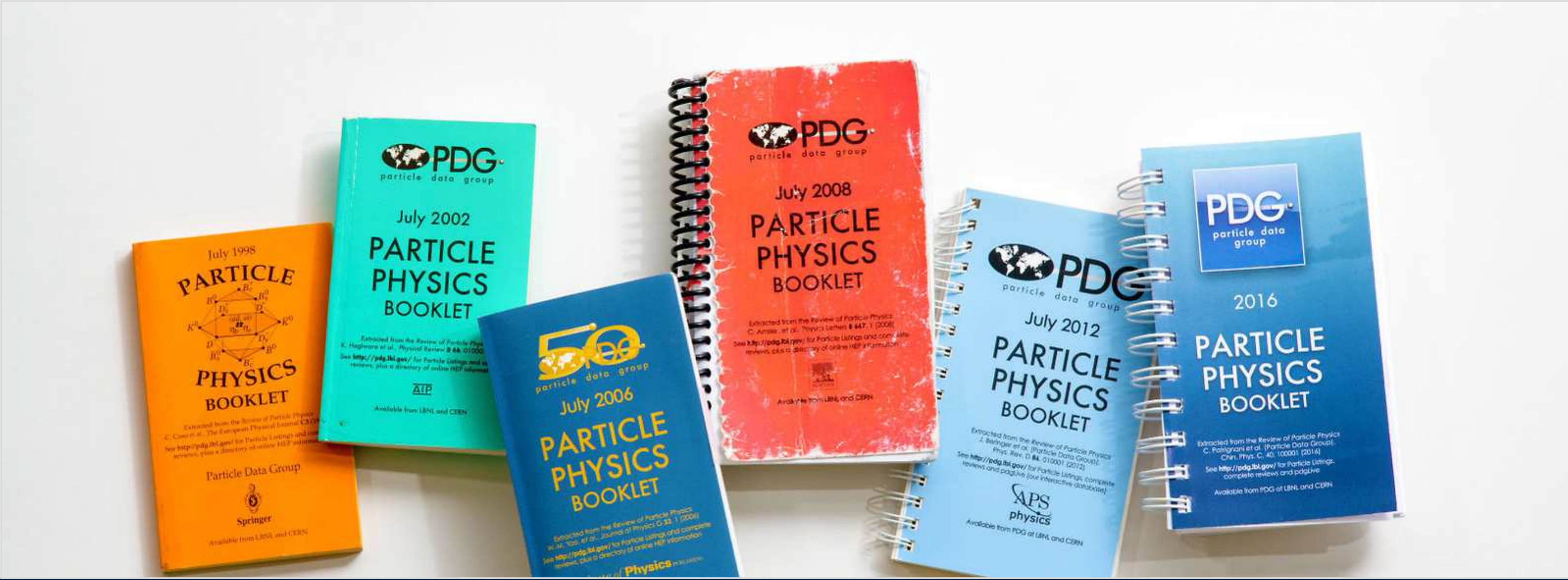


ELEMENTARY PARTICLE PHYSICS

BASIC CONCEPTS

MAY 2020 I HANS STRÖHER (FZ JÜLICH, UNIVERSITY OF COLOGNE)

- Outline:
  - A brief **introduction** (history …)
  - The **tools** (accelerators, targets, detectors … concepts, …)
  - The **particles** (hadrons, baryons, mesons …)
  - The ***fundamental* particles** (quarks, leptons)
  - The **forces** (gravitation, nuclear forces)
  - The ***fundamental* interactions** (strong and electro-weak IA)
  - The **Standard Model** of EPP
  - Physics **Beyond the Standard Model** (BSM)
  - Spin-offs – **Applications** of EPP

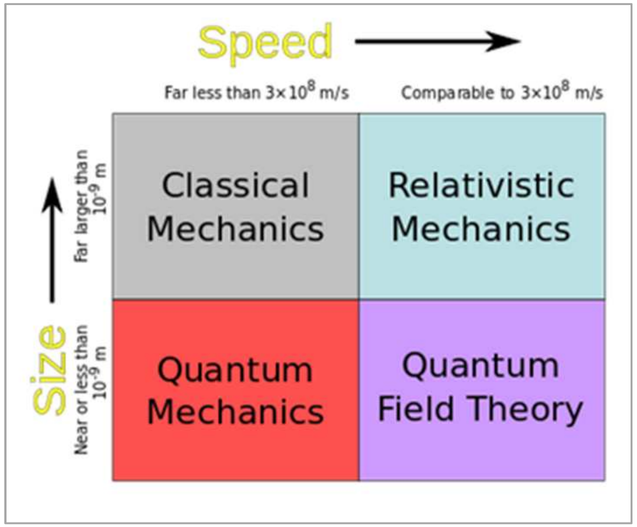
BASIC CONCEPTS

What is Particle Physics?

Particle Physics – studies of building blocks of **matter** and **interactions**

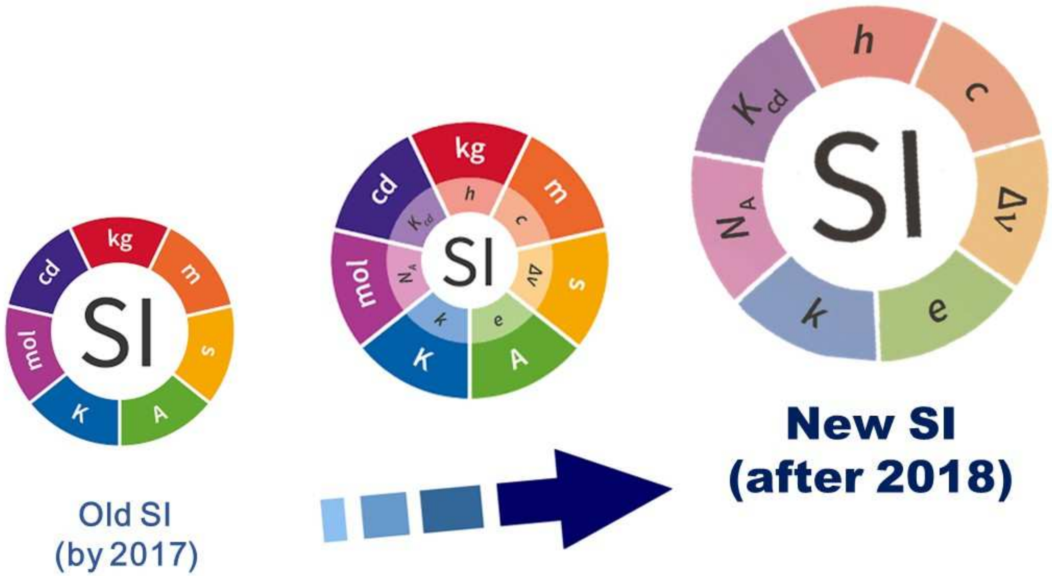
- Matter consists of particles – **fermions** at the fundamental level
- Particles interact via forces, mediated by force-carrying particles – **bosons**

Particle physics is **relativistic** and **quantum mechanical**:



BASIC CONCEPTS

The Units of Particle Physics



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BASIC CONCEPTS

The Units of Particle Physics

Natural units – how to simplify calculations

In physics, the SI-units (with base quantities are *mass*, *length*, *time* …) is most frequently used; in particle physics, since it relies on **special relativity** and **quantum mechanics**, it is more convenient to use *energy* [GeV], *velocity* [c] and *angular momentum* [h] as base units: since “c” (velocity of light) and “h” (Planck´s constant) are “**natural units**”:

Units become (i.e. with the correct dimensions):

Energy	GeV	Time	$(\mathrm{GeV}/\hbar)^{-1}$
Momentum	GeV/c	Length	$(\mathrm{GeV}/\hbar c)^{-1}$
Mass	GeV/c^2	Area	$(\mathrm{GeV}/\hbar c)^{-2}$

Simplify algebra by setting: $\boxed{\hbar = c = 1}$

- Now all quantities expressed in powers of **GeV**

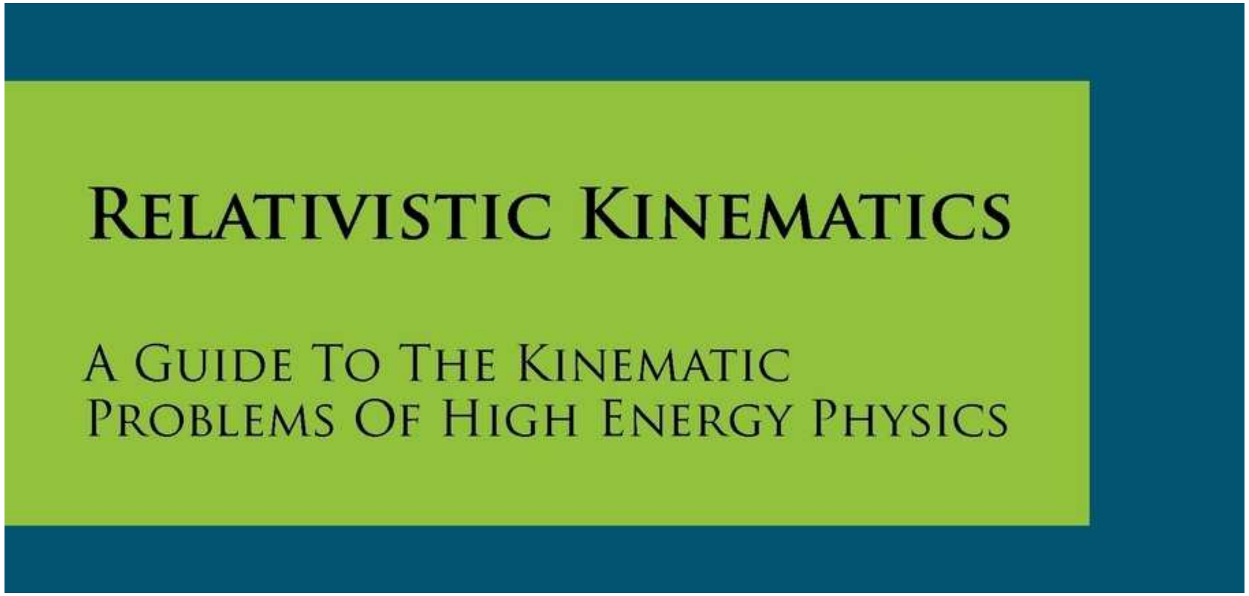
Energy	GeV	Time	GeV^{-1}
Momentum	GeV	Length	GeV^{-1}
Mass	GeV	Area	GeV^{-2}

To convert back to S.I. units, need to restore missing factors of $\hbar$ and c

Useful relations: $\boxed{\hbar c = 197 \text{ MeV fm}}$ $\boxed{\hbar = 6.582 \cdot 10^{-22} \text{ MeV s}}$

BASIC CONCEPTS

Kinematics in Particle Physics



BASIC CONCEPTS

Kinematics in Particle Physics

4-vectors – taking special relativity into account

In special relativity, a "**four-vector**" (4-vector) is an object with four components, which describes, e.g., the particle position in spacetime or its momentum:

- Space-time 4-vector: $x=(ct,\mathbf{x})$ where **x** is a normal 3-vector
- Momentum 4-vector: $p=(E/c,\mathbf{p})$ where **p** is particle momentum
- 4-vector rules (recap)
  - $a \pm b = (a_0 \pm b_0, a_1 \pm b_1, a_2 \pm b_2, a_3 \pm b_3)$
  - Scalar product (minus sign!)
    $a \cdot b = a_0 b_0 - a_1 b_1 - a_2 b_2 - a_3 b_3 = a_0 b_0 - \mathbf{a} \cdot \mathbf{b}$
  - Scalar product of momentum and space-time 4-vectors are thus:
    $x \cdot p = Et - x_x p_x - x_y p_y - x_z p_z = Et - \mathbf{x} \cdot \mathbf{p}$

$a = (a_0,a_1,a_2,a_3)$ $b = (b_0,b_1,b_2,b_3)$

$x = (t,\mathbf{x})$
$p = (E,\mathbf{p})$

The **length of a 4-vector** is a scalar and an invariant quantity.

BASIC CONCEPTS

Kinematics in Particle Physics

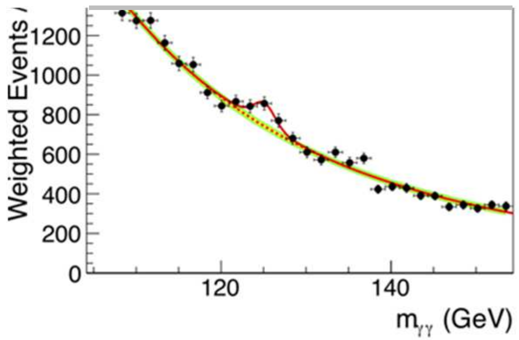
4-vectors – taking special relativity into account

The scalar product of the "**energy-momentum 4-vector**" p =(E,**p**) represents the "**invariant mass**" of a particle:

$$\boxed{m^2 = E^2 - \vec{p}^{\,2}}$$

Note: an invariant mass of zero is possible – it simply means that $E^2 = p^2$ (e.g. E = p for massless photons)

An **invariant mass analysis** is a powerful tool to identify a (new) particle, e.g. Higgs-boson:

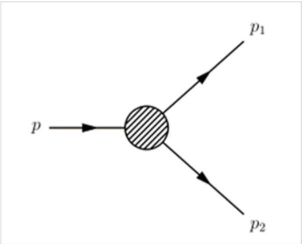


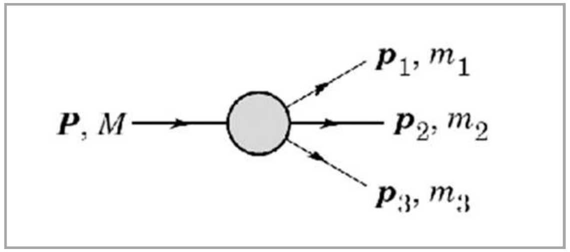
BASIC CONCEPTS

Kinematics in Particle Physics

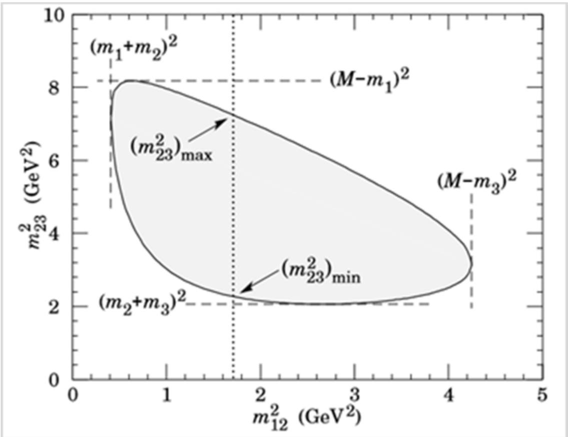
Dalitz plots – analyzing 3-body decays

Particles frequently **decay** into lighter “daughter particles”:





4-momentum conservation restricts events in the **shaded 2D-region**:



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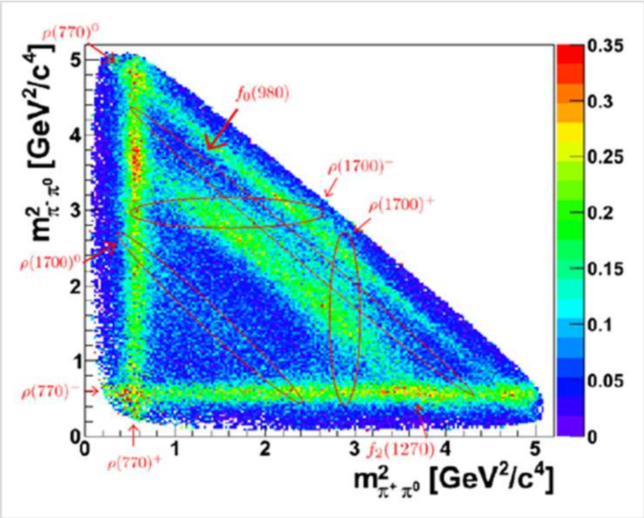
BASIC CONCEPTS

Kinematics in Particle Physics

Dalitz plots – analyzing 3-body decays

If no angular correlations between the decay products (“phase space”) → **uniform Dalitz plot distribution**; symmetries may impose certain restrictions on the distribution; resonant processes: (**A → a b → (a$_1$a$_2$) b**) result in a **non-uniform distribution**

<u>Example</u>: pp $\rightarrow \pi^+\pi^-\pi^0$ at 1940 MeV/c beam momentum

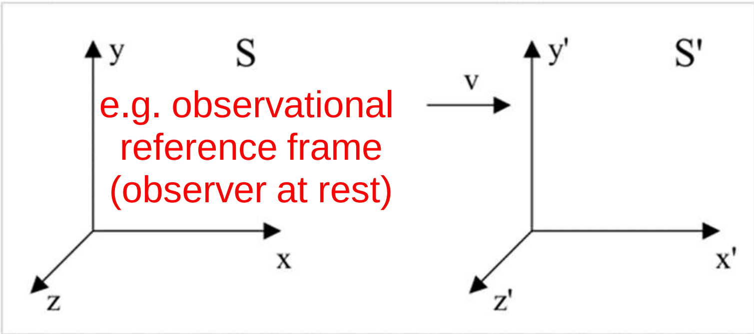


BASIC CONCEPTS

Kinematics in Particle Physics

Reference frames – Galilei and Lorentz-transformation (I)

The "**Lorentz-transformation**" is a linear transformation from a coordinate frame in spacetime to another frame that moves at a **constant velocity** (v) relative to the former:



$$x' = \gamma(x - vt) \qquad x = \gamma(x' + vt')$$
$$y' = y \qquad y = y'$$
$$z' = z \qquad z = z'$$
$$t' = \gamma\left(t - vx/c^2\right) \qquad t = \gamma\left(t' + vx'/c^2\right)$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

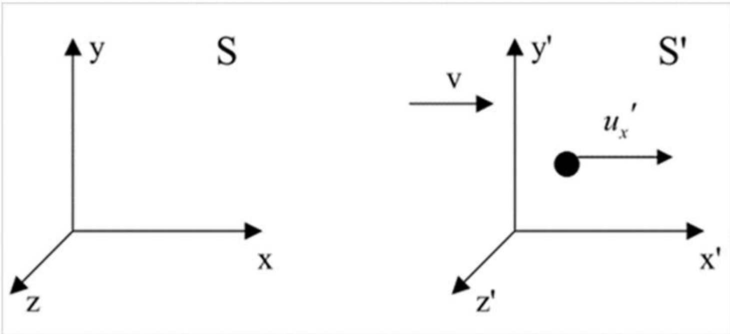
Notes: for v → 0 (γ → 1), **Galilean transformation** is recovered
space and time coordinates are mixed
only relative velocities matter

BASIC CONCEPTS

Kinematics in Particle Physics

Reference frames – Galilei and Lorentz-transformation (II)

Consider 2 inertial frames S and S´ with a **relative velocity v** (e.g. in x-direction) and an **object in S´ moving with the velocity u_x´** :



$$u_x = \frac{u_x' + v}{1 + v u_x' / c^2}$$

$$u_y = \frac{u_y'}{\gamma\left(1 + v u_x' / c^2\right)} \qquad u_z = \frac{u_z'}{\gamma\left(1 + v u_x' / c^2\right)}$$

<u>Notes</u>: although y = y´ and z = z´, $u_y \neq u_y$´ and $u_z \neq u_z$´

speed-of-light (c) is independent of the reference frame

BASIC CONCEPTS

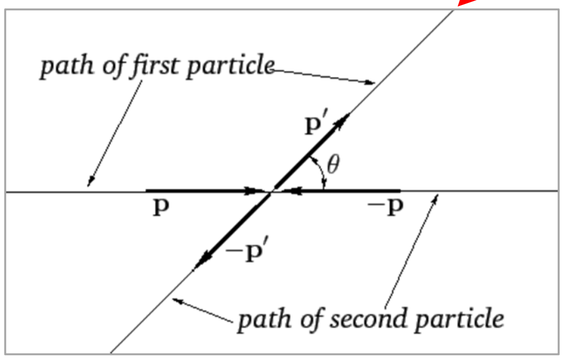
Kinematics in Particle Physics

Reference frames – center-of-momentum (COM) frame

The “**center-of-momentum frame**” (also: zero-momentum frame or COM frame) of a system is the unique inertial frame in which the **total momentum of the system vanishes**; in all COM frames, the center of mass (CM) is at rest:

particle trajectories
after the collision

collision event
is completely
specified by
the angle θ



particle trajectories
before the collision

A special COM case is the “**center-of-mass frame”** in which the center of mass (of the system) remains at the origin

BASIC CONCEPTS

Kinematics in Particle Physics

Reference frames – energy in collider vs. fixed target experiments (I)

Consider **colliding beams** of symmetric particles (e-e, p-p, …) at same energy: the laboratory frame is equal to CM frame; the **total energy** is:

$$E_a = E_b \qquad \mathbf{p_a} = -\mathbf{p_b}$$
$$s = (E_a + E_b)^2 + 0 = 4E_a{}^2$$
$$\sqrt{s} \propto E_a$$

energy available, e.g., for particle production

This is advantageous to a **fixed target** experiment (with "b" at rest):

