The Physics Program of the High Luminosity LHC and Beyond

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The 3rd KMI International Symposium
Introduction

- Higgs discovery huge success for the LHC program
- Detailed measurements of its properties in progress
  - So far appears consistent with SM predictions
- Searches for BSM signals so far negative and are quite constraining
- However, to achieve ultimate possible precision much more luminosity needed in many cases

Strong motivation for High-Luminosity LHC
HL-LHC Upgrade
HL-LHC Planning

- LHC to deliver 300 fb$^{-1}$ by 2023 (end of Run-3)
- HL-LHC goal is deliver 3000 fb$^{-1}$ in 10 years
  - Implies integrated luminosity of 250-300 fb$^{-1}$ per year
  - Requires peak luminosities of $5-7 \times 10^{34}$ cm$^{-2}$s$^{-1}$ while using luminosity leveling (3-5 hours at peak luminosity)
- Design for “ultimate” performance $7.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ and 4000 fb$^{-1}$
HL-LHC Project
Major intervention on more than 1.2 km of the LHC

- New IR-quads $\text{Nb}_3\text{Sn}$ (inner triplets)
- New 11 T $\text{Nb}_3\text{Sn}$ (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- ...

Machine upgrade approved by CERN council in June 2016
The High-Luminosity Challenge

HL-LHC provides an extreme challenge to the experiments

Very high pile-up

Intense radiation levels

- Major experiment upgrades needed to:
  - Improve radiation hardness and replace detectors at end-of-life
  - Provide handles for mitigating pile-up (high granularity, fast timing)
  - Allow higher event rates to maintain/improve trigger acceptance
- Goal is to maintain or improve over current performance
Detector Upgrade – ATLAS

**Calorimeters**
- New BE/FE electronics
- New HV power supplies
- Lower LAr temperature

**Tracker**
- All silicon tracker (strip and pixel)
- Radiation tolerant, high granularity
- Low material budget
- Coverage up to $|\eta|=4$

**Muon System**
- New BE/FE electronics
- New RPC layer in inner barrel
- Muon-tagging in $2.7<|\eta|<4.0$ (under study)

**Timing detector**
- High granularity timing detector
- Coverage: $2.5<|\eta|<4.2$
- Possibly absorber for $|\eta|<3.2$

**Trigger and DAQ**
- L0 rate at ~ 1 MHz (latency up to 10 μs)
- Possible hardware L1 track trigger
- HLT output ~10 kHz
Extended Silicon-based Tracker

- ATLAS (and CMS) plan to extend tracker coverage to $\eta \sim 4$ with pixel extension
- Provides multiple benefits
  - Extended lepton coverage (with forward muon tagger)
  - Forward b-tagging
  - Improved vertexing
- Primary benefit is pile-up suppression

Possible support structures for large $\eta$ pixel detector
Muon System Upgrades

Readout electronics to be replaced everywhere to support higher trigger rate and MDT hardware trigger

Power system to be replaced (maintenance and radiation issues)

RPCs added to inner station to increase acceptance/robustness

Will replace some MDT chambers to make space for RPCs

Possible replacement of low radius TGCs

Studying options for large $\eta$ muon tagger

Inner wheel is replaced in Phase-I
Higgs Physics at HL-LHC
Higgs program at HL-LHC

- Higgs boson studies are a major component of HL-LHC physics program
- Main Higgs measurements at HL-LHC:
  - Higgs couplings
  - Rare Higgs decays
  - Higgs differential distributions
  - Higgs self-coupling
  - Heavy Higgs searches

Higgs Production Channels

- \(3000 \text{ fb}^{-1}\)
- \(HH \sim 100k\)

Higgs Decay Channels

- \(3000 \text{ fb}^{-1}\)
Physics Projections

HL-LHC Physics prospects done in two ways:

- **Parameterized detector performance**
  - Event-generator level particles smeared with detector performance parameterized from full simulation and reconstruction of upgraded HL-LHC detectors
  - Effects of pile-up included for either $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ (140 pile-up events) or $7 \times 10^{34}$ cm$^{-2}$s$^{-1}$ (200 pile-up events)
  - Analysis mostly based on existing 8 TeV analyses with simple re-optimization for higher luminosity

- **Extrapolation of Run-1 or Run-2 results**
  - Scale signal and background to higher luminosities
  - Correct for different center-of-mass energy
  - Assume unchanged analysis (not re-optimized for higher luminosity)
  - Assume same detector performance as in Run-1/2 (some use corrections based on studies in first approach)
Projections for Higgs Couplings

- Full set of HL-LHC coupling projections are based on Run-1 analyses
  - For $\mu=140$ in case of ATLAS
  - Same as Run-1 performance for CMS
- Higgs coupling precision (per experiment):
  - 3-5% for $W$, $Z$ and $\gamma$
  - $\sim7\%$ for $\mu$
  - 5-10% for $t$, $b$ and $\tau$
- Do not include improved detector designs or improvements in analysis techniques

**Figure:**

- CMS Projection
- Expected uncertainties on Higgs boson couplings
- 300 fb$^{-1}$ at $\sqrt{s} = 14$ TeV Scenario 1
- 300 fb$^{-1}$ at $\sqrt{s} = 14$ TeV Scenario 2

**ATLAS Simulation Preliminary**

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

- $\kappa_{gZ}$
- $\lambda_{WZ}$
- $\lambda_{tt}$
- $\lambda_{tZ}$
- $\lambda_{t\gamma}$
- $\lambda_{Z\gamma}$

**CERN-LHCC-2015-010**

- 300 fb$^{-1}$

**ATL-PHYS-PUB-2014-016**

- 3000 fb$^{-1}$
Rare decays: $H \rightarrow \mu^+\mu^-$ and $H \rightarrow J/\psi\gamma$

Probes Higgs coupling to 2\textsuperscript{nd} generation quarks/leptons

$H \rightarrow \mu^+\mu^-$
- BR($H \rightarrow \mu^+\mu^-$) = $2.2 \times 10^{-4}$ in SM
  - Combined Run-1 and Run-2 limit is $3.5 \times $SM
- Expect significance of $\sim 2\sigma$ with 300 fb\(^{-1}\) and $\sim 7\sigma$ with 3000 fb\(^{-1}\) in inclusive channel
  - Improved tracker resolution not accounted for ($\sim 30\%$ improvement on mass resolution)
  - Also specific channels like ttH, $H \rightarrow \mu^+\mu^-$

