Higgs Physics - Theory
Lecture 2

Higgs-boson physics at the LHC

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Outline of these lectures

- **Lecture 1: the Standard-Model Higgs boson.**
  - ↪ EW gauge symmetry, Higgs mechanism.
  - ↪ Higgs-boson interactions.
  - ↪ Quantum constraints.
- **Lecture 2: Higgs-boson physics at the LHC.**
  - ↪ Production and decay modes, what do they probe.
  - ↪ Theoretical predictions and their accuracy.
- **Lecture 3: from Higgs-boson properties to new physics.**
  - ↪ Probing specific extensions of the SM.
  - ↪ Probing classes of interactions within SM boundaries.

Testing EWSB: precision physics at the energy frontier

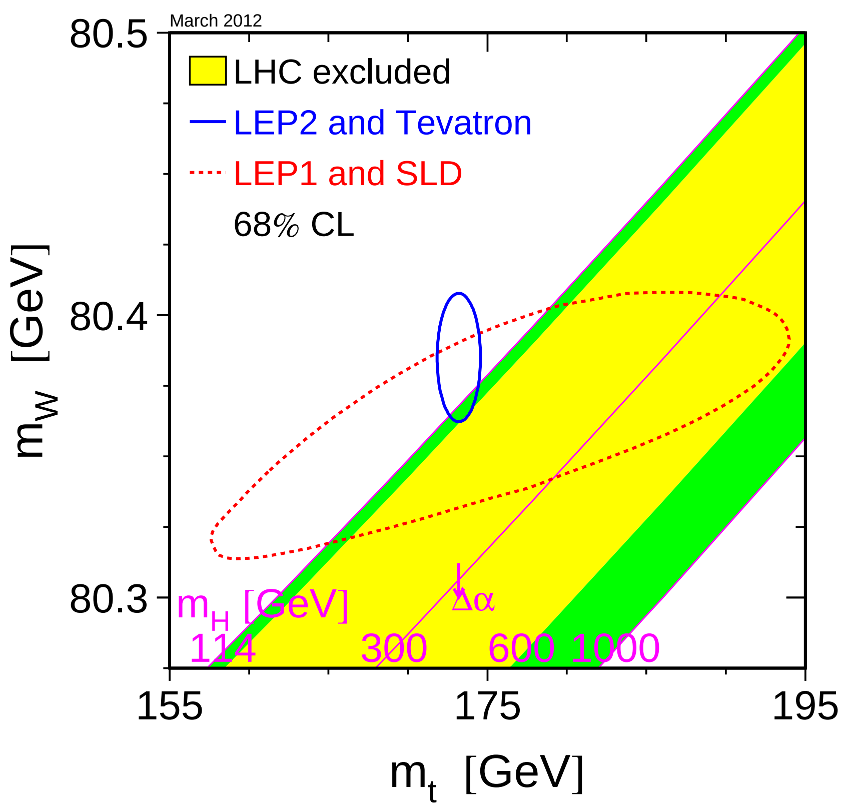
- Precision is intrinsic to having a predictive theory like the Standard Model of particle physics.
- Precision is effective when both theory and experiments have a way to reach comparable accuracy and improve it systematically.
- Particle physics has a very succesful history of constraining *new physics* through precision measurements in:
  - $\rightarrow$ Precision fits of electroweak observables (LEP, SLD, Tevatron, LHC)
    $\hookrightarrow$ indirectly constrained M_H
- From Run 1 to Run 2 and beyond: crucial to develop the LHC Higgs precision program:
  - $\rightarrow$ precision measurement of Higgs properties (mass, couplings, width)
  - $\rightarrow$ constraints on anomalous interactions

Explore indirect evidence of new physics while searching for direct one.

Higgs boson: a remarkable prediction of precision EW fits

Spontaneous symmetry breaking of $SU(2)_L \times U(1)_Y \to U(1)_Q$ via **the SM Higgs mechanism + SM renormalizability imply**:

$\rightarrow$ systematic control of M_H dependence in renormalized parameters.



$M_{\rm H}$ only free parameter of the SM:

$$\Downarrow$$

$$m_W = 80.385 \pm 0.015 \text{ GeV}$$

$$m_t = 173.2 \pm 0.90 \text{ GeV}$$

$$\Downarrow$$

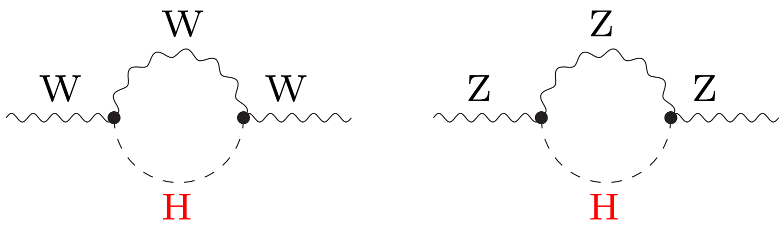
$$M_H = 94^{+29}_{-24} \text{ GeV}$$

$$M_H < 152\,(171) \text{ GeV}$$

Measured in Run 1 of the LHC: $M_{\rm H} = 125.09 \pm 0.24$ GeV

Example: M_H-dependence in M_W quantum corrections

$\Pi^{\mu\nu}_{VV}(q^2) \quad \longleftarrow$



where $(V = W, Z)$

$$\Pi^{\mu\nu}_{VV}(q^2) = \Pi_{VV}(q^2) g^{\mu\nu} + \Sigma_{VV}(q^2) q^\mu q^\nu$$

and

$$M^2_{V,0} = M^2_V + \Pi_{VV}(M^2_V)$$

State of the art (full EW 2-loop + leading 3-loop + some 4-loop)
[Awramik, Czakon, Freitas, Weiglein, Phys. Rev D69 (2004) 053006]

$$M_W = M_{W,0} - c_1 \mathbf{dh} - c_2 \, \mathbf{dh}^2 - c_3 \, \mathbf{dh}^4 + \ldots$$

where $\mathbf{dh} = \ln(M_H/100\,\mathrm{GeV})$.

EW prescision fits, strategy

Having a variety of measurement for different observables, test the SM by comparing theory and experiment.

- Pick a set of input parameters, typical choice:

$$\alpha_s\,,\,\alpha\,,\,G_F\,,\,M_Z\,,\,M_H\,,\,m_t\,,\,m_f,\ldots$$

- Compute theoretical predictions for all available electroweak precision observables (EWPO), including radiative corrections, in a given renormalization scheme treating the best measured parameters as inputs (typically α, G_F), i.e. as fixed parameters.

