ATLAS and CMS prospects for Higgs measurements and searches at the High Luminosity LHC

Evangelos –Leonidas Gkougkousis (IFAE)

On behalf of the ATLAS & CMS collaborations

OAC– July 11th, 2018
Introduction

- LHC Timeline and planning
- HL-LHC Conditions
- ATLAS & CMS Detector Upgrades
- Strategies for Prospects estimation

Di-boson channels

- Higgs Couplings (ATLAS)
- $H \rightarrow \gamma\gamma$ (CMS)
- $H \rightarrow ZZ^* \rightarrow 4l$ (ATLAS + CMS)
- $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ (ATLAS)

Di-fermion channels

- $H \rightarrow \mu^+\mu^-$ (ATLAS + CMS)
- $H \rightarrow \tau\tau$ (CMS)
- $H \rightarrow cc$ (ATLAS)

Di-Higgs channels

- HH Mechanisms
- $H(\rightarrow \gamma\gamma)H(\rightarrow bb)$ (ATLAS)
- $H(\rightarrow bb)H(\rightarrow bb)$ (ATLAS)
- HH sensitivity (CMS)

BSM Searches

- Di-Higgs Resonances (CMS)
- $H \rightarrow \tau\tau$ (CMS)

Conclusions

- Conclusions and Outlook
• Related Talks

ATLAS and CMS

**General**
- Louis Fayard – Tuesday July 10th
  “BEH at LHC from the start of data taking until precision measurements and HL-LHC”
  [https://indico.cern.ch/event/663474/contributions/3063474/](https://indico.cern.ch/event/663474/contributions/3063474/)

**CMS**
- Colin Jessop – Wednesday July 11th
  “Upgrades, future plans and prospects (CMS)”
  [https://indico.cern.ch/event/663474/contributions/3063607/](https://indico.cern.ch/event/663474/contributions/3063607/)

**ATLAS**
- Christos Lampoudis – Wednesday July 11th
  “The Micromegas construction project for the ATLAS New Small Wheel”
  [https://indico.cern.ch/event/663474/contributions/3061222/](https://indico.cern.ch/event/663474/contributions/3061222/)
• Towards HL-LHC

Timeline and planning

LHC / HL-LHC Plan

- Higgs Discovery
  - September 2012

- Phase 0 upgrades
  - ATLAS
    - IBL
    - MTDs
  - CMS
    - L1 trigger
    - Muon acceptance

- Phase 1 upgrades
  - ATLAS
    - AFP
  - CMS
    - FTK
    - L1 LAr Trigger
    - Muon Small Wheel
    - Pixel tracker replacement
    - HCAL photodetectors

- Phase 2 upgrades
  - Barrel MTDs
  - ITk
  - HGTD
  - Inner Tracker
  - HCAL
  - Endcap EMCAL
  - Timing layer

- PileUp ≈ 34.4 (2017)
- PileUp ≈ 13
- PileUp ≈ 200
• HL-LHC Conditions

Pileup density

Luminosity
✓ Phase I: $< 2.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} (300 \text{ fb}^{-1})$
✓ Phase-II: $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} (3000 \text{ fb}^{-1})$

Conditions
✓ 14 TeV center of mass energy beam - 6000 primary tracks per event
✓ No. of collisions per crossing from 34 to 200 within 150 ps at 50 mm space
✓ Extended tracking up to $|\eta| < 4.0$

Major Challenge: PileUp

“Stochastic” pileup jet

Hard scatter jet

QCD pileup jet

* $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} (4000 \text{ fb}^{-1})$
• HL-LHC Conditions

Pileup density

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**ATLAS @ HL-LHC**

**In Short…..**

- **AToroidal LHC Apparatus**
  - Biggest LHC experiment with several sub-detectors
    - 2.6 T – 5.3 m long Central solenoid
    - 3.1 T – 20.1m barrel toroid
    - ~ 139 fb⁻¹ total integrated luminosity

**TDAQ System**
- New DAQ high rate (FELIX) boards
- Distributed FPGA communication

**Inner Tracker (iTk)**
- 5 pixel & 4 strip barrel layers
- Coverage up to |\(\eta| < 4.0
- 180 m² of Si, 2 – 3 billion channels

