

Italian Teachers' Programme

CERN

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**INTRODUZIONE ALLA
FISICA DELLE PARTICELLE**

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Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, S. Beckwith (STScI) and the HUDF Team

STScI-PRC04-07a

**LE QUESTIONI CHE AFFRONTA LA FISICA
DELLE PARTICELLE SONO LE STESSA CHE
HANNO GUIDATO LO SVILUPPO DEL
PENSIERO FILOSOFICO NEL CORSO DEI
MILLENNI**

- ✦ **COME FUNZIONA
L'UNIVERSO?**
- ✦ **DA DOVE VIENE?**
- ✦ **DOVE VA?**



- ✦ **QUALI SONO I
COMPONENTI ULTIMI
DELLA MATERIA?**
- ✦ **COME “SI MUOVONO”?**
- ✦ **CHE COSA “LI MUOVE”?**

**LA PIÚ AMBIZIOSA FRA TUTTE LE
SCIENZE!**

Anche il modo di affrontare il problema usato dai filosofi antichi è simile a quello del fisico moderno:

identificare pochi principi fondamentali, dai quali derivare le proprietà di tutti i fenomeni naturali, sia quelli pertinenti al macro cosmo (il cielo, l'universo), che quelli pertinenti alla scala umana

Ciò che è cambiato nel corso dei secoli è la percezione della vera complessità dei fenomeni, la capacità di eseguire misure quantitative, ed i criteri epistemologici di adeguatezza della loro descrizione

In comune, l'identificazione di due categorie:

(a) I componenti della materia

(b) Le forze che governano i loro comportamenti

Esempio dal passato remoto

Componenti:

aria, acqua fuoco, terra

Forze:

- aria e fuoco spinti verso l'alto
- terra ed acqua spinti verso il basso

Valutazione di correttezza:

come mai un tronco di legno immerso a fondo nell'acqua viene a galla, spinto verso l'alto?

Rivalutazione della teoria (Principio di Archimede):

- tutta la materia viene spinta verso il basso, ma con intensità proporzionale al proprio peso:

Un corpo immerso nell'acqua riceve una spinta verso l'alto pari al peso dell'acqua spostata.

