Introduction to Elementary Particle Physics

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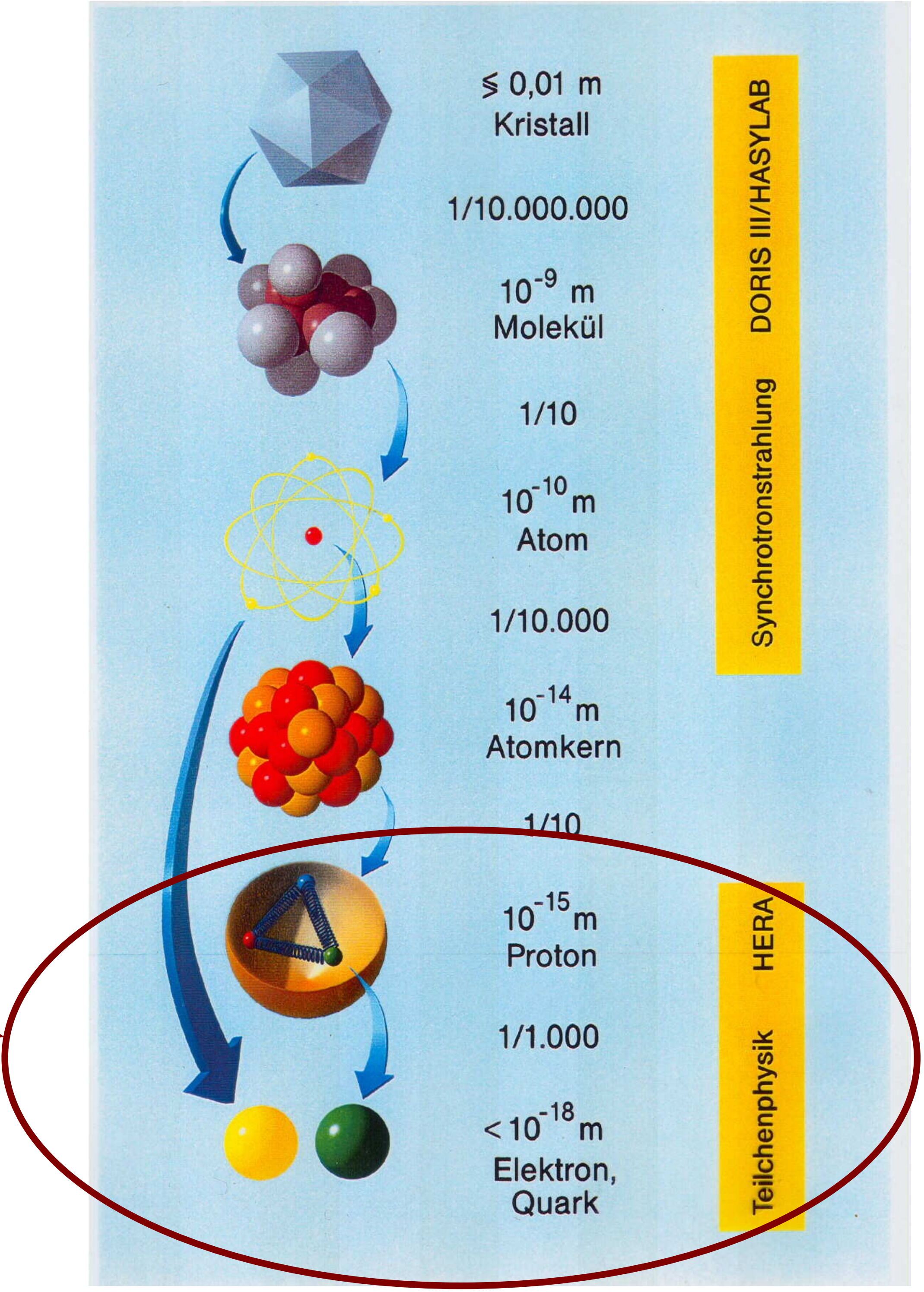
Lectures DESY Summer Student Program 2009

Preface

- This lecture is not a powerpoint show
- This lecture does not substitute an university course
- I know that your knowledge about the topic varies a lot
- So we have to make compromises in simplicity and depth
- Still I hope that all of you may profit somehow
- The viewgraphs shown are only for illustrations
- We will develop things **together** in discussion and at blackboard
- I hope there are lots of **questions.** I shall ask you a lot

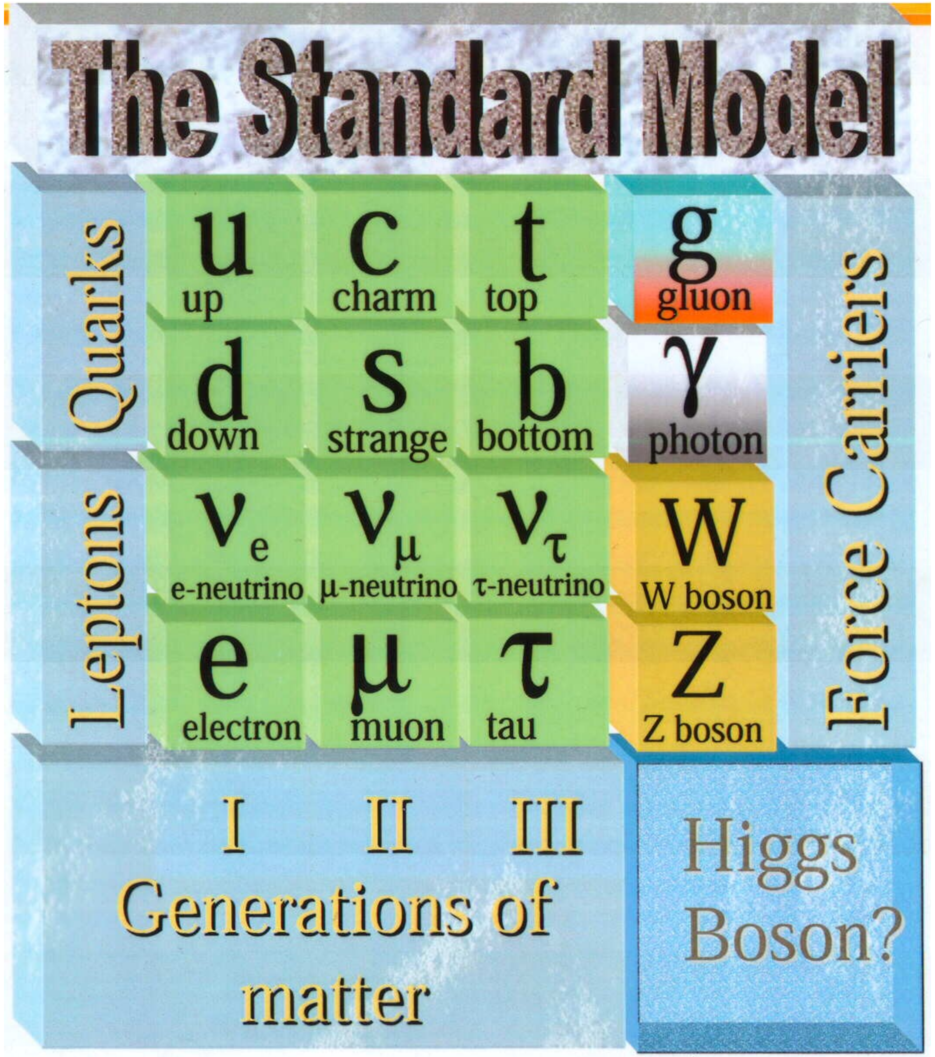
Structures at different sizes



Elementary
Particle
Physics

3 Fermion Generations

Interactions through
Gauge Boson Exchange



This lecture is going to tell you something about HOW we arrived at this picture

Content of this lectures .

Its only a sketch :
Depending on your preknowledge we will go more or less in detail in the different subjects

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    Introduction to Elementary Particle Physics
      -----------------------------------------

        Lectures  for DESY summer students 2007


1. Introduction : What are the questions ?
                  Why high energies ?
                  Relativistic kinematics

2. The answer 40 years ago : The particle zoo
               Mesons, Baryons, Decays, lifetimes

3. The answer today : The standard model

  a) The fermions :
               Quarks and leptons
  b) The interactions
               Exchange particles
               Feyman-diagrams
               Propagators and vertices
               Fundamental processes
               Electroweak unification


4. How did this picture emerge ?   The Particle Generations

   a) The first generation (electron electron-neutrino u,d quarks)
        Neutron beta-decay
        Positron discovery
        Neutrino evidence
        Nucleon - Pion Scattering
        Resonances
        Antiparticles

   b) The second generation (muon muon-neutrino s-quark c-quark)
        Muon decay
        First neutrino-experiment (nu_e, nu_mu)
        Neutrino mass
        Production and decay of strange particles
        Strong / weak interactions
        The quark model
        Omega particle
        'Evidence' for quarks (Deep inelastic scattering)
        CHARM : the November revolution in elem. particle physics
        Quarkonium physics
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c) The third generation (tau tau-neutrino b-quark t-quark)

- Discovery of the third heavy lepton
- Observation of the tau--neutrino
- Discovery of the bottom quark
- Production of heavy quarks in hadron collisions
- Production of heavy quarks in e+ e- collisions
- Impact of e+ e- storage rings
- B - physics
- CP-Violationmain.ps
- Top quark discovery

5. How did this picture emerge ? The Interactions
==================

a) Electromagnetic interactions (QED)

- g-2
- e+ e- annihilation

b) Weak interactions

- Charged currents
- Decays
- Neutrino scattering
- Neutral currents
- Experimentation with neutrinos
- Inclusive neutrino nucleon scattering
- V - A, Helicity
- Pion and muon decay

c) Elektroweak interactions

- Interference of electromagnetic and weak processes
- W, Z particles: Production and decays
- e+ e- --> Z
- e+ e- from low to high cm energies

d) Strong interactions (QCD)

- Jets and gluons
  - e+ e- interactions
  - p pbar interactions
  - e p interactions
- Structure of the protron

6. Outlook

- Open questions
- Hot Topics
- The next projects
- Plans for the future

WHY
High
Energies ?

Elementary Particle Physics = High Energy Physics (HEP)

Two aspects:

- High CMS-Energies $\Rightarrow$ Produce Massive Particles

  $E = mc^2$ e.g. $M_Z = 92\,GeV$, $m_{top} = 175\,GeV$

- High CMS-Energies $\Rightarrow$ High spatial Resolution Δx

  De Broglie Particle-Wave dualism

  $\boxed{\lambda = \hbar / p}$ $\Rightarrow$ High momenta $\Downarrow$ small wavelength $\Downarrow$ increased resolution

other view:

Heisenberg uncertainty principle

$\Delta E \cdot \Delta t \geq \hbar$

$\boxed{\Delta E \cdot \Delta x \geq \hbar c = 0.2\,GeV \cdot f}$ PDG

Needed Energytransfer to achieve resolution in Scattering experiment

size of proton

$\Delta E = 0.2\,GeV \mathrel{\hat{=}} 1\,f$

$\Delta E = 200\,GeV \mathrel{\hat{=}} 10^{-3}\,f$

achievable at HERA

What matters is ΔE in CMS-System!

The very basic minimum you have to know about **Relativistic Kinematics**

Relativistic Kinematics

- Particle (or system of particles) described by $\boxed{\text{FOURVECTORS}}$

$$\underline{X} = (ct, \vec{x}) \quad [m]$$
$$\underline{P} = (E, \vec{p}\cdot c) \quad [GeV]$$

- PRODUCT of fourvectors is INVARIANT

$$\underline{P}_1 \cdot \underline{P}_2 = (E_1 \cdot E_2 - \vec{p}_1 \cdot \vec{p}_2 c^2) = \text{constant}$$

Special case:

$$\underline{P}^2 = \underline{P}\cdot\underline{P} = (E_L^2 - (\vec{p}_L c)^2) = (E_{cm}^2 - 0) = E_{cm}^2 = (m_0 c^2)^2$$

HEP convention:

$c = 1 \Rightarrow E, \vec{p}, m$ [GeV]

$(m_0 \equiv m)$

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

Side remark: m_R 'relativistic mass'

energy $E = m_R c^2 = m_0 \gamma c^2$

momentum $|\vec{p}| = m_R \cdot v = m_0 \gamma \beta \cdot c$

$$\Rightarrow \boxed{\gamma = \frac{E}{m}, \quad \beta = \frac{|\vec{p}|}{E}}$$

Note:

$E, \vec{p}, \gamma, \beta$ depend on reference frame (lab, CMS, ...)

(m_R never 'used' in HEP!)

a1

Which CM-energy do we reach at HERA ?

High energy limit $E \gg m$

$\Rightarrow E \approx p \; , \; \beta \approx 1$

Application:

What is the centre of mass energy $E_{cm} = \sqrt{s}$ of the Electron-Proton-System at HERA ?

$\vec{p}_p \xrightarrow{E_p = 920\,\text{GeV}} \quad \xleftarrow{E_e = 27.5} \vec{p}_e$

Four Vectors

$$\mathbb{P}_p = \begin{pmatrix} E_p \\ \vec{p}_p \end{pmatrix} \quad \mathbb{P}_e = \begin{pmatrix} E_e \\ \vec{p}_e \end{pmatrix}$$

$$\mathbb{P}_p = \begin{pmatrix} E_p \\ E_p \end{pmatrix} \quad \mathbb{P}_e = \begin{pmatrix} E_e \\ -E_e \end{pmatrix}$$

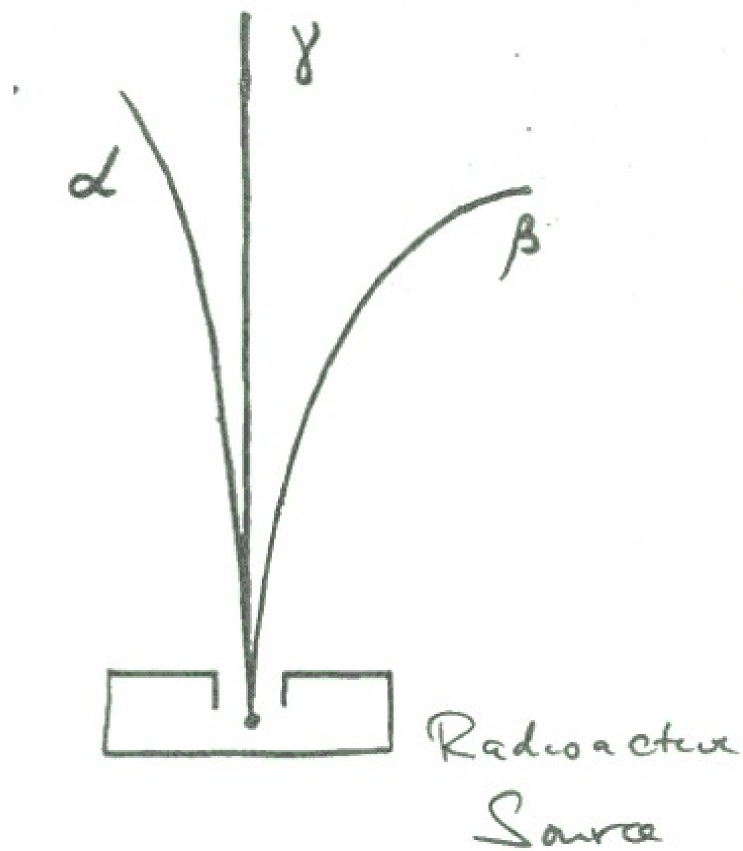
$$\mathbb{P}^2_{HERA} = \left(\mathbb{P}_p + \mathbb{P}_e\right)^2 = \left(E_p + E_e\right)^2 - \left(E_p - E_e\right)^2 = 4 E_e E_p = \underset{= 10^5\,\text{GeV}^2}{s}$$

$$\underline{\underline{E_{cm}^{Hera}}} = \sqrt{s} = \underline{\underline{318\,\text{GeV}}}$$

Homework:

Which Electron energy is needed to reach the same CMS energy when shooting electrons on a Stationary Proton Target ?

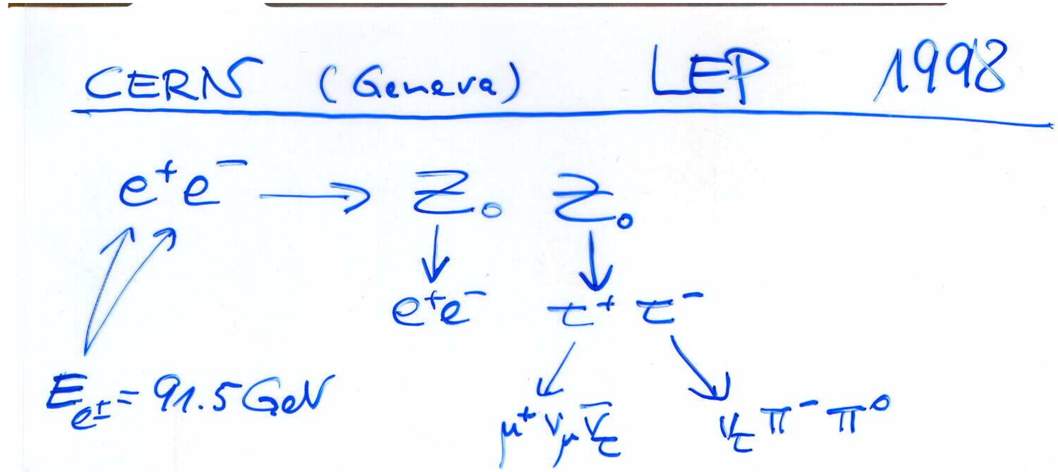
HEP 100 Years ago : Radioactive Decay

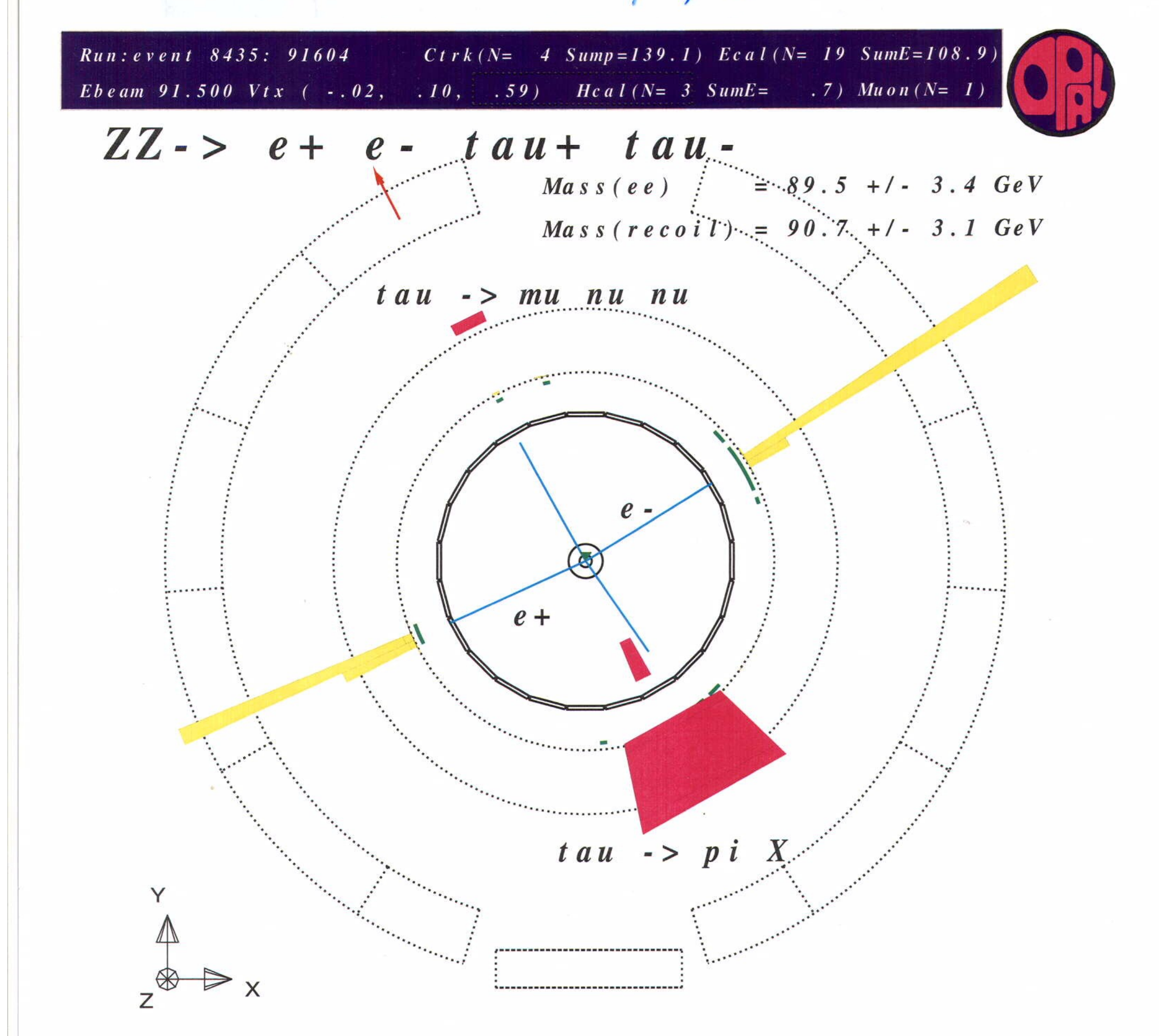


Energy region : MeV

$$\alpha = He - nucleus \ldots . \beta = electron \ldots \gamma = photon$$

Today :
Some more particles :



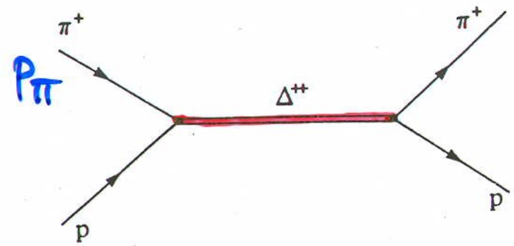


The Particle Zoo

I can't spare you this chapter.
Quarks are nice to EXPLAIN observed phenomena.
But, what we OBSERVE are particles like
protons, muons, pions,..........

