THE LHC PROJECT: BEYOND THE HIGGS BOSON DISCOVERY

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THE 4TH OF JULY, PHYSICISTS’ STYLE

Today is also a special day
THE HUNT FOR HIGGS IS OFFICIALLY OVER

... or is it not?
WHAT IS HIGGS BOSON AND WHY ALL THE COMMOTION?
STANDARD MODEL OF PARTICLE PHYSICS

- Physical content:
  - 12 basic particles (fermions)
    - Each has an antiparticle
  - Interact via force carriers called gauge bosons
- Includes 2.5 forces:
  - Electroweak force = “electromagnetic+weak” combined force
    - All basic particles participate, transmitted by W/Z/g bosons
    - Responsible for radioactive decays and electromagnetic interactions
  - Strong force:
    - Only quarks participate, transmitted by gluons
    - Holds proton and other composite hadrons together
HIGGS MECHANISM

- From Quantum E&M we know that nature likes symmetries and gauge theories
- A problem if applying to weak interaction:
  - In renormalizable theories gauge bosons must be massless
    - They aren’t: $m(W) \sim m(Z) \sim 100 \times$ proton mass
  - A scalar particle with Mexican hat potential (Higgs boson):
    - Can solve the mass problem
    - Also “marries” the weak force and electromagnetism
Higgs Mechanism: Masses

- The vacuum is effectively filled with a condensate of these Higgs bosons.
- Masses are acquired dynamically through the interaction with the Higgs field.
  - Can think of fermions acquiring mass as sort of like walking in a swimming pool makes you feel “heavy”.
- The stronger the coupling for a particular fermion to Higgs, the heavier the fermion is.
  - Why they are so different, we don’t know.

Fermions

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Spin</th>
<th>Mass GeV/c²</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>νₑ, electron neutrino</td>
<td>&lt;1x10⁻⁸</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>e, electron</td>
<td>0.000511</td>
<td>-1</td>
<td></td>
</tr>
<tr>
<td>νₘ, muon neutrino</td>
<td>&lt;0.0002</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>μ, muon</td>
<td>0.106</td>
<td>-1</td>
<td></td>
</tr>
<tr>
<td>νₜ, tau neutrino</td>
<td>&lt;0.02</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>τ, tau</td>
<td>1.7771</td>
<td>-1</td>
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</table>

Quarks

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Spin</th>
<th>Approx. Mass GeV/c²</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>u, up</td>
<td>0.003</td>
<td>2/3</td>
<td></td>
</tr>
<tr>
<td>d, down</td>
<td>0.006</td>
<td>-1/3</td>
<td></td>
</tr>
<tr>
<td>c, charm</td>
<td>1.3</td>
<td>2/3</td>
<td></td>
</tr>
<tr>
<td>s, strange</td>
<td>0.1</td>
<td>-1/3</td>
<td></td>
</tr>
<tr>
<td>t, top</td>
<td>175</td>
<td>2/3</td>
<td></td>
</tr>
<tr>
<td>b, bottom</td>
<td>4.3</td>
<td>-1/3</td>
<td></td>
</tr>
</tbody>
</table>
IS BROKEN SYMMETRY STILL A SYMMETRY?

- Symmetry is there, but it got broken as the world cooled off.
- Not that strange, we see this a lot:
  - Symmetric equations do not necessarily mean symmetric solutions.
  - The world is not symmetrical, but the theory, the “World Equation”, is symmetrical.
- Likely that Higgs is not yet the full story:
  - Large divergences in taking SM towards Plank scale (hierarchy problem).
  - Potential comes completely out of the blue, no explanation…

A symmetrical equation:
- \( x+y=4 \)

Solutions \((x,y)\):
- Symmetrical: \((2, 2)\)
- And asymmetrical: \((1,3), (4,0),(3,1)\)…
“A HIGGS” VERSUS “THE HIGGS” DILEMMA

• “A Higgs” is a generic mechanism to generate masses for W, Z-bosons and fermions
  • Coupling to fermions is proportional to the mass of the fermion
  • A spin-0 particle
  • Almost every model of new physics has a Higgs or even a few
    • Five of them in minimal Supersymmetry: h, H, H±, A
• “The Higgs” as in the SM Higgs implies SM is true:
  • Has couplings exactly as prescribed by the Standard Model
  • Decays where it is supposed to with the correct rates and all (or many) decay modes are accounted for
  • Has correct self-couplings
• Differences could be small:
  • Most models of “new physics” have at least one “a Higgs” boson that looks a lot like “the Higgs”
WHAT DO WE KNOW ABOUT HIGGS TODAY?
Higgs Stats: Mass, Spin, Couplings

