THE PHYSICS REACH OF THE LHC UPGRADES AND THE DETECTORS NEEDED TO UNVEIL IT

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The LHC is a big (27km), cold (1.8K), high energy collider (7,8 TeV → 13 TeV) built to:

- Cover all possible Higgs masses from 100 GeV to 1 TeV (100 – 1000 times the proton mass)
- Search for new particles with masses into the multi-TeV range
Excellent performance of the LHC delivered \( \approx 25/\text{fb} \) for data analysis at 7-8 TeV.

Collision rate poses challenging problems for the experiments:

<table>
<thead>
<tr>
<th>Year</th>
<th>Pile-up Events</th>
<th>Inter-bunch Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>O(2)</td>
<td>150 ns</td>
</tr>
<tr>
<td>2011</td>
<td>O(5-10)</td>
<td>50-75 ns</td>
</tr>
<tr>
<td>2012</td>
<td>O(20-30)</td>
<td>50 ns</td>
</tr>
</tbody>
</table>

Experiments design value:

- 2010: \( L = 2.1 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \)
- 2012: \( L = 7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \)
Higgs Discovery

Increase of energy from 7 TeV to 8 TeV
Increase of instantaneous luminosity from $2.1 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ to $7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

### ATLAS and CMS

**LHC Run 1**

**ATLAS** $H \rightarrow \gamma\gamma$

**CMS** $H \rightarrow \gamma\gamma$

**ATLAS** $H \rightarrow ZZ \rightarrow 4l$

**CMS** $H \rightarrow ZZ \rightarrow 4l$

**ATLAS+CMS** $\gamma\gamma$

**ATLAS+CMS** $4l$

**ATLAS+CMS** $\gamma\gamma+4l$

---

$m_H$ [GeV]

<table>
<thead>
<tr>
<th></th>
<th><strong>Total</strong></th>
<th><strong>Stat.</strong></th>
<th><strong>Syst.</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATLAS</strong> $H \rightarrow \gamma\gamma$</td>
<td>126.02 ± 0.51</td>
<td>(± 0.43 ± 0.27) GeV</td>
<td></td>
</tr>
<tr>
<td><strong>CMS</strong> $H \rightarrow \gamma\gamma$</td>
<td>124.70 ± 0.34</td>
<td>(± 0.31 ± 0.15) GeV</td>
<td></td>
</tr>
<tr>
<td><strong>ATLAS</strong> $H \rightarrow ZZ \rightarrow 4l$</td>
<td>124.51 ± 0.52</td>
<td>(± 0.52 ± 0.04) GeV</td>
<td></td>
</tr>
<tr>
<td><strong>CMS</strong> $H \rightarrow ZZ \rightarrow 4l$</td>
<td>125.59 ± 0.45</td>
<td>(± 0.42 ± 0.17) GeV</td>
<td></td>
</tr>
<tr>
<td><strong>ATLAS+CMS</strong> $\gamma\gamma$</td>
<td>125.07 ± 0.29</td>
<td>(± 0.25 ± 0.14) GeV</td>
<td></td>
</tr>
<tr>
<td><strong>ATLAS+CMS</strong> $4l$</td>
<td>125.15 ± 0.40</td>
<td>(± 0.37 ± 0.15) GeV</td>
<td></td>
</tr>
<tr>
<td><strong>ATLAS+CMS</strong> $\gamma\gamma+4l$</td>
<td>125.09 ± 0.24</td>
<td>(± 0.21 ± 0.11) GeV</td>
<td></td>
</tr>
</tbody>
</table>
Higgs Discovery

Increase of energy from 7 TeV to 8 TeV
Increase of instantaneous luminosity from $2.1 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ to $7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

Combined Higgs Mass from CMS and ATLAS at the end of LHC Run 1

$m_H = 125.09 \pm 0.24 \text{ GeV}$
Signal strength

**ATLAS Preliminary**

\( m_H = 125.36 \text{ GeV} \)

**Total uncertainty**

- \( \sigma(\text{stat.}) \)
- \( \sigma(\text{sys inc.}) \)
- \( \sigma(\text{theory}) \)