'Artificial' Production of New Particles (Resonances):

$\pi - p$ *scattering*



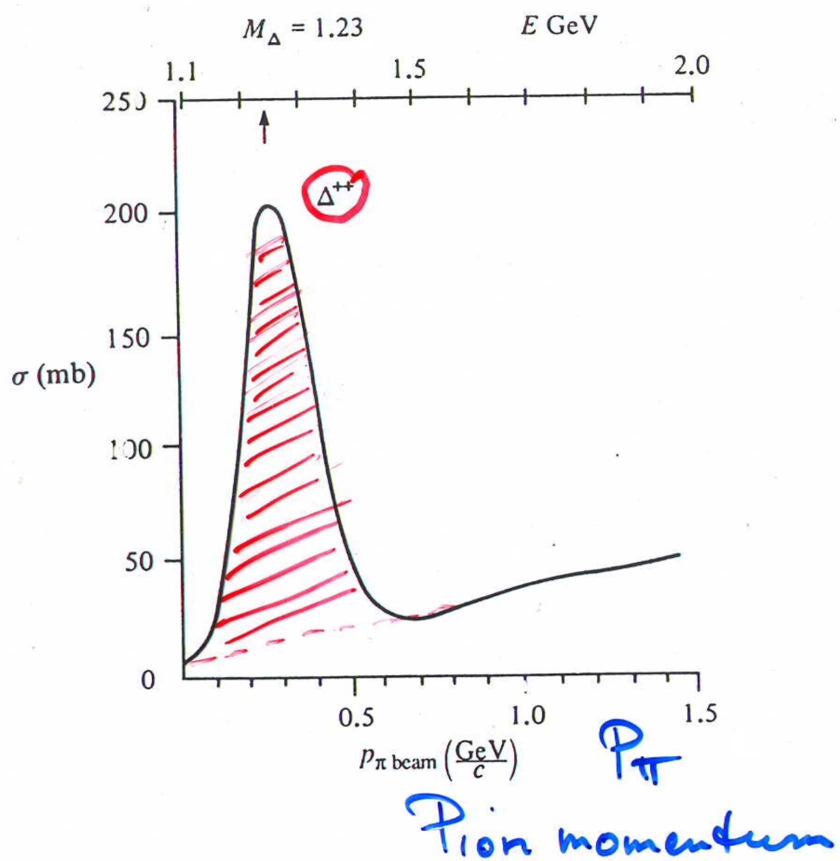
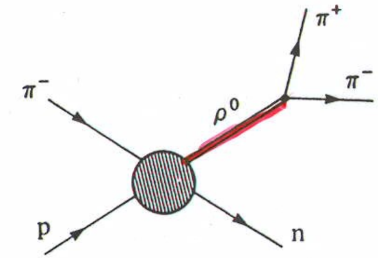
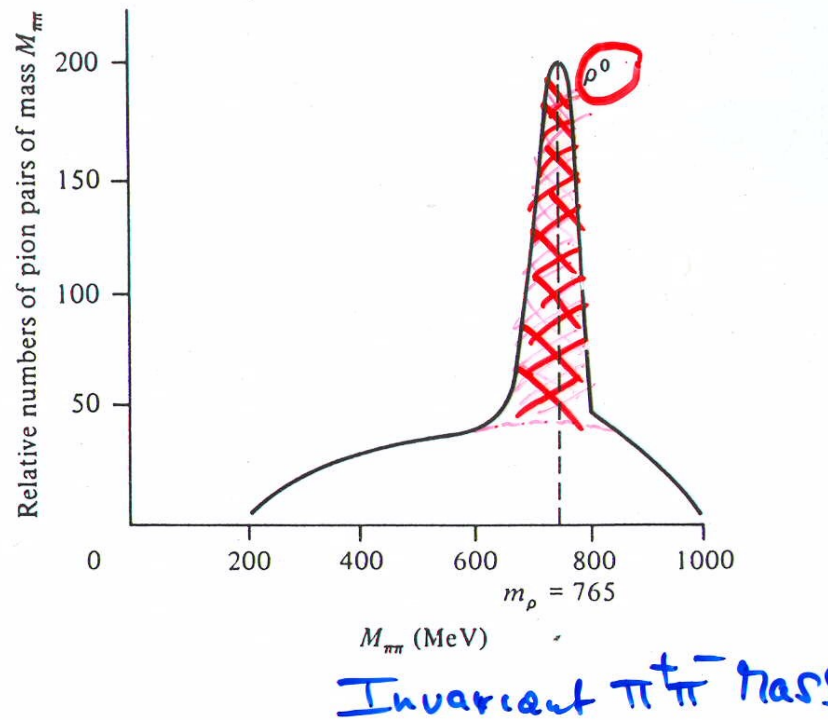


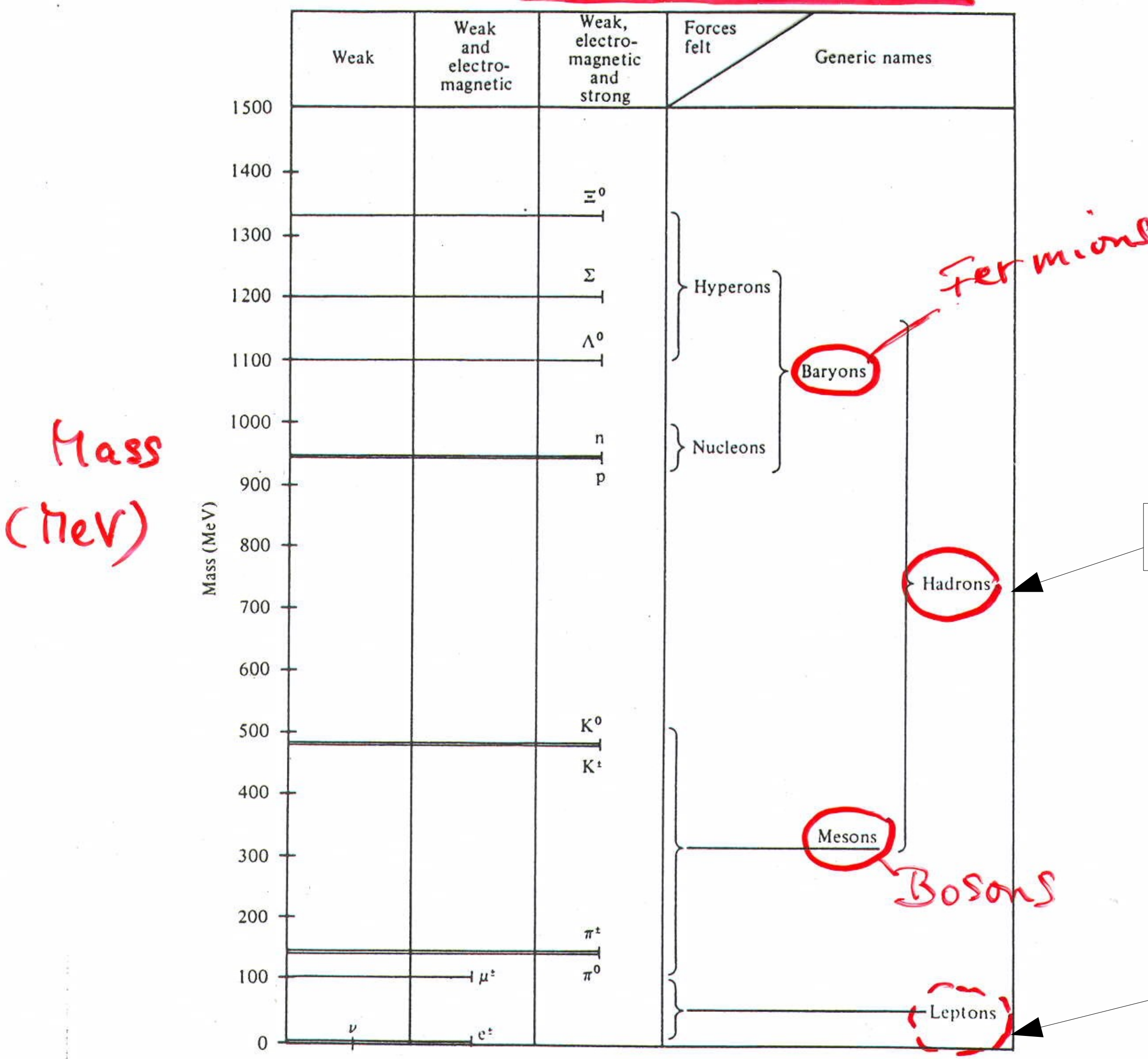
Fig. 9.2. An example of resonance production.





Particle classification

Fig. 8.4. The basic set of elementary particles known by the early 1950s.



Hadrons : strongly interacting

Leptons : not Strongly interacting

All these particles are listed
in the
Particle Data Booklet

PDG

A 'real HEP physicists' is never
without this HEP-bible

There are lots of particles

but

you have to know only
VERY FEW

Here are the MESONS

$\pi\,,\phi\,,K\,,D\,,B\,,J/\Psi\,,Y$

from PDG-table :

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Meson Summary Table

See also the table of suggested $q\bar{q}$ quark-model assignments in the Quark Model section.

- • Indicates particles that appear in the preceding Meson Summary Table. We do not regard the other entries as being established.
- † Indicates that the value of J given is preferred, but needs confirmation.

LIGHT UNFLAVORED ($S = C = B = 0$)

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$	$X(1650)$	$0^+(?^{?-})$
• π^0	$1^-(0^{-+})$	• $\omega_3(1670)$	$0^-(3^{--})$
• η	$0^+(0^{-+})$	• $\pi_2(1670)$	$1^-(2^{-+})$
• $f_0(400\text{–}1200)$	$0^+(0^{++})$	• $\phi(1680)$	$0^-(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $\omega(782)$	$0^-(1^{--})$	• $\rho(1700)$	$1^+(1^{--})$
• $\eta'(958)$	$0^+(0^{-+})$	• $f_J(1710)$	$0^+(\text{even}^{++})$
• $f_0(980)$	$0^+(0^{++})$	$\eta(1760)$	$0^+(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	$X(1775)$	$1^-(?^{-+})$
• $\phi(1020)$	$0^-(1^{--})$	• $\pi(1800)$	$1^-(0^{-+})$
• $h_1(1170)$	$0^-(1^{+-})$	$f_2(1810)$	$0^+(2^{++})$
• $b_1(1235)$	$1^+(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $a_1(1260)$	$1^-(1^{++})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $f_2(1270)$	$0^+(2^{++})$	$X(1910)$	$0^+(?^{?+})$
• $f_1(1285)$	$0^+(1^{++})$	$f_2(1950)$	$0^+(2^{++})$
• $\eta(1295)$	$0^+(0^{-+})$	$X(2000)$	$1^-(?^{?+})$
• $\pi(1300)$	$1^-(0^{-+})$	• $f_2(2010)$	$0^+(2^{++})$
• $a_2(1320)$	$1^-(2^{++})$	$f_0(2020)$	$0^+(0^{++})$
• $f_0(1370)$	$0^+(0^{++})$	• $a_4(2040)$	$1^-(4^{++})$
$h_1(1380)$	$?^-(1^{+-})$	• $f_4(2050)$	$0^+(4^{++})$
$\hat{\rho}(1405)$	$1^-(1^{-+})$	$f_0(2060)$	$0^+(0^{++})$
• $f_1(1420)$	$0^+(1^{++})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $\omega(1420)$	$0^-(1^{--})$	$f_2(2150)$	$0^+(2^{++})$
$f_2(1430)$	$0^+(2^{++})$	$\rho(2150)$	$1^+(1^{--})$
• $\eta(1440)$	$0^+(0^{-+})$	$f_0(2200)$	$0^+(0^{++})$
• $a_0(1450)$	$1^-(0^{++})$	$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
• $\rho(1450)$	$1^+(1^{--})$		
• $f_0(1500)$	$0^+(0^{++})$	$\eta(2225)$	$0^+(0^{-+})$
$f_1(1510)$	$0^+(1^{++})$	$\rho_3(2250)$	$1^+(3^{--})$
• $f_2'(1525)$	$0^+(2^{++})$	• $f_2(2300)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$	$f_4(2300)$	$0^+(4^{++})$
• $\omega(1600)$	$0^-(1^{--})$	• $f_2(2340)$	$0^+(2^{++})$
$X(1600)$	$2^+(2^{++})$	$\rho_5(2350)$	$1^+(5^{--})$
$f_2(1640)$	$0^+(2^{++})$	$a_6(2450)$	$1^-(6^{++})$
$\eta_2(1645)$	$0^+(2^{-+})$	$f_6(2510)$	$0^+(6^{++})$
		$X(3250)$	$?^?(?^{??})$

OTHER LIGHT UNFLAVORED ($S = C = B = 0$)

$e^+e^-(1100\text{–}2200)$	$?^?(1^{--})$
$\overline{N}N(1100\text{–}3600)$	
$X(1900\text{–}3600)$	

STRANGE ($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K^0_S	$1/2(0^-)$
• K^0_L	$1/2(0^-)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K^*_0(1430)$	$1/2(0^+)$
• $K^*_2(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K^*_3(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K^*_0(1950)$	$1/2(0^+)$
$K^*_2(1980)$	$1/2(2^+)$
• $K^*_4(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K^*_5(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED ($C = \pm1$)

• $D^\pm$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^\pm$	$1/2(?^?)$
• $D^*_2(2460)^0$	$1/2(2^+)$
• $D^*_2(2460)^+$	$1/2(2^+)$

CHARMED, STRANGE ($C = S = \pm1$)

• $D^\pm_s$	$0(0^-)$
• $D^{*\pm}_s$	$0(?^?)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{sJ}(2573)^\pm$	$0(?^?)$

BOTTOM ($B = \pm1$)

• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• B^*	$1/2(1^-)$
$B^*_J(5732)$	$?(?^?)$

BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$)

	$I^G(J^{PC})$
• B^0_s	$0(0^-)$
B^*_s	$0(1^-)$
$B^*_{sJ}(5850)$	$?(?^?)$

BOTTOM, CHARMED ($B = C = \pm1$)

$B^\pm_c$	$0(0^-)$

$c\bar{c}$

• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
$h_c(1P)$	$?^?(?^{??})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
$\eta_c(2S)$	$?^?(?^{?+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$?^?(1^{--})$
• $\psi(4040)$	$?^?(1^{--})$
• $\psi(4160)$	$?^?(1^{--})$
• $\psi(4415)$	$?^?(1^{--})$

$b\bar{b}$

• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\Upsilon(4S)$	$?^?(1^{--})$
• $\Upsilon(10860)$	$?^?(1^{--})$
• $\Upsilon(11020)$	$?^?(1^{--})$

NON-$q\bar{q}$ CANDIDATES

Non-$q\bar{q}$ Candidates

π   φ   K   D   B   J/ψ   Y

Name

Mass [MeV]

QUANTUM Numbers

Parity

$I^G\,(J^{PC})$

Isospin

Spin

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Baryon Summary Table

999

This short table gives the name, the quantum numbers (where known), and the status of baryons in the Review. Only the baryons with 3- or 4-star status are included in the main Baryon Summary Table. Due to insufficient data or uncertain interpretation, the other entries in the short table are not established as baryons. The names with masses are of baryons that decay strongly. See our 1986 edition (Physics Letters **170B**) for listings of evidence for Z baryons (KN resonances).

p n

p, n	P_{11}	****	$\Delta(1232)$	P_{33}	****	Λ	P_{01}	****	$\Sigma^+, \Sigma^0, \Sigma^-$	P_{11}	****	Ξ^0, Ξ^-	P_{11}	****
$N(1440)$	P_{11}	****	$\Delta(1600)$	P_{33}	***	$\Lambda(1405)$	S_{01}	****	$\Sigma(1385)$	P_{13}	****	$\Xi(1530)$	P_{13}	****
$N(1520)$	D_{13}	****	$\Delta(1620)$	S_{31}	****	$\Lambda(1520)$	D_{03}	****	$\Sigma(1480)$		*	$\Xi(1620)$		*
$N(1535)$	S_{11}	****	$\Delta(1700)$	D_{33}	****	$\Lambda(1600)$	P_{01}	***	$\Sigma(1560)$		**	$\Xi(1690)$		***
$N(1650)$	S_{11}	****	$\Delta(1750)$	P_{31}	*	$\Lambda(1670)$	S_{01}	****	$\Sigma(1580)$	D_{13}	**	$\Xi(1820)$	D_{13}	***
$N(1675)$	D_{15}	****	$\Delta(1900)$	S_{31}	**	$\Lambda(1690)$	D_{03}	****	$\Sigma(1620)$	S_{11}	**	$\Xi(1950)$		***
$N(1680)$	F_{15}	****	$\Delta(1905)$	F_{35}	****	$\Lambda(1800)$	S_{01}	***	$\Sigma(1660)$	P_{11}	***	$\Xi(2030)$		***
$N(1700)$	D_{13}	***	$\Delta(1910)$	P_{31}	****	$\Lambda(1810)$	P_{01}	***	$\Sigma(1670)$	D_{13}	****	$\Xi(2120)$		*
$N(1710)$	P_{11}	***	$\Delta(1920)$	P_{33}	***	$\Lambda(1820)$	F_{05}	****	$\Sigma(1690)$		**	$\Xi(2250)$		**
$N(1720)$	P_{13}	****	$\Delta(1930)$	D_{35}	***	$\Lambda(1830)$	D_{05}	****	$\Sigma(1750)$	S_{11}	***	$\Xi(2370)$		**
$N(1900)$	P_{13}	**	$\Delta(1940)$	D_{33}	*	$\Lambda(1890)$	P_{03}	****	$\Sigma(1770)$	P_{11}	*	$\Xi(2500)$		*
$N(1990)$	F_{17}	**	$\Delta(1950)$	F_{37}	****	$\Lambda(2000)$		*	$\Sigma(1775)$	D_{15}	****			
$N(2000)$	F_{15}	**	$\Delta(2000)$	F_{35}	**	$\Lambda(2020)$	F_{07}	*	$\Sigma(1840)$	P_{13}	*	Ω^-		****
$N(2080)$	D_{13}	**	$\Delta(2150)$	S_{31}	*	$\Lambda(2100)$	G_{07}	****	$\Sigma(1880)$	P_{11}	**	$\Omega(2250)^-$		***
$N(2090)$	S_{11}	*	$\Delta(2200)$	G_{37}	*	$\Lambda(2110)$	F_{05}	***	$\Sigma(1915)$	F_{15}	****	$\Omega(2380)^-$		**
$N(2100)$	P_{11}	*	$\Delta(2300)$	H_{39}	**	$\Lambda(2325)$	D_{03}	*	$\Sigma(1940)$	D_{13}	***	$\Omega(2470)^-$		**
$N(2190)$	G_{17}	****	$\Delta(2350)$	D_{35}	*	$\Lambda(2350)$	H_{09}	***	$\Sigma(2000)$	S_{11}	*			
$N(2200)$	D_{15}	**	$\Delta(2390)$	F_{37}	*	$\Lambda(2585)$		**	$\Sigma(2030)$	F_{17}	****	Λ_c^+		****
$N(2220)$	H_{19}	****	$\Delta(2400)$	G_{39}	**				$\Sigma(2070)$	F_{15}	*	$\Lambda_c(2593)^+$		***
$N(2250)$	G_{19}	****	$\Delta(2420)$	$H_{3,11}$	****				$\Sigma(2080)$	P_{13}	**	$\Lambda_c(2625)^+$		***
$N(2600)$	$I_{1,11}$	***	$\Delta(2750)$	$I_{3,13}$	**				$\Sigma(2100)$	G_{17}	*	$\Sigma_c(2455)$		****
$N(2700)$	$K_{1,13}$	**	$\Delta(2950)$	$K_{3,15}$	**				$\Sigma(2250)$		***	$\Sigma_c(2520)$		***
									$\Sigma(2455)$		**	Ξ_c^+, Ξ_c^0		***
									$\Sigma(2620)$		**	$\Xi_c'^+, \Xi_c'^0$		***
									$\Sigma(3000)$		*	$\Xi_c(2645)$		***
									$\Sigma(3170)$		*	$\Xi_c(2815)$		***
												Ω_c^0		***
												Λ_b^0		***
												Ξ_b^0, Ξ_b^-		*
												b-baryon ADMIXTURE		

NON Strange

Strange

**** Existence is certain, and properties are at least fairly well explored.

*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.

** Evidence of existence is only fair.

* Evidence of existence is poor.

And here are the BARYONS

$$p\,,n\,,\Lambda\,,\Omega\,,\Sigma$$

Leptons :
Fermions not participating in strong interactions

$$e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$$

E.2 LEPTONS

All the leptons have, or are believed to have, $J^P = \frac{1}{2}^+$.

Particle	Mass (MeV/c^2)	Mean life (s)	Decay Mode	Decay Fraction (%)
ν_e	$< 15\, eV/c^2$	stable		
ν_μ	< 0.17	stable		
ν_τ	< 24	stable		
$e^\pm$	0.511^a	stable		
$\mu^\pm$	105.658^b	$2.197 \times 10^{-6\,c}$	$e^+\nu_e\bar{\nu}_\mu$	100
$\tau^\pm$	$1777.0(\pm 3)$	$2.910(\pm 15) \times 10^{-13}$	$\mu^+\nu_\mu\bar{\nu}_\tau$	$17.35(\pm 10)$
			$e^+\nu_e\bar{\nu}_\tau$	$17.83(\pm 8)$
			hadrons $+ \bar{\nu}_\tau$	~ 64

[a] The error on the $e^\pm$ mass is $1.5 \times 10^{-7}\, MeV/c^2$.
[b] The error on the $\mu^\pm$ mass is $3.4 \times 10^{-5}\, MeV/c^2$.
[c] The error on the $\mu^\pm$ l lifetimes is 4×10^{-11} s.

