Introduction to Particle Physics and The Standard Model

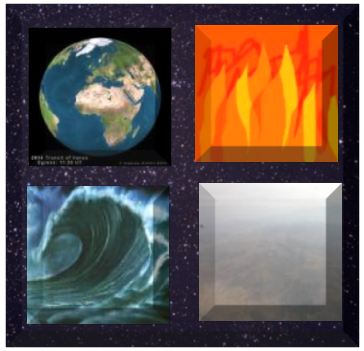
4th School on Cosmic Rays and Astrophysics

Program

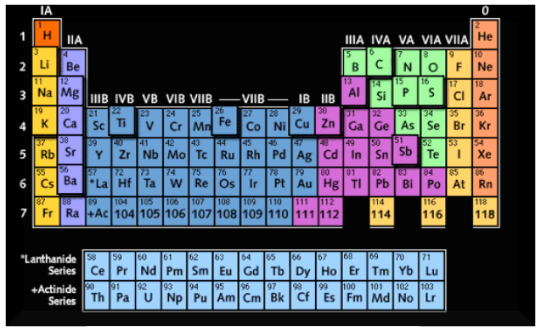
- A general view of particles and interactions.
- Experimental basis of Particle Physics
- General aspects of the Standard Model of particle and fields
- Future developments and challenges

What is the world made of?

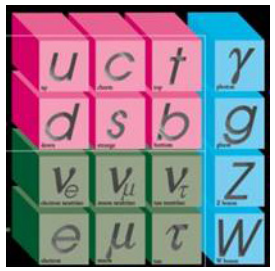
- Four Elements Model (5th Century BC)
  - Simple and economical
  - Last for more than 2,000 years
  - Did not survive scientific method



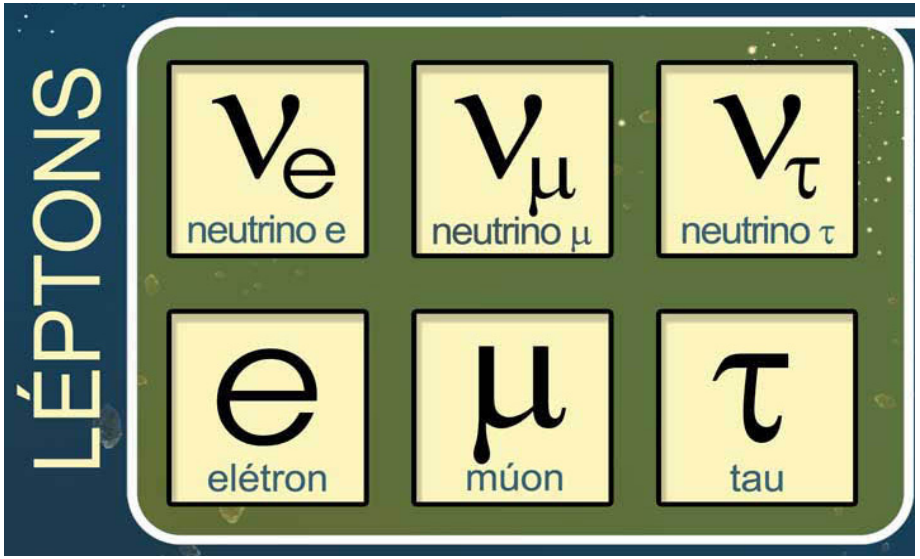
- Chemical Elements (19th Century)
  - Correct
  - Too complex to be elementary



- Quantized Fields (20th Century)
  - Economical
  - Bosons and Fermions (Leptons and Quarks)
  - Correct (up to now)



Fermions: Leptons



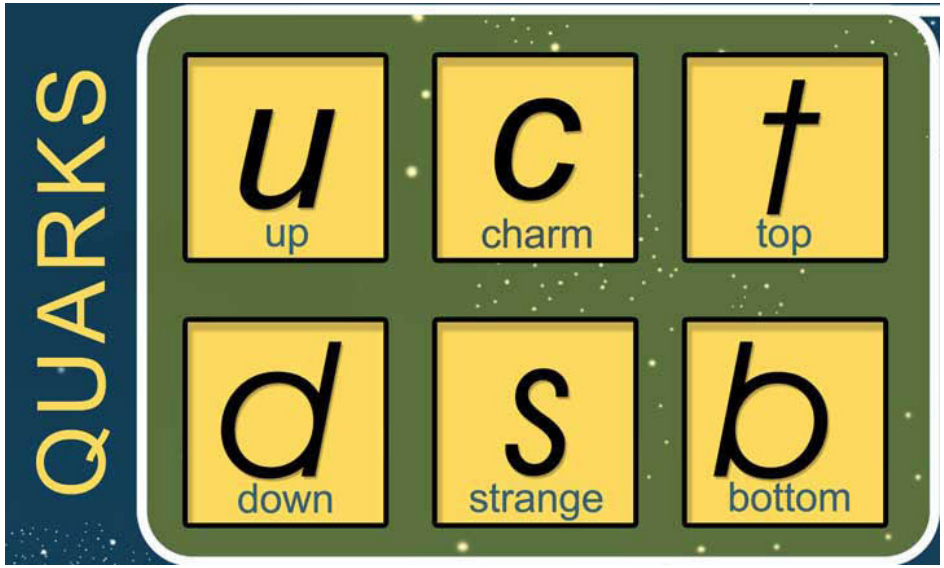
- Neutral Leptons $(Q = 0)$
  - Isospin $I_3 = +1/2$
  - Hypercharge $Y_W = -1$
- Charged Leptons $(Q = -1)$
  - Isospin $I_3 = -1/2$
  - Hypercharge $Y_W = -1$

- Three fermion generations with same Weak Hypercharge and Isospin quantum numbers.

$$Q = I_3 + 1/2\, Y_W$$

- Three fermion generations with two states each.
- Same dynamics for all three generations.

Fermions: Quarks



- Charged Quark $(Q = 2/3)$
  - Isospin $I_3 = +1/2$
  - Hypercharge $Y_W = 1/3$
- Charged Quark $(Q = -1/3)$
  - Isospin $I_3 = -1/2$
  - Hypercharge $Y_W = 1/3$

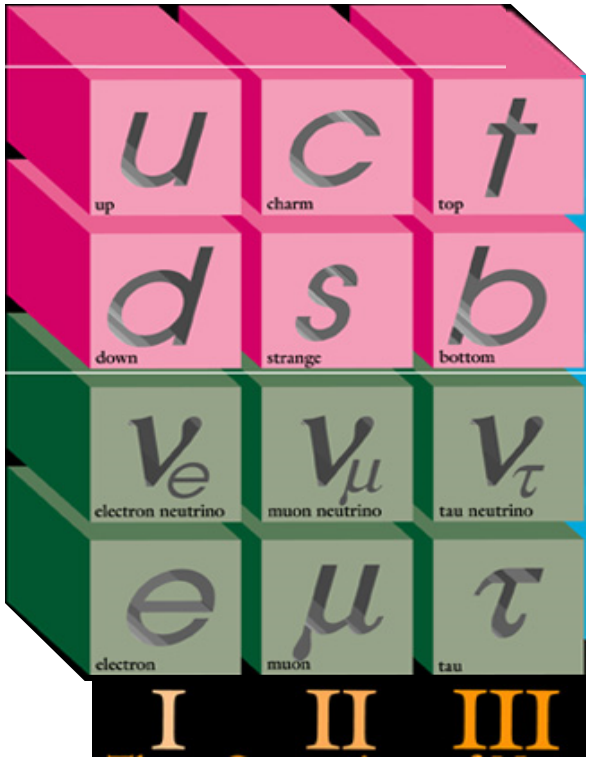
- Three fermion generations with same Hypercharge and Isospin quantum numbers.

$$Q = I_3 + 1/2\, Y_W$$

- Three fermion generations with two states each.
- Same dynamics for all three generations.

Fermion Families

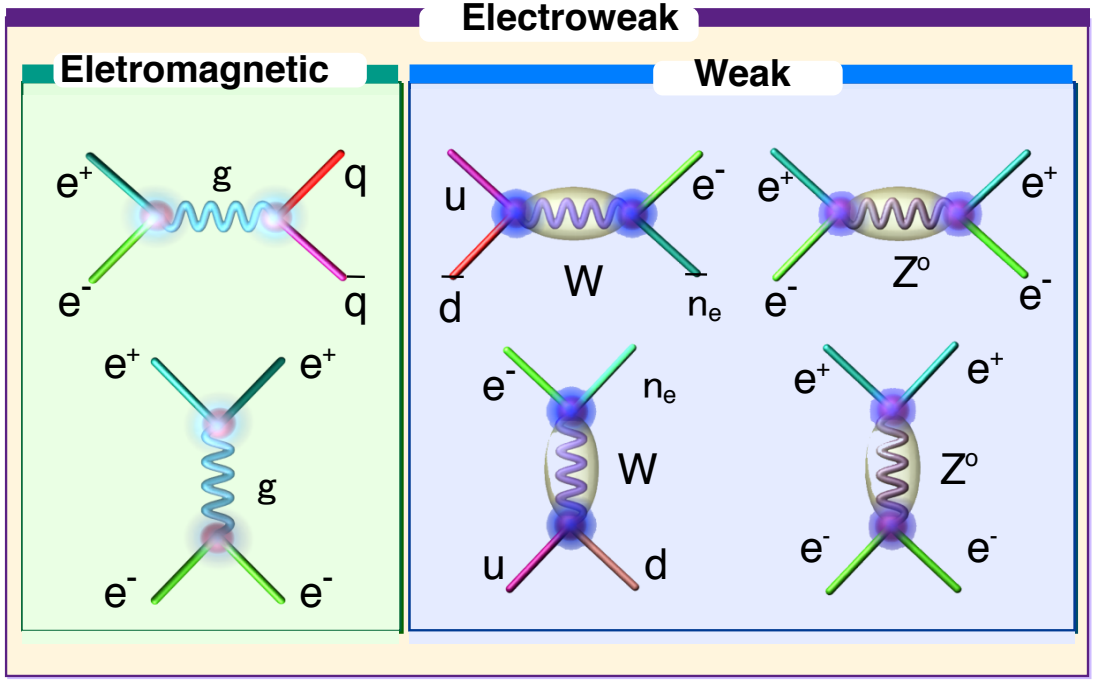
- Quarks
  - 1 Hypercharge (+1/3)
  - 2 Isospin Charges (+1/2, -1/2)
  - 3 Color Charges (R, B, G)
- Leptons
  - 1 Hypercharge (-1)
  - 2 Isospin Charges (+1/2, -1/2)
  - No Color Charge.

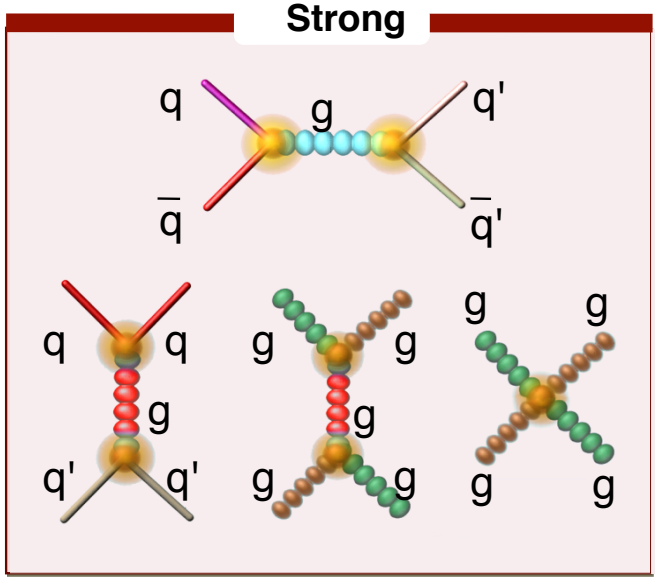


- Anti-Fermions:
  - Exact symmetry:
    - Same masses with opposite quantum numbers.
- **Total number of elementary fermions: 48 !**

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





Intermediate Vector Bosons

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

- Electromagnetic Interaction
  - Mediated by 1 vector boson.
  - Couples electrical charged particles.
  - Has no electrical charge.
    - Do not couple to itself.
    - Decreases with distance
- Weak Interaction
  - Mediated by 3 vector bosons.
  - Couples Isospin charged particles.
  - Has Isospin charge.
    - Couples to themselves.
    - Increases with distance.
- Strong Interaction
  - Mediated by 8 vector bosons.
  - Couples Color charged particles.
  - Has Color charge.
    - Couples to themselves.
    - Increases with distance
- Gravitational Interaction
  - Is there a gravitational vector boson?
  - Couples everything that has some energy.
  - Is there a gravitational charge?
    - Does the graviton couples to itself?
    - Decreases with distance
  - What is Gravity in this context?

Composite Fermions: Barions

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/c^2	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

- Formed by three quarks (three anti-quarks)
- No strong color charge
- Integer electric charge

Composite Bosons: Mesons ($q\bar{q}$)

Mesons $q\bar{q}$ Mesons are bosonic hadrons. There are about 140 types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	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

- Formed by a quark and an anti-quark.
- No strong color charge.
- May have isospin charge.
- Integer electric charge.
- Nuclear interaction carrier (residual strong interaction).

Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

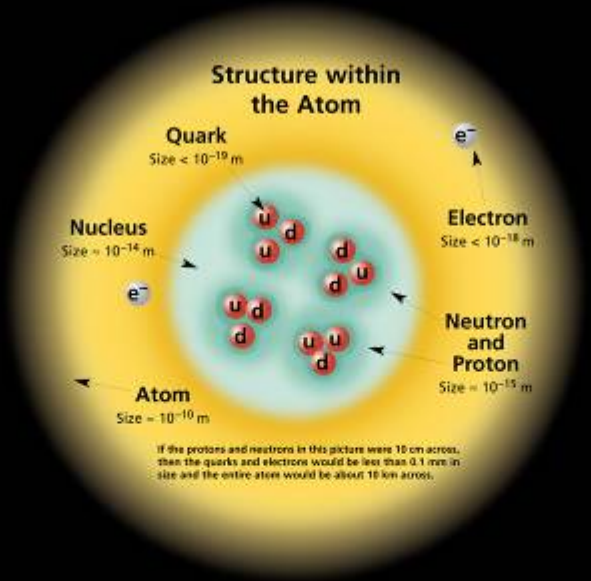
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where ħ = $h/2\pi$ = 6.58×10^{-25} GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
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Strong (color) spin = 1

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Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and **W** and **Z** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons
One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

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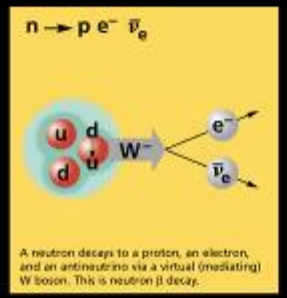
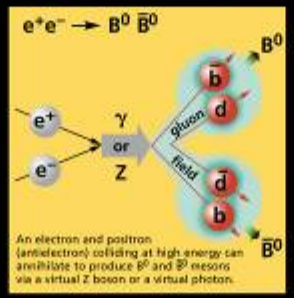
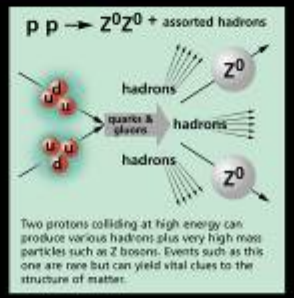
Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or − charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.







The Particle Adventure
Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

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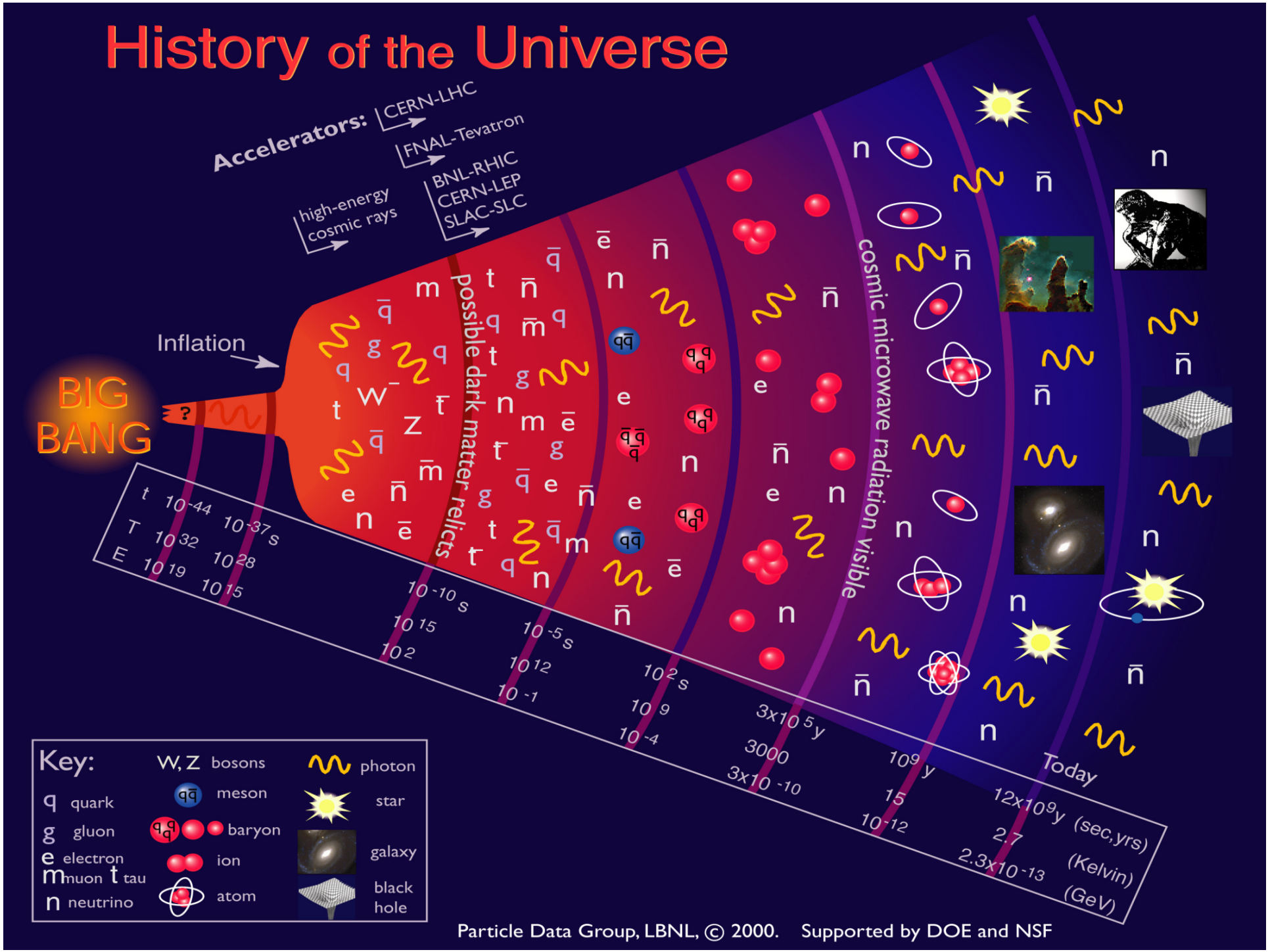
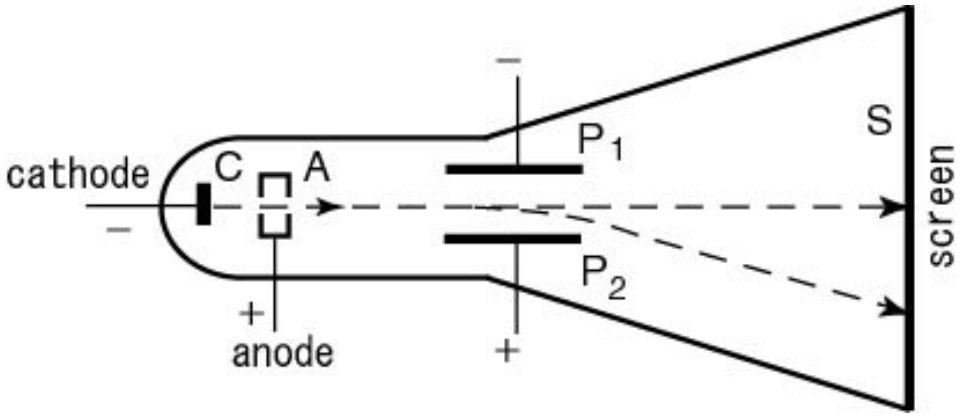
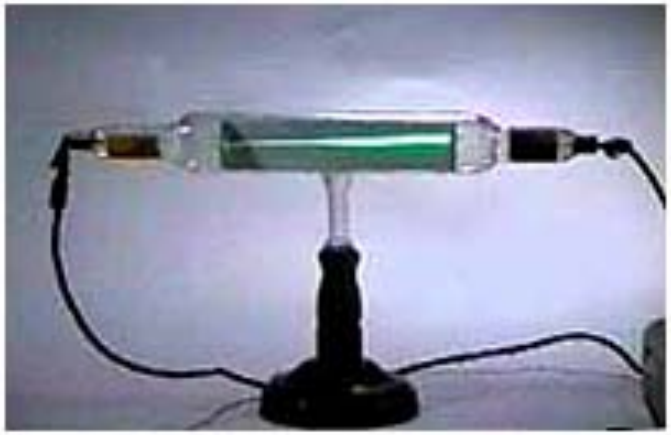

History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
12x109y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

[1897] Electron Discovery

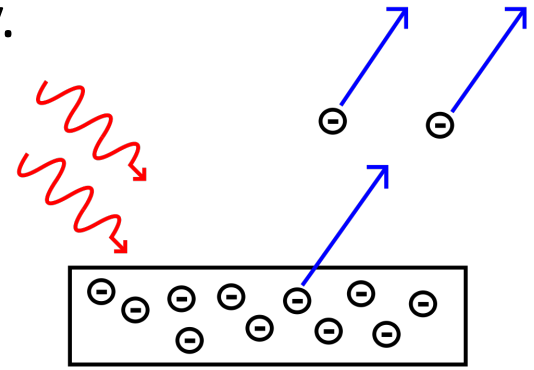
- J.J. Thomson (Cavendish Laboratory)
- Cathode Ray Tube





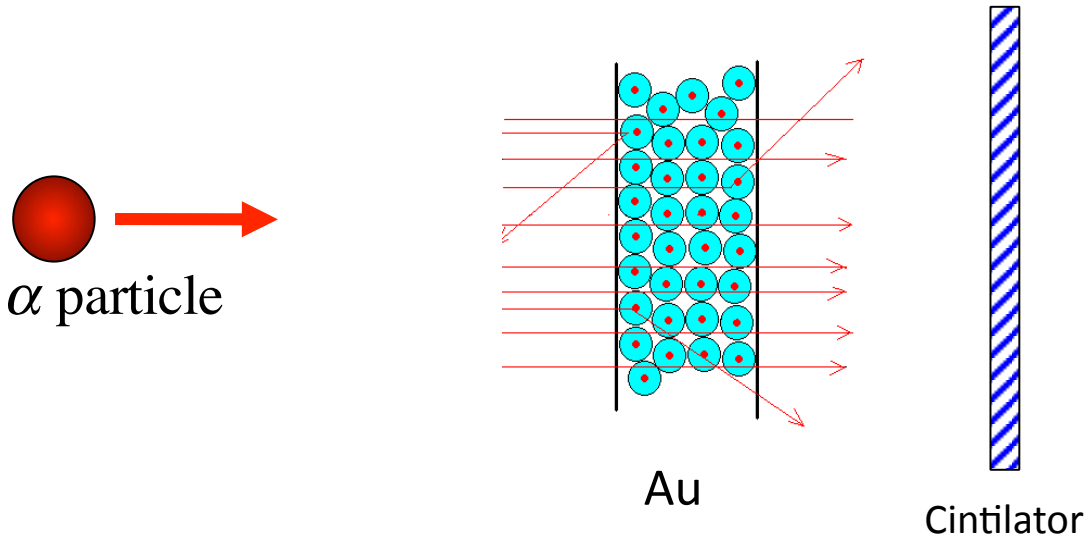
[1905] Photon Proposal

- Photoelectric Effect
  - First observed by Heinrich Hertz in 1887
  - Electrons are emitted from matter as a consequence of their absorption of energy from electromagnetic radiation.
  - Electrons energy proportional to light frequency and not its intensity.
  - No emission below some frequency threshold.
- Albert Einstein:
  - Light composed of of discrete quanta, called photons, rather than continuous waves.
  - Photons energy proportional to frequency.
- Particle X Wave duality



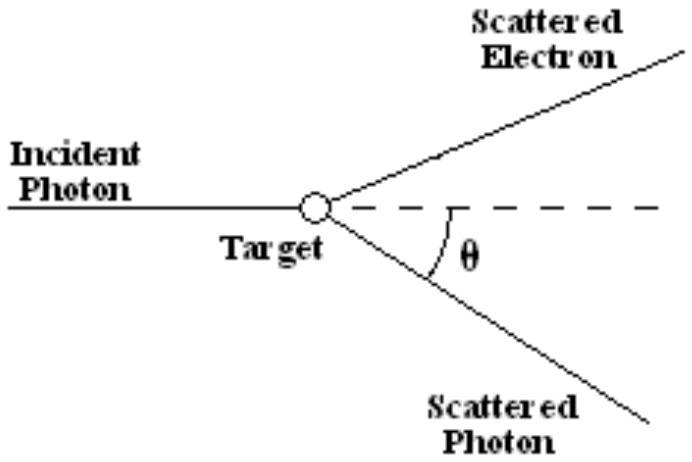
[1909] Atom Sub-Structure

- Rutherford Experiment (Geiger & Marsden)
  - Evidence of the atom nucleus.
  - Birth of atomic model.
- Basic particle physics experiment: Beam + Target + Detector



[1923] Photon Discovery

- First proposed by A. Einstein on 1905 (Photoelectric Effect)
- Experimentally confirmed by Arthur H. Compton on 1923
  - Compton Effect: change on photon wavelength when interacting electrons
  - Scattering of free electrons by X Rays. Just like classical scattering of two particles.
  - Photon behaves as a particles.
- Lesson: You need experimental evidence to affirm something exists, no matter how sound is your theory.



$$\lambda_2 = \frac{h}{m_e c}(1 - \cos\theta) + \lambda_1$$

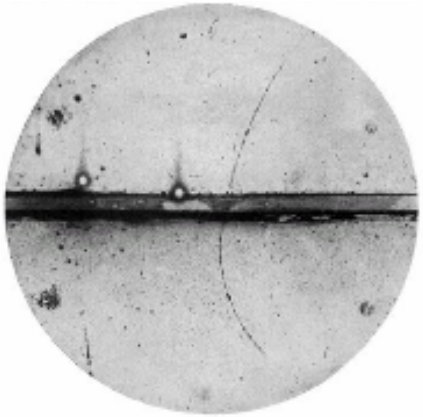
[1928] Antimatter proposal

- Paul Dirac quantum mechanical equation for relativistic electrons

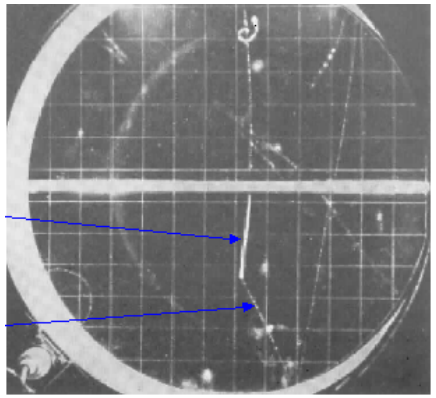
$$\left(\beta mc^2 + \sum_{k=1}^{3} \alpha_k p_k c\right)\psi(\mathrm{x},t) = i\hbar \frac{\partial \psi(x,t)}{\partial t}$$

- Allow for electrons having either positive or negative energy as solutions.
- Demands the existence of antiparticles as its negative energy solution.

