Karlsruhe Institute of Technology

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Precision Higgs physics: theory

Gudrun Heinrich

Institute for Theoretical Physics,
Karlsruhe Institute of Technology

LHCP 2022

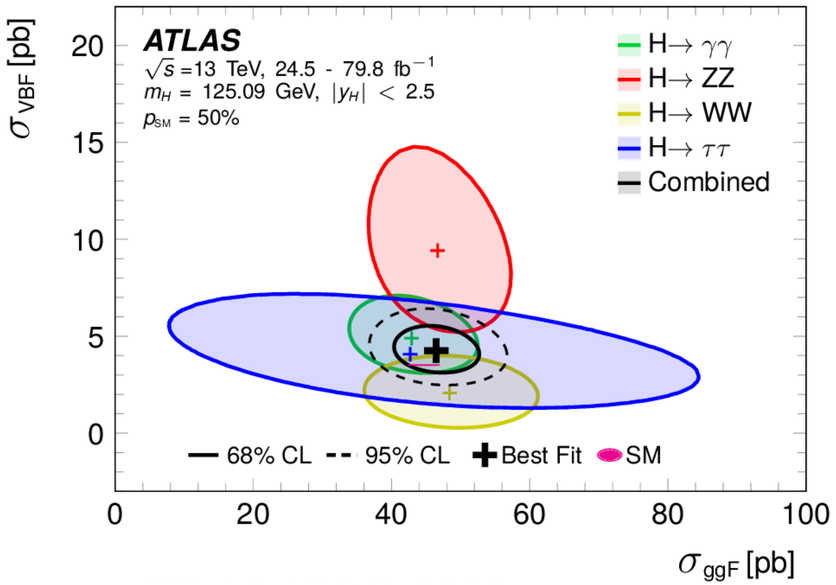
Taipei/Zoom 18.05.2022

Motivation

opinionatedgamers.com

- the Higgs boson is close to its 10th anniversary, mass measured to permil level
- we are in the era of precision physics: LHCP ⟶ “LHC Precision”:
- *aim:* distinguish small indirect signs of New Physics from deficiencies in modelling (e.g. missing higher orders, parton shower uncertainties, mass effects, PDF uncertainties, etc.)
- Higgs sector is “young” ⟶ transition from *“Higgs Hunter’s Guide”* to *“Higgs as a Guide to New Phenomena”*
- focus points: signal strengths, couplings, differential observables

Higgs as a guide

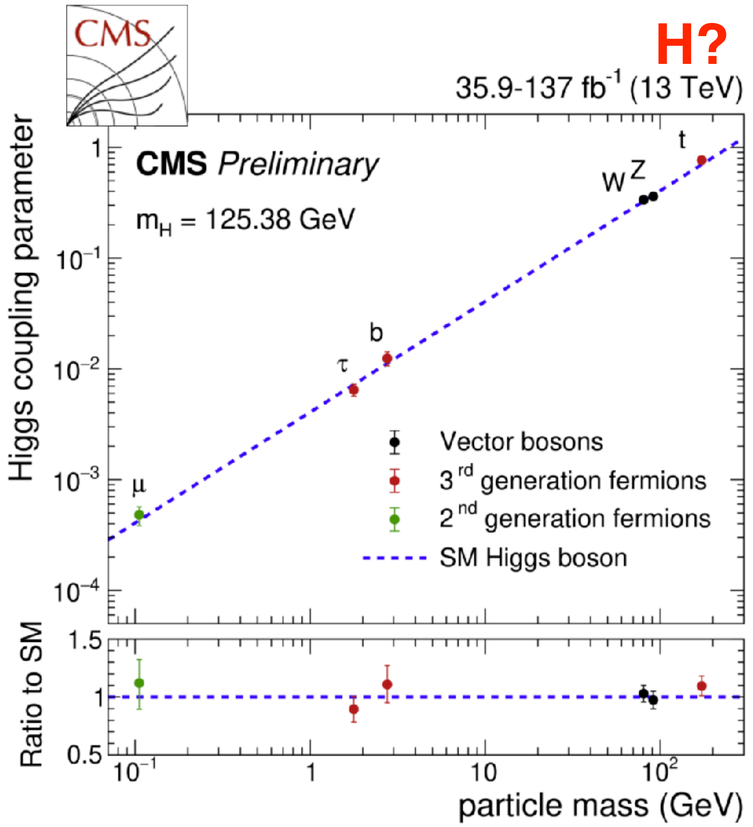


ATLAS-HIGG-2018-57

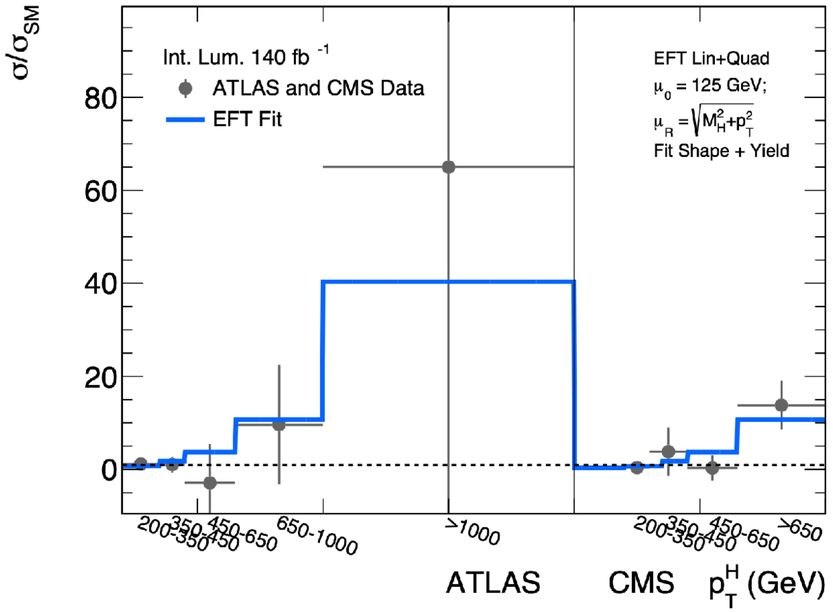
cross sections/decay rates

couplings

CMS PAS HIG-19-006



distributions

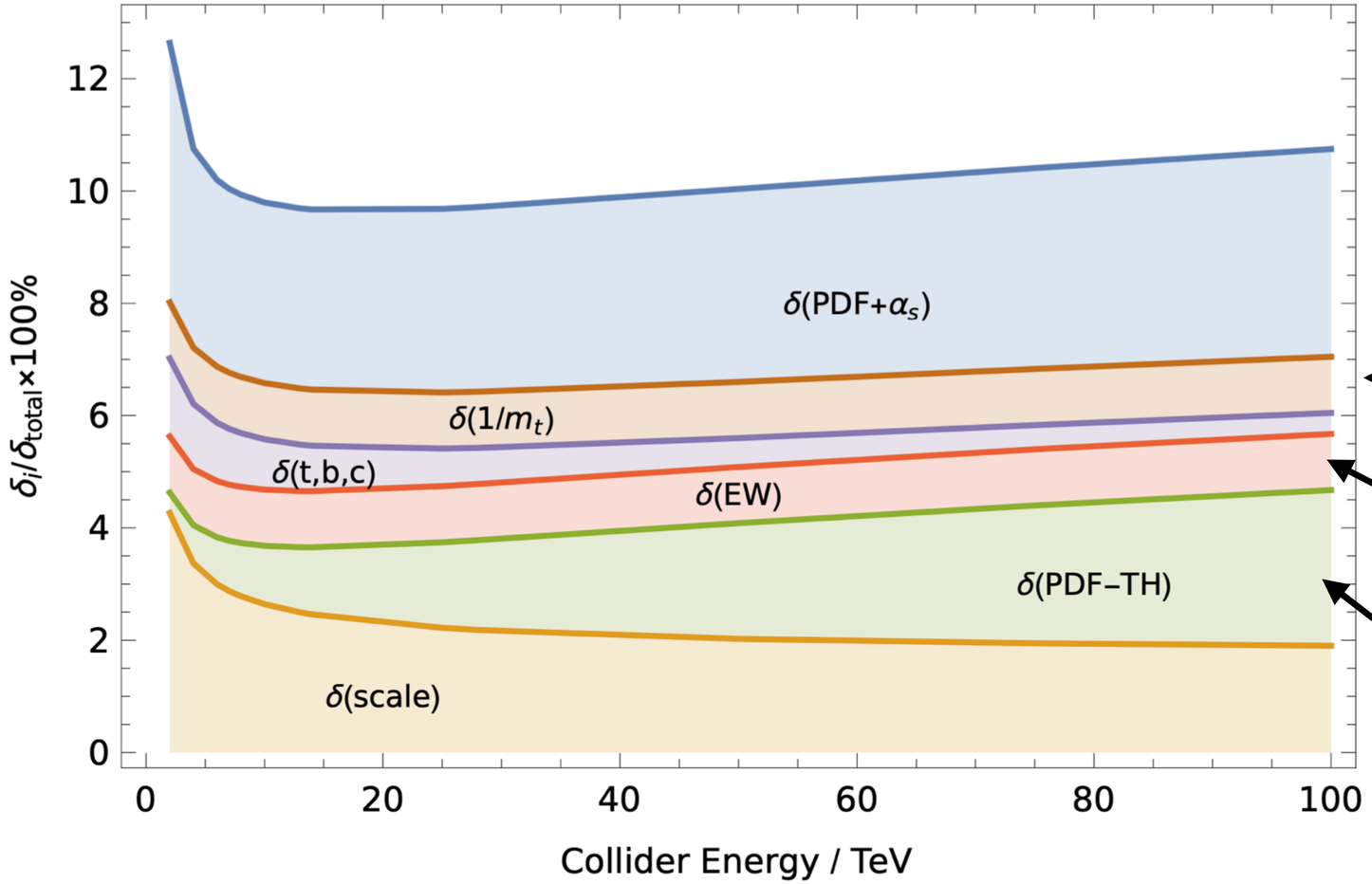


best fit $c_g = -0.08, c_{tg} = -0.13$

Battaglia, Grazzini, Spira, Wiesemann ‘21

Higgs production in gluon fusion

uncertainty budget Dulat, Lazopoulos, Mistlberger ‘18



basically removed recently
Czakon, Harlander, Klappert, Niggetiedt ‘20

reduced substantially
Bechetti et al ’20, ’21, Bonetti et al ’18, ’20, ‘22

mismatch between PDF (NNLO) and ME (N3LO)

