Run 2 proton physics run just ended marking the conclusion of an extremely successful data taking period.

Over 150 fb$^{-1}$ of 13TeV pp collisions recorded for analysis (36fb$^{-1}$/80fb$^{-1}$ analysed so far)

Enormous success of the LHC program in the amount and quality of measurements performed way beyond expectations

Standard Model working impeccably, but we know many questions still unanswered

Latest big results of 2018: Observation of Higgs coupling to third generation quarks H$\rightarrow$bb
HL-LHC PLAN

LHC

Run 1 | Run 2 | Run 3
---|---|---
7 TeV | 13-14 TeV | 14 TeV
2011 | 2013 | 2021
2012 | 2014 | 2015
2015 | 2016 | 2017
2018 | 2020 | 2021
2022 | 2023 | 2024
2025 | 2026 | 2027

LS1
splice consolidation button collimators R2E project
nominal luminosity
30 fb⁻¹
Run 2: Design $\mathcal{L} = 10^{34} / \text{cm}^2 / \text{s}$

EYETS
14 TeV
2018
150 fb⁻¹
Run 3: $\mathcal{L} = 2 \times 10^{34} / \text{cm}^2 / \text{s}$ for 300/fb

LS2
Injector upgrade cryo Point 4 Civil Eng. P1-P5
nominal luminosity
5 to 7 x nominal luminosity
2 x nominal luminosity

LS3
HL-LHC Installation
experiment upgrade phase 2
2024 | 2025 | 2026 | 2027

Upgrade of injector chain to deliver brighter bunches

New interaction region layout and crab cavity

HL-LHC: Peak $\mathcal{L} = 2 \times 10^{35} / \text{cm}^2 / \text{s}$

Level luminosity to
Nominal scenario: $\mathcal{L} = 5 \times 10^{34} / \text{cm}^2 / \text{s}$ for 3000/fb; Pile-up $\langle \mu \rangle = 140$
Ultimate Scenario: $\mathcal{L} = 7.5 \times 10^{34} / \text{cm}^2 / \text{s}$ for 4000/fb; Pile-up $\langle \mu \rangle = 200$
$\Rightarrow$ 25% increase in integrated lum.
SWARMS OF PARTICLES AND HIGH RADIATION

- High luminosity → 200 soft pp interactions per crossing
  - Increased combinatorial complexity, rate of fake tracks, spurious energy in calorimeters, increased data volume to be read out in each event
- Detector elements and electronics are exposed to high radiation dose
  - Requires new tracker, endcap calorimeters, forward muons, replacing readout systems

Goal of ATLAS and CMS detector upgrades
- to achieve same performance at 200PU as in Run2 with ~40PU (or better)
- For precision measurements and observations of very rare processes, we need to at least maintain current performance for all physics objects. Requires excellence in every corner
- associating particles with primary hard scatter collision with high efficiency
- increase detector acceptance
- Increased spatial granularity to resolve signals from individual particles
- Precise timing measurements to provide an additional dimension for discrimination

Roughly reaching limits of current techniques in several systems
The physics potential of HL-LHC

Editors:
W1 organizers: P. Azzi, S. Farry, P. Nason, A. Tricoli, and D. Zappeph
W2 organizers: M. Capua, S. Gori, P. Illar, M. Kado, and F. Riva
W3 organizers: X. Cot-Ridral, M. D’Onofrio, P.J. Fox, R. Tonelli, and K. Ulmer
W4 organizers: A. Cari, V.V. Gligorov, S. Mazzocchi, J. Martin Camalich, and J. Zupan

Contributing authors: see Addendum

ABSTRACT
This document presents the executive summary of the findings of the Workshop on “The physics of HL-LHC, and perspectives on HE-LHC”, which has run for over a year since its kickoff meeting on 30 October – 1 November 2017. We discuss here the HL-LHC physics programme. As approved today, this covers 14 fb⁻¹ at 13 TeV and an integrated luminosity of 3 ab⁻¹ reach for ATLAS and CMS and 50 fb⁻¹ for LHCb, and (a) Pb-Pb and (b) p-Pb collisions with integrated luminosities of 10 fb⁻¹ and 50 fb⁻¹, respectively. In view of possible further upgrades of LHCb and of the 13 TeV programme, the WGs report assume a 30 fb⁻¹ of luminosity delivered to an Upgrade of LHCb, 1.2 fb⁻¹ of integrated luminosity for p-Pb collisions, and the addition of collisions with other nuclear species. A separate summary covers the physics. The activity has been carried out by the working groups (WGs): “Standard Model” (W1), “Higgs” (W2), “Beyond the Standard Model” (W3), “Flavour” (W4) and “QCD matter at high density” (W5). Their reports, extending this executive summary with more results and details, are available on the CERN Document Server [4], [5], and will appear on arXiv. The WGs report include both phenomenological studies and detailed simulations of the anticipated performance of the LHC detectors under HL-LHC conditions. These latter studies implement the knowledge acquired during the preparation of the technical design reports for the upgraded detectors, and reflect the experience gained by the experiments during the first two runs of the LHC.

