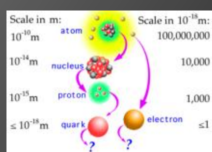
THE SEARCH FOR THE TRULY ELEMENTARY PARTICLE



Britney Rutherford
EIU Physics Department

The First EIU Technology & Science Symposium
Revolutions in Science and Technology Paradigms

Elementary Particle: Contains no measurable internal structure

- The Greek philosopher Democritus (460?-370? BC) named the smallest unit atomus, meaning "not able to be cut."
- 18th Century: Lavoisier- All substances made up of chemical elements.

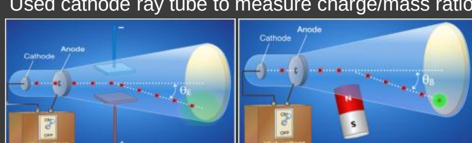
By the end of the 19th Century:

- Newton's Laws to describe motion
- Maxwell's Equations uniting electricity and magnetism
- Mendeleyev's Periodic Table of the Elements
- Becquerel- radioactivity
- Roentgen- x-rays

1897: J.J. Thompson's Electron

Thompson finds the 1st subatomic particle

- Used cathode ray tube to measure charge/mass ratio.

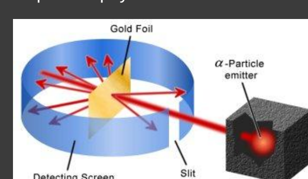


- Finds evidence of negatively charged object with very small mass. e/m= -1.76 X 108 coulombs/gram
- "Plum Pudding Model"

1911-Rutherford's Nucleus

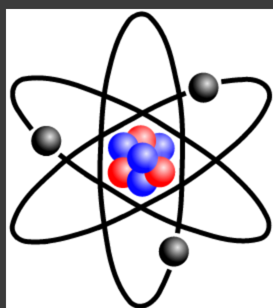
Ernest Rutherford discovers atomic nucleus

- Used "scattering" experiment – Now considered a classic technique of particle physics



- RESULT: Atoms consist of heavily charged nuclei surrounded by negative, light electrons. Lightest nucleus (hydrogen) called "proton."

1914-Bohr Atom

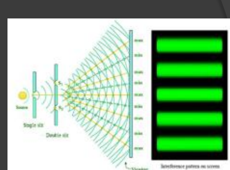


1932- Third Elementary Particle

- Dilemma:
  - Helium (2 electrons) is 4x heavier than Hydrogen.
  - Lithium (3 electrons) is 7x heavier than Hydrogen.
  - …..must be something else in there…
- J. Chadwick discovers Neutron while bombarding Beryllium with alpha particles
- Werner Heisenberg declares Neutron and Proton 2 manifestations of the same state, the Nucleon

Light: Wave or Particle?

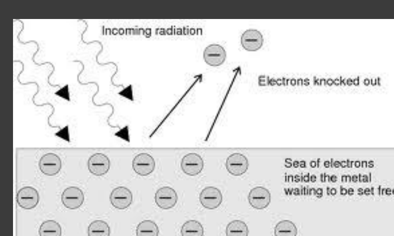
1801: Young's Double-Slit Experiment: Light interferes constructively and destructively like a wave.



19th Century Maxwell:
Energy of light is proportional to intensity. Light is a WAVE and energy should be a continuous spectrum.

1887: Hertz Photoelectric Effect

- Classically:

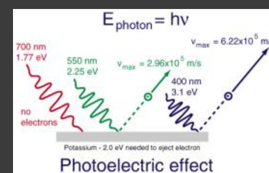


Paradigm Shift: Quantum Mechanics

- (1905) Einstein's Special Relativity
  - Space and Time can change in different reference frames
  - Describes behavior of particles moving at high velocities
  - $E=mc^2$
  - Mass and Energy are two forms of the SAME THING!
- (1926) Erwin Schrodinger: At the atomic scale, Newton's Laws of Classical Mechanics give way to mathematical functions that describe particle behavior in terms of probabilities
- (1925) Werner Heisenberg: Uncertainty Principle- cannot precisely know both momentum and position of subatomic particle.

