Progress & Puzzles at the TeV scale: Recent results from the CMS experiment at the Large Hadron Collider

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Colloquium, University of Pittsburgh
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Outline

• The LHC and the CMS detector
• Basics of LHC physics
• Foundations: standard model physics
• Progress on the Higgs boson
• Puzzles and mysteries at the TeV scale
• Searches for supersymmetry and other new physics; implications
• Looking forward: the HL-LHC

Note: extremely close collaboration with theoretical physics/particle phenomenology community has been essential for this physics program!

Drawing courtesy Sergio Cittolin, CMS
The LHC in popular culture
Large Hadron Collider

$pp$ collisions: $E_{CM} = 2E_{beam} = 7, 8$ TeV (Run 1), $13$ TeV (Run 2)

- Beam injection into LHC from SPS at 0.45 TeV
- Magnets used to guide & focus beam; RF cavities to accelerate
Inside the LHC Ring

Tunnel depth ~ 100 m
Total magnets - 9593
Num. main dipoles - 1232 (L = 15 m)
Num. main quads - 392 (L = 5 to 7 m)

RF cavities/beam - 8
Energy per revolution - ~16 MeV
Beam revolutions/s - 11245
RF cavity frequency - 400 MHz
Bunches/beam - 2808
Protons/bunch - 1.1 $10^{11}$
Bunch spacing - 7.5 m (25 ns)

1232 superconducting main dipoles
Two-in-one coil design
Maximum B field 8.4 T ($E_{beam} = 7$ TeV)
Cooled to 1.9K with 90 tonnes of LHe

Collisions/sec - ~$10^9$
Design luminosity - $10^{34}$ cm$^{-2}$s$^{-1}$
Transverse beam size at IP - 20 $\mu$m
Bunch length ~7.5 cm
Surface buildings at LHC Point 5 (CMS) near Cessy, France

Access tunnel to LHC cavern for CMS experiment

Security system at LHC Point 5 (CMS)

View from floor of cavern at LHC Point 5
Installing muon system readout electronics.
End view of CMS detector barrel region, viewed from top of endcap detector
Try to cover as much of $4\pi$ solid angle as possible...
Animated event display

Reconstruction of decays of short lived particles.

\[ p^\mu = p_1^\mu + p_2^\mu + ... \quad m = \sqrt{(p_1^\mu + p_2^\mu + ...)^2} \]
LHC & CMS Data Taking History: Luminosity

- LHC operations have been remarkably stable, with steadily improving performance. CMS data collection effic. ~94% (2018).

$$L = \frac{N_1 N_2 \cdot f}{4 \pi \sigma_x \sigma_y}$$

$$R_{i=\text{process}} = L \cdot \sigma_i$$

$$N_{i\text{\hspace{1em}events}} = \int L dt \cdot \sigma_i$$

$${\mathbf{CMS Integrated Luminosity, \, pp}}$$

$$L_{\text{peak}} \approx 2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$$

Data included from 2010-03-30 11:22 to 2018-10-24 04:00 UTC

Achieved goal of >150 fb\(^{-1}\) at 13 TeV by end of 2018.

2012: Higgs discovery

Energy increase: \(E_{\text{cm}} = 8 \rightarrow 13\) TeV

2010

2016
Basics of LHC physics: cross sections

• Basic pp cross section is very roughly geometrical.

\[ \sigma_{pp} \sim \pi r_{proton}^2 \sim \pi \cdot (1 \text{ fm})^2 \]

\[ \sim \pi (10^{-26} \text{ cm}^2) \sim 30 \text{ mb} \]

• But cross sections for key processes are much smaller and vary over many (~15) orders of magnitude.

• Depending on how you count, there are ~hundreds of processes to measure and study.

