Places to learn more:
Particle and nuclear physics links

http://pdg.lbl.gov

http://particleadventure.org

http://www.slac.stanford.edu/gen/edu/aboutslac.html

http://www.bnl.gov/bnlweb/sciindex.html

http://www.bnl.gov/rhic/

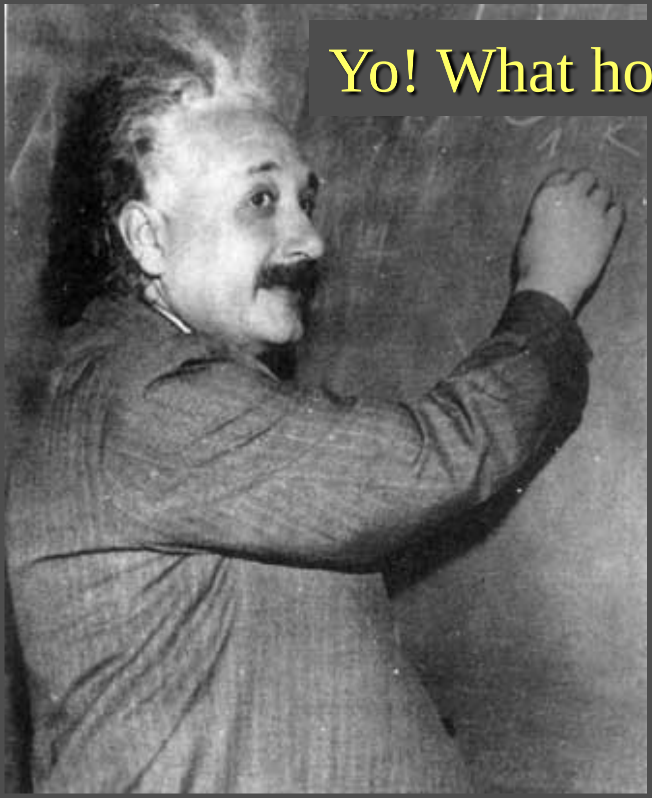
http://public.web.cern.ch/public/

http://www.fnal.gov/

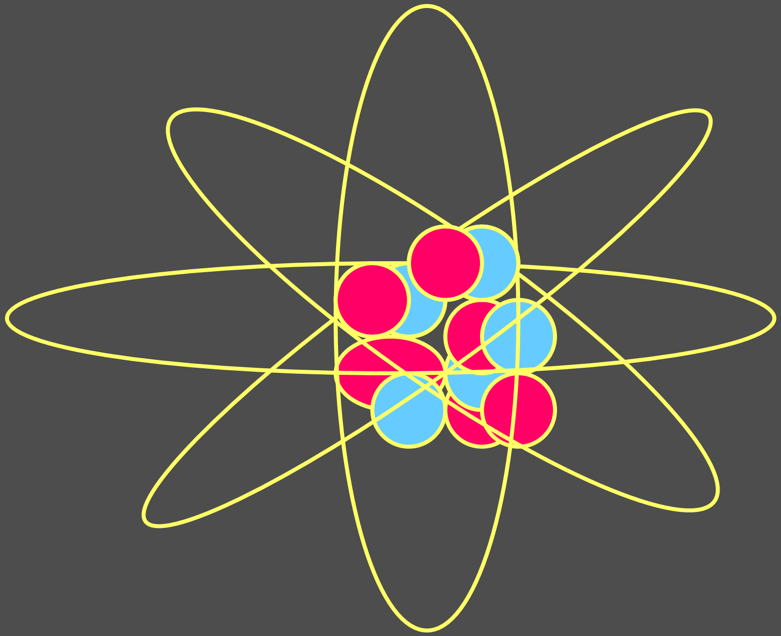
http://www.er.doe.gov/production/henp/np/index.html

http://www.science.doe.gov/hep/index.shtm

Inquiring minds want to know ...



Yo! What holds it together?



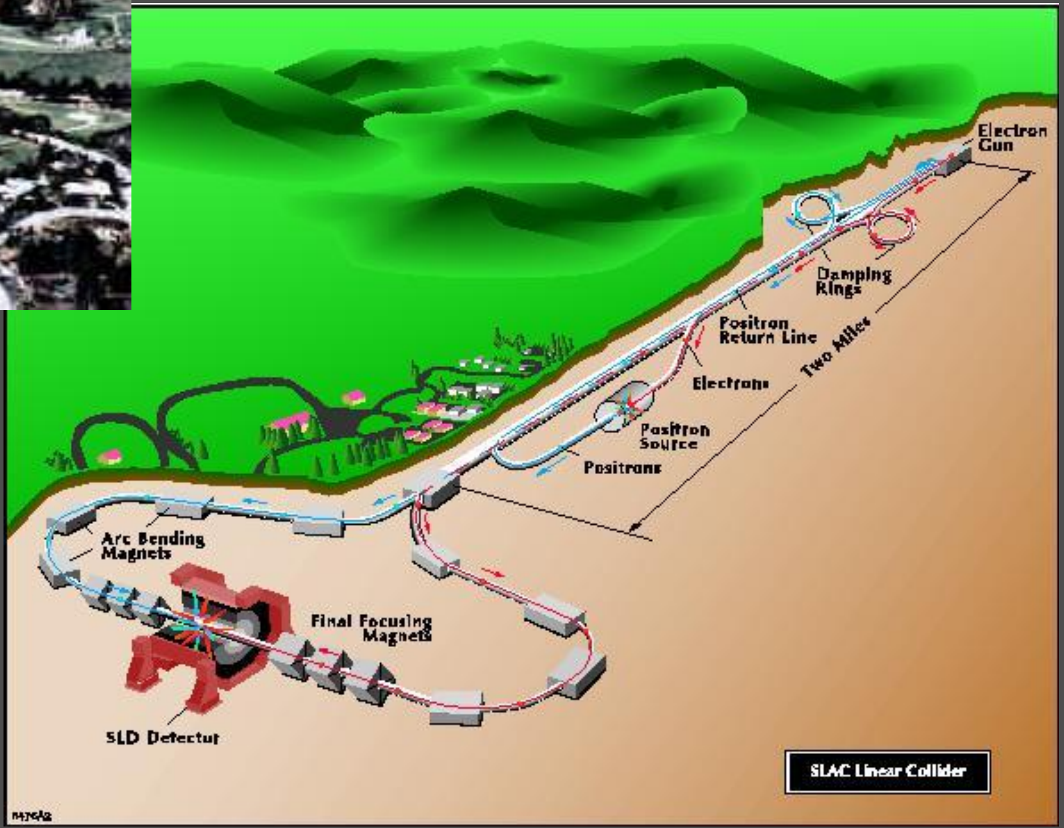

52
46
ACXIOM
27
HASTINGS

Fermi National Accelerator Laboratory (near Chicago)