Photon: 1st Force-Carrying Particle

- 1900-Max Planck: Proposed that EM radiation comes quantized



- 1905- Einstein's Photoelectric Effect

Process depends on frequency of light only, not on intensity

$$E_{electron} = h\nu - W_{out}$$

1924: Compton Effect

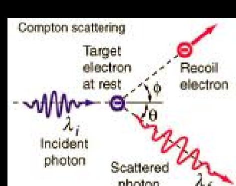
- Light scattered off a particle with mass m at rest changes wavelength:

$$\lambda_f = \lambda_i + \frac{h}{mc}(1-\cos\theta)$$

- Exactly behavior of massless Relativistic particle of momentum

$$p_{photon} = h\lambda$$

- Quanta of E-M radiation are PHOTONS! (γ)
- E-M interactions mediated by Exchange of photons: Photon=Force-carrying particle



But wait…there's more!

- In 1932, matter is made of protons, electrons, and neutrons (and there are photons).
- (1930-1960) 3 great ideas complicate this model:
  - Yukawa's meson
  - Dirac's positron
  - Pauli's neutrino

Mesons (1934-1947)

•"classical" model does not address the problem: What holds the nucleus together?
•Must be a strong force with range about the size of nucleus itself.

Yukawa 1934: Theory for the mediator (quantum) of this force.

Estimated mass:

- 300 times $m_{electron}$
- 1/6 m_{proton}

Yukawa's particle became known as "meson" (middle-weight).
Electron is "lepton" (light-weight)
Proton and neutron "baryons" (heavy-weight)

BREAK FOR WWII

1947: Cosmic Ray experiments produce 2 middle-weight candidates for the Yukawa Meson

- **Pion π**- True Yukawa particle that interacts with nuclei. Copiously produced in upper atmosphere but ordinarily disintegrates long before reaching the ground.
- **Muon μ**- Lighter and longer-lived imposter having nothing to do with strong interactions. Behaves like heavier version of electron and belongs in lepton family.

Rabi- "Who ordered that?"

Photographic emulsion exposed to cosmic rays at high altitude

Antiparticles (1930-1956)

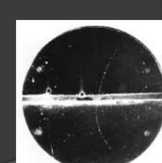
- **1927 Dirac Equation**: Relativistic energy of free electron

$$E^2 - p^2c^2 = m^2c^4 \qquad E = \pm\sqrt{p^2c^2 + m^2c^4}$$

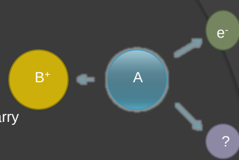
- **1932 Anderson Cloud Chamber Track:** Positively charged particle with mass of electron
- POSITRON! (antielectron)

e^+/ ē

- If matter and anti-matter annihilate upon contact…then why is there *so much more* matter than antimatter?



(1930-1962) Neutrinos



1930 Beta Decay Problem

A -> B^+ + e^-

Conservation of charge requires that B carry one more unit of positive charge than A

ENERGY NOT CONSERVED! In order for energy conservation equations to balance, need a massless, neutral-charge particle that passes through detectors!

Pauli's Neutrino $n^0 + \rightarrow p^+ + e^- + \bar{\nu}_e$

1950's: Cowan and Reines detect inverse beta-decay reaction in large water tank, verifying the neutrino's existence.

Lepton Number also conserved:
L= +1 for electron, muon, and neutrino
L= -1 for positron, positive muon, and antineutrino