The documents describing in full detail the 14 TeV studies performed by the experiments can be found in Ref. [4] [5] (available in early 2018) and Ref. [5].

The three goals set for the Workshop: (1) to update and extend the projections for the precision and reach of the HL-LHC measurements, and for their interpretation, (2) to highlight new opportunities for discovery of phenomena beyond the Standard Model (BSM), in view of the latest theoretical developments and of recent data, (3) to explore possible new directions and/or extensions of the approved HL-LHC programme, particularly in the flavour area, in search for elusive BSM phenomena, and in the study of QCD matter at high density. In addition to enriching and complementing the physics class of HL-LHC, and highlighting the significant advances that the full HL-LHC programme will bring relative to today’s landscape, this contribution to the European Strategy for Particle Physics Update process is intended to help put in perspective the physics potential of future projects beyond HL-LHC.

References

BSM - CERN-LPCC-2018-05

SM & TOP - CERN-LPCC-2018-03

Higgs - CERN-LPCC-2018-04

Flavor - CERN-LPCC-2018-06

Heavy Ions - CERN-LPCC-2018-07

The physics potential of HE-LHC

Editors:
W1 organizers: P. Azzi, S. Farry, P. Nason, A. Tricoli, and D. Zappeph
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Contributing authors: see Addendum

ABSTRACT
This document summarizes the physics potential of the High-Energy LHC (HE-LHC), under consideration as a possible future project at CERN. The HE-LHC is a 27 TeV pp collider, to be installed in the LHC tunnel, relying on the 17 TeV magnet technology being developed for LHC Phase-1 (P1) and the future CERN Future Circular Collider (FCC). The HE-LHC is designed to deliver 10⁻¹⁵ asb⁻¹ of integrated luminosity to two general purpose detectors, during 50 years of operation. As for the LHC, the facility could host a dedicated interaction point focused on flavour physics, delivering 30 fb⁻¹ of integrated luminosity to an upgraded LHC detector, and would continue the programme of heavy-ion collisions. The results presented here were obtained in the context of the physics of HL-LHC, and perspectives on HE-LHC, which ran for over a year since its kickoff meeting on 30 October – 1 November 2017. These studies complemented these focused on the engineering and technological aspects of the project, performed in the context of the FCC conceptual design report (CDR) for the HE-LHC, and documented elsewhere [4]. The activity has been carried out by the working groups (WGs): “Standard Model” (W1), “Higgs” (W2), “Beyond the Standard Model” (W3), “Flavour” (W4) and “QCD matter at high density” (W5). The reports from the WGs, extending this executive summary with much more detail and many more results, are available on the CERN Document Server [5], and will appear on arXiv. The documents describing in full detail the HE-LHC and HE-LHC studies performed by the ATLAS and CMS Collaborations can be found in Ref. [7] (available in early 2019).

References
The large HL-LHC dataset will enable accurate measurements and unprecedented sensitivity to very rare phenomena.

In several analyses, systematic uncertainties will become a limiting factor.

Several sources of systematics to consider:

- Detector driven
- Data statistics in control regions
- Theory normalization and modeling
- Luminosity
- Method uncertainties
- MC statistics

Synergy of ATLAS and CMS in many physics projections and complexity of the problem required development of a common set of guidelines.

Focus on experimental systematics that are most important for the projection studies we need (can't be comprehensive!)

- Jet Energy Scale/Resolution, MET, B-tagging, Tau-ID, and many more...