Cosmic Rays based experiments



- More energy then alpha radiation
- Less control over the experiment
- [1932] Antimatter (positron) Discovery
  - By Anderson
  - Curved track → Positive charged particle
  - Could not be a proton
  - Just like Dirac's theorical.



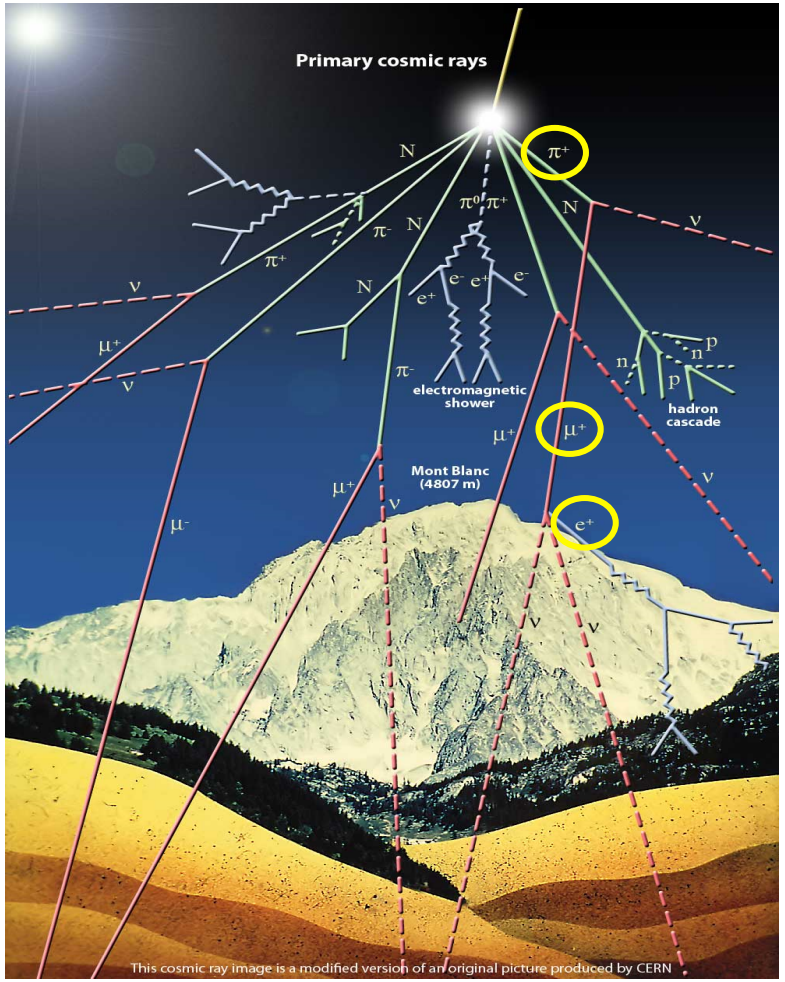
- [1937] Muon discovery $\mu \rightarrow e + \overline{\nu}_e + \nu_\mu$
  - by Neddermeyer e Anderson
  - Surprise: Not like Yukawa theoretical prediction (pion)
  - "Who ordered that"? (I. Rabi)
  - Just like a heavy electron. First second generation particle.

[1947] The Pion

- Lattes, Ochialini e Powel

$$\pi \rightarrow \mu + \bar{\nu}_\mu \rightarrow e + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$$

Monte Chacaltaya, Bolívia, 5.600 m



Strange (weird) Particles

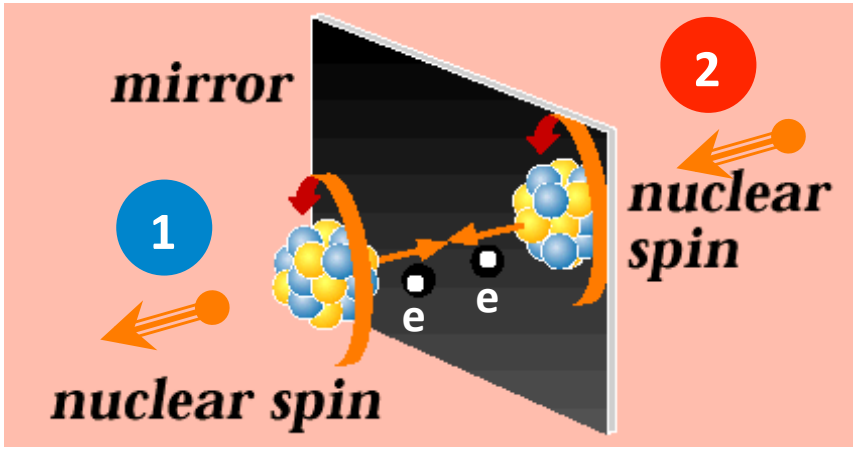
- [1943-59] First observed on cosmic rays experiments
  - Bristol, Manchester, Ecole Polythecnique, Caltech, Berkeley
- [1953-54] Cosmotron (BNL), Bevatron (LBL)
  - Proton beam (3 to 6 GeV) on fixed target.
  - Laboratory controled production of new particles
  - Long lived strange behaving particles (Λ, K, Σ, ...)
  - Pair produced through strong interactions and decaying into other strange particles by strong interactions.
  - Mean life time 10^{10} larger than expected for strong interactions.
- [1952-53] Pais, Gell-Mann
  - Strangeness is conserved by strong and electromagnetic interactions but violated by weak interactions.
  - There is a new conservative quantum number: **Strangeness**

Beta Decay and Parity Violation

- Proposed by T.D. Lee and C.N. Yang for weak interactions.
  - Inclusion of intermediate vector boson for weak interactions.
  - Only left hand fermions would feel the weak interaction.
- [1957] Wu et al.:
  - First evidence of the non-conservation of parity on beta decay under strong magnetic field.

$$^{60}\mathrm{Co}\ (\mathrm{polarized}) \rightarrow\ ^{60}\mathrm{Ni} + e^{-} + \bar{\nu}_e$$

  - Electrons are only emitted opposed to the magnetic field.
- [1957] Garwin, Lederman e Weinrich:
  - Confirmed parity violation on muon decay



Discrete Symmetries

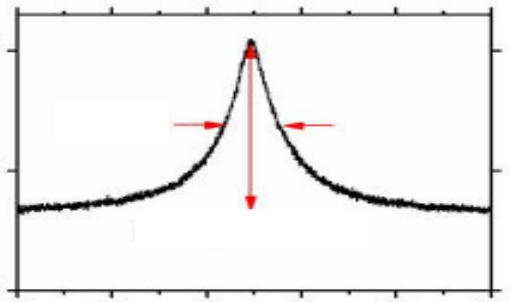
- Parity (P)
  - Inversion of all three spatial coordinates
  - Left hand and right hand
  - Violated on Weak Interaction
  - Only left hand particles feels weak interactions
- Temporal Reversion (T)
  - Reversion of the direction of time.
- Charge Conjugation (C)
  - Changing of charge signal.
- Nothing forbids individual violations (C, P or T individually)
- CPT Theorem: The product of the three of them cannot be violated
- CP violation ➔ T violation ➔ Matter – Antimatter asymmetry
  - Needed to explain why the universe is made of matter only.
  - Discovered in 1964 in the decays of neutral kaons by Cronin and Fitch.
  - **The Standard Model does not provide the amount needed to explain the observed imbalance between matter and antimatter.**

50's: Accelerators + Detectors

- [1953] Invention of Bubble Chamber.
- [1955] Anti-Proton Discovery at Bevatron

  $p + p \rightarrow p + p + p + \bar{p}$
- [1956] Anti-Neutron Discovery
- [1952-1964] Discovery of many ressonances
  - Very small mean life time (broad ressonances)

$\Delta, \Sigma, \mathrm{K}^*, \rho, \eta, \phi, \Omega, \ldots$



$\Delta_E \sim 10 - 200\ \mathrm{MeV}$

50's Theoretical Framework

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  - 40's by Feynman, Schwinger, Tomonaga and others.
  - Described in terms of an Abelian Quantum Fields theory.
  - Invariant under Group Symmetry transformation (Gauge Symmetry).
  - Renormalizable.
  - Quantum Electrodynamics (QED)
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  - Described by scattering amplitudes.
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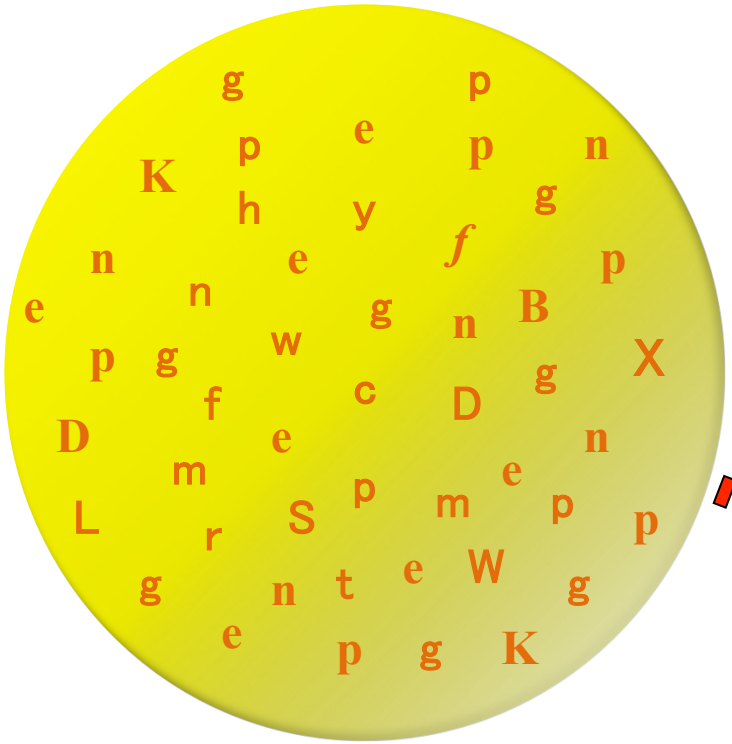
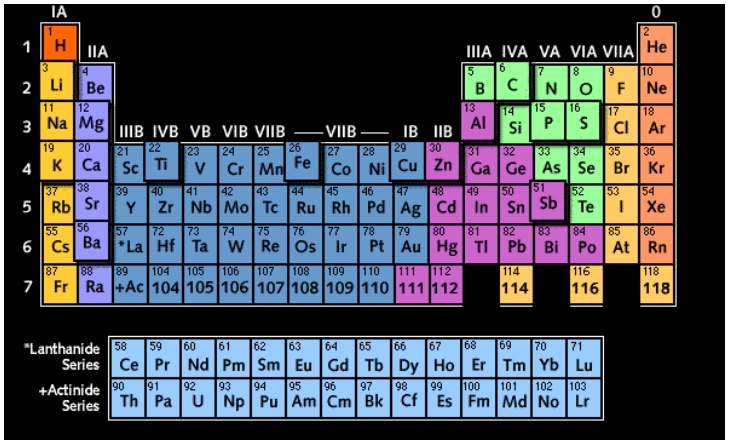
  - Gauge mediated interaction through massive vector bosons (W boson) .
  - Not a consistently quantized formalism.
  - Non renormalizable.