$H \rightarrow J/\psi\gamma$
- BR($H \rightarrow J/\psi\gamma$) = $2.9 \times 10^{-6}$ in SM
  - ATLAS Run-1 limit at 95% CL: BR($H \rightarrow J/\psi\gamma$) < $1.5 \times 10^{-3}$
  - Multivariate analysis for HL-LHC projection
    - With 3000 fb\(^{-1}\) will have just 3 signal events and 1700 background events
    - Expected limit at 95% CL: BR($H \rightarrow J/\psi\gamma$) < $(44^{+19}_{-12}) \times 10^{-6}$
Higgs Self Coupling

- Measurement of Higgs pair production
  - major goal of HL-LHC program
  - Requires full HL-LHC luminosity to reach SM sensitivity
  - Allows for a measurement of self coupling $\lambda$

- Extremely challenging due to low cross section (SM: 40 fb)

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Branching Ratio</th>
<th>Total Yield $(3000 \text{ fb}^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b} + b\bar{b}$</td>
<td>33%</td>
<td>$4.1 \times 10^4$</td>
</tr>
<tr>
<td>$b\bar{b} + W^+W^-$</td>
<td>25%</td>
<td>$3.1 \times 10^4$</td>
</tr>
<tr>
<td>$b\bar{b} + \tau^+\tau^-$</td>
<td>7.4%</td>
<td>$9.0 \times 10^3$</td>
</tr>
<tr>
<td>$W^+W^- + \tau^+\tau^-$</td>
<td>5.4%</td>
<td>$6.6 \times 10^3$</td>
</tr>
<tr>
<td>$ZZ + b\bar{b}$</td>
<td>3.1%</td>
<td>$3.8 \times 10^3$</td>
</tr>
<tr>
<td>$ZZ + W^+W^-$</td>
<td>1.2%</td>
<td>$1.4 \times 10^3$</td>
</tr>
<tr>
<td>$\gamma\gamma + b\bar{b}$</td>
<td>0.3%</td>
<td>$3.3 \times 10^2$</td>
</tr>
<tr>
<td>$\gamma\gamma + \gamma\gamma$</td>
<td>0.0010%</td>
<td>1</td>
</tr>
</tbody>
</table>
HH→b\bar{b}γγ Analysis

- Low statistics, but high purity channel
- After selections expect 8.4 signal events and 47 background events
- Corresponds to signal significance of 1.3σ

95% CL limits on self-coupling (ignoring systematics): -1.3<\frac{\lambda}{\lambda_{SM}}<8.7
HH$\rightarrow$bb$\tau^+\tau^-$ Analysis

- Consider all combinations of leptonic/hadronic $\tau\tau$ final states:

Event yields for 3000 fb$^{-1}$ using a cut-based analysis strategy:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Significance</th>
<th>Combined in channel</th>
<th>Total combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e + \text{jets}$</td>
<td>0.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu + \text{jets}$</td>
<td>0.30</td>
<td>0.43</td>
<td>0.60</td>
</tr>
<tr>
<td>$\tau_{\text{had}}\tau_{\text{had}}$</td>
<td>0.41</td>
<td>0.41</td>
<td></td>
</tr>
</tbody>
</table>

Signal significance for SM coupling:

$m(\tau^+\tau^-)$  
$m(bb)$

95% CL limits on self-coupling: $-4<\lambda/\lambda_{\text{SM}}<12$
HH→bbbb Analysis

- HH→bbbb analysis dominated by large multi-jet background
  - Very difficult to simulate
  - Instead extrapolate from Run-2 assuming unchanged performance
- Multijet background is estimated from control regions (CRs)
  - Systematics uncertainty assigned from CR differences
  - These will decrease with luminosity

- Neglecting systematics expect $0.2<\lambda/\lambda_{SM}<7$ at 95% CL
- Best of the measurements
- If assuming todays systematics:
  - $-3.5<\lambda/\lambda_{SM}<11$ at 95% CL
- Similar to HH→bτ⁺τ⁻

Run-2 $m_{4j}$ extrapolated to 3000 fb⁻¹, 14 TeV
Search for $\bar{t}tHH$ Production

- $\sigma(\bar{t}tHH)$ only $\sim1$ fb, but more handles to suppress backgrounds
  - Use $HH \rightarrow bbb\bar{b}$ final state and semi-leptonic $tt$ decay
  - Signature: 6 b-jets, 2 light jets, lepton and missing energy

- Simple cut-based analysis
  - No cuts on Higgs candidate mass due to combinatorics

- Selection with $\geq5$ b-tags:
  - 25 signal events, 7100 background events
  - Background dominated by c-jets from W mis-tagged as b

- Significance for $\bar{t}tHH$ production without systematics: $0.35\sigma$
Precision Measurements
Vector Boson Scattering

- Vector Boson Scattering probes the quartic gauge boson couplings and EW symmetry breaking
- Striking experimental signature of two forward jets
  - Provides additional motivation for forward tracker extension
- Using leptonic decays clean observations on ZZ, WZ and $W^\pm W^\pm$ boson scattering
  - Sensitive to dimension-6/8 operators at TeV scale
  - Precision on SM $W^\pm W^\pm$ boson scattering ~6% with 3000 fb$^{-1}$

**Graphs:**
- ZZ → $\ell\ell\ell\ell$
- WZ → $\ell\nu\ell\ell$
- W$^\pm$W$^\pm$ → $\ell\nu\ell\nu$

**Legend:**
- ATLAS Simulation Preliminary
- VBS ZZ (SM)
- SM VBS ZZ + $C_{WW} = 15$/TeV$^2$
- SM ZZ QCD
- ATL-PHYS-PUB-2013-006
- VBS WZ (SM)
- SM VBS WZ + $f_{T1} = 1.0$ TeV$^{-2}$
- SM WZ QCD
- ATL-PHYS-PUB-2013-006
- W$^\pm$W$^\pm$ QCD

**Reference:**
- LHCC-G-166
- ATL-PHYS-PUB-2013-006
Flavor-Changing Neutral Currents in top quark decays

ATLAS+CMS Preliminary

95%CL upper limits

ATLAS

CMS

LHC top WG

November 2016

Each limit assumes that all other processes are zero

Theory predictions from arXiv:1311.2028

SM

2HDM(FV)

2HDM(FC)

MSSM

RPV

RS

Branching ratio

$10^{-16}$

$10^{-13}$

$10^{-10}$

$10^{-7}$

$10^{-4}$

$10^{-1}$

[t→Hc]

[t→Hu]

[t→γc]

[t→γu]

[t→gc]

[t→gu]

[t→Zc]

[t→Zu]
Search for \( t \to Zq \) and \( t \to Hq \) Decays

- Search for \( t \bar{t} \) with one \( t \to Wb \) decay and one FCNC \( t \) decay
- Reconstruct as much as possible of top decays to obtain maximal discrimination

For \( t \to Zq \) use kinematic \( \chi^2 \) fit using leptonic \( Z \) decays:

\[
\chi^2 = \frac{(m_Z - m_{Z_{\text{reco}}})^2}{\sigma_Z^2} + \frac{(m_W - m_{W_{\text{reco}}})^2}{\sigma_W^2} + \frac{(m_{t_{\text{reco}}})^2}{\sigma_{t \to Wb}^2} + \frac{(m_{t_{\text{reco}}})^2}{\sigma_{t \to Zq}^2}
\]

Expected 95\% CL limit assuming equal \( t \to Zu \) and \( t \to Zc \): \(~2.5 \times 10^{-5}~\)

For \( t \to Hq \) use \( H \to b\bar{b} \) and kinematic discriminant

Furthermore split in categories based on reconstructed topology (#jets, #b-jets, ...)