Evaluation of theory uncertainties improvement
7 COMMON GUIDING PRINCIPLES FOR YR18

* Statistics-driven sources: data → √L, simulation → 0
  * account for larger data sample statistics available
  * to better understand full potential of HL-LHC

* Theory uncertainties typically halved
  * applies to both normalization (x-sec) and modeling
  * due to higher-order calculation and PDF improvements

* Uncertainties on methods kept as latest published results
  * Trigger thresholds same or better(lower) than current

* Intrinsic detector limitations stay ~constant
  * usage of full simulation tools for detailed analysis of expected performance, thanks to the large effort for TDRs preparation
  * detector understanding and operational experience may compensate for e.g. detector aging
  * harmonized definition of « floor » values for experimental systematics

* Luminosity uncertainty 1%
Whenever feasible present results as

\[ \text{value} \pm \text{stat} \pm \text{syst}_\text{exp} \pm \text{syst}_\text{theory} \ [\pm \text{syst}_\text{lumi}] \]

Baseline scenario defined as:

\* **YR18(S2):** based on synchronised estimates of ultimate performance for experimental and theory uncertainties, and applying guidelines as in previous slide

Summary (simplified) table of some values of experimental systematics harmonized between ATLAS & CMS:

<table>
<thead>
<tr>
<th>Object</th>
<th>WP</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muons</td>
<td>reco+ID(+ISO)</td>
<td>0.1%(0.5%)</td>
</tr>
<tr>
<td>Electrons</td>
<td>reco+ID+ISO</td>
<td>0,5%</td>
</tr>
<tr>
<td>Taus</td>
<td>reco+ID+ISO</td>
<td>5%(as in Run2)</td>
</tr>
<tr>
<td>B-jet tag</td>
<td>30&lt;pt&lt;300GeV (pt&gt;300GeV)</td>
<td>~1%(2-6%)</td>
</tr>
<tr>
<td>c-jet tag</td>
<td></td>
<td>~2%</td>
</tr>
<tr>
<td>Light jets</td>
<td>L/M/T WP</td>
<td>5/10/15%</td>
</tr>
<tr>
<td>JES</td>
<td>abs/rel scale</td>
<td>0.1-0.2%(0.1-0.5%)</td>
</tr>
<tr>
<td>JEC</td>
<td>Pile-Up</td>
<td>0-2%</td>
</tr>
<tr>
<td>JEC</td>
<td>Flavor</td>
<td>0,75%</td>
</tr>
<tr>
<td>Integrated Luminosity</td>
<td></td>
<td>1%</td>
</tr>
</tbody>
</table>
Exercise trying to quantify the precision of the PDF at the end of the HL-LHC running and use them in the systematic estimate of the experimental extrapolations.

- Pseudo-data generated for various inputs: top Drell-Yan, iso photons, W+charm, W and Z in the forward region, inclusive jets...
- Scenario A(C) corresponds to factor 2(5) reduction of uncertainties on exp. inputs.
- LHeC could provide improvement of a factor 5 on PDF uncertainties.
- Tested effect on some SM and BSM processes. Justifies assumptions used for YR18 scenario.

**tt differential analysis**

![Graphs showing differential cross-sections for tt production at HL-LHC](image)

**Dijet production @ HL-LHC \( \sqrt{s} = 14 \text{ TeV} \)**

![Graphs showing ratio to baseline for dijet production](image)

**Di-photon production @ HL-LHC**

![Graphs showing ratio to baseline for di-photon production](image)
THE HIGGS SECTOR
We have come a long way since the Higgs discovery in 2012.

The available LHC Run1 (7.8 TeV ~ 25 fb⁻¹) & Run2 (13 TeV ~ 150 fb⁻¹) datasets have pushed Higgs physics from search mode to measurement mode, probing the nature of the boson and its agreement with the SM.

All the main production and decay modes under scrutiny by ATLAS and CMS.

**Diagram:**
- Proton-proton → Higgs (48.52 pb)
- Higgs → q̅q (3.78 pb)
- Higgs → t̅b (1.373 pb + 0.8839 pb)
- Higgs → 0.5071 pb

**Pie Chart:**
- bb: 58%
- WW: 21%
- ZZ: 3%
- ττ: 3%
- gg: 8%
- cc: 6%
- VV: 0.2%
At HL-LHC, we expect to produce ~170M Higgs Bosons, including ~120k of HH pair produced events.

Over 1 Million for each of the main production mechanisms, spread over many decay modes.

Enables a broad program:
- Precision O(few%) measurements of couplings across broad kinematics
- Exploration of Higgs potential (hh production)
- Sensitivity to rare decays involving new physics
- Extend BSM Higgs searches (extra scalars, BSM Higgs resonances, exotic decays...)
WHERE WILL BE THE IMPACT OF THE HL-LHC?

What do we need to know? Where will the HL-LHC impact?

- **Precision Measurements**: Couplings to ~5%, Cross Sections, Differential Distributions, Width

- **Rare decays**

- **Di-Higgs production** → self coupling

- **BSM Higgs searches** (extra scalars, BSM Higgs resonances, anomalous couplings)

See presentation by E. Petit

BSM group of EPPSU
* Old studies (before YR) comprehensive, BUT
  * mostly based on extrapolations of Run1/early Run2 results
    * plus specific analyses with parametrised full simulation.
  * Not harmonized uncertainty assumptions
  * Single experiment only!