Higgs production in gluon fusion

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

missing N3LO PDFS

light quark and mass scheme effects

improved: approximate N4LO corrections

Das, Moch, Vogt ‘20

removed

B. Mistlberger ‘18

reduced to ~0.6%

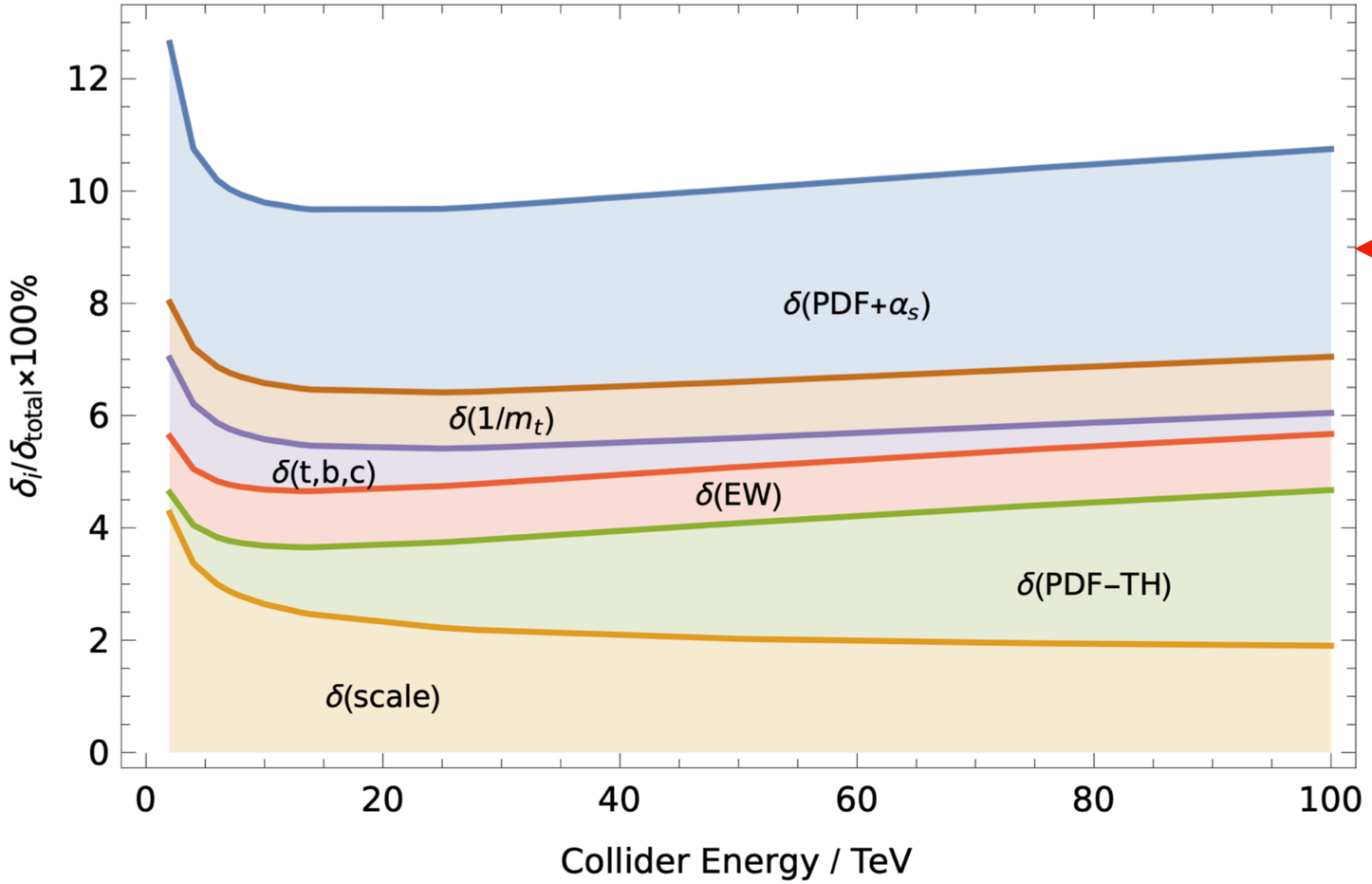
Bechetti et al ’20, ’21, Bonetti et al ’18, ’20, ‘22

reduced, -0.26%

Czakon, Harlander, Klappert, Niggetiedt ‘20

Higgs production in gluon fusion

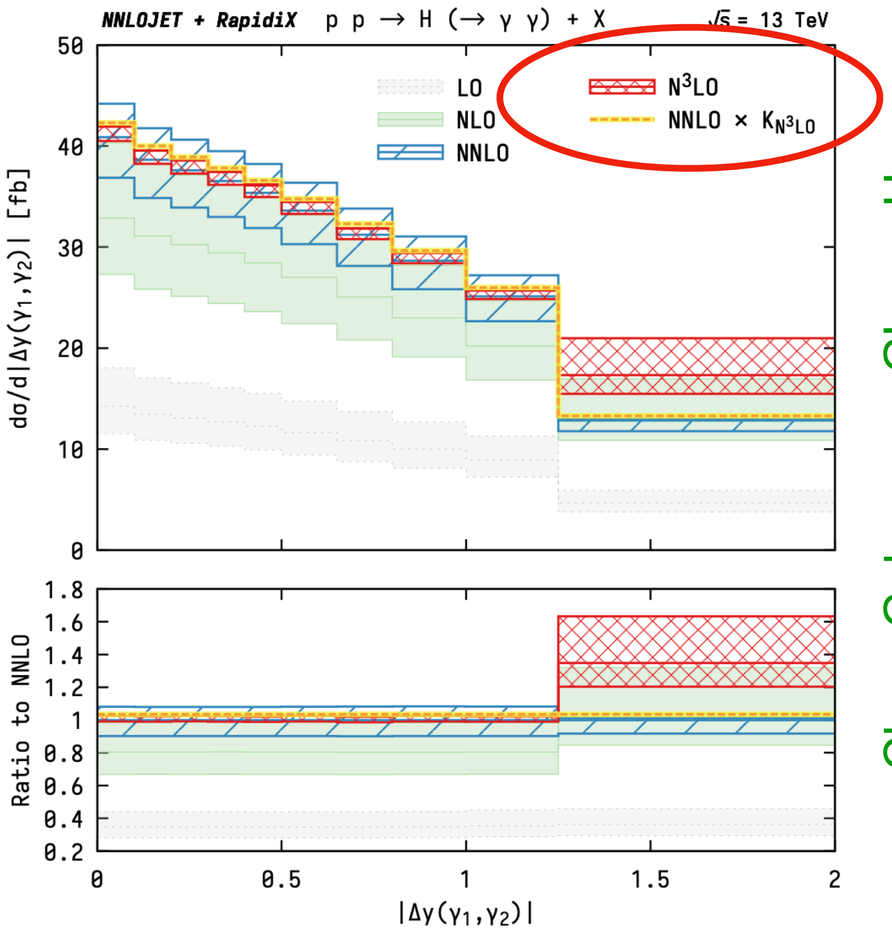
uncertainty budget Dulat, Lazopoulos, Mistlberger ‘18