Expected 95\% CL limit assuming equal \( t \to Hu \) and \( t \to Hc \): \(~1.1 \times 10^{-4}~\)
Beyond the Standard Model
Supersymmetry Production at LHC

Lightest neutralino normally assumed to stable (Dark Matter candidate)

neutralinos ($\tilde{\chi}^0$) & charginos ($\tilde{\chi}^\pm$): superpositions of Higgsinos, Wino, Bino
Search for Gluino Pair Production

In “natural SUSY” expect relatively light gluinos (~few TeV)
For example search in four jets+$E_{T,\text{miss}}$ channel for $g\rightarrow qq\chi$

Expect to discover gluinos up to ~2 TeV for neutralinos up to 1 TeV
Exclude gluinos up to ~3 TeV
Search for Stop Pair Production

In “natural SUSY” also expect light stops (\(<\sim 1\) TeV)

- Search for $\tilde{t} \rightarrow t\tilde{\chi}$ in two scenarios:
  - $m(\tilde{t}) \gg m(t)+m(\tilde{\chi})$ using both 0 and 1 leptonic top decay
  - $m(\tilde{t}) \sim m(t)+m(\tilde{\chi})$ (compressed) using 2 leptonic top decays

\[m(\tilde{t}) \gg m(t)+m(\tilde{\chi})\]

For uncompressed stop, can discover up to 1.2 TeV
For compressed stop, only 0.5 TeV
Search for Chargino-Neutralino Production

Projection for chargino-neutralino production in 2 channels:

Discovery reach up to ~850 GeV
Finally HL-LHC will have sensitivity to direct slepton production

- Studied search for stau pairs
  - Require two hadronic tau decays and large $E_{T\text{miss}}$
  - Final discriminant: $m_T(\tau_1, E_{T\text{miss}}) + m_T(\tau_2, E_{T\text{miss}})$

For $\tilde{\tau}_L$, expect to have $5\sigma$ discovery up to $\sim 420$ GeV, while even with 3000 fb$^{-1}$, do not achieve $5\sigma$ sensitivity for $\tilde{\tau}_R$. 
Search for Heavy Resonances

- New physics could be anywhere
  - Search for resonances in all final states
di-leptons, di-jets, di-top, di-bosons (γγ, WW, WZ, ZZ, hh)...
- Only a few of these projected up to 3000 fb\(^{-1}\) so far
  - Many channels do not gain that much by more luminosity
    as they are close to kinematic end-point
  - More luminosity most interesting if something seen before

Kaluza-Klein gluon excitation $\rightarrow t\bar{t}$

\[
\int L \, dt = 3000 \text{fb}^{-1}
\]

ATLAS Preliminary
(Simulation)

\[
g_{\text{gg}} / g = \pm 0.20
\]

Expected limit
Expected $\pm 1\sigma$
Expected $\pm 2\sigma$

\[g_{kk} \rightarrow t\bar{t}\]
\[\sqrt{s} = 14 \text{ TeV}\]

Kaluza-Klein graviton excitation $\rightarrow t\bar{t}$

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

Reference $\sigma_B = 2.5\%$
Reference $\sigma_B = 5.0\%$
Middle $\sigma_B = 2.5\%$
Middle $\sigma_B = 5.0\%$
Low $\sigma_B = 2.5\%$
Low $\sigma_B = 5.0\%$

Signal significance

Resonance mass [TeV]
Search for WIMP Candidates

- ATLAS also has sensitivity to non-SUSY WIMP models

For example with canonical mono-jet signature:

Or invisible Higgs Boson decays:

\[
q \rightarrow \bar{q} \quad \text{or} \quad H \rightarrow Z \chi \rightarrow \gamma^* \chi \rightarrow \nu\bar{\nu} \chi
\]
Future Circular Colliders
CERN is Studying Next Collider

Conceptual design studies of colliders in ~100 km ring

- **pp collider (FCC-hh)**
  - Primary motivation for FCC studies
  - $\sqrt{s} \sim 100$ TeV, $L \sim 2 \times 10^{35}$ cm$^{-2}$s$^{-1}$
  - 4 IPs and 20 ab$^{-1}$/expt
  - Also studying FCC-hh dipoles (16T) in LHC tunnel (HE-LHC with $\sqrt{s} \sim 30$ TeV)

- **e$^+$e$^-$ collider (FCC-ee)**
  - $\sqrt{s} \sim 90$-350 GeV, $L \sim 200$-$2 \times 10^{34}$ cm$^{-2}$s$^{-1}$
  - 2 IPs and 20 ab$^{-1}$/expt

- **pe collider (FCC-he):**
  - $\sqrt{s} \sim 3.5$ TeV, $L \sim 10^{34}$ cm$^{-2}$s$^{-1}$


Machine studies are site-neutral, but FCC at CERN would greatly benefit from existing laboratory infrastructure and accelerators
Physics Program for FCC-hh

- Main physics goals of FCC-hh
  - Directly explore energy range up to 50 TeV for New Physics
  - Conclusive exploration of EWSB dynamics
  - Give final verdict on heavy WIMP dark matter

Expected reach for supersymmetry

<table>
<thead>
<tr>
<th>Process</th>
<th>95% CL Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tilde{\chi}^0 \to \tilde{\chi}^0 )</td>
<td>14 TeV, 0.3 ab(^{-1})</td>
</tr>
<tr>
<td>( \tilde{\chi}^0 \to \tilde{\chi}^0 )</td>
<td>14 TeV, 3 ab(^{-1})</td>
</tr>
<tr>
<td>5 ( \sigma ) Discovery</td>
<td>100 TeV, 3 ab(^{-1})</td>
</tr>
<tr>
<td>100 TeV, 30 ab(^{-1})</td>
<td></td>
</tr>
</tbody>
</table>

