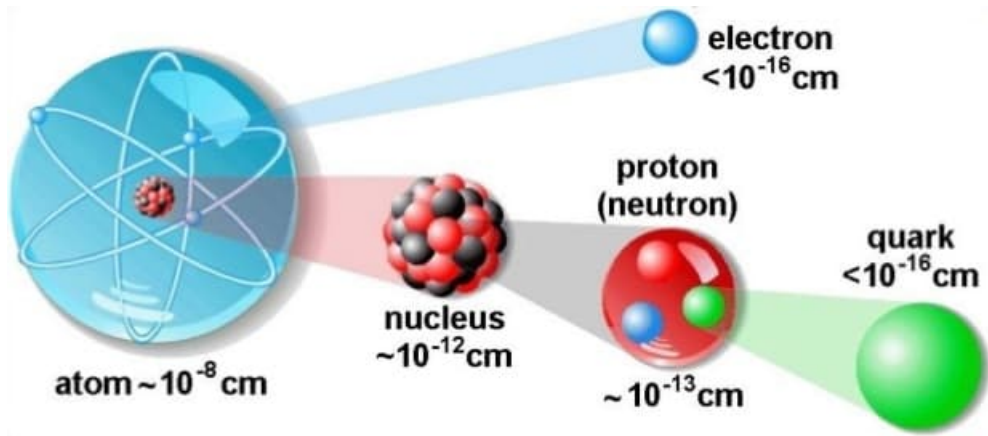


# Basic Concepts

- Particle physics studies the elementary “building blocks” of *matter* and interaction between them.
- Matter consists of *particles* and *fields*.
- Particles interact via *forces* caused by fields.
- Forces are being carried by special particles, called *gauge bosons*.



## Forces of nature:

1) gravitational

2) weak

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

3) electromagnetic

$$e^{+} + e^{-} \rightarrow \gamma + \gamma$$

4) strong

$$\pi^{-}(d\bar{u}) + p(uud) \rightarrow K^{+}(u\bar{s}) + \Sigma^{-}(dds)$$

# Forces of Nature

	Acts on:	Carrier	Range	Strength	Stable systems	Induced reaction
Gravity	all particles	graviton	long $F \propto 1/r^2$	$\sim 10^{-39}$	Solar system	Object falling
Weak force	fermions	bosons W and Z	$< 10^{-17} m$	$10^{-5}$	None	$\beta$ -decay
Electromagnetism	particles with electric charge	photon	long $F \propto 1/r^2$	1/137	Atoms, stones	Chemical reactions
Strong force	quarks and gluons	gluon	$10^{-15} m$	1	Hadrons, nuclei	Nuclear reactions



- Two people are standing in boats. One person moves their arm and is pushed backwards; a moment later the other person grabs at an invisible object and is driven backwards. Even though you cannot see a basketball, you can assume that one person threw a basketball to the other person because you see its effect on the people.

- It turns out that all interactions which affect matter particles are due to an exchange of *force carrier particles*, a different type of particle altogether. These particles are like basketballs tossed between matter particles (which are like the basketball players). What we normally think of as "forces" are actually the effects of force carrier particles on matter particles.

# The Standard Model

- Electromagnetic and weak forces can be described by a single theory  $\Rightarrow$  the “*Electroweak Theory*” was developed in 1960s (Glashow, Weinberg, Salam).
- Theory of strong interactions appeared in 1970s: “*Quantum Chromodynamics*” (QCD)
- The “*Standard Model*” (SM) combines both.



Abdu Salam, Steven Weinberg, Sheldon L. Glashow

## Main postulates of SM:

- 1) Basic constituents of matter are *quarks* and *leptons* (spin 1/2).
- 2) They interact by means of gauge bosons (spin 1).
- 3) Quarks and leptons are subdivided into *3 generations*.

# The Standard Model

Fermions		Bosons	
Leptons and Quarks	Spin = $\frac{1}{2}$	Spin = $1^*$	Force Carrier Particles
<b>Baryons (<math>qqq</math>)</b>	Spin = $\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \dots$	Spin = $0, 1, 2, \dots$	<b>Meson (<math>q\bar{q}</math>)</b>

Baryons ( $qqq$ ) and Mesons ( $q\bar{q}$ ) are **Hadrons**

$$\text{Baryon \#} = (qqq) = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = 1 \quad \text{and} \quad (q\bar{q}) = \frac{1}{3} + \left(-\frac{1}{3}\right) = 0$$


















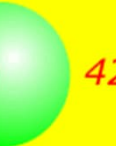






Lepton	lepton #	electron #	muon #
$e^-$	1	1	0
$\nu_e$	1	1	0
$\mu$	1	0	1
$\nu_\mu$	1	0	1

Lepton numbers are conserved in any reaction  
(for anti-leptons L = -1)

# Consequence of Lepton-Number Conservation

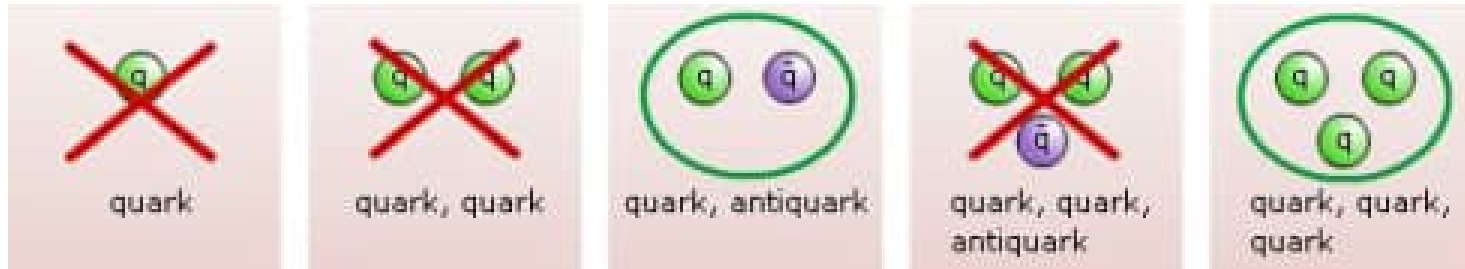
reaction	lepton #	electron #	muon #
$\nu_e + n \rightarrow p + e^-$			
$\bar{\nu}_e + n \rightarrow p + e^-$			
$\mu^- \rightarrow e^- + \gamma$			
$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$			
$\bar{\nu}_\mu + p \rightarrow e^+ + n$			

# Fermions: The Elementary Players

	1st generation	2nd generation	3rd generation	charge [e]
Quarks	 <b>u</b>   $\sim 3$	 <b>c</b>   $1250$	 <b>t</b>   $174300$	$2/3$
	 <b>d</b>   $\sim 6$	 <b>s</b>   $120$	 <b>b</b>   $4200$	$-1/3$
Leptons	 <b><math>\nu_e</math></b> $\sim 0$	 <b><math>\nu_\mu</math></b> $\sim 0$	 <b><math>\nu_\tau</math></b> $\sim 0$	$0$
	 <b>e</b> $0.511$	 <b><math>\mu</math></b> $106$	 <b><math>\tau</math></b> $1770$	$-1$

# Color charge of quarks

- So one had to explain why one saw only those combinations of quarks and antiquarks that had integer charge, and why no one ever saw a  $q$ ,  $qq$ ,  $qqq\bar{q}$ , or countless other combinations.



- Gell-Mann and others proposed that quarks can have three color charges. This type of charge was called "color" because certain combinations of quark colors would be "neutral" in the sense that three ordinary colors can yield white, a neutral color.
- This also resolve a problem with Pauli principle



# Quantum Numbers and Flavours

“Strangeness”

$$S = -[N(s) - N(\bar{s})]$$

“Charm”

$$C = [N(c) - N(\bar{c})]$$

“Bottomness”

$$\tilde{B} = -[N(b) - N(\bar{b})]$$

“Topness”

$$T = [N(t) - N(\bar{t})]$$

$$K^+ = u\bar{s}, \quad K^0 = d\bar{s}$$

$$K^- = \bar{u}s, \quad \bar{K}^0 = \bar{d}s$$

$$\Sigma^+ = uus, \Sigma^0 = uds, \Sigma^- = dds$$

$$D^+ = c\bar{d}, \quad D^0 = c\bar{u}$$

$$D^- = \bar{c}d, \quad \bar{D}^0 = \bar{c}u$$

$$B^+ = u\bar{b}, \quad B^0 = d\bar{b}$$

$$B^- = \bar{u}b, \quad \bar{B}^0 = \bar{d}b$$

No composite hadrons are formed that contain the top (anti) quark

- ❖ Majority of hadrons are unstable and tend to decay by the strong interaction to the state with the lowest possible mass ( $\tau \sim 10^{-23}$  s)
- ❖ Hadrons with the lowest possible mass for each quark number (C, S, etc.) may live much longer before decaying weakly ( $\tau \sim 10^{-7} - 10^{13}$  s) or electromagnetically (mesons,  $\tau \sim 10^{-16} - 10^{-21}$  s)

# Quantum Numbers and Flavours

Some examples of baryons:

particle	mass (GeV/c <sup>2</sup> )	quark composition	charge (units of e)	S	C	B
p	0.938	uud				
n	0.940	udd				
$\Lambda$	1.116	uds				
$\Lambda_c$	2.285	udc				

Some examples of mesons:

particle	mass (GeV/c <sup>2</sup> )	quark composition	charge (units of e)	S	C	B
$\pi^+$	0.140	$u\bar{d}$				
$K^-$	0.494	$s\bar{u}$				
$D^-$	1.869	$d\bar{c}$				
$D_s^+$	1.969	$c\bar{s}$				
$B^-$	5.279	$b\bar{u}$				
$Y$	9.460	$b\bar{b}$				

# Table of Baryons and Mesons

## Table of Baryons

Particle	Symbol	Makeup	Rest mass MeV/c <sup>2</sup>	Spin	B	S	Lifetime (seconds>	Decay Modes
<a href="#">Proton</a>	<b>p</b>	uud	938.3	1/2	+1	0	Stable	...
<a href="#">Neutron</a>	<b>n</b>	ddu	939.6	1/2	+1	0	920	$p e \bar{\nu}_e$
<a href="#">Lambda</a>	$\Lambda^0$	uds	1115.6	1/2	+1	-1	$2.6 \times 10^{-10}$	$p \pi^-, n \pi^0$
<a href="#">Sigma</a>	$\Sigma^+$	uus	1189.4	1/2	+1	-1	$0.8 \times 10^{-10}$	$p \pi^0, n \pi^+$
<a href="#">Sigma</a>	$\Sigma^0$	uds	1192.5	1/2	+1	-1	$6 \times 10^{-20}$	$\Lambda^0 \gamma$
<a href="#">Sigma</a>	$\Sigma^-$	dds	1197.3	1/2	+1	-1	$1.5 \times 10^{-10}$	$n \pi^-$
<a href="#">Delta</a>	$\Delta^{++}$	uuu	1232	3/2	+1	0	$0.6 \times 10^{-23}$	$p \pi^+$
<a href="#">Delta</a>	$\Delta^+$	uud	1232	3/2	+1	0	$0.6 \times 10^{-23}$	$p \pi^0$
<a href="#">Delta</a>	$\Delta^0$	udd	1232	3/2	+1	0	$0.6 \times 10^{-23}$	$n \pi^0$
<a href="#">Delta</a>	$\Delta^-$	ddd	1232	3/2	+1	0	$0.6 \times 10^{-23}$	$n \pi^-$
<a href="#">Xi Cascade</a>	$\Xi^0$	uss	1315	1/2	+1	-2	$2.9 \times 10^{-10}$	$\Lambda^0 \pi^0$
<a href="#">Xi Cascade</a>	$\Xi^-$	dss	1321	1/2	+1	-2	$1.64 \times 10^{-10}$	$\Lambda^0 \pi^-$
<a href="#">Omega</a>	$\Omega^-$	sss	1672	3/2	+1	-3	$0.82 \times 10^{-10}$	$\Xi^0 \pi^-, \Lambda^0 K^-$
<a href="#">Lambda</a>	$\Lambda_c^+$	udc	2281	1/2	+1	0	$2 \times 10^{-13}$	...