\( \pm 1\sigma \) on \( \mu \)

- **H \rightarrow \gamma\gamma**
  - \( \mu = 1.17^{+0.28}_{-0.26} \)

- **H \rightarrow ZZ^*\**
  - \( \mu = 1.46^{+0.40}_{-0.34} \)

- **H \rightarrow WW^*\**
  - \( \mu = 1.18^{+0.24}_{-0.21} \)

- **H \rightarrow bb\**
  - \( \mu = 0.63^{+0.39}_{-0.37} \)

- **H \rightarrow \tau\tau\**
  - \( \mu = 1.44^{+0.42}_{-0.37} \)

- **H \rightarrow \mu\mu\**
  - \( \mu = -0.7^{+3.7}_{-3.7} \)

- **H \rightarrow Z\gamma\**
  - \( \mu = 2.7^{+4.6}_{-4.5} \)

**Combined**

- \( \mu = 1.18^{+0.15}_{-0.14} \)

**CMS Preliminary**

\( m_H = 125 \text{ GeV} \)

- **Combined**
  - \( \mu = 1.00 \pm 0.13 \)

- **Untagged**
  - \( \mu = 0.87 \pm 0.16 \)

- **VBF tagged**
  - \( \mu = 1.14 \pm 0.27 \)

- **VH tagged**
  - \( \mu = 0.89 \pm 0.38 \)

- **ttH tagged**
  - \( \mu = 2.76 \pm 0.99 \)

- **Best fit** \( \sigma/\sigma_{\text{SM}} \)

- **19.7 fb\(^{-1}\) (8 TeV) + 5.1 fb\(^{-1}\) (7 TeV)**

- **Signal strength (\( \mu \))**

- **1\( \sigma \) = 7 \text{ TeV}, 4.5-4.7 fb\(^{-1}\)**

- **1\( \sigma \) = 8 \text{ TeV}, 20.3 fb\(^{-1}\)**

- **Theoretical uncertainties relevant for the precise measurements of diboson decay modes**

- **Rare decay modes statistics limited**
Higgs Coupling

Interpret production and decay rates in leading-order tree level coupling framework

- Treat correlations between production and decay
- Measurements very compatible with the SM prediction
Many fundamental questions remains:

- What is Dark Matter and Dark Energy (~95% of the universe!)?
- Why is Gravity so weak? Are there extra dimensions of space time?
- What is the origin of the matter-antimatter asymmetry in our universe?
- Why Three Generations?
- What is the origin of Neutrino Masses?
Key questions after LHC8

- The Higgs has been discovered and it is Standard Model like but many questions remain:
  - Is electroweak symmetry breaking due to a single scalar field?
  - What is the solution to hierarchy problem?
  - Is there an Extended Higgs sector?
  - Does the Higgs play a role in CP violation?
  - What is the shape of the Higgs potential?
  - Does it interact with dark matter (Higgs Portal)?
  - Are there exotic Higgs decays?
  - Is it elementary or composite?
FUTURE PLANS

- Energy increase from 8 TeV to 13 TeV

To reach 3000 1/fb a luminosity of $7.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ maybe needed – Pile-up of 200 events
13 & 14 TeV vs 8 TeV Cross Sections

![Graph showing cross sections for different processes at 13 & 14 TeV compared to 8 TeV.](image-url)

- Ratios of LHC parton luminosities:
  - $13 \text{ TeV} / 8 \text{ TeV}$, $7 \text{ TeV} / 8 \text{ TeV}$

- Graph parameters:
  - $\sigma(14 \text{ TeV})/\sigma(8 \text{ TeV})$
  - $M_x (\text{GeV})$
  - $10^2$ to $10^4$
  - $10^3$ to $10^4$
  - $10$ to $10^2$
  - $0.1$ to $100$
  - $\tau$, $M=0.5 \text{ TeV}$
  - $\tau$, $M=1.6 \text{ TeV}$
  - $\tau$, $M=2.0 \text{ TeV}$
  - $H$, $M_{TH}=6 \text{ TeV}$
  - $H$, $M_{TH}=1 \text{ TeV}$, $n_d=4$