Expected precision for di- and tri-Higgs production and Higgs self-couplings:

<table>
<thead>
<tr>
<th>Process</th>
<th>precision on ( \sigma_{SM} )</th>
<th>68% CL interval on Higgs self-couplings</th>
</tr>
</thead>
<tbody>
<tr>
<td>( HH \to b \bar{b}\gamma\gamma )</td>
<td>3%</td>
<td>( \lambda_3 \in [0.97, 1.03] )</td>
</tr>
<tr>
<td>( HH \to b \bar{b}b \bar{b} )</td>
<td>5%</td>
<td>( \lambda_3 \in [0.9, 1.5] )</td>
</tr>
<tr>
<td>( HH \to b \bar{b}4\ell )</td>
<td>( O(25%) )</td>
<td>( \lambda_3 \in [0.6, 1.4] )</td>
</tr>
<tr>
<td>( HH \to b \bar{b}\ell^+\ell^- )</td>
<td>( O(15%) )</td>
<td>( \lambda_3 \in [0.8, 1.2] )</td>
</tr>
<tr>
<td>( HH \to b \bar{b}\ell^+\ell^- \gamma )</td>
<td>( O(25%) )</td>
<td>( \lambda_4 \in [-4, 16] )</td>
</tr>
<tr>
<td>( HHH \to b bb\gamma\gamma )</td>
<td>( O(100%) )</td>
<td>( \lambda_4 \in [-4, 16] )</td>
</tr>
</tbody>
</table>
Physics Program for FCC-ee

- High-precision Higgs couplings
- Indirect sensitivity to energy-scale of O(100 TeV) through precision EW parameter measurements

Possible Higgs coupling precision

<table>
<thead>
<tr>
<th>Coupling</th>
<th>ILC</th>
<th>FCC-ee</th>
<th>CEPC</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(ZH)$</td>
<td>0.7%</td>
<td>0.4%</td>
<td>0.51%</td>
<td>1.65%</td>
</tr>
<tr>
<td>$g_{bb}$</td>
<td>0.7%</td>
<td>0.42%</td>
<td>0.57%</td>
<td>0.9%</td>
</tr>
<tr>
<td>$g_{cc}$</td>
<td>1.2%</td>
<td>0.71%</td>
<td>2.3%</td>
<td>1.9%</td>
</tr>
<tr>
<td>$g_{gg}$</td>
<td>1.0%</td>
<td>0.80%</td>
<td>1.7%</td>
<td>1.4%</td>
</tr>
<tr>
<td>$g_{WW}$</td>
<td>0.42%</td>
<td>0.19%</td>
<td>1.6%</td>
<td>0.9%</td>
</tr>
<tr>
<td>$g_{\tau\tau}$</td>
<td>0.9%</td>
<td>0.54%</td>
<td>1.3%</td>
<td>1.4%</td>
</tr>
<tr>
<td>$g_{\mu\mu}$</td>
<td>9.2%</td>
<td>6.2%</td>
<td>17%</td>
<td>7.8%</td>
</tr>
<tr>
<td>$g_{inv}$</td>
<td>&lt;0.29%</td>
<td>&lt;0.45%</td>
<td>&lt;0.28%</td>
<td>&lt;0.97%</td>
</tr>
</tbody>
</table>

Current EW precision

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Theory error</th>
<th>Exp. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_W$ [MeV]</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>$\sin^2 \theta^\ell_{\text{eff}}$ [10^{-5}]</td>
<td>4.5</td>
<td>16</td>
</tr>
<tr>
<td>$\Gamma_Z$ [MeV]</td>
<td>0.5</td>
<td>2.3</td>
</tr>
<tr>
<td>$R_b$ [10^{-5}]</td>
<td>15</td>
<td>66</td>
</tr>
</tbody>
</table>

Future EW precision?

<table>
<thead>
<tr>
<th>Quantity</th>
<th>ILC</th>
<th>FCC-ee</th>
<th>CEPC</th>
<th>Projected theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_W$ [MeV]</td>
<td>3–4</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>$\sin^2 \theta^\ell_{\text{eff}}$ [10^{-5}]</td>
<td>1</td>
<td>0.6</td>
<td>2.3</td>
<td>1.5</td>
</tr>
<tr>
<td>$\Gamma_Z$ [MeV]</td>
<td>0.8</td>
<td>0.1</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>$R_b$ [10^{-5}]</td>
<td>14</td>
<td>6</td>
<td>17</td>
<td>5–10</td>
</tr>
</tbody>
</table>

Also $m_{top}$ measured to ~10 MeV precision from threshold scan
Summary
Summary

- High-Luminosity LHC very challenging environment, but maximizes the physics output of the LHC project
- Major detector upgrades planned for optimal performance
  - Should be as good or better than now in most areas
- Precision Higgs measurements are the main physics driver for HL-LHC and detector upgrades, but wide range of measurements and Beyond Standard Models searches are possible
- Technical Design Reports in preparation and will come over the next ~1 year
- Next generation colliders for the ultimate studies of Higgs and multi-TeV New Physics are under study at CERN
  - Conceptual Design Reports in ~2 years

Please stay tuned

Much more information in presentations at HL-LHC Experiments workshop in Aix-Les-Bains in October:
https://indico.cern.ch/event/524795/timetable/
Backup
Detector Upgrades – CMS

**Endcap Calorimeter**
- High-granularity calorimeter based on Si sensors
- Radiation-tolerant scintillator
- 3D capability and timing

**Barrel Calorimeter**
- New BE/FE electronics
- ECAL: lower temperature
- HCAL: partially new scintillator
- Possibly precision timing layer

**Tracker**
- Radiation tolerant, high granularity
- Low material budget
- Coverage up to $|\eta|=4$
- Trigger capability at L1

**Muon System**
- New Be/FE electronics
- GEM/RPC coverage in $1.5<|\eta|<2.4$
- Muon-tagging in $2.4<|\eta|<3.0$

**Trigger and DAQ**
- Track-trigger at L1 (latency up to 12.5 $\mu$s)
- L1 rate at ~ 750 kHz
- HLT output ~7.5 kHz
Anomalous HZZ Coupling

Generic decay amplitude of $H \rightarrow ZZ$ for spin-0 particle:

$$A(H \rightarrow VV) \sim \left[ a_1 - e^{i\phi_{\Lambda\phi}} \frac{(q_{v_1} + q_{v_2})^2}{\Lambda_Q^2} - e^{i\phi_{\Lambda\Lambda}} \frac{(q_{v_1}^2 + q_{v_2}^2)}{\Lambda_1^2} \right] m_V^2 \epsilon_1^* \epsilon_2^* + a_2 f^{(1)}_{\mu\nu} f^{(2)}_{\mu\nu} + a_3 f^{(1)}_{\mu\nu} f^{(2)}_{\mu\nu}$$