- The mass is about 126 GeV
  - \((m_Z + m_{W^+} + m_{W^-})/2 = 125.992\) GeV
  - Did you know that?
- Seems to decay to pairs of taus (charged fermions), pairs of W’s (charged bosons), pairs of Z’s and pairs of photons (neutral)
  - Charge is zero
  - Several possibilities spin/parity
- The production yields look about right when compared to the SM predictions
  - It does look like the Higgs, right?
- Couplings can presumably be extracted from the rate:
HIGGS SPIN AND PARITY

- Higgs should have spin 0 and even parity ($J^P=0^+$)
- Various angular distributions are sensitive to the new particle’s spin and parity
- Compare expectations for various combinations of $J$ and $P$ to the data
- It does look like what you expect for Higgs!

**Pseudo-scalar 0^-**

**2^+ : 2.8-3σ inconsistent**
HIGGS COUPLINGS

- Turns out to be not an easy measurement
- Let’s simplify:
  - Assume all couplings to fermions (taus, tops, b’s) can at most be off from SM by a common factor $k_f$; assume the same for all bosonic couplings - $k_V$
- Result: well, not that great
  - Even in this simplified case fermionic couplings are measured to $\sim 30\%$ accuracy, boson couplings to $\sim 10\%$
- Ask a different question: how much the accounted Higgs decays allow to say about hypothetical non-SM decays of higgs
  - Higgs could be decaying 40% of the time into something totally new and we wouldn’t know about it
“A HIGGS” VERSUS “THE HIGGS”
FIGURING THE HIGGS STORY OUT

- The challenge is that most models have a Higgs boson
  - Most have at least one that is much like the SM-higgs
  - Differences are frequently at percentage level
- SUSY predicts the lightest SM-like higgs to have $m< 135$ GeV. Is 125 a coincidence? Maybe…
  - Need precision Higgs measurements to distinguish these hypotheses
    - Decay modes in many channels to verify couplings and exclude non-standard decay modes

- Two paths:
  - Long and tedious precision measurements of couplings
  - Look for viable alternatives
    - Can be quick, but need to know what to look for
WHAT ARE VIABLE ALTERNATIVES?

- We now know how technically the electroweak symmetry is broken, but we have no clue why
- The hierarchy problem:
  - In SM, Higgs mass at higher orders acquires infinite mass corrections
  - Need an extreme fine tuning ($10^{-30}$)
- Several other big issues:
  - Dark Matter is unexplained at all
  - Neutrino mass
  - Matter-antimatter asymmetry
- Quite a few unexplained mysteries:
  - E.g. rising positron fraction observed by the satellite experiments
    - Could be a hint of a new dark force

\[
\delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2} \left[ -2\Lambda_{UV}^2 + \ldots \right]
\]
DARK FORCES IN UNIVERSE’S HIDDEN VALLEYS?
DARK FORCES IN HIDDEN VALLEYS?

- One interesting scenario is motivated by the measured by satellite experiments rising positron fraction towards higher energy
- Unknown pulsar? Cosmic rays interacting with giant molecular clouds?
- Or TeV-scale dark matter annihilation in the galactic halo with a large x-section:
  - Dark photon $\gamma_D$: an attractive long-distance force between slow WIMPs
    - Sommerfeld enhancement
  - Hidden: $\gamma_D$ only weakly couples to SM via kinetic mixing with photon
    - As no antiproton excess observed, $M(\gamma_D) \lesssim O(1 \text{ GeV})$
NEXT-TO-MINIMAL SUPERSYMMETRY

- NMSSM has been around for a while as a solution to naturalness and fine tuning issues in minimal SUSY
  - Adds a new singlet field and makes a much better behaving theory
    - An extended Higgs sector
      - 3 CP-even Higgses $h_{1,2,3}$ + 2 CP-odd Higgses $a_{1,2}$
      - Higgs-to-Higgs decay: $h_{1,2} \rightarrow 2a_1$
    - And the same weird feature: a hidden sector
      - $a_1$ can be light, but it very weakly couples to SM particles so we would have never seen it before
      - Need to produce a heavier higgs first and then watch it decay
        - Only nature and the LHC can do that.
EXPERIMENTAL SIGNATURES AT THE LHC