← **the elephant in the room!**

see e.g. talk by Pavel Nadolski

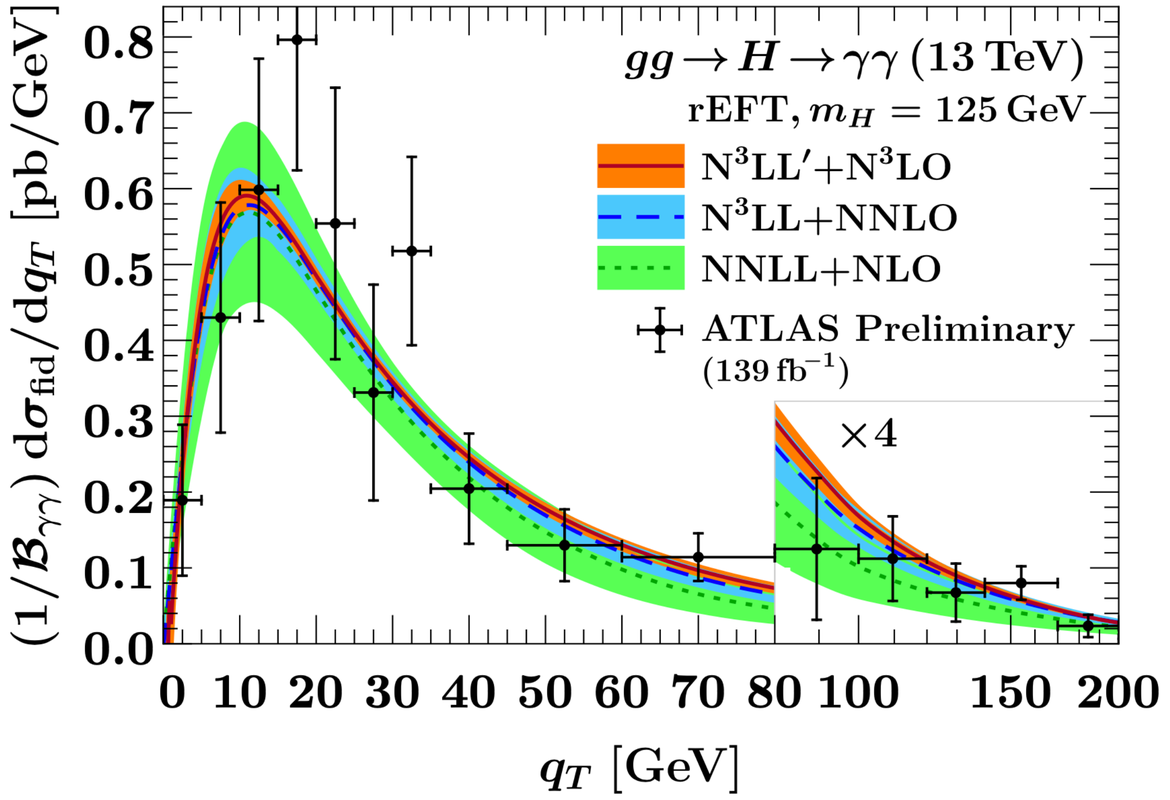
gg -> H: highest orders fiducial



Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni, 2102.07607

differential information important

$$pp \to H \to \gamma\gamma$$

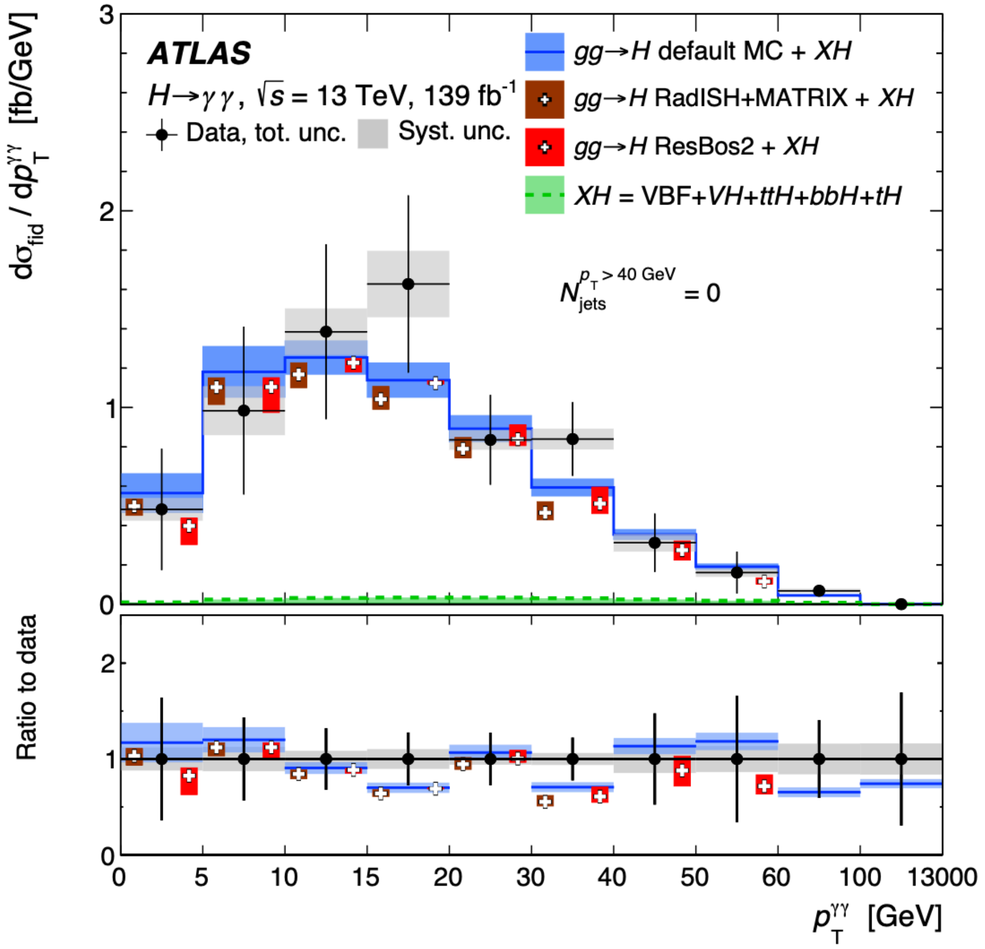


Billis, Dehnadi, Ebert, Michel, Tackmann, 2102.08039

scale uncertainties not the dominant uncertainties anymore

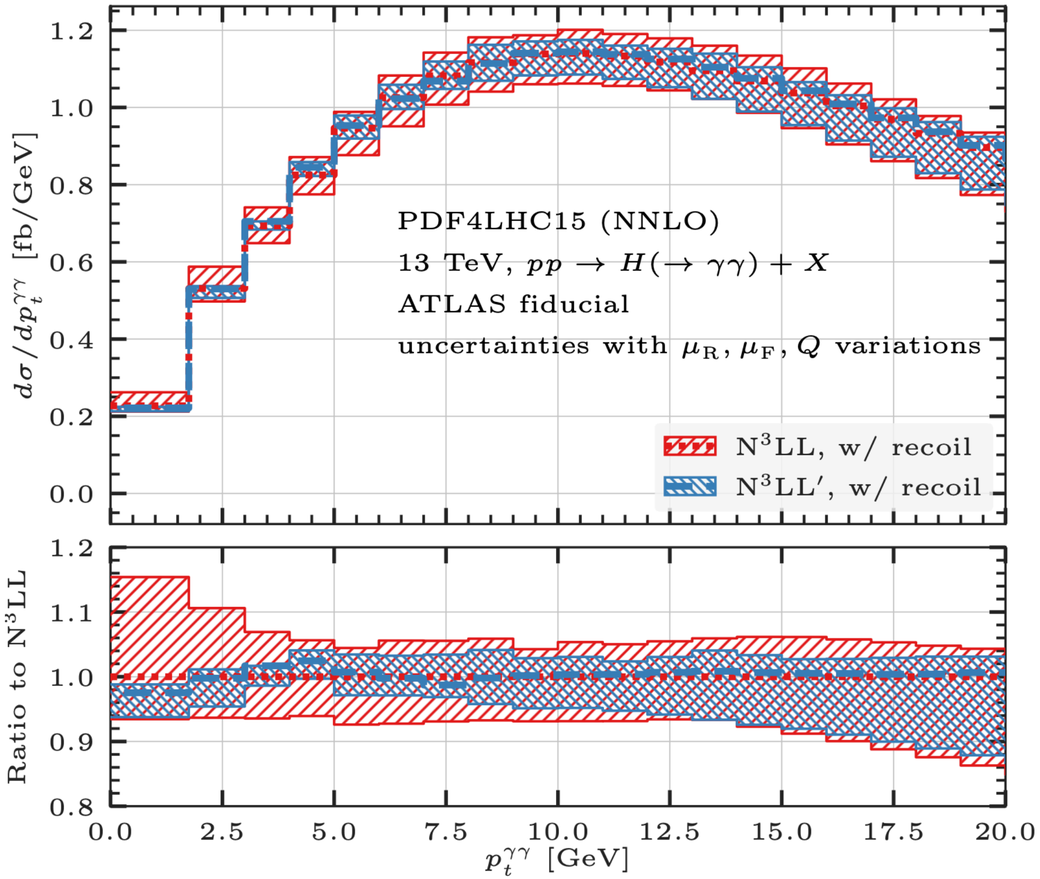
gg -> H: high orders + resummation

ATLAS 2202.00487



resum logarithms of type $\ln(p_T^{\gamma\gamma}/m_H)$ to control region of small $p_T^{\gamma\gamma}$

(important region e.g. for light quark Yukawa couplings)

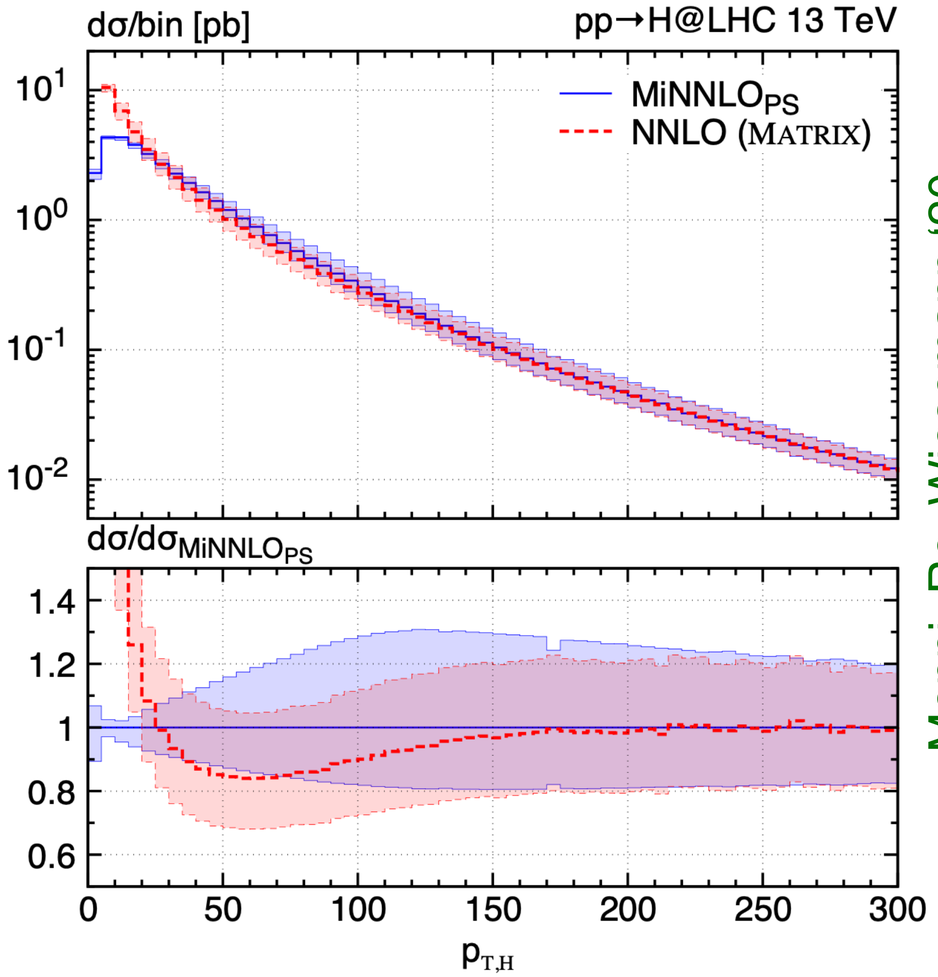


Re, Rotttoli, Torrielli ’21 (RadISH)

N3LL’: include all constant terms up to $\mathcal{O}(\alpha_s^3)$

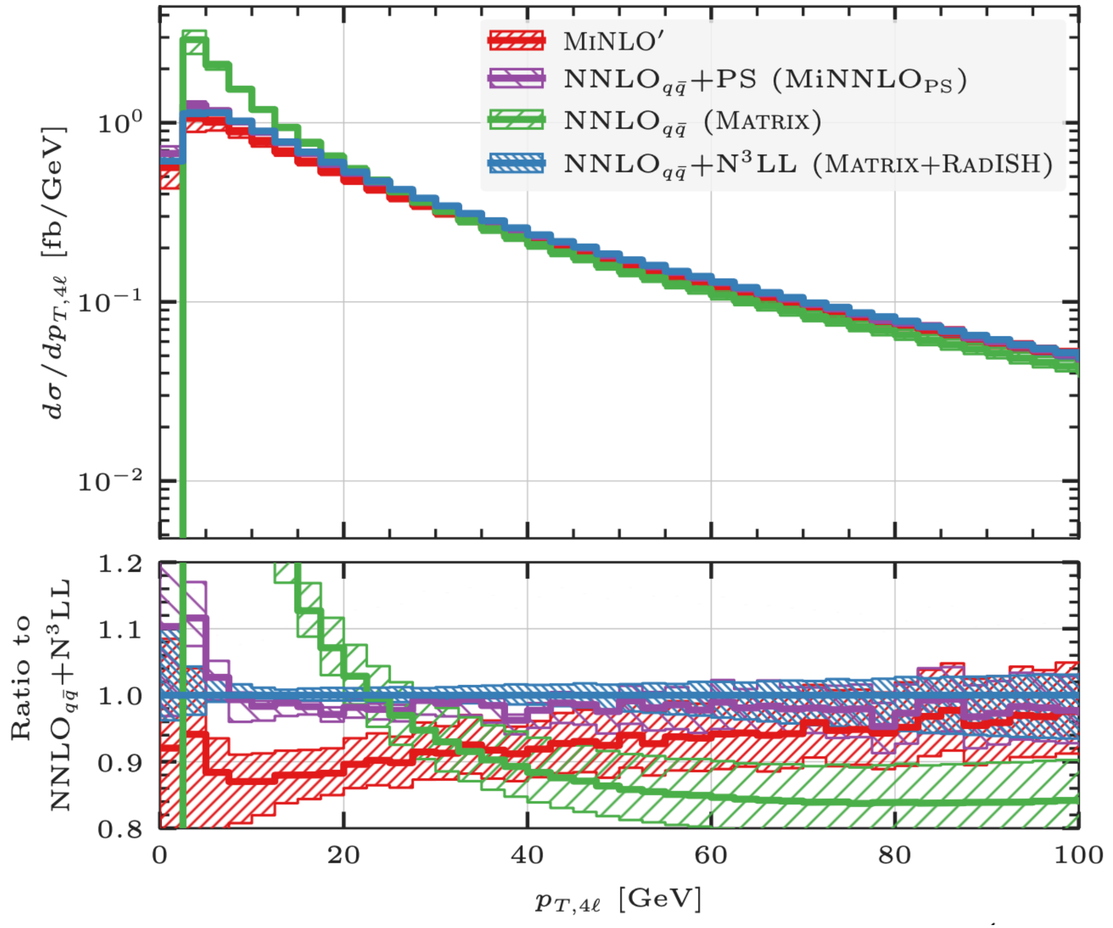
(e.g. 3-loop hard-virtual coefficient)