Gauge Bosons :
The mediators of the fundamental interactions

Photon, W , Z, gluon

E.1 GAUGE BOSONS

The gauge bosons all have $J^P = 1^-$. The table shows the properties of the γ, $W^\pm$ and Z^0 only, as the gluons are not observed as free particles.

Particle	Mass	Full width	Decay Mode	Decay Fraction (%)
γ	$< 6 \times 10^{-22}\, MeV/c^2$	stable		
$W^\pm$	$80.33(\pm 15)\, GeV/c^2$	$2.07(\pm 6)\, GeV$	$e^+\nu_e$	$10.8(\pm 4)$
			$\mu^+\nu_\mu$	$10.4(\pm 6)$
			$\tau^+\nu_\tau$	$10.9(\pm 10)$
			hadrons	$67.9(\pm 15)$
Z^0	$91.187(\pm 7)\, GeV/c^2$	$2.490(\pm 7)\, GeV$	e^+e^-	$3.366(\pm 8)$
			$\mu^+\mu^-$	$3.367(\pm 13)$
			$\tau^+\tau^-$	$3.360(\pm 15)$
			$\nu\bar{\nu}$	$20.01(\pm 16)$
			hadrons	$69.90(\pm 15)$

Particle Lifetimes

Depend on type of decay and particle mass

Produce beams of unstable particles or even store them (muon storage rings) ?

Yes, thats possible ! !

Most particles are unstable

Some typical lifetimes τ $(N = N_0 e^{-t/\tau})$

Proton	p	$\tau > 10^{33}$ years	
Neutron	n	$\tau = 889$ sec	Weak decay
Pion	π^+	$\tau = 2.6 \cdot 10^{-8}$ sec	Weak decay
Muon	μ^+	$\tau = 2.2 \cdot 10^{-6}$ sec	Weak decay
Kaon	K^+	$\tau = 1.2 \cdot 10^{-8}$ sec	Weak decay
Pion	π^0	$\tau = 8 \cdot 10^{-17}$ sec	e.m. decay
Delta	Δ	$\tau = 5 \cdot 10^{-24}$ sec	strong decay

'Practical' consequences : $\boxed{\text{Pion beam ?}}$

$\tau_{\pi^\pm} = (2.6033 \pm 0.0005)\, 10^{-8}$ sec $\Rightarrow c \cdot \tau = 7.8$ m

Decaylength in Lab. system

$$\ell = \tau_\ell \cdot v_\ell$$
$$= \tau_\pi \cdot \gamma \cdot \beta c$$
$$\boxed{\ell = \frac{p}{m} \cdot c\tau}$$

Remember: $\gamma = \frac{E}{m}$, $\beta = \frac{p}{E}$

Example $p_\pi = 140$ GeV (CERN-SPS)

$\frac{p}{m} = \frac{140 \text{ GeV}}{140 \text{ MeV}} = 10^3$ $\qquad \boxed{\ell = 7.8 \text{ Km}}$

Easy to make a $\pi^\pm$ beam !

The lightest Hadron (strongly interacting particle) is the PION

$\boxed{\pi^\pm}$

$$I^G(J^P) = 1^-(0^-)$$

Mass $m = 139.57018 \pm 0.00035$ MeV $(S = 1.2)$

Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s $(S = 1.2)$ ← Longlived

$c\tau = 7.8045$ m

Nearly 100 %

WHY ?????

Very Rare

π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level
$\mu^+\nu_\mu$	[b]	(99.98770 ± 0.00004) %	
$\mu^+\nu_\mu\gamma$	[c]	$(2.00 \pm 0.25) \times 10^{-4}$	
$e^+\nu_e$	[b]	$(1.230 \pm 0.004) \times 10^{-4}$	
$e^+\nu_e\gamma$	[c]	$(1.61 \pm 0.23) \times 10^{-7}$	
$e^+\nu_e\pi^0$		$(1.025 \pm 0.034) \times 10^{-8}$	
$e^+\nu_e e^+ e^-$		$(3.2 \pm 0.5) \times 10^{-9}$	
$e^+\nu_e\nu\overline{\nu}$		$< 5 \times 10^{-6}$	90%

There is also a NEUTRAL PION

Shortlived

WHY ?????

Nearly 100 %

$\boxed{\pi^0}$

$I^G(J^{PC}) = 1^-(0^{-+})$

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 setions (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	$(1.82\pm0.29) \times 10^{-9}$		67
$e^+e^+e^-e^-$	$(3.14\pm0.30) \times 10^{-5}$		67
e^+e^-	$(6.2\pm0.5) \times 10^{-8}$		67
4γ	$< 2 \times 10^{-8}$	CL=90%	67
$\nu\overline{\nu}$	[e] $< 8.3 \times 10^{-7}$	CL=90%	67

There are also 'Strange Particles'   The lightest one is the   KAON

STRANGE MESONS
($S = \pm 1$, $C = B = 0$)

$K^+ = u\bar{s}$, $K^0 = d\bar{s}$, $\overline{K}^0 = \bar{d}s$, $K^- = \bar{u}s$,   similarly for K^*'s

$K^\pm$ $I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 493.677 \pm 0.016$ MeV [v]   ($S = 2.8$)
Mean life $\tau = (1.2384 \pm 0.0024) \times 10^{-8}$ s   ($S = 2.0$)
$c\tau = 3.713$ m

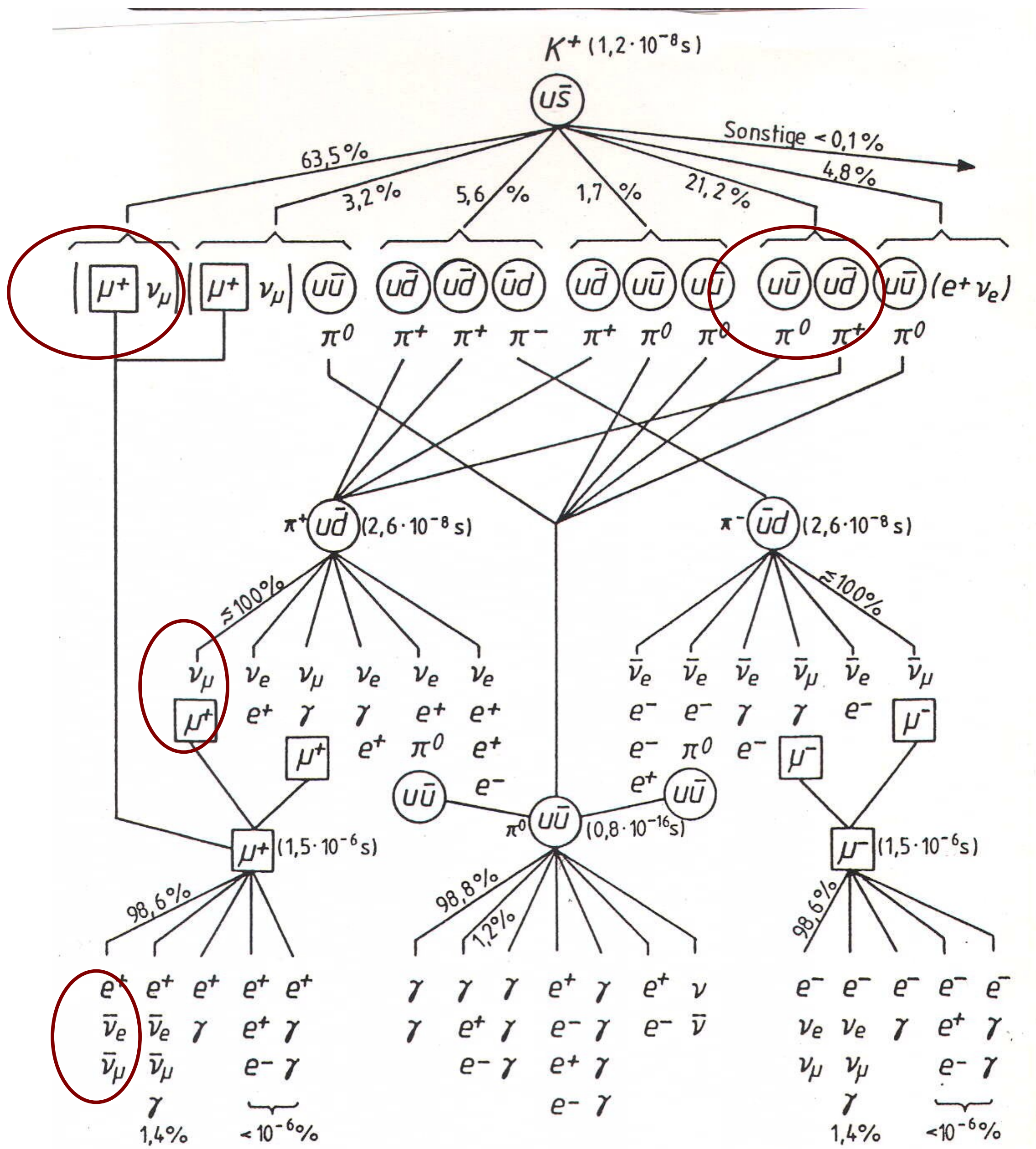
K^+ DECAY MODES	Fraction (Γ_i/Γ)	Scal Confide
Leptonic and semileptonic modes		
$e^+\nu_e$	$(1.55 \pm 0.07) \times 10^{-5}$	
$\mu^+\nu_\mu$	(63.43 ± 0.17) %	
$\pi^0 e^+\nu_e$	(4.87 ± 0.06) %	
Called K^+_{e3}.		
$\pi^0\mu^+\nu_\mu$	(3.27 ± 0.06) %	
Called $K^+_{\mu3}$.		
Hadronic modes		
$\pi^+\pi^0$	(21.13 ± 0.14) %	
$\pi^+\pi^0\pi^0$	(1.73 ± 0.04) %	
$\pi^+\pi^+\pi^-$	(5.576 ± 0.031) %	

Why are KAON decays so different from PION decays ?

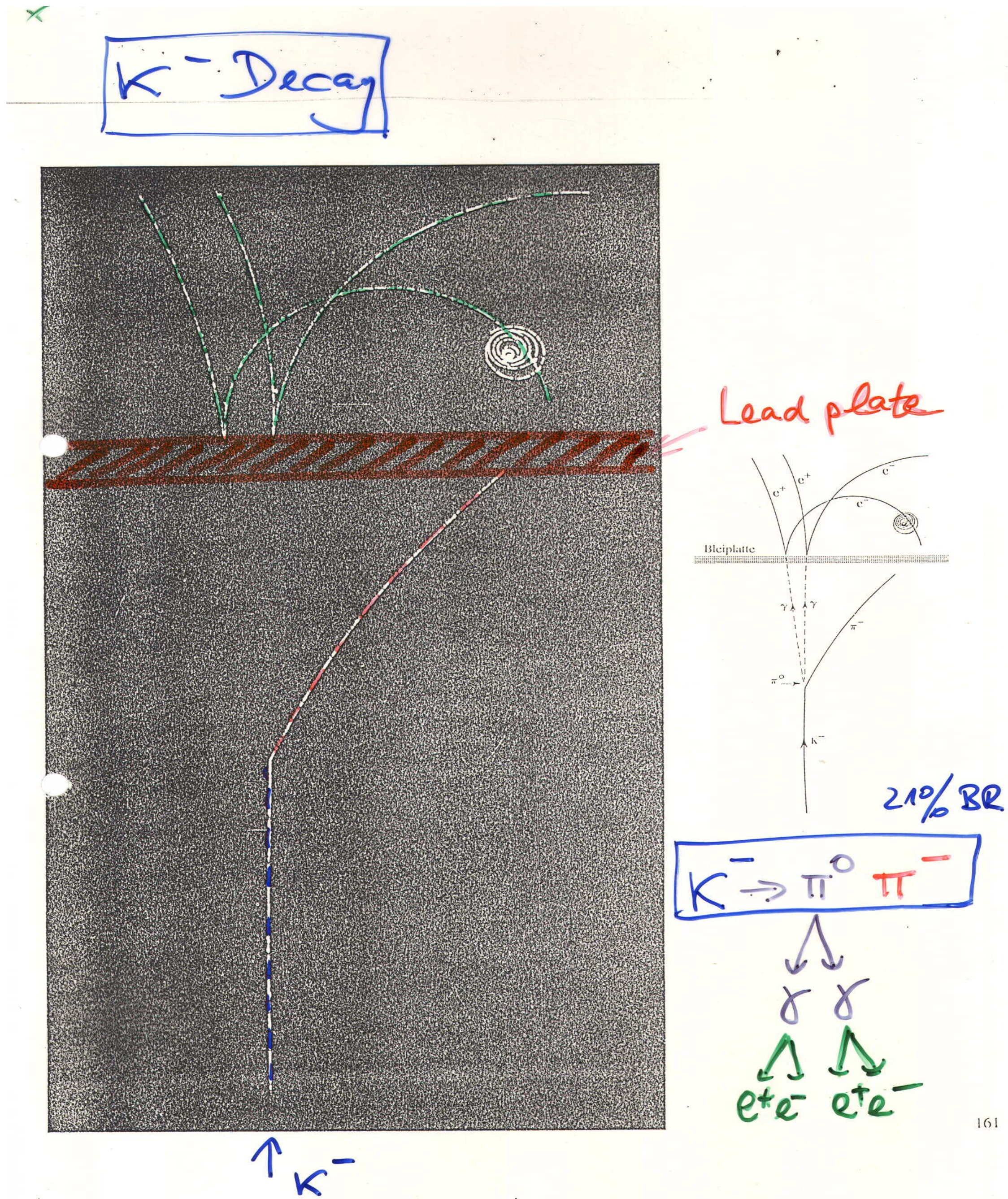
The KAON Decay Chain :

K, π, μ, e

Dominant decays



A Kaon decay seen in a Cloud Chamber



The famous J/Psi Particle (charm)
has a mass of 3.1 GeV and thus a very big variety of decay possibilities

$J/\psi(1S)$ $I^G(J^{PC}) = 0^-(1^{--}$

Mass $m = 3096.916 \pm 0.011$ MeV
Full width $\Gamma = 91.0 \pm 3.2$ keV ⟶
$\Gamma_{ee} = 5.40 \pm 0.15 \pm 0.07$ keV

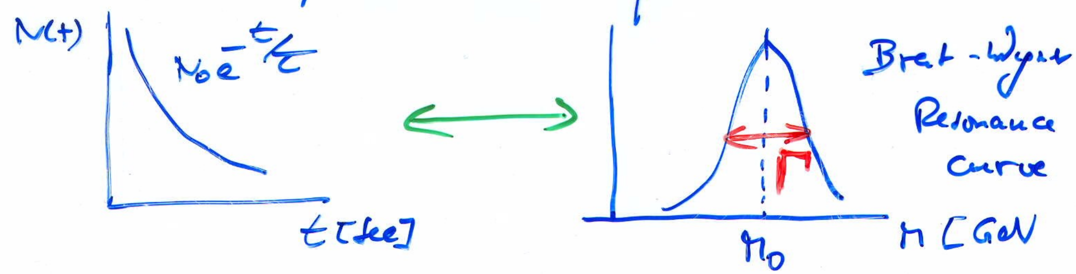
$J/\psi(1S)$ DECAY MODES		Fraction (Γ_i/Γ)	Scale Confider
hadrons		$(87.7 \pm 0.5)\ \%$	
virtual $\gamma \to$ hadrons		$(17.0 \pm 2.0)\ \%$	
e^+e^-		$(5.93 \pm 0.10)\ \%$	
$\mu^+\mu^-$		$(5.88 \pm 0.10)\ \%$	
Decays involving hadronic resonances			
$\rho\pi$		$(1.27 \pm 0.09)\ \%$	
$\rho^0\pi^0$		$(4.2 \pm 0.5) \times 10^{-3}$	
$a_2(1320)\rho$		$(1.09 \pm 0.22)\ \%$	
$\omega\pi^+\pi^+\pi^-\pi^-$		$(8.5 \pm 3.4) \times 10^{-3}$	
$\omega\pi^+\pi^-$		$(7.2 \pm 1.0) \times 10^{-3}$	
$\omega f_2(1270)$		$(4.3 \pm 0.6) \times 10^{-3}$	
$K^*(892)^0\overline{K}_2^*(1430)^0 +$ c.c.		$(6.7 \pm 2.6) \times 10^{-3}$	
$\omega K^*(892)\overline{K} +$ c.c.		$(5.3 \pm 2.0) \times 10^{-3}$	
$K^+\overline{K}^*(892)^- +$ c.c.		$(5.0 \pm 0.4) \times 10^{-3}$	
$K^0\overline{K}^*(892)^0 +$ c.c.		$(4.2 \pm 0.4) \times 10^{-3}$	
$K_1(1400)^\pm K^\mp$		$(3.8 \pm 1.4) \times 10^{-3}$	
$\omega\pi^0\pi^0$		$(3.4 \pm 0.8) \times 10^{-3}$	
$b_1(1235)^\pm\pi^\mp$	[gg]	$(3.0 \pm 0.5) \times 10^{-3}$	

....and this continues over some pages in the PDG booklet....

Relation between Particle lifetime and Particle width

Unstable Particles ↔ Resonances

An unstable particle has no fixed mass



$$\boxed{\tau \cdot \Gamma = \hbar} = 6.6 \cdot 10^{-22}\ \text{MeV} \cdot \text{sec}$$

Decay time

Decay width

[Recall Heisenberg uncertainty $\Delta t \cdot \Delta E = \hbar$]

For shortlived (strong decays) particles one gives Γ!

