Disclaimers:
• Impossible to give a comprehensive lecture
• I will focus on some highlights based on personal choice (and with a strong bias towards the ATLAS experiment, in which I work).
• Some examples are inspired by Concepts of Elementary Particle Physics, Prof. M. Peskin

Assignments:
• Topical “homework” is indicated with throughout the slides
• Happy to talk more in the Q&A
Profound open questions about the Universe connected to Higgs physics

From the movie Particle Fever
Key to addressing these mysteries is the measurement of the Higgs boson properties and couplings.
RECAP: THE STANDARD MODEL

More in Bernhard’s, Marius’ and Josh’s lectures

Electromagnetic, weak, and strong interactions

Higgs-Vector Bosons interactions

Force carriers and their interactions

Higgs Yukawa couplings

Higgs energy potential

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i F D \psi + h.c. + \sum y_{ij} X_{ij} \phi + h.c. + m_{\phi}^2 \phi^2 - V(\phi) \]
THE BROUT-ENGLERT-HIGGS MECHANISM

- Due to underlying symmetry of the Standard Model, particles should be massless
  - Particles do have mass → symmetry must have been broken

- ~ 1 picosecond after the Big Bang, the BEH mechanism caused a symmetry breaking and particles acquired mass

- Universe living ever since in a state of minimum energy with Higgs field turned on, shape of its potential predicted to look like a Mexican hat
The Higgs field permeates the Universe, different particles interact with it differently and acquire mass...

The **Higgs Boson** is the quantum of the **Higgs field** and it has itself mass!
It was in 1964 when Brout, Englert and Higgs brought the concept of spontaneous symmetry breaking into particle physics from matter physics to explain how otherwise massless particle acquire mass...

“Of no obvious relevance to physics” was how an editor of Physics Letters is said to have remarked on rejecting one of Higgs’ manuscripts. The papers went from fewer than 50 citations by the turn of the decade to around 18 000 today.

https://home.cern/news/series/higgs10/higgs10-boson-born
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON (1975)

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.
THE HIGGS MASS AND DECAYS

If $m_H > 2m_W$ and $2m_Z$, its dominant decays would be to $WW$ or $ZZ$
Below this threshold, the dominant decay is to $b\bar{b}$
THE HIGGS PRODUCTION MODES

Reversing the decay processes, we get the production modes.

\[ \sqrt{s} = 7 \text{ TeV} \]
THE HIGGS PRODUCTION MODES

Reversing the decay processes, we get the production modes.

Which does gluon fusion Higgs production dominate in pp collisions?
A lesson learned from the W and Z discovery at the UA1 and UA2 experiments was that hadron colliders had great discovery potential…
THE EXPERIMENTAL JOURNEY TO DISCOVERY

1984

From one of P. Jenni’s Colloquia

1992

ATLAS & CMS LOIs

1995

We propose to build a general purpose detector designed to run at the highest luminosity at the LHC. The CMS (Compact Muon Solenoid) detector has been optimized for the search of the SM Higgs boson over a mass range from 90 GeV to 1 TeV, but it also allows detection of a wide range of possible signatures from alternative electro-weak symmetry breaking mechanisms. CMS is also well adapted for the study of top, beauty and tau physics at lower luminosities and will cover several important aspects of the heavy ion physics programme. We have chosen to identify and measure muons, photons and electrons with high precision. The energy resolution for the above particles will be better than 1% at 100 GeV. At the core of

The Standard Model (SM) Higgs search can be used as a first benchmark for the detector optimization. The search strategies and metodi are rather well known from general studies. In order to cover the full mass range above the expected discovery limit at level of about 130 GeV, one needs sensitivity to the following processes (f = a or p):

\[ f \rightarrow \gamma \gamma \text{ from WH, ZH and t\overline{t} using a } t^\pm \text{ tag, mass range } 80 < m_H < 130 \text{ GeV}; \]
\[ f \rightarrow \gamma \gamma \text{ direct production, mass range } 90 < m_H < 150 \text{ GeV}; \]
\[ H \rightarrow ZZ^{-} \rightarrow 4\ell \ell \text{, mass range } 120 \text{ GeV} < m_H < 2m_Z; \]
\[ H \rightarrow ZZ^{-} \rightarrow 4\ell \ell \text{, mass range } 2m_Z < m_H < 800 \text{ GeV}; \]
\[ H \rightarrow WW, ZZ \rightarrow f^+ f^- 2 \text{ jets, } t^\pm t^\mp 2 \text{ jets, } t^\pm t^\mp 2\nu, 4\ell \text{ from WW, ZZ fusion using tagging of forward jets for } m_H \text{ up to about } 1 \text{ TeV.} \]

The expected observable cross-sections at LHC are small both for the low (\( m_H < 2m_Z \)) and very high mass range, hence the need to operate at high luminosities. Also it is well documented that good mass resolution is important for efficient Higgs searches in the range \( m_H < 2m_Z \).

The expected observable cross-sections at LHC are small both for the low (\( m_H < 2m_Z \)) and very high mass range, hence the need to operate at high luminosities. Also it is well documented that good mass resolution is important for efficient Higgs searches in the range \( m_H < 2m_Z \).

The LHC Study Group
In the meanwhile, in 1995, the CDF and D0 experiments at the Tevatron (first colliders with beam energies at the TeV level) discovered the top quark…

You can read more [here](#).
THE HIGGS HUNT @ THE LHC

Sensitivity for all yet unexplored Higgs boson masses (in the late 1980s) called for a detector concept offering as many final state signatures as possible

It was also clear for the lower mass range that the instrumental resolution would dominate the width of the reconstructed H mass peak, and thus determine the signal/background ratio

Best channels at the LHC:
- < 130 GeV: $H \rightarrow \gamma \gamma$
- 125-180 GeV: $H \rightarrow WW^{\pm} \rightarrow l\nu \nu$
- 125-300 GeV: $H \rightarrow ZZ^{\pm} \rightarrow lll$
- 300-600 GeV: $H \rightarrow ZZ \rightarrow llvv$

Cross-section times branching ratios (left) and the natural width (right) from the Handbook of LHC Higgs cross-sections, Yellow Report CERN-2011-002 (for the LHC start-up energy)

Arguing around the mid-1980s of being ambitious and design a general-purpose detector ...

A very simplified summary:
- $\mu^\pm$ channel
- $\mu^\pm$, jets, $\ell^\pm$ channel

Lepton detection at LHC is crucial. Small rates are expected for many potential signals:
- $e^\pm$ and $\mu^\pm$
- Muons are relatively easy to identify but hard to measure well
- Precise $\mu$ measurements may mean hundreds of MeV
- Electrons are relatively easy to measure but hard to identify at $10^{34}$
- Radiation-hard inner detector
- Lepton isolation criteria are also important to reject backgrounds from heavy flavour decays

From one of P. Jenni’s Colloquia

https://indico.cern.ch/event/1135177/
# THE HIGGS HUNT @ THE LHC

From one of P. Jenni’s Colloquia

## Complementary Approaches in ATLAS and CMS

<table>
<thead>
<tr>
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<th>ATLAS</th>
<th>CMS</th>
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<tr>
<td><strong>MAGNET (S)</strong></td>
<td>Toroidal LHC ApparatuS</td>
<td>Compact Muon Solenoid</td>
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<tr>
<td>Air-core toroids + solenoid in inner cavity (4 magnets)</td>
<td>Solenoid</td>
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<td>Calorimeters in field-free region</td>
<td>Only 1 magnet</td>
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<td>Si pixels + strips</td>
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<td>TRT → particle identification</td>
<td>Calorimeters inside field</td>
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<td>$B=2T$</td>
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<tr>
<td>$\alpha/p_t \sim 3.8 \times 10^{-4} p_t \otimes 0.015$</td>
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| **TRACKER** | Si pixels + strips |
| Si pixels + strips | No particle identification |
| TRT | $B=4T$ |
| $\alpha/p_t \sim 1.5 \times 10^{-4} p_t \otimes 0.005$ | |

| **EM CALO** | Pb-liquid argon |
| Pb-liquid argon | PbWO$_4$ crystals |
| $\alpha/E \sim 10\% \sqrt{E}$ | $\alpha/E \sim 2-5\% \sqrt{E}$ |
| uniform longitudinal segmentation | no longitudinal segm. |

| **HAD CALO** | Fe-scint. + Cu-liquid argon (10 $\lambda$) |
| Fe-scint. + Cu-liquid argon (10 $\lambda$) | Cu-scint. ($> 5.8 \lambda$, +catcher) |
| $\alpha/E \sim 50\% \sqrt{E} \otimes 0.03$ | $\alpha/E \sim 100\% \sqrt{E} \otimes 0.05$ |

| **MUON** | Air → $\alpha/p_t \sim 10\%$ at 1 TeV standalone ($\sim 7\%$ combined with tracker) |
| Air → $\alpha/p_t \sim 10\%$ at 1 TeV standalone ($\sim 7\%$ combined with tracker) | Fe → $\alpha/p_t \sim 15-30\%$ at 1 TeV standalone (5% with tracker) |
b-quark-initiated jet (more on this later)
muon
electron
b-quark-initiated jet (more on this later)
tracks
Primary and secondary vertices