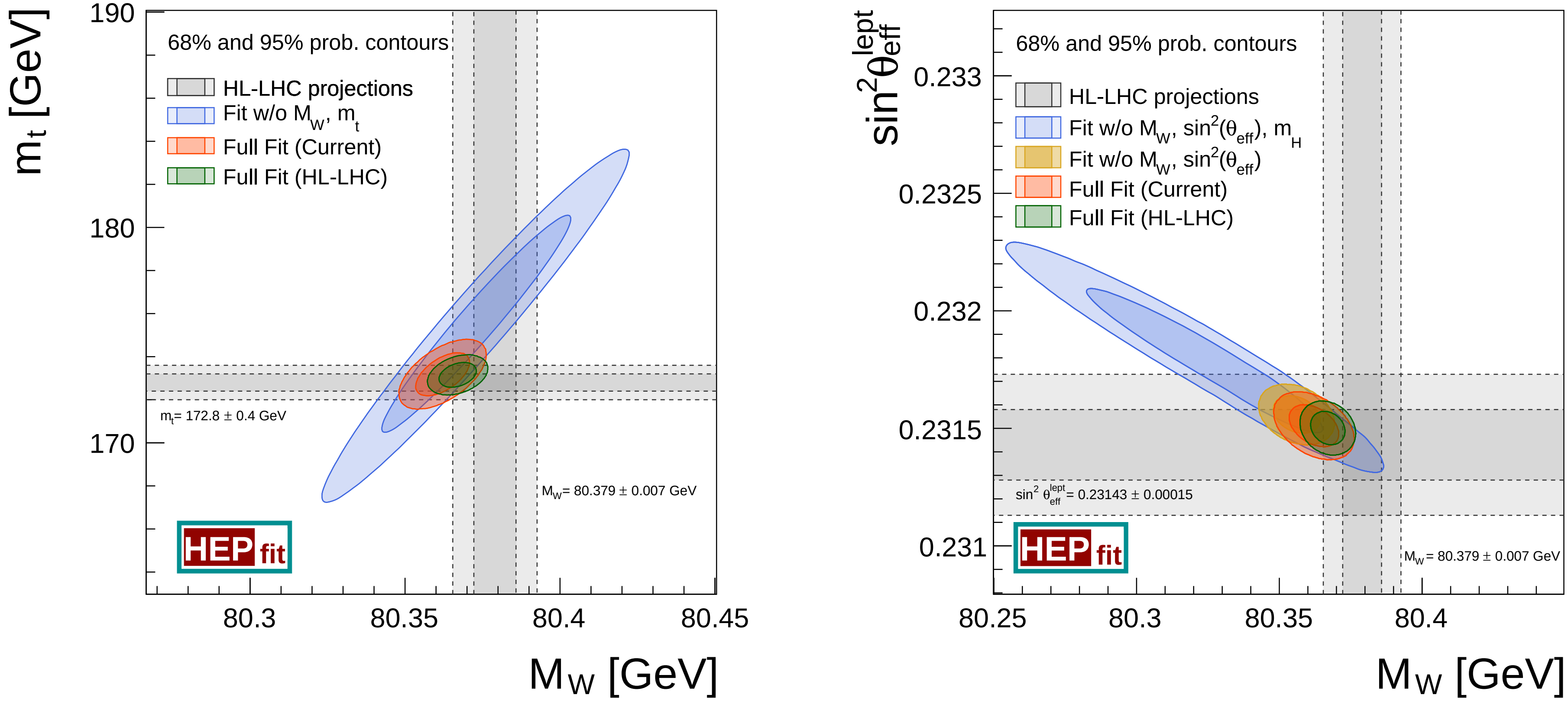
- Perform a best fit to the electroweak data, defined by a χ^2 test

$$\chi^2(\alpha, G_F, \ldots) = \sum_i \frac{(\hat{O}_i^{\mathrm{exp}} - O_i^{\mathrm{th}}(\alpha, G_F, \ldots))^2}{(\Delta\hat{O}_I^{\mathrm{exp}})^2}$$

  This results in a best fit of the non-fixed or floating parameters. Compare best-fit values to measurements if available (ex.: M_W, m_t, α_s, M_H!)

- For the best-fit values of <u>all</u> input parameters, quote the SM theoretical prediction for each observable and compare with the experimental measurements. “Tensions” may signal new physics . . .

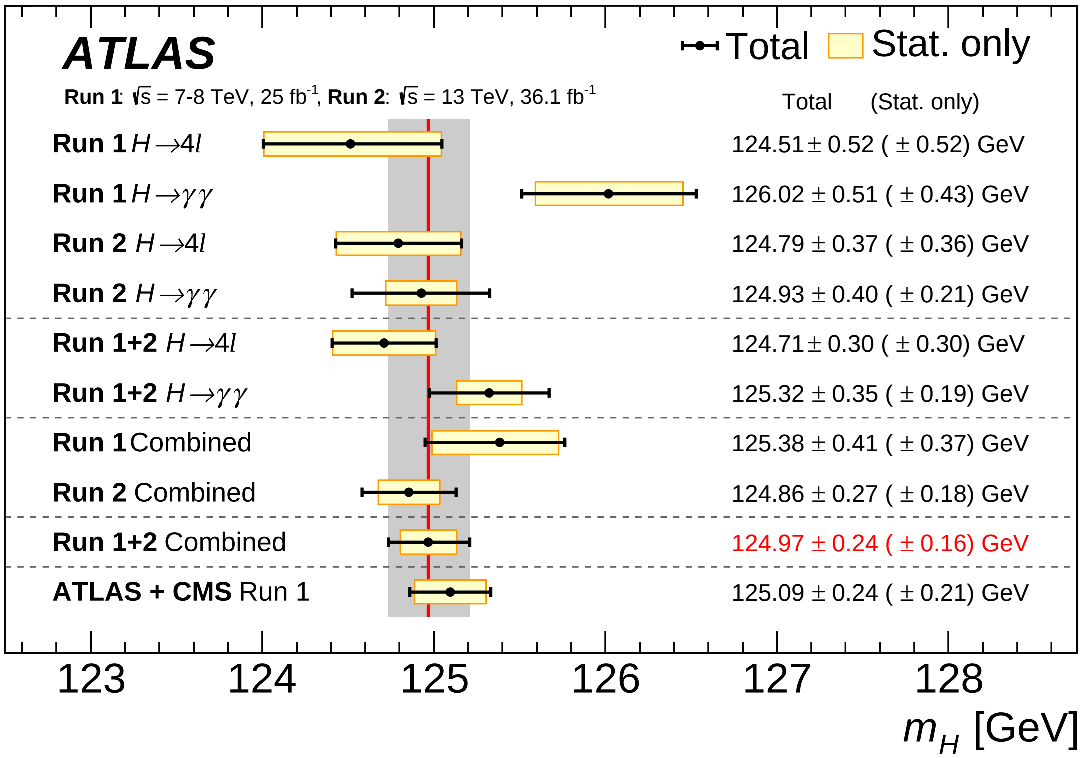
Fully stress-testing the SM consistency



↪ Very good agreement between indirect determination of EWPO and experimental measurements

↪ Very strong constraint on any physics beyond the SM.

LHC Run 1+Run 2: promoted M_H to EW precision observable



[ATLAS-CONF-2019-005]

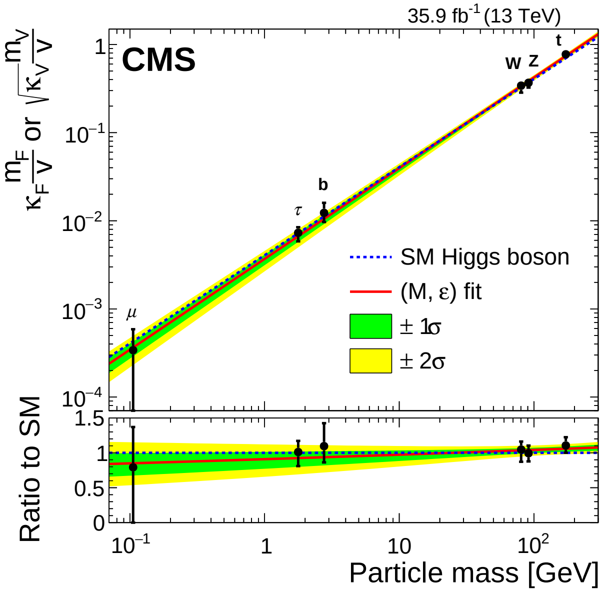
Effects of New Physics can now be more clearly disentangled in both EW observables and Higgs-boson couplings $\longleftrightarrow$ $\boxed{\text{probing EWSB}}$

