Theoretical Summary

Oleg Lebedev

Rencontres de Moriond 2017
QCD and High Energy Interactions
Sessions:

- Higgs
- Electroweak
- Heavy Flavour
- New Phenomena
- Top
- QCD
- Heavy Ion
- Special talk: neutrinos + Higgs
QCD: beauty or beast?
Higgs physics: still more popular than string theory

Courtesy A. Strumia
Electroweak symmetry breaking appears to be as in the SM
Higgs issues covered:

- triple Higgs coupling

\[ \mathcal{L} = -\frac{1}{2}m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4 \]

- EFT Higgs couplings

\[
\begin{align*}
\mathcal{O}_{WW} &= g^2 |H|^2 W^a_{\mu\nu} W^{a,\mu\nu} \\
\mathcal{O}_{BB} &= g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu} \\
\mathcal{O}_{WB} &= gg' H^\dagger \sigma^a HW^a_{\mu\nu} B^{\mu\nu} \\
\mathcal{O}_H &= \frac{1}{2} (\partial_{\mu}|H|^2)^2
\end{align*}
\]

- BSM Higgses

2HDM, composite Higgs, …
- CP properties in multi-Higgs models

\[ H, A, \ldots \]

- Dark Matter in multi-Higgs models

\[ Z_2 : H_1 \rightarrow -H_1 \]

- Higgs as the only scalar in Nature

\[ \Delta L = \xi R |H|^2 \]
**Higgs boson pair production:**  
Stephen Jones

**New result:** NLO $m_t$ dependence

**Gluon Fusion**
- Key measurement for probing the self coupling (HL-LHC era)
- NLO deviates from Born Improved HEFT
  - $-14\%$ @ 14 TeV, $-24\%$ @ 100 TeV
- Distributions altered significantly
Higgs EFT and $p_T$ dependence: Agnieszka Ilnicka

$$O_1 = |H|^2 G_{\mu\nu}^a G^{a,\mu\nu}$$
$$O_2 = |H|^2 \bar{Q}_L H^c u_R + h.c.$$  
$$O_3 = |H|^2 \bar{Q}_L H d_R + h.c.$$  
$$O_4 = \bar{Q}_L H \sigma^{\mu\nu} T^a u_R G_{\mu\nu}^a + h.c.$$ 

Peculiar new physics dependence compared to that of $\sigma$
**BSM Higgs:** Marcela Carena

**2HDM:**

\[
V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c.) + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\
+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
+ \left\{ \frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + [\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)]\Phi_1^\dagger \Phi_2 + h.c. \right\},
\]

**Alignment:**

- heavy BSM Higgses
- alignment w/o decoupling

\[
\eta = \cos \beta \cdot \alpha_t \beta \\
\Rightarrow g_{hVV} \approx \left(1 - \frac{1}{2} t_\beta^2 \eta^2 \right) g_V \\
\text{highlighted: } g_{hdd} \approx (1 - \eta) g_f, \\
\text{highlighted: } g_{h_{\mu\mu}} \approx (1 + t_\beta^2 \eta) g_f,
\]
Composite models:

$$\xi = \frac{v^2}{f^2} \ll 1 \quad (f = \text{strong dynamics scale})$$

Higgs coupling modifications:

$$\kappa_V = \sqrt{1 - \xi} \quad K_F = \frac{1-2\xi}{\sqrt{1-\xi}}$$

<table>
<thead>
<tr>
<th>Model</th>
<th>Lower limit on $f$</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Obs.</td>
</tr>
<tr>
<td>MCHM4</td>
<td>710 GeV</td>
</tr>
<tr>
<td>MCHM5</td>
<td>780 GeV</td>
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</tbody>
</table>

Dark Matter in multi-HDM: Dorota Sokolowska

Inert 2HDM:

$Z_2$: $H \rightarrow H, \quad H_i \rightarrow -H_i$  \quad \rightarrow \quad DM, \text{ but quite constrained}

$(2+1)$ HDM:

