Experimental Outlook for Run 3 and the HL-LHC

Elizabeth Brost, on behalf of the ATLAS and CMS collaborations
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Higgs@10 Symposium - CERN, Geneva, Switzerland
The LHC schedule, from the ATLAS and CMS perspective

Run 1

- $\sqrt{s} = 7.8$ TeV
- $\langle \mu \rangle = 20$

Run 2

- $\sqrt{s} = 13$ TeV
- $\langle \mu \rangle = 30$

Run 3

- $\sqrt{s} = 13.6$ TeV
- $\langle \mu \rangle = 60$

Run 4-6

- $\sqrt{s} = 14$ TeV
- $\langle \mu \rangle = 140-200$

Phase 1 upgrades

Phase 2 upgrades
LHC proton-proton dataset

Run 1
Run 2
Run 3
Run 4
...

2010 2015 2022 2029

Run 3: ~10% of total dataset collected
Run 2: ~5% of total dataset collected

Total HL-LHC dataset (3000 fb$^{-1}$)

Start of HL-LHC operations

Higgs discovery

lhc-commissioning.web.cern.ch
10 years later, what are we planning?

A detailed exploration of the mechanism of electroweak symmetry breaking through the properties of the Higgs boson, including:

- Couplings to other SM particles, mass, and width
- Rare decays
- HH cross section and trilinear self-coupling
- Connections to new physics through Higgs sector?

Cross sections from the LHC Higgs Working Group
Larger center-of-mass energy = larger Higgs cross sections

Minimum bias
- Minimum bias
- VH
- ggF, VBF H

SM Higgs
- HH
- ttH
- tttt

SM 4-top quark
- tttt

Beyond the SM
- Z' (5 TeV)

proton-proton cross section ratio (compare to 13 TeV)

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Challenge: Pileup

High pileup environment at the HL-LHC brings new challenges: detector irradiation, higher detector occupancy, higher trigger rates
Experiment Upgrades for the HL-LHC

The harsh conditions at the HL-LHC will challenge the experiments in all areas, and will require improvements to:

- Detectors themselves
- Trigger menu and hardware
- Event reconstruction
- Software & computing
- Physics analysis techniques
Upgraded Trigger and Data Acquisition system:
- L0 rate: 1 MHz
- Event Filter: 10 kHz

Upgraded electronics:
- Liquid Argon Calorimeter, Tile Calorimeter, Muon system

NEW all-silicon Inner Tracker, coverage up to |η| = 4.0

Improved muon coverage and trigger

NEW endcap high granularity timing detector
CMS Detector Upgrade

Upgraded Trigger and Data Acquisition system:
- Add tracks at L1 (1 MHz)
- High Level Trigger output 7.5 kHz

NEW High-granularity calorimeter endcap

NEW Inner Tracker, coverage up to |η| = 4, reduced material

Electronics upgrade: barrel calorimeters and muon system

Extended muon coverage to |η| ~ 2.8

NEW MIP timing detector with 30 - 50 ps time resolution
Recent efforts for HL-LHC projections

- **European Strategy Update** *(2018-2020)*
  - “The European Strategy for Particle Physics provides a clear prioritisation of European ambitions in advancing the science of particle physics. It takes into account the worldwide particle physics landscape and developments in related fields”

- **Snowmass Community Planning Exercise** *(2020-2022)*
  - “The Particle Physics Community Planning Exercise (a.k.a. “Snowmass”) … provides an opportunity for the entire particle physics community to come together to identify and document a scientific vision for the future of particle physics in the U.S. and its international partners.”

→ ATLAS and CMS produced many new HL-LHC projections for Snowmass this year, and I will focus on these results today
How HL-LHC projections are made

● **Start from:**
  ○ published LHC Run 2 results, or
  ○ simulations (usually using a simplified detector simulation such as DELPHES)

● **Adapt to HL-LHC conditions:**
  ○ center-of-mass energy: 13 TeV → 14 TeV
  ○ pileup: 30 → 200
  ○ larger dataset: 150 fb$^{-1}$ → 3000 fb$^{-1}$
  ○ simulated detector and reconstruction performance
  ○ theory and experimental uncertainties: usually present a few scenarios

● **We already see the effect of advancements in analysis techniques since the last round of projections!**
Systematic Uncertainties

