Standard Model and New Physics in the Higgs Sector: The New Precision Era
Hints of where the Higgs could be existed from precision physics

In 2012, the Higgs was found in 2 decay channels, $H \to ZZ$ and $H \to \gamma\gamma$
What is the cosmological context of the Higgs?

- Cosmological history
- Inflation
- Dark matter
- Matter/anti-matter asymmetry

→ Precision Higgs physics has enormous potential to solve some cosmologically relevant questions
The Legacy of Run 1

- About 40 papers submitted by ATLAS on the full Run 1 dataset on Higgs physics

To understand what we can do with Run 2 data, I will focus on three key aspects of the Run 1 results:

1. The mass measurement
2. The measurement of its branching ratios
3. New physics searches in the Higgs sector
The ATLAS Detector

- High precision silicon and micro-tube tracking
- Fine-granularity/longitudinally segmented calorimeter
- Air-core toroid muon spectrometer
The ATLAS calorimeters

• Read-out in several segments along shower development
• Fine position resolution in electromagnetic calorimeter
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Measuring $m_H$: experimental challenges

- Mass measurement comes from $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$ (e or $\mu$) measurements
  - $H \rightarrow ZZ \rightarrow 4\ell$ has virtually no backgrounds
  - $H \rightarrow \gamma\gamma$ has smooth background

- Electron, photon and muon energy scale and resolution determination (0.1-0.5% for electron scale systematic uncertainties!)
Dominant uncertainties all related to electron/photon reconstruction $\approx 50\text{--}100$ MeV

- Higgs mass determined to 0.2% accuracy and statistically dominated!
The value of $m_H$: implications

- At high scales ($\sim 10^9$ TeV), Higgs potential changes sign, our universe is in a local minimum, but hasn’t had time to tunnel into the true minimum.

- Metastability challenged by inflationary cosmology.

- Hints of new physics (but not enough for TeV-scale new physics).
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Branching Ratios: what couples to the Higgs

initial state (i) → H → final state (f)

What we measure

\[ \mu_i^f \equiv \frac{\sigma_i \cdot BR^f}{(\sigma_i \cdot BR^f)_{SM}} \]
Measuring branching ratios: $H \rightarrow bb$

1. Kinematic discriminant built using machine learning

![Graph showing kinematic discriminant](image-url)

**ATLAS**

$\sqrt{s} = 8$ TeV $\int L dt = 20.3$ fb$^{-1}$

1 lep., 2 jets, 2 Medium+Tight tags

$p_T < 120$ GeV

Data/Pred

$Higgss \times 60$


\[\]
1. Kinematic discriminant built using machine learning
2. Many analysis regions (38) to fit different background normalizations and shapes
3. Final results from a likelihood fit, including theoretical and experimental systematic uncertainties

ATLAS measurement
\[ \mu = 0.52 \pm 0.32 \text{(stat.)} \pm 0.24 \text{(syst.)} \]
Branching Ratios: what couples to the Higgs

Assume no invisible Higgs decays and only SM physics in loops

Consistent with SM Higgs couplings to bosons and fermions
Can we see new physics in Branching Ratios?

- Depending on how we interpret our measurements, there are certain tantalizing deviations, which will be clarified by Run 2 measurements.
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Searching for New Particles in the Higgs Sector

- Composite Higgs

- Electroweak baryogenesis (matter/antimatter asymmetry)

- Dark matter (invisible decays)

- Supersymmetry
  - Good dark matter candidate
  - Potential for baryogenesis
  - Solves the hierarchy problem
  - Very many parameters to tweak
  - Very well studied

- …
2 Higgs doublet models necessary for a variety of new physics models

- 2 Higgs doublets: $H_1$ and $H_2$
- Both can acquire a vev: $\tan \beta = \frac{v_2}{v_1}$
- 4 new degrees of freedom, 4 more Higgs particles: $H^0, A^0, H^\pm$, heavier than discovered particle, $h^0$

- Complementary information from new particle searches and coupling measurements
What we know from Run I

- A Higgs boson has been found that looks very similar to the SM Higgs boson with $m_H=125$ GeV

- Spin-0 (spin-2 ruled out at 99.9% CL), CP-even (arXiv:1411.3441,1503.03643)

