.2\%}_{-5.0\%}$	$13.81^{+2.1\%}_{-4.9\%}$	$13.1^{+2.3\%}_{-5.1\%}$	$18.67^{+2.7\%}_{-7.3\%}$	$94.82^{+4.9\%}_{-8.8\%}$
$\sigma/\sigma^{\mathrm{SM}}$	4.25	2.27	1	0.445	0.422	0.601	3.05
$\sigma/\sigma_{\mathrm{NLO}}$	1.13	1.13	1.12	1.11	1.12	1.15	1.16

$\mathrm{NNLO_{NLO-i}}$ corrections show rather mild dependence on λ_3

Higgs Self-Coupling from Single Higgs Production

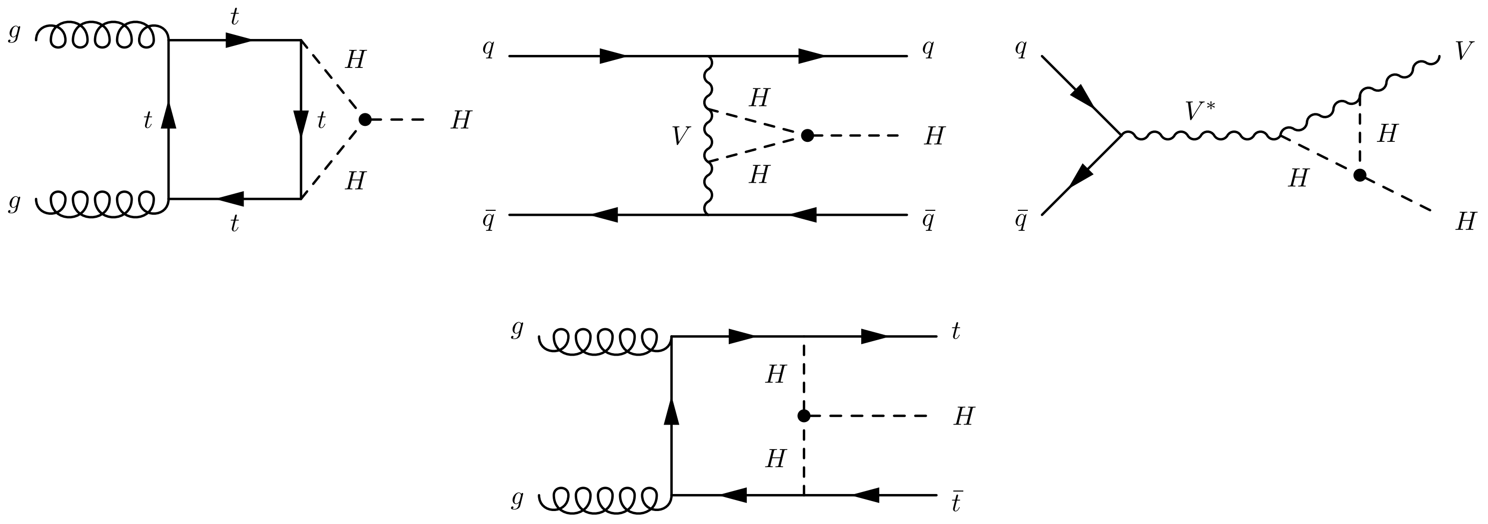
So far focused on HH production where λ_3 appears at LO
Can also constrain this coupling from high-order effects in single Higgs production