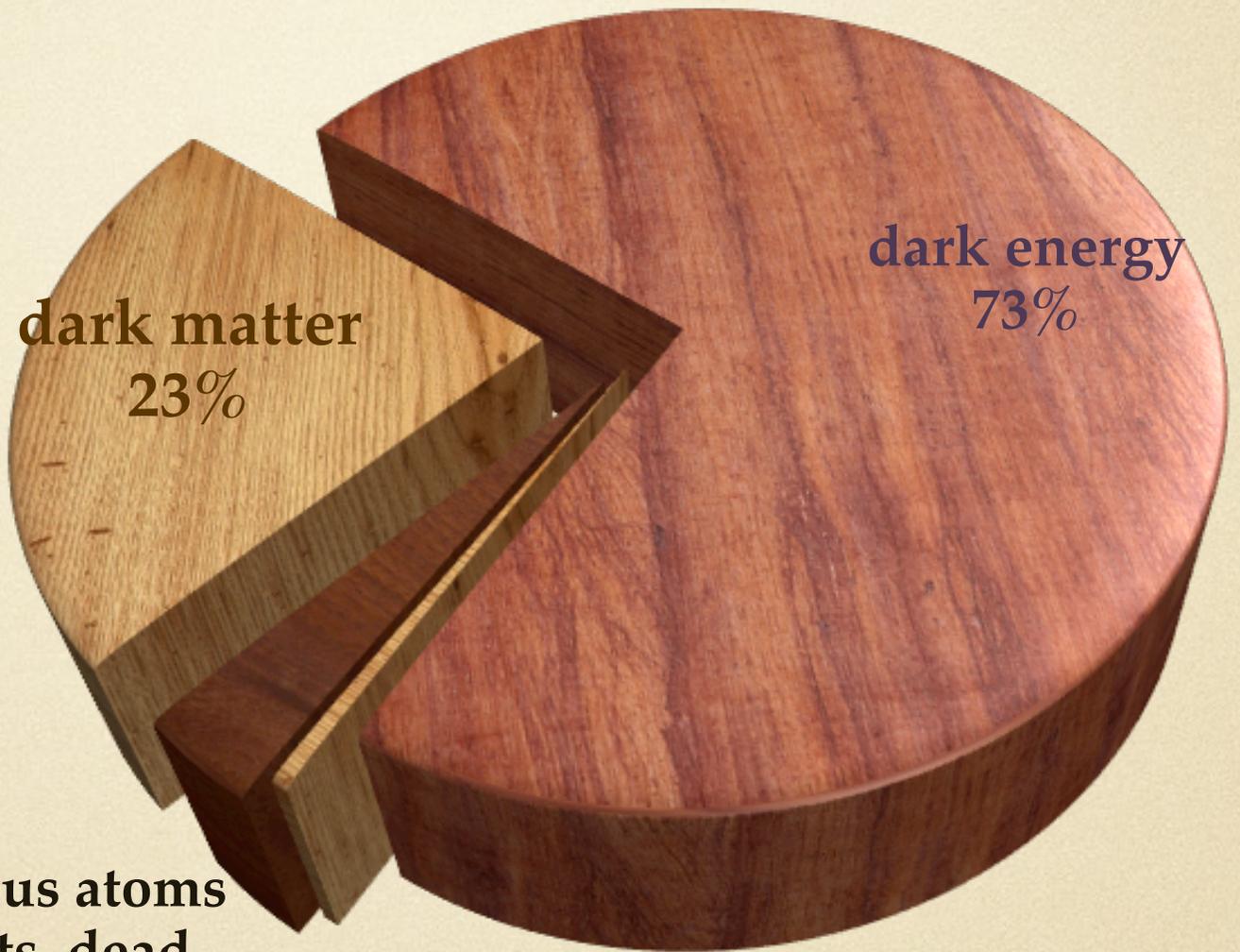
Questa teoria e' piu' semplice, e migliore della precedente, perche' d'un tratto spiega anche nuovi fenomeni, per es. il vento: l'aria calda e' piu' leggera della fredda, e' spinta verso l'alto, e la fredda si muove dentro, creando il vento

Il primo esempio di "unificazione delle forze" ?

Si noti che non esiste garanzia a priori che la natura possa essere descritta da un numero limitato di principi, o che questi valgano ovunque e sempre.

Per es., la conservazione dell'energia su scala microscopica e' stata messa in dubbio dai primi studi quantitativi dei decadimenti beta nucleari, negli anni 20..

Il grande successo della fisica moderna e' nella sua descrizione, incredibilmente accurata, della totale moltitudine dei fenomeni naturali osservati



dark energy
73%

dark matter
23%

non-luminous atoms
(e.g. planets, dead
stars, dust, etc), ~4%

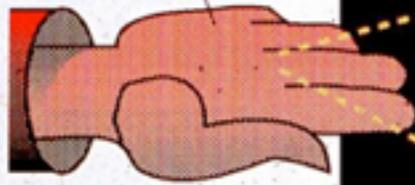
stars, neutrinos,
photons ~0.5%

- The understanding of the **Big Bang** and of what preceded it requires the understanding of the behaviour of Nature in presence of gravitational fields of intensity similar to that of nuclear forces (Quantum Gravity).
- The sources of **Inflation** and of **Dark Matter** and **Dark Energy**, which, respectively, shaped and will determine the future of the large-scale structure of the Universe, have to be found within the spectrum of particles which will form our ultimate "*theory of everything*".

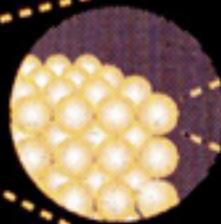
Level 0: what? how?

- Are there fundamental building blocks?
- If so, what are they?
- How do they interact?
- How do they determine the properties of the Universe?

