Introduction to Particle Physics

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HELMHOLTZ ASSOCIATION

DESY

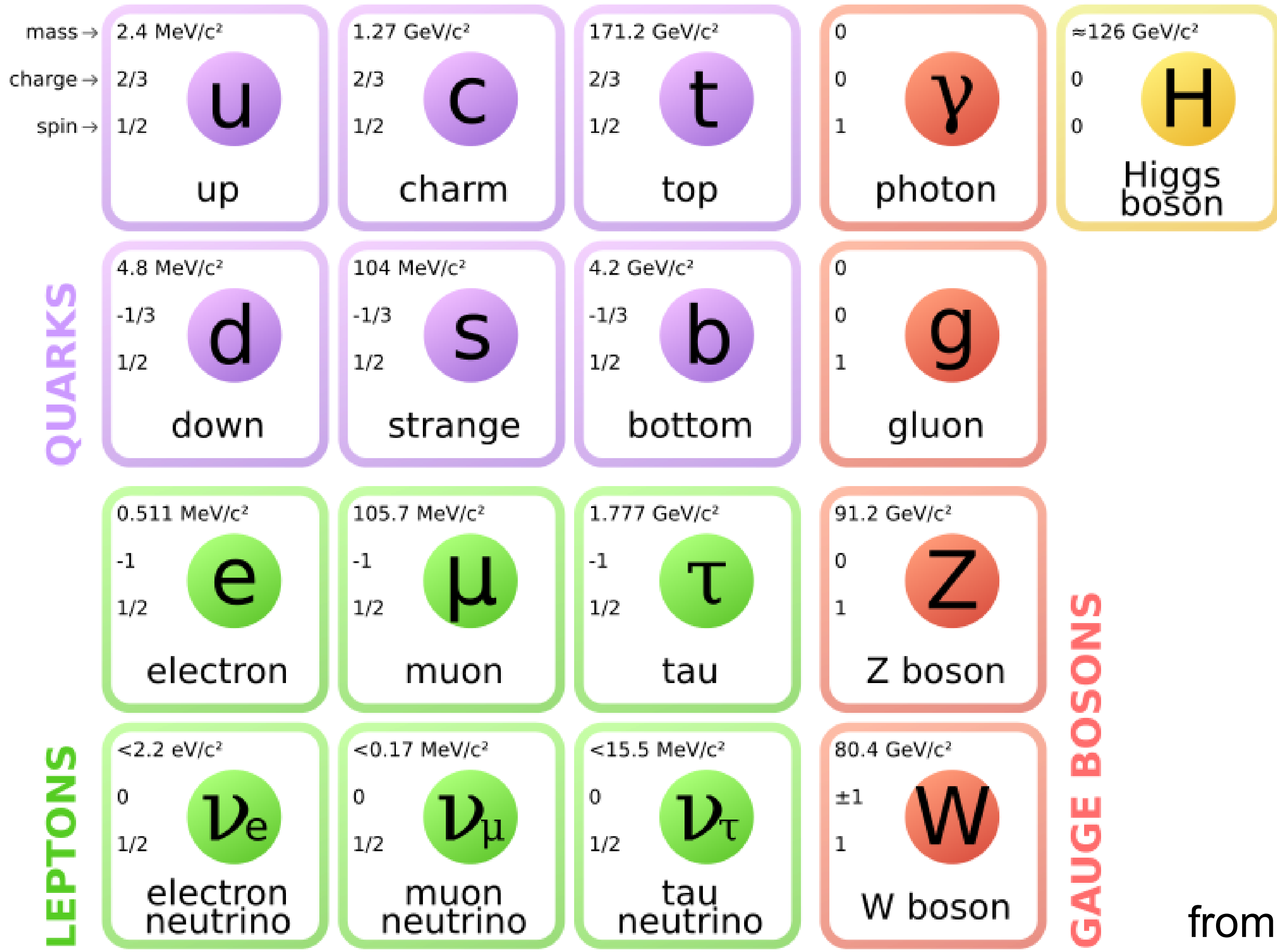
Preface

- this lecture cannot replace a university course on particle physics
- you have heard already many things in the general *Introduction to Particle Physics* and in the lecture on *Accelerator Physics*, and you will get more detailed information in specialised lectures on
  - Detectors
  - Electroweak and Higgs physics
  - QCD
  - Searches for SUSY and Exotica
  - Theory
  - …
- will try to concentrate on important concepts and on history how we arrived at the current picture of the Standard Model
- if you have questions, please ask!

Overview

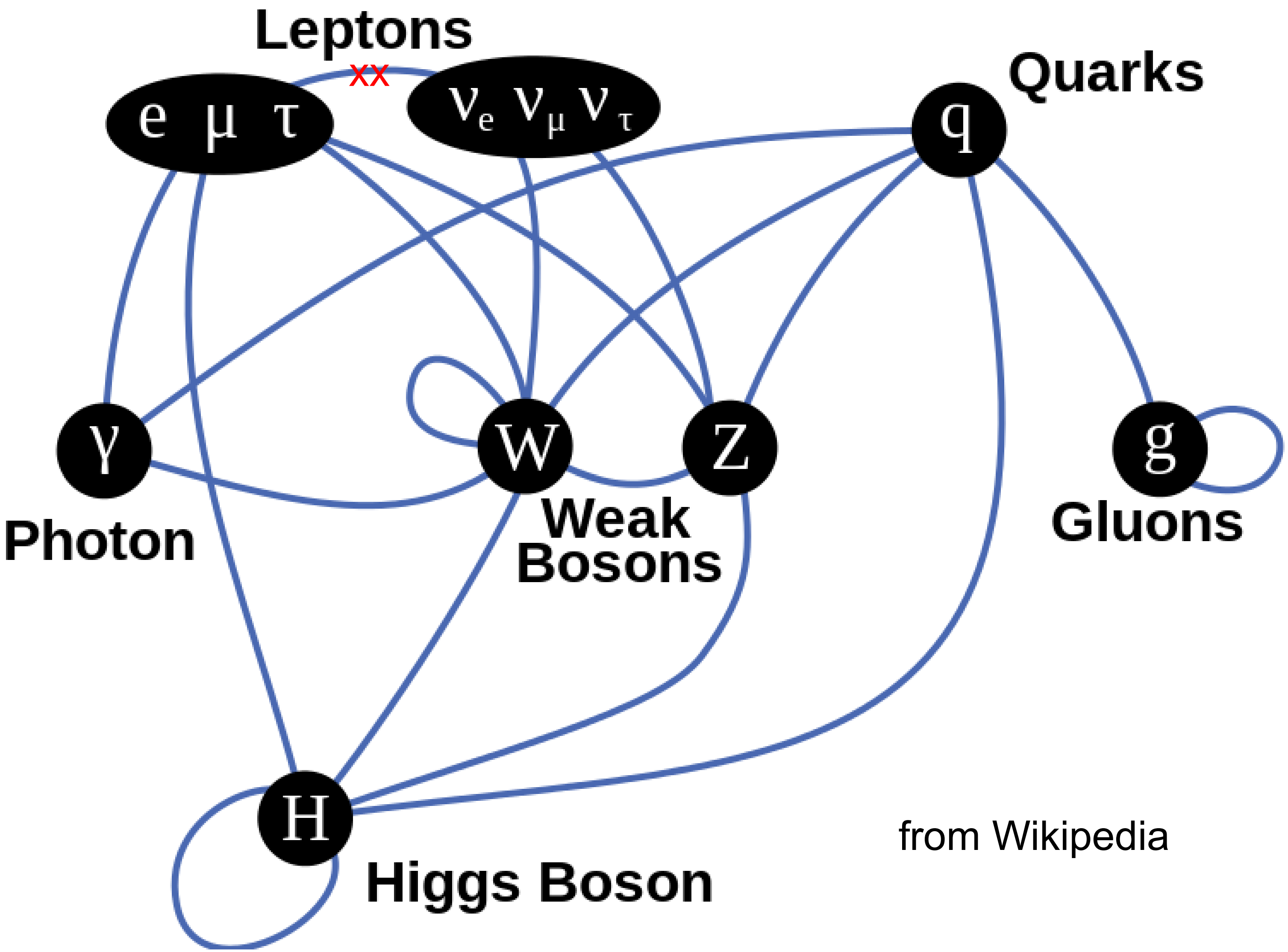
- Introduction
- Pre-requisites
  - relativistic kinematics
  - cross section measurement
  - symmetries and conserved quantities
  - Feynman diagrams
- Fermions
  - first generation
  - second generation
  - third generation
- Gauge Bosons / Forces
  - gluon
  - W and Z
  - Higgs
- Open Questions

Standard Model: Particles



from Wikipedia

Standard Model: Interactions



from Wikipedia

The Standard Model

- looks rather neat and tidy:
  - only 12 matter fermions, 4 gauge bosons and the Higgs
  - can explain (nearly) all observations
  - looks very “natural” today, but its history was not always straight-forward
- does this mean there is nothing else?
  - not the first time in history in a similar situation:

    1874, the Munich physics professor Philipp von Jolly advised Max Planck against going into physics, saying, "in this field, almost every-thing is already discovered, and all that remains is to fill a few holes.”
  - small things that didn't fit the picture often lead to new discoveries and new theories
  - clear hints that we do not understand certain things

Questions?

Relativistic Kinematics

- "natural units": c=1, $\hbar$=1

  $\rightarrow$ masses, energies and momenta are measured in GeV

- particle quantities are described as 4-vectors:

  energy/momentum: $p=(E,\vec{p})$

  time/space: $x=(t,\vec{x})$

- product of 4-vectors is invariant: $p_1\cdot p_2=(E_1\cdot E_2-\vec{p}_1\cdot\vec{p}_2)=\mathrm{constant}$

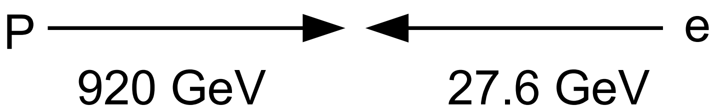
  $\rightarrow$ can use the "easiest" reference frame for calculations

  special case: $p\cdot p=(E^2-\vec{p}\cdot\vec{p})=(E_0^2-0)=m^2$

- with $\beta=v/c$ and $\gamma=1/\sqrt{1-\beta^2}$: $E=\gamma m$ and $|\vec{p}|=\beta\gamma m$

Relativistic Kinematics: applications

- centre-of-mass energy of a collider, e.g. HERA



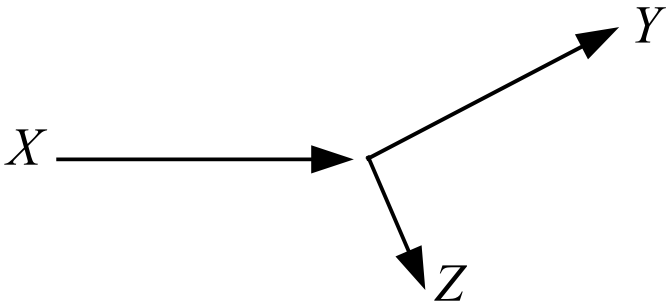
$$p_P = (E_P, \vec{p}_P) = (E_P, 0, 0, E_P)$$

$$p_e = (E_e, \vec{p}_e) = (E_e, 0, 0, -E_e)$$

$$s = (p_P + p_e)^2 = (E_P + E_e)^2 - (E_P - E_e)^2 = 4 E_P E_e \approx 10^5\,\mathrm{GeV}^2$$

$$\Rightarrow \quad \sqrt{s} = 318\,\mathrm{GeV}$$

- decay of a particle $X \to Y Z$:



$$\begin{aligned} M_X^2 &= (p_X)^2 = (p_Y + p_Z)^2 \\ &= m_Y^2 + m_Z^2 + 2\, p_Y\, p_Z \\ &= m_Y^2 + m_Z^2 + 2(E_Y E_Z - \vec{p}_Y \cdot \vec{p}_Z) \end{aligned}$$

and $E_Y^2 = m_Y^2 + |p_Y|^2, \quad E_Z^2 = m_Z^2 + |p_Z|^2$

$\Rightarrow$ if daughter particle types are known (or their masses are negligible), mass of decaying mother particle can be reconstructed from the momenta of the daughters ("invariant mass")

Heisenberg's Uncertainty Principle

- limits the precision with which (certain) pairs of physical quantities can be determined
- relation momentum ↔ position: $\Delta p \, \Delta x \geq \hbar c \approx 200\,\mathrm{MeV\,fm}$