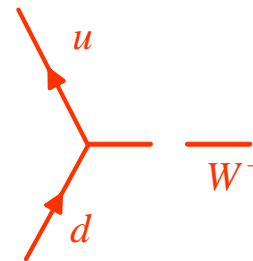
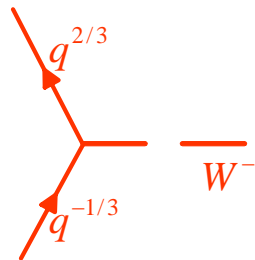
## Mesons

Particle	Symbol	Anti-particle	Makeup	Rest mass MeV/c <sup>2</sup>	S	C	B	Lifetime	Decay Modes
<a href="#">Pion</a>	$\pi^+$	$\pi^-$	$u\bar{d}$	139.6	0	0	0	$2.60 \times 10^{-8}$	$\mu^+ \nu_\mu$
<a href="#">Pion</a>	$\pi^0$	Self	$\frac{u\bar{u} - d\bar{d}}{\sqrt{2}}$	135.0	0	0	0	$0.83 \times 10^{-16}$	$2\gamma$
<a href="#">Kaon</a>	$K^+$	$K^-$	$u\bar{s}$	493.7	+1	0	0	$1.24 \times 10^{-8}$	$\mu^+ \nu_\mu, \pi^+ \pi^0$
<a href="#">Kaon</a>	$K_s^0$	$K_s^0$	$1^*$	497.7	+1	0	0	$0.89 \times 10^{-10}$	$\pi^+ \pi^-, 2\pi^0$
<a href="#">Kaon</a>	$K_L^0$	$K_L^0$	$1^*$	497.7	+1	0	0	$5.2 \times 10^{-8}$	$\pi^+ e \bar{\nu}_e$
<a href="#">Eta</a>	$\eta^0$	Self	$2^*$	548.8	0	0	0	$< 10^{-18}$	$2\gamma, 3\mu$
<a href="#">Eta prime</a>	$\eta'$	Self	$2^*$	958	0	0	0	...	$\pi^+ \pi^- \eta$
<a href="#">Rho</a>	$\rho^+$	$\rho^-$	$u\bar{d}$	770	0	0	0	$0.4 \times 10^{-23}$	$\pi^+ \pi^0$
<a href="#">Rho</a>	$\rho^0$	Self	$u\bar{u}, d\bar{d}$	770	0	0	0	$0.4 \times 10^{-23}$	$\pi^+ \pi^-$
<a href="#">Omega</a>	$\omega^0$	Self	$u\bar{u}, d\bar{d}$	782	0	0	0	$0.8 \times 10^{-22}$	$\pi^+ \pi^- \pi^0$
<a href="#">Phi</a>	$\phi$	Self	$s\bar{s}$	1020	0	0	0	$20 \times 10^{-23}$	$K^+ K^-, K^0 \bar{K}^0$
<a href="#">D</a>	$D^+$	$D^-$	$c\bar{d}$	1869.4	0	+1	0	$10.6 \times 10^{-13}$	$K^+ \pi^-, e^+ \pi^-$
<a href="#">D</a>	$D^0$	$\bar{D}^0$	$c\bar{u}$	1864.6	0	+1	0	$4.2 \times 10^{-13}$	$[K, \mu, e]^+ \pi^-$
<a href="#">D</a>	$D_s^+$	$D_s^-$	$c\bar{s}$	1969	+1	+1	0	$4.7 \times 10^{-13}$	$K^+ \pi^-$
<a href="#">J/Psi</a>	$J/\psi$	Self	$c\bar{c}$	3096.9	0	0	0	$0.8 \times 10^{-20}$	$e^+ e^-, \mu^+ \mu^- \dots$
<a href="#">B</a>	$B^-$	$B^+$	$b\bar{u}$	5279	0	0	-1	$1.5 \times 10^{-12}$	$D^0 \pi^-$
<a href="#">B</a>	$B^0$	$\bar{B}^0$	$d\bar{b}$	5279	0	0	-1	$1.5 \times 10^{-12}$	$D^0 \pi^-$
<a href="#">B_s</a>	$B_s^-$	$B_s^+$	$s\bar{b}$	5370	-1	0	-1	...	$B_s^+ \pi^-$
<a href="#">Upsilon</a>	$\Upsilon$	Self	$b\bar{b}$	9460.4	0	0	0	$1.3 \times 10^{-20}$	$e^+ e^-, \mu^+ \mu^- \dots$

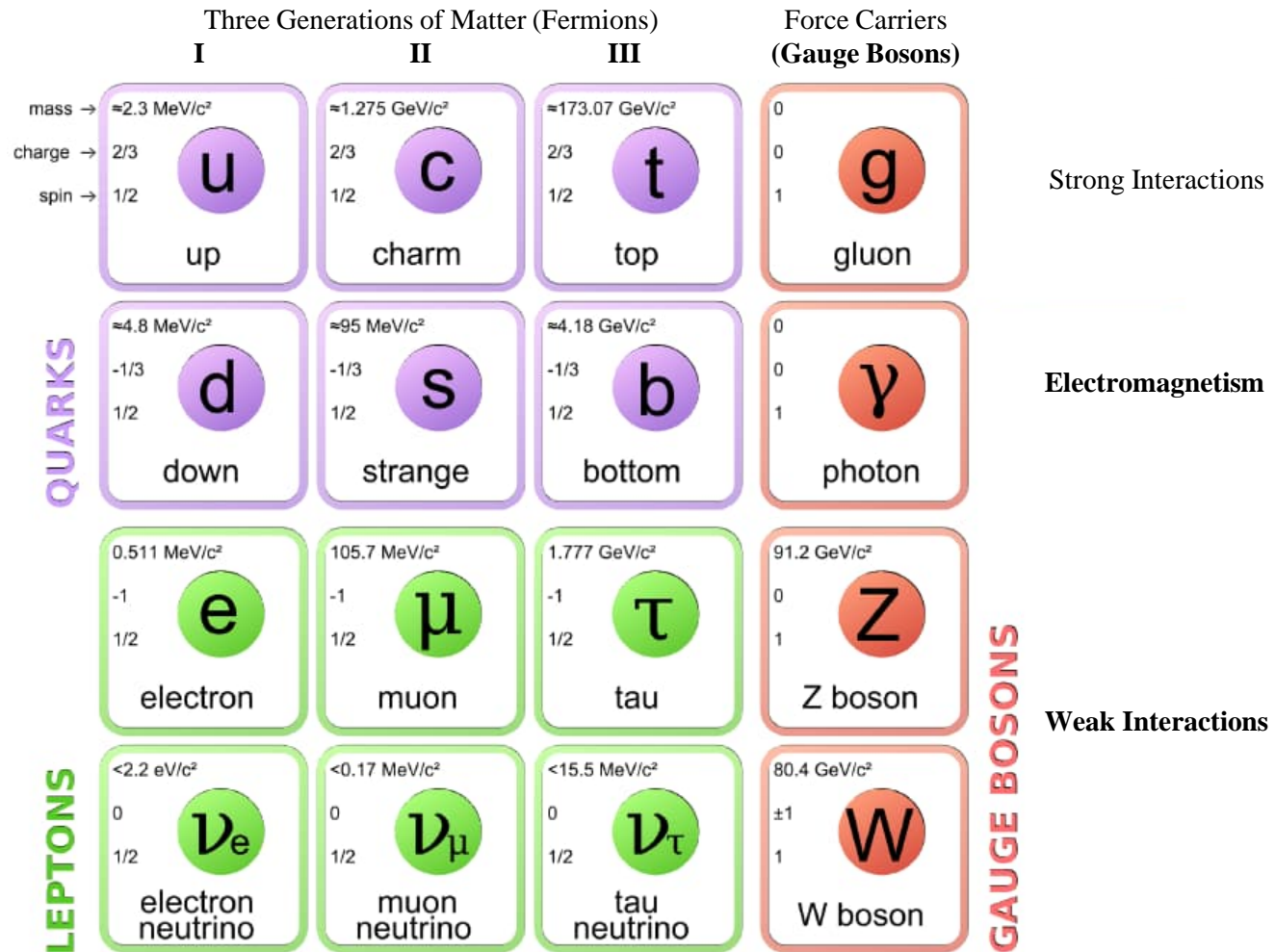
# Consequence of Quark-Number Conservation

reaction	Quark configuration	charge	baryon #	strangeness #
$\bar{p} + p \rightarrow \pi^0 + n$				
$\pi^- + p \rightarrow K^0(d\bar{s}) + n$				
$p + p \rightarrow \pi^+ + n + n$				

decay	Quark configuration	
$\Omega^- \rightarrow \Lambda^0 + K^-$		
$K^+ \rightarrow \pi^+ + \pi^0$		
$\Xi^+ \rightarrow \Lambda^0 + \pi^+$		



# The Standard Model Chart



- ❖ Standard Model does not explain neither appearance of the mass nor the reason for existence of 3 generations.

# Why colored Quarks?

Three Generations			Force Carriers
I	II	III	
mass → charge → spin → <b>u</b> up	mass → charge → spin → <b>c</b> charm	mass → charge → spin → <b>t</b> top	<b>g</b> gluon
<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>γ</b> photon
<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>Z</b> Z boson
<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>W</b> W boson

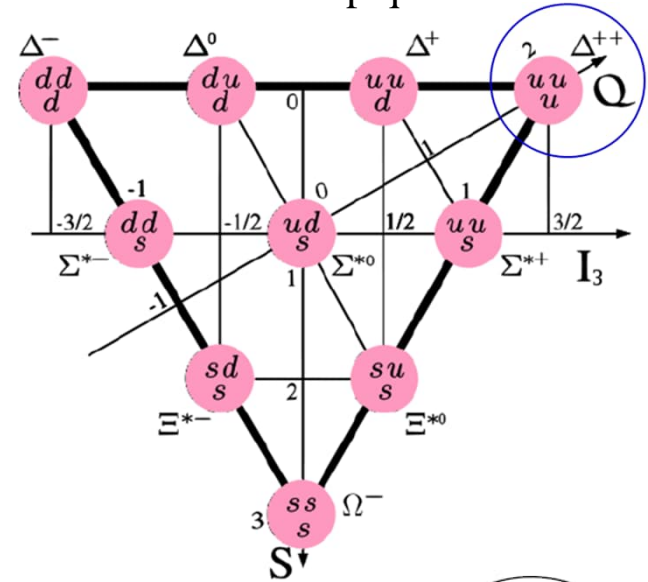
GAUGE BOSONS

Strong Interactions

Electromagnetism

Weak Interactions

$\Delta^{++}$  is a isospin  $3/2$  particle with 3 “identical” up quarks!



