High Luminosity Yellow Report: what does HL-LHC physics look like in ATLAS and CMS?

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on behalf of ATLAS and CMS Collaborations
Topics covered in this talk

- **Higgs** coupling prospects
- **Di-Higgs** boson production sensitivity
- **BSM Higgs** physics
- **Vector Boson Scattering** prospects
- **W** and **Top** mass SM precision measurements
- **Weak mixing angle**
- Discovery potential for strong and electroweak **SUSY**
- And other **Exotic** benchmark scenarios

Disclaimer: obviously only a (small) selection of available results.
Total luminosity of **3 ab⁻¹ at 14 TeV** each for ATLAS and CMS (ultimate scenario is 4 ab⁻¹).

- Baseline instantaneous luminosity of $\mathcal{L} = 5.10^{34} cm^{-2}s^{-1}$ (ultimate achievable $\mathcal{L} = 7.5\ 10^{34} cm^{-2}s^{-1}$).
- Number of collisions per bunch crossing $\langle \mu \rangle \sim 140$ (ultimate scenario $\langle \mu \rangle \sim 200$).
- Requires **new components** to be developed:
  - More powerful focusing magnets and new advanced technologies in the domain of superconductivity, cryogenics, rad-hard materials, electronics...
  - Construction of the HL-LHC should be completed in 2026 and will be followed by at least ten years of operation.
ATLAS and CMS Detector HL-LHC Upgrades

- The overall upgrade strategy is described in detail in the various ATLAS/CMS-TDR of each systems:

**Muons:** ATLAS-TDR-026
- New trigger chambers RPC for $\eta<1$.
- Incorporation of precision tracking chambers sMDT into trigger decision + new readout elect.
- New small wheel

**Options:**
- High Granularity Timing Detector (forward) - Proposal
- High muon-$\eta$ detector (2.7<\eta<4) - TDR

**Tracker:** CMS-TDR-014
- Si-Strip and Pixels high granularity with less material.
- Design for tracking in L1-Trigger.
- Extended coverage to $\eta<3$.

**MIP Timing detector:** CERN-LHCC-2017-027
- Reconstruct the timing of particles (30 ps resolution).
- Sensitive to minimum ionizing particles MIP.
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

- Extend the $\eta$ coverage.
- Improve the trigger systems.
- Computational challenge on CPU and disks for HL-LHC.
Update and extend the projections for the precision, reach and interpretation of the HL-LHC measurements.

Highlight new opportunities for discovery of phenomena beyond the Standard Model (BSM), in view of the latest theoretical developments and of recent data.

Explore possible new directions and/or extensions of the approved HL-LHC program.

⇒ Full HL-LHC ATLAS+CMS documentation/references:

- Standard Model Physics CERN-LPCC-2018-03
- Higgs Physics CERN-LPCC-2018-04
- Beyond the Standard Model Physics CERN-LPCC-2018-05
Treatment of Systematic Uncertainties
(“YR18 systematics uncertainties” scenario)

• Theoretical uncertainties:
  • Assumed to be reduced by a factor of two with respect to the current knowledge,
  • Thanks to both higher-order calculation as well as reduced PDF uncertainties (from projections of what LHC will be able to constrain).

• Limited number of simulated events:
  • Neglected ⇒ under the assumption that sufficiently large simulation samples will be available.

• Statistical uncertainty:
  • Reduced by a factor \(1/\sqrt{\mathcal{L}}\) with respect to the reference Run 2 analysis.

• Detector limitations:
  • Left unchanged (or revised according to detailed simulation studies of the upgraded detector)

• Uncertainties on methods:
  • Kept at the same value as in the latest public results available ⇒ assuming that the harsher HL-LHC conditions will be compensated by method improvements.

