Prospects for the high luminosity LHC (ATLAS and CMS)

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on behalf of the ATLAS & CMS Collaborations
LHC physics achievements: Run I

- p-p collisions: 29 fb^{-1} delivered at 7-8 TeV (25 fb^{-1} used for analysis)
- Measurements of Standard Model (SM) properties (W, Z, top, ...)
- *Discovery of a Higgs particle with mass ~ 125 GeV*
- First measurements of its properties (branching ratio, coupling, ...)
- Many limits on search of Beyond Standard Model (BSM) particles
- Also Heavy-Ion program
LHC: The 20-year plan

- LHC startup, $\sqrt{s} = 900$ GeV
- $\sqrt{s} = 7$–8 TeV, $L = 6 \times 10^{33}$ cm$^{-2}$ s$^{-1}$, bunch spacing 50 ns
- Go to design energy, nominal luminosity
- $\sqrt{s} = 13$–14 TeV, $L = 1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, bunch spacing 25 ns
- Injector and LHC Phase-1 upgrade to ultimate design luminosity
- $\sqrt{s} = 14$ TeV, $L = 5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, luminosity leveling
- HL-LHC Phase-2 upgrade, IR, crab cavities?

CMS: Also address HE-LHC program (300 fb$^{-1}$ @ 33 TeV)
Detector challenges at higher luminosity

- Require detector and trigger with high performances from low to high scale energy
  - Measurements for 125 GeV Higgs boson
  - Search for new physics objects at TeV scale

- ATLAS and CMS detectors designed for luminosity $10^{34}$ cm$^{-2}$s$^{-1}$

  Phase 1: 2x LHC design luminosity
  - Event pileup: O(50) collisions per beam crossing each 25 ns
  - Trigger rate: Increase by factor 5 compared to run 1

  Phase 2: 5x LHC design luminosity (called HL-LHC in next slides)
  - Event pileup: O(140) collisions per beam crossing each 25 ns
  - Need solutions to cope with trigger rate, radiation and pileup
Physics program

Phase 1 : ~2018-2020 : **x10 luminosity compared to run1**
- Measure Higgs boson properties
- Individual branching ratios with 10-15% precision
- Search for new physics at higher mass scale
- SUSY
- Exotics

Phase 2- HL-LHC : ~2022- : **x100 luminosity compared to run1**
- Precision Higgs boson measurements
- Study Higgs boson self-coupling
- Measure Vector Boson scattering
- Characterize any New Physics discovered during Phase 1
- Search for new physics in very rare processes

Default : results quoted with 3000 fb$^{-1}$ (3 ab$^{-1}$)
Higgs production rate (@ 300 fb⁻¹)

- Assume same experimental systematic uncertainty as run1
- With/without theory uncertainty
- Reach 10-15 % precision on signal strength for each channel

* All CMS HL-LHC results grouped in this note
NEW ACCESSIBLE CHANNELS FOR HIGGS BOSON COUPLING MEASUREMENT

ANALYSIS RESTRICTED TO $H \rightarrow \gamma\gamma$ DECAY MODE

SELECTION OF ASSOCIATED PARTICLES: LEPTON(S) + JETS (TOP)

S/B : $t\bar{t}H : 20 \%$ ; ZH : $10 \%$ ; WH : $2 \%$

$t\bar{t}H$ : PROBE FOR TOP-YUKAWA COUPLING
- Expected branching ratio: $O(10^{-4}) \rightarrow$ few thousand events
- Some BSM models predicts higher branching ratios
- Cons: $S/B: 0.2\%$ (Background: Mainly $Z \rightarrow \mu\mu$)
- Pros: Reconstructed invariant mass with narrow peak (few %)
- Signal significance > 6 $\sigma$
### Higgs boson coupling

**Scenario 1**: Same systematic as run1

**Scenario 2**:
- Theory syst. reduced by factor 2
- Other syst. scaled by $1/\sqrt{L}$

<table>
<thead>
<tr>
<th>CMS Coupling</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scenario 1</td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>5.4</td>
</tr>
<tr>
<td>$\kappa_V$</td>
<td>4.5</td>
</tr>
<tr>
<td>$\kappa_g$</td>
<td>7.5</td>
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<tr>
<td>$\kappa_b$</td>
<td>11</td>
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<tr>
<td>$\kappa_t$</td>
<td>8.0</td>
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<tr>
<td>$\kappa_\tau$</td>
<td>5.4</td>
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</table>

Higgs boson couplings can be measured at few % level

ATLAS expectation with 3000 fb$^{-1}$

- $K_V : 4.5 \% (1.9 \%)$
- $K_F : 5.9 \% (3.6 \%)$

without theory syst. with theory syst.
Higgs boson self-coupling

Gluon fusion: Dominant channels for double Higgs boson production

- Only most sensitive channels studied
  - $HH \rightarrow b\bar{b}\gamma\gamma$ (B.R. : 0.27 %)
  - $HH \rightarrow b\bar{b}W^+W^-$ (B.R. : 25 %)

- 3 $\sigma$ sensitivity to HH production per exp.

