ATLAS Results on Higgs Boson Couplings

Reisaburo TANAKA (LAL-Orsay)
on behalf of ATLAS Collaboration
August 24th, 2019
ICNFP 2019, Crete, Greece
Higgs Boson Property Measurements

1. Higgs boson mass ($M_H$) & decay width ($\Gamma_H$)
2. Higgs boson quantum numbers $J^{PC}$ and tensor structure
3. Higgs couplings to gauge bosons ($g_V$) and fermions ($g_F$)
4. Higgs potential - Higgs self-coupling ($\lambda$)

The Standard Model Lagrangian - Higgs sector

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2} (H^\dagger H)^2 - (y_{ij} H \bar{\psi}_i \psi_j + h.c.)$$

Couplings to EW gauge bosons

$$\left[ m_W^2 W^\mu W^\nu - \frac{1}{2} m_Z^2 Z^\mu Z^\nu \right] \cdot (1 + \frac{h}{v})^2$$

Higgs self-couplings

$$-\mu^2 h^2 - \frac{\lambda}{2} vh^3 - \frac{1}{8} \lambda h^4$$

Couplings to fermions

$$- \sum_f m_f \bar{f} f \left( 1 + \frac{h}{v} \right)$$

$$m_H = \sqrt{2\mu} = \sqrt{\lambda} v \ (v = \text{vacuum expectation value, } 246 \text{ GeV})$$
Higgs Boson Property Measurements

1. Higgs boson mass ($M_H$) & decay width ($\Gamma_H$)
2. Higgs boson quantum numbers $J^{PC}$ and tensor structure
3. Higgs couplings to gauge bosons ($g_V$) and fermions ($g_F$)
4. Higgs potential - Higgs self-coupling ($\lambda$)

The ultimate goal of particle physics of today is to test the Standard Model (SM) Lagrangian and find the physics beyond the Standard Model (BSM).
What do we know about the scalar sector 7 years after July 4th 2012 discovery?
1. Higgs Boson Production and Decay at LHC
### Data Analysed for Higgs Coupling Study in ATLAS

- **Higgs Gauge Boson Coupling**: HVV
- **Higgs Yukawa Coupling**: Hff

#### Production and Decay

<table>
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*√s = 13 TeV, ∫Ldt = 24.5 - 79.8 fb⁻¹*

- ✓: Analysed but not included in the combination
- ✓✓: Used in a subset of combined results
- ✓ H→invisible decay, on-shell/off-shell width measurement results

Talk by P. Francavilla on statistical combination method.
Higgs signal-strength

**LO \( \kappa \)-framework**

\[
\mu = \frac{\sigma \cdot \text{BR}}{(\sigma \cdot \text{BR})_{\text{SM}}}
\]

- Measure with coupling scale factors \( \kappa_i \).
- The coupling of SM particles to Higgs boson scales with particle mass:
  \[ g_F = \sqrt{2} \frac{m_F}{v}, \quad g_V = 2 \frac{m_V}{v} \]
- Holds up to electroweak effects of \( O(5-10\%) \).

**Assumptions**
1. narrow width approx.
2. only 1 SM-like Higgs
3. SM tensor structure (spin 0, CP-even)
4. on-shell production and decay

\[
\mu = \frac{(\sigma \cdot \text{BR})(gg \rightarrow H \rightarrow \gamma\gamma)}{\{\sigma(gg \rightarrow H) \cdot \text{BR}(H \rightarrow \gamma\gamma)\}_{\text{SM}}} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}
\]

\[
\kappa_H^2 = \sum_{jj=WW^*, ZZ^*, b\bar{b}, \tau^-\tau^+, \gamma\gamma, Z\gamma, gg, t\bar{t}, c\bar{c}, ss, \mu^-\mu^+} \frac{\kappa_j^2 \Gamma^\text{SM}_{jj}}{\Gamma^\text{SM}_H}
\]

- Measure with coupling scale factors \( \kappa_i \).
- The coupling of SM particles to Higgs boson scales with particle mass:
  \[ g_F = \sqrt{2} \frac{m_F}{v}, \quad g_V = 2 \frac{m_V}{v} \]
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Global Signal Strength & Production Cross Section

ATLAS Combined $\gamma\gamma$, ZZ, WW, $\tau\tau$, $\mu\mu$, bb with 80 fb$^{-1}$ data at $\sqrt{s}=13$ TeV

$\mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05$ (stat.) $+0.05_{-0.04}$ (exp.) $+0.05_{-0.04}$ (sig. th.) $\pm 0.03$ (bkg. th.)

