The Physics Program of the High Luminosity LHC

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Outline

• Brief LHC introduction

• The High Luminosity LHC upgrade

• The physics case for High Luminosity LHC
  • Understanding Electro-weak Symmetry Breaking
  • Search for Beyond the Standard Model physics

• Summary and Outlook
The Large Hadron Collider
Large Hadron Collider

27 km proton-proton collider at CERN
Large Hadron Collider Goals

Electroweak Symmetry Breaking
Beyond SM Physics Searches
Matter-antimatter Asymmetry
New States of Matter
The CMS Experiment

Not shown:
Trigger system for selecting the 0.0025% most interesting collisions
The ATLAS Experiment

Inner Detector
- Pixel (pixel detector)
- SCT (silicon strip detector)
- TRT (transition radiation tracker)

Calorimeter
- LAr (EM calorimeter)
- Tile (Fe/Scintillator tile)

Magnet System
- 2 T solenoid
- 0.5 T toroid

Muon Spectrometer
- MDT,CSC (precise momentum measurement)
- RPC,TGC (trigger chambers)

Trigger/DAQ System
- 100 kHz L1 rate (HW trigger)
- ~1 kHz to tape

7 TeV proton

25m

44m
Collision Energy and Luminosity

- Particle production in LHC driven by two parameters
  - Center-of-mass energy ($\sqrt{s}$)
    - sets the cross-section ($\sigma$)
    (probability of interaction)
  - Luminosity (L)
    - measure of collision rate

- Instantaneous production rate:
  Rate = $\sigma(\sqrt{s}) \times L$  
  $[10^{34} \text{ cm}^{-2}\text{s}^{-1}]$
  $[\text{barn} = 100 \text{ fm}^2 = 10^{-24} \text{ cm}^2]$
  $[\text{femtobarn} = 10^{-39} \text{ cm}^2]$

- Integrated rate most important:
  Events = $\sigma(\sqrt{s}) \times \int L \, dt$
  $[\text{fb}^{-1}]$
Collision Energy

- Center-of-mass energy is limited by bending power in main dipole magnets
  - Superconducting magnets
  - Need to be “trained” by having controlled quenches as current is ramped up
  - Limited by time and safety

- Started at $\sqrt{s} = 7$ TeV
- Now at $\sqrt{s} = 13$ TeV after safety upgrade in 2013/14
- Design is $\sqrt{s} = 14$ TeV, while ultimate could be $\sqrt{s} = 15.4$ TeV
Luminosity

- Luminosity is a function of the LHC beam parameters

\[ L = \frac{N^2 n_b f}{4\pi \sigma_x^* \sigma_y^*} F = \frac{N^2 n_b f \gamma}{4\pi \varepsilon_n \beta^*} F \]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>number of particles per bunch</td>
</tr>
<tr>
<td>( n_b )</td>
<td>number of bunches / beam</td>
</tr>
<tr>
<td>f</td>
<td>revolution frequency</td>
</tr>
<tr>
<td>( \sigma^* )</td>
<td>beam size at interaction point</td>
</tr>
<tr>
<td>F</td>
<td>reduction factor due to crossing angle</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>emittance</td>
</tr>
<tr>
<td>( \varepsilon_n )</td>
<td>normalized emittance = ( \varepsilon \gamma \beta )</td>
</tr>
<tr>
<td>( \beta^* )</td>
<td>beta function at IP</td>
</tr>
</tbody>
</table>
LHC Performance so far

- 2016 was a record breaking year for LHC p-p collisions
  - Peak luminosity: \(~1.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\) (design: \(10^{34} \text{ cm}^{-2}\text{s}^{-1}\))
  - \(~40 \text{ fb}^{-1}\) delivered to ATLAS and CMS each

- About 90% of delivered luminosity was recorded and is good for physics analysis
Pile-up Interactions

Down-side to high luminosity:
multiple simultaneous interactions per crossing (pile-up) as crossing rate is limited to $\sim 31.5$ MHz

Introduces potential confusion and performance degradation as not all particles are coming from collision of interest
LHC Physics Output

- Full set of physics results here:
  - **ATLAS**: https://twiki.cern.ch/twiki/bin/view/AtlasPublic
- Will later show a small selection of current Run-1/2 results
  - Primarily to highlight where higher luminosity is needed
- Many more results from 2016 data to come in next months
The High Luminosity LHC Upgrade
HL-LHC Upgrade Plans

- 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\(\times10^{34}\) cm\(^{-2}\)s\(^{-1}\) while using luminosity leveling (3-5 hours at peak luminosity)
- Design for “ultimate” performance 7.5\(\times10^{34}\) cm\(^{-2}\)s\(^{-1}\) and 4000 fb\(^{-1}\)
HL-LHC Upgrade Project
Major intervention on more than 1.2 km of the LHC

- New IR-quads Nb$_3$Sn (more focusing in inner triplet magnets)
- Crab Cavities (compensate crossing angle by tilting beams)
- New 11 T Nb$_3$Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- 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 experimental 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 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 $\sim$750 kHz
- HLT output $\sim$7.5 kHz
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

- Higher granularity trackers
  - Pixel size: 50x50 or 25x100 μm²
- Both ATLAS and CMS plan to extend tracker coverage from \( \eta \sim 2.7 \) to \( \eta \sim 4 \) with pixel extension

Provides multiple benefits

- Extended lepton coverage (with forward muon tagger)
- Forward b-tagging
- Improved vertexing
- Pileup suppression
The HL-LHC Physics case

Understanding EW Symmetry Breaking
Standard Model

**Pre-LHC:**
Is the Higgs Mechanism responsible for masses?

**Quarks**
- $u$, $c$, $t$, $d$, $s$, $b$
  - up, charm, top
  - down, strange, bottom

**Leptons**
- $e$, $\mu$, $\tau$
- $\nu_e$, $\nu_\mu$, $\nu_\tau$
- electron, muon, tau
- electron neutrino, muon neutrino, tau neutrino

**Forces**
- $H$ (Higgs boson)
- $Z$, $W$, $g$
  - $Z$ boson, photon, $W$ boson, gluon
The Brout-Englert-Higgs Mechanism

- In electro-weak gauge theory, gauge symmetry implies all bosons are massless
  - But W and Z bosons massive
- Brout-Englert-Higgs mechanism introduces mass by spontaneous symmetry breaking of Higgs field
  \[ V(\phi) = \mu^2 \phi^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi \]
- Results in one new scalar boson (Higgs boson)
  - Only fundamental scalar particle in SM
  - Couples to other particles in proportion to their mass
  - Mass of boson itself not predicted
Higgs Boson Discovery

- In 2012 (Run-1) ATLAS and CMS both saw new 125 GeV particle at >5σ significance
- Consistent with Higgs Boson
- Nobel Prize to François Englert, Peter Higgs
Standard Model Complete?

