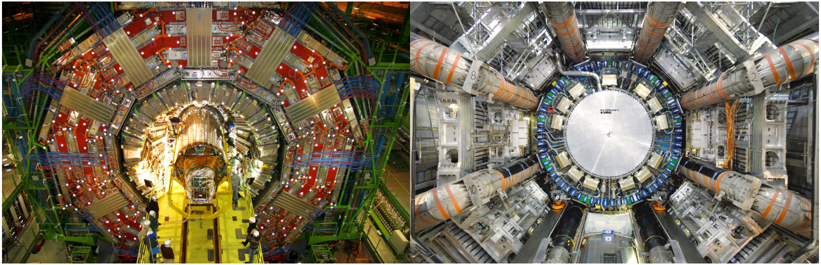


LHC PHYSICS

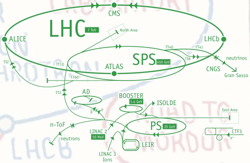
Andrés G. Delannoy[1]

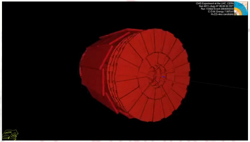
[1]Vanderbilt University

The Large Hadron Collider

- Largest and most powerful particle accelerator
- 26.6 km (16.5 mi) circumference tunnel, from 50-175 m (165-575 ft) underground
- 1232 dipoles operating at 1.9 K (-456 °F) generating $\sim$ 8 T
- Beam tube under ultra-high vacuum (10^{-13} atm)
- 2808 bunches of protons circulate around the tunnel (each bunch $\sim 10^{11}$ protons)
  - Each proton traverses the tunnel more than 11,000 times per second
  - Roughly 600M collisions per second ($\sim$ 1000 TB/s)
    - CERN Tier0 stores and distributes $\sim$ 10 GB/s globally

Quantity	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy, protons	7 TeV
Nominal energy, ions	2.76 TeV/u (*)
Peak magnetic dipole field	8.33 T
Min. distance between bunches	~7 m
Design luminosity	10^{34} cm^{-2} s^{-1}
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	1.1×10^{11}
Number of turns per second	11 245
Number of collisions per second	600 million

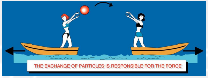


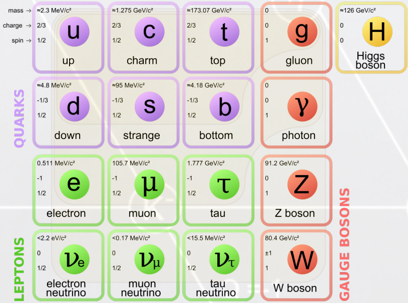


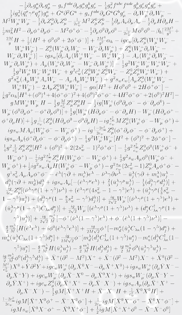
The Standard Model

- Describes the universe as a collection of interacting *quantized fields* (each corresponding to an elementary particle)
  - excitations in the *matter fields* → quarks and leptons
  - excitations in the *gauge fields* → gauge bosons
- Gauge fields mediate the interactions between matter fields

- “Quarks and leptons interact by exchanging gauge bosons”

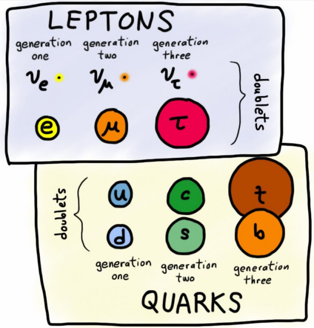




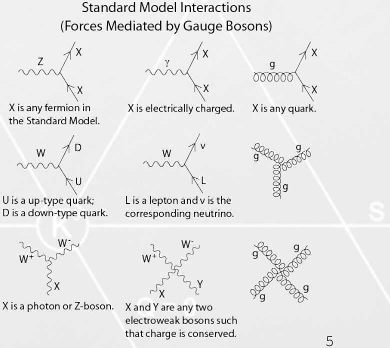


The Standard Model

- Fundamental *fermions* are spin-1/2 “matter” particles:
  - Quarks: u, d, c, s, t, b
    - Participate in EM, weak, and strong interactions
  - Leptons: $e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$
    - Only participate in EM and weak interactions



