Theory concluding talk

Dieter Zeppenfeld
Higgs Hunting 2018, July 23-25, Paris
Outline of talk:

- Introduction: The SM
- More elementary scalars
- Measurement of Higgs couplings
- HO corrections
- VBF and QCD corrections
- Vector boson scattering
- Conclusions
Introduction: the wonderful SM

SM is very efficient in describing observed phenomena

- Mass generation for W and Z

\[
(D^\mu \Phi)\dagger D_\mu \Phi = \frac{1}{2} \partial^\mu H \partial_\mu H + \left[ \left( \frac{g v}{2} \right)^2 W^\mu W^-_\mu + \frac{1}{2} \left( \frac{g^2 + g'^2}{4} \right) v^2 Z^\mu Z_\mu \right] \left( 1 + \frac{H}{v} \right)^2
\]

Prediction for HVV coupling as bonus ... agrees with data

- Interactions of gauge bosons to known fermions

\[
\mathcal{L}_\psi = \sum_f \bar{\psi}_f i \gamma^\mu D_\mu \psi_f \quad \quad D_\mu = \partial_\mu + i g_s A^a_\mu(x) T^a + i g W^i_\mu \frac{\tau^i}{2} + i g' Y B_\mu
\]

extremely well tested and confirmed experimentally

- Leaves SM with large flavor symmetry
Representations of SM fermions

\[
Q^i_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad u^i_R = \begin{pmatrix} c_R \\ t_R \end{pmatrix}, \quad d^i_R = \begin{pmatrix} s_R \\ b_R \end{pmatrix}, \quad L^i_L = \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix}, \quad e^i_R = \begin{pmatrix} \nu_{eR} \\ \nu_{\mu R} \\ \nu_{\tau R} \end{pmatrix}
\]

<table>
<thead>
<tr>
<th></th>
<th>SU(3)</th>
<th>SU(2)</th>
<th>U(1)_Y</th>
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<td>(\frac{1}{6})</td>
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<tr>
<td>(u^i_R)</td>
<td>3</td>
<td>1</td>
<td>(\frac{2}{3})</td>
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<td>(d^i_R)</td>
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<td>(L^i_L)</td>
<td>1</td>
<td>2</td>
<td>(-\frac{1}{2})</td>
</tr>
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<td>(e^i_R)</td>
<td>1</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>(\nu^i_R)</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

6 multiplets of three generations each $\Rightarrow$ U(3)$^6$ flavor symmetry

U(3)$^6$ symmetry is broken explicitly in nature

SU(3) x SU(3) quark and lepton vector currents unaffected by anomalies
Yukawa couplings

- Explicit breaking of $U(3)^6$ flavor symmetry by Yukawa sector of Higgs Lagrangian

$$\mathcal{L}_{\text{Yukawa}} = -\Gamma^i_d \bar{Q}^i_L \Phi d^j_R - \Gamma^i_{d*} \bar{d}^j_R \Phi^\dagger Q^i_L$$

$$-\Gamma^i_u \bar{Q}^i_L \Phi c u^j_R + \text{h.c.}$$

$$\Phi_c = i\sigma_2 \Phi^* = \frac{1}{\sqrt{2}} \begin{pmatrix} v + H(x) \\ 0 \end{pmatrix}$$

$$-\Gamma^i_e \bar{L}^i_L \Phi e^j_R - \Gamma^i_\nu \bar{L}^i_L \Phi c \nu^j_R + \text{h.c.}$$

- Generates fermion masses, CKM and PMNS mixing as a bonus when mass matrix $M_{ij} = \Gamma^{ij} \frac{v}{\sqrt{2}}$ is diagonalized, e.g.

$$(U_L^u)^\dagger M_u U_R^u = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix}$$

$$(U_L^d)^\dagger M_d U_R^d = \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix}$$

and $V_{\text{CKM}} = (U_L^u)^\dagger U_L^d$
The „curse“ of renormalizability

- Lowest dimensional, renormalizable fermionic operators for Lagrangian:

\[ \mathcal{L}_{\text{mass}} = \sum_{i,j} M_{ij} \bar{\psi}_i \psi_j \]

is forbidden by chiral gauge structure of SM

\[ \mathcal{L}_\psi = \sum_f \bar{\psi}_f i \gamma^\mu D_\mu \psi_f \]

is bilinear in fermion fields \( \rightarrow \) can be diagonalized and renormalized to unit matrix in flavor space

- Gauge generational symmetry? Broken by scalar v.e.v. ….

