A DECADE TURNING THE POSSIBLE INTO THE KNOWN

André David (CERN)
On behalf of the CMS and ATLAS Collaborations
WHERE WE DISCOVERED A BOSON...
...BUT WHAT SORT OF BOSON?
5 YEARS AGO

LANDSCAPE IN 2017

A decade turning the possible into the known

A. DAVID (CERN)
5 YEARS AGO
MY EXPECTATIONS IN 2017

A decade turning the possible into the known

A. DAVID (CERN)
MUCH PROGRESS SINCE 2017

A decade turning the possible into the known

A. DAVID (CERN)
MUCH PROGRESS SINCE 2017

High-$Q^2$
MUCH PROGRESS SINCE 2017
QUANTUM NUMBERS

A decade turning the possible into the known

A. DAVID (CERN)
QUANTUM NUMBERS
A PARTICLE’S FINGERPRINT

J = Spin angular momentum,
PC = Parity-Charge conjugation, and
q = Electric charge.

Each related to a symmetry.

GAUGE AND HIGGS BOSONS

<table>
<thead>
<tr>
<th>Particle</th>
<th>J((P^C))</th>
<th>Additional Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\gamma) (photon)</td>
<td>0(1(^{-}))</td>
<td>Mass (m &lt; 1 \times 10^{-18}) eV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Charge (q &lt; 1 \times 10^{-46}) e (mixed charge)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Charge (q &lt; 1 \times 10^{-35}) e (single charge)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean life (\tau =) Stable</td>
</tr>
<tr>
<td>(g) or gluon</td>
<td>0(1(^{-}))</td>
<td>Mass (m = 0) [(a)]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SU(3) color octet</td>
</tr>
<tr>
<td>graviton</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>(W)</td>
<td>1</td>
<td>Charge = (\pm 1) e</td>
</tr>
<tr>
<td>(Z)</td>
<td>1</td>
<td>Charge = 0</td>
</tr>
<tr>
<td>(H^0)</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
ZERO ELECTRIC CHARGE

$J = \text{Spin angular momentum,}$

$PC = \text{Parity-Charge conjugation,}$

$q = 0$. Each related to a symmetry.

A decade turning the possible into the known

Candidate $H^0(125)$ event decaying into two photons.
SPIN-PARITY
FROM DI-BOSON DECAYS

Probed via angular correlations in di-boson decays (WW*, ZZ*, γγ).

Higgs decay to four charged leptons, an important channel for angular correlations.
SPIN-PARITY FROM DI-BOSON DECAYS

Probed via angular correlations in di-boson decays (WW*, ZZ*, γγ).

Many alternative spin-parity hypotheses tested.

Data invariably compatible with spin zero and even parity, as predicted by SM.
PARITY IN DI-TAU DECAYS

Higgs boson has many possible interactions.
Higgs boson has many possible interactions.

$H^0(125)$ may interact differently with tau leptons and bosons.

SM predicts same parity in both.
PARITY IN DI-TAU DECAYS

$H^0(125)$ may interact differently with tau leptons and bosons.
- SM predicts same parity for both.

Probed via **angular correlations** in $H^0(125)\rightarrow\tau\tau$ decays.
PARITY IN DI-TAU DECAYS

Tau leptons and bosons may interact differently with $H^0(125)$.
- SM predicts same parity for both.

Probed via angular correlations in $H^0(125) \rightarrow \tau\tau$ decays.

Data compatible with even parity and SM prediction.
MUCH PROGRESS SINCE 2017
RARE DECAYS

A decade turning the possible into the known

A. DAVID (CERN)
**RARE DECAYS**

Low mass particles, feeble interactions with the Higgs boson, rare decays.

MASSES OF THE PARTICLES of the Standard Model differ by at least 11 orders of magnitude and are believed to be generated by interactions with the Higgs field. At least five Higgs particles are likely to exist. Their masses are not known; possible Higgs masses are indicated.
RARE DECAYS — THE SECOND GENERATION

Low mass particles, feeble interactions with the Higgs boson, rare decays.
**HIGGS & MUONS**

Exploit all production modes.

- Candidate events compatible with different associated production modes and a $H^0(125) \rightarrow \mu\mu$ decay.

**Diagram:**

$H \rightarrow \kappa f \bar{f}$

SM predicts Higgs decays into a pair of fermions, like muons.
HIGGS & MUONS

Exploit all production modes.

- Candidate events compatible with different associated production modes and a $H^0(125) \rightarrow \mu\mu$ decay.

SM predicts Higgs decays into a pair of fermions, like muons.
Exploit all production modes.

- Candidate events compatible with different associated production modes and a $H^0(125) \rightarrow \mu\mu$ decay.

SM predicts Higgs decays into a pair of fermions, like muons.
Exploit all production modes.

Exquisitely small signal.
HIGGS & MUONS

Exploit all production modes.