• NMSSM: \( pp \rightarrow h_{1,2} \rightarrow a_1 a_1 \rightarrow 4\mu \)

• Dark SUSY with light dark photons:
  • \( pp \rightarrow h \rightarrow 2n_1 \rightarrow 2n_D + 2\gamma_D \rightarrow 2n_D + 4\mu \)
  • Neutralino \( n_1 \) decays to a light dark neutralino \( n_D \) and a dark photon \( \gamma_D \)
  • Similar signature, but softer dimuons and missing energy
SEARCH FOR NEW HIGGS DECAYS

- Seems like a simple analysis
  - ... So a few years later, after
    - a hundred sleepless nights looking at thousands of various graphs
    - half a dozen nervous breakdowns
    - a few shouting matches at the approval meetings
  - You open the signal box!
    - We see one event with a signal-like topology
    - Consistent with our prediction for the yield from background processes
- Public results are available as CMS-PAS-HIG-13-010
THE EVENT AND THE PEOPLE

- Will submit this year, will be our latest in a series of related studies:
  - JHEP 1107:098, (2011)

- People:
  Yuriy Pakhotin,
  Aysen Tatarinov,
  Vadim Khotilovich,
  Alfredo Castaneda,
  A.S. + T.K. and
  O.B.
THE TEDIOUS PATH

- We also work as part of a large team of collaborators on Higgs measurements predicted by the Standard Model to compare data and predictions
  - WH associated production
  - Our channel is where W decays to lepton and neutrino and Higgs decays to two tau leptons, each decaying hadronically

- Anthony Rose, Indara Suarez, Jeff Roe, Aysen Tatarinov, A.S.
  - CMS-PAS-HIG-12-053
  - A paper to be published this year
FIGURING THE TWO HIGGSES STORY
IT WILL TAKE A WHILE

• We will need much more data to get to the needed precision for the Higgs couplings
  • Of course, Higgs is only part of the program, we are looking for much more than just Higgs couplings
• Consider that an improvement by a factor of 2 in the statistical precision of a measurement requires 4 times more data
  • We need about a factor of 10 or more in precision
  • That’s 100 times more data compared to what we have collected in 2011-2012!
  • It will take us 200 years
• Need to collect data faster
  • Shoot for “doubling time” of ~3-5 years?
• Can we do that?
CERN ACCELERATOR COMPLEX: YES, WE CAN

- A major upgrade of the LHC accelerator complex is required
  - Increase beam brightness (new injectors)
  - Improve interaction regions (reduce squeeze $\beta^*$, new large aperture triplets, collimation and separation systems, optics at IR, later on crab RF cavities)
- Doable, but requires time, a lot of work, R&D and planning
LHC: THE FUTURE

- The LHC has an ambitious program designed to tackle the Higgs and hopefully make new discoveries:
  - **Today:** ~25 fb$^{-1}$ of data
  - **2013-2014:** Long Shutdown 1, LHC becomes HL-LHC
    - Increase energy to 13-14 TeV, higher beam intensity
  - **2014-2017:** Collect 120 fb$^{-1}$ of data
  - **2018:** Long Shutdown 2
    - Increase beam intensity
  - **2018-2022:** Collect 300-500 fb$^{-1}$ of data
  - **2022-2023:** Long Shutdown 3
    - Even higher beam intensity
  - **2023-2033:** Collect 2500 fb$^{-1}$ of data
  - **2033-2035:** HL-LHC becomes HE-LHC
    - Double the beam energy
  - ...
**HL-LHC: CAN THE DETECTORS HANDLE THAT?**

- Every experimentalist’s ultimate nightmare!
CMS DETECTOR UPGRADES

• Need to rebuild many components of the CMS detector to withstand these intensities and maintain top notch efficiency
  • A complicated endeavor requiring
    • Studies and detailed software simulation to find out which elements need replacement
    • Studies to develop new ideas and algorithms
    • R&D to develop detector technologies and electronics, design and prototyping, testing, construction
    • Control software, firmware, computing to handle much increased amounts of data
    • Logistics of simultaneous installation of multiple new systems, recabling millions of channels, and rerouting everything within a limited amount of time in a cavern that just barely fits the detector
    • Commissioning and integration of the new systems: everything must work as a Swiss watch on day one of the colliding beams
THE CMS DETECTOR
UPGRADE R&D AT TEXAS A&M

