QCD overview

Giulia Zanderighi

Max Planck Institute for Physics & Technische Universität München

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Current status

- Only about 5% of data collected so far (compared to High-Lumi), yet no leap in energy in the coming years
- Hard to expect a striking signature in a signal process/observable
- Likely, if there will be a discovery, it will manifest itself first as a range of small deviations in various measurements
- Role of precision theory is clear: the more accurate the theory predictions are, the sooner, or the more sensitive, one can be to these small deviations
- Precision crucial to extract/constrain fundamental parameters of the theory (e.g. Higgs self-coupling)

⇒ **Precise theory augments the discovery reach of the LHC and anticipates possible discoveries and novel measurements**

The master formula

Factorisation implies the following form of hadronic cross sections

$$d\sigma_{\mathrm{PP}\to\mathrm{final}} = \sum_{\mathrm{i,j,final}} \int dx_1 dx_2 d\Phi_{\mathrm{final}} f_i(x_1,\mu_F^2) f_j(x_2,\mu_F^2) \frac{d\hat{\sigma}_{\mathrm{ij}\to\mathrm{final}}}{d\Phi_{\mathrm{final}}} \Theta_{\mathrm{cuts}}$$

Parton Distributions Functions

Extracted from data at various experiments/energies. PDFs are universal and their evolution is perturbative (LO, NLO, NNLO...)

Partonic Cross Sections

Expansion in the coupling constants (LO, NLO, NNLO...), also including enhanced all-order terms (LL, NLL, NNLL…)

Precision theory is a multilateral challenge

- push frontier of the perturbative QCD expansion (NLO, NNLO, N^3LO)
- heavy-top and bottom/charm mass effects
- mixed QCD-electroweak corrections
- resummation of large logarithmically enhanced terms to all orders
- fully exclusive description of the final state through parton showers
  - improving the accuracy of parton showers
  - matching fixed-order calculations and parton showers
- modelling of non-perturbative effects (or ways to reduce them)
- issues with jet-flavour
- uncertainties due to input parameters: strong coupling, PDFs, masses… ⇒ ways to reduce these uncertainties
- …

NLO QCD: the past

Example: double Higgs production processes (similar results available for all SM processes of similar complexity)

Alwall et al 1405.0301

Process		Syntax	Cross section (pb)			
Higgs pair production			LO 13 TeV		NLO 13 TeV	
h.1	$pp \to HH$ (Loop improved)	`p p > h h`	$1.772 \pm 0.006 \cdot 10^{-2}$	$^{+29.5\%}_{-21.4\%}$ $^{+2.1\%}_{-2.6\%}$	$2.763 \pm 0.008 \cdot 10^{-2}$	$^{+11.4\%}_{-11.8\%}$ $^{+2.1\%}_{-2.6\%}$
h.2	$pp \to HHjj$ (VBF)	`p p > h h j j $$ w+ w- z`	$6.503 \pm 0.019 \cdot 10^{-4}$	$^{+7.2\%}_{-6.4\%}$ $^{+2.3\%}_{-1.6\%}$	$6.820 \pm 0.026 \cdot 10^{-4}$	$^{+0.8\%}_{-1.0\%}$ $^{+2.4\%}_{-1.7\%}$
h.3	$pp \to HHW^\pm$	`p p > h h wpm`	$4.303 \pm 0.005 \cdot 10^{-4}$	$^{+0.9\%}_{-1.3\%}$ $^{+2.0\%}_{-1.5\%}$	$5.002 \pm 0.014 \cdot 10^{-4}$	$^{+1.5\%}_{-1.2\%}$ $^{+2.0\%}_{-1.6\%}$
h.4*	$pp \to HHW^\pm j$	`p p > h h wpm j`	$1.922 \pm 0.002 \cdot 10^{-4}$	$^{+14.2\%}_{-11.7\%}$ $^{+1.5\%}_{-1.1\%}$	$2.218 \pm 0.009 \cdot 10^{-4}$	$^{+2.7\%}_{-3.3\%}$ $^{+1.6\%}_{-1.1\%}$
h.5*	$pp \to HHW^\pm \gamma$	`p p > h h wpm a`	$1.952 \pm 0.004 \cdot 10^{-6}$	$^{+3.0\%}_{-3.0\%}$ $^{+2.2\%}_{-1.6\%}$	$2.347 \pm 0.007 \cdot 10^{-6}$	$^{+2.4\%}_{-2.0\%}$ $^{+2.1\%}_{-1.6\%}$
h.6	$pp \to HHZ$	`p p > h h z`	$2.701 \pm 0.007 \cdot 10^{-4}$	$^{+0.9\%}_{-1.3\%}$ $^{+2.0\%}_{-1.5\%}$	$3.130 \pm 0.008 \cdot 10^{-4}$	$^{+1.6\%}_{-1.2\%}$ $^{+2.0\%}_{-1.5\%}$
h.7*	$pp \to HHZj$	`p p > h h z j`	$1.211 \pm 0.001 \cdot 10^{-4}$	$^{+14.1\%}_{-11.7\%}$ $^{+1.4\%}_{-1.1\%}$	$1.394 \pm 0.006 \cdot 10^{-4}$	$^{+2.7\%}_{-3.2\%}$ $^{+1.5\%}_{-1.1\%}$
h.8*	$pp \to HHZ\gamma$	`p p > h h z a`	$1.397 \pm 0.003 \cdot 10^{-6}$	$^{+2.4\%}_{-2.5\%}$ $^{+2.2\%}_{-1.7\%}$	$1.604 \pm 0.005 \cdot 10^{-6}$	$^{+1.7\%}_{-1.4\%}$ $^{+2.3\%}_{-1.7\%}$
h.9*	$pp \to HHZZ$	`p p > h h z z`	$2.309 \pm 0.005 \cdot 10^{-6}$	$^{+3.9\%}_{-3.8\%}$ $^{+2.2\%}_{-1.7\%}$	$2.754 \pm 0.009 \cdot 10^{-6}$	$^{+2.3\%}_{-2.0\%}$ $^{+2.3\%}_{-1.7\%}$
h.10*	$pp \to HHZW^\pm$	`p p > h h z wpm`	$3.708 \pm 0.013 \cdot 10^{-6}$	$^{+4.8\%}_{-4.5\%}$ $^{+2.3\%}_{-1.7\%}$	$4.904 \pm 0.029 \cdot 10^{-6}$	$^{+3.7\%}_{-3.2\%}$ $^{+2.2\%}_{-1.6\%}$
h.11*	$pp \to HHW^+W^-$ (4f)	`p p > h h w+ w-`	$7.524 \pm 0.070 \cdot 10^{-6}$	$^{+3.5\%}_{-3.4\%}$ $^{+2.3\%}_{-1.7\%}$	$9.268 \pm 0.030 \cdot 10^{-6}$	$^{+2.3\%}_{-2.1\%}$ $^{+2.3\%}_{-1.7\%}$
h.12	$pp \to HHt\bar{t}$	`p p > h h t t~`	$6.756 \pm 0.007 \cdot 10^{-4}$	$^{+30.2\%}_{-21.6\%}$ $^{+1.8\%}_{-1.8\%}$	$7.301 \pm 0.024 \cdot 10^{-4}$	$^{+1.4\%}_{-5.7\%}$ $^{+2.2\%}_{-2.3\%}$
h.13	$pp \to HHtj$	`p p > h h tt j`	$1.844 \pm 0.008 \cdot 10^{-5}$	$^{+0.0\%}_{-0.6\%}$ $^{+1.8\%}_{-1.8\%}$	$2.444 \pm 0.009 \cdot 10^{-5}$	$^{+4.5\%}_{-3.1\%}$ $^{+2.8\%}_{-3.0\%}$
h.14*	$pp \to HHb\bar{b}$	`p p > h h b b~`	$7.849 \pm 0.022 \cdot 10^{-8}$	$^{+34.3\%}_{-23.9\%}$ $^{+3.1\%}_{-3.7\%}$	$1.084 \pm 0.012 \cdot 10^{-7}$	$^{+7.4\%}_{-10.8\%}$ $^{+3.1\%}_{-3.7\%}$

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✓ A solved problem

NLO: the present

Today focus on

- automation of NLO for BSM signals
- loop-induced processes: higher-order, but enhanced by gluon PDF
- automation of NLO electroweak corrections (necessary to match accuracy of NNLO)
- automation of NLO in SMEFT

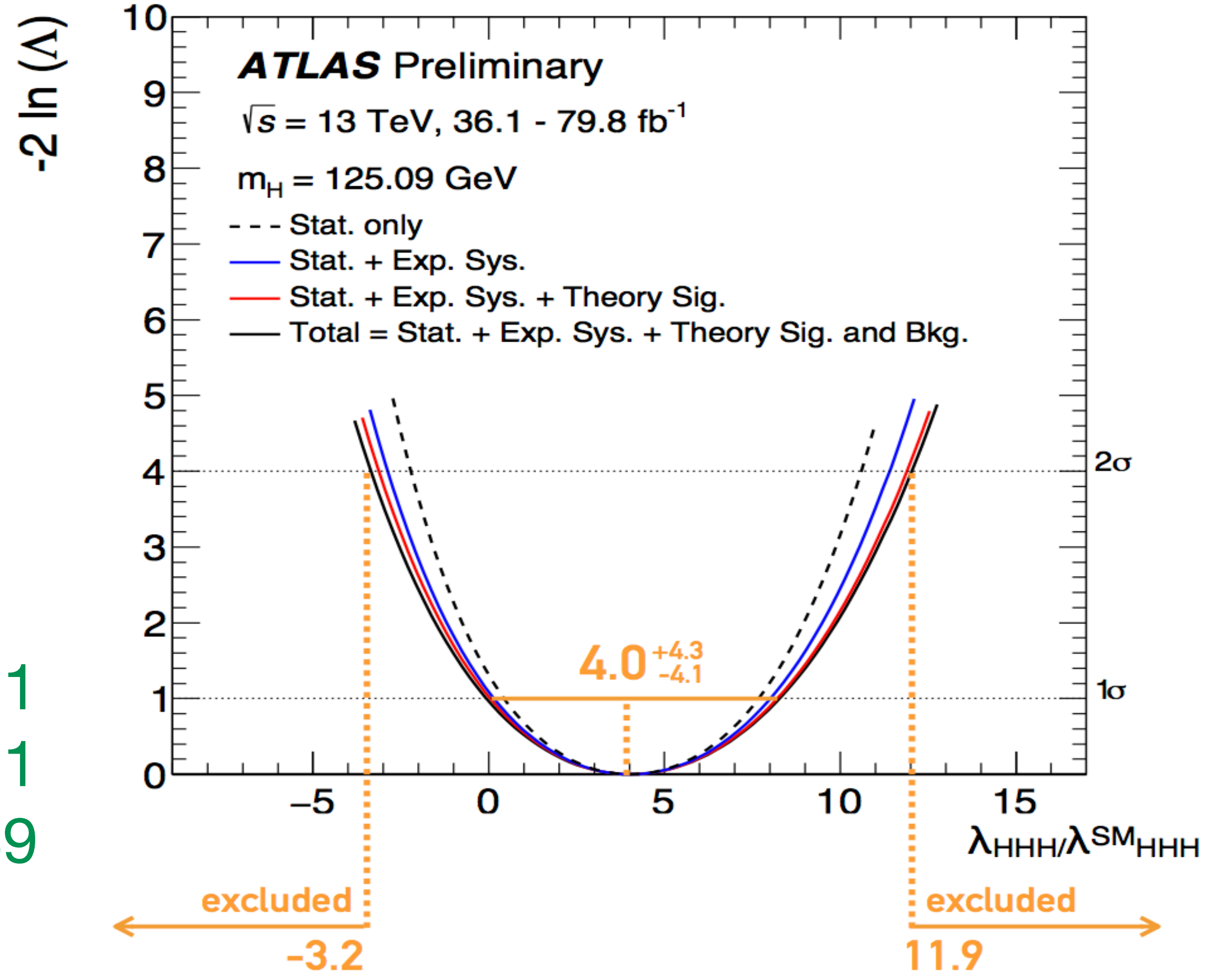
➡ Practical limitation: high-multiplicity difficult because of numerical instabilities, long run-time on clusters to obtain stable results (edge: about 6 particles in the final state, depending on the process)

NLO is the first order were one can constrain coupling indirectly, through loop effects

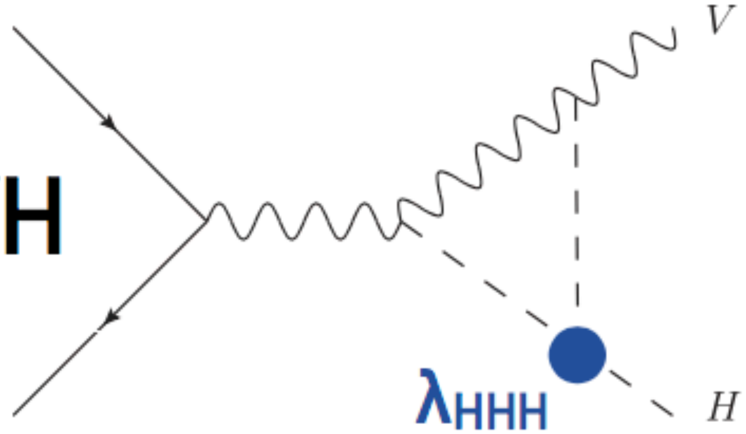
The Higgs self-coupling

- Single-Higgs production modes indirectly sensitive to the self-coupling through electro-weak effects
- Precision theory predictions absolutely crucial

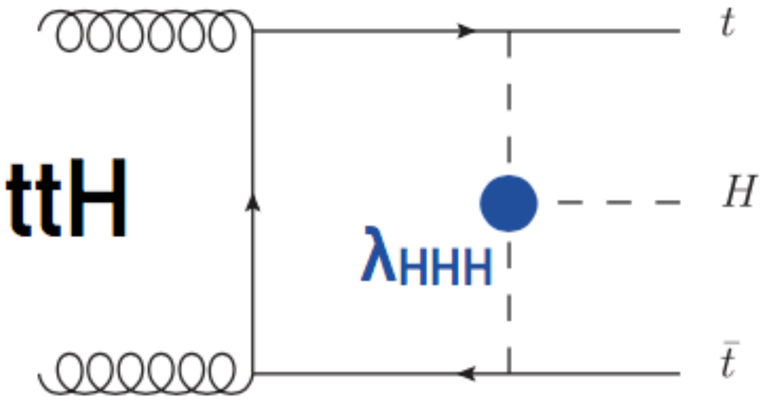
De Grassi et al 1607.04251
Bizon et al 1610.05771
Maltoni et al 1709.08649



VH

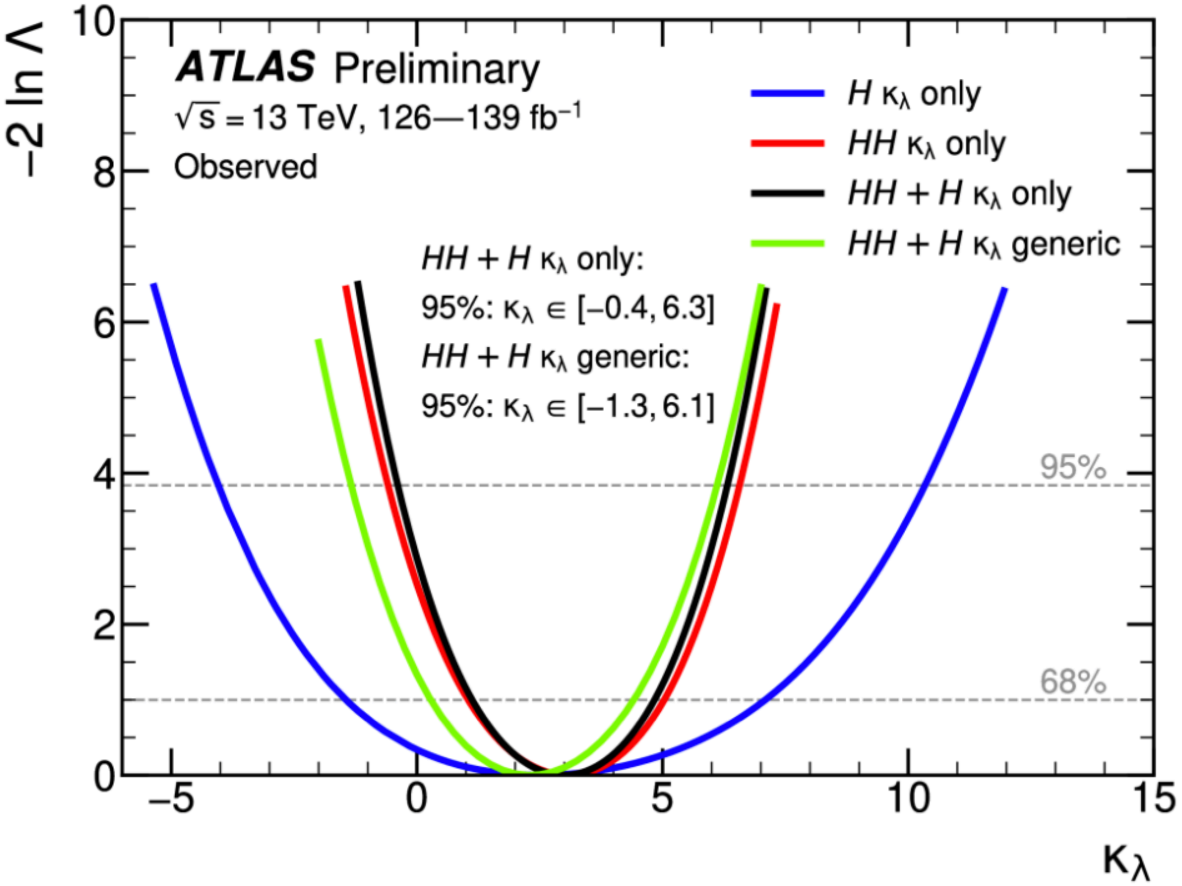


ttH



H+HH combination

ATLAS-CONF-2022-050 (see also 2211.01216)