NNLO + parton shower



Monni, Re, Wiesemann '20

importance of resummation at low pT

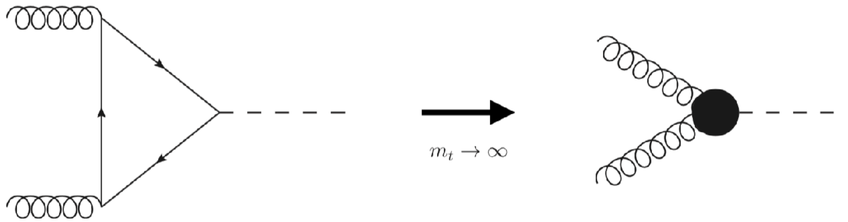


Buonocore, Chiesa, Koole et al. '22

ZZ production (background to $H \to 4l$)

gg -> H: top quark mass effects

N3LO results have been obtained in heavy top limit (HTL)



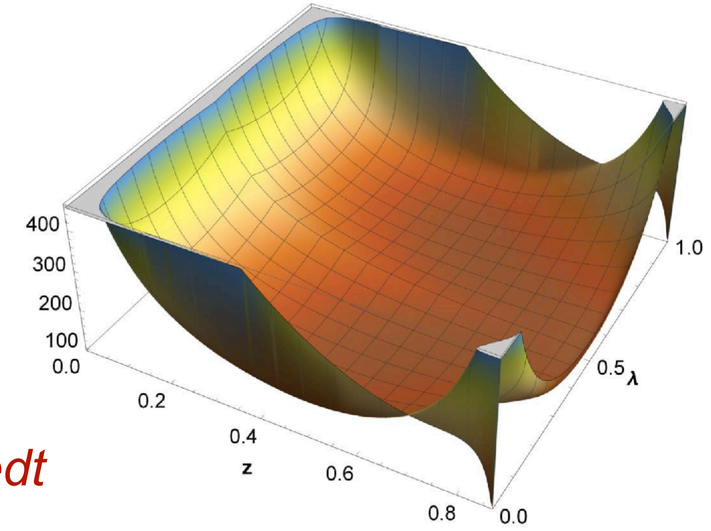
now available:

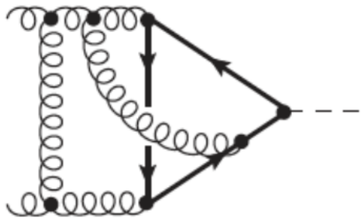
full top mass effects at NNLO

Czakon, Harlander, Klappert, Niggetiedt ‘20

-0.26% @13TeV

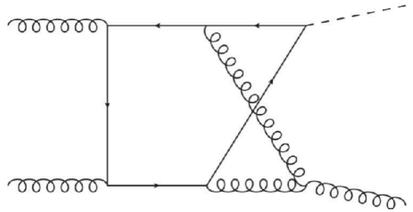
relative to HTL





virtual 3-loop

Davies, Gröber, Maier, Rauh ’19; Czakon, Niggetiedt ‘20



real-virtual

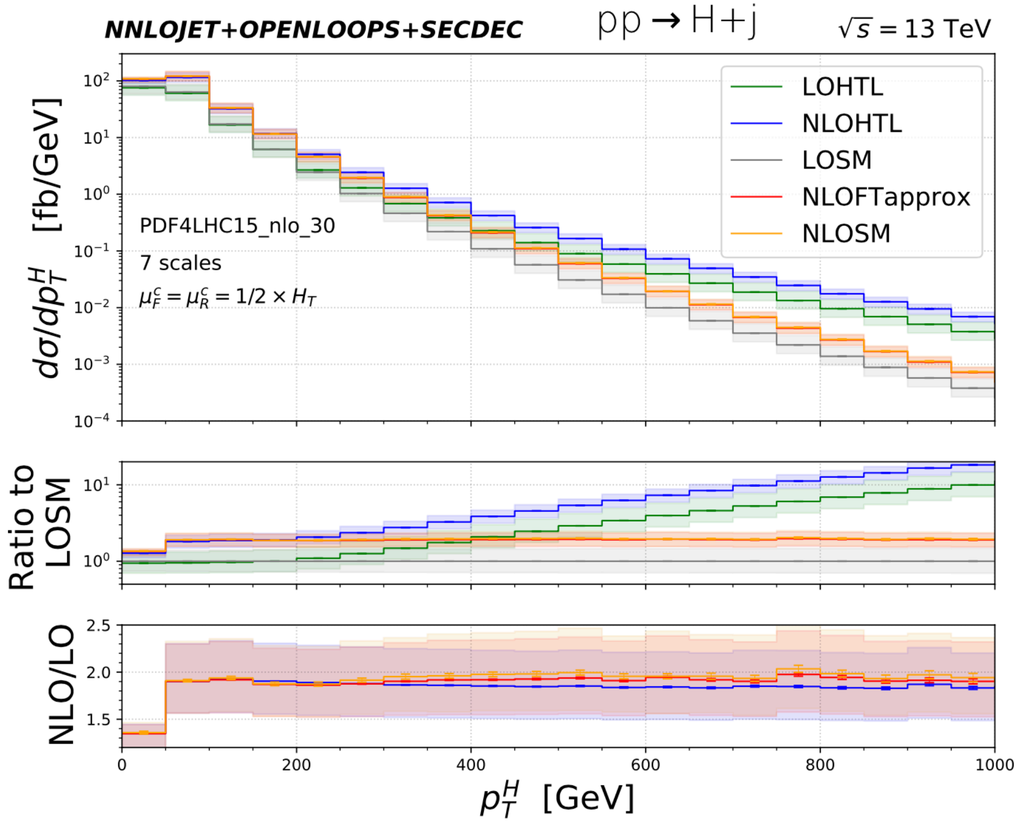
recalculated by Czakon et al see also Jones, Kerner, Luisoni ’18; Frellesvig, Hidding et al ‘19

numerical results for integrals

see talk by Marco Niggetiedt

Higgs+jet

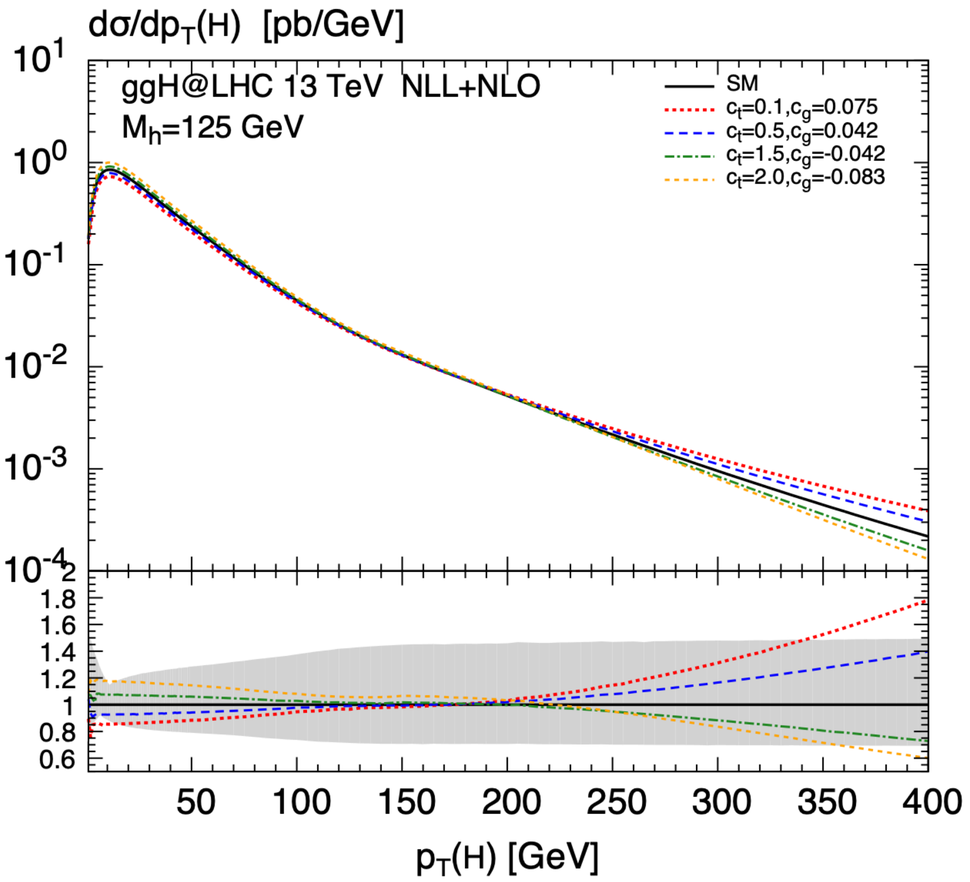
Chen, Huss, Jones, Kerner, Lang, Lindert, Zhang ‘21



HTL: wrong scaling in the tail, FTapprox: within 5% of full

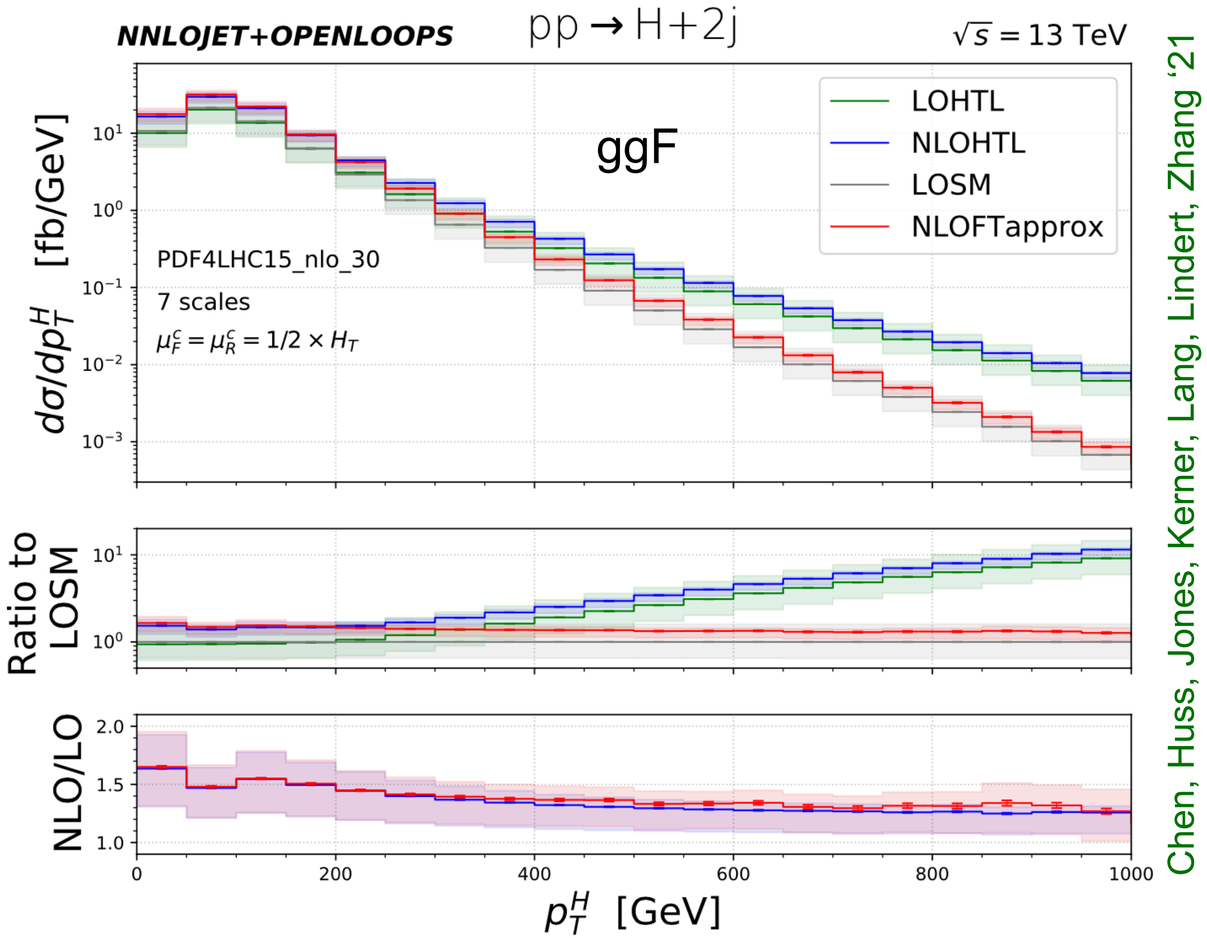
NLO scale (and mass scheme) uncertainties $\mathcal{O}(20\%)$

