Physics 661

Particle Physics Phenomenology

October 16, 2003

Interactions and Fields

- Quantum Picture of Interactions ✓
- Yukawa Theory ✓
- Boson Propagator
- Feynman Diagrams
- Electromagnetic Interactions
- Renormalization and Gauge Invariance
- Strong Interactions
- Weak and Electroweak Interactions
- Gravitational Interactions
- Cross-sections
- Decays and resonances
- The Δ^{++} pion-proton resonance
- The Z^0 resonance
- Resonances in astrophysics

Boson Propagator

- The boson "propagator" is:

$$f(q) = g_0 g \,/\, (|q|^2 + m^2)$$

where q is the momentum of the boson, and m is its mass.

- This "propagator" can be derived by taking the Fourier transform of the potential:

$$f(q) = g \int U(r)\, e^{iq \cdot r}\, dV$$

- Therefore, the "propagator" describes the potential in momentum space

Boson Propagator

The “propagator” can be generalized to four-momentum transfer:

$$f(q) = g_0 g \,/\, (q^2 + m^2),$$

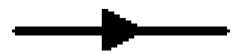
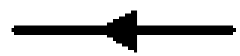
where now $q^2 = (\Delta p)^2 - (\Delta E)^2$,

is the 4-momentum transfer

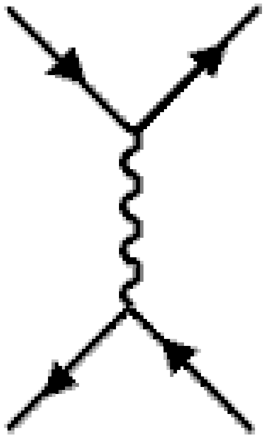
Rates are proportional to the propagator:

$$W = |f|^2 \times \text{Phase Space} \ldots$$

Feynman Diagrams

- Interactions can be depicted with Feynman diagrams
  - electrons 
  - photons 
  - positrons 
    - (equivalent to electron moving backward in time)
  - electron emits a photon 
  - electron absorbs a photon 

Feynman Diagrams



- Virtual particles
  - lines joining vertices represent virtual particles (undefined mass)

- Vertices are represented by coupling constants, and virtual particles by propagators

Electromagnetic Interactions

- The fine structure constant specifies the strength of the EM interaction between particle and photons:

$$\alpha = e^2 / 4\pi\hbar c = 1 / 137.0360.....$$

- Emission and absorption of a photon represents the basic EM interaction

vertex amplitude = $\sqrt{\alpha} = e$

cannot occur for free particle

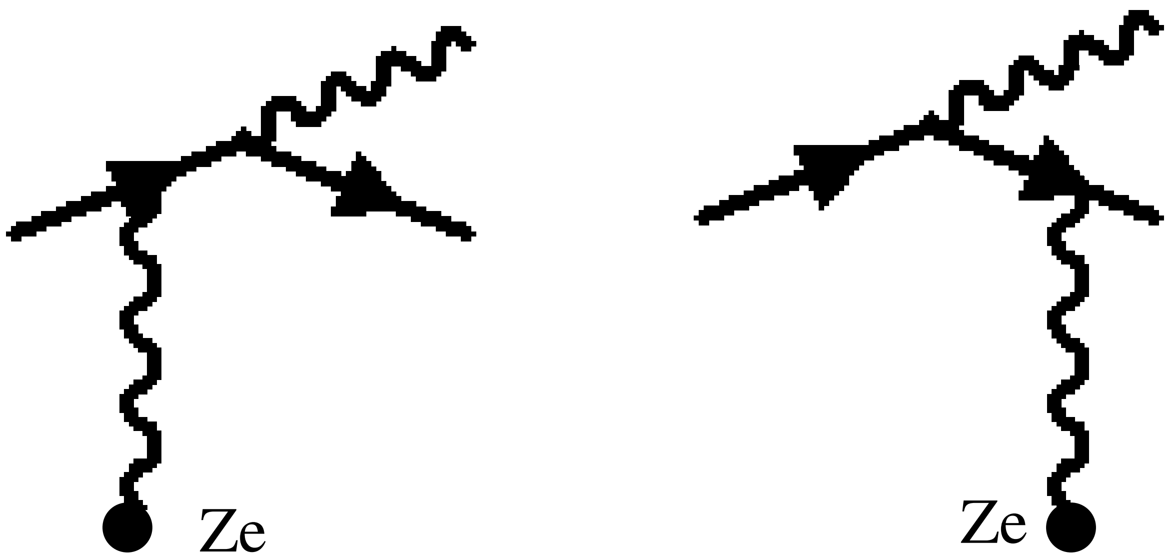
Electromagnetic Interactions

- Coulomb scattering between two electrons:

- Amplitude: α / q^2
- Cross Section = |Amp|^2: α^2 / q^4
  - the Rutherford scattering formula

Electromagnetic Interactions

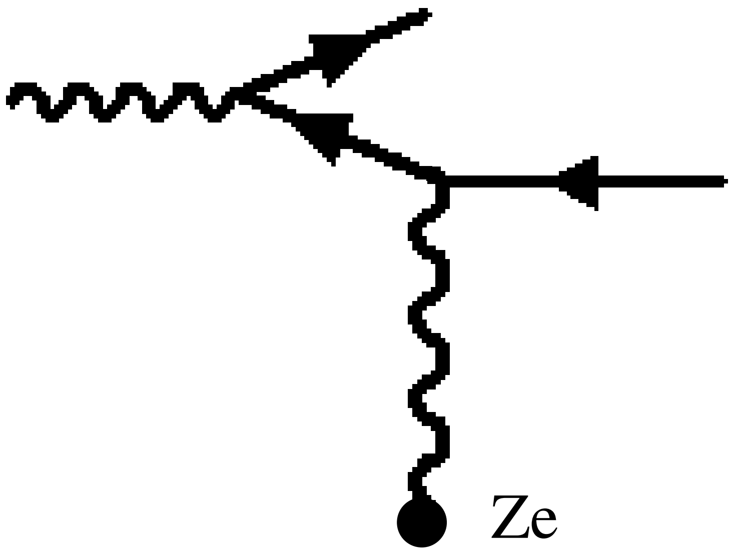
- Bremstrahlung:
  - electron emits photon in field of the nucleus



  - cross section: $\sim \alpha^3 Z^2$

Electromagnetic Interactions

- Pair production ($\gamma \rightarrow e^+e^-$)



cross section:

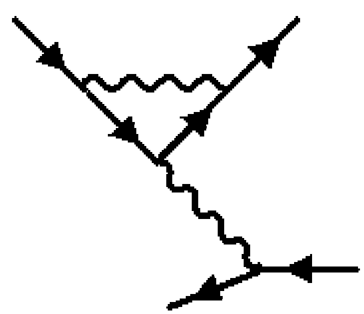
$\sim \alpha^3 Z^2$

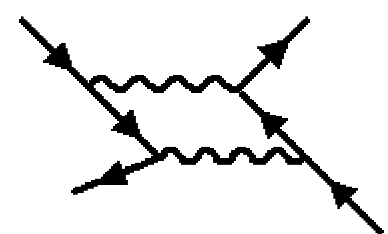
- This process is closely related to bremstrahlung ("crossed diagrams")

Electromagnetic Interactions

- Higher order processes
  - the diagrams we have seen so far are leading order diagrams, but the rate for a process will be the sum of all orders:
  - For example, Bhabha scattering: $e^+e^- \rightarrow e^+e^-$
    - leading order:

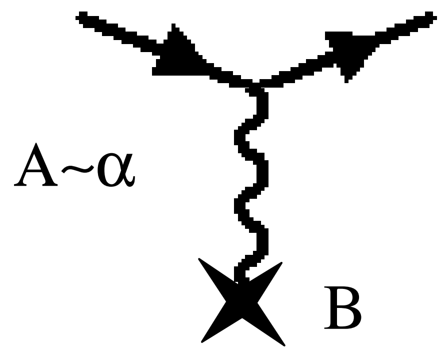
    - higher order:



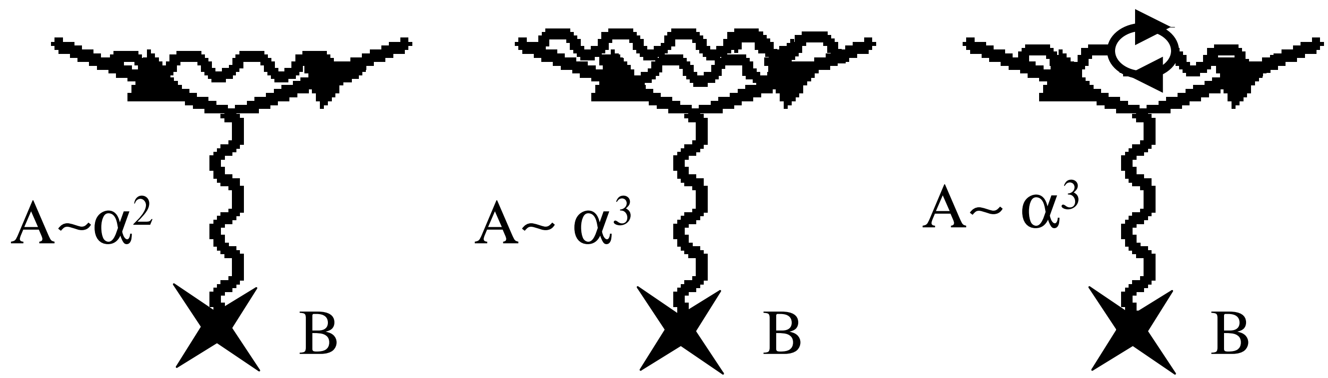


Electromagnetic Interactions

- Example of higher order processes: the electron magnetic moment
  - lowest order:



  - higher order:



Electromagnetic Interactions

- Electron magnetic moment:
  - a Dirac electron has a magnetic moment of

$\mu = g\,\mu_B\, s$, $\quad s = 1/2 \quad g = 2 \quad \mu_B = e\hbar/mc$

$(g-2)/2$ is the anomaly due to higher order terms

$$(g-2)^{th}/2 = 0.5\,(\alpha/\pi) - 0.32848\,(\alpha/\pi)^2 + 1.19\,(\alpha/\pi)^3 + ..$$
$$= (115965230 \pm 10) \times 10^{-11}$$

$$\text{experiment} = (115965218.7 \pm 0.4) \times 10^{-11}$$

Renormalization and Gauge Invariance

- Electron line represents “bare” electron
- Observable particles are “dressed” by “infinite” number of virtual photons:
  - logarithmically divergent
- These divergences are swept away through renormalization:
  - “Bare” electron mass and charge is always multiplied by divergent integrals. We know this product must be the physical values of the mass and charge, so we set them to be, and the divergences are removed

Renormalization and Gauge Invariance

- The coupling constants that appear in the theory are actually not "constants", but "run" with energy.
  - This is due again to virtual processes
  - For example, $\alpha = 1/137$ at very low energy, but $\alpha = 1/128$ at $\sqrt{s} = M_Z$

Renormalization and Gauge Invariance

- In order for a theory to be "renormalizable" it must satisfy local gauge invariance
  - Examples of gauge invariance are familiar in EM and quantum
    - gauge transformations of scalar and vector potential in E&M do not change physical effects
    - wavefunction can change by an arbitrary phase without altering physics

Strong Interactions

- Decay of the Σ baryons

Baryon	Composition	Q-value, MeV	Decay Mode	Lifetime, s
Σ^0 (1192)	uds	74	$\Lambda\gamma$	10^{-19}
Σ^+ (1189)	uus	189	$p\pi^0$	10^{-10}
Σ^0 (1385)	uds	208	$\Lambda\pi^0$	10^{-23}

