

# Particles and Interactions

- Particles
  - ▶ Fermions and bosons
  - ▶ Mesons and baryons
  - ▶ Energy, mass and momentum
- Interactions
- Mass versus Range
- deBroglie wavelength
- Vacuum polarization
- Running coupling constants
- Unification of forces

# Summary

## ■ From PDG

BOSONS			FERMIONS			matter constituents		
force carriers			spin = 1/2			spin = 1/2, 3/2, 5/2, ...		
spin = 0, 1, 2, ...			Leptons			Quarks		
Name	Mass GeV/c <sup>2</sup>	Electric charge	Flavor	Mass GeV/c <sup>2</sup>	Electric charge	Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
Unified Electroweak	spin = 1		$\nu_e$ electron neutrino	<1·10 <sup>-8</sup>	0	u up	0.003	2/3
$\gamma$ photon	0	0	e electron	0.000511	-1	d down	0.006	-1/3
$W^-$	80.4	-1	$\nu_\mu$ muon neutrino	<0.0002	0	c charm	1.3	2/3
$W^+$	80.4	+1	$\mu$ muon	0.106	-1	s strange	0.1	-1/3
$Z^0$	91.187	0	$\nu_\tau$ tau neutrino	<0.02	0	t top	175	2/3
			$\tau$ tau	1.7771	-1	b bottom	4.3	-1/3

PROPERTIES OF THE INTERACTIONS					
Property	Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	Strong
Acts on:		Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:		All	Quarks, Leptons	Electrically charged	Quarks, Gluons
Particles mediating:		Graviton (not yet observed)	$W^+$ $W^-$ $Z^0$	$\gamma$	Gluons
Strength relative to electromag for two u quarks at:		10 <sup>-41</sup>	0.8	1	25
for two protons in nucleus		10 <sup>-41</sup>	10 <sup>-4</sup>	1	60
		10 <sup>-36</sup>	10 <sup>-7</sup>	1	Not applicable to hadrons
					20




To name but a few... see "PDG" (online) for details

Mesons $q\bar{q}$					
Mesons are bosonic hadrons. There are about 140 types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c <sup>2</sup>	Spin
$\pi^+$	pion	$u\bar{d}$	+1	0.140	0
$K^-$	kaon	$s\bar{u}$	-1	0.494	0
$\rho^+$	rho	$u\bar{d}$	+1	0.770	1
$B^0$	B-zero	$d\bar{b}$	0	5.279	0
$\eta_c$	eta-c	$c\bar{c}$	0	2.980	0

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 <sup>2</sup>	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
$\Lambda$	lambda	uds	0	1.116	1/2
$\Omega^-$	omega	sss	-1	1.672	3/2

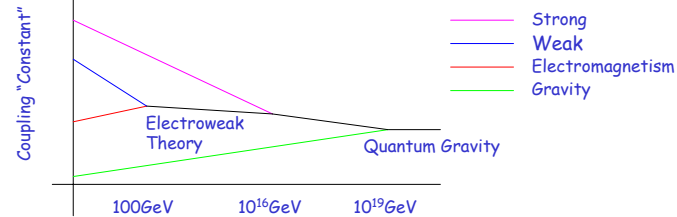
# Unification of forces

- James Clerk Maxwell (1831-1879) unifies Electrostatics and Magnetism into the theory of Electromagnetism (19th Century) 
- Albert Einstein (1879-1955) tried to develop a UNIFIED theory of nature without success from 1916 until 1955 
- Quantum Theory of Electromagnetism developed by Feynman, Dyson, Schwinger, Tomonaga. Quantum Electrodynamics (QED) in 1940 
- Glashow, Salam and Weinberg unify Electromagnetism and Weak force into the ElectroWeak theory (1979 Nobel prize)
- Unification of strong / electroweak forces at 10<sup>16</sup>GeV?
- Unification of all forces of nature (Electromagnetism, Weak, Strong and Gravity) at the Planck scale of 10<sup>19</sup>GeV??
  - ▶ BUT THEORISTS ARE WORKING ON THIS

Remember that coupling constants "run", or that they change their strength, with energy.

For electromagnetism we saw the coupling constant increase with energy.