Rates can be measured at the few % level (10-20% for rarer modes)

Couplings can be measured at the few % level

* Complete revamp of the SM Higgs projections, starting from Run2 results and incorporating the current understanding of the future ATLAS&CMS performance.
  * Profit of the lesson learned in the Run1 combination
  * All main decays x production modes incorporated into the study (γγ, WW, ZZ, ττ, bb, µµ, Zγ x ggF, VBF, WH, ZH, ttH)

* COMBINATION of the individual results of the ATLAS and CMS, for a definition of the overall HL-LHC reach
  * Theoretical systematics assumed fully correlated, experimental uncertainties uncorrelated
**15 COUPLINGS - RESULTS OF COMBINATION**

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

**ATLAS and CMS**

**HL-LHC Projection**

- **Total**
- **Statistical**
- **Experimental**
- **Theory**

### Expected uncertainty

<table>
<thead>
<tr>
<th>Process</th>
<th>Tot</th>
<th>Stat</th>
<th>Exp</th>
<th>Th</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\gamma\gamma$</td>
<td>2.6</td>
<td>1.0</td>
<td>1.5</td>
<td>1.9</td>
</tr>
<tr>
<td>$B^{ZZ}$</td>
<td>2.9</td>
<td>1.2</td>
<td>1.5</td>
<td>2.2</td>
</tr>
<tr>
<td>$B^{WW}$</td>
<td>2.8</td>
<td>1.1</td>
<td>1.2</td>
<td>2.3</td>
</tr>
<tr>
<td>$B^{\tau\tau}$</td>
<td>2.9</td>
<td>1.4</td>
<td>1.3</td>
<td>2.2</td>
</tr>
<tr>
<td>$B^{b\overline{b}}$</td>
<td>4.4</td>
<td>1.5</td>
<td>1.3</td>
<td>4.0</td>
</tr>
<tr>
<td>$B^{\mu\overline{\mu}}$</td>
<td>8.2</td>
<td>7.4</td>
<td>1.5</td>
<td>3.0</td>
</tr>
<tr>
<td>$B^{Z\gamma}$</td>
<td>19.1</td>
<td>14.3</td>
<td>3.2</td>
<td>12.2</td>
</tr>
</tbody>
</table>

### By decay mode

### By production mode

<table>
<thead>
<tr>
<th>Process</th>
<th>Tot</th>
<th>Stat</th>
<th>Exp</th>
<th>Th</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{ggH}$</td>
<td>1.6</td>
<td>0.7</td>
<td>0.8</td>
<td>1.2</td>
</tr>
<tr>
<td>$\sigma_{VBF}$</td>
<td>3.1</td>
<td>1.8</td>
<td>1.3</td>
<td>2.1</td>
</tr>
<tr>
<td>$\sigma_{WH}$</td>
<td>5.7</td>
<td>3.3</td>
<td>2.4</td>
<td>4.0</td>
</tr>
<tr>
<td>$\sigma_{ZH}$</td>
<td>4.2</td>
<td>2.6</td>
<td>1.3</td>
<td>3.1</td>
</tr>
<tr>
<td>$\sigma_{ttH}$</td>
<td>4.3</td>
<td>1.3</td>
<td>1.8</td>
<td>3.7</td>
</tr>
</tbody>
</table>
Precision on kappas of 2-4% can be reached with $3ab^{-1}$ for the non-statistically dominated modes.

Measurements become systematically limited rather quickly -> challenge.

$\sqrt{s} = 14$ TeV, 3000 fb$^{-1}$ per experiment.