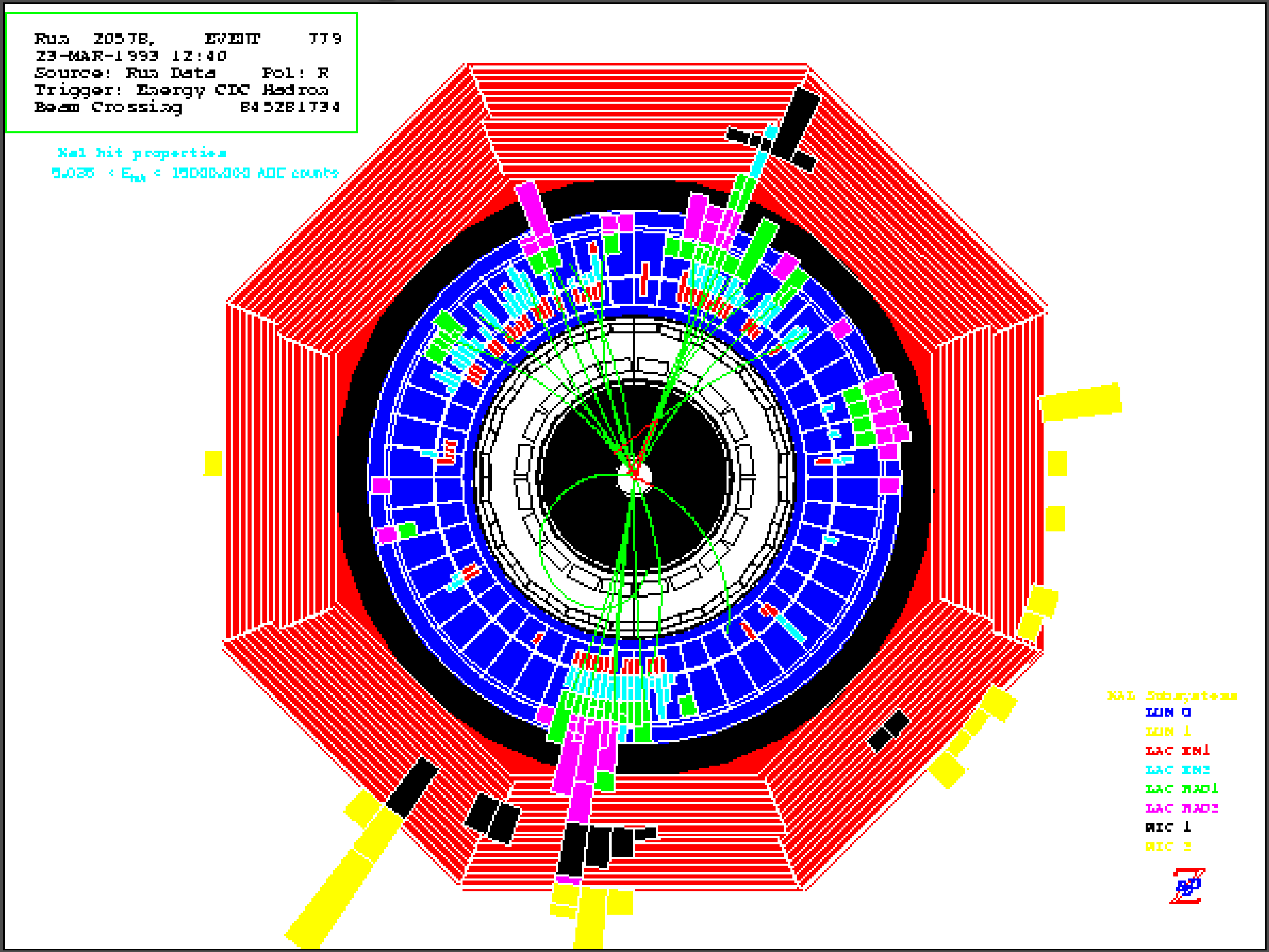
CDF

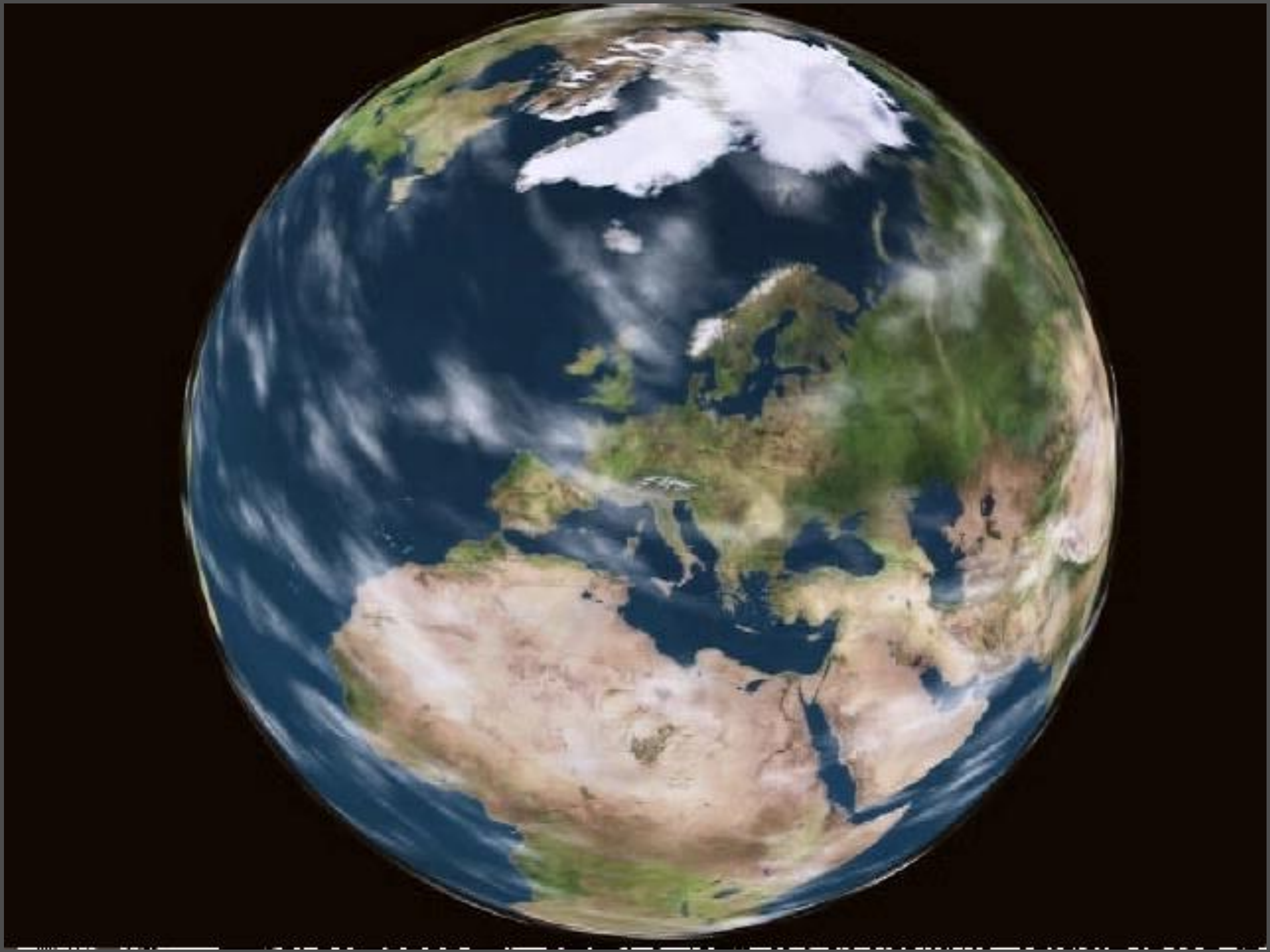
Minos

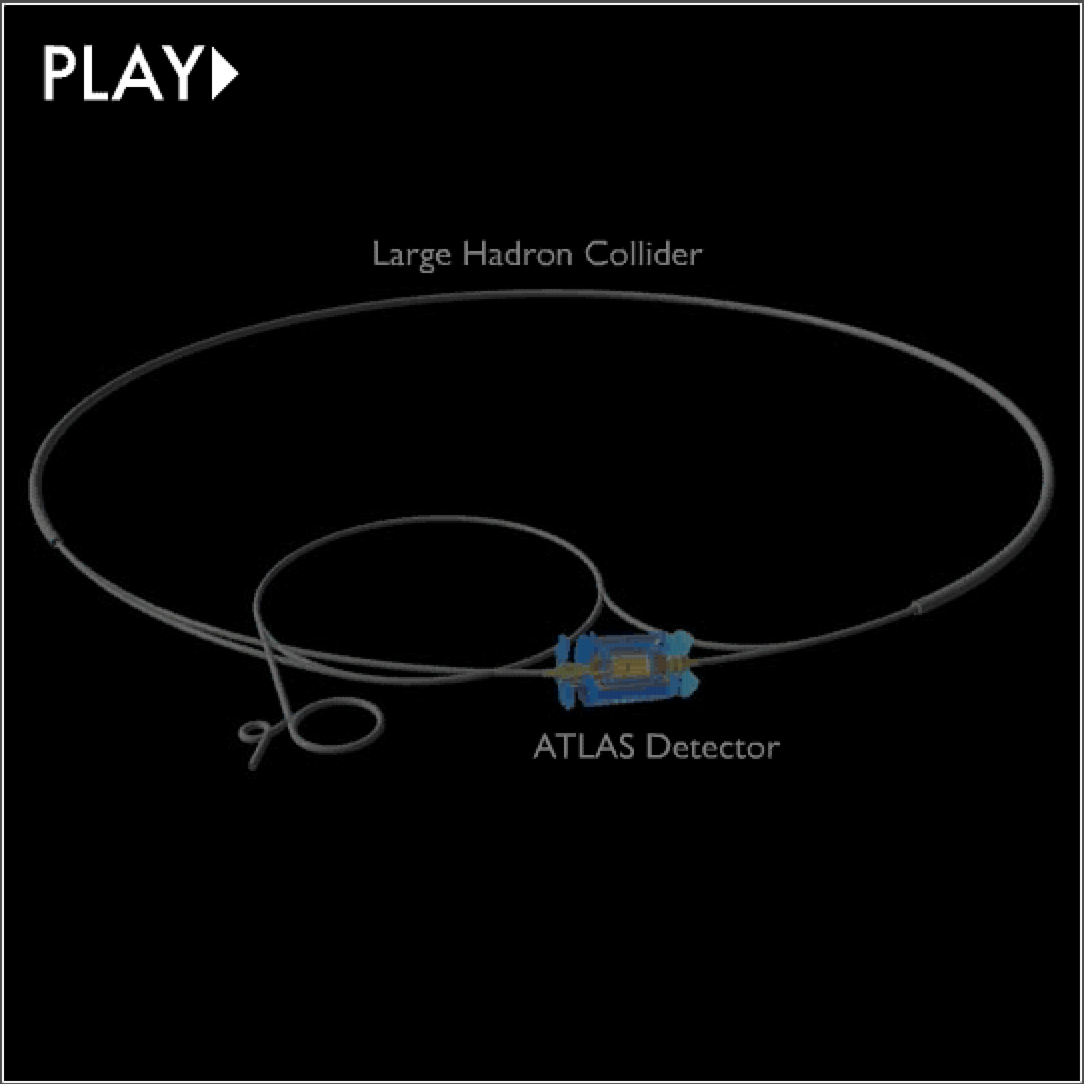
Stanford Linear Accelerator Center



Event display from the SLD experiment at SLAC

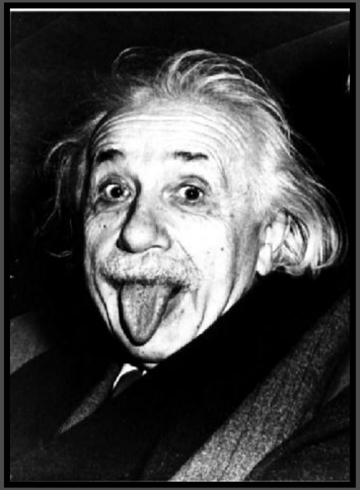





PLAY
Large Hadron Collider
ATLAS Detector

What forces exist in nature?