- Mass points to a metastable vacuum, which might be unstable with current understanding of inflation, which implies new physics (but not necessarily at TeV scale)

- Experimentally, couplings are determined indirectly to bosons and 3rd generation fermions and mostly consistent with SM expectations

- Coupling measurements are capable of constraining new physics, but not yet with precision

- No other new physics obvious
What we can do with Run 2 data

- Factor of 5 luminosity (expect about 30 fb-1 by the end of 2016)

- Large increase in production cross sections of interesting processes
Preparing for Run 2 Data: the Detector

- New detector complementing the pixel detector
- Upgraded trigger to cope with 100 kHz rate at level-1 (including changes in calorimeter reconstruction)
Detector Changes and Hadronic Final States

- Improvements in capabilities to identify b-jets due to IBL
- Changes on the calorimeter manageable: small systematic uncertainties right from the start
Higher energy implies more Ws/Zs/tops and Higgs boson with high $p_T$ (reconstructed as one jet)
Preparing for Run 2 Data: New Tools

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Preparing for Run 2 Data: New Tools

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Run 2 Data 2016 and 2017

Run 1 → End of 2016 → End of Run 2

Z' SSM (3 TeV):

- stat. increase x 10
- stat. increase x 3

Cross section ratios: 13/8 TeV

- Searches for exotic particles important early on
- Complex analyses and those limited statistically in Run 1 most important in 2017 and 2018
What we can do with Run 2 data

- We will be able to see the $H \rightarrow bb$ with high significance.

- We may also observe the direct coupling of the Higgs and the top.

- Both measurements will require:
  - Maintaining high precision reached in Run 1 in hadronic physics.
  - Clever use of new techniques (boosted regime).
Measuring $H \to bb$: Run 2 Improvements

- $p_T^H=67 \text{ GeV}$
- $p_T^H=140 \text{ GeV}$
- $p_T^H=360 \text{ GeV}$

- Early $H \to bb$ tagger developed and systematic uncertainties established
Measuring $H \rightarrow bb$: Run 2 Improvements

Looking at both large and small jets provide insight into emergent properties of jets

That insight can be used to exploit differences between signal and backgrounds

$p_T^H = 140$ GeV
H → bb Measurement and 2HDM Implications

- H → bb coupling has large constraining power over SUSY

- But also the same final state can be used to look for new Higgs bosons with high reach!
Boosting the Higgs Sector: $A \rightarrow tt$

- Capable of strong constraints on minimal SUSY using just Higgs searches

- Analyses using new boosted techniques (tops) important for high-mass searches
5-10% measurements can be obtained in all accessible decays and couplings

Better than Higgs factories (ILC), in certain cases

High precision, in case no new physics was found, could point in the direction for where to look
Pile-up: an old enemy
Pile-up: an old enemy

- Pile-up already depositing about 15 GeV of energy in our jets in Run 2
- Tracking provides us with powerful handles for pile-up rejection
- In HL-LHC we expect 10 times as much pile-up as in Run 2!! (effectively as much energy as in heavy ion collisions at the LHC)
Hardware solutions for high pile-up
Hardware solutions for high pile-up

- New forward tracker critical for pile-up rejection in the forward region

- Very important for all analyses with neutrinos in final state and forward jets (ttH, vector boson fusion Higgs...)

Yale NPA Seminar, January 27th 2016

D. Lopez Mateos (Harvard)
Event reconstruction for high pile-up

- Improvements in calorimeter reconstruction also needed

- Particle-level techniques exist, but not clear that they work at the detector level
Conclusions

- The consequences of the Higgs discovery (and its properties) are still resonating across the theoretical community.

- The Higgs mass was the first instance of Higgs precision physics, but much more is to come during Run 2.

- Hadronic final states stand to make huge progress in Run 2, due to the increased statistics, which will allow for $5\sigma$ observations, and exploiting new techniques.

- Nice complementarity exists between coupling measurements and new physics searches, and this still needs to be studied in detail for hadronic final states of the Higgs.

- The HL-LHC will provide precision measurements that even some Higgs factories will be unable to repeat, but with a new detector to build a lot of challenges remain ahead.