- Integer-spin *Gauge Bosons* are “force carrier” particles:
  - Photon (γ)
    - Mediates EM interactions
  - Weak vector bosons ($Z^0, W^\pm$)
    - Mediates weak interactions
  - Gluon (g)
    - Mediates strong interactions



The Brout-Englert-Higgs Mechanism

- Why is the range of EM and weak interactions different ⁈

- Consider two candles, identical upon close inspection
- However, one candle dims when observed from afar
- When the room temperature is raised enough, this difference disappears
- Perhaps a strange "fog" affects only one of the candles?

- The Higgs field behaves analogously to this "selective fog"
  - Limits the range of weak interactions [*parity violation*]
  - Implies weak bosons, and all other particles interacting with Higgs field, are massive
    - The difference between a massive and massless particle is whether or not it can travel at the speed of light!
  - EM and weak interactions are *identical* and *symmetric* at the electro-weak scale

The Brout-Englert-Higgs Mechanism

- Crowd analogy

- A regular person (massless particle) has no trouble moving across a crowded room
- A famous person (massive particle) is slowed-down by the crowd
- A juicy rumor (Higgs particle) can spread through the crowd

- Remark on macroscopic mass
  - Higgs mechanism is only responsible for the masses of *elementary* particles
    - The Higgs has *nothing* to do with gravitational mass
  - Bound states (nucleons, nuclei, atoms, molecules) get most of their mass from "binding energy"
    - e.g. $m_H > (m_p - m_e)$, $\Delta m \sim 1.13$ MeV

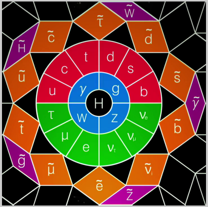
Dark Matter

- Around 85% of the matter in the universe is composed of Dark Matter
  - Only evidence for gravitational interaction
    - Galaxy rotation curves
    - Gravitational lensing
    - Cosmic microwave background
  - Does not interact electro-magnetically
- Assumptions: Streetlight effect
  - Perhaps dark matter is made up of new kind of elementary particle
    - Would be massive (gravitational interaction)
    - Would not have charge (no EM interaction)
    - May or may not interact weakly

SuperSymmetry

- Can resolve issues not addressed by Standard Model
  - Hierarchy Problem ▸ more
  - Dark Matter
  - Failure to describe gravitational interactions

- SUSY postulates a symmetry between bosons and fermions
  - Predicts a "superpartner" for each Standard Model particle
  - Can predict a stable dark matter particle candidate (LSP)
  - Avoids fine-tuning (Hierarchy Problem) via particle-sparticle quantum correction cancellations
  - Given local gauge symmetry, General Relativity can be integrated in SUSY



LHC Physics Program

- Higgs Program:
  - Is the BEH mechanism responsible for EW symmetry breaking?
  - Is the recently–discovered Higgs boson *the* SM Higgs boson?
- Beyond the Standard Model Physics Program:
  - What is the nature of Dark Matter?
  - Is broken SuperSymmetry a feature of Nature?
  - Are there observable compactified extra dimensions at LHC scales?
  - Are there additional elementary particles (e.g. additional gauge–bosons, gravitons, leptoquarks, heavy neutrinos, black holes, etc.)?
- Standard Model Physics Program:
  - Bottom–quark physics
  - Top–quark physics
  - Heavy–Ion Physics