**ATLAS and CMS**

**HL-LHC Projection**

<table>
<thead>
<tr>
<th>Uncertainty [%]</th>
<th>Total</th>
<th>Stat</th>
<th>Exp</th>
<th>Th</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_Y$</td>
<td>1.8</td>
<td>0.8</td>
<td>1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>$K_W$</td>
<td>1.7</td>
<td>0.8</td>
<td>0.7</td>
<td>1.3</td>
</tr>
<tr>
<td>$K_Z$</td>
<td>1.5</td>
<td>0.7</td>
<td>0.6</td>
<td>1.2</td>
</tr>
<tr>
<td>$K_g$</td>
<td>2.5</td>
<td>0.9</td>
<td>0.8</td>
<td>2.1</td>
</tr>
<tr>
<td>$K_t$</td>
<td>3.4</td>
<td>0.9</td>
<td>1.1</td>
<td>3.1</td>
</tr>
<tr>
<td>$K_b$</td>
<td>3.7</td>
<td>1.3</td>
<td>1.3</td>
<td>3.2</td>
</tr>
<tr>
<td>$K_{\tau}$</td>
<td>1.9</td>
<td>0.9</td>
<td>0.8</td>
<td>1.5</td>
</tr>
<tr>
<td>$K_{\mu}$</td>
<td>4.3</td>
<td>3.8</td>
<td>1.0</td>
<td>1.7</td>
</tr>
<tr>
<td>$K_{Z\gamma}$</td>
<td>9.8</td>
<td>7.2</td>
<td>1.7</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Expected uncertainty
Comparing Run2(S1) with YR18(S2) scenarios

**ATLAS** Preliminary
Projection from Run 2 data
\( \sqrt{s} = 14 \text{ TeV}, 3000 \text{ fb}^{-1} \)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( ggF )</td>
<td>( \pm 0.035 )</td>
<td>( \pm 0.008 )</td>
<td>( \pm 0.034 )</td>
</tr>
<tr>
<td>( VBF )</td>
<td>( \pm 0.055 )</td>
<td>( \pm 0.020 )</td>
<td>( \pm 0.051 )</td>
</tr>
<tr>
<td>( WH )</td>
<td>( \pm 0.093 )</td>
<td>( \pm 0.041 )</td>
<td>( \pm 0.084 )</td>
</tr>
<tr>
<td>( ZH )</td>
<td>( \pm 0.062 )</td>
<td>( \pm 0.034 )</td>
<td>( \pm 0.052 )</td>
</tr>
<tr>
<td>( ttH )</td>
<td>( \pm 0.068 )</td>
<td>( \pm 0.019 )</td>
<td>( \pm 0.065 )</td>
</tr>
</tbody>
</table>

Cross section norm. to SM value

**CMS**

Projection

\( B_{BSM} = 0 \)

- \( K_\gamma \):
  - 0.03 (Stat); 0.04 (S2); 0.06 (S1)
- \( K_W \):
  - 0.03 (Stat); 0.04 (S2); 0.05 (S1)
- \( K_Z \):
  - 0.03 (Stat); 0.04 (S2); 0.05 (S1)
- \( K_g \):
  - 0.03 (Stat); 0.05 (S2); 0.06 (S1)
- \( K_t \):
  - 0.03 (Stat); 0.06 (S2); 0.08 (S1)
- \( K_b \):
  - 0.06 (Stat); 0.09 (S2); 0.11 (S1)
- \( K_\tau \):
  - 0.04 (Stat); 0.05 (S2); 0.06 (S1)
- \( K_\mu \):
  - 0.22 (Stat); 0.22 (S2); 0.22 (S1)

Expected uncertainty

\( 300 \text{ fb}^{-1} (13 \text{ TeV}) \)
**Differential Cross Section**

### CMS Projection

- **3000 fb⁻¹ (13 TeV)**
- **W/ YR18 syst. uncert. (S2)**

- $\Delta\alpha(p_T^H > 600) / 250$
- $\Delta\alpha(p_T^H > 200) / 120$
- $\Delta\alpha(p_T^H > 600) / 250$

---

### ATLAS Preliminary Projection from Run 2 data

- $\sqrt{s}=14$ TeV, 3000 fb⁻¹
- $\gamma\gamma + H \rightarrow ZZ \rightarrow 4l$

---

### ATLAS Preliminary Projection from Run 2 data

- $\sqrt{s}=14$ TeV, 3000 fb⁻¹
- $\gamma\gamma + H \rightarrow ZZ \rightarrow 4l$

---

**Notes:**

- Sensitive to $k_b/k_c$ at low $p_T$ and $k_t/BSM$ at high $p_T$
- Expected precision of $\sim 10\%$ for $p_T(H) > 350$ GeV, statistically limited
**Mass**: most precise measurement using H→ZZ→4μ, 2e2μ events. Reach of 10-20 MeV precision plausible goal dependent on future improvements on muon momentum measurements.