Run: 311071
Event: 1452867343
2016-10-21 06:34:07 CEST
Primary and secondary vertices

Hard scatter vertex

Pile-up vertices

Radial view

Longitudinal view
$p_T(\tau^1_{\text{had}}) = 292 \text{ GeV}$

$E_{\text{T}}^{\text{miss}} = 33 \text{ GeV}$

$E_{\text{T}}$
Not only detectors are designed and built to meet the physics requirements, but also all the algorithms we use have to fully exploit their capabilities → Need efficiency and precision at all steps:

**Simulated datasets**
- Generation of events
  - Monte Carlo Event Generators
- Simulation
  - Detector Description, interactions
- Reconstruction
  - Algorithm performance

**Real Datasets**
- Trigger
  - Bandwidth, efficiency
- Reconstruction
  - Algorithm performance

Use and compare simulation and data to calibrate with highest precision

Much more in Josh's lectures
LHC TIMELINE

LHC Data Collection: Integrated Luminosity over Time

- Integrated Luminosity
- Current Year (2024)

- Run 1 (7-8 TeV)
- Run 2 (13 TeV)
- Run 3 (13.6 TeV, expected)
- HL-LHC (14 TeV, expected)

Year:
- 2010
- 2015
- 2020
- 2025
- 2030
- 2035
- 2040

Integrated Luminosity (fb⁻¹):
- 0
- 500
- 1000
- 1500
- 2000
- 2500
- 3000
- 3500
THE ART OF PRECISION EXPERIMENTALLY: DATA ANALYSIS

Analysis: a scientific statement from experimentation – a number with an associated uncertainty (just like lab)

Broadly three types:

• **performance**: this algorithm works this well

• **measurements**: this (known) process looks like this

• **searches**: this new process exists or not
THE ART OF PRECISION
EXPERIMENTALLY: DATA ANALYSIS

Analysis: a scientific statement from experimentation – a number with an associated uncertainty (just like lab)

Broadly three types:

• performance: this algorithm works this well

• measurements: this (known) process looks like this

• searches: this new process exists or not

Don’t forget what statement you intend to make ➔ Analysis decisions depend on that
Analysis: a scientific statement from experimentation – a number with an associated uncertainty (just like lab)

Broadly three types:

- **performance**: this algorithm works this well
- **measurements**: this (known) process looks like this
- **searches**: this new process exists or not

Don’t forget what statement you intend to make! Analysis decisions depend on that.

Also, to fully benefit from adding more data requires to re-design an analysis.
FROM THE IDEAL TO THE REAL WORLD

WHEN ???

WELCOME TO THE REAL WORLD!

IT SUCKS.

YOU'RE GONNA LOVE IT!
FROM THE IDEAL TO THE REAL WORLD

These three analysis types are far from being disconnected, very often one is an ingredient of the other, in particular when it comes to the Higgs boson...
Search

$HH \rightarrow b\bar{b}\gamma\gamma$
Search

\[ HH \rightarrow b\bar{b}\gamma\gamma \]
Search

\( HH \to b\bar{b}\gamma\gamma \)

Measurement

\(~60\%\)

Performance
WHAT WE MEASURE AND WHAT WE CALCULATE

We don’t have direct access to the forces between elementary particles or to some of the particles themselves.
WHAT WE MEASURE AND WHAT WE CALCULATE

We don’t have direct access to the forces between elementary particles or to some of the particles themselves.

Particle physics experiments are designed to allow us to **measure** a set of quantities, for example:

- Cross-sections
- Decay rates
A FIDUCIAL VOLUME
A FIDUCIAL VOLUME
A FIDUCIAL VOLUME

**Fiducial volume:**
- The phase space in which a given final state is measurable

**E.g. typical fiducial volume:**
- Truth-level leptons with $E_T > 25$ GeV and $|\eta| < 2.5$
- Truth-level jets with $E_T > 30$ GeV and $|\eta| < 2.5$
- Truth-level $E_T^{\text{miss}} > 35$ GeV

Courtesy of A. Sfyrla
**CROSS-SECTION**

Total cross-section:

\[
\sigma = \frac{N \text{ events}}{A \times \epsilon \times L}
\]

- **Acceptance**: ratio of events of a specific process over the events of that process measurable in the experiment’s fiducial volume
- Estimated using Monte Carlo simulations

- **Integrated luminosity**

- **Efficiency**: experimental efficiency of online and offline (reconstruction) selections
- Estimated using Monte Carlo simulations and/or measurements in data

And there is more: **Differential cross-section**

Fiducial cross-section: \[\sigma \times A\]

Courtesy of A. Sfyrla
CROSS-SECTION

Total cross-section:
\[ \sigma = \frac{N \text{ events}}{A \times \epsilon \times L} \]

- **Acceptance**: ratio of events of a specific process over the events of that process measurable in the experiment’s fiducial volume
  - Estimated using Monte Carlo simulations
- **Efficiency**: experimental efficiency of online and offline (reconstruction) selections
  - Estimated using Monte Carlo simulations and/or measurements in data

Fiducial cross-section:
\[ \sigma \times A \]

How about the precision of these numbers?

And there is more: Differential cross-section

Courtesy of A. Sfyrla
ONE EXAMPLE: LUMINOSITY

Measuring the luminosity precisely is critical for every analysis at the LHC

Average number of particles produced in pp interactions proportional to the average number of pp interactions per bunch crossing → Use this average to monitor instantaneous luminosity during data-taking, and to measure the integrated luminosity over specific time periods

Luminosity sensitive detectors (e.g. LUCID-2 in ATLAS) are used for relative measures, along with trackers and calorimeters

Absolute luminosity requires special LHC beam configuration that allows detector signals to be calibrated → ~yearly Van der Meer scans

Why is it called Van der Meer scan?
ATLAS delivers most precise luminosity measurement at the LHC

Precise knowledge of luminosity is crucial for both searches for new phenomena and precision measurements of known Standard Model processes

24 JANUARY, 2023 | By ATLAS collaboration

“ATLAS physicists determined the integrated luminosity of the full Run 2 dataset that had been recorded by ATLAS and certified as good for physics analysis, to be $140.1 \pm 1.2 \text{ fb}^{-1}$. For comparison, 1 inverse femtobarn (fb$^{-1}$) corresponds to about 100 trillion proton–proton collisions. With its uncertainty of 0.83%, the result represents the most precise luminosity measurement at a hadron collider to date.”

For more info about how this was achieved Ref 1, 2
“ATLAS physicists determined the integrated luminosity of the full Run 2 dataset that had been recorded by ATLAS and certified as good for physics analysis, to be $140.1 \pm 1.2 \text{ fb}^{-1}$. For comparison, 1 inverse femtobarn (fb$^{-1}$) corresponds to about 100 trillion proton–proton collisions. With its uncertainty of 0.83%, the result represents the most precise luminosity measurement at a hadron collider to date.”