Moreover, from decays ($H \to VV$ and $H \to f\bar{f}$)

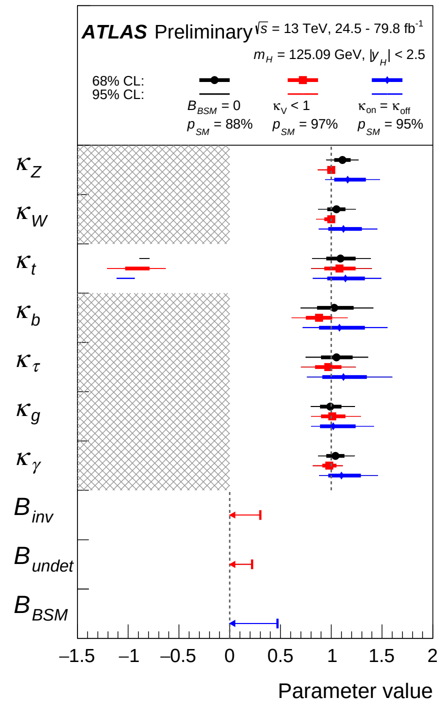
$\to$ Spin: highly constrained to be $s = 0$

$\to$ Parity: scalar vs pseudoscalar, from structure of decay amplitudes.

LHC Run 1+Run 2: first measurements of Higgs couplings



[CMS, arXiv:1809.10733]



[ATLAS-CONF-2019-005]

κ_i	ATLAS	CMS	HL-LHC
κ_Z	$1.10^{+0.08}_{-0.08}$	$0.99^{+0.11}_{-0.12}$	2.4%
κ_W	$1.05^{+0.08}_{-0.08}$	$1.10^{+0.12}_{-0.17}$	2.2%
κ_t	$1.02^{+0.11}_{-0.10}$	$1.11^{+0.12}_{-0.10}$	3.4%
κ_b	$1.06^{+0.19}_{-0.18}$	$-1.10^{+0.33}_{-0.23}$	3.7%
κ_τ	$1.07^{+0.15}_{-0.15}$	$1.01^{+0.16}_{-0.20}$	1.9%
κ_μ	< 1.51 at 95% CL.	$0.79^{+0.58}_{-0.79}$	4.3%

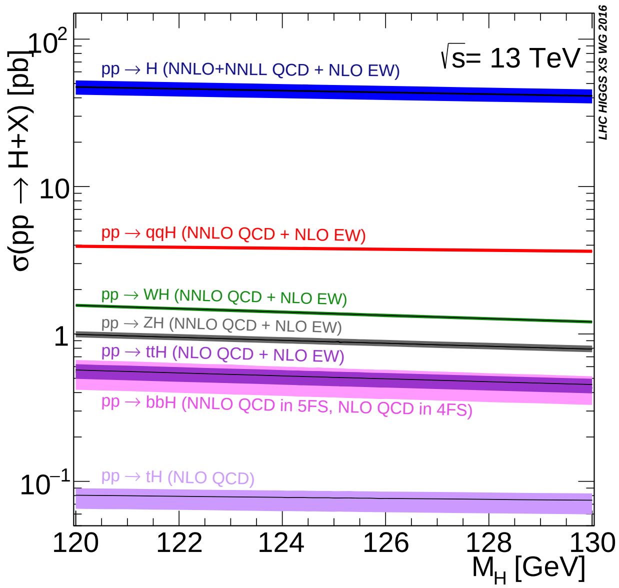
$$\kappa_i = g_{Hi}/g_{Hi}^{\mathrm{SM}}$$

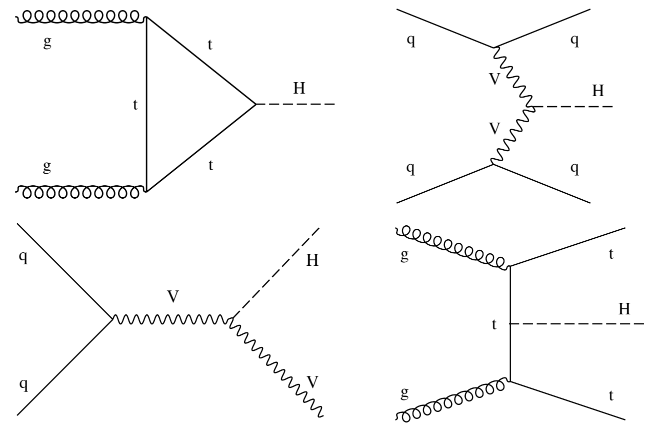
→ Higgs couplings to gauge bosons measured to 10-15% level.

→ Higgs couplings to 3^{rd}-generation fermions measured at 20-30% level.

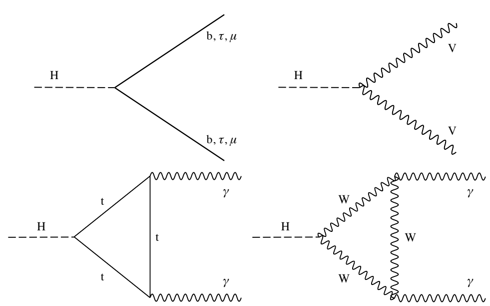
→ First bound on Higgs self-coupling ($\kappa_\lambda = \lambda_3/\lambda_3^{\mathrm{SM}}$).

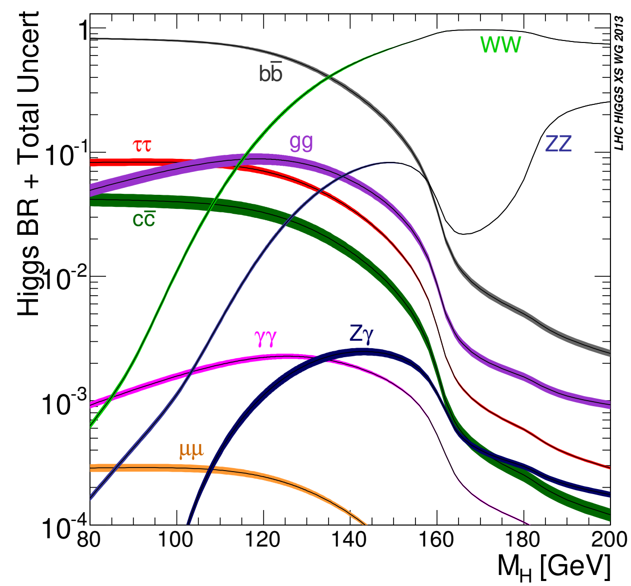
Extracted from production and decay strength measurements



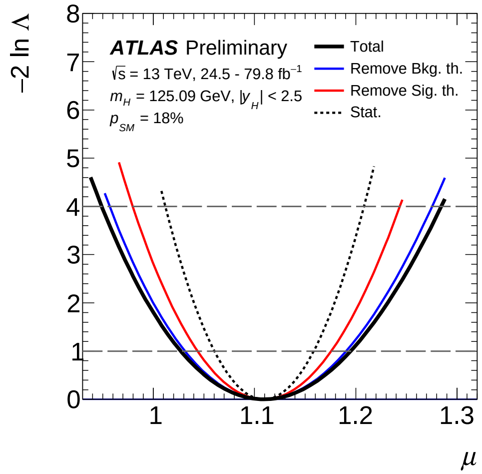


[The Higgs XS WG, arXiv:1610.07922]