**LAr & Tile CAL electronics**
- New 12 bit digitization boards at 40MHz
- New pre-processors with 140Tb/s for Lar and 80Tb/s for Tile

**Inner Muon Spectrometer**
- New on and off detector and trigger electronics
- Additional RPCs and new MDTs in barrel region

**High Granularity Timing detector**
- < 30 psec/ track timing resolution
- 2.4 < \(\eta <4.0\), 2 Silicon based, layers/side

**Phase II Detector Upgrades**

E. L. Gkougkousis 11 / 7 / 2018
**Phase II Detector Upgrades**

**CMS @ HL-LHC**

- **CMS Tracker**
  - 4 pixel & 6 strip barrel layers, fully silicon
  - Coverage up to $|\eta| < 4.0$
  - 100 m$^2$ of pixels Si, 1.9 – 2 billion channels

**Barrel and end-cap ECAL/HCAL**

- New barrel readout electronics
- 12 bit 160 MHz ASIC
- Crystal Colling to 8 - 6 °C
- LYSO Crystals in endcap region

**Muon system**

- Improve coverage in $1.5 \leq |\eta| \leq 2.4$
- Extend to $|\eta| \leq 3.0$ using GEM/ RPCs

**Timing Layer**

- LYSO + SiPMs in barrel region
- LGADs in forward region
- < 30 psec per track, single layer
- Full coverage

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**Compact Muon Solenoid**

- Heaviest LHC experiment with several sub-detectors
  - 4 T – 12.5 m long solenoid
  - 10000 t. steel return yoke
- ~ 142.8 fb$^{-1}$ total integrated luminosity

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For details see Colin’s Talk here
• Physics results projection

HL-LHC Promises

Increased statistics

✓ Significant increase in production cross section from $\sqrt{s}=13$ TeV to $\sqrt{s}=14$ TeV
✓ 3000 fb$^{-1}$ very useful to test Higgs properties and have global picture of couplings to initial and final state particles
✓ Shape of the Higgs potential (HH)

Precision measurements

✓ Achieve high-precision measurements on coupling and signal strengths and access to sensitivity for possible deviations to SM values revealing New Physics
✓ Sensitivity to rare decays ($H\rightarrow J/\psi\gamma$, $H\rightarrow Z\gamma$)
✓ Couplings with 2$^{nd}$ generation fermions ($H\rightarrow \mu\mu$)

New Physics

✓ Heavy resonances decaying to di-higgs pairs
✓ Extended Higgs Sector
• Physics results projection

ATLAS Strategy

Samples
✓ Truth-level 14 TeV samples
✓ PileUp overlay in an event by event basis from fully simulated samples
✓ Extrapolated results from Run I - II

HL-LHC Performances
✓ Detector performances extracted from single particle fully simulated samples
✓ Applied in form of $P_T/\eta$ dependent smearing on truth quantities
✓ Efficiencies for $e$, $\mu$, $\tau$, $\gamma$, jets (b-tagging and tracking), $E_{T\text{miss}}$ and trigger

Theoretical Uncertainties (3 options)
✓ Same as for Run II
- or - ✓ Neglected w/r to smearing uncertainties
- or - ✓ ½ of current uncertainty

Effort toward a unified ATLAS-CMS approach
• Physics results projection

CMS Strategy

**Samples**
✓ Extrapolation of analyses performed at 13 TeV on 2015 (2.3-2.7 fb\(^{-1}\)) or 2016 datasets (12.9 fb\(^{-1}\))
✓ PileUp not simulated. Implemented as a detector performance degradation

**HL-LHC Performances and uncertainties**
✓ Several scenarios exist:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Syst. &amp; theor. uncertainties</th>
<th>High-PU + detector improvements</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>constant</td>
<td>no</td>
<td>All systematic uncertainties are kept constant.</td>
</tr>
<tr>
<td>S1+</td>
<td>constant</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>scaled</td>
<td>no</td>
<td>Theoretical uncertainty (\times \frac{1}{2}), experimental systematic uncertainty (\propto 1/\sqrt{L}) until detector-driven lower limit reached.</td>
</tr>
<tr>
<td>S2+</td>
<td>scaled</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>Stat. only</td>
<td>--</td>
<td>no</td>
<td></td>
</tr>
</tbody>
</table>
• Higgs in di-boson channels