Grazzini, Ilnicka, Spira, Wiesemann ‘16



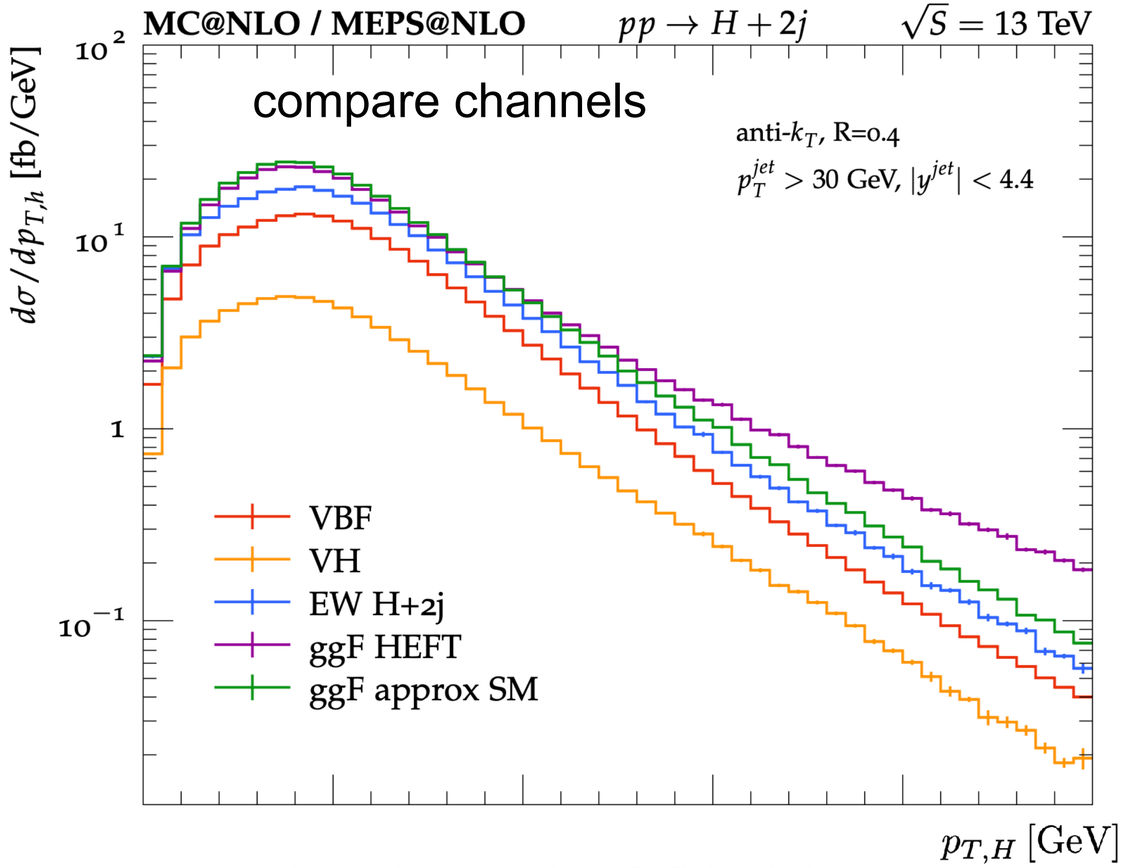
pT-tail important for effects of anomalous couplings

Higgs+2 jets: ggF and VBF



Chen, Huss, Jones, Kerner, Lang, Lindert, Zhang '21

full NLO not available,
FTapprox QCD corrections ~60% at small pT



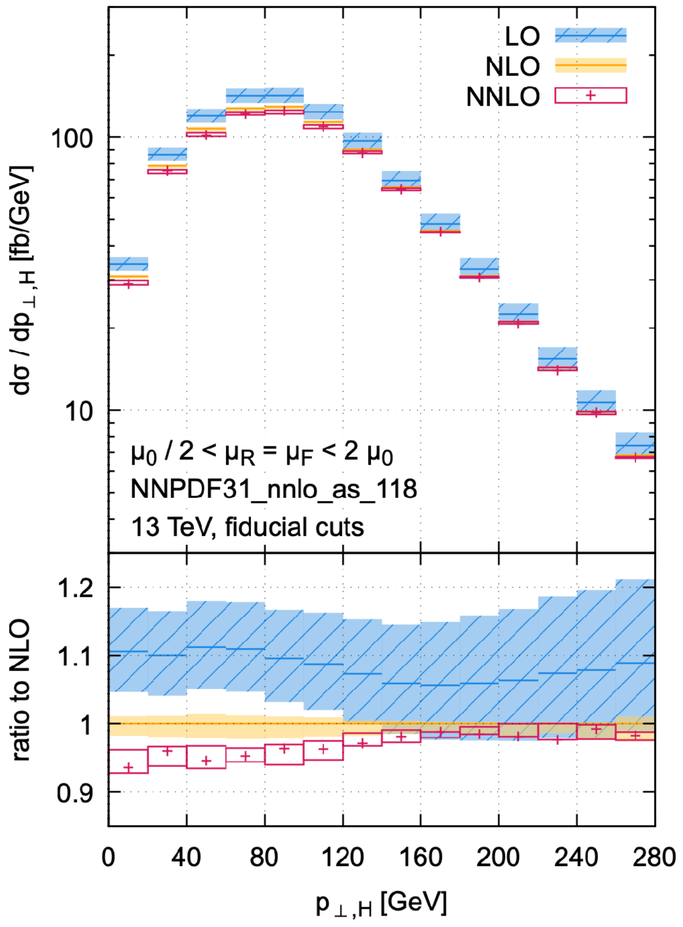
Buckley, Chen, Cruz-Martinez, Ferrario-Ravasio et al. '21

comprehensive study of fiducial cuts,
EW corrections, different tools

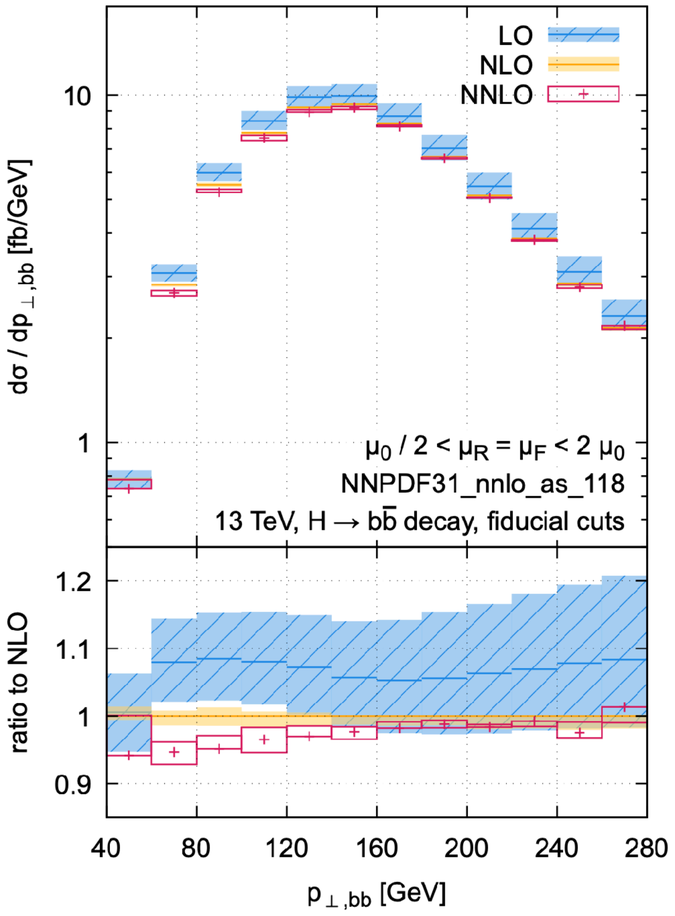
see also talk by Xuan Chen 17.5.