J/ψ: $\Gamma = 0.07$ MeV $\Rightarrow$ $\tau = 9.4 \cdot 10^{-21}$ sec

Δ : $\Gamma = 120$ MeV $\Rightarrow$ $\tau = 5.5 \cdot 10^{-24}$ sec

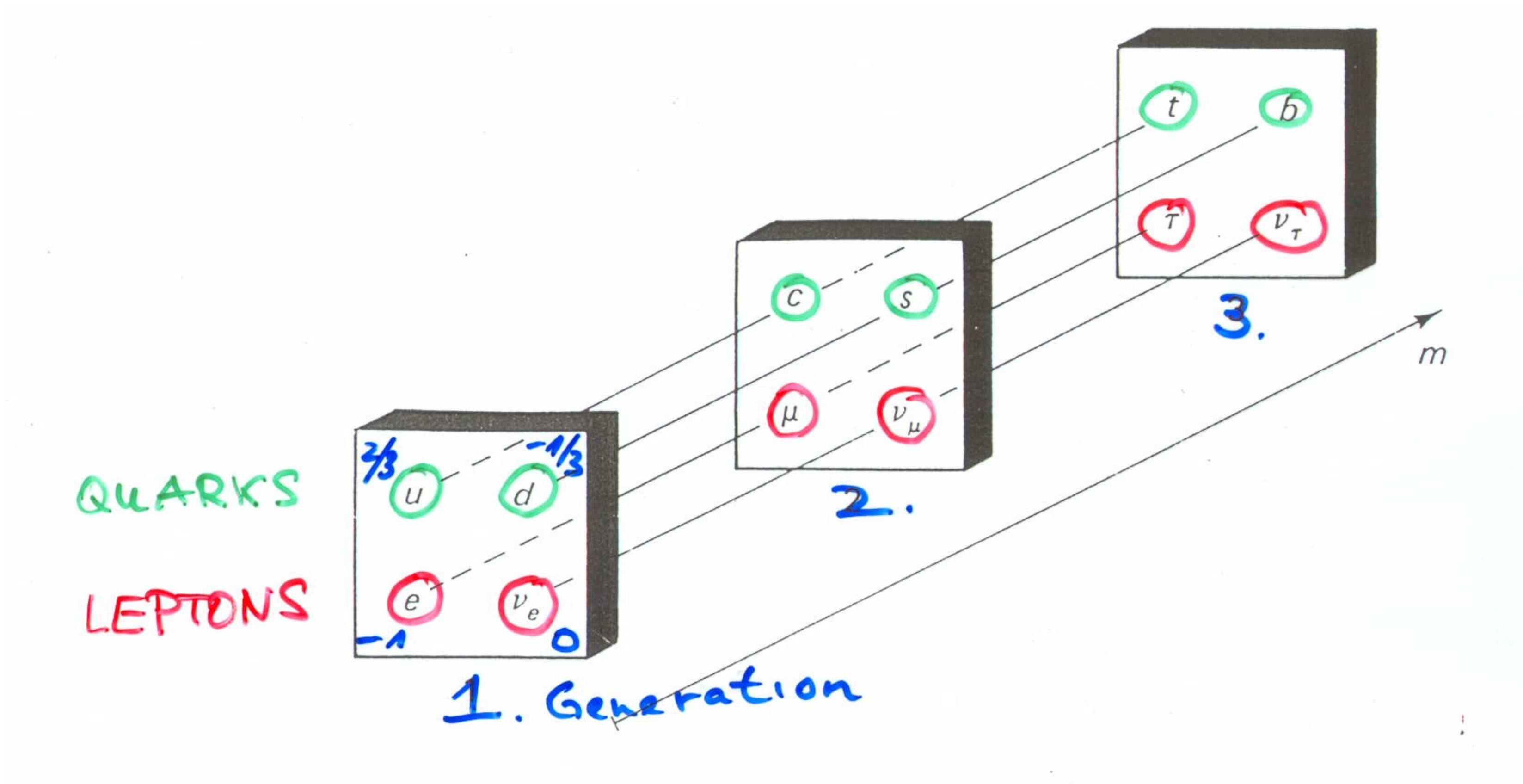
The Standard Model

Matter Particles (Fermions) interacting with Gauge Bosons

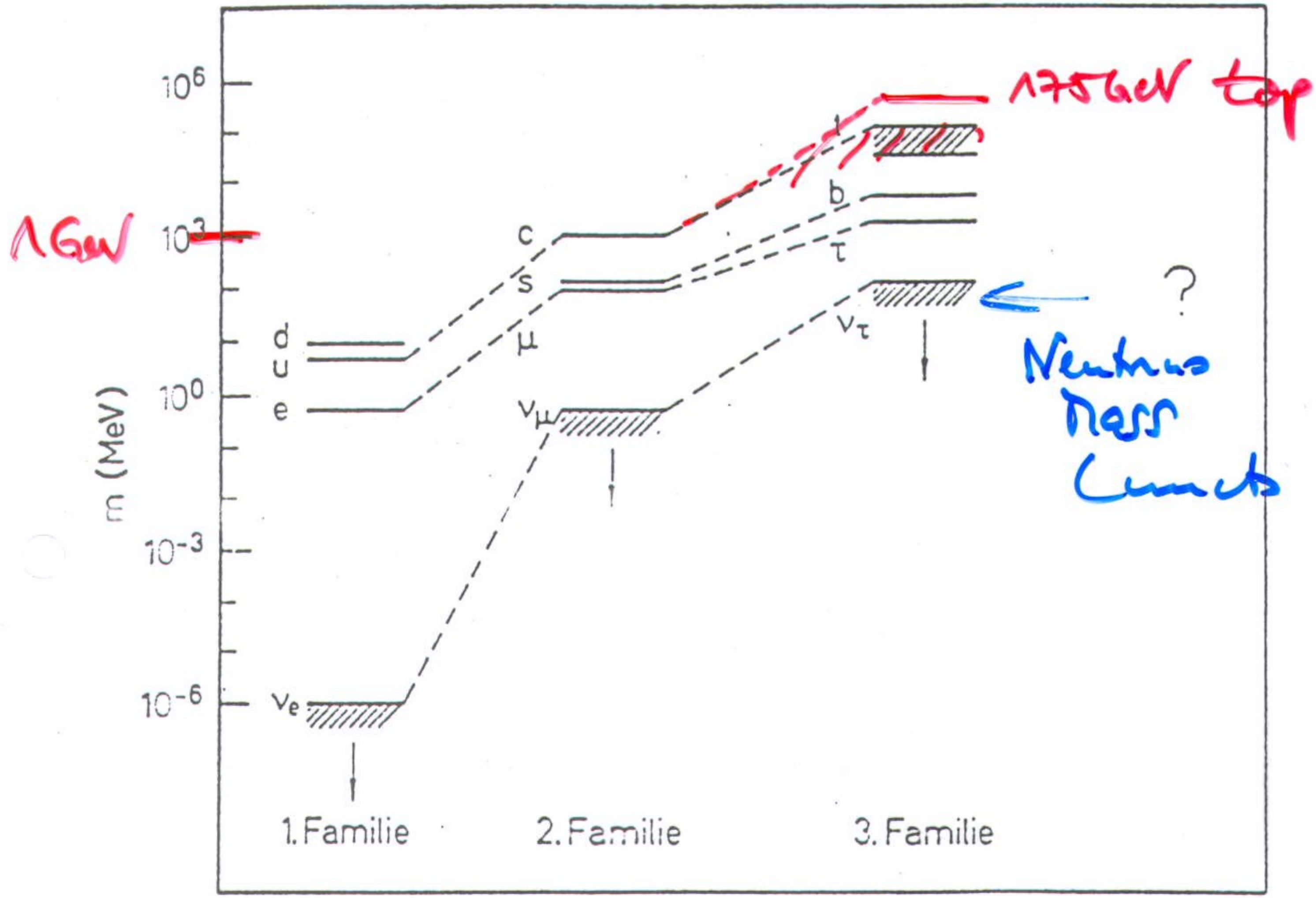
Fermions : 3 Generations of Quarks and Leptons

Interactions :
Electromagnetic : Photon
Weak : W, Z
Strong : Gluons

The Fermions of the STANDARD MODEL

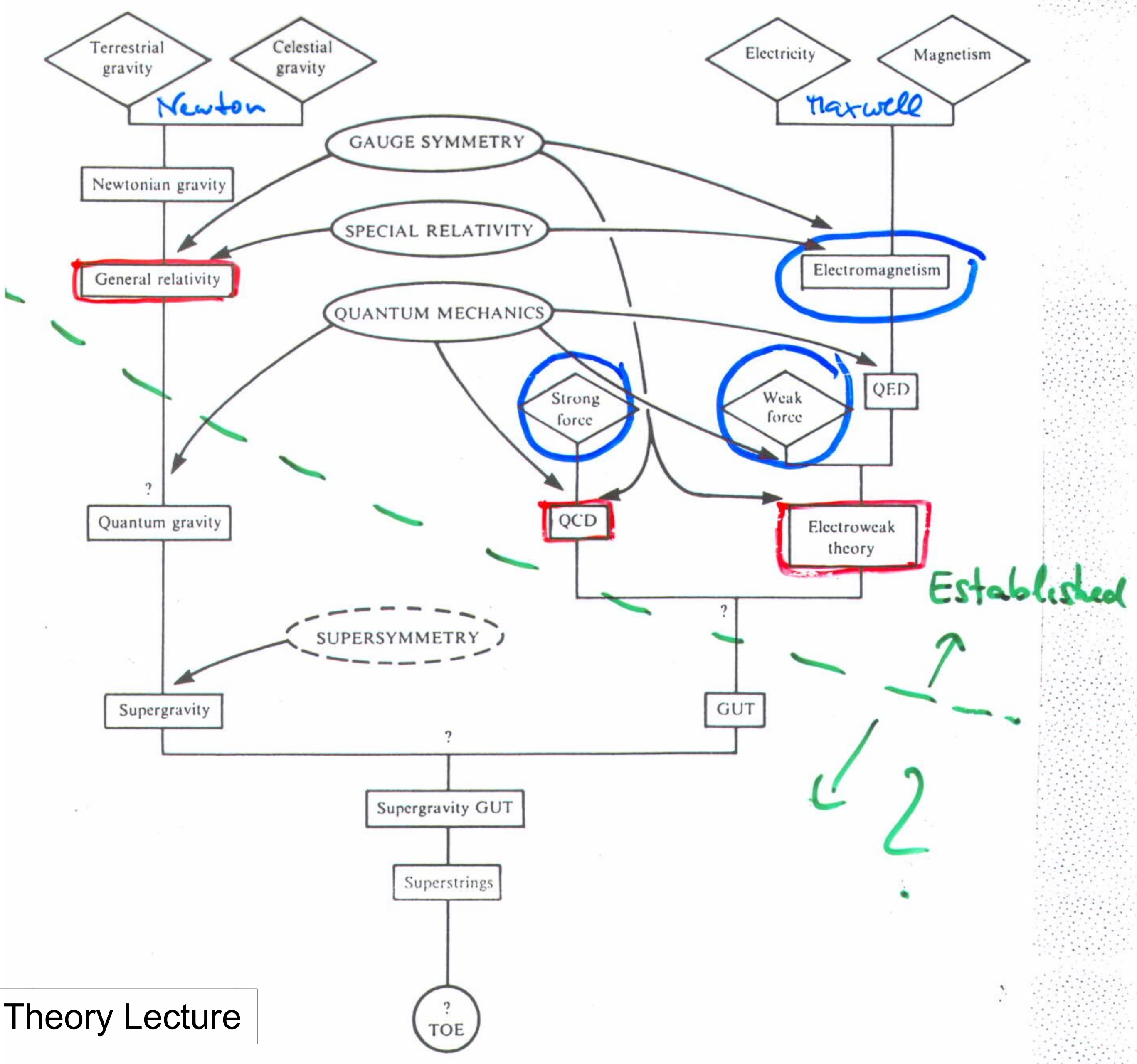


The elementary Fermions span a huge range of Masses



The interactions and their related Theories

Fig. 45.1. The road to unification of the fundamental forces.



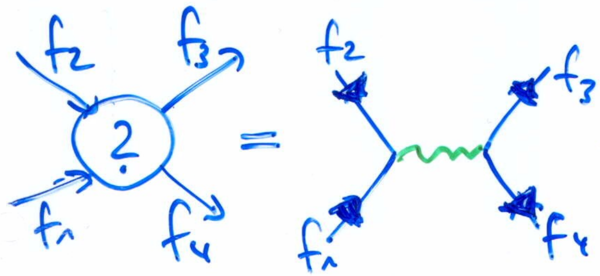
Details in HEP Theory Lecture

Interactions :

Feynman Diagram
Concept

Fermion – Fermion – Interactions

$$f_1 + f_2 \rightarrow f_3 + f_4$$



$+ \underbrace{\ldots}_{\text{higher Order terms}}$

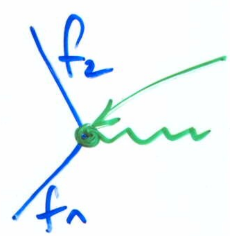
Perturbative Calculation

Amplitude $A = \underbrace{A_1 + A_2 + \ldots}_{\text{convergence ?}}$

$e^2 \sim \alpha_{em} = 1/137$

Transition Probability $\sim$ cross-section $\sim A^2$

Decompose the $\boxed{\text{Feynman Diagram}}$ into fundamental fermion – fermion – Boson couplings



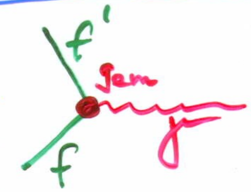
Vertex coupling Strength

Vertex Couplings :

The different interactions have different properties

Properties of fundamental couplings between Fermions and Gauge Bosons

e.m

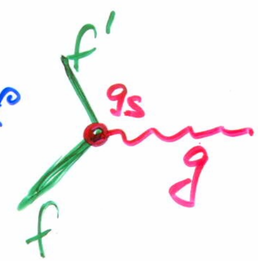


All <u>charged</u> fermions, $f=f'$

$g_{em} \sim$ electric charge q

$g_{em}^2 \sim \alpha_{em} = 1/137$

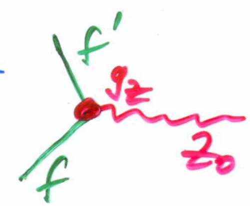
strong



All quarks, $f=f'$ (apart color)

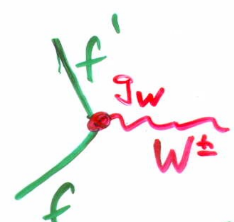
$g_s^2 \sim \alpha_s$

weak NC



All fermions, $f=f'$

weak CC



All fermions, $\Delta Q_{ff'} = 1$

Generation mixing in quark sector

No(?) " " " lepton "

Specific Helicity couplings !

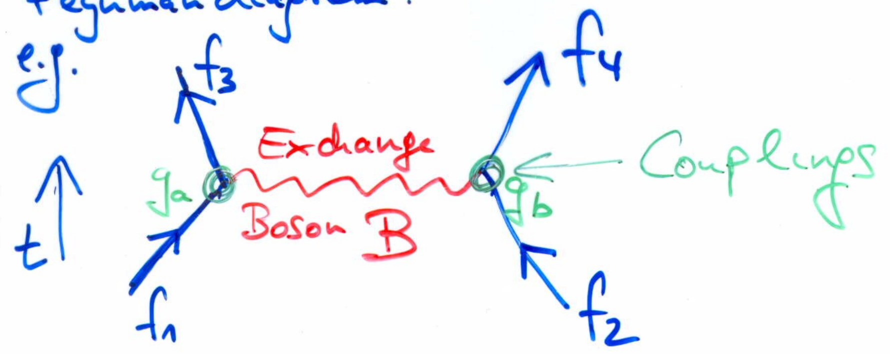
Feynman Diagrams :

Vertices
Fermionlines
Exchange Boson
Fourmomentum Transfer
Transition Amplitude
Cross Section

$$\boxed{\text{Interaction } f_1 + f_2 \longrightarrow f_3 + f_4}$$

Feynman diagram :

e.g.



$$(\text{Fourmomentum of } B)^2 : \quad q^2 = (p_3 - p_1)^2 = (p_4 - p_2)^2$$

⇒ Transition Amplitude

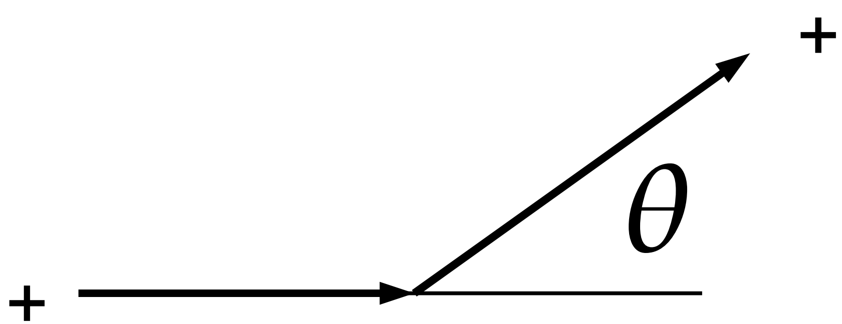
$$A \sim \underbrace{f(f_1, f_2, f_3, f_4)}_{\text{Fermion Wave-function}} \cdot \underbrace{g_a \cdot g_b}_{\text{Vertex Coupling}} \cdot \underbrace{\frac{1}{q^2 - M_B^2}}_{\text{Propagator}}$$

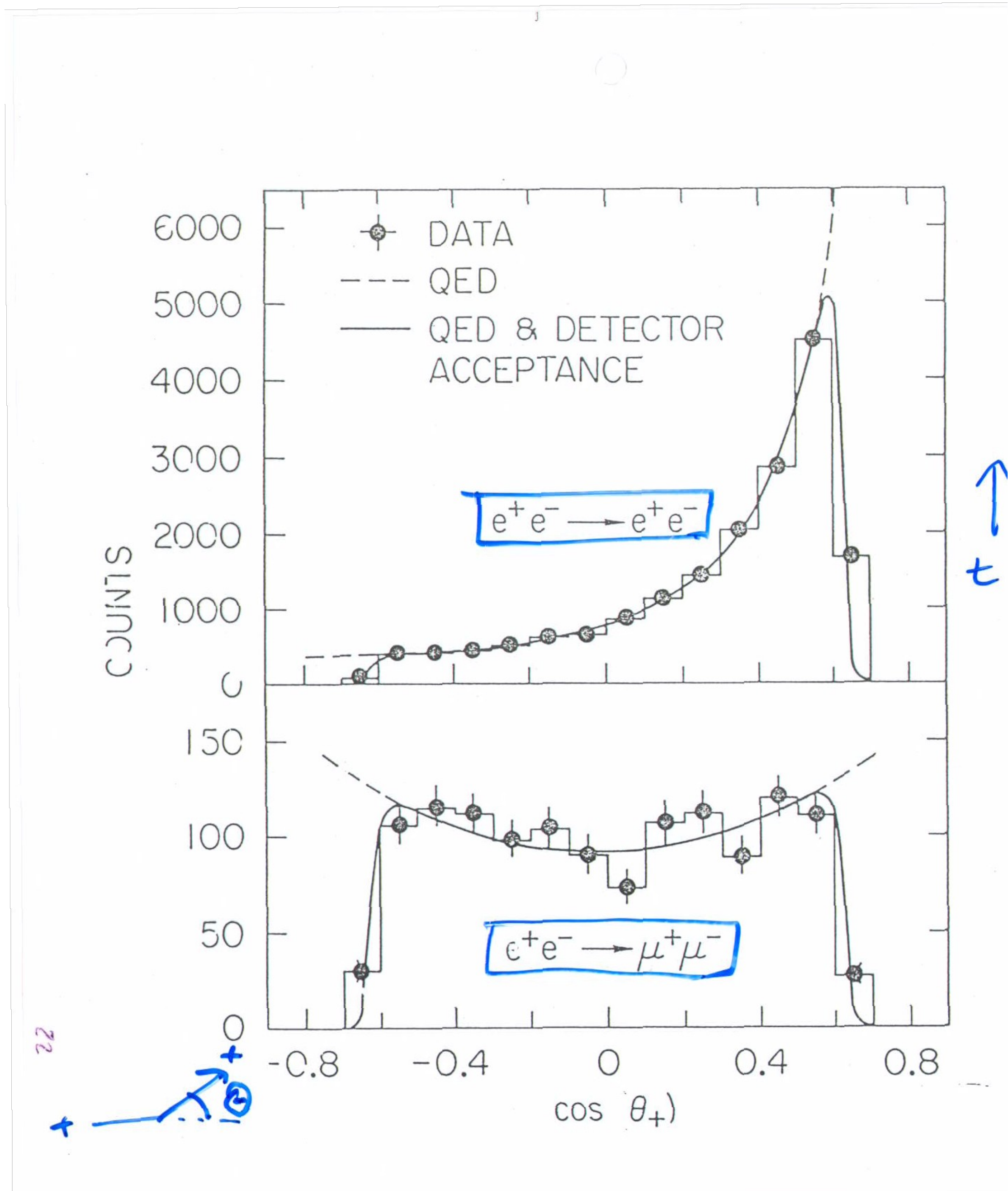
⇒ Cross-section

$$\sigma \sim |A_1 + A_2 + \dots|^2 \cdot \text{Phasespace}$$

Application :
e+ e- Annihilation into
- e+ e- pair
- mu+ mu- pair

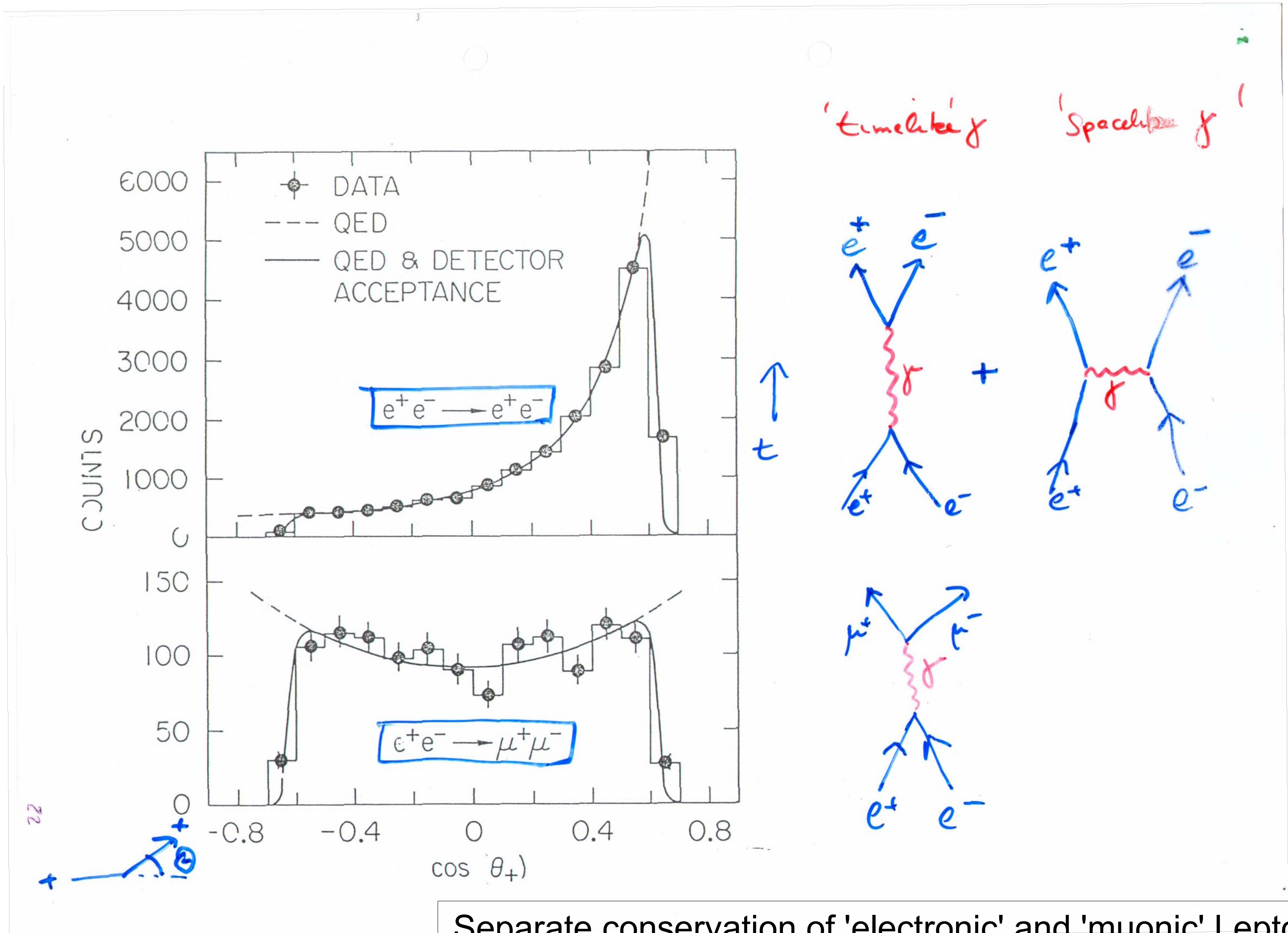
Why do the angular spectra differ so drastically ?





e+ e- Annihilation into Lepton pairs

Why do the angular spectra differ so drastically ?



Separate conservation of 'electronic' and 'muonic' Lepton Number !