**Width**: Direct measurement will be challenging also with HL-LHC statistics. Probe New Physics in the Higgs domain at large momenta

- **4L Onshell and Offshell**: 20% precision at 68% CL combining CMS+ATLAS
- **From couplings**: $\Gamma_H$ 5% precision at 95% CL, but model dependent ($kV<1$ and $B_{unt}=0$)
- **Diphoton** interference study, only weaker constraints
Connection between Higgs & Dark Matter

- Run2 Limit ~20% @ 95%CL (in both experiments sensitivity dominated by the VBF channel)

- From the global coupling fit $B_{BSM} < 2.5\% @ 95\%$ CL if $B_{BSM} \geq 0$ (any invisible or undetected states):

- Prospects of direct searches @14TeV:

**VH: ATLAS, 2013: <8% @ 95%CL**

**VBF: CMS, 2018: <3.8% @ 95%CL**

- In the VBF case: full reoptimization of the analysis at 200PU to study how to handle the impact of PU in MET
**Hμμ**: Probe coupling to 2nd generation —> prospects for cross section and coupling measurement → 8% & 5% uncertainty@3000fb⁻¹ respectively

Indirect constraints will complement the direct searches (eg from differential distributions, off-shell couplings, or from the global coupling fits)

The combined LHC (ATLAS+CMS+LHCb) reach for kappa_c could reach the 1% level

\[ \mu(ZH, Hcc, ATLAS) < 6.3 \text{ @ 95\% CL, 3000fb}^{-1}, 14 \text{ TeV (Best fit: } \Delta \mu = 3.2) \]

Indirect constraints will complement the direct searches (eg from differential distributions, off-shell couplings, or from the global coupling fits)
* $\sigma \sim 39.5 \text{ fb}@14\text{TeV} \rightarrow \text{HL-LHC benchmark}$
  
* Access the $H$ self-coupling $\lambda$
  
* Low cross section: destructive interference
  
* Expanding list of final states w. Run2 & extrapolated to HL-LHC

<table>
<thead>
<tr>
<th>Final State</th>
<th>Statistical-only</th>
<th></th>
<th>Statistical + Systematic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ATLAS</td>
<td>CMS</td>
<td>ATLAS</td>
</tr>
<tr>
<td>$HH \rightarrow bbbb$</td>
<td>1.4</td>
<td>1.2</td>
<td>0.61</td>
</tr>
<tr>
<td>$HH \rightarrow bb\tau\tau$</td>
<td>2.5</td>
<td>1.6</td>
<td>2.1</td>
</tr>
<tr>
<td>$HH \rightarrow bb\gamma\gamma$</td>
<td>2.1</td>
<td>1.8</td>
<td>2.0</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}VV(ll\nu\nu)$</td>
<td>-</td>
<td>0.59</td>
<td>-</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}ZZ(4l)$</td>
<td>-</td>
<td>0.37</td>
<td>-</td>
</tr>
<tr>
<td>combined</td>
<td>3.5</td>
<td>2.8</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>Combined</td>
<td></td>
<td>Combined</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td></td>
<td>4.0</td>
</tr>
</tbody>
</table>

* Combined significance of a single experiment $\sim 3$ standard deviations

* Combining the ATLAS and CMS results a significance of $4$ standard deviation can be achieved (including systematic uncertainties).
ELECTROWEAK PRECISION MEASUREMENTS
Only moderate increase in energy ... but incredibly large statistics: many bosons, many tops!

- Need to improve our understanding of systematic uncertainties and their interplay
- Improve techniques for uncertainty mitigation
- High precision differential measurements
- Era of ‘dark’ corners of phase space (BSM sensitivity in the tails!)

- Renewed recognition of importance of Standard model measurements for their contribution to EWPO fits
- Engagement of theory community to match experimental precision
**Vector boson scattering**

- Sensitive to anomalous EWK couplings and effects from new physics at higher scales
  - dim-8 EFT operators interpretation
- Distinct signature in the detector allows to mitigate effects from large PU, large statistics allows a comprehensive study in every channel
- $3\sigma$ Evidence for longitudinal polarization component $V_L V_L$ can be achieved combining channels and experiments
W and top mass are key parameters of the SM

Motivation for low PileUp run: 200 pb-1 of Low PU data ($\mu \sim 2$) at 14 TeV
  * 5-10 weeks of running $\rightarrow$ ~3 MeV (stat only)
  * Exp syst assumed to be at same level of Stat uncertainty
  * PDF unc ~4 MeV with ultimate PDF

Goal $\Delta m(W) \sim 6$ MeV (extended coverage + combination + ultimate PDF)
  * PDF syst can go down to ~2 MeV with LHeC PDF set
27  **EWK PRECISION MEASUREMENTS - TOP MASS**

* The methods that can be employed for the top mass reconstruction are characterized by different experimental and theoretical issues and uncertainties.