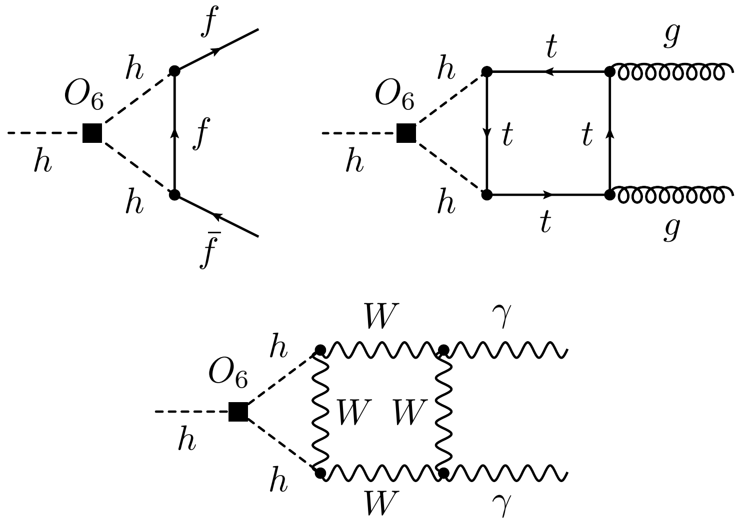


E.g. can constrain λ_3 below HH threshold from EW corrections to $e^+e^- \to ZH$

McCullough 13

At LHC, λ_3 appears in main Higgs production and decay channels

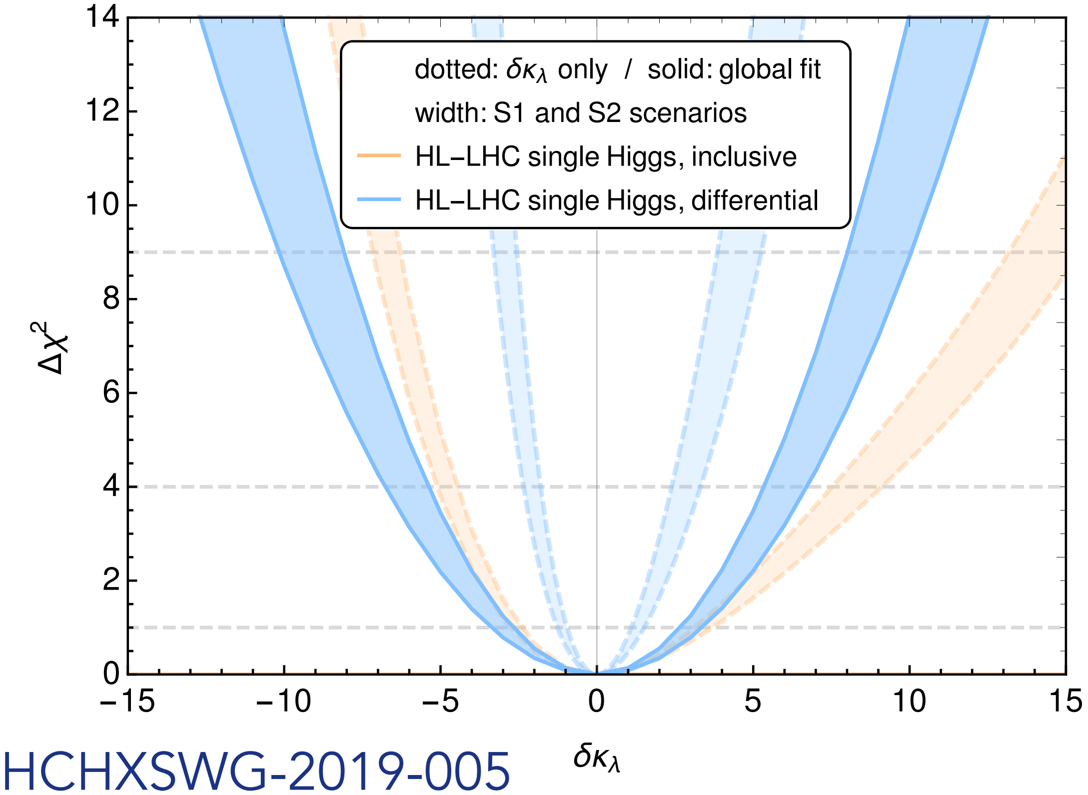


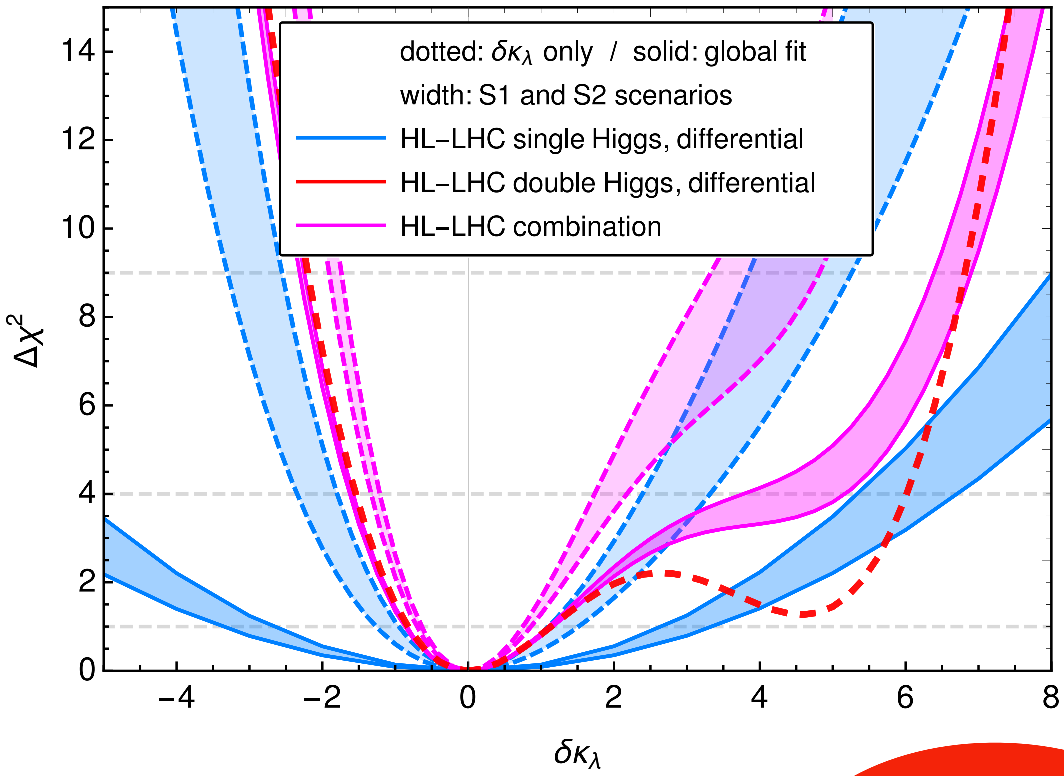


Gorbahn, Haisch 16, 19; Bizon, Gorbahn, Haisch, Zanderighi 16; Degrassi, Giardino, Maltoni, Pagani 16; Maltoni, Pagani, Shivaji, Zhao 17; Di Vita, Grojean, Panico, Riembau, Vantalon 17

Single Higgs Constraints

Assuming that only λ_3 is modified single Higgs can provide very useful constraints





LHCHXSWG-2019-005

Warning:
see EXP talks for updates

Impressive results have already been obtained with current data

Limits on λ_3 from HH production (ATLAS $b\bar{b}b\bar{b}, b\bar{b}\tau^+\tau^-, b\bar{b}\gamma\gamma$)

$\sigma_{\text{tot}} \leq 6.9\sigma_{\text{SM}}$ (95% CL) and $-5.0 < \kappa_\lambda < 12.0$ CERN-EP-2019-099

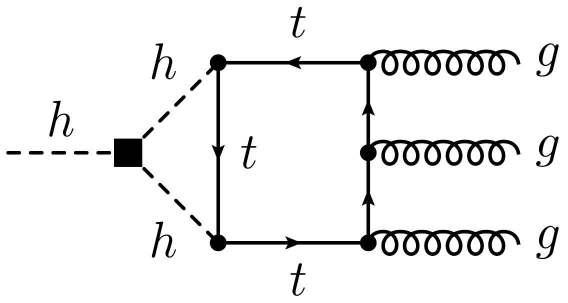
Complementary limits on λ_3 from single Higgs: $-3.2 < \kappa_\lambda < 11.9$

