The Physics Potential of the HL-LHC Programme

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Academia Sinica

On behalf of the ATLAS and CMS Collaborations

Particle Physics
Gordon Research Conference

New Tools for the Next Generation of Particle Physics and Cosmology
June 30 - July 5, 2019
The LHC (Large Hadron Collider)

LHC: 27 km long, up to 175m underground

- p-p collider
- Design parameters:
  - $\sqrt{s} = 14$ TeV, $L_{\text{inst}} = 10^{34}$ cm$^{-2}$ s$^{-1}$
  - Can also collide heavy ion particles
    - Pb, Xe
Run 2

- $\sqrt{s}=13$ TeV
- $\int L \sim 140$ fb$^{-1}$ (good for physics)
- $L_{\text{max}} \sim 2 \times 10^{34}$ cm$^{-2}$s$^{-1}$
- Ave. #of interactions per crossing $\sim 34$

- $Z\rightarrow\mu\mu$ candidate event
- #of interacting per crossing = 65

We are here
- √s = 14 TeV
- \( \int L \approx 3000 \text{ fb}^{-1} \)
- \( L \approx 5-7 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1} \)
- Ave. # of interactions per crossing ~200

- A lot of data for
  - QCD and EWK precision measurements
  - Deep understanding of Higgs properties
  - Probe BSM in both direct searches and in precision measurements
Detectors

• Large sophisticated general purpose particle detectors.

<table>
<thead>
<tr>
<th>Upgrade for HL-LHC</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAQ &amp; Trigger</td>
<td>L1, HLT~10 kHz</td>
<td>L1, HLT~7.5 kHz</td>
</tr>
<tr>
<td>Inner Tracker</td>
<td>New, up to</td>
<td>η</td>
</tr>
<tr>
<td>Calorimeter</td>
<td>Electronics upgrade for LAr &amp; Tile</td>
<td>New high granularity endcap calorimeter</td>
</tr>
<tr>
<td>Muon</td>
<td>Electronics upgrade + new muon chamber</td>
<td>Improve muon system coverage</td>
</tr>
<tr>
<td>Timing detector</td>
<td>New High Gransularity Timing Detector in endcap</td>
<td>Precise MIP timing layer in barrel &amp; endcap</td>
</tr>
</tbody>
</table>
Expect similar or better reconstruction of physics objects at HL-LHC compared to Run-2
Physics Projection at HL-LHC

• Assume center of mass energy at 14 TeV and total integrated luminosity is 3000 fb⁻¹

• Methods for projection:
  • **Detailed simulations** are used to access performance of upgraded detector and HL-LHC condition
  • Existing results are **extrapolated** and take into account of increase in energy and performance of upgraded detector, or **parametric simulations** are used to allow full re-optimization of the analyses

• Systematic uncertainties:
  • Baseline scenario ("YR18" or "S2"):
    • Theory uncertainties ½ of Run-2
    • No simulation statistical uncertainty
    • Luminosity uncertainty ~1%
    • Statistical uncertainty reduced by 1/√L
    • Uncertainties due to detector limitations remain unchanged or revised according to simulation studies of upgraded detector.

  • Conservative scenario ("S1"):
    • Use uncertainties of Run-2 measurements, assuming the higher pile-up effects will be compensated by detector upgrades.
Can only present short summary of recent results on a few topics and show their potentials at HL-LHC

- Higgs
- Exotics searches
- Supersymmetry

Projections for HL-LHC can be found in the Yellow Report:
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop
Standard Model Higgs Boson
Updates on $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4l$

• Analyzed ~80 - 140 fb$^{-1}$ Run-2 data
• Measure cross sections of individual production modes
• Study kinematic properties of Higgs production
  • Differential cross section
  • Production rates in excl. regions (simplified template cross section framework (STXS)).
    • Reduce model dependency
    • Maximize sensitivity to BSM

• Up to ~10-15% precision for best channel

ATLAS-CONF-2018-028
ATLAS-CONF-2018-018
CMS PAS HIG-18-029
CMS PAS HIG-19-001
Observation of Higgs Couplings to 3\textsuperscript{rd} Generation Quarks

- $H \rightarrow bb$ finally observed at LHC
- Most sensitive prod. channel : VH
- Include other prod. channel :
  - $ggF$, VBF, $ttH$
- Combined Run1 + Run2 ($\sim 80\text{fb}^{-1}$)
- Observed $H \rightarrow bb$ :
  - ATLAS : $5.4\sigma$, CMS : $5.6\sigma$

\begin{itemize}
  \item New updates from both experiments since observing $ttH$ production
  \item ATLAS (full Run2) : in $\gamma\gamma$
    \begin{itemize}
      \item Obs.(exp.) sign=$4.9$ ($4.2$) $\sigma$
      \item $\sigma_{ttH} \times B_{\gamma\gamma} = 1.59^{+0.43}_{-0.39}$ fb (SM: $1.15^{+0.09}_{-0.12}$ fb)
    \end{itemize}
  \item CMS (2016+2017) :
    \begin{itemize}
      \item update multi-lepton, $\gamma\gamma$, $bb$
      \item Extended categorization, dedicated BDT training, additional observables, new b-tagging
    \end{itemize}
\end{itemize}

\begin{tabular}{c|c|c|c}

<table>
<thead>
<tr>
<th>Decay ch</th>
<th>CMS</th>
<th>ATLAS-CONF-2019-004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-lep</td>
<td>$0.96^{+0.34}_{-0.31}$</td>
<td>$3.2\sigma$</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>$1.7^{+0.6}_{-0.5}$</td>
<td>$4.1\sigma$</td>
</tr>
<tr>
<td>$bb$</td>
<td>$1.15^{+0.32}_{-0.29}$</td>
<td>$3.9\sigma$</td>
</tr>
</tbody>
</table>