* High statistics allows new methods to become competitive
  * different systematics effects

* Theoretical advances in the contribution to the uncertainties have a major role in the ability to reach the ultimate precision at a hadron collider

<table>
<thead>
<tr>
<th>Method: $\Delta m_{top}$ (GeV)</th>
<th>$t\bar{t}$ lepton+jets</th>
<th>t-channel single top</th>
<th>$m_{SV\ell}$</th>
<th>$J/\psi$</th>
<th>$\sigma_{t\bar{t}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.17</td>
<td>0.45</td>
<td></td>
<td>0.62</td>
<td>0.50</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Standard $\rightarrow \ell+$jets measurement  Statistically dominated

Limited by theory uncertainty and luminosity measurement
Indirect determination of \( M_W \) and \( \sin^2 \theta_{\text{eff}} \) more precise than the experimental measurement:

- This call for a precise direct Measurement
- Stringent test of the self consistency of the SM

\* Statistical uncertainty of single experiment better than \( 5 \times 10^{-5} \)
\* Strong benefit from extended eta coverage of upgraded detectors
Careful studies and projections for the physics at the HL-LHC we have shown:

* we have designed amazing detectors that will be able to fully mitigate the 200PU conditions
* we can expand the knowledge of the SM with improved precision and the observation of new processes that become accessible
* we can expand the search for BSM physics with tools that allow to probe new and unusual processes

We believe the extrapolations have been made on solid assumptions, and we are ready to see even bigger improvement once the data comes!
Precision physics at the HL-LHC?

- Studies of detector performance with fully simulated Monte Carlo samples in HL-LHC conditions allow us to have an understanding of the expected future performance of the detectors.

- These studies, performed extensively in 2017 for the ATLAS&CMS Technical Design Reports, are critical to support our updated physics prospects (both those based on projections of Run2 analysis and those directly using fast/parameterized simulations of the HL-LHC performance).
* Maintain performance similar or better than Run 2
* Effective pileup mitigation & extended capabilities with new algorithms

**DETECTOR PERFORMANCE**

- **BTAG**
- **MUON**
- **JETS**
- **MET**

...just selected plots, more available in the TDRs
Systematics in “truth-based” projections

- Parametrized detector performance or delphes “reconstruction”
  - more rarely full-simulation samples too
  - allows re-optimization of selections and direct usage of parametrized performance of upgraded detector

- Consider leading systematic uncertainties if dominant over stat.
  - Applied shifting “reconstructed” quantities and assessing impact

- Non-trivial extrapolation to run-2 “inaccessible” regions/features
  - detector capabilities (timing, ...)
  - kinematics (large h tracking, high p<sub>T</sub>,...)

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Method/Modeling uncertainties

- Expected background often constrained in dedicated control regions
- Extrapolation from control to signal region:
  - MC prediction → modeling uncertainty
  - entirely data-driven methods → check assumptions often in MC
- In both cases expect:
  - closure of method → harder to predict, keep same
  - statistics in control region → \( \sim \sqrt{L} \)
  - theory uncertainty critical → halved

\[ D = \frac{C \times A}{B} \]

- Theorists' input crucial on a case by case
### Systematic Uncertainties (II)

<table>
<thead>
<tr>
<th>Object Efficiency</th>
<th>uncertainty</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muons</td>
<td>muon reco+ID (all WP)</td>
<td>0.1%</td>
</tr>
<tr>
<td></td>
<td>muon reco+ID+isolation (all WP)</td>
<td>0.5%</td>
</tr>
<tr>
<td>Electrons/photons</td>
<td>electron reco=ID (incl. isolation), all WP (pt &gt; 20 GeV)</td>
<td>0.5%</td>
</tr>
<tr>
<td></td>
<td>photon reco+ID+incl. isolation</td>
<td>~2% (?)</td>
</tr>
<tr>
<td>tau</td>
<td>tau reco+ID+isolation (all WP)</td>
<td>5% as in Run2</td>
</tr>
<tr>
<td></td>
<td>recommend 2.5% for analyses where tau efficiency is one of the dominant uncertainties</td>
<td></td>
</tr>
<tr>
<td>flavor tagging</td>
<td>b-jets (all working points)</td>
<td>~ 1% for 30&lt;pt&lt;300 GeV, 2–6% for pt&gt;300 GeV</td>
</tr>
<tr>
<td></td>
<td>c-jets (all working points)</td>
<td>~2%</td>
</tr>
<tr>
<td></td>
<td>light jets (loose WP)</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>light jets (medium WP)</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>light jets (tight WP)</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td>subjet b-tagging</td>
<td></td>
</tr>
<tr>
<td></td>
<td>double b-tag</td>
<td></td>
</tr>
</tbody>
</table>

See [https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCCommonSystematics](https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCCommonSystematics) for more details
### Systematic Uncertainties (III)

**Integrated luminosity uncertainty already dominant in some SM measurements**

Dominant for HL-LHC SM analyses. Sub-leading only if at the ~1% level.