... where theoretical systematics plays a substantial role



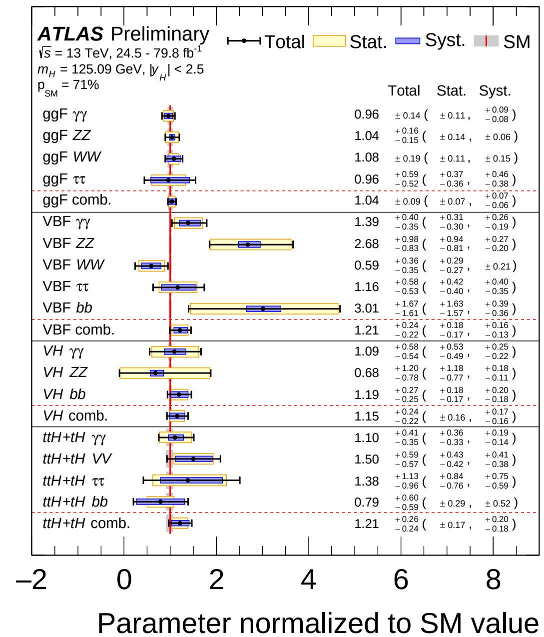
Uncertainty source	$\Delta\mu/\mu$ [%]
Statistical uncertainty	4.4
Systematic uncertainties	6.2
Theory uncertainties	4.8
Signal	4.2
Background	2.6
Experimental uncertainties (excl. MC stat.)	4.1
Luminosity	2.0
Background modeling	1.6
Jets, E_T^{miss}	1.4
Flavour tagging	1.1
Electrons, photons	2.2
Muons	0.2
τ-lepton	0.4
Other	1.6
MC statistical uncertainty	1.7
Total uncertainty	7.6

$$\mu_{if} = \frac{\sigma_i}{\sigma_i^{\text{SM}}} \times \frac{B_f}{B_f^{\text{SM}}}$$

$$\mu = 1.11^{+0.09}_{-0.08} \text{ (combined)}$$

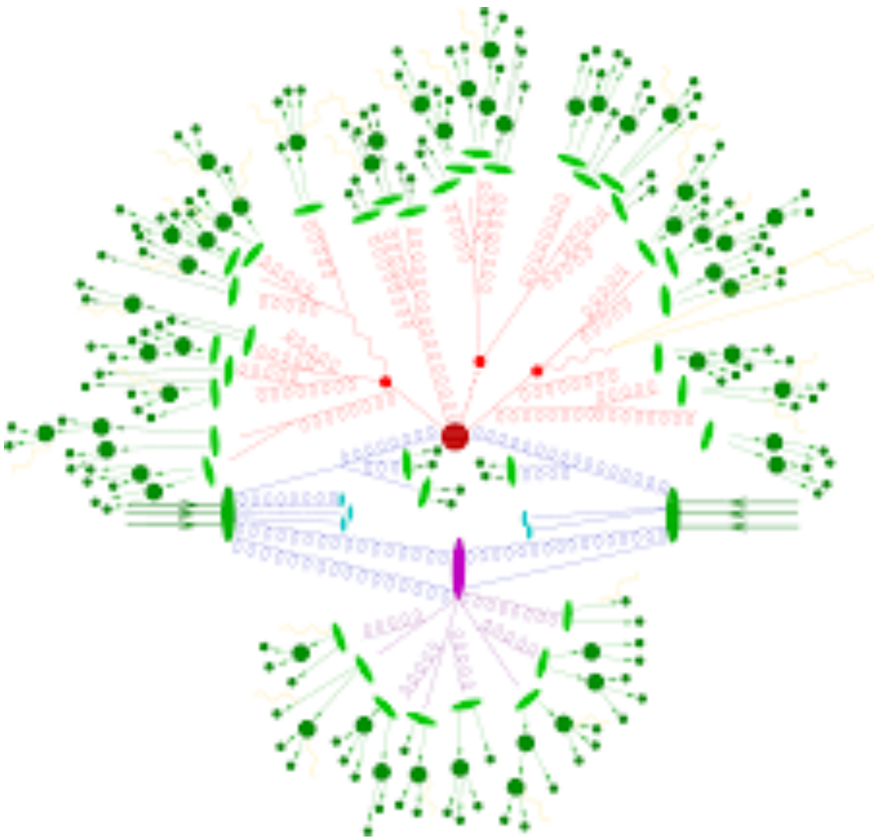
by production channel:

Uncertainty source	$\frac{\Delta\sigma_{\text{ggF}}}{\sigma_{\text{ggF}}}$ [%]	$\frac{\Delta\sigma_{\text{VBF}}}{\sigma_{\text{VBF}}}$ [%]	$\frac{\Delta\sigma_{WH}}{\sigma_{WH}}$ [%]	$\frac{\Delta\sigma_{ZH}}{\sigma_{ZH}}$ [%]	$\frac{\Delta\sigma_{t\bar{t}H+tH}}{\sigma_{t\bar{t}H+tH}}$ [%]
Statistical uncertainties	6.4	15	21	23	14
Systematic uncertainties	6.2	12	22	17	15
Theory uncertainties	3.4	9.2	14	14	12
Signal	2.0	8.7	5.8	6.7	6.3
Background	2.7	3.0	13	12	10
Experimental uncertainties (excl. MC stat.)	5.0	6.5	9.9	9.6	9.2
Luminosity	2.1	1.8	1.8	1.8	3.1
Background modeling	2.5	2.2	4.7	2.9	5.7
Jets, E_T^{miss}	0.9	5.4	3.0	3.3	4.0
Flavour tagging	0.9	1.3	7.9	8.0	1.8
Electrons, photons	2.5	1.7	1.8	1.5	3.8
Muons	0.4	0.3	0.1	0.2	0.5
τ-lepton	0.2	1.3	0.3	0.1	2.4
Other	2.5	1.2	0.3	1.1	0.8
MC statistical uncertainties	1.6	4.8	8.8	7.9	4.4
Total uncertainties	8.9	19	30	29	21



[ATLAS-CONF-2019-005]

Anatomy of theoretical predictions for hadronic collisions . . .



Structure mainly **QCD dominated**

$\hookrightarrow$ M. Grazzini's lectures

initial/final-state radiation: **parton shower**

red blob : **hard collision** (partons)

blue radiation : initial-state radiation (PS)

red radiation : final-state radiation (PS)

purple blobs : secondary scattering events

light green blobs : parton to hadron transitions

dark green blobs : hadron decays

Theoretical uncertainty affects predictions at multiple levels. Relevance of each is process dependent.

Starting point, schematically . . .

The hard cross section is calculated perturbatively

$$\hat{\sigma}(ij \to X) = \alpha_s^k \alpha_e^h \sum_{m=0}^{n} \sum_{l=0}^{n-m} \hat{\sigma}_{ij}^{(m,l)} \alpha_s^m \alpha_e^l$$

n=0 : Leading Order (LO), or tree level or Born level

n=1 : Next to Leading Order (NLO), include $O(\alpha_s)$ and $O(\alpha_e)$ corrections

. . . . . .

and convoluted with initial state parton densities at the same order.