$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}$ (stat) $+0.04_{-0.04}$ (expt) $+0.03_{-0.03}$ (thbgd) $+0.07_{-0.06}$ (thsig)

$\sqrt{s}=7$ TeV 5 fb$^{-1}$
$\sqrt{s}=8$ TeV 20 fb$^{-1}$

Major TH uncertainty due to ggF QCD scale

Large theory uncertainties in VBF, VH and ttH channels due to ggF contamination, UE/PS uncertainty etc.

$\mu = \frac{\sigma \cdot BR}{(\sigma \cdot BR)_{SM}}$
Higgs Boson Decay Width and Branching Ratio

Various Higgs-boson decay channels at $M_H = 125$ GeV
Narrow Higgs-boson decay width $\Gamma_H = 4.1$ MeV
Dominated by $H \rightarrow bb$ decay (BR=58%)

$$BR(H \rightarrow VV) = \frac{\Gamma_{VV}}{\Gamma_{tot}} = \frac{\Gamma_{VV}}{\Gamma_{ff} + \Gamma_{VV}}$$

$\Gamma_{ff} : \Gamma_{VV} \simeq 3 : 1$ (dominated by $\Gamma_{bb}$)

Interesting quantity $\Gamma_{\gamma\gamma}/\Gamma_{zz}$:
- sensitive to new physics via loop in $\gamma\gamma$
- Theory uncertainty is $\pm 1.1\% (+\Delta M_H)$
- But current EXP error is $\pm 20\%$. Long way to go…
2. Higgs Boson
Yukawa Coupling

湯川秀樹 (1949)
Hττ Yukawa in H→ττ

- Boosted ggF and VBF topologies in ττ→ll, lh and hh channels
- Large Z→ττ backgrounds
- Observation of H→ττ decay process:
  - 6.4σ significance (5.4σ expected) with Run 1+2 data
Hbb Yukawa in VH(\(H \rightarrow \text{bb}\))

- Most sensitive to Hbb Yukawa coupling (along with \(\text{ttH}(\text{H} \rightarrow \text{bb})\)).
- Search in channels with 0,1,2 leptons (e/\(\mu\)) with \(V \rightarrow \nu\nu, lv, ll\).
- Large variety of the SM backgrounds from \(V+\text{HF}(\text{Zbb etc.}), \text{VV}, \text{ttbar}\).
- Use of BDT & profile likelihood fits to isolate signal and measure background parameters from data in control region.
- Observation of VH production process: \(5.4 \sigma\) significance (\(5.5 \sigma\) expected) with Run 1+2 data.

**ATLAS**

\(\sqrt{s} = 13\) TeV, 79.8 fb\(^{-1}\)

0+1+2 leptons

2+3 jets, 2 b-tags

Weighted by Higgs S/B

Di-jet mass analysis

**RUN-2**

**ATLAS**

\(H \rightarrow \text{bb}\)

\(\sqrt{s} = 7\) TeV, 8 TeV, and 13 TeV

4.7 fb\(^{-1}\), 20.3 fb\(^{-1}\), and 24.5-79.8 fb\(^{-1}\)

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**Dijet mass analysis**

**ZZ**

**WZ**

**WW**

VH(\(H \rightarrow \text{bb}\))

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**Events / 10 GeV (Weighted, backgr. sub.)**

**m_{bb} [GeV]**
Htt/Hbb Yukawa in ttH(H→bb)

- Associated Higgs boson production with ttbar
- Probe ttH Yukawa coupling directly (ggF in indirect way).
- Different Higgs boson decay channels are studied in H→γγ, ZZ*(→4l), WW*, ττ and bb.
- H→γγ: despite very small BR(2.3×10⁻³), clean signature. Statistical error dominated.
- H→bb: very complicated final state (4 b-jets), large backgrounds from ttbar+V/HF (ttbb etc.)
- Observation of ttH production process: 6.3σ significance (5.1σ expected) with Run 1+2 data