• Currently, ~800 CMS papers.

http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html
• Protons are composite objects!
• The nominal $uud$ quark content of a proton is just a rough approximation. The full “parton” content includes other types of quarks as well as gluons. Much of the LHC physics program results from gluon-gluon collisions.
• CM frame of parton-parton collision is boosted w.r.t. lab frame.
Basics of LHC physics: partons in the proton

- Fraction of proton momentum carried by a parton: $x$

- Parton distribution functions from the NNPDF collaboration.

https://arxiv.org/abs/1706.00428
Particle content of the Standard Model

**Quarks: spin-1/2**
- **u** (up)
- **d** (down)
- **c** (charm)
- **s** (strange)
- **t** (top)
- **b** (bottom)

**Leptons: spin-1/2**
- **e** (electron)
- **ν_e** (electron neutrino)
- **μ** (muon)
- **ν_μ** (muon neutrino)
- **τ** (tau)
- **ν_τ** (tau neutrino)

**Gauge bosons: spin-1**
- Strong force: **g** (gluon (8))
- Weak force: **W^+** (W boson), **W^-** (W boson), **Z^0** (Z boson)
- EM force: **γ** (photon)

**Higgs boson: spin-0**
- Higgs boson: **H**

& field vacuum expectation value

\[
\begin{align*}
\text{SU}(3)_C & : \quad g_s \\
\text{SU}(2)_L \times U(1)_Y & : \quad \frac{gg'}{\sqrt{g^2 + (g')^2}} = g \sin \theta_W
\end{align*}
\]
**Particle content of the Standard Model**

**Quarks:** spin-1/2
- $u$ (up)
- $d$ (down)
- $c$ (charm)
- $s$ (strange)
- $t$ (top)
- $b$ (bottom)

**Leptons:** spin-1/2
- $e^-$ (electron)
- $\mu^-$ (muon)
- $\tau^-$ (tau)
- $\bar{e}$ (electron neutrino)
- $\bar{\mu}$ (muon neutrino)
- $\bar{\tau}$ (tau neutrino)

**Gauge Bosons:** spin-1
- $g$ (gluon)
- $W^+$
- $W^-$
- $Z^0$
- $\gamma$ (photon)

**Higgs Boson:** spin-0
- $H$ (Higgs boson)

**Matter** (J=1/2)

**Force mediators** (J=1)
Particle content of the Standard Model

**Quarks: spin-1/2**

- Quarks: have color charge, electric charge, and weak charge ⇒ strong, EM, weak interactions.
- $u$, $c$, $t$, $d$, $s$, $b$ (up, charm, top, down, strange, bottom)

**Leptons: spin-1/2**

- $e^-$, $\mu^-$, $\tau^-$ (electron, muon, tau)
- $\nu_e$, $\nu_\mu$, $\nu_\tau$ (electron neutrino, muon neutrino, tau neutrino)

**Gauge bosons: spin-1**

- Strong force: $g$ (gluon, 8)
- Weak force: $W^+$, $W^-$, $Z^0$
- EM force: $\gamma$ (photon)

**Higgs boson: spin-0**

- $H$ (Higgs boson)

**Gauge groups**

- $SU(3)_C$
- $SU(2)_L \times U(1)_Y$
Particle content of the Standard Model

Quarks: spin-1/2
- u (up)
- c (charm)
- t (top)
- d (down)
- s (strange)
- b (bottom)

Leptons: spin-1/2
- e\(^{-}\) (electron)
- \(\mu^{-}\) (muon)
- \(\tau^{-}\) (tau)
- \(\nu_{e}\) (electron neutrino)
- \(\nu_{\mu}\) (muon neutrino)
- \(\nu_{\tau}\) (tau neutrino)

Charged leptons: EM and weak interactions.

Neutrinos: weak interactions only.

Gauge bosons: spin-1
- Gluon (8) \(g\)
- W\(^{+}\) and W\(^{-}\) bosons
- Z\(^{0}\) boson
- Photon \(\gamma\)

Higgs boson: spin-0

Strong force:
- \(SU(3)_{C}\)

Weak force:
- \(SU(2)_{L} \times U(1)_{Y}\)

& field vacuum expectation value

Higgs boson:
- \(H\)
Particle content of the Standard Model

**Quarks:** spin-1/2

- u (up)
- d (down)
- c (charm)
- s (strange)
- t (top)
- b (bottom)

**Leptons:** No color charge: invisible to gluons!

- e^− (electron)
- μ^− (muon)
- τ^− (tau)
- ν_e (electron neutrino)
- ν_μ (muon neutrino)
- ν_τ (tau neutrino)