Higgs Couplings

- Extrapolations from Run 1 analyses at pileup of 140 (first shown at ECFA 2014)
- $\mu$ to ~4%, couplings to ~7%
- $\tau/b/t$ couplings to 8-12%

Pub. Note: presented at HL-LHC Workshop → June 2018
• **Higgs in di-boson channels**

\[ H \rightarrow \gamma\gamma \]

- Projections performed on 2016 13 TeV dataset (12.9 fb\(^{-1}\))
  - Production modes: gluon fusion, VBF, ttH
  - No specific VH categorization
  - PileUp emulated with photon and vertex ID degradation
  - In S2 and S2+ scenarios, uncertainty dominated by JES and luminosity measurement

\[ \mu_{\gamma\gamma} = 1 \pm 8 \text{(stat)} \pm 6 \text{(theo)} \quad \text{S1+} \]
\[ 1 \pm 2 \text{(stat)} \pm 3 \text{(theo)} \quad \text{S2+} \]

- Timing on calorimeter clusters and/or tracks improves photon vertex association
  - effective for well separated photons in |\(\eta|\) (~50% of events)
  - Up to 5x PileUp suppression in combination with tracking
- Most optimistic case, S2+ with timing for all events, efficiency at 75% of 2016 performance
- **15% Improvement with all events timing**
**Higgs in di-boson channels**

\[ \text{VBF } H \rightarrow ZZ^* \rightarrow 4\ell \]

- 14 TeV MC14 Truth level samples scaled to 3000 fb\(^{-1}\)
- Cut based analysis followed by BDT Classifier
- Initial selection:
  - 2 jets with \( m_{jj} > 130 \) GeV
  - 2 di-lepton pairs consistent with \( H \rightarrow ZZ^* \) process (SF – OS)
  - \( 50 \) GeV \(< m_{12} < 106 \) GeV, \( m_{Th} < m_{34} < 115 \) GeV
- Strong PileUp jet suppression thanks to forward tracker extension \(|\eta| < 4.0\)

Study conducted for \( \mu = 200 \):
- Including only statistical uncertainties
- Including both systematic and statistical uncertainties

A significance of \( 10.2 \pm 0.2 \) is expected in the nominal case

<table>
<thead>
<tr>
<th>Tracker Scenario</th>
<th>( \Delta \mu / \mu )</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference: (</td>
<td>\eta</td>
<td>&lt; 4)</td>
</tr>
<tr>
<td>Middle: (</td>
<td>\eta</td>
<td>&lt; 3.2)</td>
</tr>
<tr>
<td>Low: (</td>
<td>\eta</td>
<td>&lt; 2.7)</td>
</tr>
</tbody>
</table>

**ATLAS Simulation**

- \( ggF H(4\ell) + 2j \)
- \( \sqrt{s} = 14 \) TeV, \( L dt = 3.0 \) ab\(^{-1}\)

**Reference scenario**

**VBF H(4\ell)**

**BDTG response**

**Reference:** \(|\eta| < 4\)

**Middle:** \(|\eta| < 3.2\)

**Low:** \(|\eta| < 2.7\)

**Signal unc.**

**w/syst.**

**stat only**

**w/syst.**

**stat only**
• Higgs in di-boson channels

\[ H \rightarrow ZZ^* \rightarrow 4l \]

Phase II Tracker TDR: CMS-TDR-014 → June 2017

- 20000 events form ggF and 1550 from VBF
- 15% acceptance increase from tracker extension
- Tigger on low \( P_T \) leptons, < 5Gev
- No worsening on mass resolution from Run II
- Breit Wigner and Crystal Ball Fits

- Very clean, low backgrounds, expect huge benefit from high luminosity
- Projection of 2016 data (12.9 fb\(^{-1}\)) to 3000 fb\(^{-1}\)
- Sub-leading production modes are dominated by statistical component
- Theory uncertainties are crucial

ECFA 2016 Summary: CMS PAS FTR-16-002 → May 2017
• Higgs in di-boson channels

$VBF \, H \rightarrow WW^* \rightarrow e\nu\mu\nu$

- Truth level smeared MC for jets, fully simulated 2012 scaled samples for $e$ and $\mu$
- 8 TeV 2012 MC, scaled to 14 TeV
- Cut based analysis
- Main selection:
  - 2 forward jets with $|\eta| > 2$ in opposite hemispheres
  - b-jet veto (to suppress top-backgrounds)
  - no additional jets between forward jets
  - $E_T^{miss} > 20 \, GeV$

