The Higgs Boson: Discovery of the Millennium (So Far)

UC Davis HEFTI Frontiers of Physics Symposium
April 6, 2013
Maxwell Chertok, UC Davis
Outline

Particle Physics & Symmetry
A Little History of Charged Particles
The Large Hadron Collider
  Machine, CMS and ATLAS
Search for the Higgs
Results (we found it!)
Conclusions
We study the microworld $\sim 10^{-19}$ m to better understand the universe at a fundamental scale.

World’s biggest scientific apparatus needed to study smallest phenomena

Accelerators or Cosmic Rays or Reactors

High-energy particle collisions recreate conditions immediately after Big Bang
Symmetry
Study fundamental symmetries of nature

Emmy Noether, 1918

Symmetry $\iff$ Conserved Quantity

Rotational invariance $\iff$ Angular momentum conserved

Time translation invariance $\iff$ Energy conserved

These ideas are cornerstones of physics!
Use symmetry principles to understand fundamental forces of nature

**Gravity**

**Strong**

**Weak**

**Electromagnetic**
Tho’ phenomena seem wildly different, try to unify EM and Weak forces. One gauge theory.

Weak interactions appear weak, not because of some fundamental coupling constant, but because mediated by massive gauge particles. (short-range)

On the other hand, photon is massless. (infinite-range)
Enter Mr. Higgs
Or, should we call it...

The Englert-Brout-Higgs-Guralnik-Hagen-Kibble Boson
Generating mass

We can’t just add massive particles, but we can introduce a new field, the scalar Higgs field.

Higgs field preserves gauge symmetry

This field permeates all time and space (ether, anyone?) The other particles interact with the Higgs field and thereby acquire an effective mass.

Without the Higgs, all the particles would be massless and travel at the speed of light. The universe would have no structure!
Spontaneous Symmetry Breaking

**Higgs field potential designed so that non-zero field values have lowest energy**

*Must choose a specific place on that circle. This breaks the symmetry.*

*Rotations about minimum circle lead to massive W,Z*

*Example from solid state physics: a ferromagnet above Tc has spins randomly oriented (symmetric). At T<Tc, the spins align spontaneously, breaking the symmetry.*
A little history of charged particles
Discovery of the electron, 1897

“Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen?” --J.J. Thomson

The electron has no size
\[ M(\text{electron}) = 2.000 \times 10^{-30} \text{ lbs} \]
Fermilab - Tevatron

Was world’s most powerful particle collider

Collided Protons and Antiprotons
Collider Detector at Fermilab
Discovery of Truth (top quark), 1992

Collide 2 tennis balls and a bowling ball comes out...

175 GeV

2 t

Jet 2

Jet 3

Jet 1

Jet 4

$M_{\text{top}}^{\text{fit}} = 170 \pm 10 \text{ GeV}/c^2$

24 September, 1992
run #40758, event #44414

Actually, 2 bowling balls...
Top quark as heavy as...
The Standard Model, 1897-2011
CERN and the Large Hadron Collider
CERN: at the foot of the Jura
CMS Experiment

39 Countries, 169 Institutes, 3170 scientists and engineers (including about 800 students)

MUON CHAMBERS
Barrel: Austria, Bulgaria, CERN, China, Germany, Hungary, Italy, Spain
Endcap: Belarus, Bulgaria, China, Colombia, Egypt, Korea, Pakistan, Russia, USA

HCAL
Barrel: Bulgaria, India, USA
Endcap: Belarus, Bulgaria, Georgia, Russia, Ukraine, Uzbekistan
HO: India

CRYSTAL ECAL
Belarus, CERN, China, Croatia, Cyprus, France, Italy, Portugal, Russia, Serbia, Switzerland, UK, USA

PRESHOWER
Armenia, CERN, Greece, India, Russia, Taiwan

SUPERCONDUCTING MAGNET & YOKE
All countries in CMS contribute to Magnet financing