**LHC-wide integrated luminosity uncertainty target agreed upon**

**Luminosity: 1.0% precision (and no worse than 1.5%) to fully exploit HL-LHC potential**

<table>
<thead>
<tr>
<th>JME for Delphes based analysis</th>
<th>Total</th>
<th>for recommendations see slides 1 and 2 of JEC-CommonWithATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>JES reduction factors for Run2 projection - eta independent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>0.5%</td>
<td>N/A</td>
</tr>
<tr>
<td>abs. scale</td>
<td>0.5%</td>
<td>N/A</td>
</tr>
<tr>
<td>rel. scale</td>
<td>0.1-3%</td>
<td>N/A</td>
</tr>
<tr>
<td>Pile up</td>
<td>0-2%</td>
<td>N/A</td>
</tr>
<tr>
<td>Method and Sample</td>
<td>0.5-5%</td>
<td>N/A</td>
</tr>
<tr>
<td>Jet Flavour</td>
<td>1.5%</td>
<td>N/A</td>
</tr>
<tr>
<td>Time Stability</td>
<td>0.2%</td>
<td>N/A</td>
</tr>
</tbody>
</table>

| JER | N/A | 3-5% as a function of eta |
| MET | propagate JEC uncs. | propagate JEC uncs. (must) |
| | propagate JER uncs. (recommended) | vary unclustered energy by 10% (recommended) |
**Requirements for Trigger and DAQ for CMS-ATLAS:**

- L1 latency increase to ~10-12.5μs (~2.5-3.2μs today)
- Readout rate increase to 750-1000kHz (100 kHz today)
- Overall throughput to ~50 Tb/s (~2Tb/s today)
- Rate to permanent storage to ~7.5-10kHz (~1kHz today)

**Phase-II Muon Trigger Performance**

- The current barrel trigger requires three layer coincidence 3/3 in the RPC.
- Holes in coverage caused by magnet supports limit trigger acceptance.
- Upgrades to barrel will allow for 3/4 instead.
- Increasing acceptance of the barrel trigger from 82% to 90%.
- Excellent trigger efficiency even in the worst case scenario for HL-LHC run conditions.

**Efficiency x Acceptance**

Improve: with redundancy and new features!
Expected relative uncertainty

**ATLAS and CMS**

*HL-LHC Projection*

- $B^{\gamma\gamma}$
- $B^{ZZ}$
- $B^{WW}$
- $B^{\tau\tau}$
- $B^{bb}$
- $B^{\mu\mu}$
- $B^{Z\gamma}$

3000 fb$^{-1}$

Stat. + Exp.

ATLAS

CMS

+ Theory
Time evolution

- Measurements became systematically limited rather fast in almost all cases -> challenge
- Most Coupling modifier uncertainties projected to reach ~4-6% precision by the end of Run 3, and 2-4% after 3000 fb$^{-1}$ at HL-LHC
Example: can be used to constrain the Higgs self coupling in an alternative way to the traditional HH analysis.

- Additional characterisation of the kinematics of the H boson
- Rarer production modes (tth) x differential measurements provide further insight

20-40% precision
Complementary to QGC

Study production of Z bosons in association with 2 photons

Contributions from BSM (EFT) in tails

Sensitivities higher $3\sigma$ in WWW, WWZ, and WZZ - in progress!
In the SM the Z and H exchange diagrams diverge but exactly cancel each other.

Anomalous couplings, as hints from New Physics, would have dramatic effects.

The total WW scattering/Higgs pair cross section diverge with $m_{WW,HH}^4$.

\[
W^+ W^+ = a g_{WW}^{SM} \quad W^- W^- = b g_{HH}^{SM}
\]

\[
Z^0 + H^0 \quad (1-a^2) \frac{E^2}{M_W^2} + ...
\]

\[
E \to \infty
\]

\[
W^+ H^0 = a b E^2 / M_W^2 + ...
\]

\[
E \to \infty
\]

\[
(b-a^2) \frac{E^2}{M_W^2} + ...
\]

Threshold terms proportional to HHH coupling.

Precision on $a$ and $b$:

- $30\%$ at HL-LHC 14 TeV
- $1\%$ with FCC-hh 100 TeV

Precision on $a$:

- $1\%$ with ILC
- $0.1\%$ with FCC-ee