What is a force?



How do they interact?

How do forces change with energy or temperature?

How has the universe evolved?

π^0 $I^G(J^{PC}) = 1^-(0^{-+})$

Mass $m = 134.9766 \pm 0.0006$ MeV (S = 1.1)

$m_{\pi^\pm} - m_{\pi^0} = 4.5936 \pm 0.0005$ MeV

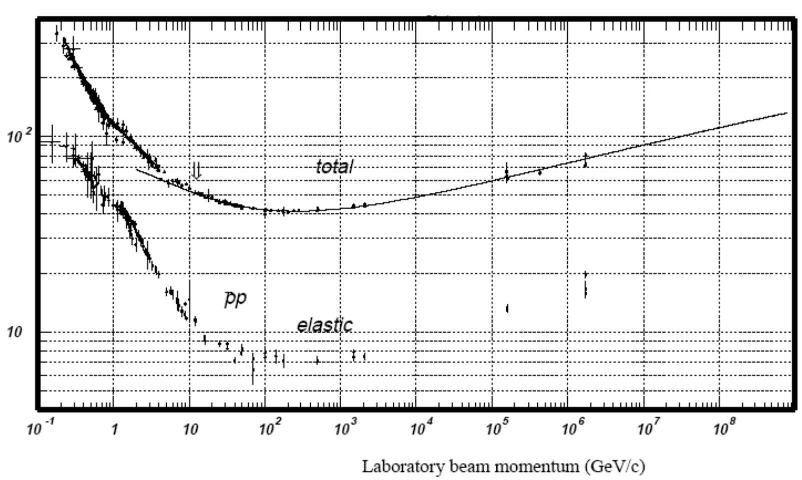
Mean life $\tau = (8.4 \pm 0.6) \times 10^{-17}$ s (S = 3.0)

$c\tau = 25.1$ nm

For decay limits to particles which are not established, see the appropriate Search sections (A^0 (axion), and Other Light Boson (X^0) Searches, etc.).

π^0 DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
2γ		(98.798 ± 0.032) %	S=1.1	67
$e^+e^-\gamma$		(1.198 ± 0.032) %	S=1.1	67
γ positronium		$(1.82 \pm 0.29) \times 10^{-9}$		67
$e^+e^+e^-e^-$		$(3.14 \pm 0.30) \times 10^{-5}$		67
e^+e^-		$(6.2 \pm 0.5) \times 10^{-8}$		67
4γ		$< 2 \times 10^{-8}$	CL=90%	67
$\nu\overline{\nu}$	[a]	$< 8.3 \times 10^{-7}$	CL=90%	67
$\nu_e\overline{\nu}_e$		$< 1.7 \times 10^{-6}$	CL=90%	67
$\nu_\mu\overline{\nu}_\mu$		$< 3.1 \times 10^{-6}$	CL=90%	67
$\nu_\tau\overline{\nu}_\tau$		$< 2.1 \times 10^{-6}$	CL=90%	67
$\gamma\nu\overline{\nu}$		$< 6 \times 10^{-4}$	CL=90%	–
Charge conjugation (*C*) or Lepton Family number (*LF*) violating modes				
3γ	C	$< 3.1 \times 10^{-8}$	CL=90%	67
μ^+e^-	LF	$< 3.8 \times 10^{-10}$	CL=90%	26
μ^-e^+	LF	$< 3.4 \times 10^{-9}$	CL=90%	–
$\mu^+e^- + \mu^-e^+$	LF	$< 1.72 \times 10^{-8}$	CL=90%	26

Cross section (mb)



week ending 4 JUNE 2004

→ $\omega\Upsilon(1S)$

E. Coan,[2] Y. S. Gao,[2] F. Liu,[2]
Dorjkhaidav,[3] R. Mountain,[3]
. Mahmood,[4] S. E. Csorna,[5]
pas,[7] A. Shapiro,[7] W. M. Sun,[7]

.S 30 MARCH 1998

ass

mendolia,[27] D. Amidei,[20] J. Antos,[33]
[8] M. Atac,[7] P. Azzi-Bacchetta,[25]

1 MARCH 1999

ıe Measurement
miokande

Itow,[1] T. Kajita,[1] J. Kameda,[1]

26 MAY 1975

e $\psi(3095)$†

ischer, D. Fryberger, G. Hanson,
, D. Lyon, C. C. Morehouse,
R. F. Schwitters,

ıford, California 94305

G. Golhaber, J. A. Kadyk,
Trilling, J. S. Whitaker,

ılifornia, Berkeley, California 94720

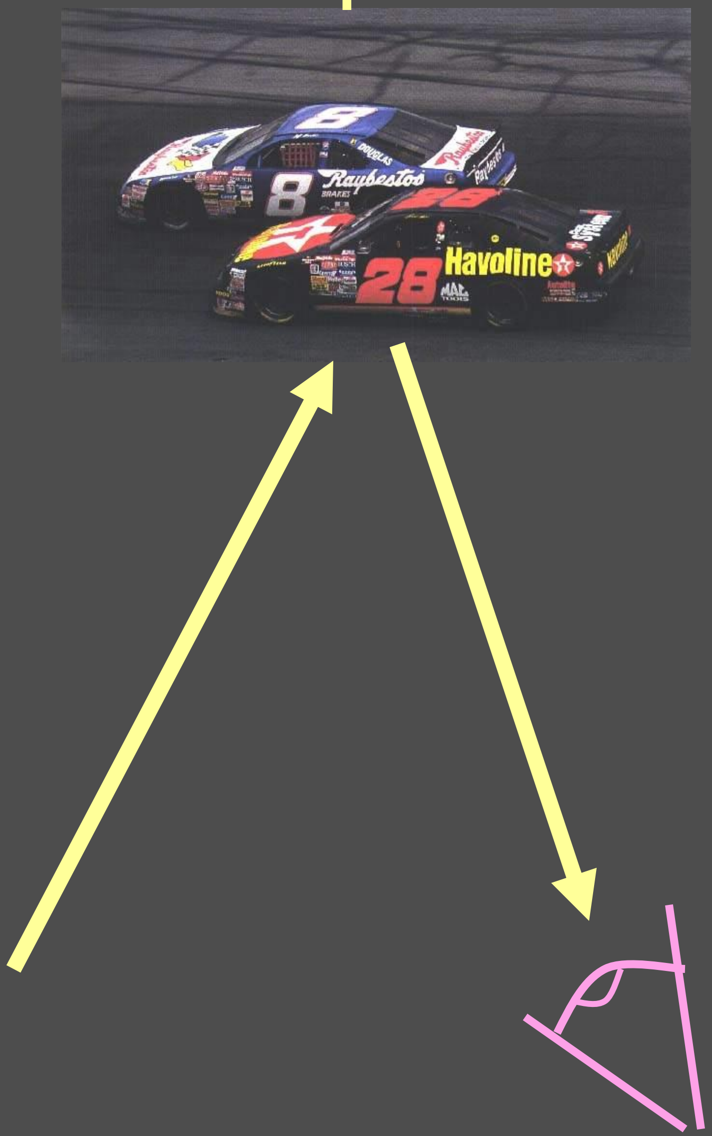
near 3095 MeV. The

Mini-Ph.D. – Quantum Mechanics 101

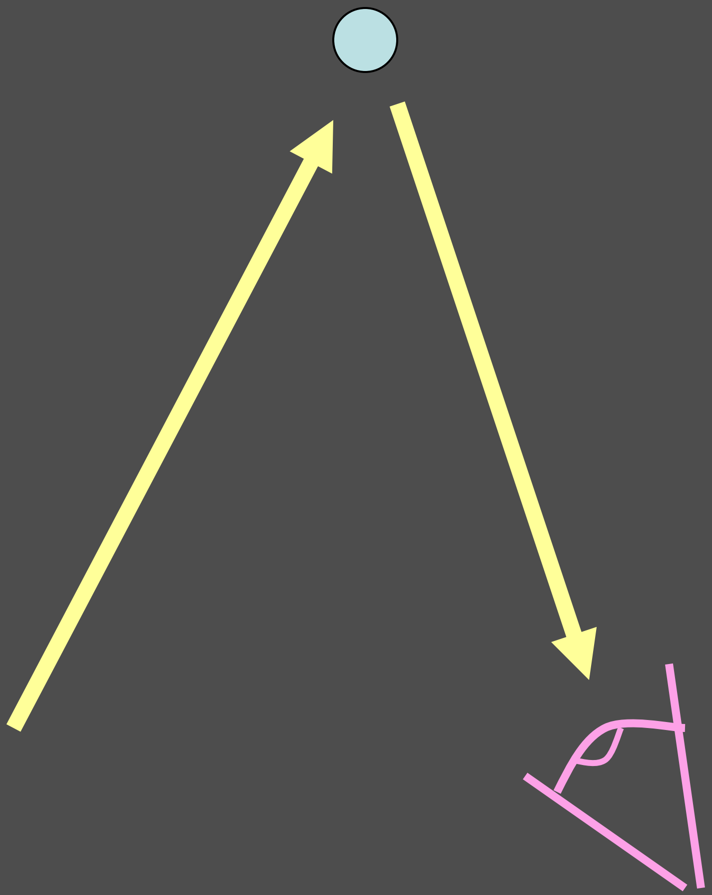
Lesson 1:

Size actually does matter.