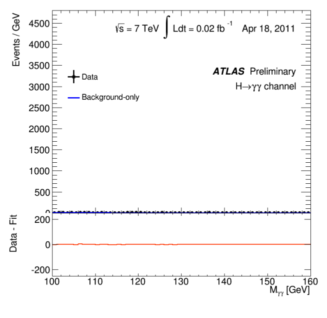
Search for New Physics

- How do we find evidence of new particles...?
  - We hunt for Bigfoot!
  - No chance of direct observation.
    - Next best thing: *footprints*
  - Not enough to find a distinctive footprint.
    - Must first predict or calculate how many known species' footprints will mimic Bigfoot's
  - Then comb the field for all footprints with the "Bigfoot signature"
  - Compare data with prediction.
    - Is there a *statistically significant* excess of footprints?
    - *Maybe* due to new species!
  - Are the excess footprints all around the same size?
    - This may tell us about Bigfoot's size and weight

Search for New Physics

Run/Event: 195099 / 137440354

- Case Study: The recent Higgs boson discovery
  - No chance of direct observation.
    - Next best thing: *decay products*
  - Not enough to find a distinctive "event".
    - Must first predict or calculate how many known SM processes will mimic Higgs decay
  - Then collect LHC data for all events with the "Higgs–decay signature"
  - Compare data with prediction.
    - Is there a *statistically significant* excess of events?
    - *Maybe* due to new particle!
  - Are the excess events all around the same energy?
    - This may tell us about the Higgs mass

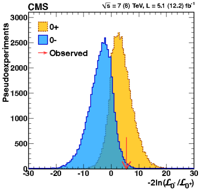


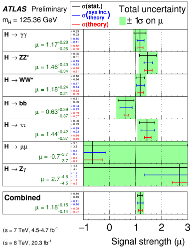
Higgs Physics Results

- In July 2012, the CMS and ATLAS collaborations announced the observation of a new boson
  - On March 2013, both stated that the spin-parity is consistent with *a* Higgs boson
- Is it *the* Standard Model predicted Higgs?
  - Precision measurements of Higgs mass
  - Precision measurements of Higgs spin-parity
    - SM predicts 0–spin, +parity
  - Fermionic Higgs decay
  - Given the Higgs boson mass, we can predict how often it will decay into each "channel"
  - Resonance features can tell us about the boson's properties
    - width of resonance $\rightarrow$ Higgs lifetime

Higgs Physics Results

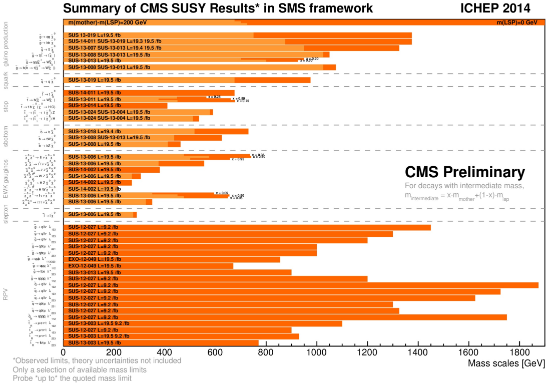
- Is it *the* Standard Model predicted Higgs? Current Status:
  - Higgs mass 125.09 ± 0.21(stat.)±0.11(syst.) GeV
    - CMS-HIG-14-042, ATLAS-HIGG-2014-14
  - Higgs spin-parity results consistent with $J^P = 0^+$
    - CMS-HIG-12-041, ATLAS-CONF-2015-008,
  - Observation of fermionic Higgs decay
    - CMS-HIG-13-003: $VH \to b\bar{b}, H \to \tau\tau$, ATLAS-CONF-2013-108: $H \to \tau\tau$, ATLAS-HIGG-2013-27: $Ht \to b\bar{b}$
  - Higgs coupling measurements consistent with SM
    - ATLAS-CONF-2015-007: $\mu = 1.30 \pm 0.26$, CMS-HIG-14-009: $\mu = 1.00 \pm 0.15$
  - Higgs width consistent with SM $\Gamma_H < 4.2\Gamma_H(SM)$
    - CMS-HIG-14-002