- Process categories:
  - H (ggF)
  - H (VBF)
  - $t\bar{t}H$
  - $t\bar{t}$
  - $g$, $M=1.6 \text{ TeV}$
  - $g$, $M=2.0 \text{ TeV}$
  - BH: $M_{TH}=6 \text{ TeV}$, $M_{TH}=1 \text{ TeV}$, $n_d=4$
Collisions at 13 TeV

$L \approx 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$ but already some pile up

All detectors ON Including PIX/IBL
Challenging environment

Simulated Event Display at 140 PU (102 Vertices)
Higgs production

- The Higgs couples to mass hence the best way to create the Higgs would be to collide top quarks!!!
Higgs Decays

![Graph showing Higgs BR + Total Uncert vs. M_H [GeV] with various decay channels like WW, ZZ, b\bar{b}, \tau\tau, gg, c\bar{c}, \gamma\gamma, Z\gamma, \mu\mu.](image-url)
### Higgs Decays

#### Detector Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Higgs production or Decay channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>b-tagging</td>
<td>$H \rightarrow bb$</td>
</tr>
<tr>
<td></td>
<td>ttH and bbH production</td>
</tr>
<tr>
<td>Forward jets</td>
<td>vector boson fusion</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>$H \rightarrow bb$</td>
</tr>
<tr>
<td>Measuring and identify low momentum leptons (below 10 GeV)</td>
<td>$H \rightarrow ZZ^* \rightarrow 4l$</td>
</tr>
<tr>
<td>Good EM energy resolution for $\gamma$</td>
<td>$H \rightarrow \gamma\gamma$</td>
</tr>
<tr>
<td>Missing energy</td>
<td>$H \rightarrow \tau\tau$</td>
</tr>
<tr>
<td>Triggering</td>
<td>$H \rightarrow \tau\tau$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$M_H$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>[likely to be filled in with data]</td>
</tr>
</tbody>
</table>
**HL-LHC: the Higgs factory**

<table>
<thead>
<tr>
<th>Process Description</th>
<th>Total Higgs Bosons</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC Run 1</td>
<td>660k</td>
</tr>
<tr>
<td>HL-LHC, 3000 fb⁻¹</td>
<td>170M</td>
</tr>
<tr>
<td>VBF (all decays)</td>
<td>13M</td>
</tr>
<tr>
<td>ttH (all decays)</td>
<td>1.8M</td>
</tr>
<tr>
<td>H → γγ</td>
<td>390k</td>
</tr>
<tr>
<td>H → Zγ</td>
<td>230k</td>
</tr>
<tr>
<td>H → μμ</td>
<td>37k</td>
</tr>
<tr>
<td>H → J/ψγ</td>
<td>400</td>
</tr>
<tr>
<td>HH (all)</td>
<td>121K</td>
</tr>
<tr>
<td>HH → WWWWW</td>
<td>9200</td>
</tr>
<tr>
<td>HH → bbγγ</td>
<td>320</td>
</tr>
<tr>
<td>HH → γγγγ</td>
<td>1</td>
</tr>
</tbody>
</table>

ATLAS+CMS in run 1: 1400 Higgs events after selection cuts

170 M Higgs events
More than 1 M in each main production mode

→ Access to rare processes
→ 4-10 times better precision on couplings than today
Rare Higgs decays

\( H \rightarrow \mu^+ \mu^- \)
- 2.3 \( \sigma \) with 300fb\(^{-1} \)
- 7 \( \sigma \) with 3000fb\(^{-1} \)
- Observation of \( ttH, H \rightarrow \mu \mu \)
  - Involves only fermion couplings
  - Relevant for CP violation studies

Test the loop structure by measuring \( H \rightarrow Z\gamma \)

D. Bortoletto, Royal Halloway, May 2015
Signal strength and couplings

- Signal strength

\[ \mu(A, B) = \frac{\sigma(AA \rightarrow h)Br(h \rightarrow B\bar{B})}{SM \text{ Expectation}} \]