For comparison, at D0 and CDF, ~6% unc. on lumi, excellent at that time.
FEBRUARY 2012

https://tevnphwg.fnal.gov/results/SM_Higgs_Winter_12/
THE DISCOVERY OF A HIGGS BOSON


THE DISCOVERY CHANNELS IN ATLAS


$H \to ZZ^* \to 4l$

$H \to WW^* \to e\nu\mu\nu$

Best channels at the LHC:

- $< 130$ GeV: $H \to \gamma\gamma$
- 125-180 GeV: $H \to WW^* \to lvlv$
- 125-300 GeV: $H \to ZZ^* \to ll\ll$

$H \to \gamma\gamma$

$H \to WW^*$

$H \to ZZ^*$

$H \to ZZ^* \to ll\ll$

$H \to WW^* \to e\nu\mu\nu$

$H \to ZZ^* \to ll\ll$

$H \to WW^* \to e\nu\mu\nu$

$H \to ZZ^* \to ll\ll$

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$H \to ZZ^* \to ll\ll$
THE DISCOVERY CHANNELS IN ATLAS

\[ H \rightarrow Z Z^* \rightarrow 4l \]

\[ H \rightarrow \gamma\gamma \]

\[ H \rightarrow W W^* \rightarrow e\nu\nu \]

Why not in the most abundant \( H \rightarrow bb \)?
THE DISCOVERY CHANNELS IN ATLAS

\[ H \rightarrow ZZ^* \rightarrow 4l \]

\[ H \rightarrow \gamma\gamma \]

\[ H \rightarrow WW^* \rightarrow e\nu\mu\nu \]
\( H \rightarrow \gamma\gamma \) ANALYSIS IN A NUTSHELL

- Small BR
- Very clean signal extraction
  - LHC experiments designed to maximize the Higgs discovery potential in this channel
  - Energy resolution from the electromagnetic calorimeter %-level

\[
m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos \theta)}
\]
**H → γγ** ANALYSIS IN A NUTSHELL

- Small BR
- Very **clean signal extraction**
  - LHC experiments designed to maximize the Higgs discovery potential in this channel
  - Energy resolution from the electromagnetic calorimeter %

Great $m_{γγ}$ resolution

![Graph showing $m_{γγ}$ distribution with O(1%) resolution.]

As opposed e.g. to $m_{b̅b}$

![Graph showing $m_{b̅b}$ distribution with O(10%) resolution.]

And also different backgrounds
IMPORTANCE OF MASS RESOLUTION

- Search for narrow peak in invariant mass over a smoothly falling background arising from other di-photon signatures or fakes
IMPORTANCE OF MASS RESOLUTION

• Search for narrow peak in invariant mass over a smoothly falling background arising from other di-photon signatures or fakes
IMPORTANCE OF MASS RESOLUTION

- Search for narrow peak in invariant mass over a smoothly falling background arising from other di-photon signatures or fakes

Why bkg not flat?
IMPORTANCE OF MASS RESOLUTION

- Search for narrow peak in invariant mass over a smoothly falling background arising from other di-photon signatures or fakes

Why bkg not flat?
IMPORTANCE OF MASS RESOLUTION

• Search for narrow peak in invariant mass over a smoothly falling background arising from other di-photon signatures or fakes

Why bkg not flat?
IMPORTANCE OF MASS RESOLUTION

• Search for narrow peak in invariant mass over a smoothly falling background arising from other di-photon signatures or fakes

Why bkg not flat?
A Higgs boson-like particle was found!
WHAT DOES $5\sigma$ MEAN?

In a *normal distribution*, the peak is called *mean* and the data spread is measured using *standard deviation* $\sigma$.

Measured by numbers of standard deviations from the mean, *statistical significance* is how far away a certain data point lies from its expected value.

"Five sigma is considered the "gold standard" in particle physics because it guarantees an extremely low likelihood of a claim being false."

Is $5\sigma$ really enough? Read [here](#) if you want to know more
SIGNSIFICANCE AND P-VALUE

1007.1727

Figure 1: (a) Illustration of the relation between the p-value obtained from an observed value of the test statistic \( t_\mu \). (b) The standard normal distribution \( \varphi(x) = (1/\sqrt{2\pi}) \exp(-x^2/2) \) showing the relation between the significance \( Z \) and the p-value.

5 \( \sigma \) corresponds to a p-value, or probability, of \( 3 \times 10^{-7} \), or about 1 in 3.5 million.
STATISTICS OF THE DISCOVERY

Question #1:
• Is there more than only background?

\[ N = \mu \cdot s(m_H) + b \]

95% CL Limit on signal strength

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

The upper limit on \( \mu \) at a confidence level \( CL = 1 - \alpha \) is the value of \( \mu \) for which the p-value is \( p_{\mu} = \alpha \)
Question #1:
- Is there more than only background?

\[ N = \mu \cdot s(m_H) + b \]

95% CL Limit on signal strength

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

The upper limit on \( \mu \) at a confidence level \( CL = 1 - \alpha \) is the value of \( \mu \) for which the p-value is \( p_\mu = \alpha \)

Answer #1:
- YES!
Question #2:
- How likely is it that the background can produce a statistical fluctuation greater than what we observe?
Question #2:
• How likely is it that the background can produce a statistical fluctuation $\geq$ than what we observe?

Answer #2:
• Very unlikely!
STATISTICS OF THE DISCOVERY

Question #3:
• What is the strength of the signal?

Profile likelihood ratio

\[
\lambda(\mu) = \frac{L(\mu, \hat{\theta})}{L(\hat{\mu}, \hat{\theta})}.
\]
Question #3:

- What is the strength of the signal?

Profile likelihood ratio

\[
\lambda(\mu) = \frac{L(\mu, \hat{\theta})}{L(\hat{\mu}, \theta)}.
\]

Answer #3:

- \(1.4 \pm 0.3\)
Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC

CMS Collaboration

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

ABSTRACT

Results are presented from searches for the standard model Higgs boson in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of 5.3, 14, 19.5, and 5.0 fb$^{-1}$ at 7 TeV and 4.1 fb$^{-1}$ at 8 TeV. The search is performed in two decay modes: $H \rightarrow \gamma\gamma$, $H \rightarrow WW^{(*)}$, and $H \rightarrow ZZ^{(*)}$. The search is sensitive to a standard model Higgs boson of mass 125 GeV, with a 95% confidence level lower limit of 120 GeV.

ATLAS Collaboration

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

ABSTRACT

A search for the Standard Model Higgs boson in proton-proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb$^{-1}$ collected at $\sqrt{s} = 7$ TeV in 2011 and 5.0 fb$^{-1}$ at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \rightarrow Z\gamma \rightarrow 4\ell$, $H \rightarrow Z\gamma \rightarrow 2 \ell$ and $H \rightarrow Zh \rightarrow 2 \ell$ in the 8 TeV data are combined with previously published results of searches for $H \rightarrow ZZ^{(*)}$, $H \rightarrow WW^{(*)}$, and $H \rightarrow H \rightarrow \gamma\gamma$ in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 125.0 ± 0.4 (stat) ± 0.6 (syst) GeV is presented. This observation, which has a significance of 5.0 standard deviations, corresponding to a background fluctuation probability of $1.7 \times 10^{-5}$, is compatible with the production and decay of the Standard Model Higgs boson.
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider."

It is the first example we’ve seen of the simplest possible type of elementary particle. It has no spin, no charge, only mass, and this extreme simplicity makes it theoretically perplexing.

_Nima Arkani Hamed_
AND NOW?

Precise measurements achieved for xs that differ by several orders of magnitude!
AND NOW?

Assume $140 \text{ fb}^{-1}$ and calculate number of Higgs boson produced per production mode

Measured Higgs mass

- $57\%$
- $22\%$
- $8\%$
- $6\%$
- $3\%$
- $3\%$
- $0.2\%$
- $0.2\%$
- $0.02\%$

LHC HIGGS XS WG 2016

V.M.M.CAIRO
MEASURING XS AND BR

Main production/decays measured within ~10-20%
MEASURING DIFFERENTIAL XS

- High energy tails of kinematic observables enhance experimental sensitivity to SM deviations
- Differential & precise measurements are key

More about Effective Field Theories in I. Brivio’s lecture
WHAT CAN WE LEARN ABOUT THE THEORY WHEN WE MEASURE CROSS-SECTIONS AND DECAYS?
IN THE LAST 10 YEARS, WE STUDIED THE HIGGS BOSON MASS, WIDTH, SPIN AND MANY OF ITS COUPLINGS...
Characterising the Higgs boson with ATLAS data from Run 2 of the LHC