Post-LHC run 1: Is it the Standard Model Higgs Boson?
Higgs Boson Production at the LHC

- At LHC, Higgs dominantly produced in gluon fusion
- Other production channels important too
  - Helps identify Higgs production
  - More precise predictions

Total cross section at $\sqrt{s}=14$ TeV: 57 pb $\rightarrow \sim 0.5$ Hz of Higgs at $L=10^{34}$ cm$^{-2}$s$^{-1}$
The Higgs Boson Properties

- Higgs boson couples to mass of decays particles
  - Will decay mostly to heaviest particles allowed

- The Higgs does not couple directly to photons and gluons
  - Decays to these through loops with heavy particles (top quarks, W bosons)
Higgs Boson Properties from Run-1

Mass measured to 0.2% precision
\[ M_H = 125.09 \pm 0.24 \text{ GeV} \]

Angular distributions consistent with spin-0 and even parity

Still room for much more detailed studies with more luminosity
Clear observation of Higgs Boson at 13 TeV in bosonic decay modes

Overall significance of Higgs Boson signal: ~10σ
With the new data have started detailed studies of Higgs Boson production

- Dependence on center-of-mass energy
- Differential cross sections
- Productions channels
Search for ttH Production at 13 TeV

- ttH directly probes the top-Higgs Yukawa coupling instead of loop in ggH
- Benefits from higher x-section at 13 TeV
- See slight excess in many channels
- Also seen in some Run-1 results
- Less so in recent CMS results

Observed significance: Multi-leptons: 3.3σ (Expected: 2.5σ)

Observed significance: 2.8σ
Expected: 1.8σ
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
Projections for Higgs Couplings

- Full set of HL-LHC coupling projections are based on Run-1 analyses
  - Assumes $\mu=140$ in case of ATLAS
  - Same as Run-1 performance for CMS
- Higgs coupling precision (per experiment):
  - 3-5% for W, Z and $\gamma$
  - 5-10% for t, b and $\tau$
  - ~7% for $\mu$
- Do not include improved detector designs or improvements in analysis techniques
Projections based on Run-2 Analysis

- H→γγ and H→ZZ projections updated to 13 TeV (12.9 fb⁻¹) based Run-2 analyses
- H→ZZ added expected degradation at μ=200
  - Reduced lepton efficiency
  - Increased misidentification
- Can make precise differential p_T(H) cross section measurements
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
- $H \rightarrow \gamma\gamma$ 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 can become dominant at HL-LHC
- Decouple by measuring fiducial cross section
  - Can achieve ~4% precision
Advantage of Vector-Boson-Fusion

- Possible to reduce theoretical uncertainties by measuring Higgs decays in Vector-Boson-Fusion production
  - Total cross section uncertainty reduced by factor \( \sim 4 \)
  - Factor 10 less statistics
  - Better signal/background from requiring two forward jets from VBF scattering
Pile-up Jet Suppression

- At 200 pile-up, every event has \( \sim 5 \) pile-up jets (\( p_T > 30 \) GeV)
- Can suppress these by using tracking to associate them to either pile-up or hard-scatter vertex
- 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 VBF H→WW analysis

- VBF selection with forward tracker:
  - ~200 signal events
  - ~400 background events from t̄t and non Higgs WW

Signal precision and significance

<table>
<thead>
<tr>
<th>Tracker coverage</th>
<th>Full $\Delta_{\mu}$</th>
<th>1/2 $\Delta_{\mu}$</th>
<th>None $\Delta_{\mu}$</th>
<th>Significance (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full</td>
<td>1/2</td>
<td>None</td>
<td>Full</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt;4.0$</td>
<td>0.20</td>
<td>0.16</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt;3.2$</td>
<td>0.25</td>
<td>0.21</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt;2.7$</td>
<td>0.39</td>
<td>0.32</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
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 $2.8 \times $SM
- Expect significance of $\sim 2\sigma$ with 300 fb\textsuperscript{-1} and $\sim 7\sigma$ with 3000 fb\textsuperscript{-1} in inclusive channel
- Improved tracker resolution not accounted for ($\sim 30\%$ improvement on mass resolution)
- Also specific channels like $t\bar{t}H$, $H \rightarrow \mu^+\mu^-$

$H \rightarrow J/\psi\gamma$ (coupling to charm quark)

- 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\textsuperscript{-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 $\lambda$

$$V(\phi) = \mu_0^2 |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi^i_L \psi^j_R \phi$$

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

### Decay Channels and Branching Ratios

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Branching Ratio</th>
<th>Total Yield ($3000$ 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→b̄bbγγ Analysis

- Low statistics, but high purity channel
- After selections expect 9.5 signal events and 91 background events
- Corresponds to signal significance of 1.05σ

95% CL limits on self-coupling (ignoring systematics): -0.8<\frac{\lambda}{\lambda_{SM}}<7.7
# Higgs Self Coupling Projections

## 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</td>
<td>S2</td>
<td>Stat. Only</td>
</tr>
<tr>
<td>$gg \to HH \to \gamma\gamma bb$ ($S1+/S2+$)</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>$gg \to HH \to \tau\tau bb$</td>
<td>7.4</td>
<td>5.2</td>
<td>3.9</td>
</tr>
<tr>
<td>$gg \to HH \to VVbb$</td>
<td>4.8</td>
<td>4.6</td>
<td>4.6</td>
</tr>
<tr>
<td>$gg \to HH \to bbbb$</td>
<td>7.0</td>
<td>2.9</td>
<td>7.0</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Channel</th>
<th>Expected limit in $\mu$</th>
<th>Significance</th>
<th>Limits on $\lambda/\lambda_{SM}$ at 95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full Syst.</td>
<td>Stat. only</td>
<td>Full Syst.</td>
</tr>
<tr>
<td>$gg\to HH \to \gamma\gamma bb$</td>
<td>[ATL-PHYS-PUB-2017-001]</td>
<td>4.3</td>
<td>1.05σ</td>
</tr>
<tr>
<td>$gg \to HH \to \tau\tau bb$</td>
<td>[ATL-PHYS-PUB-2015-046]</td>
<td>5.2</td>
<td>0.6σ</td>
</tr>
<tr>
<td>$gg \to HH \to bbbb$</td>
<td>[ATL-PHYS-PUB-2016-024]</td>
<td>1.5</td>
<td>0.35σ</td>
</tr>
<tr>
<td>$ttHH \to t_{had} t_{lep} bbbb$</td>
<td>[ATL-PHYS-PUB-2016-023]</td>
<td>0.35σ</td>
<td>0.2&lt;\lambda/\lambda_{SM} &lt;7</td>
</tr>
</tbody>
</table>
**Higgs Self Coupling Projections**

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

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<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>4.6</td>
</tr>
<tr>
<td>$gg \rightarrow HH \rightarrow bbbb$</td>
<td>7.0</td>
<td>2.9</td>
<td>2.9</td>
</tr>
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**ATLAS simulations (HH→bbbb is Runs-2 extrapolations):**