- Higgs coupling scale factors

Total decay width scales with \( k_H^2 = \sum_{jj} \frac{k_{jj}^2}{\Gamma_H^{SM}} \)

\[ \sigma \cdot BR(gg \rightarrow H \rightarrow \gamma\gamma) = \sigma_{SM}(gg \rightarrow H) \cdot BR_{SM}(H \rightarrow \gamma\gamma) \cdot \frac{k_g^2 \cdot k_\gamma^2}{k_H^2} \]

\[ \Rightarrow \frac{k_g^2 k_\gamma^2}{k_H^2} = \frac{\sigma \cdot B(gg \rightarrow H \rightarrow \gamma\gamma)}{\sigma_{SM} \cdot B_{SM}(gg \rightarrow H \rightarrow \gamma\gamma)} \]

\[ \sigma(gg \rightarrow H) \propto k_g^2 \approx 1.058k_t^2 + 0.007k_b^2 - 0.065k_t k_b \]

\[ \Gamma(H \rightarrow \gamma\gamma) \propto k_\gamma^2 \]

\[ \approx |1.26k_W - 0.27k_t|^2 \]
Higgs couplings at the HL-LHC

High precision on signal strength achieved by combining various production modes

Measurements of the couplings is interpreted in $k$ framework

Significance for $H_{bb}$ 3.9σ (8.8σ) for 300/fb (3000/fb)

Significance for $H_{\mu\mu}$ 2.3σ (7.0σ) for 300/fb (3000/fb). First proof of $H$ coupling to 2nd generation fermions

ATLAS Simulation Preliminary

$\sqrt{s} = 14$ TeV: $\int L dt = 300$ fb$^{-1}$; $\int L dt = 3000$ fb$^{-1}$

<table>
<thead>
<tr>
<th>Couplings</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$ (comb.)</td>
<td>0.2</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$ (comb.)</td>
<td>0.3</td>
</tr>
<tr>
<td>$H \rightarrow WW$ (comb.)</td>
<td>0.1</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$ (incl.)</td>
<td>0.4</td>
</tr>
<tr>
<td>$H \rightarrow b\bar{b}$ (comb.)</td>
<td>0.1</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$ (VBF-like)</td>
<td>0.2</td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$ (comb.)</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Impact of theoretical uncertainties

CMS, scaling of signal and background yields as:

- **Scenario 1**: Systematic uncertainties remain the same
- **Scenario 2**: Theoretical uncertainties scaled by 1/2, other systematic uncertainties scaled by 1/√L

![Graph showing CMS projection of Higgs boson couplings](image)

- 300 fb⁻¹ at √s = 14 TeV Scenarios
- 3000 fb⁻¹ at √s = 14 TeV Scenarios

- Expected uncertainties on Higgs boson couplings:
  - $\kappa_\gamma$
  - $\kappa_V$
  - $\kappa_g$
  - $\kappa_B$
  - $\kappa_t$
  - $\kappa_\tau$

  **300 /fb**
  - [4-15]%

  **3000 /fb**
  - [2-10]%
Impact of theoretical uncertainties

CMS, scaling of signal and background yields as:

- **Scenario 1**: Systematic uncertainties remain the same
- **Scenario 2**: Theoretical uncertainties scaled by $1/2$, other systematic uncertainties scaled by $1/\sqrt{L}$

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**SUSY**

MSSM ($\tan\beta = 5$, $M_A = 700$ GeV)

- $t$: 5\% deviation from SM
- $b$: 0\% deviation from SM
- $\tau$: 0\% deviation from SM
- $c$: 0\% deviation from SM
- $Z$: 0\% deviation from SM
- $W$: 0\% deviation from SM

**COMPOSITE HIGGS**

MCHM5 ($f = 1.5$ TeV)

- $t$: 5\% deviation from SM
- $b$: 0\% deviation from SM
- $\tau$: 0\% deviation from SM
- $c$: 0\% deviation from SM
- $Z$: 0\% deviation from SM
- $W$: 0\% deviation from SM