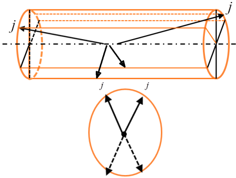


SUSY Physics Results

- No evidence for SUSY, despite decades in pursuit
  - SUSY is a concept that a given theory may or may not feature. Hence, it is very difficult to entirely rule out
  - Typically, exclusion limits are assigned to a given SUSY model, when it fails to exhibit signs of new physics

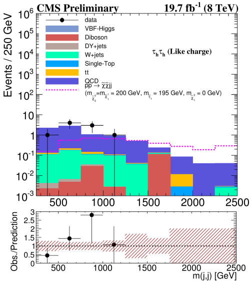


- Case Study: SUS-14-005
  - Search for supersymmetry with the VBF topology



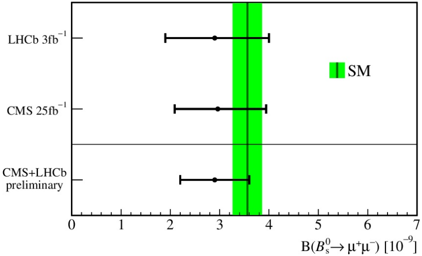
- Gluon-boson fusion is the dominant process at the LHC. The most common types of events are quark/gluon “sprays” or “jets” (hadronization)
- Vector-boson fusion (VBF) can lead to rarer EW processes and its “forward-jet” signature make it easy to distinguish

- Search Signature:
  - 2 highly-energetic forward jets, two leptons, and momentum imbalance



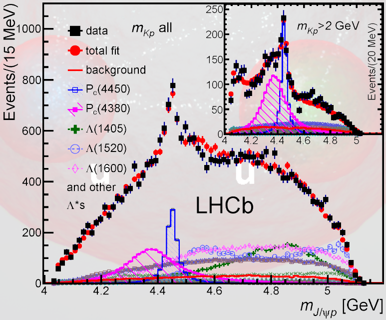
Standard Model Physics Results

- Case Study: BPH-13-007
  - Combination of results on the rare decays $B_s^0 \to \mu^+\mu^-$ from the CMS and LHCb experiments
    - Very very rare flavour-changing neutral-current decay: $B(B_s^0 \to \mu^+\mu^-) = (3.56 \pm 0.30)10^{-9}$
    - Any observation of this decay above the SM rate would be clear evidence of new physics
    - A large number of SUSY models are inconsistent with this measurement and are therefore ruled out



Standard Model Physics Results

- Case Study: LHCb-PAPER-2015-029 (Pentaquarks!)
  - Last week, the LHCb collaboration reported the first-ever observation of pentaquark particles: $P_c(4450)^+$ and $P_c(4380)^+$ $(c, \bar{c}, u, u, d)$ $[J^P = (3/2^{\pm}, 5/2^{\mp})]$
    - $\Lambda_b(b, u, d) \to J/\psi P_c^+ \to J/\psi(pK^-)$
    - $\Lambda_b(b, u, d) \to J/\psi \Lambda^*(s, u, d) \to J/\psi(pK^-)$ ($\sim 5\%$ of background contamination)
    - Signal significance: $P_c(4450)^+ \to 12\sigma$ and $P_c(4380)^+ \to 9\sigma$



Summary

- The Standard Model seems stubbornly robust
- The Higgs discovery was a great victory for the High–Energy Physics community, and an incredible achievement for humankind
- SUSY is slowly being cornered, but some hope remains that it may hide in unexplored parameter space
- With the restart of the LHC at its design center–of–mass energy, the community is anxious with anticipation of new physics
- Meanwhile, physics analyses are chugging along and continue to publish new results by analysing the volumes of LHC data already recorded

References and Resources

- CMS Experiment
  - CMS detector overview
  - CMS Experiment Public Physics Results
  - CMS interactive online event display
  - CMS International Masterclasses
- ATLAS Experiment
  - ATLAS multimedia
  - ATLAS Experiment Public Physics Results
- US–LHC
  - CERN F.A.Q. – LHC: The Guide [pdf]
  - LHC Milestones
- CERN
  - Resources for Students & Educators
  - Bubble Chamber interactive guide
  - CERN Open Data

