Theoretical predictions for Higgs physics: status and prospects

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Is theory in shape to distinguish between these possibilities?

Roughly a year ago, the announcement of the Higgs discovery generated great excitement. With the excitement reduced, it’s time to analyze the discovery.

Outline

- Summary
- H+jet @NNLO in QCD
- Inclusive Higgs production

Thursday, May 2, 13

theoretical predictions within the SM and attention to subtle details

theoretical predictions within the SM and attention to subtle details

that searches for BSM physics in Higgs production and decay will require good control of

Higgs at the LHC: a very short childhood

2012
Higgs at the LHC: a very short childhood

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 24.5 - 79.8 fb$^{-1}$$

$m_H = 125.09$ GeV, $|y_H| < 2.5$

$p_{SM} = 76\%$

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<thead>
<tr>
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<tbody>
<tr>
<td>ggF</td>
<td>1.04</td>
<td>$\pm 0.09$</td>
<td>$\pm 0.07, +0.07, -0.06$</td>
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<td>VBF</td>
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<td>$\pm 0.24, -0.22$</td>
<td>$\pm 0.18, +0.18, -0.16$</td>
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<td>$\pm 0.40, -0.38$</td>
<td>$\pm 0.28, +0.29, -0.27$</td>
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<tr>
<td>ZH</td>
<td>1.05</td>
<td>$\pm 0.31, -0.29$</td>
<td>$\pm 0.24, +0.19, -0.17$</td>
</tr>
<tr>
<td>$tH + tH$</td>
<td>1.21</td>
<td>$\pm 0.26, -0.24$</td>
<td>$\pm 0.17, +0.20, -0.18$</td>
</tr>
</tbody>
</table>

Cross-section normalized to SM value

**CMS**

$35.9$ fb$^{-1}$ (13 TeV)

$M_H$ or $m_H$ vs $k_{VV}$

$\frac{m_F}{k_{VV}}$ or $\frac{m_H}{k_{VV}}$

$\frac{m_F}{k_{VV}}$ or $\frac{m_H}{k_{VV}}$

**Higgs Boson Mass**

$125.10 \pm 0.14$ OUR AVERAGE

**Higgs Boson Decay Width**

$<$ 0.0144  95

$<$ 1.10  95

$<$ 0.013  95

$<$ 1.7  95

$>$ 3.5 $\times 10^{-12}$  95

$<$ 5.0  95

$<$ 2.6  95

**Higgs Boson Signal Strengths**

Combined Final States

$1.10 \pm 0.11$ OUR AVERAGE

After LHC Run II
Higgs\textsubscript{125} at the LHC: a sweet spot

**Production modes**

Production modes:
- $pp \rightarrow H$ (N3LO QCD + NLO EW)
- $pp \rightarrow qqH$ (NNLO QCD + NLO EW)
- $pp \rightarrow WH$ (NNLO QCD + NLO EW)
- $pp \rightarrow ZH$ (NNLO QCD in 5FS, NLO QCD in 4FS)
- $pp \rightarrow bbH$ (NNLO QCD in 5FS, NLO QCD in 4FS)
- $pp \rightarrow t\bar{t}H$ (NLO QCD, t-ch + s-ch)
- $pp \rightarrow HH$

**Decay channels**

Decay channels:
- $\tau\tau$
- $gg$
- $cc$
- $\gamma\gamma$
- $Z\gamma$
- $\mu\mu$
- $WW$
- $ZZ$

- Comprehensive studies at the LHC are possible, in many different channels

- "Nature has been kind"
Higgs$_{125}$ and QCD: a sweet spot

By and large, most of the Higgs cross section accessible with perturbative QCD methods

Large part of the cross section in a region with little contamination from soft physics
**Higgs$_{125}$ and QCD: a sweet spot**

- Good knowledge of relevant PDFs
- A lot of experimental (LHC data) and theoretical progress (*see S. Forte’s talk*)

**GLUON**

Relative uncertainty for gg-luminosity
NNPDF31_nnlo_as_0118 - $\sqrt{s} = 13000.0$ GeV