TRIGGER, DATA ACQUISITION & OFFLINE COMPUTING
Austria, Brazil, CERN, Finland, France, Greece, Hungary, Ireland, Italy, Korea, Lithuania, New Zealand, Poland, Portugal, Switzerland, UK, USA

TRACKER
Austria, Belgium, CERN, Finland, France, Germany, Italy, Mexico, New Zealand, Switzerland, UK, USA

FORWARD CALORIMETER
Hungary, Iran, Russia, Turkey, USA

FEET
Pakistan, China

Total weight: 14000 tonnes
Overall diameter: 15.0 m
Overall length: 28.7 m
Magnetic field: 3.8 T

July 2010
CMS: World’s largest solenoid
Then we installed the Forward Pixel Detector...
UC Davis Signed original CMS Letter of Intent, 1992
Collision in CMS
dimuon spectrum

2011 Run, L = 1.1 fb⁻¹
CMS \(\sqrt{s} = 7\) TeV

trigger paths
- \(\psi'\)
- \(J/\psi\)
- \(B_s \rightarrow \mu^+\mu^-\)
- \(Y\)
- low \(p_T\) double muon
- high \(p_T\) double muon

Events per 10 MeV

dimuon mass [GeV]
A Toroidal LHC Apparatus
Searching for the Higgs

The idea:

Collide protons at high energy at LHC

Repeat 40 million times per second for a year

in 1 year = $3 \times 10^7 \text{ s} \times 4 \times 10^7 \text{ /s} = 10^{14} = 100 \text{ trillion collisions!}$

Look for distinctive “signature” in decay products, as recorded with detector

TYPES (electrons, photons, quarks, muons...)

ENERGIES and MOMENTA: ($E, p_x, p_y, p_z$)

Analyze all the tracks and energy deposits from each collision, create sample of Higgs-like events
Higgs Decay Signatures

Higgs should couple to fermions, too.
Higgs Decays?

“This is not exactly, what theory predicted for the Higgs decay!”
CMS $\gamma\gamma$ event
CMS ZZ→eeμμ candidate
ATLAS: $M_{2e2\mu} = 123.9$ GeV

$p_T(e,e,\mu,\mu) = 18.7, 76, 19.6, 7.9$ GeV,

$m(e^+e^-) = 87.9$ GeV, $m(\mu^+\mu^-) = 19.6$ GeV

12 reconstructed vertices
We waited as the data slowly accumulated
CMS Higgs Results: Presented July 4, 2012

**H → photon + photon**

**H → Z Z → 4 leptons**

![Graph showing CMS Preliminary results for H→γγ and H→ZZ→4L, with data points and fit components highlighted.](image)
I FOUND A NEW PARTICLE
ATLAS Higgs Results

$H \rightarrow \text{photon} + \text{photon}$

$H \rightarrow ZZ \rightarrow 4\text{ leptons}$

- Data S/B Weighted
- Sig+Bkg Fit ($m_H = 126.5$ GeV)
- Bkg (4th order polynomial)

$m_{\gamma\gamma}$ [GeV]

100 110 120 130 140 150 160

Events/5 GeV

10 15 20 25

$m_{4\ell}$ [GeV]

100 150 200 250

- Data
- Background ZZ$^{(*)}$
- Background Z+jets, $t\bar{t}$
- Signal ($m_H = 125$ GeV)
- Syst. Unc.

$s = 7$ TeV: $\int L dt = 4.8$ fb$^{-1}$

$s = 8$ TeV: $\int L dt = 5.8$ fb$^{-1}$
Significance of Results

\[ m_H \text{ (GeV)} \]

\[ m_H \text{ (GeV)} \]

\[ \text{CMS} \quad \sqrt{s} = 7 \text{ TeV}, \ L = 5.1 \text{ fb}^{-1} \quad \sqrt{s} = 8 \text{ TeV}, \ L = 5.3 \text{ fb}^{-1} \]

\[ \text{ATLAS} \quad 2011 - 2012 \]

\[ \sqrt{s} = 7 \text{ TeV}: \ L_{\text{int}} = 4.6-4.8 \text{ fb}^{-1} \]

\[ \sqrt{s} = 8 \text{ TeV}: \ L_{\text{int}} = 5.8-5.9 \text{ fb}^{-1} \]
The Standard Model, July 4, 2012