Determine the postion and velocity of a car … no problem

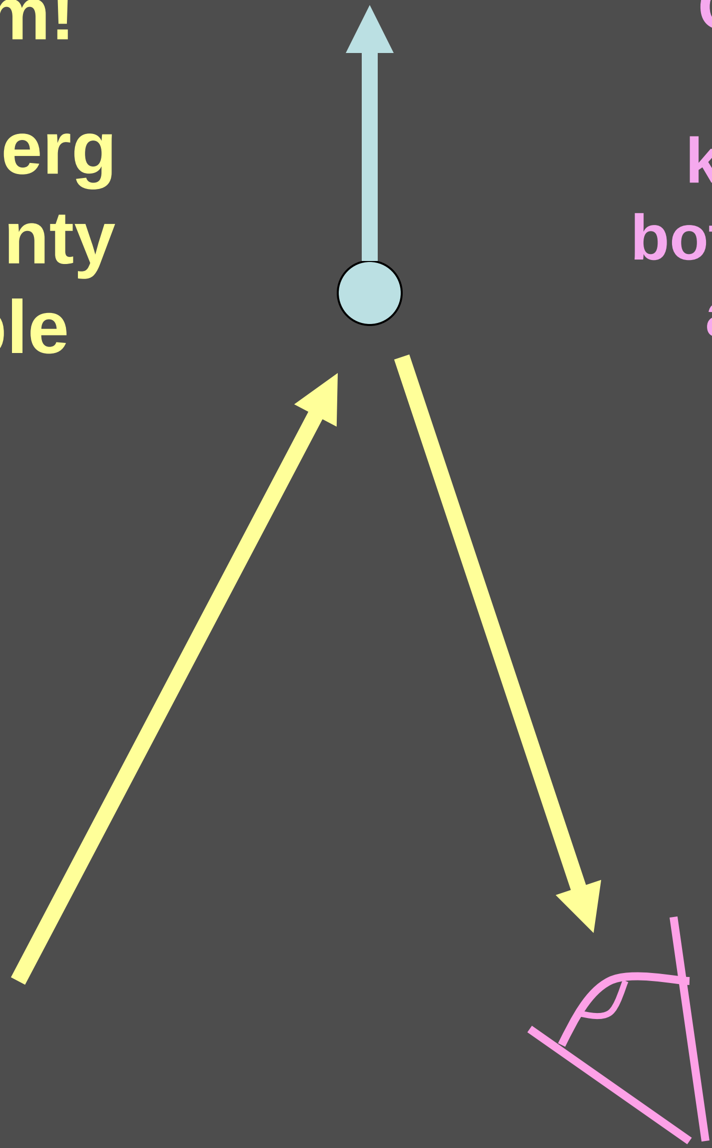


Determine the postion and velocity of a small particle … no problem



Problem!

Heisenberg uncertainty principle



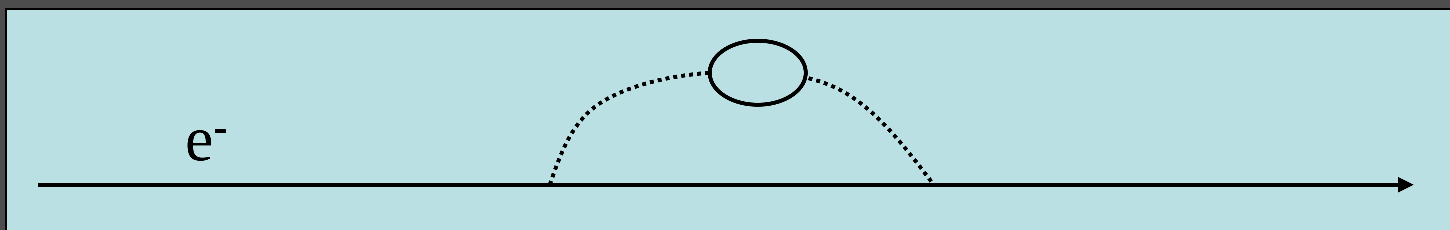
Cannot have perfect knowledge of both the position and velocity

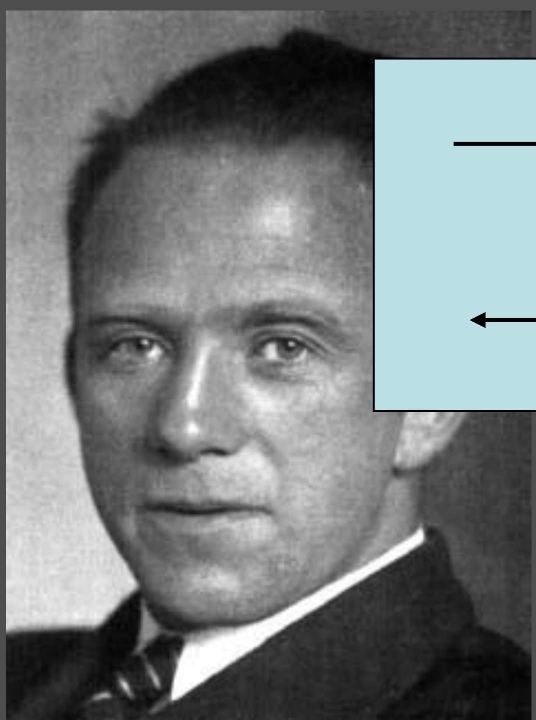
Heisenberg

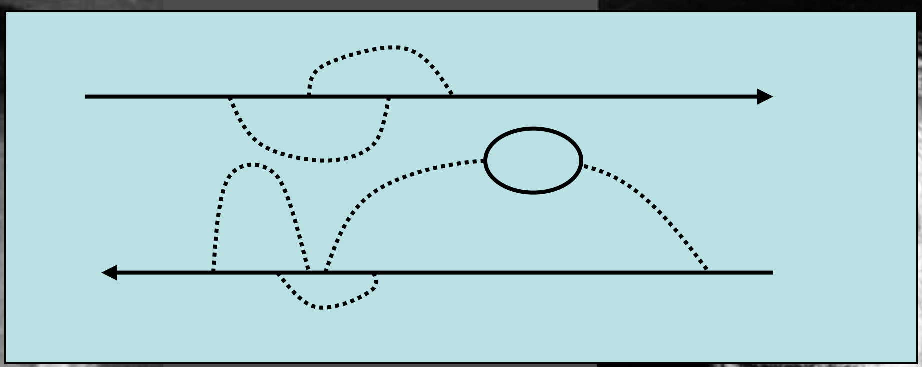
The fundamental nature of forces: virtual particles

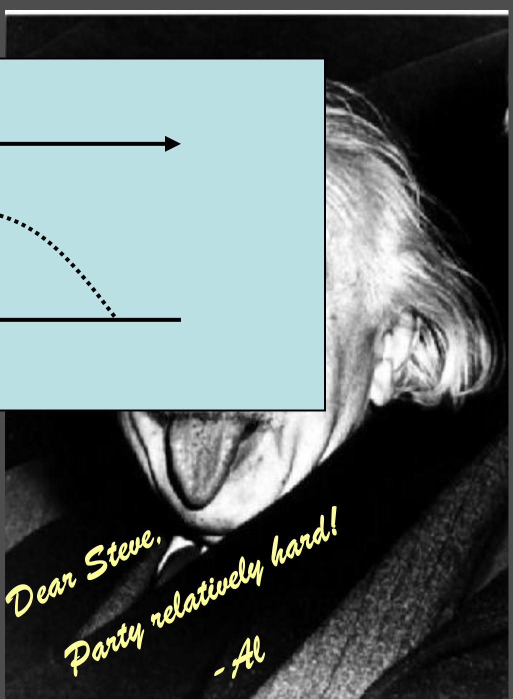
$\Delta E \Delta t \approx h$ Heisenberg