- Test for anomalous HZZ couplings $a_i$:
  $$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j}, \quad \phi_{ai} = \tan^{-1}(a_i/a_1)$$

- Interference contribution becomes more dominant at smaller values of $f_{ai} \times \cos(\phi_{ai})$
Projections based on Run-2 Analysis

- $H \to \gamma\gamma$ and $H \to ZZ$ projections updated to 13 TeV (12.9 fb$^{-1}$) based Run-2 analyses
- $H \to \gamma\gamma$ added expected degradation at $\mu = 200$
  - Beamspot ~5cm
  - Vertex identification reduced from 80% to 40%
  - Photon ID efficiency decreased by 2.3% (10%) in EB (EE)
- Theory uncertainties become dominate at HL-LHC
- Decouple by measuring fiducial cross section
  - Can achieve ~4% precision
Projections based on Run-2 Analysis

- $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$
  projections updated to 13 TeV (12.9 fb$^{-1}$) based Run-2 analyses
- $H \rightarrow ZZ$ added expected degradation at $\mu=200$
  - Reduced lepton efficiency
  - Increased misidentification
- Can make precise differential $p_T(H)$ cross section measurements
Higgs to Invisible

- Main backgrounds:
  - $Z(\ell\ell)$+jets
  - $W(\ell\nu)$+jets
  - QCD multijet

- Current BR($H \rightarrow \text{inv}$) limit (expected):
  - BR<0.30 @ 95% CL (CMS)
  - BR<0.31 @ 95% CL (ATLAS)

- Projected upper limit (CMS) as a function of luminosity:

<table>
<thead>
<tr>
<th>Luminosity [fb$^{-1}$]</th>
<th>ECFA16 S1</th>
<th>ECFA16 S2</th>
<th>$1/\sqrt{L}$ scaling</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>0.210</td>
<td>0.092</td>
<td>0.084</td>
</tr>
<tr>
<td>3000</td>
<td>0.200</td>
<td>0.056</td>
<td>0.028</td>
</tr>
</tbody>
</table>
## Summary of Recent ATLAS Higgs Results

<table>
<thead>
<tr>
<th>Channel</th>
<th>Result</th>
<th>$HH$ Channel</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF $H \rightarrow W^+W^-$</td>
<td>$\Delta \mu/\mu = 14$ to $20%$</td>
<td>$HH \rightarrow b\tau\tau$ (FULL uncertainties)</td>
<td>$0.6 \sigma$</td>
</tr>
<tr>
<td>VBF $H \rightarrow ZZ \rightarrow 4\ell$</td>
<td>$\Delta \mu/\mu = 15$ to $18%$</td>
<td></td>
<td>$- 4 &lt; \lambda_{HHH} / \lambda_{SM} &lt; 12$</td>
</tr>
<tr>
<td>$ttH, H \rightarrow \gamma\gamma$</td>
<td>$\Delta \mu/\mu = 17$ to $20%$</td>
<td>$HH \rightarrow bbbb$ ($p_T^{(jet)}&gt; 75$ GeV, FULL uncertainties)</td>
<td>$- 3.4 &lt; \lambda_{HHH} / \lambda_{SM} &lt; 12$</td>
</tr>
<tr>
<td>$VH, H \rightarrow \gamma\gamma$</td>
<td>$\Delta \mu/\mu = 25$ to $35%$</td>
<td>$HH \rightarrow b\gamma\gamma$ (stat. uncertainties only)</td>
<td>$1.3 \sigma$</td>
</tr>
<tr>
<td>off-shell $H \rightarrow ZZ \rightarrow 4\ell$</td>
<td>$\Delta \mu/\mu = 50%$ $\Gamma_H = 4.2^{+1.5}_{-2.1}$ MeV</td>
<td></td>
<td>$- 1.3 &lt; \lambda_{HHH} / \lambda_{SM} &lt; 8.7$</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>$\Delta \mu/\mu = 30%$  $3.9 \sigma$</td>
<td>$ttHH, HH \rightarrow bbbb$ (stat. uncertainties only)</td>
<td>$0.35 \sigma$</td>
</tr>
<tr>
<td>$H \rightarrow J/\psi \gamma$</td>
<td>BR $&lt; 44 \times 10^{-6}$ @95% CL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t \rightarrow Hq$</td>
<td>BR $\lesssim 10^{-4}$ @95% CL</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**VBF H → ZZ* → ℓℓℓℓ**

- **Initial selection:**
  - 2 jets with m(jj) > 130 GeV
  - 4 leptons consistent with H → ZZ* → ℓℓℓℓ
- **Use BDR to separate ggF and VBF**
  - Large pile-up contribution in ggF
- **190 signal events and 330 background events**
- **Results with full systematics (signal QCD scale) and statistics only:**

<table>
<thead>
<tr>
<th></th>
<th>&lt;μ&lt;sub&gt;PU&lt;/sub&gt; = 200</th>
<th>&lt;μ&lt;sub&gt;PU&lt;/sub&gt; = 200</th>
<th>&lt;μ&lt;sub&gt;PU&lt;/sub&gt; = 140</th>
<th>&lt;μ&lt;sub&gt;PU&lt;/sub&gt; = 140</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>FULL</strong></td>
<td><strong>NONE</strong></td>
<td><strong>FULL</strong></td>
<td><strong>NONE</strong></td>
</tr>
<tr>
<td>Δμ</td>
<td>0.18</td>
<td>0.15</td>
<td>0.17</td>
<td>0.13</td>
</tr>
<tr>
<td>Significance</td>
<td>7.2 σ</td>
<td>10.2 σ</td>
<td>7.7 σ</td>
<td>11.1 σ</td>
</tr>
</tbody>
</table>
Systematics Treatment

- With large statistics at HL-LHC, systematics can be dominating in measurement precision
  - Hard to predict how these will evolve with luminosity/time
- Both experiments start from current systematics with a slightly different approach
- ATLAS approach:
  - Experimental systematics scaled to best guess for HL-LHC
  - Results provided with current theory systematics and without theory systematics
- CMS approach:
  - Provide results in two scenarios:
    - Scenario 1: Current experimental and theory systematics
    - Scenario 2: Experimental scaled with luminosity \((1/\sqrt{L})\) until a certain best achievable uncertainty level
      The current theory systematics is halved
- Both approach aim to bracket the achievable precision
Table 6: Estimation of the deduced size of theory uncertainties, in percent (%), for different Higgs coupling measurements in the generic Model 15 from Table 5, requiring that each source of theory systematic uncertainty affects the measurement by less than 30% of the total experimental uncertainty and hence increase the total uncertainty by less than 10%. A dash “-” indicates that the theory uncertainty from existing calculations [10–12] is already sufficiently small to fulfill the condition above for some measurements. The same applies to theory uncertainties not mentioned in the table for any measurement. The impact of the jet-bin and $p_T$ related uncertainties in $gg \rightarrow H$ depends on analysis selections and hence no single number can be quoted. Therefore the range of uncertainty values used in the different analysis is shown.
## Higgs Self Coupling Projections