THREE GENERATIONS OF MATTER

I  II  III

CHARGE:

<table>
<thead>
<tr>
<th>MATTER CONSTITUENTS: FERMIONS</th>
<th>FORCE CARRIERS: BOSONS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>QUARKS</strong></td>
<td></td>
</tr>
<tr>
<td>Up</td>
<td>Z°</td>
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<tr>
<td>Charm</td>
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<tr>
<td>Top</td>
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<tr>
<td>Down</td>
<td>W°/W−</td>
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<tr>
<td>Strange</td>
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<tr>
<td>Bottom</td>
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<tr>
<td><strong>LEPTONS</strong></td>
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<tr>
<td>Electron</td>
<td>Photon</td>
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<tr>
<td>Muon</td>
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<tr>
<td>Tau</td>
<td>Gluon</td>
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<td>Neutrino</td>
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<td>Neutrino</td>
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<tr>
<td>Neutrino</td>
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</table>

12 elephants

HIGGS-LIKE

125000
Adding in the newest data from 2012: H→ WW candidate
H → tau pair candidate
CMS Preliminary

\[ \sqrt{s} = 7 \text{ TeV}: L = 0.0 \text{ fb}^{-1} \]

- Data
- \( m_H = 126 \text{ GeV} \)
- \( Z\gamma^*, ZZ \)
- \( Z + X \)
\( \sqrt{s} = 7 \text{ TeV} \int \text{Ldt} = 0.18 \text{ fb}^{-1} \)

**May 4, 2011**

**ATLAS Preliminary**

**H\rightarrow ZZ^{(*)} \rightarrow 4l channel**

- **Signal (m_\text{H} = 125 \text{ GeV})**
- **Background ZZ^{(*)}**
- **Background Z+jets, t\bar{t}**
- **Data**
Press release from CERN

New results indicate that particle discovered at CERN is a Higgs boson -- Geneva, 14 March 2013

Some quotes:

“The preliminary results with the full 2012 data set are magnificent and to me it is clear that we are dealing with a Higgs boson though we still have a long way to go to know what kind of Higgs boson it is.” said CMS spokesperson Joe Incandela.

"The beautiful new results represent a huge effort by many dedicated people. They point to the new particle having the spin-parity of a Higgs boson as in the Standard Model. We are now well started on the measurement programme in the Higgs sector," said ATLAS spokesperson Dave Charlton.

(Notice it says “A Higgs boson” not “THE Higgs boson”)
Why is this theory still incomplete?

Why do these particles have the masses that they do?
Why are there three families?
Do the 4 forces all unify at some scale?
Is gravity special?
Why is there CP violation?
Where did the universe's antimatter go?
What is the source of dark matter in the universe?
What is the source of dark energy in the universe?
Terascale & Beyond

**Electromagnetic Force**

**Electroweak Unification**

**Weak Nuclear Force**

**Strong Nuclear Force**

**Gravitation**

**The Terascale**

**“Grand Unification”**

**Planck Scale**

**Big Bang**

**Energy (TeV)**

$10^{-15}$ $10^{-12}$ $10^{-9}$ $10^{-6}$ $1$ $10^3$ $10^6$ $10^9$ $10^{12}$ $10^{15}$

**Time (s)**

$10^6$ $10^9$ $10^{12}$ $10^{15}$ $10^{18}$
SUPERSYMMETRY is a theory with intriguing features:

- **Plays nicely with string theory**
- **Resolves the “hierarchy” problem**
- **Unifies force couplings at high energy**
- **Includes dark matter candidate**