Combination: $-2.3 < k_\lambda < 10.3$

ATL-PHYS-PUB-2019-009
ATLAS-CONF-2019-049

Higgs Self-Coupling from Single Higgs Production

Desirable to have differential effects for gluon fusion: need 2-loop EW diagrams for $pp \to HJ$

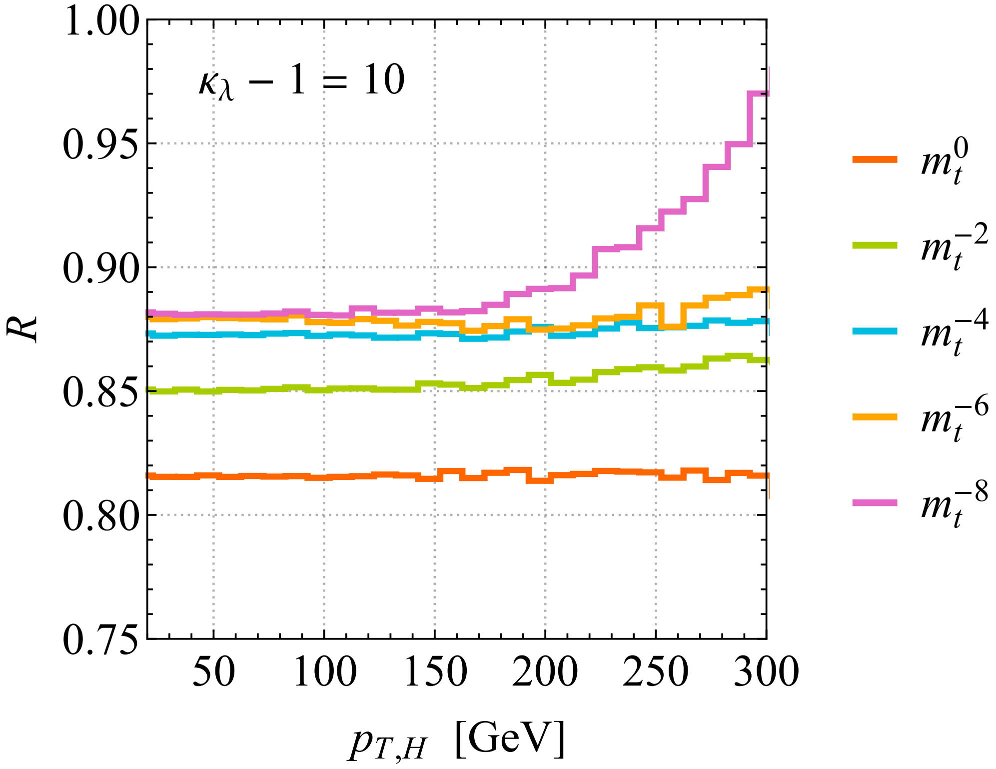


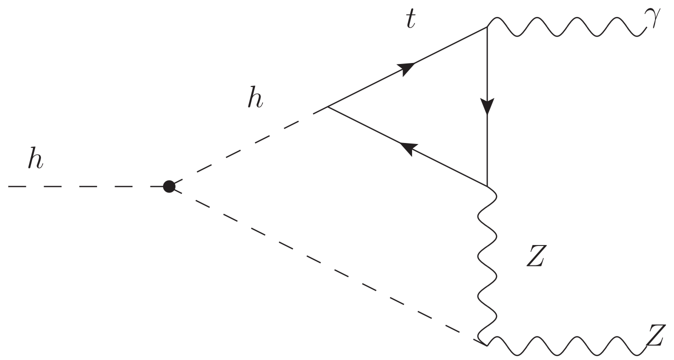
Computed in $1/m_T^2$ expansion (valid for $p_{T,H} < m_T$)

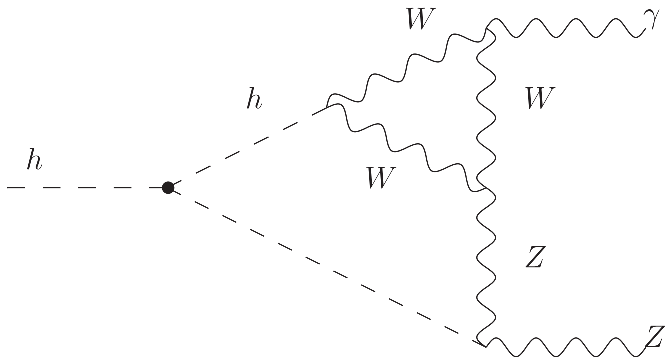
Gorbahn, Haisch 19

Ratio to SM rather flat below top threshold

Interesting to explore λ_3 effects above threshold (?)







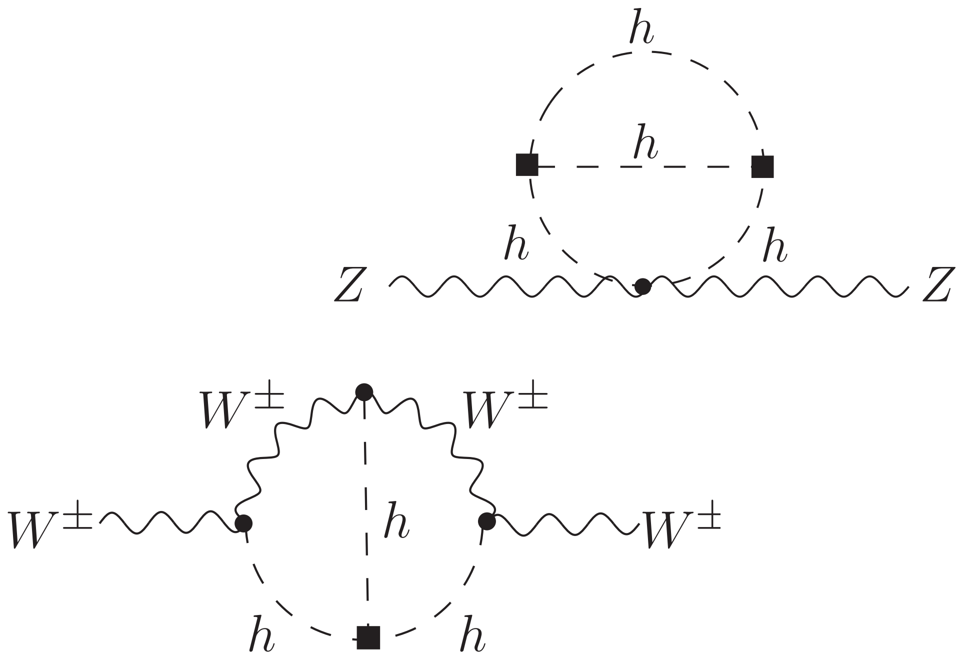
Self-coupling dependent contributions to $h \to \gamma Z$ now known Degrassi, Vitti 19