\end{tabular}
Higgs Combination

• Combined all major production/decay mode measurements (13 TeV, L~36-80 fb⁻¹)

• Global signal strength: \( \mu_{global} = \frac{\sigma(\text{exp})}{\sigma(\text{SM})} \)

ATLAS: \( \mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05(\text{stat})^{+0.05}_{-0.04}(\text{exp})^{+0.05}_{-0.04}(\text{sign theo}) \pm 0.03(\text{bkg theo}) \)

CMS: \( \mu = 1.17 \pm 0.10 = 1.17 \pm 0.06(\text{stat})^{+0.06}_{-0.05}(\text{sig theo}) \pm 0.06(\text{other syst}) \)

• Productions and decays are already probed with up to ~10-15% precision in best channels

• Extract coupling strength modifiers (in \( \kappa \) framework) as function of particle mass

• Assume no BSM contribution to Higgs decay

• Compatible to SM
Di-Higgs Production

• Observation of di-Higgs production provides a direct measurement of the Higgs boson self-coupling $\lambda_{HHH}$ and validate the BEH mechanism
• Performed search via ggF production in several di-Higgs decay channels

Most sensitive channels:
• $HH\rightarrow bbb\bar{b}$: highest BR, large BG from multi-jets
• $HH\rightarrow b\bar{b}\gamma\gamma$: clean, but small BR
• $HH\rightarrow b\bar{b}\tau\tau$: moderate BG and BR
• $HH\rightarrow b\bar{b}VV$: V(W,Z) decays leptonically

• Analyzed up to 36 fb$^{-1}$ at 13 TeV
• Set limits on $\sigma(gg\rightarrow HH)$ at 95% CL
  • ATLAS: 6.9 (10) $\times$ SM
  • CMS: 22.2 (12.8) $\times$ SM

• Scanned $\kappa_{\lambda} = \frac{\lambda_{HHH}}{\lambda_{SM}}$ (Higgs self-coupling modifier)
  • $\kappa_{\lambda}^{SM} = 1$
• Constraint $\kappa_{\lambda}$ at 95% CL
  • ATLAS: $-5.0 < \kappa_{\lambda} < 12.0$ (exp. $-5.8 < \kappa_{\lambda} < 12.0$)
  • CMS: $-11.8 < \kappa_{\lambda} < 18.8$ (exp. $-7.1 < \kappa_{\lambda} < 13.6$)
Projection of Higgs Measurements at the HL-LHC
Projections for Production and Decay Measurements

- Combined all major production/decay mode measurements (assume S2 scenario)

**Productions (ATLAS+CMS)**

- \( \sigma_{ggF} \) can be measured at \(~2\%\)
- \( \sigma_{WH} \) can be measured at \(~6\%\)

**Decays (ATLAS+CMS)**

- Gauge boson decays can reach \(~3\%\) precision
- Fermion decays (\(bb,\tau\tau\)) can reach \(~3-4\%\)
- \( \mu\mu \) can be observed with \(~8\%\)

In several cases the uncertainties will be dominated by theory.
Projection for Higgs Mass Measurement

• Current PDG average (ATLAS+CMS) $m_H = 125.10 \pm 0.14$ GeV (from $\gamma\gamma$, 4l(ZZ*) )
• $\gamma\gamma$ is now systematically limited
• 4l is statistically limited
  • Mass value will be driven by 4l (muon) channel

• Extrapolate ATLAS Run2 4$\mu$ results to 3000 fb$^{-1}$ in four scenarios
  • Total uncertainty vary between 33 to 52 MeV

<table>
<thead>
<tr>
<th>Expected Higgs mass precision with 3 ab$^{-1}$ (ATLAS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta_{tot}$ (MeV)</td>
</tr>
<tr>
<td>Current Detector</td>
</tr>
<tr>
<td>$\mu$ momentum resolution improvement by 30% or similar</td>
</tr>
<tr>
<td>$\mu$ momentum resolution/scale improvement of 30% / 50%</td>
</tr>
<tr>
<td>$\mu$ momentum resolution/scale improvement 30% / 80%</td>
</tr>
</tbody>
</table>

• Expect better resolution from CMS due to stronger magnetic field
  • $\Rightarrow$ expect uncertainty $< 20$ MeV when combining CMS and ATLAS