**Charged leptons:** EM and weak interactions.

- electron
- muon
- tau

**Neutrinos:** weak interactions only.

**Gauge bosons:** spin-1

- g (gluon, 8)
- W^+ (W bosons)
- W^− (W bosons)
- Z^0 (Z boson)
- γ (photon)

**Higgs boson:** spin-0 & field vacuum expectation value

- H

**Gauge groups:**

- SU(3)_c
- SU(2)_L × U(1)_Y

Strong force: g
Weak force: W^+ → W^−, Z^0
EM force: γ
Higgs boson: H
Particle content of the Standard Model

Quarks: spin-1/2
- u (up)
- d (down)
- c (charm)
- s (strange)
- t (top)
- b (bottom)

Leptons: spin-1/2
- e− (electron)
- μ− (muon)
- τ− (tau)
- νe (electron neutrino)
- νμ (muon neutrino)
- ντ (tau neutrino)

Gauge bosons: spin-1
- g (gluon (8))
- W⁺
- W⁻
- Z⁰
- γ (photon)

Higgs boson: spin-0
- H (Higgs boson)

Gauge bosons: spin-1
- Strong force (g)
- Weak force
- EM force

Higgs boson: spin-0
- Higgs boson

Higgs physics program: want to fully test all experimentally accessible processes to test SM predictions.
Mass scales in particle physics

Generation puzzle
(leptons)

Hadronic mass
scale

Generation puzzle
(quarks)

Electroweak scale

Dark matter?

Neutrino masses! $m(\nu) \approx 0.1 \text{ eV (?) - another key mass scale!}$
Some key people and ideas

- Emmy Noether
- Richard Feynman
- Peter Higgs
- Vera Rubin

**Crucial role of symmetries in physics**

**Calculating amplitudes for particle interactions**

**Properties of the vacuum can hide symmetries**

**The dominant component of matter in the universe has not been identified**
A dialog about the weak interactions

• Student: “Why are the weak interactions *weak*?”
• Professor: “They aren’t *actually* weak, at least compared with electromagnetic interactions. In fact, they are unified into a single electroweak theory.”
• Student: “Well, then, why are these interactions that aren’t really weak called weak interactions?”
• Professor: “The weak coupling is similar to the EM coupling, but weak processes at low energies are suppressed by the large mass of the mediating particle, either a W or a Z boson.”
• Student: “I get it: electromagnetic processes don’t have this suppression because the photon, the quantum of the field mediating the interaction, is massless.”
• Professor: “Precisely.”
...the next day

• Student: “I think there is a problem with your story about the weak interactions and the heavy W and Z bosons.”
• Professor: “What is that?”
• Student: “The weak interactions are described by a gauge theory, and the gauge bosons are not allowed to have mass, because this would destroy the gauge symmetry. Mass terms are not permitted in the Lagrangian.”
• Professor: “Go away!”
• Professor Higgs (entering): “Wait, your student is right! Interactions with a special spin-0 field can give masses to gauge bosons, making it appear that the gauge symmetry is broken, even though it actually isn’t! If my theory is correct, there should be a new J=0 particle with remarkable properties!”
The role of the Higgs field in the SM

• The SM is a gauge theory built on the symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y$. The SM is highly predictive.

• But, explicit mass terms in the Lagrangian violate this symmetry. **How are particle masses compatible with the gauge symmetry?**

• Higgs mechanism: spontaneous symmetry breaking (SSB) hides the underlying symmetry and explains how particles acquire masses.

Complex Higgs doublet field

$$\varphi(x) \equiv \begin{pmatrix} \varphi_1(x) + i\varphi_2(x) \\ \varphi_3(x) + i\varphi_4(x) \end{pmatrix}$$

$$\varphi(x) \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} \sigma_1(x) + i\sigma_2(x) \\ v + \eta_1(x) + i\eta_2(x) \end{pmatrix}$$

Higgs field vacuum expectation value

$$L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} D\psi$$

$$+ \psi_i y_{ij} x_j \phi + h.c. + |D_m \phi|^2 - V(\phi)$$
SM processes at the LHC: dijet production

Strong interaction process $\Rightarrow$ very large cross section.