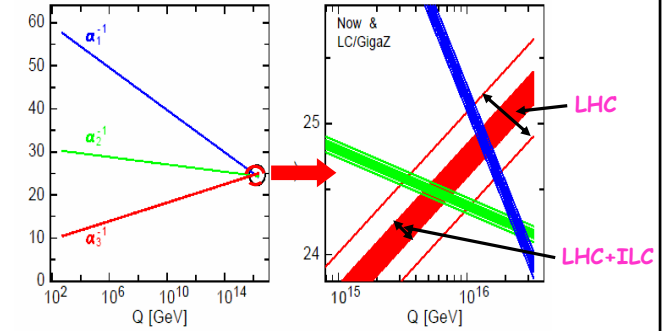
For the weak force the coupling constant decreases with energy. E.M. and weak become UNIFIED at  $\sim 100\text{GeV}$ .



Requires gauge coupling unification

Low energy SUSY

Nucleon decay



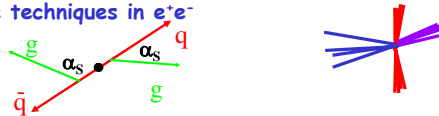
[Allanach, Blair, Kraml, Martyn, Polesello, Porod, Zerwas, LHC-LC Report, p339]

## Strong Coupling "constant", $\alpha_s$

- $\alpha_s$  the fundamental, universal QCD parameter
- Standard Model predicts "momentum scale",  $Q$  ( $\sim \sqrt{s}$ ) evolution, but not absolute value
  - ▶ Perturbative effects, varying as  $\sim 1/\ln Q$
  - ▶ Non-perturbative effects, varying as  $\sim 1/Q$

- Test: measure different processes, energies

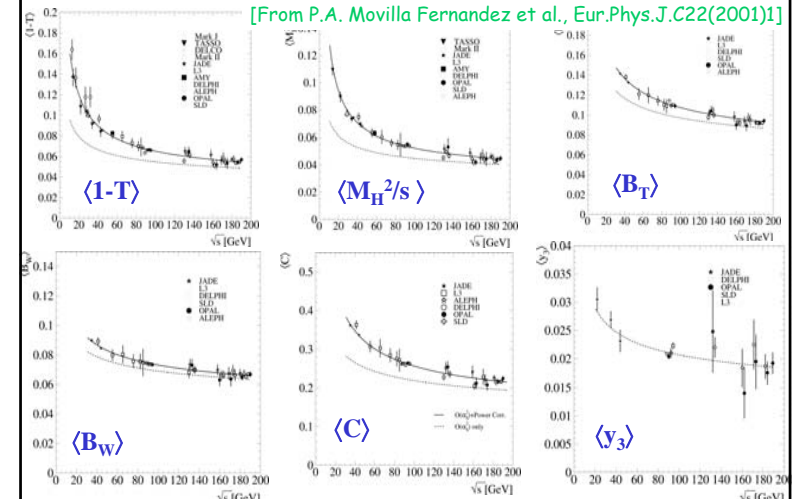
- Intuitive techniques in  $e^+e^-$



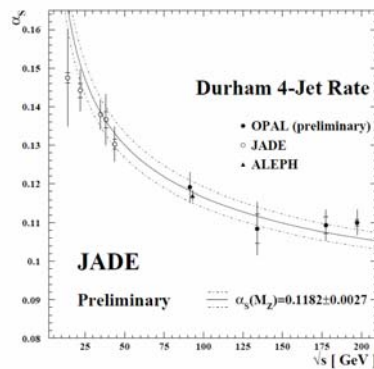
- Precision low, O(%) cf. electroweak O( $10^{-5}$ )

## Global $\alpha_s$ measurements, various $e^+e^-$ observables

[From P.A. Movilla Fernandez et al., Eur.Phys.J.C22(2001)1]



## Strong coupling constant



- $\alpha_s$  is strong force coupling constant
- Momentum scale-dependent value
  - ▶ Illustrate by measurement at different centre-of-mass energies in  $e^+e^-$  collisions



## Lectures 3-4

- Symmetries in HEP
  - ▶ Including Higgs Mechanism
- Puzzles in HEP
  - ▶ SUSY, GUTs, ...