- Flavor symmetry can be broken explicitly by dimension-6 operators, like

\[ \mathcal{L}_{4f} = \sum_{i,j,k,l} \frac{c_{ijkl}}{\Lambda^2} \bar{\psi}_i \gamma^\mu \psi_j \bar{\psi}_k \gamma^\mu \psi_l \]

but these render theory non-renormalizable

UV model with gauge fields and spin \( \frac{1}{2} \) matter fields only is too restrictive
Strong case for elementary scalars

Break flavor symmetry of Lagrangian via renormalizable Yukawa couplings

Allow for spontaneous symmetry breaking via non-trivial minimum of scalar potential and

- Generate gauge boson masses
- Generate fermion masses
- Provide CKM and PMNS mixing

SM does full job with just a single scalar doublet
BSM Higgs sectors

- SM Higgs couplings completely fixed by masses
  More complex Higgs sector decouples rapidly
  Simplest possibility: 2 Higgs doublets
  (nice example: talk by W. Buchmüller)

- Two doublet extension: 5 scalars and modified couplings
  extra coupling factors for $hVV$ and $HVV$ couplings as compared to SM

\[
\mathcal{L}_{\text{Yuk.}} = -\frac{m_b}{v} \bar{b} \left( v + H \frac{\cos \alpha}{\cos \beta} - h \frac{\sin \alpha}{\cos \beta} - i \gamma_5 A \tan \beta \right) b - \frac{m_t}{v} \bar{t} \left( v + H \frac{\sin \alpha}{\sin \beta} + h \frac{\cos \alpha}{\sin \beta} - i \gamma_5 A \cot \beta \right) t
\]

$\Rightarrow$ coupling factors compared to SM $hff$ coupling $-i \frac{m_f}{v}$
Most direct: search for H/A/H±

- No extra resonances yet... e.g. in H/A→ττ
But enough fluctuations to keep Sven excited…

2.4 $\sigma$ global
But enough fluctuations to keep Sven excited…

... one of the fluctuations might develop into a discovery
Great to have two experiments to keep us grounded in reality

2.4 $\sigma$ global

CMS PAS HIG-17-013
BSM Higgs sectors

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- Two doublet extension: 5 scalars and modified couplings
  extra coupling factors for $hVV$ and $HVV$ couplings as compared to SM

\[ hVV \sim \sin(\beta - \alpha) \quad HVV \sim \cos(\beta - \alpha) \]

\[ \mathcal{L}_{\text{Yuk.}} = -\frac{m_b}{v} \bar{b} \left( v + H \frac{\cos \alpha}{\cos \beta} - h \frac{\sin \alpha}{\cos \beta} - i \gamma_5 A \tan \beta \right) b - \frac{m_t}{v} \bar{t} \left( v + H \frac{\sin \alpha}{\sin \beta} + h \frac{\cos \alpha}{\sin \beta} - i \gamma_5 A \cot \beta \right) t \]

\[ \Rightarrow \text{coupling factors compared to SM } h f f \text{ coupling } -i \frac{m_f}{v} \]
SM relation of Higgs coupling to mass disappears with dimension-6 operators in effective Lagrangian: add

\[ \mathcal{L}_{\text{eff}} = \frac{f_\phi}{\Lambda^2} \left( \phi^\dagger \phi - \frac{v^2}{2} \right) \mathcal{L}_{\text{Mass}} = \frac{f_\phi}{\Lambda^2} \left( 2vH + H^2 \right)^2 \mathcal{L}_{\text{Mass}} / 4 \]

For example, arbitrary \( \Delta \kappa_V \) is generated by

\[ \mathcal{L}_{\text{eff}} = \frac{f_\phi}{\Lambda^2} \left( \phi^\dagger \phi - \frac{v^2}{2} \right) (D_\mu \phi)^\dagger D^\mu \phi + \cdots \]

and similar for fermion couplings (with independent \( f_\phi \) )
**k-framework**: modify couplings of the Higgs to other particles in both the *production* and the *decay*.

- Loops \((ggH\) and \(H \rightarrow \gamma\gamma\)) are here resolved:
  \[ggH: \quad 1.04 \cdot \kappa_t^2 + 0.002 \cdot \kappa_b^2 - 0.038 \cdot \kappa_t \kappa_b\]
  \[H \rightarrow \gamma\gamma: \quad 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.67 \cdot \kappa_W \kappa_t\]

- Linear terms break degeneracy

- Still an overall symmetry under: \((\kappa_t, \kappa_W) \rightarrow (-\kappa_t, -\kappa_W)\)

_Slightly preferred over positive \(\kappa_b\)_
Effective photon and gluon couplings

- Probe for invisible/undetectable decays with possibility of new particles in $gg \rightarrow H$ production and $H \rightarrow \gamma \gamma$ decay i.e. $\kappa_\gamma$ and $\kappa_\gamma$ effective coupling modifiers left free in the fit.