$E = mc^2$ Einstein





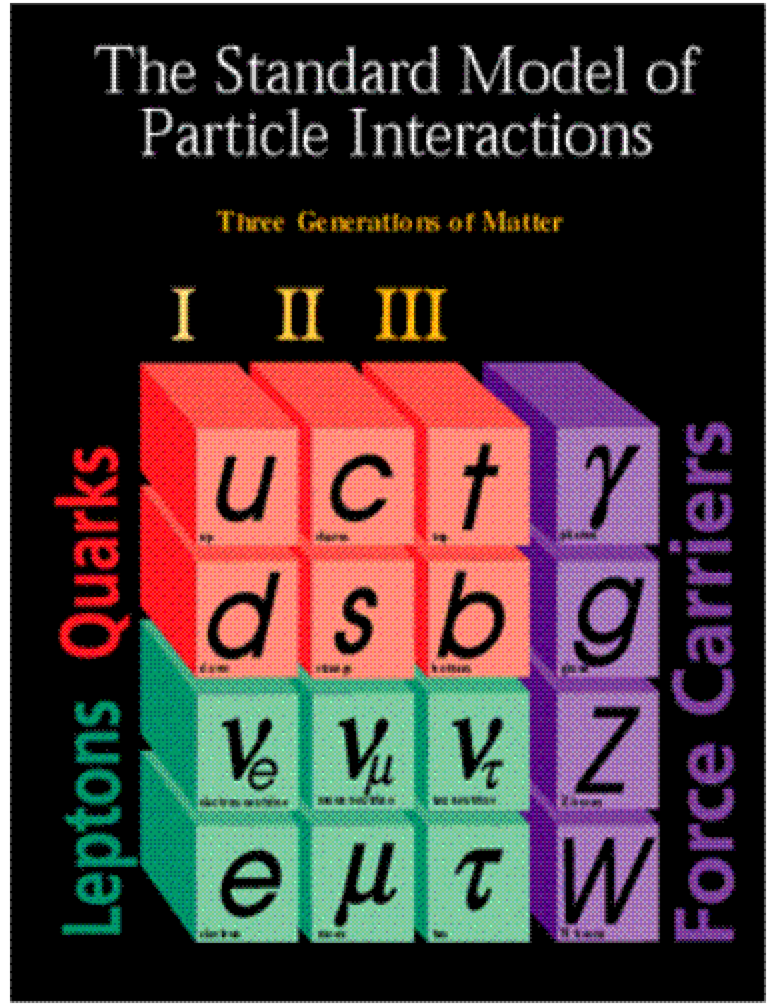




Quantum Field Theory → Exchange force

Force	***Source***	***Range***	***Strength***
Gravitation	mass	infinite	10^{-39}
Electromagnetism	Electric charge	infinite	10^{-2}
Strong nuclear	Color charge	10^{-15} m	1
Weak nuclear	Weak charge	10^{-18} m	10^{-5}

The "Fundamental" particles



Anti Matter

e^- ~ e^+ positron
Anti-electron

$$e^- + e^+ \longrightarrow \gamma\gamma$$

All particles have antiparticles

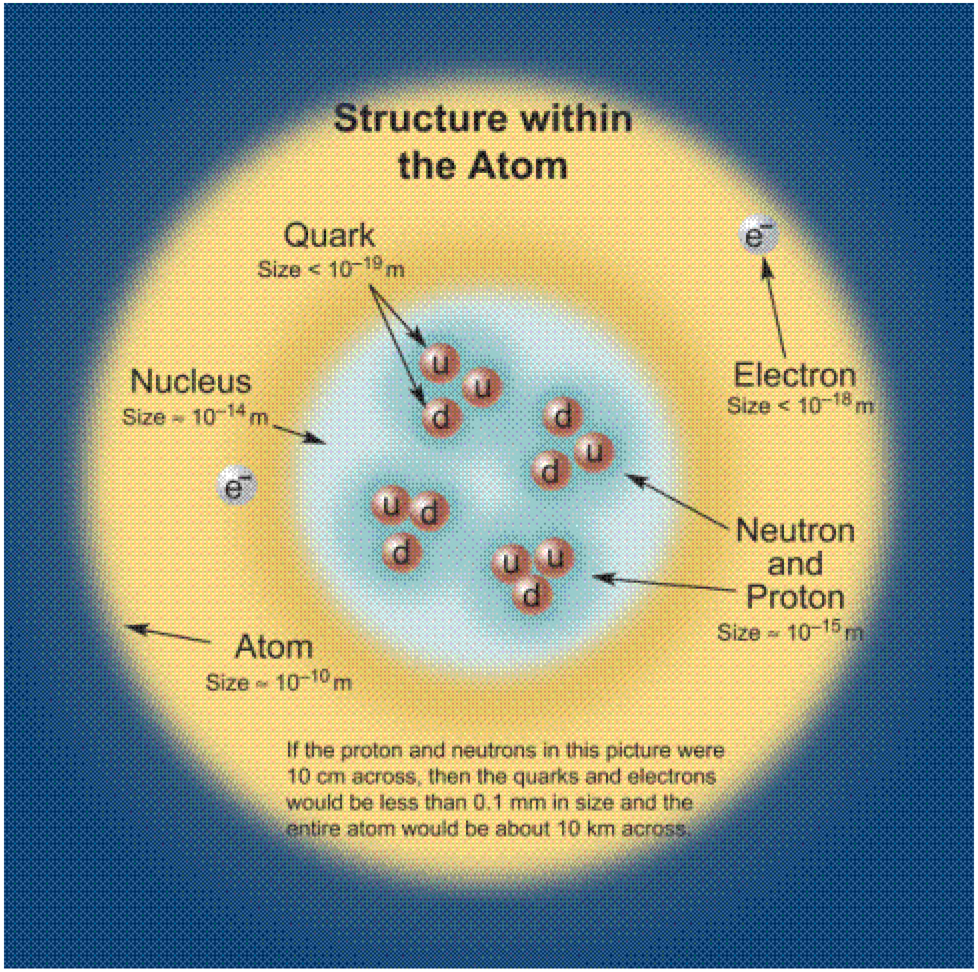
Why is universe made of matter rather than antimatter?
we don't know why this is true ... yet.
Active area of study ... believe it is probably due to a basic matter-Antimatter asymmetry in one of the forces of Nature.

→ Standard Model of Particle Physics

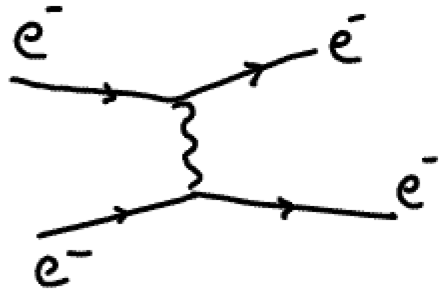
http://particleadventure.org/

http://hepwww.rl.ac.uk/Pub/Phil/ppintro/ppintro.html

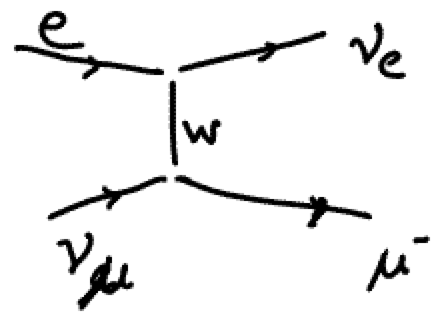
Decent online sources of information - please read



$\Delta E \Delta T \gtrsim h$



Electromagnetism



weak interaction

Strong force

BOSONS

force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

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

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

other particles

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.

These are a few of the many types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	**uud**	1	0.938	1/2
$\bar{\mathbf{p}}$	antiproton	$\bar{\mathbf{u}}\bar{\mathbf{u}}\bar{\mathbf{d}}$	–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

qqq

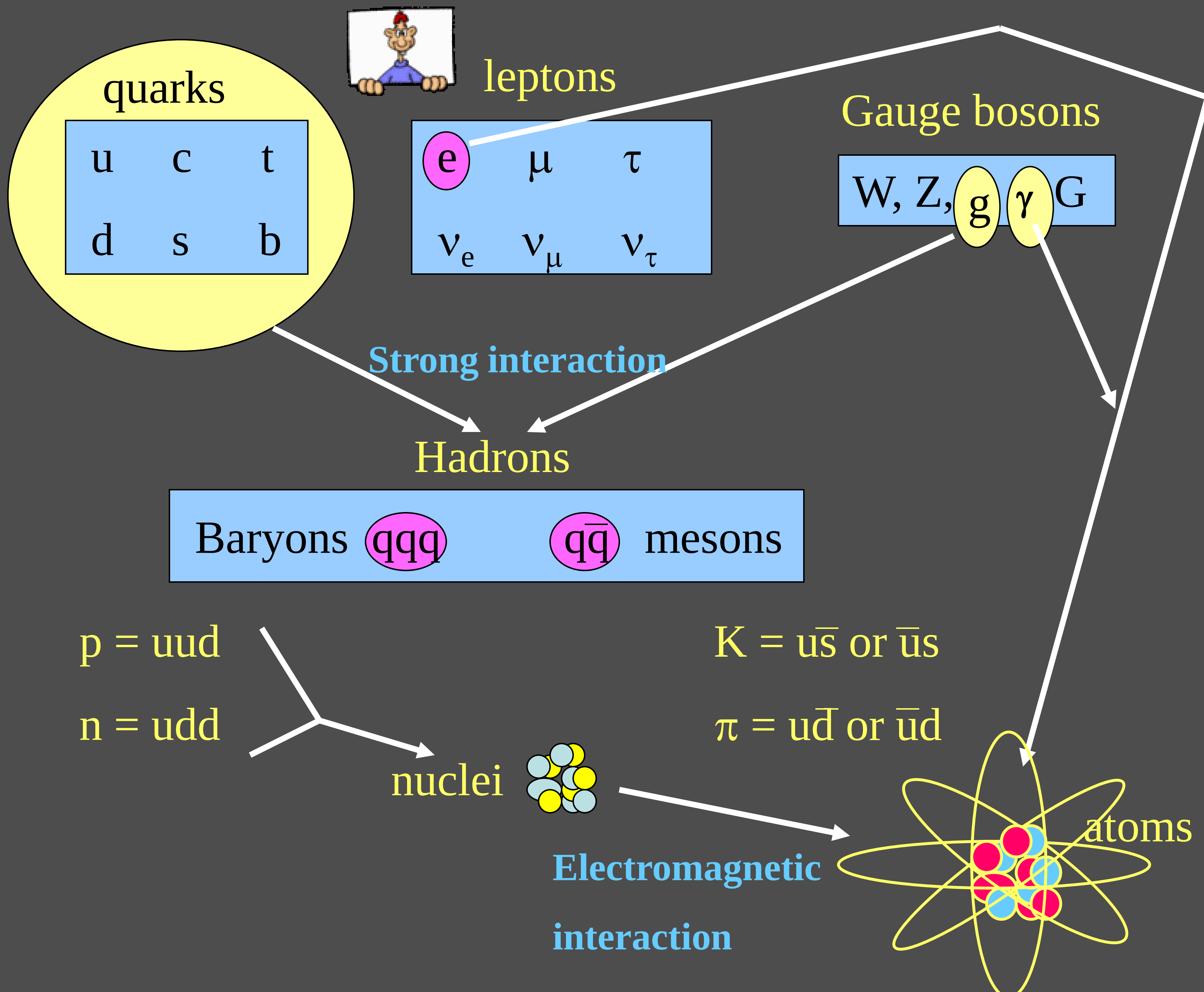
$q\bar{q}$

Mesons $q\bar{q}$

Mesons are bosonic hadrons

These are a few of the many types of mesons.