The ATLAS Collaboration

The Higgs boson was discovered by the ATLAS and CMS Collaborations in 2012 using data from Run 1 of the Large Hadron Collider (2010–2012). In Run 2 (2015–2018), about 140 fb^{-1} of proton-proton collisions at a centre-of-mass energy of 13 TeV were collected by the ATLAS experiment. This review presents the most important Run 2 results obtained by the ATLAS Collaboration regarding the properties of the Higgs boson and its interactions with other particles. The performed studies significantly enhance the understanding of the Higgs boson, while hunting for deviations from the predictions of the Standard Model of particle physics.
HIGGS MASS

Not predicted by SM, must be determined experimentally, interactions with other particles depend on it

- Use high resolution channels ($\gamma\gamma$, 4 leptons), fit decay product mass to extract position of the peak

Most precise single measurement of the mass to date per single channel:

$$m_H = 125.08 \pm 0.12 \text{ GeV} = 125.08 \pm 0.10 \text{(stat.)} \pm 0.07 \text{(syst.)} \text{ GeV}$$

Most precise measurement of the Higgs boson mass, reaching a 0.09% precision on this fundamental quantity.
HIGGS MASS

Not predicted by SM, must be determined experimentally, interactions with other particles depend on it

- Use high resolution channels ($\gamma\gamma$, 4leptons), fit decay product mass to extract position of the peak

Z-boson often used for calibration in H results

Most precise single measurement of the mass to date per single channel:

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$$m_{\gamma\gamma} = \sqrt{(2E_1E_2(1 - \cos \theta))}$$
WHAT’S THE ENERGY OF THE PHOTONS?

The $H \rightarrow \gamma \gamma$ mass analysis uses several categories according to the photon resolution.
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The $H \rightarrow \gamma\gamma$ mass analysis uses several categories according to the photon resolution.

“[…]dramatic improvements to the calibration of the photon energy response – reducing the systematic uncertainties by nearly a factor of four.” Ref1, Ref2
WHAT’S THE ENERGY OF THE PHOTONS?

The $H \rightarrow \gamma\gamma$ mass analysis uses several categories according to the photon resolution:

<table>
<thead>
<tr>
<th>Source</th>
<th>Impact [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon energy scale</td>
<td>83</td>
</tr>
<tr>
<td>$Z \rightarrow e^+e^-$ calibration</td>
<td>59</td>
</tr>
<tr>
<td>$E_T$-dependent electron energy scale</td>
<td>44</td>
</tr>
<tr>
<td>$e^\pm \rightarrow \gamma$ extrapolation</td>
<td>30</td>
</tr>
<tr>
<td>Conversion modelling</td>
<td>24</td>
</tr>
</tbody>
</table>

Linearity: how accurately the detector’s response to photons is proportional to their true energy.

Detector non-uniformities, electronic effects, shower development, etc affect linearity.

“[…] dramatic improvements to the calibration of the photon energy response – reducing the systematic uncertainties by nearly a factor of four.” Ref1, Ref2
A NARROW PARTICLE

Breit-Wigner Distribution of Selected Standard Model Particles

Zoomed-in Higgs Boson Breit-Wigner Distribution with Experimental Mass Resolution

125.11 ± 0.11 (± 0.09) GeV

V.M.M.CAIRO
How long do these particles live?
For a mass of 125 GeV, the SM predicts a very narrow width of 4.1 MeV for the Higgs boson.

Best resolution channels have O(0.1-1 GeV) mass resolution.

Best direct constraints from such channels give upper limits of 330 MeV at 95% CL [Ref].

Powerful approach from indirect measurements → off-shell vs on-shell Higgs production

- Assuming that no new particles enter the production of the virtual Higgs boson.

\[
\sigma_{\text{on-shell}}^{gg \rightarrow H \rightarrow ZZ} \sim \frac{g_{ggF}^2 g_{HZZ}^2}{m_H \Gamma_H}
\]

\[
\sigma_{\text{off-shell}}^{gg \rightarrow H \rightarrow ZZ} \sim \frac{g_{ggF}^2 g_{HZZ}^2}{m_{ZZ}^2}
\]
HIGGS WIDTH

$2304.01532$
Multiplying the measured $\Gamma_H/\Gamma_H^{SM}$ by the width of the SM Higgs boson, the measured $\Gamma_H$ is $4.5^{+3.3}_{-2.5}$ MeV.
Multiplying the measured $\Gamma_H/\Gamma_H^{SM}$ by the width of the SM Higgs boson, the measured $\Gamma_H$ is $4.5^{+3.3}_{-2.5}$ MeV.
HIGGS COUPLINGS

- According to the SM, interaction rate of the Higgs boson with a particle related to the particle’s mass
  - Testing it vital for understanding the mechanism of mass generation and probing for new physics phenomena
  - Measuring these interaction rates is challenging, particularly with quarks
HIGGS COUPLINGS

Modifiers which scale the Higgs boson couplings, both fermion and boson
Similar for Higgs boson width, i.e. accounting for decays

E.g. for ggF: \( \sigma(ggF \rightarrow H) = \kappa_t^2 \sigma_{tt} + \kappa_b^2 \sigma_{bb} + \kappa_t \kappa_b \sigma_{tb} \)

And so \( \kappa_j \) for \( j=g \):

\[ \kappa_g^2 = \frac{\sigma(ggF \rightarrow H)}{\sigma_{SM}} = \frac{\kappa_t^2 \sigma_{tt} + \kappa_b^2 \sigma_{bb} + \kappa_t \kappa_b \sigma_{tb}}{\sigma_{tt} + \sigma_{bb} + \sigma_{tb}} \]

\[ \approx 1.06 \kappa_t^2 + 0.01 \kappa_b^2 - 0.07 \kappa_t \kappa_b \]

And for photon decays:

\[ \kappa_\gamma^2 = \frac{\Gamma_{\gamma \gamma}}{\Gamma_{SM}} = \frac{\kappa_t^2 \Gamma_{tt}^\gamma + \kappa_b^2 \Gamma_W^\gamma + \kappa_t \kappa_b \Gamma_{WW}^\gamma}{\Gamma_{tt}^\gamma + \Gamma_W^\gamma + \Gamma_{WW}^\gamma} \]

\[ \approx 0.07 \kappa_t^2 + 1.59 \kappa_W^2 - 0.66 \kappa_t \kappa_W \]
Inspired by L. Gouskos and N. Hartman’s talks

$H \rightarrow bb$, which has the largest branching ratio in this mass range. Due to the huge backgrounds from QCD jet production in this decay mode, only the associated production modes have sensitivity. It has been demonstrated that the discovery potential for a Standard Model Higgs boson in the $WH$ production mode at the LHC is marginal.\cite{68,97,98} It is limited by large backgrounds from $Wb\bar{b}$, $Wq\bar{q}$, and $tt$ production. For small integrated luminosities, the extraction of a signal appears to be very difficult, even under the most optimistic assumptions for $b$-tagging performance and calibration of the shape and magnitude of the various backgrounds from data itself. If backgrounds are well
WHAT IS A $b$-QUARK JET?
WHAT IS A $b$-QUARK JET?

Similar for a $c$-quark jet, but with shorter lifetimes $\rightarrow$ more challenging
Long lifetime of B-hadrons requires selecting tracks with large IPs → large selection windows around the longitudinal IP → more pile-up contamination that can lead to fake secondary vertices.
THE HEAVY FLAVOUR CHALLENGE

• Requires both advanced detectors and algorithms!
• Detector developments and AI applications hand-in-hand

Fake rate improved by ~2 orders of magnitude since the Tevatron! Ref 1, 2
New results from ATLAS exploit “resolved and boosted” b/c-tagging

https://atlas.cern/Updates/Briefing/Higgs-beauty-charm
13 fiducial regions!
Results:
- \( WH \) and \( ZH \) production with \( H \to b\bar{b} \)
established with observed (expected) 5.3 (5.5) and 4.9 (5.7) \( \sigma \)
- \( H \to c\bar{c} \) decay yields an observed (expected) upper limit of 11.3 (10.4) \( x \) SM
- \( |\kappa_c| < 4.2 \) at the 95% CL
- Confirmed at 99.7% CL charm coupling weaker than bottom coupling
HOW ABOUT THE OTHER COUPLINGS?

So far, the SM rules, but the exploration has just begun…
HOW ABOUT THE OTHER COUPLINGS?