**ATLAS simulations (HH→bbbb is Run-2 extrapolations):**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Expected limit in μ</th>
<th>Significance</th>
<th>Limits on $\lambda/\lambda_{SM}$ at 95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full Syst. Stat. only</td>
<td>Full Syst. Stat. only</td>
<td>Full Syst. Stat. only</td>
</tr>
<tr>
<td>$gg\rightarrow HH\rightarrow \gamma\gamma bb$</td>
<td>4.3</td>
<td>1.3σ</td>
<td>-1.3$&lt;\lambda/\lambda_{SM}$&lt;8.7</td>
</tr>
<tr>
<td>$gg\rightarrow HH\rightarrow \tau\tau bb$</td>
<td>5.2</td>
<td>0.6σ</td>
<td>-4$&lt;\lambda/\lambda_{SM}$&lt;12</td>
</tr>
<tr>
<td>$gg\rightarrow HH\rightarrow bbb\bar{b}$</td>
<td>1.5</td>
<td>-3.5$&lt;\lambda/\lambda_{SM}$&lt;11</td>
<td></td>
</tr>
<tr>
<td>$ttHH\rightarrow t_{had}t_{lep}bb$</td>
<td>0.35σ</td>
<td>0.2$&lt;\lambda/\lambda_{SM}$&lt;7</td>
<td></td>
</tr>
</tbody>
</table>

**CMS extrapolations from Run-2 analyses:**

<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></td>
<td>ECFA16 S1 S2 Stat. Only</td>
<td>ECFA16 S1 S2 Stat. Only</td>
<td>ECFA16 S1 S2 Stat. Only</td>
</tr>
<tr>
<td>$gg \rightarrow HH \rightarrow \gamma\gamma bb$ (S1+/S2+)</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>$gg \rightarrow HH \rightarrow \tau\tau bb$</td>
<td>7.4</td>
<td>5.2</td>
<td>3.9</td>
</tr>
<tr>
<td>$gg \rightarrow HH \rightarrow VVbb$</td>
<td>4.8</td>
<td>4.6</td>
<td>6.0</td>
</tr>
<tr>
<td>$gg \rightarrow HH \rightarrow bbb\bar{b}$</td>
<td>7.0</td>
<td>2.9</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Search for Heavy Higgs → ττ

- One of the most sensitive channels for constraining extended Higgs
- Cross section limits:
  - $gg\phi \rightarrow \tau\tau$
  - $bb\phi \rightarrow \tau\tau$
- Model dependent limits:
  - $m_{mod+}$ benchmark
- Sensitivity at high $m_A$ is still dominated by statistics
# CMS Tracker Changes

## Phase-1

<table>
<thead>
<tr>
<th>Outer Tracker</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>9.3 M</td>
<td>15 148 M</td>
<td>100 kHz</td>
</tr>
<tr>
<td>~200 m²</td>
<td>Silicon surface</td>
<td>Strips</td>
</tr>
<tr>
<td>–</td>
<td>MacroPixels</td>
<td>Modules</td>
</tr>
<tr>
<td>100 kHz</td>
<td>readout rate</td>
<td></td>
</tr>
</tbody>
</table>

## Phase-2

<table>
<thead>
<tr>
<th>Inner Tracker</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>164 M</td>
<td>13 556 M</td>
<td>750 kHz /40 MHz</td>
</tr>
<tr>
<td>~200 m²</td>
<td>43.7 M</td>
<td></td>
</tr>
</tbody>
</table>

## Pixel Bar + Fw + Ext

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>66 M</td>
<td>Pixels</td>
<td>1870 M</td>
</tr>
<tr>
<td>1440</td>
<td>Modules</td>
<td>4136</td>
</tr>
<tr>
<td>100 kHz</td>
<td>readout rate</td>
<td>750 kHz</td>
</tr>
</tbody>
</table>
CMS Tracker Comparison

Phase-1
OT 3.6.2
Pix 4.0.2.1

Phase-2

Material amount [X/X₀]

Number of hits in full readout
CMS Preliminary Simulation
ATLAS Tracker Hits and Material

Optimized for at least 13 hits, minimum material and coverage up to $\eta=4$
B-tagging for HH→bbbb

- Efficient and highly rejecting b-tagging also critical for HH→bbbb measurement
- Current projections assume performance as in Run-2
- Both experiments have demonstrated ability to match current performance at pile-up of 140 events
- Both pixel detectors still being optimized
  - Aim to achieve Run-2 performance at pile-up of 200
New CMS Endcap Calorimeter

Construction:
- Hexagonal Si-sensors built into modules.
- Modules with a W/Cu backing plate and PCB readout board.
- Modules mounted on copper cooling plates to make wedge-shaped cassettes.
- Cassettes inserted into absorber structures at integration site (CERN)

Key parameters:
- 593 m² of silicon
- 6M ch, 0.5 or 1 cm² cell-size
- 21,660 modules (8” or 2x6” sensors)
- 92,000 front-end ASICS.
- Power at end of life 115 kW.

System Divided into three separate parts:
EE – Silicon with tungsten absorber – 28 sampling layers – 25 X₀ (~1.3 λ)
FH – Silicon with brass (now stainless steel) absorber – 12 sampling layers – 3.5 λ
BH – Scintillator with brass absorber – 11 layers – 5.5 λ

EE and FH are maintained at – 30°C. BH is at room temperature.
ATLAS Trigger Schemes

Level-0 + Level-1 hardware trigger

Level-0 only hardware trigger

Rates and Latencies

Level 0: 1 MHz, 10 μs
Level 1: 400 kHz, 60 μs
EF output: 10 kHz

Level 0: 1 MHz, 10 μs
EF output: 10 kHz
Currently, the Level-1 trigger uses only calorimeter and muon information. The Phase-II upgrades include:

- Replace calorimeter electronics
- Increase latency and Level-1 accept rate
- Use tracking at Level-1 based on doublet seeds
- Global track-trigger correlator