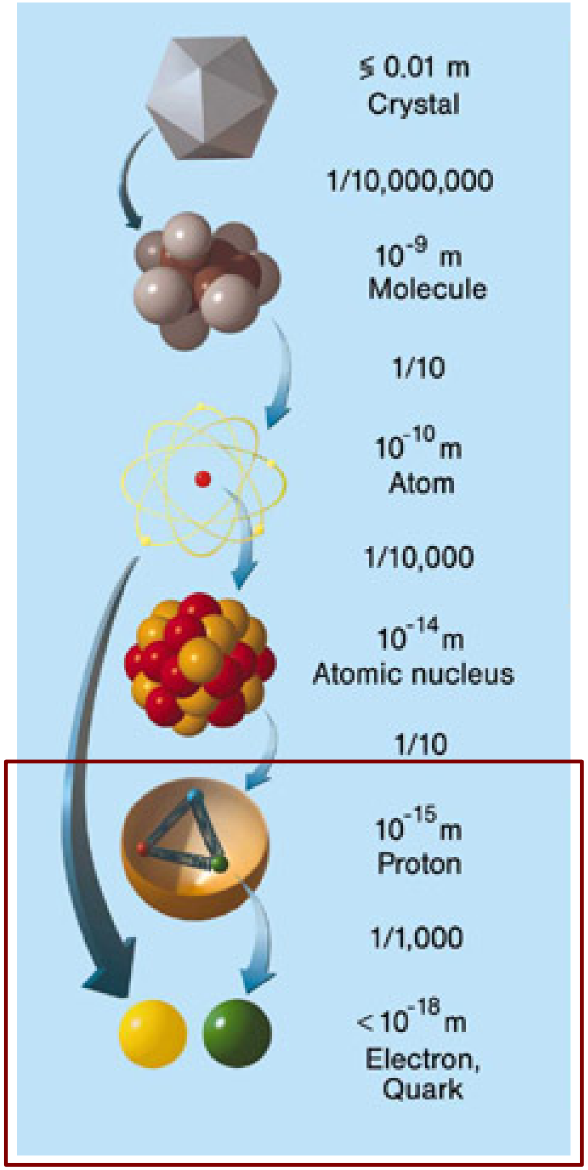
possible application: the maximum possible momentum transfer in a reaction limits the size of structures you can resolve

(what counts is the momentum transfer in the center-of-mass frame)

examples:

  – you need a momentum transfer of 200 MeV to resolve structures of the size of a proton (1 fm)
  – with an energy transfer of 200 GeV (possible at HERA) you can resolve 1/1000 fm (roughly our current limit of the maximum size of quarks)

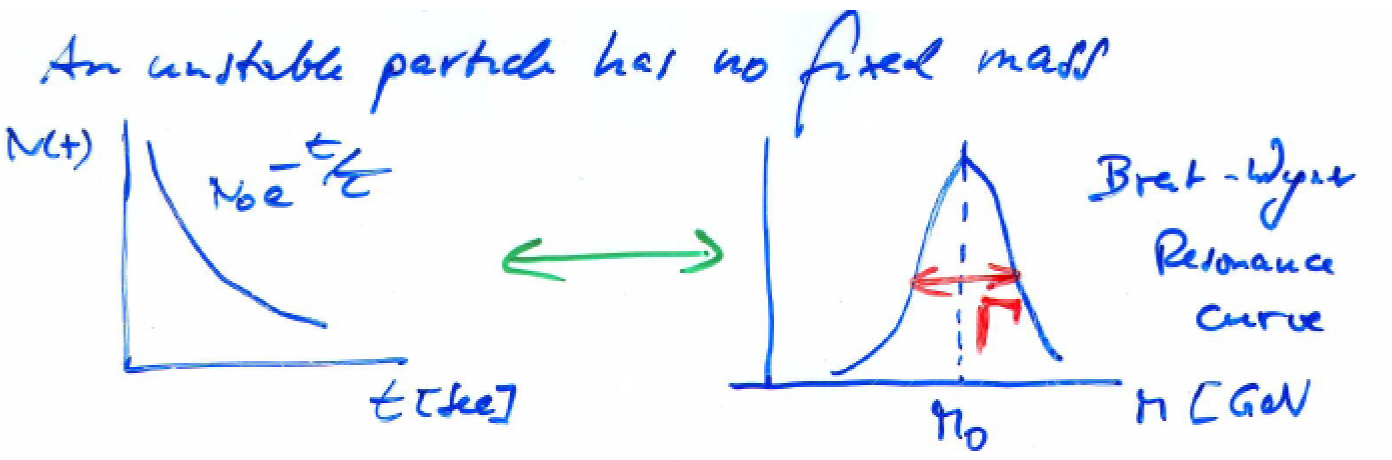
Heisenberg's Uncertainty Principle



Heisenberg's Uncertainty Principle

- limits the precision with which (certain) pairs of physical quantities can be determined
- relation energy ↔ time: $\Delta E \, \Delta t \ \geq \ \hbar \ \approx \ 6.6 \cdot 10^{-22} \,\mathrm{MeV\,s}$

since in a particles rest frame the energy is given by the mass, this implies that only stable particles have an exact mass!



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

- in the PDG either Γ or τ is listed, depending what is measured for this particle

Questions?

How to measure a cross section

- very generally:

$$N_{\text{evt}} = \sigma \int L\,dt \quad \Rightarrow \quad \sigma = \frac{N_{\text{evt}}}{\int L\,dt} \quad \text{and} \quad L = \frac{n\,f\,N_1 N_2}{\sigma_X \sigma_Y} \quad \text{for a collider}$$

- in practice:
  – selected events contain background N_{Bkg}
  – detectors are not perfect, but have an efficiency ε
  – events are only measured in a specific decay channel with a branching ratio BR

$$\sigma = \frac{(N_{\text{evt}} - N_{\text{Bkg}})}{\epsilon\ BR \int L\,dt}$$

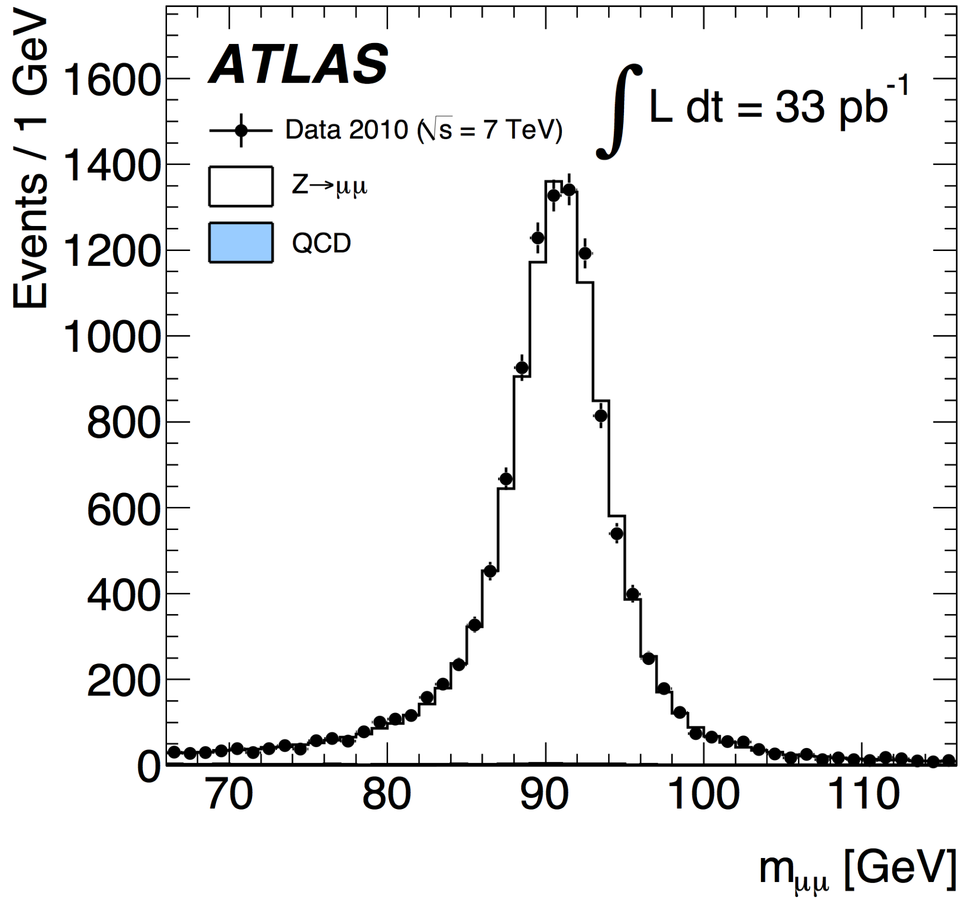
How to measure a total cross section

- (simple) example:

  $Z^0 \rightarrow \mu^+\mu^-$ from ATLAS

- identify muons in the detector, select events with at least 2 muons of opposite charge, calculate the invariant mass, fill the mass into a histogram

- determine how much background
  - use the prediction from a MC simulation (works if background is well known)
  - fit a function of the form f(m) = signal(m) + bkg(m) to the data (works if expected shapes are known)

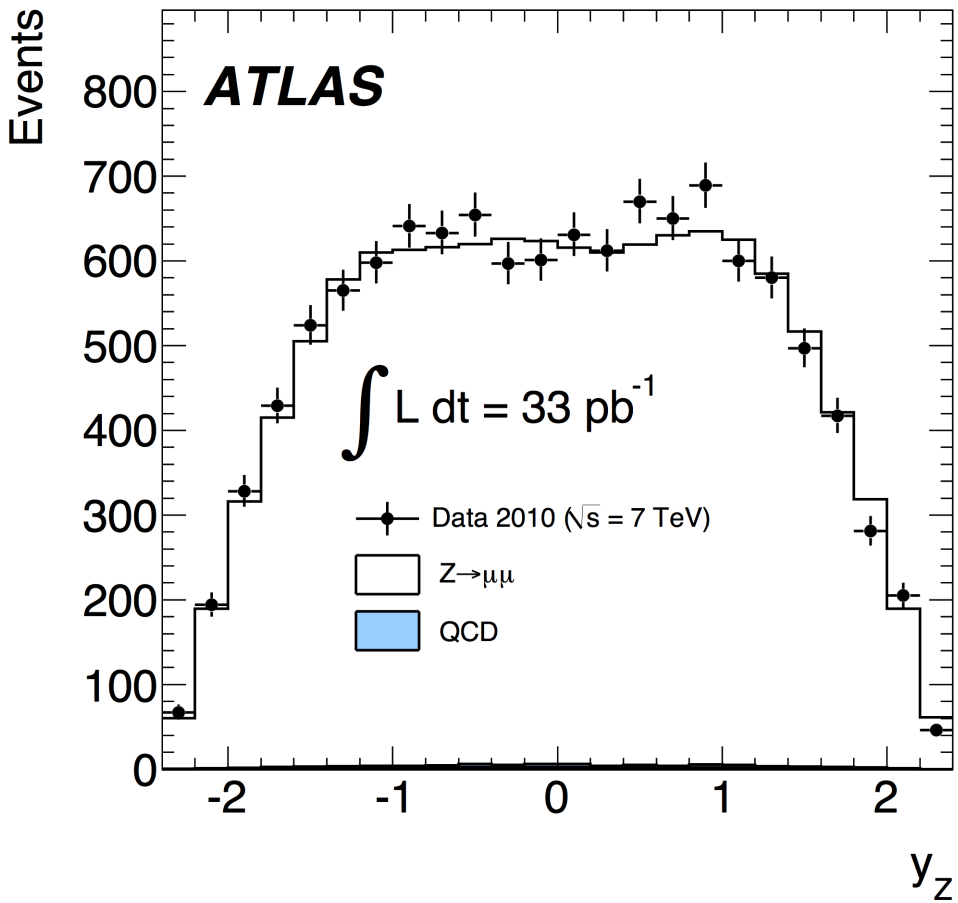


$$\sigma = \frac{(N_{\mathrm{evt}} - N_{\mathrm{Bkg}})}{\epsilon\ BR \int L\,dt}$$

How to measure a differential cross section

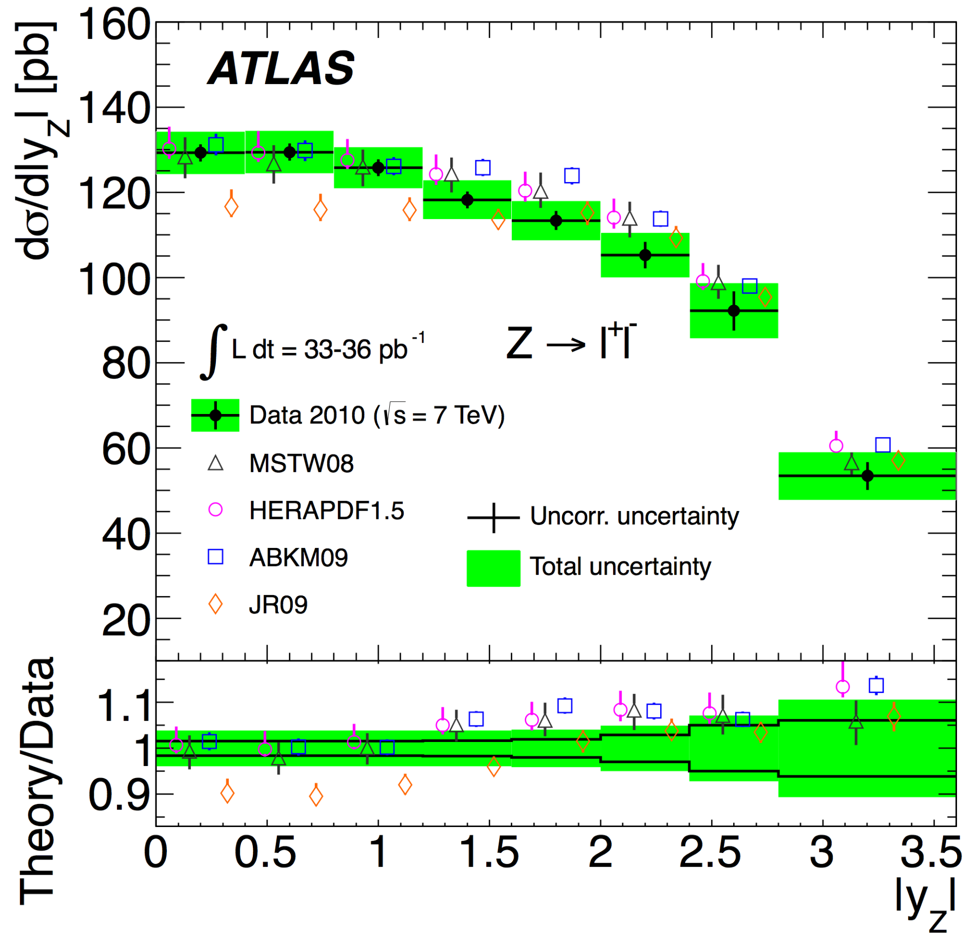
- quite often more can be learned by the dependence of the cross section on some quantities
- determine the number of signal (and background) events in bins of that quantity and fill it into a histogram (here: rapidity y)
- but now the number of events depends on the bin size!
- take bin size into account by measuring differential cross section

$$\frac{d\sigma}{dy} \approx \frac{\Delta\sigma}{\Delta y} = \frac{(N_{\text{evt}} - N_{\text{Bkg}})_{bin}}{\Delta y \; \epsilon \; BR \int L\, dt}$$