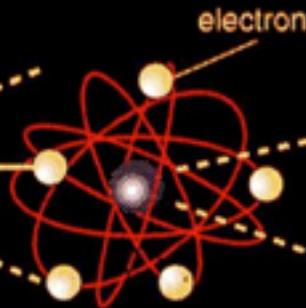
MATTER



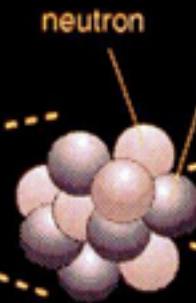
ATOM



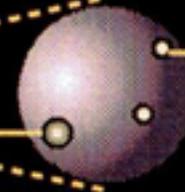
NUCLEUS



PROTON



QUARK



LEPTONS

QUARKS

ALL ORDINARY MATTER BELONGS TO THIS GROUP.



electron

Electric charge -1 .

Responsible for electricity and chemical reactions

electron neutrino

Electric charge 0 .

Rarely interacts with other matter.

up

Electric charge $+2/3$.

Protons have 2 up quarks
Neutrons have 1 up quark

down

Electric charge $-1/3$.

... and one down quark.
... and two down quarks.

THESE PARTICLES EXISTED JUST AFTER THE BIG BANG.



NOW THEY ARE FOUND ONLY IN COSMIC RAYS AND ACCELERATORS.

muon

A heavier relative of the electron.



muon neutrino

Created with muons when some particles decay.



charm

A heavier relative of the up.



strange

A heavier relative of the down.



tau

Heavier still.



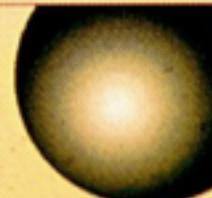
tau neutrino

Not yet observed directly.



top

Heavier still, recently observed.



bottom

Heavier still.



ANTIMATTER

Each particle also has an antimatter counterpart ... sort of a mirror image.



INTERAZIONI (O “FORZE”)

- Responsabili di:
 - Formazione di **stati legati** ($E < 0$):
 - Terra-sole
 - Elettrone-nucleo
 - Processi di **collisione/diffusione** ($E > 0$):
 - Moto di elettroni in un metallo
 - Propagazione della luce
 - Deflessione di particelle cariche in moto in un campo elettromagnetico *per es. i protoni nell' LHC*
 - **Transmutazioni:**
 - transizioni atomiche (emissione di radiazione quanto un elettrone cambia orbita)
 - Decadimenti ($n \rightarrow p$ e neutrino, radioattività)

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c ²	Electric charge
γ photon	0	0
W^-	80.39	-1
W^+	80.39	+1
W bosons		
Z^0 Z boson	91.188	0

Strong (color) spin = 1		
Name	Mass GeV/c ²	Electric charge
g gluon	0	0

EW symmetry breaking spin=0		
H higgs	125	0

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at $\left\{ \begin{array}{l} 10^{-18} \text{ m} \\ 3 \times 10^{-17} \text{ m} \end{array} \right.$	10^{-41} 10^{-41}	0.8 10^{-4}	1 1	25 60

Principali risultati concettuali

- ***Semplicita'*** (dei componenti fondamentali, e delle loro interazioni): la complessita' emerge dalla gran varieta' di combinazioni di aggregati di oggetti elementari (come il gioco dei LEGO!)
- ***Unita'*** (delle leggi di interazione)
- ***Unita'*** (degli elementi):

“un protone e' un protone e' un protone”
- ***Unicita'*** (delle leggi fondamentali): indipendenti da posizione, tempo e condizioni esterne