How does the Higgs boson couple to itself?
THE HIGGS POTENTIAL AND SELF-COUPLING

\[ \mathcal{L} = -\frac{1}{4} F_{\mu \nu} F^{\mu \nu} + i \bar{\psi} D \psi + h.c. + y_1 y_2 \phi + h.c. + m^2 \phi^2 - V(\phi) \]

\[ V(\phi^* \phi) = \mu^2 \phi^* \phi + \lambda(\phi^* \phi)^2 \]

An alternative potential

Standard Model potential

Higgs field value in our Universe

Current experimental knowledge

Nature 607, pages 41-47 (2022), G.Salam et al.
MATTER OF STABILITY

J. Ellis, The Higgs and the fate of the universe

\[ V[H] \]

JHEP08(2012)098

J. Ellis, The Higgs and the fate of the universe
Known $m_H$ ($\sim 125$ GeV), SM predicts $\lambda$ ($\sim 0.13$)
Known $m_H \sim 125 \text{ GeV}$, SM predicts $\lambda \sim 0.13$

New physics can alter these numbers $\rightarrow$ Implications on the origin, evolution and stability of the Universe $\rightarrow$ Probing the Higgs-self coupling is a key goal for LHC and HL-LHC!
THE HIGGS SELF-COUPLING

$\lambda_{HHH}$ can be measured in two complementary ways

- **di-Higgs**
  - $g \gamma \gamma \rightarrow H H$
  - $g g \rightarrow H H$

- **Single-Higgs**
  - $q \gamma \rightarrow H$
  - $q q \rightarrow H$

proton - (anti)proton cross sections

$\sigma (\text{nb})$ vs $\sqrt{s}$ (TeV)

- Tevatron
- LHC

$\sigma_{HH}(E_{T}^{mH} > 100 \text{ GeV})$
$\sigma_{HH_{p}}$
$\sigma_{HH_{p}}$
$\sigma_{HH_{p}}$
$\sigma_{HH_{p}}$
$\sigma_{HH_{p}}$
$\sigma_{HH_{p}}$
$\sigma_{HH_{p}}$
$\sigma_{HH_{p}}$
$\sigma_{HH_{p}}$

W.J. Stirling, private communication
HH PRODUCTION AT THE LHC

Non-resonant $\sigma_{HH}^{ggF} = 31.05$ fb at 13 TeV for $m_H = 125.00$ GeV
HH PRODUCTION AT THE LHC

Non-resonant $\sigma_{HH}^{ggF} = 31.05$ fb at 13 TeV for $m_H = 125.00$ GeV

Softer spectrum for large $\kappa_\lambda$ values
HH PRODUCTION AT THE LHC

\[ \sqrt{s} = 13 \text{ TeV} \]
\[ HH \rightarrow b\bar{b}\gamma\gamma \ 	ext{ggF} \]

**Key experimental handle**

- \( \kappa_\lambda = -6 \) for **Only box**
- \( \kappa_\lambda = 0 \) for **SM**
- \( \kappa_\lambda = 1 \) for **Close to max int.**
- \( \kappa_\lambda = 2 \) for **Mainly triangle**
- \( \kappa_\lambda = 10 \) for **Mainly triangle**

**Softer spectrum for large \( \kappa_\lambda \) values**
TWICE THE HIGGS, TWICE THE CHALLENGE

Extremely rare process, 1000 times rarer than producing a single Higgs boson!

Need to combine multiple signatures of Higgs boson decays to increase sensitivity
$HH \rightarrow b\bar{b}g\gamma\gamma$

$HH \rightarrow b\bar{b}\tau\tau$

$HH \rightarrow b\bar{b}b\bar{b}$
~60% of the times

\[ HH \rightarrow b\bar{b}b\bar{b} \]

\[ HH \rightarrow b\bar{b}γγ \]

\[ HH \rightarrow b\bar{b}ττ \]
PUTTING EVERYTHING TOGETHER

**ATLAS**

$\sqrt{s} = 13$ TeV, 126—140 fb$^{-1}$

$\sigma_{99\% + VBF}^{SM}(HH) = 32.8$ fb

<table>
<thead>
<tr>
<th>Obs.</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>17</td>
<td>11</td>
</tr>
<tr>
<td>5.3</td>
<td>8.1</td>
</tr>
<tr>
<td>4.0</td>
<td>5.0</td>
</tr>
<tr>
<td>5.9</td>
<td>3.3</td>
</tr>
<tr>
<td>2.9</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Similar from CMS

1 SM prediction

Increasing sensitivity to SM
From HH cross-section to Higgs self-coupling constraints

Observed (expected): $-1.2 < k_\lambda < 7.2$ (-1.6 < $k_\lambda$ < 7.2)

Similar from CMS

G. Salam
• Draw the shape of the Higgs potential given its SM description

• How does it change for different values of the Higgs self-coupling?
• Add the uncertainty bands given the current experimental results
• What do you observe for the minimum value?
• What are the implications on the Higgs mass?
PUTTING EVERYTHING TOGETHER

From HH cross-section to VVHH coupling constraints

$\kappa_{2V} = 0$ is excluded, with a significance of 6.6 $\sigma$

Similar from ATLAS
HOW MAY HH LOOK IN HL-LHC?

<table>
<thead>
<tr>
<th>Uncertainty scenario</th>
<th>Significance [σ]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( b\bar{b}\gamma \gamma )</td>
</tr>
<tr>
<td>No syst. unc.</td>
<td>2.3</td>
</tr>
<tr>
<td>Baseline</td>
<td>2.2</td>
</tr>
</tbody>
</table>

\[ 0.5 \lesssim k_\lambda \lesssim 1.6 \text{ at } 1\sigma \]

\( \sqrt{s} = 14 \text{ TeV}, 3000 \text{ fb}^{-1} \)
Non-resonant HH
Baseline
Asimov data (\( k_\lambda = 1 \))
- \( b\bar{b}\tau^+\tau^- \)
- \( b\bar{b}\gamma\gamma \)
- \( b\bar{b}b\bar{b} \)
- Combined

\( V(\phi), 2040 \text{ (HL-LHC)} \)

universe lives here
Standard Model potential
what we may know in 2040

\( \lambda_\chi = \text{SM} \)
IMPLICATIONS ON THE HIGGS POTENTIAL

As an example: arXiv:1907.02078v2
IMPLICATIONS ON THE HIGGS POTENTIAL

As an example: arXiv:1907.02078v2
“We’ve scratched the surface,” said Peter Higgs in 2019. “But we have clearly much more to discover.”

https://home.cern/news/series/higgs10/higgs10-boson-born
THE HIGGS BOSON RE-DISCOVERY!

https://atlas.cern/Updates/Briefing/Run3-Higgs
• $pp$: high energy $\rightarrow$ ideal for HH (Higgs self-coupling)

• $e^+e^-$: clean environment, initial states well defined $\rightarrow$ ideal for precision measurements and for probing light Yukawas (more in S. Eno’s lecture)
Are the Yukawa couplings **universal** between families?
A strange AND EXCITING RESEARCH LINE

Next step in detector technologies, algorithms and analysis!

Cutting edge detectors for high momentum PID

Complex and extensive jet flavour identification, including specific light flavours

Probing rare Higgs decays to strange quarks… SM or BSM?
CONCLUSIONS

• Interplay between detector design, algorithm performance, measurements and searches is of paramount importance to probe Higgs physics with precision at the LHC and beyond

• 10+ years after its discovery, the Higgs boson remains a fascinating particle for the role it plays in our understanding of the Universe and for the properties that are still to measure

• **Exciting science ahead** to solve some of the yet-to-be answered questions in Particle Physics
  • E.g. **ordinary matter composed by electron and light quarks**
  • *none of the Higgs boson couplings to such particles has been verified yet!*
Thanks for your attention!