- **Baseline scenario:**
  - detector and trigger performance comparable to Run 2
  - most experimental uncertainties scaled down with $\sqrt{\mathcal{L}}$
  - theoretical uncertainties halved with respect to current values
  - 1% luminosity uncertainty
  - used in these studies, unless otherwise specified

- Studied improvements to object reconstruction and the impact of detector upgrades, using simulation
The Higgs boson at the HL-LHC

- **Higgs couplings move into precision regime**
  - those not dominated by statistical uncertainty will be known at few-% level
  - most dominated by theory uncertainties

- **More difficult to access at the HL-LHC:**
  - Higgs coupling to charm, invisible
  - Higgs self-coupling
Higgs coupling to charm, bottom

Use VH production mode to probe $H(bb)$ and $H(cc)$ couplings

Observation of Higgs coupling to charm will be difficult to achieve at the HL-LHC - new analysis techniques, such as the use of multivariate techniques and jet substructure variables, are making great progress in the right direction
Higgs coupling to muons

- $H \rightarrow \mu\mu$ projection based on the CMS Run 2 $3\sigma$ evidence analysis
- Estimate increases in signal and background yields due to new detectors
  - larger muon $\eta$ acceptance
  - use DELPHES simulation
- Improvement over previous projection: $\sim 30\%$
Searches for Higgs → invisible

The SM Higgs branching ratio to invisible is below current O(10%) experimental limits:
\[ \text{BR}(H \rightarrow ZZ \rightarrow 4\nu) \sim 0.1\% \]

Higgs → invisible searches rely on the MET trigger - significantly more difficult with more pileup

- CMS search for H → dark matter in VBF events:
  \[ \text{BR}(H \rightarrow \text{invisible}) < 3.8\%, \text{ for MET} > 190 \text{ GeV} \]

→ ATLAS+CMS VBF+VH combination gives
\[ \text{BR}(H \rightarrow \text{invisible}) < 2.5\% \]

CERN-2019-007
Higgs pair production is rare at the LHC…

…1000x more rare than single Higgs production. HH searches are stats-limited.

We’ve already seen a factor of ~1.7 improvement due to improved reconstruction and analysis techniques in full Run 2 dataset (compared to simple projection based on $\sqrt{\mathcal{L}}$).

SM expectation within reach for Run 3 limits if we:

- Continue the same pace of analysis improvements, or
- Combine ATLAS+CMS results
HH projections for the HL-LHC

European Strategy (2018)
- Combination of 5 HH channels, many based on partial Run 2 analysis strategy
- 50% precision on self-coupling
- 4σ SM HH significance (ATLAS+CMS)

Snowmass update (2022)
- ATLAS γγbb+bτbτ combination: 3.2σ
- CMS updated γγbb results, added γγWW, γγττ, ttHH(bbbb)
- 5σ SM HH significance from back-of-the-envelope combination

ATLAS Preliminary
\[ \sqrt{s} = 14 \text{ TeV}, 3000 \text{ fb}^{-1} \]
HH → b\bar{b}τ^+τ^- + bbγγ
Projection from Run 2 data
Asimov data (κ_λ = 1)
- No syst. unc.
- Baseline
- Theoretical unc. halved
- Run 2 syst. unc.

ATL-PHYS-PUB-2022-005

CERN-2019-007

ATLAS and CMS HL-LHC prospects

3 ab^{-1} (14 TeV)

SM HH significance: 4σ
- 0.1 < κ_λ < 2.3 [95% CL]
- 0.5 < κ_λ < 1.5 [68% CL]

- Combination
- b\bar{b}γγ
- b\bar{b}ττ
- bbb\bar{b}
- bZZ*(4l)
- b\bar{b}VV(h\bar{h})
Conclusions and Outlook

- **ATLAS and CMS detector upgrades will maintain or improve upon current performance**
  - Phase 1 upgrades already being exercised as Run 3 begins

- **HL-LHC will bring new challenges**

- **Hard work and creativity in reconstruction and analysis techniques already evident since last round of projections**
  - Imagine what we can do in the next twenty years!

A simulated HL-LHC event in the ATLAS Inner Tracker, with 40 signal muons plus pileup of 140.
BACKUP