LHC Run1 : PRL 114 (2015) 191803
CMS (Run2, 36 fb$^{-1}$, 4l) : JHEP 11 (2017) 047
ATLAS (Run2, 36 fb$^{-1}$, $\gamma\gamma$, 4l) : PLB 784 (2018) 345
Projections for Differential Distributions Measurements

- Important to measure the differential distributions of Higgs production
  - Provide a probe of the SM
  - Constraint effects from beyond the SM
- Make projections based on Run 2 analyses
- Most precisely measured by $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4l$ channels

- Expect to probe with precision of $\sim 10\%$ at $p_T^H \sim 350-600$ GeV
Projections for Rare Higgs Decays

- **$H \rightarrow cc$**

  - Extrapolate from Run2 36 fb$^{-1}$ search in $pp \rightarrow ZH \rightarrow llcc$
  - Expect to set an upper limit on $\sigma \times BR$ at 95% CL of 6.3$x$SM
    - Current limit : 110$x$SM
  - Sensitivity can further improve by including other channels :
    - $WH \rightarrow l\nu cc$
    - $ZH \rightarrow \nu\nu cc$

- **$H \rightarrow \mu\mu$**

  - Expect to observe such decay via $ggH$ and VBF productions with significance $>9\sigma$ and uncertainty on $\sigma \times BR < 13\%$
  - Current limit : $\sigma \times BR < 2.1-2.9 \times$SM
Projections for Higgs to Invisible Decays

• In some BSM Higgs boson may act as a portal between SM sector and dark sector
  • => Higgs can decay into dark matter particles (invisible decay)

• Potential is studied with VBF channel
• Pileup suppression will be very important
  • Degrade MET resolution
  • False identification of pileup jets as VBF jets in forward region
• Expected reach of upper limit BR(H→inv)~3.8% at 95% CL (assume SM VBF production)
  • 5X smaller than current best limit
  • SM: BR(H→ZZ→νννν) ~ 0.1%

In some BSM Higgs boson may act as a portal between SM sector and dark sector
  => Higgs can decay into dark matter particles (invisible decay)
Di-Higgs: Projection for HL-LHC

- Extrapolation based on current analyses and on the estimate of upgraded detector performance

- Vary the scenarios of systematic uncertainties
- High pileup at HL-LHC may require to raise trigger threshold (maybe a challenge for $b\bar{b}b\bar{b}$ channel)

**ATLAS**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Statistical-only</th>
<th>Statistical + Systematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$HH \rightarrow b\bar{b}b\bar{b}$</td>
<td>1.4</td>
<td>0.61</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}\tau^+\tau^-$</td>
<td>2.5</td>
<td>2.1</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}\gamma\gamma$</td>
<td>2.1</td>
<td>2.0</td>
</tr>
<tr>
<td>Combined</td>
<td>3.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>

**Significance**

- Combine ATLAS + CMS: 4.0 $\sigma$ (stat.+syst.) (4.5 $\sigma$ (stat. only))
- Precision of self-coupling modifier $\kappa_\lambda$ can reach ~50%
- May even reach the discovery level of di-Higgs production at the end of HL-LHC!
Search for New Physics: Exotics, SUSY
New Heavy Resonances

- Predicted by several beyond Standard Models theories

- Spin-0:
  - Higgs like particles in Minimal Supersymmetric SM (MSSM)

- Spin-1:
  - New gauge bosons (e.g. $W'$, $Z'$) in extended Gauge Symmetry or in Heavy Vector Triplet (HVT) model

- Spin-2:
  - Graviton as Kaluza-Klein excitation in models of Extra Dimensions

- Excited quarks: in compositeness model

Leads to final states signature: di-lepton, di-jet, di-boson
Resonance Search: di-lepton, lepton+$E_T^{\text{miss}}$

- Sensitive to heavy gauge boson from new symmetries
- Searched using full Run2 dataset in $ee$, $\mu\mu$ or $e/\mu+E_T^{\text{miss}}$ final states
- Search for bumps: no anomaly seen
- Set upper limits (at 95% CL) on heavy resonance mass for various models

<table>
<thead>
<tr>
<th>Model</th>
<th>Lower limits on $m_{Z'}$ [TeV]</th>
<th>Lower limits on $m_{\ell\ell}$ [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$ee$</td>
<td>$\mu\mu$</td>
</tr>
<tr>
<td>$Z'_\psi$</td>
<td>4.1</td>
<td>4.0</td>
</tr>
<tr>
<td>$Z'_\chi$</td>
<td>4.6</td>
<td>4.2</td>
</tr>
<tr>
<td>$Z'_{\text{SSM}}$</td>
<td>4.9</td>
<td>4.5</td>
</tr>
</tbody>
</table>

- Lower limits on SSM $W' (\rightarrow \ell\nu)$
  - exclude mass below 6 TeV (5.8 TeV exp)

SSM: Sequential SM, assume same fermion couplings as SM
Highest di-electron Mass Event at ATLAS

\[ m_{ee} = 4.06 \text{ TeV} \]
Resonance Search: di-jet, di-boson

• Set limits on various models in narrow-width approximation

<table>
<thead>
<tr>
<th>Excited Quark</th>
<th>Obs. (TeV)</th>
<th>Exp. (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS (139 fb⁻¹)</td>
<td>&lt;6.7</td>
<td>&lt;6.4</td>
</tr>
<tr>
<td>CMS (77.8 fb⁻¹)</td>
<td>&lt;6.0</td>
<td>&lt;6.0</td>
</tr>
</tbody>
</table>