**Dijet production @ HL-LHC**

- On-shell
- Off-shell

**Higgs production in gluon fusion @ LHC $\sqrt{s}=14$ TeV**

- PDF4LHC15
- $+$ HL-LHC (scen A)
- $+$ HL-LHC (scen C)

**Boosted Higgs**

$2$ TeV
Higgs_125 and QCD: a sweet spot

To a large extent, success of the Higgs Program at the LHC depends on our understanding of (p)QCD and SM dynamics at colliders

- Higgs: a drive towards better understanding of SM physics at the LHC
- Higgs: behind many breakthrough (first N^3LO calculation, first NNLO \"+J\" calculation, multi-differential resummations, new generation of PS…)
- At the forefront of theoretical developments in QCD
- In the following: some illustrative examples

Disclaimer: not a comprehensive review!
“In QFT, corrections are typically either large and then trivial, or small and then irrelevant”, a celebrated quantum-field theorist.

The golden channel: ggF

Despite some arguments, and a lot of experience, ggF K-factor is still something we do not really understand in pQCD…
The golden channel: ggF

The way out: $N^3LO$

$H\rightarrow \gamma \gamma, H\rightarrow ZZ^*\rightarrow 4l$ combined

$pp\rightarrow H, \sqrt{s} = 13 \text{ TeV}, m_H = 125 \text{ GeV}$

- Preliminary data

$XH = VBF + VH + t\bar{t}H + b\bar{b}H$

- QCD scale uncertainty
- Tot. uncert. (scale, PDF+$\alpha_s$)

$\sigma_{N^3LO} = 55.5 \pm 2.9 \text{ pb}$

$\sigma_{exp} = 59 \pm 9.5 \text{ pb}$

Can we trust perturbation theory?

- Good convergence, eventually ✔
- Different ways of approximating $\sigma$ give approximately the same result ✔

[Anastasiou et al. (2015), Mistlberger (2018)]
Life beyond $N^3$LO

$N^3$LO residual uncertainty: few percent. At this level, many other effects play a role…

\[ \sigma = 48.58 \text{ pb} \pm 2.22 \text{ pb} (4.56\%) \pm 3.27 \text{ pb} (6.72\%) \text{ (theory)} \pm 1.56 \text{ pb} (3.2\%) \text{ (PDF+}\alpha_s\text{)}. \]

\[ 48.58 \text{ pb} = \begin{align*}
16.00 \text{ pb} & \quad (+32.9\%) & \text{(LO, rEFT)} \\
+ 20.84 \text{ pb} & \quad (+42.9\%) & \text{(NLO, rEFT)} \\
- 2.05 \text{ pb} & \quad (-4.2\%) & \text{((t, b, c), exact NLO)} \\
+ 9.56 \text{ pb} & \quad (+19.7\%) & \text{(NNLO, rEFT)} \\
+ 0.34 \text{ pb} & \quad (+0.7\%) & \text{(NNLO, 1/m_t)} \\
+ 2.40 \text{ pb} & \quad (+4.9\%) & \text{(EW, QCD-EW)} \\
+ 1.49 \text{ pb} & \quad (+3.1\%) & \text{(N^3LO, rEFT)} 
\end{align*} \]

Todo List:
- Full mass dependent NNLO
- Mixed $\mathcal{O}(\alpha \alpha_s)$ corrections
- $N^3$LO PDFs

\[ \begin{array}{cccccc}
\delta(\text{scale}) & \delta(\text{trunc}) & \delta(\text{PDF-TH}) & \delta(\text{EW}) & \delta(\text{t, b, c}) & \delta(1/m_t) \\
\hline
+0.10 \text{ pb} & -0.18 \text{ pb} & \pm 0.56 \text{ pb} & \pm 0.49 \text{ pb} & \pm 0.40 \text{ pb} & \pm 0.49 \text{ pb} \\
-1.15 \text{ pb} & & & & & \\
+0.21\% & -0.37\% & \pm 1.16\% & \pm 1\% & \pm 0.83\% & \pm 1\% \\
\end{array} \]

progress: Melnikov, Penin (2016); Melnikov, et al. (2016-18); Jones, Kerner, Luisoni (2018)

progress: Bonetti, Melnikov, Tancredi (2017-18); Anastasiou et al (2018)