IA
IIA
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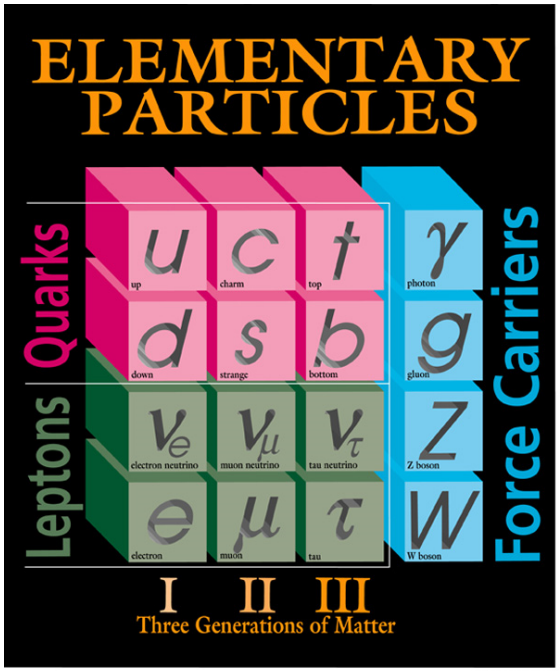
*Lanthanide Series
+Actinide Series


ELEMENTARY PARTICLES
Quarks
Leptons
Force Carriers
up
charm
top
down
strange
bottom
electron neutrino
muon neutrino
tau neutrino
electron
muon
tau
photon
gluon
Z boson
W boson
I II III
Three Generations of Matter
Fermilab 95-759

Quark Model
Murray Gell-Mann e George Zweig

- Barions (proton, neutron, etc) and mesons (pion, kaon, etc) composed by more fundamental particles, the quarks.
- Quarks: Abstract realization of SU(3) symmetry group
- Combination of quarks would form all know hadrons
- Named: Up (u), Down (d) and Strange (s).
- Barions: composed of three quarks

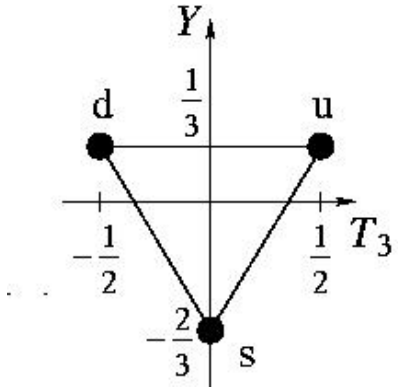
  $\text{proton} = (u\ u\ d) \qquad \text{neutron} = (u\ d\ d)$

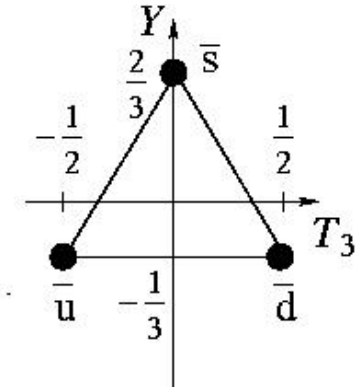
- Mesons: composed of a pair of quark-antiquark

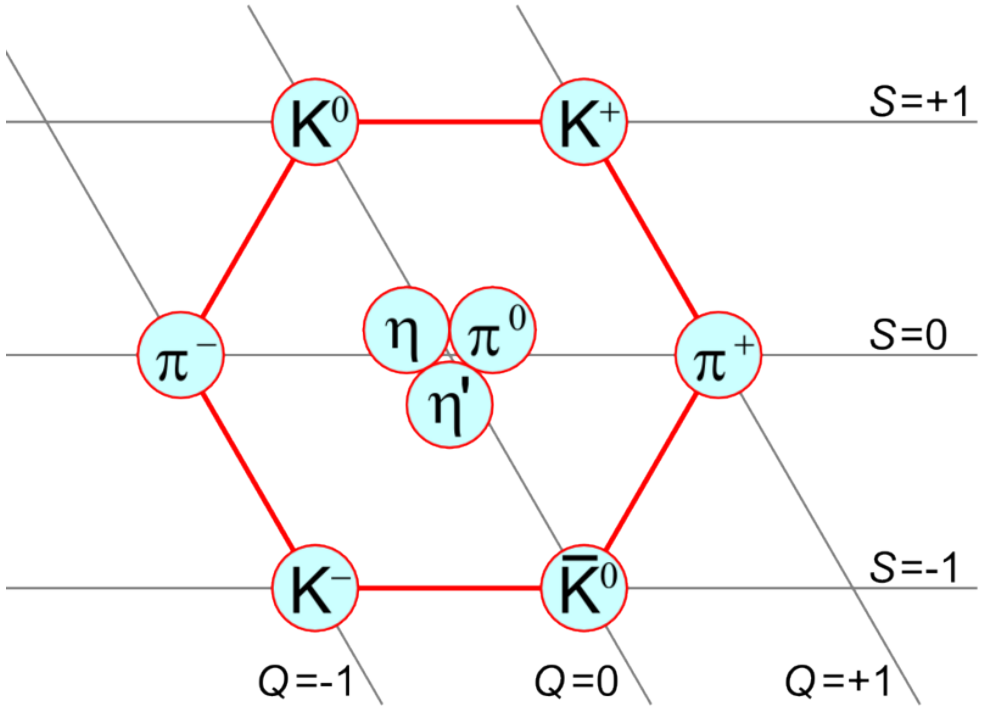
  $\pi^+ = (u\ \bar{d}) \qquad \pi^- = (\bar{u}\ d)$

Mesonic Octet

- Quark – Antiquark ➔ $3 \otimes \overline{3} = 8 \oplus 1$
- One mesonic octet plus one singlet.



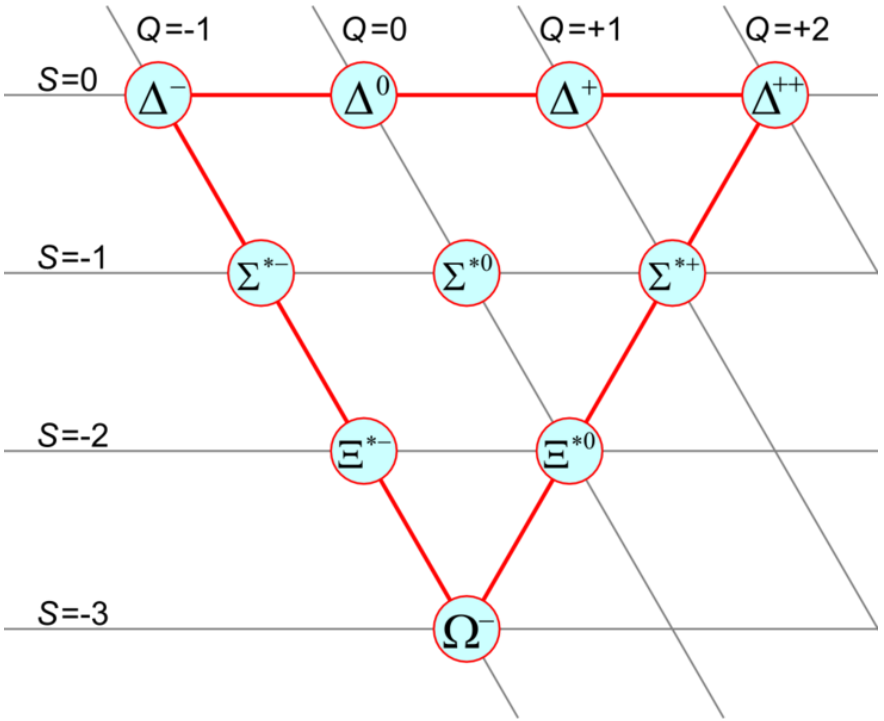




Barionic Decuplet

$$3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$$

- **Ω**: It was not yet known. Observed as predicted
- **Ω**: Made of three identical **s** quarks
  - Forbidden by exclusion principle.
- **Solution:** A new triplet quantum number should exist.
  - Named "**Color**" with values **Red**, **Blue** and **Green**.
- Each quark flavor should have one of the three colors.
- A combination of **S**+**S**+**S** would form a white **Ω**



Parton Model

- [1967] Bjorken
  - Bjorken: If there were loose charged objects inside nucleons, then a "scalling" of a particular combination of kinematic variables should be observed on Deep Inelastic Scattering.
  - Feynman: Named "parton" these would be proton "parts".
- [1969] SLAC-MIT Collaboration
  - Ongoing experimental program to determine nucleon form factors.
  - Performed at the Stanford Linear Accelerator Center (SLAC).
    - Elastic: $e\,N \rightarrow e\,N$ with exchange of real photons $(Q^2=0)$
    - Inelastic: $e\,N \rightarrow e\,X$ with exchange of virtual photons $(Q^2>0)$
    - Deep Inelastic: $Q^2>>0$. Probes very small distances (small wavelenght)
  - Observed Bjorken Scalling exactly as indicated!!
  - Evidence of loose charged objects inside the nucleon.
  - Quarks? Not yet. No evidence of fractional electric charge. Why?
- Feynman: Parton Model
  - Modelled the behaviour of these observed loose nucleon "parts".
  - Parton momentum distribution function (PDF's).

70's: The birth of the Standard Model

- [1961] Salam and Ward
  - Formulation of the Gauge Invariance principle as basis for interactions.
- [1964] Greemberg, Han and Nambu
  - "Color" quantum number for Gell-Mann quarks.
- [1967] Fadeev and Popov
  - Consistent quantization of non-Abelian gauge fields.
  - Feynman rules for Yang-Mills theory.
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  - Uses Higgs Spontaneous Symmetry Breaking mechanism
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  - Yang-Mills theory are Renormalizable
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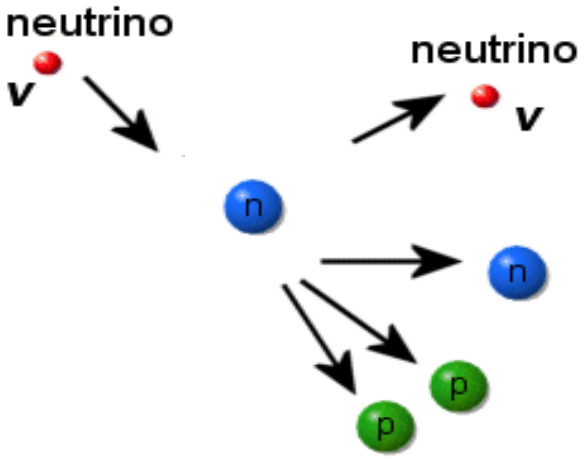
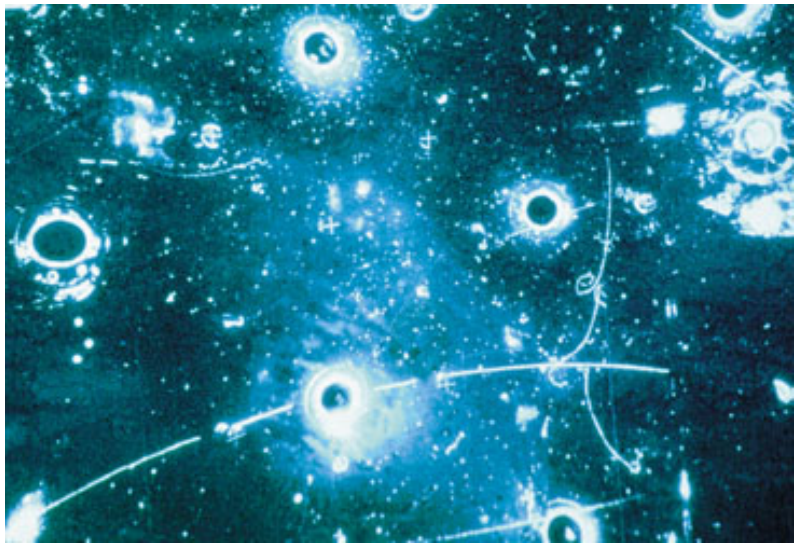
  - Yang-Mills theory leads to "Assimptotic Freedom"
  - Assimptotic Freedom ➔ Confinement
- [1973] Colleman
  - Assimptotic Freedom ➔ Yang-Mills theory
- [1973] Fritsch, Gell-Mann and Leutwyler
  - Formulation of Strong Interaction as Yang-Mills quantum field
  - Quantum Chromodynamics (QCD)

[1972] Neutral Current Observation

- CERN Gargamelle Bubble Chamber (Hasert et al.)
- First evidence of the existence of the Z Boson.
- Predicted by the Weimberg model of weak interactions.
- First confirmation of what would become the Standard Model.