<table>
<thead>
<tr>
<th>Tracking coverage</th>
<th>Expected precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
</tbody>
</table>

Large impact of tracker acceptance increase to $|\eta| < 4$:

- Enhanced Pileup suppression and high $\eta$ (~ 60% effect)
- b-jet suppression from tracker exertion (~ 55% improvement)

Pub Note: ATL-PHYS-PUB-2016-018  →  October 2016
Phase II Strip Tracker TDR: ATLAS-TDR-025  →  April 2017
• Higgs in di-fermion channels

\[ H \rightarrow \mu^+\mu^- \]

- Truth level smeared 14 TeV MC samples
- 14 TeV 2016 MC samples scaled to HL-LHC luminosity
- Initial cut base approach followed by event categorization
- Main selection:
  - 1 opposite sign \( \mu \) pair with \( P_T > 15 \text{ GeV} \) and \( |\eta| < 2.5 \)
  - Leading muon \( P_T > 25 \text{ GeV} \) and jet-muon isolation
  - Single or demon triggers
  - \( 110 \text{ GeV} < m_{\mu\mu} < 160 \text{ GeV} \)
- 7 Categories based on di-mon pair \( |\eta| \), including 2 VBF-like
- Gaussian + Crystal ball simultaneous fit for signal
- Background exponential + Breit-Winer conv. Gaussian (Z)

Signal strength: \( \mu = 1.00 \pm 0.15 \)
Combined Significance: \( \sigma = 9.53 \)

Pub Note: ATL-PHYS-PUB-2018-006 → May 2018
Phase II Strip Tracker TDR: ATLAS-TDR-025 → April 2017
Higgs in di-fermion channels

\[ H \rightarrow \mu^+ \mu^- \]

- Discovered already and coupling expected to be measured by end of Run III
- Precision measurements of couplings to 2\(^{nd}\) generation fermions
- Peak on top of Drell-Yan background, di-muon mass resolution crucial

Main selection:
- 1 opposite sign \( \mu \) pair with \( P_T > 120 \text{ GeV} \) and \( |\eta| < 2.4 \)
- Six categories following eta, barrel, overlap, endcap
- Mass by Gaussian fit on \( 122.5 < m_{\mu\mu} < 127.5 \) GeV
- \( 110 \text{ GeV} < m_{\mu\mu} < 160 \text{ GeV} \)

65% better inv. Mass resolution than Phase I

Higgs coupling to muons: 5% uncertainty
\[ \sigma_{H}^{H} \]

xSection \( \sigma_{\mu\mu}^{H} \): 10% uncertainty
• Higgs in di-fermion channels

\[ H \rightarrow \tau\tau \]

- 10% acceptance increase with extension from \(|\eta| < 2.5\) to \(|\eta| < 4.0\)
- Enhancement of events on smooth background
- S/B depends on \(\tau\tau\) inv. mass resolution
- Tag VBF events:
  - Associate forward jets to primary vertexes
  - Jet \(P_T > 20\) GeV
  - 10% of total jet energy comes from PV associated tracks
  - Tracks originate within 0.1 cm of PV

| Scenario         | \(\epsilon\) (inclusive) | \(\epsilon\) (\(|\eta| > 2.0\)) | \(\epsilon\) (\(|\eta| > 2.4\)) |
|------------------|---------------------------|---------------------------------|---------------------------------|
| Phase-1          | 57%                       | 27%                             | 11%                             |
| Phase-2 (200 PU) | 84%                       | 79%                             | 76%                             |
| Phase-2 (140 PU) | 88%                       | 83%                             | 80%                             |
| Phase-2 (0 PU)   | 89%                       | 84%                             | 81%                             |

Phase II Tracker TDR: [CMS-TDR-014](#) → June 2017
• Higgs in di-fermion channels

$H \rightarrow cc$

- 2.9 % Branching Ratio
- Z to 2 leptons in association with $H \rightarrow cc$
- Run II analysis scaled to HL-LHC
  - Scaling signal and bkg events with luminosity
  - Scaling events with 14TeV XSections
  - Higher c0taggig yield
- Simultaneous 10 GeV bin likelihood fit of $m_{cc}$
- Categorization with no. of c-jets and $P_T$