• Uncertainty on the luminosity:
  • ~1% level (understanding of the calibration methods, new capabilities of the upgraded detectors)

• Other scenario of comparison:
  • Where the current level of understanding of systematic uncertainties is assumed (“Run-2 systematic uncertainties”) or to the case of statistical-only uncertainties.
Higgs Coupling at HL-LHC

• Determination of Higgs boson properties ⇒ primary target of the HL-LHC physics program
• Main production and decay modes:

\[ H \rightarrow \gamma\gamma, ZZ^*, WW^*, \tau^+\tau^-, bb, \mu^+\mu^- \text{ and } Z\gamma \]

“\( \kappa \)-framework”:

- The rate measurements in the production and decay channels ⇒ measurements of the Higgs couplings in the so-called "\( \kappa \) framework".
- This introduces a set of \( \kappa_i \) factors that linearly modify the coupling of the Higgs boson to SM elementary particles.
- Including the effective couplings to gluons \( \kappa_g \) and photons \( \kappa_\gamma \)
- Assuming no additional BSM contribution to the Higgs total width \( \Gamma_H \) where \( \Gamma_H/\Gamma_H^{SM} = \sum_j B R_j^{SM} \kappa_j^2 (1 - \text{BSM}) \)

SM branching fraction \( H \rightarrow jj \)

Projected 1σ uncertainties on \( \kappa_i \) ~ at % level
Higgs Self-Coupling Sensitivity

- Is one of the key goals of the high-luminosity program
  - The Run 2 experience in searches for Higgs pair production led to a reappraisal of the HL-LHC sensitivity.
  - 100,000 HH pairs should be produced/exp.
  - Approximation around the v.e.v:
    \[ V(\Phi) \approx \lambda \Phi^2 h^2 + \lambda_\vev \Phi h^3 + \frac{1}{4} \lambda_\vev^2 h^4 \]
    - mass term self-coupling terms
  - Define deviation of trilinear term:
    \[ \kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} \]

- HL-LHC prospect:
  - HH mass spectrum shape → result in the likelihood profile as a function of \( \kappa_\lambda \)
  - The results on HH production studies are statistics limited ⇒ ATLAS+CMS combination essential to achieve the objective.
  - Assuming the SM Higgs self-coupling \( \lambda \):
    ⇒ HL-LHC: \( 4\sigma \) evidence of the HH process + 50% uncertainty on \( \kappa_\lambda \)
    ⇒ secondary minimum can be excluded at 99.4% CL
**BSM Higgs Physics**

- **Sensitivity to BSM Higgs physics:**
  - Exploiting indirect probes via precision measurements and direct search targets.
  - Searches for exotic decays of the 125 GeV Higgs boson: e.g. decays including light scalars, light dark photons or axion-like particles, decays to long-lived BSM particles.
  - Production of new Higgs bosons, neutral and charged, at masses above or below 125 GeV.

- **Benchmark scenario:** e.g. “$M_{h}^{125}$”
  - All superparticles are chosen to be so heavy that production and decays of the MSSM Higgs bosons are only mildly affected by their presence.

MSSM prediction for $M_{h}$ falls outside the window 125±3 GeV

From Higgs precision coupling measurements

- **Probe new heavy Higgs bosons up to 2.5 TeV for tan β>50**
Higgs and Electroweak data in EFT framework

- Indirect constraints on BSM, using the formalism of Effective Field Theories:
  - SM Lagrangian is supplemented with dimension-6 operators $O_i$
    \[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum_i c_i O_i + \cdots \]
  - Exploiting the fact that heavy BSM dynamics can still have an impact on processes at smaller energy, via virtual effects.
  - Allows to systematically parametrize BSM effects and how they modify SM processes.
  - SMEFT = Standard Model Effective Field Theory.

- Global fit to observables in Higgs physics, as well as diboson and Drell-Yan processes.
  - The fit includes all operators generated by new physics that only couples to SM bosons.
  - 95% probability limits on the new physics interaction scale $\Lambda/\sqrt{|c_i|} \ [\text{TeV}]$ and coefficients $|c_i|/\Lambda^2 \ [\text{TeV}^2]$
    \[ \frac{c_i}{\Lambda^2 \text{[TeV]}^2} \]
  - The ratio gives the linear new physics correction to each observable.