Slight change in the perspective: no longer “one big contribution”, many (very difficult to control) small effects…
N$^3$LO: going differential

- Inclusive cross section is an idealised quantity, very far from what we measure
- Reliable prediction: properly model fiducial volume of experiment → fully differential. Only known at NNLO [+PS]
- Although fiducial volume seem relatively stable under perturbative corrections, desirable + very interesting QCD problem
- H is scalar: fully differential:
  - $p_t$ → known since quite some time ``H+J@NNLO”
  - $y$ → (very reliable) approximate results appeared [Dulat, Mistlberger, Pelloni (2018)]

Is the full rapidity dependence required for N$^3$LO differential?

- No: if you know NNLO $p_t$ distribution, you only need to know N$^3$LO rapidity at zero $p_t$ → “beam function”
- Very recently: first results (for DY) appeared [Behring, Melnikov, Rietkerk, Tancredi, Wever (2019); Luo, Yang, Zhu, Zhu (2019)]

→ see X. Chen’s talk tomorrow
Why going differential?

**Low $p_T$**

Light Yukawas...

**Bulk of the distribution**

Highest precision

**Boosted**

$ggH$ vs $ttH$, EFT...

see X. Chen’s talk tomorrow
Low $p_t$: light quark effects

- For $m_q \ll p_t \ll m_H$: amplitude develops non-Sudakov double logs
  \[ y_q m_q/m_H \left[ \ln^2 (m_H^2/m_q^2), \ln^2 (p_t^2/m_q^2) \right] \]

- Despite $y_{b,c,\ldots} \ll y_t$, interference effects may be visible → constrain Yukawas!

- Also: direct $q\bar{q} \rightarrow Hg$ impacts Higgs $p_t$ → powerful constraints for light Yukawas

**PROBLEM: control over QCD corrections**

- Resolved quark loop → very difficult loop amplitudes
  * beyond state-of-the-art for analytic calculations
  * large logs → numerical approached difficult

- Low $p_t$, large logs → all-order effects must be considered?

[Bishara et al. (2017)]
Low $p_t$: light quark effects

- Key idea: exploit the physics → large hierarchies $m_q \ll p_t \ll m_H$
- **This can be systematically use to massively simplify multi-loop amplitude calculations** [Melnikov, Tancredi, Wever (2016-18); see also Mueller and Öztürk (2016)]

### $t/b$ interference

$pp \to H + j @ 13$ TeV

![Diagram showing interference](image)

### $p_t$ spectrum

$pp \to H$, $13$ TeV, $m_H = 125$ GeV

- $\mu_R = \mu_F = m_T/2$
- On-shell, multipl. scheme
- PDF4LHC15 (NNLO) uncertainties with $\mu_R, \mu_F, Q$ variations

<table>
<thead>
<tr>
<th>$p_T$ [GeV]</th>
<th>$d^2\sigma/dp_T^2 [pb/GeV]$</th>
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<td>10</td>
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<td>20</td>
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<tr>
<td>50</td>
<td>0.2</td>
</tr>
<tr>
<td>60</td>
<td>0.1</td>
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- Reasonable f.o. control
- **All-order structure still elusive, beyond "standard" resummation toolkit** [some work in this direction: Melnikov, Penin (2016); Forte et al (2016); Penin, Liu (2018)]
Beyond ggF: vector boson fusion

- VBF has a much more complex kinematical structure w.r.t. gluon fusion (2→3 vs 2→1). Very rich phenomenology, very difficult to calculate in pQCD
- However: two very forward/backward color lines, linked by color-singlet exchange → expect little cross-talk between the two quark lines
- Neglecting cross-talk: VBF = DIS², much simpler: "Factorized approach, DIS/structure function approach" [Han, Valencia, Willenbrock (1992)]
- Exact at NLO (1-L amplitude: color octet, no interference with color-singlet LO)
- Beyond NLO: non-factorized corrections color and kinematics suppressed in the deep VBF region
Beyond $ggF$: vector boson fusion