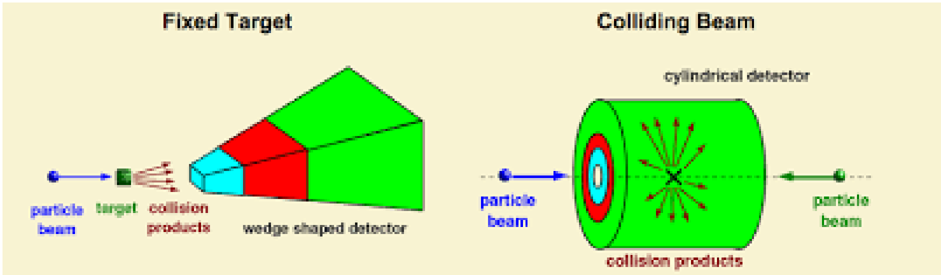
$$s = (E_a + m_b)^2 - p_a{}^2 \approx 2E_a m_b \quad \text{for} \quad E_a >> m_a, m_b$$
$$\sqrt{s} \propto E_a^{\frac{1}{2}}$$

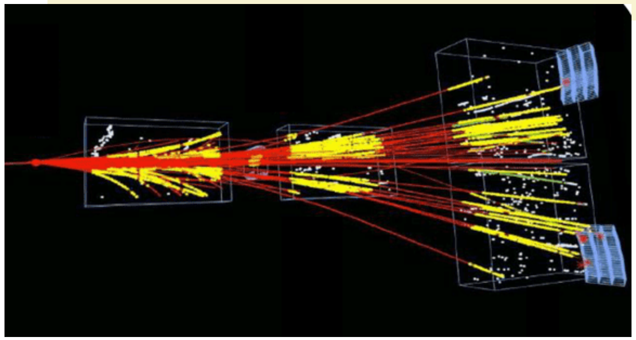
BASIC CONCEPTS

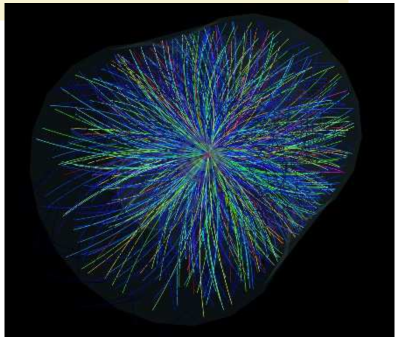
Kinematics in Particle Physics

Reference frames – energy in collider vs. fixed target experiments (II)

Produced particles are emitted in forward direction (fixed target) or concentrically around the interaction point (collider):



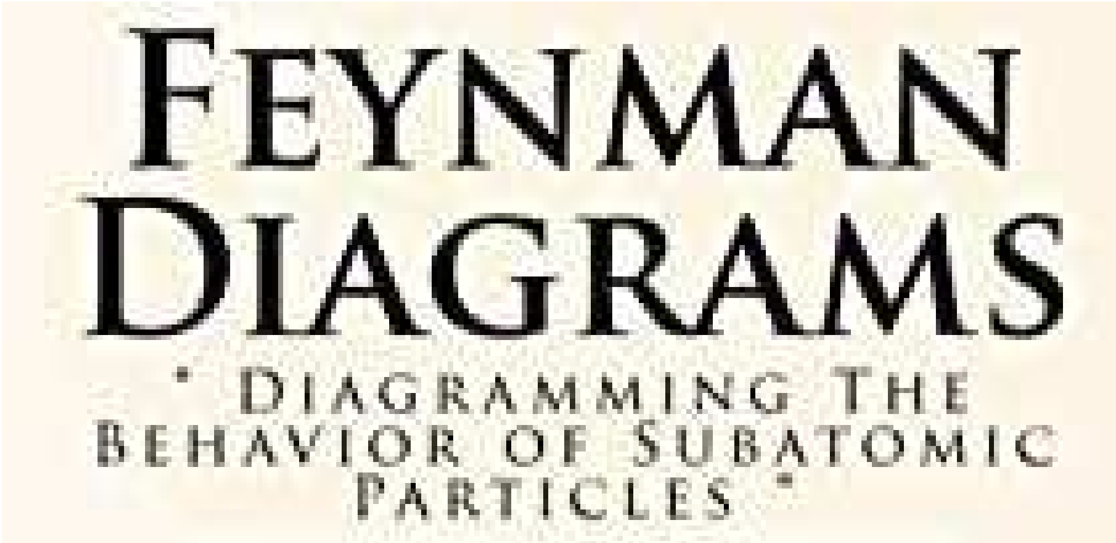




→ see “detectors”

BASIC CONCEPTS

Processes in Particle Physics



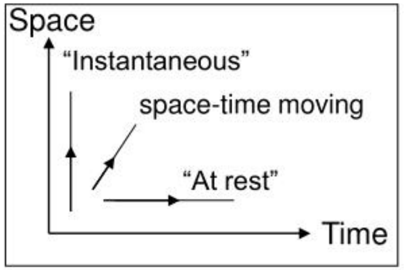
BASIC CONCEPTS

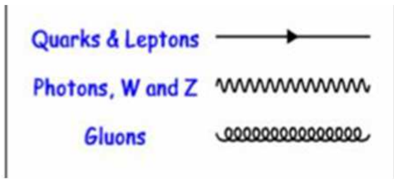
Processes in Particle Physics

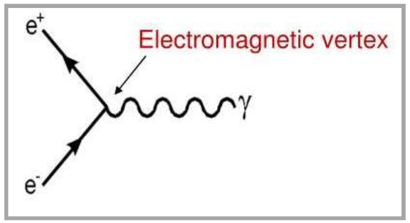
Feynman diagrams – a pictorial representation of subatomic processes (I)

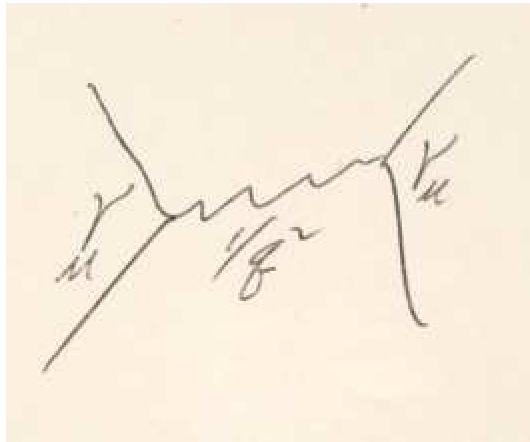
In 1948 **Richard Feynman** introduced/developed these diagram technique for describing the behavior and interaction of subatomic particles:

- Time from left to right
  (may also be other way!)
- Particle: →
- Anti-particle ←
- Different lines for each
  group of particles
- Interaction at "vertices"