- Understanding of modified Higgs couplings (via $O_H$)
- Sensitivity to the Higgs compositeness scale $f > 1.6 \text{ TeV}$
- Corresponding to a new physics mass scale of 20 TeV
Vector Boson Scattering

• Great importance to test the mechanism of EW symmetry breaking:
  • It is still unknown whether the discovered Higgs boson preserves unitarity of the longitudinal VV (V=W,Z) scattering amplitude at all energies.
  • Or if other new physics processes are involved.
  • Can signal the presence of anomalous couplings and NP at energy scales beyond the reach of direct resonance production.

<table>
<thead>
<tr>
<th>Process</th>
<th>Final state</th>
<th>Precision</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^\pm W^\mp$</td>
<td>$\ell^\pm/\ell^\pm jj$</td>
<td>6%</td>
<td>&gt; 5σ</td>
</tr>
<tr>
<td>WZ</td>
<td>3/3j</td>
<td>6%</td>
<td>&gt; 5σ</td>
</tr>
<tr>
<td>WV</td>
<td>3/4j</td>
<td>6.5%</td>
<td>&gt; 5σ</td>
</tr>
<tr>
<td>ZZ</td>
<td>4/4j</td>
<td>10–40%</td>
<td>&gt; 5σ</td>
</tr>
<tr>
<td>WWW</td>
<td>3/3/3ν</td>
<td>11%</td>
<td>&gt; 5σ</td>
</tr>
<tr>
<td>WWZ</td>
<td>4/2/2ν</td>
<td>27%</td>
<td>3.0σ</td>
</tr>
<tr>
<td>WZZ</td>
<td>5/5ν</td>
<td>36%</td>
<td>3.0σ</td>
</tr>
</tbody>
</table>

• $W^\pm W^\mp$ cross section can be decomposed into the polarized (L or T) components based on the decays of the individual W bosons.
• ATLAS+CMS $W^\pm W^\mp jj$ is expected to reach an expected significance of $3\sigma$ with 2000 fb$^{-1}$.

Estimated uncertainty of the EWK $W^\pm W^\mp$ cross section measurement as a function of the integrated luminosity
**EWK Precision : W and top Mass**

### W mass:
- **Motivation for low PileUp run:** 200 pb\(^{-1}\) of Low PU data (\(\mu \sim 2\)) at 14 TeV.
- Exp. syst. assumed to be at same level of stat uncertainty (~3 MeV).
- Limiting the PDF sensitivity via the extended leptonic coverage \(|\eta| < 4\) (ultimate PDF unc. ~4 MeV)

**Goal \(\Delta(M_W)\sim 6\) MeV**

### Top mass:
- Mostly negligible statistical uncertainty.
- Progress here will be driven by future **theoretical developments**.
- Analyses with independent theoretical systematics will be important.

**Projected total uncertainties on the top quark mass obtained with different methods:**

![Graph showing projected uncertainties on top quark mass]

### Syst. uncertainties on m_[W]

<table>
<thead>
<tr>
<th>Method</th>
<th>(\tilde{t}) lepton+jets</th>
<th>t-channel single top</th>
<th>(m_{SV}^{\tilde{t}})</th>
<th>(J/\psi)</th>
<th>(\sigma_{\tilde{t}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta m_{top}) (GeV):</td>
<td>0.17</td>
<td>0.45</td>
<td>0.62</td>
<td>0.50</td>
<td>1.2</td>
</tr>
</tbody>
</table>
• Effective weak mixing angle:
  \[ \sin^2 \theta_{\text{eff}}^f = \kappa_f \sin^2 \theta_W, \quad \sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2} \]
  where flavor-dependent \( \kappa_f \) is determined by electroweak corrections.
  
  \( q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^- \Rightarrow \text{precise measurements of angular distributions} \) of leptons from Drell-Yan can be used to extract the effective leptonic weak mixing angle.