Renormalization and factorization scale dependence left at any fixed order (μ: $\mu_{R,F}$)

$$\sigma(pp, p\bar{p} \to X) = \sum_{ij} \int dx_1 dx_2 f_i^p(x_1, \mu) f_j^{p,\bar{p}}(x_2, \mu) \hat{\sigma}_{ij}(\mu, Q^2)$$

Systematic theoretical error from:

- PDF and $\alpha_s(\mu)$;
- left over scale dependence;
- input parameters.

$\hookrightarrow$After which the parton shower takes over.

EW+Higgs precision physics in the LHC era:

What does it imply for theory?

Q1: How accurate?

- Experimental errors on inclusive and exclusive observables will be significantly reduced to below 10%
  - $\hookrightarrow$ **NNLO QCD** known for all processes (except $t\bar{t}H$), **N^{3}LO QCD** known for $gg \to H$ and $b\bar{b} \to H$.
  - $\hookrightarrow$ NLO **EW+QCD corrections** known for all processes.
  - $\hookrightarrow$ **Resummation** of specific kinematic- or cut-induced large (logarithmic) need to be included.
  - $\hookrightarrow$ Effects previously neglected need to be reconsidered (mass effects, ...).
- Higher statistics gives access to distributions
  - $\hookrightarrow$ Need **at least NLO accuracy**, for both **signal** and **background**.
  - $\hookrightarrow$ Need systematic control in **matching to parton-shower Monte Carlo** event generators.
  - $\hookrightarrow$ Need to assure validity of theory predictions in all kinematic regimes (ex.: high p_T, low p_T, ...).

$\Longrightarrow$ Illustrated with <u>several examples</u> in the following

Q2: How to interpret deviations from SM prediction?

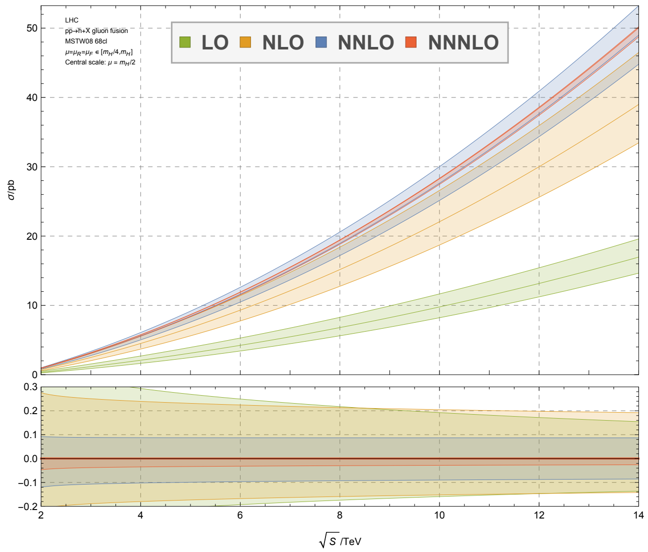
- Disentangling evidence of new physics.
  - $\hookrightarrow$ Model-specific approach: more stringent, yet arbitrary.
  - $\hookrightarrow$ **NP** can just **rescale the Higgs-boson couplings**: $\kappa_i = g_{Hi}/g_{Hi}^{SM}$: limited scope.
  - $\hookrightarrow$ **NP** can **introduce new structures** in Higgs couplings: how to explore?
  - $\hookrightarrow$ **Effective Field Theory** approach: less arbitrary, systematic, but less prone to simple prescriptions.

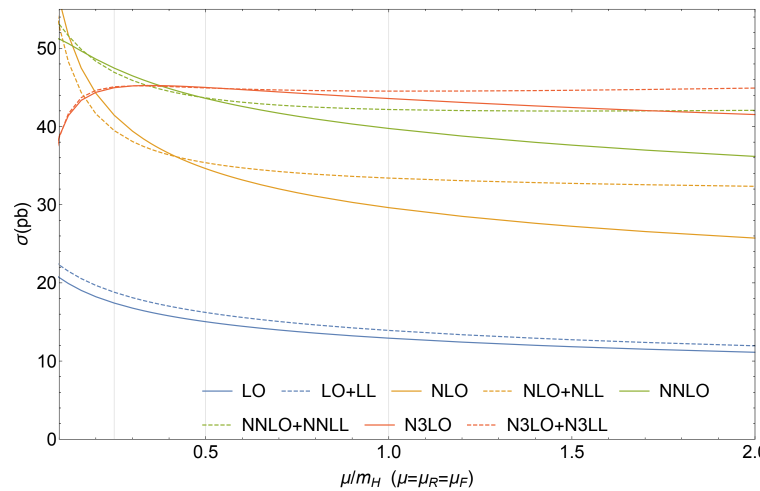
$$\Downarrow$$

<u>Tomorrow's Lecture</u>

$gg \to H$ calculated at N^{3}LO

Fundamental building block of the whole Higgs-boson physics program: overall signal normalization.

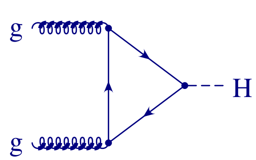




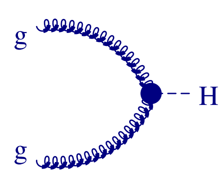
[Anastasiou et al., arXiv:1503.06056, arXiv:1602.00695]

dominated by soft-dynamics: **cannot resolve Higgs coupling to gluons** ($z \to 1, z = M_H^2/\hat{s}$).

HEFT: $m_t \to \infty$ limit



$\to$



$$\boxed{\mathcal{L}_{eff} = \frac{H}{4v} C(\alpha_s) G^{a\,\mu\nu} G^a_{\mu\nu}}$$

ggH@N^{3}LO: why is this a meaningful accuracy?

Dramatically improves theoretical accuracy to 5-6%:

$$\sigma(13\,\mathrm{TeV}) = 48.58^{+2.22}_{-3.27}(\mathrm{th}) + 1.56(\alpha_s + \mathrm{PDF})\,\mathrm{pb}$$

where:

$$\begin{aligned}
48.58\,\mathrm{pb} = \quad & 16.00\,\mathrm{pb} && (+32.9\%) && (\mathrm{LO,\ rEFT})\\
& +20.84\,\mathrm{pb} && (+42.9\%) && (\mathrm{NLO,\ rEFT})\\
& -\ \ 2.05\,\mathrm{pb} && (-4.2\%) && ((t,b,c),\ \mathrm{exact\ NLO})\\
& +\ \ 9.56\,\mathrm{pb} && (+19.7\%) && (\mathrm{NNLO,\ rEFT})\\
& +\ \ 0.34\,\mathrm{pb} && (+0.2\%) && (\mathrm{NNLO},\ 1/m_t)\\
& +\ \ 2.40\,\mathrm{pb} && (+4.9\%) && (\mathrm{EW,\ QCD\text{-}EW})\\
& +\ \ 1.49\,\mathrm{pb} && (+3.1\%) && (\mathrm{N^3LO,\ rEFT})
\end{aligned}$$

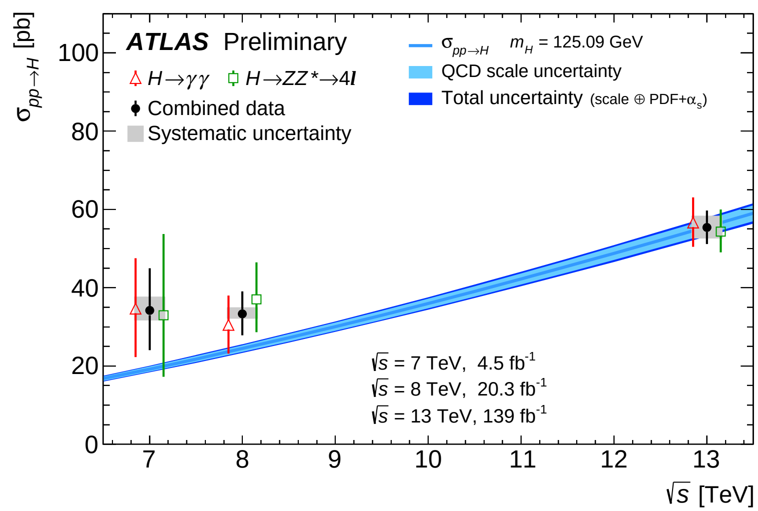
sensitive to

- $\hookrightarrow$ m_t effects ($m_t \to \infty$).
- $\hookrightarrow$ ... but also m_b, m_c effects.
- $\hookrightarrow$ EW and EW-QCD corrects.