- In a parameterisation studied, all other modifiers fixed to the SM values - in the present one, seven free parameters: $\kappa_Z$, $\kappa_W$, $\kappa_b$, $\kappa_t$, $\kappa_\tau$, $\kappa_g$ and $\kappa_\gamma$.

- Sign of $\kappa_t$ can be either positive or negative, while $\kappa_\gamma$ assumed positive (to solve relative sign ambiguity).

1. $B_{BSM} = 0$
   - Compatibility with SM predictions with $p$-value $= 87\%$

2. $B_{BSM} \geq 0$ and left free, $|\kappa_{Z,W}| < 1$
   - Limit: $B_{BSM} < 0.26$ at 95\% CL
   - (expected upper limit: 0.37 at 95\% CL)
SMEFT parameterization, e.g. in Warsaw basis

\[ \mathcal{L}_{\text{Warsaw, SMEFT}}^{(3)} \frac{C_{HH}}{v^2} (H^\dagger i \overleftrightarrow{D}^I \mu H) (\bar{l} \tau^I \gamma^\mu l) + \frac{C_{Hl}}{v^2} (H^\dagger i \overleftrightarrow{D} \mu H) (\bar{l} \gamma^\mu l) + \frac{C_{ll}}{v^2} (\bar{l} \gamma^\mu l) (\bar{l} \gamma^\mu l) \\
+ \frac{C_{HD}}{v^2} \left| H^\dagger D \mu H \right|^2 + \frac{C_{HWB}}{v^2} H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu} \\
+ \frac{C_{He}}{v^2} (H^\dagger i \overleftrightarrow{D} \mu H) (\bar{e} \gamma^\mu e) + \frac{C_{Hu}}{v^2} (H^\dagger i \overleftrightarrow{D}^I \mu H) (\bar{u} \gamma^\mu u) + \frac{C_{Hd}}{v^2} (H^\dagger i \overleftrightarrow{D} \mu H) (\bar{d} \gamma^\mu d) \\
+ \frac{C_{Hq}}{v^2} (H^\dagger i \overleftrightarrow{D}^I \mu H) (\bar{q} \tau^I \gamma^\mu q) + \frac{C_{Hq}}{v^2} (H^\dagger i \overleftrightarrow{D}^I \mu H) (\bar{q} \gamma^\mu q) + \frac{C_{W}}{v^2} \epsilon^{IJK} W^I_{\mu} W^J_{\nu} W^K_{\rho} W^{I\rho} \\
\mathcal{L}_{\text{Warsaw, SMEFT}}^{(1)} \frac{C_{cH}}{v^2} y_c (H^\dagger H) (\bar{l} e H) + \frac{C_{dH}}{v^2} y_d (H^\dagger H) (\bar{q} d H) + \frac{C_{uH}}{v^2} y_u (H^\dagger H) (\bar{q} u H) \\
+ \frac{C_{G}}{v^2} f^{ABC} G^A_{\mu\nu} G^B_{\rho\sigma} G^C_{\mu\nu} + \frac{C_{\square H}}{v^2} (H^\dagger H) \square (H^\dagger H) + \frac{C_{uG}}{v^2} y_u (\bar{q} \sigma^{\mu\nu} T^A u) \tilde{H} G^A_{\mu\nu} \\
+ \frac{C_{HW}}{v^2} H^\dagger H W^I_{\mu\nu} W^J_{I\mu\nu} + \frac{C_{HB}}{v^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{C_{HG}}{v^2} H^\dagger H G^A_{\mu\nu} G^{A\mu\nu} \]  

Recent global fit to Higgs data, EW precision data and VV production by Ellis, Murphy, Sanz, and You: arXiv:1803.03252
Comprehensive talk by Eleni Vryonidou
Fit results of Ellis et al. arXiv:1803.03252

Bounds on new physics scale $\Lambda$

No evidence for deviations from SM

Very large correlations between different terms in SILH Lagrangian
$\rightarrow$ Basis not optimal for fit with reduced parameter set
Optimising EFT interpretations (1)
Towards precision calculations in the EFT

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{g^2}{4\Lambda^2} \bar{c}_{BB} \Phi^\dagger \Phi B_{\mu\nu} B^{\mu\nu} \]
\[ + \frac{ig}{2\Lambda^2} \bar{c}_W [\Phi^\dagger T_{2k} \tilde{D}_{\mu} \Phi] D_{\nu} W^{k,\mu\nu} \]
\[ + \frac{ig'}{2\Lambda^2} \bar{c}_B [\Phi^\dagger \tilde{D}_{\mu} \Phi] \partial_{\nu} B^{\mu\nu} \]
\[ + \frac{ig}{\Lambda^2} \bar{c}_{HW} [D_{\mu} \Phi^\dagger T_{2k} D_{\nu} \Phi] W^{k,\mu\nu} \]
\[ + \frac{ig'}{\Lambda^2} \bar{c}_{HB} [D_{\mu} \Phi^\dagger D_{\nu} \Phi] B^{\mu\nu}. \]

