



Higgs cross sections and theory uncertainties for HL & HE LHC

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[for the LHCHXSWG1 - Higgs Cross Sections and BRs]

Higgs @ HL/HE-LHC - Autumn WG2 Meeting

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Introduction

- Work within [LHCHXSWG1](#) to ensure the same levels of sophistication for HL and HE LHC as currently used.
 - state-of-the art predictions for cross-sections at HE LHC, including uncertainty analysis (same setup as YR4 except where otherwise noted)
 - projections for expected theory improvements on timescale of HL-LHC, including assessment of remaining limiting factors
- Note containing details of relevant studies still being finalized, but all results already available:

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG1HELHCXsecs>

- contributions from ggF, VBF, VH, ttH/tH subgroups

Gluon fusion: cross-sections

[Becker, Massironi, Mistlberger, Monni]

- N³LO QCD, EW, approx. mixed QCD-EW corrections, finite quark masses.
 - numerical predictions obtained using `iHixs`.

E _{CM}	σ	$\delta(\text{theory})$	$\delta(\text{PDF})$	$\delta(\alpha_s)$
13 TeV	48.61 pb	$+2.08\text{pb}$ ($+4.27\%$) -3.15pb (-6.49%)	$\pm 0.89\text{ pb}$ ($\pm 1.85\%$)	$+1.24\text{pb}$ ($+2.59\%$) -1.26pb (-2.62%)
14 TeV	54.72 pb	$+2.35\text{pb}$ ($+4.28\%$) -3.54pb (-6.46%)	$\pm 1.00\text{ pb}$ ($\pm 1.85\%$)	$+1.40\text{pb}$ ($+2.60\%$) -1.41pb (-2.62%)
27 TeV	146.65 pb	$+6.65\text{pb}$ ($+4.53\%$) -9.44pb (-6.43%)	$\pm 2.81\text{ pb}$ ($\pm 1.95\%$)	$+3.88\text{pb}$ ($+2.69\%$) -3.82pb (-2.64%)

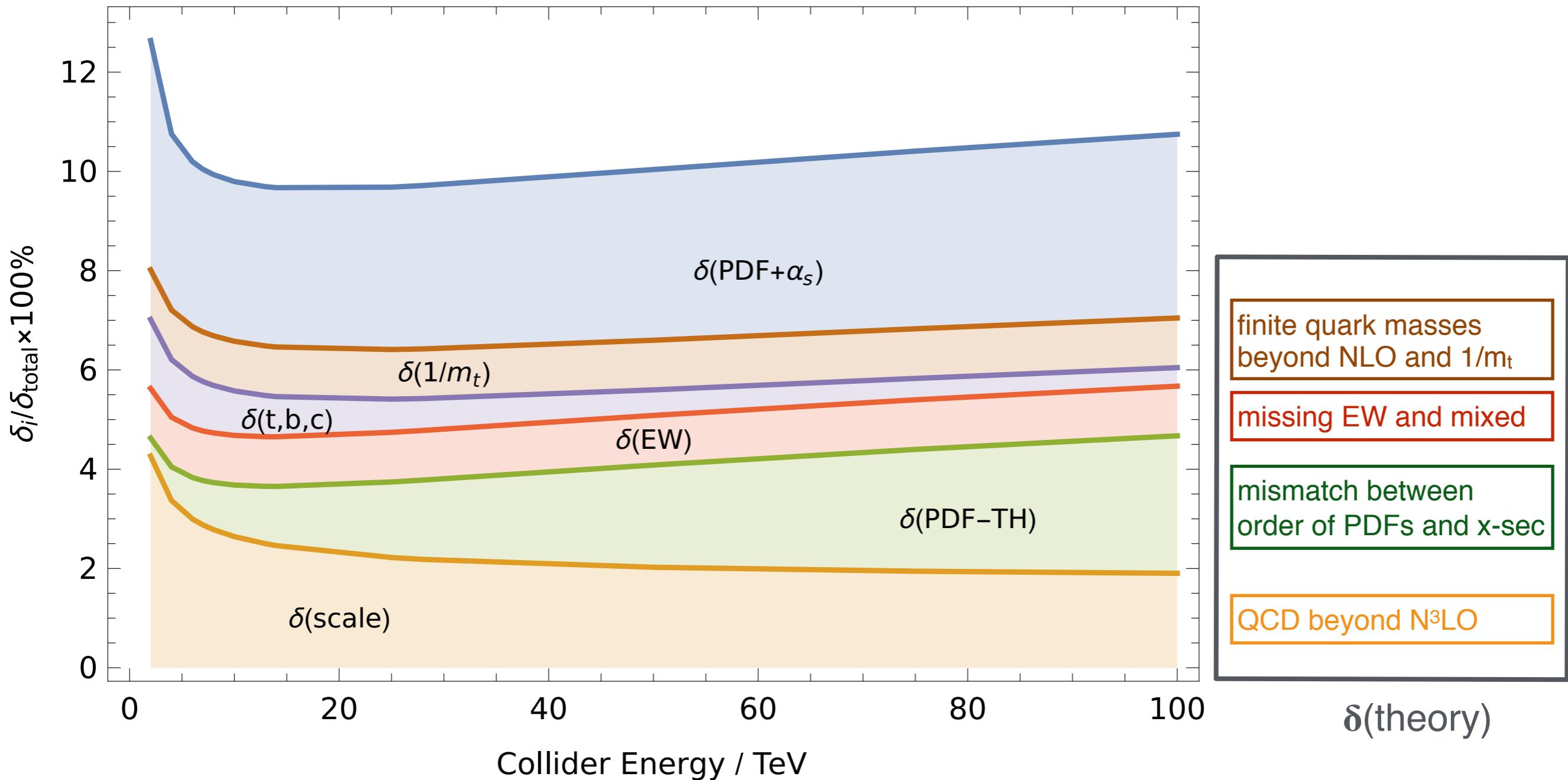
- Change wrt. YR4: exact N³LO EFT cross-section instead of previous threshold expansion (unknown at time) [Mistlberger, 1802.00833]
 - small shift in the cross-section and uncertainties reported in YR4 for 13 TeV:

$$\sigma = 48.58 \text{ pb}^{+2.22 \text{ pb} (+4.56\%)}_{-3.27 \text{ pb} (-6.72\%)} (\text{theory})$$



Gluon fusion: uncertainties

- Relative importance of uncertainties almost independent of \sqrt{s} .



Gluon fusion: impact of resummation

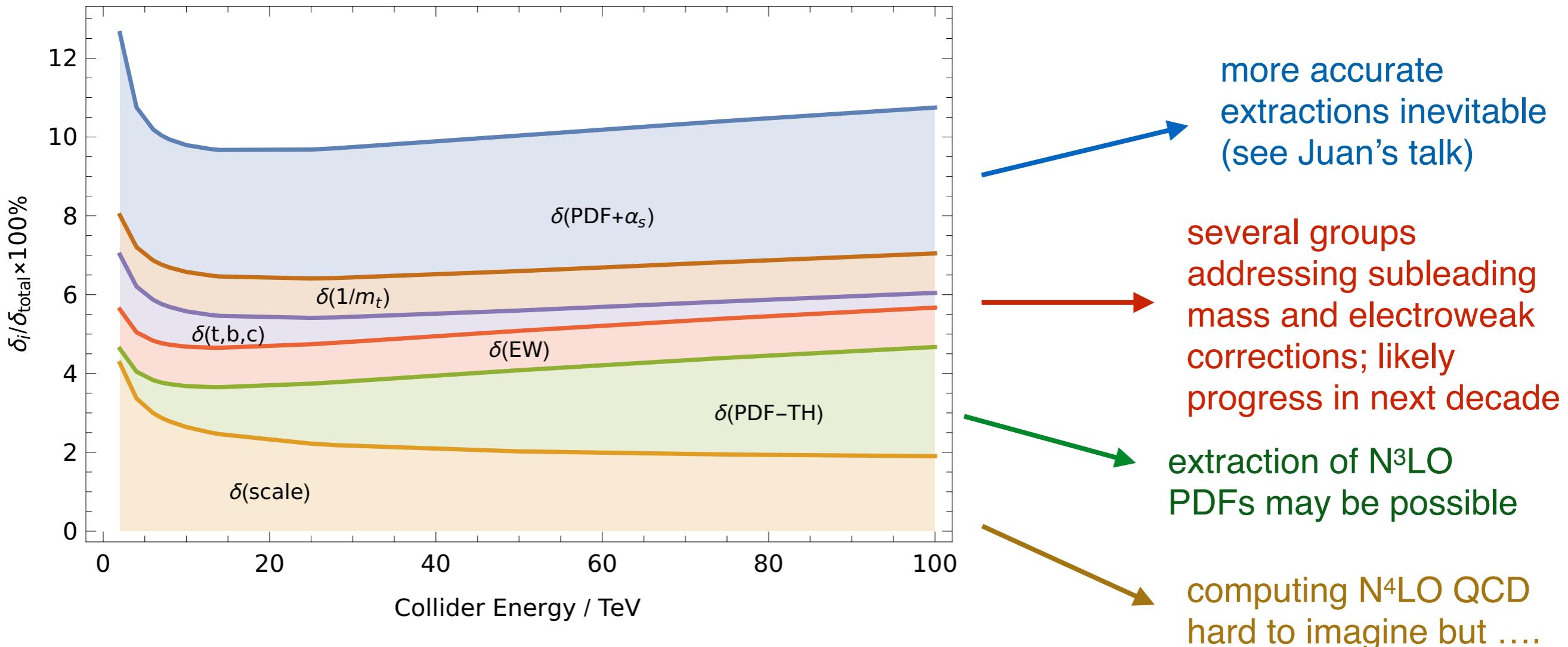
[Bonvini, Marzani; 1802.07768]