- VBF has a much more complex kinematical structure w.r.t. gluon fusion ($2 \rightarrow 3$ vs $2 \rightarrow 1$).
- Very rich phenomenology, very difficult to calculate in pQCD
- However: two very forward/backward color lines, linked by color-singlet exchange
- Expect little cross-talk between the two quark lines
- Neglecting cross-talk: VBF = DIS
- Exact at NLO ($1$-L amplitude: color octet, no interference with color-singlet LO)
- Beyond NLO: non-factorized corrections color and kinematics suppressed in the deep VBF region

Stress-testing the factorized approach 

Valid if tight VBF cuts applied

[Campanario et al (2018)]
VBF beyond the DIS approximation

- NNLO exact VBF calculation out of reach (*two-loop 2→3 amplitudes well beyond what we can imagine doing in the near future*)

- However, possible to estimate the leading non-factorizable contributions the VBF region (two forward/backward tagging jets) [Liu, Melnikov, Penin (2019)]

- As expected, corrections to inclusive quantities small (~4 permill), although larger than inclusive N^3LO [Dreyer, Karlberg (2016)]

- Interestingly, small corrections come as a cancellation between positive and negative corrections to differential distributions → *can reach percent-level in differential distributions. Color suppressed, but π²-enhanced*
VBF: fully differential results

- For VBF, crucial to properly model the experimental setup (*jet requirements*)
- Full NNLO(+NLO EW) results in the DIS approximation known

[Cacciari et al (2015)]

- Corrections in the VBF region *much larger than for the inclusive* case (most likely due to non-trivial jet dynamics)
- Residual uncertainty ~2-3% → non-factorizable contributions smaller, but barely
- For some distribution, bad disagreement with PS → NNLOPS?
VBF: fully differential results

• For VBF, crucial to properly model the experimental setup (jet requirements)
• Large differential corrections: VBF very sensitive to tagging jet cuts and jet radius

- NNLO corrections change by ~20% from R=0.1 to R=1.0
- It would be interesting to understand it better
  • NNLO for VBF+j
  • NNLOPS [only major channel where this is missing…]
The path towards \( H \to bb: VH \)

- At large \( p_t \): tagging \( V \) allows for \( H \to bb \) reconstruction [Butterworth et al (2008)]

- Currently: \( p_{t,V} > 150 \text{ GeV} \), not yet asymptotic \( \to \) concurrence of many interesting subtle effects (fixed-order hard dynamics, sub-leading logs, improved parton shower…)

- \( H \to bb \): see W. Bizon’s talk

- \( VH \): at the forefront of PS developments. Very recently: new generation of NNLO PS, theoretically nicer \( \to \) much more efficient [Monni, Nason, Re, Zanderighi (2019)]
VH: is NNLOPS enough?

With realistic cuts: large bin-to-bin migration…

Example: associated HW production with cuts used by HXSWG

- PS and hadronization cause migration
- Difficult to reach high accuracy in jet-binned observables

- Jet rates difficult to predict

- Is it the end of it?

- Recall: NNLOPS is NLO for jet rates…
VH: is NNLOPS enough?

Lessons from ggF: control extra jet dramatically improves the situation

**ggF Higgs production with jet veto: H+J@NNLO + N^3LO**

- VH: quark-induced $\rightarrow$ should be even better behaved
- NNLO for VH+J? N^3LO?
\( \bar{t}tH \): the devil in the background…

- Direct probe of top Yukawa coupling
- Known to NLOQCD (+NNLL) + NLOEW, including off-shellness and interference
- Fiducial cuts enhance tails \( \rightarrow \) NLOEW
- \( d\sigma \propto y_t^2 \) no longer true @NLOEW
- Better signal predictions: see A. Kulesza's talk

- Proper description of background problematic.
  Most famous example: \( ttbb \)