**CURRENT**
- L1 input: calor + muon
- L1 output: ~100 kHz
- HLT output: ~1 kHz
- 40 MHz
- 4 µs latency

**PHASE-2**
- L1 input: calor + muon + tracker
- L1 output: ~750 kHz
- HLT output: ~7.5 kHz
- 40 MHz
- 12.5 µs latency
**ATLAS Example Trigger Menu**

- For most trigger channels, expect to maintain same or even lower trigger threshold as in Run-1
- Hadronic triggers challenging due to pile-up

<table>
<thead>
<tr>
<th>Description</th>
<th>Run 1 Threshold</th>
<th>HL-LHC Threshold</th>
<th>L0 Rate</th>
<th>EF Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolated e</td>
<td>20-25</td>
<td>22</td>
<td>200</td>
<td>2.20</td>
</tr>
<tr>
<td>di-electron</td>
<td>17, 17</td>
<td>15, 15</td>
<td>90</td>
<td>0.08</td>
</tr>
<tr>
<td>forward e</td>
<td>-</td>
<td>35</td>
<td>40</td>
<td>0.23</td>
</tr>
<tr>
<td>single γ</td>
<td>40–60</td>
<td>120</td>
<td>66</td>
<td>0.27</td>
</tr>
<tr>
<td>di-photon</td>
<td>25, 25</td>
<td>25, 25</td>
<td>8</td>
<td>0.18</td>
</tr>
<tr>
<td>single μ</td>
<td>25</td>
<td>20</td>
<td>40</td>
<td>2.20</td>
</tr>
<tr>
<td>di-muon</td>
<td>12, 12</td>
<td>11, 11</td>
<td>20</td>
<td>0.25</td>
</tr>
<tr>
<td>e-μ</td>
<td>17, 6</td>
<td>15, 15</td>
<td>65</td>
<td>0.08</td>
</tr>
<tr>
<td>τ</td>
<td>100</td>
<td>150</td>
<td>20</td>
<td>0.13</td>
</tr>
<tr>
<td>di-tau</td>
<td>40,30</td>
<td>40, 30</td>
<td>200</td>
<td>0.08</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
<th>Run 1 Threshold</th>
<th>HL-LHC Threshold</th>
<th>L0 Rate</th>
<th>EF Rate*</th>
</tr>
</thead>
<tbody>
<tr>
<td>single jet</td>
<td>200</td>
<td>180</td>
<td>60</td>
<td>0.6</td>
</tr>
<tr>
<td>large-R jet</td>
<td>-</td>
<td>375</td>
<td>35</td>
<td>0.35</td>
</tr>
<tr>
<td>four jet</td>
<td>55</td>
<td>4 x 75</td>
<td>50</td>
<td>0.50</td>
</tr>
<tr>
<td>forward jets</td>
<td>-</td>
<td>180</td>
<td>30</td>
<td>0.30</td>
</tr>
<tr>
<td>HT</td>
<td>-</td>
<td>500</td>
<td>60</td>
<td>0.60</td>
</tr>
<tr>
<td>MET</td>
<td>120</td>
<td>200</td>
<td>50</td>
<td>0.50</td>
</tr>
<tr>
<td>JET + MET</td>
<td>150, 120</td>
<td>140, 125</td>
<td>60</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Total hadronic L0 Rate: ~250 kHz, EF Rate: 3.15 kHz
750 kHz (leptonic) + 250 kHz (hadronic) = 1000 kHz

Total non-hadronic L0 rate: ~750 kHz, EF rate: 5.7 kHz
CMS Example Trigger Menu

- Menu without track-trigger has 1.5 MHz rate $\mu=140$
  - Track-trigger gives factor 5.5 reduction: 260 kHz
  - Use 1.5 safety factor: 390 kHz
- Menu with track-trigger has 500 kHz rate $\mu=200$
  - With 1.5 safety factor: 750 kHz
  - Without track-trigger: ~4 MHz
CMS Precision Timing for Charged Particles

- Assume sufficient timing performance for charged hadrons, e.g. from dedicated LYSO+SiPM layer in the central region, and from HGCAL or dedicated layer in the forward region.
- Traditional three-dimensional vertex fit can be upgraded to a four-dimensional fit, with vertices reconstructed both in position along the beamline and in time within the bunch crossing.
- Provides further suppression of charged particles from pile-up for jets, missing energy, lepton isolation etc.

20 ps resolution assumed for charged particles with $p_T > 1$ GeV.
Pile-up vs Pile-up Density

- So far mostly considered effects due to overall pile-up
- Find that many quantities depend more on pile-up density – how many in pile-up collisions per mm in z
- This can be mitigated by changing beam-profile
  - I.e. spreading vertices out better in z

Lepton isolation efficiency

B-tagging efficiency

CMS-DP-2016-065

IDTR-2016-012
Higgs Impact on Upgrade Design

- The design of the upgraded HL-LHC detectors is complex process
  - Want ultimate performance, but limited by what can reasonably be upgraded during long shutdown and by cost
- Higgs measurements are corner stone of the HL-LHC physics program and they provide prime motivation for many upgrades beyond current detector capabilities

- Will highlight four different cases:
  - Pile-up jet suppression in VBF Higgs production
  - $H \rightarrow \gamma \gamma$ reconstruction with precision timing detector
  - $H \rightarrow \tau \tau$ triggering
  - $HH \rightarrow bbbb$ triggering and reconstruction
Pile-up Jet Suppression

- At 200 pile-up, every event has ~5 pile-up jets ($p_T > 30$ GeV)
- Can suppress these by using tracking to associate them to either pile-up or hard-scatter vtx
- For VBF Higgs production need to use jets out to $\eta \sim 4$
  - Extended tracker enables this
VBF H→WW→evμν Analysis

- Physics gain of forward tracker studied in H→WW analysis
- Simple cut based analysis:
  - 2 forward jets (|η|>2) in opposite hemispheres
  - No jet above 30 GeV in between jets
  - e/μ in between forward jets
  - Missing E_T>20 GeV
- After selection:
  - ~200 signal events
  - ~400 background events from t̅t and non Higgs WW

Signal precision and significance

<table>
<thead>
<tr>
<th>Tracker coverage</th>
<th>Δμ</th>
<th>Significance (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full</td>
<td>1/2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Factor two gain in precision from extended tracker coverage

Different levels of background uncertainties with respect to Run-1 H→WW analysis
High Granularity Timing Detector

- Additional pile-up rejection can be achieved using precise timing
  - Different time of flight and different collisions times in event
- ATLAS considering thin timing device
  - Four layers silicon sensors
  - Coverage for $2.4<|\eta|<4.2$
  - Possible Tungsten absorber for $|\eta|<3.2$
  - Timing target: 30-50 ps per MIP
- Provide additional sensitivity to VBF
  - Possibly also enhance the jet trigger

