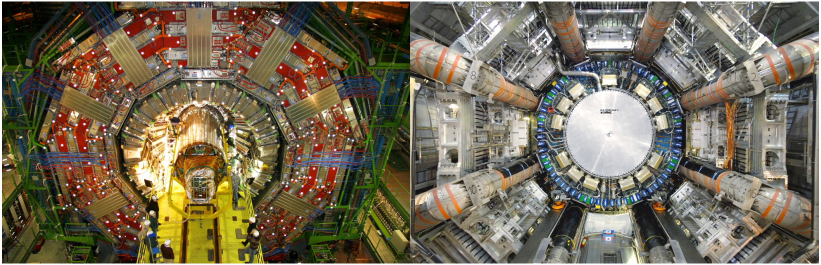

LHC PHYSICS

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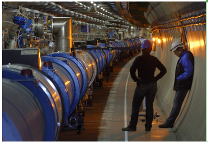
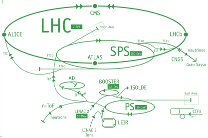
THE LARGE HADRON COLLIDER

- Largest and most powerful particle accelerator
- 26.6 km (16.5 mi) circumference tunnel, from 50-175 m (165-575 ft) underground
- 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
- 1232 dipoles operating at 1.9 K (-456 °F) generating $\sim$ 8 T
- Beam tube under ultrahigh vacuum (10^{-13} atm)

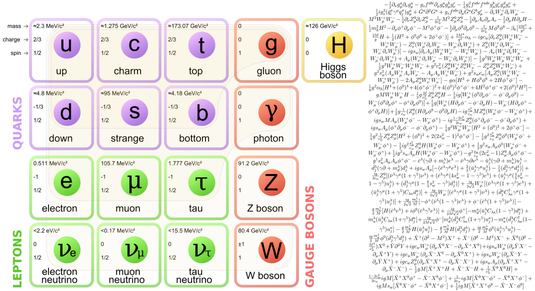


Quantity	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy, protons	7 TeV
Nominal energy, ions	2.76 TeV/u (*)
Peak magnetic dipole field	8.33 T
Min. 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 x 10^{11}
Number of turns per second	11 245
Number of collisions per second	600 million



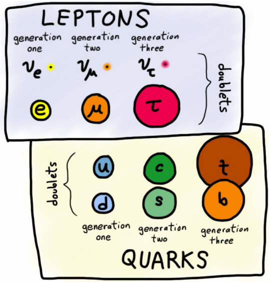
THE STANDARD MODEL

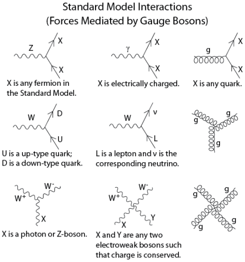
- Describes the universe as a collection of interacting *quantized fields* (each corresponding to an elementary particle)
  - excitations in the *matter fields* → quarks and leptons
  - excitations in the *gauge fields* → gauge bosons
- Gauge bosons mediate the interactions between matter fields (i.e.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



Interacting Quarks and Leptons

- Fundamental *fermions* are spin-1/2 "matter" particles:
  - Quarks: *udcstb*
    - 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, $W^\pm$) mediate weak interactions
  - Gluon (g) mediates strong interactions





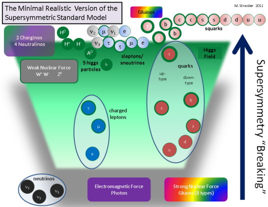
THE BROUT-ENGLERT-HIGGS MECHANISM

- 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, the 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
  - Implies weak bosons, and all other particles interacting with Higgs field, are massive
  - EM and weak interactions are *identical* at electro-weak scale

SuperSymmetry

- Unresolved issues not addressed by Standard Model
  - Observation of dark matter
  - Failure to describe gravitational interactions
- SUSY postulates a symmetry between bosons and fermions
  - Predicts a "superpartner" for each Standard Model particle
  - Predicts a stable dark matter particle candidate
  - Avoid fine-tuning (solves Hierarchy Problem) via particle-sparticle quantum correction cancellations
  - Given local gauge symmetry, General Relativity can be automatically integrated in SUSY



LHC Physics Program

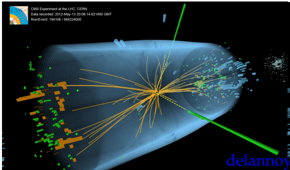
- Higgs Program:
  - Is the BEH mechanism responsible for EW symmetry breaking?
  - Is the recently–discovered Higgs–like bosons *the* SM Higgs boson?
- Beyond the Standard Model Physics Program:
  - What is the nature of Dark Matter?
  - Is broken SuperSymmetry a feature of Nature?
  - Are there observable 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

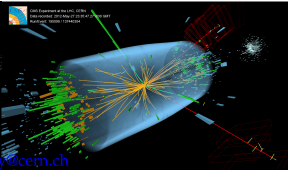
SEARCH FOR NEW PHYSICS

- 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 peculiar 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

- Case Study: The recent Higgs boson discovery
  - No chance of direct observation. Next best thing: decay products
  - Not enough to find a peculiar "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)?
  - Animations: Hgg, H4L, HWW.



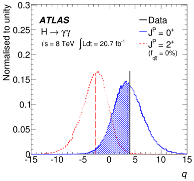


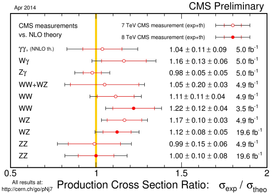
HIGGS PHYSICS RESULTS

- 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

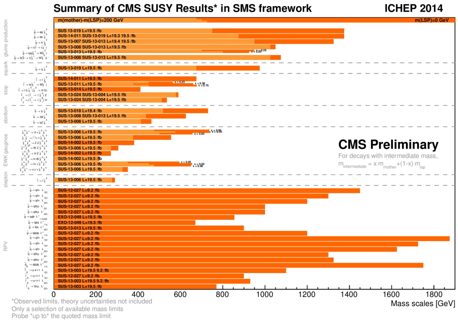
- Is it *the* Standard Model predicted Higgs? Current Status:
  - Higgs mass 125 ± 0.5 GeV (HIG-14-009,CONF-2013-12)
  - Higgs spin-parity results consistent with $J^P = 0^+$ (HIG-12-041,CONF-2013-040)
  - Observation of fermionic Higgs decay (HIG-13-003: $VH \to b\bar{b}, H \to \tau\tau$, CONF-2013-108: $H \to \tau\tau$)
  - Higgs coupling measurements consistent with SM (CONF-2014-009: $\mu = 1.30 \pm 0.26$, HIG-14-009: $\mu = 1.00 \pm 0.15$)
  - Higgs width consistent with SM $\Gamma_H < 4.2\Gamma_H(SM)$ (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



SUSY Physics Results

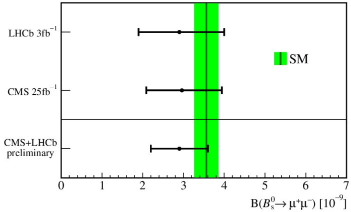
- Case Study: SUS-13-013
  - Search for new physics in events with same-sign dileptons and jets
  - $pp \rightarrow SUSY \rightarrow (ee, e\mu, \mu\mu) + jets + E_T^{miss}$
    - expect significant hadronic activity in addition to two leptons and E_T^{miss} from stable LSP
  - $pp \rightarrow SUSY \rightarrow (ee, e\mu, \mu\mu) + jets$
    - 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

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



SUMMARY

- The Standard Model seems quite 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

COMMENTS