- Assess inclusion of both threshold (large- x) N³LL and high-energy (small- x) LL resummation to all orders, on top of N³LO.
 - must use NNPDF small- x resummed PDFs [Ball et al, 1710.05935]

\sqrt{s}	$\sigma_{\text{N}^3\text{LO+N}^3\text{LL+LL}_x}$	$= \sigma_t + \Delta\sigma_{bc} + \Delta\sigma_{\text{EW}}$	$\delta_{\text{scale}}^{42\text{var}}$	δ_{PDFs}	$\delta_{\text{subl.logs}}$	$\frac{\sigma_{\text{N}^3\text{LO+N}^3\text{LL+LL}_x}}{\sigma_{\text{N}^3\text{LO}}}$
13 TeV	48.93 pb	(49.26 – 2.66 + 2.33) pb	${}^{+4.0\%}_{-3.8\%}$	$\pm 1.2\%$	$\pm 1.8\%$	1.020
14 TeV	55.22 pb	(55.56 – 2.96 + 2.63) pb	${}^{+4.0\%}_{-3.8\%}$	$\pm 1.1\%$	$\pm 1.9\%$	1.023
27 TeV	151.6 pb	(151.6 – 7.2 + 7.2) pb	${}^{+4.0\%}_{-4.0\%}$	$\pm 1.0\%$	$\pm 2.3\%$	1.046

- Appears to indicate substantial effect from resummation, but ...
- Threshold expansion known to be a small +1% effect, compatible with expected higher-order uncertainty.
- Small- x data from HERA appears to require small- x resummation for fit to be robust → effect is driven by different PDFs (NNPDF, resummed or not).
- Conclusion: for now, **need better understanding of small- x dynamics and corresponding data that could be included in fits.**

Gluon-fusion: uncertainty projections



- Also, any reductions will likely lead to better understanding of correlations between sources of uncertainty (linear → quadratic combination).

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... ?? 2016 2002 1991 1978

Vector boson fusion: cross-sections

[Bertella, Haddad, Karlberg, Rauch]

- NNLO QCD, NLO EW, computed using `proVBFH` and `HAWK`
 - $N^3\text{LO}$ known, but important for consistency with fiducial cuts
- Change wrt. YR4: uses LUXqed instead of NNPDF to account for small photon contribution more precisely.

$\sqrt{s}[\text{TeV}]$	$\sigma^{\text{VBF}}[\text{fb}]$	$\Delta_{\text{scale}}[\%]$	$\Delta_{\text{PDF} \oplus \alpha_s}[\%]$	$\sigma_{\text{NNLO QCD}}^{\text{DIS}}[\text{fb}]$	$\delta_{\text{ELWK}}[\%]$	$\sigma_\gamma[\text{fb}]$	$\sigma_{s\text{-channel}}[\text{fb}]$
7	1241	$^{+0.19}_{-0.21}$	± 2.2	1281	-4.4	17.1	585
8	1601	$^{+0.25}_{-0.24}$	± 2.2	1655	-4.6	22.1	710
13	3766	$^{+0.43}_{-0.33}$	± 2.1	3939	-5.3	35.3	1412
14	4260	$^{+0.45}_{-0.34}$	± 2.1	4460	-5.4	40.7	1555
27	11838	$^{+0.66}_{-0.36}$	± 2.1	12483	-6.2	129	3495

- No significant new features for HE-LHC.

VBF: projected progress

- Current calculations use the VBF approximation (corrections DIS-like and factorize on each quark line).
 - Full NLO corrections — in both QCD and EW coupling — available outside VBF approximation; NLO EW as large as NNLO QCD corrections in VBF approx.
 - suggests current accuracy around 1%.
- Could lift the VBF approximation on HL-LHC timescale.
 - requires calculation of 2-loop diagrams with gluon exchange between quark lines
 - no current methods for computing such a $2 \rightarrow 3$ process, but might become available
- Ideally would like to connect all fixed-order input with event generator.
 - merged 2- and 3-jet samples at NLOPS or NNLOPS level
 - realistic to expect this in the next few years, well before HL phase

VH: cross-sections

[Palmer, Pandini, Re, Tramontano]

- NNLO QCD, NLO EW, combined as in YR4.
- Change wrt. YR4: again uses LUXqed instead of NNPDF
 - significant since photon contribution large, esp. for WH channels (5% to 7% at HE-LHC)

$\ell^+ \nu$ H (“WH”)