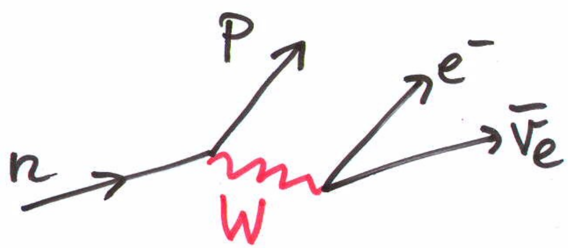
How did this Picture emerge :

The Particle Generations

Start with FIRST Generation Fermions
* Electron
* Neutrino
* u-Quark
* d-Quark

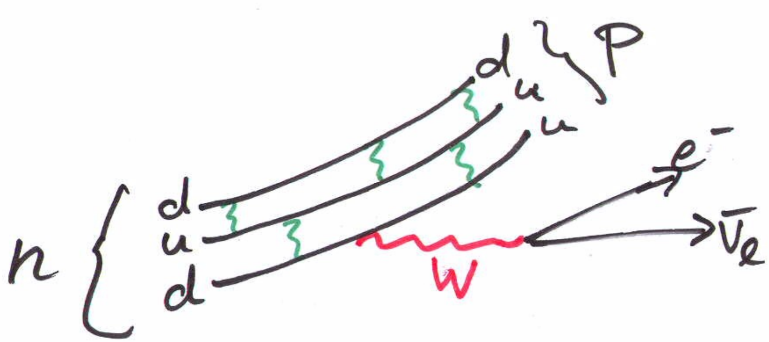
$\boxed{\text{All first generation particles are players in the } \beta\text{-decay}}$ ← u, d, e, ν_e

$$n \to p\, e^- \, \bar{\nu}_e$$



WEAK Interaction! mediated by Virtual W

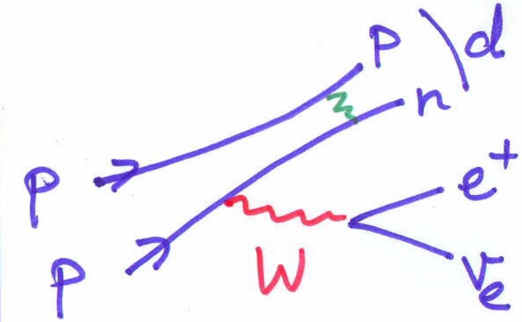
on 'quark level':



Side remark:

Burning of Sun is similar process

$$\boxed{pp \to d\, e^+ \nu_e}$$



FUSION!

Antiparticles :

Proposed by DIRAC

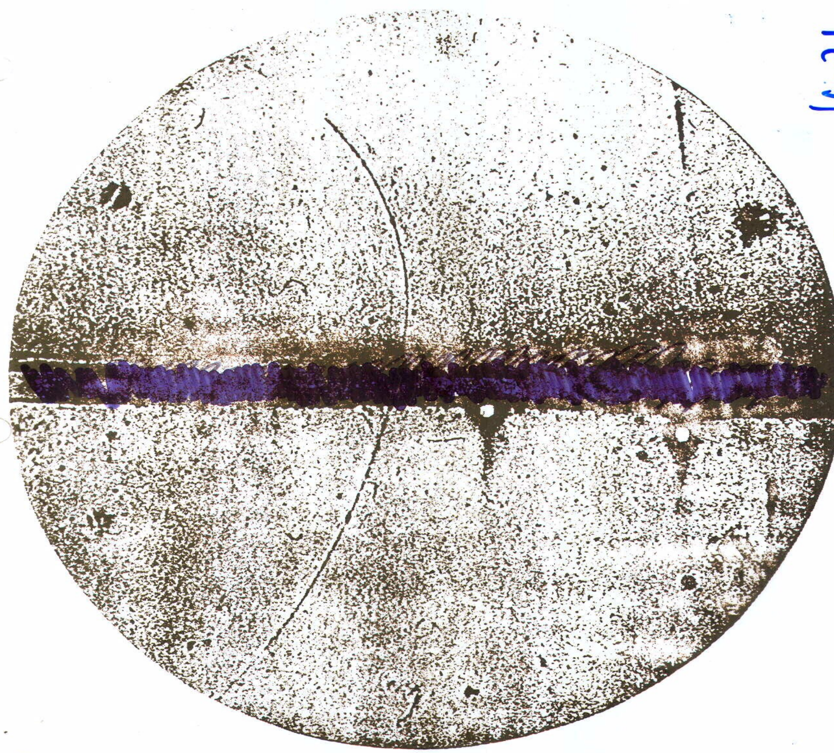
e+ discovered by Anderson 1933

Physical Review (March 1933), Vol. 43

Title: THE POSITIVE ELECTRON

e^+

CARL D. ANDERSON



$\vec{B}$-Field:

e^+ e^-

e^- e^+

6mm Pb-plak

FIG. 1. A 63 million volt positron ($H\rho = 2.1\times10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5\times10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

28

The NEUTRINO :

Postulated by PAULI 1930
(energy and spin violation
in beta-decay)

Observed at Reactor
1956

First DIRECT NEUTRINO EVIDENCE

Reines, Cowan 1956 — Nobel prize 1995

$10^{20}\ \bar{\nu}_e/\mathrm{sec}$ from Reactor $\Rightarrow$ 2.9 $\frac{\text{Events}}{\text{hour}}$

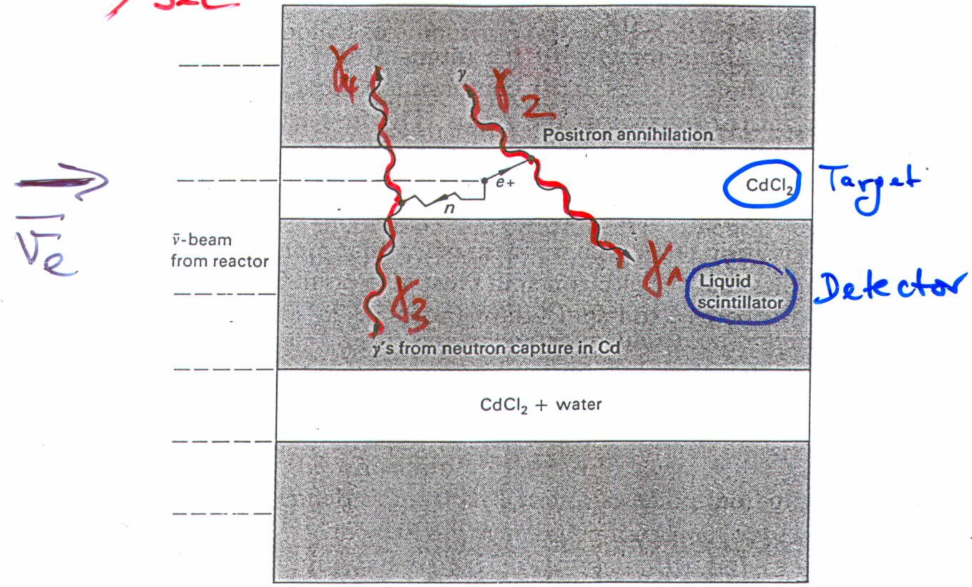


Figure 7.4 Schematic diagram of the experiment by Reines and Cowan (1959), detecting the interactions of free antineutrinos from a reactor.

$$\bar{\nu}_e\, p \to n\ e^+$$

$e^+ + e^- \to \gamma_1 \gamma_2$ — prompt coincidence

n: Moderation and Capture in Cd

$$Cd^* \to Cd + \gamma_3 \gamma_4$$

delayed coincidence (μsec)

HADRONS :

Strongly interacting particles
Built up by QUARKS

Hydrogen Bubble Chamber

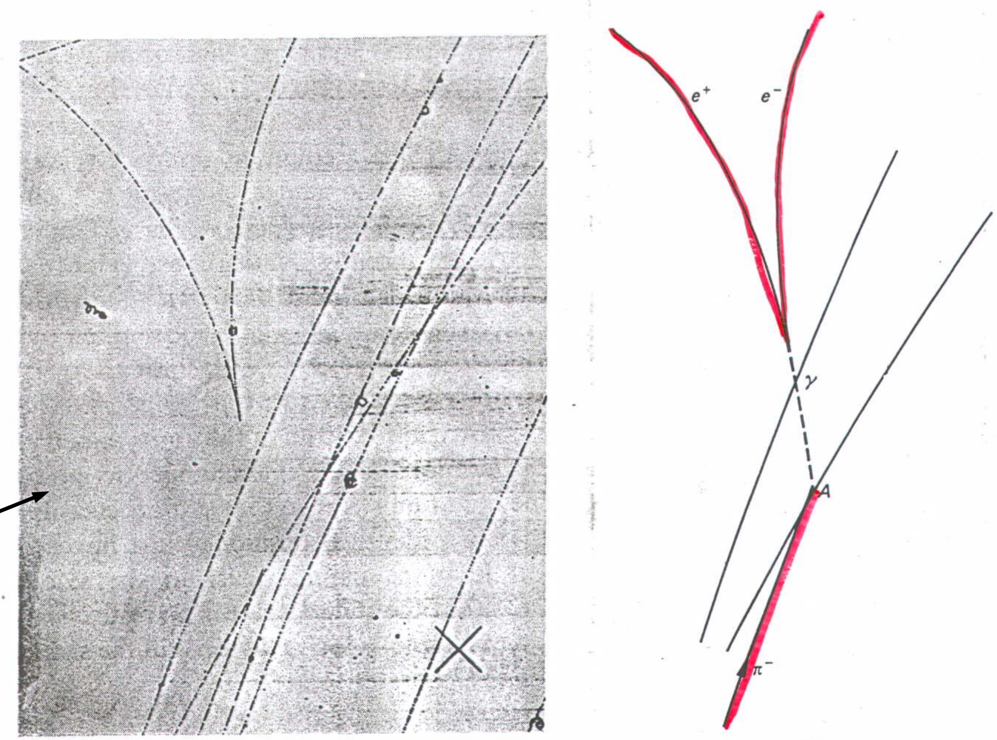


Figure 1.2 Conversion of a photon to an electron-positron pair in a bubble chamber. An incoming negative pion undergoes charge-exchange at point A: $\pi^- + p \to n + \pi^\circ$, followed by decay of the neutral pion, $\pi^\circ \to 2\gamma$. Since the π° lifetime is only 10^{-16} s, the pair appears to point straight to the interaction vertex.

Pion charge exchange scattering

$$\pi^- p \to \pi^0 n$$
$$\pi^0 \to \gamma\gamma$$
$$\gamma \to e^+ e^-$$

π^- found
1947 in
COSMIC RAYS

.. and the corresponding Feynman diagram :

$$\boxed{\pi^- p \to \pi^0 n}$$

$$\pi^0 \to \gamma\gamma$$

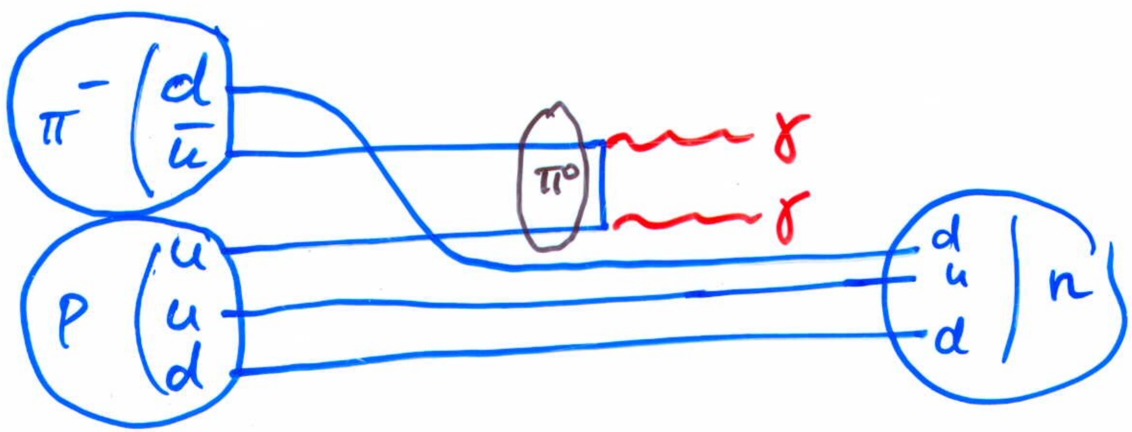
$$p = uud$$

$$n = udd$$

$$\pi^- = d\bar{u}$$

$$\pi^0 = q\bar{q} = u\bar{u} + d\bar{d}$$

Reaction Feynman Diagram on Quarklevel:



The Antiproton was found in 1955 at the then highest energy proton accelerator

Here an antiproton is seen annihilating in an emulsion target

Figure 4.1: The first antiproton star observed in an emulsion. The incident antiproton track L. The light tracks a and b are pions. Track c is a proton. The remaining tracks a protons or alpha particles. The exposure was made at the Bevatron. (Ref. 4.2)

1955, Berkeley/CA

$\bar{p}p \rightarrow$ pions

$E^*_{cm} = 1.9$ GeV

What is the minimal Proton energy to produce in pp scattering Antiprotons ?

SECOND Generation Fermions
* Muon
* Muon-Neutrino
* c-Quark
* s-Quark

The second generation Lepton : The MUON

$\pi^- \to \mu^- \bar{\nu}_\mu$

$\hookrightarrow e^- \bar{\nu}_e \nu_\mu$

EMULSION

Tracks from COSMIC RAYS

Muon mass = 105 MeV

$\tau_{\pi^\pm} = 2.6 \times 10^{-8}$ sec

$\tau_\mu = 2.2 \cdot 10^{-6}$ sec

Figure 1.1 Examples of the decay sequence $\pi^+ \to \mu^+ \to e^+$ in G5 emulsion exposed at Pic du Midi. The constancy of range ($\simeq 600\ \mu m$) of the muon implies two-body decay at rest of the pion: $\pi^+ \to \mu^+ + \nu_\mu$. The first examples of pion decay were observed by Lattes, Muirhead, Occhialini, and Powell in 1947. Note the very dense ionization of both pion and muon tracks near the end of the range, compared with the thin track of the relativistic electron, as well as the lateral