Jet $p_T$ resolution: 15% for $p_T=10$ GeV, 8% for $p_T =100$ GeV, 4% for $p_T= 1$ TeV
SM processes at the LHC - top quark production

- Top quark is the heaviest particle (173 GeV) in the SM.
- Top quark production is key background in new physics searches.
- Plays key role in Higgs boson production.
- Searches for new physics often involve top quarks.

\[ Z' \rightarrow t\bar{t} \quad \tilde{t} \rightarrow t\tilde{\chi}_1^0 \]

Top quark pair production

Top quark decay: essentially only 1 mode!

Top quarks decay before they hadronize!
SM processes at the LHC - list of main ingredients

- **Gluons and quarks** (except top) - QCD “jets,” collimated streams of hadrons following the momentum direction of the gluon/quark. **b-quark jets** (“b jets”) have displaced vertices due to long lifetime of b quark. Also: jets from initial-state radiation.

- **Muons, electrons and photons** - highly distinctive

- **Taus** - difficult because they decay with a short lifetime.

- **Neutrinos** give “missing” momentum; measure $\perp$ to beam-axis.
Cross section measurements for SM processes

Provides broad check of our understanding of SM backgrounds for new physics searches.
Top quark pair production

Production rate $\sim 10$ Hz

CMS:

- Tevatron combined 1.96 TeV ($L \leq 8.8$ fb$^{-1}$)
- CMS dilepton, l+jets* 5.02 TeV ($L = 27.4$ pb$^{-1}$)
- CMS $e\mu$ 7 TeV ($L = 5$ fb$^{-1}$)
- CMS $l$+jets 7 TeV ($L = 2.3$ fb$^{-1}$)
- CMS all-jets 7 TeV ($L = 3.54$ fb$^{-1}$)
- CMS $e\mu$ 8 TeV ($L = 19.7$ fb$^{-1}$)
- CMS $l$+jets 8 TeV ($L = 19.6$ fb$^{-1}$)
- CMS all-jets 8 TeV ($L = 18.4$ fb$^{-1}$)
- CMS $e\mu$ 13 TeV ($L = 43$ pb$^{-1}$, 50 ns)
- CMS $e\mu$ 13 TeV ($L = 2.2$ fb$^{-1}$)
- CMS $l$+jets* 13 TeV ($L = 42$ pb$^{-1}$, 50 ns)
- CMS $l$+jets 13 TeV ($L = 2.2$ fb$^{-1}$)
- CMS all-jets* 13 TeV ($L = 2.53$ fb$^{-1}$)

* Preliminary

$835 \pm 33$ pb

SM theory: $816 \pm 42$ pb
Higgs boson production processes

Gluon-gluon fusion “ggF”: 48.5 pb (88%) N3LO QCD, NLO EW

Vector-boson fusion “VBF” or “qqH”: 3.78 pb (7%) NNLO QCD, NLO EW

(W, Z) + H associated production
0.88 (ZH) + 1.37 (WH) pb (4%) NNLO QCD, NLO EW

ttH associated production
0.51 fb (1%) NLO QCD, NLO EW

All of these production processes have now been observed, adding to confidence in our picture of the Higgs boson and providing more ways to study it.

https://arxiv.org/abs/1610.07922v2
Higgs boson decay modes (SM)

Most accessible experimental modes with high mass resolution.

- $H \rightarrow ZZ^*, WW^*$
- $H \rightarrow \gamma\gamma$
- $X(J = 1) \rightarrow \gamma\gamma$
- $H \rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-$
- $H \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}, b\bar{b}$

G. Piacquadio, ICHEP 2018
**Cross section, all channels:** $\sigma/\sigma_{SM} = 1.10^{+0.19}_{-0.17}$

**Fitted Higgs mass:** $m(H) = 125.26 \pm 0.20$ (stat) $\pm 0.08$ (sys) GeV ([CMS HIG-16-041](https://cms.cern.ch/publications/nt/d07315))

*use per event (from per-lepton) resolutions.*

**Lepton momentum scale uncertainty 0.05%-0.3%**
H → ZZ* → $\mu^+\mu^-\mu^+\mu^-$ candidate event

CMS Experiment at LHC, CERN
Data recorded: Thu Oct 13 03:39:46 2011 CEST
Run/Event: 178421 / 87514902
Lumi section: 86

$4\mu+\gamma$ Mass: 126.1 GeV

$(Z_1) E_T : 8$ GeV
$\mu^+(Z_1) p_T : 28$ GeV
$\mu^+(Z_2) p_T : 6$ GeV
$\mu^-(Z_2) p_T : 14$ GeV
$\mu^-(Z_1) p_T : 67$ GeV

7 TeV DATA
H → γγ

- Surprising decay mode, because the “H couples to mass”

- Discovery mode even with large background and small branching fraction. Excellent photon energy resolution.