H→γγ

RUN-2

![Graph showing H→γγ events and ttH production](source: ATLAS-CONF-2019-004)
Higgs Yukawa Coupling in the 2\textsuperscript{nd} Generation

\textbf{2\textsuperscript{nd} & 1\textsuperscript{st} generation}: branching ratios (Yukawa) are very small

- BR(H→μ⁺μ⁻) = 2.2×10⁻⁴, BR(H→e⁺e⁻) = 4.9×10⁻⁹ for M_H = 125 GeV.
- Higgs Dalitz decay BR(H→Zγ) = 1.5×10⁻³, should be searched in ffγ.

Search for H→μ⁺μ⁻ decay: very large Drell-Yan backgrounds.

\textbf{RUN-2}

Observed (Expected) Upper limit: 1.7 (1.3) × σ_{SM} at 95\% C.L.

\[ H \rightarrow \mu^+\mu^- \]
Yukawa sector: search for $H \rightarrow cc$, $e^+ e^-$

Search performed via associated production $VH(H\rightarrow cc)$

Observed (expected) limit $\sigma(pp \rightarrow ZH) \times B(H \rightarrow c\bar{c}) = 2.7 (3.9) \text{ pb}$ at 95% C.L. (SM 26 fb)

Charm coupling via Higgs $p_T$ (light quark modifies Higgs spectrum at low $p_T$)

Maybe accessible to charm via $J/\psi + \gamma$ ($\text{BR}(H \rightarrow J/\psi + \gamma) = 2.5 \times 10^{-6}$), $\gamma \gamma$, $\phi \gamma$ and $\rho \gamma$.

Observed limit $B(H \rightarrow J/\psi + \gamma) = 3.5 \times 10^{-4}$ at 95% C.L. (Phys. Lett. B 786 (2018) 134)

Search for the 1st generation Yukawa has also been performed in $H \rightarrow e^+ e^-$ decay.

Observed (expected) limit $B(H \rightarrow e^+ e^-) = 3.6 (3.5) \times 10^{-4}$ at 95% C.L. ($\text{BR}_{\text{SM}} = 4.9 \times 10^{-9}$)
Generic $\kappa$-parametrization

LHC cannot measure Higgs boson total decay width

“Coupling modifier” $\kappa$ at each Higgs vertex

$$\sigma (i \rightarrow H \rightarrow f) = \kappa_i^2 \sigma_i^{SM} \frac{\kappa_f^2 \Gamma_f^{SM}}{\kappa_H^2 \Gamma_H^{SM}}$$

Can accommodate Higgs-boson invisible decay or undetected mode

$$\Gamma_H (\kappa_i, \mathcal{B}_{\text{invisible}}, \mathcal{B}_{\text{undetected}}) = \frac{\kappa_H^2 (\kappa_i)}{1 - \mathcal{B}_{\text{invisible}} - \mathcal{B}_{\text{undetected}}} \Gamma_H^{SM}$$

Many BSM models predict $\kappa < 1$

In principle Higgs couplings are running, but we assume on-shell and off-shell couplings are the same.

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1) Assuming $\text{BR}_{\text{invisible}} = \text{BR}_{\text{undetected}} = 0$
2) Constrain $\text{BR}_{\text{invisible}}$ and $\text{BR}_{\text{undetected}}$ using $H \rightarrow \text{invisible}$ decay analysis and $\kappa < 1$
3) Constrain $\text{BR}_{\text{BSM}} = \text{BR}_{\text{invisible}} = \text{BR}_{\text{undetected}}$ using off-shell analysis and assuming $\kappa_{\text{on-shell}} = \kappa_{\text{off-shell}}$
**Couplings ($\kappa_V, \kappa_F$) in $\kappa$-framework in LO**

- Assume all fermion couplings scale as $\kappa_F$ while all vector boson couplings scale as $\kappa_V$.
- Assume no BSM contributions to $\Gamma_H$.
- Quad-fold ambiguity in sign of $\kappa_F$ and $\kappa_V$ and we need information from interference to resolve the degeneracy.
  - $\kappa_V > 0$ by convention
  - $\kappa_F < 0$ excluded by RUN-1 ATLAS+CMS