Use of differential information will be crucial


VBF

WH

E. Vryonidou

HiggsHunting2018

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Towards EFT global fits

A Global fit: LEP and LHC Run I and II

\[ L^{\text{SMEFT}} = \frac{C_{\tilde{L}}}{v^2} (H^+ D^- H)(\ell^- \gamma \ell) + \frac{C_{\tilde{H}}}{v^2} (H^+ D^- H)(\tilde{\tau}^+ \tilde{\tau}^-) + \frac{C_{\tilde{W}}}{v^2} \left( \pi \pi^+ \right) \]

Using differential information will be crucial

Ellis et al arXiv:1803.03252

Englert, Kogler, Spannowsky arXiv:1511.05170

E.Vryonidou

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Comment on triple Higgs coupling within EFT

- $\lambda_3$: single Higgs at one (more) loop
  Attract lots of attention recently!

  (from talk by X.Zhao
  See also talk by Tao Han)

McCullough '14  Gorbahn and Haisch '16  Degrassi et.al. '16  Bizon et.al. '16  Di Vita et.al. '17  Maltoni et.al. '17

Loop contribution is mostly renormalization of dimension 6 operators modifying
Hgg vertex or W propagator at tree level

- Not much sense in discussing contribution from HHH coupling alone
- Expect huge correlations with Wilson coefficients of other dimension 6 operators
  (See also talk by G.Heinrich)
Exotic Higgs decays: talk by Zhen Liu

- Higgs has tiny width $\sim 4$ MeV
  $$\frac{\Gamma}{M} = O(10^{-5})$$

*all* its decay modes are suppressed by various factors, couplings, loop-factors, phase-space, etc.
Dominant decays into bottom quark pairs are suppressed by the tiny coupling $y_b = 0.017$

- small couplings to BSM could have sizable branching, e.g.,
  $$L = \frac{\zeta}{2} s^2 |H|^2$$
(common building block in extended Higgs sectors) can give $\text{BR}(h\to ss) \sim O(10\%)$ for $\zeta$ as small as 0.01!
Organizing the study: A List

<table>
<thead>
<tr>
<th>Decay Topologies</th>
<th>Decay mode $F_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h \to 2$</td>
<td>$h \to \not{p}_T$</td>
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<tr>
<td>$h \to 2 \to 3$</td>
<td>$h \to \gamma + \not{p}_T$</td>
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<td></td>
<td>$h \to (b\bar{b}) + \not{p}_T$</td>
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<td>$h \to (j\bar{j}) + \not{p}_T$</td>
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<td></td>
<td>$h \to (\gamma\gamma) + \not{p}_T$</td>
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<td>$h \to (\ell^+\ell^-) + \not{p}_T$</td>
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<tr>
<td>$h \to 2 \to 3 \to 4$</td>
<td>$h \to (b\bar{b}) + \not{p}_T$</td>
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<td></td>
<td>$h \to (\ell^+\ell^-) + \not{p}_T$</td>
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<tr>
<td>$h \to 2 \to (1 + 3)$</td>
<td>$h \to bb + \not{p}_T$</td>
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<td>$h \to jj + \not{p}_T$</td>
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<td></td>
<td>$h \to (b\bar{b})(\mu^+\mu^-)$</td>
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</table>
QCD corrections for Higgs signals

- Nice summary by Gudrun Heinrich on Monday
  - improvements to gluon fusion cross section
  - Higgs pT distribution with full $m_t$ dependence
  - and more…

- Higgs pT distribution: talk by Chris Wever

- QCD corrections to VBF
status before 2018: N3LO in $m_t \to \infty$ limit

Anastasiou et al. 1602.00695

<table>
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<tr>
<th>$E_{CM}$</th>
<th>$\sigma$</th>
<th>$\delta$(theory)</th>
<th>$\delta$(PDF)</th>
<th>$\delta$((\alpha_s))</th>
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<td>13 TeV</td>
<td>48.58 pb</td>
<td>+2.22 pb (+4.56%)</td>
<td>$\pm$ 0.90 pb ($\pm$ 1.86%)</td>
<td>+1.27 pb (+2.61%)</td>
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<tr>
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<td>$-$3.27 pb ($-$6.72%)</td>
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<td>$-$1.25 pb ($-$2.58%)</td>
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$\delta$(theory)

