LHC: A New Era Has Just Started

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Outline

• Particle Physics introduction and some history
• Large Hadron Collider (LHC) Project
• CMS Experiment and Collaboration:
  • Detector Layout and Subsystems
  • Discovery Potential
  • Doing physics analyses at colliders
  • Role of Texas A&M in the CMS project
• Summary
Particle Discoveries

- Radioactive materials and cosmic ray era:
  - Discoveries:
    - Electron (1890s), photon (1905) and nucleus (1909)
    - Proton (1919)
    - Neutrino prop. (1930), neutron (1931), positron (1932)
    - Muon (1937-1947), light mesons (1947+)
  - Status: A lot of knowledge, but things look pretty chaotic, it was clear that the picture is incomplete

- Accelerators era:
  - Streak of discoveries:
    - 1983 – Z/W, 1989 - 3 types of light neutrinos
    - 1995 – top quark (Tevatron)
  - End of 20th century: Standard Model as we know it largely complete except for Higgs boson
    - Important precision measurements mostly confirm SM, but no major discoveries
Standard Model in Pre-LHC Era

- And then in the last decade we have been witnessing mounting problems
  - Feeling of imminent changes just like before the start of accelerator era
- Particle physics got stuck with a number of problems that cannot be explained with existing data
  - Higgs boson has not been seen in spite of less and less room left for it
  - Precision data shows signs of inconsistencies
  - We know Dark Matter is there, but haven’t seen it directly
  - Discovery of neutrino oscillations has already delivered a strong punch in the face of Standard Model
Tevatron: 20 Years Later...

• Tevatron discovered top, but failed to do much more even though we got 50 times more data since top

• Why? Apparently we did not get high enough in energy
  • All the fun stuff must be happening at a bit higher energies

• LHC: next large step
  • Many reasons why we should get it this time
Large Hadron Collider

27 km in Circumference!

One of the largest and the most complex scientific instrument ever conceived & built by humankind

E-beam = 7 TeV

CMS

ALICE

ATLAS

LHCb
Collisions at LHC

14 000 x mass of proton (14 TeV) = Collision Energy
Protons fly at 99.999999% of speed of light
2808 = Bunches/Beam
100 billion (10^{11}) = Protons/Bunch

7 TeV Proton Proton colliding beams

Bunch Crossing 40 million (10^6) Hz

Proton Collisions 1 billion (10^9) Hz

Parton Collisions

New Particles 1 Hz to 10 micro (10^{-5}) Hz (Higgs, SUSY, ....)

One “discovery” event in 10,000,000,000,000
Our goal is to find that one event!
“Largest Science Project Ever”

- Circular 27 km long tunnel
  - 50 - 175 meters underground
  - 2 beam pipes, 8 sectors
- Enormous and very sophisticated magnetic system:
  - 1,232 superconducting dipole magnets keep protons in the orbit
    - $B = 0.5 \text{ – } 8.3 \text{ T}$ as protons accelerate from 450 GeV to 7 TeV
  - 392 superconducting quadrupole magnets to focus beams
  - Every magnet in sync with all others to keep the beam running
  - Total magnetic energy stored is that of Aerobus A380 flying at 700 km/h
- Largest “refrigerator” in the world:
  - 40,000 tons of cold mass spread over 27 km
  - 10,000 tons of Liquid Nitrogen (at $T=80\text{ K}$)
  - 60 tons of Liquid Helium (cools ring to final 1.9 K)
“One short trip for a proton, but one giant leap for mankind!”

• On September 10 2008 at 10:28 AM Geneva time (3:28 AM in College Station), the new era in science has started as LHC had its first beam circulated the full orbit.

• Result of hard work of a global collaboration of scientists, universities and governments.
  • Over 10,000 scientists from 500 institutions from 60 countries!
LHC: Long Way to Get to Here

- B.L.H.C era:
  - October 1995 – TDR published, production starts
  - November 2000 – first magnets arrived
  - May 2005 – connecting magnets
  - October 2006 – cryogenic system is completed
  - November 2006 – last magnet arrived
  - November 2007 – the whole infrastructure in place (but not enough helium)
  - August 2008 – all 8 sectors of the ring are finally cooled down

- Startup:
  - September 10, 2008 – first beams circulated in both directions
  - September 12, 2008 – the LHC was able to keep beam running for 30 minutes

- Before end of 2008:
  - Beam comissionning and optics measurements with 450 GeV beam
  - Short collisions with 450 GeV (possibly even this weekend)
  - Ramping up beam energy to 5 TeV per beam
  - Intensity and squeezing studies
  - **Collisions at 10 TeV (end of October?)**
  - Detectors collect ~10 ipb of data
  - Winter shutdown: train quadrupoles to full current (for 7 TeV)