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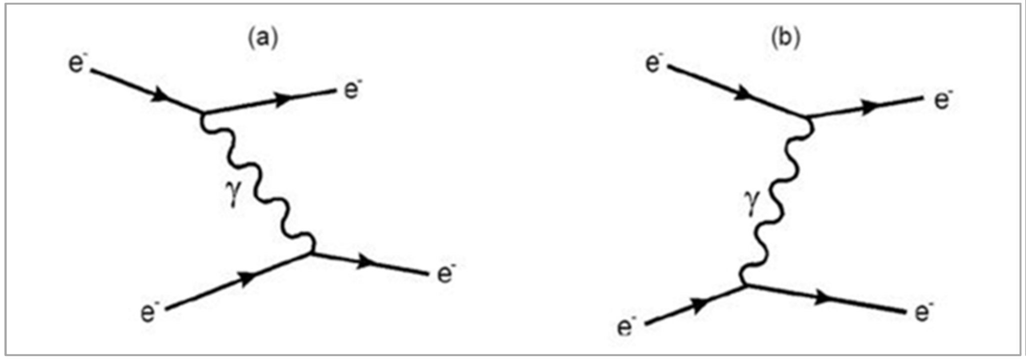
BASIC CONCEPTS

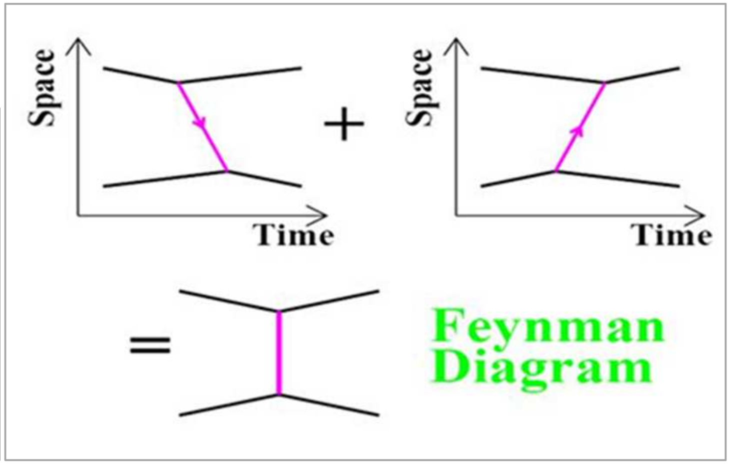
Processes in Particle Physics

Feynman diagrams – a pictorial representation of subatomic processes (II)

At a vertex, charge and momentum is conserved, but not energy; since in a physics process, **energy conservation** has to be fulfilled, one needs to combine (at least) two of them:

Example: electron-electron scattering





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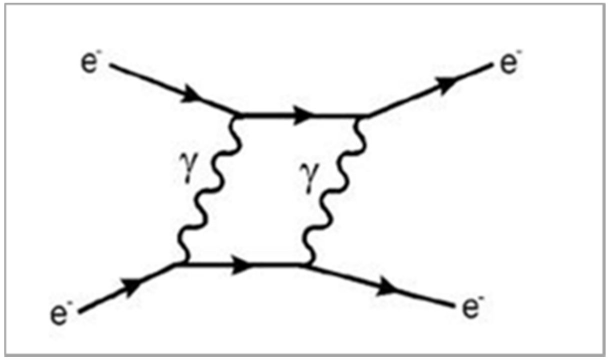
BASIC CONCEPTS

Processes in Particle Physics

Feynman diagrams – a pictorial representation of subatomic processes (III)

Any **physical process** is the sum of contributions from all possible **virtual processes**:

Example: two-photon exchange in electron scattering



This includes "**loop diagrams**" and originally lead to divergencies, cured by the process of "renormalization"

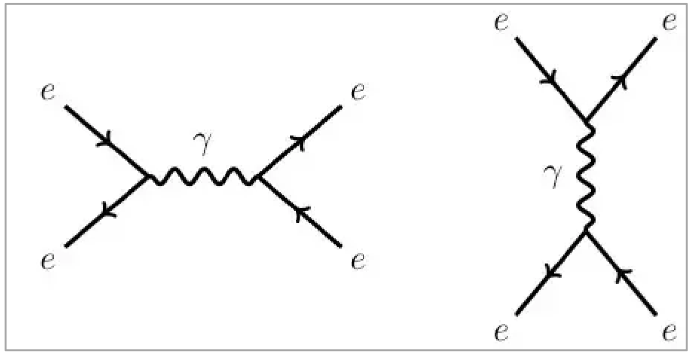
BASIC CONCEPTS

Processes in Particle Physics

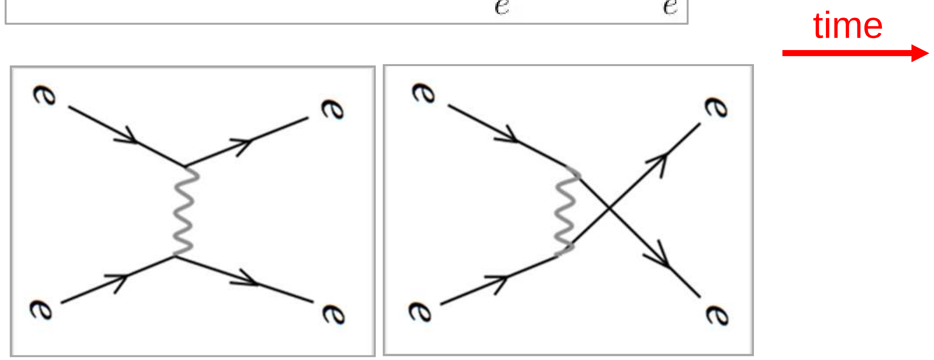
Feynman diagrams – a pictorial representation of subatomic processes (IV)

Examples:

(i) annihilation vs. scattering:



(ii) identical particles (e):



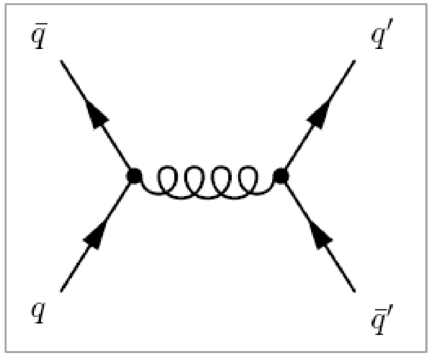
BASIC CONCEPTS

Processes in Particle Physics

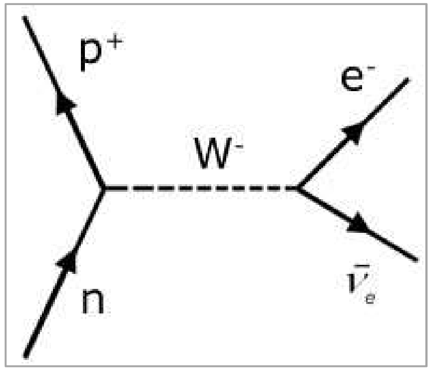
Feynman diagrams – a pictorial representation of subatomic processes (V)

Examples:

(iii) strong interaction:



(iv) weak interaction:



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BASIC CONCEPTS

Processes in Particle Physics

Feynman diagrams – a pictorial representation of subatomic processes (VI)

It is perfectly acceptable to appreciate Feynman diagrams at face value as pictorial representations of particle interactions