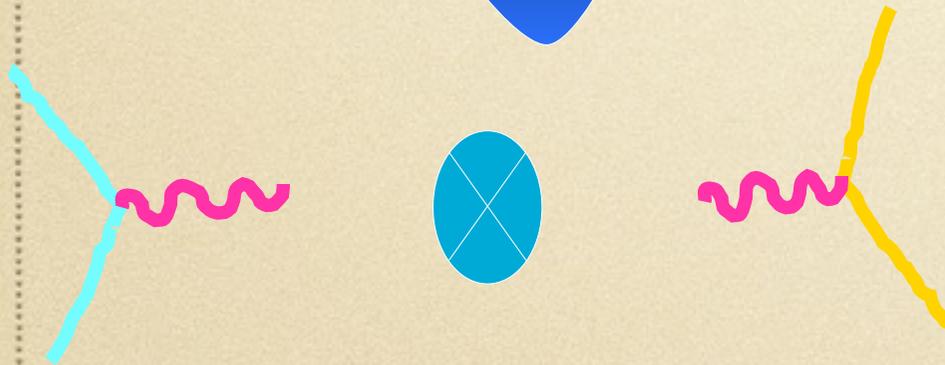
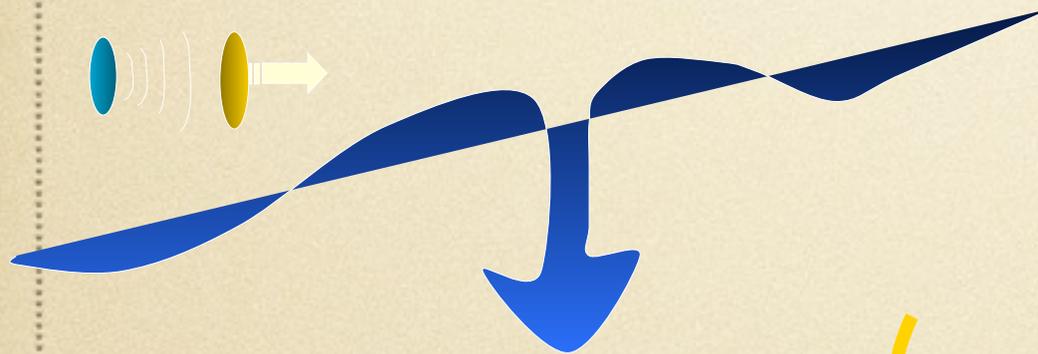
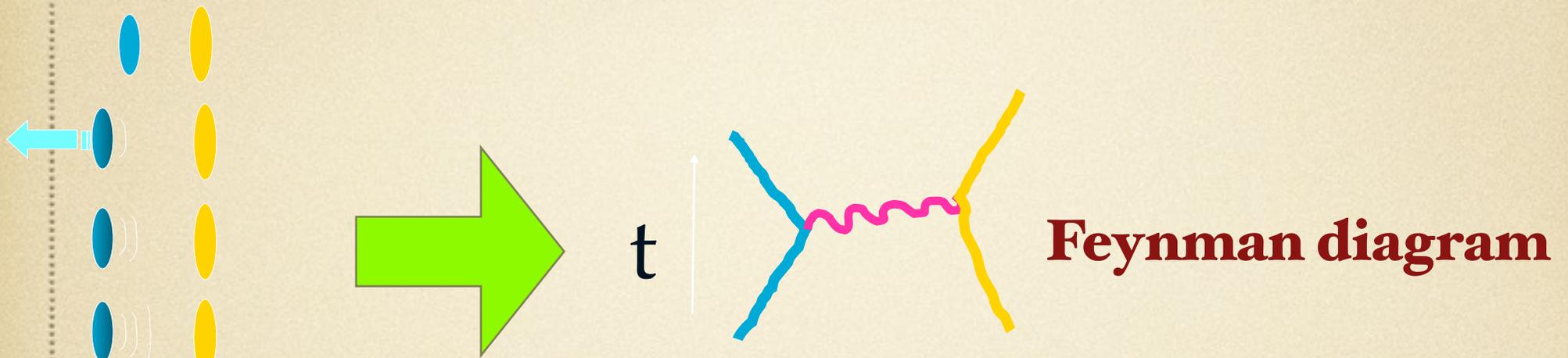
I principi fondamentali della fisica, e le particelle elementari

- Le particelle elementari sono soggette agli stessi principi fondamentali della fisica che si imparano a scuola:
 - “ $F=ma$ ”
 - causalita' (la causa precede l'effetto)
 - conservazione dell'energia (E), impulso (p) e momento angolare (L) (invarianza delle leggi fisiche rispetto a traslazioni spaziali e temporali e rotazioni)
 - Principio della relativita' speciale (Einstein)
 - Meccanica quantistica (dualita' onda-particella, principio di indeterminazione, quantizzazione dei livelli energetici, etc.)