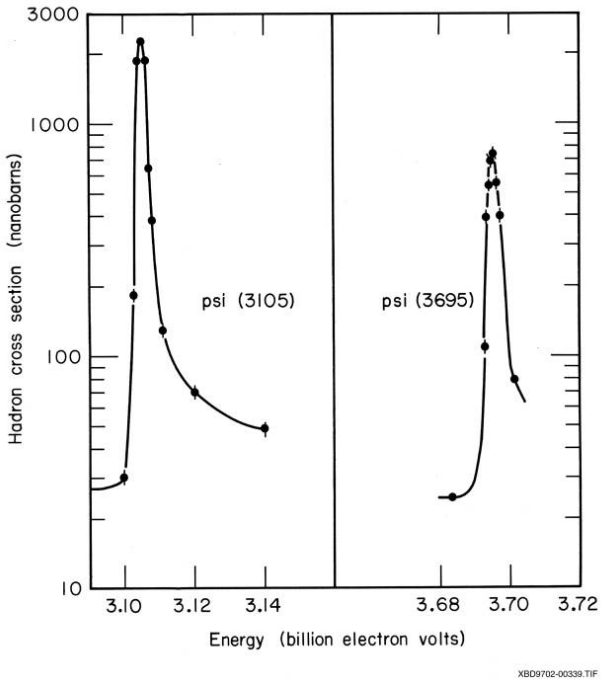
$$\nu + N \rightarrow \nu + N + X$$



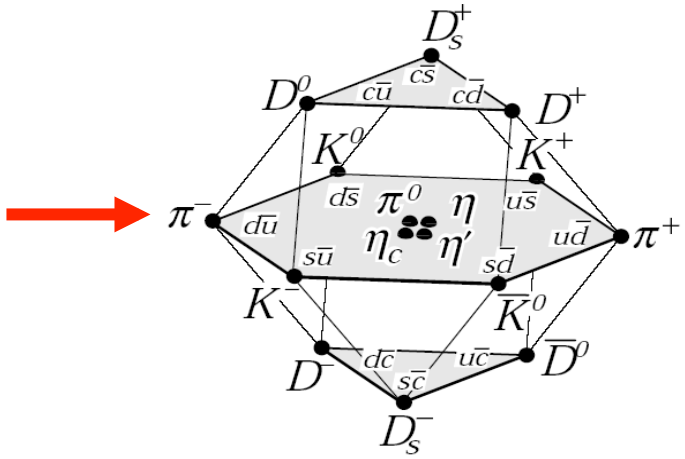


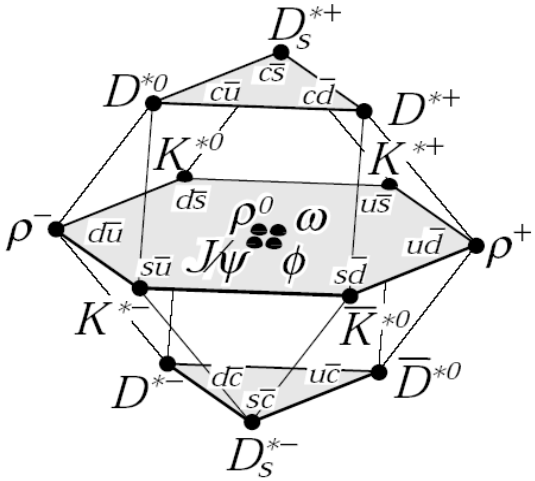
[1974] The November Revolution

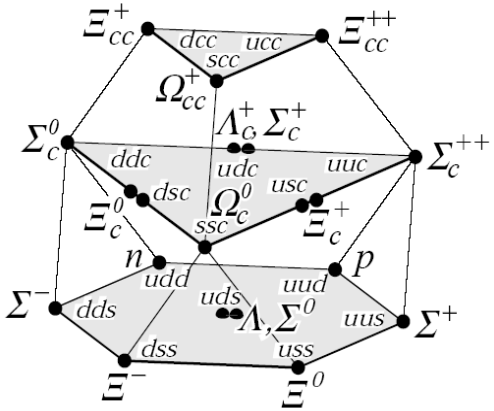
- MIT-BNL Collaboration, Ting et al.
  - AGS proton accelerator at BNL
  - *J* particle discovery $(p + \mathrm{Be} \rightarrow e^+ + e^- + X)$
  - e^+e^- invariant mass peak at $M_{e^+e^-} = 3.1\,\mathrm{GeV}$
  - Submited for publication on 12/11/74
- Mark I Collaboration, Richter et al.
  - SPEAR electron-positron collider at SLAC
  - Ψ particle discovery $(e^+ + e^- \rightarrow \mathrm{hadrons})$
  - Reaction cross section peak at $E = 3.1\,\mathrm{GeV}$
  - Submited for publication on 13/11/74
- Charm quark is discovered
  - Predicted in 1970 by Glashow, Illiopoulos and Maiani in the framework of the electroweak Weimberg-Salam model.
  - Charmonium bound state renamed as *J/Ψ*
  - Charmonium spectrum identification follows $(\psi', \psi'', \chi_c, \Lambda_c, \ldots)$

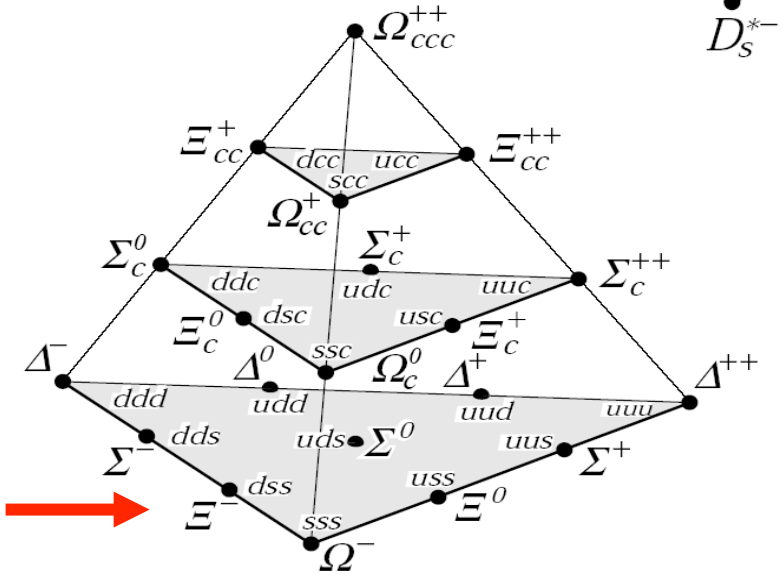


[1974] Quark Charm → SU(4)









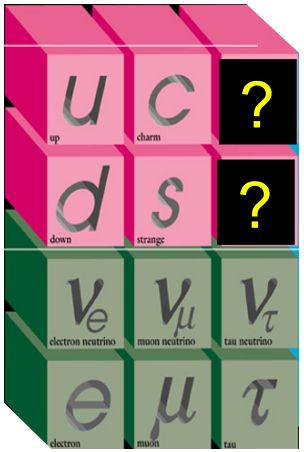
[1975] A New Lepton

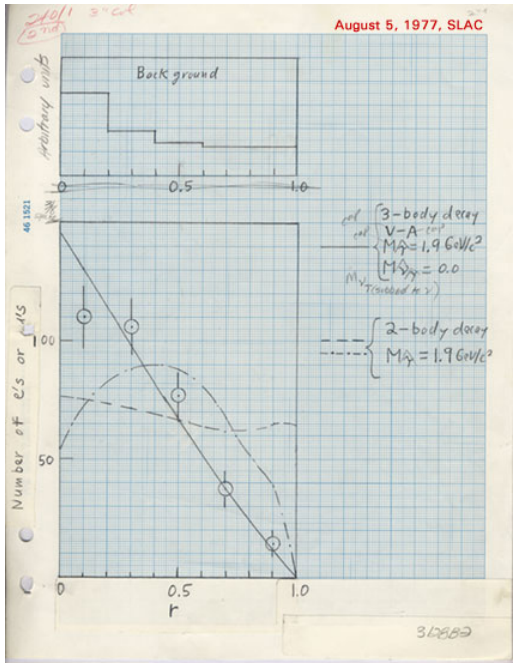
- SLAC Mark I Collaboration, Perl et al.

$$e^+ + e^- \rightarrow \tau^+ + \tau^- \rightarrow \nu_\tau + e^+ + \bar{\nu}_e + \nu_\tau + \mu^- + \bar{\nu}_\mu$$

$$M_\tau = 1.8\,\mathrm{GeV}$$

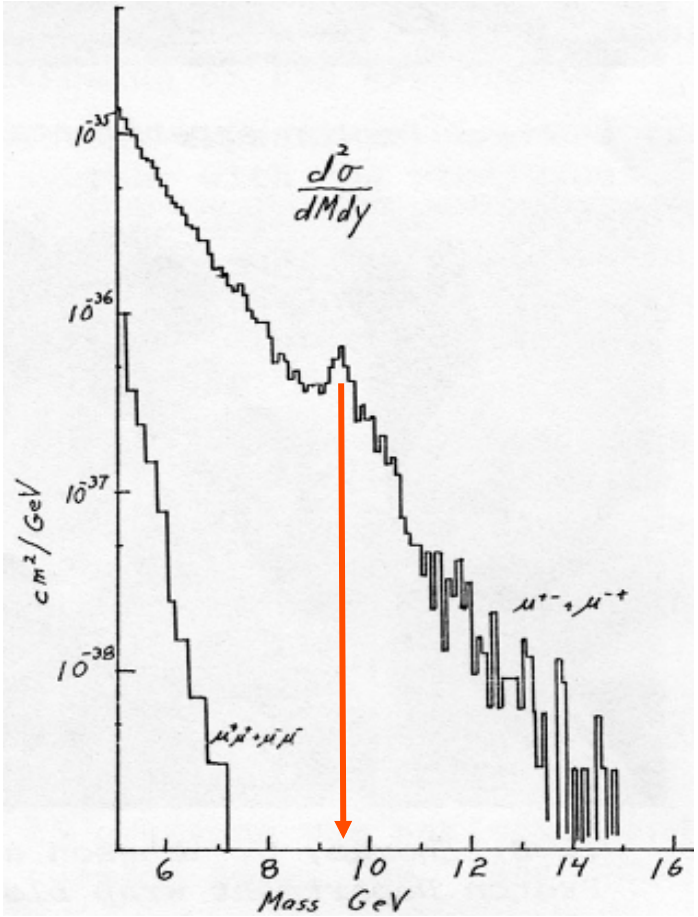
- Suggests the existence of two other quarks.





[1977] Discovery of Bottom Quark

- 400 GeV proton-nucleon @ Fermilab
- Leon Lederman et al.
- $p + (\mathrm{Cu}, \mathrm{Pt}) \rightarrow \mu^+ + \mu^- + X$
- $\mu^+\mu^-$ invariant mass peak
- $M_{e^+e^-} = 4.5\,\mathrm{GeV}$
- Full spectra also discovered $(\Upsilon, \Upsilon', \ldots)$



4th SCRA – Introduction to Particle Physics and the Standard Model

THIRD DAY

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The Standard Model

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \Rightarrow SU(3)_C \otimes SU(2)_W \otimes U(1)_{EM}$$

Hidden Symmetry
Massless

Symmetry Breaking
Higgs Mechanism

Visible Symmetry
Massive

- Gauge Bosons:
  - $SU(3)_C$ → Gluons (G_i, i=1…8)
  - $SU(2)_W$ → W^+, W^-, Z^0
  - $U(1)_{EM}$ → Photon
- Gauge couplings:
  - g_S, g_W, g_e
- Higgs Boson: H

- Leptons

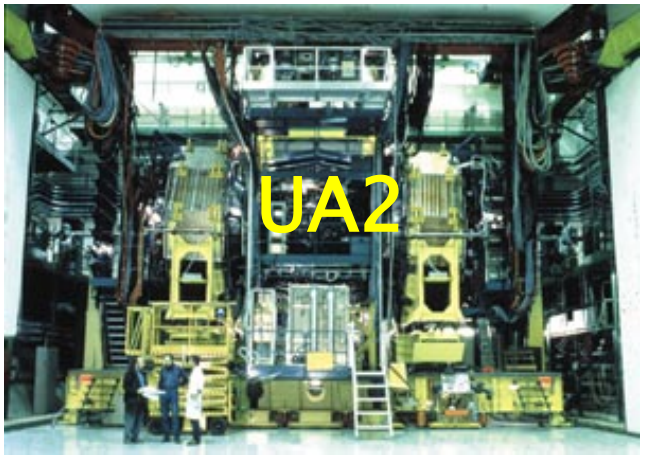
$$L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad e_R$$

- Quarks

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad u_R\,, \quad d_R$$

[80's] Searching W and Z Bosons

- Predicted by Weimberg-Salam model.
- Masses in the range 80 to 90 GeV.
- Too heavy to be produced by the time existing facilities.
- Carlo Rubia proposed the construction of a new kind of accelerator: The CERN Super Proton-Antiproton Synchrotron (SppS).
- Two beams colliding head-on.
- New generation of detectors.
  - End of the Bubble Chamber + Photography era.
  - Begin of the electronic era.



[1983] W and Z Boson Discovery

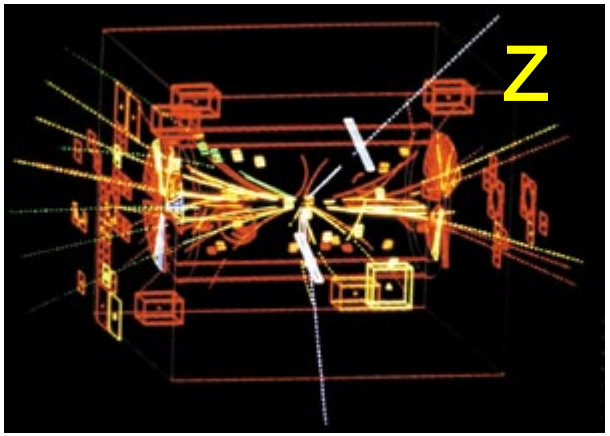
- UA1 and UA2 Collaborations.

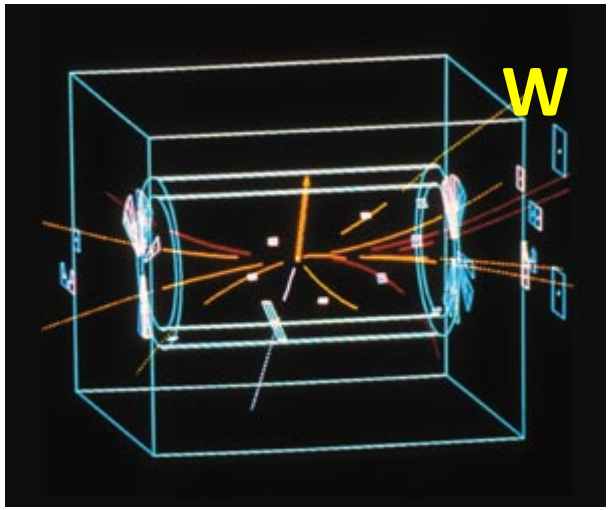
$$p + \bar{p} \rightarrow W + X \rightarrow l + \nu + X$$

$$p + \bar{p} \rightarrow Z + X \rightarrow l + \bar{l} + X$$

$$M_W = 80\,\mathrm{GeV} \quad \text{and} \quad M_Z = 91\,\mathrm{GeV}$$

- Exactly as preditcted by Weimberg in 1967.
- Rubbia → Nobel Prize!
- Begin of the era of big experiments.