Add an extra inert doublet  \quad \rightarrow \quad open up efficient co-annihilation
Generalized CP in 3HDM: Igor Ivanov

\[ J : \phi_i \xrightarrow{\text{CP}} X_{ij} \phi_j^* , \quad X = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & i \\ 0 & -i & 0 \end{pmatrix} \]

Mass degenerate neutral scalars H,A and h,a:

\[ H \xrightarrow{\text{CP}} A, \quad A \xrightarrow{\text{CP}} -H, \quad h \xrightarrow{\text{CP}} -a, \quad a \xrightarrow{\text{CP}} h. \]

\[ \Phi = \frac{1}{\sqrt{2}} (H - iA), \quad \varphi = \frac{1}{\sqrt{2}} (h + ia), \quad \Phi \xrightarrow{\text{CP}} i\Phi, \quad \varphi \xrightarrow{\text{CP}} i\varphi. \]

CP-half-odd scalars (CP is order 4)
νMSM: Mikhail Shaposhnikov

Higgs-gravity coupling:

\[ \mathcal{L}_G = - \left( M_P^2 + 2\xi_h \varphi \varphi^\dagger \right) \frac{R}{2} \]

\( \chi = \) canonically normalized Higgs = inflaton
FLAVOR PHYSICS

CKM picture is in excellent agreement with data
Flavor issues covered:

- B-physics anomalies/new insights
  \[ R_D, R_K, \ldots \]

- Lattice progress
  \[ \varepsilon' / \varepsilon \]

- Heavy flavor production at the LHC
  \[ \sigma_{bb}, \sigma_{cc} \]

- CP violation
  \[ \phi_s \]

- Hadronic B decays
  \[ B \to PP, \ldots \]
**Anomalies:**  Matthias Neubert,  Javier Virto

Clean observables!
:: $B \rightarrow K^*\mu\mu$ Angular Observables

\[
\frac{d^4\Gamma}{dq^2 \, d\cos\theta_K \, d\cos\theta_l \, d\phi} = \frac{9}{32\pi} \times \\
\left[ J_{1s} \sin^2 \theta_K + J_{1c} \cos^2 \theta_K + J_{2s} \sin^2 \theta_K \cos 2\theta_l \right. \\
\left. + J_{2c} \cos^2 \theta_K \cos 2\theta_l + J_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi \\
+ J_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + J_5 \sin 2\theta_K \sin \theta_l \cos \phi \\
+ J_6 \sin^2 \theta_K \cos \theta_l + J_6c \cos^2 \theta_K \cos \theta_l \\
+ J_7 \sin 2\theta_K \sin \theta_l \sin \phi + J_8 \sin 2\theta_K \sin 2\theta_l \sin \phi \\
\left. + J_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right]
\]

\[ P'_5 = \frac{J_5}{(2\sqrt{-J_{2c}J_{1s}})} \]

about $3\sigma$ anomaly
Javier Virto: 

\[ \mathcal{O}_{9\ell} = \frac{\alpha}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma_\mu \ell) \]

1. Assuming KMPW is the right ballpark for $c\bar{c}$.
2. Assuming Fact. PCs are $\sim 10 - 20\%$ (supported by LCSR calculations).
3. Assuming the OPE for the large-$q^2$ bin is correct up to $\sim 10\%$

then, a NP contribution $C_{9\mu}^{NP} \sim -1$ gives a substantially improved fit for

- $B \to K\mu\mu$, $B \to K^*\mu\mu$ and $B_\phi \to \Phi\mu\mu$
- BRs and angular observables (including $P_\zeta$)
- Low $q^2$ and large $q^2$
- $R_K$

Siavash Neshatpour: hadronic corrections do not improve the fit

Hadronic power correction effect:

\[ \delta H_V^{PC}(\lambda) = iN' m_B^2 \frac{16\pi^2}{q^2} h_\lambda(q^2) = iN' m_B^2 \frac{16\pi^2}{q^2} \left( h^{(0)}_\lambda + q^2 h^{(1)}_\lambda + q^4 h^{(2)}_\lambda \right) \]