Cosmic Muon recorded in the H1 Detector

$\boxed{\mu}$

$J = \frac{1}{2}$

Mass $m = 0.1134289264 \pm 0.0000000030$ u

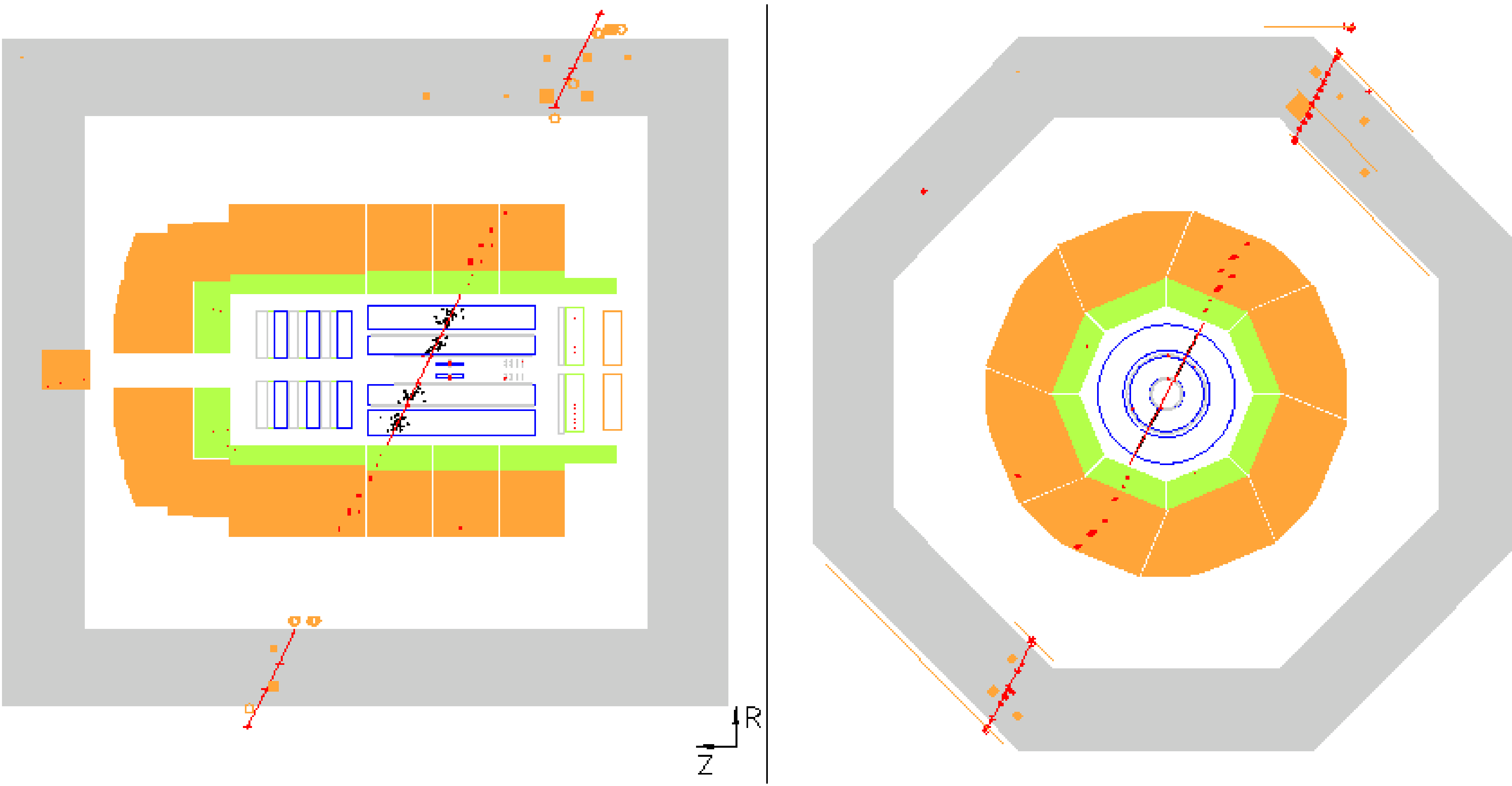
Mass $m = 105.658369 \pm 0.000009$ MeV

Mean life $\tau = (2.19703 \pm 0.00004) \times 10^{-6}$ s

$\tau_{\mu^+}/\tau_{\mu^-} = 1.00002 \pm 0.00008$

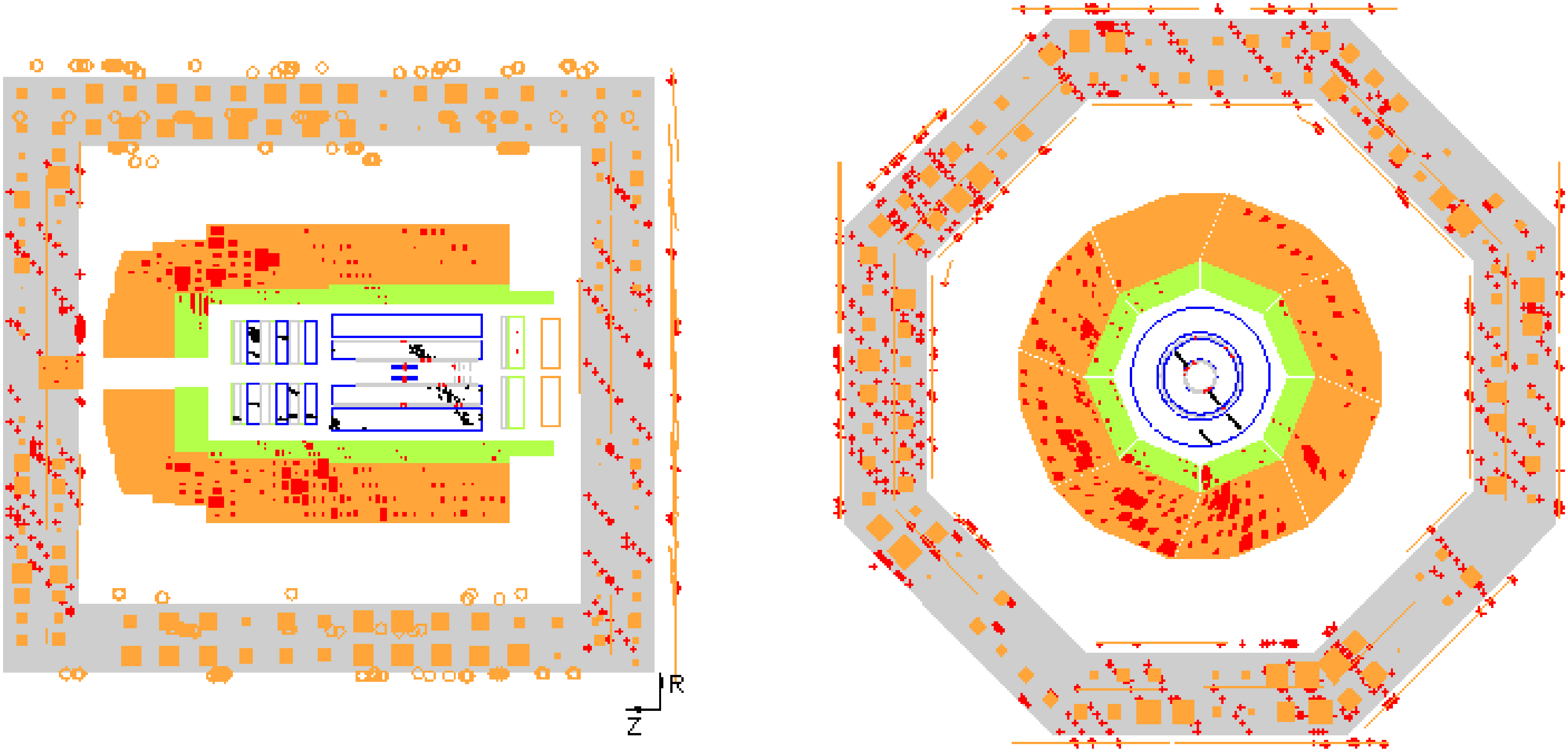
$c\tau = 658.654$ m

Magnetic moment $\mu = 1.0011659203 \pm 0.0000000007\ e\hbar/2m_\mu$



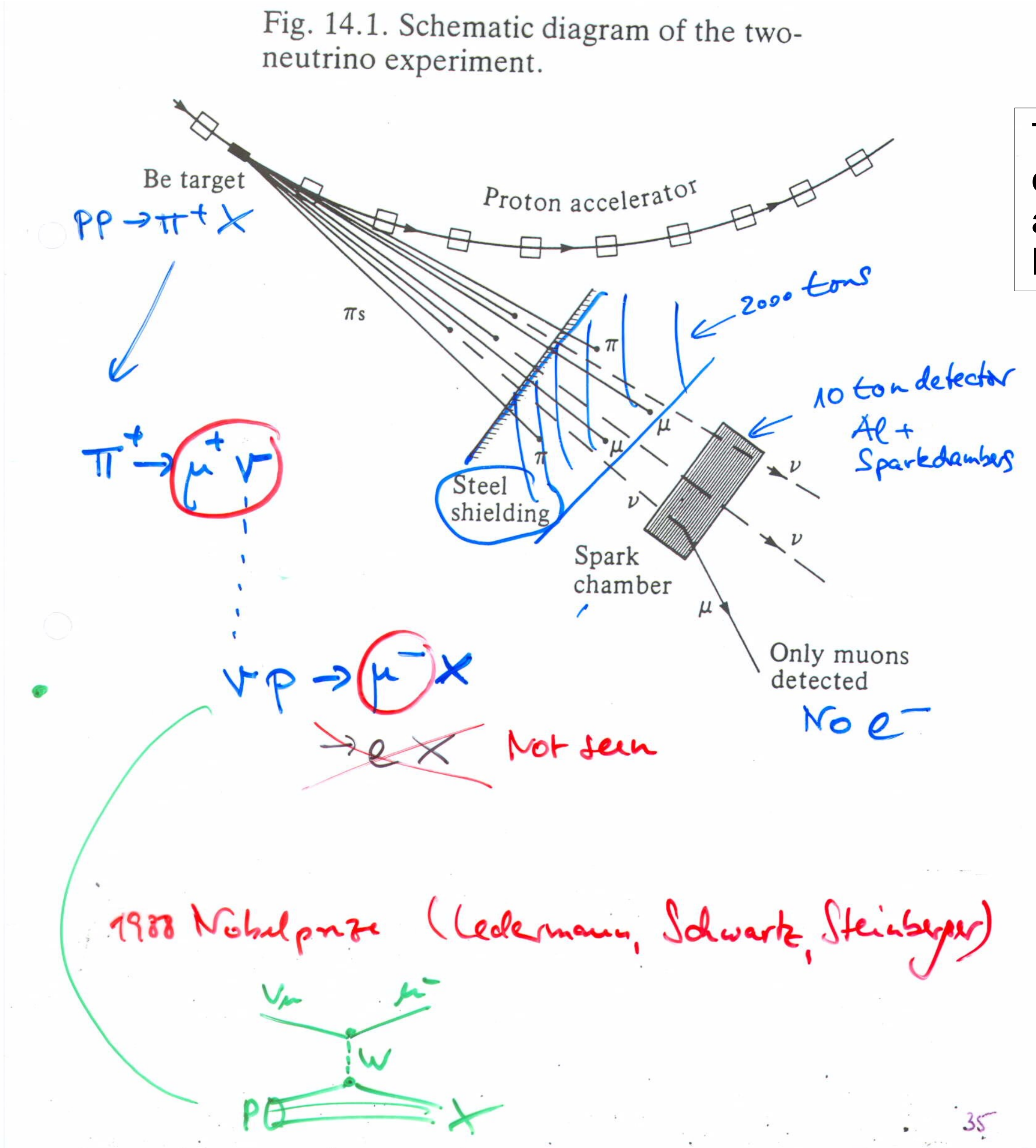
Muons do not interact strongly and do not radiate:
They thus have a strong penetration power through matter

There are also COSMIC SHOWERS producing MULTIMUONS :



Of courses when doing e-p physics at HERA
we do not really like these 'Disturbances'

The muon has its own neutrino partner



The first neutrino experiment at accelerators .1962 Brookhaven, USA

Discovery of STRANGE HADRONS :

π^- beam on H_2-Bubble chamber

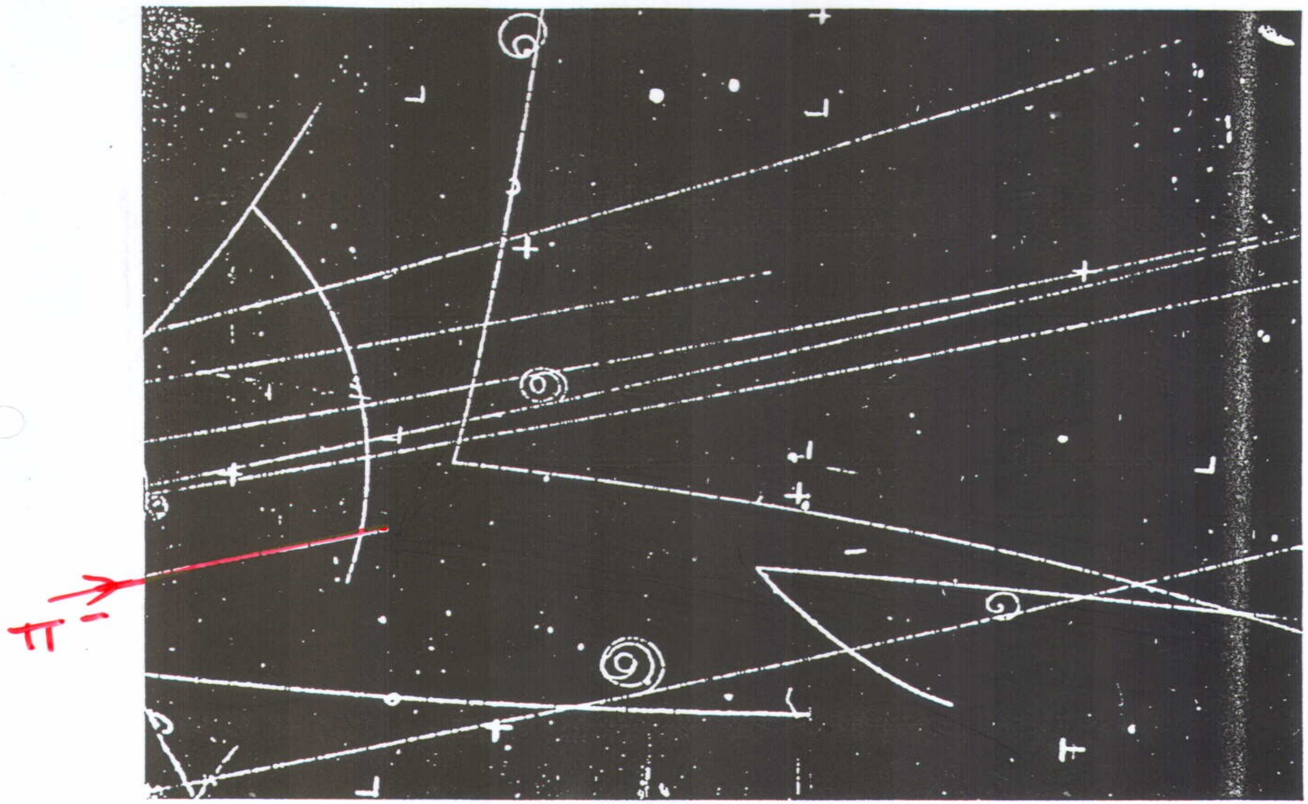


Fig. 10.8 A photograph of an interaction of a 1 GeV/c π^- [illegible]on with a proton in a liquid hydrogen bubble chamber. The reaction is

$$\pi^- + p \rightarrow K^0 + \Lambda,$$

Strong production

followed by

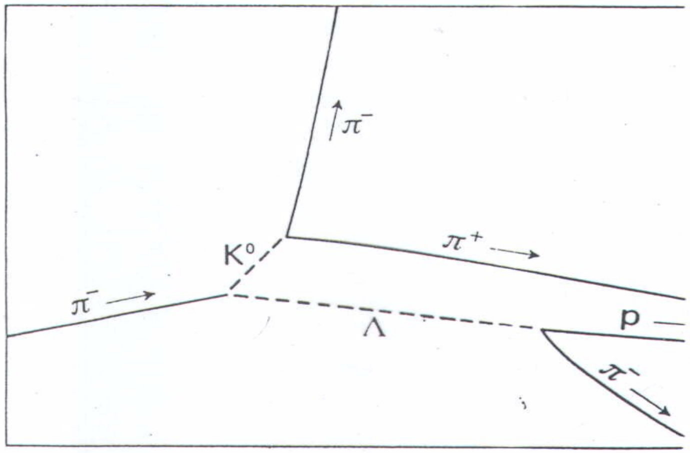
$$K^0 \rightarrow \pi^+ + \pi^-,$$

and

$$\Lambda \rightarrow \pi^- + p.$$

weak decays

This is an example of associated production of two strange particles.



High cross section

Long lifetime

Postulating a third Quark (s-quark) can explain the observations

$$\pi^- p \rightarrow \Lambda\ K^0 \rightarrow p\,\pi^+\pi^-\pi^-$$

$K^0 \rightarrow \pi^+\pi^-$

$\Lambda \rightarrow p\,\pi^-$

$m_{\pi^+\pi^-} = 0.497\ \mathrm{GeV}$

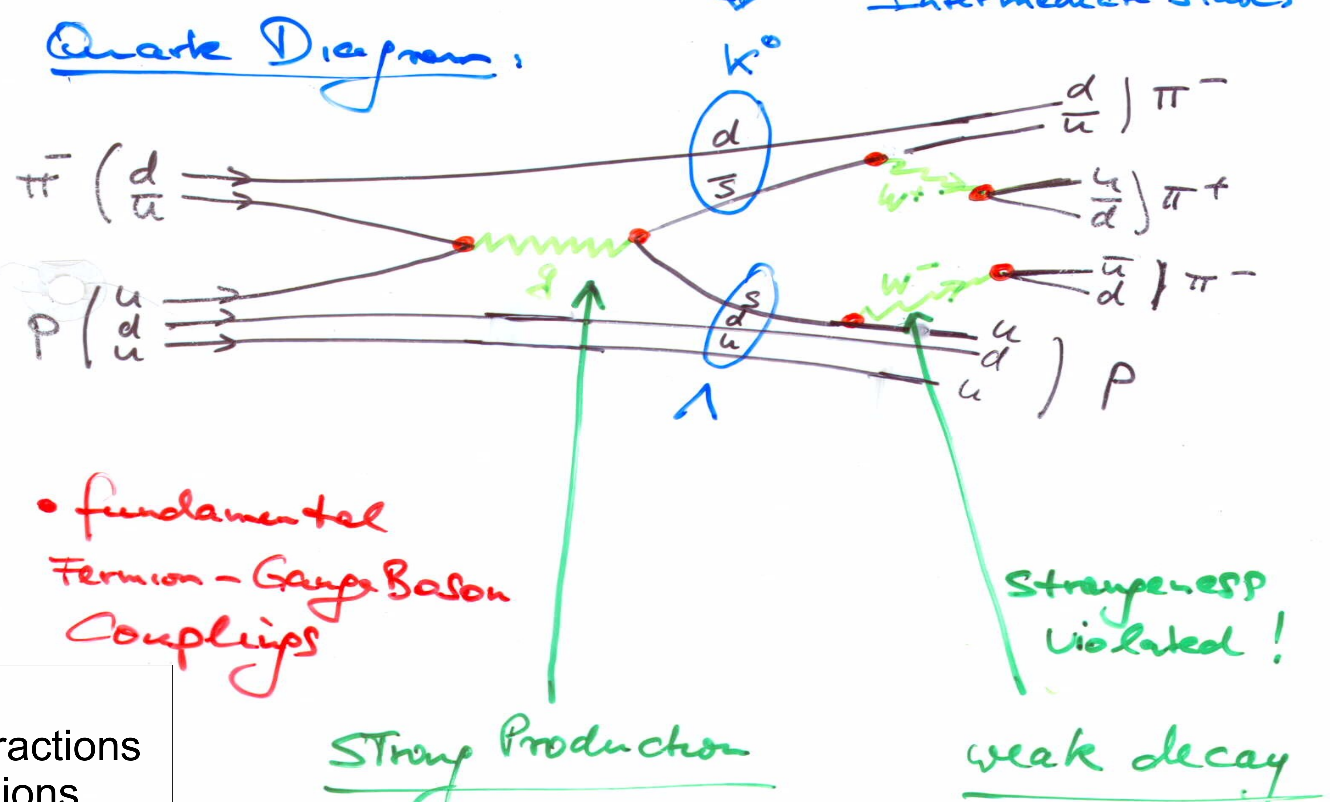
$m_{p\pi^-} = 1.115\ \mathrm{GeV}$

invariante Masses !

$$\boxed{\begin{array}{ll} \pi^- = d\bar{u} & p = uud \\ (\pi^+ = \bar{d}u) & \\ \Lambda = sdu & (S=-1) \\ K^0 = \bar{s}d & (S=+1) \end{array}}$$

Intermediate States

Quark Diagram:



Strangeness :
Conserved in strong Interactions
NOT in CC-weak interactions

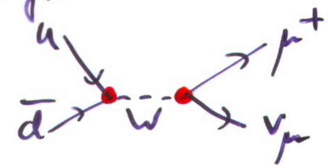
Compare the decay rates of the lightest non-strange (PION) and strange (KAON) mesons

Compare:

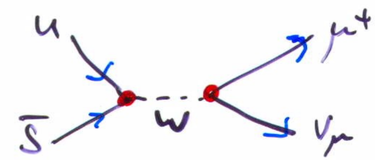
$\boxed{\pi^+ = u\bar{d}}$ $\qquad$ $\boxed{K^+ = u\bar{s}}$ lightest strange particle!

$m_\pi = 135$ MeV $\qquad$ $m_K = 494$ MeV

Decays

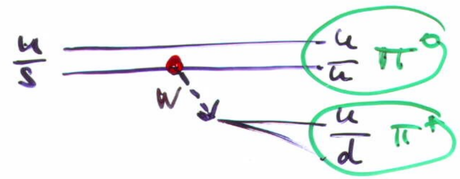


100%



63%

Leptonic decays



21%

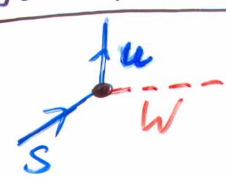
Hadronic decay

$\tau_\pi = 2.6 \cdot 10^{-8}$ sec $\qquad$ $\tau_K = 1.2 \cdot 10^{-8}$

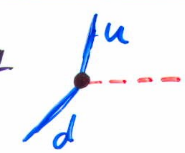
K^+ is factor 3.6 more massive than π^+

↳ expect $\tau_K \ll \tau_\pi$

⇒ Some mechanism hinders the K to decay

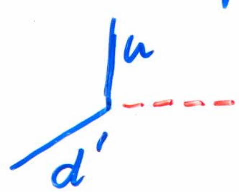


is suppressed w.r.t



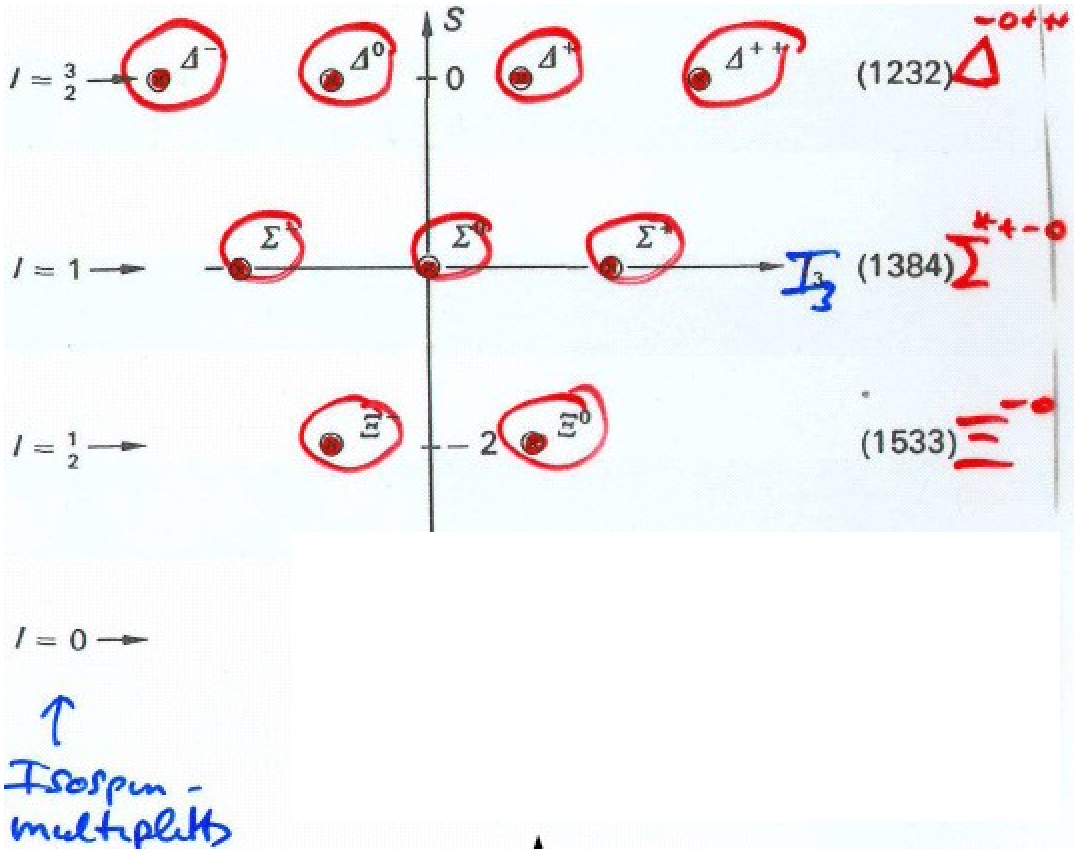
Generation changing weak (CC) decays are suppressed

'Cabbibo' Suppression of '(family) flavor-changing CC'



$$d' = d \underbrace{\cos\theta_c}_{0.98} + s \underbrace{\sin\theta_c}_{\simeq 0.2}$$

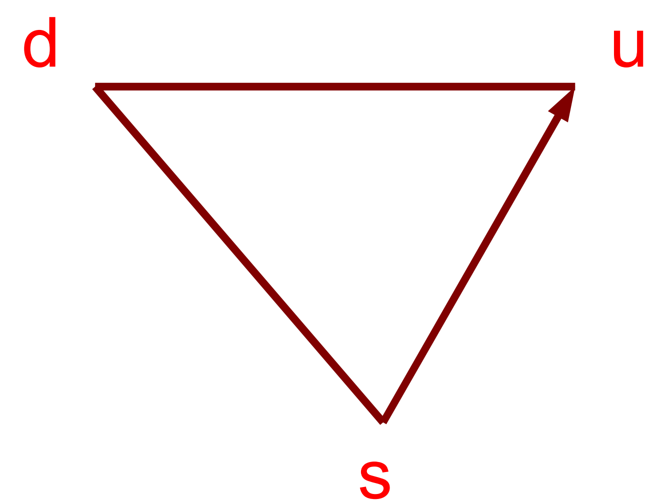
Particles of the Spin 3/2 Baryon Dekuplett