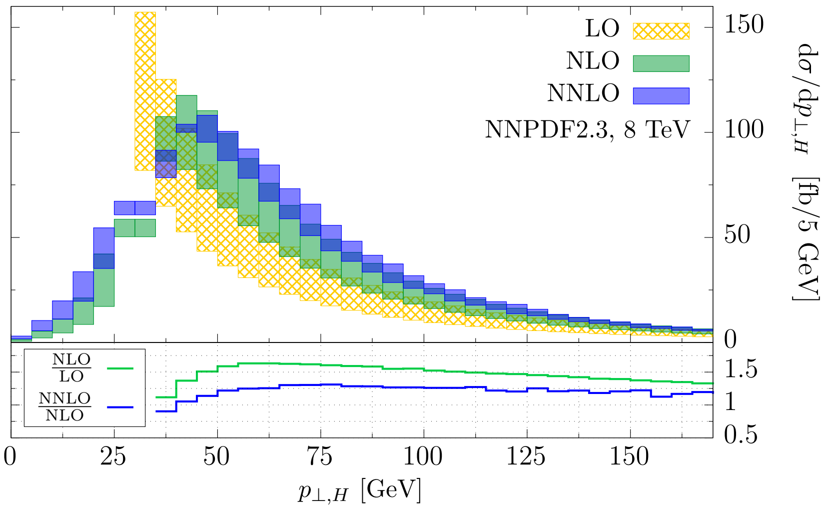
Also, sensitive to other production modes:

Process ($\lvert y_H\rvert < 2.5$)	Result [pb]	Uncertainty [pb] Total	Stat.	Exp.	Th.	SM prediction [pb]
ggF	43.9	$^{+6.2}_{-6.0}$	$^{+5.5}_{-5.4}$	$^{+2.7}_{-2.3}$	±1.2	$44.5^{+2.0}_{-3.0}$
VBF	7.9	$^{+2.1}_{-1.8}$	$^{+1.7}_{-1.6}$	$^{+0.8}_{-0.6}$	$^{+1.0}_{-0.7}$	$3.52^{+0.08}_{-0.07}$
VH	0.3	$^{+1.6}_{-1.4}$	$^{+1.5}_{-1.3}$	±0.4	$^{+0.3}_{-0.2}$	$1.99^{+0.06}_{-0.05}$
$t\bar{t}H$	0.27	$^{+0.37}_{-0.32}$	$^{+0.36}_{-0.31}$	$^{+0.06}_{-0.05}$	$^{+0.05}_{-0.02}$	$0.59^{+0.03}_{-0.05}$

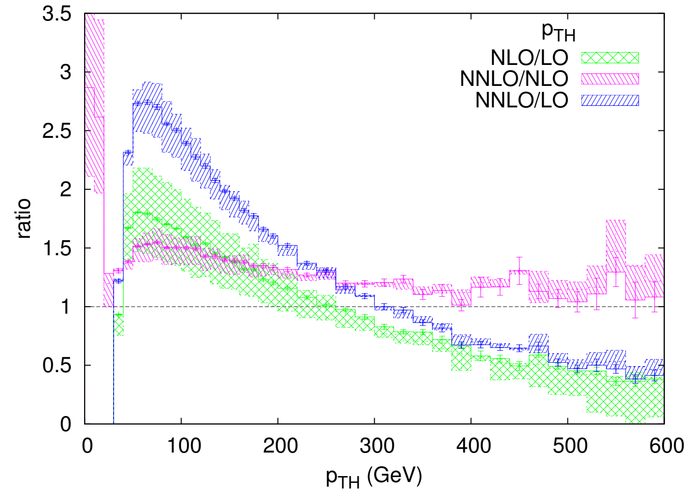
[ATLAS-CONF-2017-047]



$H + j$ calculated at NNLO in HEFT ($m_t \to \infty$)



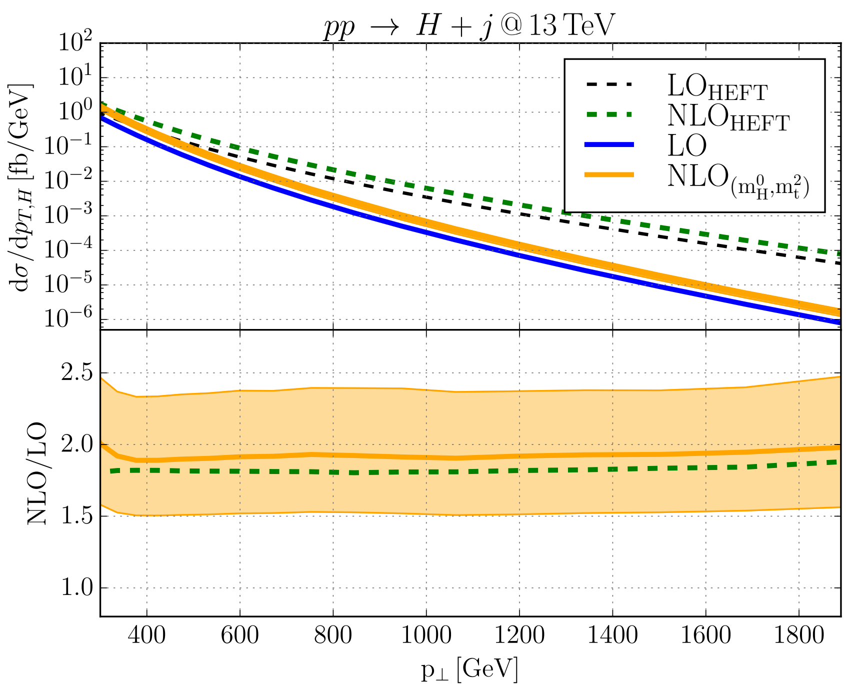
[Bhoughezal et al., arXiv:1504.07922]