Strong Interactions

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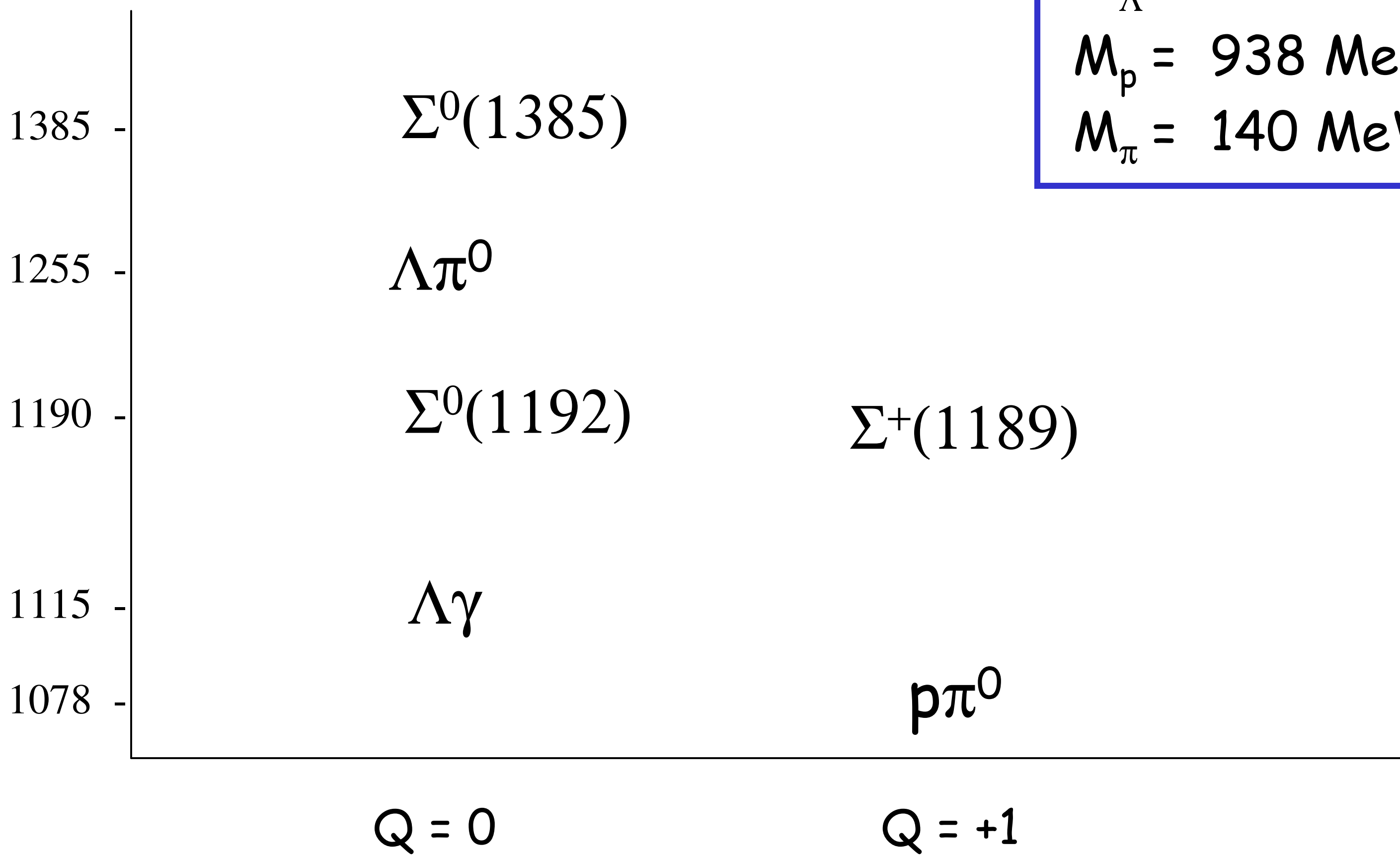
  – why is the Σ^0 (1192) 3 MeV heavier than the Σ^+ (1189) ?

  – why does the Σ^+ (1189) live a billion times longer than the Σ^0 (1192) ?