  • Angular distribution \( \propto A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \)

  • A precision extraction using HL-LHC data can help settle the long-standing issue of the discrepancy between most precise measurement from LEP and SLD data.
    • Stat. better than 5.10^{-5} for ATLAS, CMS and LHCb.
    • Overall uncertainty will remain dominated by the PDFs \( \sim 13.10^{-5} \)
    • With LHeC \( \rightarrow \) reduction of PDF syst. of additional x5.
    • Note that extending the pseudorapidity acceptance with the upgraded detectors significantly reduces both the statistical and PDF uncertainties.
Beyond the Standard Model at HL-LHC

• Searches at HL-LHC are profiting from the much larger statistics, slightly higher energy (14 TeV), and upgraded detectors.

• Highlight only of a subset of key results, selected among a large number of studies for different new physics scenarios:
  
  • **Supersymmetry:**
    • Searches cover strong and electroweak particles production in R-parity conserving (RPC) and violating (RPV) SUSY models, considering prompt and non-prompt decays.
    • Phenomenology depends on the model and on the sparticle mass hierarchy → R-parity conserving SUSY is characterized by the presence of missing transverse momentum (MET) and lightest neutralino $\tilde{\chi}_1^0$ is the LSP in most cases.

  • **Long-Lived particles**
  • **Dark sector**
  • **Resonances**
Strong Supersymmetry Production

- **Strong production** → gluinos, 1st and 2nd generation squarks, top squarks.

<table>
<thead>
<tr>
<th>Model</th>
<th>$e, \mu, \tau, \gamma$</th>
<th>Jets</th>
<th>Mass limit</th>
<th>HL-LHC, $\int L dt = 3 \text{ab}^{-1}$: 5$\sigma$ discovery (95% CL exclusion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluino</td>
<td>$\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}^0_1$</td>
<td>0</td>
<td>4 jets</td>
<td>$\tilde{g}$</td>
</tr>
<tr>
<td>Gluino</td>
<td>$\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}^0_1$</td>
<td>0</td>
<td>Multiple</td>
<td>$\tilde{g}$</td>
</tr>
<tr>
<td>Gluino</td>
<td>$\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}^0_1$</td>
<td>0</td>
<td>Multiple</td>
<td>$\tilde{g}$</td>
</tr>
<tr>
<td>Stop</td>
<td>$\tilde{t}_1, \tilde{t}_1 \rightarrow q\tilde{\chi}^0_1$</td>
<td>0</td>
<td>Multiple/2b</td>
<td>$\tilde{t}_1$</td>
</tr>
<tr>
<td>Stop</td>
<td>$\tilde{t}_1, \tilde{t}_1 \rightarrow q\tilde{\chi}^0_1$</td>
<td>0</td>
<td>Multiple/2b</td>
<td>$\tilde{t}_1$</td>
</tr>
</tbody>
</table>

- Probing **gluino masses up to 3.2 TeV** with discovery reach around 3 TeV.
- **Top squarks** can be excluded up to masses of **1.7 TeV**.
### Weak Supersymmetry Production