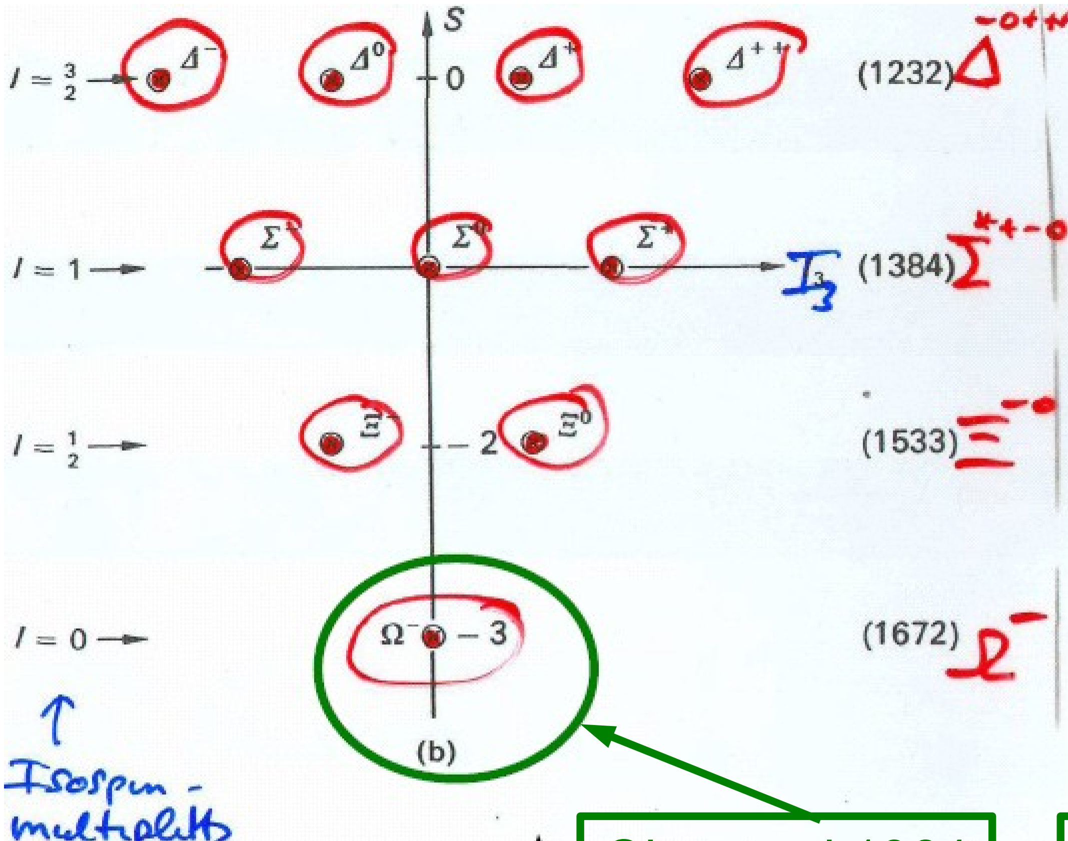
Strangeness-Isospin Diagram

Observation 1963

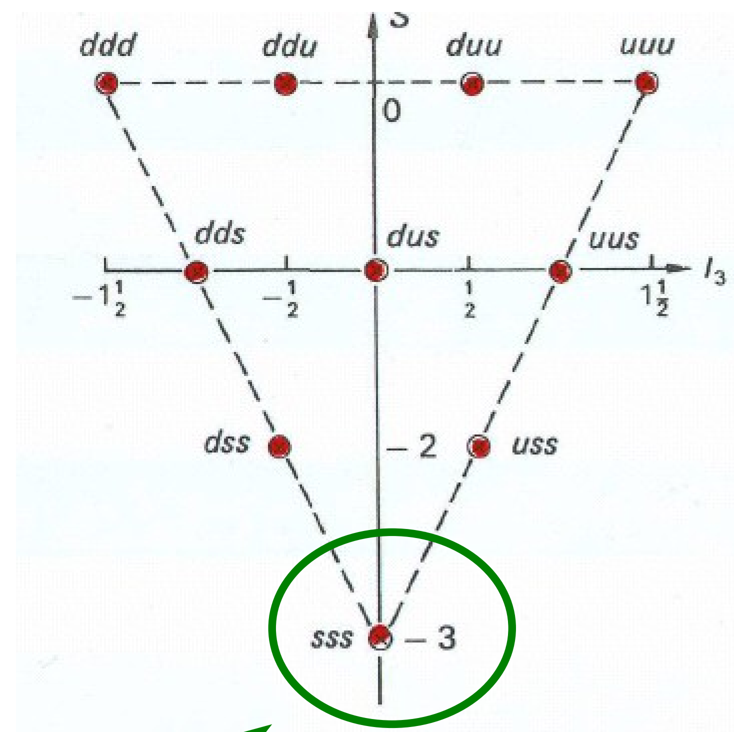
Quark model(1963 Gell-Man) :
- u,d Isospindoublett (S=0)
- s Isospinsiglett (S=-1)



Quark model : Gell-Mann SU_3
(Nobel prize 1969)



(b)



(a)

Observed 1964

Predicted 1963

Observation

QPM Interpretation

TRIUMPH of the QUARK Model :

Discovery of the predicted OMEGA-Particle

DISCOVERY OF $\Omega^- = sss$

1964

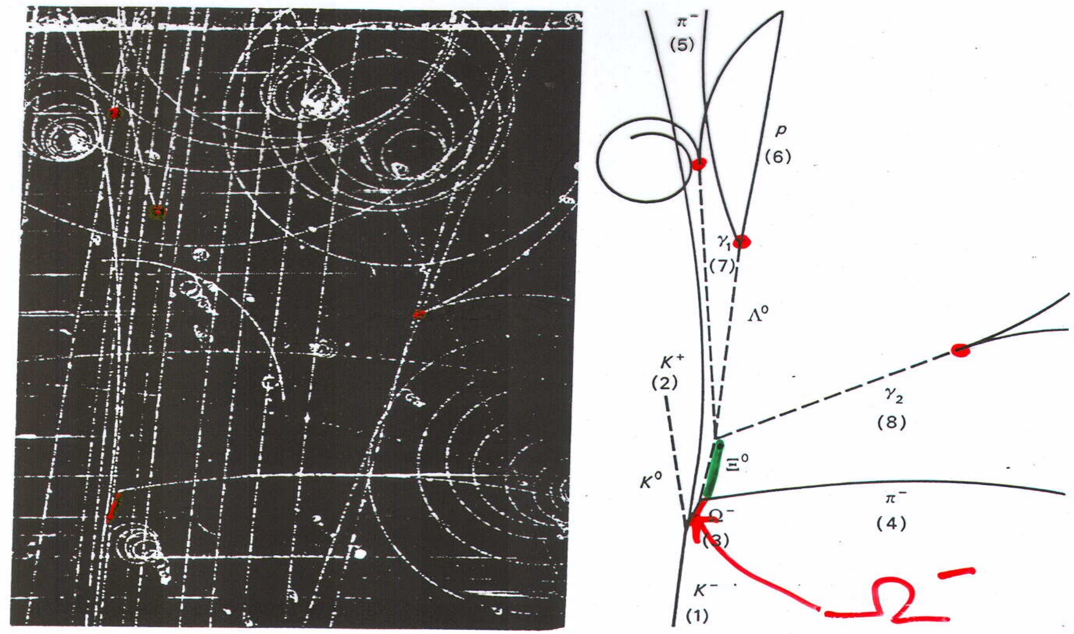


Figure 5.2 The first Ω^- event (Barnes *et al.* (1964).) (Courtesy Brookhaven National Laboratory.) It depicts the following chain of events:

$$
\begin{aligned}
&K^- + p \to \Omega^- + K^+ + K^0 \\
&\quad \hookrightarrow \Xi^0 + \pi^- \ (\Delta S = 1 \text{ weak decay}) \\
&\qquad \hookrightarrow \pi^0 + \Lambda \ (\Delta S = 1 \text{ weak decay}) \\
&\qquad\qquad\quad \hookrightarrow \pi + p \ (\Delta S = 1 \text{ weak decay}) \\
&\qquad\quad \hookrightarrow \gamma + \gamma \ (\text{e.m. decay}) \\
&\qquad\qquad\ \downarrow \qquad \downarrow \\
&\qquad\qquad e^+e^- \quad e^+e^-.
\end{aligned}
$$

$M_{\Omega^-} = 1672$ MeV

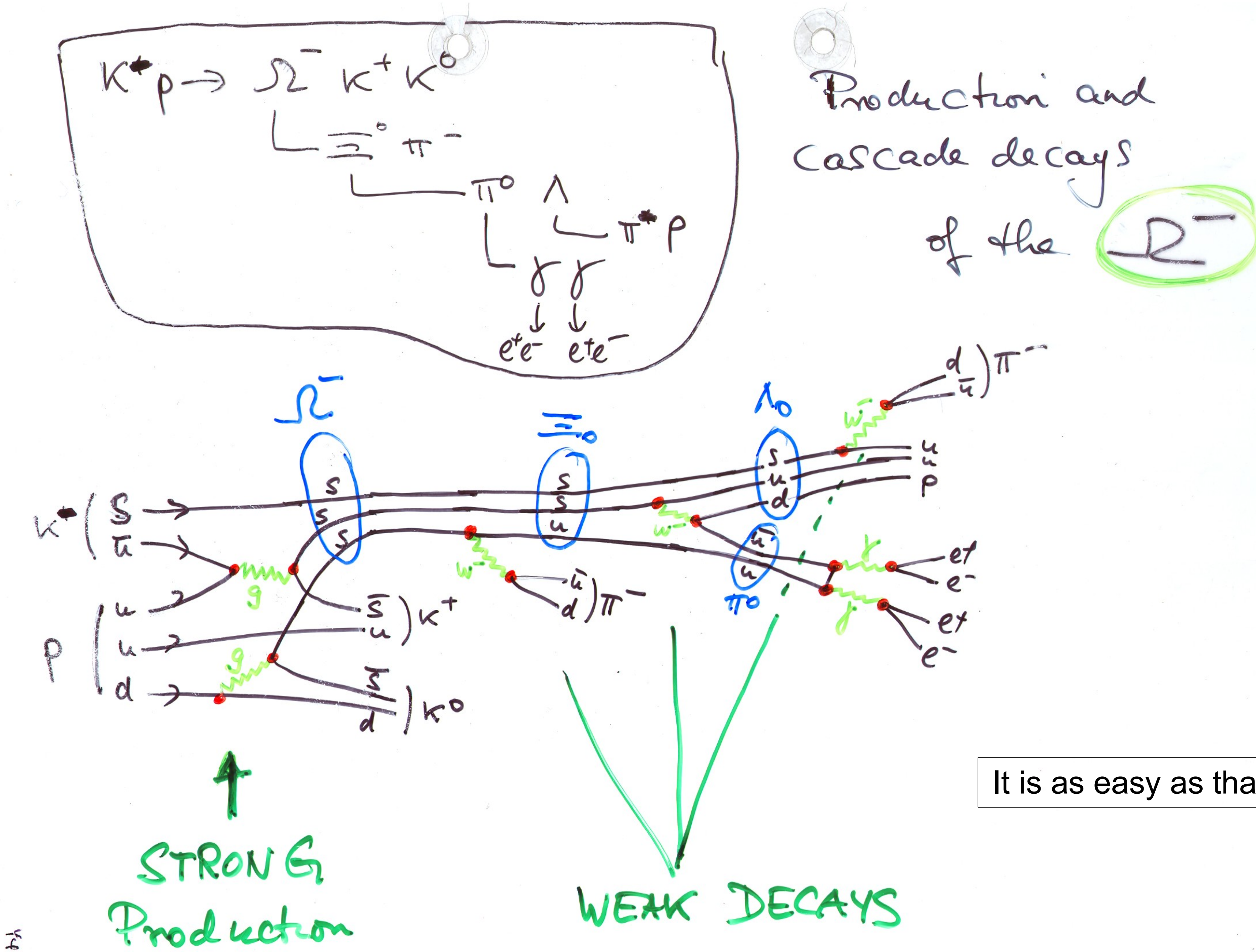
$\tau_{\Omega^-} = 0.8 \cdot 10^{-10}$ sec

$\downarrow$

$c\tau = 2.4$ cm

43

The Feynman Diagram for OMEGA- production and decay chain :

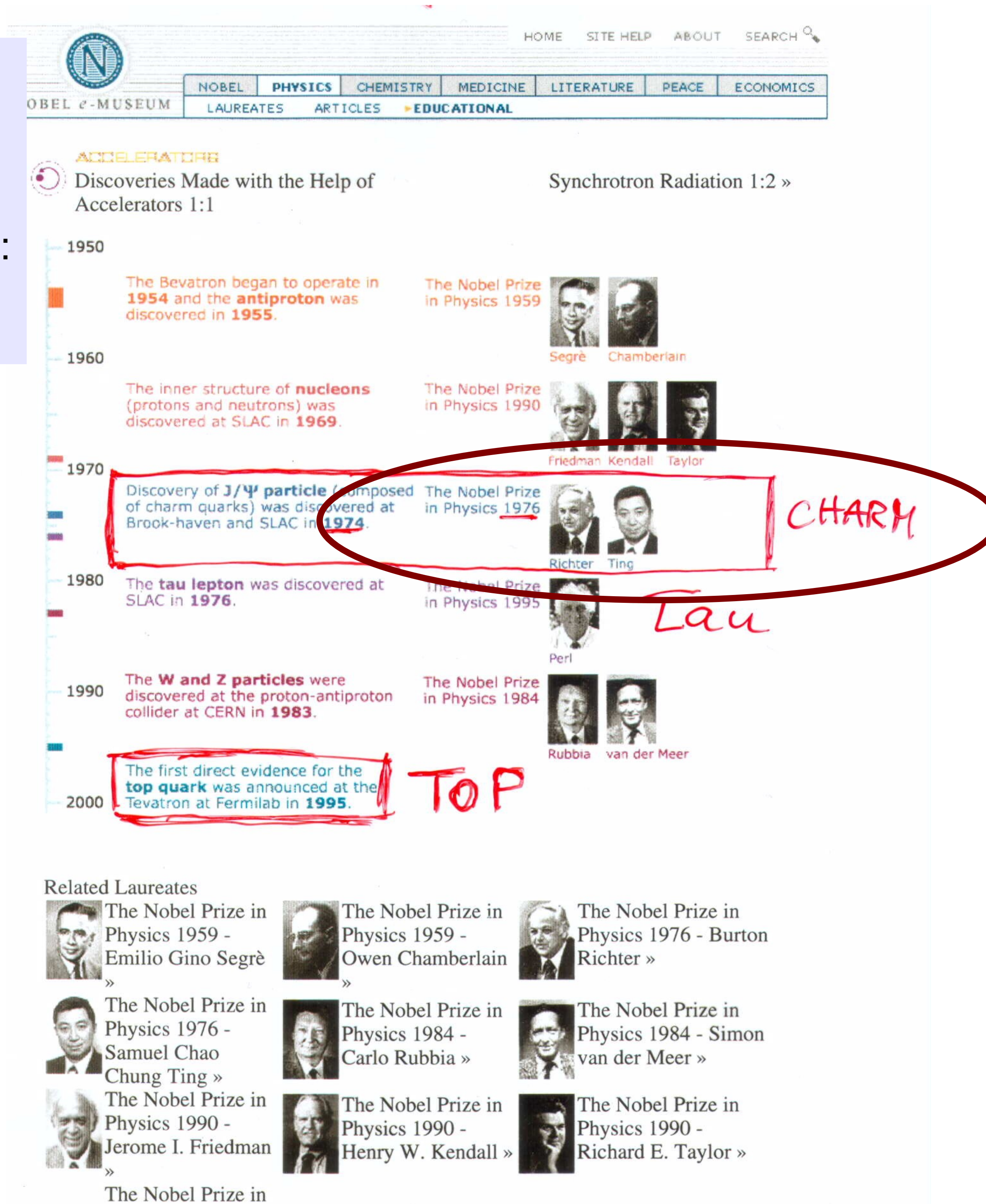


It is as easy as that !

The 1974
November Revolution
of HEP :

Discovery of a new QUARK :

CHARM



www.nobel.no

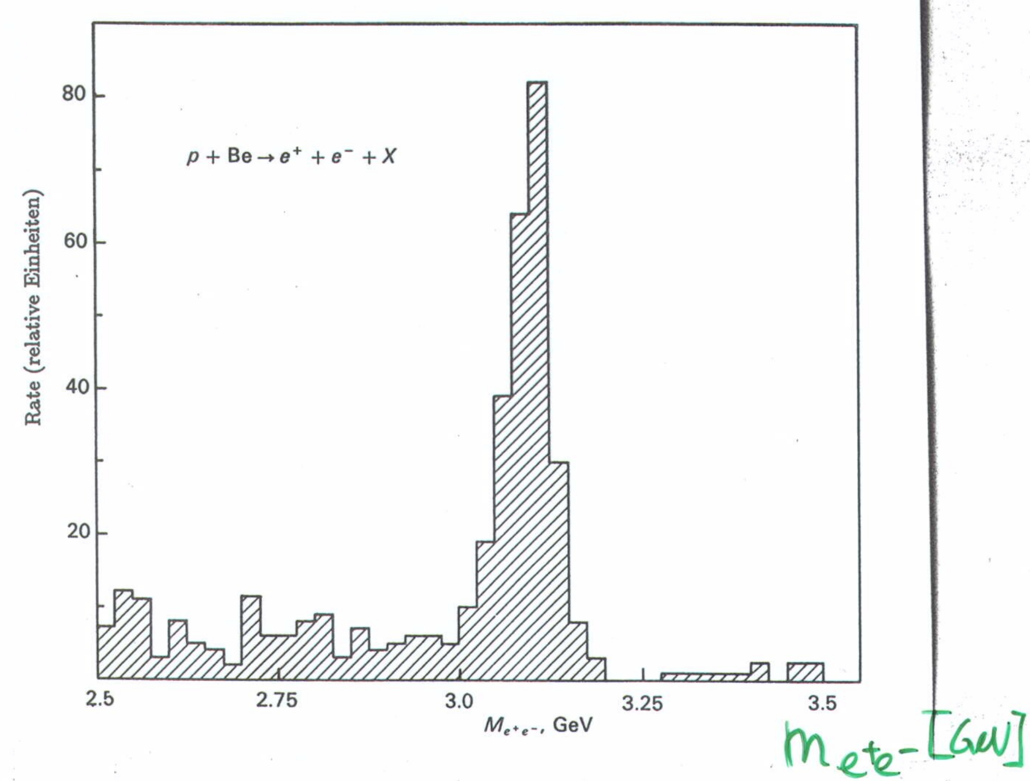
.. at the East coast of US

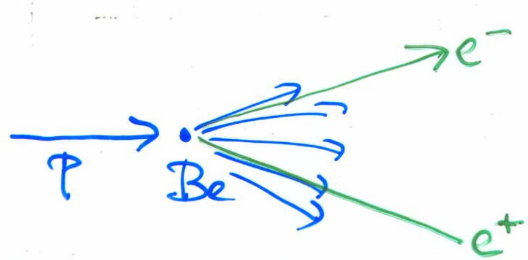
Brookhaven
Proton Synchrotron

November 1974

1974 Discovery of J/ψ particle $c\bar{c}$

$p + Be \to J/\psi + X$ Brookhaven
$\hookrightarrow e^+e^-$ S. Ting





.. and at the West coast.

SLAC
e+ e- Collider

November 1974

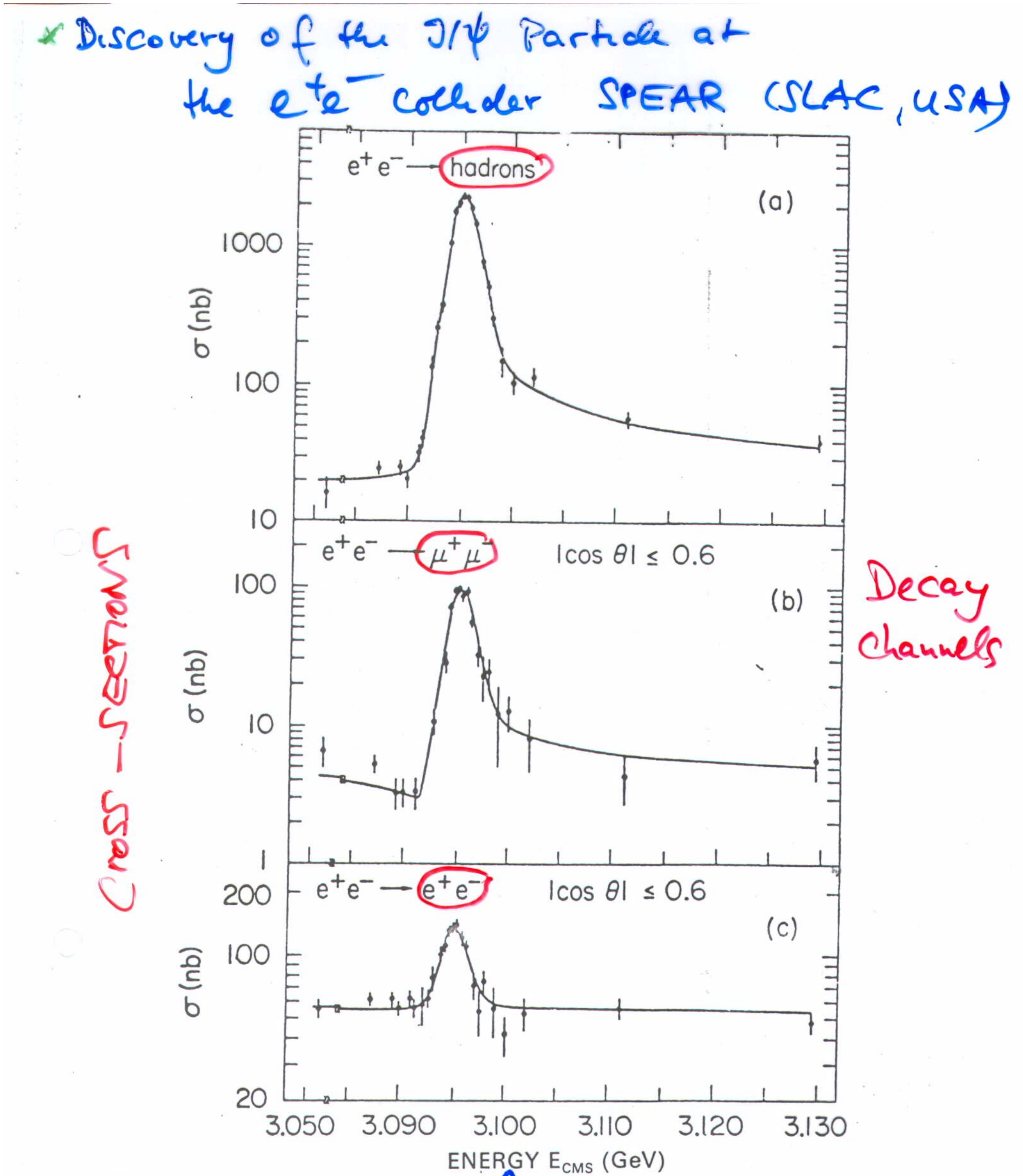


Figure 5.9 Results of Augustin *et al.* (1974) showing the observation of the ψ/J resonance of mass 3.1 GeV, produced in e^+e^- annihilation at the SPEAR storage ring, SLAC.