⇒ no relevant gain from single-Higgs

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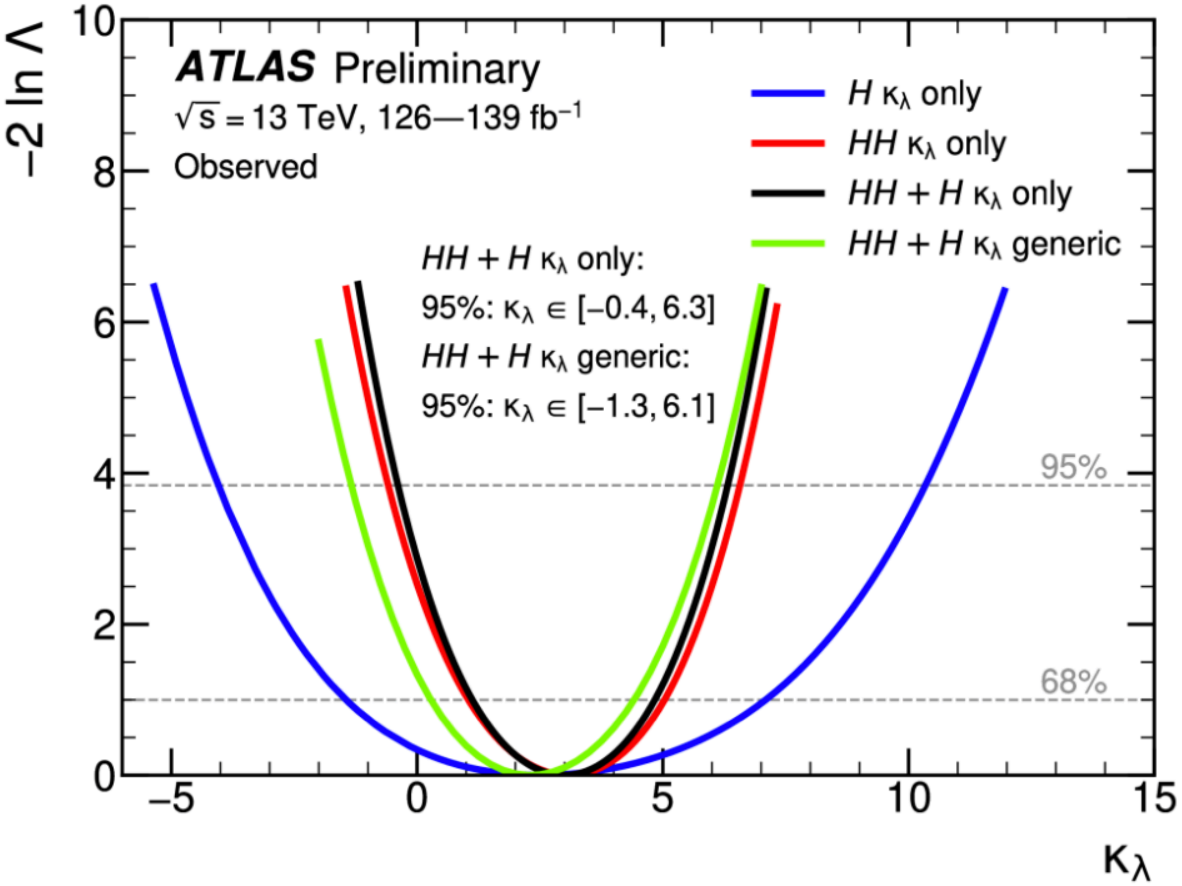

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BUT

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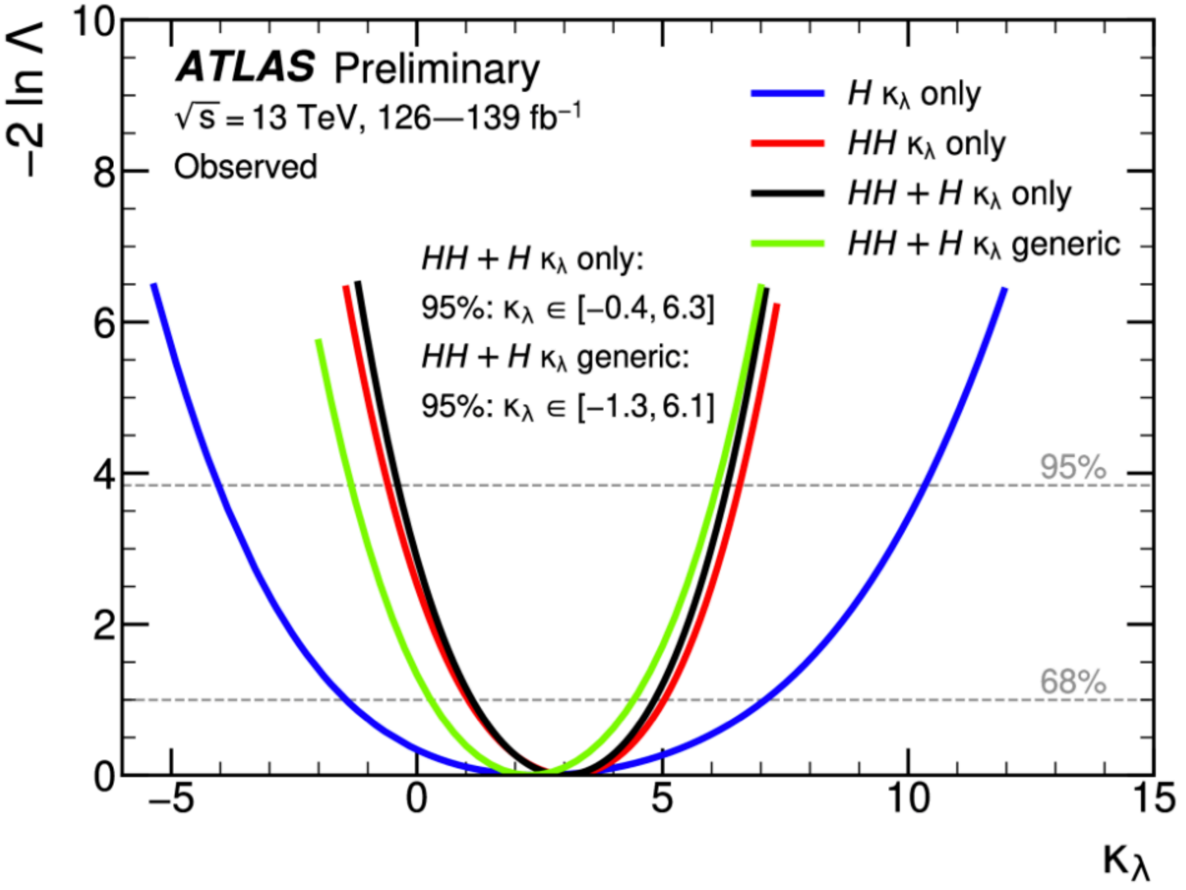
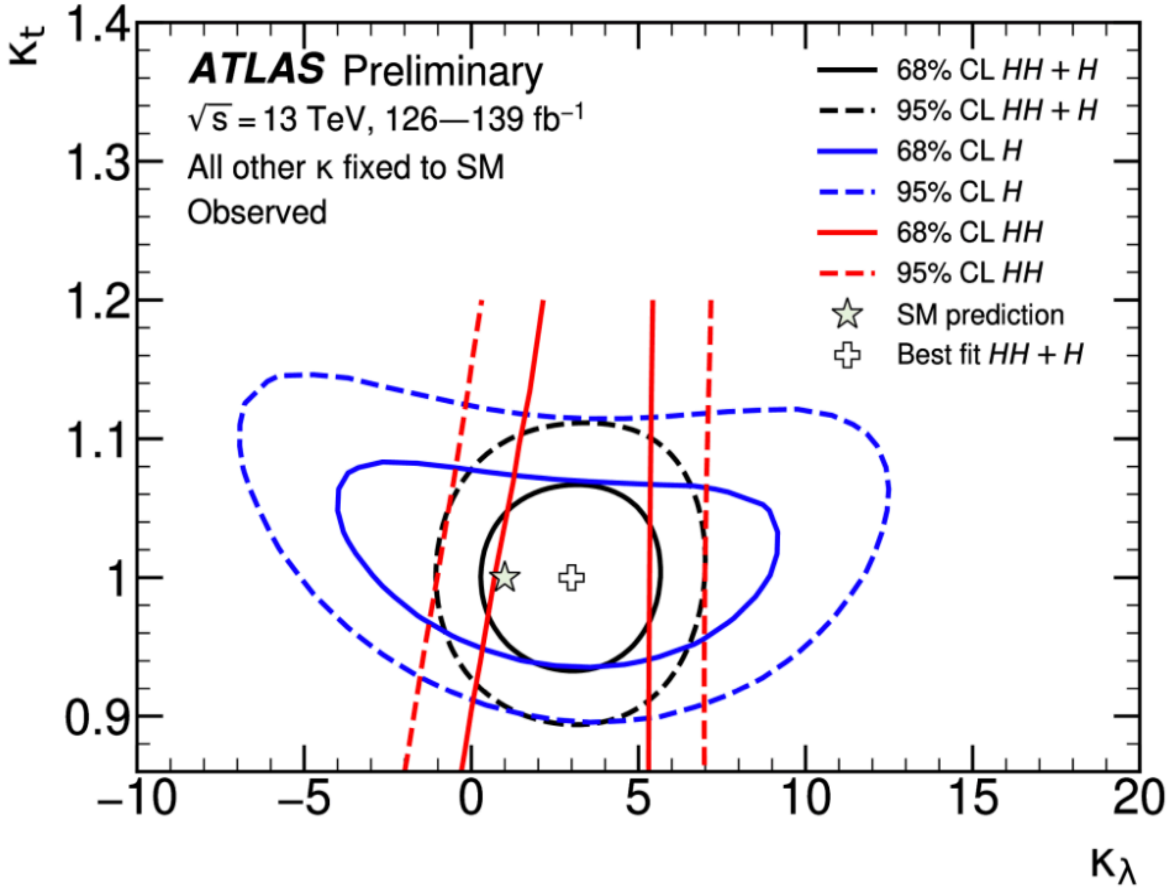




⇒ no relevant gain from single-Higgs

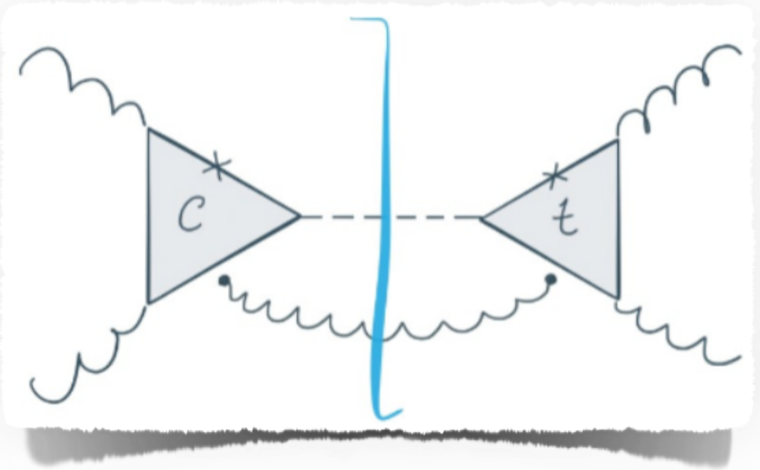
BUT

⇒ the combination of H and HH allows to constrain κ_λ and other “κ” (e.g. κ_t)

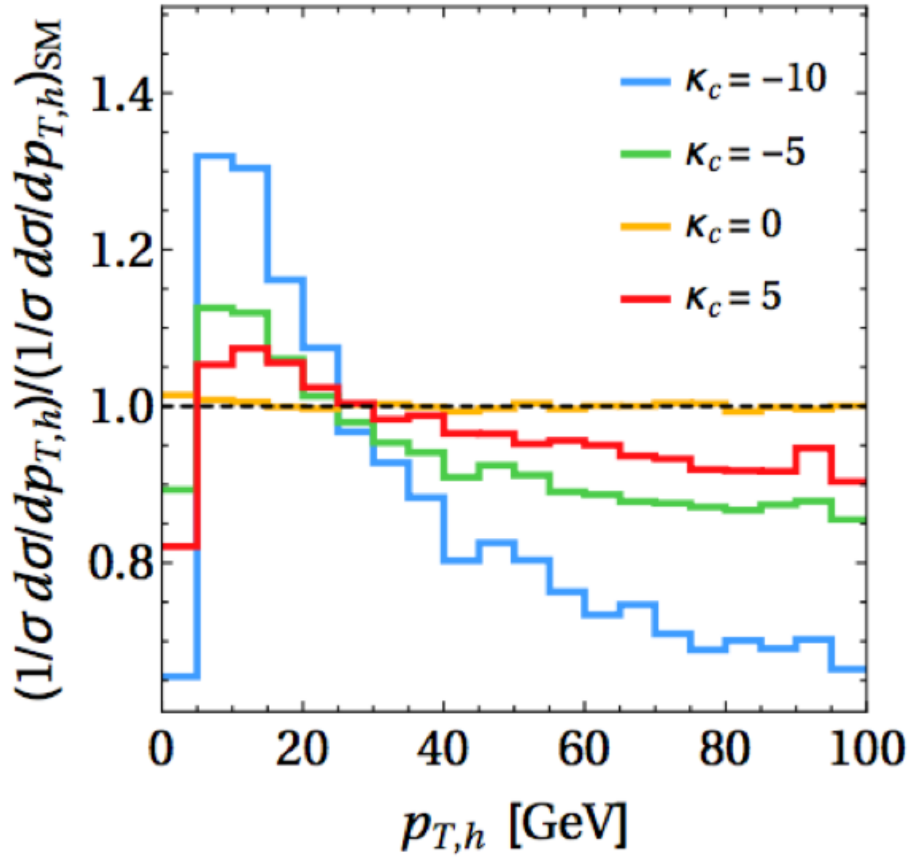
Charm Yukawa through $p_{t,H}$

Interference between top and charm loops create a distortion of the Higgs transverse momentum (at low pt)