**Weak production** → charginos, neutralinos, sleptons

<table>
<thead>
<tr>
<th>Chargino, neutralino</th>
<th>Process</th>
<th>Etc.</th>
<th>Visible probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\chi}^±_1 \tilde{\chi}^0_1 \rightarrow W^± \tilde{\chi}^0_1$</td>
<td>$2 , e, \mu$</td>
<td>0-1 jets</td>
<td>$\tilde{\chi}^±_1$</td>
</tr>
<tr>
<td>$\tilde{\chi}^±_2 \tilde{\chi}^0_2$ via WZ</td>
<td>$3 , e, \mu$</td>
<td>0-1 jets</td>
<td>$\tilde{\chi}^±_2 \tilde{\chi}^0_2$</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_2 \tilde{\chi}^0_3$ via Wh, Wh→lνb̅b</td>
<td>$1 , e, \mu$</td>
<td>2-3 jets/2b</td>
<td>$\tilde{\chi}^0_2 \tilde{\chi}^0_3$</td>
</tr>
<tr>
<td>$\tilde{\chi}^±_1 \tilde{\chi}^0_1 \rightarrow W^±W^±$</td>
<td>$2 , e, \mu$</td>
<td>-</td>
<td>$\tilde{\chi}^±_1 \tilde{\chi}^0_1$</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow Z\tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow W^±W^±$</td>
<td>$2 , e, \mu$</td>
<td>1 jet</td>
<td>$\tilde{\chi}^0_1 \tilde{\chi}^0_1$</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_2 \tilde{\chi}^0_2$, $\tilde{\chi}^±_1 \tilde{\chi}^0_2$, $\tilde{\chi}^0_2 \tilde{\chi}^0_2$</td>
<td>$2 , \mu$</td>
<td>1 jet</td>
<td>$\tilde{\chi}^0_2 \tilde{\chi}^0_2$</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_2 \tilde{\chi}^0_2$ via same-sign WW</td>
<td>$2 , e, \mu$</td>
<td>0</td>
<td>Wino</td>
</tr>
</tbody>
</table>

| Higgsino |
|-------------------------|---------|------|
| $\tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow Z\tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow W^±W^±$ | $2 \, e, \mu$ | 1 jet | $\tilde{\chi}^0_1 \tilde{\chi}^0_1$ |

**E.g. wino-like chargino** pair production processes are studied considering dilepton final states:

- Masses up to 840 (660) GeV can be excluded (discovered) for charginos decaying as $\tilde{\chi}^±_1 \rightarrow W^± \tilde{\chi}^0_1$
- Results **extend the mass reach** obtained with 80 fb$^{-1}$ of 13 TeV pp collisions by **about 500 GeV**.
- Beyond the LEP limit by almost an order of magnitude.

- Conventional searches for SUSY require that the **mass splitting** between the invisible LSP and the next-to-lightest SUSY particle is large enough to produce a visible probe (e.g. a charged lepton).
- HL-LHC analyses now target also **“compressed” SUSY scenarios** with soft-lepton + ISR analyses and/or monojet:
  - “compressed” = two lightest particles have a small mass splitting.
  - Theoretically well motivated but are among the most challenging scenarios experimentally (barely covered by the Run 2 analyses).
Long-Lived Particles

• Long lifetimes may be due to small couplings, small mass splittings, a high multiplicity of the decay final state, or a combination of these effects.
• New detector upgrades will enable searches in the long-lived particle regime:
  • e.g. new fast timing detectors will also be sensitive to displaced photon signatures arising from long lived particles in the $0.1 < c\tau < 300$ cm range.

Traditional analyses are unlikely to be sensitive to LLP:

• EWK sector: e.g. disappearing track
  • If the LLP is charged and decays to neutral or too soft ($\pi^\pm$) to be reconstructed → appears as a disappearing track (“tracklet”).
  • Needs to evaluate SM particles that are reconstructed as tracklets (probability computed with single electrons or pions MC samples used).
  • Events which contain fake tracklets (e.g. $Z \rightarrow \nu\nu$)
  • Possibility to exclude $m(\tilde{\chi}_1^\pm)$ up to 600 GeV for $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) < 0.2$ GeV
• DM system recoils against visible activity ⇒ it can be searched for as **missing transverse energy and momentum.**

  e.g: DM produced in association with a Z boson

• Signal is determined from a fit of the $p_T^{miss}$ spectrum of selected events, which would be hardened by the presence of a DM signal relative to the SM backgrounds (like $Z \rightarrow \nu \nu$).

• Model assumes a mediator ($Z'$) with a vector couplings $g_q$ and $g_{DM}$ to quarks and DM ($\chi$).