References and Resources

- Videos, Talks, Documentaries:
  - Particle Fever – [netflix] – [youtube]
  - Nova – Big Bang Machine – [youtube]
  - M.Peskin on LHC Physics – [youtube]
  - S.Carroll on the Higgs Mechanism – [youtube]
  - HEP/Cosmology videos by D.Lincoln (FNAL) – [youtube]
  - Animated ATLAS detector overview – [youtube]
  - Animation of LHC accelerator complex – [youtube]
  - Animation of LHC computing data flow – [youtube]
  - PhD Comics on the Higgs – [vimeo]
  - PhD Comics on Dark Matter – [vimeo]
- Blogs:
  - M.Strassler [Rutgers]
  - S.Carroll [Caltech]
  - J.Butterworth [University College London]
  - Quantum Diaries [Multiple Bloggers]
- Games:
  - Collider
  - Particle Clicker

Questions/Comments

SUSY Physics Results

- Case Study: SUS-13-013
  - Search for new physics in events with same-sign dileptons and jets
  - $pp \rightarrow SUSY \rightarrow (ee, e\mu, \mu\mu) + jets + E_T^{miss}$
    - expect significant hadronic activity in addition to two leptons and E_T^{miss} from stable LSP
  - $pp \rightarrow SUSY \rightarrow (ee, e\mu, \mu\mu) + jets$
    - expect significant hadronic activity in addition to two leptons and sensitive R-parity violating models
  - Backgrounds:"Non-Prompt leptons", charge misidentification, $t\bar{t}W$, $t\bar{t}Z$, and diboson

Region	Low-p_T		High-p_T	
	Expected	Observed	Expected	Observed
SR01	44 ± 16	50	51 ± 18	48
SR02	12 ± 4	17	9.0 ± 3.5	11
SR03	12 ± 5	13	8.0 ± 3.1	5
SR04	9.1 ± 3.4	4	5.6 ± 2.1	2
SR05	21 ± 8	22	20 ± 7	12
SR06	13 ± 5	18	9 ± 4	11
SR07	3.5 ± 1.4	2	2.4 ± 1.0	1
SR08	5.8 ± 2.1	4	3.6 ± 1.5	3

SR	Expected	Observed
RPV0	38 ± 14	35
RPV2	5.3 ± 2.1	5
SStop1	160 ± 59	152
SStop1++	90 ± 32	92
SStop2	40 ± 13	52
SStop2++	22 ± 8	25

The Hierarchy Problem: electron self-energy

Electrostatics

- Energy of a uniformly-charged spherical shell
  - $E = \frac{1}{2}\frac{1}{4\pi\epsilon_0}\frac{q^2}{R}$
    - See Griffiths E&M, Section 2.4.3, Example 2.8
- Electron "self-energy":
  - $(m_e c^2)_{\text{observed}} = (m_e c^2)_{\text{bare}} + \frac{1}{2}\frac{1}{4\pi\epsilon_0}\frac{q^2}{R}$
  - $511 \text{ keV} = (m_e c^2)_{\text{bare}} + 7.18 \cdot 10^6 \text{ keV}$
    - where $R \sim R_e^{\text{experimental}} < 10^{-19} m$
    - $(m_e c^2)_{\text{bare}}$ needs "fine-tuning" to cancel electron's self-energy

Quantum Mechanics: positron

- $\Delta t \Delta E \sim \hbar$
  - Virtual electron-positron pairs "smear out" electron charge
  - These effects become important at length scales:
    - $r = c\Delta t \sim \hbar c/\Delta E \sim \hbar c/2mc^2 \sim 2 \cdot 10^{-13} m$
  - $(m_e c^2)_{\text{observed}} = (m_e c^2)_{\text{bare}}[1 + \frac{3\alpha}{4\pi} log \frac{\hbar}{m_e c r_e}]$
    - See arXiv:hep-ph/0002232

back