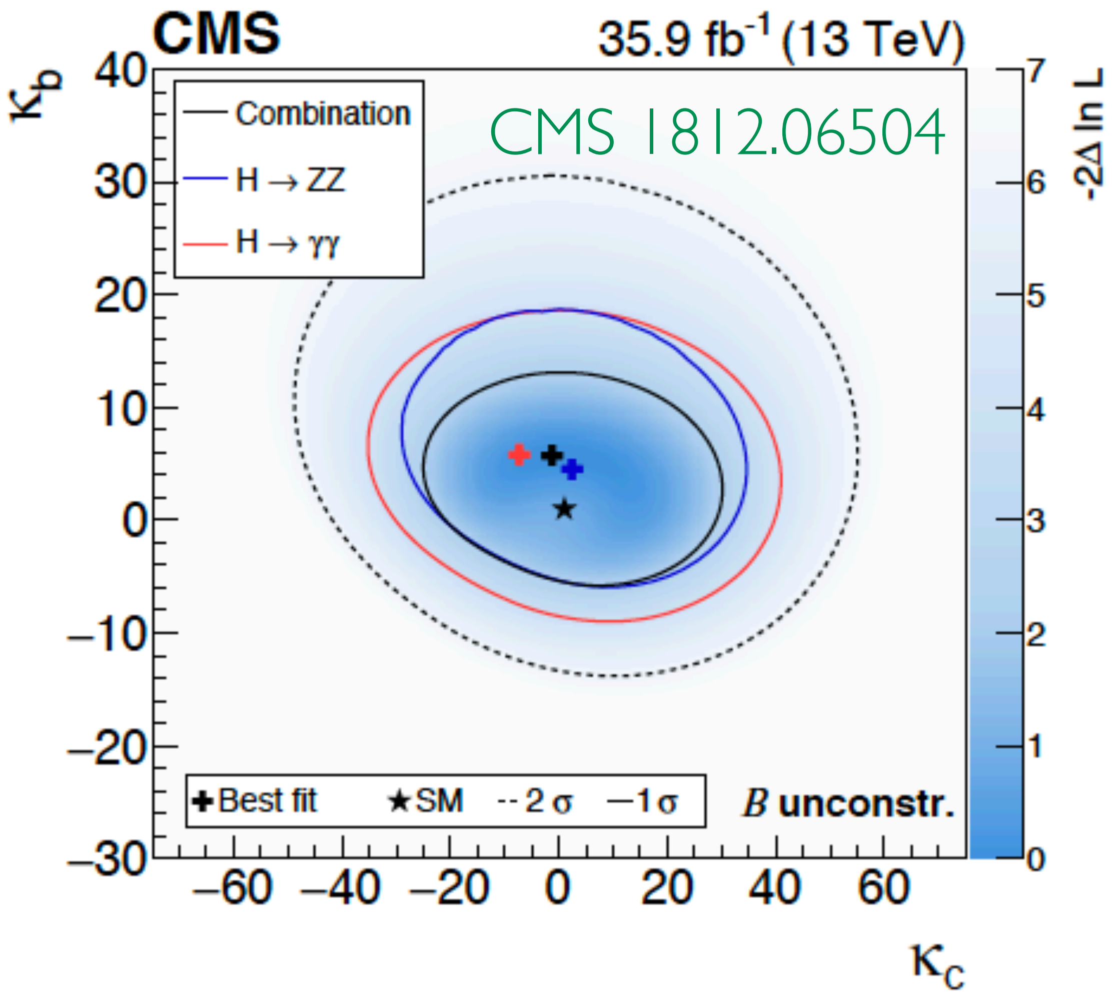
⇒ sensitivity to charm Yukawa coupling



Bishara et al 1606.09253



CMS 1812.06504



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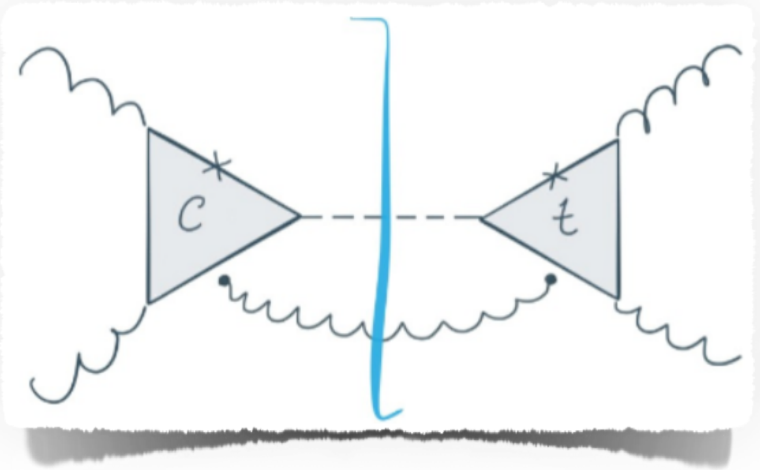
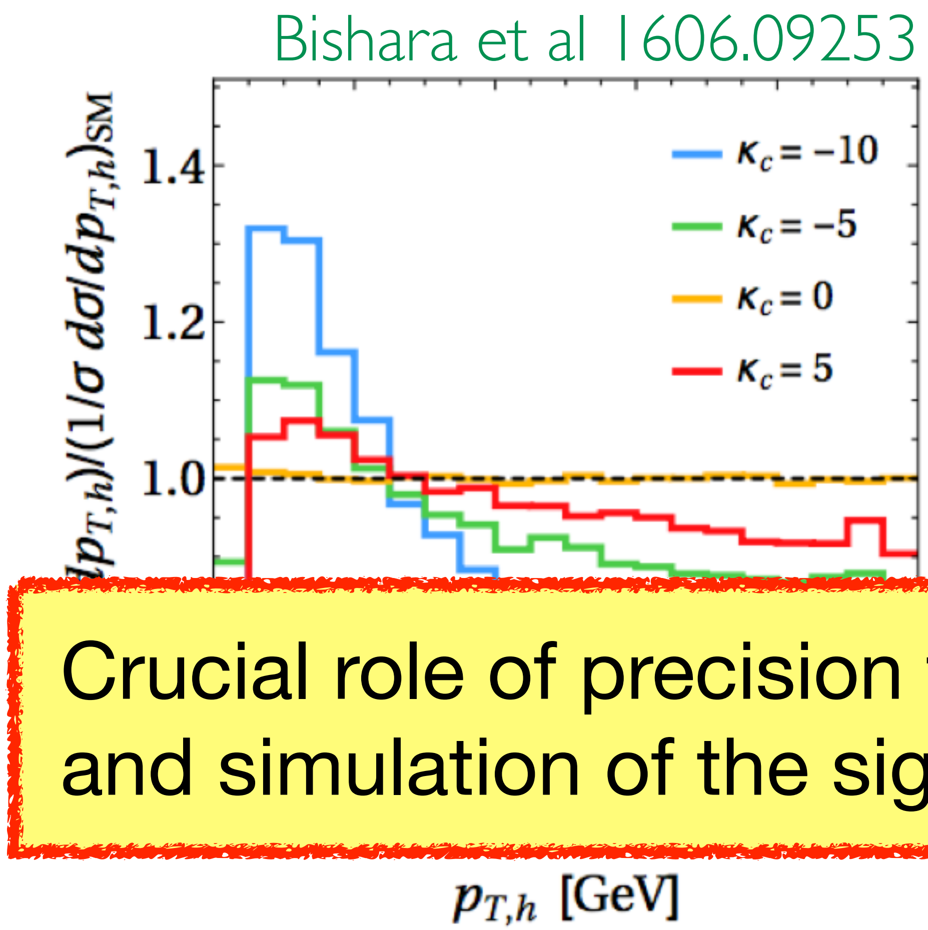
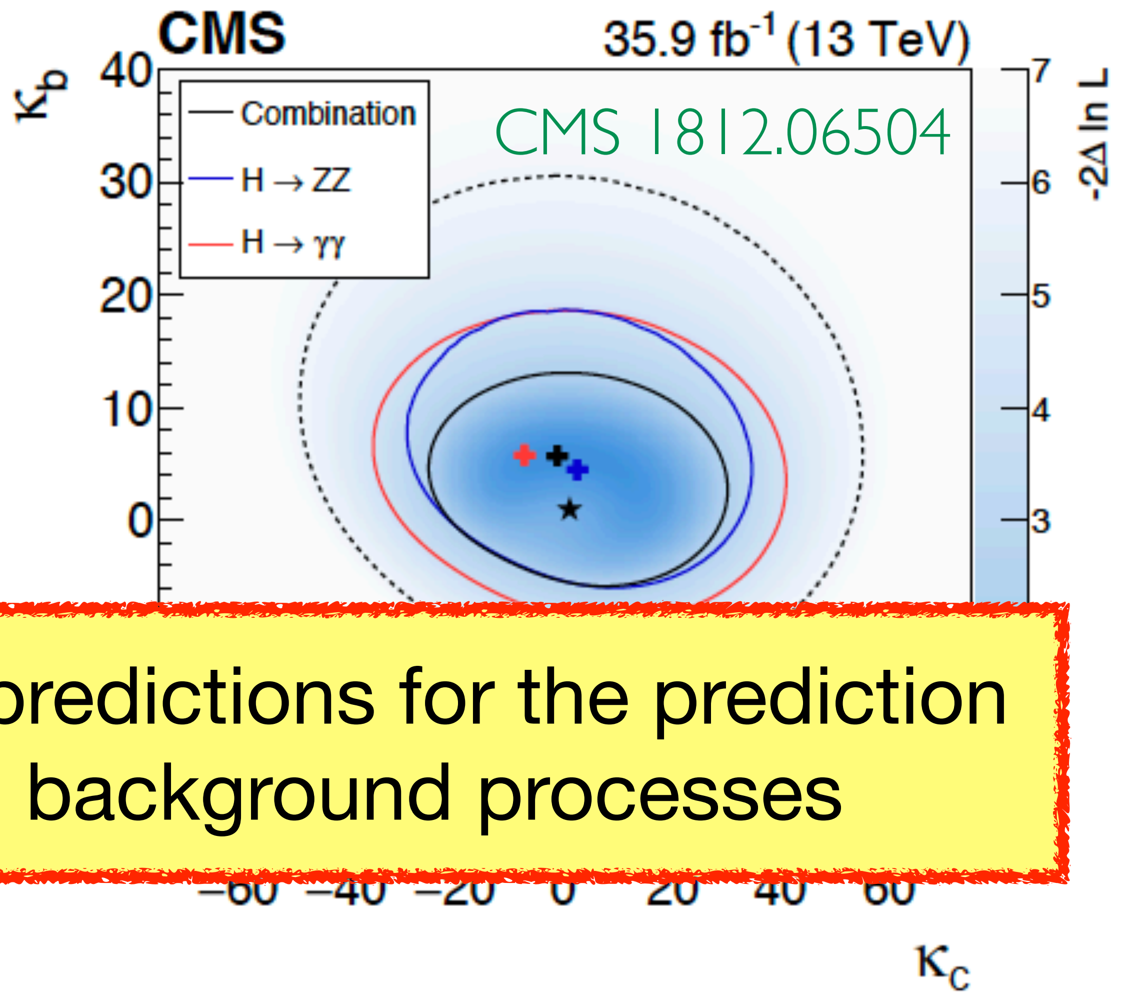


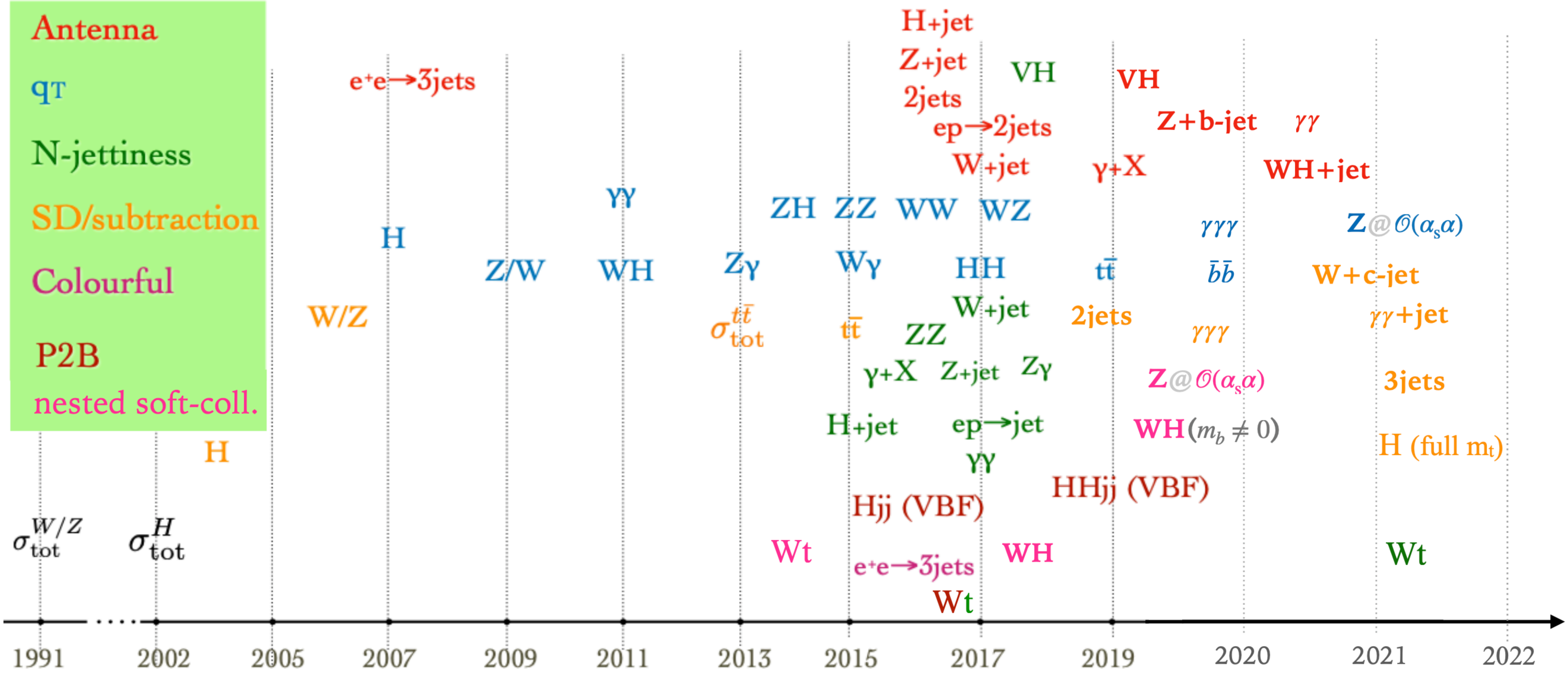

Bishara et al 1606.09253


CMS 1812.06504

Crucial role of precision theory predictions for the prediction and simulation of the signal and background processes

NNLO: status

adapted from A. Huss/G. Salam



Different colour: different way to handle intermediate divergences

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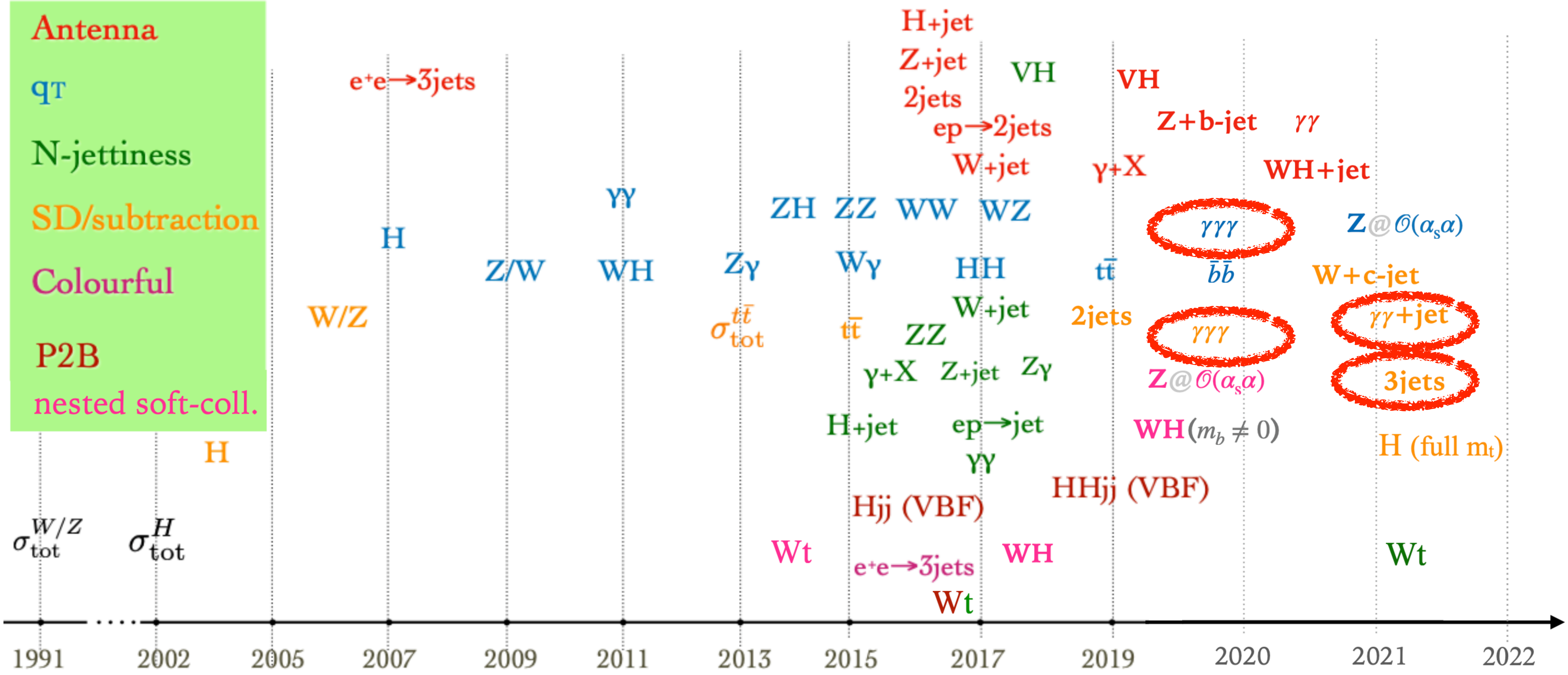


Different colour: different way to handle intermediate divergences

NNLO: status

adapted from A. Huss/G. Salam

Different colour: c

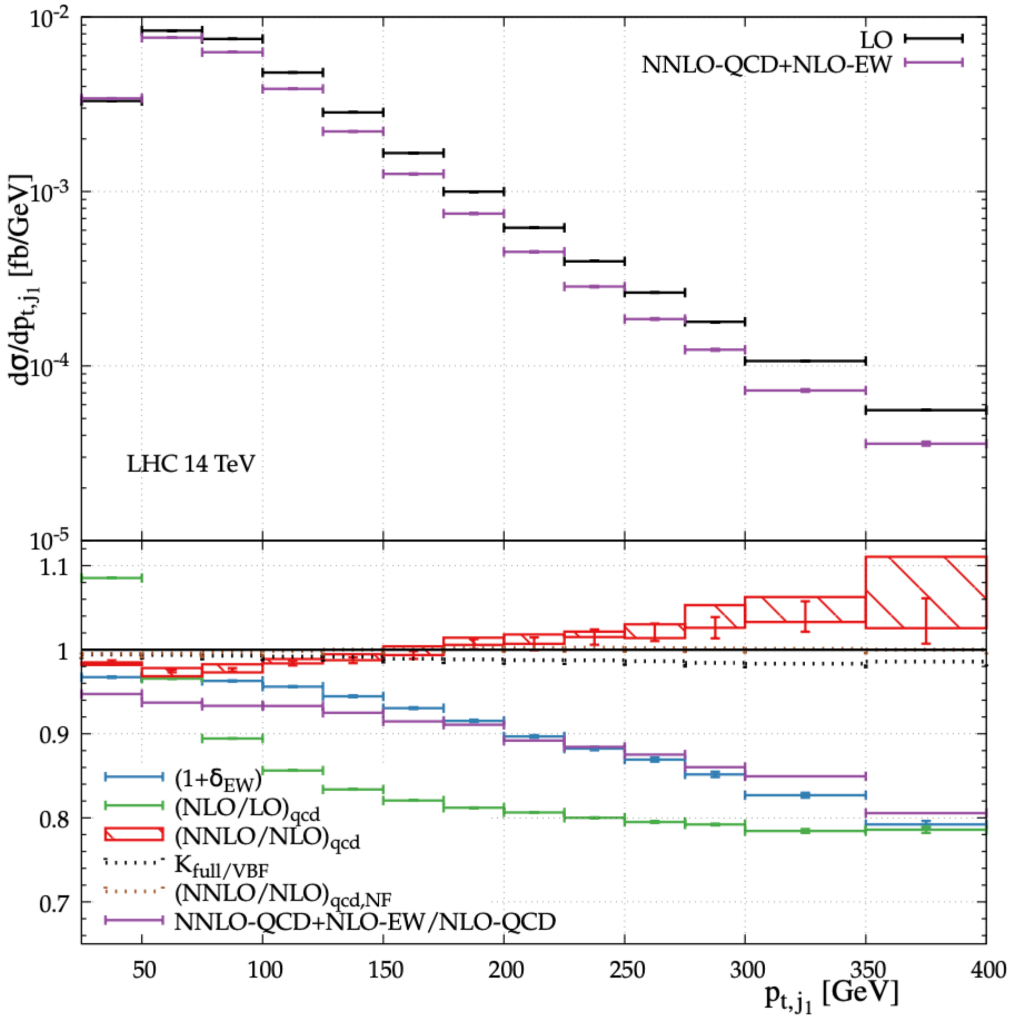
✓2 to 2 processes in the SM

➡ frontier is 2 to 3

NNLO VBF diHiggs

Dreyer and Karlberg 1811.07918
Dreyer, Karlberg, Lang, Pellen 2005.13341

Realistic fiducial cuts available at NNLO



⇒ Impact of EW effects rather large (6% for fiducial cross-sections, -(10-20)% in tails

⇒ Largest ambiguity from combination of NNLO QCD and NLO EW (additive/multiplicative scheme)

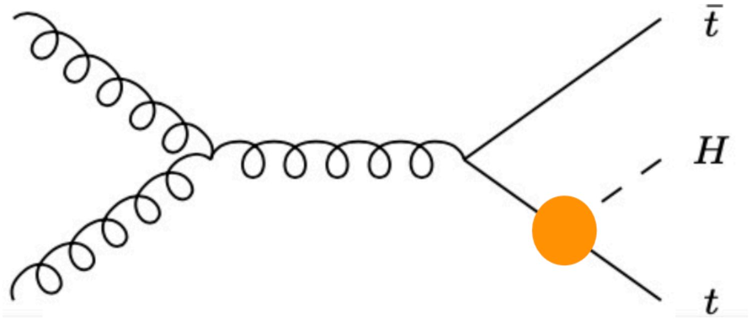
$\sigma^{\text{full}}_{\text{LO}}$	$\delta^{\text{full}}_{\text{NLO QCD}}$	$\delta^{\text{VBF}}_{\text{NNLO QCD}}$	$\delta^{\text{full}}_{\text{NLO EW}}$	$\sigma_{\text{NNLO QCD}\times\text{NLO EW}}$	$\delta^{\text{NF}}_{\text{NNLO QCD}}$ [fb]
$0.78444(9)^{+0.0825}_{-0.0694}$	$-0.07110(13)$	$-0.0115(5)$	$-0.0476(2)$	$0.6684(5)^{+0.002}_{-0.0004}$	$-0.001766(7)$
${}^{+10.5\%}_{-8.8\%}$	-9.1%	-1.5%	-6.1%	$-14.8\%^{+0.3\%}_{-0.06\%}$	-0.23%

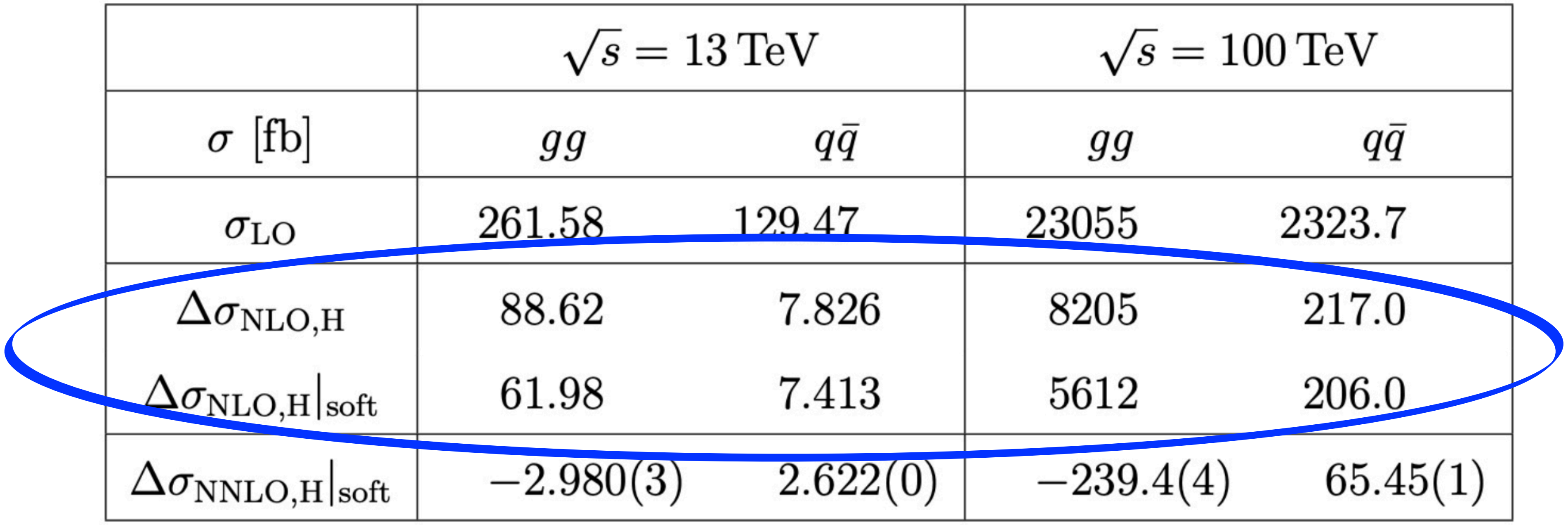
Approximate ttH at NNLO

Catani et al 2210.04846

Two-loop pp → ttH amplitudes still missing.