- Possible gain by adding other channels and combining ATLAS/CMS

→ Could reach sensitivity for H self-coupling
Vector boson scattering

- SM Higgs boson restores unitarity for VV scattering
- If Higgs particle is not SM, new effects (resonances) can appear in VV scattering

**a4 parameter in effective Lagrangian for WW without Higgs**

<table>
<thead>
<tr>
<th>model</th>
<th>300 fb$^{-1}$</th>
<th>1 ab$^{-1}$</th>
<th>3 ab$^{-1}$</th>
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</thead>
<tbody>
<tr>
<td>a$_4$</td>
<td>0.066</td>
<td>0.025</td>
<td>0.016</td>
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</tbody>
</table>

Search for resonances in **ZZ+2j final state**

**ATLAS Preliminary**

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

- SM VV
- Non-VV Diboson
- SM VV + 1.0 TeV Res
  (\(g = 1.75\))

<table>
<thead>
<tr>
<th>m$_{\text{resonance}}$</th>
<th>300 fb$^{-1}$</th>
<th>3000 fb$^{-1}$</th>
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</thead>
<tbody>
<tr>
<td>500 GeV, (g = 1.0)</td>
<td>2.4$\sigma$</td>
<td>7.5$\sigma$</td>
</tr>
<tr>
<td>1 TeV, (g = 1.75)</td>
<td>1.7$\sigma$</td>
<td>5.5$\sigma$</td>
</tr>
<tr>
<td>1 TeV, (g = 2.5)</td>
<td>3.0$\sigma$</td>
<td>9.4$\sigma$</td>
</tr>
</tbody>
</table>

ATLAS-PHYS-PUB-2012-005
**SUSY searches: squarks and gluinos**

- **1\textsuperscript{st}/2\textsuperscript{nd} generation squark/gluinos**
  - 95\% C.L. limit with run 1: 1.8 TeV for $m_{\text{squark}} = m_{\text{gluino}}$ (optimistic case)
  - Selection based on multi-jet event + large missing transverse energy (MET)
  - HL-LHC: Extend 95\% C.L. up to 2.5-3 TeV for $m_{\text{LSP}} = 0$

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**ATLAS-PHYS-PUB-2013-002**

**Graph 1:** Squark-gluino grid, $m_{\text{LSP}} = 0$. $\sqrt{s} = 14$ TeV, $\text{MET} + \text{HT} > 15 \text{GeV}^{1/2}$

**Graph 2:**

- **EWKino**
- **Stops/sbottoms**
- **Squarks/gluinos**

**CMS**

- HE-LHC33
- HL-LHC14 (300 fb$^{-1}$)
'Natural mass range'

→ neutralino/chargino mass up to 800-900 GeV

→ lightest top squark $\tilde{t} < 1$ TeV

→ HL-LHC : Important discovery potential

Selection : 3 leptons + large MET

→ lightest top squark $\tilde{t} < 1$ TeV

Selection : 1 or 2 leptons + jets (including b) + large MET

HL-LHC : Important discovery potential

Run 1 : 95 % C.L. limit (LHCP13) $m_{\text{LSP}} = 0$
FCNC in top decays

- Flavour Changing Neutral Current: $< 10^{-12}$ at SM through loops
- Different BSM models predict higher rate (up to $10^{-4}$)
- Large sample of top pairs (Analysis done by ATLAS and CMS)
- Signal: $\bar{t}t$ production with $t \rightarrow bW + t \rightarrow q Z/\gamma$
- Background: $\bar{t}t \rightarrow WbWb$, W+jets, Z+jets, ...
- Reach limits: $10^{-4}$ - $10^{-5}$
Models (Current 95% C.L. limit at run1)

\[ Z'_\text{SSM} \rightarrow \text{lepton pair (~}2.9 \text{ TeV) } \]

\[ Z'_\text{Top} \rightarrow \text{gluon} \rightarrow \text{tt resonance} \]

selected from lepton + jet final state (or dilepton)

<table>
<thead>
<tr>
<th>model</th>
<th>300 fb⁻¹</th>
<th>1000 fb⁻¹</th>
<th>3000 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>( g_{KK} )</td>
<td>4.3 (4.0)</td>
<td>5.6 (4.9)</td>
<td>6.7 (5.6)</td>
</tr>
<tr>
<td>( Z'_\text{Top} )</td>
<td>3.3 (1.8)</td>
<td>4.5 (2.6)</td>
<td>5.5 (3.2)</td>
</tr>
</tbody>
</table>

\[ Z'_\text{SSM} \rightarrow ee \]

\[ Z'_\text{SSM} \rightarrow \mu\mu \]