We need more data.
Search for a Light Pseudoscalar Higgs Boson

Next-to-minimal SUSY Higgs spectrum:

3 CP even scalars \( h_1, h_2, h_3 \)

2 CP odd scalars \( a_1, a_2 \)

2 charged scalars \( H^+, H^- \)

Dimuon mass [GeV]

Events/[0.1 GeV]

CMS \( \sqrt{s} = 7 \text{ TeV} \)

L = 1.3 fb⁻¹

Barrel Data

Total Fit

7 GeV Signal x10

12 GeV Signal x10

\(|\cos\beta_A|\) max

CMS \( \sqrt{s} = 7 \text{ TeV} \)

L = 1.3 fb⁻¹

CMS Limits

BaBar Limits

Much more to come!
Conclusions

**Particle physics ~century of discoveries**

*Experimental and theoretical*

Electroweak theory → Higgs prediction

**Major Discovery, 2012**

Higgs spin, parity, and couplings are SM-like

**Is the Standard Model all there is?**

Or, are there more exotic new particles and forces to be discovered?

LHC: protons 12 MPH faster in 2014!
Backup
Cyclotron invention 1931

Muon 1936, Charged Pion 1947

Omega Minus 1964

Neutral Current 1973

Quarks 1969
antiquark (antilepton) ((new particle))
quark (lepton) ((new particle))

Stanford Linear Collider

ALEPH DELPHI L3 OPAL
average measurements, error bars increased by factor 10
The Photon, W, and Z

Start with 4 massless quantum fields

\((W_1, W_2, W_3)\); a triplet with a certain kind of symmetry

\(B\); a singlet with a different symmetry

These mix to give:

\[
W^\pm = \frac{1}{\sqrt{2}}(W_1 \pm iW_2)
\]

\[
Z^0 = W_3 \cos \theta_W - B \sin \theta_W
\]

\[
A = W_3 \sin \theta_W + B \cos \theta_W
\]

The weak mixing angle (measured: \(\theta_W \approx 29^0\)) relates the two neutral interactions.
Predicting the W and Z masses

Use this “Electroweak” Theory with measurements from EM, weak phenomena: predict W, Z masses!

EM charge and weak charge related as: $e = g \sin \theta_W$

Then,

$M_W = \frac{\sqrt{\pi \alpha / \sqrt{2} G_F}}{\sin \theta_W} \sim 80 \text{ GeV}$

$M_Z = M_W / \cos \theta_W \sim 90 \text{ GeV}$
Higgs Production

- **gg Fusion**
  - 

- **tt Fusion**
  - 

- **Higgs-Strahlung**
  - 

- **WZ Fusion**
  - 

Graph showing Higgs production cross-sections for different processes:

- $\sigma(pp \rightarrow H+X)$ [pb]
- $\sqrt{s} = 8$ TeV
- Higgs production cross-sections for $pp \rightarrow \sigma_{\text{Higgs}}$ at NNLO+NNLL QCD + NLO EW for $H \rightarrow WZ$.

Graph with axes for $M_H$ [GeV] and $\sigma_{pp \rightarrow H+X}$ [pb].
Guinness World Records

LHC: Largest Machine Ever Built
LHC: Largest cryogenic system ever
CMS: Heaviest particle detector ever
CMS: Largest superconducting solenoid ever
CMS: Largest silicon detector ever
H → tau pair results from Moriond, 2013
Spin-Parity Results

$gg \rightarrow 2m_{+} \rightarrow ZZ$

$gg \rightarrow 2m_{+} \rightarrow WW$

$qq \rightarrow 2m_{+}$
Mass Measurement

- Combined mass using HZZ and H\gamma\gamma
  - Resolutions of 1-2%
  - signal strength for H\gamma\gamma, H\gamma\gamma +2j, and HZZ profiled (model independent)
    - Results consistent when relative yields are fixed to SM

\[ m_H = 125.8 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (syst) GeV} \]
# Signal Strength