Il ruolo della Relativita' Speciale

- Le particelle elementari hanno masse piccolissime, e le forze tipiche presenti negli acceleratori e nell'universo le accelerano a velocita' vicine a quella della luce. La descrizione del loro comportamento deve essere consistente con le leggi della Relativita' Speciale (Einstein).
- In particolare, ogni modello delle interazioni fra particelle elementari deve rispettare il principio che le forze non possono essere trasmesse *istantaneamente*, ma al piu' alla velocita' della luce

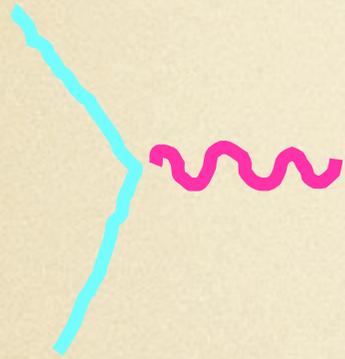
La rappresentazione delle interazioni



Locality

N.B.: in meccanica quantistica onde e particelle sono rappresentazioni diverse ma equivalenti dello stesso oggetto. Dunque all'onda che trasmette il segnale dell'interazione associamo una particella

Semplice ... ma sottile!



prima: ●

dopo: ● + ●

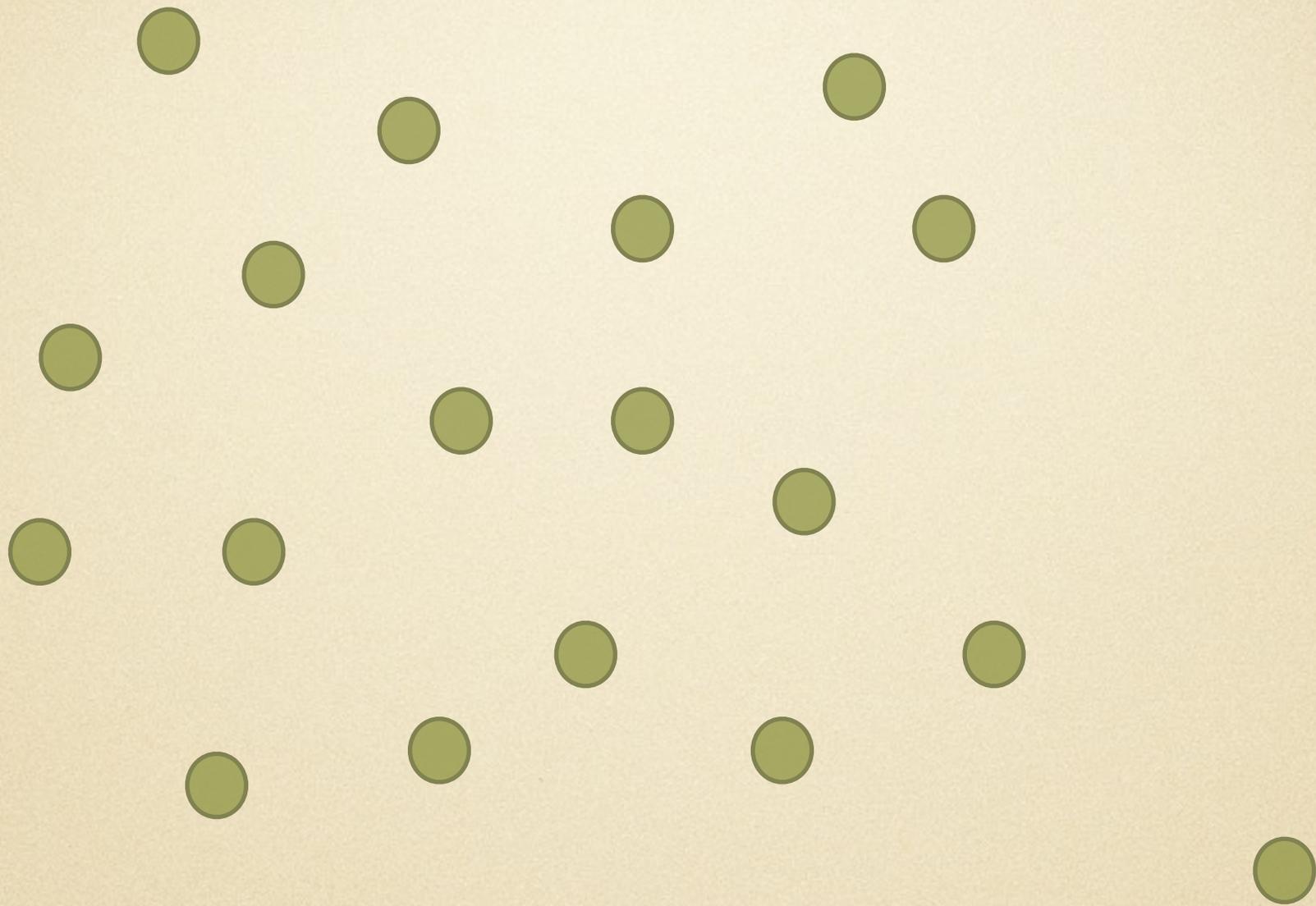


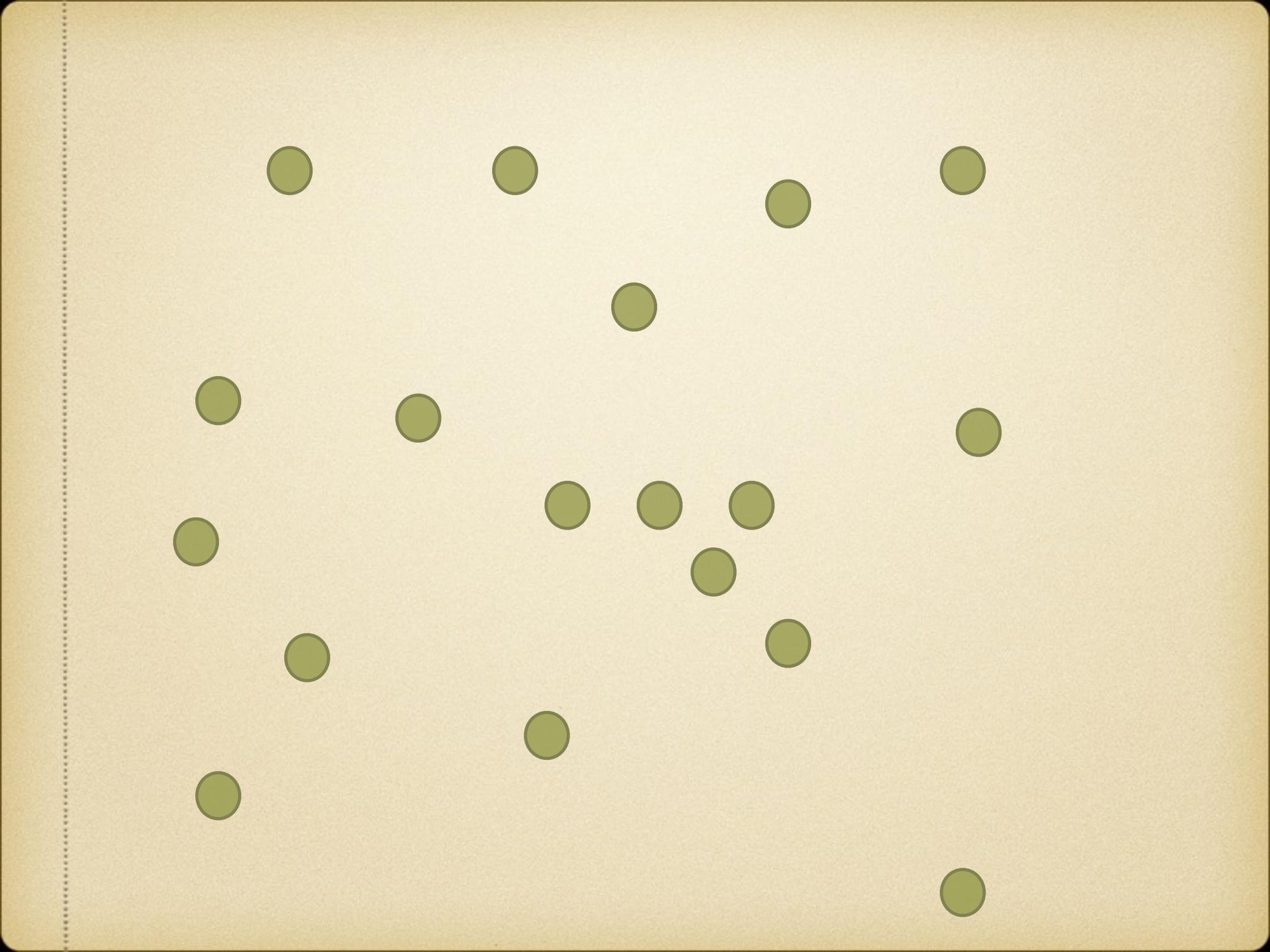
Energia(dopo) \neq Energia(prima)