![High-granularity timing detector with Minimum bias scintillators](image-url)
Timing Detectors in CMS

- Endcap calorimeter (1.5<|\eta|<3) replaced by multi-layer silicon-based calorimeter
  - Current calorimeter not rad-hard enough
- Use of silicon allows intrinsic time resolution down to 50 ps for large signal
- Barrel calorimeter electronics upgraded to also provide precision timing (30 ps)
- Additional timing layer for charged particles in front of calorimeter under consideration

Allows to reconstruct vertex time

Example: Improved $H\rightarrow\gamma\gamma$ vertex association
H→γγ with Timing Detector

- Vertex selection efficiency drops with increase in pileup
  - ~80% now → ~40% at 200 pileup
- Results in large degradation of mass resolution
- Impact on fiducial cross section measurement investigated

With full use of calorimeter and charged particle timing information vertexing efficiency can be almost full recovered

Corresponds to effectively 30% more luminosity
Triggering on $H \rightarrow \tau \tau$

- $H \rightarrow \tau \tau$ channel critical for understanding fermionic coupling and measuring Higgs CP properties
- Difficult to trigger on efficiently
  - Two narrow, fairly soft jets with 1-3 charged tracks
- Existing calorimeter-only L1 triggers not sufficient
  - Acceptance drops quickly as thresholds are raised
- Adding fast track trigger can give large rate reduction
- CMS estimate: 50 kHz L1 rate for 45% eff. for VBF $H \rightarrow \tau \tau$
  - Same triggers also useful for $HH \rightarrow bb\tau\tau$

---

CERN-LHCC-2015-010
LAr Calorimeter Upgrades

- Upgrade of all readout electronics
  - To remove trigger constraints and improved radiation hardness
- Possibly add new high-granularity precision timing detector in front of endcap calorimeters
  - Primarily to reduce effect of pile-up on jets
- Replacement of FCal evaluated, but found risky and unnecessary
LAr Electronics Upgrade

- In Phase-I upgrade Level-1 trigger output path
  - Factor 10 increase in granularity – reused in Phase-II
- Phase-II upgrade of readout electronics
  - Digital readout to back-end at 40 MHz
  - Alleviates current latency and trigger rate constraints
  - In addition original electronics only designed for 1000 fb⁻¹

LAr Phase II Electronics Upgrade:
- Re-use Phase I Trigger Upgrade
- New FE Boards (FEB2)
- High Bandwidth Optical Links
- BE: LAr Pre-PRocessor Boards (LPPR)

LAr Phase I Upgrade:
- New Layer Summing Boards
- New Baseplanes
- FE: Trigger Digitizer Board (LTDB)
- BE: Digital Processing System (LDPB)
High-Granularity Timing Detector

- Evaluating option of adding thin, high-granularity timing detector in front of end-cap calorimeter (2.5<|\eta|<4.2)
  - Multiple layers of silicon and optional tungsten absorber
  - Pad size: 1x1mm\(^2\) – 3x3 mm\(^2\)
  - Timing precision: 30-50 ps
- Precise timing use to reject pile-up jets
- Possibility for use in trigger also being studied

![Efficiency for pile-up jets vs. hard-scatter jets](image)

Efficiency strongly dependent on timing resolution

Pile-up jet rejection power:

- \( \sigma_t = 0 \) ps
- \( \sigma_t = 10 \) ps
- \( \sigma_t = 20 \) ps
- \( \sigma_t = 30 \) ps

\( \sqrt{s} = 14 \) TeV, \( \mu = 200 \)

Pythia8 dijets
\( p_T > 20 \) GeV
New Small Wheel

- Will replace inner wheel of muon end-cap in Phase-I
  - Increased hit rate capability
  - Rejection of fake L1 muon triggers
- MicroMegas – precision tracker
  - Spatial resolution <100μm
  - Good track separation
- Small strip TGC – trigger detector
  - Bunch ID with good timing resolution
  - Track vector with <1mrad resolution

Chamber production expected to start very soon
Muon Barrel Upgrade

- To survive HL-LHC, gains on existing RPCs will need to be lowered
  - Reduces muon trigger efficiency
  - Also existing acceptance only 78%
- Will add new inner RPC station
  - Allows for 3 out of 4 layer coincidence or even inner and outer RPC only
  - Increases efficiency to 92-96%
- RPC chosen over MicroMegas
  - Also add RPCs at $1<|\eta|<1.3$ in Phase-I

Acceptance without BI upgrade

Acceptance with BI upgrade
Upgrade of TDAQ Architecture

Deciding between two-level hardware trigger with hardware tracking at Level-1 and a high bandwidth single-level trigger

Low latency (25 μs) two-level system also under consideration

Trades latency for higher trigger rate and thus increased trigger acceptance in certain channels – max rate TBD
TDAQ Upgrades

- **Level-0 trigger use Phase-I upgrades**
  - Advanced algos with finer-granularity calo data:
    - Incl. longitudinal segmentation for $e/\gamma/\tau$
    - $0.1\times0.1$ towers for jets/$E_T,miss$
  - Use NSW hits to confirm endcap muons
- **MDT information added to muon trigger**
  - Sharpens turn-on curve and thus rejection power
  - Also allows looser RPC trigger selection, increasing acceptance
  - Multiple options for MDT track finding under consideration

- **Level-1 mainly adds tracking**
  - Also plan to have full granularity calorimeter data available
- **Track-trigger builds on FTK design**
  - Pattern recognition with custom-made Associate-Memory chips
  - Track fitting in FPGAs
- **FTK currently under installation**
  - Expected to be commissioned in 2017
Triggering on $HH\to b\bar{b}b\bar{b}$

- $HH\to b\bar{b}b\bar{b}$ channel also difficult to trigger on at L1
  - Very large rate of multi-jets and pile-up jets
- Plan to also use track trigger to suppress pile-up jets in 4-jet trigger
- Still likely to only be efficient at 70-75 GeV
- ATLAS estimate this will reduce sensitivity by $\sim 30\%$ compared to current 30 GeV
  - Better trigger strategy is under investigation

<table>
<thead>
<tr>
<th>Jet Threshold [GeV]</th>
<th>Background Systematics</th>
<th>$\sigma/\sigma_{SM}$ 95% Exclusion</th>
<th>$\lambda_{HHH}/\lambda_{SM_{HHH}}$ Lower Limit</th>
<th>$\lambda_{HHH}/\lambda_{SM_{HHH}}$ Upper Limit</th>
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<tbody>
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