H→γγ candidate event
Higgs decays to fermions: $H \to ff$

- Major progress in observing $H \to ff$ decays, including some very recent results included here.
- Now have set of measurements for decays to 3rd generation quarks and leptons: $H \to \tau^+\tau^-, ZH$ with $H \to b\bar{b}$, $t\bar{t}H$
- A long term goal is to measure $H \to \mu^+\mu^-$, providing confirmation of the couplings to second-generation fermions.
- Backgrounds are an enormous challenge. Data analysis needs to be very clever!

QCD dijet events are an enormous background

Beating the QCD background: VH associated production

- Some Higgs bosons are produced in association with a vector boson (V = W or Z), providing a powerful tool for suppressing QCD background. Price is the lower production cross section.
- Search for processes with $Z \to e^+e^-, \mu^+\mu^-, \nu\bar{\nu}$ and $W \to e\nu, \mu\nu$.
- Significance: $5.6\sigma$ (expected $5.5\sigma$), Signal strength $1.04 \pm 0.20$

Event display for $pp \rightarrow ZH, H \rightarrow b\bar{b}$
Beating the QCD background: Doing the “impossible”?

- Measurement of $H \rightarrow b\bar{b}$ in the gluon-gluon fusion channel long regarded as impossible.
- Enormous QCD dijet background ($10^7$ larger).
- New method uses Higgs production with high $p_T$ extra jet from ISR; gives highly boosted Higgs. Merged $b$ jets!
- $Z(bb)$ - merged jets: $5.1\sigma$ observed (expected $5.8\sigma$).
- $H(bb)$ - merged jets: $1.5\sigma$ ($0.7\sigma$) expected.

Higgs production in association with top quarks

- Probe the large Higgs-top quark coupling.
- Cross section is small $\sigma(\text{ttH}) \approx 0.5$ pb
- Backgrounds: $\sigma(\text{tt}) \approx 830$ pb, also ttbb, ttZ, and ttW


- Observed ttH production at 5.2$\sigma$ significance (4.2$\sigma$ expected).
Summary of Higgs couplings vs. mass

- Impressive pattern of agreement with SM, but precision is not yet high.

[Graph showing ratio of measured σB values relative to SM predictions and mass dependence of measured couplings compared to SM predictions.]

### Some puzzles and mysteries

<table>
<thead>
<tr>
<th>Hierarchy problem</th>
<th>Unification of couplings</th>
<th>Dark matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>(~10^{18}) GeV</td>
<td>SM (no SUSY)</td>
<td>Atoms: 4.9%</td>
</tr>
<tr>
<td>Planck scale</td>
<td></td>
<td>Dark matter: 26.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dark energy: 68.3%</td>
</tr>
<tr>
<td>(~10^{16})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electroweak scale</td>
<td>Minimal SUSY</td>
<td></td>
</tr>
<tr>
<td>(~10^2 - 10^3) GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(unstable in SM)</td>
<td>S. Raby, Particle Data Book.</td>
<td></td>
</tr>
</tbody>
</table>

- **Planck scale**: \(~10^{18}\) GeV
- **Electroweak scale**: \(~10^2 - 10^3\) GeV

SUSY provides dark matter candidate particle (Lightest Supersymmetric Particle); in MSSM this is neutralino.
Supersymmetry basics

- The symmetry operation in SUSY is a mapping between fermionic and bosonic degrees of freedom.
- “For every SM particle, there is a SUSY particle.” (Well, sort of.)
- Must be a broken symmetry: we don’t observe SUSY partners with SM mass values. SUSY breaking $\rightarrow$ phenomenology
- SUSY preserves the SM couplings (charges) of particles.