Idea: approximate with amplitudes with a soft Higgs emitted off heavy quarks





	$\sqrt{s} = 13$ TeV		$\sqrt{s} = 100$ TeV	
σ [fb]	gg	$q\bar{q}$	gg	$q\bar{q}$
σ_{LO}	261.58	129.47	23055	2323.7
$\Delta\sigma_{\mathrm{NLO,H}}$	88.62	7.826	8205	217.0
$\Delta\sigma_{\mathrm{NLO,H}}\vert_{\mathrm{soft}}$	61.98	7.413	5612	206.0
$\Delta\sigma_{\mathrm{NNLO,H}}\vert_{\mathrm{soft}}$	−2.980(3)	2.622(0)	−239.4(4)	65.45(1)

Test the procedure at NLO

- approximation not that great! Works better for qq then gg channel

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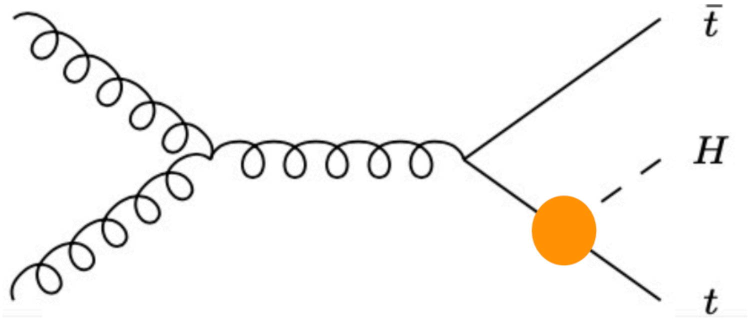

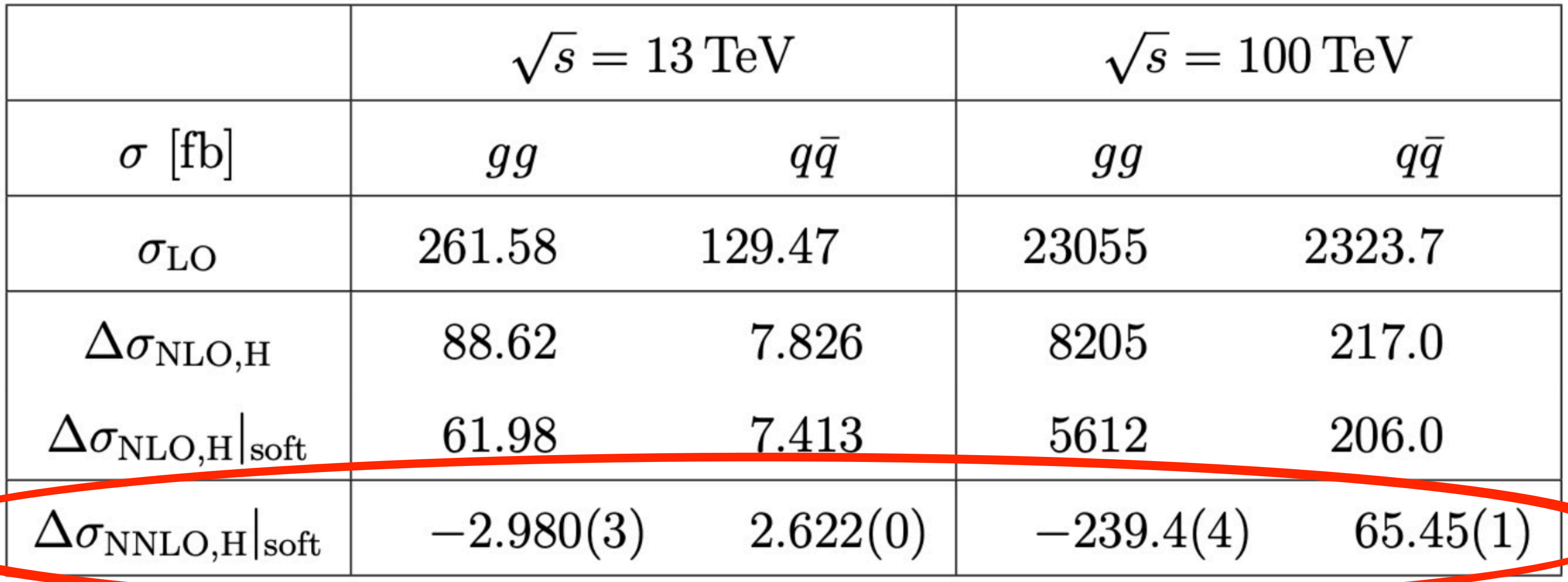

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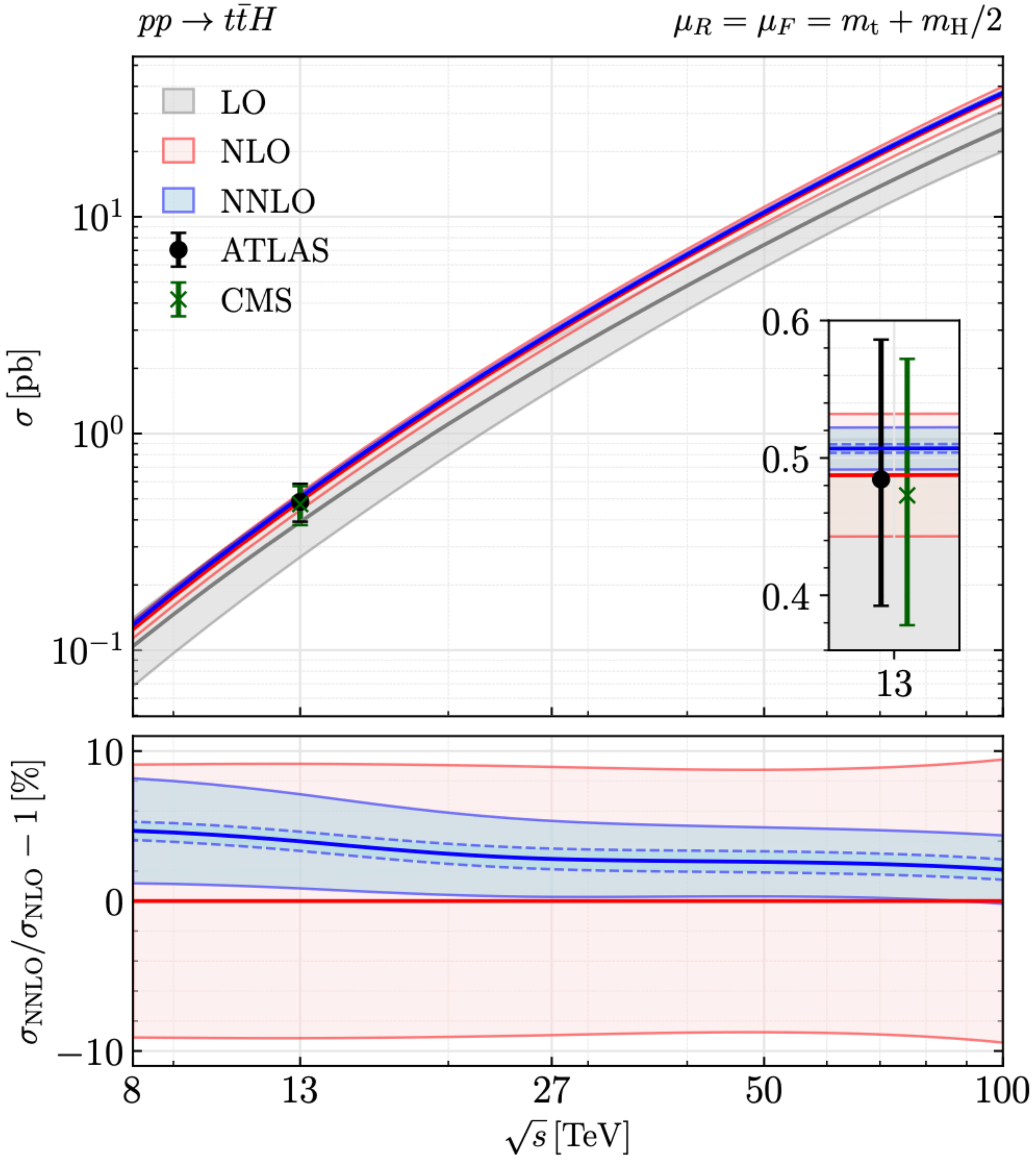
Size of approx. NNLO

- approximation works better for qq then gg channel
- but two-loop corrections are very small (below a %)

Approximate ttH at NNLO

Catani et al 2210.04846

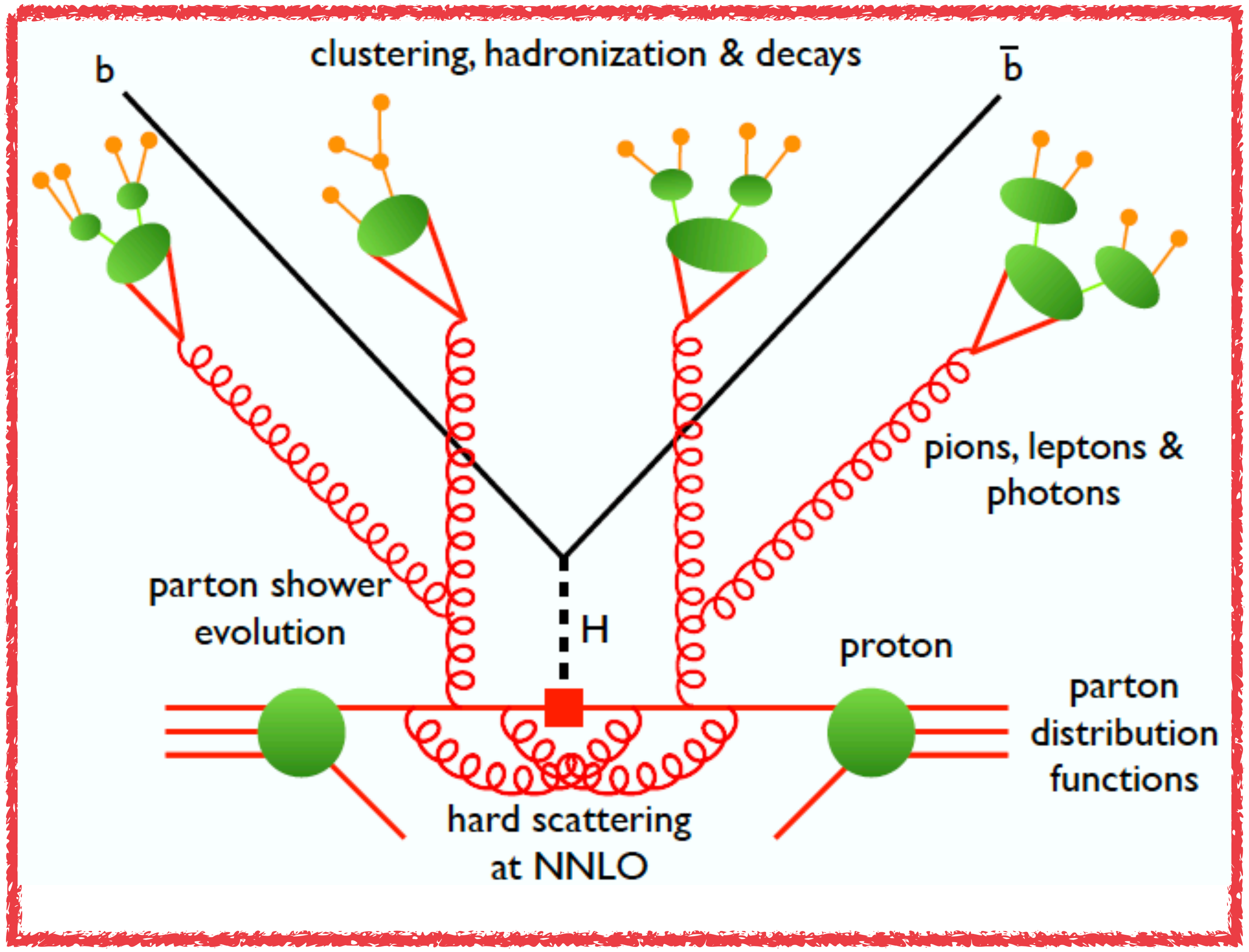


⇒ estimated uncertainty on the total cross section at the few percent level

Interesting to validate this once full is NNLO available

NNLO + parton shower

Merging NNLO and parton shower (NNLOPS) is a must to have the best perturbative accuracy with a realistic description of final state