2-loop diagrams computed in a small external momentum expansion

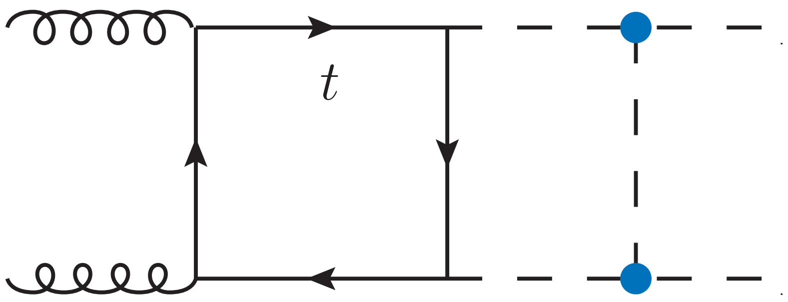
Sensitivity of $\Gamma(h \to \gamma Z)$ & BR to λ_3 found to be similar to $h \to WW$

Higgs Self-Coupling from Single Higgs Production

Can also constrain λ_3 by considering the modification of precision EW observables (EW oblique corrections) S, T



Weaker bounds than single Higgs production:
$-14.0 \leq \kappa_\lambda \leq 17.4$ (but complementary)
Degrassi, Fedele, Giardino 17;
Kribs, Maier, Rzehak, Spannowsky, Waite 17;



Aside: can play similar games with HH to set indirect limits on λ_4 from (partial) EW corrections to HH

Bizon, Haisch, Rottoli 18; Borowka, Duhr, Maltoni, Pagani, Shivaji, Zhao 18

Important caveat: If λ_3 is modified by BSM physics we may expect other Higgs couplings to be affected, can have drastic effects on indirect constraints, need to be careful how we interpret deviations (+global EFT approach motivated)
Di Vita, Grojean, Panico, Riembau, Vantalon 17

Summary

Incredible progress in HH theory over the last few years

- Gluon fusion - Full SM result: NLO
- Gluon fusion - HTL result: N^{3}LO (also differential)
- Vector Boson Fusion - N^{3}LO inclusive, NNLO differentially + NLO EW
- Progress matched by amazing work from the experiments

Uncertainties beyond scale variations are becoming relevant

- Mass scheme uncertainties at the level of >10% percent @ NLO
- Motivates studies of m_T dependence beyond 2-loop

Combination with constraints from single Higgs production & EW precision observables can improve λ_3 determination

Many other fascinating developments were not covered in this talk (e.g. prospects at future collider prospects, EFT fits, …)

See talks of Konstantinos Nikolopoulos, Michele Selvaggi & Shankha Banerjee from this morning

Thank you for listening

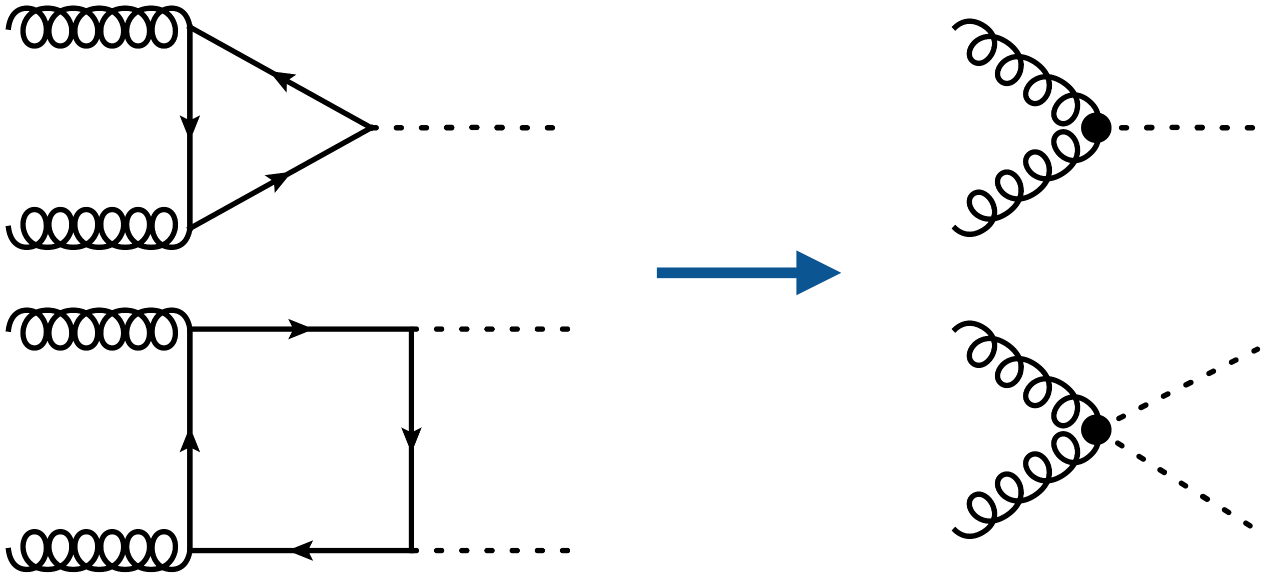
Backup

Heavy Top Limit

Heavy Top Limit (HTL): $m_T \to \infty$

Effective tree-level couplings between gluons and Higgs

Lowers number of loops by 1



HTL valid for: $\sqrt{\hat{s}} \ll 2m_T$

HH production for: $2m_H < \sqrt{\hat{s}}$

HJ: high p_T not well described

Born improved NLO HTL:

$$\mathrm{d}\sigma_{\mathrm{NLO}}(m_T) \approx \mathrm{d}\bar{\sigma}_{\mathrm{NLO}}(m_T) \equiv \underbrace{\frac{\mathrm{d}\sigma_{\mathrm{LO}}(m_T)}{\mathrm{d}\sigma_{\mathrm{LO}}(m_T \to \infty)}}_{\mathrm{N}} \mathrm{d}\sigma_{\mathrm{NLO}}(m_T \to \infty)$$