<table>
<thead>
<tr>
<th>H → γγ</th>
<th>ggH</th>
<th>VBFH</th>
<th>VH</th>
<th>ttH</th>
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</thead>
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<tr>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
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<tr>
<td>H → ZZ</td>
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<tr>
<td>✓</td>
<td>✓</td>
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<tr>
<td>H → WW</td>
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<td>✓</td>
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<tr>
<td>✓</td>
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<tr>
<td>H → bb</td>
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</table>

CMS Preliminary

- $\sqrt{s} = 7$ TeV, $L \leq 5.1$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV, $L \leq 12.2$ fb$^{-1}$

$m_H = 125.8$ GeV

- $H \rightarrow bb$ (VH tag)
- $H \rightarrow bb$ (ttH tag)
- $H \rightarrow \tau\tau$ (0/1 jet)
- $H \rightarrow \tau\tau$ (VBF tag)
- $H \rightarrow \tau\tau$ (VH tag)
- $H \rightarrow \gamma\gamma$ (untagged)
- $H \rightarrow \gamma\gamma$ (VBF tag)
- $H \rightarrow WW$ (0/1 jet)
- $H \rightarrow WW$ (VBF tag)
- $H \rightarrow WW$ (VH tag)

$\sigma/\sigma_{SM} = 0.88 \pm 0.21$
Latest ATLAS Results on Higgs Properties

- \( m_H = 125.5 \pm 0.2 \text{ (stat) } ^{+0.5}_{-0.6} \text{ (sys) GeV} \)
- \( \mu = 1.30 \pm 0.13 \text{ (stat) } \pm 0.14 \text{ (sys) } \)
- \( \mu_{VBF+VH}/\mu_{ggF+ttH} = 1.2^{+0.7}_{-0.5} \)
- 3.1\sigma evidence for VBF production

- Higgs couplings consistent with SM
- Spin and parity (from Eleni’s talk):
  - compatible with 0⁺
  - start to exclude 2⁺_m in \( \gamma \gamma \) and \( WW \), and 0⁻, 1⁺ in \( ZZ \)
Higgs searches have guided conception, design and technological choices of ATLAS and CMS:
- one of the primary LHC goals
- among the most challenging processes → have set some of the most stringent performance (hence technical) requirements: lepton identification and energy/momentum resolution, b-tagging, $E_T^{\text{miss}}$ measurement, forward-jet tagging, etc.

<table>
<thead>
<tr>
<th>MAGNET (S)</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air-core toroids + solenoid 4 magnets Calorimeters in field-free region</td>
<td>Solenoid 1 magnet Calorimeters inside field</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TRACKER</th>
<th>ATLAS</th>
<th>CMS</th>
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</thead>
<tbody>
<tr>
<td>Si pixels + strips TRT → particle identification B=2T $\sigma/p_T \sim 5\times10^{-4} p_T \oplus 0.01$</td>
<td>Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\times10^{-4} p_T \oplus 0.005$</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>EM CALO</th>
<th>ATLAS</th>
<th>CMS</th>
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<tbody>
<tr>
<td>Pb-liquid argon $\sigma / E \sim 10% / \sqrt{E}$ longitudinal segmentation</td>
<td>PbWO$_4$ crystals $\sigma / E \sim 2-5% / \sqrt{E}$ no longitudinal segmentation</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HAD CALO</th>
<th>ATLAS</th>
<th>CMS</th>
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<tbody>
<tr>
<td>Fe-scint. + Cu-liquid argon (10 λ) $\sigma / E \sim 50% / \sqrt{E} \oplus 0.03$</td>
<td>Cu-scint. ($&gt; 5.8 \lambda$ +catcher) $\sigma / E \sim 100% / \sqrt{E} \oplus 0.05$</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>MUON</th>
<th>ATLAS</th>
<th>CMS</th>
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<tbody>
<tr>
<td>Air → $\sigma / p_T \sim 7%$ at 1 TeV standalone</td>
<td>Fe → $\sigma / p_T \sim 5%$ at 1 TeV combining with tracker</td>
<td></td>
</tr>
</tbody>
</table>