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<th>$\delta$(scale)</th>
<th>$\delta$(trunc)</th>
<th>$\delta$(PDF-TH)</th>
<th>$\delta$(EW)</th>
<th>$\delta$(t, b, c)</th>
<th>$\delta$(1/$m_t$)</th>
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<td>$\pm 0.18$ pb</td>
<td>$\pm 0.56$ pb</td>
<td>$\pm 0.49$ pb</td>
<td>$\pm 0.40$ pb</td>
<td>$\pm 0.49$ pb</td>
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<td>$-1.15$ pb</td>
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<tr>
<td>$+0.21%$</td>
<td>$\pm 0.37%$</td>
<td>$\pm 1.16%$</td>
<td>$\pm 1%$</td>
<td>$\pm 0.83%$</td>
<td>$\pm 1%$</td>
</tr>
<tr>
<td>$-2.37%$</td>
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gone!

no expansion around soft limit anymore

B. Mistlberger 1802.00833
gluon fusion: total cross section

calculation of NLO QCD corrections to mixed QCD-EW corrections

Bonetti, Melnikov, Tancredi 1711.11113, 1801.10403

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

multi-scale 3-loop diagrams

corresponding real radiation contribution

calculated in soft approximation

\[
\frac{\delta \sigma_{\text{QCD-EW}}^{\text{NLO}}}{\sigma_{\text{QCD, full}}^{\text{NLO}}} \sim (4.7 - 5.5) \times 10^{-2}
\]

confirming previous estimates
H+jet at NLO including full top quark mass dependence

HEFT: $m_t \to \infty$ limit

settles a longstanding question about the uncertainties due to unknown top mass effects at NLO

full NLO: different scaling behaviour at large $p_T$

K-factors full vs HEFT: similar shape for $\mu = \frac{H_T}{2}$ ...
H+jet at NLO including full top quark mass dependence

Dieter Zeppenfeld

Jones, Kerner, Luisoni, 1802.00349

... but K-factors not flat for fixed scale choice $\mu = m_H$
gluon fusion: Higgs pT spectrum

- Top-bottom interference effects in Higgs boson production
  Lindert, Melnikov, Tancredi, Wever ‘17

- b-quark effects in Higgs production at intermediate pT(H):
  resummation in region $m_b \lesssim p_{T,H} \lesssim m_H$
  Caola, Lindert, Kudashkin, Melnikov, Monni, Tancredi, Wever 1804.07632

  see also Grazzini, Sargsyan ‘13

  current uncertainty in top-bottom interference contribution to pT(H) spectrum estimated to be O(20%)
  (scales, matching scheme, b-mass scheme)

  talk by Chris Wever
Below top threshold

- Constrain bottom- and charm-quark Yukawa couplings

- Light quark contributions appear pre-dominantly through interference with top. However relative contribution of direct $q\bar{q} \rightarrow Hg, qg \rightarrow Hq$ contribution increases with light Yukawa coupling

- Shape of $p_{T,H}$ distribution may put strong constraints on light-quark Yukawa couplings

![Graphs showing the impact of different Yukawa couplings on $p_{T,j}$ distribution.]

- Bounds expected from HL-LHC

$$\kappa_C \in [-0.6, 3.0], \quad \kappa_b \in [0.7, 1.6]$$

[Bishara, Monni et al '16, Soreq et al '16]
QCD corrections to VBF at NNLO and beyond

- Very small scale uncertainties at NLO of order 1-2%
- Does this represent true theory error?
- NNLO and N3LO corrections are known for VBF Higgs production…..
VBF Higgs in Structure Function Approach

QCD corrections on 2 quark lines independent, inclusive over „DIS jet hadronization“

- NLO: Han, Valencia, Willenbrock (1992)
- NNLO: Bolzoni, Maltoni, Moch, Zaro (2010)
- N3LO: Dreyer, Karlberg (2016)

- Inclusive cross section has 1-2 permille scale uncertainty
  pdf errors, alphas uncertainty, EW corrections dominate and are substantially larger, in percent range

- Some distributions for inclusive production
VBF Higgs in Structure Function Approach

- NLO: Han, Valencia, Willenbrock (1992)
- NNLO: Bolzoni, Maltoni, Moch, Zaro (2010)
- N3LO: Dreyer, Karlberg (2016)

- Inclusive cross section has 1-2 permille scale uncertainty; pdf errors, alphas uncertainty, EW corrections dominate

- Some distributions for inclusive production

- No VBF cuts to distinguish VBF from gluon fusion Higgs signal or from backgrounds

- Need tagging jets and their distributions
Fully differential VBF Higgs cross section and fiducial cross section at NNLO

Cacciari, Dreyer, Karlberg, Salam, Zanderighi, arXiv:1506.02660
DIS approximation: treat QCD corrections to 2 quark lines as independent
no t-channel gluon ladders