New Physics effect:

\[ \delta H_V^{NP}(\lambda) = -iN' \tilde{V}_{\lambda}(q^2) C_{9\mu}^{NP} = iN' m_B^2 \frac{16\pi^2}{q^2} \left( a_\lambda^{NP} C_{9\mu}^{NP} + q^2 b_\lambda^{NP} C_{9\mu}^{NP} + q^4 c_\lambda^{NP} C_{9\mu}^{NP} \right) \]
Lattice calculation progress: Enrico Lunghi

The long standing mysterious enhancement of the $\Delta I=1/2$ channel (the so-called $\Delta I=1/2$ rule) is explained as an accidental cancellation between contributions to $\text{Re}(A_2)$ which does not occur for $\text{Re}(A_0)$.

\[
\text{Re} \left( \frac{\varepsilon'}{\varepsilon} \right) = \begin{cases} 
(16.6 \pm 2.3) \times 10^{-4} & \text{exp} \\
(1.36 \pm 5.15 \pm 4.59) \times 10^{-4} & \text{th}
\end{cases}
\]
Total bottom/charm $\sigma$ at NNLO: David d’Enterria

Bottom: Very good agreement at all $\sqrt{s}$ within large uncertainties

Charm production $\sigma$ not as good
**Determination of $\phi_s$ to 0.5%:** Keri Vos

**Hadronic B decays:** Cai-Dian Lu

- Only 14 universal non-perturbative parameters to be fitted from all $B \to PP$, $VP$ and $PV$ decay channels, more predictive power than ever.
- Results are consistent with data. SU(3) breakings are studied.
- Predictions for more than 100 channels to be tested by future exp. Power corrections are needed.
PRECISION CALCULATIONS

Matter of life and death
Topics covered:

- $\alpha_s$ extraction

- top mass at LHC

- single top production

- PDFs

- jet production in DIS and at LHC

- vector boson pair production at LHC
Strong coupling from top production: Thomas Klijnsma

ATLAS + CMS + Tevatron

3.8% precision depending on PDF
Top mass from di-photons: Hyung Do Kim

Toponium production at the threshold

There is a hope for $\Delta m_t < 0.5 \text{ GeV}$ from a single channel measurement
Single top production and decay: Hua-Xing Zhu

Direct probe of $Wtb$ vertex in \textit{both} production and decay

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W^-_\mu - \frac{g}{\sqrt{2}} \bar{b} \frac{i \gamma^\mu q_\mu}{m_W} (q_L P_L + q_R P_R) t W^-_\mu + \text{h.c.}$$

Direct measurement of $|V_{tb}|^2$

<table>
<thead>
<tr>
<th>Fiducial [pb]</th>
<th>LO</th>
<th>NLO</th>
<th>NNLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t$ quark</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>total</td>
<td>$4.07^{+1.2}_{-0.8}$</td>
<td>$2.95^{+3.1}_{-2.7}$</td>
<td>$2.70^{+1.2}_{-1.0}$</td>
</tr>
<tr>
<td>corr. in pro.</td>
<td>$-0.87$</td>
<td>$-0.79$</td>
<td>$-0.24$</td>
</tr>
<tr>
<td>corr. in dec.</td>
<td>$-0.33$</td>
<td>$-0.33$</td>
<td>$-0.13$</td>
</tr>
</tbody>
</table>

| $f$ quark     |    |     |      |
| total         | $2.45^{+1.8}_{-0.9}$ | $1.78^{+1.3}_{-1.0}$ | $1.62^{+1.2}_{-0.8}$ |
| corr. in pro. | $-0.46$ | $-0.46$ | $-0.15$ |
| corr. in dec. | $-0.21$ | $-0.21$ | $-0.08$ |

NNLO: -6% correction
In the Higgs production region (MX=125 GeV), all PDFs now agree as a result of dedicated benchmarking. The uncertainty on sigma_tot(Higgs) was reduced from 7% in 2012 to 3% in 2015. Can we reduce it more?