How to measure a differential cross section

- differential cross section can be compared to theory predictions
  - can exclude predictions that describe the total cross section but differ in shape
- meaningful comparison only possible if uncertainties are known!
  - statistical uncertainties (from signal and background events!)
  - systematic uncertainties (efficiency, branching ratio, luminosity)
  - are there correlations between the bins? (e.g. uncertainty on luminosity shifts all data points the same way → correlated)

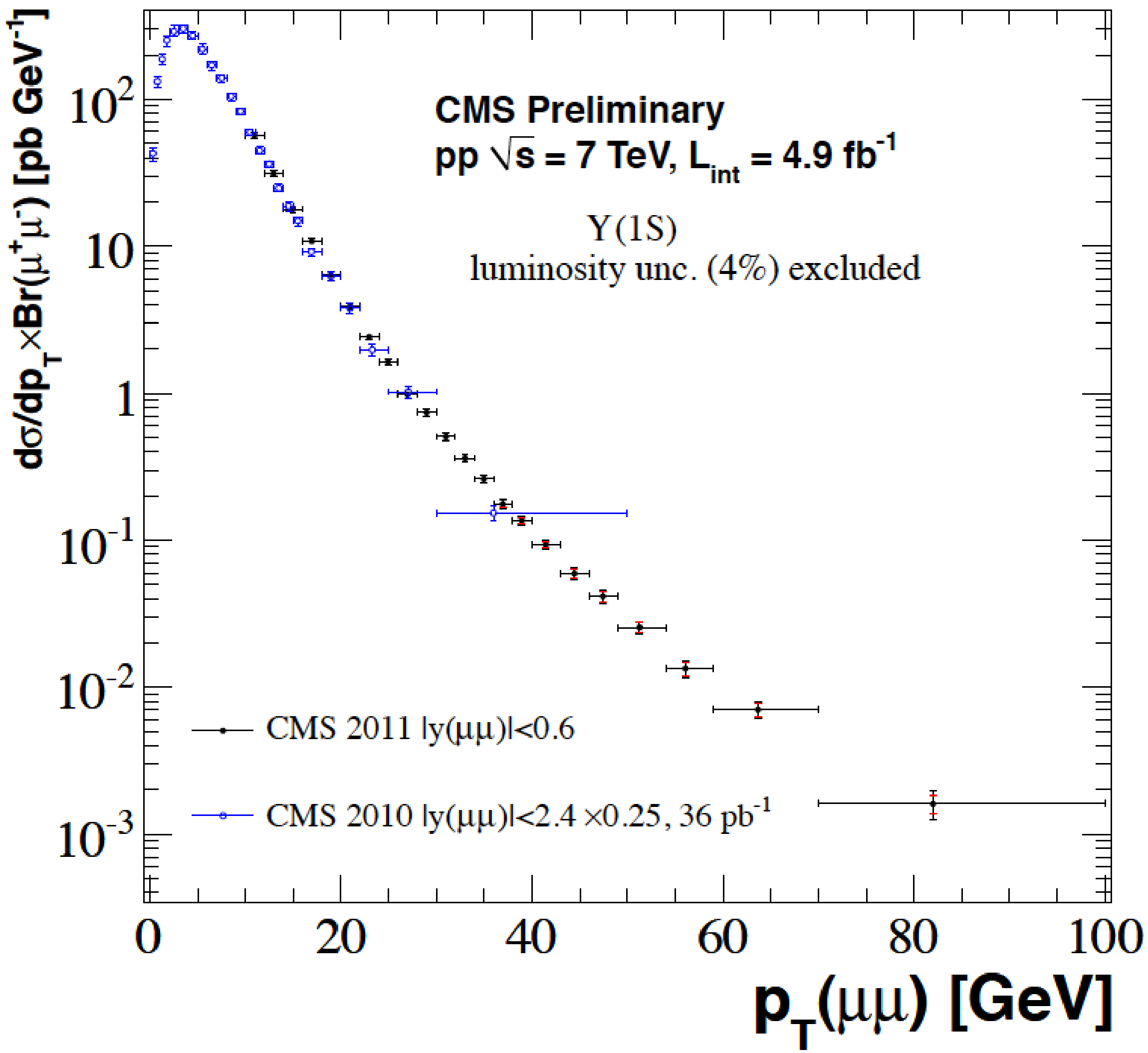


How to measure a differential cross section

- other example:

  $\Upsilon \rightarrow \mu^+\mu^-$ from CMS

- differential cross section with different bin sizes can be compared directly!



Questions?

Symmetries and Conserved Quantities

Attention, this makes the connection plausible, this is no proof!

Quantum mechanics:

- (system of) particles is described by a wave function or state vector ψ
- observables are described by operators *O*, their expectation values *o* as

$$o = \int \psi^* O \psi \, dV$$

- the time dependence of *o* can be put either into ψ (Schrödinger picture) or into *O* (Heisenberg picture)
- time development (in the non-relativistic case) is determined by the Hamilton operator *H* according to the Schrödinger equation:

$$i\hbar \frac{\partial}{\partial t} \psi(t) = H \psi(t)$$

for a stationary state: $E\psi = H\psi$

Symmetries and Conserved Quantities

- Schrödinger picture (if H does not depend on t explicitly):

  $\psi(t)=T(t,t_0)\psi(t_0)$ with $T(t,t_0)=\exp[-i(t-t_0)H/\hbar]$ and

  $\psi(t)^*=\psi(t_0)^* T^{-1}(t,t_0)$

- Heisenberg and Schrödinger picture have to describe the same expectation value:

$$o=\underbrace{\int \psi(t_0)^* O\,\psi(t_0)\,dV}_{\text{Heisenberg}}\equiv\underbrace{\int \psi(t)^* O_0\,\psi(t)\,dV}_{\text{Schrödinger}}$$

$$\Rightarrow \quad O=T^{-1}O_0 T$$

$$\Rightarrow \quad i\hbar\frac{d}{dt}O=-HO+OH=[O,H] \quad \text{if} \quad \frac{\partial}{\partial t}O=0$$

➔ in general: if an operator commutates with the Hamilton operator, [O,H]=0, then the operator O describes a conserved quantity

Symmetries and Conserved Quantities

example for continuous symmetry: translation in space

- infinitely small translation *δr*

$$\psi' = \psi(r+\delta r) = \psi(r) + \delta r \frac{\partial}{\partial r}\psi = \left(1+\delta r \frac{\partial}{\partial r}\right)\psi = D\psi \quad \text{with} \quad D = 1+\delta r \frac{\partial}{\partial r}$$

- the operator for the momentum is

$$p = -i\hbar\,\partial/\partial r \quad \Rightarrow \quad D = 1 + (i/\hbar)\,p\,\delta r$$

- then a finite translation *Δr* = n**δr* can be described by

$$D = \lim_{n\to\infty}\left(1+\frac{i}{\hbar}p\,\delta r\right)^n = \exp\left(\frac{i}{\hbar}p\,\Delta r\right)$$

- if Hamiltonian is invariant for translations in space ⇔ [*D*,*H*]=0

  ⇒ [*p*,*H*]=0 ⇒ momentum is conserved

Noether's theorem (informal version):
If a system has a continuous symmetry property, then there are corresponding quantities whose values are conserved in time.

Symmetries and Conserved Quantities

example for discrete symmetry: parity

- parity operator P describes what happens if you look into a mirror: inversion of all space coordinates:

  $$P\psi(\vec{r}) \rightarrow \psi(-\vec{r})$$

- since repeating P leads to the same state, $P^2=1$
- if it exists, the eigenvalue of P can be +1 or −1

  examples:

  $$\psi(x)=\cos(x),\quad P\psi(x)\rightarrow\cos(-x)=\cos(x)=+\psi$$
  $$\psi(x)=\sin(x),\quad P\psi(x)\rightarrow\sin(-x)=-\sin(x)=-\psi$$
  $$\psi(x)=\cos(x)+\sin(x),\quad P\psi(x)\rightarrow\cos(x)-\sin(x)\neq\pm\psi$$

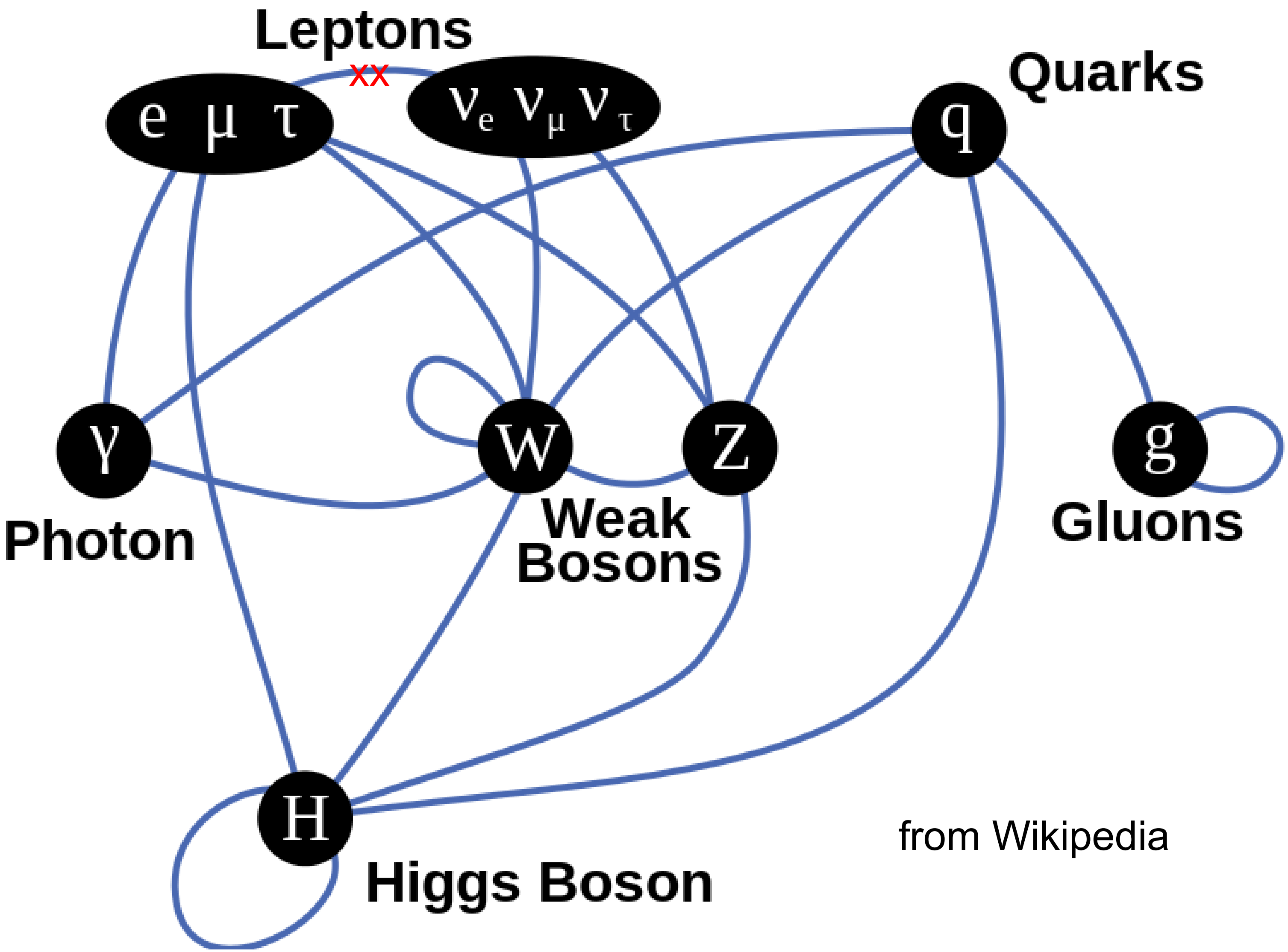
- if the Hamiltonian is invariant for the parity operation, eigenstates have a defined parity P which is conserved

Conserved Quantities

quantity	interaction			invariance
	strong	elm.	weak	
energy	yes	yes	yes	translation in time
momentum	yes	yes	yes	translation in space
angular momentum	yes	yes	yes	rotation in space
P (parity)	yes	yes	no	coordinate inversion
C (charge parity)	yes	yes	no	charge conjugation (particle ↔ anti-particle)
T (time parity)	yes	yes	no	time inversion
CPT	yes	yes	yes	
lepton number	yes	yes	yes	
baryon number	yes	yes	yes	
isospin	yes	no	no	

Questions?