CMS: excellent $\mu$ momentum resolution (H→ 4$\mu$ !) but B=4T solenoid constrains HCAL radius

H→ $\gamma\gamma$:
- CMS: E-resolution
- ATLAS: $\gamma$ "pointing" and $\gamma$/jet separation

ATLAS: excellent HCAL → jets and $E_T^{\text{miss}} (H \rightarrow l\nu l\nu)$
LHC performance projection

Energy increase 7 TeV \rightarrow 13/14 TeV

Injection upgrade

Interaction region upgrade

Phase 1: 2 \times 10^{34} \text{ Hz/cm}^2 \ 500 \text{ fb}^{-1}

Phase 2: HL-LHC
5 \times 10^{34} \text{ Hz/cm}^2 \ 3000 \text{ fb}^{-1}

LHC - European Strategy Aug. 12
LS1 Projects: in production

- Complete muon coverage (ME4)
- Improve muon operation (ME1), DT electronics
- Replace HCAL photo-detectors in HF (new PMTs) and HO (HPD $\rightarrow$ SiPM)

Phase 1 Upgrades (TDRs)

- Pixel detector replacement
- HCAL electronics upgrade
- L1-Trigger upgrade
- Preparatory work during LS1
  - New beam pipe for pixel upgrade
  - Install test slices of pixel, HCAL, L1-trigger
  - Install ECAL optical splitters for L1-trigger upgrade and on to operations

Phase 2: Now being defined

- Tracker Replacement, Track Trigger
- Forward: Calorimetry and Muons and tracking
- Further Trigger upgrade
Both CMS and ATLAS will upgrade their detectors.

- CMS Plans
- Upgraded Pixel Detector
  - Less material, better radial distribution
- Upgraded HCAL
  - Improve background rejection
  - Improve MET resolution
  - Improve Particle Flow
    - via improved S/N photodetectors
  - Identify depth of shower max
    - via longitudinal segmentation, timing

Figure 3.1: Current proposed depth segmentation structure for the HB and HE calorimeters, made possible by the use of SIPM photodetectors.
Upgrades: Impact on Higgs Physics

\( H \rightarrow ZZ \rightarrow 4l \)
- Key channel very sensitive to efficiency
  - 50% improved

\( ZH \rightarrow \mu\mu bb \)
- High muon ID efficiency high b-tagging efficiency good dijet mass resolution.
  - 65% improved

\( H \rightarrow \tau\tau \) (VBF)
- MET resolution, forward jet tagging, \( \tau \) Identification
  - Better mass resolution

Improved signal yield (relative to current detector):
shaded regions indicate cuts with biggest gains expected

- More good leptons
  - better tracking & isolation

Improved \( m_{\tau\tau} \) resolution
Signal strengths, couplings: 300,3000 fb$^{-1}$

- **Signal Strengths: ~10-15%**
- Present (Green). Present systematics at 300 / fb 14 TeV (Red). Setting theoretical uncertainties to zero (Black).

Simple scenarios for couplings

1. Systematics unchanged
2. Theory uncertainties reduced $\frac{1}{2}$, all other systematics $\sim \frac{1}{\sqrt{\int L dt}}$
Phase 2 HL-LHC Projects

- Study longevity of detectors through phase 1 and phase 2
- Study constraints at experimental area
- Develop scope for phase 2 detector:
  - Motivation and requirements on detector performance
  - Trigger Performance and Strategy
  - Develop requirements (rates) and architecture
- Forward Detector
  - Develop detector concept including tracking, calorimetry and muons
- Tracker project
  - Develop concept with hardware trigger capability
- Simulation and reconstruction
  - Develop tools for new geometries and high pile-up

- Target R&D programs

- Technical Proposal in 2014
Theorists vs Experimentalists

Einstein

Ting