Particle Zoo

Table 46.2

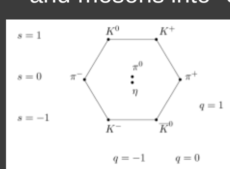
Some Particles and Their Properties

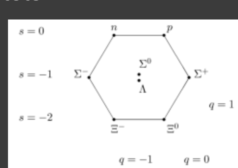
Category	Particle Name	Symbol	Anti-particle	Mass (MeV/c^2)	B	L_e	L_μ	L_τ	S	Lifetime(s)	Principal Decay Modes*
Leptons	Electron	e^-	e^+	0.511	0	+1	0	0	0	Stable	
	Electron-neutrino	ν_e	$\bar{\nu}_e$	$< 7\ eV/c^2$	0	+1	0	0	0	Stable	
	Muon	μ^-	μ^+	105.7	0	0	+1	0	0	2.20×10^{-6}	$e^-\bar{\nu}_e\nu_\mu$
	Muon-neutrino	ν_μ	$\bar{\nu}_\mu$	< 0.3	0	0	+1	0	0	Stable	
	Tau	τ^-	τ^+	1 784	0	0	0	+1	0	$< 4 \times 10^{-13}$	$\mu^-\bar{\nu}_\mu\nu_\tau$, $e^-\bar{\nu}_e\nu_\tau$
	Tau-neutrino	ν_τ	$\bar{\nu}_\tau$	< 30	0	0	0	+1	0	Stable	
Hadrons Mesons	Pion	π^+	π^-	139.6	0	0	0	0	0	2.60×10^{-8}	$\mu^+\nu_\mu$
		π^0	Self	135.0	0	0	0	0	0	0.83×10^{-16}	2γ
	Kaon	K^+	K^-	493.7	0	0	0	0	+1	1.24×10^{-8}	$\mu^+\nu_\mu$, $\pi^+\pi^0$
		K^0_S	$\bar{K}^0_S$	497.7	0	0	0	0	+1	0.89×10^{-10}	$\pi^+\pi^-$, $2\pi^0$
		K^0_L	$\bar{K}^0_L$	497.7	0	0	0	0	+1	5.2×10^{-8}	$\pi^\pm e^\mp\bar{\nu}_e$, $3\pi^0$ $\pi^\pm\mu^\mp\bar{\nu}_\mu$
	Eta	η	Self	548.8	0	0	0	0	0	$< 10^{-18}$	2γ, $3\pi^0$
		η'	Self	958	0	0	0	0	0	2.2×10^{-21}	$\eta\pi^+\pi^-$
Baryons	Proton	p	$\bar{p}$	938.3	+1	0	0	0	0	Stable	
	Neutron	n	$\bar{n}$	939.6	+1	0	0	0	0	614	$pe^-\bar{\nu}_e$
	Lambda	Λ^0	$\bar{\Lambda}^0$	1 115.6	+1	0	0	0	−1	2.6×10^{-10}	$p\pi^-$, $n\pi^0$
	Sigma	Σ^+	$\bar{\Sigma}^-$	1 189.4	+1	0	0	0	−1	0.80×10^{-10}	$p\pi^0$, $n\pi^+$
		Σ^0	$\bar{\Sigma}^0$	1 192.5	+1	0	0	0	−1	6×10^{-20}	$\Lambda^0\gamma$
		Σ^-	$\bar{\Sigma}^+$	1 197.3	+1	0	0	0	−1	1.5×10^{-10}	$n\pi^-$
	Delta	Δ^{++}	$\bar{\Delta}^{--}$	1 230	+1	0	0	0	0	6×10^{-24}	$p\pi^+$
		Δ^+	$\bar{\Delta}^-$	1 231	+1	0	0	0	0	6×10^{-24}	$p\pi^0$, $n\pi^+$
		Δ^0	$\bar{\Delta}^0$	1 232	+1	0	0	0	0	6×10^{-24}	$n\pi^0$, $p\pi^-$
		Δ^-	$\bar{\Delta}^+$	1 234	+1	0	0	0	0	6×10^{-24}	$n\pi^-$
	Xi	Ξ^0	$\bar{\Xi}^0$	1 315	+1	0	0	0	−2	2.9×10^{-10}	$\Lambda^0\pi^0$
		Ξ^-	Ξ^+	1 321	+1	0	0	0	−2	1.64×10^{-10}	$\Lambda^0\pi^-$
	Omega	Ω^-	Ω^+	1 672	+1	0	0	0	−3	0.82×10^{-10}	$\Xi^-\pi^0$, $\Xi^0\pi^-$, Λ^0K^-

* Notations in this column such as $p\pi^-$, $n\pi^0$ mean two possible decay modes. In this case, the two possible decays are $\Lambda^0 \rightarrow p + \pi^-$ and $\Lambda^0 \rightarrow n + \pi^0$.

Eightfold Way (1961-1964)

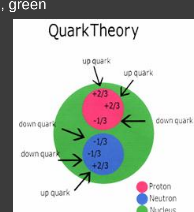
- Theory organizing subatomic baryons and mesons into "octets."

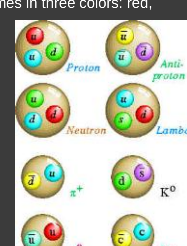




Quark Model (1964)

- Gell-Mann and Zweig independently proposed that all hadrons are composed of even more elementary constituents, "quarks."
- Quarks come in 3 types: up, down, strange
- (1964) O.W. Greenberg- each flavor comes in three colors: red, blue, green

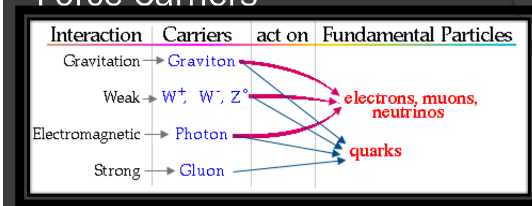




1974-1983

- Nov 1974: C.C. Ting at Brookhaven observes J (charm, anti-charm) meson.
- Nov 1974: Burton Richter at SLAC observes same particle, calls it Ψ.
- Both teams publish simultaneously- known now as the J/Ψ
- 1975- "Upsilon" Υ (bottom, anti-bottom)
- 1983- Intermediate Vector Bosons (W±, Z)

Force Carriers



- Those who joined the quest for a single unified master force declared that the first step toward unification had been achieved with the discovery of the discovery of the W and Z particles, the intermediate vector bosons, in 1983

Hadrons: held together by strong force

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
There are about 120 types of baryons.