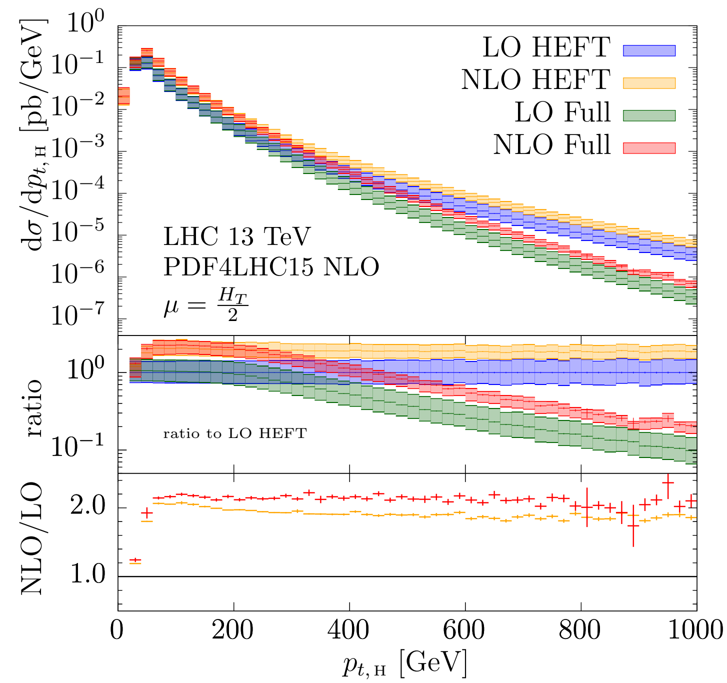


[Chen et al., arXiv:1408.5325]

- ↪ Extra jets present in all Higgs signatures: used to improve S/B ratios.
- ↪ **Impact ubiquitously all Higgs searching channels** (events binned by number of jets: H+0j, H+1j, . . .).
- ↪ **High-$\mathbf{p_T}$**: very important to improve by retrieving exact m_t dependence $\to$ disentangle **new-physics loop effects** in Hgg and $H\gamma\gamma$, and **anomalous structures** in Higgs couplings.
- ↪ **Low-$\mathbf{p_T}$**: sensitive to light-quark masses in ggH loop $\to$ measure $\mathbf{g_{Hb}}$, $\mathbf{g_{Hc}}$ [Bishara et al., arXiv:1606.09253]. Need to calculate it reliably $\to$ resummation of large logs. of p_T/m_H, m_q/p_T, and m_q/m_H.

Higgs p_T spectrum: high p_T, exact m_t dependence at NLO



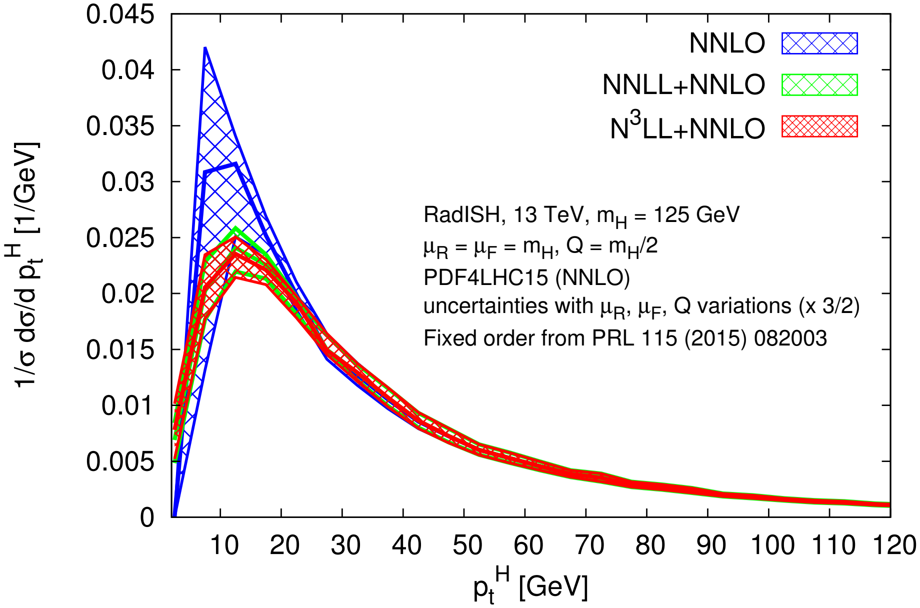


[Kudashkin et al., arXiv:1801.08226]

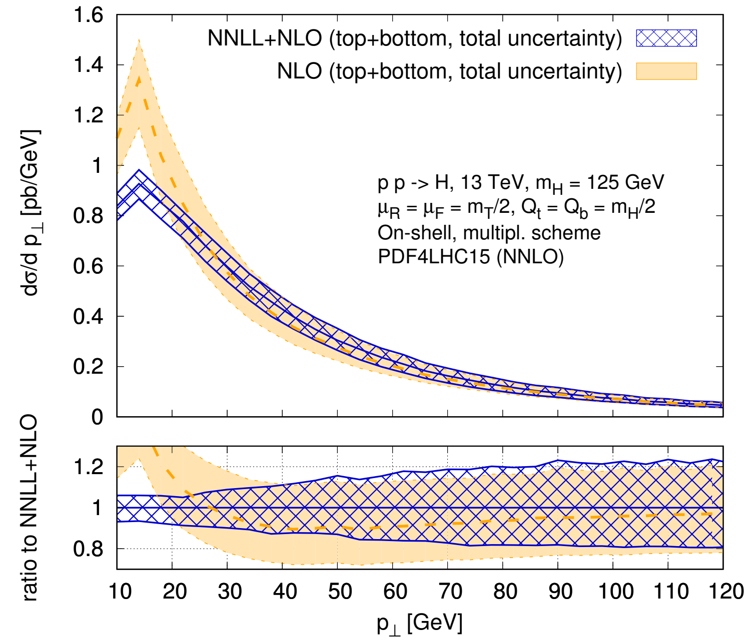
[Jones et al., arXiv:1802.00349]

- $\hookrightarrow$ Important agreement: analytical result under the assumption $m_{t,H} \ll p_T^H$ (Kudashkin et al.) vs exact numerical result (Jones et al.)
- $\hookrightarrow$ Large QCD effects (K factor), but very similar to HEFT.
- $\hookrightarrow$ Can combine with NNLO HEFT K factor?

Higgs p_T spectrum: low p_T, resum large log. corrections



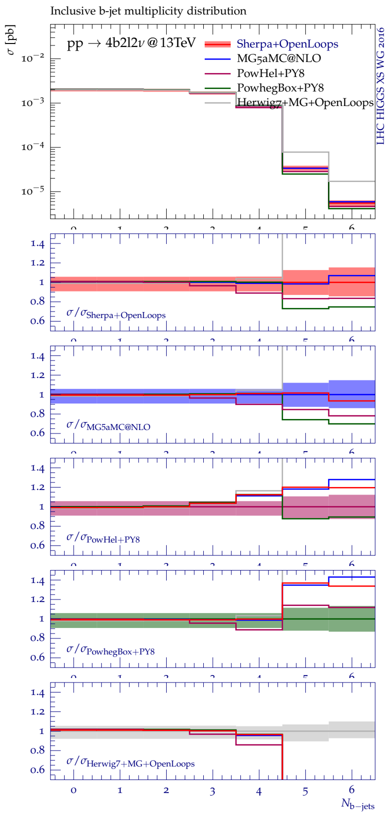
[Caola et al., arXiv:1705.09127]