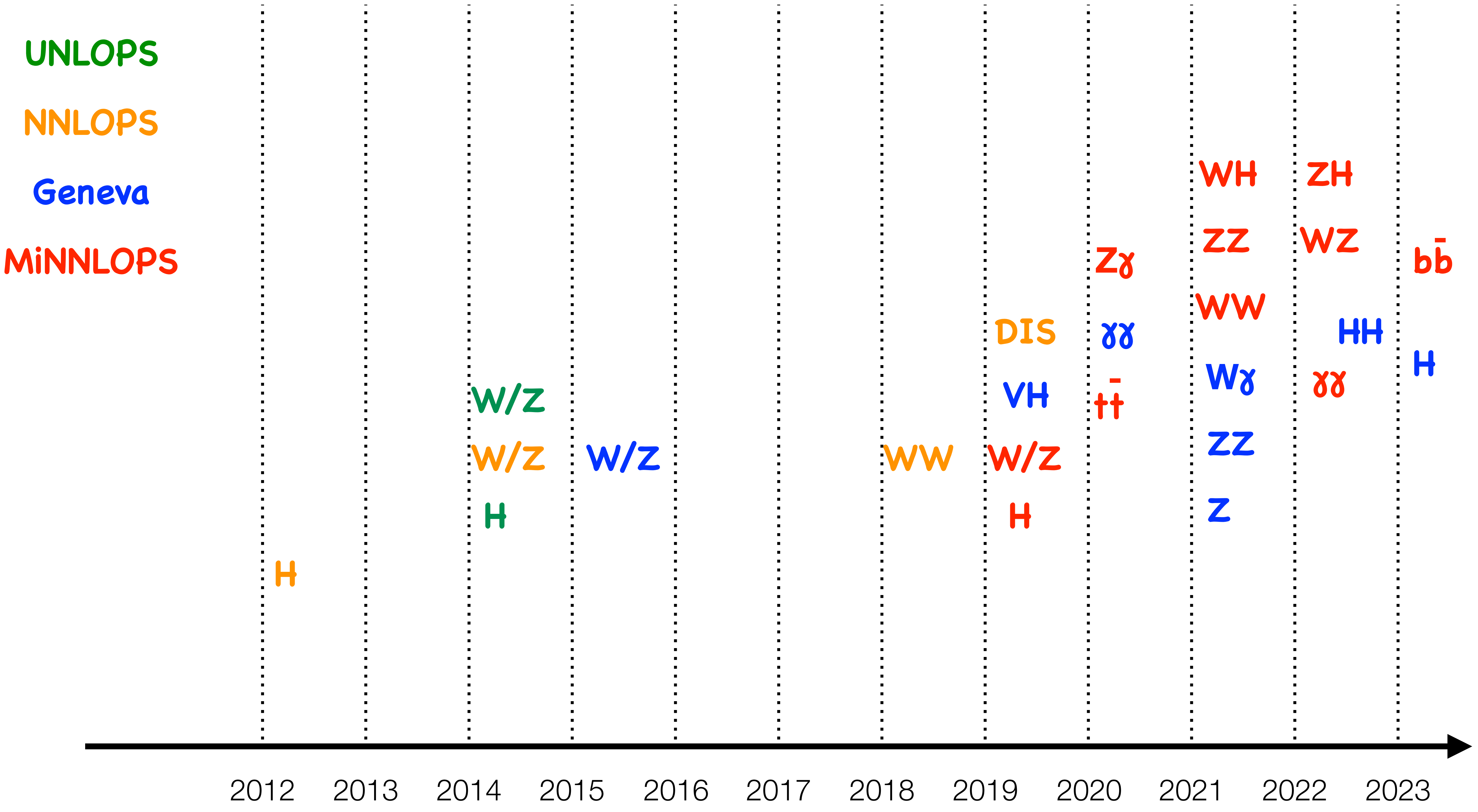
NNLO+PS timeline

UNLOPS

NNLOPS

Geneva

MiNNLOPS



H

W/Z
W/Z
H

W/Z

WW

DIS
VH
W/Z
H

Zγ
γγ
$t\bar{t}$

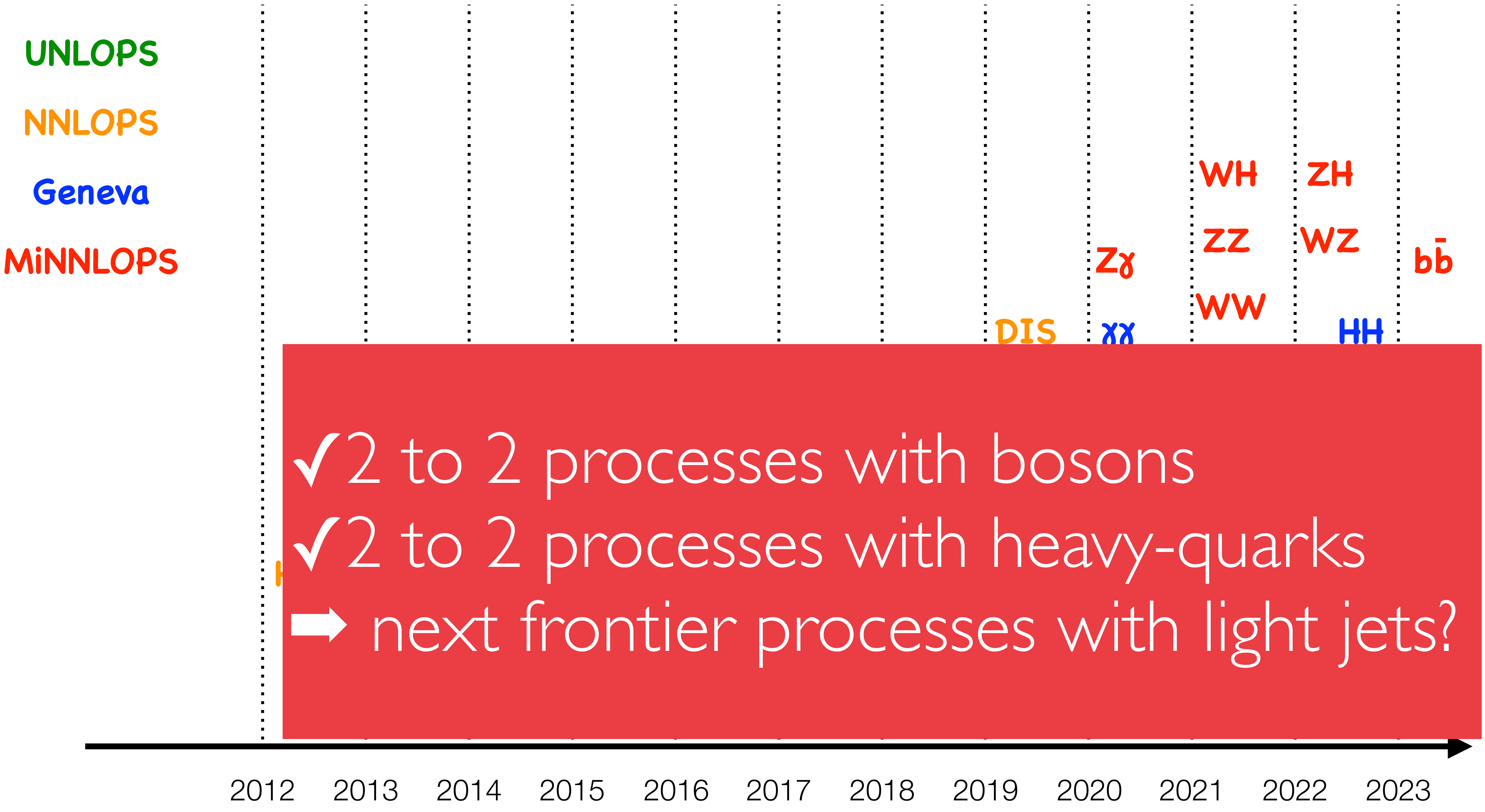
WH
ZZ
WW
Wγ
ZZ
Z

ZH
WZ
HH
γγ

$b\bar{b}$
H

2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023

NNLO+PS timeline



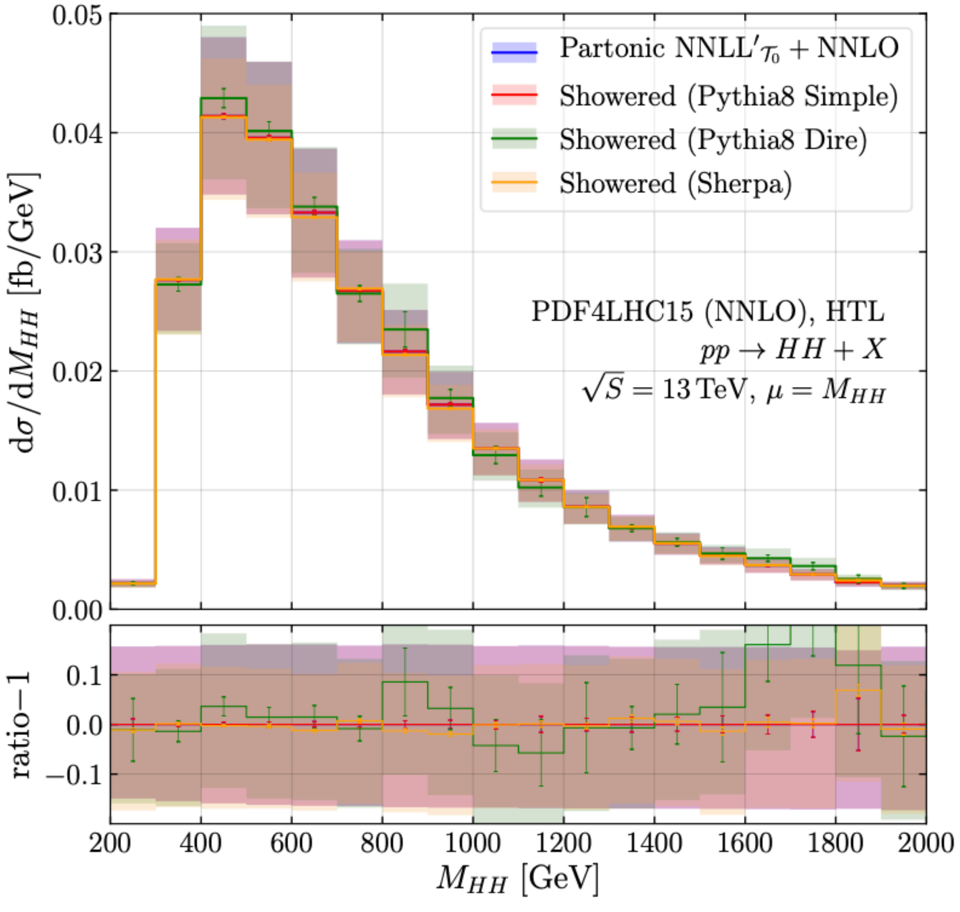
✓2 to 2 processes with bosons

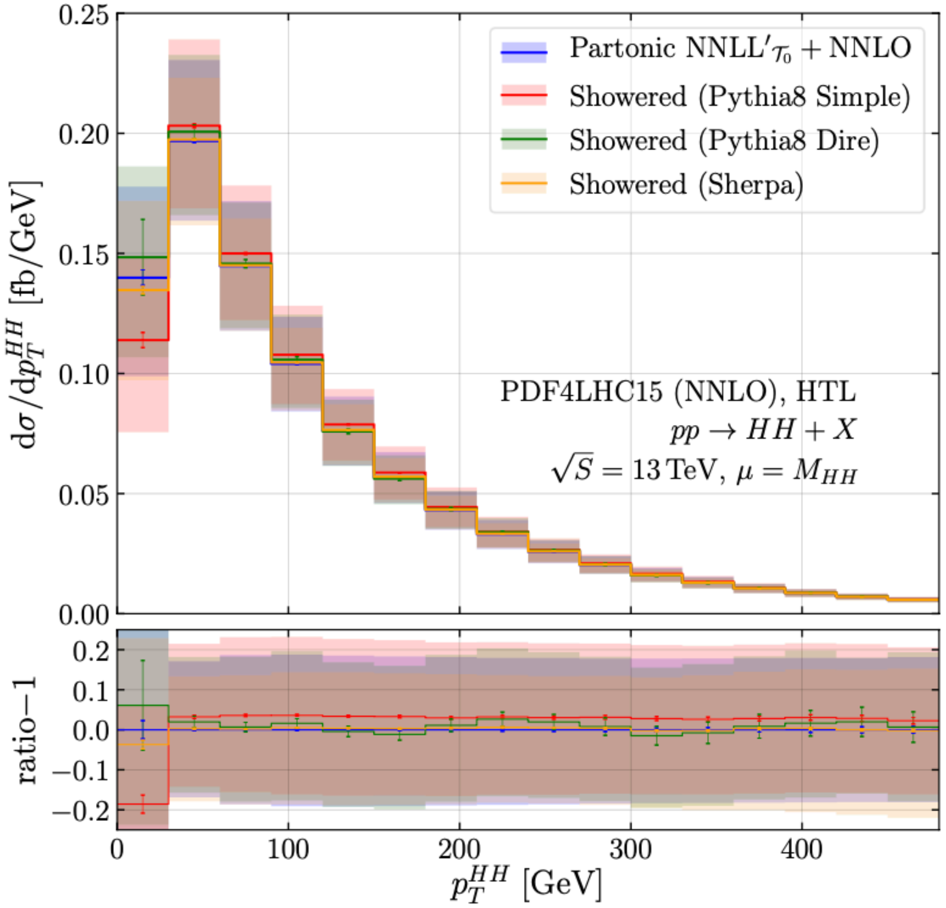
✓2 to 2 processes with heavy-quarks

➡ next frontier processes with light jets?

NNLO+PS: gg → HH

Alioli et al 2212.10489

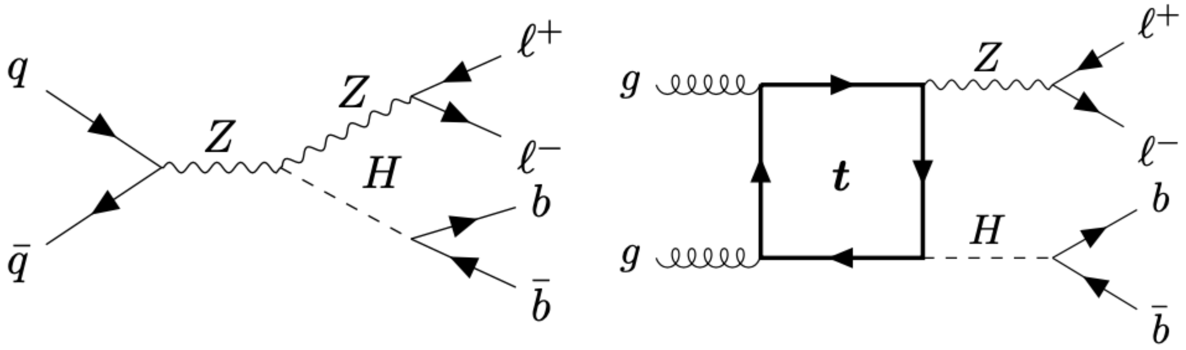


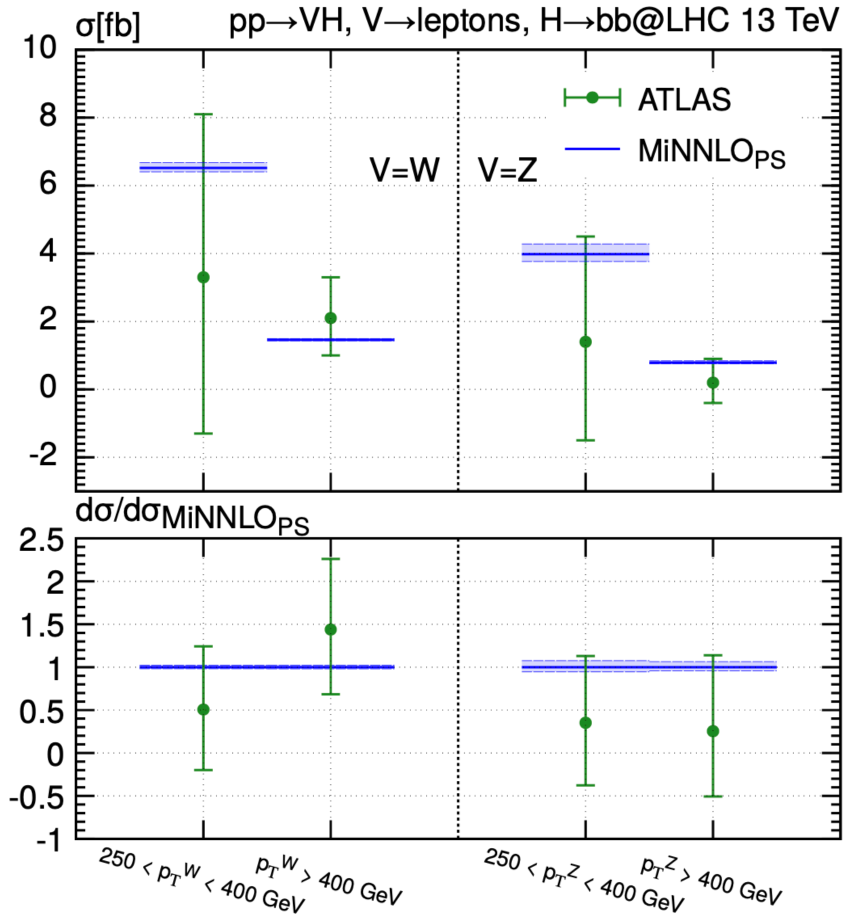


Good agreement with analytic results for inclusive quantities. Exclusive simulations allow to implement fiducial cuts and exclusive distributions accurately

NNLO+PS: HV with H → bb

- Needed for precision in the Higgs sector
- One of the main production channels + largest branching fraction in decay
- NNLO+PS accuracy in production of decay





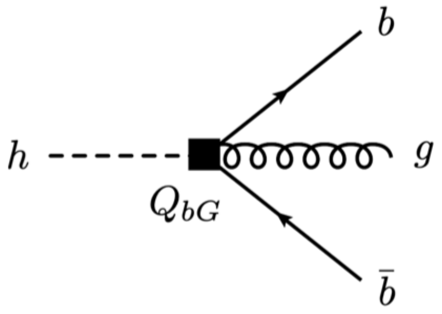
Zanoli, Chiesa, Re, Wiesemann, GZ *JHEP* 11 (2022) 072

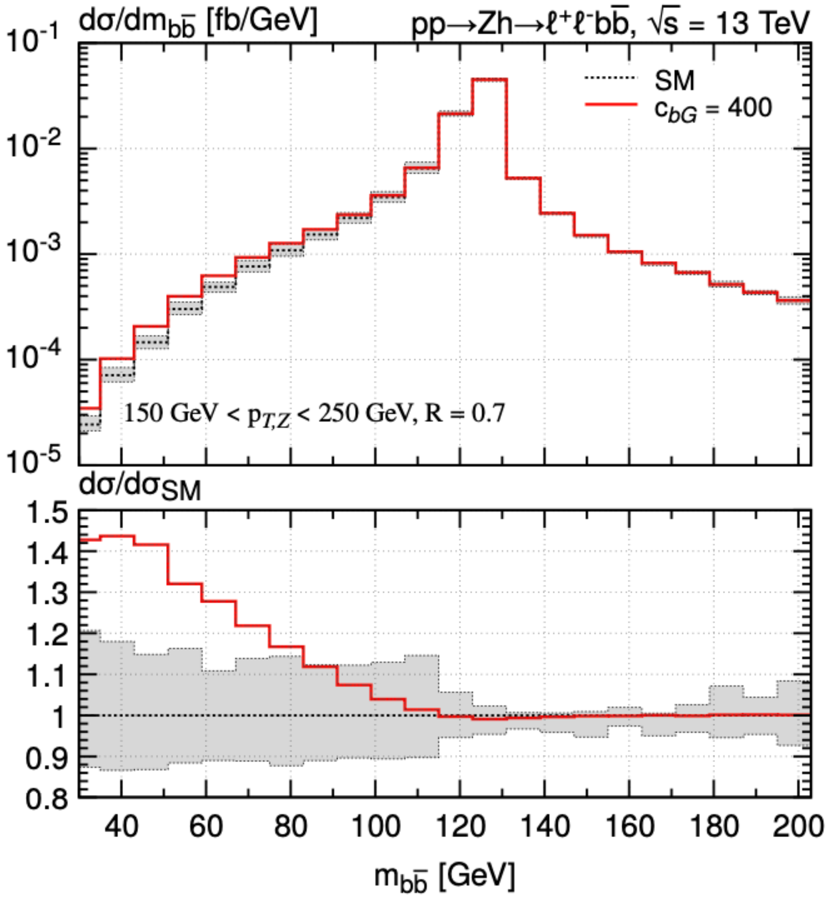
ZH with SMEFT H → bb

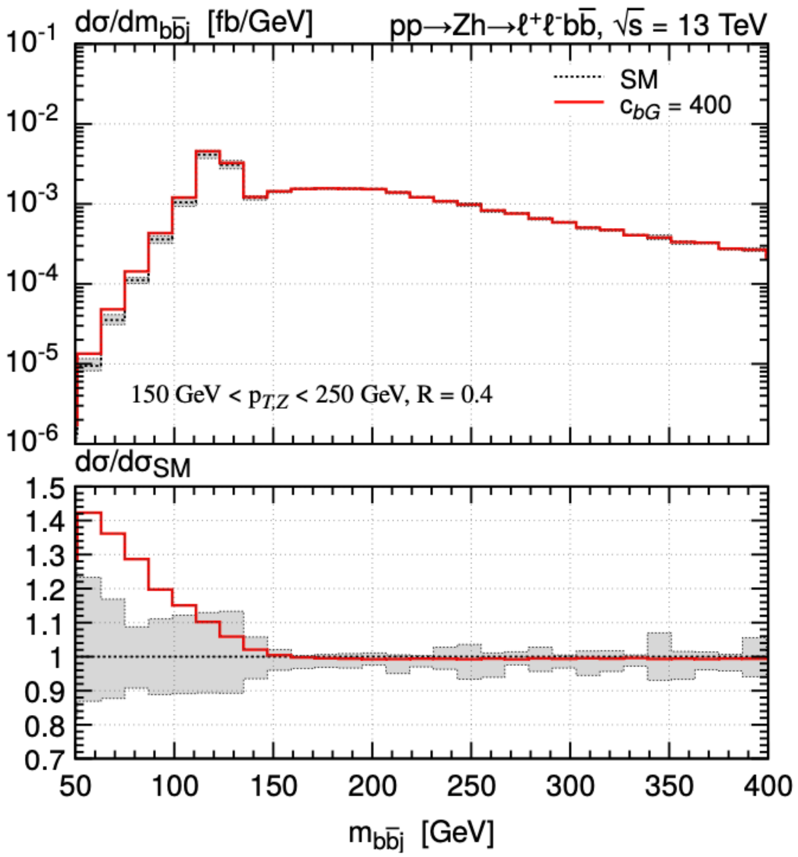
$$Q_{H\Box} = (H^\dagger H)\,\Box\,(H^\dagger H)\,, \qquad Q_{HD} = (H^\dagger D_\mu H)^* (H^\dagger D^\mu H)\,,$$

$$Q_{bH} = y_b (H^\dagger H)\,\bar{q}_L b_R H\,, \qquad Q_{bG} = \frac{g_s^3}{(4\pi)^2}\, y_b\, \bar{q}_L \sigma_{\mu\nu} T^a b_R H G^{a,\mu\nu}\,,$$

$$Q_{HG} = \frac{g_s^2}{(4\pi)^2}\,(H^\dagger H)\, G^a_{\mu\nu} G^{a,\mu\nu}\,, \qquad Q_{3G} = \frac{g_s^3}{(4\pi)^2}\, f^{abc} G^{a,\nu}_\mu G^{b,\sigma}_\nu G^{c,\mu}_\sigma\,,$$