Eight gluon colors

$$(r\bar{b} + b\bar{r})/\sqrt{2}$$

$$(r\bar{g} + g\bar{r})/\sqrt{2}$$

$$(b\bar{g} + g\bar{b})/\sqrt{2}$$

$$(r\bar{r} + b\bar{b})/\sqrt{2}$$

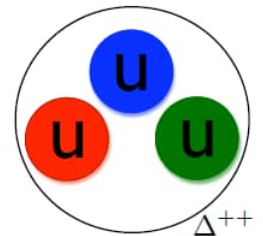
$$-i(r\bar{b} - b\bar{r})/\sqrt{2}$$

$$-i(r\bar{g} - g\bar{r})/\sqrt{2}$$

$$-i(b\bar{g} - g\bar{b})/\sqrt{2}$$

$$(r\bar{r} + b\bar{b} - 2g\bar{g})/\sqrt{6}$$

Pauli principle

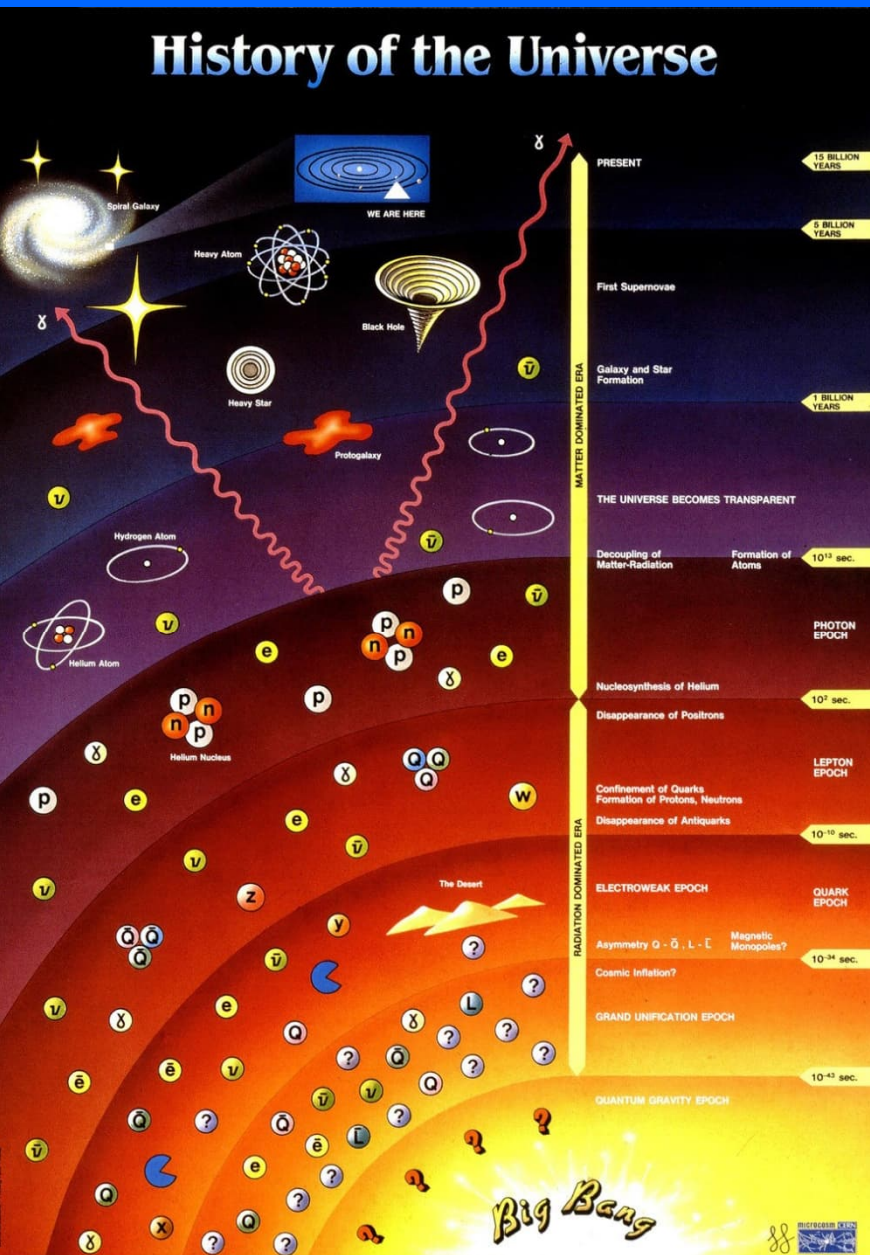


# Particles and Interactions

Force \ Particles	Quarks	Charged Leptons	Neutrinos
Strong	yes	no	no
Electromagnetic	yes	yes	no
Weak	yes	yes	yes

**Quarks (hence hadrons) have all types of interactions!**

# History of the Universe



era of gravitation

10<sup>13</sup> s

era of particle physics

# Units and Dimensions

- The energy is measured in **electron-Volts**:

$$1 \text{ eV} = 1.602 \cdot 10^{-19} \text{ J}$$

$$1 \text{ keV} = 10^3 \text{ eV}; 1 \text{ MeV} = 10^6 \text{ eV}; 1 \text{ GeV} = 10^9 \text{ eV}; 1 \text{ TeV} = 10^{12} \text{ eV}$$

- The Planck constant (reduced) is:

$$\hbar \equiv h/2\pi = 6.582 \cdot 10^{-22} \text{ MeV s}$$

and the “conversion constant” is:

$$\hbar c = 197.327 \cdot 10^{-15} \text{ MeV m}$$

$\begin{aligned} \Delta E \cdot \Delta t &= \hbar = \text{energy} * \text{time} \\ \therefore \hbar c &= \text{energy} * \text{time} * \text{velocity} \\ &= \text{energy} * \text{distance} \end{aligned}$
---

- **Charges** measured in terms of electronic charges  $e = 1.6 \cdot 10^{-19} \text{ C}$
- **Cross sections** measured in terms of barns.  $1 \text{ barn} = 10^{-28} \text{ m}^2$

# Units and Dimensions

Because  $E^2 = p^2c^2 + m^2c^4$  where  $E$  is the energy,  $p$  the momentum,  $m$  the rest mass:  $pc$  and  $mc^2$  have dimensions of energy and it is convenient to measure momentum in units of  $\text{GeV}/c$  and mass in units of  $\text{GeV}/c^2$ .

$$[E(\text{GeV})]^2 = [p(\text{GeV}/c)]^2c^2 + [m(\text{GeV}/c^2)]^2c^4$$

$$1 \text{ eV}/c^2 = 1.78 \cdot 10^{-36} \text{ kg}$$

Because  $c$  cancels out we often omit the  $c$  i.e. put  $c=1$  (and  $\hbar = 1$ ), so momenta and masses are also measured in  $\text{GeV}$ .

# Units and Dimensions

This implies, however, that the results of calculations must be translated back to measurable quantities in the end. Conversion factors are the following:

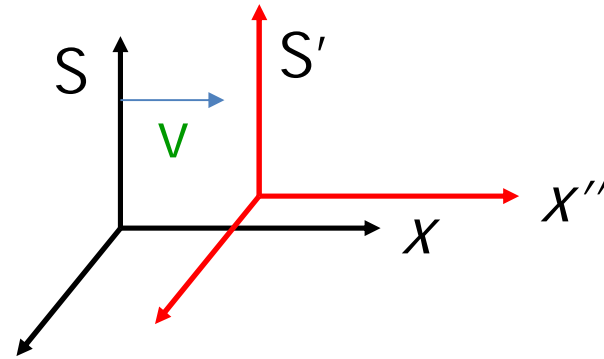
quantity	conversion factor	natural unit	normal unit
mass	$1kg = 5.61 \cdot 10^{26} GeV$	GeV	$GeV/c^2$
length	$1m = 5.07 \cdot 10^{15} GeV^{-1}$	$GeV^{-1}$	$\hbar c / GeV$
time	$1s = 1.52 \cdot 10^{24} GeV^{-1}$	$GeV^{-1}$	$\hbar / GeV$
unit charge	$e = \sqrt{4\pi\alpha}$	1	$\sqrt{\hbar c}$

*Excercise-1:*

*Derive the conversion factors for mass, length and time in the table above.*

# Lorentz Transformation

Co-moving coordinate systems



$$S \rightarrow S' : \begin{cases} t' = \gamma(t - \frac{vx}{c^2}) \\ x' = \gamma(x - vt) \\ y' = y \\ z' = z \end{cases}$$

$$S' \rightarrow S : \begin{cases} t = \gamma(t' + \frac{vx'}{c^2}) \\ x = \gamma(x' + vt') \\ y = y' \\ z = z' \end{cases}$$

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

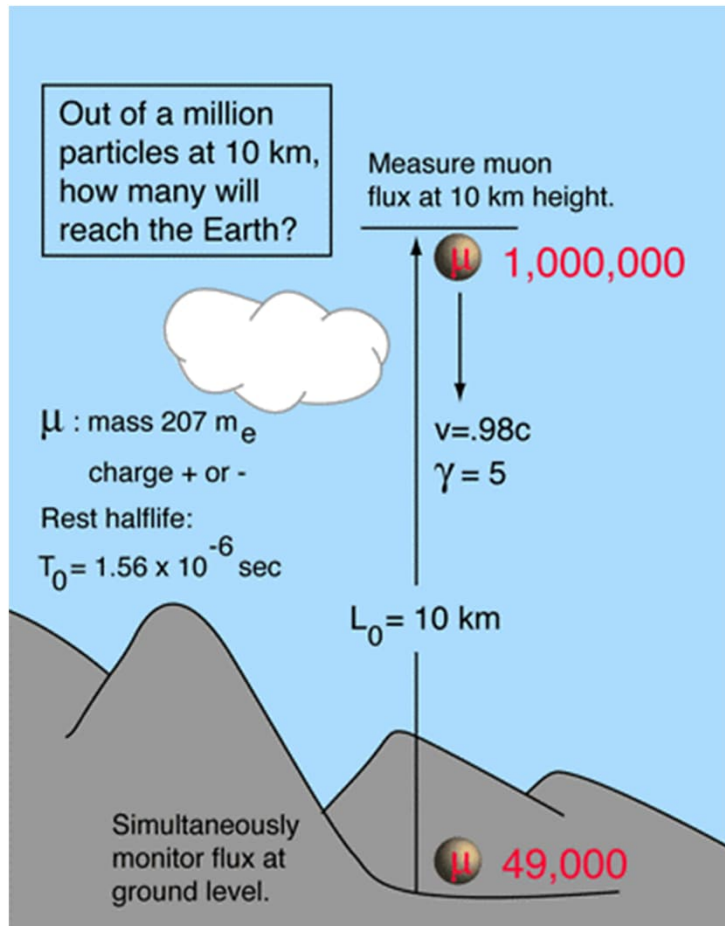
Lorentz contraction:

$$L = L_0 / \gamma$$

Time dilatation:

$$t = t_0 \cdot \gamma$$

# Time Dilatation



*non-relativistic*

Distance:  $L_0 = 10^4 \text{ meters}$

$$\text{Time: } T = \frac{10^4 \text{ m}}{(0.98) \cdot (3 \cdot 10^8 \text{ m/s})}$$

$$T = 34 \cdot 10^{-6} \text{ s} = 21.8 \text{ halflives} \quad = 4.36 \text{ halflives}$$