**H$\rightarrow\gamma\gamma$**
Slope due to negative interference between top and $W$-boson in $H\rightarrow\gamma\gamma$ decay

$$\kappa_\gamma^2(\kappa_W, \kappa_t) \simeq |1.26\kappa_W - 0.27\kappa_t|^2$$

slope: $$\frac{d\kappa_F}{d\kappa_V} \simeq 4.7$$

**H$\rightarrowZZ/WW$**
Mostly sensitive to $\kappa_V$, but can constrain on $\kappa_F$ with associated productions in VBF and VH. ($\therefore$ too large $\kappa_F$ means small $\text{BR} = \Gamma_{ZZ}/\Gamma_{tot}$).

$$\text{BR}(H \rightarrow VV) = \frac{\Gamma_{VV}}{\Gamma_{tot}} = \frac{\Gamma_{VV}}{\Gamma_{ff} + \Gamma_{VV}}$$

$$\Gamma_{ff} : \Gamma_{VV} \simeq 3 : 1 \text{ (dominated by } \Gamma_{bb})$$
Electroweak symmetry breaking needs to explain:
- Non-zero mass of W/Z gauge bosons and fermions and unitarity conservation below 1 TeV.
- Non-linear relation would indicate the Higgs sector is not single doublet.

\[
GF = \sqrt{2} \frac{m_f}{v}
\]

\[
GV = 2 \frac{m_V^2}{v}
\]

\[
\begin{align*}
y_F &= \kappa_F \frac{m_f}{v} \\
y_V &= \sqrt{\kappa_V} \frac{m_V}{v}
\end{align*}
\]

Challenges in Higgs self-coupling \( \lambda \) and fermion coupling \( H \rightarrow \mu^+\mu^- \), cc, etc. \((e^+e^-\text{ hopeless})\).
3. Higgs Boson Self-Couplings
Higgs potential - Higgs self-coupling

One of the core physics programs at HL-LHC, but very challenging in both experiment and theory.

Is it feasible to measure Higgs self-coupling at HL-LHC?

Explore all possible channels like $HH \rightarrow bbbb$, $bb\gamma\gamma$, $bb\tau\tau$ etc.

New ideas like boosted Higgs analysis, via single-Higgs production (2-loop).

Non-trivial interference between different diagrams.

Destructive interference between box (a) and triangle (b) diagrams.
Higgs self-coupling modifier due to BSM scenarios: $\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$

Largest statistics in bbbb channel. Good compromise between statistics and S/B in bb\gamma\gamma and bb\tau\tau channels.

Currently at O(10)\times SM sensitivity level.

95% CL limit for $\kappa_\lambda=1$: is 6.9(10)\times SM Obs(Expected)

95% CL confidence level intervals: $\kappa_\lambda = [-5,12]$ observed, [-5.8,12] expected
Higgs self-coupling could occur in electroweak loops in single Higgs production.

Assume new physics affects only to the Higgs boson self-coupling ($\lambda_{HHH}$).

Higgs self-energy contributing to the ggF Higgs production

Vector Boson Fusion

Higgs boson Associated Production

Complete 2-loop NLO EW correction calculation desired.
4. Higgs Couplings via Effective Field Theory
κ-framework aimed to “detect the deviation from the SM” at O(5-10%) 

- It is only at lowest-order (LO) and does not incorporate differential distributions which are sensitive to BSM.

Model independent framework exists, *i.e.* the Effective Field Theory (EFT)

\[
\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}}^{(4)} + \sum_{i} \frac{1}{\Lambda^{d_i-4}} c_i O_i
\]

- Neglecting dimension-5 operator, dimension-6 consists of 59 operators.
- Search for BSM physics indirectly via precision Higgs coupling measurements.
- Capable to combine EWPD, aTGC, Higgs and Top data with common Lagrangian.
Higgs EFT Analysis $H \rightarrow \gamma\gamma$

- EFT analysis in $H \rightarrow \gamma\gamma$ decay with 5 differential distributions
- CP-even Wilson coefficients ($C_{HG}$, $C_{HW}$, $C_{HB}$, $C_{HWB}$)
  - $C_{HG}$: ggF
  - $C_{HW}$, $C_{HB}$, $C_{HWB}$: VBF, VH, $H \rightarrow \gamma\gamma$
- EWPD constraints: $C_{HWB}$ (S), $C_{HD}$ (T)