<table>
<thead>
<tr>
<th></th>
<th>$\sigma^{(\text{no cuts})}$ [pb]</th>
<th>$\sigma^{(\text{VBF cuts})}$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO</td>
<td>4.032 $^{+0.057}_{-0.069}$</td>
<td>0.957 $^{+0.066}_{-0.059}$</td>
</tr>
<tr>
<td>NLO</td>
<td>3.929 $^{+0.024}_{-0.023}$</td>
<td>0.876 $^{+0.008}_{-0.018}$</td>
</tr>
<tr>
<td>NNLO</td>
<td>3.888 $^{+0.016}_{-0.012}$</td>
<td>0.844 $^{+0.008}_{-0.008}$</td>
</tr>
</tbody>
</table>

VBF cuts:
m(jj) > 600 GeV,
$\Delta y(jj)$ > 4.5,
$\vec{p}T(j) > 25$ GeV,
Opposite hemispheres for tagging jets

NNLO correction to NLO inclusive cross section: 1%
with VBF cuts: 4%
NNLO distributions with VBF cuts

Anti-kT jets with $R=0.4$: $m(jj) > 600$ GeV $\Delta y(jj) > 4.5$

Corrections at NNLO (as compared to NLO): up to 6% (was 10% before bug fix)

Cacciari, Dreyer, Karlberg, Salam, Zanderighi, arXiv:1506.02660v2
Energy flow in DIS jets: NLO correction to Jet shape

Definition: Jet shape = \( \psi(r) = \text{fraction of jet ET in cone of radius } r \)

Differential jet shape: \( \rho(r) = \frac{d\psi}{dr} \)

Observation for DIS at HERA (1999)

Energy flow is considerably narrower in NLO quarks jets (=LO jet shape) than in NNLO jets (with up to 3 partons)

Small cone (R=0.4) misses some fraction of jet energy \( \rightarrow \) reduced \( m(jj) \) \( \rightarrow \) fewer events survive \( m(jj) > 600 \text{ GeV cut} \)
VBFNLO study using NLO hjjj code (with Michael Rauch)

- hjjj (NLO) code has virtual corrections to h+3 partons and real emission of 4 partons.
- h+2 parton 2-loop corrections are missing. They only contribute to jet shape at r=0.
- Change (in cross sections or distributions) between R=0.4 and other values does not require 2-loop contributions.
- Start from Cacciari et al. results and study dependence on jet radius R in anti-kT algorithm at full NNLO.
  - Cuts and parameters identical to arXiv:1506.02660

- We find dependence on jet algorithm (kT vs anti-kT vs Durham/Aachen) to be small at NNLO
R-dependence of h\(jj\) cross section with VBF cuts

Anti-kT jets \(m(jj) > 600\ \text{GeV}\) \(\Delta y(jj) > 4.5\)

(M. Rauch)
pT of hardest tagging jet: anti-kT, R=0.4, 1.0, 1.6

At R=1 also most distributions show best agreement between NLO and NNLO
Rapidity separation of tagging jet pair

Change in shape of the $\Delta y(jj) = |y(j1) - y(j2)|$ distribution is not simply a result of the change in jet-shape. Possible explanations:

- Suppressed radiation between tagging jets
- Effect of 2-loop contribution

(M. Rauch)
Beware of jet observables

- For any process with jets at LO, an NLO cross section calculation simulates only LO jet shapes (and LO dependence on jet algorithms).
- This results in sizable QCD corrections at higher order since jet shapes change substantially from LO to NLO (i.e., when going to an NNLO calculation). NLO and NNLO results cannot agree at all jet radii $R$.
- Jet shape variation, $R$-dependence and jet algorithm dependence is not captured by scale variation of NLO cross sections. From VBF Higgs example, assign an additional (order 5%) uncertainty to NLO cross sections with jets in the final state, especially when scale variation is exceptionally small, like in VBF.
- Uncertainty will depend on number of jets in LO process, quark vs gluon jet, steepness of jet $p_T$ distributions etc.
- Disclaimer: There is nothing special or good about a fat jet choice with $R=1$ in the case of VBF Higgs production. It would induce large corrections due to underlying event or pile-up...
**WW scattering and unitarity**

Consider longitudinal $W$'s

$$W^+_L W^-_L \rightarrow W^+_L W^-_L$$

Polarisation vector

$$\epsilon^m_L = \frac{P^m}{m_W} + O\left(\frac{m_W}{E}\right) \sim \frac{\sqrt{s}}{m_W}$$

$$m \sim \frac{s^2}{m_W^2} \quad \frac{s^2}{m_W^2} \quad \frac{s^2}{m_W^2}$$

$$s/m_W^2 \quad \frac{s/m_W^2}{s/m_W^2}$$

$$s_{\text{HM}} \sim s$$

for $s \gg m_H^2$
Vector boson scattering as probe of EW symmetry breaking

The $m_h = 125$ GeV Higgs will unitarize $VV\rightarrow VV$ scattering provided it has SM $hVV$ couplings $\Rightarrow$ Check this by either