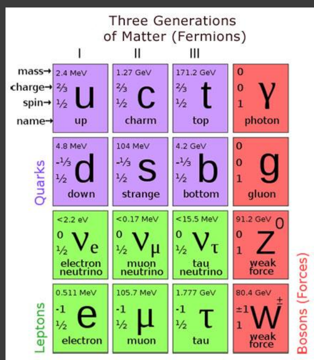
Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$
Mesons are bosonic hadrons.
There are about 140 types of mesons.

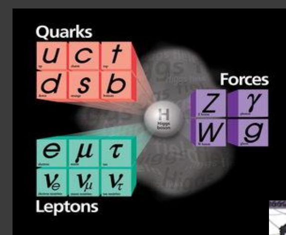
Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20



The Standard Model



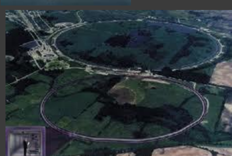
Standard Model Lagrangian

Why Search for the Higgs Boson?

- Higgs Mechanism: Non-zero field which generates mass and permeates the universe.
  - ✓ W/Z bosons gain mass through d.o.f. of Higgs field
  - ✓ Fermions gain mass by interacting with Higgs field
  - ✓ Higgs Boson predicted!
- Electro-Weak Symmetry Breaking
  - ✓ W/Z weak bosons massive, photon massless
  - ✓ EM and weak forces unify at high energies, but EWSB occurs at low energies.
- Finding the Higgs boson means the Higgs field exists and our theory for the origin of mass is confirmed!

How To Produce Subatomic Particles

Tevatron at Fermilab



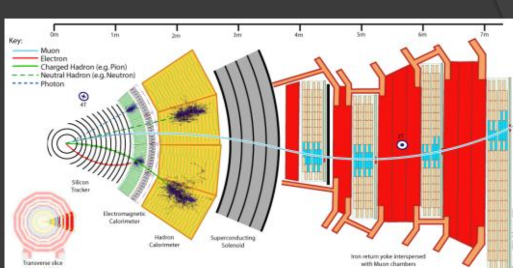
Large Hadron Collider at CERN

Particle Detectors

CDF (Collider Detector at Fermilab), Tevatron

CMS (Compact Muon Solenoid), LHC

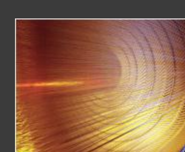
How to Detect Subatomic Particles



CDF Detector Elements

1. Silicon Detector

2. Central Outer Tracker

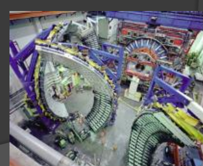


3. Magnet

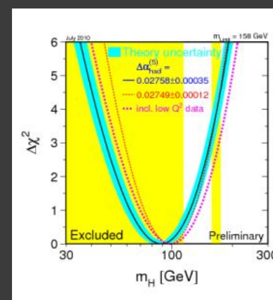
CDF Detector Elements

4. Calorimeters

5. Muon Detectors

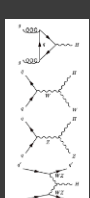


Constraints on Higgs Mass



- •Direct search at LEP:
  M > 114GeV at 95% CL,
- •Including indirect electroweak constraints
  M <185Gev at 95% CL

SM Higgs Production Mechanisms at the Tevatron

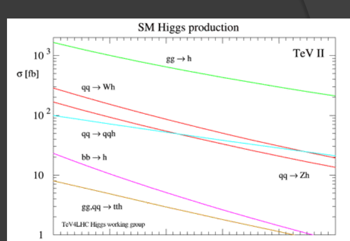


gg->H (78%)

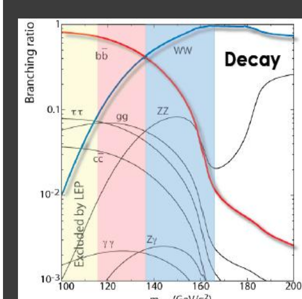
WH (9%)