• Mediator of $M_{med} = 1$ TeV can be discovered with 3 $ab^{-1}$

• Improved handling of systematic uncertainties could reduce the integrated luminosity required for a discovery by a factor 3.
Resonances

- New heavy particles $Z'$ and $W'$
- Leptoquarks (LQ):
  - Models related to the apparent flavor anomalies in B decays suggest the presence of heavy resonances ($Z'$, LQ) coupling to 2nd and/or 3rd generation SM fermions.
  - The HL-LHC will be able to cover a significant portion of the parameter space allowed by flavor constraints.
  - Pair produced scalar LQs coupling to $\mu$ ($\tau$) and b-quarks can be excluded up to masses of 2.5 (1.5) TeV.

$Z' \rightarrow tt \rightarrow WbWb \rightarrow l\nu bqq'b$

$W' \rightarrow l\nu$ ($l=e, \mu$)

Pair LQ prod.

$M(Z') > 4$ TeV @95% (x2 compared to now)

$W'$ discovery potential up to 7.7 TeV
ATLAS and CMS will be fully upgraded by 2026 ⇒ expect 3000 fb\(^{-1}\) at 14 TeV by 2037
- **Hardware modifications** opens new possibilities for precision test of the Standard Model and direct discovery beyond the SM.
- The assessment of the future **systematic uncertainties** (experimental and theoretical) and **new experimental techniques** will be critical to reach maximum sensitivity (at higher luminosities or energies, the efficiency for identifying physics objects will change compared to current extrapolation ⇒ studies to be revisited/continued).

In record time **Higgs physics** has moved from a spectacular discovery of a new particle to a systematic and comprehensive study of its properties ⇒ primary target of the HL-LHC physics program
- Except for rare decays, the overall uncertainties will be dominated by the theoretical systematics with a **precision close to percent level**.
- Higgs studies at HL-LHC will enhance the sensitivity to BSM physics, exploiting indirect probes **via precision measurements**

Recent studies performed have confirmed the immense physics potential of **BSM searches** at HL-LHC
- A long list of contributions from the theory and experimental (ATLAS, CMS, LHCb) communities have been collected and merged together to give a complete, wide, and consistent view of what can be **discovered/excluded** at the HL-LHC (and beyond).
- On top of the usual standard candles, such as supersymmetric simplified models and resonances, studies contains results on dark matter and dark sectors, long lived particles, leptoquarks, sterile neutrinos, axion-like particles, heavy scalars, vector-like quarks, and more!
- **Extend the current reach by 20% to 50%** on most new physics scenarios at HL-LHC.
BACKUP
Rare Decays: Light Quarks

- The Higgs mechanism of the SM predicts that the Yukawa couplings are proportional to the fermion mass:

\[ y_f^{\text{SM}} = \sqrt{2m_f/v} \]

- Currently, only the third generation (ττ, bb, tt) Yukawa couplings were directly measured and found to be in agreement with the SM prediction.

- For first and second generations there are only upper bounds.

- Projected limits on \( \kappa_{c,s,d,u} \) using several methods:
  - Exclusive decays of the Higgs,
  - Fits of differential cross-sections,
  - Constraints from the total Higgs width assuming a value of 200 MeV,
  - A global fit of Higgs production cross-sections,
  - Direct searches for a \( c\bar{c} \) final state.

- Assuming SM coupling, e.g. projected coupling limits on \( \kappa_c < 2 \)
Ultimate PDFs Uncertainties

- All hard production processes at the LHC start from a partonic collision and their rate is determined by the PDFs.
  - LHCb data + large rapidities in ATLAS and CMS → will enhance the PDF sensitivity.
  - For M>100 GeV, the HL-LHC can improve the PDF uncertainties by a factor between 2 and 4.
- HL-LHC pseudo-data have been generated
  - For a number of PDF-sensitive measurements such as top-quark, Drell-Yan, isolated photon, and W+charm production → quantify the impact on PDFs of the pseudodata.
  - Note that data correlation models (which may limit the PDF impact in some cases) have been ignored in current estimate.
- Scenario A (C) assumes a reduction by a factor of 2 (5) of the experimental cross-section systematics relative to Run 2.
  - e.g. for gg→H, the PDF systematics will be reduced to below 2%.