*ILC Projection [Ref. arXiv:1310.0763]*

250 GeV, 1150 fb$^{-1}$ ⊕ 500 GeV, 1800 fb$^{-1}$
Impact of theoretical uncertainties

CMS, scaling of signal and background yields as:

• **Scenario 1** - Systematic uncertainties remain the same
• **Scenario 2** - Theoretical uncertainties scaled by 1/2, other systematic uncertainties scaled by $1/\sqrt{L}$

### SUSY

**Kanemura, Tsumura, Yagyu, Yokoya**

- Important to continue decreasing the uncertainties including the theoretical ones which are critical for estimating cross sections and acceptances
- Missing higher order QCD correction
- Electroweak corrections (up to 20% at high mass)
- PDF uncertainties
Impact of backgrounds

• Impact of background modeling
  • $ttH$ with $H\rightarrow bb$
    • $ttbb$ background limiting factor
    • no full NLO $tt+cc$ simulation available

Measurement of $ttbb/ttjj$ ratio: some tension with NLO calculations at 8 TeV

ATLAS, arXiv:1503.05066
Higgs Pair Production

The most challenging measurement at the HL-LHC

- Small cross section and at high energy \( \approx (m_h)^2/s \)
- Negative interference with box diagram
- \( bb\gamma\gamma \) is a promising final state ATLAS expects \( S/\sqrt{B}=1.2 \)

\[ V = \mu^2 \phi^2 + \lambda \phi^4 \]

ATLAS Simulation Preliminary

\( \sqrt{s}=14 \) TeV, 3000 fb\(^{-1} \)

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected events in 3000 fb(^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM HH ( \rightarrow bb\gamma\gamma )</td>
<td>8.4 ( \pm ) 0.1</td>
</tr>
<tr>
<td>( bb\gamma\gamma )</td>
<td>9.7 ( \pm ) 1.5</td>
</tr>
<tr>
<td>cc(\gamma\gamma ), bbjj, jj(\gamma\gamma )</td>
<td>24.1 ( \pm ) 2.2</td>
</tr>
<tr>
<td>Top background</td>
<td>3.4 ( \pm ) 2.2</td>
</tr>
<tr>
<td>ttH((\gamma\gamma ))</td>
<td>6.1 ( \pm ) 0.5</td>
</tr>
<tr>
<td>Z(bb)H((\gamma\gamma ))</td>
<td>2.7 ( \pm ) 0.1</td>
</tr>
<tr>
<td>bbH((\gamma\gamma ))</td>
<td>1.2 ( \pm ) 0.1</td>
</tr>
<tr>
<td>Total background</td>
<td>47.1 ( \pm ) 3.5</td>
</tr>
<tr>
<td>( S/\sqrt{B} ) (barrel+endcap)</td>
<td>1.2</td>
</tr>
<tr>
<td>( S/\sqrt{B} ) (split barrel and endcap)</td>
<td>1.3</td>
</tr>
</tbody>
</table>

ATLAS S=8

\( S/\sqrt{B}=1.2 \)
Higgs Pair Production

Search approach based 2D fit of $M_{bb}$ and $M_{\gamma\gamma}$

Parameterized object performance tuned to the Phase 2 detector
Higgs Pair Production

Search approach based 2D fit of $M_{bb}$ and $M_{\gamma\gamma}$

Parameterized object performance tuned to the Phase 2 detector

- Both ATLAS and CMS are exploring more production modes (e.g. VBF, tthh) and decays (bbbb, bb\tau\tau, WWbb)
Why is the Higgs so light?

Is $m_H$ stabilized by $\sim$TeV scale new physics (e.g. SUSY) or is it fine-tuned?

- At the quantum level, scalar masses are extremely sensitive to heavy states

Reasons to (still) like SUSY
- Unifies couplings
- Predicts SM-like Higgs $m_h < 130$ GeV
- Dark matter candidate(s)

Energy increase from 8 TeV to 13 TeV expected this year and HL-LHC larger data samples will allow a more thorough exploration
Dark Matter at the HL-LHC

At the LHC

Contact interactions

Effective Theories

Simplified models

Full models like MSSM and PMSSM
How to see dark matter?