- 2009 and after:
  - Nominal 14 TeV collisions
  - Likely 1-2 ifb of data in 2009, more in future years
  - **2013-2018: increasing beam intensity by an order of magnitude**
LHC Experiments:

- CMS and ATLAS:
  - “General purpose” detectors
  - Search for Higgs and new physics
  - Different detectors technologies and techniques to allow cross-checks of results
    - Known to be important

- ALICE: quark-gluon plasma studies
  - Special dedicated LHC runs with lead ion collisions instead of protons

- LHCb: studies CP violation in b-sector
  - Precision measurements of B-meson decays may explain the matter-anti-matter asymmetry
CMS Sub-Detectors

- **SUPERCONDUCTING COIL**
- **CALORIMETERS**
  - ECAL: Scintillating PbWO₄ Crystals
  - HCAL: Plastic scintillator copper sandwich
  - Overall length: 21.6 m
  - Magnetic field: 4 Tesla

- **IRON YOKE**
- **TRACKERs**
  - Silicon Microstrips
  - Pixels
  - Cathode Strip Chambers
  - Resistive Plate Chambers
  - Drift Tube Chambers

- **MUON ENDCAPS**
  - Resistive Plate Chambers
  - Cathode Strip Chambers

Each layer identifies and enables the measurement of the momentum (P) or energy (E) of particles produced in a collision.

- Total weight: 12,500 t
- Overall diameter: 15 m
- Overall length: 21.6 m
CMS: Construction

- **1992: Letter of Intent**
  - Four US Universities:
    - UT Dallas, UC Davis, UCLA, UC Riverside
- **1994: Technical Proposal**
  - Approval signaled official start of building the detector
  - 35 US Institutions
- **CMS Detector Construction:**
  - Actually started in ~1998, distributed over many countries and institutions
    - Daunting logistics
  - Detector assembled on surface in large chunks, then lowered into the cavern (2006)
- **Many challenges on the way:**
  - E.g. when boring the CMS shaft, an underground river had to be frozen with liquid nitrogen
CMS Collaboration

• International collaboration of scientists runs the experiment:
  • 2k researchers from 155 institutions from ~37 countries
  • With a recent wave of newcomers, now 49 US Universities

• Stunning logistics task!
  • Elaborate structure of managing tasks and responsibilities
    • University groups take responsibilities for specific tasks and analyses
    • Elected and designated coordinators of super-tasks

• TAMU is a CMS member:
  • TAMU group expanded to 12 people (3 senior faculty scientists)
CMS: Physics Potential

- CMS Physics Potential:
  - Higgs boson (“God’s particle”)
    - or another mechanism of electroweak symmetry breaking
  - Supersymmetry
    - May hold keys to explaining Dark Matter
  - Shed light on unification of forces (strong and EW)
  - Extra Space Dimensions and Graviton (inspired by string theory)
  - Finding the unexpected:
    - Arguably the most likely outcome
    - ...and the most exciting too!
Higgs: Why Do We Need It?

• Proposed to explain masses of bosons:
  • In good renormalizable theories bosons must be massless
  • LEP collider has directly measured masses of W and Z and they are ~100 GeV, so they are hardly zero!
  • Higgs potential resolves that and gives masses to particles
    • As a result, the world around us is not symmetrical, but the theory explaining it is
    • Sounds like a trick?

• Many reasons why this is likely not the full story:
  • Large divergences in taking SM towards Plank scale (hierarchy problem)
  • EWSB potential comes completely out of the blue, no explanation...

Nice illustration from Gordy K.:
Symmetrical equation:
  • $x+y=4$
Solutions $(x,y)$:
  • Symmetrical: $(2, 2)$
  • And asymmetrical: $(1,3), (4,0),(3,1)...$
Higgs: Can It Not Be There?

• Forget theorists and their smarty pants hierarchy problems…

• Here is a real deal:
  • Despite some new problems, SM (with Higgs) is still a pretty good model that passed many tests to enormous precision
  • Higgs regulates some striking divergences in SM
  • Consider WW scattering, take out Higgs and probability of \( WW \rightarrow WW \) is greater than one above 1 TeV!
  • LHC will either see Higgs or, if it is not there, will see whatever is playing its role
What We Know about Higgs

- Direct attempts to measure:
  - LEP and Tevatron:
    - $M_H > 114$ & not 170 GeV

- Indirect measurements:
  - Higgs shows up through loop corrections
  - E.g. Tevatron $M_W$ vs $M_{top}$
CMS Reach for Higgs

• Bring together direct and indirect:
  • Construct $\chi^2$ vs plausible higgs masses
  • Data likes light Higgs

• LHC discovery:
  • If $M_H \sim M_{WW}$: 1 fb$^{-1}$ (1 yr)
    • Or rule out SM Higgs
  • Anywhere: 10 fb$^{-1}$
    • Might take $\sim$3 yrs
Searching For Higgs

• Slightly simplifying, we are going to:
  • Go over millions of events
  • Reconstruct each and every particle in all of the events
  • Look for that one collision where higgs was produced
    • But do we know what are we looking for if we don’t even know its mass?