Collisions That Changed The World

Valentina Maria Martina Cairo
Looking forward to the poster session!
EXTRA SLIDES

F. Cairo, From Conn(ll)ecting the dots
COLLIDER PHYSICS: CHALLENGES AND BREAKTHROUGHS

The Higgs boson (and more!) and the silicon pixel era

The top quark and the silicon strip era

The W,Z bosons and the drift chamber era

The weak neutral currents and the bubble chamber era
ATLAS DETECTOR AND PHYSICS PERFORMANCE

Technical Design Report

Volume II

https://cds.cern.ch/record/391177
Figure 19-30: Sensitivity for the discovery of a Standard Model Higgs boson in the intermediate mass range. The statistical significances are plotted for individual channels as well as for the combination of all channels, assuming integrated luminosities of 30 fb$^{-1}$ (left) and 100 fb$^{-1}$ (right). Depending on the numbers of signal and background events, the statistical significance has been computed as $S/\sqrt{B}$ or using Poisson statistics. In the case of the $H \rightarrow WW^{*} \rightarrow 4\nu$ channel, a systematic uncertainty of $\pm 5\%$ on the total number of background events has been included (see Section 19.2.6).
**P-P INTERACTION TERMINOLOGY**

- Interacting **protons as “bags” of partons** (quarks and gluons)
- Parton flavour and momentum described by **Parton Distribution Functions** (PDFs)
- QCD does not predict the parton content of the proton → shapes of the PDFs determined by a fit to data from experimental observables in various processes
- **Cross sections** calculated by convoluting the parton level cross section with the PDFs
- **Hard scatter** (HS) described by perturbative QCD (Matrix element)
- HS partons evolve into collimated particle systems (jets)
- Spectator partons interact in a non-perturbative regime and fragment in detectable hadrons (underlying event)
- **Initial and final state gluon radiation** (alike Bremsstrahlung) to complicate the picture further

---

hadron-hadron collision as simulated by a Monte Carlo event generator for a $ttH$ event (by F.Krauss)
DIFFERENTIAL X-SECTIONS AND UNFOLDING

**Differential cross-section:**
- Cross-section $\sigma_{\text{diff}}(x_r)$ calculated in bins of a specific (reconstructed) variable $x_r$
- “Unfolded” to estimate the generator-level behavior $\sigma_{\text{diff}}^{\text{unf}}(x_t)$ as a function of the (truth) variable $x_t$

\[ \sigma_{\text{diff}}(x_r) \rightarrow \sigma_{\text{diff}}^{\text{unf}}(x_t) \]

**A simpler image:**
- Using MC, derive a map that links MC reco to MC truth
- Use that map to go from reco to “truth” in Data
- Unfolded measurements can be directly compared to theory!

**In reality:**
- A very complicated topic…

Courtesy of A. Sfyrla
**b-JET TAGGING**

**ATLAS Simulation Preliminary**

- $\sqrt{s} = 13$ TeV, $t\bar{t}$
- Light-flavour jet tracks
- $c$-jet tracks
- $b$-jet tracks

- $s_{d0} = d_0/\sigma_{d0}$

- $s_{z0} = z_0\sin\theta/\sigma_{z0}\sin\theta$
b-JET TAGGING

**ATLAS Simulation Preliminary**

\[ \sqrt{s} = 14 \text{ TeV}, \ (\mu) = 200 \]

\[ t\bar{t}, \ 20 < p_T < 250 \text{ GeV} \]
Photon reconstruction: dynamic, topological cell clustering-based approach

- Recovers brem effects (electrons radiating photons due to material interactions)
- For photons that convert to electron-positron pairs, superclusters can include more of the energy of the primary photon.
  - Photons can produce multiple topo-clusters, which can then be merged into one supercluster. The use of fixed-size clusters is suboptimal in this scenario, as the fixed cluster size cannot properly accommodate the growth of two independent EM showers, particularly when the two clusters share cells.
- The reconstruction algorithm matches tracks to the electron superclusters and conversion vertices to the photon superclusters.
- **Electron** = object consisting of a cluster built in the calorimeter (supercluster) and a matched track (or tracks)
- **Converted photon** = calorimeter cluster matched to a conversion vertex (or vertices)
- **Unconverted photon** = cluster matched to neither an electron track nor a conversion vertex.

About 20% of photons at low $|\eta|$ convert in the ID, and up to about 65% convert at $|\eta| \approx 2.3$. 

https://iopscience.iop.org/article/10.1088/1748-0221/14/12/P12006/pdf
PHOTONS

https://iopscience.iop.org/article/10.1088/1748-0221/14/12/P12006/pdf
• Based on the lateral and longitudinal energy profiles of the shower measured in the calorimeter
• Rectangular cuts are imposed on discriminating variables describes the energy fraction released in the hadronic calorimeter and photon’s shower shapes in the EM calorimeter.
• *loose* PID: uses shower shapes in the hadronic calorimeter and the EM calorimeter’s second layer, providing a highly efficient selection with quite fair background rejection.
• *tight* PID: uses the full granularity of the EM calorimeter, including the fine segmentation of the first sampling layer, and applies tighter requirements on the shower shapes.
A NARROW PARTICLE

Decay Width of Selected Standard Model Particles

- Z Boson
- W Boson
- Top Quark
- Higgs Boson

Decay Width (MeV)
The invariant mass resolution \( \sigma \) for C-type events is 10%–20% worse than for U-type events, due to asymmetric \( \gamma \rightarrow e^+e^- \) conversions producing a low-energy electron or positron, and to bremsstrahlung photons emitted by the \( e^+e^- \) pair.

energy of the original photon. The resolution is 6%–20% better in the central-barrel categories than in the corresponding outer-barrel categories, due to the smaller amount of material upstream of the electromagnetic calorimeter in the central region of the detector.

Better resolution for high p\( T \) photons
HIGGS MASS

https://arxiv.org/pdf/2308.07216

scattering, has a softer $p_{Tt}^{\gamma\gamma}$ spectrum than the signal. The photon energy scale uncertainty is smaller for C-type events and central-barrel events than for U-type events and outer-barrel or endcap events; it increases with $p_{Tt}^{\gamma\gamma}$ due to uncertainties in the linearity of the response and in the extrapolation to photons in the energy scale calibration, which is mainly determined using electron and positron candidates with relatively low transverse momentum from $Z \to e^+e^-$ decays.
HIGGS MASS

https://arxiv.org/pdf/2308.07216

ATLAS Simulation

√s = 13 TeV
H → γγ, m_H = 125 GeV

1/N dN/dm_{γγ} / 0.5 GeV

m_{γγ} [GeV]
nuisance parameters in the likelihood function, fully correlated among the categories. The 67 independent sources of uncertainty in the photon energy scale can be classified roughly into four main groups. The first group ($Z \rightarrow e^+e^-$ calibration) is related to the determination of the $\eta$-dependent energy scale factors for electrons and positrons from $Z$ boson decays, effectively constraining their energy scale for a transverse energy $E_T \approx 45$ GeV. The second group ($E_T$-dependent electron energy scale) includes uncertainties in the $E_T$-dependence of the energy scale from sources such as the calorimeter readout non-linearity, the calorimeter layer intercalibration, and the amount of material upstream of the calorimeter. The third group ($e^\pm \rightarrow \gamma$ extrapolation) includes the uncertainties in the extrapolation of the energy scale from electrons to photons, arising, for instance, from potential mismodelling of differences in lateral shower development between electrons and photons in the calorimeter. Finally, the fourth group (conversion modelling) contains the uncertainties related to the accuracy of the photon conversion modelling in the simulation. Since the simulation-based photon energy calibration [14] is trained and applied separately for unconverted and converted photon candidates, any mismodelling of the conversion reconstruction performance in the simulation may affect the calibrated photon energy scale.
WHAT’S THE ENERGY OF THE PHOTONS?

“[…]dramatic improvements to the calibration of the photon energy response – reducing the systematic uncertainties by nearly a factor of four.” Ref1, Ref2

<table>
<thead>
<tr>
<th>Category</th>
<th>(\sigma_{90}^{\gamma\gamma}[\text{GeV}])</th>
<th>(S_{90})</th>
<th>(B_{90})</th>
<th>(f_{90}) [%]</th>
<th>(Z_{90})</th>
</tr>
</thead>
<tbody>
<tr>
<td>U, Central-barrel, high (p_{T\gamma})</td>
<td>1.88</td>
<td>42</td>
<td>65</td>
<td>39.1</td>
<td>4.7</td>
</tr>
<tr>
<td>U, Central-barrel, medium (p_{T\gamma})</td>
<td>2.34</td>
<td>102</td>
<td>559</td>
<td>15.4</td>
<td>4.2</td>
</tr>
<tr>
<td>U, Central-barrel, low (p_{T\gamma})</td>
<td>2.63</td>
<td>837</td>
<td>13226</td>
<td>6.0</td>
<td>7.2</td>
</tr>
<tr>
<td>U, Outer-barrel, high (p_{T\gamma})</td>
<td>2.16</td>
<td>31</td>
<td>83</td>
<td>27.4</td>
<td>3.3</td>
</tr>
<tr>
<td>U, Outer-barrel, medium (p_{T\gamma})</td>
<td>2.63</td>
<td>108</td>
<td>981</td>
<td>9.9</td>
<td>3.4</td>
</tr>
<tr>
<td>U, Outer-barrel, low (p_{T\gamma})</td>
<td>3.00</td>
<td>869</td>
<td>22919</td>
<td>3.7</td>
<td>5.7</td>
</tr>
<tr>
<td>U, Endcap</td>
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WHAT’S THE ENERGY OF THE PHOTONS?