Survival rate:

$$\frac{I}{I_0} = 2^{-21.8} = 0.27 \cdot 10^{-6}$$

Or only about 0.3  
out of a million

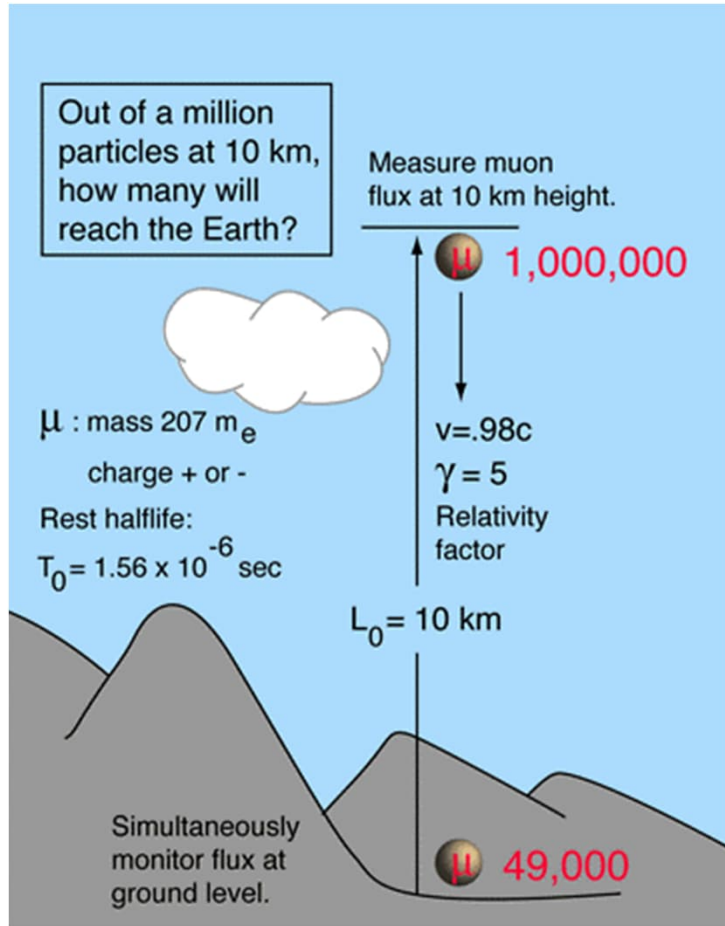
*Earth-frame observer*

$$\frac{I}{I_0} = 2^{-4.36} = 0.049$$

Or only about 49000  
out of a million

The muon's clock is time-dilated, or running slow by a factor  $T = \gamma \cdot T_0$  so its measured half-life is  $5 \cdot 1.56 \mu\text{s} = 7.8 \mu\text{s}$ .

# Lorentz Contraction



*non-relativistic*

Distance:  $L_0 = 10^4$  meters

$$\text{Time: } T = \frac{10^4 \text{ m}}{(0.98) \cdot (3 \cdot 10^8 \text{ m/s})}$$

$$T = 34 \cdot 10^{-6} \text{ s} = 21.8 \text{ halflives}$$

Survival rate:

$$\frac{I}{I_0} = 2^{-21.8} = 0.27 \cdot 10^{-6}$$

Or only about 0.3  
out of a million

*Muon-frame observer*

$$= \frac{2000 \text{ m}}{(0.98) \cdot (3 \cdot 10^8 \text{ m/s})}$$

$$= 6.8 \cdot 10^6 \text{ s}$$

$$= 4.36 \text{ halflives}$$

$$\frac{I}{I_0} = 2^{-4.36} = 0.049$$

Or only about 49000  
out of a million

The muon sees distance as length-contracted, so that  $L = L_0/\gamma = 0.2 \cdot L_0 = 2$  km.

# Relativistic Kinematics

The relativistic relationship between the total energy  $E$ , momentum  $p$  and rest mass  $m$  is

$$E^2 = p^2 c^2 + m^2 c^4$$

or

$$E^2 = p_x^2 c^2 + p_y^2 c^2 + p_z^2 c^2 + m^2 c^4$$

Non relativistic ( $p \ll m$ ):

$$\begin{aligned} E &= (p^2 c^2 + m^2 c^4)^{1/2} \\ &= mc^2 \cdot (1 + p^2 c^2 / m^2 c^4)^{1/2} \\ &= mc^2 \cdot (1 + p^2 / 2m^2 c^2 + \dots) \\ &\cong mc^2 + p^2 / 2m \quad (p = mv) \\ &\cong mc^2 + \frac{1}{2} mv^2 \end{aligned}$$

The particle velocity  $v = \beta c$  or  $\beta = v/c$  and the Lorentz factor

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

So that  $\gamma^2(1 - \beta^2) = 1$  or  $\gamma^2 = \gamma^2\beta^2 + 1$  - multiplied by  $m^2 c^4$

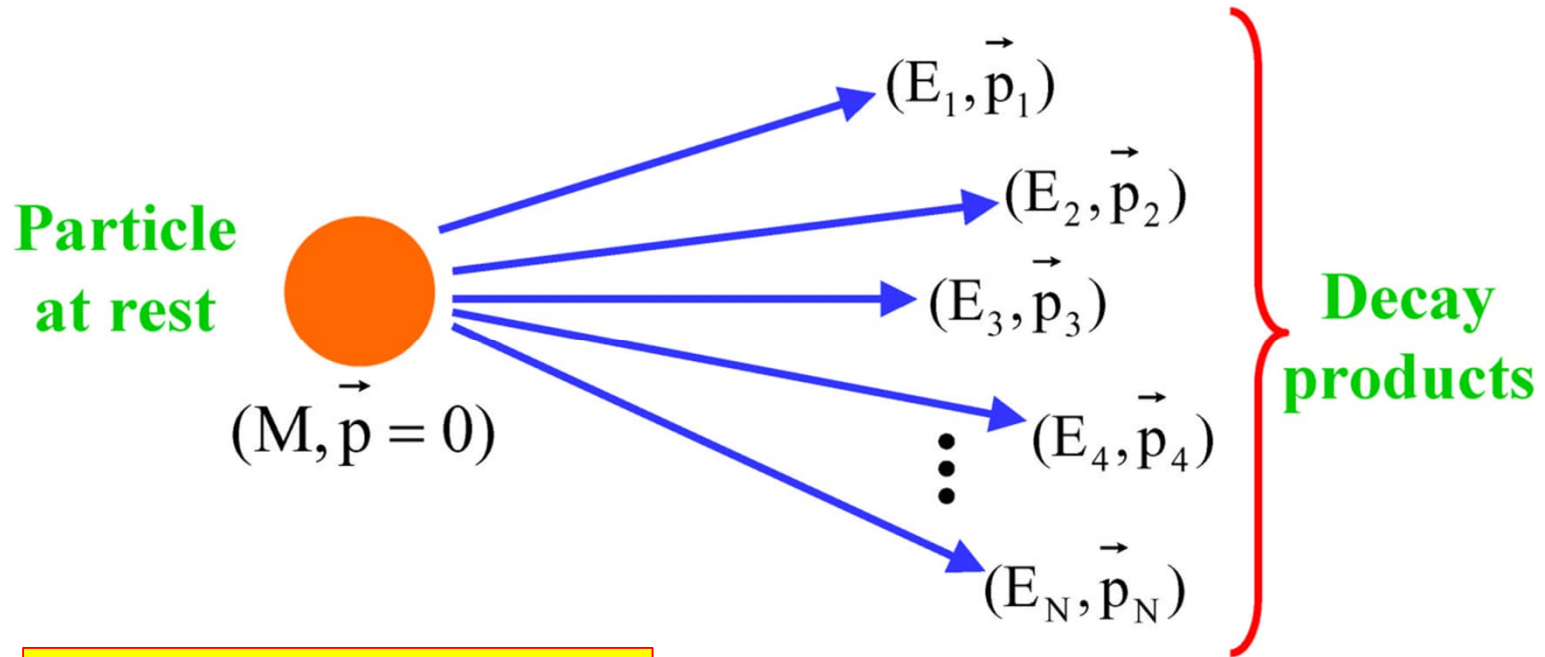
$$\gamma^2 m^2 c^4 = \gamma^2 \beta^2 m^2 c^4 + m^2 c^4$$

Compare with

$$E^2 = p^2 c^2 + m^2 c^4$$

$E = \gamma mc^2$  and  $p = \gamma \beta mc$  or  $\gamma = E/mc^2$  and  $\beta = p/\gamma mc = pc/E$

# Invariant Mass



$$M^2 = \left( \sum_i E_i \right)^2 - \left( \sum_i \vec{p}_i \right)^2$$

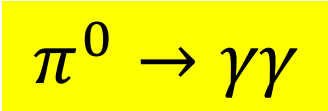
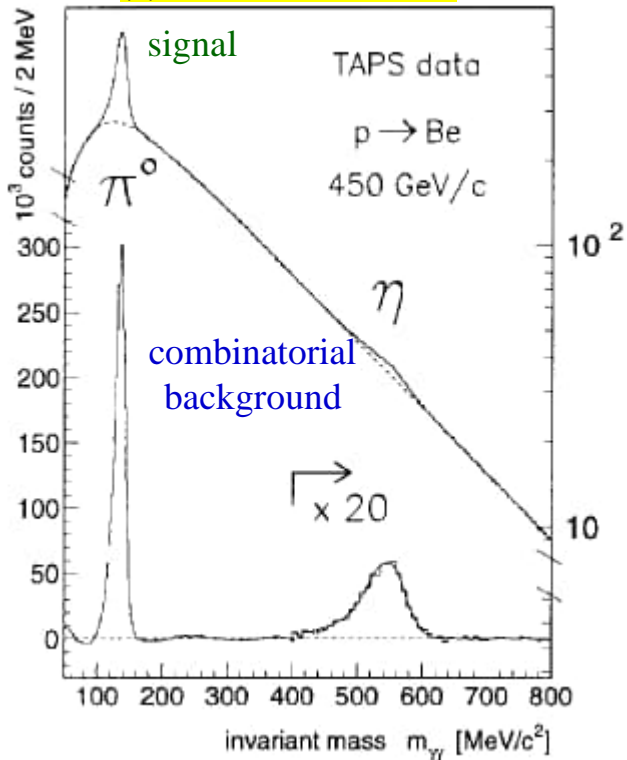
$\pi^0 \rightarrow \gamma\gamma$  decay: (two massless particles)

$$\begin{aligned} M^2 &= [(p_1, 0, 0, p_1) + (p_2, 0, p_2 \sin\theta, p_2 \cos\theta)]^2 = (p_1 + p_2)^2 - p_2^2 \sin^2\theta - (p_1 + p_2 \cos\theta)^2 \\ &= 2p_1 p_2 (1 - \cos\theta) \end{aligned}$$