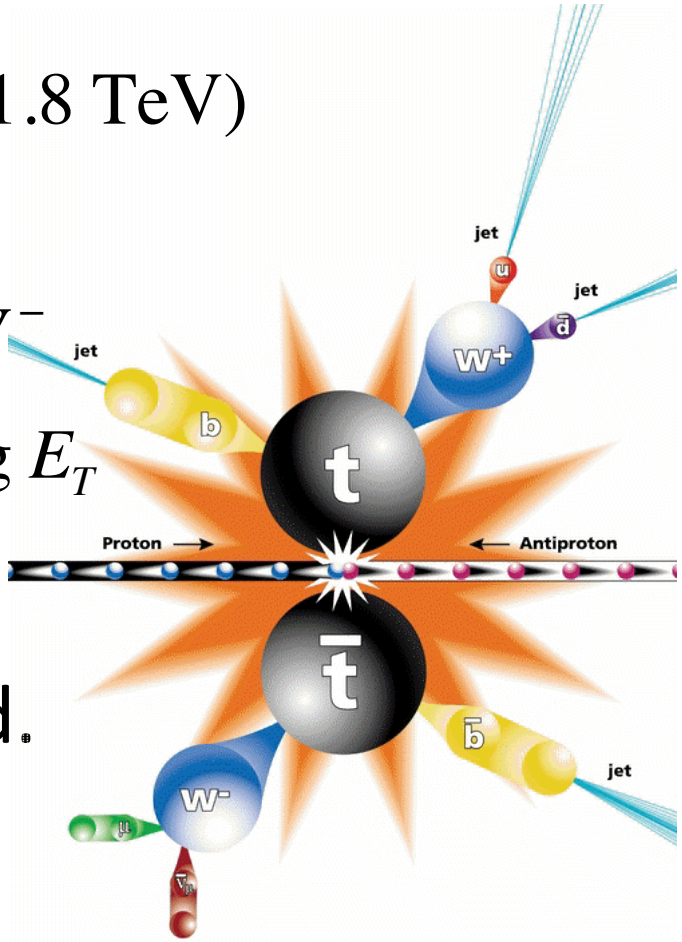
[1995] The Top Quark

- Fermilab Tevatron ($p\bar{p}$ at $\sqrt{s} = 1.8$ TeV)
- CDF e DØ Collaboration

$$p + \bar{p} \rightarrow t + \bar{t} \rightarrow b + W^+ + \bar{b} + W^-$$

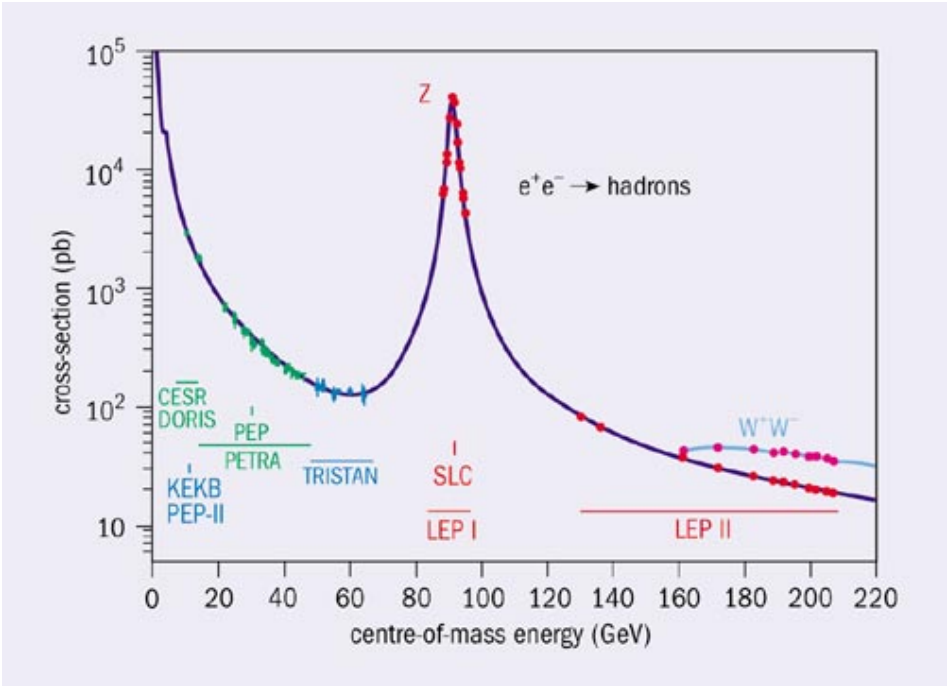
$$\rightarrow b + \bar{b} + l + 2\,\text{jets} + \text{missing } E_T$$

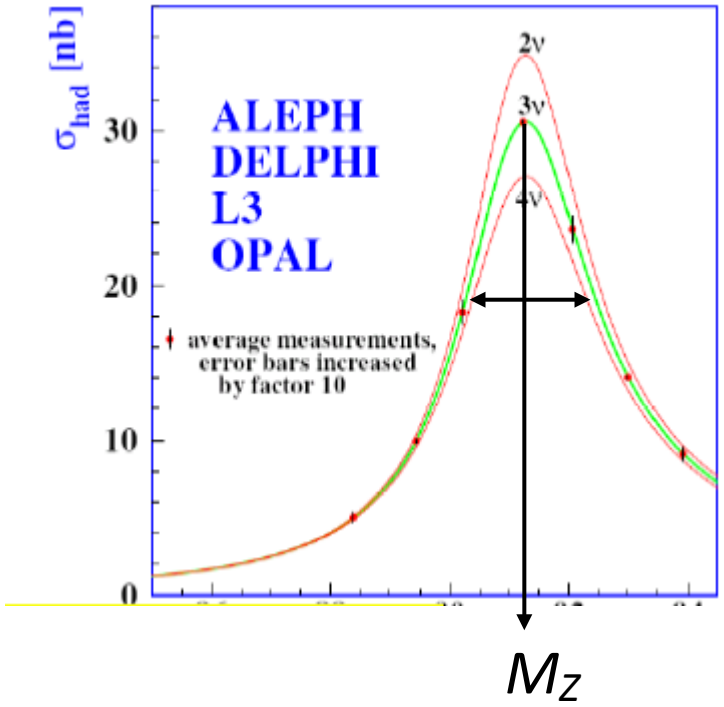
- $M_t = 180$ GeV
- Last fermion to be discovered.
- But not the last puzzle piece!



[90's] Precision Measurements

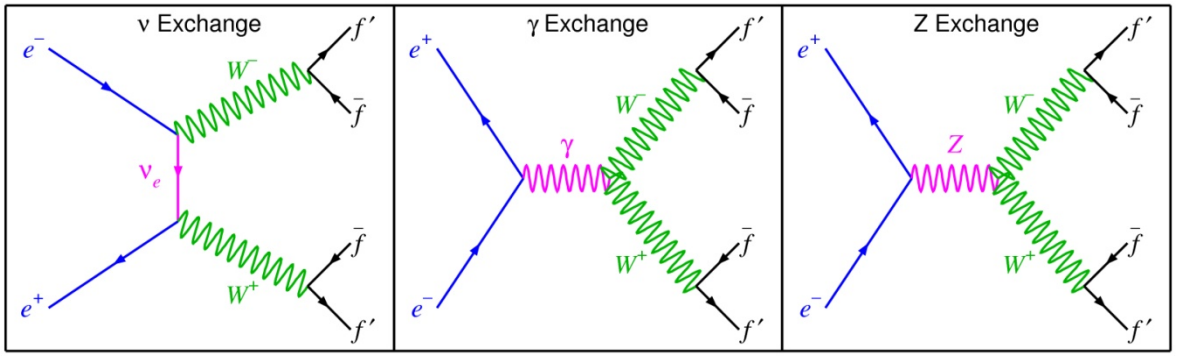
- Large Electron-Positron Collider (LEP) at CERN
- Four experimental Collaborations:
  - ALEPH, DELPHI, L3 and OPAL
- Z Boson factory. Energy tunned at Z peak.
- Precision measurements of Z properties.





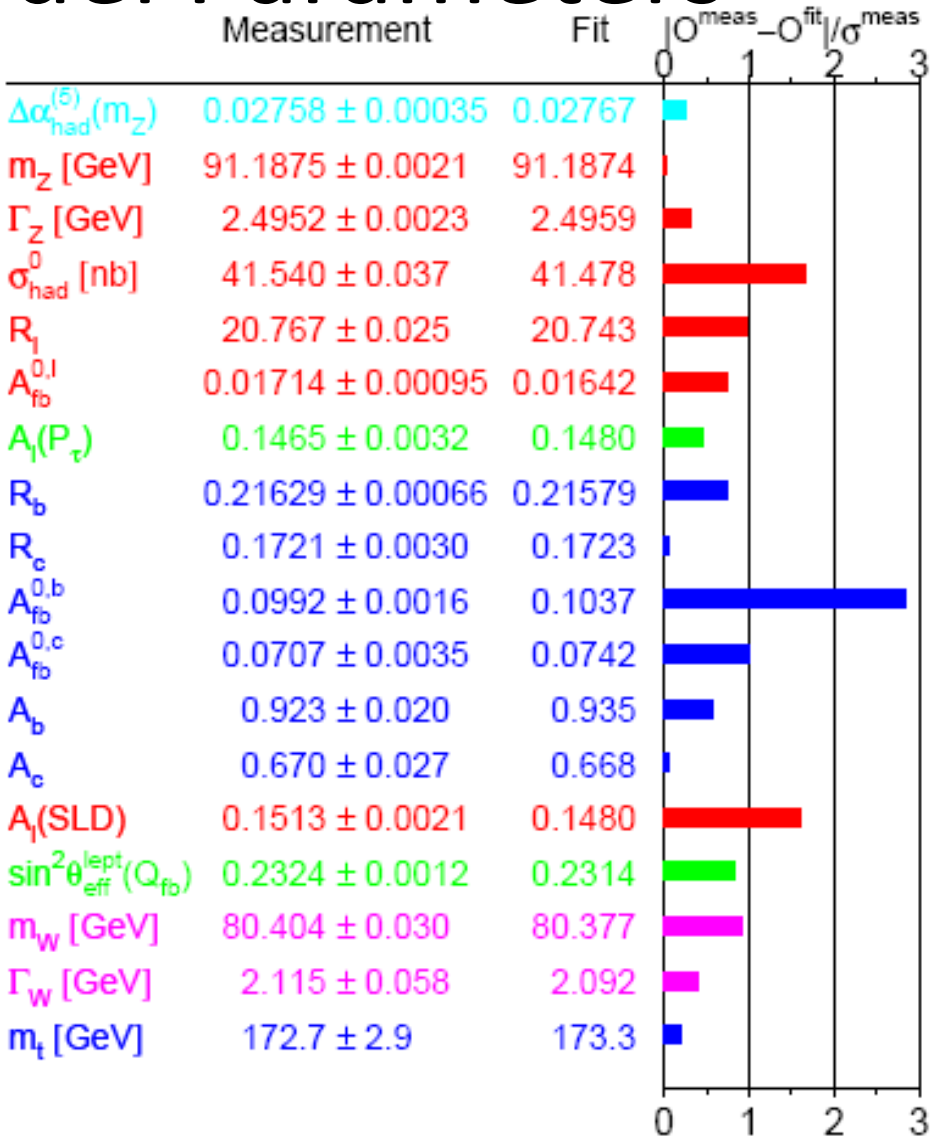
[Late 90's] LEP II Program

- Production of W pairs (about 160 GeV).
- Probing gauge boson self couplings.
- No deviation from Standard Model assertions.
- No hint for new particles or symmetries found.
- The Standard Model works extremely well.
- Only one piece still missing.



Standar Model Parameters

- A huge success
- There is no experimental evidence of failure.
- All mesured parameters are compatible with the standard model.
- No deviation found.
- It is almost complete

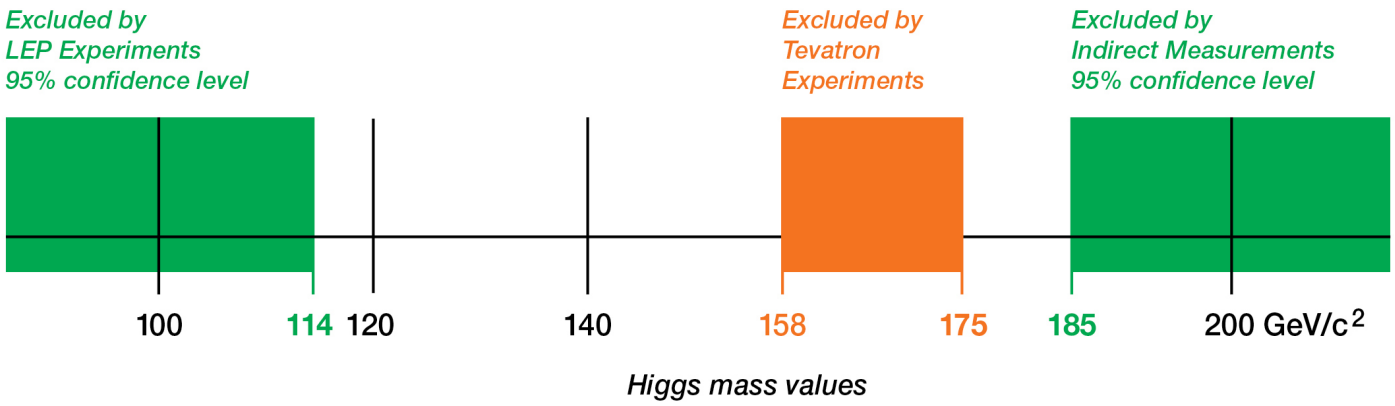


The Standard Model

- Strong, Weak and Electromagnetic Interactions model.
- Renormalizable gauge theory with intermediate massive vector bosons.
- Reproduces extremely well all observed particle physics phenomenology.
- Built upon:
  - Quantum Fields Theory
  - Gauge Group Symmetry Invariance
  - The assumption that **there is a fundamental scalar field**.
- Predicted:
  - The existence of neutral current mediated weak interactions (Z boson). ✔
  - The mass value of the W and Z bosons. ✔
  - Equal number of leptons and quarks isospin dublets. ✔
  - **The existence of a massive scalar boson (Higgs boson). ?**