- precise measurements of the $hVV$ couplings at the light Higgs resonance
- measurement of $VV\rightarrow VV$ differential cross sections at high $p_T$ and invariant mass

Full $qq\rightarrow qqVV$ with $VV$ leptonic and semileptonic decay is implemented in VBFNLO with NLO QCD corrections and large set of dimension 6 and 8 terms in the effective Lagrangian
Going beyond dimension 6

Reason for dimension 8 operators like

\[
\mathcal{L}_{S,0} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi\right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi\right]
\]

\[
\mathcal{L}_{M,1} = \text{Tr} \left[\hat{\mathcal{W}}_{\mu\nu} \hat{\mathcal{W}}^{\nu\beta}\right] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi\right]
\]

\[
\mathcal{L}_{T,1} = \text{Tr} \left[\hat{\mathcal{W}}_{\alpha\nu} \hat{\mathcal{W}}^{\mu\beta}\right] \times \text{Tr} \left[\hat{\mathcal{W}}_{\mu\beta} \hat{\mathcal{W}}^{\alpha\nu}\right]
\]

- Dimension 6 operators only do not allow to parameterize $VVVV$ vertex with arbitrary helicities of the four gauge bosons

For example: $\mathcal{L}_{S,0}$ is needed to describe $V_L V_L \rightarrow V_L V_L$ scattering

- New physics may appear at 1-loop level for dimension 6 operators but at tree level for some dimension 8 operators

Building blocks:

\[
D_\mu \Phi \equiv \left(\partial_\mu + \frac{g'}{2} B_\mu + ig W^i_\mu \frac{\tau^i}{2}\right) \Phi
\]

\[
\Phi = \left(\begin{array}{c}
0 \\
\frac{v + H}{\sqrt{2}}
\end{array}\right)
\]

\[
W_{\mu\nu} = \frac{i}{2} g T^I (\partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g \epsilon_{ijk} W^j_\mu W^k_\nu),
\]

\[
B_{\mu\nu} = \frac{i}{2} g' (\partial_\mu B_\nu - \partial_\nu B_\mu).
\]
$V V \rightarrow W^+ W^-$ with dimension 8 operators

Effect of $\mathcal{L}_{\text{eff}} = \frac{f_{M,1}}{\Lambda^4} \text{Tr} \left[ \hat{W}_{\alpha\nu} \hat{W}^{\mu\beta} \right] \times \text{Tr} \left[ \hat{W}_{\mu\beta} \hat{W}^{\alpha\nu} \right]$

with $T_1 = \frac{f_{M,1}}{\Lambda^4}$ constant on $p p \rightarrow W^+ W^- j j \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu j j$

- Small increase in cross section at high $W W$ invariant mass??
Effect of constant $T_1 = \frac{f_{M,1}}{\Lambda^4}$ on $pp \rightarrow W^+W^- jj \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu jj$

- Huge increase in cross section at high $m_{WW}$ is completely unphysical
- Need form factor for analysis or some other unitarization procedure
K matrix unitarization

Project amplitude $k_j$, which exceeds (tree-level) unitarity, back onto Argand circle
$\rightarrow$ K matrix unitarized amplitude $a_j$

[VBFNLO implementation: Löschner, Perez;
following: Alboteanu, Kilian, Reuter]

Comparison with Whizard, which has this method already implemented:

Example: VBF-ZZ ($e^+e^-\mu^+\mu^-$)
good agreement between both codes
for longitudinal ops. at LO

$\rightarrow$ can now generate distributions
also at NLO via VBFNLO

Numerical unitarization now available for
all operators: work with Genessis Perez
and Marco Sekulla arXiv:1807.02707
Application to same sign W scattering

- Observed (with modest background) by ATLAS and CMS
- Useful bounds on Wilson coefficients of dim-8 operators
Definition of fiducial VBS cross sections

- Phase space cuts

\[ m_{\ell\ell} > 20 \text{ GeV}, \quad m_{jj} > 500 \text{ GeV}, \]
\[ p_T^\ell > 20 \text{ GeV}, \quad p_T^j > 30 \text{ GeV}, \quad p_T^{\text{miss}} > 30 \text{ GeV} \]
\[ \eta_{\ell} < 2.5, \quad |\eta_j| < 5, \quad \Delta \eta_{jj} > 2.5. \]