Upper Limit: $\mu_{ZH(cc)} = 6.3^{+2.8}_{-1.8}$

<table>
<thead>
<tr>
<th>Category</th>
<th>Total Events yield</th>
<th>$S/\sqrt{S/B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 c-tag</td>
<td>75 &lt; $P_T$ &lt; 150</td>
<td>291000 ± 3200</td>
</tr>
<tr>
<td></td>
<td>$P_T$ &gt; 150</td>
<td>63000 ± 700</td>
</tr>
<tr>
<td>2 c-tag</td>
<td>75 &lt; $P_T$ &lt; 150</td>
<td>4710 ± 51</td>
</tr>
<tr>
<td></td>
<td>$P_T$ &gt; 150</td>
<td>1040 ± 11</td>
</tr>
</tbody>
</table>

Pub Note: ATL-COM-PHYS-2018-337 → June 2018
• Measurement of Higgs self coupling
   prime goal of the HL-LHC
   - Shape of scalar Higgs potential
   - Dominant production mode: gg fusion
• Destructive interference of two diagrams
   - Combine many decay channels
   - Choose at least one $H \to bb$ decay (large BR)
• Probe BSM effects
  - Effective Lagrangian
  - Anomalous $\lambda_{HHH}$ and $y_t$ couplings

$\sigma_{gg}^{HH} = 36.69^{+2.1\%}_{-4.9\%}(\text{scale}) \pm 2.1(\text{PDF}) \pm 2.4(\alpha_s)$
Di-Higgs Channels

$H(\rightarrow \gamma \gamma)H(\rightarrow bb)$

- **Channel characteristics**
  - Clear narrow mass peak at $H\rightarrow \gamma \gamma$
  - Low expected signal due to 0.26% BR

- **Truth level Analysis with 14TeV MC16 scaled to 3000 fb$^{-1}$**

- **Backgrounds**
  - Cut based analysis:
    - $P_T(\gamma) > 30$ GeV $|\eta| < 2.5$, $122$ GeV $< m_{\gamma\gamma} < 128$ GeV
    - $P_T(b) > 40$ GeV $|\eta| < 2.5$, $100$ GeV $< m_{\gamma\gamma} < 150$ GeV
    - Separated into central and forward events

- **Expected Events:**
  - **Signal:** $9.54 \pm 0.03$
  - **Background:** $90.9 \pm 2.0$

- If systematic uncertainties are neglected:
  
  $-0.9 < \lambda_{HHH}/\lambda_{HHH}^{SM} < 7.7$ (at 95% CL)
• Di-Higgs Channels

\( H(\rightarrow\text{bb})H(\rightarrow\text{bb}) \)

- Extrapolated from Run II 13 TeV \( H(\rightarrow\text{bb})H(\rightarrow\text{bb}) \) analysis
- Cut based analysis followed by DBT classifier:
  - \( 200 \text{ GeV} < m_{4j} < 1300 \text{ GeV} \)
  - Mass dependent criteria for the \( P_T \) of the di-jet pairs
  - Higgs candidate separation \( \Delta R_{(H,H)} > 1.5 \)
  - Selection on the width of the mass of the selected pairs
  - Final discriinant: \( m_{4j} \)
- Main background QCD multi-jet (\( \sim 95\% \))
  - Data driven estimation, will improve by data

**Coupling limits**

- No systematic uncertainties:
  \[ 0.2 < \frac{\lambda_{HH}}{\lambda_{HHH}^{SM}} < 7.0 \]
- With Systematics:
  \[ -3.5 < \frac{\lambda_{HH}}{\lambda_{HHH}^{SM}} < 11.0 \]
• **Di-Higgs Channels**

**HH Sensitivity**

- Extrapolate searches using 2015 data 2.3-2.7 fb$^{-1}$ to 3000 fb$^{-1}$
- Channels studied: $H(\rightarrow \gamma\gamma)H(\rightarrow bb)$, $H(\rightarrow \tau)H(\rightarrow bb)$, $H(\rightarrow bb)H(\rightarrow bb)$, $H(\rightarrow VV) H(\rightarrow bb)$
- Based on S2 scenario*: 
  - Experimental uncertainty $\propto 1/\sqrt{L}$ until detector-driven lower limit reached,
  - Theoretical uncertainty $\times \sqrt{2}$
  - Expected 15% improvement because of resection estimate
- Impact of systematics differs across the channels. $(\gamma\gamma)(bb)$ most sensitive.