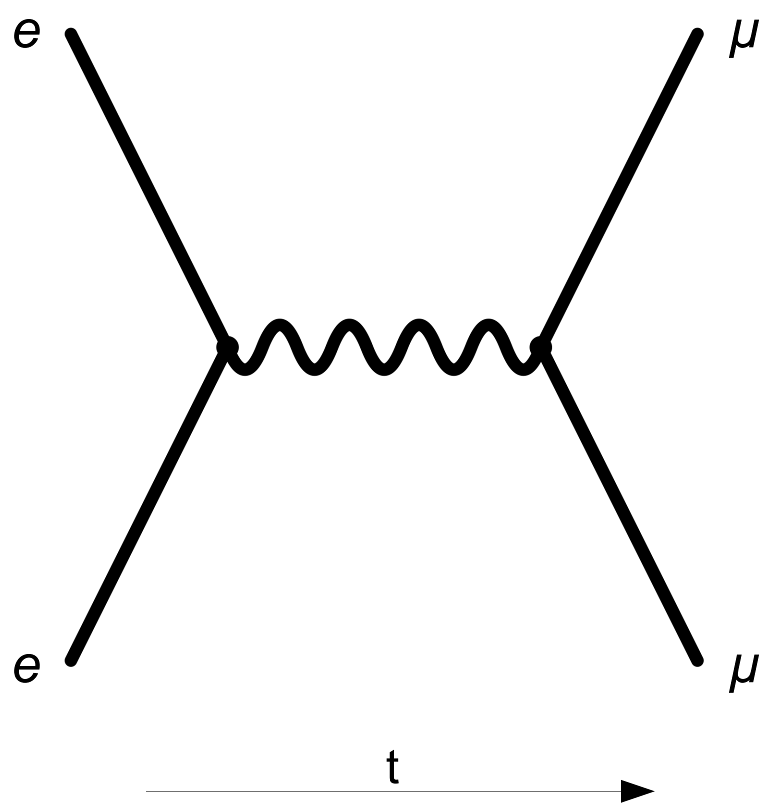
Standard Model: Interactions



from Wikipedia

Feynman Diagrams

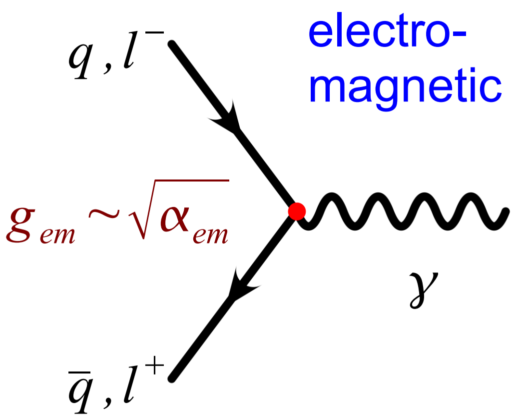
not only a visualisation of how a process happens, but also a recipe for calculating cross sections

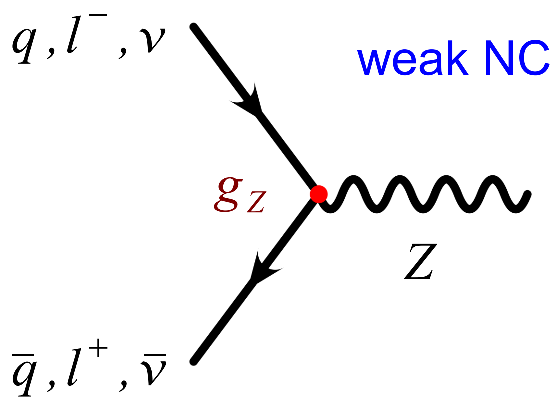


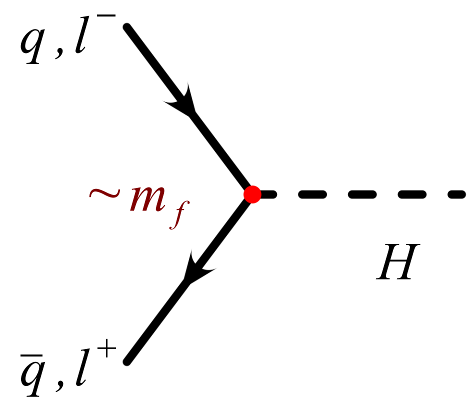
- the amplitude of each possible interaction is described by a diagram
- the cross section is proportional to the sum of the amplitudes squared:

$$\sigma \sim |A|^2 = \left|\sum_i A_i\right|^2$$

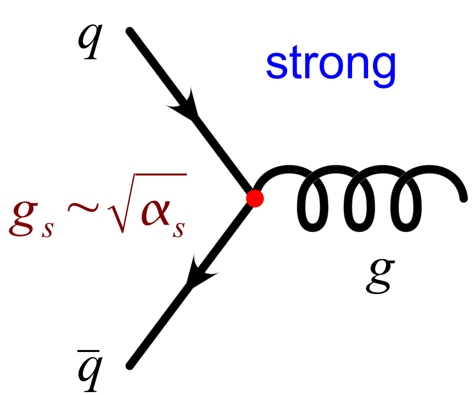
⇒ diagrams do not just add up, but also interfere

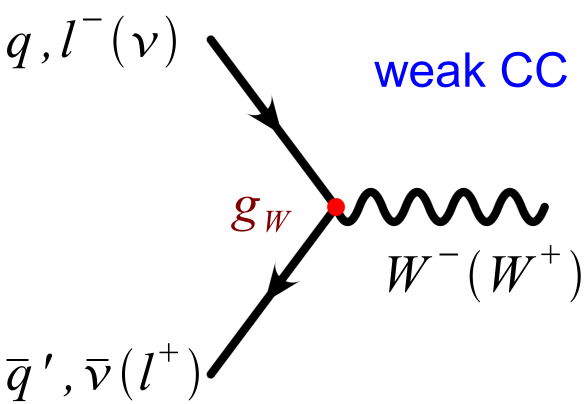






neutrinos???

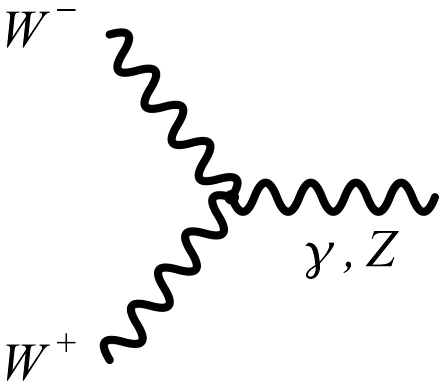


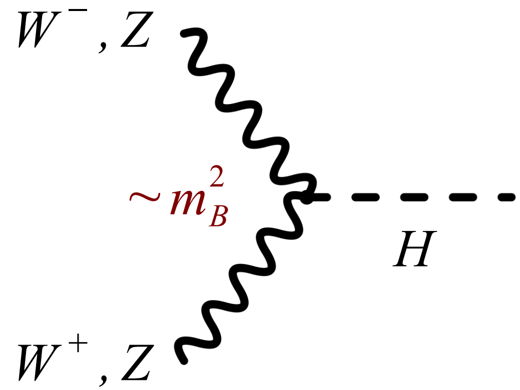


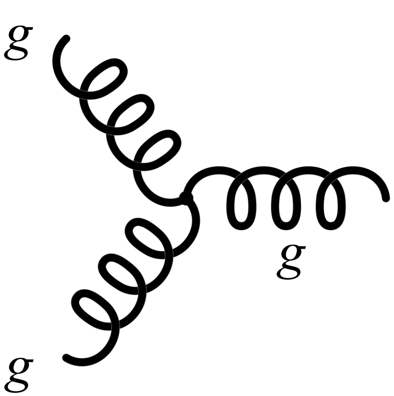
- mixes generations for quarks
- specific helicity structure

always 2 fermions and 1 boson

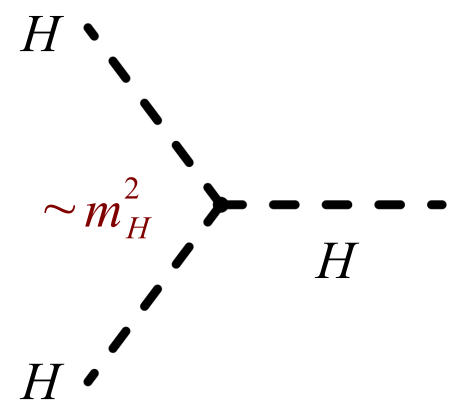
Feynman Diagrams: Boson Vertices



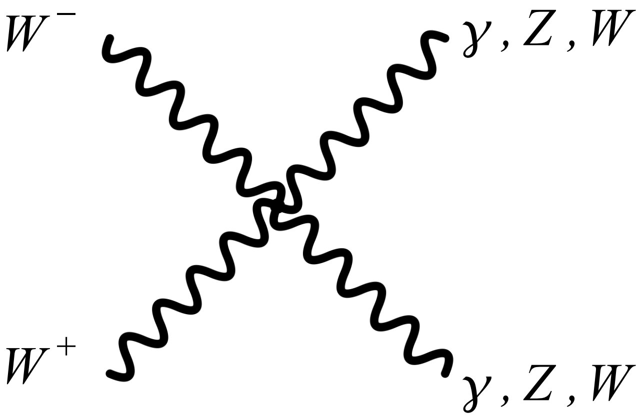


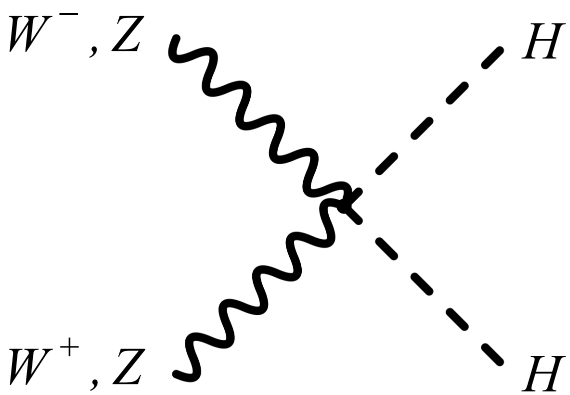


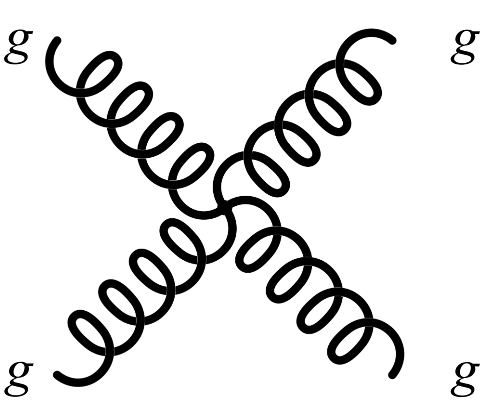
makes QCD very
different from QED

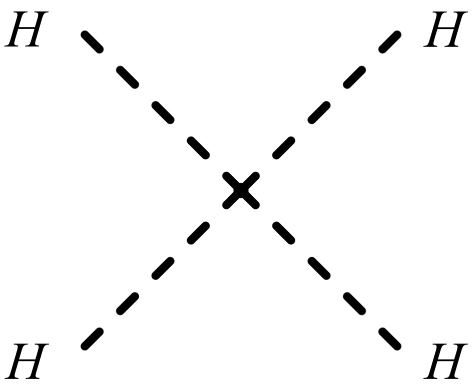


Feynman Diagrams: More Boson Vertices



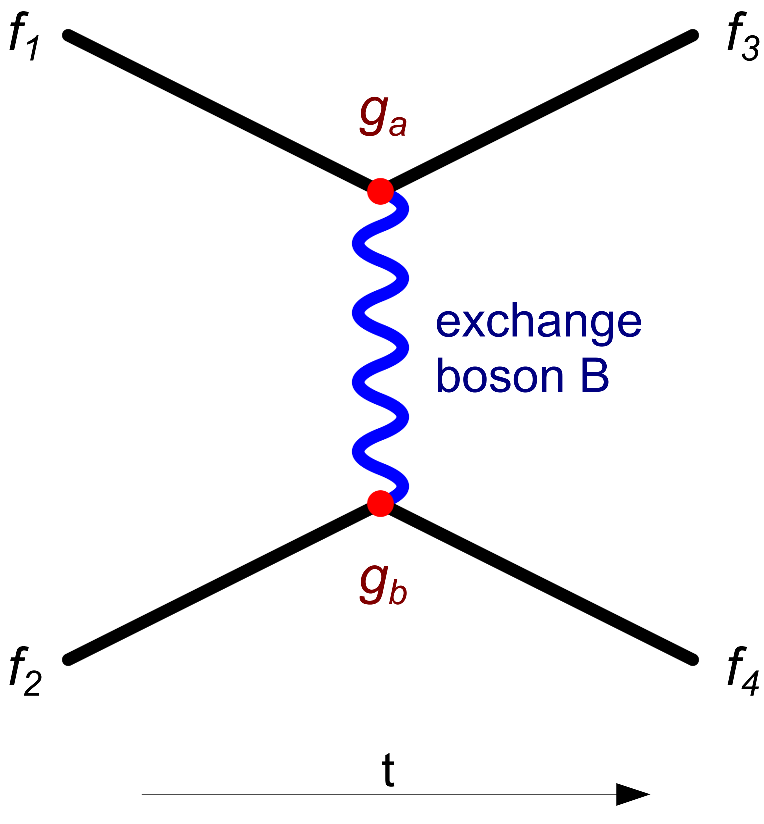






more details in theory lecture

Feynman Diagrams: Example



$f_1 + f_2 \rightarrow f_3 + f_4$

four-momentum of exchange boson B:

$$q = p_3 - p_1 = p_4 - p_2$$

transition amplitude:

$$A \sim f(f_1, f_2, f_3, f_4) \cdot g_a g_b \cdot \frac{1}{q^2 - m_B^2}$$

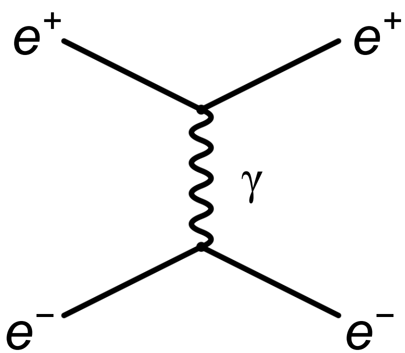
fermion wave function | vertex coupling | propa-gator