ZH (6%)

VBF (7%)



Higgs Decay Modes at the Tevatron

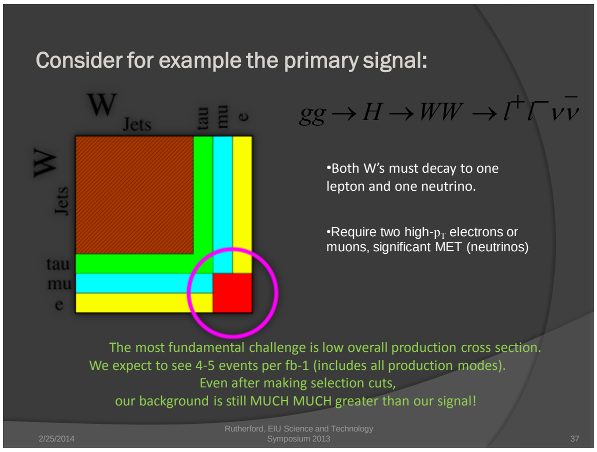


Low-Mass Higgs (<135 GeV)

- Primary Decay to bb
- The “b-tag” distinguishes b-quark jets from light (u,d,s,g) jets and separates W+bb/Z+bb from W+light favor/Z+ light flavor jets

High-Mass Higgs (>135 GeV)

- H to WW most important channel


Consider for example the primary signal:
W
Jets
tau
mu
e
W
Jets
tau
mu
e
$gg \rightarrow H \rightarrow WW \rightarrow l^+ l^- \nu \bar{\nu}$
•Both W's must decay to one lepton and one neutrino.
•Require two high-p_T electrons or muons, significant MET (neutrinos)
The most fundamental challenge is low overall production cross section.
We expect to see 4-5 events per fb-1 (includes all production modes).
Even after making selection cuts,
our background is still MUCH MUCH greater than our signal!
2/25/2014
Rutherford, EIU Science and Technology Symposium 2013
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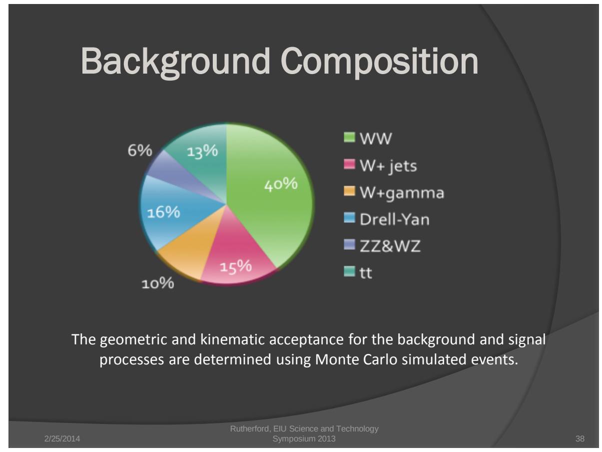
Background Composition
40%
15%
10%
16%
6%
13%
WW
W+ jets
W+gamma
Drell-Yan
ZZ&WZ
tt
The geometric and kinematic acceptance for the background and signal processes are determined using Monte Carlo simulated events.
2/25/2014
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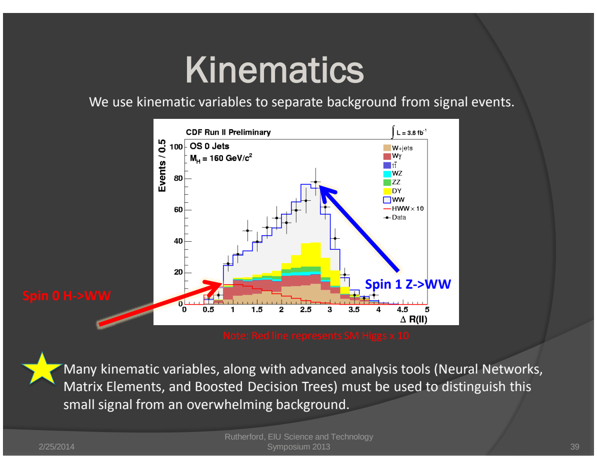
Kinematics
We use kinematic variables to separate background from signal events.
CDF Run II Preliminary
OS 0 Jets
Events / 0.5
Δ R(ll)
Spin 0 H->WW
Spin 1 Z->WW
Note: Red line represents SM Higgs x 10
Many kinematic variables, along with advanced analysis tools (Neural Networks, Matrix Elements, and Boosted Decision Trees) must be used to distinguish this small signal from an overwhelming background.
2/25/2014
Rutherford, EIU Science and Technology Symposium 2013
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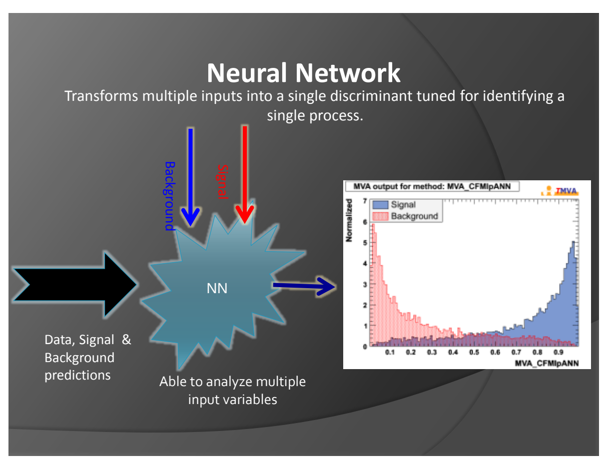
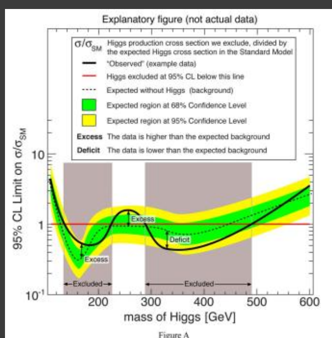
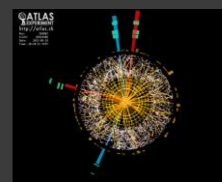