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**ECFA 2016 Summary:** CMS PAS FTR-16-002 → May 2017
Phase II Tracker TDR: CMS-TDR-014 → June 2017

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Combined significance of all channels 1.9 $\sigma$
• BSM Searches

Di-Higgs resonances

- New physics could reflect in a heavy resonance decaying to HH final state: $X \rightarrow HH$
  - motivation: warped extra dimension theory
  - here: massive spin 0 particle (Radiation)
- Projection of search from 2.3 fb$^{-1}$ to 3000 fb$^{-1}$ using HH $\rightarrow 4b$ channel
  - experimental uncertainty $\propto 1/\sqrt{L}$, theoretical uncertainty $\times \frac{1}{2}$
  - three mass points: $m_X=300, 700, 1000$ GeV
- Huge improvement compared to current sensitivity

<table>
<thead>
<tr>
<th>$m_X$ (TeV)</th>
<th>Median expected limits on $\sigma$ (fb)</th>
<th>$\sigma_{R}^{NLO}$ ($\Lambda_{R} = 1$ TeV) (fb)</th>
<th>$\Lambda_{R}$ (TeV) excluded ECFA16 S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>46</td>
<td>41</td>
<td>7130</td>
</tr>
<tr>
<td>0.7</td>
<td>7.3</td>
<td>3.4</td>
<td>584</td>
</tr>
<tr>
<td>1.0</td>
<td>4.4</td>
<td>2.4</td>
<td>190</td>
</tr>
</tbody>
</table>
• **BSM Searches**

**H → ττ**

- Search for neutral Higgs bosons of Minimal Supersymmetric SM (MSSM): h, H, A
  - production enhanced \( \sim \tan \beta \)
- Projection of search from 2.3 fb\(^{-1}\) to 300 and 3000 fb\(^{-1}\) at ggF and b-associated processes
- Scenarios: ✓ **unchanged systematic uncertainties**
  ✓ **experimental uncertainty \( \propto 1/\sqrt{L} \), theoretical uncertainty \( \times \frac{1}{2} \)**
  ✓ **Statistical uncertainties only**
- Differences between scenarios shrink towards higher masses, smaller background expectation

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**ECFA 2016 Summary: CMS PAS FTR-16-002 → May 2017**

- **gluon fusion**
- **b-associated**

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Exclusion up to 2TeV Statistically limited \( m_h \), mod+ scenario

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\[ m_h, m_{\text{mod}+} \text{ scenario} \]

- 300 fb\(^{-1}\)
- 3000 fb\(^{-1}\)
• Conclusions

Summary and outlook

So far....

**LHC environment**
- Very harsh high PileUp environment, challenging tracking and DAQ
- Major Detector Updates on both ATLAS, CMS to improve performances

**Accessible channels**
- High luminosity key to access rare decays
- Boost on Higgs coupling measurements
- Access on di-Higgs channels and Higgs self couplings
- Improved sensitivity to BSM searches

**Outlook and Plans**
- Uniformed way of systematics calculation between ATLAS – CMS
- Coordination with theorist to evaluate uncertainties
- CERN Yellow report at end of this year
- High physics potential in HL-LHC

new accelerator projects need to over perform HL-LHC
• Backup
Higgs in di-lepton channels

\[ H \rightarrow \mu^+\mu^- \]