NNLO PDFs CT17, MMHT'16, NNPDF3.1 to be released
xFitter: Valerio Bertone

- provides a unique QCD framework to address theoretical differences:
  → benchmark exercises/collaborative efforts/topical studies
- provides means to the experimentalists to optimise the measurements:
  → assess impact/consistency of new data
EPPS16 nuclear PDFs: Carlos Salgado

New in EPPS16

Larger uncertainties reflect more realistic analysis
more freedom in parametrization

Supersedes EPS09
NNLO dijet production in DIS:  Jan Niehues (+ Daniel Britzger)

- sensitive to $\alpha_s$
- sensitive to gluon PDF

$\sigma_{\text{tot}}$ at NNLO:  - reduced scale uncertainty
- normalization issue (30%) $\rightarrow$ PDF

[D. Britzger et al. 2017]
Single jet production at NNLO at LHC: Joao Pires

- Rigorous tests of pQCD dynamics across a huge range of kinematics
- Constrain PDF's
- Determine $\alpha_s(M_Z)$ and running coupling from a single experiment

Percent level scale uncertainty!
Vector boson pair production at NLO: Raoul Röntsch

Strong destructive interference (probe unitarizing behavior of Higgs)

$$|A_{ZZ}|^2 = |A_H|^2 + |A_b|^2 + 2\text{Re}[A_H A_b^*]$$

$$\rightarrow \sigma_{\text{full}} = \sigma_{\text{sig1}} + \sigma_{\text{bkgd}} + \sigma_{\text{intf}}$$

Interference effects $\sim 5\%$

Scale uncertainty reduced to 10%
WW, WZ production at NNLO QCD: Stefan Kallweit, Marius Wiesemann

NNLO/NLO ranges from 10% to 14% (7 TeV to 14 TeV).

NNLO scale variation \( \approx \pm 3\% \).
Fluctuations of EM field in heavy ion collisions: Bronislav Zakharov

quantum effects reduce magnetic field fluctuations (!)
NEW PHENOMENA

Fine-tuned?
Beyond the Standard Model: Aldo Deandrea

\[ \Delta m^2_h = -\frac{y_t^2}{16\pi^2} \left( 2 \Lambda^2 + 6 m_t^2 \log \left( \Lambda/m_t \right) \right) \]

a) Renormalizable theory example (SWY):

\[ \frac{\Lambda_5}{16\pi^2} \left( \Lambda^2 - 2 m_5^2 \log \left( \Lambda/m_5 \right) + \cdots \right) \]

b) Effective model example (with a fermion, as in composite Higgs):

A cut-off, but here physical meaning
Probe the form factor:

\[ F(p) \]

- elementary
- composite

LHC reach

\[ \begin{align*}
\text{a few TeV} & \rightarrow e, \gamma, ... \\
125 \text{ GeV} & \rightarrow h
\end{align*} \]
Supersymmetry: Werner Porod

\[(125 \text{ GeV})^2 \simeq m_W^2 + (86 \text{ GeV})^2 \Rightarrow \text{large corrections within MSSM}\]

- GMSB, CMSSM, NUHM: \(m_{\tilde{g}}, m_{\tilde{q}} \gtrsim 2\text{ TeV}\)
- CMSSM, NUHM: large \(A_0\), danger of color and charge breaking minima

- general MSSM: SUSY particles with masses of few 100 GeV still allowed if spectra compressed, in particular light \(\tilde{t}_1\) still allowed
- ‘Natural SUSY’: take only those states light which contribute to EWSB: \(\tilde{h}^{0,\pm}, \tilde{t}_1, \tilde{g}, \tilde{b}_t\)

\[m_W^2 \simeq -1.8 \mu^2 + 5.9 M_3^2 - 0.4 M_2^2 - 1.2 m_{H_u}^2 + 0.9 m_{q_L^{(3)}}^2 + 0.7 m_{u_R^{(3)}}^2 - 0.6 A_t M_3 + 0.4 M_2 M_3 + \ldots ,\]
SUSY Searches:

BSM theories so far: "We tried to do good, but it turned out as usual."

Виктор Черномырдин
SUMMARY OF SUMMARY

✧ Remarkable progress in calculations: NNLO = commonplace

✧ Intriguing B-physics anomalies

✧ Higgs precision era

✧ Data-driven theory: test “unmotivated” ideas