Neural Network
Transforms multiple inputs into a single discriminant tuned for identifying a single process.
Background
Signal
NN
Data, Signal & Background predictions
Able to analyze multiple input variables
MVA output for method: MVA_CFMlpANN
Signal
Background
Normalized
MVA_CFMlpANN

Interpreting the Results

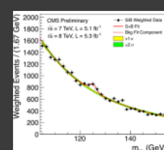


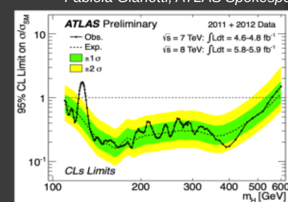
The "Money Plot"



July 4, 2012

"We observe in our data clear signs of a new particle, at the level of 5 sigma, in the mass region around 126 GeV. "
-Fabiola Gianotti, ATLAS Spokesperson





Nobel Prize in Physics 2013

- "For the theortical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider."

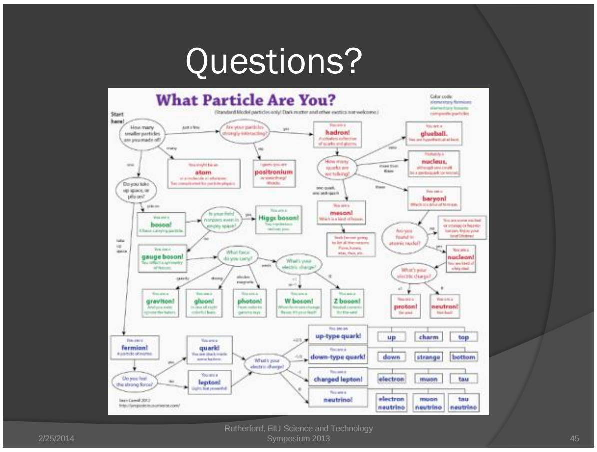
Beyond Standard Model Higgs Searches

Supersymmetric Higgs
- **Doubles the number of quarks and leptons, and predicts that there are five Higgs bosons instead of one.**
- $\Phi = (H^0, A^0, h^0)$, and $H^\pm$
  - Tevatron has comprehensive MSSM Higgs program
    - $\Phi \rightarrow \tau\tau$
    - Φ+b → bb+b
    - Φ+b → ττ+b

Fermio-phobic Higgs
Only interacts with fermions, not with bosons
- **Technicolor**

Holds that there is no Higgs boson, but instead there are new interactions that generate the masses. These technicolor models predict new particles which can be observed in similar ways to how we observe the Higgs boson, and CDF and D0 searched for these particles as well

Low mass SM Higgs searches may be first indication of MSSM
Though we wouldn't know it from SM until LHC finds the others!


Questions?
What Particle Are You?
2/25/2014
Rutherford, EIU Science and Technology Symposium 2013
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