• Also set upper limits on Gaussian-shaped signals of various widths in di-jet mass distribution

• Search for X→VV→qqqq (V=W or Z)

• Use large-radius jet substructure to identify W or Z decays to hadrons

• Constraint extra dimension and heavy bosons models
  • E.g. exclude Heavy Vector Triplet W’/Z’ masses below ~3 – 3.8 TeV

ATLAS-CONF-2019-007  CMS PAS EXO-17-026
Prospect of Heavy Resonance Search at HL-LHC
Resonance Search: di-lepton, lepton+$E_T^{miss}$

- Extend $Z'$ SSM exclusion limit by $\sim 1.4$ TeV
- Overall uncertainty $\sim 6.5\% \times m_{ll}$ [TeV]
  - expt. (rec. Id, resolution) : $\sim 2.9\% \times m_{ll}$ [TeV]
  - theory (dominated by PDF) : $\sim 5.6\% \times m_{ll}$ [TeV]

<table>
<thead>
<tr>
<th>Model</th>
<th>HL-LHC Exclusion [TeV]</th>
<th>Discovery [TeV]</th>
<th>Run2 (139 fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z'(SSM)$</td>
<td>6.5</td>
<td>6.4</td>
<td>5.1</td>
</tr>
<tr>
<td>$Z'(\psi)$</td>
<td>5.8</td>
<td>5.7</td>
<td>4.5</td>
</tr>
</tbody>
</table>

$W'^{SSM}$

<table>
<thead>
<tr>
<th></th>
<th>HL-LHC Exclusion [TeV]</th>
<th>Discovery [TeV]</th>
<th>Run2 Exclusion [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS (e$\nu$, $\mu\nu$)</td>
<td>7.9</td>
<td>7.7</td>
<td>5.8 (139 fb$^{-1}$)</td>
</tr>
<tr>
<td>CMS ($\tau_h\nu$)</td>
<td>7.0</td>
<td>6.4</td>
<td>4.0 (36 fb$^{-1}$)</td>
</tr>
<tr>
<td>ATLAS ($\tau_h\nu$)</td>
<td></td>
<td></td>
<td>3.8 (36 fb$^{-1}$)</td>
</tr>
</tbody>
</table>

- Extend exclusion $W'^{SSM}$ mass by $\sim 2$ TeV
Dark Matter Searches

• At LHC dark matter (DM) can be produced via decay of a mediator (med) to the dark sector, and indirectly detected by measuring the SM particles recoiling against it.

• Signature: Large $E_T^{\text{miss}} + X$
  
  Mono-Z ($E_T^{\text{miss}} + 2\text{leptons}$)  
  (Exclusion)

  Mono-jet ($E_T^{\text{miss}} + \text{jet}$)  
  (Exclusion)

  Searches are sensitive to systematic uncertainties

Large improvement compared to current LHC results!

CMS, 36fb$^{-1}$  

CMS PAS FTR-18-007

ATLAS, 36fb$^{-1}$  
JHEP 01 (2018) 126

ATLAS Simulation Preliminary

$\sqrt{s} = 13$ TeV, 3 ab$^{-1}$

Axial-Vector Mediator

Dirac Fermion DM

$g_q = 0.25$, $g_{DM} = 1.0$

95% CL limits

Projection from Run-2 data

Discovery could be reached for a signal with DM mass of 1 GeV and mediator mass of 2.25 TeV
Long Lived Dark-Photons

• In some BSM a pair of long lived dark-photons ($\gamma_d$) can be produced from Higgs boson decay ($H \rightarrow 2\gamma_d + X$)
• Each dark-photon can decay to a pair of displaced muons
• Dedicated triggers are required to select events with displaced $\mu$ pairs
• Specially designed low level triggers and muon detector upgrade from ATLAS at HL-LHC can improve search sensitivity

![Image](image_url)

- Additional inner muon RPC layer
- Dedicated trigger algorithm to select multi-$\mu$ in a single “region of interest”
- Overall efficiency improvement ~7%

• Expected $c\tau$ range exclusion at 95% CL:

<table>
<thead>
<tr>
<th>Excluded $c\tau$ [mm]</th>
<th>Run-2 (3.4 fb$^{-1}$)</th>
<th>Run-3</th>
<th>HL-LHC</th>
<th>HL-LHC w/ L0 muon-scan</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{BR}(H \rightarrow 2\gamma_d + X)=10%$</td>
<td>$2.2 \leq c\tau \leq 111$</td>
<td>$1.15 \leq c\tau \leq 435$</td>
<td>$0.97 \leq c\tau \leq 553$</td>
<td>$0.97 \leq c\tau \leq 597$</td>
</tr>
<tr>
<td>$\text{BR}(H \rightarrow 2\gamma_d + X)=1%$</td>
<td>-</td>
<td>$2.76 \leq c\tau \leq 102$</td>
<td>$2.18 \leq c\tau \leq 142$</td>
<td>$2.13 \leq c\tau \leq 148$</td>
</tr>
</tbody>
</table>