“[…]dramatic improvements to the calibration of the photon energy response – **reducing the systematic uncertainties by nearly a factor of four.**” [Ref1, Ref2]

<table>
<thead>
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<th>Source</th>
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<td>Photon energy scale</td>
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<tr>
<td>( Z \to e^+ e^- ) calibration</td>
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<tr>
<td>( E_T )-dependent electron energy scale</td>
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<td>( e^\pm \to \gamma ) extrapolation</td>
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<td>Conversion modelling</td>
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<td>Signal–background interference</td>
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<td>Resolution</td>
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<td>Background model</td>
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<td>Selection of the diphoton production vertex</td>
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<td>Signal model</td>
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<td><strong>Total</strong></td>
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WHAT’S THE ENERGY OF THE PHOTONS?

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<table>
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<tr>
<th>C-type (&gt;0 $\gamma_{\text{conv}}$)</th>
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<td>low $p_{T_1}$</td>
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<tr>
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<td>medium $p_{T_1}$</td>
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</tr>
<tr>
<td>low $p_{T_1}$</td>
<td>low $p_{T_1}$</td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing the distribution of photon energies in different barrel and endcap segments](image-url)
WHAT’S THE ENERGY OF THE PHOTONS?

The $H \rightarrow \gamma \gamma$ mass analysis uses several categories according to the photon resolution.

Linearity: how accurately the detector’s response to photons is proportional to their true energy.

Detector non-uniformities, electronic effects, shower development, etc affect linearity.

“[...] dramatic improvements to the calibration of the photon energy response – reducing the systematic uncertainties by nearly a factor of four.” Ref1, Ref2
WHAT’S THE ENERGY OF THE PHOTONS?

“[...]dramatic improvements to the calibration of the photon energy response – reducing the systematic uncertainties by nearly a factor of four.” Ref1, Ref2
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Source | Impact [MeV]
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Conversion modelling | 24
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“[…]dramatic improvements to the calibration of the photon energy response – reducing the systematic uncertainties by nearly a factor of four.” Ref1, Ref2

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Detector non-uniformities, electronic effects, shower development, etc affect linearity.
BOTTOM & CHARM
YUKAWA COUPLINGS

ATLAS CONF-2024-010/
BOTTOM & CHARM YUKAWA COUPLINGS
F. Di Bello’s talk at ICHEP

Simultaneous extraction of VH(bb/cc). Sensitivities:

1. WH(bb): 5.3 (5.5) obs (exp) ; ZH(bb): 4.9 (5.7) std. dev., VH(bb) around 15% precision

2. VH(cc) limits at 95% CL is 11.2 (10.4), strongest observed limit to date

\[ \rho_{VH}^{bb} = 0.91^{+0.16}_{-0.14} = 0.91 \pm 0.10 \text{ (stat.)}^{+0.12}_{-0.11} \text{ (syst.)} \]

\[ \rho_{VH}^{cc} = 1.0^{+5.4}_{-5.2} = 1.0^{+4.0}_{-3.9} \text{ (stat.)}^{+3.6}_{-3.5} \text{ (syst.)} \]
CROSS-SECTION MEASUREMENTS

Standard Model Total Production Cross Section Measurements

ATLAS Preliminary
\( \sqrt{s} = 7,8,13 \text{ TeV} \)

- Theory
  - LHC pp \( \sqrt{s} = 13 \text{ TeV} \)
    - Data 3.2 - 139 fb\(^{-1}\)
  - LHC pp \( \sqrt{s} = 8 \text{ TeV} \)
    - Data 20.2 - 20.3 fb\(^{-1}\)
  - LHC pp \( \sqrt{s} = 7 \text{ TeV} \)
    - Data 4.5 - 4.6 fb\(^{-1}\)

Ref
PROTON-PROTON INTERACTIONS

For e+e−, see Sarah’s lecture
protons = “bags” of partons (quarks and gluons) whose flavour and momentum are described by Parton Distribution Functions (PDFs)

Hard scatter (HS) described by perturbative QCD (Matrix element)

Spectator partons interact in a non-perturbative QCD regime

Cross sections calculated by convoluting the parton level cross section with the PDFs
At central rapidity $y=0$ and $M \sim m_Z \Rightarrow x \sim 10^{-3}$

Figure 1: MSTW 2008 NLO PDFs at $Q^2 = 10$ GeV$^2$ and $Q^2 = 10^4$ GeV$^2$.

THE HIGGS PRODUCTION MODES

Reversing the decay processes, we get the production modes.

Then an obvious production mode would be $b\bar{b} \rightarrow H$, but is this the case at the LHC?

No, it is not! Because the cross-section of a process is the convolution of the parton level cross section with the Parton Density Function (PDF)
• The $b$-quark PDF in the proton is very small! (see back-up if you are curious)

The most abundant $H$ production mode at the LHC is instead gluon-gluon fusion. The intrinsic strength of the interaction is smaller, but the initial gluons can be taken from the very large gluon pdf in the proton.
• Most abundant processes at the LHC arise from QCD
PROTON-PROTON INTERACTIONS

• Most abundant processes at the LHC arise from QCD

Hard QCD events constitute only a tiny fraction of the total cross-section, which is then dominated by soft events (peripheral processes). In fact, the total production cross-section is orders of magnitude larger than very abundant hard QCD processes such as the production of b-quarks.

V.M.M.CAIRO
The restriction of the strong force to subatomic distances is related to two features called asymptotic freedom and confinement.

- Asymptotic freedom: A phenomenon where the running coupling constant decreases as the energy scale increases, indicating that the force becomes weaker at high energies.
- Confinement: A property of QCD where the strong force is only effective at short distances, and quarks are confined within hadrons and cannot be directly observed.

Diagram:

- **Running coupling constant** $\alpha_s(Q^2)$
- **QCD $\alpha_s(M_Z) = 0.1181 \pm 0.0011$**
- **Soft processes** $\rightarrow$ soft QCD
- **Hard processes** $\rightarrow$ perturbative QCD
The restriction of the strong force to subatomic distances is related to two features called asymptotic freedom and confinement.

![Graph showing running coupling constant vs. Q^2](image)

The strong coupling is the least precisely measured of the fundamental couplings of nature.
HIGGS TO PHOTONS

One-loop diagrams of the W-boson loop contribution in the Higgs boson decay into two photons. Crossed diagrams are not shown. Curved, wiggled, dashed, dashed with arrows and dotted lines correspond to the photon, W-boson, Higgs scalar, Goldstone bosons and the Faddeev–Popov ghosts, respectively. arXiv:1804.04852
GLOBAL FITS

- Tevatron $\sin^2(\theta^L_{\text{eff}})$
- Tevatron $M_W$
- ATLAS $M_W$
- LEP $M_W$
- LEP $A_{FB}^{0,b}$
- LEP $A_l$
- SLD $A_l$
- SM fit w/o $M_H$
- LHC average

For $M_H$ [GeV]:
- Tevatron $\sin^2(\theta^L_{\text{eff}})$: $0.2 \pm 0.12$
- Tevatron $M_W$: $107_{-64}^{+143}$
- ATLAS $M_W$: $66_{-32}^{+44}$
- LEP $M_W$: $92_{-42}^{+62}$
- LEP $A_{FB}^{0,b}$: $82_{-53}^{+94}$
- LEP $A_l$: $463_{-88}^{+530}$
- SLD $A_l$: $132_{-88}^{+235}$
- SM fit w/o $M_H$: $35_{-23}^{+41}$
- LHC average: $90_{-18}^{+21}$
- $M_H$: $125.1 \pm 0.2$
**SM Higgs spin and CP properties**

- SM Higgs has spin 0 and positive (even) parity ($J^P = 0^{++}$)
- At the end of Run 1 we knew Higgs had spin 0…
  - Spin 1 and 2 hypotheses excluded at > 99.9% CL using $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^*$ and $H \rightarrow WW^*$