VBF H -> bb at NNLO

Asteriadis, Caola, Melnikov, Röntsch ‘21



including decay (massless b)



difference between

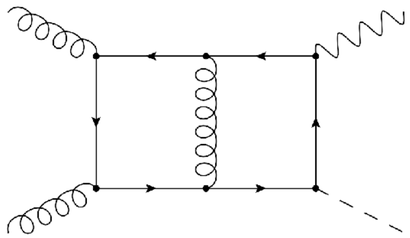
$\sigma^{H}_{NNLO}/\sigma^{H}_{LO}$

and

$\sigma^{b\bar{b}}_{NNLO}/\sigma^{b\bar{b}}_{LO}$

similar to size of NNLO corrections

gg -> Higgs+Z @NLO

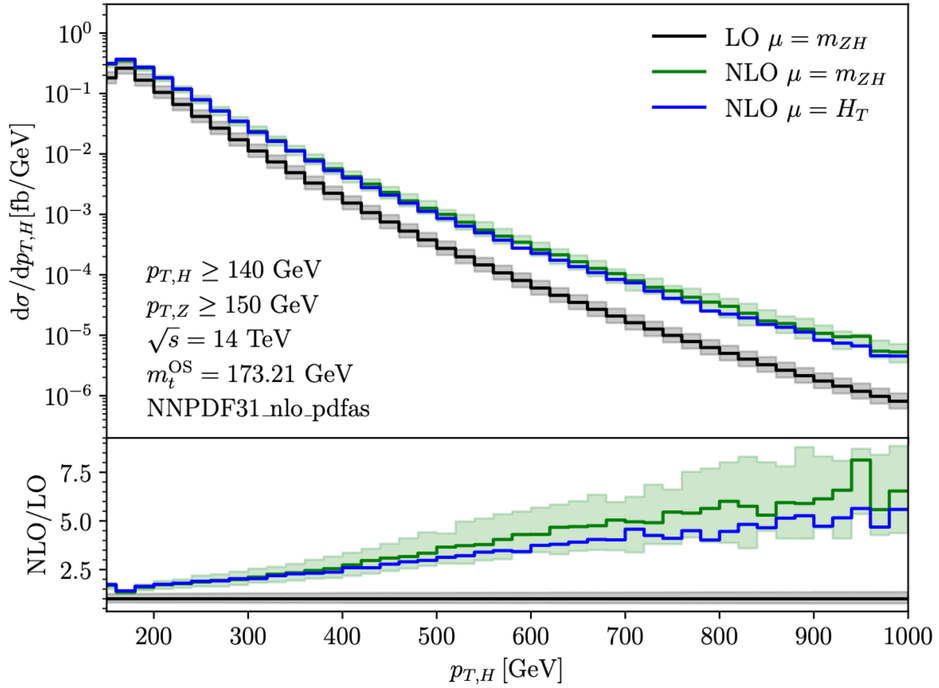


Wang, Xu, Xu, Yang ’21 (small mass expansion)

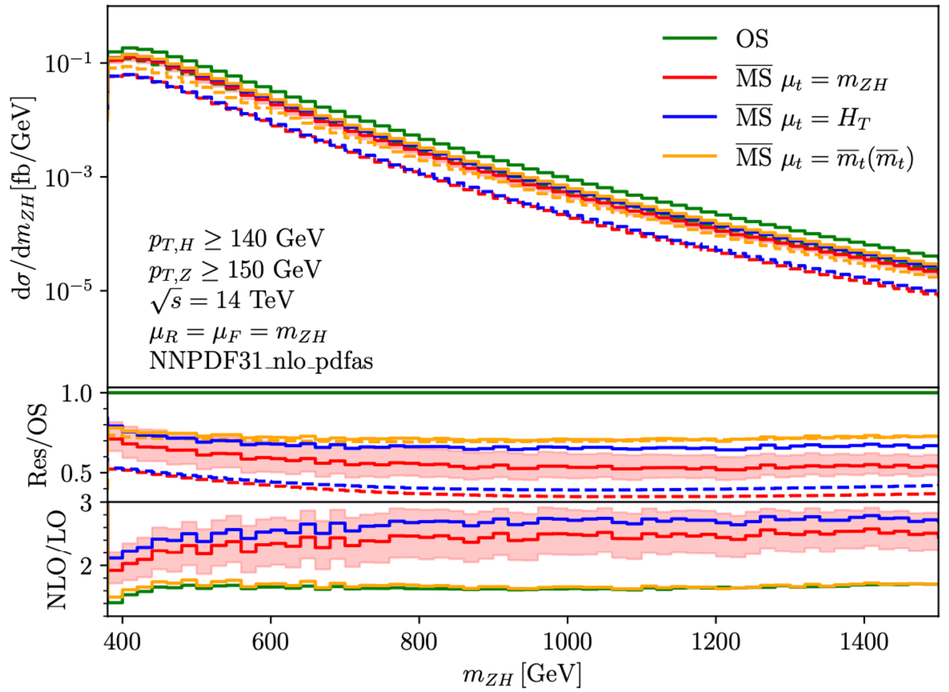
Degrassi, Gröber, Vitti, Zhao ’22 (small pT and HE expansion)

Chen, Davies, GH, Jones, Kerner, Mishima, Schlenk, Steinhauser ’22 (full+high energy expansion)

2204.05225

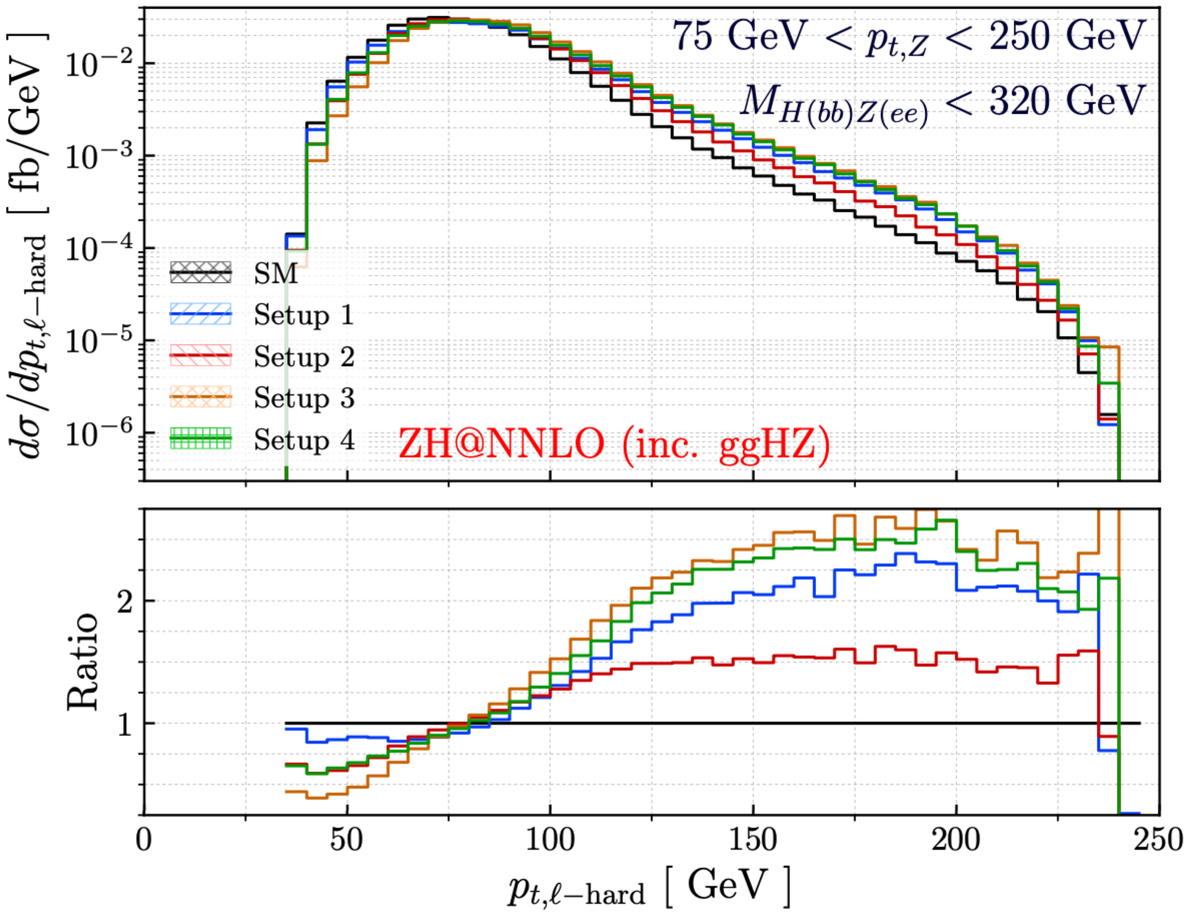


very large K-factor in pT,H tail

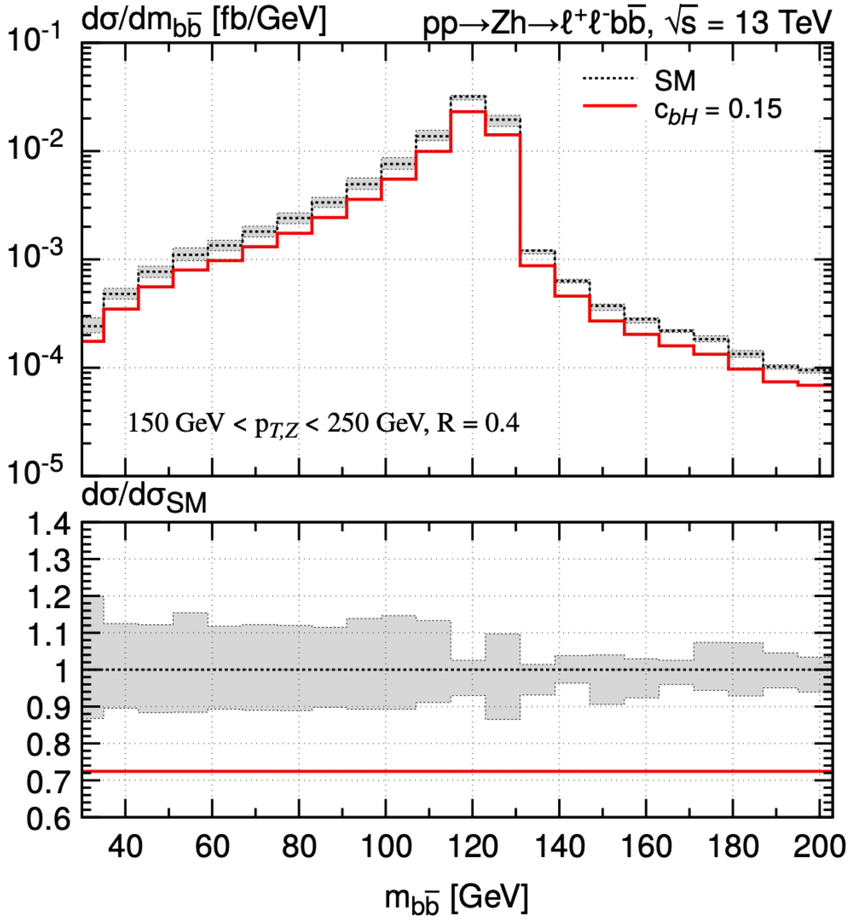


mass scheme uncertainty: difference between on-shell (OS) and $\overline{\rm MS}(\mu_t = m_{ZH})$?

pp-> ZH: anomalous couplings



Bizon, Caola, Melnikov, Röntsch '21



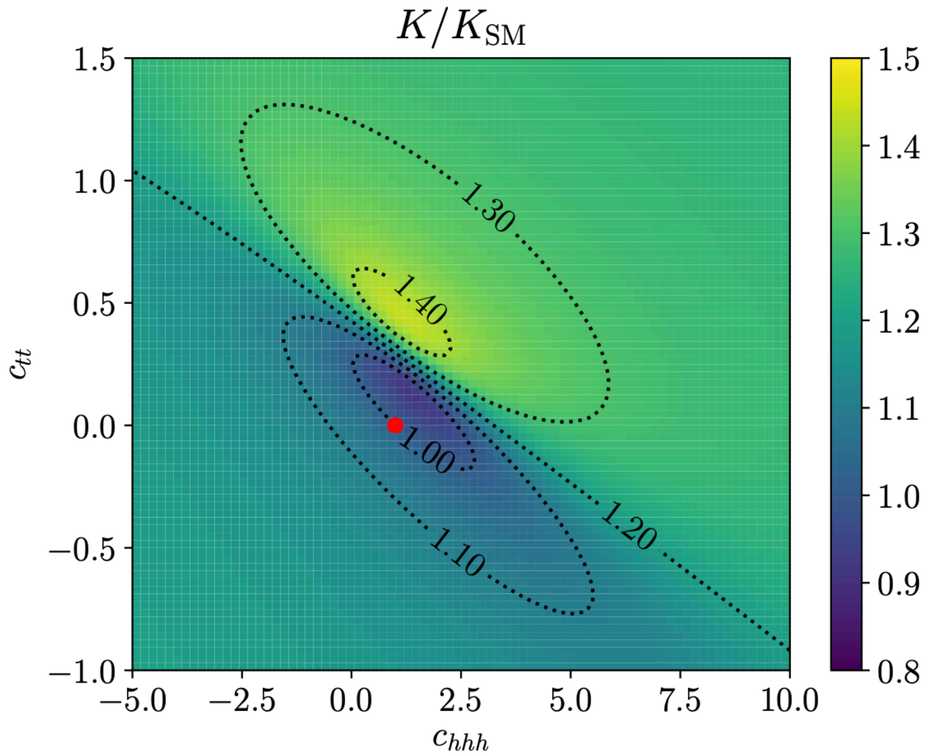
Haisch, Scott, Wiesemann, Zanderighi, Zanoli '22