• Depending on higgs mass, one would look in one of several different ways
  • We don’t know higgs mass, so we will look for all possibilities at once:
    • All possible production mechanisms and decay channels
New Physics Discovery in October?

• Not so fast: no physics results till detector performance is well understood with real data:
  • Precision in understanding sub-systems will continuously improve with more data, more experience and better understanding of other sub-systems
    • Alignment, calibrations, jet energy scale, MET

• Two closely inter-related directions
  • Object-based commissioning:
    • Tracks for alignment, min-bias for equalizing calorimeter tower calibrations etc.
  • Validation with “standard candles”:
    • Z mass, resolution, MET in Z/W/top events etc.
Detector Alignment

• Critical for any physics analysis
  • Three detectors to align:
    • Tracker, calorimeter, muon system
• Texas A&M in charge of muon alignment project with data:
  • Jim Pivarski, A.S., Sergey Senkin (just joined)
• On the right: the very first real LHC data showing muons passing through CMS muon detectors
  • The plot made by Jim on September 10, 2008 in ENPH 114T
  • That’s day 1 of the new LHC era!
Physics with Muons

• When alignment task completed:
  • Re-discover “old physics” in 2008
    • Z and W bosons
  • And onwards on the path to new physics:
    • New heavy resonances decaying to $\mu\mu$, e.g. $Z'$ or extra dimensions (all)
    • New heavy quarks decaying to Z’s (Pivarski)
    • “Higgs with a twist” $H\rightarrow\alpha\alpha\rightarrow\mu\mu\mu\mu$ (Senkin)
Physics with Taus

- Heaviest lepton, notoriously difficult to reconstruct at hadron colliders, but very important
  - TAMU came to CMS with world-best expertise in tau reconstruction
- We are now the key leader in taus at CMS
  - Gurrola, Kamon, Mason, Nguyen (CMS tau trigger coordinator, on the picture), A.S. (CMS tau group convener)
- Road Map:
  - 2008: rediscover $Z \rightarrow \tau \tau$ (Gurrola, Nguyen)
  - Onto new physics: Higgs and Z-prime (Gurrola, Nguyen, Mason)
Physics with Missing Energy

- Good calibration is crucial for SUSY searches, but notoriously difficult
  - J. Asaadi, A. Gurrola, T. Kamon, D. Toback

- We will join our MET and tau expertise in searches for Dark Matter
  - see Bhaskar’ colloquium last week
  - Kamon, Toback, Asaadi, Arnowitt, Dutta, A.S.
Detector Building: SLHC

- **LHC to SuperLHC:**
  - Two Phases: 2013 and 2018
  - Accelerator upgrades: 200-400 collisions per bunch crossing vs 20-50 for LHC
    - An enormous analysis and trigger challenge
  - Substantial upgrade of all detectors necessary to work in new environment
  - Now is the time to start building
    - Compare to 10-15 years to build CMS
- **TAMU is a leader in several upgrade projects**
Muon Trigger Electronics Project

• We took a major responsibility to build a Muon Trigger Motherboard
• New turf, implies state of the art in-home fast electronics design and building capabilities
  • Sasha Golyash, a highly experienced EE (13+ years in HEP) joined us in 2006
    • A complete test stand assembled at CERN, will be shipped to TAMU in early 2009
    • Sasha relocates to TAMU in May 2009
  • Will join V. Khotilovich, our software engineer (+ A.S + postdocs, students)
• Success of this project will greatly enhance our standing in the field
  • Also a unique and highly sought for training for students and postdocs
  • Major leverage in joining new projects
Track and Tau Trigger Upgrades

- SLHC environment will require much better triggering:
  - One major (and most expensive) upgrade is Level 1 track trigger
    - R&D and simulations work ongoing
    - Kamon, Weinberger
  - Tau trigger setup has to undergo a complete overhaul as well:
    - R&D, simulations, algorithm development
    - Khotilovich, Mason, A.S.
Summary

• The startup of Large Hadron Collider opens a new era in particle physics
  • While there is a lot of hard work ahead of us, we are on threshold of making major discoveries:
    • Higgs, origin of electroweak symmetry breaking, unification of forces, Dark matter, mater-antimatter asymmetry, and anything unexpected
    • Next 2-3 years may completely change our understanding of the world around us
• Texas A&M will be on the forefront of making these breakthrough discoveries
  • Stay tuned!