<table>
<thead>
<tr>
<th>Selection</th>
<th>Tool</th>
<th>( \sigma_{NLO} ) [fb]</th>
<th>( \sigma_{NLO+PS} ) [fb]</th>
<th>( \sigma_{NLO+PS}/\sigma_{NLO} )</th>
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<tbody>
<tr>
<td>( n_b \geq 1 )</td>
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<td>12939^{+30%}_{-27%}</td>
<td>1.01</td>
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<td>PowHEl</td>
<td>2570^{+35%}_{-28%}</td>
<td></td>
<td>1.13</td>
</tr>
</tbody>
</table>

- Shower effects enhanced in the Higgs region…
\[ \bar{t}tH: \text{the devil in the background} \ldots \]


- A lot of complex delicate issues… cannot make justice to it in a few minutes. Just few highlights, see talks by S. Pozzorini at the HXSWG meetings for more details

**Most likely cause of bad behavior:** \textbf{LARGE K-FACTOR ENHANCED BY SHOWER}

**NLOPS YR4 scales**

- The good news: a more appropriate scale choice removes part of the issue
- The bad news: this does not remove large shower corrections in the \( N_b=2 \) bin
**ttH: the devil in the background…**

Most likely cause of bad behavior: **LARGE K-FACTOR ENHANCED BY SHOWER**

- **The bad news:** clever scale choice does not remove large shower corrections in the $N_b=2$ bin
- **Most likely culprit:** large recoil effect / bin migration
- **To fix it:** need to understand better QCD radiation pattern, find good observables sensitive to it

Once again, it would be crucial to better understand jet dynamics, $g\rightarrow b\bar{b}$ splitting etc…

Very interesting theoretical problem, not limited to $t\bar{t}H$ (e.g.: $V+HF$ for VH…)

Azimuthal correlation $\Delta\phi_{rec,t}$ between recoil and 1st top

\[
\frac{d\sigma}{d\Delta\phi} \quad \mu_R = \frac{\langle E_T \rangle_{geom}}{2}, \quad \mu_F = \frac{H_T}{4}
\]

<table>
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<tr>
<th>$\Delta \phi$</th>
<th>$\frac{d\sigma}{d\Delta\phi}$</th>
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<td>$-\pi$</td>
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<td>$1$</td>
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<tr>
<td>$\pi$</td>
<td>$1$</td>
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</table>

10 GeV rec, $t_1$ (ttbb cuts)

YR4 scales 0.5 rescaling

$\mu_R = \langle E_T \rangle_{geom}/2$, $\mu_F = H_T/4$
Beyond standard channels: off-shell

• An interesting probe of Higgs properties (ggH vs ttH, off-shell couplings, width...)

![Graph showing gg → H → ZZ → ℓℓνℓ̅ν, M_H = 125 GeV](image)

- Large ~10% off-shell tail in the VV channel
- Non-trivial interplay with gg→VV SM background (unitarity cancellations...)

• Very difficult to predict: 2-loop amplitudes with internal masses... we cannot compute it analytically (although within reach numerically...)

![Diagram of LO and NLO processes](image)
Towards 2L: *divide et impera*

- We cannot obtain exact 2L result, but we can compute it in many different limits (low m\(_{vv}\), threshold) \(\rightarrow\) join all the knowledge together

![Graphs showing form factors](image)

- Validated with HH

- “An analytic multi-loop result is a result which can give you a number” E. Remiddi
Conclusions

• A 125 GeV Higgs: sweet spot for thorough studies of its properties
• LHC measurements progressing very fast
• Higgs has always been one of the main player in pushing our understanding of QCD and collider phenomenology
• A lot of recent progress, virtually in any field of QCD and collider pheno (PDFs, fixed-order, resummations, PS…) → could not make justice to it
• A pattern is emerging:
  • No longer "one big issue". Several small effects
  • New ideas, ingenuity can achieve results unreachable by brute force methods
  • In several cases, this requires a good and wide knowledge of pQFT

• Summing up: non-trivial improvement in our understanding of QFT/QCD/EW/collider pheno, that would have actual implication for real-world Higgs explorations → **EXCITING TIMES AHEAD!**
Thank you very much!