NNLO, massive b's, HVV anomalous couplings

NNLO+PS, no HVV, sensitivity to c_{bH}

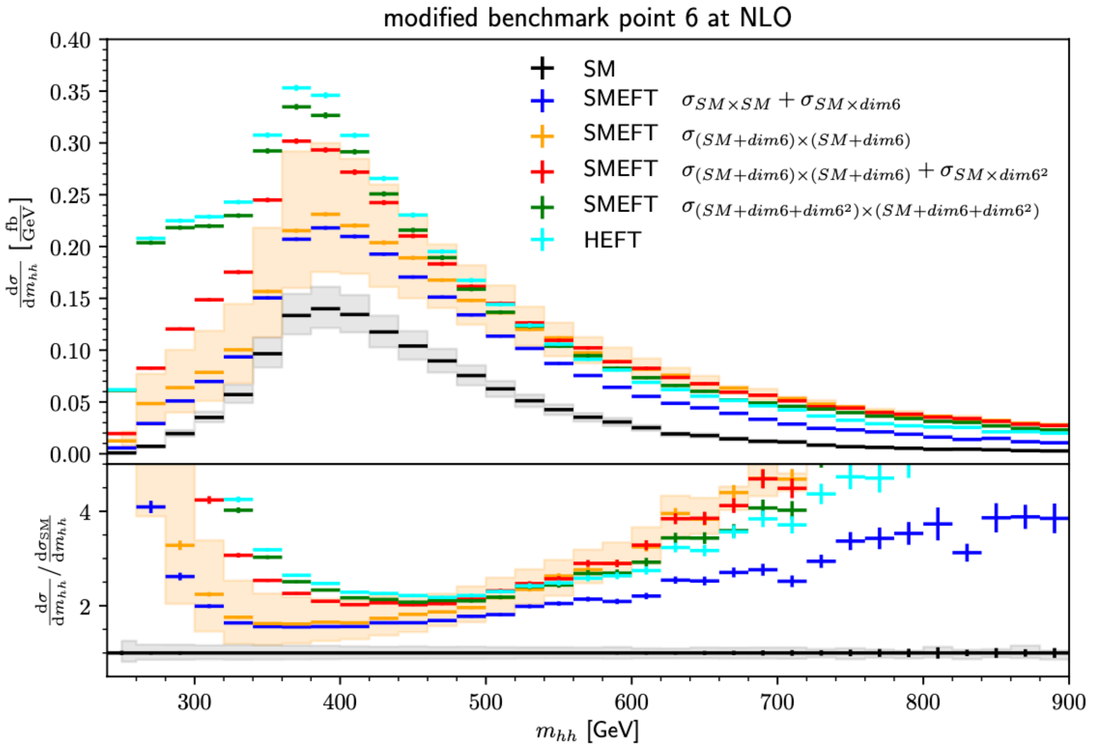
HH in gluon fusion: anomalous couplings

De Florian, Fabre, GH, Mazzitelli, Scyboz ’21



NNLO’: full NLO combined with approximate NNLO

GH, Lang, Scyboz ’22

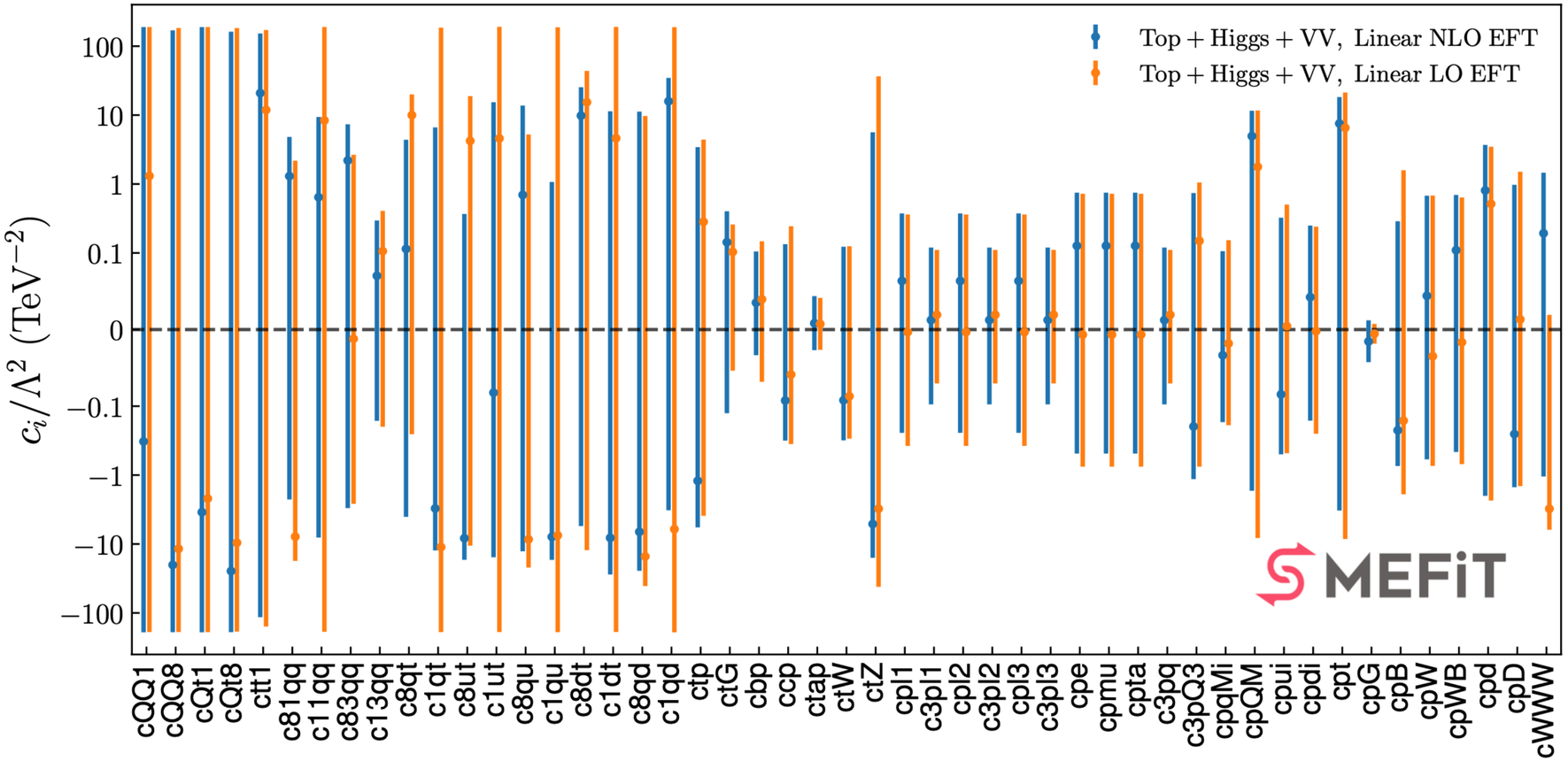


SMEFT at full NLO with different truncation options

http://powhegbox.mib.infn.it/User-Process-V2/ggHH_SMEFT

Higgs Couplings

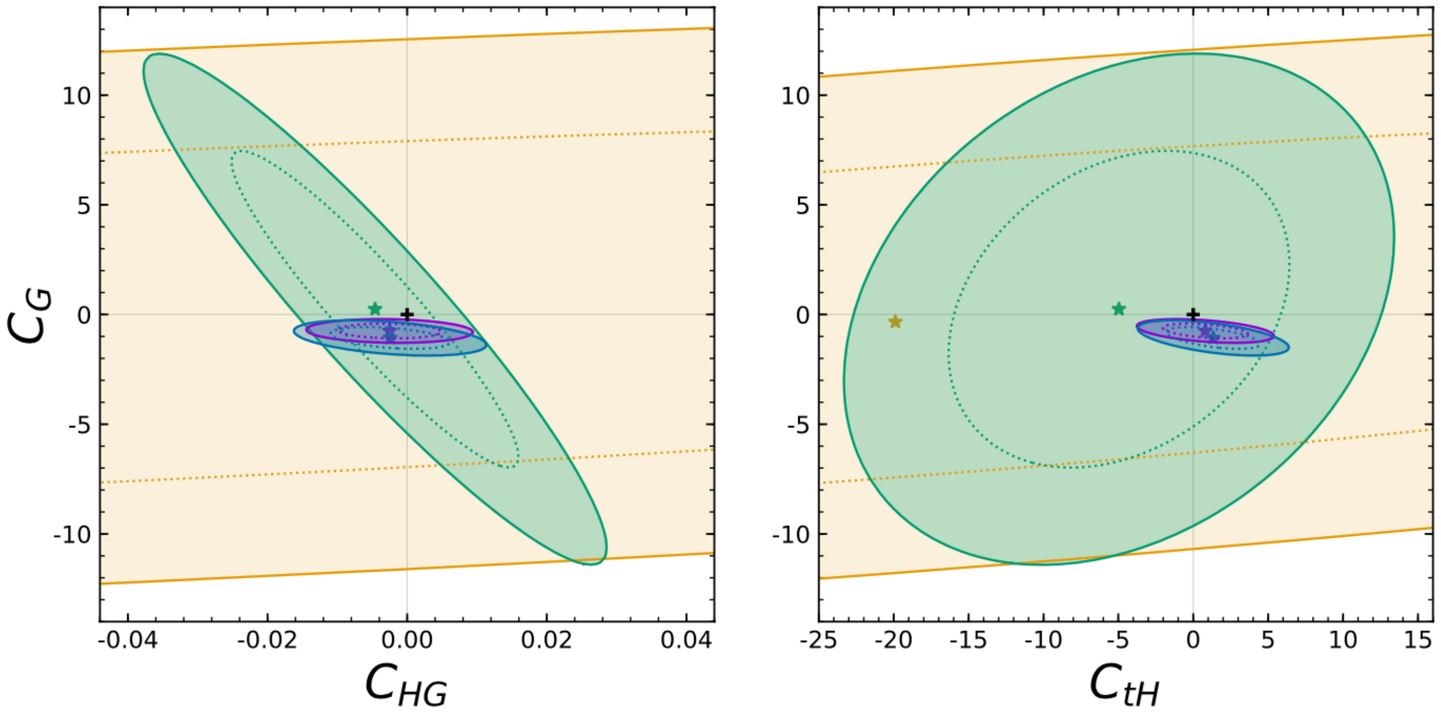
Ethier et al. 2105.00006 global fit of Higgs, diboson and top quark data



NLO matters!