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<th>Uncertainty</th>
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<tr>
<td></td>
<td>Full Syst.</td>
<td>Stat. only</td>
<td>Full Syst.</td>
</tr>
<tr>
<td>$gg\rightarrow HH\rightarrow \gamma\gamma bb$</td>
<td>1.05$\sigma$</td>
<td>1.05$\sigma$</td>
<td>-0.8$&lt;\lambda/\lambda_{SM}$</td>
</tr>
<tr>
<td>$gg \rightarrow HH \rightarrow \tau\tau bb$</td>
<td>4.3</td>
<td>4.3</td>
<td>-4$&lt;\lambda/\lambda_{SM}$</td>
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<tr>
<td>$gg \rightarrow HH \rightarrow bbbb$</td>
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<td>$ttHH \rightarrow t_{had} t_{lep} bbbb$</td>
<td>0.35$\sigma$</td>
<td>0.35$\sigma$</td>
<td>0.2$&lt;\lambda/\lambda_{SM}$</td>
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</table>

**Even with HL-LHC will need to combine multiple channels and expect to be sensitive to SM $\lambda$.**
The HL-LHC Physics case

Beyond the Standard Model
Standard Model Complete?

Post-LHC run 1:
Is it the Standard Model Higgs Boson?

Are there more than this?
Motivation for Beyond SM Physics

Nature of Dark Matter?

- Atoms: 4.6%
- Dark Energy: 71.4%
- Dark Matter: 24%

Finetuning?

\[ \Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2} \Lambda_{UV}^2 + \ldots \]

New physics cut-off

Unification of forces?

Origin of mass hierarchy and flavor?

\[ Y_u \approx \begin{pmatrix} 10^{-5} & -0.002 & 0.007 + 0.004i \\ 10^{-6} & 0.007 & -0.04 + 0.0008i \\ 10^{-8} + 10^{-7}i & 0.0003 & 0.92 \end{pmatrix} \]
Very wide range of BSM models to address open questions
- Some already (partly) excluded by LHC results
- Some need HL-LHC data or cannot be excluded
Supersymmetry

- Well-motivated SM extension
  - Solution to hierarchy problem
  - Provides DM candidate
  - Unifies gauge-couplings

To be “Natural” SUSY has to have some new particles at TeV-scale

- Light stop and gluino to regularize light Higgs boson

- Light higgsinos

---

L. Hall, 2011
Status of Gluino Searches

- LHC highly sensitive to TeV-scale colored sparticles
- Wide set of searches for gluinos in different decay modes

Gluino limits for light neutralino at 1.6-2.0 TeV
At the high end of “Natural SUSY” expectation
Search for Gluino Pairs at HL-LHC

HL-LHC would significantly extend sensitivity to higher mass gluinos

Expect to discover gluinos up to ~2 TeV for neutralinos up to 1 TeV

Exclude gluinos up to ~3 TeV
Stop Quark Searches

- Multiple Run-1 and Run-2 searches dedicated to stop searches
- Specialized search regions to fill in low-mass stop “holes”

Stop mass mostly constrained to be above 1050 GeV
HL-LHC will push this toward 1.5 TeV
Chargino/Neutralino Searches

Electroweakinos primarily searched for in leptonic channels

Exclusion reach strongly dependent on decay modes

Note: above limits assume pure wino-nature for $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^+$

Higgsino production cross section is lower

Mass degenerate states require specialized searches
Chargino/Neutralino HL-LHC Searches

Projection for chargino-neutralino production in two channels:

Discovery reach up to ~800 GeV
Very limited reach without HL-LHC
Search for Dark Matter at the LHC

- LHC can complement direct and indirect searches for dark matter by directly producing dark matter.

Use “mono-X” topology to boost DM particles and make them visible.
Mono-Jet Search at HL-LHC

- Mono-jet search typically most sensitive to DM production
- Has been projected to full HL-LHC based on Run-2 analysis

- Fit for excess in $E_T^{\text{miss}}$ bins
  - Extend to 2.4 TeV for HL-LHC
- Main backgrounds assumed to be real $E_T^{\text{miss}}$ from
  - $Z(\rightarrow\nu\nu)+\text{jet}(s)$
  - $W(\rightarrow\nu\ell)+\text{jet}(s)$
- Backgrounds will be estimated using data-driven techniques
  - Projection depends strongly on how well systematics can be controlled
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  - $W(\rightarrow \nu \ell)+\text{jet(s)}$
- Backgrounds will be estimated using data-driven techniques
  - Projection depends strongly on how well systematics can be controlled

Sensitivity to axial-vector mediator driven by high $E_T^{\text{miss}}$ bins
Mono-Jet Search at HL-LHC

- Mono-jet search typically most sensitive to DM production
- Has been projected to full HL-LHC based on Run-2 analysis

LHC has unique sensitivity to pseudo-scalar mediator Driven by lower $E_T^{\text{miss}}$ bins

- Fit for excess in $E_T^{\text{miss}}$ bins
  - Extend to 2.4 TeV for HL-LHC
- Main backgrounds assumed to be real $E_T^{\text{miss}}$ from
  - $Z(\rightarrow\nu\nu)+\text{jet(s)}$
  - $W(\rightarrow\nu\ell)+\text{jet(s)}$
- Backgrounds will be estimated using data-driven techniques
  - Projection depends strongly on how well systematics can be controlled
Comparison to non-LHC Searches

- For vector and scalar mediators, only competitive with direct detection searches for very light DM
- For axial-vector and pseudoscalar mediators competitive
  - No comparison plot for projection
  - Cross section scales as \((m_{\text{med}})^{-4}\)

Cross section scales as \((m_{\text{med}})^{-4}\)

ArXiv: 1703.01651
Vast set of other BSM Searches

Vector-like quark pair production

- \(Q \rightarrow qW\): 20 fb
- \(T \rightarrow tH\): 35 fb
- \(T \rightarrow tZ\): 25 fb
- \(T \rightarrow bW\): 7 fb
- \(B \rightarrow bH\): 7 fb
- \(B \rightarrow bZ\): 35 fb
- \(B \rightarrow tW\): 9 fb
- \(X5/3 \rightarrow tW\): 4 fb
- \(X5/3 \rightarrow tW\): 300 fb
- \(T \rightarrow bW\): 60 fb

8 TeV

13 TeV

Resonances to heavy quarks

- \(Z'(1.2\%) \rightarrow tt\): 8 fb
- \(Z'(10\%) \rightarrow tt\): 15 fb
- \(gKK \rightarrow tt\): 40 fb
- \(W' \rightarrow tb\): 40 fb
- \(W' \rightarrow tb\) \(M_W < M_{W'}\): 50 fb
- \(W' \rightarrow tb\) \(M_W > M_{W'}\): 50 fb
- \(Z'(1\%) \rightarrow tt\): 100 fb
- \(Z'(10\%) \rightarrow tt\): 120 fb
- \(Z'(30\%) \rightarrow tt\): 200 fb
- \(gKK \rightarrow tt\): 200 fb
- \(W' \rightarrow tb\): 400 fb
- \(Z' \rightarrow Tt \rightarrow tZt\): 150 fb