Missing Momentum
How to see dark matter?

Detectors must maintain good capability of measuring missing momentum/energy in the HL-LHC high pile-up environment.
Searches for dark matter

Models

- Contact interactions (CI) in charged-current process $qq \rightarrow l\nu$
- Dark matter in $pp \rightarrow W$ DM DM and $W \rightarrow l\nu$ (“mono-lepton”)

Discrimination in transverse mass

1 fb signal from CI or dark matter

Significant separation from SM shape achieved at HL-LHC
Exotic Physics Prospects

Sensitivity in multi-TeV range increases by ~20% with HL-LHC

**CMS Projection**

\[ \sqrt{s} = 14 \text{ TeV} \]

arXiv:1307.7135

<table>
<thead>
<tr>
<th>Particle mass (( \Delta ) in case of DM EFT)</th>
<th>300/fb</th>
<th>3000/fb</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z' \rightarrow ee \text{ SSM} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( g_{KK} \rightarrow t \bar{t} \text{ RS} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dark matter pair-produced ( \tau )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T-quark pair production</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**ATLAS Projection**

<table>
<thead>
<tr>
<th>Run 3 @ 14 TeV (300 fb(^{-1}))</th>
<th>6.5 TeV</th>
<th>4.3 TeV</th>
<th>2.2 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>HL-LHC @ 14 TeV (3000 fb(^{-1}))</td>
<td>7.8 TeV</td>
<td>6.7 TeV</td>
<td>2.6 TeV</td>
</tr>
</tbody>
</table>
Model Discrimination at HL-LHC

Ability to discriminate improves dramatically with HL-LHC

- Separation between spin-1 ($Z'$) or spin-2 (GKK) interpretation and other interpretations ranges from $\sim 2$ to 5 $\sigma$
- 2D likelihood with dilepton angular and rapidity distributions or forward-backward asymmetry

![Graph showing separation in sigmas for different scenarios with CMS Simulation and 2D likelihood](image)

![Graph showing CMS Preliminary and Simulation with 3,000 fb](image)
SUSY

- Naturalness: requires stop mass < ~1 TeV
- ATLAS: 0/1 lepton + ≥ 4 jets + ≥ 1 b-tag + \( E_{\text{Tmiss}} \)
- CMS: 1 lepton + ≥ 6 jets + ≥ 1 b-tag + \( E_{\text{Tmiss}} \)

**ATLAS Simulation Preliminary**

\( s=14 \text{ TeV} \)

\[ m_{\tilde{g}} \times m_{\tilde{t}} \]

5\( \sigma \) discovery

Simplified model

<table>
<thead>
<tr>
<th>Run 3 @ 14 TeV (300 fb(^{-1}))</th>
<th>HL-LHC @ 14 TeV (3000 fb(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>stop mass from direct production [ATLAS]</td>
<td>Up to 1.0 TeV</td>
</tr>
<tr>
<td>gluino mass with decay to stop [CMS]</td>
<td>Up to 1.9 TeV</td>
</tr>
</tbody>
</table>
SUSY: electroweak production

Importance of Phase II detector upgrade

- WH: 1 lepton + $E_T$ miss + 2 b-tags [CMS]

\[ \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow W \tilde{\chi}_1^0 H \tilde{\chi}_1^0 \]

- Mass reach more than doubled
  - 450 GeV discovery reach with 300 fb-1, $\mu=50$, existing detector
  - 950 GeV discovery reach with 3000 fb-1, $\mu=140$, and upgraded detector

Continued running with degraded detector increases the physics reach only marginally for this SUSY signature
Experimental challenges

Rate effects

- Trigger have to become increasingly selective as luminosity increases.
- Trackers and muon systems can saturate at high luminosity and readout rate.
- Calorimeters can suffer from pileup.