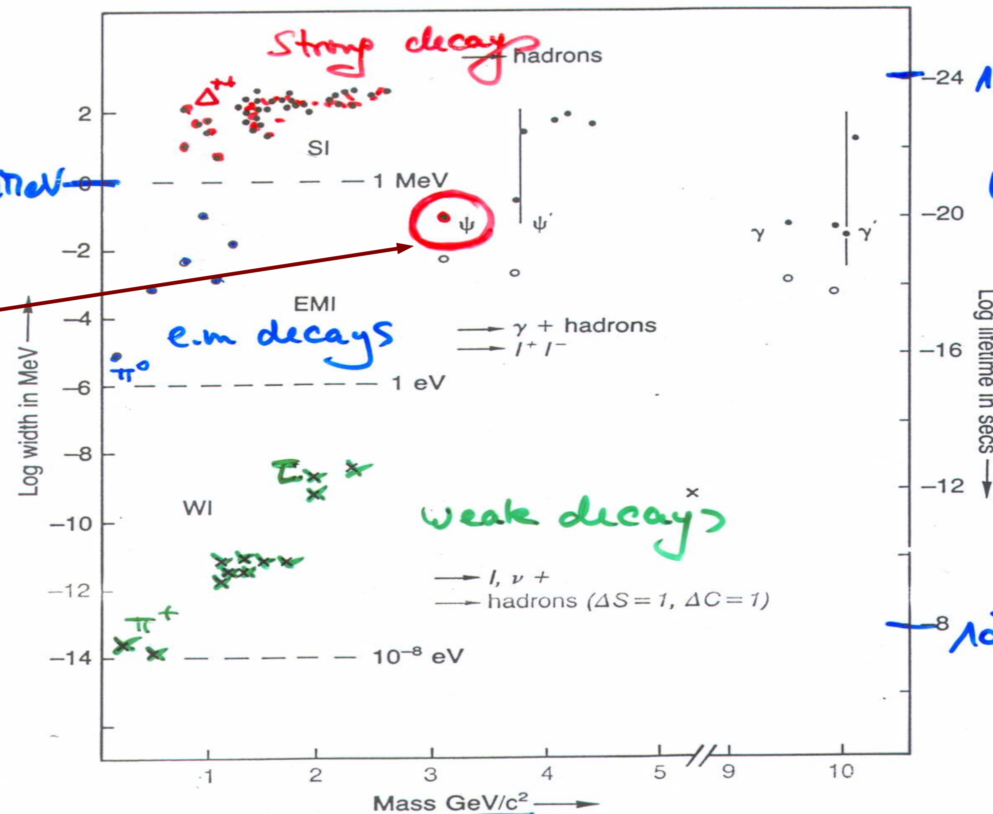
e^+e^- CM Energy $= 2 \times E_{beam}$

Unstable Particles

Γ, τ depends on
- Mass
- decay type (strong, em, weak)

Widths of hadron states

Decay width Γ



Lifetime [sec]

Γ τ

The most spectacular aspect of the J/Psi particle is its relatively long lifetime

Particle Mass

Reminder:

$$\Gamma \cdot \tau = \hbar = 6.6 \cdot 10^{-22}\ \mathrm{MeV \cdot sec}$$

Compare the J/Psi with other particles of same quantum numbers (Vectormesons : spin 1 ; parity -1)

J/ψ mass $M = 3.1$ GeV $\quad J^P = 1^-$ Vector meson $q\bar{q}$

Width $\boxed{\Gamma = 0.09 \text{ MeV}}$

expect $\Gamma_{J/\psi}$ few 100 MeV

Compare to other $J^P = 1^-$ vector mesons:

ρ: $M_\rho = 0.77$ GeV $\quad \Gamma = 151$ MeV $\quad$ both $u\bar{u} + d\bar{d}$

ρ': $M_{\rho'} = 1.47$ GeV $\quad \Gamma = 310$ MeV $\quad$ both $\rho, \rho' \to \pi\pi$

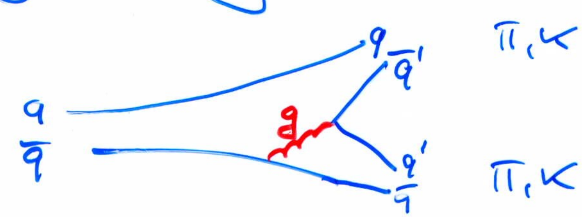
ϕ: $M_\phi = 1.019$ GeV $\quad \Gamma = 4$ MeV $\quad s\bar{s}$, $\phi \to K^+K^-$

$m_K = 494$ MeV $\to$ Very small phase space

All decay via strong interaction:

ρ, ρ', ϕ

$u\bar{u}$, $d\bar{d}$ $\quad s\bar{s}$



Quarkonia

Compare the J/Psi with its 'cousin', the Phi

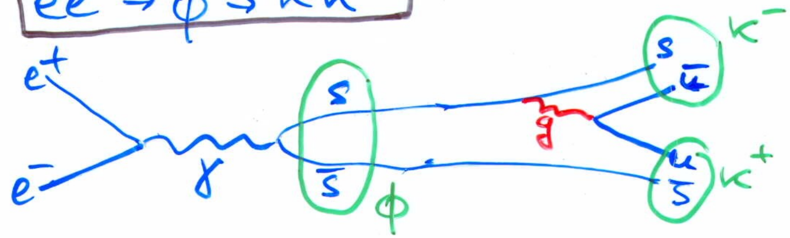
$\Gamma_{J/\psi} = 0.09$ MeV
BUT expect few 100 MeV !

Decay of J/ψ suppressed by factor ≈ 5000

Something hinders the strong decay of J/ψ !

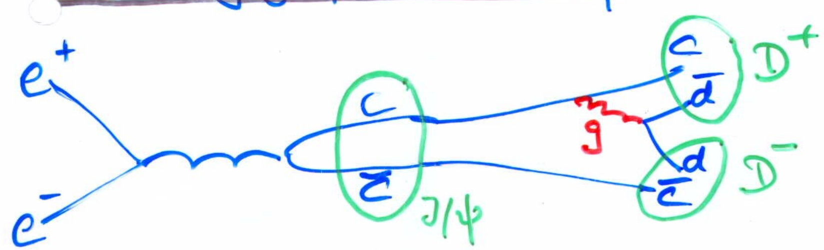
Compare Quarkonia Production and Decay in e^+e^-

$\boxed{e^+e^- \to \phi \to K^+K^-}$



$m_\phi = 1019$ MeV
$m_{K^\pm} = 494$ MeV
Decay just possible

In analogy postulate $J/\psi = c\bar{c}$:



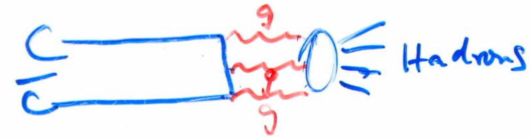
$M_{J/\psi} = 3.1$ GeV
$M_{D^\pm} = 1.87$ GeV (later found)

This prominent decay is kinematically impossible

The J/Psi can't decay in the 'easiest' strong mode. The lightest charmed mesons are too heavy !

Only the strong decay into 3 gluons is possible.

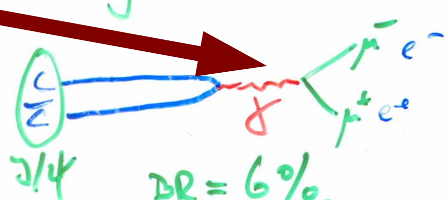
The strong decay of J/ψ has to go via higher order diagrams $\Rightarrow$ SUPPRESSION $\Downarrow$ "long" lifetime



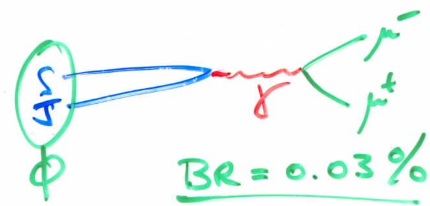
Side remark:

Since strong decays are suppressed, electromagnetic decays are 'relatively' pronounced

Electromagnetic decays are relatively enhenced



$BR = 6\%$



$BR = 0.03\,\%$

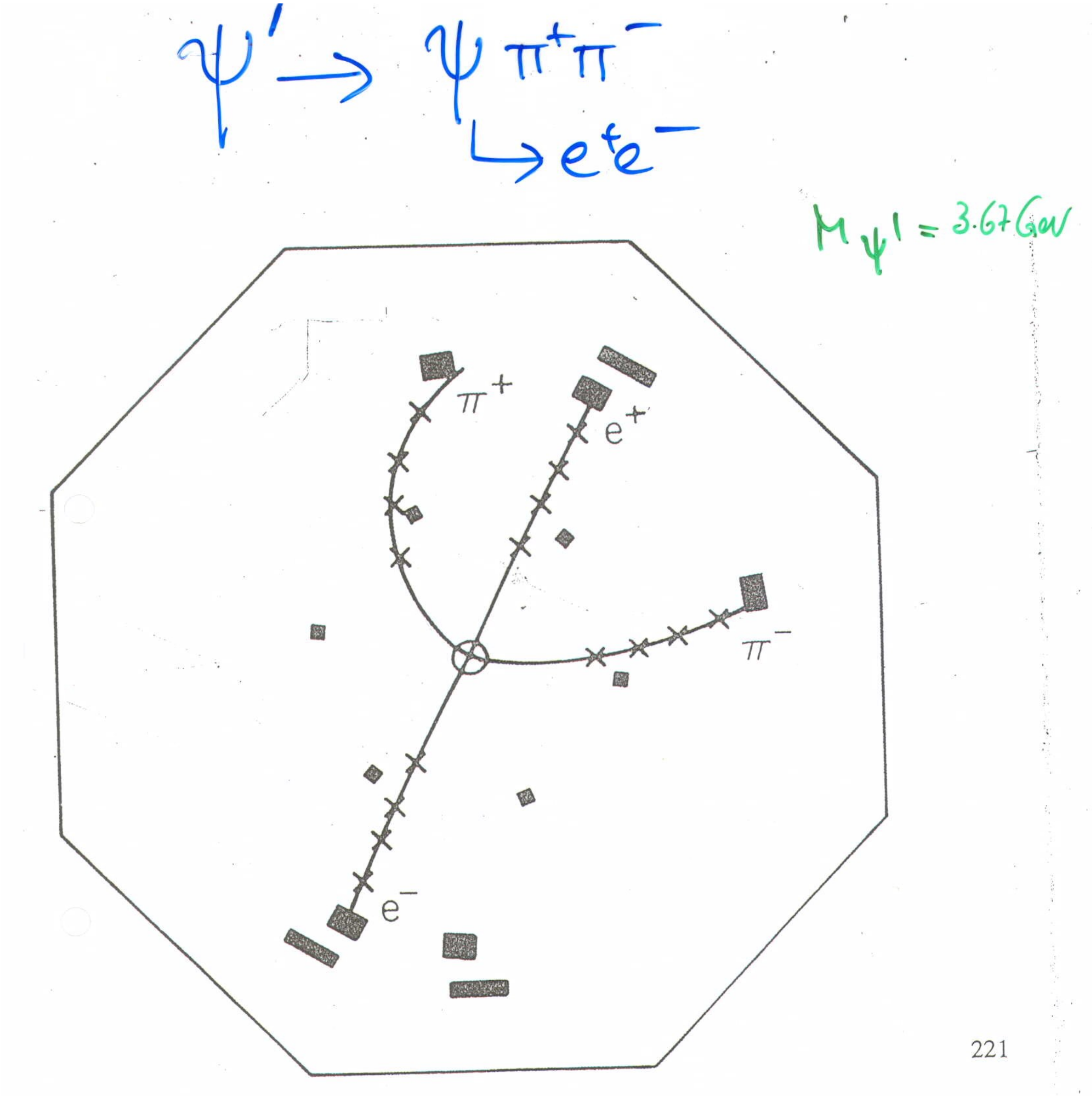
One week after the J/Psi discovery an exited Psi' was found.
It is also a charm-anticharm Meson

later:

		M [GeV]	Γ [MeV]
$e^+e^- \to$	J/ψ	3.1	0.09
	ψ'	3.67	0.28
	ψ''	3.77	24 MeV !!

$2 M_{D^\pm} = 3.74$ GeV
Just above threshold $\psi'' \to D^+D^-$

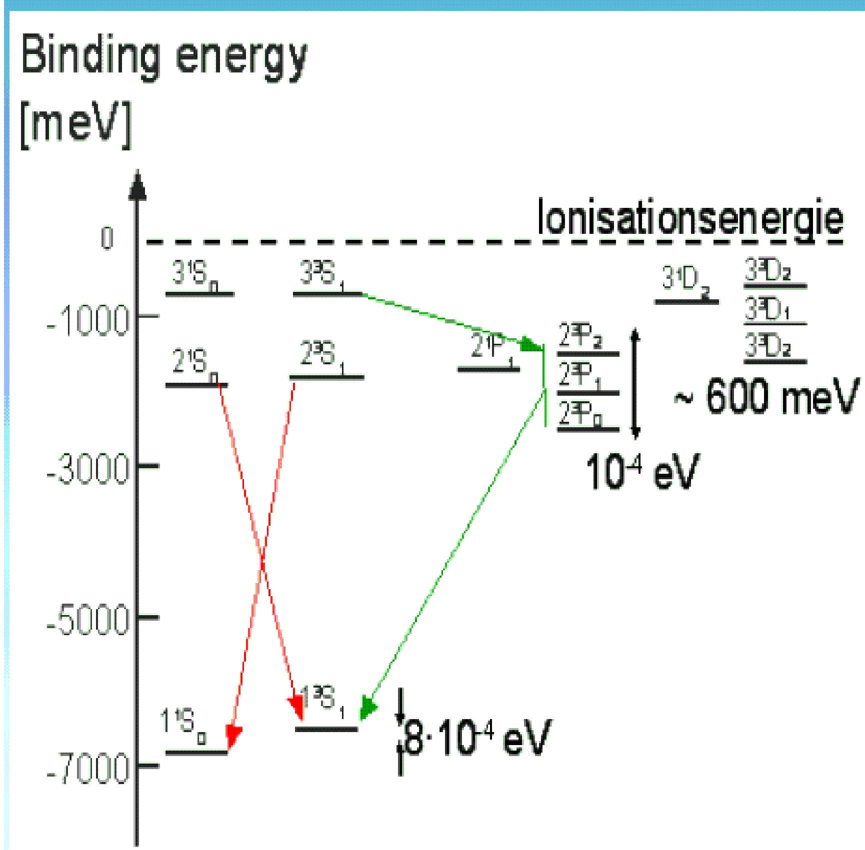
How the Psi particles became their names :



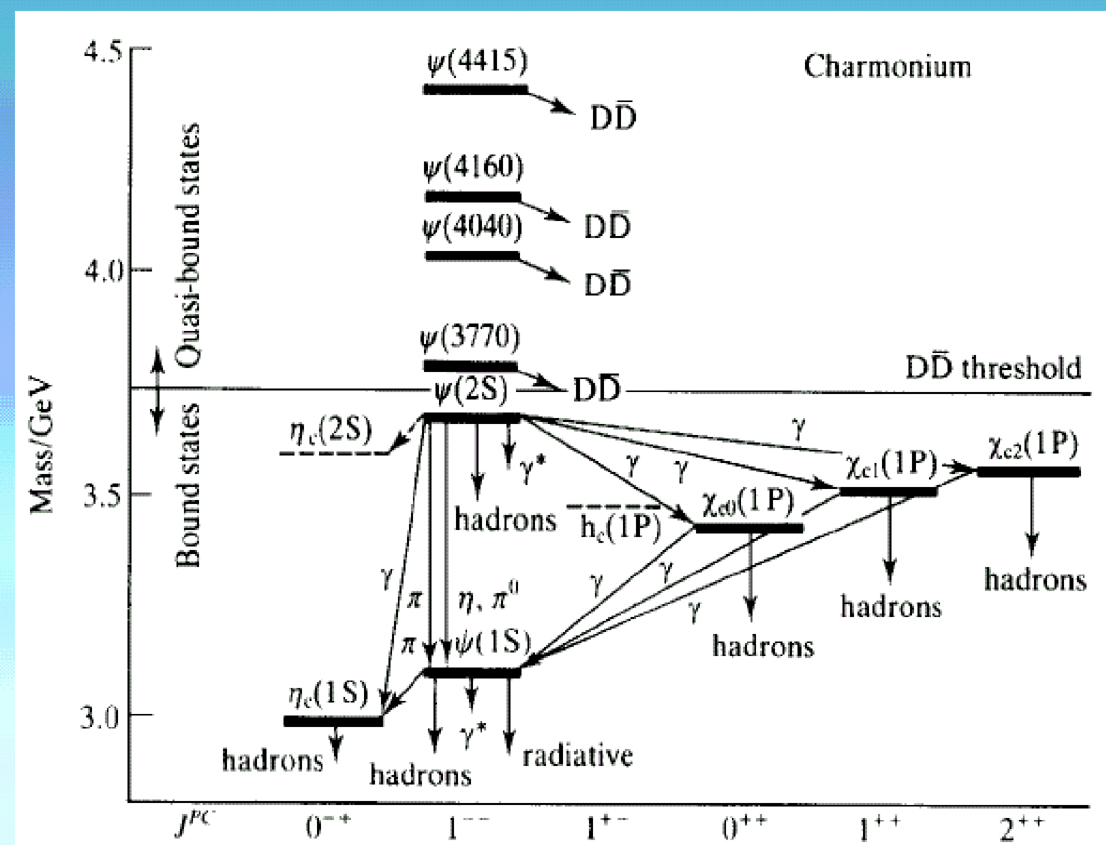
Similarity between
Bound State Systems :

POSITRONIUM : e+ e- bound system ; e.m. Interaction ; eV level spacings
CHARMONIUM : c c_bar bound system; strong interaction ; GeV level spacings

Positronium



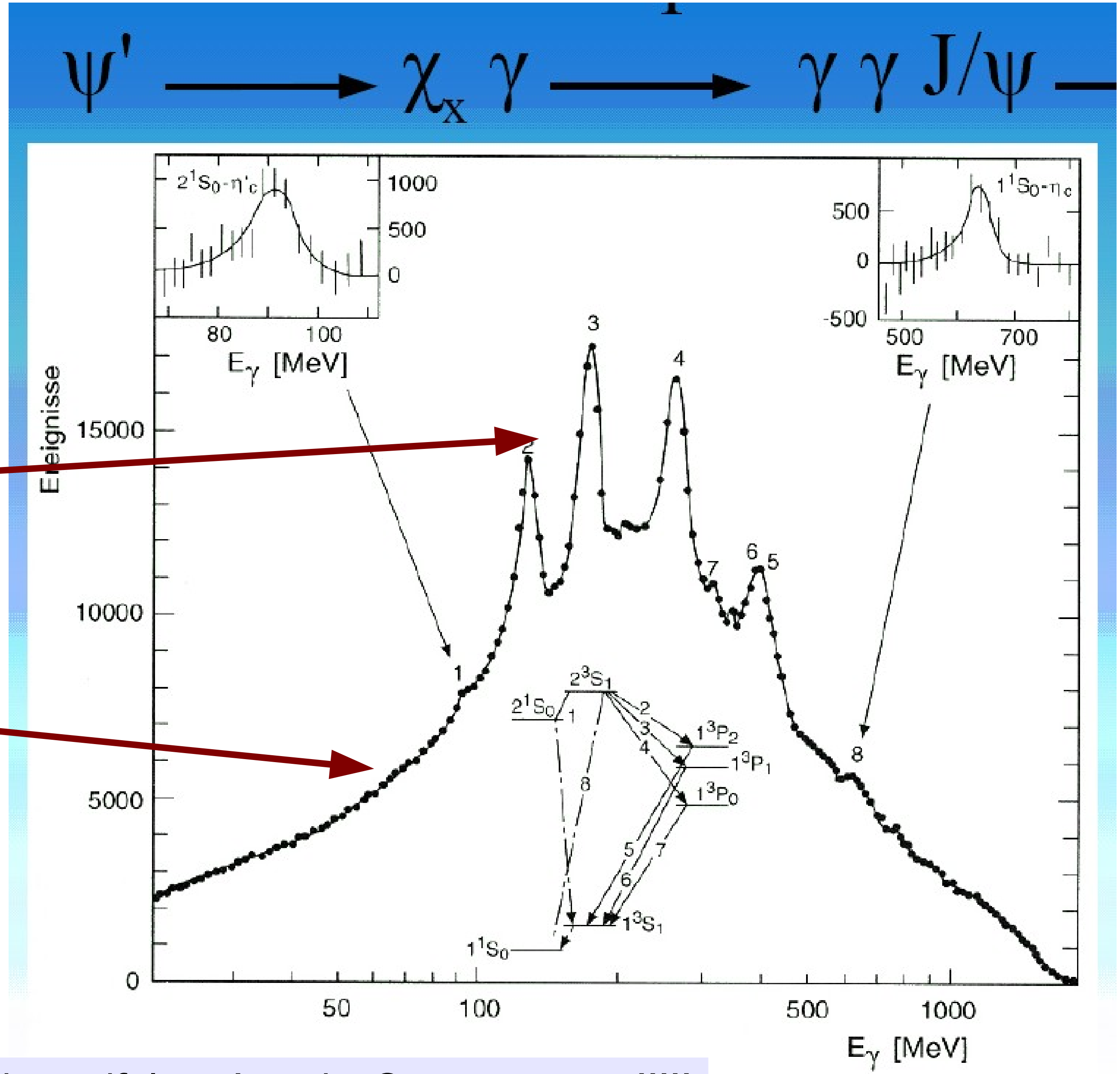
Charmonium



Inclusive Photon Spectra from Psi' decay :

Spectral Lines

Continuum background



Quark Spectroscopy as beautiful as Atomic Spectroscopy !!!!!