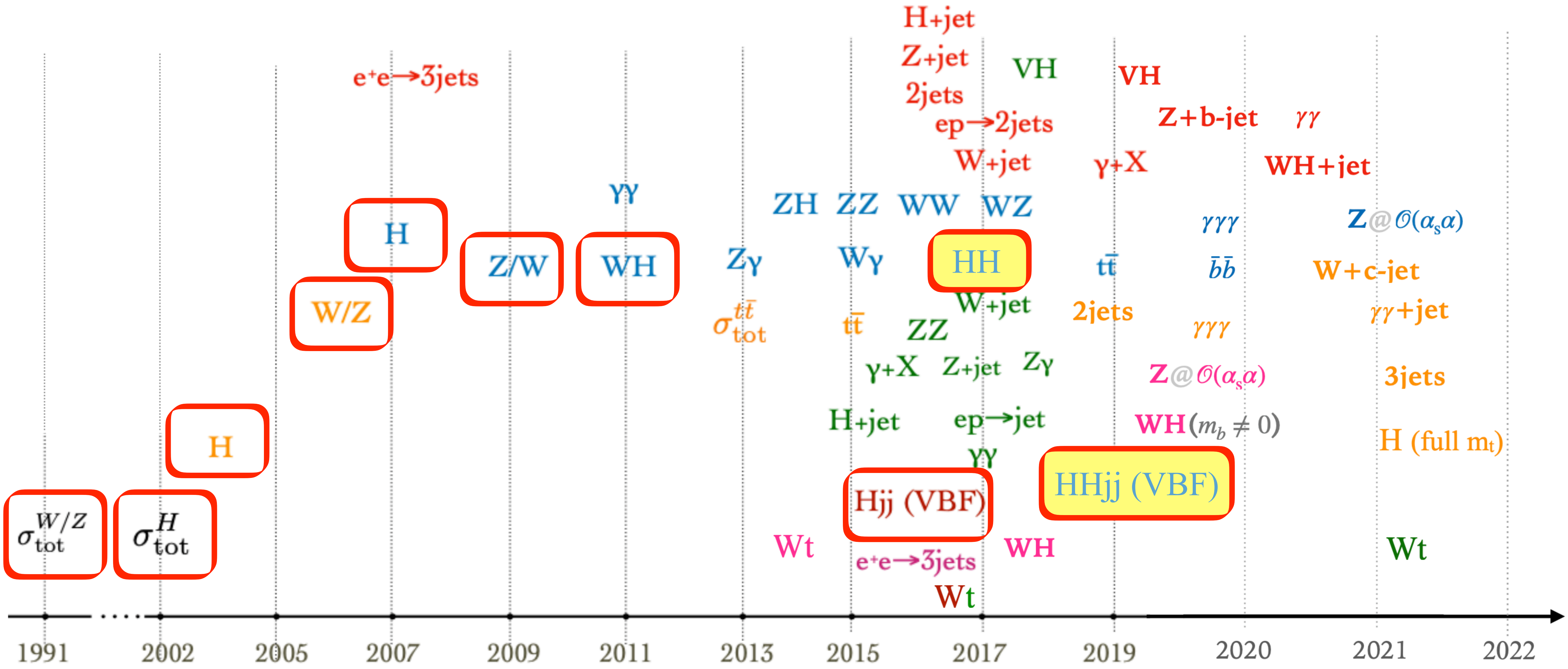
$$\Gamma(h \to b\bar{b})^{\rm NNLO,non}_{\rm SMEFT} = \Delta_{\rm non}\, c_{bG}\, \Gamma(h \to b\bar{b})^{\rm LO}_{\rm SM}\,,$$

$$\Delta_{\rm non} = \left(\frac{\alpha_s}{\pi}\right)^2 \frac{m_h^2}{3v^2}$$

⇒ very interesting and distinctive shape differences

Haisch, Scott, Wiesemann, Zanoli, GZ *JHEP* 07 (2022) 054

NNLO → N^3LO



2015 **…** **2023** **N^3LO**

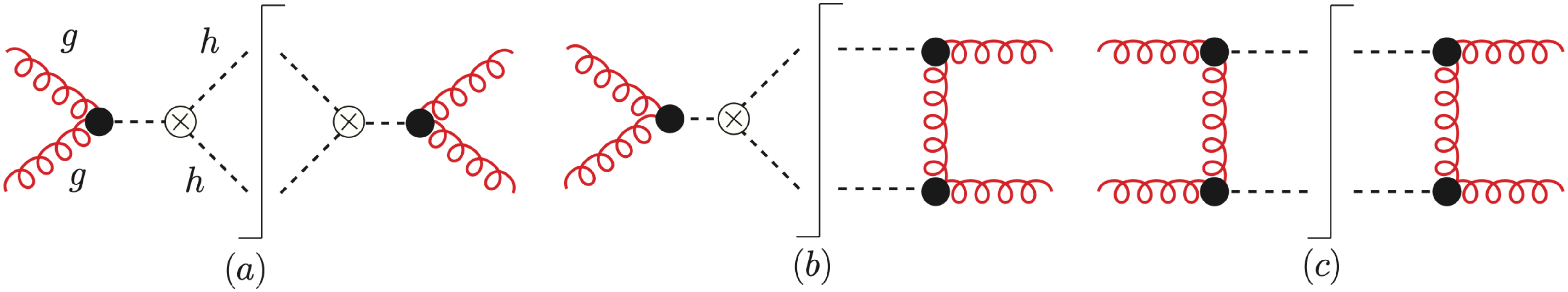
N^{3}LO status

Range of calculations and **public codes** allow comprehensive phenomenological studies at N^{3}LO:

- `iHixs2` H (gg) N^{3}LO+EW+threshold,HQ effects Dulat et al. 1802.00827
- `ggHiggs` H (gg) N^{3}LO+N^{3}LL threshold Bonvini et al. 1603.08000
- `SusHi` H (gg), also CP-odd Harlander et al 1605.03190
- `ProVBFH` inclusive VBF Higgs and di-Higgs Dreyer&Karlberg 1606.00840
- `n3loxs` inclusive H (gg or bb induced), Drell Yan and Higgsstrahlung (HV) Baglio et al 2209.06138

N^3LO gluon-fusion di-Higgs

Chen et al 1909.06808 and 1912.13001



<u>NB:</u> Since more complicated topologies (b) and (c) enter at NLO and NNLO, respectively, one can obtain N^3LO accuracy by considering off-shell single Higgs production, i.e. topology (a)

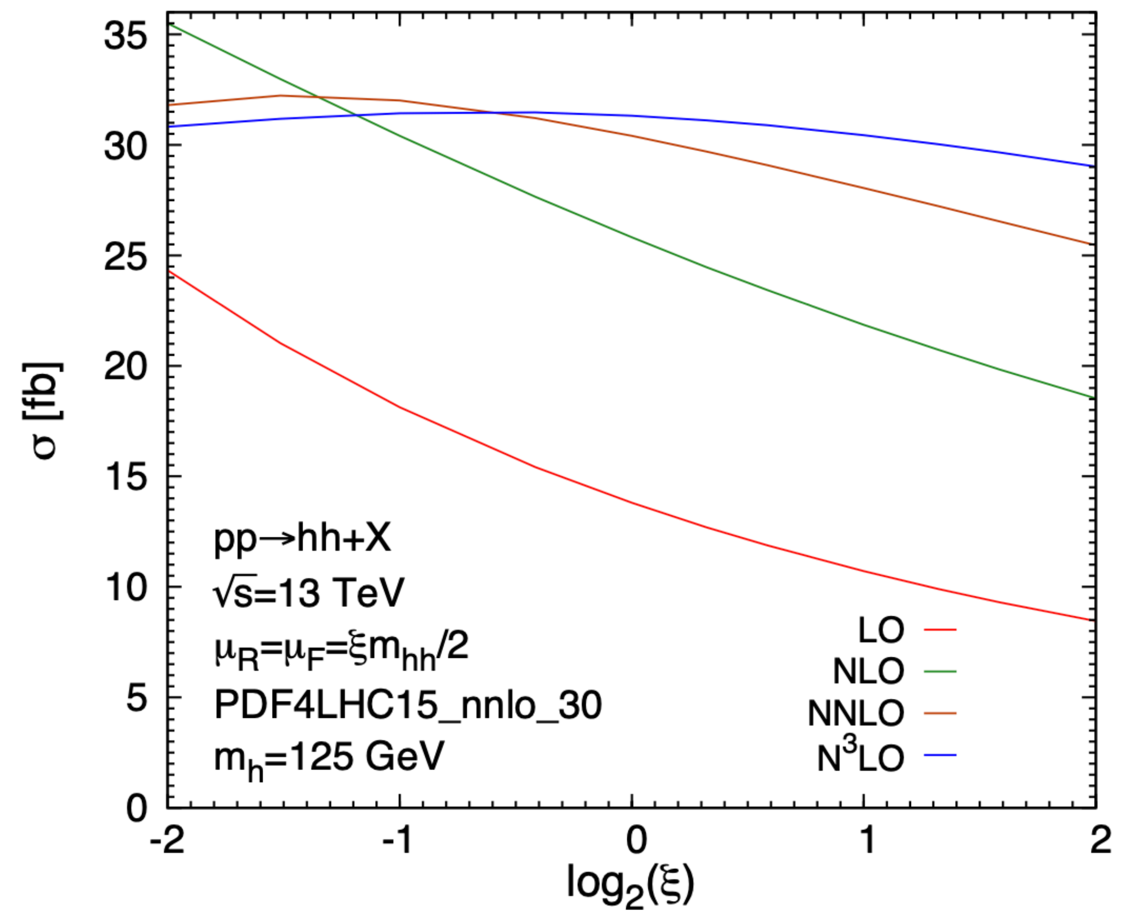
	LO	NLO	NNLO	N^3LO
Total	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^4)$	$\mathcal{O}(\alpha_s^5)$
a	LO_a $\mathcal{O}(\alpha_s^2)$	NLO_a $\mathcal{O}(\alpha_s^3)$	$NNLO_a$ $\mathcal{O}(\alpha_s^4)$	N^3LO_a $\mathcal{O}(\alpha_s^5)$
b	— 0	LO_b $\mathcal{O}(\alpha_s^3)$	NLO_b $\mathcal{O}(\alpha_s^4)$	$NNLO_b$ $\mathcal{O}(\alpha_s^5)$
c	— 0	— 0	LO_c $\mathcal{O}(\alpha_s^4)$	NLO_c $\mathcal{O}(\alpha_s^5)$

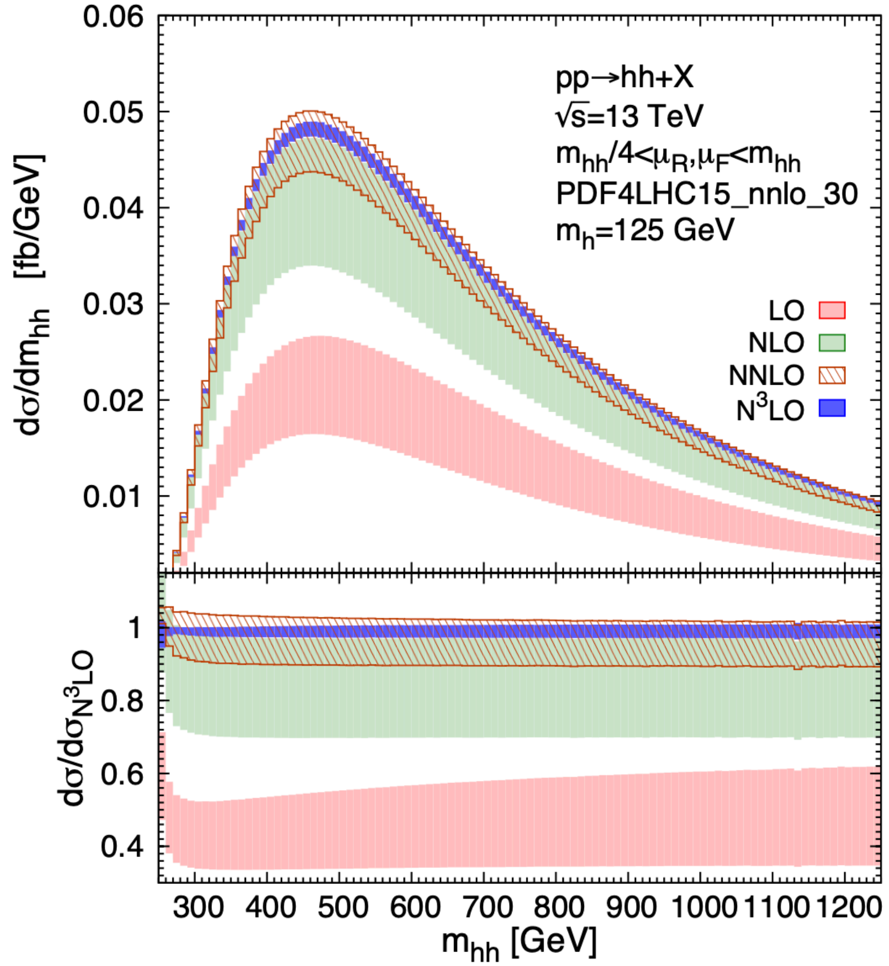
Similar arguments hold for triple-Higgs production

N^3LO gluon-fusion di-Higgs

Chen et al 1909.06808 and 1912.13001
Including resummation effects in Ajjath and Shao 2209.03914
Top mass scheme uncertainty in Baglio et al. 2008.11626

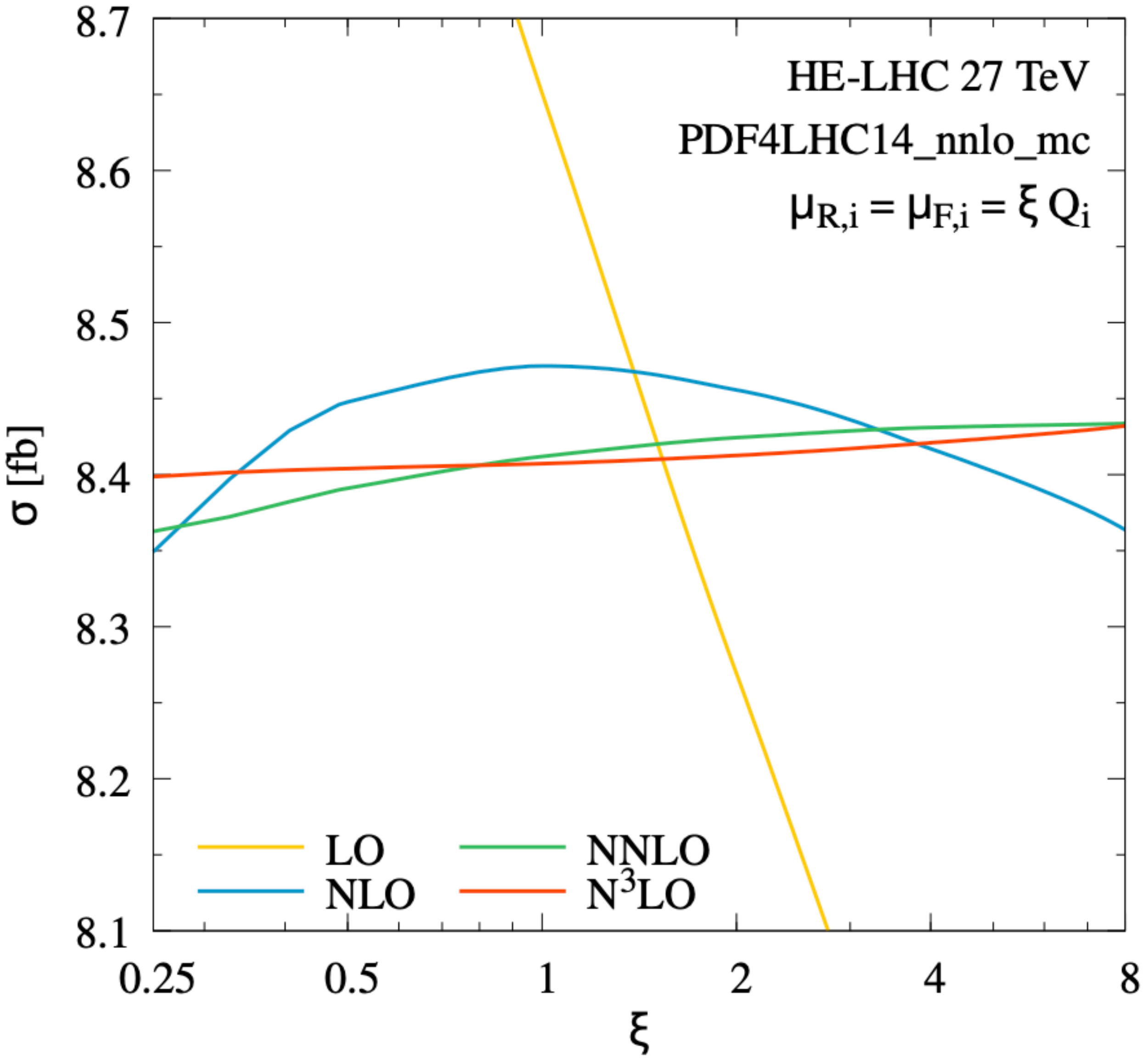
Not surprisingly, the pattern of higher order corrections is very similar to single-Higgs production:



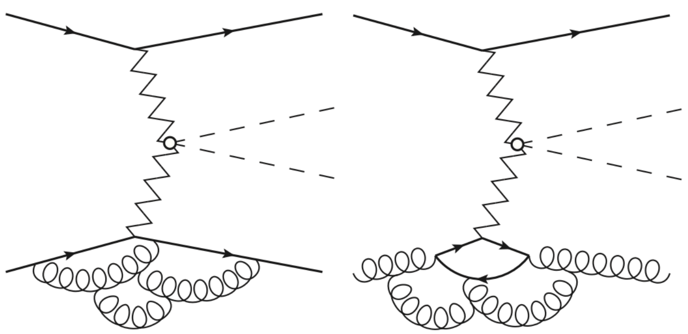


Leading residual uncertainties from missing N^3LO PDFs and missing NNLO top-loop effects (both effects are about 3%)

N^3LO VBF diHiggs



Dreyer and Karlberg 1811.07906



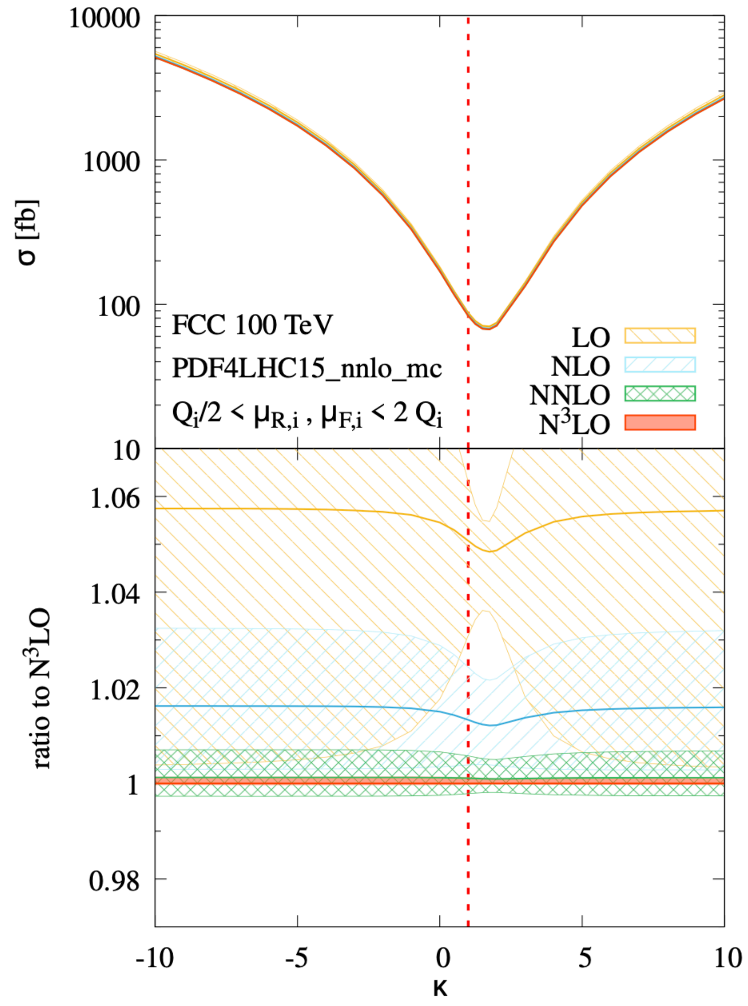
	$\sigma^{(14\ \mathrm{TeV})}$ [fb]	$\sigma^{(27\ \mathrm{TeV})}$ [fb]	$\sigma^{(100\ \mathrm{TeV})}$ [fb]
LO	$2.079^{+0.177}_{-0.152}$	$8.651^{+0.411}_{-0.382}$	$87.104^{+1.023}_{-1.633}$
NLO	$2.065^{+0.022}_{-0.018}$	$8.471^{+0.046}_{-0.024}$	$84.026^{+0.781}_{-0.860}$
NNLO	$2.056^{+0.003}_{-0.005}$	$8.412^{+0.014}_{-0.021}$	$83.000^{+0.340}_{-0.269}$
N^3LO	$2.055^{+0.001}_{-0.001}$	$8.407^{+0.005}_{-0.003}$	$82.901^{+0.097}_{-0.035}$

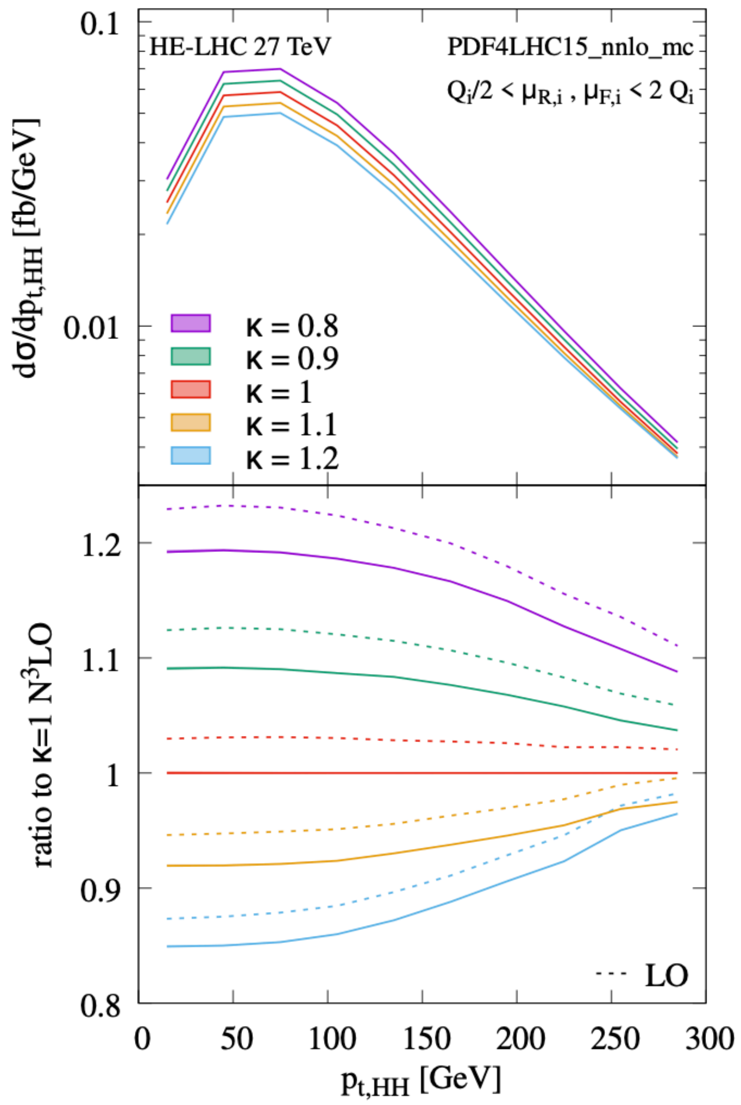
⇒ small N^3LO corrections, stable perturbative expansion

N^{3}LO VBF diHiggs

Impact of rescaling trilinear coupling λ:

Dreyer and Karlberg 1811.07906

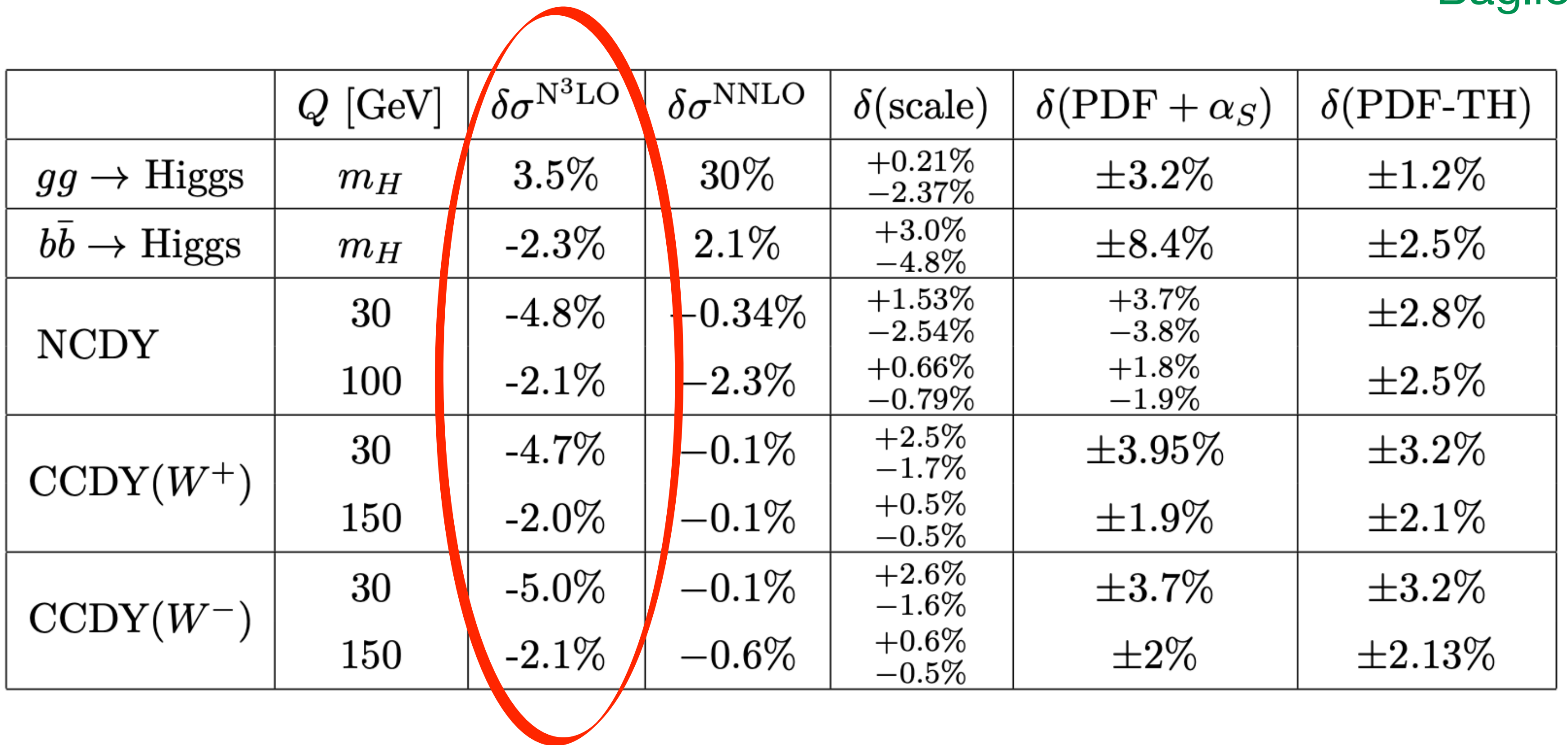




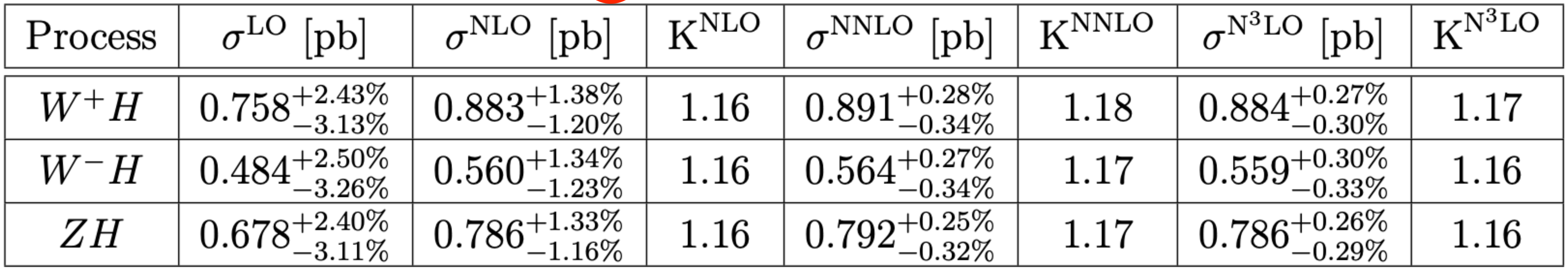
⇒ small deviations in λ can have sizeable effects in cross sections and distributions. K-factors largely unchanged

Sample N³LO results

Baglio et al 2209.06138



	Q [GeV]	$\delta\sigma^{\mathrm{N^3LO}}$	$\delta\sigma^{\mathrm{NNLO}}$	δ(scale)	$\delta(\mathrm{PDF}+\alpha_S)$	δ(PDF-TH)
$gg \to$ Higgs	m_H	3.5%	30%	$^{+0.21\%}_{-2.37\%}$	±3.2%	±1.2%
$b\bar{b} \to$ Higgs	m_H	-2.3%	2.1%	$^{+3.0\%}_{-4.8\%}$	±8.4%	±2.5%
NCDY	30	-4.8%	−0.34%	$^{+1.53\%}_{-2.54\%}$	$^{+3.7\%}_{-3.8\%}$	±2.8%
	100	-2.1%	−2.3%	$^{+0.66\%}_{-0.79\%}$	$^{+1.8\%}_{-1.9\%}$	±2.5%
CCDY(W^+)	30	-4.7%	−0.1%	$^{+2.5\%}_{-1.7\%}$	±3.95%	±3.2%
	150	-2.0%	−0.1%	$^{+0.5\%}_{-0.5\%}$	±1.9%	±2.1%
CCDY(W^-)	30	-5.0%	−0.1%	$^{+2.6\%}_{-1.6\%}$	±3.7%	±3.2%
	150	-2.1%	−0.6%	$^{+0.6\%}_{-0.5\%}$	±2%	±2.13%

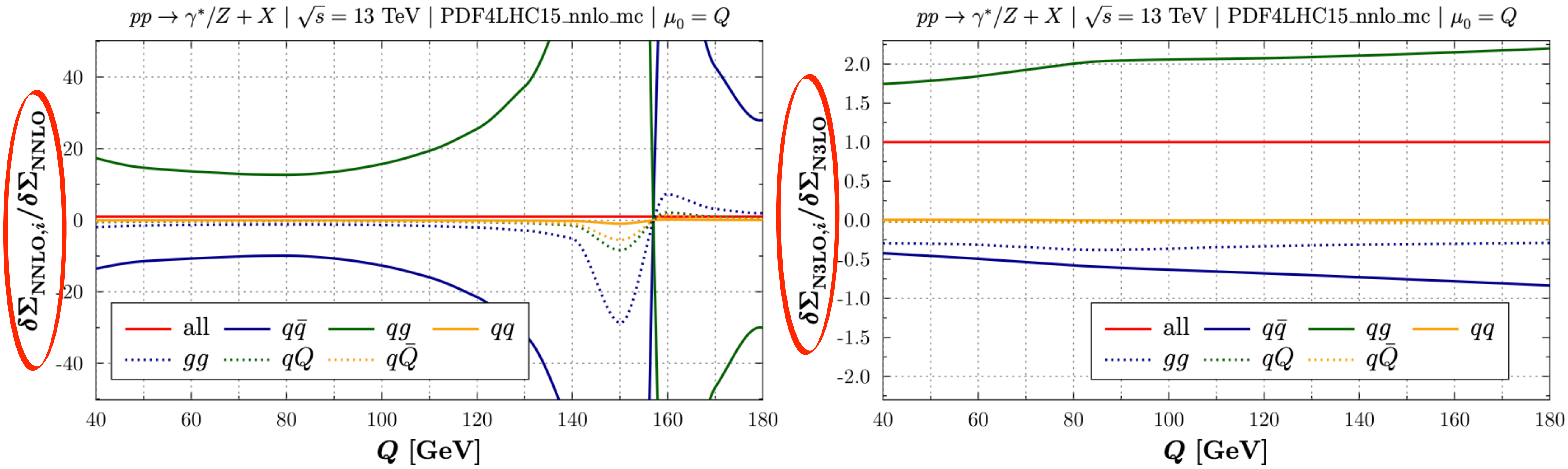


Process	σ^{LO} [pb]	σ^{NLO} [pb]	$\mathrm{K}^{\mathrm{NLO}}$	σ^{NNLO} [pb]	$\mathrm{K}^{\mathrm{NNLO}}$	$\sigma^{\mathrm{N^3LO}}$ [pb]	$\mathrm{K}^{\mathrm{N^3LO}}$
W^+H	$0.758^{+2.43\%}_{-3.13\%}$	$0.883^{+1.38\%}_{-1.20\%}$	1.16	$0.891^{+0.28\%}_{-0.34\%}$	1.18	$0.884^{+0.27\%}_{-0.30\%}$	1.17
W^-H	$0.484^{+2.50\%}_{-3.26\%}$	$0.560^{+1.34\%}_{-1.23\%}$	1.16	$0.564^{+0.27\%}_{-0.34\%}$	1.17	$0.559^{+0.30\%}_{-0.33\%}$	1.16
ZH	$0.678^{+2.40\%}_{-3.11\%}$	$0.786^{+1.33\%}_{-1.16\%}$	1.16	$0.792^{+0.25\%}_{-0.32\%}$	1.17	$0.786^{+0.26\%}_{-0.29\%}$	1.16

⇒ N³LO corrections sizeable (several %), often outside NNLO band

Sample N^{3}LO results

Partonic channel contributions for e.g. neutral Drell Yan



- Caveat of N^{3}LO predictions: PDFs are computed at NNLO
- Large cancelations between partonic channels can enhance PDF sensitivity ⇒ underlines the need for N^{3}LO PDFs