Excited quarks

- \(t^* \rightarrow tg S=3/2\): 80 fb
- \(t^* \rightarrow tg S=1/2\): 500 fb
- \(b^* \rightarrow tW K_{T}=1\): 70 fb
- \(b^* \rightarrow tW K_{T}=1\): 60 fb
- \(b^* \rightarrow tW K_{T}=1\): 70 fb

Resonances to dibosons

- Radion \(\rightarrow HH\): 6 fb
- \(W' \rightarrow WH\): 10 fb
- \(Z' \rightarrow ZH\): 13 fb
- \(G_{bulk} \rightarrow WW\): 20 fb
- \(G_{bulk} \rightarrow ZZ\): 30 fb
- \(W' \rightarrow VW\) HVT(B): 28 fb
- \(W' \rightarrow WH\) HVT(B): 40 fb
- \(Z' \rightarrow VH\) HVT(B): 18 fb
- Radion \(\rightarrow HH\): 20 fb

\(^\dagger\) model-independent

B2G
new physics
searches with
heavy SM particles
Vast set of other BSM Searches

- Vector-like quark pair production
  - $Q \to qW$: 20 fb
  - $T \to tH$: 35 fb
  - $T \to tZ$: 25 fb
  - $T \to bW$: 7 fb
  - $B \to bH$: 7 fb
  - $B \to bZ$: 35 fb
  - $B \to tW$: 9 fb
  - $X_{5/3} \to tW$: 4 fb
  - $X_{5/3} \to tW$: 300 fb
  - $T \to bW$: 60 fb

- Resonances to heavy quarks
  - $Z'(1.2\%) \to tt$: 8 fb
  - $Z'(10\%) \to tt$: 15 fb
  - $gKK \to tt$: 40 fb
  - $W' \to tb$: 40 fb
  - $W \to tb$ $M_{W'} < M_W$: 50 fb

- Excited quarks
  - $t^* \to tg S=3/2$: 80 fb
  - $t^* \to tg S=1/2$: 500 fb
  - $b^* \to tW$: $K_t=1$: 70 fb
  - $b^* \to tW$: $K_t=1$: 60 fb

- Only a few projected to 3000 fb$^{-1}$

- Vector-like quark single production
  - $T \to tH$ $c_{\psi}=1.5$: 800 fb
  - $T \to tH$ $c_{\psi}=2.5$: 900 fb
  - $T \to tH$ $t \to had$: $c_{\psi}=1.5$: 600 fb
  - $T \to tH$ $t \to had$: $c_{\psi}=2.5$: 400 fb
  - $T \to tz$ $c_{\psi}=1.5$: 200 fb
  - $T \to tz$ $c_{\psi}=2.5$: 200 fb
  - $B \to bZ$: $c_{\psi}=1.5$: 250 fb
  - $T \to bW$: $c_{\psi}=1.5$: 200 fb
  - $Y \to tH$: $c_{\psi}=1.0$: 200 fb

- Resonances to dibosons
  - $Z' \to Tt \to tZt$: 150 fb
  - $W' \to WH$: 10 fb
  - $Z' \to ZH$: 13 fb
  - $G_{\text{bulk}} \to WW$: 20 fb
  - $G_{\text{bulk}} \to ZZ$: 30 fb
  - $W' \to WW$ HVT(B): 28 fb
  - $Z' \to VH$ HVT(B): 18 fb
  - radion $\to HH$: 20 fb

B2G
new physics searches with heavy SM particles

*model-independent*
Heavy $Z' \rightarrow \bar{t}t$ Search

- At HL-LHC search mass reach in multi-TeV range for BSM particles
- Decay products can be very boosted
  - Requires ability to separate closely produced particles such as a boosted top
  - High-granularity trackers, such as 5-layer pixel detectors help improve performance over current detector

---

**ATLAS Simulation Internal**

<table>
<thead>
<tr>
<th>$m(Z')$ [TeV]</th>
<th>1000</th>
<th>2000</th>
<th>3000</th>
<th>4000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{Z'} \times BR(Z' \rightarrow \bar{t}t)$ [pb]</td>
<td>3000 fb$^{-1}$ limit</td>
<td>3 fb$^{-1}$ limit</td>
<td>3000 fb$^{-1}$ limit</td>
<td>3 fb$^{-1}$ limit</td>
</tr>
</tbody>
</table>

Exp. 1 $\sigma$ uncertainty
Exp. 2 $\sigma$ uncertainty
Leptophobic $Z'$ cross section

**ATL-PHYS-PUB-2017-002**
Summary and Outlook
Summary and Outlook

- High-Luminosity LHC is a 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
  - The Higgs Boson will be studied in great detail at HL-LHC
- HL-LHC also extends sensitivity to Beyond SM Physics
  - New TeV-scale physics could be discovered or be very strongly disfavored after HL-LHC
- Technical Design Reports are now in preparation and will come over the next year
  - First one just became public
    https://cds.cern.ch/record/2257755

Much more information in presentations at HL-LHC Experiments workshop
https://indico.cern.ch/event/524795/timetable/
Backup
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
Wanted Reduction in Theory Uncertainties

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Status 2014</th>
<th>Deduced size of uncertainty to increase total uncertainty by ≤10% for 300 fb⁻¹</th>
<th>Deduced size of uncertainty to increase total uncertainty by ≤10% for 3000 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\kappa_{gZ}$</td>
<td>$\lambda_{gZ}$</td>
</tr>
<tr>
<td>Theory uncertainty (%)</td>
<td>[10–12]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$gg \rightarrow H$</td>
<td></td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>PDF</td>
<td></td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>incl. QCD scale (MHOU)</td>
<td></td>
<td>10–20</td>
<td>3.5–7</td>
</tr>
<tr>
<td>$p_T$ shape and 0j → 1j mig.</td>
<td>13–28</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1j → 2j mig.</td>
<td></td>
<td>18–58</td>
<td>-</td>
</tr>
<tr>
<td>1j → VBF 2j mig.</td>
<td></td>
<td>12–38</td>
<td>-</td>
</tr>
<tr>
<td>VBF 2j → VBF 3j mig.</td>
<td></td>
<td>3.3</td>
<td>-</td>
</tr>
<tr>
<td>VBF PDF</td>
<td></td>
<td>9</td>
<td>-</td>
</tr>
<tr>
<td>incl. QCD scale (MHOU)</td>
<td></td>
<td>8</td>
<td>-</td>
</tr>
</tbody>
</table>

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.
CERN is Studying Next Collider