In fact there is a much more **mathematical interpretation** of these diagrams: it produces **mathematical expressions** which predict the **probability** of these interactions to occur

Feynman gave a **prescription for calculating the amplitude** for any given diagram from a field theory Lagrangian – the **Feynman rules** (he used Ernst Stueckelberg's interpretation of the positron as an electron moving backward in time)

Computer programs (e.g. Mathematica) available to perform calculations

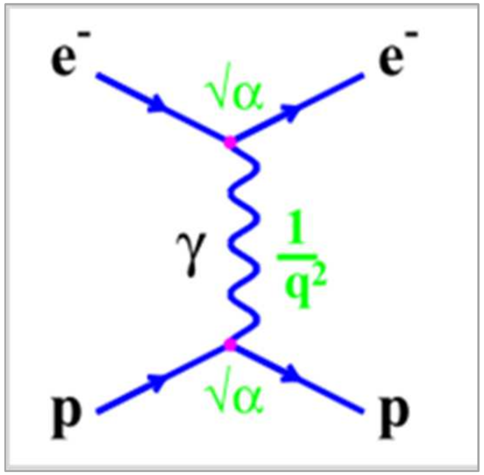
BASIC CONCEPTS

Processes in Particle Physics

Feynman diagrams – a pictorial representation of subatomic processes (VII)

Coupling strength g determines the "order of magnitude" of the **matrix element M**, the **cross section** σ is proportional to $|M|^2$

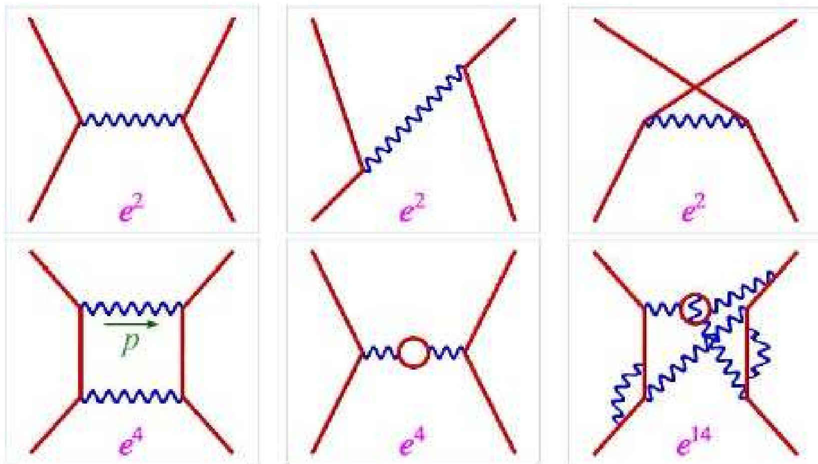
Example: electron-proton scattering



$g = \alpha = e^2/4\pi$

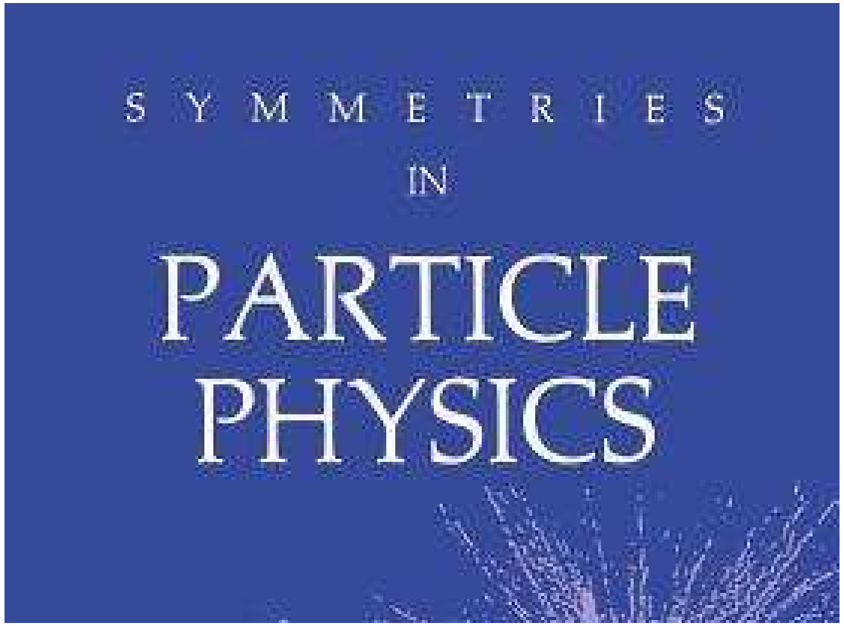
$M \sim e.e = e^2$

→ $\sigma \sim e^4 \sim \alpha^2$



BASIC CONCEPTS

Symmetries in Particle Physics

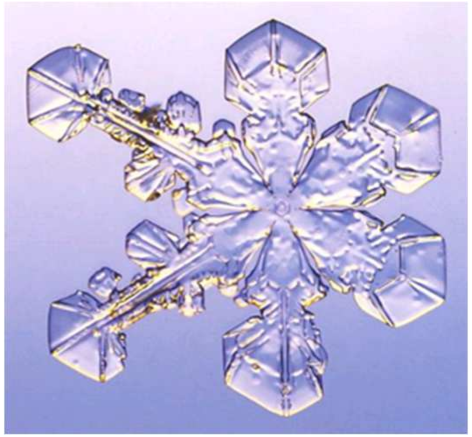


BASIC CONCEPTS

Symmetries in Particle Physics

What is a symmetry? – from “beauty” to physics

Symmetry and **asymmetry** are well known to all of us:



- In physics, there are many notations with symmetries, e.g.: T-, P-, CP- and CPT-symmetry, spontaneous symmetry breaking, supersymmetry, …
- Why is the concept of symmetries so important in physics?

BASIC CONCEPTS

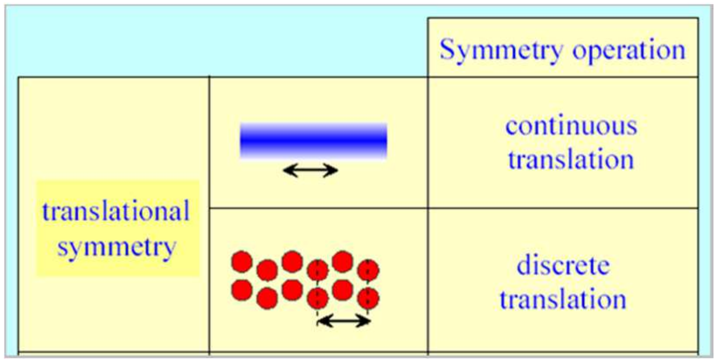
Symmetries in Particle Physics

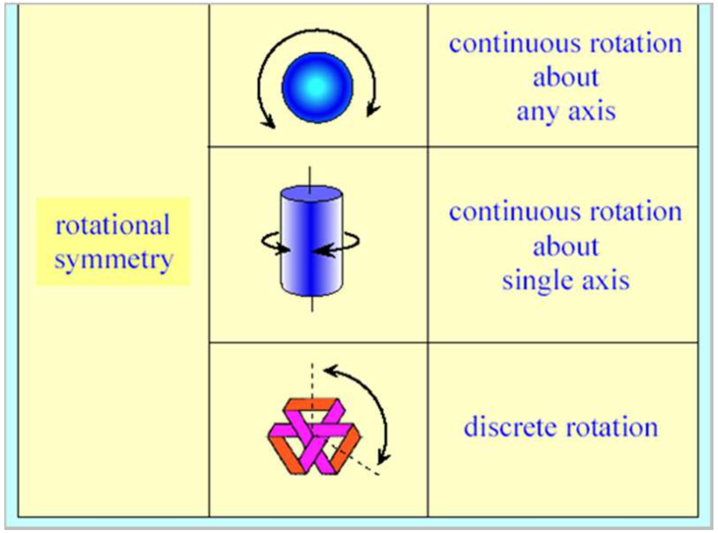
Symmetry operations – invariance under transformations