### CP-Even

**ATLAS Simulation Preliminary** $H \rightarrow \gamma\gamma$, $\sqrt{s} = 13$ TeV

- $C_{HG} = 4.5 \times 10^{-4}$
- $C_{HB} = -2.3 \times 10^{-4}$
- $C_{HW} = -7.8 \times 10^{-4}$
- $C_{HWB} = -4.2 \times 10^{-4}$

### CP-Odd

**ATLAS Simulation Preliminary** $H \rightarrow \gamma\gamma$, $\sqrt{s} = 13$ TeV

- $\tilde{C}_{HG} = 1.8 \times 10^{-2}$
- $\tilde{C}_{HB} = -13$
- $\tilde{C}_{HW} = -2.9 \times 10^{-1}$
- $\tilde{C}_{HWB} = -8.8$
Higgs EFT Analysis in VH(H→bb)

- EFT analysis in VH production with H→bb decay
  - via template cross section in vector boson p_T
- Constraints on Wilson coefficients (C_{HW}, C_{HB})
5. Higgs Boson
Spin CP
CP Violation in Higgs Sector

CP violation: immediate sign of BSM physics.

One of the 3 Sakharov conditions for EW Baryogenesis,
   i) B number violation, ii) C or CP violation and iii) out-of-equilibrium or CPT violation

CP violations for quark and neutrino sector, but totally unknown for Higgs sector.

Many BSM models (ex. 2HDM, SUSY) predict CP violation
   MSSM: no Born level CP violation, CP-violation is loop-induced.
   NMSSM: CP-violating phase at Born level.
   2HDM: the effects on Higgs couplings to gauge bosons are suppressed, hence CP-violation studies often in Yukawa sector, ex. $\tau\tau$, ttH, etc.

Strong constraints on CP-violation via Electric Dipole Moment (EDM)
   $\Lambda_{CP} \sim 1$ TeV, comparable to LHC reach !

\[ |d| < 10^{-25} e \times cm \rightarrow d \sim 10^{-2} \times \frac{1 \text{ MeV}}{\Lambda_{CP}^2} \]
Probed $CP$ nature in Higgs boson decay into 4-leptons

No event yield information (cross section) was used but shape only in the analyses.

Excluded pure $J^P=0^-, 1^+, 2^+$ (minimal coupling) at more than 99% C.L. in RUN-1.

Large $CP$-mixing/violation is still possible.

$CP$-information Geometry

VBF provides the best reach. But its initial state is not $CP$ eigenstate. Important kinematical variable like $\Delta \phi_{jj}$ in VBF

ZH associated production is less model-dependent. Initial state is $CP$ eigenstate.

$H \rightarrow ZZ^* \rightarrow 4$ leptons is clean signal but limited sensitivity due to small momentum transfer $M_H^2$
**Vector Boson Fusion (VBF) channel to probe HVV couplings**

**CP-odd Optimal Observable**

\[ \mathcal{O} \mathcal{O} = \frac{2 \text{Re} \left( \mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{CP-odd}}^* \right)}{\left| \mathcal{M}_{\text{SM}} \right|^2} \]

\( \mathcal{O} \mathcal{O} \) is CP-odd \( \rightarrow \langle \mathcal{O} \mathcal{O} \rangle \neq 0 \) is an indication of CP-violation

**Matrix element**

\[ \mathcal{M} = \mathcal{M}_{\text{SM}} + \tilde{d} \cdot \mathcal{M}_{\text{CP-odd}} \]

**CP- mixing parameter \( \tilde{d} \) in \( h \rightarrow \tau \tau \) decay**

Constrained in the interval

\([-0.11, +0.05]\) at 68%CL

Consistent with SM prediction \( \tilde{d} = 0 \)
Higgs EFT Analysis $H \rightarrow \gamma \gamma$