Higgs Couplings

Ellis, Madigan, Mimasu, Sanz, You 2012.02779



Marginalised 95% C. L.

- Higgs data (no $t\bar{t}H$)
- Higgs data
- Higgs & Top data
- Higgs & Top data (+4F)
- SM

combining Higgs + top data very important

aim to go even more global, combination of Higgs- and flavour data

Summary & Outlook

- ggF total cross section: theory uncertainties keep shrinking
- great progress on predictions for fiducial cross sections
- differential results (e.g. pT,H): progress in resummation, NNLO+PS, mass effects, inclusion of Higgs decays
- turn towards combination of precision calculations with EFT analysis
- can Higgs collider data shed more light on the flavour anomalies?

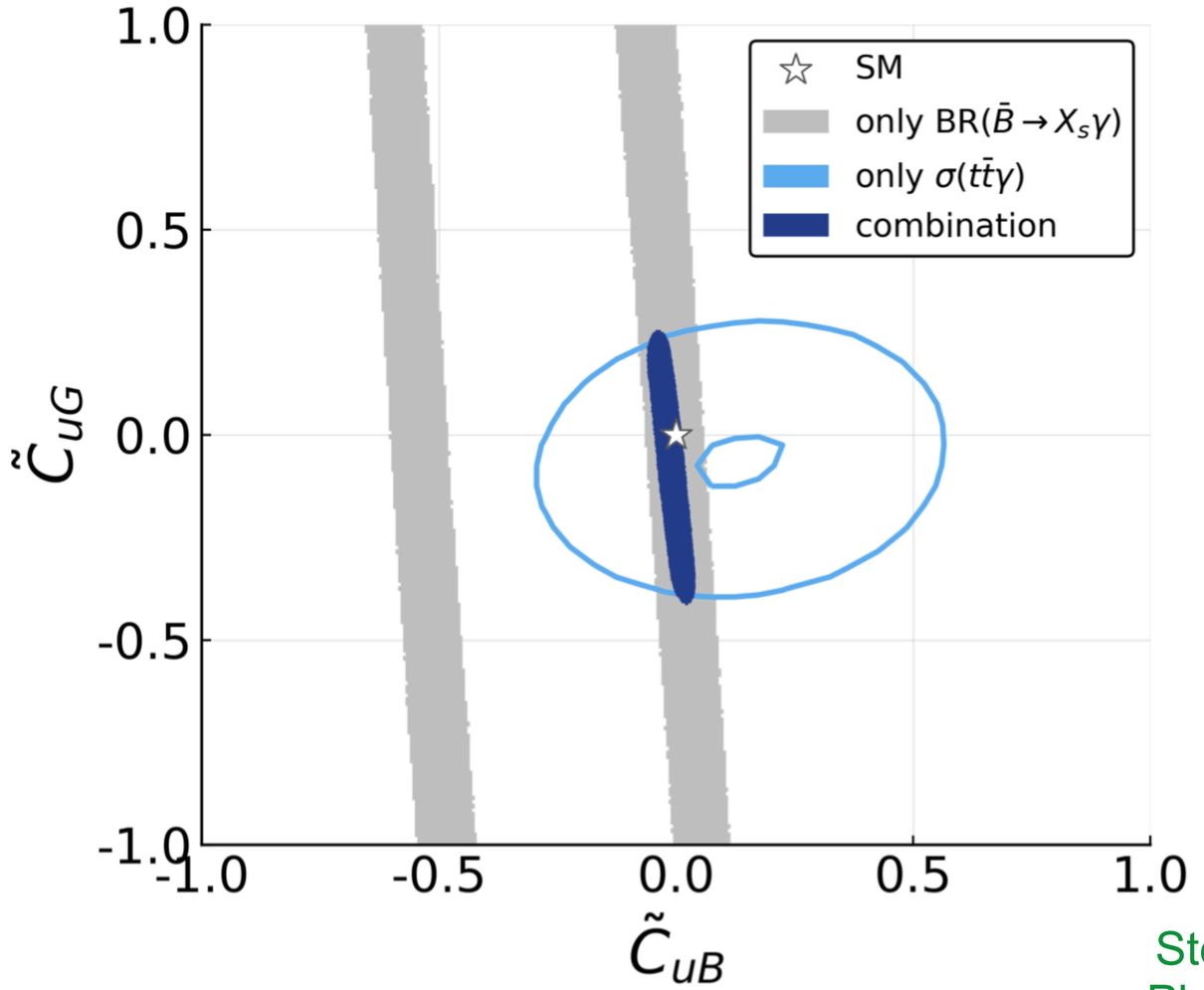
Summary & Outlook

- ggF total cross section: theory uncertainties keep shrinking
- great progress on predictions for fiducial cross sections
- differential results (e.g. pT,H): progress in resummation, NNLO+PS, mass effects, inclusion of Higgs decays
- turn towards combination of precision calculations with EFT analysis
- can Higgs collider data shed more light on the flavour anomalies?

Thank you for your attention!

combined fit high- and low energy observables

complementary information,
breaks degeneracies



Stefan Bissmann
PhD Thesis, 2021

HH benchmark points

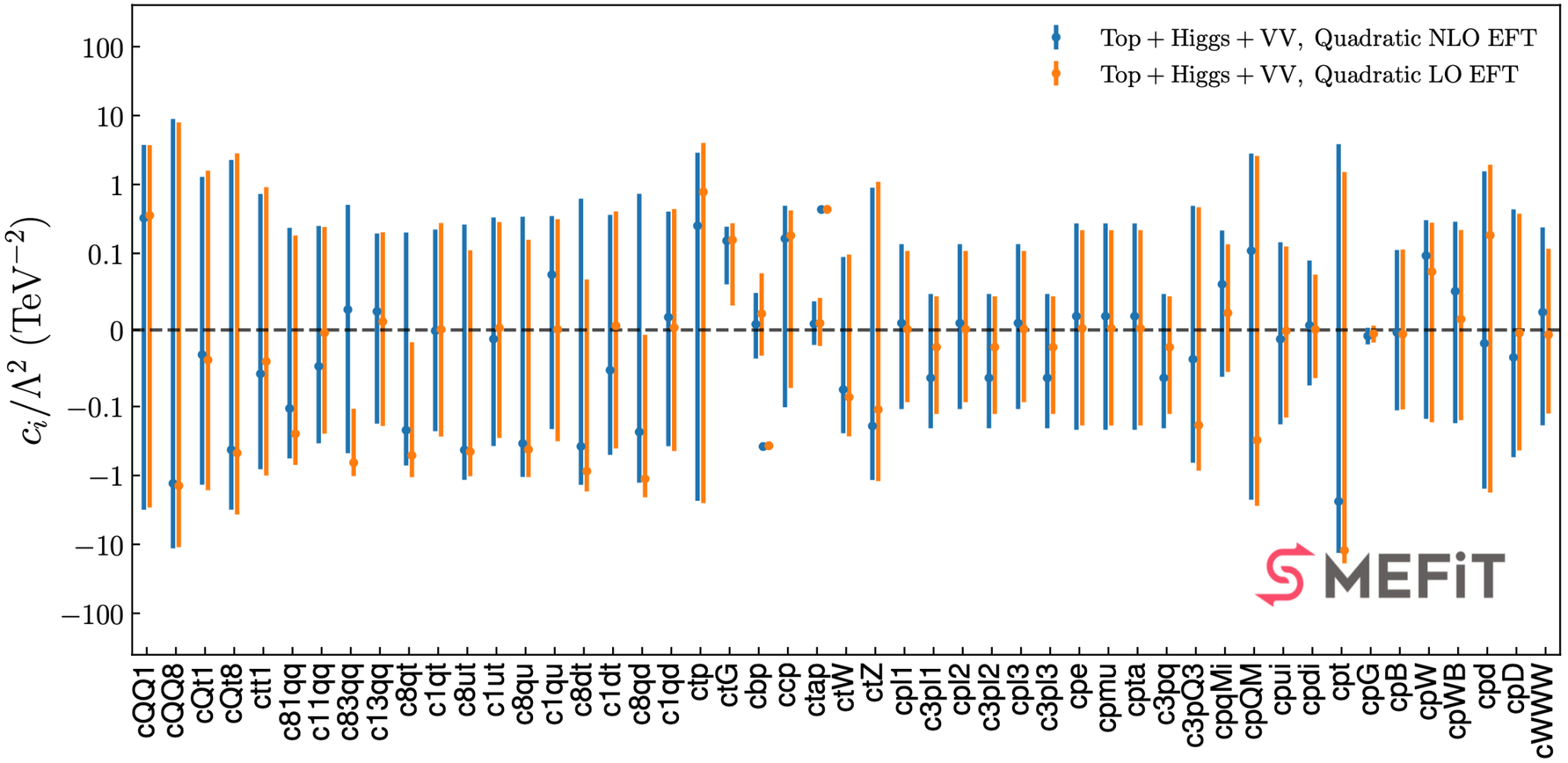
benchmark (* = modified)	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}	$C_{H,\text{kin}}$	C_H	C_{uH}	C_{HG}	Λ
SM	1	1	0	0	0	0	0	0	0	1 TeV
1*	5.105	1.1	0	0	0	4.95	−6.81	3.28	0	1 TeV
3*	2.21	1.05	$-\frac{1}{3}$	0.5	0.25*	13.5	2.64	12.6	0.0387	1 TeV
6*	−0.684	0.9	$-\frac{1}{6}$	0.5	0.25	0.561	3.80	2.20	0.0387	1 TeV

HEFT	Warsaw
c_{hhh}	$1 - 2\frac{v^2}{\Lambda^2}\frac{v^2}{m_h^2} C_H + 3\frac{v^2}{\Lambda^2} C_{H,\text{kin}}$
c_t	$1 + \frac{v^2}{\Lambda^2} C_{H,\text{kin}} - \frac{v^2}{\Lambda^2}\frac{v}{\sqrt{2}m_t} C_{uH}$
c_{tt}	$-\frac{v^2}{\Lambda^2}\frac{3v}{2\sqrt{2}m_t} C_{uH} + \frac{v^2}{\Lambda^2} C_{H,\text{kin}}$
c_{ggh}	$\frac{v^2}{\Lambda^2}\frac{8\pi}{\alpha_s} C_{HG}$
c_{gghh}	$\frac{v^2}{\Lambda^2}\frac{4\pi}{\alpha_s} C_{HG}$

$$E^2 \frac{|C_i|}{\Lambda^2} \ll 1$$ not fulfilled for $\Lambda \simeq 1\,\text{TeV}$

and $E \simeq m_{hh}$ up to ~1 TeV

Higgs Couplings

Ethier et al. 2105.00006

quadratic dim6