• R-parity: multiplicative quantum number that is conserved in many, but not all SUSY scenarios.

$$R = (-1)^{3(B-L)+2S}$$

<table>
<thead>
<tr>
<th></th>
<th>quark</th>
<th>lepton</th>
<th>gauge boson</th>
<th>Higgs boson</th>
<th>squark</th>
<th>slepton</th>
<th>gaugino/ Higgsino</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3(B-L)+2S$</td>
<td>$3(1/3 - 0)$ +2(1/2) = 2</td>
<td>$3(0 - 1)$ +2(1/2) = -2</td>
<td>$3(0 - 0)$ +2(1) = 2</td>
<td>$3(0 - 0)$ +2(0) = 0</td>
<td>$3(1/3 - 0)$ +2(0) = 1</td>
<td>$3(0 - 1)$ +2(0) = -3</td>
<td>$3(0 - 0)$ +2(1/2) = 1</td>
</tr>
<tr>
<td>$R$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
</tbody>
</table>
Supersymmetry basics

• “Curse of many parameters”: MSSM has 124 (including SM).
• If R-parity is conserved, SUSY particles must be produced in pairs.
• The decay chain of each SUSY particle ends with the lightest SUSY partner (LSP), which is stable.
• If the LSP is only weakly interacting, it is a dark matter candidate.
SUSY can (in principle) address the hierarchy problem

\[ \delta m_h^2 \approx -\frac{3\lambda_t^2}{8\pi^2} \Lambda^2 + \ldots \]

\[ m_{h_u}^2 = m_{h_u,0}^2 + \frac{3\lambda_t^2}{4\pi^2} (m_t^2 - m_{\tilde{t}}^2) \ln \left( \frac{\Lambda}{m_{\tilde{t}}} \right) + \ldots \]

but there are two of these...

SUSY particles at the TeV scale can “solve” the fine tuning problem. But current limits on the top squark and gluino masses are putting this picture under stress.
Example: a particle spectrum in the MSSM

<table>
<thead>
<tr>
<th>higgs</th>
<th>sleptons</th>
<th>EWKinos</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tilde{\ell}_L)</td>
<td>(\tilde{\ell}_R)</td>
<td>(\tilde{\tau}_2)</td>
<td>(\tilde{q}_L)</td>
</tr>
<tr>
<td>(\tilde{\ell}_L)</td>
<td>(\tilde{\ell}_R)</td>
<td>(\tilde{\tau}_1)</td>
<td>(\tilde{q}_R)</td>
</tr>
<tr>
<td>(\tilde{\nu}_L)</td>
<td>(\tilde{\nu}_\tau)</td>
<td>(\tilde{b}_2)</td>
<td>(\tilde{t}_2)</td>
</tr>
<tr>
<td>(\tilde{\tau}_2)</td>
<td>(\tilde{\tau}_1)</td>
<td>(\tilde{t}_1)</td>
<td>(\tilde{b}_1)</td>
</tr>
<tr>
<td>(H^0)</td>
<td>(A^0)</td>
<td>(H^\pm)</td>
<td>(\tilde{g})</td>
</tr>
<tr>
<td>(\tilde{H})</td>
<td>(\tilde{W})</td>
<td>(\tilde{B})</td>
<td>(\tilde{\chi}_1)</td>
</tr>
<tr>
<td>(\tilde{\chi}_1)</td>
<td>(\tilde{\chi}_2)</td>
<td>(\tilde{\chi}_3)</td>
<td>(\tilde{\chi}_4)</td>
</tr>
</tbody>
</table>

5 Higgs bosons!

1.7 TeV

1.1 TeV

CMS PAS SUS-14-012
“Natural SUSY endures”: still the current fashion (?)

M. Papucci, J.T. Ruderman, and A. Weiler http://arxiv.org/abs/1110.6926

Stabilizing the EW scale in a “natural” way (without excessive fine tuning) involves only a subset of the SUSY spectrum. Which SUSY partners are constrained?