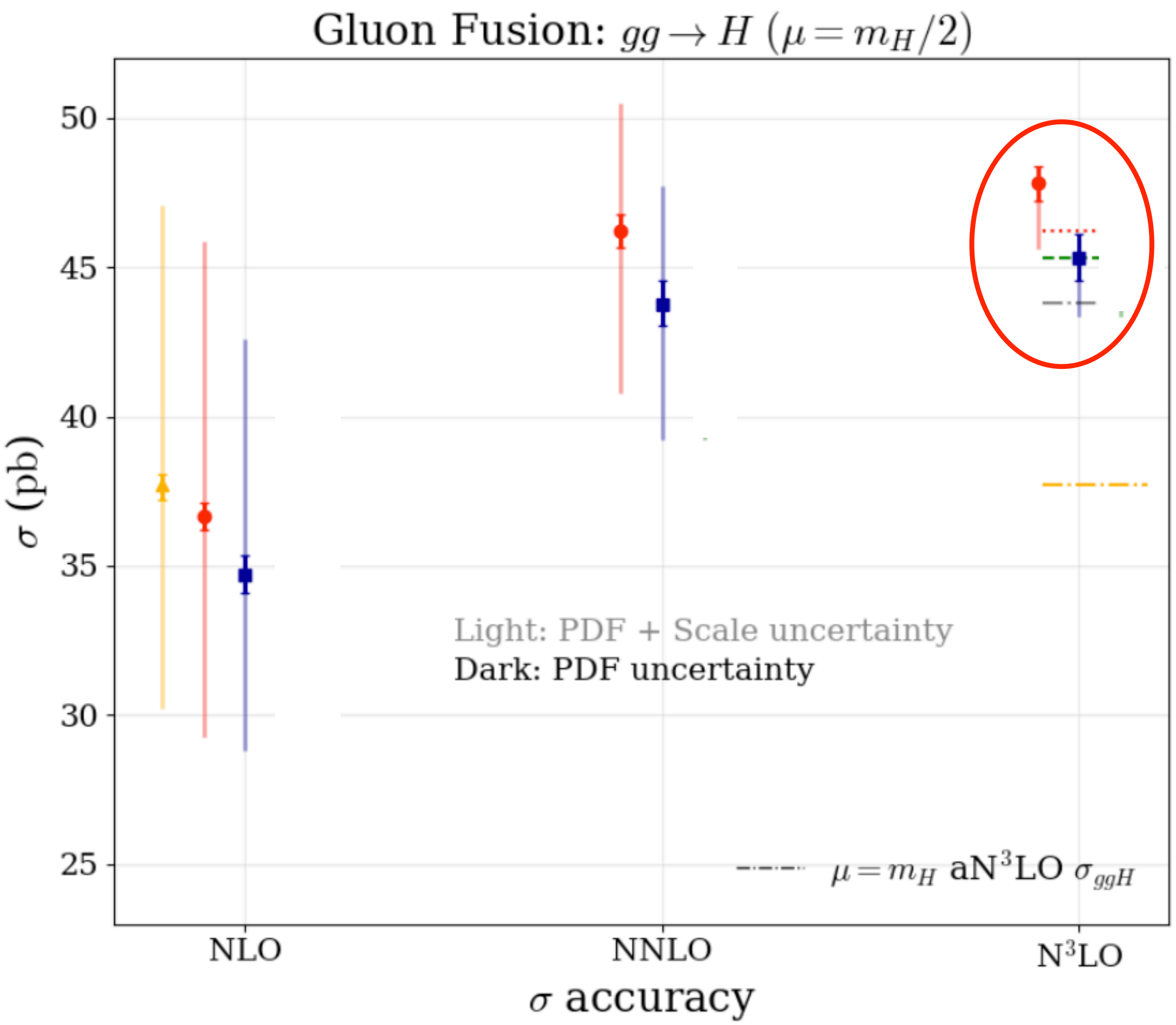
Baglio et al 2209.06138

Towards N^{3}LO PDFs

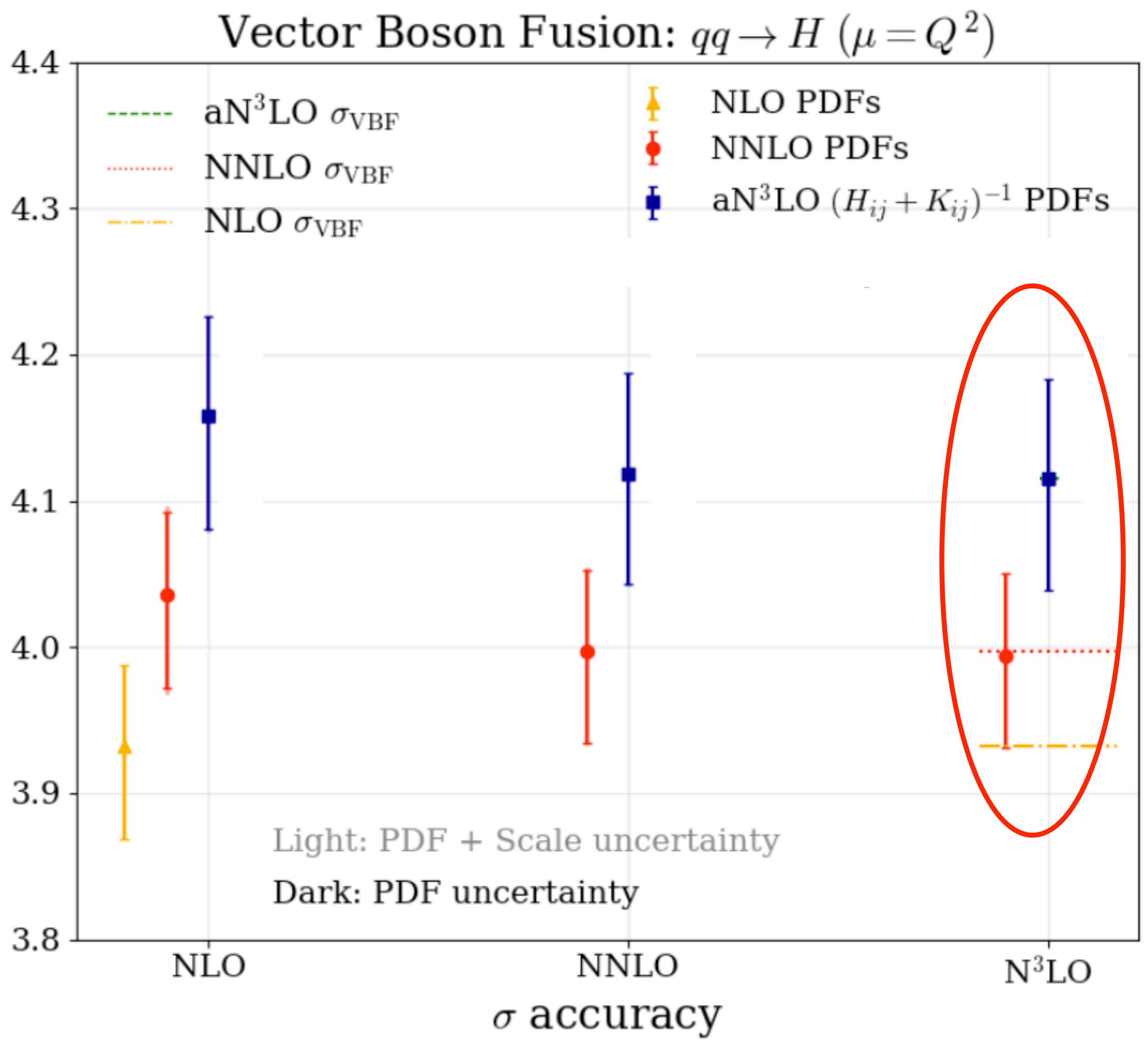
McGowan et al. 2207.04739

First approximate N^{3}LO PDF global fit (aN^{3}LO) in the MSHT framework

ggH cross-section:

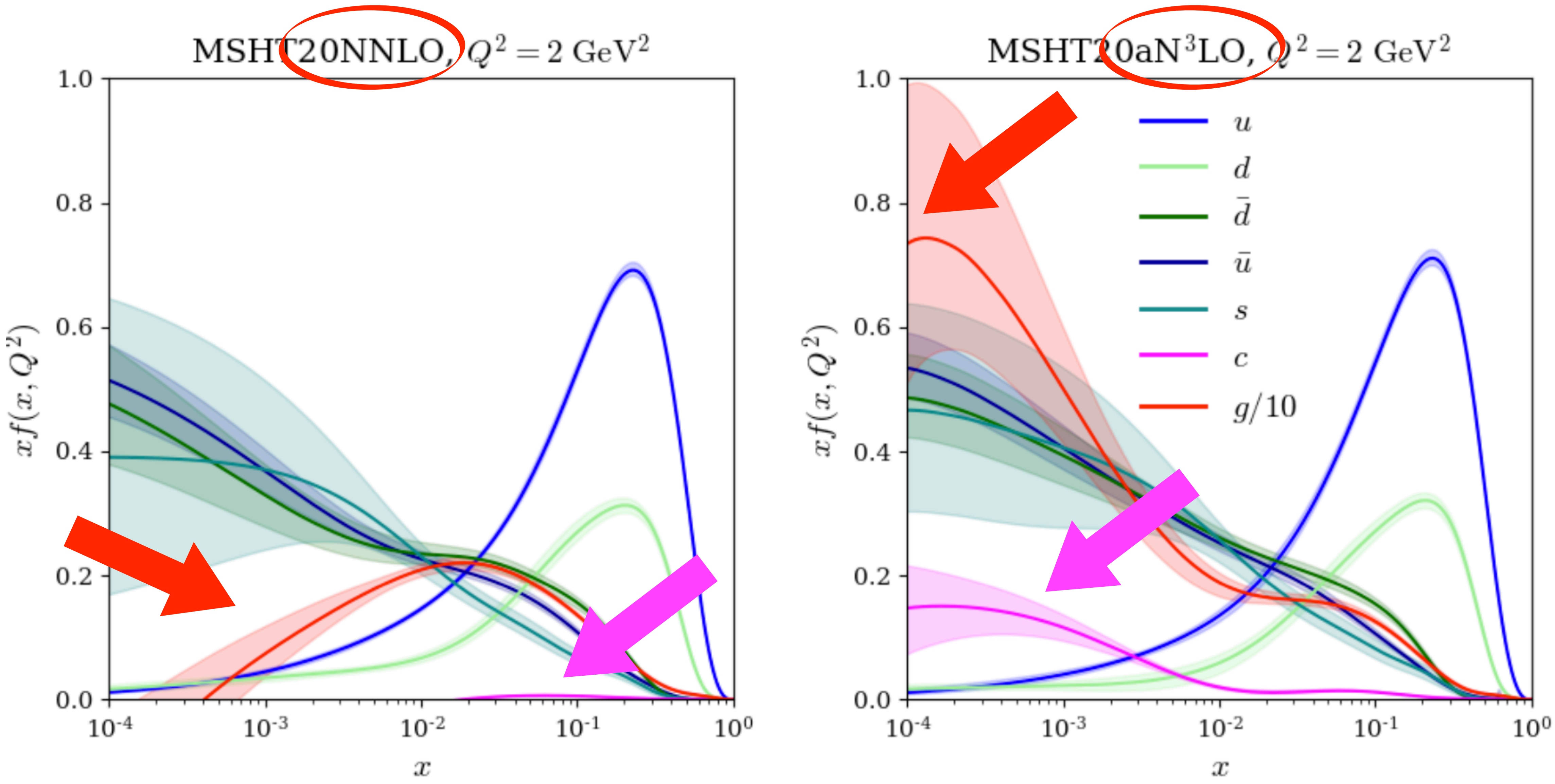


VBF H:



Towards N^{3}LO PDFs

McGowan et al. 2207.04739



Drastic change of gluon and heavy-quark PDF and low x and low Q^2. aN^{3}LO completely outside NNLO band. Needs more investigation.

Infrared safe jet definitions

Infrared unsafe jet algorithms widely used at the Tevatron
[Infrared unsafe = the structure of the hard jets can be modified by very soft or collinear splittings in QCD]

Things changed at the LHC thanks seminal work which lead to the development of the fast-k_t, the SIScone and anti-kt algorithms

Cacciari & Salam hep-ph/0512210; Salam & Soyez 0704.0292; Cacciari, Salam, Soyez 0802.1189

This progress triggered considerable more work on jet-area, pileup subtraction and paved the way to the field of jet-substructure

Infrared safe jet definitions

Nobody, today, would use any old infrared unsafe jet-algorithm.
So, you will wonder, why I am talking about this at all here?

Infrared safe jet definitions

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So, you will wonder, why I am talking about this at all here?

Because jet-algorithms specifying the flavour of jets are still a notable exception!

Jet flavour

Where does jet flavour enter?

- Top reconstruction (top mass)
- Instrumental for QCD studies, e.g. inclusive b-jet (⇒ b-PDF)
- Z + charm-jet (⇒ charm PDF)
- W +charm-jet (⇒ strange PDF)
- Higgs to bottom (⇒ di-Higgs, triple Higgs studies)
- Jet-substructure (mass reconstructions)
- …

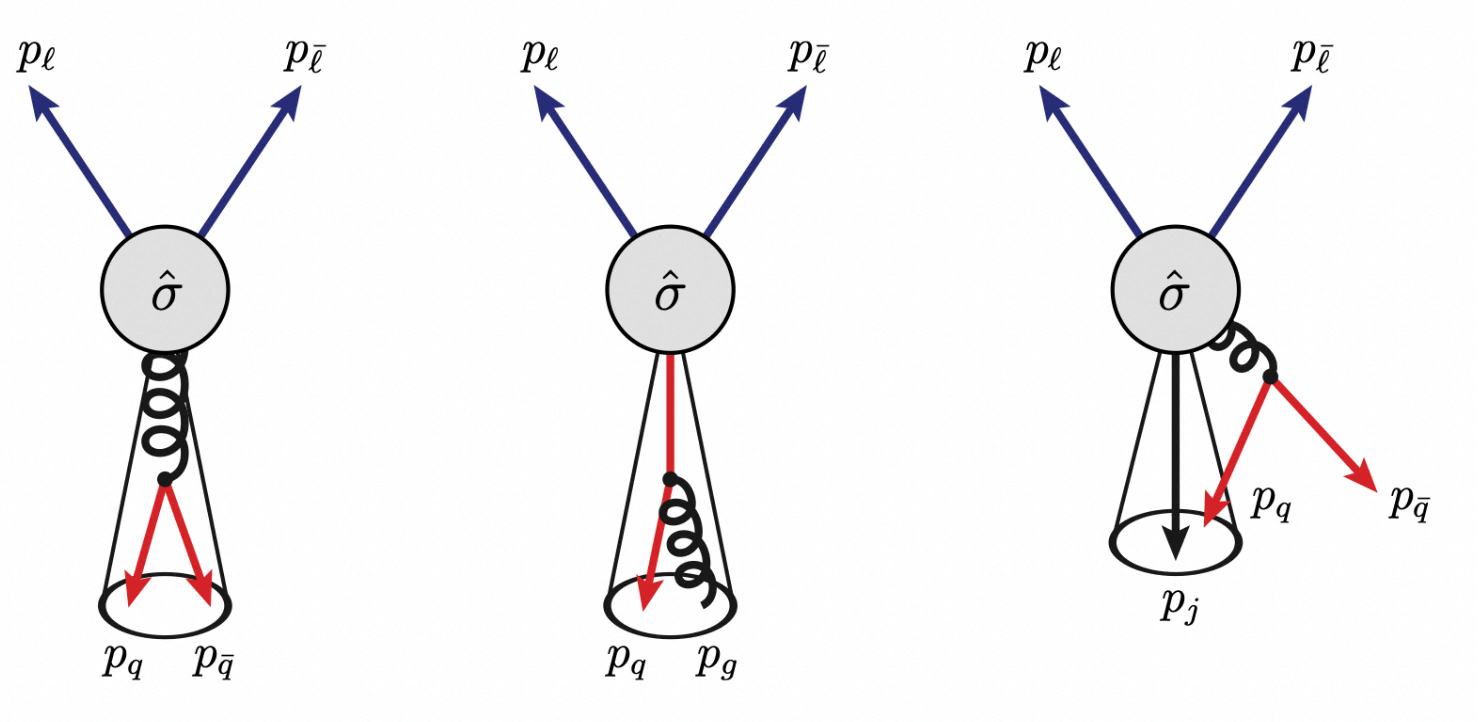
Infrared safe jet definitions

Example: LHCb charm-jet definition

LHCb 2109.08084

- reconstruct jets with anti-k_t algorithm
- require that the leading jet passes fiducial cuts
- the leading jet is considered a charm jet if there is at least one c-hadron satisfying $p_{t,\text{c-hadron}} > 5$ GeV and $\Delta R(\text{jet,c-hadron}) < 0.5$

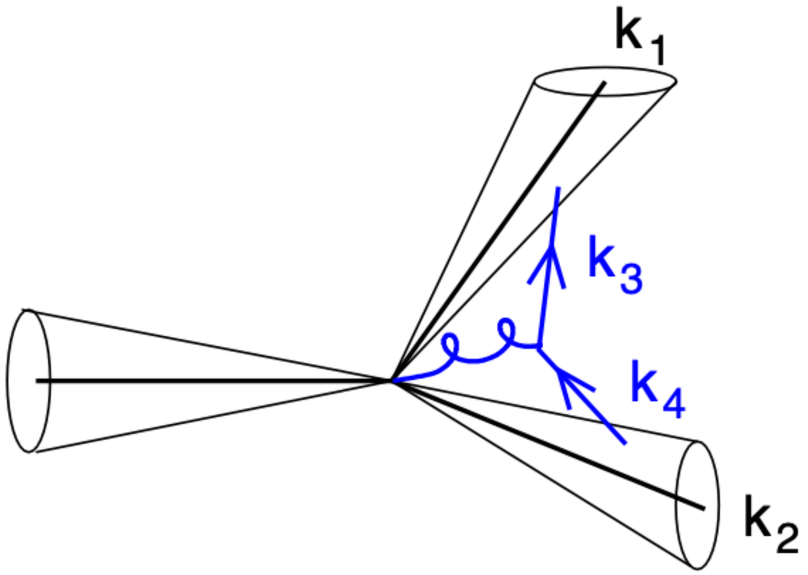
This definition is infrared and collinear unsafe



Gauld et al. 2302.12844

Jet flavour

The problem was addressed in 2006 (before the anti-k_t) and the proposed definition relies on a modification of the k_t-algorithm



Banfi, Salam, GZ hep-ph/0601139

<u>Two key elements:</u>

1) modification of the distance for flavoured particles

$$d_{ij}^{(F)} = (\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2) \times \begin{cases} \max(k_{ti}^2, k_{tj}^2) & \text{if softer of } i,j \text{ is flavoured} \\ \min(k_{ti}^2, k_{tj}^2) & \text{if softer of } i,j \text{ is flavourless} \end{cases}$$

2) classify a jet containing flavour and anti-flavour as gluon jet

Because of the k_t-like distance and the fact that it requires tagging two nearby flavoured particles, the algorithm was not adopted in practice at the LHC

Jet flavour

Recent proposals:

- Practical jet flavour through NNLO — Caletti et al. ’22
- Infrared-safe flavoured anti-k_t jets — Czakon et al. ’22
- A dress of flavour to suit any jets — Gauld et al. ’22
- Flavoured jets with exact anti-k_t kinematics — Caola et al ’23

Jet flavour

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- Flavoured jets with exact anti-k_t kinematics — Caola et al '23

Goals (in some cases not fully met yet…)

- anti-k_t like kinematics
- infrared-safe to all orders
- flavour information, e.g. for jet-substructure
- experimentally feasible

Whether or not these novel jet definitions will be used in realistic experimental analyses remains to be seen…

Conclusions

- ✓ Continuous fast progress in fixed-order calculations: NNLO 2 → 3, new N^{3}LO results. Progress driven by new ideas and methods.
- ✓ Steps towards N^{3}LO PDFs
- ✓ Progress in matching NNLO and parton shower (but not fully automated yet)
- ✓ Jet flavour: new ideas and algorithms. Theoretically interesting and useful ⇒ look forward to first experimental implementations