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>2.10e+04</td>
</tr>
<tr>
<td>VBF</td>
<td>1.74e+03</td>
</tr>
<tr>
<td>ggF+VBF</td>
<td>2.27e+04</td>
</tr>
<tr>
<td>Z+jets</td>
<td>3.67e+07</td>
</tr>
<tr>
<td>top</td>
<td>4.23e+06</td>
</tr>
<tr>
<td>WW</td>
<td>4.25e+05</td>
</tr>
<tr>
<td>Total bkg</td>
<td>4.14e+07</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Category</th>
<th>S</th>
<th>VBF</th>
<th>B</th>
<th>FWHM [GeV]</th>
<th>( \sigma_G ) [GeV]</th>
<th>( S/\sqrt{S + B} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF-like</td>
<td>386</td>
<td>197</td>
<td>19430</td>
<td>4.37</td>
<td>1.88</td>
<td>2.75</td>
</tr>
<tr>
<td>low ( p_T ), central</td>
<td>921</td>
<td>11</td>
<td>350500</td>
<td>3.21</td>
<td>1.37</td>
<td>1.55</td>
</tr>
<tr>
<td>med ( p_T ), central</td>
<td>2210</td>
<td>84</td>
<td>300500</td>
<td>3.08</td>
<td>1.32</td>
<td>4.01</td>
</tr>
<tr>
<td>hi ( p_T ), central</td>
<td>1810</td>
<td>242</td>
<td>211800</td>
<td>3.50</td>
<td>1.56</td>
<td>3.91</td>
</tr>
<tr>
<td>low ( p_T ), non central</td>
<td>2460</td>
<td>28</td>
<td>1740500</td>
<td>4.11</td>
<td>1.79</td>
<td>1.86</td>
</tr>
<tr>
<td>med ( p_T ), non central</td>
<td>5860</td>
<td>230</td>
<td>1483600</td>
<td>4.24</td>
<td>1.80</td>
<td>4.80</td>
</tr>
<tr>
<td>hi ( p_T ), non central</td>
<td>4380</td>
<td>588</td>
<td>829000</td>
<td>4.70</td>
<td>1.92</td>
<td>4.80</td>
</tr>
<tr>
<td>Total</td>
<td>18020</td>
<td>1380</td>
<td>4935500</td>
<td>3.93</td>
<td>1.69</td>
<td>9.53</td>
</tr>
</tbody>
</table>
**HL-LHC Conditions**

**Vertex Resolution**
- Need $z_0$ resolution $< 0.6$ mm
- Tracker much better for central region but reaches the limit $\sim |\eta| = 3$

**Time distribution**
- HS present a time peaked distribution with respect to PileUp that are flatter
- Exploit time spread within pp collisions for vertex separation
- 30 ps/track transfers $\mu = 200$ to $\mu = 30$ conditions
• HGTD System

Position and geometry

**Specifications for 2023**

- **Coverage**: 2.4 < $\eta$ < 4.0
- **$R_{\text{min}}$**: 12 cm
- **$R_{\text{max}}$**: 64 cm
- **$\Delta z$**: $\sim$ 7.5 cm
- **$\Delta t$**: $\sim$ 30 ps/track
- **Layers**: 2 + 1 / side
- **Z position**: ± 3500 mm
- **Cell Size**: 1.3 x 1.3 mm$^2$

**High Granularity Timing Detector**

- Excellent Time resolution (< 30 ps per track)
- Radiation Hardness (up to $4.5 \times 10^{15}$ n$_{eq}$/cm$^2$ including mid cycle replacement and safe SF)
- Low volume modular design (7.5 cm total thickness)
- Low cost optimised layout
- Occupancy < 10% pad with increased granularity

**Technology of Choice**: Silicon LGAD
Di-Higgs Channels

\( H(\rightarrow bb)H(\rightarrow bb) \)

\(-3.5 < \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} < 11 \) (at 95% CL), with systematic uncertainties as of 2016
## Di-Higgs Channels

### HH Sensitivity

<table>
<thead>
<tr>
<th>Channel</th>
<th>Median expected limits in $\mu_r$</th>
<th>Z-value</th>
<th>Uncertainty as fraction of $\mu_r = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \to HH \to \gamma\gamma bb$ (S2+)</td>
<td>1.44</td>
<td>1.37</td>
<td>1.43</td>
</tr>
<tr>
<td>$gg \to HH \to \tau\tau bb$</td>
<td>5.2</td>
<td>3.9</td>
<td>0.39</td>
</tr>
<tr>
<td>$gg \to HH \to VV bb$</td>
<td>4.8</td>
<td>4.6</td>
<td>0.45</td>
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<tr>
<td>$gg \to HH \to bbbb$</td>
<td>7.0</td>
<td>2.9</td>
<td>0.39</td>
</tr>
</tbody>
</table>