Focus of SUSY searches

Expected mass upper bound (rough):

\[ m_{\tilde{g}} \approx 2m_{\tilde{t}_1} \]
\[ m_{\tilde{t}_1} \approx 400 \text{ GeV} \]
\[ m_{\tilde{H}} \approx 200 \text{ GeV} \]

natural SUSY

decoupled SUSY
SUSY production cross sections

LPCC SUSY Cross Section WG

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

Events in 3000 fb\(^{-1}\)

Strong production

Electroweak production

8 EWKinos:
4 charginos
4 neutralinos

\( \sigma(pp \rightarrow \text{SUSY}) \text{[pb]}, \text{NLO-NLL} \)

SUSY sparticle mass [GeV]

[Graph showing SUSY production cross sections with various particles and production channels]
Jets + $p_T^{\text{miss}}$ search: candidate event

SUSY candidate event in data with 12 jets, 3 b-tagged jets

\[ \vec{p}_T^{\text{miss}} = - \sum_{i=\text{particles}} \vec{p}_i \]

\[ H_T = \sum_{j=\text{jets}} |\vec{p}_T^j| \]

\[ H_T^{\text{miss}} = 671 \text{ GeV} \]

\[ H_T = 1607 \text{ GeV} \]
Jets + $p_T^{\text{miss}}$ search: candidate event

Much lower jet multiplicity...can still be SUSY...but much more likely $Z(\nu\bar{\nu}) + \text{jets}$.
Jets + $p_T^{\text{miss}}$ search: observed yields in signal regions

In each bin, each main background is predicted separately from control sample(s) in the data that is (are) dominated by that background.
Jets + $p_T^{\text{miss}}$ search: example interpretations

Color map shows the excluded cross section (95% CL)
Comparison of this cross section with a theoretical reference cross section for the signal gives the boundary of the excluded model points.

Many more interpretations available at
This CMS search I'm trying to emulate has 160 search regions. Goddamnit CMS.

#ICHEP2016
Towards the High Luminosity LHC

- Accelerator upgrade is being accompanied by major upgrades to the detectors.
- CMS: new capabilities to handle increased data rate, multiple pp collisions per bunch crossing (pileup), radiation damage, and to improve trigger, tracking, calorimeters, and muon system.
Towards the High Luminosity LHC: CMS detector upgrade

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193
• Tracks in L1-Trigger at 40 MHz for 750 kHz PFlow-like selection rate
• HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187
• ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
• ECAL and HCAL new Back-End boards

Muon systems
https://cds.cern.ch/record/2283189
• DT & CSC new FE/BE readout
• New GEM/RPC 1.6 < η < 2.4
• Extended coverage to η ≈ 3

Calorimeter Endcap
https://cds.cern.ch/record/2293646
• Si, Scint+SiPM in Pb-W-SS
• 3D shower topology with precise timing

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

Tracker
https://cds.cern.ch/record/2272264
• Si-Strip and Pixels increased granularity
• Design for tracking in L1-Trigger
• Extended coverage to η ≈ 3.8

MIP Timing Detector
https://cds.cern.ch/record/2296612
• ≈ 30 ps resolution
• Barrel layer: Crystals + SiPMs
• Endcap layer: Low Gain Avalanche Diodes
Since the Higgs boson discovery in 2012 there has been major progress in studying its properties.

This effort has expanded into a full physics program: 4 production processes and 7 decay modes are being studied, with detailed measurements of kinematic distributions underway.

Will require very large data samples to fully explore critical Higgs decay modes. Increases in precision are extremely important for fully testing the Higgs sector of the SM.

Holy grail is Higgs self-coupling (HHH vertex).

So far, observe remarkable agreement with SM predictions involving both gauge boson and fermion couplings.
Conclusions/Perspective (II)

• But...we are puzzled.

• The SM is internally consistent (without further physics), but it appears to require an extraordinary degree of fine tuning of parameters to prevent quantum corrections from pulling the Higgs mass to the Planck scale. (Hierarchy problem.)

• This is a fundamental problem associated with the J=0 nature of the Higgs boson, assuming that it is an elementary (non-composite) particle. (We also don’t have a candidate for dark matter, or answers to many other questions.)

• So far, no evidence has emerged for any proposed explanation, including supersymmetry.

• However, the frameworks for new physics offer an enormous range of phenomenological possibilities, and there are many scenarios that are currently difficult to probe. The jury is still out.
When you are on a voyage of discovery, you don’t necessarily have a good idea of where you are. We have only analyzed ~5% of the eventual LHC data sample! There may be more “continents” to be found!

Christophe Colomb 1492-1493

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Source: Christopher Columbus Voyages (c) Semhur - CC-BY-SA 3.0
Acknowledgments

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