In physics, the symmetry of a system is defined as the **invariance** of some physical or mathematical feature **under some transformation**:

- **Discrete** and **continuous** symmetry operations:

Examples:





BASIC CONCEPTS

Symmetries in Particle Physics

Noether theorem – symmetries and conservation laws

Emmy Noether showed (in 1918) that there is an **intimate link** between **conservation laws** and the **symmetries of nature**, a connection that physicists have exploited ever since: *If a system of particles shows a symmetry, then there is a conserved quantity*:

Examples:

Symmetry	Invariance under movement in time	Homogeneity of space	Isotropy of space
Transformation	Translation in time	Translation in space	Rotation in space
Conserved quantity	Energy	Linear momentum	Angular momentum

This theorem also applies to **discrete symmetries**: parity (P), charge symmetry (C) and time reversal (T), but: "**violations**" (see below)

BASIC CONCEPTS

Symmetries in Particle Physics

Importance of symmetries – what famous physicists have to say

"Fundamental **symmetry principles** dictate the basic laws of physics, control the **structure of matter**, and define the **fundamental forces** in nature.“ (L. Lederman)

“It is only slightly overstating the case to say that **physics is the study of symmetry**.” (P. Anderson)

"The fundamental theories of physics are based on symmetry considerations, yet: our **world is filled with asymmetry**.“ (T.D. Lee)

→ During lectures … symmetries will appear over and over again!

BASIC CONCEPTS

Symmetries in Particle Physics

Symmetry violations (breaking) – this is the interesting part

The **breaking of symmetries** (i.e. symmetries are not complete …):

- Parity (P) … a big surprise, unexpected
- Charge-parity (CP) … a shock when discovered first
- Charge-parity-time (CPT) … must not happen (basic principle …)

As of today there are **fundamental unsolved questions** related to symmetry (breaking):

Examples:

- "Baryon number" (B) … breaking required for proton decay
- CP … more required for understanding matter – anti-matter asymmetry

BASIC CONCEPTS

Symmetries in Particle Physics

Matter and anti-matter – what´s the difference? (I)

Every type of **particle** has an associated **anti-particle** with the **same mass** (and magnetic moments) but with **opposite** (electric) **charges**:

Examples:	proton ($+e_0$)	$\leftarrow\rightarrow$	anti-proton ($-e_0$)
	electron ($-e_0$)	$\leftarrow\rightarrow$	positron ($+e_0$)

Neutral particles also have their anti-particle counterparts:

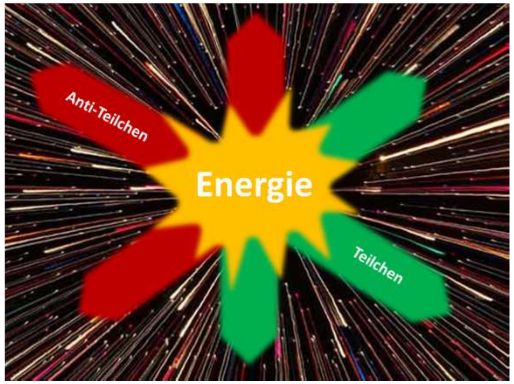
Examples:	neutron ($0e_0$)	$\leftarrow\rightarrow$	anti-neutron ($0e_0$)	difference at quark-level
	π^0 ($0e_0$)	$\leftarrow\rightarrow$	π^0 ($0e_0$)	**No** difference; own anti-particle
	γ ($0e_0$)	$\leftarrow\rightarrow$	γ ($0e_0$)	
	ν ($0e_0$)	$\leftarrow\rightarrow$	$\overline{\nu}$ ($0e_0$)	**Don´t know yet**

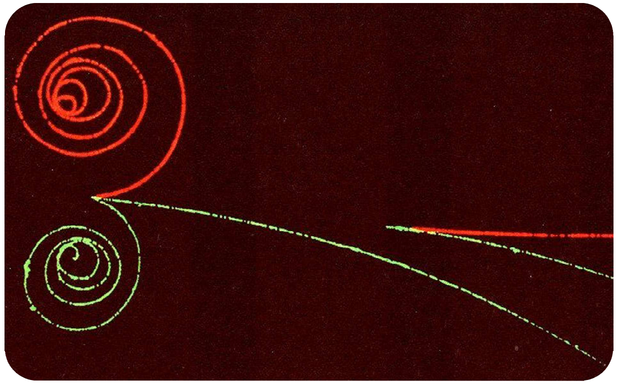
BASIC CONCEPTS

Symmetries in Particle Physics

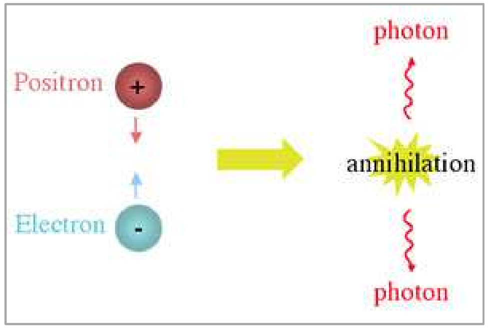
Matter and anti-matter – what´s the difference? (II)

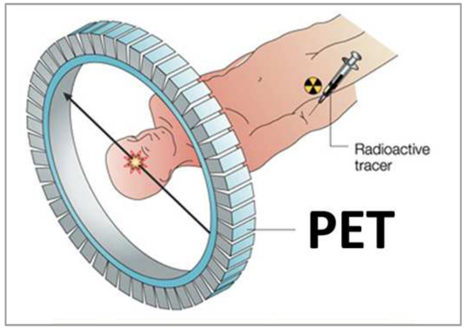
Energy produces **particle – anti-particle pairs**:





and **particle – anti-particle pairs annihilate**:





exploited
in medical
diagnostics

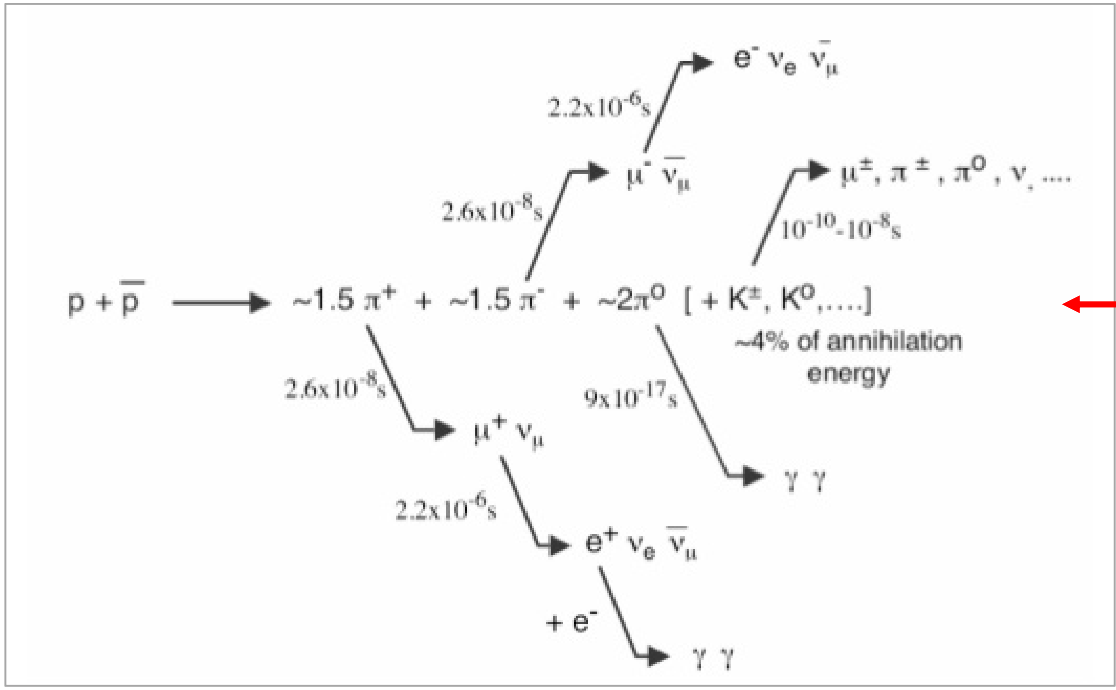
BASIC CONCEPTS

Symmetries in Particle Physics

Matter and anti-matter – what´s the difference? (III)

For non-fundamental particles, **annihilation** is more complicated:

<u>Example</u>:



… many of the particles to be discussed in next lectures

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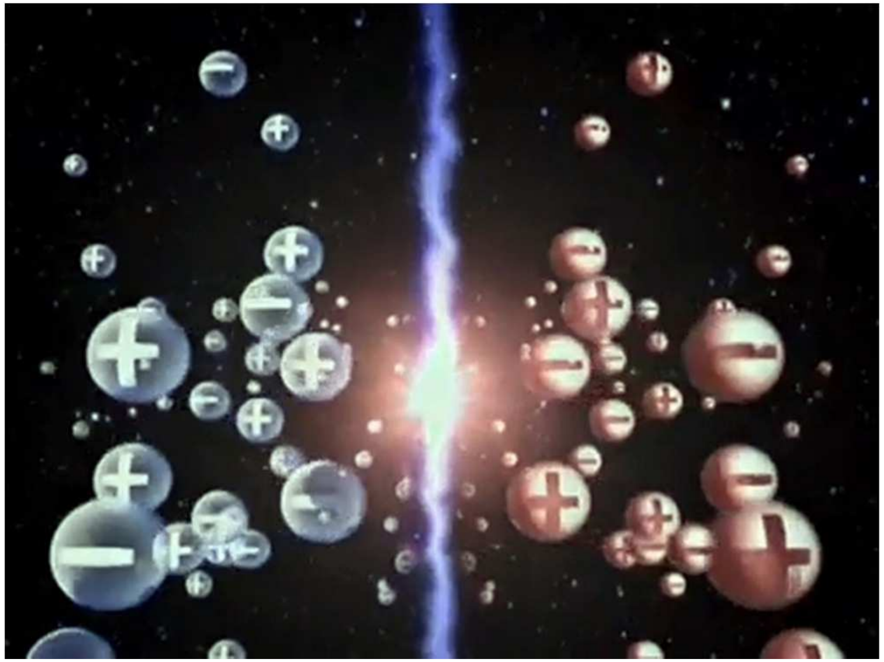
BASIC CONCEPTS

Symmetries in Particle Physics

Matter and anti-matter – what´s the difference? (IV)

A **symmetry breaking** between **matter and anti-matter** responsible for our existence:



BASIC CONCEPTS

Symmetries in Particle Physics

Bosons and fermions – what´s the difference? (I)

Consider **2 identical particles** (1 and 2) which may exist in **2 different states** (a and b) – wave functions:

$$\psi_I = \psi_a(1)\ \psi_b(2) \qquad\qquad \psi_{II} = \psi_a(2)\ \psi_b(1)$$

Since it is not possible to tell in which state they are, so write a linear combination:

- if the particles are **bosons**, the system wave function is **symmetric**:

$$\psi_B = \frac{1}{\sqrt{2}}\left[\psi_a(1)\ \psi_b(2) + \psi_a(2)\ \psi_b(1)\right] = \psi_S$$

- if the particles are **fermions**, the wave function is **anti-symmetric**:

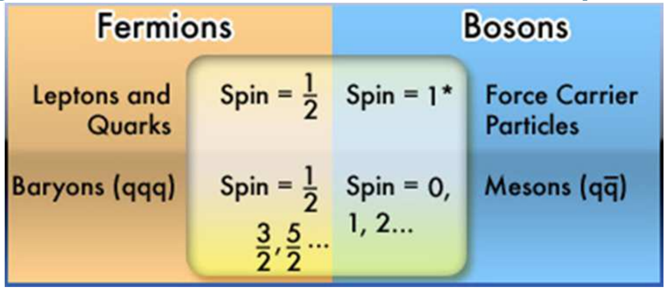
$$\psi_F = \frac{1}{\sqrt{2}}\left[\psi_a(1)\ \psi_b(2) - \psi_a(2)\ \psi_b(1)\right] = \psi_A$$

BASIC CONCEPTS

Symmetries in Particle Physics

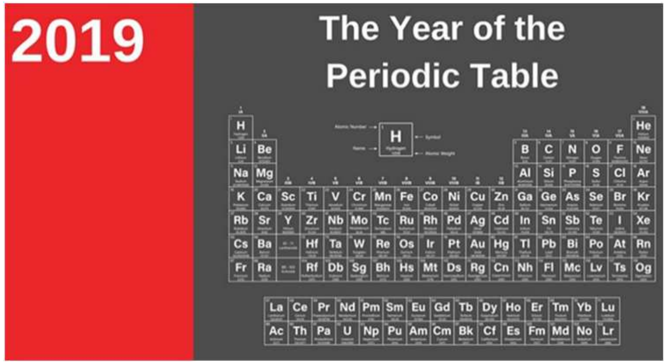
Bosons and fermions – what´s the difference? (II)

Particles with anti-symmetric wave-function (fermions) have **half-integer spin**, those with a symmetric wave-function (bosons) have **integer spin**:



Fermions obey the **Pauli exclusion principle**: no 2 fermions can occupy the same quantum-mechanical state

Example:



JÜLICH Forschungszentrum

THE PARTICLES

That´s it for today

JÜLICH
Forschungszentrum