<table>
<thead>
<tr>
<th>Period</th>
<th>$W \rightarrow l\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>80 Hz</td>
</tr>
<tr>
<td>Run 2</td>
<td>200 Hz</td>
</tr>
<tr>
<td>Run 3</td>
<td>400-600 Hz</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>1KHz</td>
</tr>
</tbody>
</table>

Radiation damage

- Inner trackers will be exposed to fluences up to $10^{16}$ n/cm$^2$ and ionizing doses of $10^5$ Gray.
- High doses also in forward calorimeters.
ATLAS Phase 1 upgrade

Muon “New Small Wheels” improved tracking & trigger on forward region

L1 Calorimeter Trigger
- Upgraded electronics
- Finer granularity readout

Fast Track Trigger (FTK)
- Hardware-based track finder
- Hit pattern matching to patterns stored in Associative Memories
- Runs after L1 Trigger
• For Phase 2 upgrade, ATLAS plans full replacement of Inner Tracker
  – All silicon tracker (pixels and Microstrips)
  – Significantly increase granularity
  – Minimise material budget within tracking acceptance
  – Sufficient hits on track to maintain high efficiency and combat combinatorics at high pile-up

• ITK “Letter of Intent” layout has been developed
  – Used as baseline for majority of performance studies

Excellent Tracking efficiency
• New Trigger Architecture
  – 2-Level Hardware trigger
  – L0: 1 MHz, 6µs latency, (Calo + Muons)
  – L1: 300-400 kHz, 24µs latency
  – L1Track: Use tracking information earlier in trigger processing – move part of HLT track reconstruction to L1
• Region-of-Interest (RoI) approach

• Calorimeters
  – Tile and Liquid Argon calorimeters require full electronics replacements
  – Needed to cope with increased radiation levels and trigger rates
  – Forward calorimeter may be fully replaced if significant degradation of current system, or higher granularity mandated by physics requirements
ATLAS–high-η extensions

- Potential for extending tracking coverage to $|\eta|<4$ under serious consideration
- Tracking performance under investigation
  - limitations from field strength in forward region
- Extension of pixel system proposed with “rings” in place of traditional endcap disks
  - offers more flexibility for placement of modules and services

- Could be combined with modifications to other systems to maximise impact
  - Additional muon chambers
  - Increase granularity in forward calorimeter

- Could lead to improved $\Sigma E_T$
- The acceptance of $H \rightarrow ZZ$ in 4µ final states increases by ~35% assuming 100% muon reconstruction efficiency
CMS Phase 1 Upgrade

New pixel detector in extended end-of-year technical stop 2016-2017
- 4 barrel layers, 3 disks
- n-in-n 100µm x150 µm pixel
- New readout chip
- DC-DC powering

Material
CMS Phase 2 Upgrade

**New Tracker**
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to $\eta \sim 4$

**Muons**
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to $\eta \sim 3$

**Barrel ECAL**
- Replace FE electronics
- Cool detector/APDs

**Trigger/DAQ**
- L1 (hardware) with tracks and rate up $\sim 750$ kHz
- L1 Latency 12.5 $\mu$s
- HLT output rate 7.5 kHz

**Other R&D**
- Fast-timing for in-time pileup suppression
- Pixel trigger

D. Bortoletto, Royal Halloway, May 2015
CMS Phase 2 Inner Tracker

- Full tracker replacement in Phase 2
  - Minimize material and increase granularity, with ample hit coverage over tracking acceptance
  - Tracking coverage up to $|\eta|<4$
  - Allow self-seeded L1 Track Trigger for tracking information at earlier stage of trigger
• Use sensor doublets to trigger on high-$p_T$ tracks
  • Different granularities in different regions (2 Strip Modules, Pixel-Strip Modules)
• Two Hardware implementations under study:
  – Associative memory
  – Tracklets in commercial FPGAs
• L1 tracking performance under study
  • Requires ~10 µs latency
Forward calorimetry must be replaced due to radiation-induced signal loss. Two concepts are under study:

- Compact Pb/LYSO Shashlik Forward EM Calorimeter with Scintillator-based HCAL
- A High Granularity Silicon Based Calorimeter