(assume $\text{BR}(\gamma_d \rightarrow \mu\mu)=45\%$)
Projection for Stau Search

- Models with light staus can lead to a dark matter relic density consistent with cosmological observation

- Interesting to search for pair production of staus at the LHC

- Assume:
  - Degenerate scenario: \( m(\tilde{\tau}_L) = m(\tilde{\tau}_R) \)
  - \( \tilde{\tau} \rightarrow \tau + \tilde{\chi}_1^0 \)

- Search in signatures of:
  - two hadronically decaying taus
  - mixed hadronic / lepton

- Can exclude stau up to mass \( \sim 650 \) GeV and discovery reach up to \( \sim 450 \) GeV for massless neutralino.
Projection for Higgsino-like Charginos and Neutralinos Search

- In natural supersymmetry scenario mass difference between the light Higgsino-like charginos and neutralinos ($\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^0$) can be small
  - This could lead to soft objects in final state
- Require a jet from initial state radiation (ISR) to boost the sparticle system in order to trigger on the signals
- Need efficient reconstruction of lepton down to a few GeV

- Can exclude $m(\tilde{\chi}_2^0)$ up to ~350 GeV
- Large gain in expected sensitivity with respect to latest full Run2 results

ATLAS Simulation Preliminary
$\sqrt{s}=14$ TeV, 3000 fb$^{-1}$
All limits at 95% CL
Soft Lepton analysis

ATLAS @140 fb$^{-1}$ (expected)
ATLAS-CONF-2019-014
Searches with Displaced Vertex Signature

• A long lived particle may decay within the tracking detector and lead to a displaced vertex signature
• Larger silicon tracking volume could detect longer lived particles

• ITK detector:
  • Larger eta coverage and larger silicon volume
  • Lower material budget

• Well reconstructed vertex require minimum number of silicon hits after decay

ITK extends the high hit acceptance to larger decay radius

• Use the search for pair production of long lived gluino as an example to study the improvement gain with the new all-silicon tracking detector
### Exotics/SUSY Search Reach at HL-LHC

<table>
<thead>
<tr>
<th>Model</th>
<th>spin</th>
<th>95% CL Limit (solid), 5 σ Discovery (dash)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KK → 4b</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>HVT → VV</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>G_Rs → W^+W^-</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>G_Rs → tt</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Z_{TC2} → tt</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Z_{SSM} → tt</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Z_{ς} → ℓ⁺⁻</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Z_{SSM} → ℓ⁺⁻</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>W_{SSM} → ℓν</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>W_{SSM} → ℓν</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Q → jj</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>v_{Mapara} → ℓ⁺qq'</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>v_{Heavy} (m_{H} = m_{t})</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>ℓ⁺⁻ → ℓ⁺⁻</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>LQ(pair prod.) → bτ</td>
<td>0</td>
<td>HE-LHC</td>
</tr>
<tr>
<td>LO → 1µ</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>LO → 1τ</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>H^+H^- → τ±e±e±e± (NH)</td>
<td>1</td>
<td>HL-LHC</td>
</tr>
<tr>
<td>H^+H^- → τ±e±e±e± (IH)</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

### Section 6.1.1

**HL/HE-LHC SUSY Searches**

<table>
<thead>
<tr>
<th>Model</th>
<th>Jets</th>
<th>Mass Limit</th>
<th>Simulation Preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>τν, τν, τν</td>
<td>4 jets</td>
<td>2.0 (0.2) TeV</td>
<td>m_{τν} &lt; 15 TeV</td>
</tr>
<tr>
<td>τν, τν, τν</td>
<td>4 jets</td>
<td>5.2 (0.7) TeV</td>
<td>m_{τν} &lt; 15 TeV</td>
</tr>
<tr>
<td>τν, τν, τν</td>
<td>Multiple</td>
<td>2.3 (0.5) TeV</td>
<td>m_{τν} &lt; 15 GeV</td>
</tr>
<tr>
<td>τν, τν, τν</td>
<td>Multiple</td>
<td>2.4 (0.6) TeV</td>
<td>m_{τν} &lt; 15 GeV</td>
</tr>
<tr>
<td>τν, τν, τν</td>
<td>Multiple</td>
<td>3.8 (0.8) TeV</td>
<td>m_{τν} &lt; 15 GeV</td>
</tr>
</tbody>
</table>

**Sim. Preliminary**

<table>
<thead>
<tr>
<th>V_{LHC} = 14, 27 TeV</th>
</tr>
</thead>
</table>

### Mass scale [TeV]

- Many more projection studies on Exotic/SUSY searches can be found at:

arXiv:1812.07831
Summary

• Many new results from ATLAS and CMS on the Run2 data have improved upon the measurements not just with more data but also with improvement in the analysis methods.