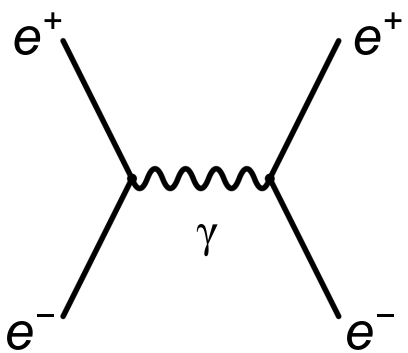
cross section:

$$\sigma \sim \left| \sum A_i \right|^2 \cdot phasespace$$

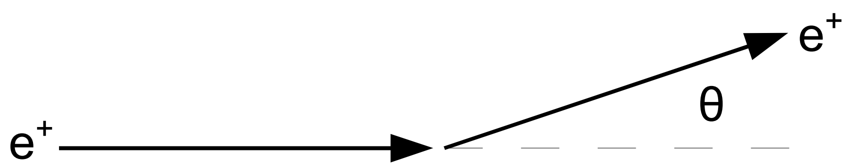
note: internal lines in diagrams describe virtual particles, for these usually $p^2 \neq m^2$

- two contributions: space-like (exchange of photon) and time-like (annihilation into photon)

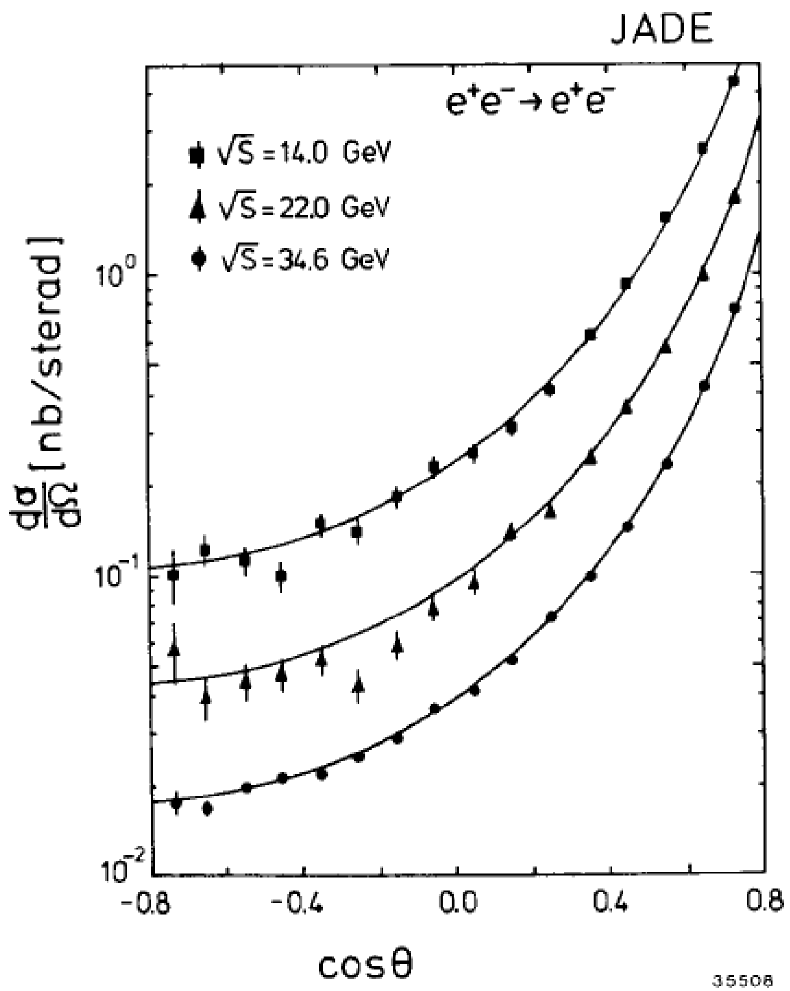




- space-like contribution is large for small scattering angles (large cos θ)

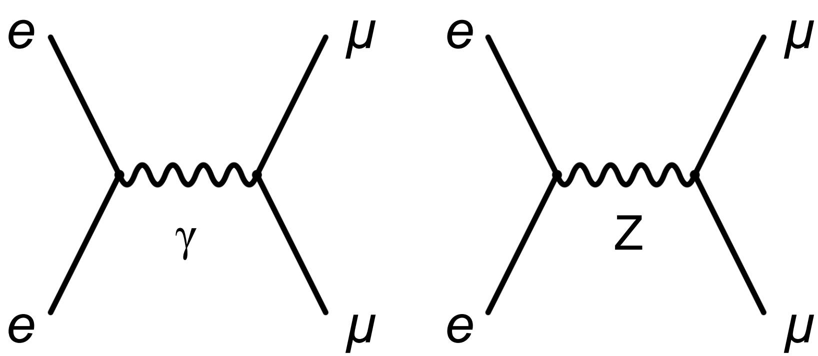


from S.L. Wu, Phys. Rep. 107 (1984) 59



$e^+ e^- \rightarrow \mu^+ \mu^-$

- pure annihilation into photon (QED) should be symmetric in cos θ (parity conservation)
- instead of the photon also an intermediate Z is possible



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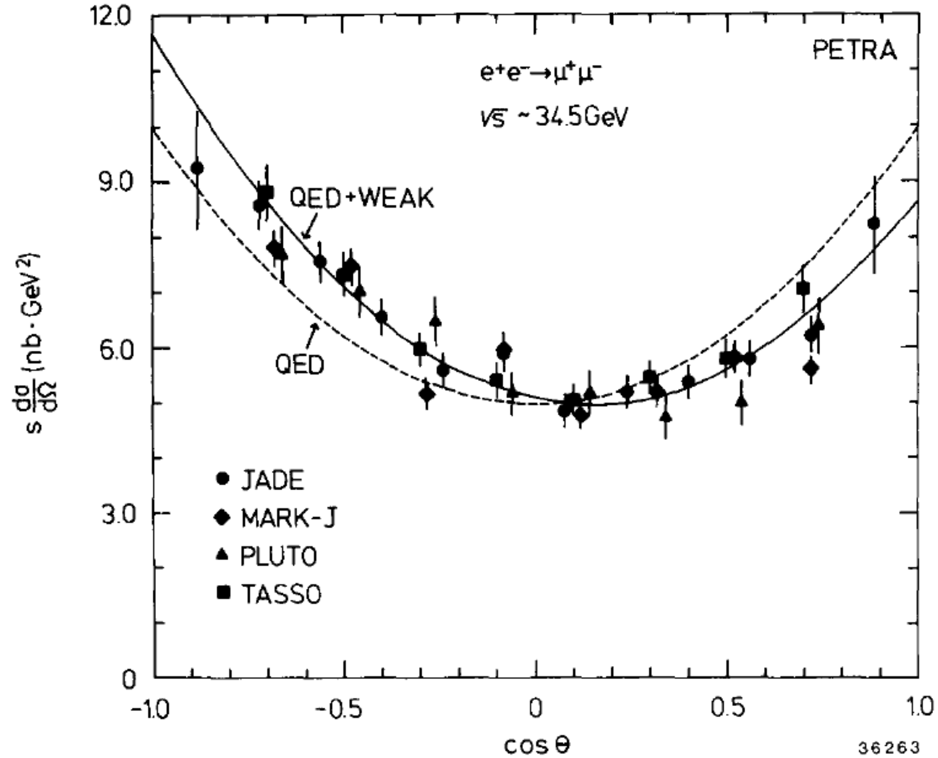
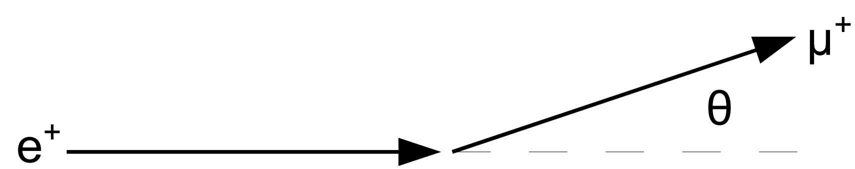
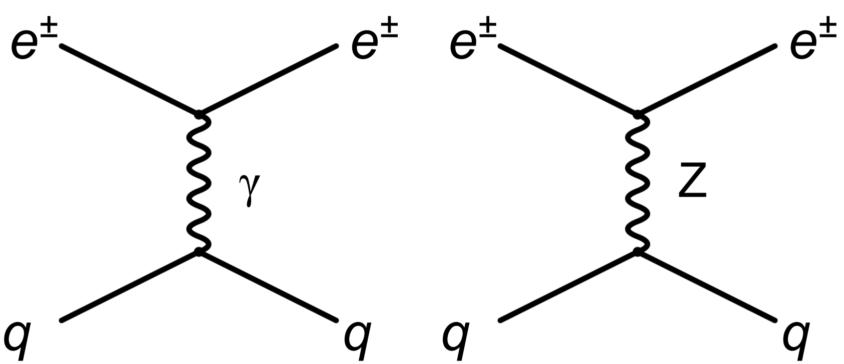


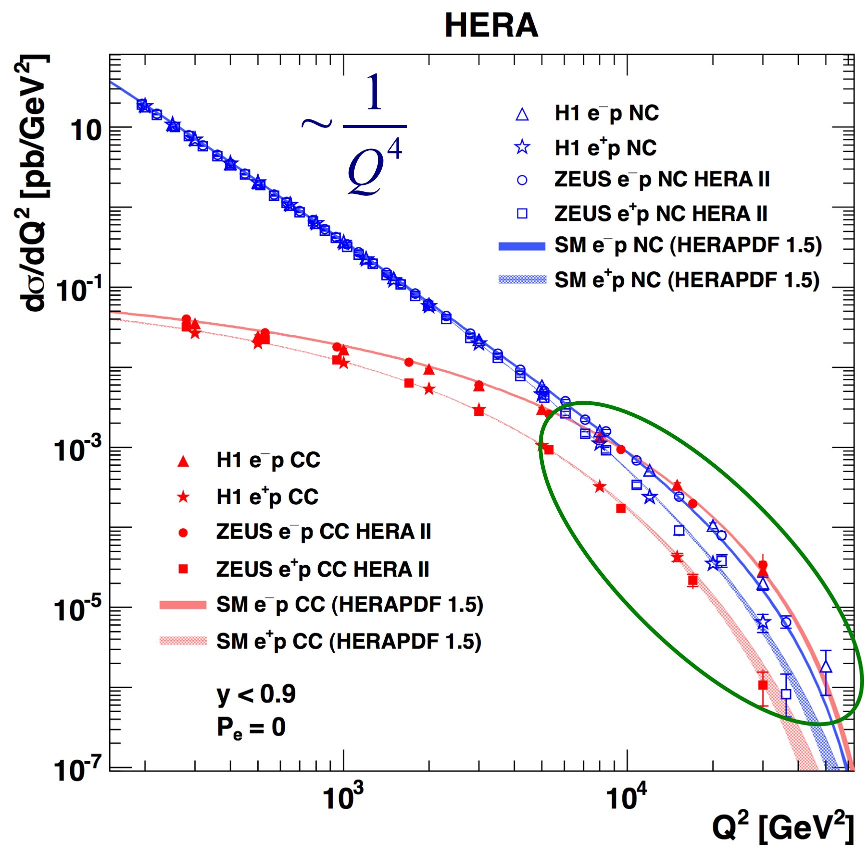
➔ weak interaction does not conserve parity, leads to "forward-backward" asymmetry



$e\,p \rightarrow e\,X$ (Neutral Current Deep Inelastic Scattering)

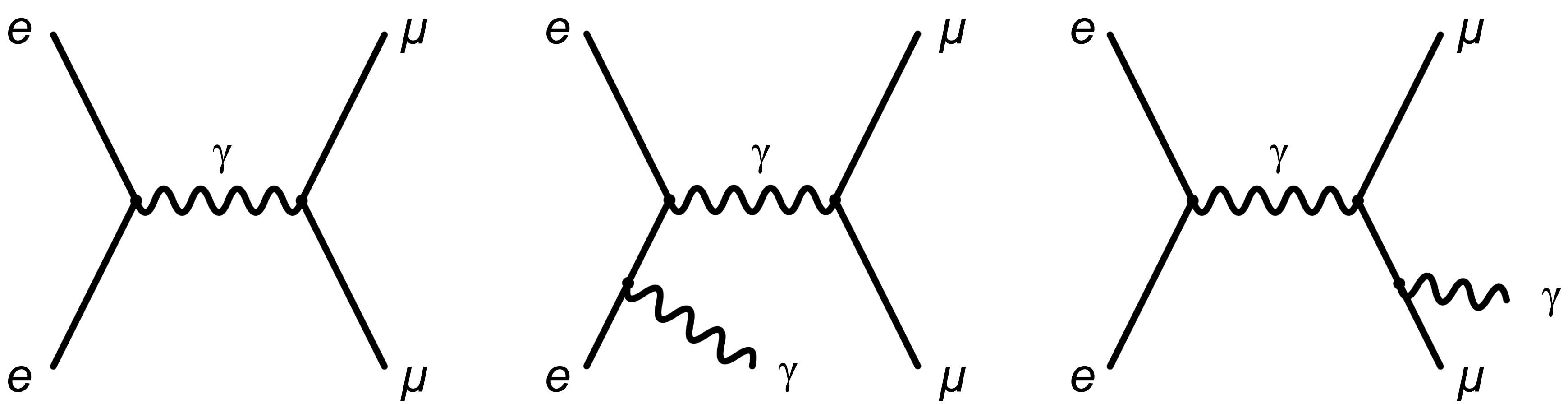
- scattering of an electron/positron on a quark inside the proton (the proton breaks up)
- at low four-momentum transfer $Q^2 = -q^2$ photon exchange dominates, for $Q^2 \approx M_Z^2$ photon and Z are equally important
- interference between photon and Z has opposite sign for electrons and positrons





Perturbation Theory: Higher Orders

- in principle, all possible Feynman diagrams contribute to a reaction
- practically, those with the smallest number of vertices are most relevant
- those with more vertices are referred to as “higher orders” since they correspond to terms with higher order in the coupling if you write the cross section as a perturbation series



$A \sim g_{em}^{2}$ $A \sim g_{em}^{3}$ $A \sim g_{em}^{3}$

higher orders

Questions?