• A lot of behind the scenes work in the past 4-5 years in parallel with physics, detector support, analysis techniques etc.
• We developed a strong expertise is the development of ultra-fast electronics for use in the CMS readout and trigger
  • Led by Jason Gilmore, our Chief Electronics Engineer
  • Ground zero for this work has been our e-lab, almost everyone in our group is contributing or has contributed:

• Yuriy Pakhotin, Vadim Khotilovich, Slava Krutelyov, Jeff Roe, Indara Suarez, Aysen Tatarinov, Heshani Jayatissa, Samir Lakdawala (undergrad thesis), Nick Amin, Austin Schneider, Irene Zawisca (REU), Will Flanagan (advisor: Teruki Kamon) and more
TRIGGER MOTHERBOARD UPGRADE

- The new TMB, a.k.a. OTMB, features
  - Receives fiber optic data from front end using 3.2 Gb/s links
  - Programmable logic platform to improves the trigger algorithm
    - Critical for efficient trigger operation
  - Full backwards compatibility with the copper data links used on other CSCs
- ~100 of these are now sitting in our lab
A LONG PATH TO THIS DAY

- Electronics we build has to highly reliably operate in fairly aggressive radiation environment
  - On detector electronics inaccessible for 3-5 years, other elements can be replaced for months
  - Has to be able to withstand long term damage and means to recover from single event failures
- Tests at TAMU and UC Davis Cyclotrons, TAMU reactor facility
- Recent papers:
  - JINST 8 C02040 (2013)
NEW ELECTRONICS: INTEGRATION AT CERN

• Our board will be part of the all new electronics that will be collecting data in ~a year from now
• A lot of things can go wrong when you put together a new system full of high performance digital chips, multi-Gb links, thousands of lines of firmware and software code
  • Integration is the key
• Already a year of intensive integration and testing at CERN
• Installation and full system integration later this year
• Commissioning to follow

• Summer of 2013: students and postdocs working at the ME-1/1 integration facility at CERN
• TAMU: Indara Suarez (resident at CERN, deputy coordinator of the integration project) and Nick Amin (our undergrad)
NEXT PROJECT: GEM DETECTOR

- TAMU has been a principal proponent behind this new novel detector proposal:
  - Critical to maintain high efficiency of muon collection at high luminosity in the difficult forward region
  - Quarter of the CMS acceptance is in that region
  - A year of detailed simulation work and analysis (absolutely critical contributions by Khotilovich)
  - Electronics design is gaining speed
  - Close collaboration with T. Kamon
  - Target installation date in 2017-2019
EVEN BEYOND THAT

- We are leading the work at CMS in defining the scope of muon upgrades for the super-high luminosity regime past 2023
  - Also organizing the overall US effort and role in these future upgrade projects
- Proposing an integrated detector combining calorimetry and muon measurements in the very forward region
  - Will almost double current CMS acceptance for muons
  - Ultra high resolution detector based on GEM technology
  - Will rely on the experience we are gaining now in the current smaller scale GEM detector
SUMMARY

- The LHC program will continue its discovery focus as we study the properties of the (or a) Higgs boson
- Large improvements in sensitivity with double the energy and ~5 times more data to be collected in Run-2a
  - Vast impact on the reach for new physics of both direct searches and precision measurements of Higgs properties
- Long term planning of the upgrade program is an important part of the LHC discovery focus
- Texas A&M CMS group’s program at the energy frontier is broad and strong
  - We play an important role, our impact and visibility at the LHC continue to grow
THANK YOU

- Senior researchers:
  - Jason Gilmore, Vadim Khotilovich, Slava Krutelyov
- Postdoctoral researchers:
  - Anthony Rose, Yuriy Pakhotin
- Graduate students:
  - Jeff Roe, Indara Suarez, Aysen Tatarinov
- Undergraduate students:
  - Nick Amin, Austin Schneider, Samir Lakdawala
- Testing the HEP waters us:
  - Heshani Jaytissa, Tao Huang, Randy White
- Alumni:
  - Andrey Elagin (postdoc at University of Chicago), Chi Nhan Nguyen (Ernest Kempton Adams Research Fellow at Columbia University and Assistant Prof. at Tan Tao University in Vietnam), Jim Pivarski (Fermilab and beyond)
- We are part of the common TAMU CMS team along with the programs of Eusebi and Kamon
- External funding agencies contributing to our operations:
  - US Department of Energy, US CMS Operations Program, Qatar National Research Foundation, National Science Foundation (Suarez’s fellowship)