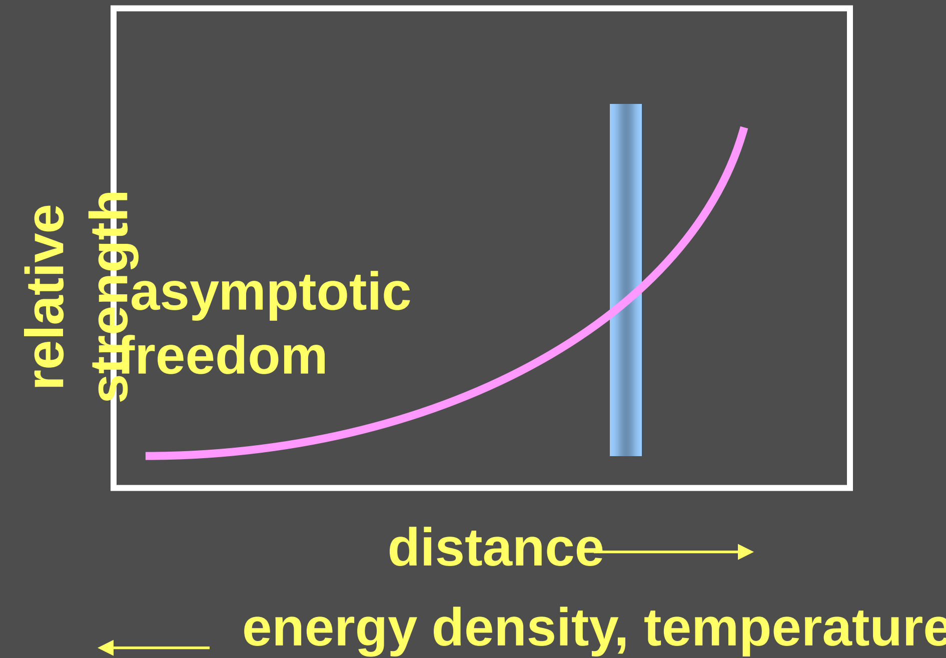
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$\mathbf{u}\bar{\mathbf{d}}$	+1	0.140	0
K^-	kaon	$\mathbf{s}\bar{\mathbf{u}}$	–1	0.494	0
ρ^+	rho	$\mathbf{u}\bar{\mathbf{d}}$	+1	0.776	1
B^0	B-zero	$\mathbf{d}\bar{\mathbf{b}}$	0	5.279	0
η_c	eta-c	$\mathbf{c}\bar{\mathbf{c}}$	0	2.980	0

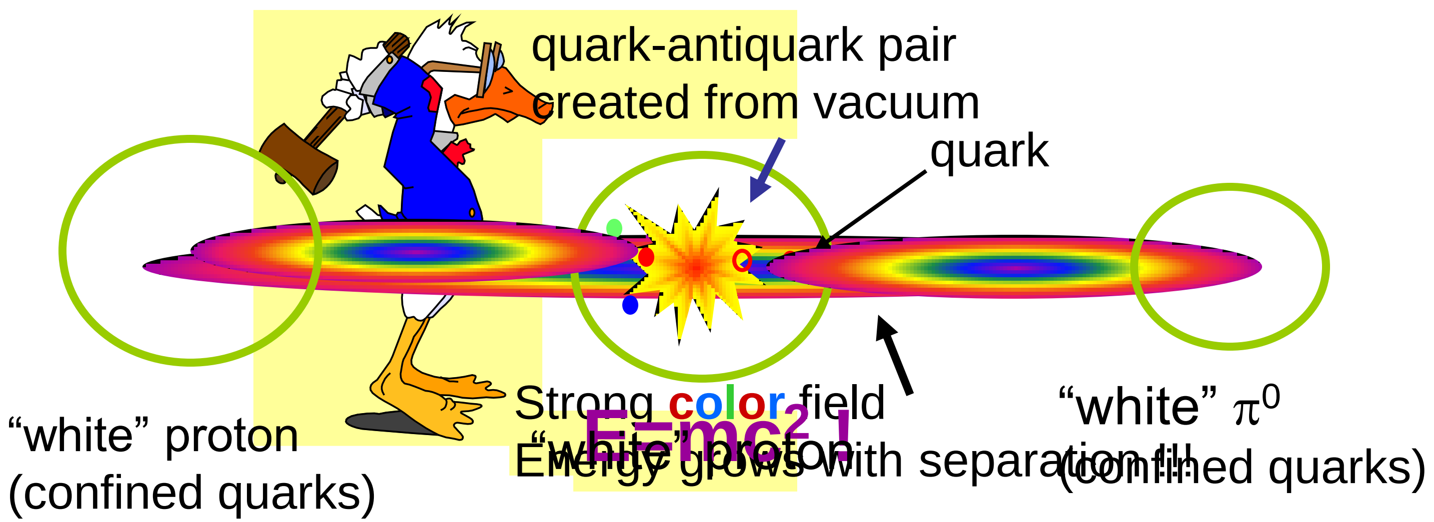


quarks
u c t
d s b
leptons
e μ τ
ν_e ν_μ ν_τ
Gauge bosons
W, Z, g γ G
Strong interaction
Hadrons
Baryons qqq
$q\bar{q}$ mesons
p = uud
n = udd
K = $u\bar{s}$ or $\bar{u}s$
π = $u\bar{d}$ or $\bar{u}d$
nuclei
atoms
Electromagnetic
interaction

Quantum Chromodynamics QCD

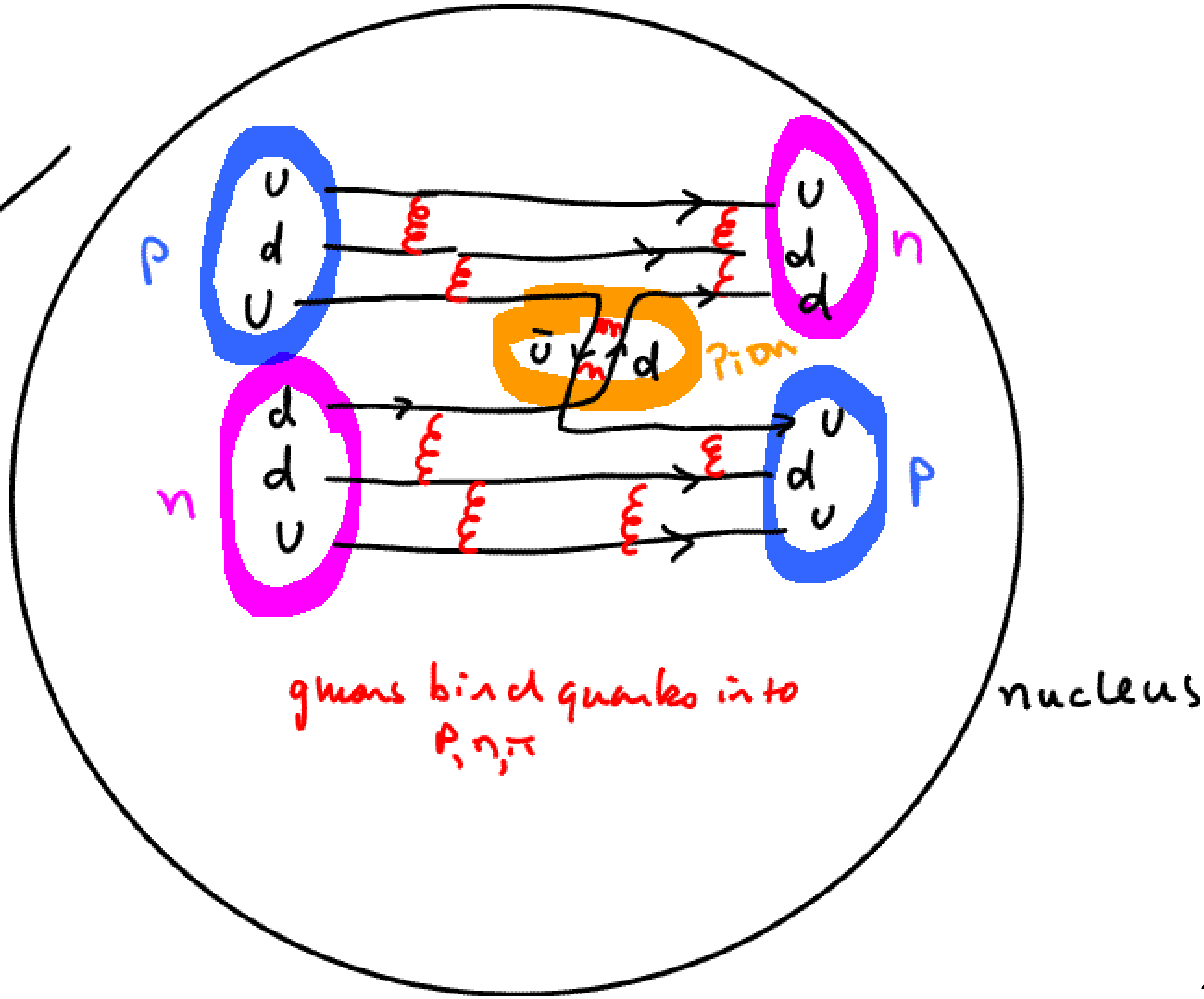
Why bare quarks have never been observed.