Elementary Particles

- all building blocks of matter are fermions with spin ½ (quarks, leptons)
- all force carriers are bosons with spin 1 (photon, Z, W, gluon)
- the Higgs boson is the only fundamental particle with spin 0, it has the same quantum numbers as the vacuum

beautiful, simple picture BUT

Elementary Particles

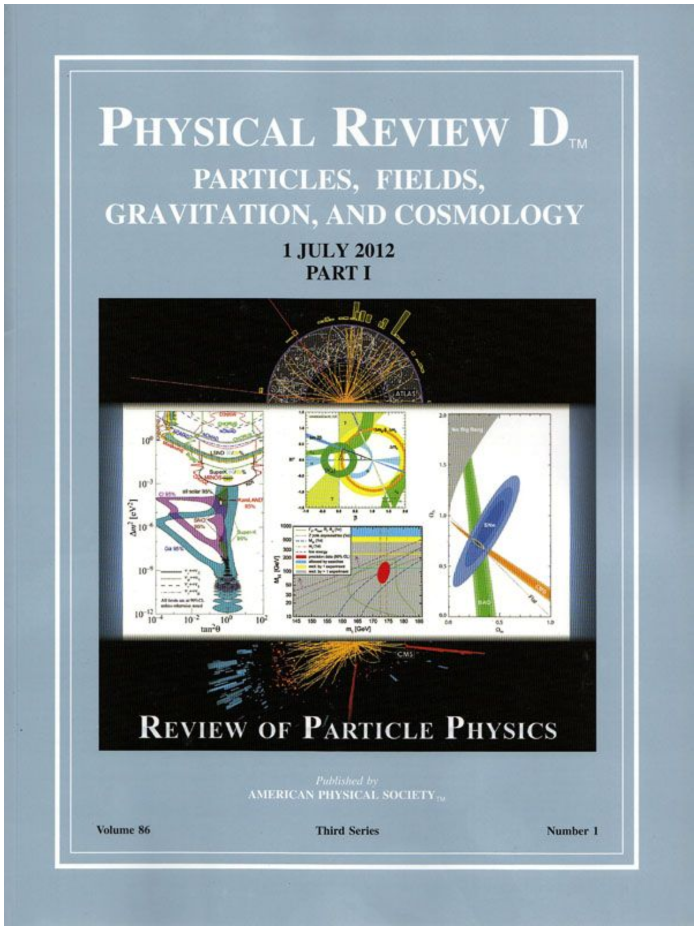
- all building blocks of matter are fermions with spin ½ (quarks, leptons)
- all force carriers are bosons with spin 1 (photon, Z, W, gluon)
- the Higgs boson is the only fundamental particle with spin 0, it has the same quantum numbers as the vacuum

beautiful, simple picture BUT

- we never observe free quarks!
- what we do observe are hadrons, particles built of quarks. they come in two variants:
  - baryons (greek “barys”: heavy): built of 3 quarks, examples: proton, neutron
  - mesons (greek “mesos”: intermediate): built of a quark and an anti-quark, examples: pion, kaon

(Not so) Elementary Particles

Everything You Always Wanted to Know About ~~Sex~~ a Particle But Were Afraid to Ask



- known as “the PDG”
- 1528 pages
- not only properties of existing particles, but also searches
- reviews on Standard Model, Statistics, Astrophysics, Colliders and Detectors, …

(very good, but extremely condensed, not a classical textbook)

- less heavy: http://pdg.lbl.gov/

(or the PDG booklet)

Baryons

this is all just u and d quarks

p	$1/2^+$	****
n	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1685)$		*
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	***
$N(1720)$	$3/2^+$	****
$N(1860)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***
$N(1880)$	$1/2^+$	**
$N(1895)$	$1/2^-$	**
$N(1900)$	$3/2^+$	***
$N(1990)$	$7/2^+$	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	**
$N(2100)$	$1/2^+$	*
$N(2120)$	$3/2^-$	**
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2300)$	$1/2^+$	**
$N(2570)$	$5/2^-$	**
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**

$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	***
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	**
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(1920)$	$3/2^+$	***
$\Delta(1930)$	$5/2^-$	***
$\Delta(1940)$	$3/2^-$	**
$\Delta(1950)$	$7/2^+$	****
$\Delta(2000)$	$5/2^+$	**
$\Delta(2150)$	$1/2^-$	*
$\Delta(2200)$	$7/2^-$	*
$\Delta(2300)$	$9/2^+$	**
$\Delta(2350)$	$5/2^-$	*
$\Delta(2390)$	$7/2^+$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
$\Delta(2750)$	$13/2^-$	**
$\Delta(2950)$	$15/2^+$	**

contain at least one s quark

Λ	$1/2^+$	****
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	***
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	$3/2^-$	****
$\Lambda(1800)$	$1/2^-$	***
$\Lambda(1810)$	$1/2^+$	***
$\Lambda(1820)$	$5/2^+$	****
$\Lambda(1830)$	$5/2^-$	****
$\Lambda(1890)$	$3/2^+$	****
$\Lambda(2000)$		*
$\Lambda(2020)$	$7/2^+$	*
$\Lambda(2100)$	$7/2^-$	****
$\Lambda(2110)$	$5/2^+$	***
$\Lambda(2325)$	$3/2^-$	*
$\Lambda(2350)$	$9/2^+$	***
$\Lambda(2585)$		**

Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
$\Sigma(1385)$	$3/2^+$	****
$\Sigma(1480)$		*
$\Sigma(1560)$		**
$\Sigma(1580)$	$3/2^-$	*
$\Sigma(1620)$	$1/2^-$	*
$\Sigma(1660)$	$1/2^+$	***
$\Sigma(1670)$	$3/2^-$	****
$\Sigma(1690)$		**
$\Sigma(1750)$	$1/2^-$	***
$\Sigma(1770)$	$1/2^+$	*
$\Sigma(1775)$	$5/2^-$	****
$\Sigma(1840)$	$3/2^+$	*
$\Sigma(1880)$	$1/2^+$	**
$\Sigma(1915)$	$5/2^+$	****
$\Sigma(1940)$	$3/2^-$	***
$\Sigma(2000)$	$1/2^-$	*
$\Sigma(2030)$	$7/2^+$	****
$\Sigma(2070)$	$5/2^+$	*
$\Sigma(2080)$	$3/2^+$	**
$\Sigma(2100)$	$7/2^-$	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(1530)$	$3/2^+$	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	$3/2^-$	***
$\Xi(1950)$		***
$\Xi(2030)$	$\geq \frac{5}{2}^?$	***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-	$3/2^+$	****
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

contain at least one c quark

Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$		***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	***
$\Xi_c'^+$	$1/2^+$	***
$\Xi_c'^0$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2930)$		*
$\Xi_c(2980)$		***
$\Xi_c(3055)$		**
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
Ξ_{cc}^+		*

contain at least one b quark

Λ_b^0	$1/2^+$	***
$\Lambda_b(5912)^0$	$1/2^-$	***
$\Lambda_b(5920)^0$	$3/2^-$	***
Σ_b	$1/2^+$	***
Σ_b^*	$3/2^+$	***
Ξ_b^0, Ξ_b^-	$1/2^+$	***
$\Xi_b(5945)^0$	$3/2^+$	***
Ω_b^-	$1/2^+$	***

something missing?

DESY

Mesons

this is all just u and d quarks (with a bit of $s\bar{s}$)

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

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $f_0(500)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	$a_2(1700)$	$1^-(2^{++})$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $\phi(1020)$	$0^-(1^{--})$	$X(1835)$	$?^?(?^{-+})$
• $h_1(1170)$	$0^-(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $b_1(1235)$	$1^+(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $a_1(1260)$	$1^-(1^{++})$	• $\pi_2(1880)$	$1^-(2^{-+})$
• $f_2(1270)$	$0^+(2^{++})$	$\rho(1900)$	$1^+(1^{--})$
• $f_1(1285)$	$0^+(1^{++})$	$f_2(1910)$	$0^+(2^{++})$
• $\eta(1295)$	$0^+(0^{-+})$	• $f_2(1950)$	$0^+(2^{++})$
• $\pi(1300)$	$1^-(0^{-+})$	$\rho_3(1990)$	$1^+(3^{--})$
• $a_2(1320)$	$1^-(2^{++})$	• $f_2(2010)$	$0^+(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$	$f_0(2020)$	$0^+(0^{++})$
$h_1(1380)$	$?^-(1^{+-})$	• $a_4(2040)$	$1^-(4^{++})$
• $\pi_1(1400)$	$1^-(1^{-+})$	• $f_4(2050)$	$0^+(4^{++})$
• $\eta(1405)$	$0^+(0^{-+})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $f_1(1420)$	$0^+(1^{++})$	$f_0(2100)$	$0^+(0^{++})$
• $\omega(1420)$	$0^-(1^{--})$	$f_2(2150)$	$0^+(2^{++})$
$f_2(1430)$	$0^+(2^{++})$	$\rho(2150)$	$1^+(1^{--})$
• $a_0(1450)$	$1^-(0^{++})$	• $\phi(2170)$	$0^-(1^{--})$
• $\rho(1450)$	$1^+(1^{--})$	$f_0(2200)$	$0^+(0^{++})$
• $\eta(1475)$	$0^+(0^{-+})$	$f_J(2220)$	$0^+(2^{++}$
• $f_0(1500)$	$0^+(0^{++})$		or $4^{++})$
$f_1(1510)$	$0^+(1^{++})$	$\eta(2225)$	$0^+(0^{-+})$
• $f_2'(1525)$	$0^+(2^{++})$	$\rho_3(2250)$	$1^+(3^{--})$
$f_2(1565)$	$0^+(2^{++})$	• $f_2(2300)$	$0^+(2^{++})$
$\rho(1570)$	$1^+(1^{--})$	$f_4(2300)$	$0^+(4^{++})$
$h_1(1595)$	$0^-(1^{+-})$	$f_0(2330)$	$0^+(0^{++})$
• $\pi_1(1600)$	$1^-(1^{-+})$	• $f_2(2340)$	$0^+(2^{++})$
$a_1(1640)$	$1^-(1^{++})$	$\rho_5(2350)$	$1^+(5^{--})$
$f_2(1640)$	$0^+(2^{++})$	$a_6(2450)$	$1^-(6^{++})$
• $\eta_2(1645)$	$0^+(2^{-+})$	$f_6(2510)$	$0^+(6^{++})$
• $\omega(1650)$	$0^-(1^{--})$	**OTHER LIGHT**	
• $\omega_3(1670)$	$0^-(3^{--})$	Further States	

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	$1/2(0^-)$
$K_0^*(800)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K_0^*(1430)$	$1/2(0^+)$
• $K_2^*(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K_3^*(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K_0^*(1950)$	$1/2(0^+)$
$K_2^*(1980)$	$1/2(2^+)$
• $K_4^*(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K_5^*(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED ($C = \pm1$)

• $D^\pm$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
• $D_0^*(2400)^0$	$1/2(0^+)$
$D_0^*(2400)^\pm$	$1/2(0^+)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^\pm$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)^0$	$1/2(2^+)$
• $D_2^*(2460)^\pm$	$1/2(2^+)$
$D(2550)^0$	$1/2(0^-)$
$D(2600)$	$1/2(?^?)$
$D^*(2640)^\pm$	$1/2(?^?)$
$D(2750)$	$1/2(?^?)$

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

	$I(J^P)$
• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}(2573)$	$0(?^?)$
• $D_{s1}^*(2700)^\pm$	$0(1^-)$
$D_{sJ}^*(2860)^\pm$	$0(?^?)$
$D_{sJ}(3040)^\pm$	$0(?^?)$

BOTTOM ($B = \pm1$)

• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B^0_s/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
$B_J^*(5732)$	$?(?^?)$
• $B_1(5721)^0$	$1/2(1^+)$
• $B_2^*(5747)^0$	$1/2(2^+)$

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

• B_s^0	$0(0^-)$
• B_s^*	$0(1^-)$
• $B_{s1}(5830)^0$	$0(1^+)$
• $B_{s2}^*(5840)^0$	$0(2^+)$
$B_{sJ}^*(5850)$	$?(?^?)$

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

• $B_c^\pm$	$0(0^-)$

$c\bar{c}$

	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$?^?(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $X(3872)$	$0^+(1^{++})$
• $\chi_{c0}(2P)$	$0^+(0^{++})$
• $\chi_{c2}(2P)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
• $\psi(4040)$	$0^-(1^{--})$
$X(4050)^\pm$	$?(?^?)$
$X(4140)$	$0^+(?^{?+})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
$X(4250)^\pm$	$?(?^?)$
• $X(4260)$	$?^?(1^{--})$
$X(4350)$	$0^+(?^{?+})$
• $X(4360)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
$X(4430)^\pm$	$?(?^?)$
• $X(4660)$	$?^?(1^{--})$

$b\bar{b}$

$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $h_b(1P)$	$?^?(1^{+-})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
$\eta_b(2S)$	$0^+(0^{-+})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\Upsilon(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
$h_b(2P)$	$?^?(1^{+-})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\chi_b(3P)$	$?^?(?^{?+})$
• $\Upsilon(4S)$	$0^-(1^{--})$
$X(10610)^\pm$	$?^+(1^+)$
$X(10650)^\pm$	$?^+(1^+)$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

something missing?