• Tremendous work has been performed by the community to determine the physics potential at the HL-LHC
  
  • Higgs productions and decays can be measured to a precision of a few percent and we may reach the discovery level of di-Higgs production at the end of HL-LHC
  
  • Large extensions can be made for Beyond SM searches with more data and improve detector performance

• However reduction of systematic uncertainties, improvement of theoretical understanding and innovation of advanced techniques will be important for the success of the HL-LHC program.

ATLAS and CMS public projection studies:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies
Backup
• Have only collected ~5% of the total dataset so far
Production and Decay

<table>
<thead>
<tr>
<th>Higgs decay</th>
<th>BR (%)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>bb</td>
<td>58</td>
<td>observed</td>
</tr>
<tr>
<td>WW</td>
<td>22</td>
<td>observed</td>
</tr>
<tr>
<td>ττ</td>
<td>6.3</td>
<td>observed</td>
</tr>
<tr>
<td>cc</td>
<td>2.9</td>
<td>limits</td>
</tr>
<tr>
<td>ZZ</td>
<td>2.8</td>
<td>observed</td>
</tr>
<tr>
<td>γγ</td>
<td>0.23</td>
<td>observed</td>
</tr>
<tr>
<td>Zγ</td>
<td>0.15</td>
<td>limits</td>
</tr>
<tr>
<td>μμ</td>
<td>0.022</td>
<td>limits</td>
</tr>
</tbody>
</table>

Higgs decay BR (%) table:

- **bb**: 58 (observed)
- **WW**: 22 (observed)
- **ττ**: 6.3 (observed)
- **cc**: 2.9 (limits)
- **ZZ**: 2.8 (observed)
- **γγ**: 0.23 (observed)
- **Zγ**: 0.15 (limits)
- **μμ**: 0.022 (limits)

Production and decay processes:
- **Gluon fusion** (ggH)
- **Vector boson fusion** (VBF)
- **Associated production with W/Z** (WZH)
- **Associated production with tt** (ttH)

Higgs mass: $m_H = 125$ GeV

Production cross-section ($\sigma(pp \rightarrow H+X)$) vs. $\sqrt{s}$ (in pb)
Fermions : $H \rightarrow \tau\tau$

- One of the decay channels to establish direct evidence for Yukawa couplings to fermions
- Observed in Run 1 by combining ATLAS and CMS. Obs. significance = 5.5 $\sigma$
- Later observed by individual experiment
- Recent update from CMS (77.4 fb$^{-1}$)
  - Focus on ggH and VBF production
  - Employ NN classification to categorize signal and BG, improve sensitivity
- Measure cross sections of different production modes and kinematic regions

![Graph showing signal at high S/(S+B) region]

$\mu = 1.09^{+0.27}_{-0.26}$ from analysis with 36 fb$^{-1}$
Rare and Invisible Decays

• Direct searches for $H \rightarrow cc$, $\mu\mu$ to probe couplings to 2\textsuperscript{nd} generation fermions
  • $H \rightarrow cc$ (13 TeV, 36 fb\textsuperscript{-1})
  • Difficult: large BG, challenging c-jet ID
    • c-jet tag eff. $\sim$40%, b-/l-jet rejection $\sim$4X/$\sim$20X
  • Upper limit on $\sigma(ZH \rightarrow llcc)$
    • Obs < 2.7 pb (110×SM)

• $H \rightarrow \mu\mu$: very small decay branching ratio
• Search signal mainly from ggH and VBF production

<table>
<thead>
<tr>
<th>Expt.</th>
<th>Limit $\sigma \times BR$</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>2.1 (2.0)</td>
<td>Run2(80fb\textsuperscript{-1})</td>
</tr>
<tr>
<td>CMS</td>
<td>2.9 (2.2)</td>
<td>Run1+Run2(36fb\textsuperscript{-1})</td>
</tr>
</tbody>
</table>

• In some BSM Higgs boson may act as a portal between SM sector and dark sector
  • $\Rightarrow$ Higgs can decay into dark matter particles (invisible decay)

• Perform direct searches in:
  • ggH : $H \rightarrow$ inv
  • VBF : qq→qqH→qq+inv (most sensitive)
  • VH : V→ll,qq, $H \rightarrow$ inv
  • ttH : $H \rightarrow$ inv (not in CMS combination)

• Combined results from all channels, set limit on BR($H \rightarrow$ inv) at 95%CL:
  • ATLAS : BR($H \rightarrow$ inv)<0.26 (0.17\textsuperscript{+0.07}_{0.05})
  • CMS : BR($H \rightarrow$ inv)<0.19 (0.15)
Highest di-jet Mass Event at CMS

- Consists of 2 wide jets
- $m_{JJ} = 8$ TeV
Resonance Search: di-boson

- Projection is studied for $X \rightarrow WV$, $W \rightarrow l\nu$ and $V(W,Z) \rightarrow qq$
- Search for heavy resonance in ggF/qq and VBF production modes, and in resolved and boosted categories (for the decay of $V$)
- Search prospect is interpreted in context of HVT, bulk RS model, narrow heavy scalar resonance