Strong Interactions

- Decay of the Σ baryon

M_Λ = 1115 MeV/c^2
M_p = 938 MeV/c^2
M_π = 140 MeV/c^2



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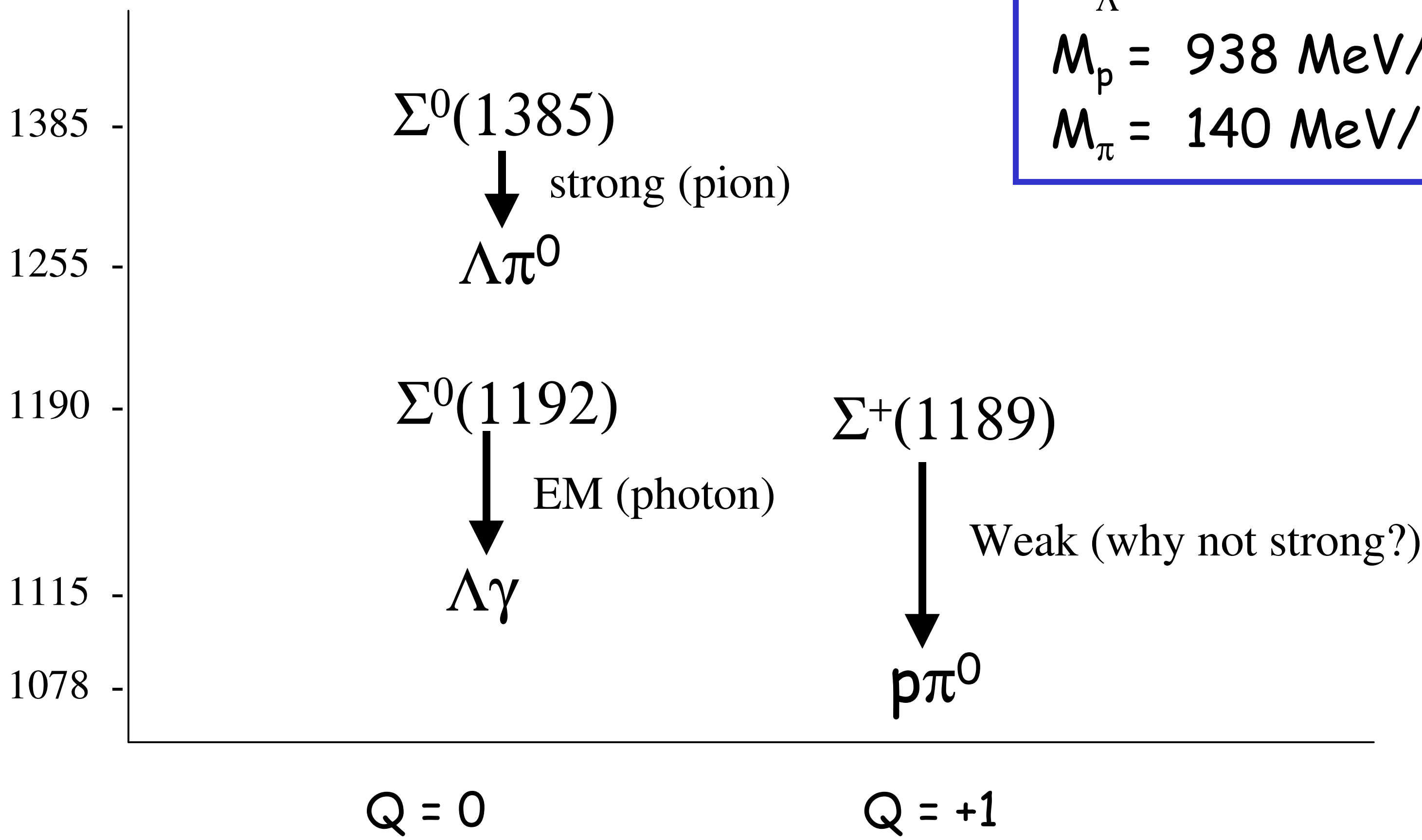

Strong Interactions

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Σ^0 (1192)	uds	74	$\Lambda\gamma$ (EM)	10^{-19}
Σ^+ (1189)	uus	189	$p\pi^0$(weak)	10^{-10}
Σ^0 (1385)	uds	208	$\Lambda\pi^0$(strong)	10^{-23}

- strong
  - Σ^0 (1192) cannot decay strongly because $M_\Lambda + M_\pi = 1250$ MeV/c^2
  - Σ^+ (1189) cannot decay strongly (same reason)
- EM
  - Σ^+ (1189) cannot decay Emly because there is no lighter charged, strange baryon (Σ^+ (1189) is lightest charged, strange baryon)

Strong Interaction

- The ratios of the decay rates give an approximate indication of the relative strengths of the interactions:

  $\{\tau[\Sigma^0 (1192)\ ] / \tau[\Sigma^0 (1385)\ ]\}^{1/2} \approx 100 \approx \alpha_s / \alpha$

- Since $\alpha = 1/137$, $\alpha_s \approx 1$

Strong Interaction

- gluon mediator
  - neutral, massless, vector particle (as with EM)
  - carries color charge (unlike EM)
- QCD (Quantum Chromodynamics)
  - Nine possible color combinations for the gluons
    - blue anti-green
    - green anti- red
    - etc.
    - however, one is a color singlet, which means it does not interact, so there are actually eight active gluon states

Strong Interaction

- The QCD (strong) coupling constant “runs”, such that at large distances (within a hadron) the coupling constant is very large and perturbation theory cannot be applied, while at small distances (which occur during violent collisions) the coupling constant is small and perturbation theory is valid
- This large distances behavior is the origin of “confinement” of quarks within hadrons

Strong Interactions

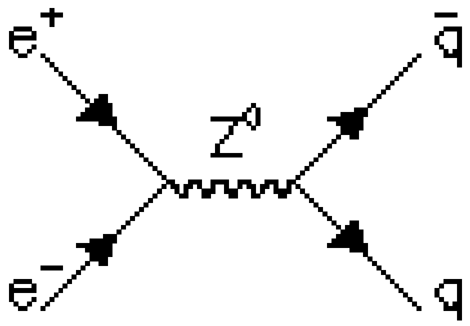
- The quark-antiquark potential is often approximated by

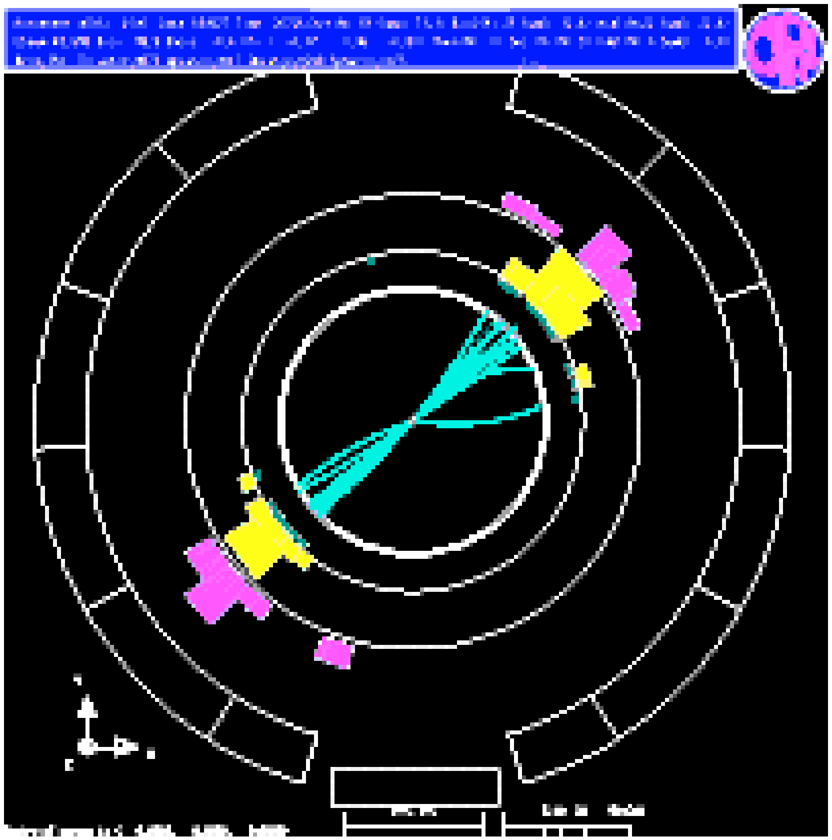
  $$V_s = -(4/3)\,\alpha_s/r + k\,r$$

- The 1/r portion of this potential is similar to the Coulomb potential
- However, the long range linear term is different
  - confinement
  - sizes and masses of hadrons $\Rightarrow k \sim 1$ GeV/fm
    - (14 tonnes)

Strong Interactions

- Two jet events





- confining potential