Conceptual design studies of colliders in ~100 km ring

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

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

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


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>$\tilde{\chi}_2^0 \rightarrow t\tilde{t}\chi_1^0$</td>
<td>14 TeV, 0.3 ab$^{-1}$</td>
</tr>
<tr>
<td>$\tilde{\chi}_2^0 \rightarrow t\tilde{t}\chi_1^0$</td>
<td>14 TeV, 3 ab$^{-1}$</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0 \rightarrow t\chi_1^0$</td>
<td>5 σ Discovery</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0 \rightarrow t\chi_1^0$</td>
<td>100 TeV, 3 ab$^{-1}$</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0 \rightarrow t\chi_1^0$</td>
<td>100 TeV, 30 ab$^{-1}$</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>$HH \rightarrow b\bar{b}\gamma\gamma$</td>
<td>3%</td>
<td>$\lambda_3 \in [0.97, 1.03]$</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}b\bar{b}$</td>
<td>5%</td>
<td>$\lambda_3 \in [0.9, 1.5]$</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}4\ell$</td>
<td>$O(25%)$</td>
<td>$\lambda_3 \in [0.6, 1.4]$</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}\ell^+\ell^-$</td>
<td>$O(15%)$</td>
<td>$\lambda_3 \in [0.8, 1.2]$</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}\ell^+\ell^-$</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 [\text{MeV}])</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>(\sin^2 \theta_{\text{eff}} [10^{-5}])</td>
<td>4.5</td>
<td>16</td>
</tr>
<tr>
<td>(\Gamma_Z [\text{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 [\text{MeV}])</td>
<td>3–4</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>(\sin^2 \theta_{\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 [\text{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 \(m_{\text{top}}\) measured to \(~10\) MeV precision from threshold scan
Anomalous HZZ Coupling

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

$$A(H \rightarrow VV) \sim \left[ a_1 - e^{i\phi_{\Lambda Q}} \frac{(q_{V1}+q_{V2})^2}{\Lambda_Q^2} - e^{i\phi_{\Lambda 1}} \frac{(q_{V1}^2+q_{V2}^2)}{\Lambda_1^2} \right] m_V^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu \nu}^{* (1)} f_{\mu \nu}^{* (2), \mu \nu} + a_3 f_{\mu \nu}^{* (1)} f_{\mu \nu}^{* (2), \mu \nu}$$

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

- Interference contribution becomes more dominant at smaller values of $f_{ai} \times \cos(\phi_{ai})$
Higgs to Invisible

- Main backgrounds:
  - $Z(\ell\ell) + \text{jets}$
  - $W(\ell\nu) + \text{jets}$
  - QCD multijet
- Current BR($H\to\text{inv}$) 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</th>
<th>ECFA16 S1 ( fb^{-1} )</th>
<th>ECFA16 S2 ( fb^{-1} )</th>
<th>$1/\sqrt{L}$ scaling ( fb^{-1} )</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>$\Delta \mu/\mu \approx 14$ to 20%</td>
<td>$HH \rightarrow b\bar{b}\tau\tau$</td>
<td>$0.6 \sigma$</td>
</tr>
<tr>
<td>VBF $H \rightarrow ZZ \rightarrow 4\ell$</td>
<td>$\Delta \mu/\mu \approx 15$ to 18%</td>
<td>(FULL uncertainties)</td>
<td>$- 4 &lt; \lambda_{HHH}/\lambda_{SM} &lt; 12$</td>
</tr>
<tr>
<td>$ttH, H \rightarrow \gamma\gamma$</td>
<td>$\Delta \mu/\mu \approx 17$ to 20%</td>
<td>$HH \rightarrow bbbb$</td>
<td>$- 3.4 &lt; \lambda_{HHH}/\lambda_{SM} &lt; 12$</td>
</tr>
<tr>
<td>$VH, H \rightarrow \gamma\gamma$</td>
<td>$\Delta \mu/\mu \approx 25$ to 35%</td>
<td>($p_T$(jet)$&gt; 75$ GeV, FULL uncertainties)</td>
<td></td>
</tr>
</tbody>
</table>
| off-shell $H \rightarrow ZZ \rightarrow 4\ell$ | $\Delta \mu/\mu \approx 50\%$  
$\Gamma_H = 4.2^{+1.5}_{-2.1}$ MeV | $HH \rightarrow bb\gamma\gamma$   | $1.3 \sigma$                     |
| $H \rightarrow Z\gamma$       | $\Delta \mu/\mu \approx 30\%$  
$3.9 \sigma$              | $ttHH, HH \rightarrow bbbb$      | $0.35 \sigma$                    |
| $H \rightarrow J/\psi \gamma$ | $BR < 44 \times 10^{-6}$  
@95% CL     | (stat. uncertainties only)       |                                   |
| $t \rightarrow Hq$            | $BR \leq 10^{-4}$  
@95% CL     | (stat. uncertainties only)       |                                   |
VBF $H \rightarrow ZZ^* \rightarrow \ell\ell\ell\ell$

- Initial selection:
  - 2 jets with $m(jj)>130$ GeV
  - 4 leptons consistent with $H \rightarrow ZZ^* \rightarrow \ell\ell\ell\ell$
- 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>$\mu_{PU}$</th>
<th>200 FULL</th>
<th>200 NONE</th>
<th>140 FULL</th>
<th>140 NONE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \mu$</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 $\sigma$</td>
<td>10.2 $\sigma$</td>
<td>7.7 $\sigma$</td>
<td>11.1 $\sigma$</td>
</tr>
</tbody>
</table>
Search for Heavy Higgs $\rightarrow \tau\tau$

- 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:
- $m^{\text{mod+}}$ benchmark
- Sensitivity at high $m_A$ is still dominated by statistics
## CMS Tracker Changes

<table>
<thead>
<tr>
<th></th>
<th>Phase-1</th>
<th>Phase-2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Outer Tracker</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area</td>
<td>~200 m²</td>
<td>~200 m²</td>
</tr>
<tr>
<td>Hits</td>
<td>9.3 M</td>
<td>43.7 M</td>
</tr>
<tr>
<td>Layers</td>
<td>-</td>
<td>164 M</td>
</tr>
<tr>
<td>Modules</td>
<td>15,148</td>
<td>13,556</td>
</tr>
<tr>
<td>Readout Rate</td>
<td>100 kHz</td>
<td>750 kHz /40 MHz</td>
</tr>
<tr>
<td><strong>Pixel Bar + Fw + Ext</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area</td>
<td>~1 m²</td>
<td>4.7 m²</td>
</tr>
<tr>
<td>Hits</td>
<td>66 M</td>
<td>1870 M</td>
</tr>
<tr>
<td>Modules</td>
<td>1440</td>
<td>4136</td>
</tr>
<tr>
<td>Readout Rate</td>
<td>100 kHz</td>
<td>750 kHz</td>
</tr>
</tbody>
</table>
CMS Tracker Comparison

**Phase-1**
- OT 3.6.2
- Pix 4.0.2.1

**Phase-2**
- OT v3.6.2
- Pixel v4.0.2.1

Number of hits vs. $\eta$

Material amount [$x/X_0$] vs. $\eta$
ATLAS Tracker Hits and Material

Optimized for at least 13 hits, minimum material and coverage up to $\eta=4$
ATLAS Tracker Performance