- EFT analysis in $H \rightarrow \gamma \gamma$ decay with 5 differential distributions
- CP-odd Wilson coefficients ($\bar{c}_{HG}$, $\bar{c}_{HW}$, $\bar{c}_{HB}$, $\bar{c}_{HWB}$)
- Sensitivity for CP-violation in $\Delta \phi_{jj}$ (opening angle in $r$-$\phi$ plane between two forward jets in Vector Boson Fusion process)

**CP-Even**

`ATLAS` Simulation Preliminary $H \rightarrow \gamma \gamma$, $\sqrt{s} = 13$ TeV

- $\bar{c}_{HG} = 4.5 \times 10^{-4}$
- $\bar{c}_{HB} = -2.3 \times 10^{-4}$
- $\bar{c}_{HW} = -7.8 \times 10^{-4}$
- $\bar{c}_{HWB} = -4.2 \times 10^{-4}$

**CP-Odd**

- $\bar{c}_{HG} = 1.8 \times 10^{-2}$
- $\bar{c}_{HB} = -13$
- $\bar{c}_{HW} = -2.9 \times 10^{-1}$
- $\bar{c}_{HWB} = -8.8$
6. Prospects at HL-LHC
High-Luminosity LHC (HL-LHC)

LHC / HL-LHC Plan

<table>
<thead>
<tr>
<th>LHC</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
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FP7 Hi-Lumi DESIGN STUDY

MAJOR CIVIL WORKS TECHNICAL INFRASTRUCTURE

PDR PREPARATION ASSESS & TDR MAIN ACCELERATOR COMPONENTS CONSTRUCTION AND TEST INSTALLATION PHYSICS

High-Luminosity LHC (HL-LHC)

- Coupling measurement at $O(\text{few\%})$ precision
- Higgs self-coupling measurement at $O(1)$ precision, 2nd minima excluded

\[ \sqrt{s} = 14 \text{ TeV}, 3000 \text{ fb}^{-1} \text{ per experiment} \]

**ATLAS and CMS**

**HL-LHC Projection**

**HL-LHC prospects**

\[ -2\Delta \ln(L) \]

**SM HH significance:** $4\sigma$

- $0.1 < \kappa_\lambda < 2.3$ [95% CL]
- $0.5 < \kappa_\lambda < 1.5$ [68% CL]

3 ab$^{-1}$ (14 TeV)

- Combination
- $b\bar{b}\gamma\gamma$
- $b\bar{b}\tau\tau$
- $b\bar{b}b\bar{b}$
- $b\bar{b}ZZ^*(4l)$
- $b\bar{b}VV(l\nu l\nu)$

**Expected uncertainty**

**Total**

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**Uncertainty [%]**

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**HL-LHC**

**SM HH significance:** $4\sigma$

- $0.1 < \kappa_\lambda < 2.3$ [95% CL]
- $0.5 < \kappa_\lambda < 1.5$ [68% CL]

arXiv:1902.00134
Summary:

**Higgs Boson Couplings to Bosons and Fermions**

- Higgs boson mass ($M_H$) & decay width ($\Gamma_H$)
  → $M_H$ measured at 2-3 per mille precision. No sign of BSM in $\Gamma_H$, $\text{BR}_{\text{inv}}$

- Higgs couplings to gauge bosons ($g_V$)
  → Consistent with the SM prediction ($g_V \propto m_V^2$). Next, study in $d\sigma/dX$

- Higgs couplings to fermions ($g_F$)
  → Direct observation in the 3$^{\text{rd}}$ generation ($g_F \propto m_f$). Next 2$^{\text{nd}}$ generation

- Higgs potential - Higgs self-coupling $\lambda$
  → Remains as an important territory to conquer in HL-LHC and FCC

- Spin-CP
  → CP-violation could be possible with large mixing between CP-even&odd.
Summary:

Higgs Boson Couplings to Bosons and Fermions

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  - Direct observation in the 3rd generation ($g_F \propto m_f$). Next 2nd generation

- Higgs potential - Higgs self-coupling $\lambda$
  - Remains as an important territory to conquer in HL-LHC and FCC

- Spin-CP
  - CP-violation could be possible with large mixing between CP-even&odd.

We have observed the first elementary scalar particle - Higgs boson.