Exquisitely small signal.

A new data point.

Evidence-level measurement at the LHC.
HIGGS & MUONS

Exploit all production modes.

Exquisitely small signal.

A new data point.

Evidence-level measurement at the LHC.

Mass range probed covers 3 orders of magnitude!

$35.9-137 \text{ fb}^{-1}$ (13 TeV)

$\mathbf{CMS}$ Supplementary

$m_{H} = 125.38 \text{ GeV}$

$p$-value = 44%

A decade turning the possible into the known

A. DAVID (CERN)

ATLAS: PLB 812 (2021) 135980

CMS: JHEP 01 (2021) 148
HIGGS & CHARM QUARKS

Charm quarks harder to individuate than muons.

- Exploit associated production with a vector boson.

Candidate $Z^0(\mu\mu)+H^0(cc)$ event.
HIGGS & CHARM QUARKS

Charm quarks harder to individuate than muons.

Use **advanced machine learning** techniques.

**Sensitivity to** $H \rightarrow cc < 10 \times$ SM.

- A testament to the ingenuity of experimentalists.
- Beyond my 2017 expectations!
RARE LOOPS — Z+PHOTON

New particles can contribute in quantum loops.
RARE LOOPS — Z+PHOTON

New particles can contribute in quantum loops.

Exploit different production modes to tease out small signal.
RARE LOOPS — Z+PHOTON

New particles can contribute in quantum loops.

Exploit different production modes to tease out small signal.

Both experiments seeing intriguing results.
DARK MATTER CONNECTION?

Dark Matter particles *could* have mass from Brout-Englert-Higgs mechanism.
DARK MATTER CONNECTION?

Dark Matter particles could have mass from Brout-Englert-Higgs mechanism.
DARK MATTER CONNECTION?

Dark Matter particles could have mass from Brout-Englert-Higgs mechanism.

Search for invisible Higgs decays (into DM particles).

Event selected in search for $qq+H^0$(inv.).
DARK MATTER CONNECTION?

Dark Matter particles could have mass from Brout-Englert-Higgs mechanism.

Search for invisible Higgs decays (into DM particles).
  - Exclude invisible branching fractions larger than about 10%.

Set limits on DM models.
  - Competitive limits for low mass DM candidates.

A decade turning the possible into the known
OTHER HIGGS BOSONS

SM extensions easily predict more Higgs bosons.
- SM is remarkably minimalist in this respect.
OTHER HIGGS BOSONS

SM extensions easily predict more Higgs bosons.

Vigorous effort using many signatures, excluding many low mass and high mass scalars.
OTHER HIGGS BOSONS

SM extensions easily predict more Higgs bosons.

Vigorous effort using many signatures, excluding many low mass and high mass scalars.
MUCH PROGRESS SINCE 2017
PAIRING UP!
THE SHAPE OF THE VACUUM

In the SM, the structure of the vacuum of the universe is intimately related to how the Higgs boson interacts with... itself.
THE SHAPE OF THE VACUUM

In the SM, the structure of the vacuum of the universe is intimately related to how the Higgs boson interacts with... itself.
In the SM, the structure of the vacuum of the universe is intimately related to how the Higgs boson interacts with... itself.

To probe this phenomenon we can study the production of Higgs boson pairs.
HIGGS BOSON PAIR PRODUCTION

In the SM, the structure of the vacuum of the universe is intimately related to how the Higgs boson interacts with... itself.

To probe this phenomenon we can study the production of Higgs boson pairs.

Higgs pairs are predicted to be 1000× rarer than single Higgs.
Higgs pairs are predicted to be 1000× rarer than single Higgs.

Must bring together many channels to achieve the best sensitivity.

Sensitivity better than 3× SM.

- On the way to challenge SM prediction.
HIGGS BOSON PAIRS

HH production searches allow to probe other rare interactions.

E.g., the \textbf{VVHH 4-particle interaction} seems to exist in nature.

\begin{itemize}
\item i.e., $\kappa_{2V} = 0$ excluded.
\end{itemize}
10 YEARS ON, WE’VE ONLY STARTED WITH THE $H^0(125)$

A fundamentally different kind of particle, a new player in our team probing nature.

CMS and ATLAS have steadily accrued knowledge about this Higgs boson.

- $H^0(125)$ remains compatible with SM predictions.
- Many more details in the afternoon session!

The coming decades are crucial to understand it and make use of it in exploring nature.
10 YEARS ON, WE’VE ONLY STARTED WITH THE H\(^0\)(125)

A fundamentally different kind of particle, a new player in our team probing nature.

**CMS and ATLAS have steadily accrued knowledge** about this Higgs boson.

- H\(^0\)(125) remains compatible with SM predictions.
- Many more results in the afternoon session!

The coming decades are crucial to understand it and make use of it in exploring nature.
10 YEARS ON, WE’VE ONLY STARTED WITH THE $H^0(125)$

A fundamentally different kind of particle, a new player in our team probing nature.