95% C. L. from run1: ~800 GeV

Many BSM models predict lepto-quarks

Example of analysis

Scalar leptoquark with \( \text{Br}(LQ \rightarrow ej)=100\% \)

Analysis done on \( ee + 2 \text{ jets} \) final state

2 scenarios addressed:

- \( S/B < 1 \) (as for run1 analysis)
- \( S/B \sim 1 \) (expected at HL-LHC)
HL-LHC: Broad scientific program

- Higgs boson coupling: Precision measurement regime (%)
- Could observe first evidence of triple-Higgs coupling
- Possibilities to look for new particles/phenomena

If new physics is found during phase 1 → HL-LHC even more interesting

HL-LHC campaign expected to start in 10 years from now

Technological challenges for detector upgrades look achievable but still require R&D
References

- ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies
- CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP
BACKUP
Higgs boson coupling

Scenario 1: Same systematic as run1

Scenario 2:
- Theory syst. reduced by factor 2
- Other syst. scaled by $1/\sqrt{L}$

Higgs boson couplings can be measured at few % level
• ATLAS: Simulation of physics objects performed through functions which approximate energy resolution, identification and reconstruction efficiencies, ...

• CMS: Assumes that event pile-up increase is compensated by detector upgrade
  Different scenarios on systematic contributions addressed
- Final states: $W\gamma$, $Z\gamma$, $W^+W^-$ and $W^\pm Z$ with $W/Z$ leptonic decays
- Only one free parameter at a time and assumed form factor $\Lambda_{FF}=10$ TeV
- Reach $10^{-3}$ sensitivity: could be sensitive to radiative corrections from BSM

<table>
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<tr>
<th>coupling</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>HE-LHC</th>
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<tbody>
<tr>
<td>$g_1^Z$</td>
<td>0.0030</td>
<td>0.0019</td>
<td>0.0013</td>
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<td>$\lambda_\gamma$</td>
<td>0.0009</td>
<td>0.0004</td>
<td>0.0004</td>
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<tr>
<td>$\lambda_Z$</td>
<td>0.0023</td>
<td>0.0014</td>
<td>0.0014</td>
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<tr>
<td>$\kappa_\gamma$</td>
<td>0.026</td>
<td>0.016</td>
<td>0.019</td>
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<tr>
<td>$\kappa_Z$</td>
<td>0.037</td>
<td>0.031</td>
<td>0.022</td>
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The super-exploitation of the CERN complex: Injectors, LEP/LHC tunnel, infrastructures

Figure 10. The possible timeline of LHC and its upgrades.

Caterina Biscari (European Strategy Group - Krakow)
ATLAS SUSY Searches - 95% CL Lower Limits

Status: LHC 2013

1. $\hat{s} = 7$, 8 TeV

<table>
<thead>
<tr>
<th>Model</th>
<th>$e$, $\mu$, $\tau$</th>
<th>Jets</th>
<th>$E_T^{miss}$</th>
<th>$\Delta m (t\bar{t})$</th>
<th>Mass limit</th>
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<tbody>
<tr>
<td>MSUGRA/MSUGM1</td>
<td>0</td>
<td>2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.8 GeV</td>
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<tr>
<td>MSUGRA/MSUGM2</td>
<td>1, $\mu$, 4 jets</td>
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<td>5.8</td>
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<tr>
<td>SUSY/DM</td>
<td>0</td>
<td>1-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.1 GeV</td>
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<tr>
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<td>0</td>
<td>2-6 jets</td>
<td>Yes</td>
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<td>1.1 GeV</td>
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<tr>
<td>GMSB</td>
<td>0</td>
<td>2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.1 GeV</td>
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<tr>
<td>GMSB (nuino NLSP)</td>
<td>0</td>
<td>2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
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*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus for theoretical signal cross-section uncertainty.
Searches at Run I: Exotics

ATLAS Exotics Searches - 95% CL Lower Limits (Status: May 2013)

- Large ED (ADD): monopole + $E_{\text{kin}}$ (min)
- Large ED (ADD): diphoton + $E_{\text{kin}}$ (max)
- UED: diphoton + $E_{\text{kin}}$
- S'2: $E_{\text{kin}}$
- RSt: $E_{\text{kin}}$
- BW: WW resonance
- RSt: $E_{\text{kin}}$
- $b \to c W (100\%)$
- $t \to c W (100\%)$
- $f \to b W (100\%)$
- $m_{\text{t}}$ (3 TeV)
- $m_{\text{c}}$ (2 TeV)
- $m_{\text{b}}$ (1 TeV)
- $m_{\text{H}}$ (100 GeV)
- $m_{\text{H}}$ (100 GeV)
- $m_{\text{H}}$ (10 GeV)
- $m_{\text{H}}$ (1 TeV)
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