- Brout-Englert-Higgs mechanism: what an incredible purely theoretical idea !!!
- Experimentalists will make every endeavor for BSM physics discovery !!
- LHC - hadron collider now in precision measurement era like LEP !
What do we know about the scalar sector 7 years after July 4th 2012 discovery?
What do we know about the scalar sector 7 years after July 4th 2012 discovery?

We know $M_H$, $\Gamma_H$, spin/CP and couplings but not much yet for direct Yukawa, Higgs potential and BSM sector!
Backup
Note on Coupling versus Mass relation

Discussions on quark mass (M. Spira)

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SMInputParameter

1. One can define quark mass for Yukawa coupling,
   \[ \bar{g}_Q(M_H), \bar{g}_Q(M_Q), g_Q^{\text{pole}} \]
2. Though above are theoretically equivalent, running mass evaluated at Higgs mass scale is better to avoid the offset due to non-universal corrections in quarks and leptons,
   \[ \Gamma(H \to Q\bar{Q}) = \bar{g}_Q^2(M_H) \frac{3M_H}{16\pi} \left\{ 1 + \frac{17}{3} \frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2) \right\} \]
   \[ m_b(m_b) = 4.16 \text{ GeV}, m_b(M_H) = 2.76 \text{ GeV} \]
3. Use pole mass for top quark (172.5 GeV).
4. Use PDG values for leptons and W/Z boson masses. The universal QED corrections for leptons are small.

\[ g_F = \sqrt{2} \frac{m_f}{v} \quad g_V = 2 \frac{m_V^2}{v} \]

\[ m_c(M_H) = 0.616 \text{ GeV}, \quad m_b(M_H) = 2.764 \text{ GeV}, \quad m_t(M_H) = 169.21 \text{ GeV} \]
Model-independent framework - HEFT

Effective Lagrangian:

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}}^{(4)} + \sum_i \frac{1}{\Lambda^{d_i-4}} c_i \mathcal{O}_i \]

where \( c_i \) is the Wilson coefficient and \( \Lambda \) is the cutoff scale.

Neglecting dimension-5 operator, consider dimension-6 (\( d_i=6 \)) basis.

Complete basis of dimension-6 consists of 59 operators for one family.

- Assuming observed Higgs is spin-0, CP-even, part of a SU(2) doublet, narrow and no overlapping resonances, SM local symmetry and global symmetry with L and B number conservation.
- With more than one family, number of operators depends on the flavor assumption.
- Projection of operators onto physical observables is basis-chosen dependent.

Capable to combine EWPD, aTGC and Higgs data with common Lagrangian.

- Discussion with LHC-EW WG (VV subgroup for aTGC).

Connection with BSM Higgs Lagrangian.

- Possible effects of heavy BSM particles encoded in higher-dimensional operators.
- Parametrization of BSM for Higgs physics: ex. 8 parameters \( \{ \kappa_g, \kappa_\gamma, \kappa_V, \kappa_t, \kappa_b, \kappa_\tau, \kappa_{Z\gamma}, \kappa_h^3 \} \).
- Assumes the scale of new physics \( \Lambda \) is heavy, i.e. there is no undiscovered low energy particle.
- Capable of dealing with off-shell effects.
What are the quantum numbers of observed state X?

J\textsuperscript{PC}: J=spin, P=parity, C=charge conjugation

Spin0: Standard Model Higgs boson
- The Standard Model Higgs boson is a scalar particle (0\textsuperscript{+}).
- CP-mixing/violation in spin-0 can exist but is small in many BSM models.

Spin1: Landau-Yang theorem
- Landau-Yang theorem forbids the direct decay of an on-shell spin-1 particle into a pair of massless particles.
- Observation of H\rightarrow\gamma\gamma rules out the possibility that the new resonance has spin 1, and fixes C=1 (barring C violating effects in the Higgs sector).
- This theorem strictly applies to an on-shell resonance (i.e. small width hypothesis).

Spin2: graviton
- Theoretically difficult. Velo-Zwanziger problem with U(1) gauge field.
- Who will be responsible for electroweak symmetry breaking?
- Why haven’t we observed analogous KK excitations of SM gauge bosons?

Studied with H\rightarrow\gamma\gamma, ZZ\textsuperscript{*} and WW\textsuperscript{*} in RUN-1 and confirmed it is 0\textsuperscript{+}. 