- Jets defined with anti-kT clustering and R=0.4
Comparison to K/T-matrix

Excellent agreement between different unitarization methods

$$F_{S_1} = \frac{f_{S_1}}{\Lambda^4}$$ coefficients adjusted for unitarized models to reproduce pure EFT cross section $$\leftrightarrow$$ CMS limits on $$F$$
Incident W polarization: $p_T(j,\text{max})$

- Typical off-shell behavior

\[ M \sim [s^2 + (q_1^2 + q_2^2 - q_3^2 - q_4^2)] s/\Lambda^4 \]

- Unitarization suppresses large incident virtualities $\rightarrow p_T(j,\text{max})$ shapes depend on polarization only

- Enhancement at small $p_T(j,\text{max})$ is sign for enhanced longitudinal scattering
Comments

- Unitarization changes shapes of distributions
- $T_u$ model suppresses high VV invariant mass and large incident virtualities: similar to what one expects from loop functions
- Unitarization is not unique $\rightarrow$ additional model dependence
Conclusions

- SM is still doing extremely well
- Strong motivation to go beyond SM: dark matter, CP violation and baryon asymmetry, naturalness…
- Search for extra scalars extremely important
- Measurement of Higgs couplings is entering precision era
  Progress on both extremely impressive and exceeding expectations!!!
- Great progress on EW and QCD corrections
- Vector boson scattering is starting to enter the game

Great times ahead of us
Backup
Decoupling in MSSM

Higgs potential in the MSSM produces distinct mass relations at tree level

\[
m^2_h, m^2_H = \frac{1}{2} \left[ m^2_A + m^2_Z \pm \sqrt{\left(m^2_A + m^2_Z\right)^2 - 4m^2_A m^2_Z \cos^2 2\beta} \right]
\]

\[m^\pm_H = \sqrt{m^2_A + m^2_W} > m_W\]

Mixing angle \(\alpha\) is also fixed by masses and \(\tan \beta\)

\[
\cos(\beta - \alpha) = \frac{m^2_h (m^2_Z - m^2_h)}{m^2_A (m^2_H - m^2_h)}
\]

Behaviour for \(m_A \gg m_Z\):

\[
m^\pm_H \approx m_A \approx m_H,
\]

\[
\cos(\beta - \alpha) \approx \frac{m^4_Z \sin^2 4\beta}{4m^4_A} \rightarrow 0 \quad \text{for} \quad m_A \rightarrow \infty \quad \text{(decoupling limit)}
\]
Decoupling limit for fermions

Consider limit \( \sin(\beta - \alpha) \to 1, \quad \cos(\beta - \alpha) \to 0 \)

- \( hbb, h\tau\tau: \)
  \[
  - \frac{\sin \alpha}{\cos \beta} = \sin(\beta - \alpha) - \tan \beta \cos(\beta - \alpha) \to 1
  \]

- \( h\tau t: \)
  \[
  \frac{\cos \alpha}{\sin \beta} = \sin(\beta - \alpha) + \frac{\cos(\beta - \alpha)}{\tan \beta} \to 1
  \]

- \( Hbb, H\tau\tau: \)
  \[
  \frac{\cos \alpha}{\cos \beta} = \cos(\beta - \alpha) + \tan \beta \sin(\beta - \alpha) \to \tan \beta
  \]

- \( Htt: \)
  \[
  \frac{\sin \alpha}{\sin \beta} = \cos(\beta - \alpha) - \frac{\sin(\beta - \alpha)}{\tan \beta} \to \frac{-1}{\tan \beta}
  \]

In the large \( m_A \) regime

- light \( h \) couplings to fermions approach SM values

- \( H\bar{b}b \) (and \( A\bar{b}b, H/A\tau\tau \)) couplings are enhanced \( \sim \tan \beta \)
  \( \implies \) potentially large cross sections at LHC
elementary-composite mixing?

- UV theory as pure gauge theory without elementary scalars
  - conserved fermion number, represented by continuous fermion line
- Example: QCD case of pn scattering by pion exchange

- mixing of elementary fermion with composite fermion???

- Fill in the box: Would like to understand mixing in terms of elementary fermions of UV complete gauge theory model without scalars....
Distributions for inclusive production up to N3LO

Extreme stability of predictions at the 2 percent (NLO) to 1 permille level (N3LO)

Dreyer, Karlberg  arXive:1606.00840
pT(j2) and Higgs pT at R=1

(M. Rauch)
NNLO distributions with VBF cuts: before bug fix

Anti-kT jets with $R=0.4$: $m(jj) > 600$ GeV $\Delta y(jj) > 4.5$

Corrections at NNLO (as compared to NLO): up to 10%

Cacciari, Dreyer, Karlberg, Salam, Zanderighi, arXiv:1506.02660