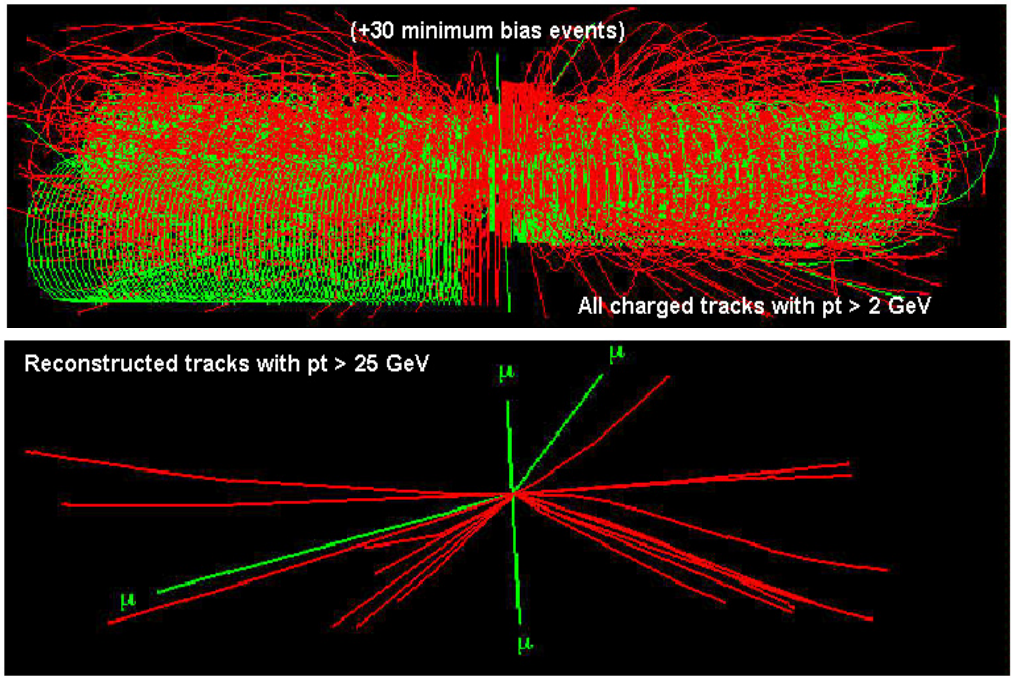
[201?] Higgs Boson Discovery

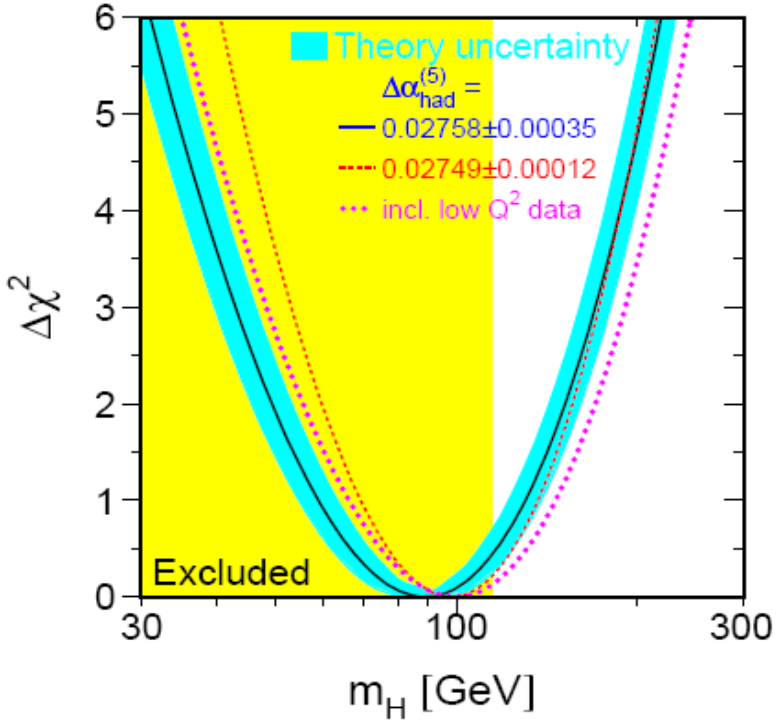
- The Large Hadron Collider (LHC) at CERN
  - Proton – Proton collider at 7/14 TeV
  - High mass Higgs: $p + p \rightarrow H \rightarrow ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-$
  - Low mass Higgs: $p + p \rightarrow H \rightarrow \gamma\gamma$
  - Discovery not expected before 2013 (5 sigma)
- Tevatron (2 TeV proton-antiproton collider)
  - Exclusion limits (3 sigmas) on some mass range.
  - Possible discovery if run extended up to 2014.
- July 2010 limits:



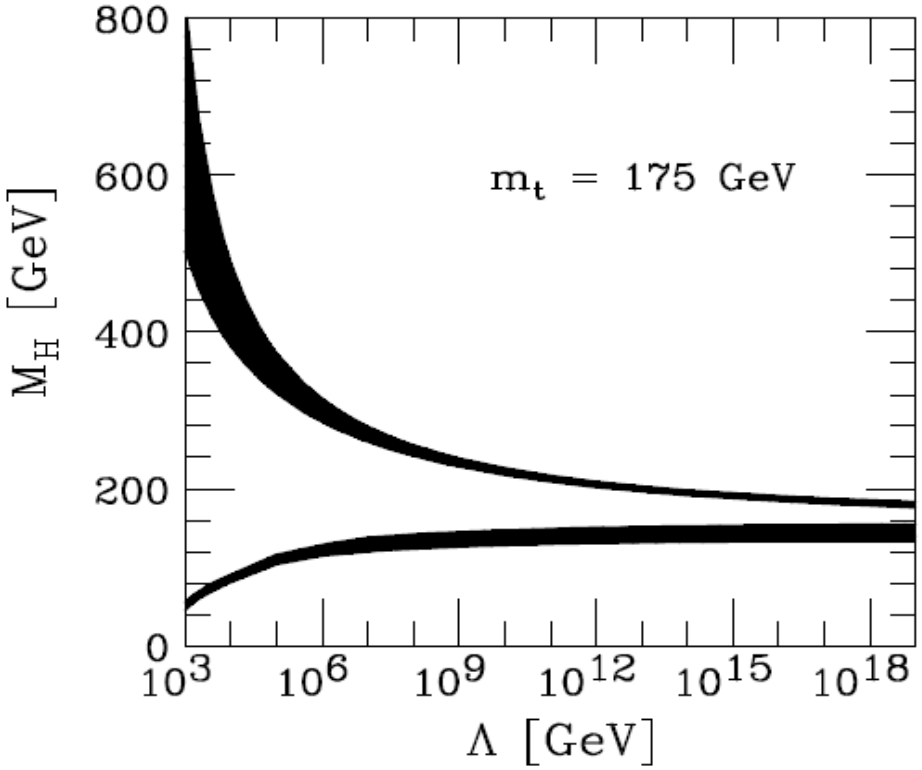
Higgs Boson: The Challenge

- It is the fundamental assumption of the whole model.
- The most compatible value of Higgs mass has already been excluded by direct search from LEP experiments.
- Without a symmetry breaking mechanism the theory is senseless.
- There is no good substitute for it.
- Very challenging to be discovered because of large backgrounds.
- LHC will either discover or rule it out.



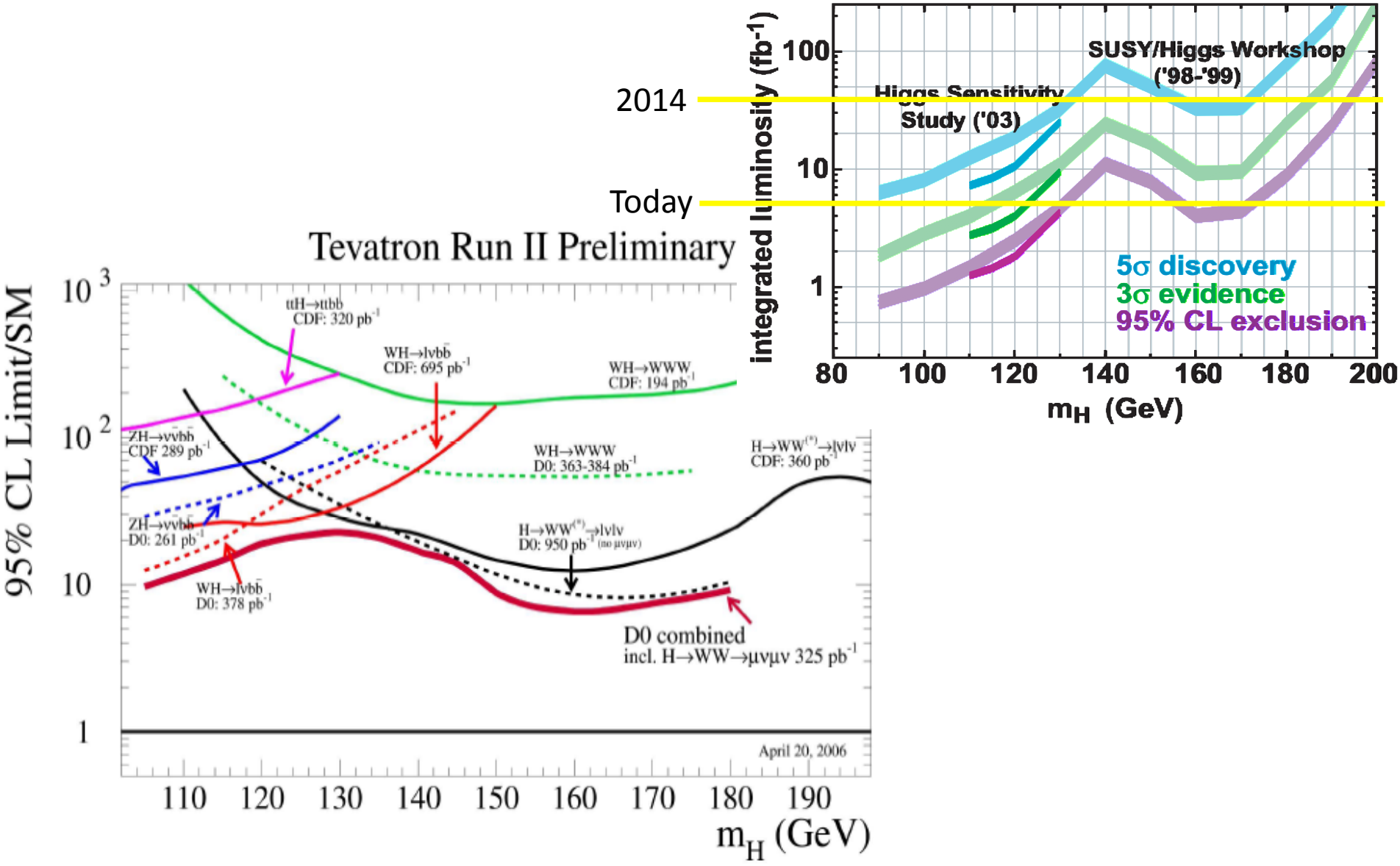


Higgs Mass Allowed Range



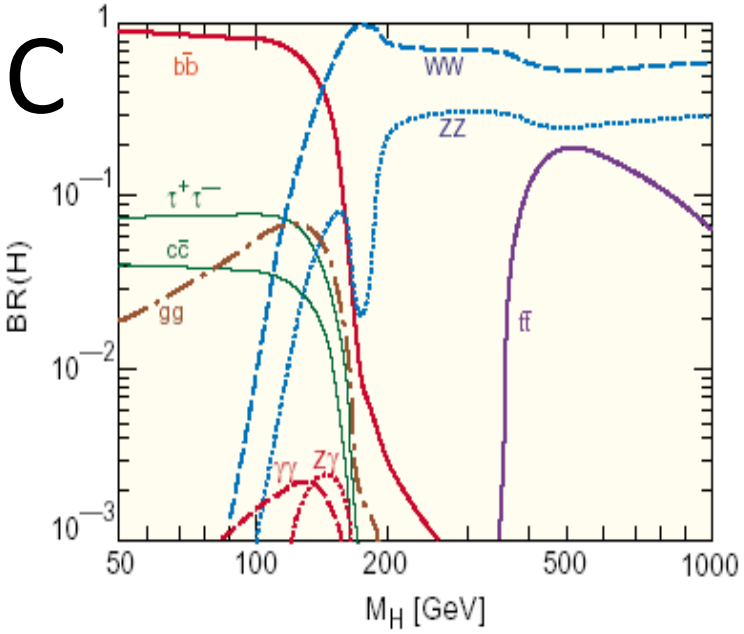
- Mass limits for the Higgs Boson as function of the scale up to where the Standard Model is still valid.
- If Standard Model is not an effective theory, it should be valida up to Planck Scale.
- Very narrow window left for it.