**ATLAS Simulation Preliminary**

$t\bar{t}$, truth $p_T > 1$ GeV, $\langle \mu \rangle = 200$

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

---

**ATLAS Preliminary Simulation**

ITk Inclined

$p_T$ = 1 GeV

$p_T$ = 10 GeV

$p_T$ = 100 GeV

Single muons, $\mu = 0$

---

**ATLAS Preliminary Simulation**

ITk Inclined

$p_T$ = 1 GeV

$p_T$ = 10 GeV

$p_T$ = 100 GeV

Single muons, $\mu = 0$
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
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

![Graph showing Lepton isolation efficiency and B-tagging efficiency vs. pile-up density](image-url)

**Lepton isolation efficiency**

**B-tagging efficiency**

**CMS Simulation Preliminary**

**IDTR-2016-012**

**CMS-DP-2016-065**
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
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
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.
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→γγ 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
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
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
ATLAS Trigger Schemes

**Level-0 + Level-1 hardware trigger**

- ITK -> Calo -> Muon
- Felix (Multi-level)
- L0 Calo
- L0 Muon
- L0 Topo/CTP/ROE
- L1 Track
- L1 Global
- L1 CTP

**Rates and Latencies**

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

**Level-0 only hardware trigger**

- ITK -> Calo -> Muon
- Felix (Multi-level)
- L0 Calo
- L0 Muon
- L0 Topo/CTP

**Rates and Latencies**

- **Level 0:** 1 MHz, 10 μs
- **EF output:** 10 kHz
CMS Trigger System

- Current Level-1 trigger uses only calorimeter and muon information
- Phase-II upgrades
  - Replace calorimeter electronics
  - Increase latency and Level-1 accept rate
  - Use tracking at Level-1 based on doublet seeds
  - Global track-trigger correlator
TDAQ Upgrades

- Level-0 trigger use Phase-I upgrades
  - Advanced algos with finer-granularity calo data:
    - Incl. longitudinal segmentation for $e/\gamma/\tau$
    - 0.1x0.1 towers for jets/$E_T^{\text{miss}}$
  - 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
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>
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<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>
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<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>
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<tr>
<td>τ</td>
<td>100</td>
<td>150</td>
<td>20</td>
<td>0.13</td>
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<tr>
<td>di-tau</td>
<td>40,30</td>
<td>40, 30</td>
<td>200</td>
<td>0.08</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: $\sim4$ MHz

---

**L1 Menu with L1 Track Trigger: PU140**

<table>
<thead>
<tr>
<th>Trigger Algorithm</th>
<th>Rate [kHz]</th>
<th>Offline Threshold(s) [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Mu (tk)</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>Double Mu (tk)</td>
<td>1.1</td>
<td>14</td>
</tr>
<tr>
<td>ele (iso tk) + Mu (tk)</td>
<td>0.7</td>
<td>19</td>
</tr>
<tr>
<td>Single Ele (tk)</td>
<td>16</td>
<td>10.5</td>
</tr>
<tr>
<td>Single iso Ele (tk)</td>
<td>13</td>
<td>27</td>
</tr>
<tr>
<td>Single $\gamma$ (tk isol)</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>ele (iso tk) + e/$\gamma$</td>
<td>11</td>
<td>22</td>
</tr>
<tr>
<td>Double $\gamma$ (tk isol)</td>
<td>17</td>
<td>22</td>
</tr>
<tr>
<td>Single Tau (tk)</td>
<td>13</td>
<td>88</td>
</tr>
<tr>
<td>Tau (tk) + Tau</td>
<td>32</td>
<td>56</td>
</tr>
<tr>
<td>ele (iso tk) + Tau</td>
<td>7.4</td>
<td>19</td>
</tr>
<tr>
<td>Tau (tk) + Mu (tk)</td>
<td>5.4</td>
<td>45</td>
</tr>
<tr>
<td>Single Jet</td>
<td>42</td>
<td>173</td>
</tr>
<tr>
<td>Double Jet (tk)</td>
<td>26</td>
<td>200</td>
</tr>
<tr>
<td>Quad Jet (tk)</td>
<td>12</td>
<td>40</td>
</tr>
<tr>
<td>Single ele (tk) + Jet (tk)</td>
<td>15</td>
<td>23</td>
</tr>
<tr>
<td>Single Mu (tk) + Jet (tk)</td>
<td>8.8</td>
<td>16</td>
</tr>
<tr>
<td>Single ele (tk) + $H_T^{miss}$ (tk)</td>
<td>10</td>
<td>23</td>
</tr>
<tr>
<td>Single Mu (tk) + $H_T^{miss}$ (tk)</td>
<td>2.7</td>
<td>16</td>
</tr>
<tr>
<td>$H_T$ (tk)</td>
<td>13</td>
<td>350</td>
</tr>
</tbody>
</table>

Rate for above Triggers: 180

Est. Total Level-1 Menu Rate: 260

---

Rates w/o L1 Track Trigger:

<table>
<thead>
<tr>
<th>Rate [kHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>139</td>
</tr>
<tr>
<td>177</td>
</tr>
<tr>
<td>160</td>
</tr>
<tr>
<td>78</td>
</tr>
<tr>
<td>89</td>
</tr>
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<td>70</td>
</tr>
<tr>
<td>88</td>
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<tr>
<td>53</td>
</tr>
<tr>
<td>34</td>
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<tr>
<td>55</td>
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<tr>
<td>42</td>
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<td>52</td>
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<tr>
<td>185</td>
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<td>144</td>
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<tr>
<td>175</td>
</tr>
<tr>
<td>60</td>
</tr>
<tr>
<td>64</td>
</tr>
<tr>
<td>73</td>
</tr>
</tbody>
</table>

1000

1500
Triggering on $H \to \tau\tau$

- $H \to \tau\tau$ 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 $H \to \tau\tau$
  - Same triggers also useful for $HH \to b\bar{b}\tau\tau$
HH→bbτ⁺τ⁻ Analysis

- Consider all combinations of leptonic/hadronic ττ final states:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Significance</th>
<th>Combined in channel</th>
<th>Total combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>e + jets</td>
<td>0.31</td>
<td></td>
<td>0.60</td>
</tr>
<tr>
<td>μ + jets</td>
<td>0.30</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td>τhad τhad</td>
<td>0.41</td>
<td>0.41</td>
<td></td>
</tr>
</tbody>
</table>

Event yields for 3000 fb⁻¹ using a cut-based analysis strategy:

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>τlep τlep</td>
<td>9</td>
<td>6,200</td>
<td></td>
</tr>
<tr>
<td>τlep τhad</td>
<td>20</td>
<td>880</td>
<td></td>
</tr>
<tr>
<td>τhad τhad</td>
<td>19</td>
<td>830</td>
<td></td>
</tr>
</tbody>
</table>

