MAJOR ANALYTIC RESULTS
THREE MILESTONES IN 2015

A prolific year for analytic calculations

• Higgs production through gluon fusion at $N^3$LO

• Higgs+jet production at NNLO
  [Boughezal, Caola, Melnikov, Petriello, Schulze] – 2015

• Fully differential vector boson fusion at NNLO
  [Cacciari, Dreyer, Karlberg, Salam, Zanderighi] – 2015
GLUON FUSION AT N3LO

Theory uncertainty pushed to \(~ 6\%\)

Approximation as a double DIS process (< 1% at NLO)

(a) Born VBF process

(b) NNLO “inclusive” part (from structure function method)

two loop

projected double real

projected one-loop single real

(c) NNLO “exclusive” part (from VBF H+3j@NLO)

double real

double–real counterevent

one–loop single real

one–loop single–real counterevent

\[
\frac{d\sigma}{dp_{t,1}} \text{ [pb/GeV]} \\
\frac{d\sigma}{dp_{t,2}} \text{ [pb/GeV]} \\
\frac{d\sigma}{dp_{t,H}} \text{ [pb/GeV]} \\
\frac{d\sigma}{d\Delta y_{j,12}} \text{ [pb]}
\]

[LO\ NLO\ NNLO\ POWHEG]

\[
\text{VBF Cuts}
\]

\[
\text{LHC 13 TeV}
\]

\[
\mu_0(p_{t,H})/2 < \mu_R = \mu_F < 2 \mu_0(p_{t,H})
\]

\[
\mu_0(p_{t,1})/2 < \mu_R = \mu_F < 2 \mu_0(p_{t,1})
\]

\[
\mu_0(p_{t,1})/2 < \mu_R = \mu_F < 2 \mu_0(p_{t,1})
\]
Fiducial cross section in the HEFT ($m_t \to \infty$)

+ LO-improved HEFT

Tension with ATLAS normalization

[Caola, Melnikov, Schulze] – 2015

Chen, Gehrmann, Glover, Jaquier – 2016
Fiducial cross section in the HEFT ($m_t \to \infty$)

Tension with ATLAS normalization
Better agreement in shape

+ LO-improved HEFT

[Caola, Melnikov, Schulze] – 2015

HIGGS+JET: PHENOMENOLOGICAL RESULTS

Fiducial cross section in the HEFT ($m_t \rightarrow \infty$)

[Caola, Melnikov, Schulze] – 2015

- Tension with ATLAS normalization
- Better agreement in shape
- Better normalization at 13 TeV

+ LO-improved HEFT

LO-improved HEFT results are unreliable when $p_T \gtrsim m_t$
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**Toward an exact NLO result**

Analytic results for planar integrals

[Bonciani, Del Duca, Frellesvig, Henn, Moriello, Smirnov] – 2017
Toward an exact NLO result
Analytic results for planar integrals

Bottom mass effects at NLO
Clear hierarchy:

\[ m_b \ll p_T, m_H, m_t \]

NLO corrections to top-bottom interference as series in \( m_b \)

[Bonciani, Del Duca, Frellesvig, Henn, Moriello, Smirnov] – 2017

[Lindert, Melnikov, Tancredi, Wever] – 2017
A HANDLE ON THE HIGGS SELF COUPLING

One of the last SM parameters with no direct constraints

Exp challenge: cross section and large negative interference

TH challenge: Only known analytically at LO

Several proposals using HEFT improved with top mass effects

[S. Dawson, S. Dittmaier, and M. Spira] – 1998,
[J. Grigo, J. Hoff, K. Melnikov, and M. Steinhauser] – 2013-2015,
[Degrassi, Giardino, Gröber] – 2016
Exact NLO results obtained numerically using the sector decomposition method

\[ \sigma_{\text{NLO}} = 27.80^{+13.8}_{-12.8} \text{ fb} \pm 0.3\%\text{(stat.)} \pm 0.1\%\text{(int.)}. \]

Daunting task: very long analytic & numeric processing

"The median GPU time per phase-space point was 2 hours"
**PHENOMENOLOGICAL RESULTS**

**NLO corrections**

![Graph showing NLO corrections with LO, NLO, and NLO+NNLO HEFT lines for different $m_{hh}$ [GeV].]