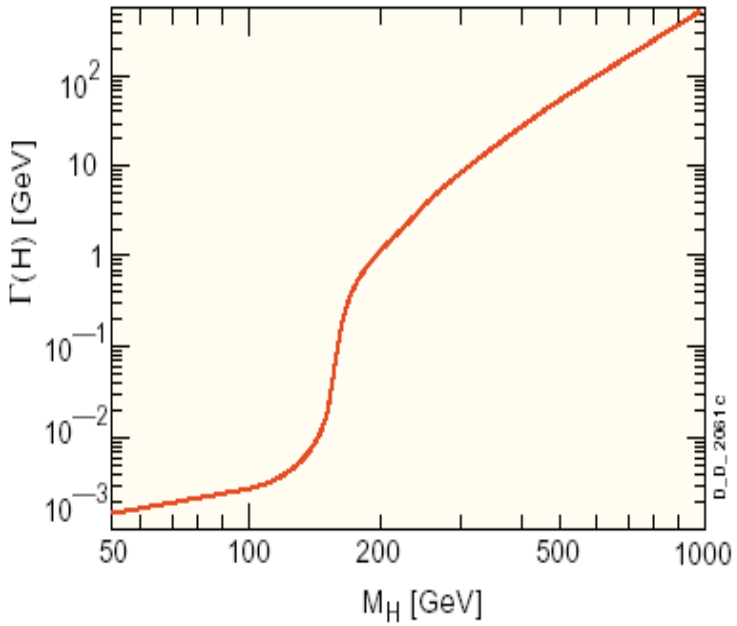
Higgs Search at Tevatron



SM Higgs at LHC

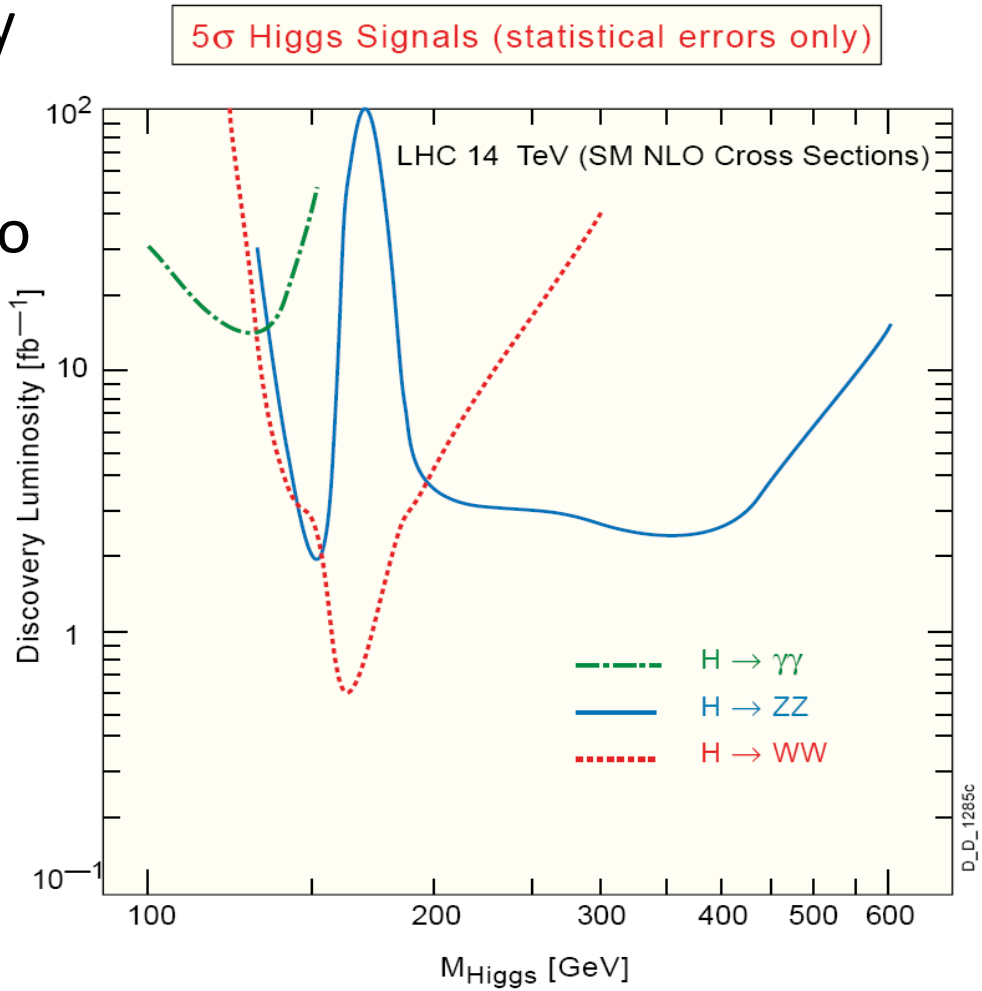
- LEP Limit: $M_H > 114.4$ GeV
- Partial decay widths defined as function of Higgs mass
- Production:
  - Gluon fusion: (gg → H)
  - Associated production: (qq→WH)
- Main decay channel for light Higgs: Two photons.
- Main decay channel for heavier Higgs: Four leptons (H → ZZ → llll)





Higgs Discovery Potencial at LHC

- Good detector sensitivity for the mass range from 100 GeV up to 1 TeV.
- In most cases at least two observable channels available
- Good detector performance:
  - Identification of b's, leptons and photons.
  - Good energy resolution.
  - Good isolation criteria

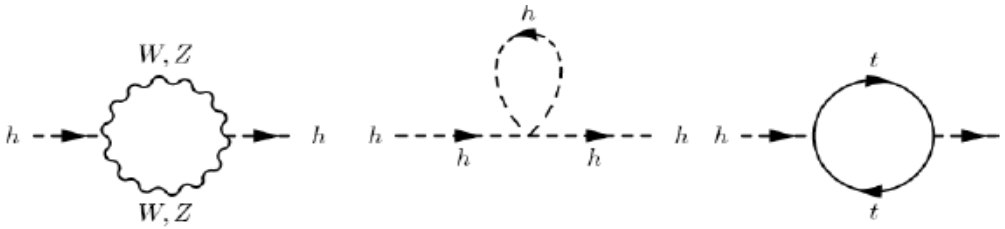


Standard Model Limits

- Strong evidences that it is not The Final Theory (does that exist?)
  - We still do not know the symmetry breaking sector.
  - Massive Neutrinos.
  - Evidence of the existence of Dark Matter
  - Evidence of the existence of Dark Energy
  - Why three generations?
  - It does not include gravity.
- Should be seen as an effective theory, valid up to some mass scale.
  - Hierarchy problem.
- Possible new dynamics at 1 TeV scale
  - If Higgs Boson is not found, it has to exist some other mechanism for the electroweak symmetry breaking.
  - Those effects must appear on longitudinally polarized gauge bosons to avoid unitarity violation at TeV scale.
  - If the Higgs bosons is not found, a new dynamic has to show up.
  - New Gauge Bosons
  - Supersymmetric models predict the existence of several of those new bosons
- LHC is capable of testing the existence of new physics up to 5 to 6 TeV.

Hierarchy Problem

- Quadratic divergences for the Higgs boson mass



$$m_h^2 = (m_h^2)_0 + \delta m_h^2$$

- New symmetry to protect the scalar sector.
- Supersymmetry
- Extra Dimensions
  - Strong gravity at TeV scale: Large Extra Dimensions
  - Electroweak protecting mechanism: Randall-Sundrum
  - New physics at TeV scale: Universal Extra Dimensions

Supersymmetry

- Symmetry between Bosons and Fermions
- For every boson there is an associated fermion and vice-versa (superpartner)
- Spin ½ Fermions →
  Spin 0 (Scalar) Boson
- Spin 1 Vector Boson →
  Spin ½ Fermion
- Spin 0 Scalar Boson →
  Spin ½ Fermion
- Doubles the know spectrum of particles
- New quantum number
  "R Parity"

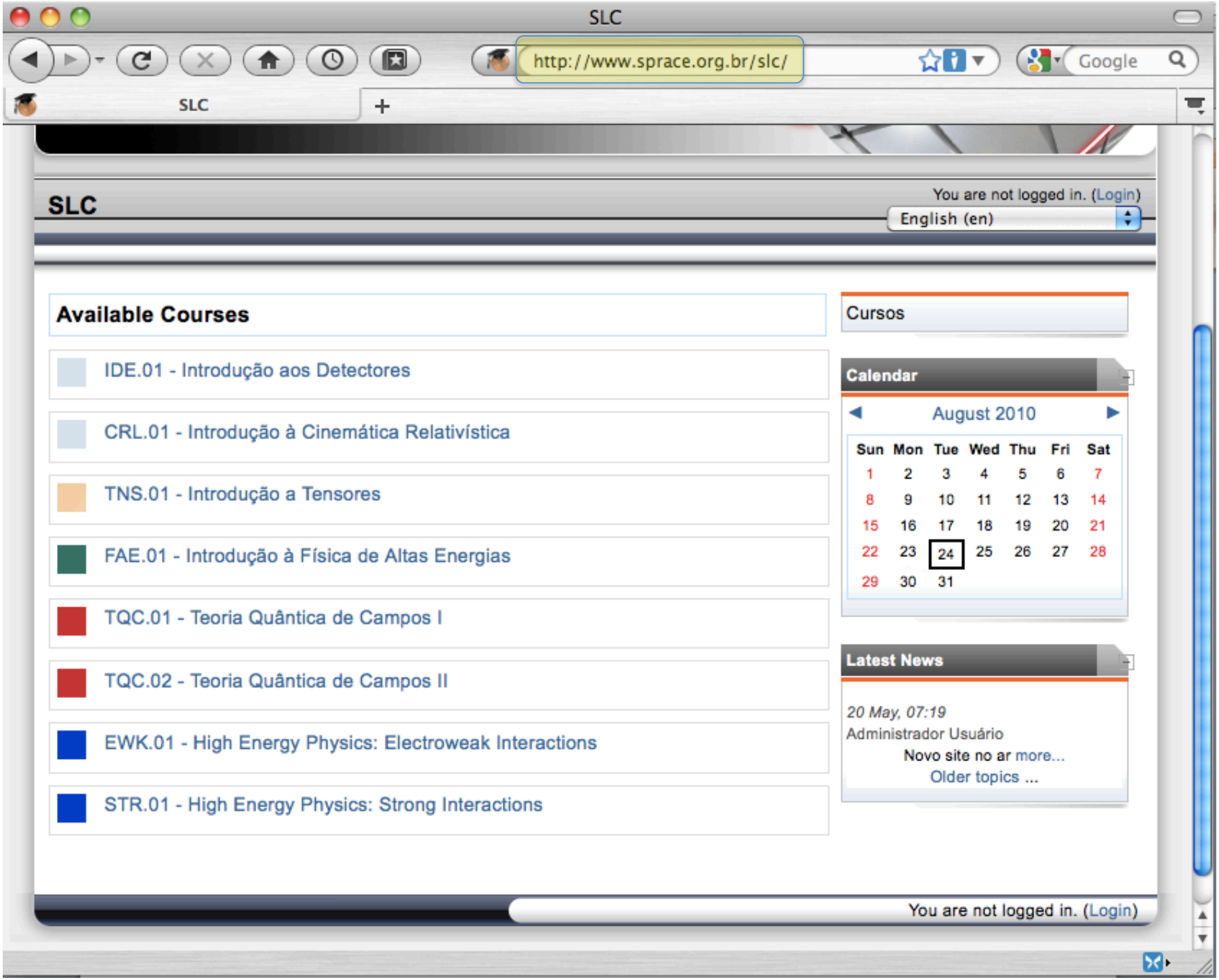
Name	Spin	Partner	Spin
Elétron	1/2	Selectron	0
Múon	1/2	Smuon	0
Tau	1/2	Stau	0
Neutrino	1/2	Sneutrino	0
Quark	1/2	Squark	0

Name	Spin	Partner	Spin
Gráviton	2	Gravitino	3/2
Fóton	1	Photino	1/2
Glúon	1	Gluino	1/2
$W^{+,-}$	1	$Wino^{+,-}$	1/2
Z^0	1	Zino	1/2
Higgs	0	Higgsino	1/2

- Supersymmetry has to be broken as we have not found the superpartners with the same mass of the known particles.
- We do not know how this symmetry breaking occurs. There are several ways to implement the supersymmetry.
- Minimal Supersymmetric Standard Model (MSSM)
  - Most general parametrization of supersymmetry breaking mechanism
  - Smallest content of new particles
  - Doubles the number of existing particles and introduces another Higgs dublet.
- Supergravity Model (Sugra)
  - Gravity is used for the supersymmetry breaking.
  - Includes Gravity in the same framework as other interactions.
- Gauge Mediated Symmetry Breaking (GMSB)
  - Implemented in such a way that the gauge interactions break the supersymmetry
- Problems
  - Despite have been proposed more then 25 years ago, there is no experimental evidence that nature presents such fundamental symmetry.
  - Too many free parameters on MSSM. Some models were able to reduce the number of those free parameters.

Some Extra Dimension Models

- Strong Gravity at TeV Scale: Large Extra Dimension (LED)
  - Extra dimensions may be large, up to submilimiter scale.
  - Only gravity can propagate into the extra dimensions. Towers of massive gravitons would originate missing tranverse momentum at collider experiments.
- New Metric: Randall-Sundrum (RS)
  - Small compactification scale, only gravity propagates into extra-dimensions.
  - There is an exponencial supression of the Planck scale, easing the hierarchy problem and leading to phenomenological effects at 1 TeV scale.
  - Gravitons would appear as heavy ressonant states.
- Universal Extra Dimensions (UED)
  - All standard model particles can propagate into extra-dimensions.
  - There are Kaluza-Klein towers of states for all particles
  - Might be observed at 1 TeV scale, decaying into usual SM states.
  - Stable lightest KK state would escape observation leading to missing transverse momentum signatures.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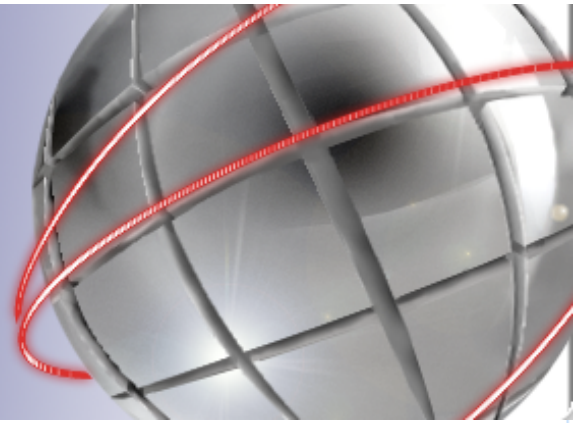

Electroweak Interactions

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