$(E, p_x, p_y, p_z)$

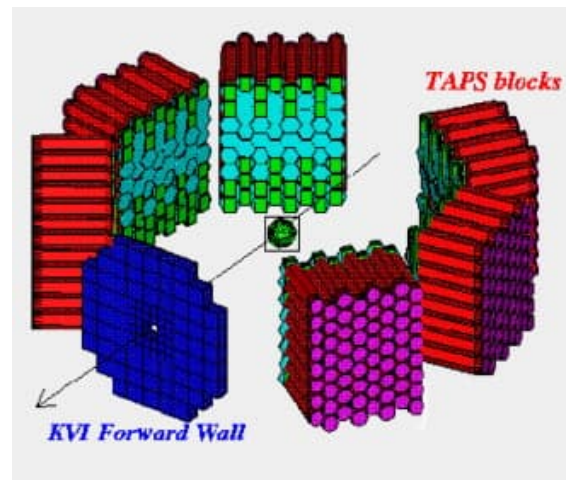
# Example: Data from Two Arm Photon Spectrometer TAPS

$\gamma\gamma$  invariant mass

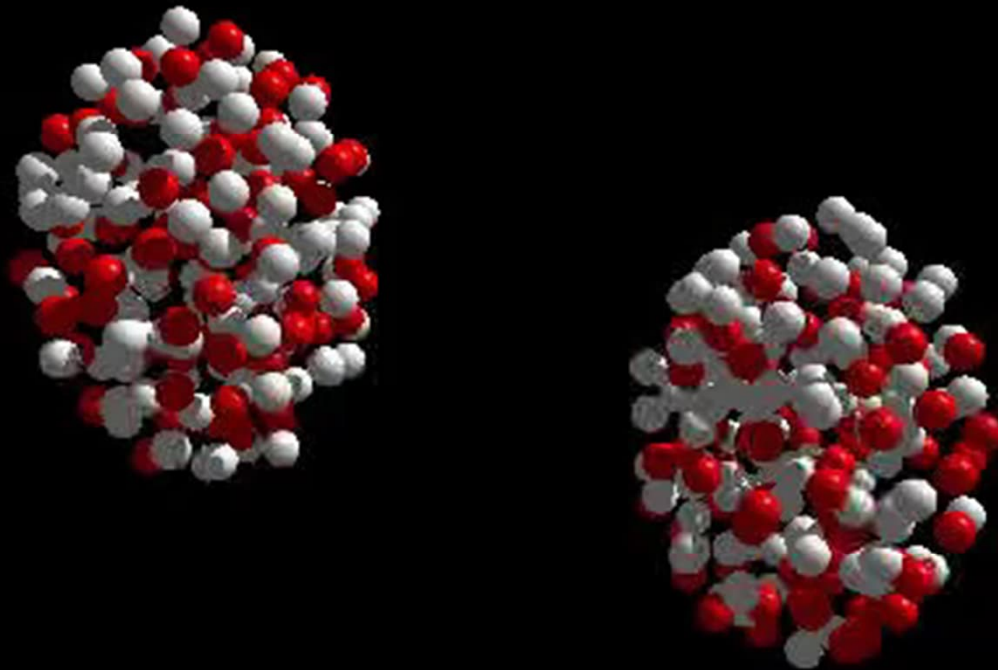


Compute invariant mass  $m_{\gamma\gamma}$   
for all possible photon pairs

$$m_{\gamma\gamma} = \sqrt{2E_{\gamma 1}E_{\gamma 2}(1 - \cos\theta_{\gamma\gamma})}$$

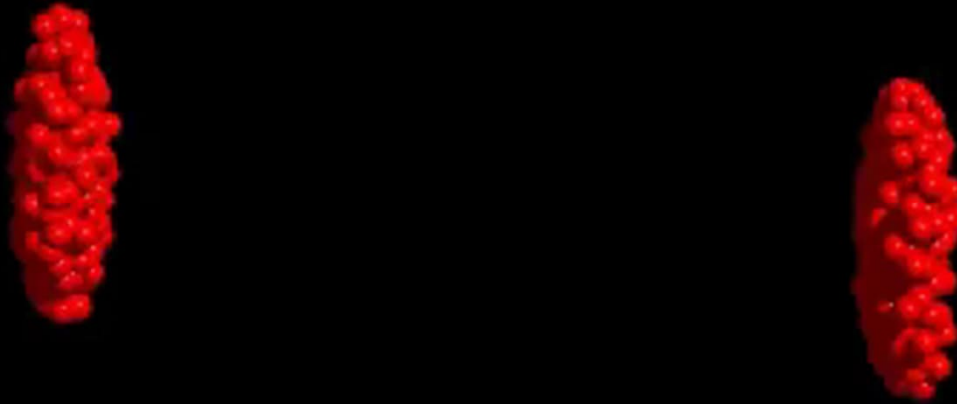


# Compressed nuclear matter



$$E=mc^2$$

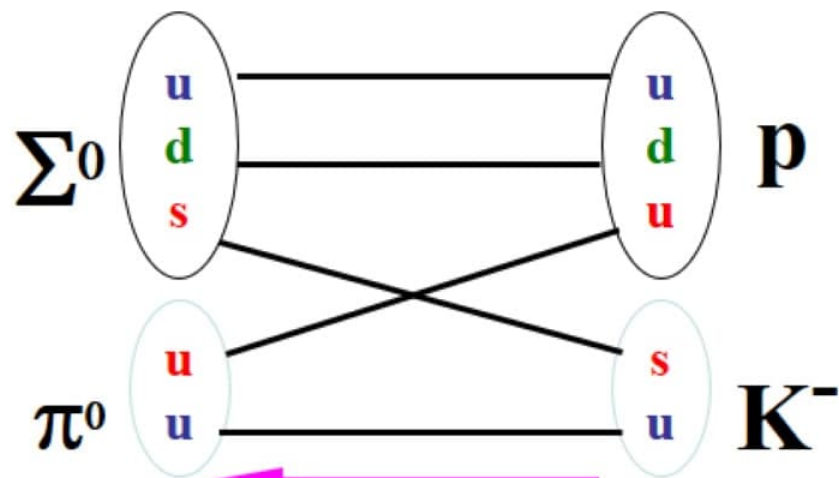
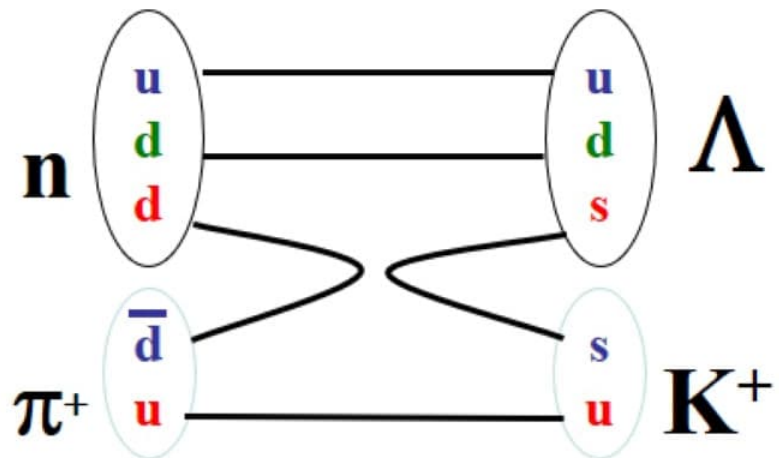
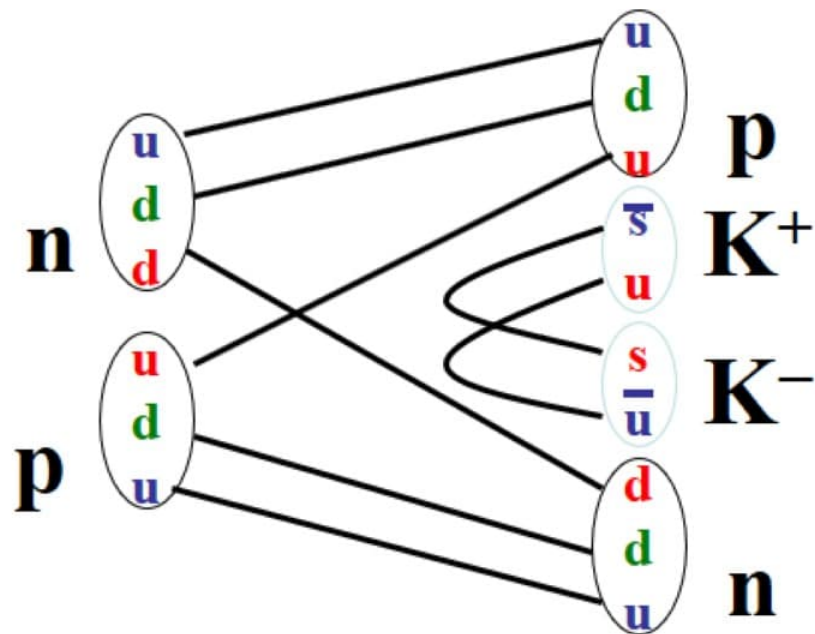
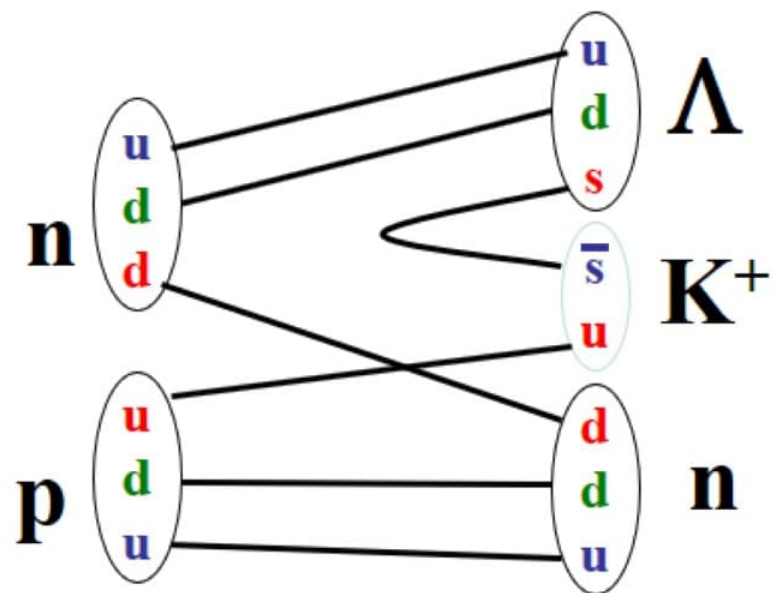
# Compressed nuclear matter