\sqrt{s} [TeV]	$\sigma_{\text{NNLO QCD} \otimes \text{NLO EW}}$ [pb]	$\Delta_{\text{scale}} [\%]$	$\Delta_{\text{PDF} \oplus \alpha_s} [\%]$	σ_γ
13	0.094	+0.71 -0.70	1.72	$4.1 \cdot 10^{-3}$
14	0.104	+0.61 -0.73	1.70	$4.7 \cdot 10^{-3}$
27	0.232	+0.40 -0.97	1.72	$1.5 \cdot 10^{-2}$

$\ell^+ \ell^-$ H (“ZH”)

\sqrt{s} [TeV]	$\sigma_{\text{NNLO QCD} \otimes \text{NLO EW}}$ [pb]	$\Delta_{\text{scale}} [\%]$	$\Delta_{\text{PDF} \oplus \alpha_s} [\%]$	σ_γ
13	$2.97 \cdot 10^{-2}$	+3.49 -2.67	1.64	$1.4 \cdot 10^{-4}$
14	$3.31 \cdot 10^{-2}$	+3.59 -2.92	1.89	$1.6 \cdot 10^{-4}$
27	$8.32 \cdot 10^{-2}$	+5.39 -3.97	1.85	$5.4 \cdot 10^{-4}$

VH: importance of gg \rightarrow ZH for HE-LHC

ZH total
gg \rightarrow ZH
only

	\sqrt{s} [TeV]	$\sigma_{\text{NNLO QCD}\otimes\text{NLO EW}}$ [pb]	$\Delta_{\text{scale}} [\%]$	$\Delta_{\text{PDF} \oplus \alpha_s} [\%]$
ZH total	13	0.880	+3.50 -2.68	1.65
	14	0.981	+3.61 -2.94	1.90
	27	2.463	+5.42 -4.00	2.24
gg \rightarrow ZH only	13	0.123	+24.9 -18.8	4.37
	14	0.145	+24.3 -19.6	7.47
	27	0.526	+25.3 -18.5	5.85

- gg luminosity means gg \rightarrow ZH is important already ($\sim 15\%$), but even more so at 27 TeV ($\sim 25\%$).
- Only enters cross-section at NNLO so scale uncertainty is like LO — large.
 - limited information (K-factor) from approximate NLO calculations included already



VH: projected progress

- Predictions mostly in good shape for HE-LHC.
- Expect finite- m_t result for NLO corrections to $gg \rightarrow ZH$
 - calculation similar to $gg \rightarrow HH$, for which equivalent calculation recently completed
 - those results suggest that scale uncertainty could decrease from $\sim 25\%$ to $\sim 15\%$
 - incorporation in NLOPS should be straightforward, improving on existing LO merging
- Expect better modeling of Higgs decay to bottom quarks
 - fixed-order studies of corrections to decay already available at current LHC energies
 - will be incorporated in event generators for better description of lineshape
- Dominant corrections are DY-like, reasonable to expect N^3LO calculation.

ttH/tH: cross-sections

[Llacer, Stieger, Pozzorini, Reina]

- NLO QCD, NLO EW (ttH), combined as in YR4.
- No qualitative changes from present energies to HE-LHC.

ttH @ 14 TeV

M_H [GeV]	$\sigma_{\text{QCD+EW}}$ [fb]	Scale[%]	α_s [%]	PDF[%]	PDF+ α_s [%]
124.59	619.3	+6.1 -9.2	1.9	2.9	3.5
125.09	612.8	+6.0 -9.2	1.9	2.9	3.5
125.59	605.6	+6.1 -9.2	1.9	2.9	3.5

ttH @ 27 TeV

M_H [GeV]	$\sigma_{\text{QCD+EW}}$ [pb]	Scale[%]	α_s [%]	PDF[%]	PDF+ α_s [%]
124.59	2.90	+7.9 -9.0	1.8	2.1	2.8
125.09	2.86	+7.8 -9.0	1.8	2.1	2.8
125.59	2.84	+7.9 -9.0	1.8	2.1	2.8



ttH/tH: projected progress

- Foreseeable that total theoretical uncertainty of 10-15% could be reduced by a factor of two within the next decade
 - based on dominance of scale uncertainty that would be reduced at NNLO QCD
 - and on ongoing rapid progress in NNLO calculations (and high importance of ttH and tH)
- Uncertainties resulting from theoretical modeling of backgrounds could be reduced by a factor of two to three within the next 5–10 years
 - extraction of signal mostly limited by modeling of ttbb and ttW+jets in MC generators
 - ongoing campaign in HXSWG to reliably assess and further reduce uncertainties

Finally ...

- More details, numerical results, references, etc. available online:
<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG1HELHCXsecs>
- Note still being updated, hope to finalize soon.
- Thanks to all the WG subgroup conveners and contributors!