Signal significance for SM coupling:

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

95% CL limits on self-coupling: $$-4 < \lambda/\lambda_{SM} < 12$$
Triggering on HH→b¯¯b¯¯b

- HH→b¯¯b¯¯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 ~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>σ/σ_{SM} 95% Exclusion</th>
<th>λ_{HHH}/ λ_{SM}^{HHH} Lower Limit</th>
<th>λ_{HHH}/ λ_{SM}^{HHH} Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 GeV</td>
<td>Negligible</td>
<td>1.5</td>
<td>0.2</td>
<td>7</td>
</tr>
<tr>
<td>30 GeV</td>
<td>Current</td>
<td>5.2</td>
<td>-3.5</td>
<td>11</td>
</tr>
<tr>
<td>75 GeV</td>
<td>Negligible</td>
<td>2.0</td>
<td>-3.4</td>
<td>12</td>
</tr>
<tr>
<td>75 GeV</td>
<td>Current</td>
<td>11.5</td>
<td>-7.4</td>
<td>14</td>
</tr>
</tbody>
</table>
Search for $\bar{t}tHH$ Production

- $\sigma(\bar{t}tHH)$ only $\sim 1$ 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 $\geq 5$ 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: $0.35\sigma$
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→b\bar{b}τ^+τ^−
SM Measurements

Vast effort on precision SM measurements with comparisons to the latest (N)NLO predictions

June 2016

CMS Preliminary

All results at: http://cern.ch/go/pNj7
SM Measurements

Total production cross section [pb]

- $pp \rightarrow X$
  - Pythia8 (LO)
  - ATLAS Preliminary 2011
  - $7 \text{ TeV, } 20 \mu b^{-1}$, Nat. Commun. 2, 463 (2011)
  - $8 \text{ TeV, } 500 \mu b^{-1}$, arXiv:1607.06605
  - $13 \text{ TeV, } 60 \mu b^{-1}$, arXiv:1606.02625

- $pp \rightarrow W$
  - NNLO
  - $7 \text{ TeV, } 36 \text{ pb}^{-1}$, PRD 85, 072004 (2012)
  - $13 \text{ TeV, } 81 \text{ pb}^{-1}$, PLB 759 (2016) 601

- $pp \rightarrow Z / \gamma^*$
  - NNLO
  - $7 \text{ TeV, } 4.6 \text{ fb}^{-1}$, Eur. Phys. J. C 74:3109 (2014)
  - $13 \text{ TeV, } 3.2 \text{ fb}^{-1}$, arXiv:1606.02699

- $pp \rightarrow t\bar{t}$
  - NNLO+NNLL
  - $7 \text{ TeV, } 4.6 \text{ fb}^{-1}$, PRD 90, 112006 (2014)
  - $8 \text{ TeV, } 20.3 \text{ fb}^{-1}$, ATLAS-CONF-2014-007
  - $13 \text{ TeV, } 3.2 \text{ fb}^{-1}$, ATLAS-CONF-2015-079

- $pp \rightarrow H$
  - LHC-XS (N^3LO ggF)
  - $7 \text{ TeV, } 4.5 \text{ fb}^{-1}$, Eur. Phys. J. C 76 (2016) 6
  - $8 \text{ TeV, } 20.3 \text{ fb}^{-1}$, Eur. Phys. J. C 76 (2016) 6
  - $13 \text{ TeV, } 13.3 \text{ fb}^{-1}$, ATLAS-CONF-2016-081

- $pp \rightarrow WW$
  - NNLO
  - $7 \text{ TeV, } 4.6 \text{ fb}^{-1}$, PRD 87, 112001 (2013)
  - $8 \text{ TeV, } 20.3 \text{ fb}^{-1}$, arXiv:1608.03086
  - $13 \text{ TeV, } 3.2 \text{ fb}^{-1}$, ATLAS-CONF-2016-090

- $pp \rightarrow WZ$
  - NNLO
  - $8 \text{ TeV, } 20.3 \text{ fb}^{-1}$, PRD 93, 092004 (2016)
  - $13 \text{ TeV, } 3.2 \text{ fb}^{-1}$, arXiv:1606.04017

- $pp \rightarrow ZZ$
  - NNLO
  - $7 \text{ TeV, } 4.5 \text{ fb}^{-1}$, JHEP 03, 128 (2013)
  - $8 \text{ TeV, } 20.3 \text{ fb}^{-1}$, ATLAS-CONF-2013-020
  - $13 \text{ TeV, } 3.2 \text{ fb}^{-1}$, PRL 116, 101801 (2016)
**Unitarity:** if only $Z$ and $W$ are exchanged, the amplitude of (longitudinal) $W_L W_L$ scattering violates unitarity

$$A_{Z,W}(W^+ W^- \rightarrow W^+ W^-) \propto \frac{1}{\nu^2} (s + t)$$

Higgs boson restores unitarity of total amplitude:

$$A_H(W^+ W^- \rightarrow W^+ W^-) \propto -\frac{m_H^2}{\nu^2} \left( \frac{s}{s - m_H^2} + \frac{t}{t - m_H^2} \right)$$

Same-sign WW selection greatly reduces strong production. Removes s-channel Higgs process:

---

Look for VBS scattering in high dijet invariant mass distributions

ATLAS finds 3.6σ evidence for EW production (2.3σ expected)
**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 $\sim 6\%$ with 3000 fb$^{-1}$

**Graphs**

- $ZZ \rightarrow \ell\ell\ell\ell$
- $WZ \rightarrow \ell\nu\ell\ell$
- $W^\pm W^\pm \rightarrow \ell\nu\ell\nu$

**ATLAS Simulation Preliminary**

- $L = 3000$ fb$^{-1}$

**ATL-PHYS-PUB-2013-006**

**ATL-PHYS-PUB-2013-006**

**LHCC-G-166**

**Reference Scenario**

- $|\eta|<4.0$
- $L_{\ell\ell}=3ab^{-1}$, $s=14$ TeV
- $p_T(\ell)>200$
**ATLAS SUSY Searches** - 95% CL Lower Limits

**Status:** August 2016

<table>
<thead>
<tr>
<th>Model</th>
<th>$e$/$\mu$/$\tau$, $t\bar{t}$ $+$ Jets</th>
<th>$E_{T}^{miss}$</th>
<th>$a_{1}$/$t$</th>
<th>Mass limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUGRA/CMSMSS</td>
<td>0-3, $e$/$\mu$/$t$/$b$</td>
<td>0</td>
<td>2-10 jets, $t$/$b$</td>
<td>Yes</td>
<td>203</td>
</tr>
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<tr>
<td>$\tilde{g}$/ $\tilde{t}$/$\tilde{b}$/$\tilde{t}$/$\tilde{b}$/ $\tilde{t}$/$\bar{t}$/$\tilde{b}$/$\tilde{t}$/$\bar{t}$</td>
<td>3</td>
<td>0 &lt; 2 jets</td>
<td>Yes</td>
<td>133</td>
<td>$\sqrt{s} = 13$ TeV</td>
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Supersymmetry Production at LHC