- Expected exclusion limits at 95% CL

<table>
<thead>
<tr>
<th>Model</th>
<th>HL-LHC</th>
<th>13 TeV, 36 fb-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVT, model A</td>
<td>4.9 TeV</td>
<td>2.9 TeV</td>
</tr>
<tr>
<td>$W'$</td>
<td>4.9 TeV</td>
<td>2.85 TeV</td>
</tr>
</tbody>
</table>

- $5\sigma$ discovery reach is up to $\approx 3.5$ TeV
- Additional improvement in W/Z tagger can extend reach to $\approx 3.9$ TeV

Expected exclusion limits at 95% CL
Long Lived Charginos and Neutralinos

• Near mass degenerate of light charginos and neutralinos may become long lived as a consequence of the heavy higgsinos

• Can use the MIP Timing Detector (MTD) of CMS HL-LHC to improve the search sensitivity

• MTD can measure minimum ionizing particles (MIPs) with time resolution of ~30ps

• Can assign timing for each vertex
  • Measure TOF of long lived particles

• Use the measured displacement between the vertices in space and time and the energy of the visible decay products ($Z^* \rightarrow ll$) to construct the $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$

• Can use $\Delta m$ as an additional discriminating variable to improve the search sensitivity

CMS CERN-LHCC-2017-027
Updates on $H \rightarrow \gamma \gamma$, $H \rightarrow ZZ^* \rightarrow 4l$

CMS Preliminary

137.1 fb$^{-1}$ (13 TeV)

For presentation purpose
Projections for Differential Distributions Measurements

\[ \Delta \sigma / \Delta p_T^H \text{ (pb/GeV)} \]

CMS *Projection* 3000 fb\(^{-1}\) (13 TeV)

- w/ YR18 syst. uncert. (S2)
  - \( \Delta \sigma(p_T^H > 600) / 250 \)
  - \( \Delta \sigma(p_T^H > 200) / 120 \)
  - \( \Delta \sigma(p_T^H > 600) / 250 \)

- Combination
- \( H \to bb \)
- \( H \to \gamma \gamma \)
- \( H \to ZZ \)
- aMC@NLO, NNLOPS

\[ \sigma_{SM} \text{ from CYRM-2017-002} \]

\[ \text{Ratio to prediction} \]

\[ p_T^H (\text{GeV}) \]

ATLAS Preliminary
Projection from Run 2 data
\( \sqrt{s}=14 \text{ TeV}, 3000 \text{ fb}^{-1} \)
\( H \rightarrow \gamma \gamma + H \rightarrow ZZ \rightarrow 4l \)

**Run2 systematics**

Scaled to expectation for HL-LHC

### Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Scale Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy scale, forward region</td>
<td>Set to 0</td>
</tr>
<tr>
<td>Jet energy scale, Jet punch-through</td>
<td>Set to 0</td>
</tr>
<tr>
<td>High-( p_T ) jet energy scale</td>
<td>Set to 0</td>
</tr>
<tr>
<td>( H \rightarrow \gamma \gamma ) background modeling</td>
<td></td>
</tr>
<tr>
<td>( 4\ell ) ( m_H )</td>
<td>Scaled by 0.25</td>
</tr>
<tr>
<td>PDF</td>
<td>Scaled by 0.41</td>
</tr>
<tr>
<td>Jet flavor</td>
<td>Scaled by 0.5</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>Scaled by 0.5</td>
</tr>
<tr>
<td>Pileup modelling</td>
<td>Scaled by 0.5</td>
</tr>
<tr>
<td>QCD scale</td>
<td>Scaled by 0.5</td>
</tr>
<tr>
<td>Underlying event and parton shower modeling</td>
<td>Scaled by 0.5</td>
</tr>
<tr>
<td>Higgs branching ratios</td>
<td>Scaled by 0.5</td>
</tr>
<tr>
<td>Photon energy scale and resolution</td>
<td>Scaled by 0.8</td>
</tr>
<tr>
<td>Photon reconstruction, ID, and isolation</td>
<td>Scaled by 0.8</td>
</tr>
<tr>
<td>( qq \rightarrow ZZ ) irreducible background</td>
<td>Set to 2%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>Set to 1% of expected integrated luminosity</td>
</tr>
</tbody>
</table>
Projection for Higgsino-like Charginos and Neutralinos Search

Softer MET cut compare to HL-LHC projection study

ATLAS @140 fb^{-1} (expected)
ATLAS-CONF-2019-014
# Possible HL-LHC Triggers

Table 2: Representative trigger menu for ATLAS operations at the HL-LHC. The offline $p_T$ thresholds indicate the momentum above which a typical analysis would use the data. Where multiple object triggers are described only one threshold is given if both objects are required to be at the same $p_T$; otherwise, each threshold is given with the two values separated by a comma. In the case of the $e - \mu$ trigger in Run 2, two sets of thresholds were used depending on running period, and both are listed. This table is a subset of Table 6.4 from the TDAQ TDR [10].