$$E=mc^2$$

UrQMD Frankfurt/M

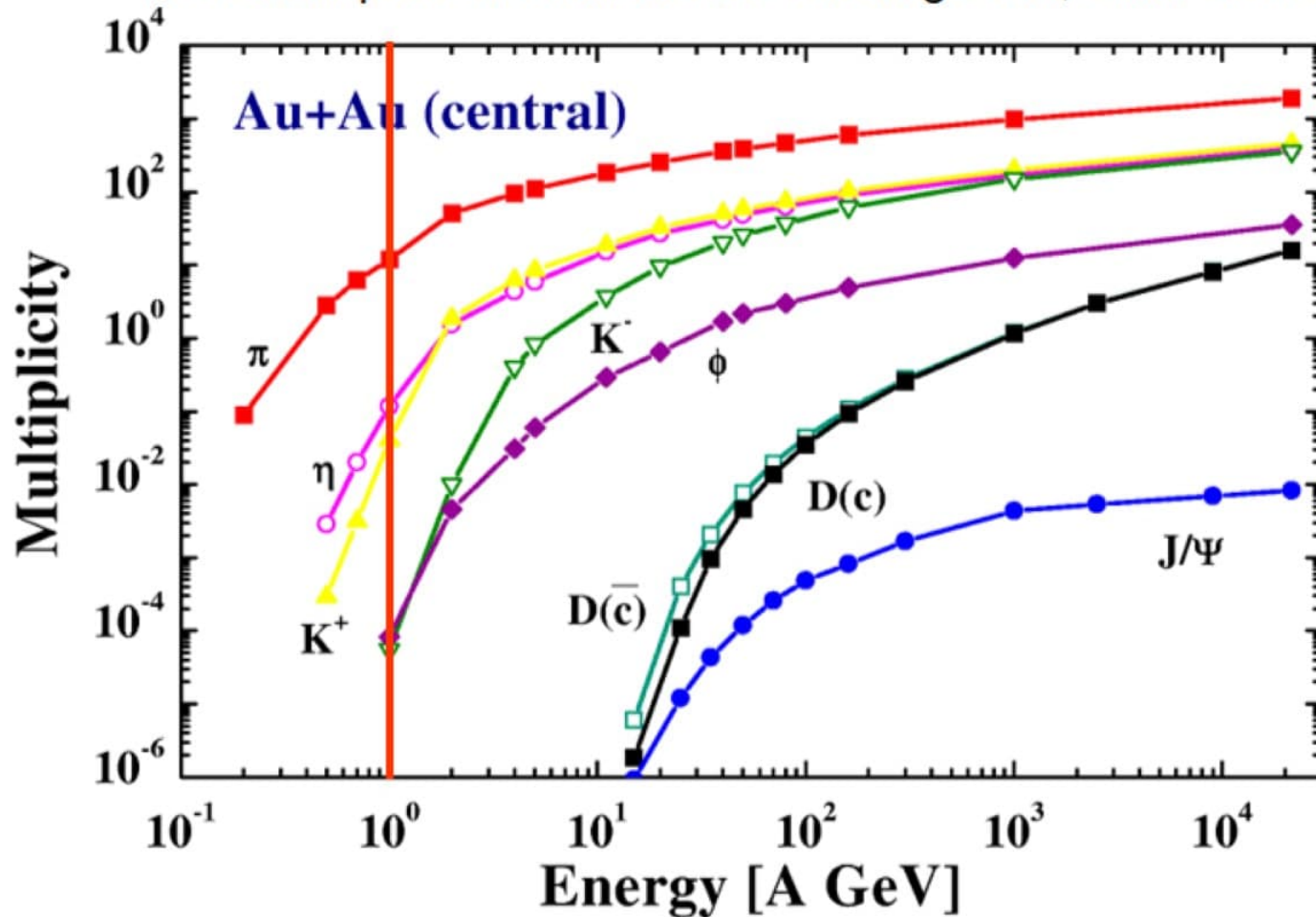
# The creation of strangeness



K<sup>-</sup> absorption

# Particle production in Au+Au collisions

HSD transport calculations: W. Cassing et al., Univ. Giessen



$$M_{K^+} \approx 2 \cdot 10^{-2}$$

$$M_{K^-} \approx 10^{-4}$$

# The Kaon-Spectrometer (KaoS) at SIS/GSI

Momentum determination:  
curvature in dipole field

$$p = mv = qBr$$

Time-of-flight measurement:

$$\Delta t = t_{\text{stop}} - t_{\text{start}}$$

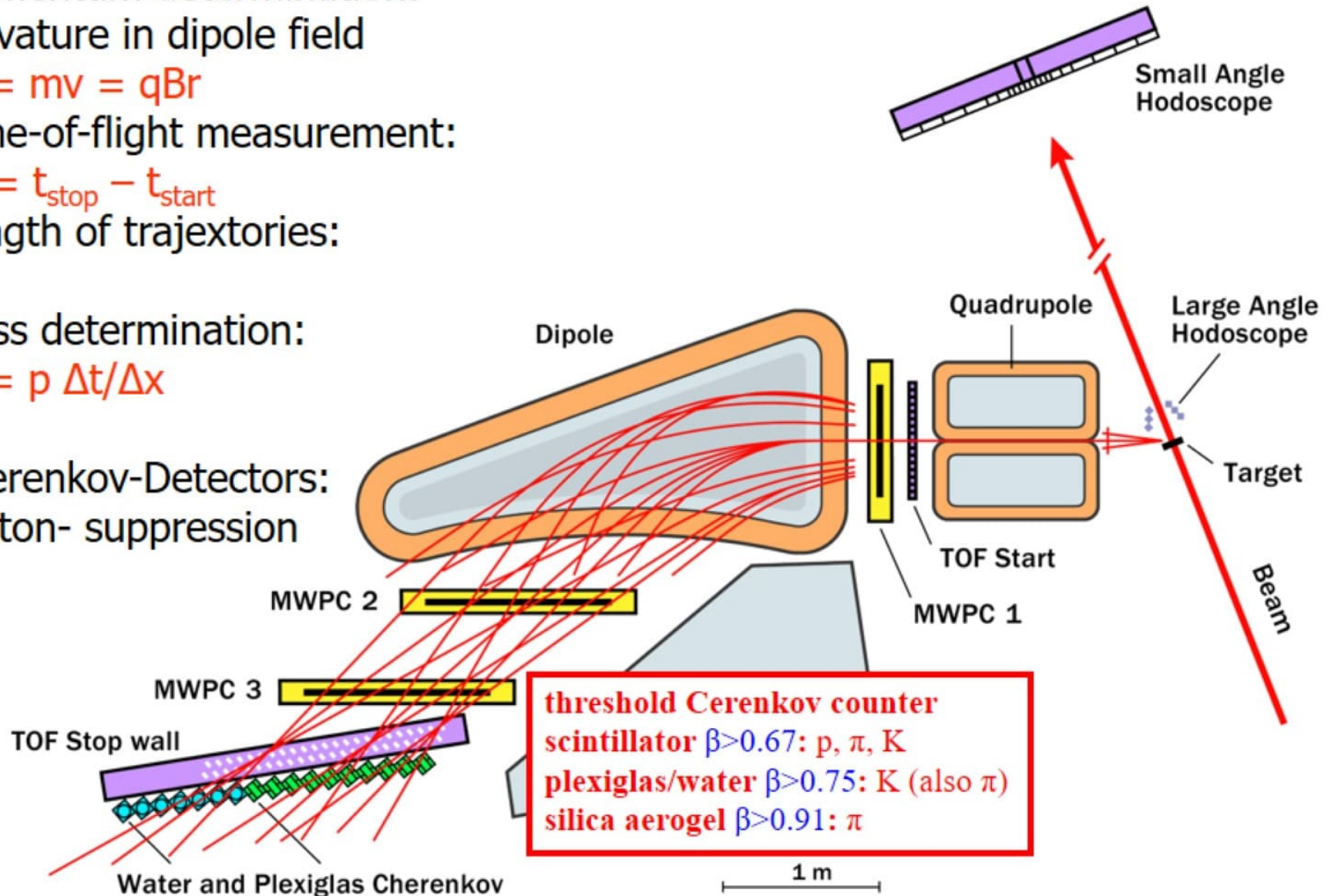
Length of trajectories:

$$\Delta x$$

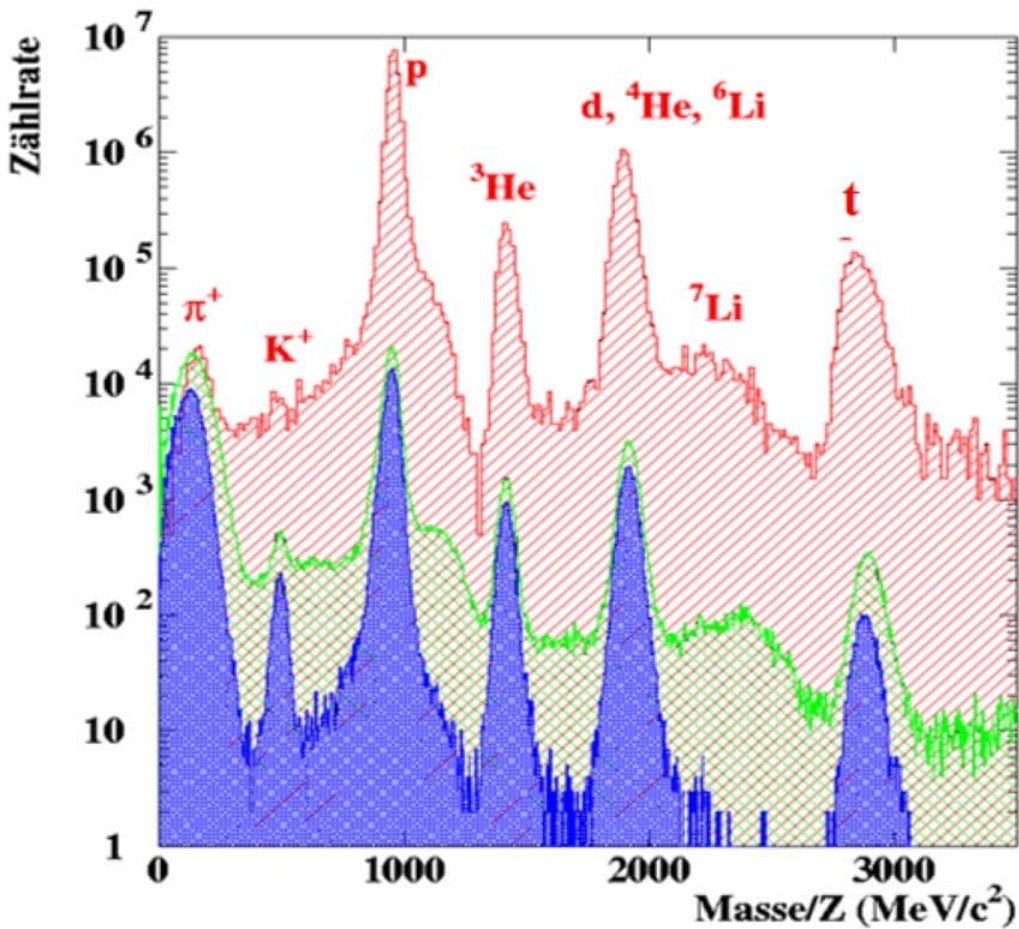
Mass determination:

$$m = p \Delta t / \Delta x$$

Cherenkov-Detectors:  
Proton- suppression



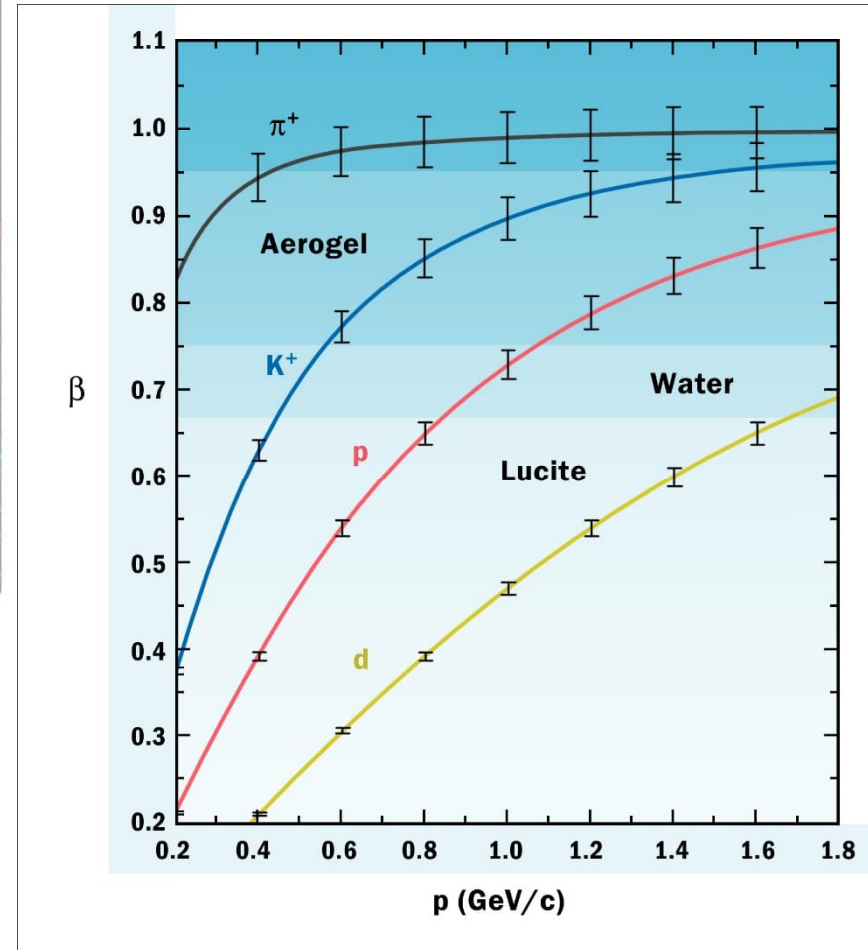
# Particle identification with KaoS



1. Minimum bias trigger
2. Kaon trigger (TOF & Cherenkov)
3. Kaon trigger & tracking & 2xTOF

Au + Au 1 AGeV:

$$p / \pi^+ / K^+ \approx 2 \cdot 10^4 / 10^3 / 1$$



# The Kaon Spectrometer at SIS (1991 – 2002)



**Collaboration:**

**GSI Darmstadt:**

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C. Müntz, E. Schwab, P. Senger,

**TU Darmstadt:**

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**Univ. Frankfurt:**

D. Brill, M. Mang, Y. Shin, T. Schuck,  
H. Ströbele

**Univ. Marburg:**

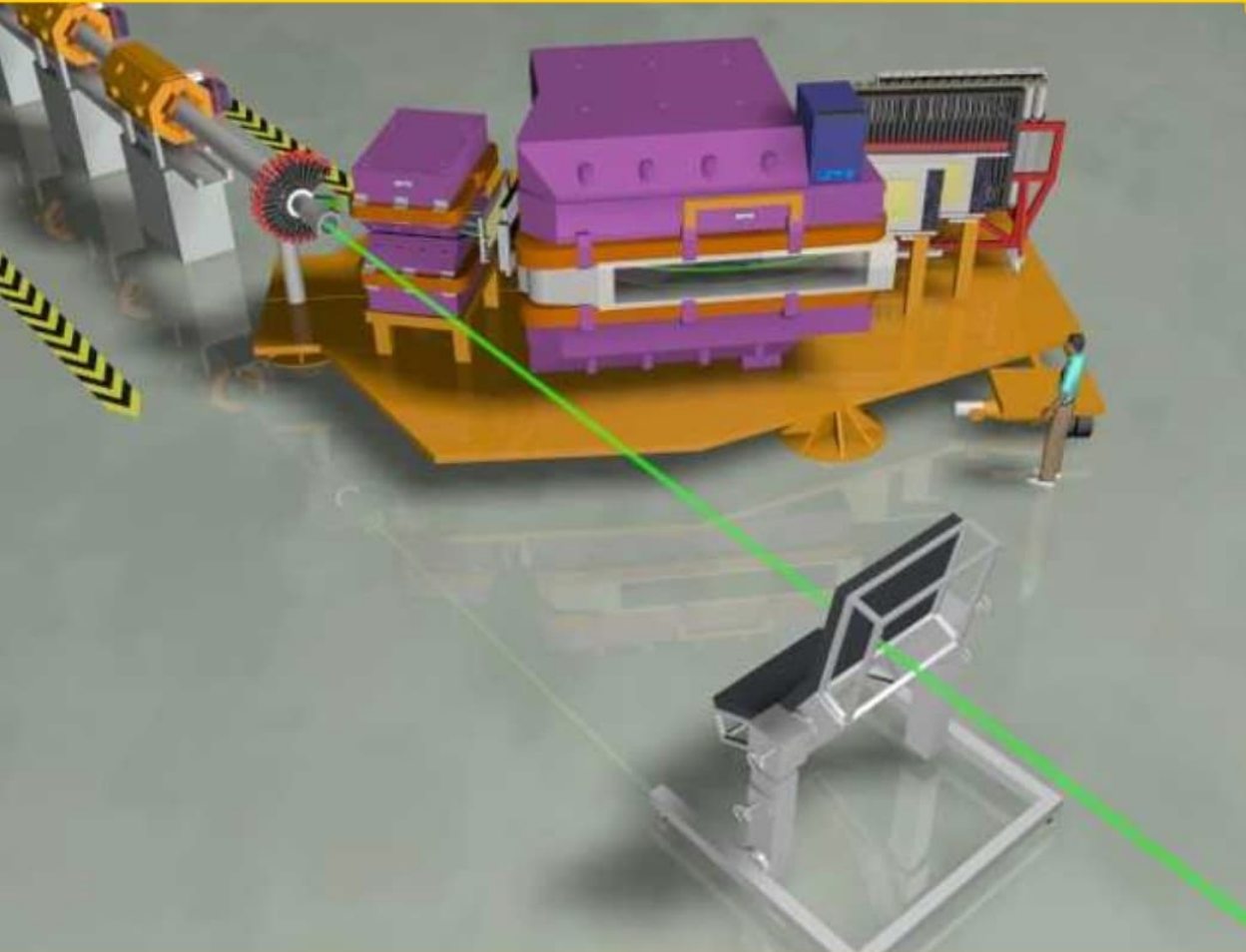
I. Böttcher, B. Kohlmeyer, H. Pöppl,  
M. Menzel, K. Völkel

**Univ. Kraków:**

M. Cieślak, M. Dębowski, D. Miśkowiec,  
M. Płoskon, W. Prokopowicz,  
G. Surówka, W. Waluś

**FZ Rossendorf:**

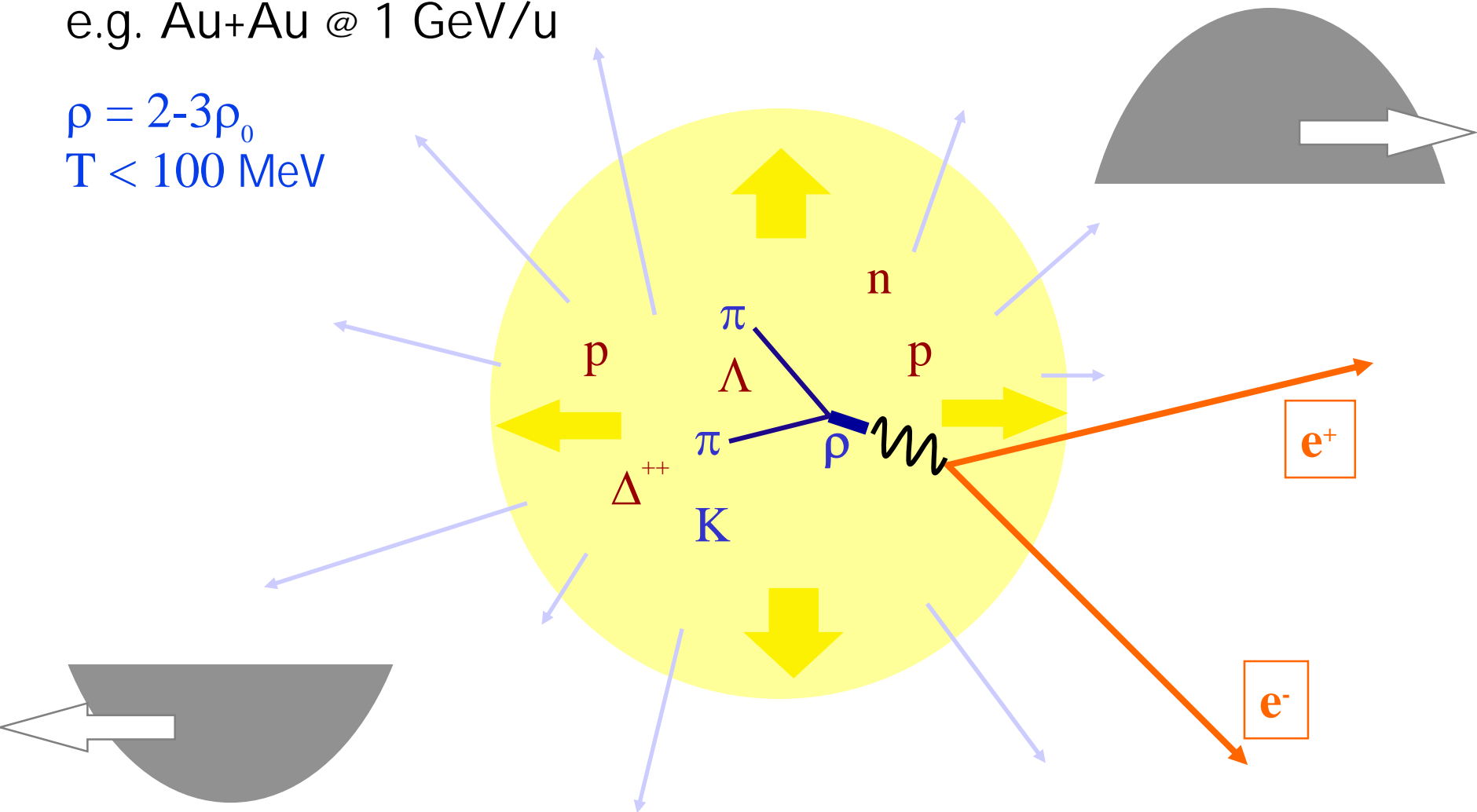
F. Dohrmann, E. Grosse, L. Naumann,  
W. Scheinast, A. Wagner