Brass & Scintillator (4.5 \(\lambda\))

Brass & Si (3.5 \(\lambda\))

Pb/W/Cu & Si
25 \(X_0\)

7 M channels Pad size 0.9 cm\(^2\) (first 20 Layers) & 1.8 cm\(^2\) (last 10 Layers)

3 M channels Pad size 1.8 cm\(^2\)
Performance: b-tagging

- The capability of tagging b-jets is critical to the success of the Higgs and BSM programmes
- Detector aging and high pile-up lead to higher mis-identification probability for fixed b-tagging probability
- Phase 2 detectors recovering the b-tagging performance goals for Run 2
Pileup Mitigation

- Experience with pile-up from run1
  - Energy subtraction techniques
    - Determine jet energy by subtracting the pile up contribution
    - \( p_T^{\text{corr}} = p_T^{\text{jet}} - \rho^* A_{\text{jet}} \)
Use of tracking information

Use tracking and vertex information

- ATLAS: Jet Vertex Fraction (JVF) in Run1

\[ \text{corrJVF} = \frac{\sum_k p_T^{\text{trk}_k}(PV_0)}{\sum_l p_T^{\text{trk}_l}(PV_0) + \sum_{n \geq 1} \frac{\sum_l p_T^{\text{trk}_l}(PV_n)}{(k \cdot n_{\text{PU}}^{\text{trk}})}} \]

- CMS Charged Hadron Subtraction (CHS) Jet reconstruction
  - Remove PF candidates assigned to another vertex
  - Cluster
  - Apply modified $\rho$ correction (modified in TK volume
  - Baseline for substructure and shape variables

Halloway, May 2015
Performance: Jet reconstruction

- Development of new techniques to improve jet reconstruction performance in High-Pileup

- CMS: New “PileUp Per Particle Id” algorithm (PUPPI) which combines
  - the event-wide pileup density
  - vertex information from charged tracks (CHS)
  - local distribution of pileup with respect to leading vertex.

- ATLAS: removal of low-\(p_T\) R=0.3 objects. Pile-up corrections applied to hard-scatter jets with R=1.0 to restore scale and improve energy resolution.

\[ Z' \rightarrow tt \]

No pile up corrections

With pile up corrections
R&D

Compared to hybrid pixel detectors, the sensitive volume and the readout circuitry is combined in one piece of silicon. The generated charge is collected on a dedicated collection electrode.

Hybrid Pixel

Monolithic Pixel Detector (example)
CMOS with deep n-well collection electrode

- Structures realized in 0.18 and 0.35 \( \mu \text{m} \) CMOS
- Substrate resistivity \( \sim 10 \) Ohm cm
- Biasing of the substrate up to \( \sim 100\text{V} \)
- Homogeneous depletion layer \( \sim 14 \) \( \mu \text{m} \) deep
  - Charge collection \( \sim 40 \) ps
  - Signal \( \sim 2000 \) e-
- First stage amplification in pixel and additional electronics (e.g. discriminator etc.) possible
- Radiation tests with FEI-4 glue bonded indicate radiation hardness up to \( 1 \times 10^{16} \text{n}_{\text{eq}} \)
Pixel readout
- unit cell corresponding to two ATLAS FEI4 readout-chip pixels
- combine sensor sub-pixels for AC readout
- different current amplitude per pixel ➡ hit position from pulse-height information

Strip readout

This technology could bring significant savings
- Lower cost
- Eliminate bump bonding for pixels
- Reduce number sensor layers
Conclusions

• Run-1 has been a fantastic success
  – We found a Higgs boson
  – Set severe constraints on physics BSM
  – ATLAS and CMS have published > 400 papers/experiment on a variety of topics

• Knowledge of TeV scale physics will be improved dramatically by future LHC and HL-LHC running
  – Going to 13 TeV and increase L by factor 100
  – Higgs couplings will be measured with precision of 2-10%
  – Mass reach for searches of new particles will be significantly extended

• Advances in experimental techniques and theory, and upgrades of the detectors will play critical role in fully exploiting the HL-LHC