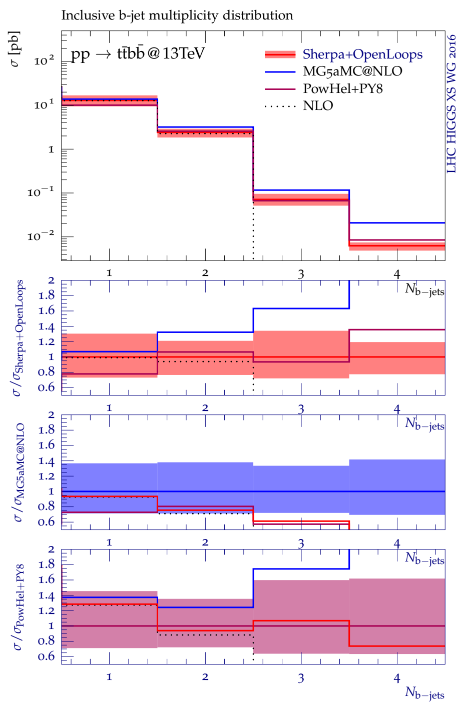


[Bizòn et al., arXiv:1804.07632]

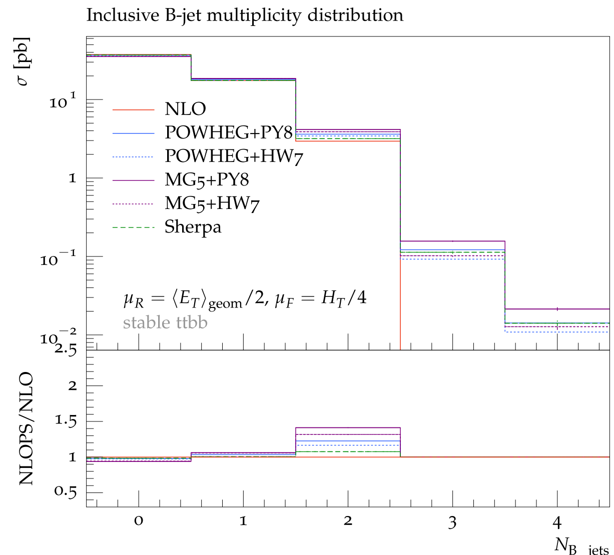
- $\hookrightarrow$ Resumming large logarithms for $p_T \ll M_H$.
- $\hookrightarrow$ Including mass corrections for $m_b \ll p_T \ll m_t$ (bottom-top interference).
- $\hookrightarrow$ Low-p_T spectrum accuracy at 10-15% level.

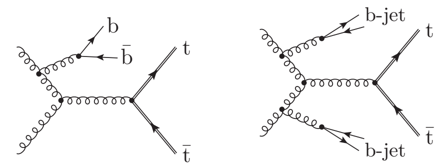
$t\bar{t}H(H \to b\bar{b})$, NLO+PS validation





[Preliminary]



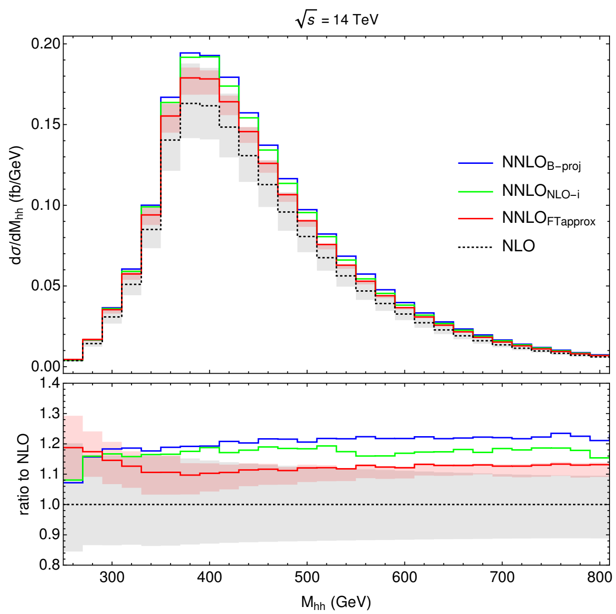


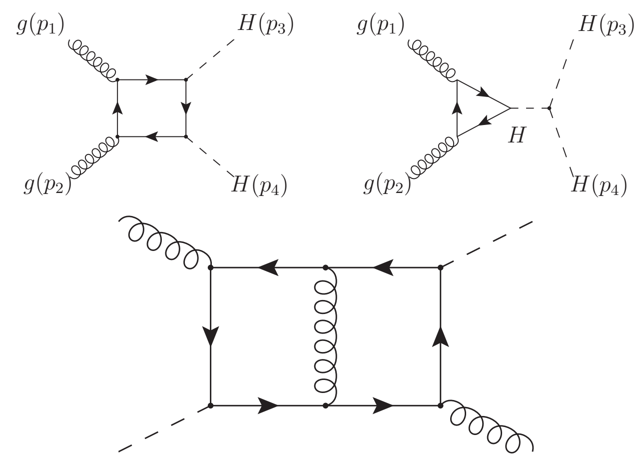
[Pozzorini, et al., Higgs XS Working Group]

- ↪ crucial to measure g_{Ht}: **discovered** (5σ!) in Run II.
- ↪ **Signal well understood** (including NLO QCD+EW and PS).
- ↪ **$\mathbf{t\bar{t}}$ + b jets**: dominant backgrounds for $t\bar{t}H(\to b\bar{b})$.
- ↪ NLO+PS tools: initially large discrepancies, being resolved by in depth **studies of NLO PS tools** plus **NLO calculation of $\mathbf{t\bar{t}b\bar{b}+j}$** [Pozzorini et al.], and NLO merging of $X+jj$ and $X+b\bar{b}$ [Siegert et al., arXiv:1904.09382]

HH production at NNLO, full m_t dependence

Measuring the Higgs-boson trilinear coupling





[Borowka, et al., arXiv:1604.06447, Grazzini, et al., arXiv:1803.02463]

↪ above top threshold $m_t \to 0$ (EFT) cannot be trusted.

↪ Including full m_t effects at NLO QCD:

$$\sigma_{\rm NLO}(13\,{\rm TeV}) = 27.78^{+13.8\%}_{-12.8\%} \quad \longrightarrow \quad \sigma_{{\rm NNLO}_{\rm FTapprox}}(13\,{\rm TeV}) = 31.05^{+2.2\%}_{-5.0\%}$$

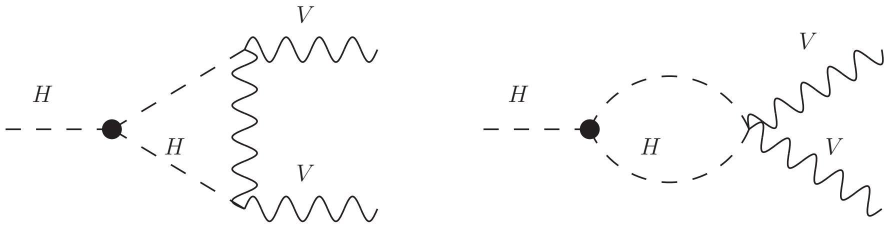
Most recent experimental result for $\kappa_\lambda = \lambda_3/\lambda_3^{\rm SM}$,

$$-11.8 \le \kappa_\lambda \le 18.8 \quad (95\%\,{\rm CL})$$ [CMS, PRL 122, 121803]

$$-5.0 \le \kappa_\lambda \le 12.0 \quad (95\%\,{\rm CL})$$ [ATLAS, arXiv:1906.02025]

Or, extract trilinear coupling from indirect loop effects

[Degrassi et al., arXiv:1607.04251] $\longrightarrow \quad \kappa_\lambda > -14.3$



[Degrassi et al., arXiv:1702.01737] $\longrightarrow \quad -14 < \kappa_\lambda < 18$

[Kribs et al., arXiv:1702.07678] $\longrightarrow \quad -14 < \kappa_\lambda < 17.4$