---

**Example:**

- $j=2$ model exclusions with $H \rightarrow ZZ$

---

**$\cos \theta^* = \frac{\sinh(\eta_{\gamma\gamma} - \eta_{\gamma\gamma})}{\sqrt{1 + (p_{T\gamma}^2 / m_{\gamma\gamma}^2)^2}} \cdot \frac{2p_T^\gamma p_T^{\gamma\gamma}}{m_{\gamma\gamma}^2}$**

$\gamma\gamma$ polar angle $\theta^*$ with respect to Z-axis in Collins-Soper frame.
SPIN & CP

Delmastro_2022-07-04_Higgs10_MassWidthCP

- Spin 0 already measured at Run 1
  - Spin 1 and 2 hypotheses excluded at > 99.9% CL

- CP structure of various Higgs couplings probed for fermions (top, $\tau$), gluons, EW vector bosons, with a variety of production and decay modes
  - Measurement globally in accord with SM CP-even hypothesis
  - Pure CP-odd $ttH$ coupling excluded 3.9 $\sigma$
  - Pure CP-odd $H\tau\tau$ coupling excluded 3.4 $\sigma$

... some analyses still need to be finalized with full Run 2 dataset, and Run 3 is coming!
CP TESTS IN $H \rightarrow \tau\tau$

- CMS full Run 2 analysis dedicated to studying anomalous couplings in ggF, VBF and VH $H \rightarrow \tau\tau$
  - Combined with $H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$
  - Measure effective cross-section ratios (reduce uncertainties)

\[ A(H_{ff}) = \frac{m_t}{v} \bar{\psi}_t (\kappa_t + i \kappa_t \gamma_5) \psi_t, \]

\[ f_{CP}^{H_{ff}} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2 + |\tilde{\kappa}_f|^2} \text{sgn} \left( \frac{\tilde{\kappa}_f}{\kappa_f} \right) \]

\[ A(H_{VV}) = \frac{1}{v} \left[ \frac{\kappa_{VV}^1}{(\Lambda_{V1}^V)^2} \right] m_{V1} e_{V1} e_{V2} \]

\[ f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_{j=1,2,3} |a_j|^2 \sigma_j} \text{sgn} \left( \frac{a_i}{a_1} \right) \]

Courtesy D. Valsecchi
CP TESTS IN $H \rightarrow \tau\tau$

- Access CP-violating effects using reconstructed $H \rightarrow \tau\tau$ events
  - correlation of $H$ and two quark jets or leptons in VBF and VH production (anomalous HVV)
  - correlation of $H$ and two quark jets in $ggH$ production (anomalous $H_{gg}$)
- Use a matrix element likelihood approach (MELA) and neural networks
  - Build optimal discriminants, e.g. $D_{gF}^{gg}$ ($J^P = 0^-$ is the BSM hypothesis)
**OFFSHELL** $H \rightarrow ZZ$ IN SMEFT

- Breaks $c_g - c_t$ degeneracy present in inclusive on-shell measurements
- High invariant mass (TeV level), $ZZ \rightarrow 4l$ and $ZZ \rightarrow 2l2\nu$ final states, with $l = e$ or $\mu$

**Diagram:**

1. **k-framework**
2. **SMEFT**

**ATLAS Preliminary**

- $H \rightarrow ZZ \rightarrow 4l + 2l2\nu$
- 13 TeV, 139 fb$^{-1}$
- Linear only
- $\Lambda = 1$ TeV

See also CMS’s Higgs width analysis, setting constraints on anomalous HVV couplings
The likelihood function is the product of Poisson probabilities for all bins:

\[
L(\mu, \theta) = \prod_{j=1}^{N} \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)} \prod_{k=1}^{M} \frac{u_k^{m_k}}{m_k!} e^{-u_k}.
\]

To test a hypothesized value of \( \mu \) we consider the profile likelihood ratio

\[
\lambda(\mu) = \frac{L(\mu, \hat{\theta})}{L(\hat{\mu}, \hat{\theta})}.
\]

Here \( \hat{\theta} \) in the numerator denotes the value of \( \theta \) that maximizes \( L \) for the specified \( \mu \), i.e., it is the conditional maximum-likelihood (ML) estimator of \( \theta \) (and thus is a function of \( \mu \)).

The denominator is the maximized (unconditional) likelihood function, i.e., \( \hat{\mu} \) and \( \hat{\theta} \) are their ML estimators. The presence of the nuisance parameters broadens the profile likelihood as a function of \( \mu \) relative to what one would have if their values were fixed. This reflects the loss of information about \( \mu \) due to the systematic uncertainties.
HH PRODUCTION AT THE LHC

Non-resonant $\sigma_{ggF}^{HH} = 31.05 \text{ fb at } 13 \text{ TeV for } m_H = 125.00 \text{ GeV}$

Non-resonant $\sigma_{VBF}^{HH} = 1.73 \text{ fb at } 13 \text{ TeV for } m_H = 125.00 \text{ GeV}$
HH PRODUCTION AT THE LHC

V.M.M. CAIRO

Courtesy of L. Cadamuro
**HH→bbγγ ANALYSIS IN A NUTSHELL**

- **Object selection**
  - Small BR, but fully reconstructible final state, no combinatoric issues, clean signal extraction

- **Event categorization**
  - Event categorization

- **Modeling of discriminant variable**
  - MVA approach, 4 categories

- **Simultaneous likelihood fit to all categories**
  - Di-Higgs Single Higgs (from MC)
  - γγ + jets (from data)

- **SM σ limits and σ vs k_λ**

---

V.M.M.CAIRO 176
STATISTICAL ANALYSIS

- Maximum likelihood fit of $m_{\gamma\gamma}$ in $105 \text{ GeV} < m_{\gamma\gamma} < 160 \text{ GeV}$, performed simultaneously over all categories

\[
\mathcal{L} = \prod_c \left( \text{Pois}(n_c | N_c(\theta)) \cdot \prod_i^{n_c} f_c(m_{\gamma\gamma}, \theta) \cdot G(\theta) \right)
\]

**Expected #events**

\[
N_c(\theta) = \mu \cdot N_{HH,c}(\theta_{HH})^\text{yield} + N_{bkg,c}(\theta_{bkg})^\text{res} + N_{SS,c} \cdot \theta_{SS,c} + N_{non-res,c}
\]

**PDF**

\[
f_c(m_{\gamma\gamma}, \theta) = [\mu \cdot N_{HH,c}(\theta_{HH})^\text{yield} \cdot f_{HH,c}(m_{\gamma\gamma}, \theta_{HH})^\text{shape} + N_{bkg,c}(\theta_{bkg})^\text{res} \cdot f_{bkg,c}(m_{\gamma\gamma}, \theta_{bkg})^\text{shape} + N_{SS,c} \cdot \theta_{SS,c}^\text{shape} + N_{non-res,c}(m_{\gamma\gamma}, \theta_{non-res})^\text{shape}]
\]

Single Higgs yields fixed to SM values, while $\mu$, non-resonant background shape and nuisance parameters for sys. floating in fit
HOW ABOUT $\lambda$?

HH events

Theory

Full Run 2

$\lambda$

SM
AN EXCITING TIME AHEAD!

Increasing sensitivity to SM

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<th>HH events</th>
<th>Theory</th>
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V.M.M.CAIRO
Run 3 data will take us very close to “seeing” HH if as predicted by the SM, but need to improve analyses' strategies to get to a statistically significant evidence of HH (in combination with CMS)…

Will we confirm the SM or find new physics?

Increasing sensitivity to SM
PUTTING EVERYTHING TOGETHER

\[ H + HH \]
IMPROVEMENTS
• **Probing $\lambda$: high priority** for particle physics both at the LHC and beyond
• **di-Higgs** require advanced reconstruction techniques & detector technologies
  • Benchmark for the **future HEP machines and driver for their detector design**!

\[50\] \[40\] \[30\] \[20\] \[10\] \[0\]

*HL-LHC* (*), ILC500, CLIC3000, FCC-ee, FCC-hh, $\mu$10TeV

(*) HL-LHC yet to be updated based on the numbers shown in the previous slides!

Snowmass 2021: The Case for Precision Higgs Physics

Run 3: 100% precision?