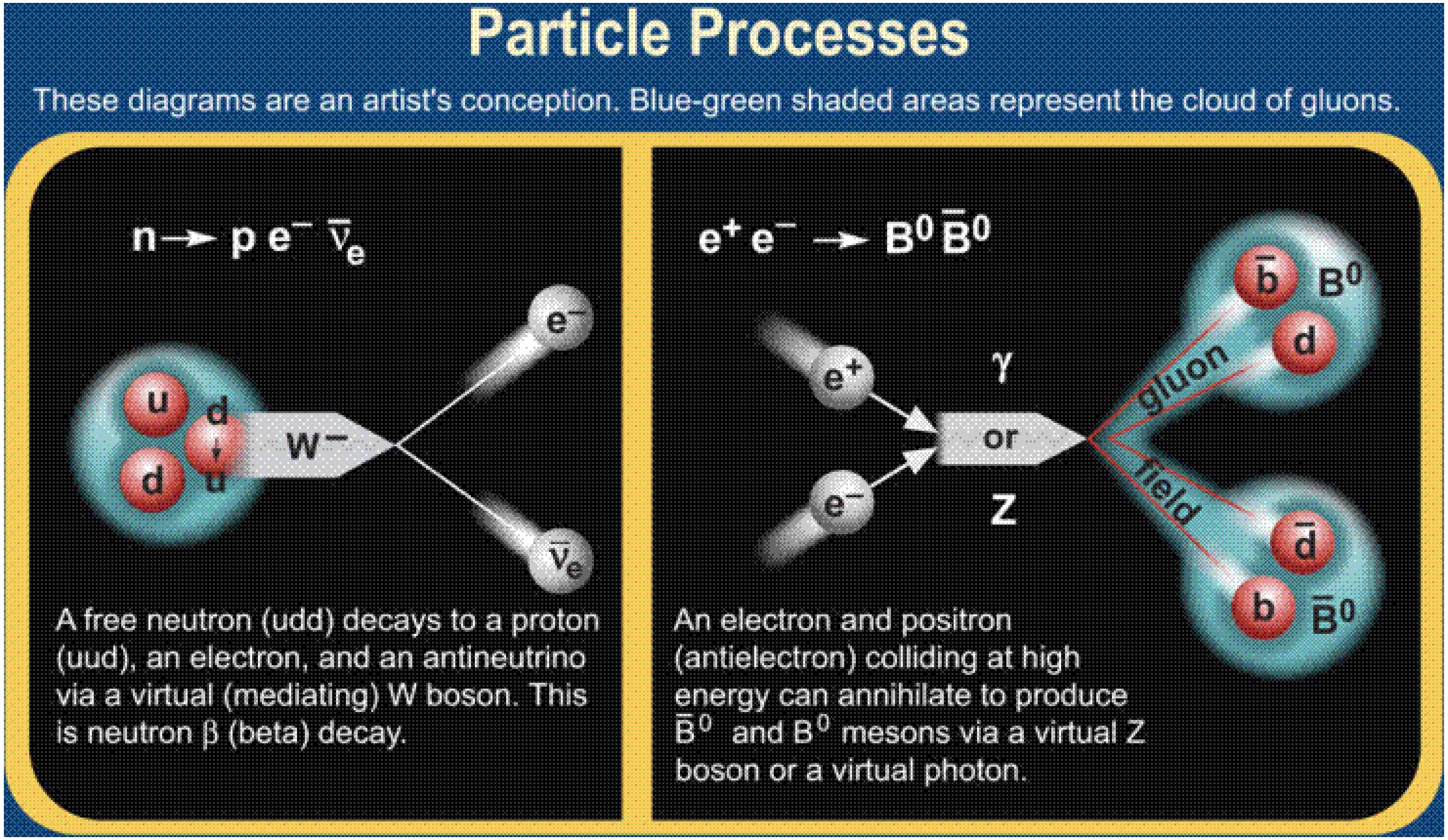


Thanks to Mike Lisa (OSU) for parts of this nucleon-nucleon force – exchange of π (pion)

fine point for completeness



Example


Particle Processes
These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.
$n \rightarrow p\, e^- \bar{\nu}_e$
u
d
d
u
W^-
e^-
$\bar{\nu}_e$
A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.
$e^+ e^- \rightarrow B^0 \bar{B}^0$
e^+
e^-
γ
or
Z
gluon
field
$\bar{b}$
d
B^0
$\bar{d}$
b
$\bar{B}^0$
An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

The Vacuum

-R. Kolb

Much ado about NOTHING:

Nothing is something

Nothing has energy

Nothing interacts with something

Electroweak Unification + the Higgs Particle

Standard Model

A few of the players

Kibble, Guralnik,
Hagen, Englert, Brout

Peter Higgs

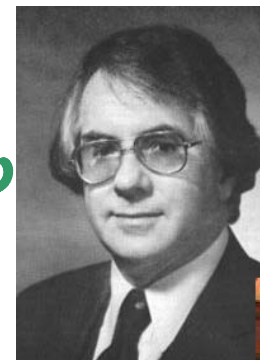
1979 Nobel Prize in physics

Abdus Salam

© Pressens Bild

10 December 1979. Salam receives the Nobel Prize from King Carl XVI Gustav of Sweden.

Sheldon Glashow



Stephen Weinberg

Weak interaction → β decay

EM interaction → Quantum Electrodynamics

} NO MASS

Weak int. + EM int + Higgs Boson

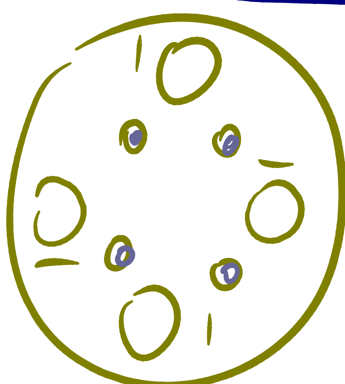
Mathematically Mix → Spontaneous Symmetry Breaking

→ Masses for particles

$W^{+/-}$, Z^0

other properties

4 place settings at table



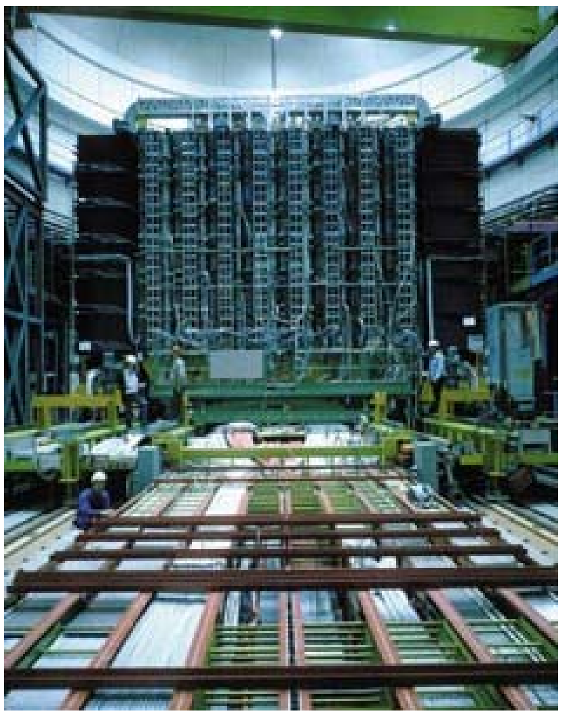
1st person sits and drinks water → Breaks symmetry for all

Discovery of the $W^{+/-}$ and Z^0 particles (along w/ large collaborations)

1984 Nobel Prize in Physics

Carlo Rubbia

Simon van der Meer



UA1 Experiment at CERN

~~Higgs~~ ?

We have yet to observe the Higgs

Phenomenal success of STANDARD Model forces us to take it seriously...