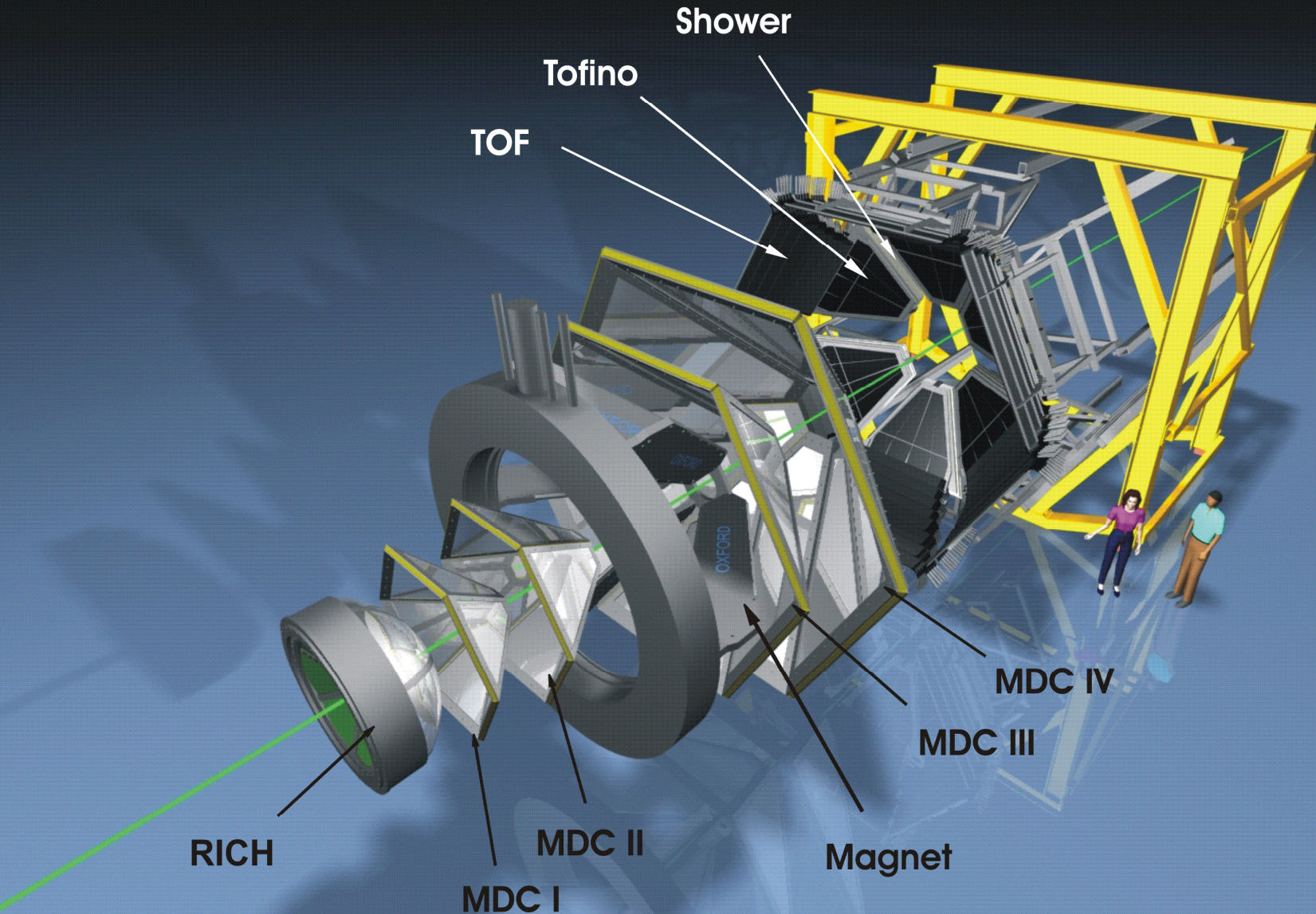
# Probing the interior of the dense interaction zone

e.g. Au+Au @ 1 GeV/u

$\rho = 2-3\rho_0$   
 $T < 100$  MeV



# The HADES experiment @ GSI



# Observables

❖ Scattering  Cross section ( $\sigma$ )

❖ Decays  Decay rate ( $\Gamma$ )

Both  $\sigma$  and  $\Gamma$  are related to the probability for the considered process to occur

# Cross Section

Consider a beam of projectiles of intensity  $\Phi_a$  particles/sec which hits a thin foil of target nuclei with the result that the beam is attenuated by reactions in the foil such that the transmitted intensity is  $\Phi$  particles/sec.

The fraction of the incident particles disappear from the beam, i.e. react, in passing through the foil is given by

$$d\Phi = -\Phi \cdot n_b \cdot \sigma \cdot dx$$

The number of reactions that are occurring is the difference between the initial and transmitted flux

$$\Phi_{initial} - \Phi_{trans} = \Phi_{initial}(1 - \exp[-n_b \cdot d \cdot \sigma])$$

$$\approx \Phi_{initial} \cdot N_b \cdot \sigma \quad (\text{for thin target})$$

## Example:

A particle current of 1 pA consists of  $6 \cdot 10^9$  projectiles/s.

A  $^{132}\text{Sn}$  target (1 mg/cm<sup>2</sup>) consists of  $5 \cdot 10^{18}$  nuclei/cm<sup>2</sup>

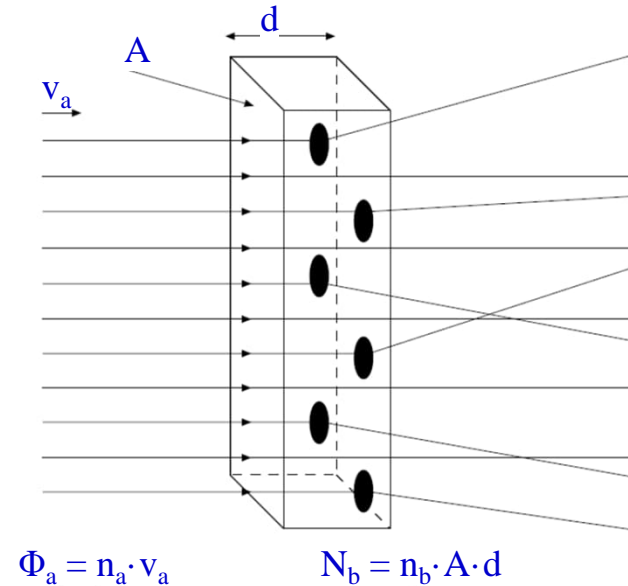
$$\frac{6 \cdot 10^{23} \cdot 10^{-3} \text{ g/cm}^2}{132 \text{ g}} = 4.5 \cdot 10^{18} \left[ \frac{\text{target nuclei}}{\text{cm}^2} \right]$$

**Luminosity** = projectiles [s<sup>-1</sup>] · target nuclei [cm<sup>-2</sup>]

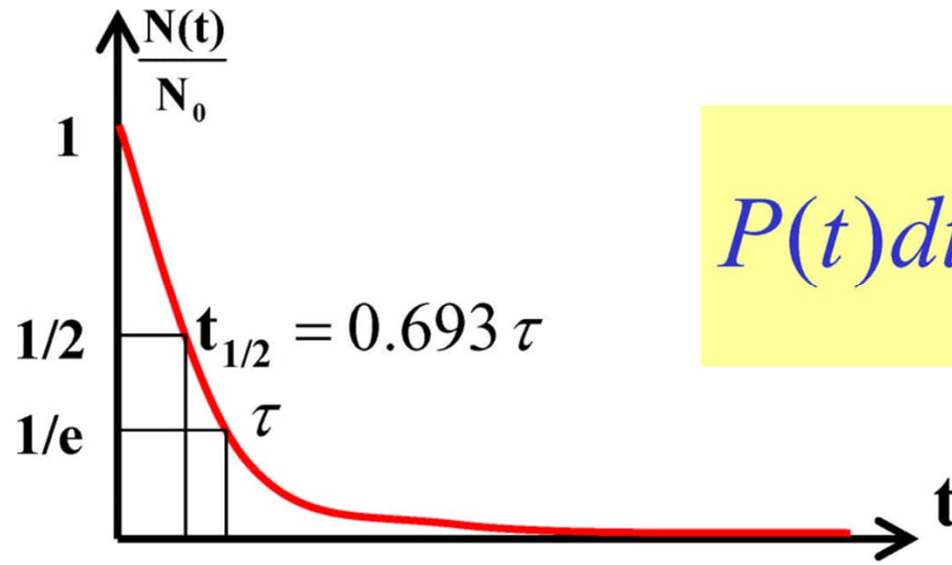
Luminosity (projectile →  $^{132}\text{Sn}$ ) =  $3 \cdot 10^{28}$  [s<sup>-1</sup>cm<sup>-2</sup>]

$$\text{Reaction rate [s}^{-1}\text{]} = \text{luminosity} \cdot \text{cross section [cm}^2\text{]}$$

$$= \text{projectiles [s}^{-1}\text{]} \cdot \text{target nuclei [cm}^{-2}\text{]} \cdot \text{cross section [cm}^2\text{]}$$



# Decay Time and Lifetime

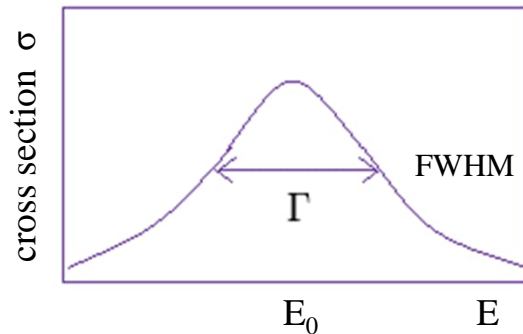


$$P(t)dt = \frac{1}{\tau} e^{-t/\tau} dt$$

$\tau = \text{proper time}$  (measured in the particle rest frame)

In laboratory frame:  $\lambda_{decay} = \gamma \beta c \cdot \tau$

# Decay Width



Uncertainty principle



$$\Gamma \equiv \frac{\hbar}{\tau}$$

If a particle has a finite lifetime  $\tau$ , it decays with probability  $e^{-t/\tau}$  and a decay width  $\Gamma$  can be defined. One can interpret  $\Gamma \cdot \tau = \hbar$  as a relationship between uncertainty in energy (mass) and lifetime i.e.  $\Delta E \cdot \Delta t = \hbar$ .

**Strongly** decaying particles have very short lifetimes and hence large width. The  $\rho(770)$  has  $\Gamma = 151 \text{ MeV}$  and  $\tau = 4.4 \cdot 10^{-24} \text{ s}$ .

**Weakly** decaying particles have longer lifetimes and hence much smaller widths. The  $K^0$  meson has  $\Gamma = 7.3 \cdot 10^{-12} \text{ MeV}$  and  $\tau = 0.9 \cdot 10^{-10} \text{ s}$ .