Mesons

• Indicates particles that appear in the preceding Meson Summary Table. We do not regard the other entries as being established.

LIGHT UNFLAVORED ($S = C = B = 0$)	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $f_0(500)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	$a_2(1700)$	$1^-(2^{++})$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $\phi(1020)$	$0^-(1^{--})$	$X(1835)$	$?^?(?^{-+})$

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	$1/2(0^-)$
$K^*_0(800)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K^*_0(1430)$	$1/2(0^+)$

CHARMED, STRANGE ($C = S = \pm1$)	$I(J^P)$
• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D^*_{s0}(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}(2573)$	$0(?^?)$
• $D^*_{s1}(2700)^\pm$	$0(1^-)$
$D^*_{sJ}(2860)^\pm$	$0(?^?)$
$D_{sJ}(3040)^\pm$	$0(?^?)$

BOTTOM

$c\bar{c}$	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$?^?(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $X(3872)$	$0^+(1^{++})$
• $\chi_{c0}(2P)$	$0^+(0^{++})$

CHARMED ($C = \pm1$)	
• $D^\pm$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
• $D^*_0(2400)^0$	$1/2(0^+)$

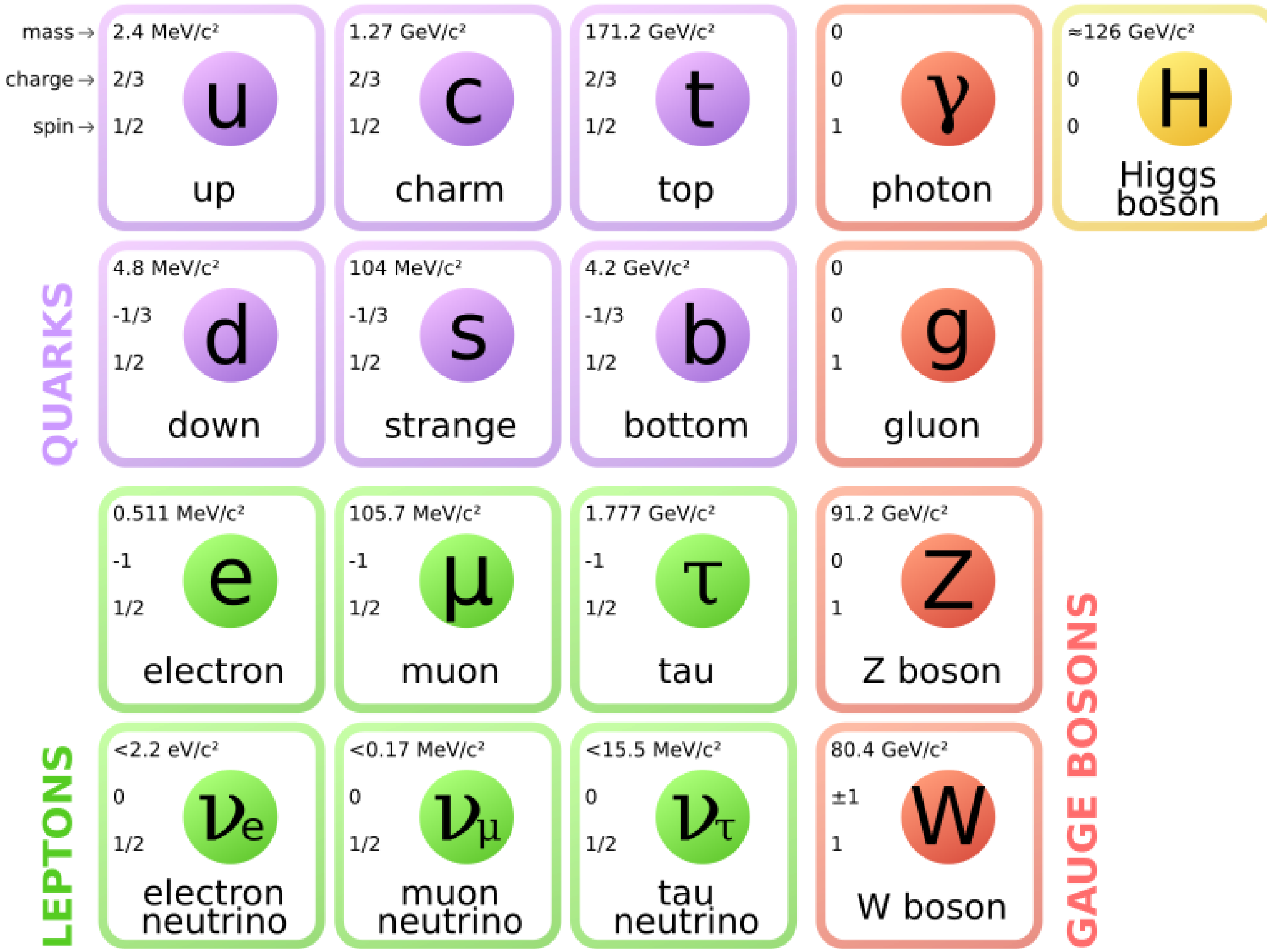
BOTTOM ($B = \pm1$)	
• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	

$b\bar{b}$	
$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$

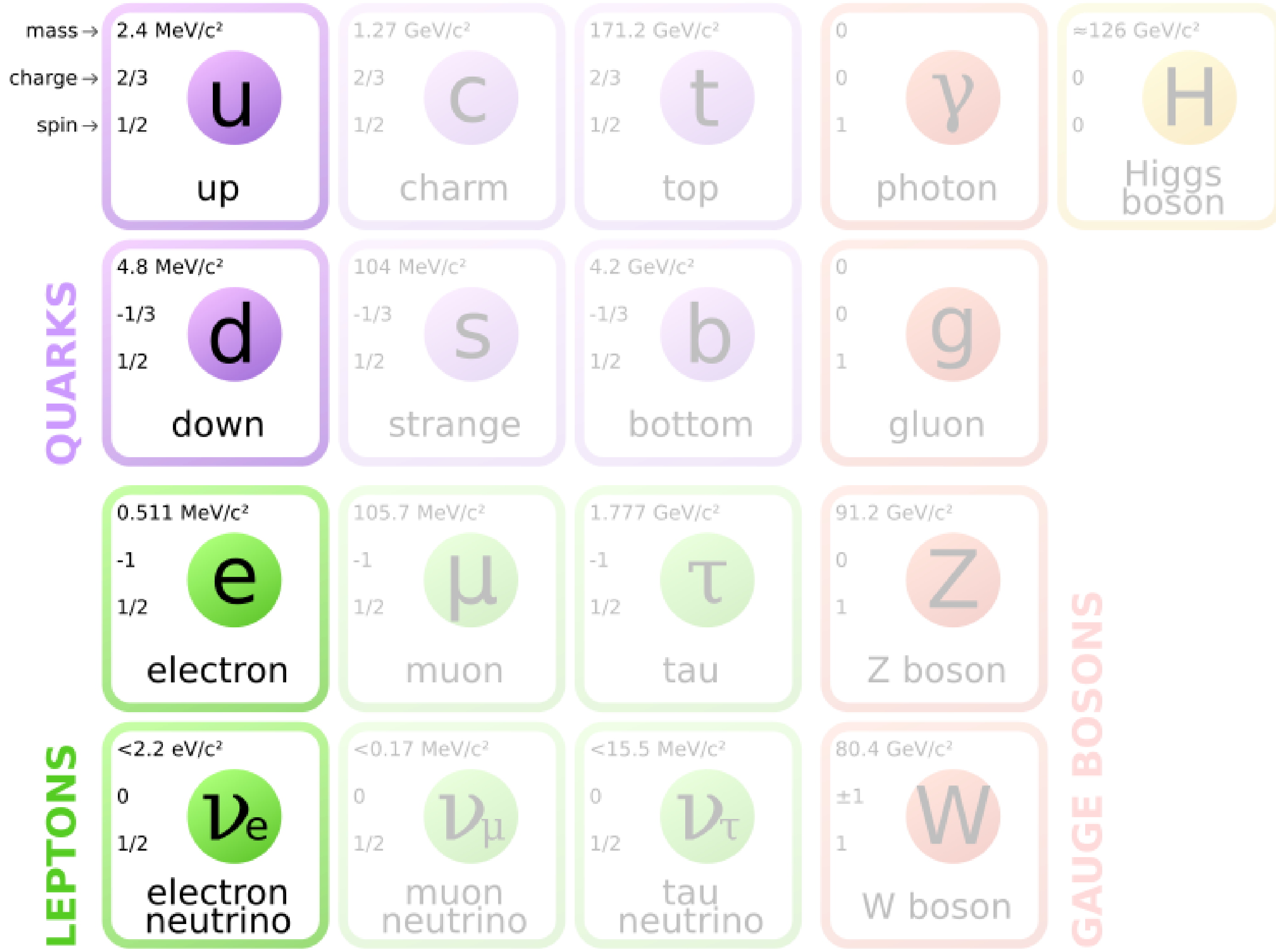
these are the mesons you should know

Questions?

Elementary Particles



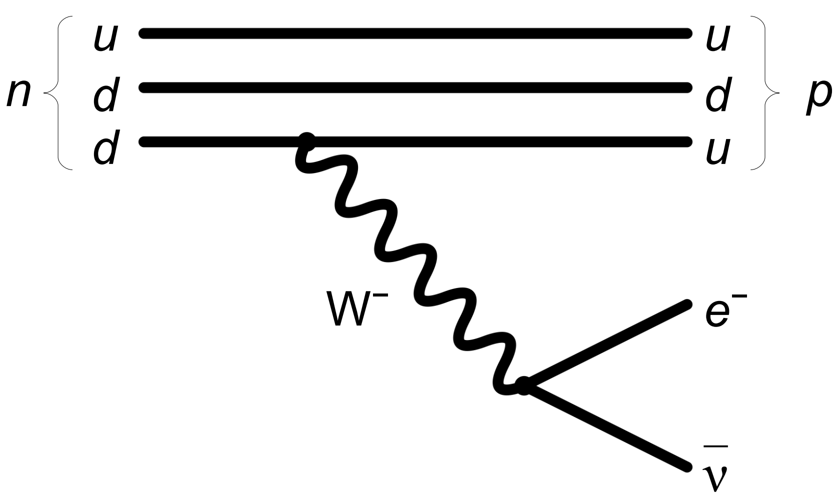
Elementary Particles: First Generation



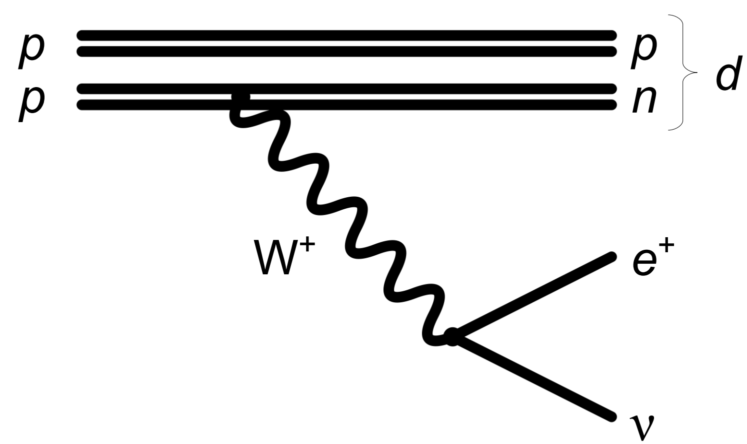
First Generation

all you need to build up our "everyday" matter:

- p=*uud*, n=*udd*
  - similarities of *u* and *d* for strong interactions can be described by isospin I
  - I=1/2 for both *u* and *d*, I_z=+1/2 for *u*, I_z=−1/2 for *d*
- *p*, *n*, e^- and $\bar{\nu}$ all take part in β decay:



e^+ and ν appear in fusion process



Positron

The Positive Electron

Carl D. Anderson, *California Institute of Technology, Pasadena, California*

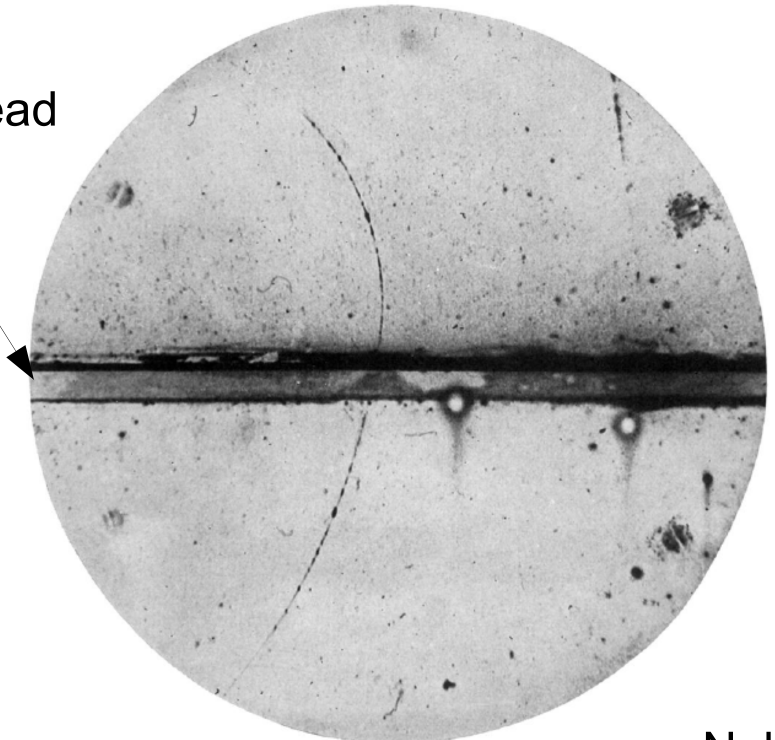
(Received February 28, 1933)

Out of a group of 1300 photographs of cosmic-ray tracks in a vertical Wilson chamber 15 tracks were of positive particles which could not have a mass as great as that of the proton. From an examination of the energy-loss and ionization produced it is concluded that the charge is less than twice, and is probably exactly equal to, that of the proton. If these particles carry unit positive charge the curvatures and ionizations produced require the mass to be less than twenty times the electron mass. These particles will be called positrons. Because they occur in groups associated with other tracks it is concluded that they must be secondary particles ejected from atomic nuclei.

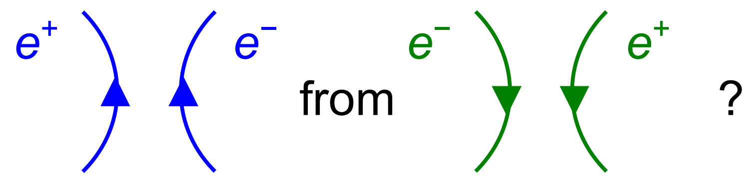
Editor

from C. Anderson, Phys. Rev. 43 (1933) 491

6mm lead plate



- cloud chamber
- B field orthogonal to chamber
- dE/dx consistent with electron
- how to distinguish



Nobel Prize 1936 for C. Anderson

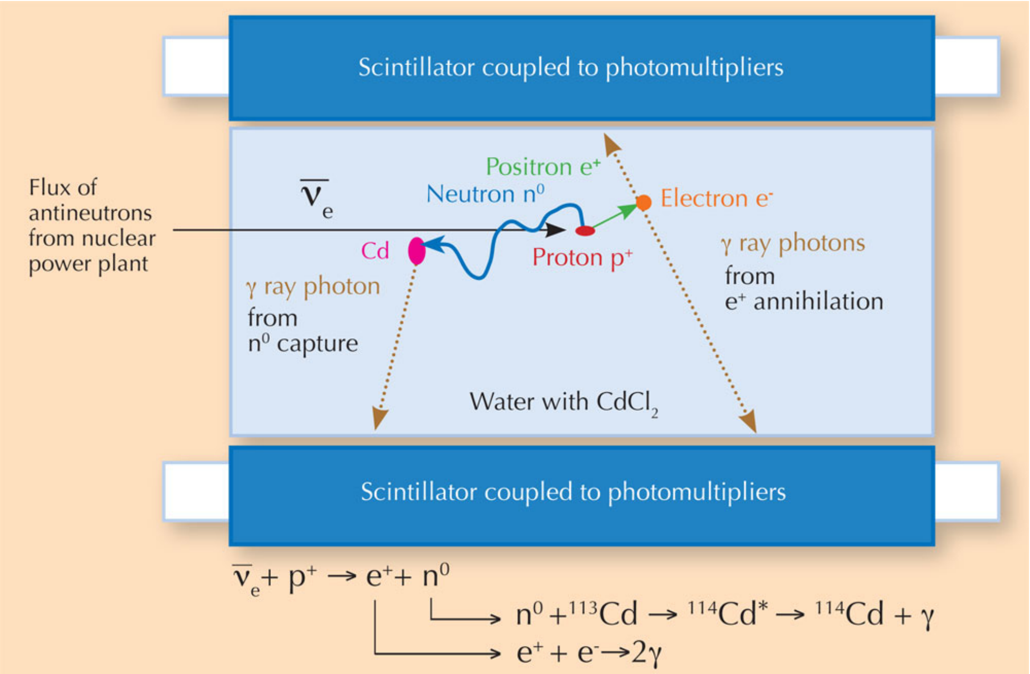
Anti-neutrino

C.L. Cowan, Jr., F. Reines, F.B. Harrison, H.W. Kruse and A.D. McGuire, Science 124, (1956) 103

- first direct detection in inverse β decay reaction: $\bar{\nu}_e \, p \rightarrow n \, e^+$
- important ingredients:
  - high flux of anti-neutrinos from nuclear reactor
  - low background (cosmic rays! → underground)
- detection:

  200 l water with $CdCl_2$

  ~3 events/h



from scienceinschool.org

Nobel Prize 1995 for F. Reines

Pions

$\boxed{\pi^0}$ $\pi^0 = (u\bar{u} - d\bar{d})/\sqrt{2}$ $I^G(J^{PC}) = 1^-(0^{-+})$

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 $\tau = (8.52 \pm 0.18) \times 10^{-17}$ s $(S = 1.2)$
$c\tau = 25.5$ nm

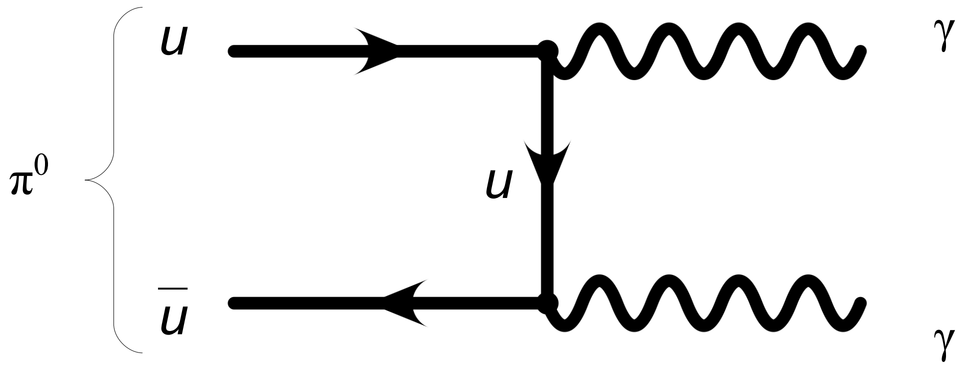
π^0 DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
2γ	(98.823 ± 0.034) %	S=1.5	67
$e^+e^-\gamma$	(1.174 ± 0.035) %	S=1.5	67

$\boxed{\pi^\pm}$ $\pi^+ = u\bar{d}, \pi^- = \bar{u}d$ $I^G(J^P) = 1^-(0^-)$

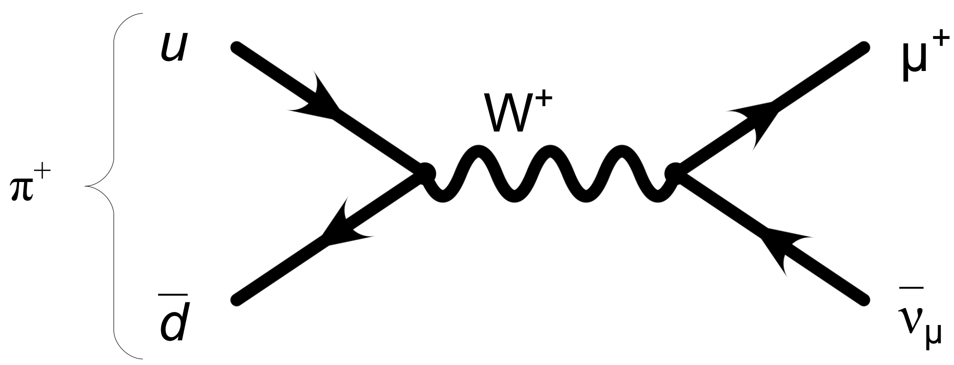
Mass $m = 139.57018 \pm 0.00035$ MeV $(S = 1.2)$
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s $(S = 1.2)$
$c\tau = 7.8045$ m

π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$	[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$	[c]	$(2.00 \pm 0.25) \times 10^{-4}$		30

Pion Decays



electromagnetic
interaction



weak
interaction

Charged Pion

$\pi^{\pm}$

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

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)
$c\tau = 7.8045$ m

⋮

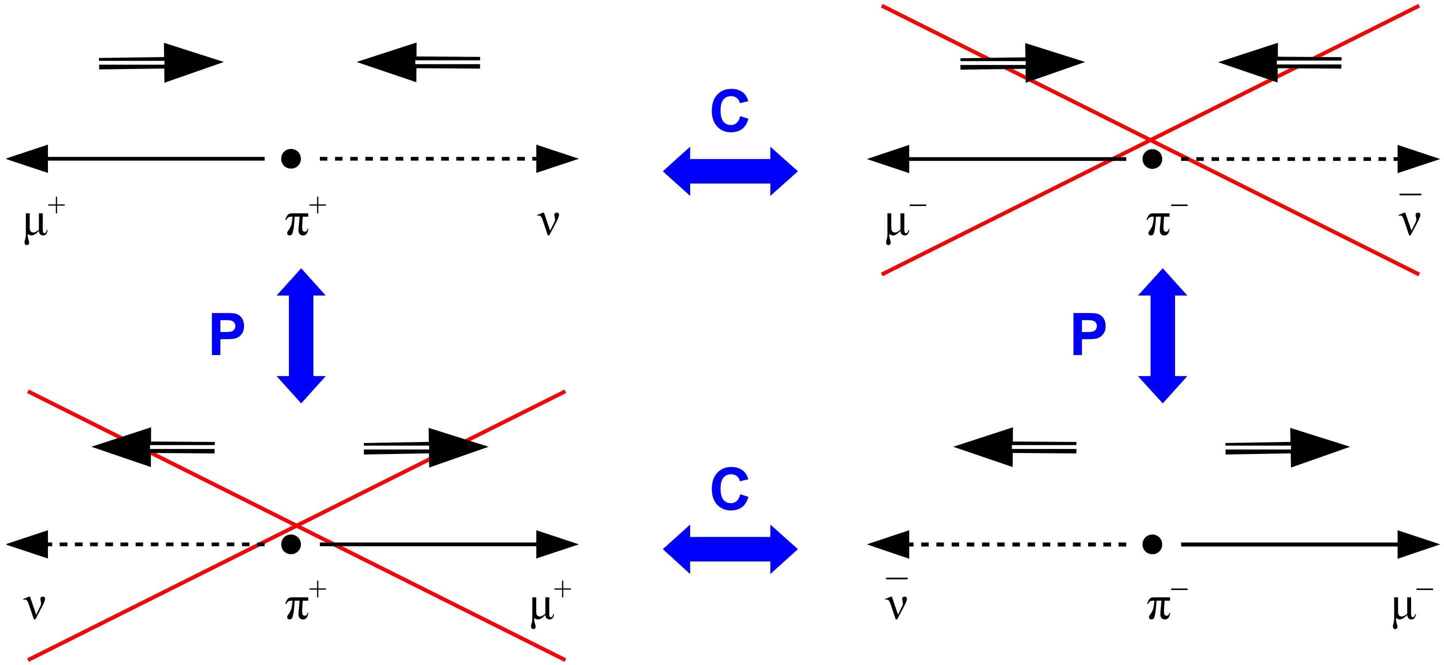
π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$	[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$	[c]	$(2.00 \pm 0.25) \times 10^{-4}$		30
$e^+\nu_e$	[b]	$(1.230 \pm 0.004) \times 10^{-4}$		70
$e^+\nu_e\gamma$	[c]	$(7.39 \pm 0.05) \times 10^{-7}$		70
$e^+\nu_e\pi^0$		$(1.036 \pm 0.006) \times 10^{-8}$		4

⋮

why is the decay to muon and neutrino so much more likely than the decay to electron and neutrino, although the muon is much heavier than the electron?

Decay of Charged Pions

- neutrino is left-handed, π has spin 0
  $\Rightarrow$ charged lepton also has to be left-handed, which is the “wrong” spin
- the heavier the charged lepton, the less suppressed is the wrong helicity, proportional to (1-v/c)



- left-handedness of neutrinos also means that weak interaction violates C, but CP can be conserved (and indeed CP violation is much smaller)