So, we know that

STANDARD Model

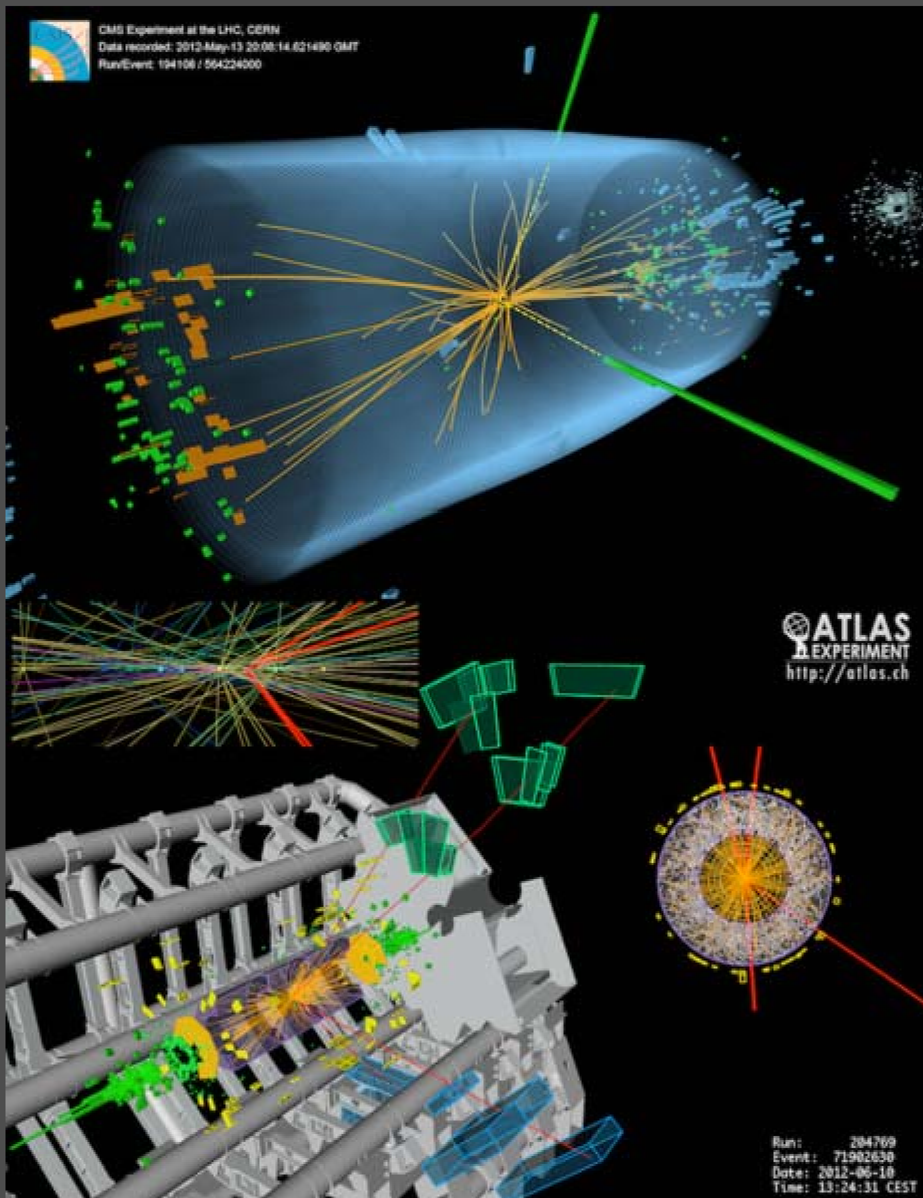
Electromagnetic } + (Strong
Weak }

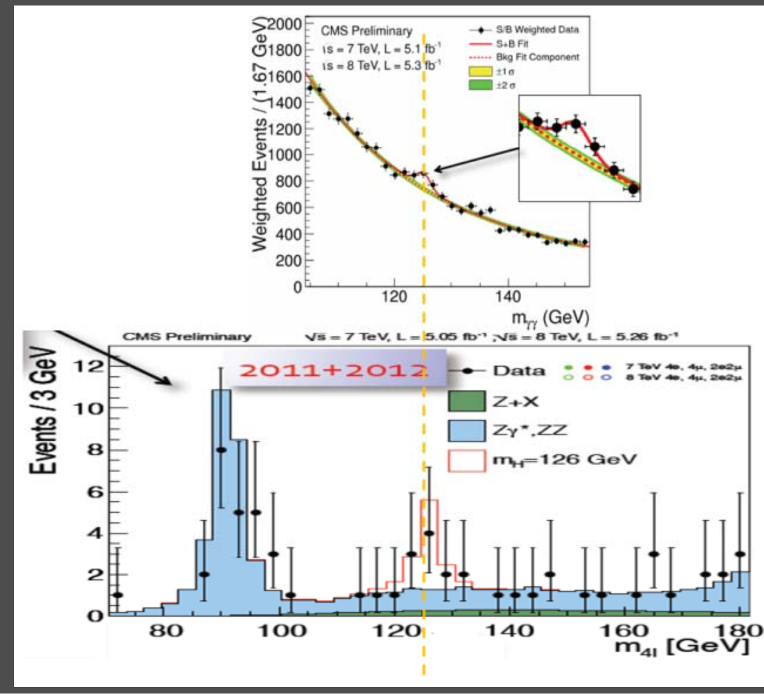
Something does what the Higgs does

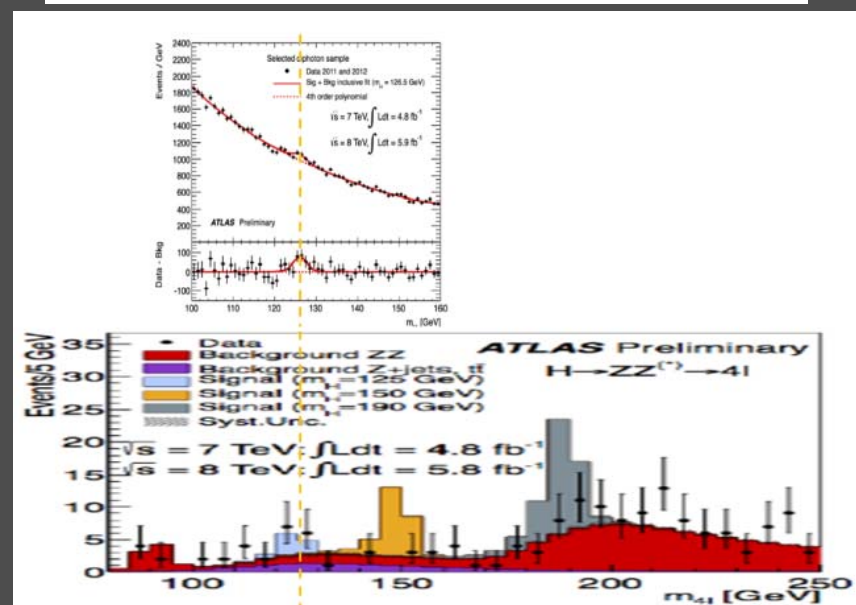
could be something besides a fundamental particle

Supersymmetry is one such possibility

May talk abt this later in course.

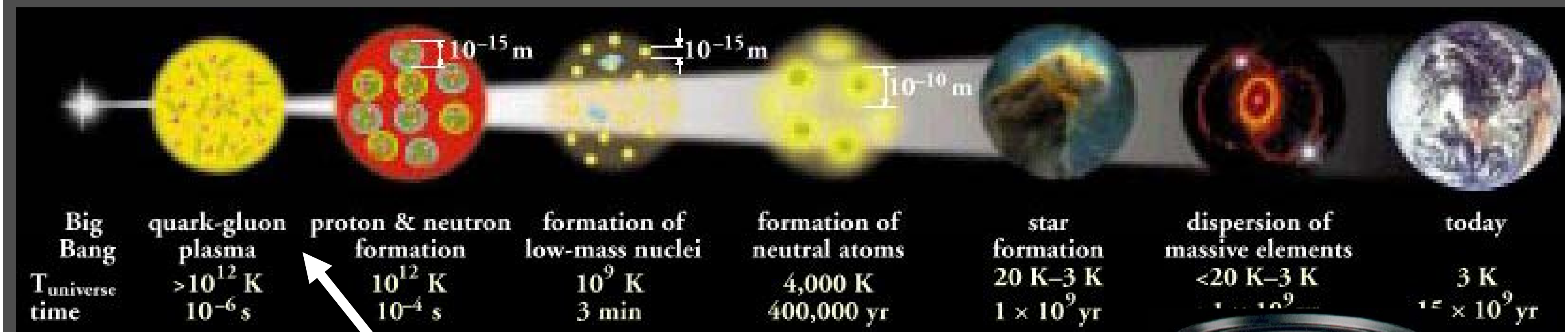

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
ATLAS EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST


CMS Preliminary
S/B Weighted Data
S+B Fit
Bkg Fit Component
Weighted Events / (1.67 GeV)
$m_{\gamma\gamma}$ (GeV)
CMS Preliminary
2011+2012
Data
Z+X
Zγ*,ZZ
m_H=126 GeV
Events / 3 GeV
m_{4l} [GeV]


ATLAS Preliminary
Data
Background ZZ
Signal
Syst.Unc.
H→ZZ(*)→4l
√s = 7 TeV: ∫Ldt = 4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 5.8 fb⁻¹
Events/5 GeV
m_{4l} [GeV]

Modern accelerators study processes at energies that existed VERY early in the universe

Another form of time travel !



What were forces like at those temperatures?

What types of particles existed?