**Parton shower effects**

![Graph showing parton shower effects with Full SM, LHC 14 TeV, PDF4LHC15 NLO, and NLO+PY8 lines for different $p_{T}^{hh}$ [GeV].]

**Self-coupling dependence**

![Graph showing self-coupling dependence with LO, NLO, and NLO+NNLO HEFT lines for different $m_{hh}$ [GeV].]

[Heinrich, Jones, Kerner, Luisoni, Vryonidou] – 2017

ASSESSMENT OF APPROXIMATE PREDICTIONS

Both high order HEFT expansion and rescaled HEFT fail

Born-improved HEFT improves distributions but still 25% off
GLUON FUSION AT NLO IN THE SMEFT
Universal EFT describing heavy new physics

\[ \mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{k=1}^{N} \frac{1}{\Lambda^k} \sum_{i} C_i \mathcal{O}_i^{[k+4]} \]  

(1)
**MODIFYING THE TOP LOOP**

Yukawa correction

\[ C_1 \bar{Q} \sigma^{\mu\nu} t_R \phi (\phi^\dagger \phi) \]

Gluon fusion

\[ g_s^2 C_2 \phi^\dagger \phi G_{\mu\nu} G^{\mu\nu} \]

Chromomagnetic

\[ g_s C_3 \bar{Q} \sigma^{\mu\nu} t_R \phi G_{\mu\nu} \]

LO: [Degrande, Gérard, Grojean, Maltoni, Servant] – 2013

NLO+NLL (O_1 & O_2) [Grazzini, Ilnicka, Spira, Wiesemann] – 2016
\[ \sigma = \sigma_{SM} + \frac{(1 \text{ TeV})^2}{\Lambda^2} (C_1 \sigma_1 + C_2 \sigma_2 + C_3 \sigma_3) \]
\[
\sigma = \sigma_{SM} + \frac{\left(1 \text{ TeV}\right)^2}{\Lambda^2} (C_1 \sigma_1 + C_2 \sigma_2 + C_3 \sigma_3)
\]

<table>
<thead>
<tr>
<th>13 TeV</th>
<th>(\sigma_1)</th>
<th>(\sigma_2)</th>
<th>(\sigma_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO (pb)</td>
<td>(-2.93^{+34%}_{-25%})</td>
<td>(2660^{+34%}_{-25%})</td>
<td>(50.5^{+34%}_{-25%})</td>
</tr>
<tr>
<td>NLO (pb)</td>
<td>(-4.70^{+25%}_{-20%})</td>
<td>(4130^{+24%}_{-20%})</td>
<td>(83.5^{+26%}_{-21%})</td>
</tr>
<tr>
<td>K-factor</td>
<td>1.61</td>
<td>1.55</td>
<td>1.65</td>
</tr>
<tr>
<td>Bound</td>
<td>(-0.3 &lt; -0.13C_1 + 111C_2 + 2.3C_3 &lt; 0.48)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[ND, Duhr, Maltoni, Vryonidou]
Higgs $p_T$

$p p \rightarrow H$ in the EFT LHC13

$\mu_R = \mu_F = \mu_{EFT} = 62.5$ GeV

NLO+PS, MMHT2014NLO

Interference with the SM

$\frac{1}{\sigma_0}$ per bin [pb]

MadGraph5_aMC@NLO

Ratio over the SM

$2.5$  $2.0$  $1.5$  $1.0$  $0.5$  $0.0$

$p_T$ [GeV]
CONCLUSION
CONCLUSION AND PERSPECTIVES

Many impressive results in SM Higgs predictions

- Analytic calculations for gluon fusion, $H + j$ and VBF
- Numerical calculation for HH
Many impressive results in SM Higgs predictions

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Further work under way

- Differential Higgs production at N3LO
- Exact $H + j$
Many impressive results in SM Higgs predictions

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New challenges to tackle

• Internal masses beyond the reach of our standard toolbox
• Analytic complexity is becoming a problem
Thank you for your attention