CMS and ATLAS have **steadily accrued knowledge** about this Higgs boson.
- $H^0(125)$ remains compatible with SM predictions.
- Many more details in the afternoon session!

The *coming decades* are crucial to understand it and make use of it in exploring nature.

---

**CMS**

<table>
<thead>
<tr>
<th>95% CL limit on $\sigma_{pp} \rightarrow H H / \sigma_{pp}$ Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$9 \rightarrow 10^2$</td>
</tr>
<tr>
<td>$1 \rightarrow 100$</td>
</tr>
</tbody>
</table>

---

**Longer term LHC schedule (2022)**

- **CMS**: Nature 607, 60 (2022)
- **SM**: Nature 607, 60 (2022)

---

A decade turning the possible into the known

---

A. DAVID (CERN)
THANK YOU!

...all who contributed to the accelerator, theory, experiments, and computing, and all supporters of science.
PARITY IN DI-TAU DECAYS

Tau leptons and bosons may interact differently with $H^0(125)$.
- SM predicts same parity for both.

Probed via angular correlations in $H^0(125) \to \tau \tau$ decays.

Data compatible with even parity and SM prediction.
HIGGS & MUONS

Exploit all production modes.

Exquisitely small signal.

**Evidence-level measurement at the LHC.**

\[
\text{SM} \Rightarrow \text{Signal strength} = \mu = 1
\]
HIGGS & CHARM QUARKS

Charm quarks harder to individuate than muons.

Use **advanced machine learning** techniques.

- Charm identification in merged jets.
- Charm jet mass regression.

Candidate $W(e\nu)+H^0(cc)$ event.
HIGGS & CHARM QUARKS

Charm quarks harder to individuate than muons.

Use **advanced machine learning** techniques.

**Sensitivity to H→cc < 10× SM.**

- A testament to the ingenuity of experimentalists.
- Beyond my 2017 expectations!

A decade turning the possible into the known

A. DAVID (CERN)
RARE LOOPS — Z+PHOTON

New particles can contribute in quantum loops.

Exploit different production modes to tease out small signal.

Both experiments seeing intriguing results.

ATLAS

<table>
<thead>
<tr>
<th>Category</th>
<th>$\mu$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF-enriched</td>
<td>$0.5^{+1.3}<em>{-1.6}$ (1.0$^{+2.0}</em>{-1.6}$)</td>
<td>0.3 (0.6)</td>
</tr>
<tr>
<td>High relative $p_T$</td>
<td>$1.6^{+1.4}<em>{-1.6}$ (1.0$^{+1.7}</em>{-1.6}$)</td>
<td>1.0 (0.6)</td>
</tr>
<tr>
<td>High $p_T$, ee</td>
<td>$4.7^{+3.0}<em>{-2.6}$ (1.0$^{+2.7}</em>{-2.6}$)</td>
<td>1.7 (0.4)</td>
</tr>
<tr>
<td>Low $p_T$, ee</td>
<td>$3.9^{+2.6}<em>{-2.5}$ (1.0$^{+2.7}</em>{-2.5}$)</td>
<td>1.5 (0.4)</td>
</tr>
<tr>
<td>High $p_T$, $\mu\mu$</td>
<td>$2.9^{+3.8}<em>{-2.8}$ (1.0$^{+2.8}</em>{-2.8}$)</td>
<td>1.0 (0.4)</td>
</tr>
<tr>
<td>Low $p_T$, $\mu\mu$</td>
<td>$0.8^{+2.6}<em>{-2.2}$ (1.0$^{+2.6}</em>{-2.2}$)</td>
<td>0.3 (0.4)</td>
</tr>
<tr>
<td>Combined</td>
<td>$2.0^{+2.0}<em>{-0.9}$ (1.0$^{+0.9}</em>{-0.9}$)</td>
<td>2.2 (1.2)</td>
</tr>
</tbody>
</table>

$\text{SM} \Rightarrow \text{Signal strength} = \mu = 1$
DARK MATTER CONNECTION?

Dark Matter particles could have mass from Brout-Englert-Higgs mechanism.

Search for invisible Higgs decays (into DM particles).

- Exclude invisible branching fractions larger than about 10%.

A decade turning the possible into the known

SM predicts $H^0(125) \rightarrow 4\nu$ invisible decay branching fraction to be $\sim 0.1\%$. 
HIGGS BOSON PAIRS

HH production searches allow to probe other rare interactions.

E.g., the **VVHH 4-particle interaction** seems to exist in nature.

- i.e., $\kappa_2V = 0$ excluded for a large range of self-interaction values, $\kappa_\lambda$. 

\[ \kappa_t = \kappa_V = 1 \]

CMS

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

- Observed
- 68% CL
- SM Higgs
- 95% CL

A decade turning the possible into the known

A. DAVID (CERN)