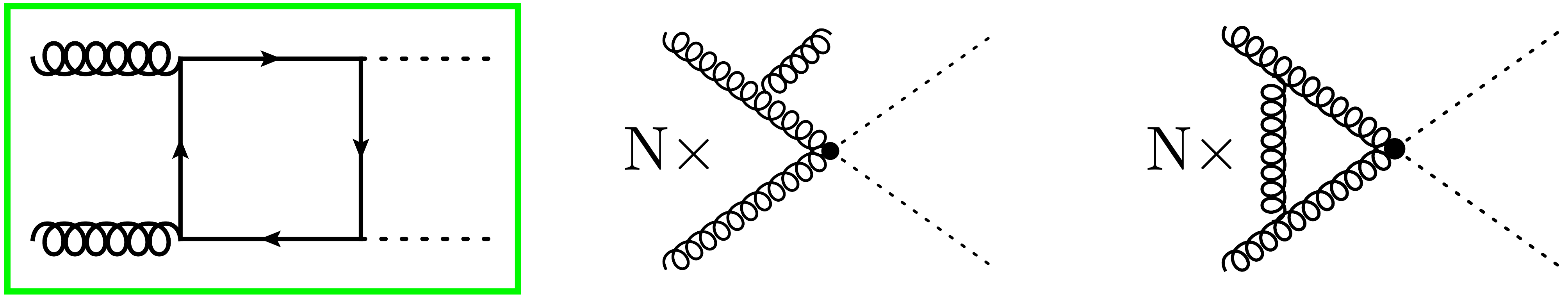
Spira et al. (HPAIR)

HH Approximations @ NLO (Schematically)

B R V

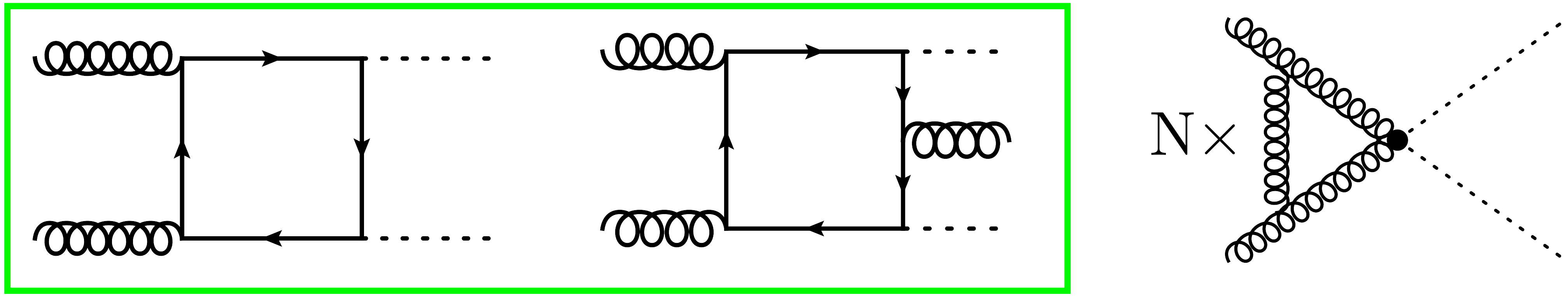
B-i HTL:

Dawson,
Dittmaier, Spira 98

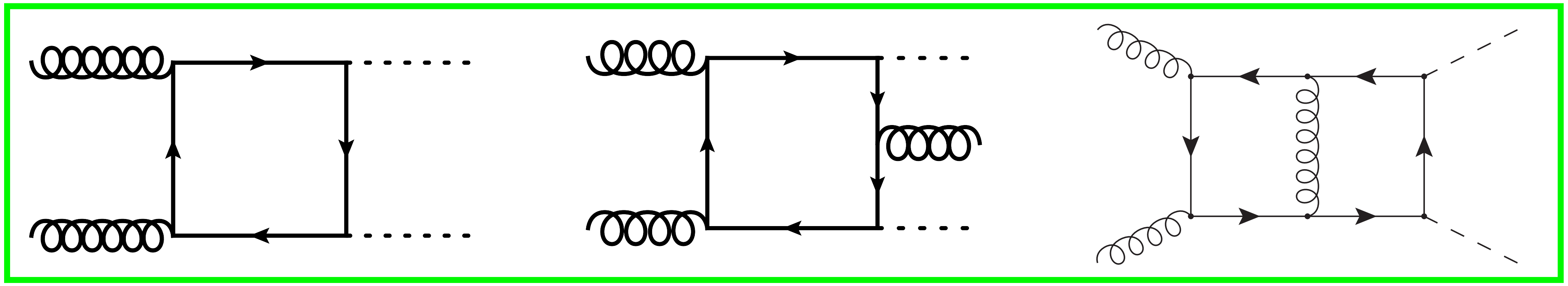


FTapprox:

Maltoni, Vryonidou,
Zaro 14



Full Theory:

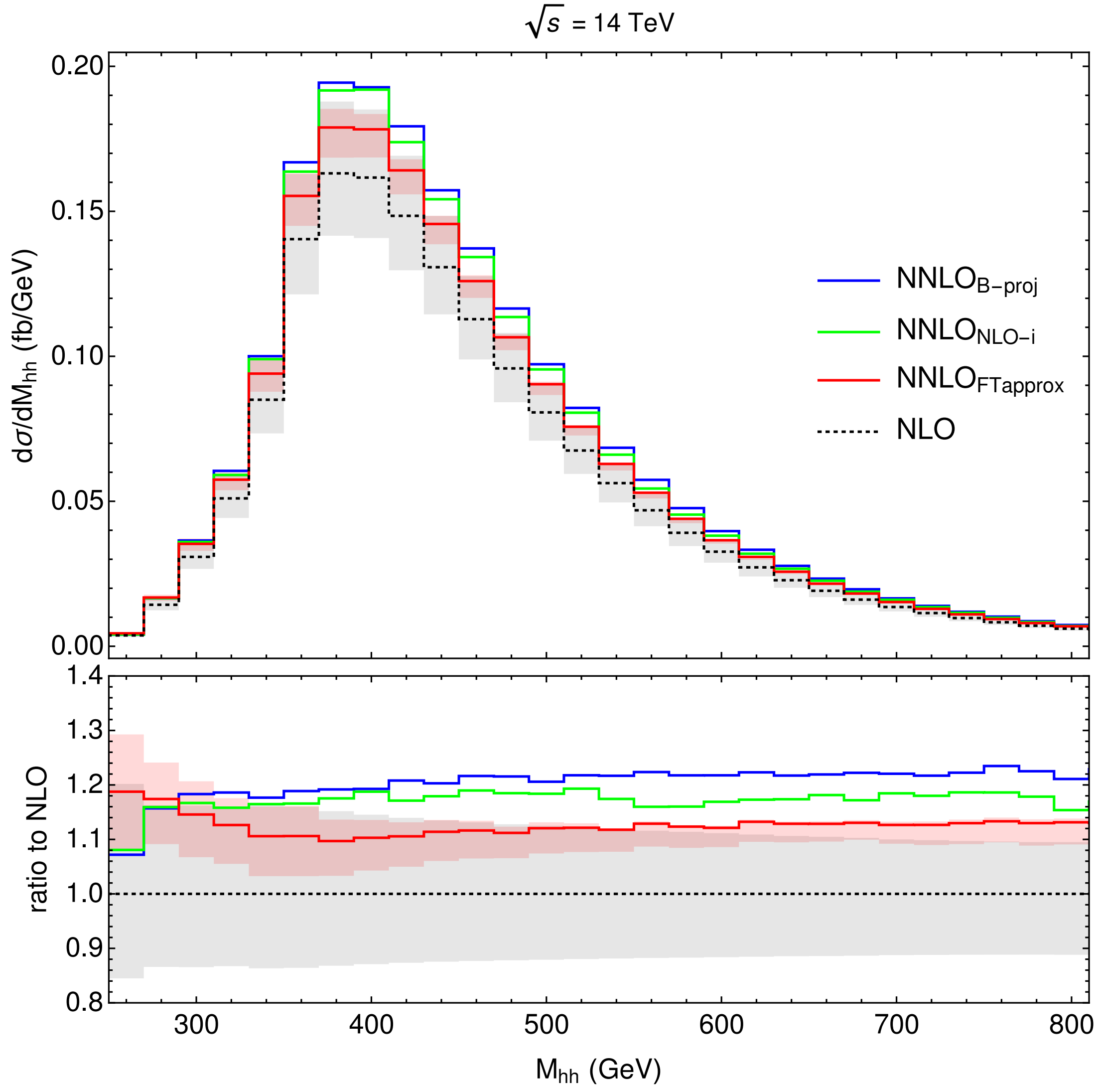


Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16;
Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16;
Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18;

HH: NNLO HTL Combined with NLO SM

Differential NNLO HTL + NLO SM

Top quark mass effects studied using 3 different approximations



Grazzini, Heinrich, SJ, Kallweit, Kerner, Lindert, Mazzitelli 18; (+NNLL) de Florian, Mazzitelli 18;

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
NLO [fb]	$27.78^{+13.8\%}_{-12.8\%}$	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$	$1147^{+10.7\%}_{-9.9\%}$
NLO$_{\text{FTapprox}}$ [fb]	$28.91^{+15.0\%}_{-13.4\%}$	$34.25^{+14.7\%}_{-13.2\%}$	$134.1^{+12.7\%}_{-11.1\%}$	$1220^{+11.9\%}_{-10.6\%}$
NNLO$_{\text{NLO-i}}$ [fb]	$32.69^{+5.3\%}_{-7.7\%}$	$38.66^{+5.3\%}_{-7.7\%}$	$149.3^{+4.8\%}_{-6.7\%}$	$1337^{+4.1\%}_{-5.4\%}$
NNLO$_{\text{B-proj}}$ [fb]	$33.42^{+1.5\%}_{-4.8\%}$	$39.58^{+1.4\%}_{-4.7\%}$	$154.2^{+0.7\%}_{-3.8\%}$	$1406^{+0.5\%}_{-2.8\%}$
NNLO$_{\text{FTapprox}}$ [fb]	$31.05^{+2.2\%}_{-5.0\%}$	$36.69^{+2.1\%}_{-4.9\%}$	$139.9^{+1.3\%}_{-3.9\%}$	$1224^{+0.9\%}_{-3.2\%}$
M_t unc. NNLO$_{\text{FTapprox}}$	±2.6%	±2.7%	±3.4%	±4.6%
NNLO$_{\text{FTapprox}}$/NLO	1.118	1.116	1.096	1.067

1) NNLO$_{\text{NLO-i}}$

Rescale NLO by K$_{\text{NNLO}}$ = NNLO$_{\text{HTL}}$/NLO$_{\text{HTL}}$

2) NNLO$_{\text{B-proj}}$

Project real radiation contributions to Born configurations, rescale by LO/LO$_{\text{HTL}}$

3) NNLO$_{\text{FTapprox}}$

NNLO HTL correction rescaled for each multiplicity by:

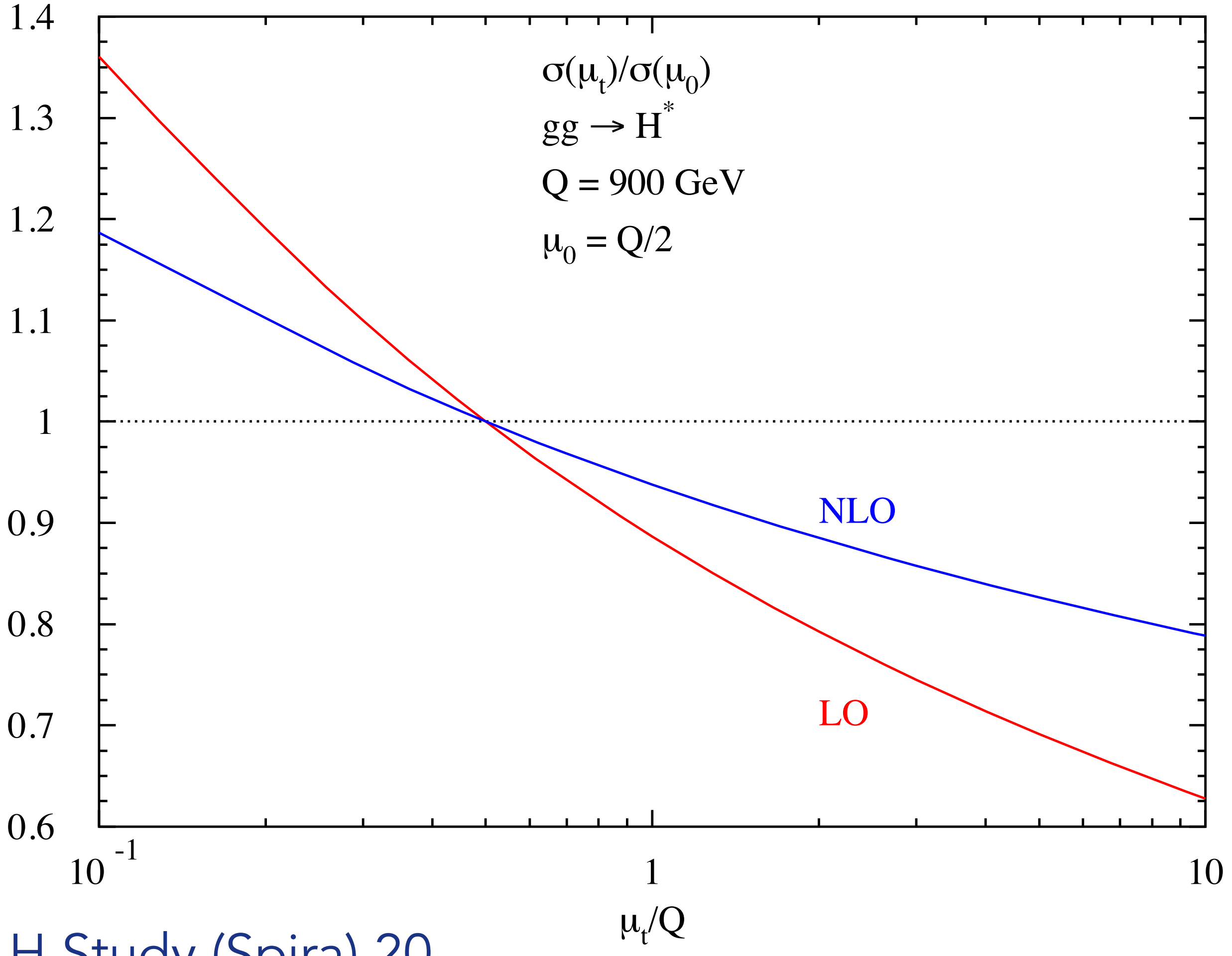
$$\mathcal{R}(ij \to HH + X) = \frac{\mathcal{A}^{\text{Born}}_{\text{Full}}(ij \to HH + X)}{\mathcal{A}^{(0)}_{\text{HEFT}}(ij \to HH + X)}$$

Mass Scheme Dependence

H* Mass Scheme Uncertainties

LH study of mass scheme dependence currently being finalised, attempts to highlight the issue by examining: H*, HH, HJ, ZZ

Consider $gg \to H^*$ @ $Q = 900$ GeV:



LH Study (Spira) 20

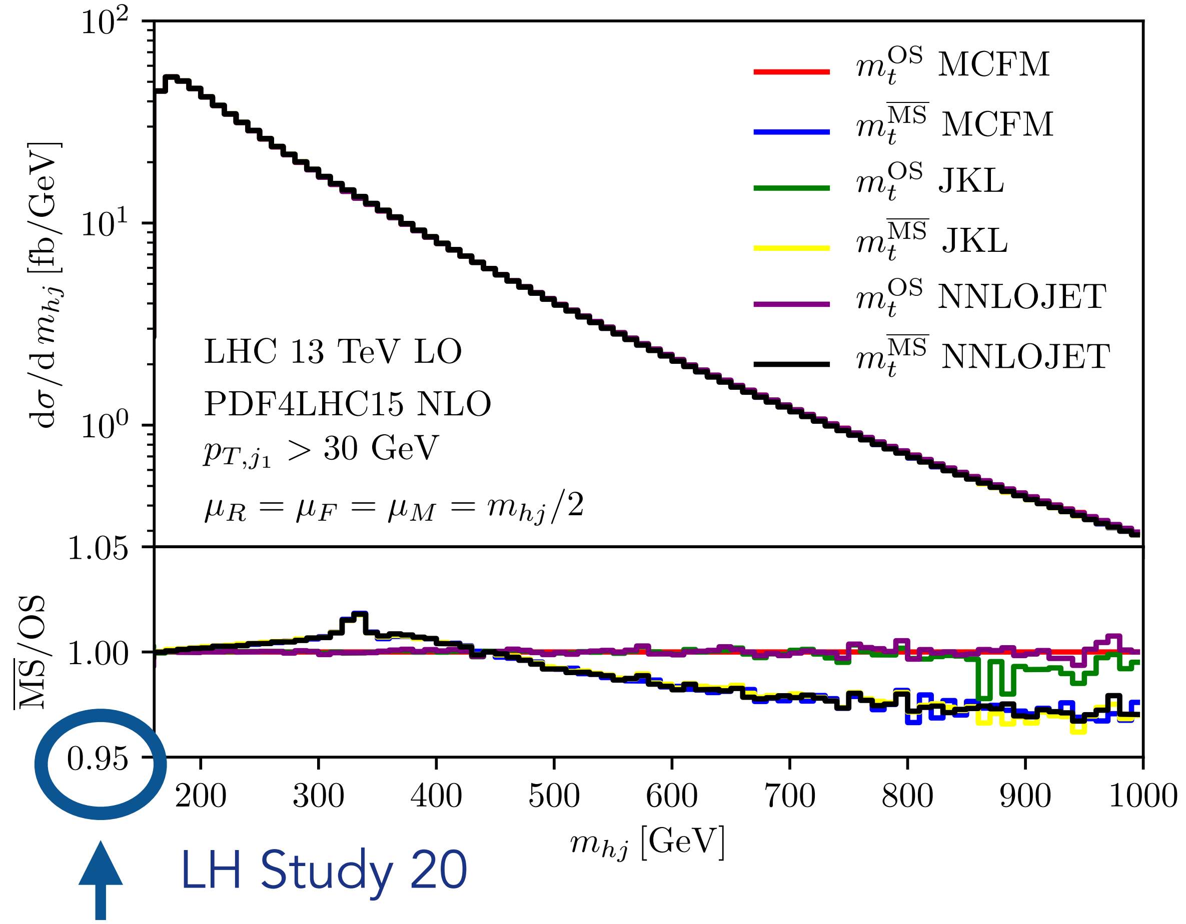
$\sigma(gg \to H^*)$ [pb]	$Q = 125$ GeV	$Q = 900$ GeV
LO	$18.43^{+0.8\%}_{-1.1\%}$	$0.139^{+0.0\%}_{-36.0\%}$
NLO	$42.17^{+0.4\%}_{-0.5\%}$	$0.230^{+0.0\%}_{-22.3\%}$

Similarly to HH production, m_T scheme dependence reduced by "only" factor ~2

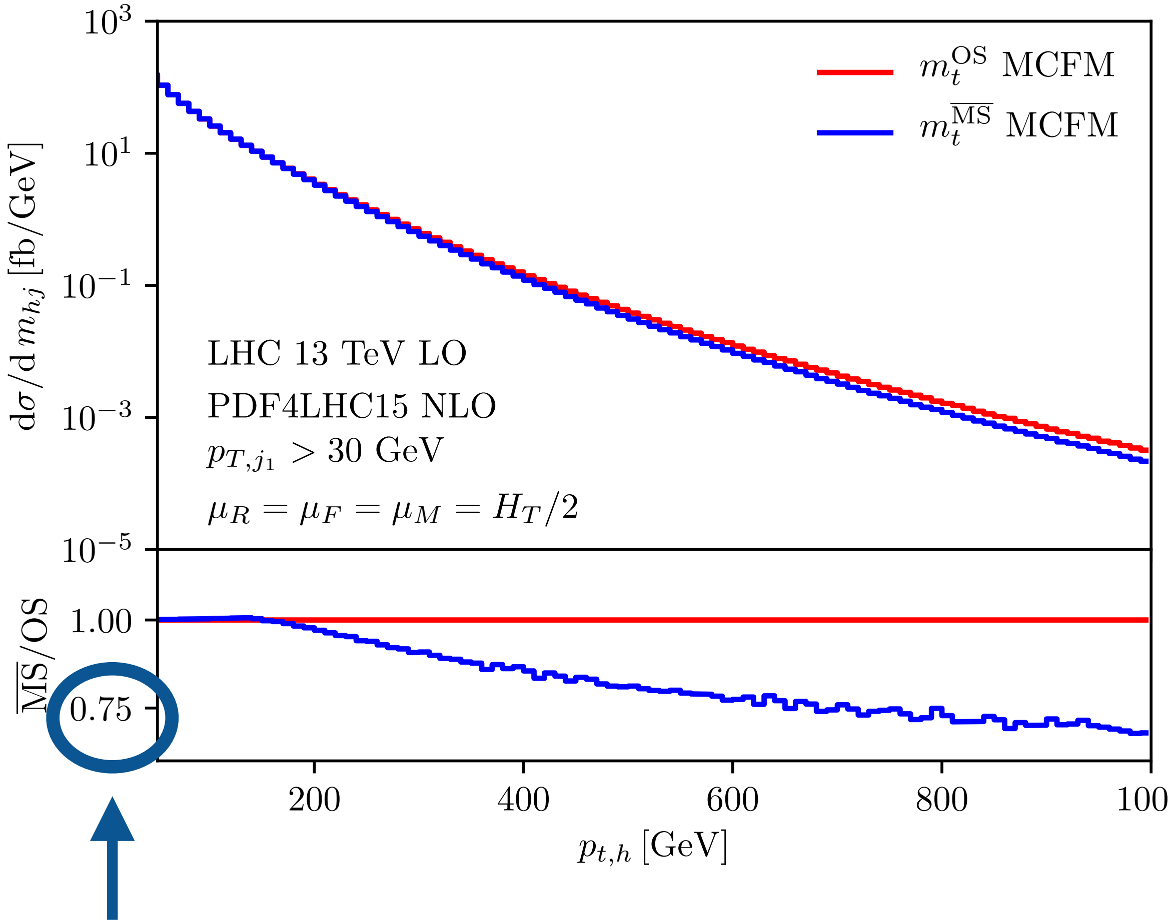
Note: For on-shell $H(125)$ production uncertainty is tiny

Suggests that mass scheme uncertainties could be quite sizeable for many (loop-induced) Higgs processes with scales $\gtrsim m_T$

HJ Mass Scheme Uncertainties



LH Study 20



Mass scheme uncertainty hugely different for each distribution

Suspicion: m_{hj} is mostly not probing the top quark loop above threshold, smaller sensitivity to mass effects (?)