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>isolated single $e$</td>
<td>25</td>
<td>27</td>
<td>22</td>
</tr>
<tr>
<td>isolated single $\mu$</td>
<td>25</td>
<td>27</td>
<td>20</td>
</tr>
<tr>
<td>single $\gamma$</td>
<td>120</td>
<td>145</td>
<td>120</td>
</tr>
<tr>
<td>forward $e$</td>
<td></td>
<td></td>
<td>35</td>
</tr>
<tr>
<td>di-$\gamma$</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>di-$e$</td>
<td>15</td>
<td>18</td>
<td>10</td>
</tr>
<tr>
<td>di-$\mu$</td>
<td>15</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>$e - \mu$</td>
<td>17.6</td>
<td>8,25 / 18,15</td>
<td>10</td>
</tr>
<tr>
<td>single $\tau$</td>
<td>100</td>
<td>170</td>
<td>150</td>
</tr>
<tr>
<td>di-$\tau$</td>
<td>40,30</td>
<td>40,30</td>
<td>40,30</td>
</tr>
<tr>
<td>single $b$-jet</td>
<td>200</td>
<td>235</td>
<td>180</td>
</tr>
<tr>
<td>single jet</td>
<td>370</td>
<td>460</td>
<td>400</td>
</tr>
<tr>
<td>large-$R$ jet</td>
<td>470</td>
<td>500</td>
<td>300</td>
</tr>
<tr>
<td>four-jet (w/ $b$-tags)</td>
<td></td>
<td>45(1-tag)</td>
<td>65(2-tags)</td>
</tr>
<tr>
<td>four-jet</td>
<td>85</td>
<td>125</td>
<td>100</td>
</tr>
<tr>
<td>$H_T$</td>
<td>700</td>
<td>700</td>
<td>375</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>150</td>
<td>200</td>
<td>210</td>
</tr>
<tr>
<td>VBF inclusive (di-jets)</td>
<td></td>
<td></td>
<td>2x75 w/ $(\Delta \eta &gt; 2.5$ &amp; $\Delta \phi &lt; 2.5)$</td>
</tr>
</tbody>
</table>
### Example of S1 and S2 Uncertainty Scenarios

**Table 1:** The **sources** of systematic uncertainty for which minimum values are applied in S2.

<table>
<thead>
<tr>
<th>Source</th>
<th>Component</th>
<th>Run 2 uncertainty</th>
<th>Projection minimum uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon ID</td>
<td></td>
<td>1–2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Electron ID</td>
<td></td>
<td>1–2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Photon ID</td>
<td></td>
<td>0.5–2%</td>
<td>0.25–1%</td>
</tr>
<tr>
<td>Hadronic tau ID</td>
<td></td>
<td>6%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>Absolute</td>
<td>0.5%</td>
<td>0.1–0.2%</td>
</tr>
<tr>
<td></td>
<td>Relative</td>
<td>0.1–3%</td>
<td>0.1–0.5%</td>
</tr>
<tr>
<td></td>
<td>Pileup</td>
<td>0–2%</td>
<td>Same as Run 2</td>
</tr>
<tr>
<td></td>
<td>Method and sample</td>
<td>0.5–5%</td>
<td>No limit</td>
</tr>
<tr>
<td></td>
<td>Jet flavour</td>
<td>1.5%</td>
<td>0.75%</td>
</tr>
<tr>
<td></td>
<td>Time stability</td>
<td>0.2%</td>
<td>No limit</td>
</tr>
<tr>
<td>Jet energy res.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MET scale</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b-Tagging</td>
<td>b-/c-jets (syst.)</td>
<td>Varies with $p_T$ and $\eta$</td>
<td>Half of Run 2</td>
</tr>
<tr>
<td></td>
<td>light mis-tag (syst.)</td>
<td>Varies with $p_T$ and $\eta$</td>
<td>Same as Run 2</td>
</tr>
<tr>
<td></td>
<td>b-/c-jets (stat.)</td>
<td>Varies with $p_T$ and $\eta$</td>
<td>Same as Run 2</td>
</tr>
<tr>
<td></td>
<td>light mis-tag (stat.)</td>
<td>Varies with $p_T$ and $\eta$</td>
<td>No limit</td>
</tr>
<tr>
<td>Integrated lumi.</td>
<td></td>
<td>2.5%</td>
<td>1%</td>
</tr>
</tbody>
</table>
Resonance Search: di-boson

**ATLAS Preliminary**

\[ \sigma (p p \rightarrow V') \times \mathcal{B}(V' \rightarrow WW + WZ) \] [fb]

\[ m(V') \text{ [TeV]} \]

- Phys. Lett. B 777 (2018) 91 (36.7 fb\(^{-1}\))
- Phys. Lett. B 777 (2018) 91 (Scaled to 139 fb\(^{-1}\))
- Current Result (139 fb\(^{-1}\))

**CMS Preliminary**

\[ \sigma \times \mathcal{B}(G_{\text{bulk}} \rightarrow WW) \] [pb]

\[ m_{G_{\text{bulk}}} \text{ [GeV]} \]

- Expected limits
  - Phys. Rev. D97, 072006, 35.9 fb\(^{-1}\)
  - This analysis 35.9 fb\(^{-1}\)
  - This analysis 77.3 fb\(^{-1}\)

\( \sqrt{s} = 13 \text{ TeV} \)