Lightest neutralino normally assumed to stable (Dark Matter candidate)
Search for Stau Pair Production

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 $\tau_L$, expect to have 5σ discovery up to $\sim 420$ GeV, while even with 3000 fb$^{-1}$, do not achieve 5σ sensitivity for $\tau_R$. 
Search for WIMP Candidates

- ATLAS also has sensitivity to non-SUSY WIMP models

For example with canonical mono-jet signature:

\[ q \rightarrow \chi \]

Or invisible Higgs Boson decays:

\[ \bar{q} \rightarrow Z \rightarrow H \rightarrow \chi \]

\[ Z \rightarrow \chi \]

\[ Z \rightarrow \chi \]

\[ \gamma \]

\[ \pi \]

\[ g_{SM}, g_{DM} \]

\[ 5\sigma \text{ discovery} \]

\[ 3\sigma \text{ evidence} \]

\[ M_s = \frac{M_{\text{mediator}}}{\sqrt{g_{SM} g_{DM}}} \text{ [TeV]} \]

Higgs Portal model for ATLAS

DM-nucleon cross-section [cm$^2$]

DM mass [GeV]
Comparison to non LHC Searches

CMS
Vector med, Dirac DM, \(g_q = 0.25, g_{DM} = 1\)
- CMS median exp. 90% CL
- CMS obs. 90% CL
- LUX
- CDMSLite
- PandaX-II
- CRESST-II

CMS
Scalar med, Dirac DM, \(g_q = 1, g_{DM} = 1\)
- CMS obs. 90% CL
- LUX
- CDMSLite
- PandaX-II
- CRESST-II
Special Signatures from LLP

Issues and opportunities with LLP signatures:

- **Non-standard** objects, **custom** trigger/reconstruction/simulation
- Need to maintain **dedicated** detector capabilities

Potential gains from HL-LHC from high luminosity, track-trigger, fast timing, better directionality.
Displaced Muons from LLP

Long-lived neutral particle (X) decays after some $c\tau$ to displaced leptons or jets. Example signature: displaced muons (possibly collimated)

**Experimental challenge:** trigger such displaced signatures (note: phase-II track triggers with vertex constraint).

Possible models: dark photons, inelastic thermal-relic DM, etc.

See also talk by Alexei Safonov on CMS muon performance & trigger
Impact of Detector Capabilities

Impact of dE/dx readout in CMS tracker

dE/dx information used in searches for heavy stable charged particles (HSCP), fractionally/multiple charged particles. But also to identify noise and background in „standard analyses“.

Physics studied demonstrated the need to keep dE/dx capability.
Flavor-Changing Neutral Currents in top

ATLAS+CMS Preliminary 95%CL upper limits

LHCTopWG

November 2016

Each limit assumes that all other processes are zero

Theory predictions from arXiv:1311.2028

10^{-16} 10^{-13} 10^{-10} 10^{-7} 10^{-4} 10^{-1}

Branching ratio

1. $t \rightarrow H_c$
2. $t \rightarrow H_u$
3. $t \rightarrow \gamma_c$
4. $t \rightarrow \gamma_u$
5. $t \rightarrow g_c$
6. $t \rightarrow g_u$
7. $t \rightarrow Z_c$
8. $t \rightarrow Z_u$

References:
[7] CMS-PAS-TOP-12-039
Search for $t\rightarrow Zq$ and $t\rightarrow Hq$ Decays

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

For $t\rightarrow Zq$ use kinematic $\chi^2$ fit using leptonic $Z$ decays:

$$\chi^2 = \frac{(m_Z - m_{Z_{\text{reco}}})^2}{\sigma^2_Z} + \frac{(m_W - m_{W_{\text{reco}}})^2}{\sigma^2_W} + \frac{(m_t - m_{t_{\text{reco}}})^2}{\sigma^2_{t\rightarrow Wb}} + \frac{(m_{t_{\text{reco}}})^2}{\sigma^2_{t\rightarrow Zq}}$$

Expected 95% CL limit assuming equal $t\rightarrow Zu$ and $t\rightarrow Zc$: $\sim 2.5 \times 10^{-5}$

For $t\rightarrow Hq$ use $H\rightarrow b\bar{b}$ and kinematic discriminant

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

Expected 95% CL limit assuming equal $t\rightarrow Hu$ and $t\rightarrow Hc$: $\sim 1.1 \times 10^{-4}$
DM through Di-jet Searches

- LHC can detect mediator between DM and SM if it is light enough
  - Complements mono-X searches

Search for bump in di-jet mass spectrum – dedicated techniques at low mass
DM Simplified Model Exclusions  ATLAS Preliminary  August 2016

Axial-vector mediator, Dirac DM

$g_q = 0.25, g_{DM} = 1$

$\Omega_c h^2 = 0.12$

$\Omega_c h^2 < 0.12$

$2 \times \text{DM Mass} = \text{Mediator Mass}$

$\text{Pertrubative unitarity}$

$E_T^{\text{miss}} + \text{jet}$

arXiv:1604.07773

$E_T^{\text{miss}} + \gamma$

JHEP 06 (2016) 059

Dijet

ATLAS-CONF-2016-000
ATLAS-CONF-2016-068
ATLAS-CONF-2016-070
Exclusion for Different Model Point

DM Simplified Model Exclusions  ATLAS Preliminary  August 2016

Dijet TLA
ATLAS-CONF-2016-030

Dijet 8 TeV

Perturbative unitarity

$\Omega c h^2 = 0.12$

thermal relic $\Omega c h^2 = 0.12$

$2 \times$ DM Mass = Mediator Mass

$E_T^{\text{miss}} + \gamma$
JHEP 06 (2016) 059

$E_T^{\text{miss}} + \text{jet}$
arXiv:1604.07773

Axial-vector mediator, Dirac DM
$g_q = 0.1$, $g_{DM} = 1.5$
Search for ttH Production at 13 TeV

- ttH directly probes the top-Higgs Yukawa coupling instead of loop in ggH
- Benefits from higher x-section at 13 TeV
- See slight excess in many channels
- Also seen in some Run-1 results

**Observed significance:** 3.2σ (Expected: 1.7σ)
Search for ttH Production at 13 TeV

- ttH directly probes the top-Higgs Yukawa coupling instead of loop in ggH
  - Benefits from higher x-section at 13 TeV
- See slight excess in many channels
  - Also seen in some Run-1 results

Latest CMS result for ttH, H→bb has a slight deficit wrt SM

All are still consistent with SM due to the large uncertainties

![Diagram showing ttH production](Image)

**CMS Preliminary**

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Best fit $\mu = \sigma/\sigma_{SM}$ at $m_H = 125$ GeV
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 $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (140 pile-up events) or $7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (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)