Cosa succede alla conservazione dell'energia ?!

Count fast!



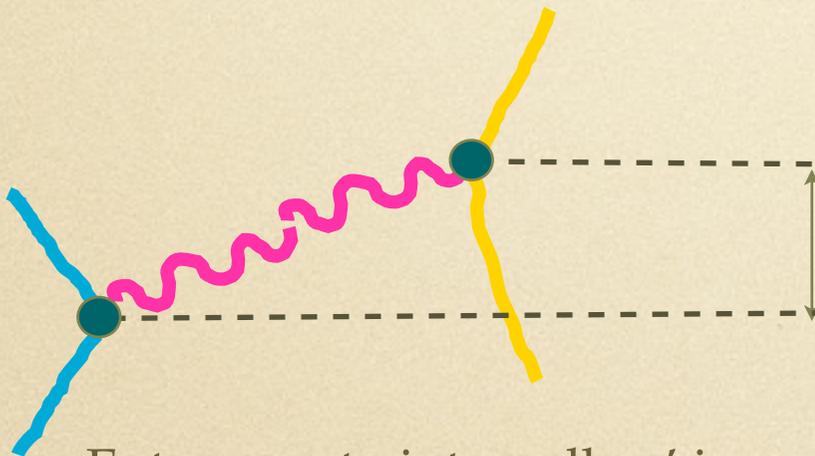
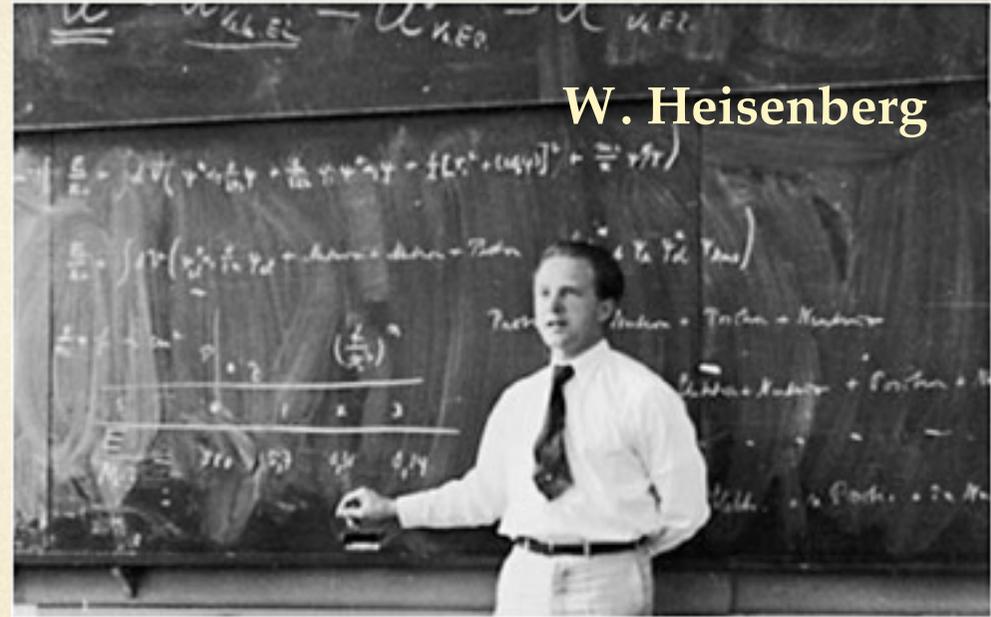




Meccanica quantistica

Principio di indeterminazione di Heisenberg:

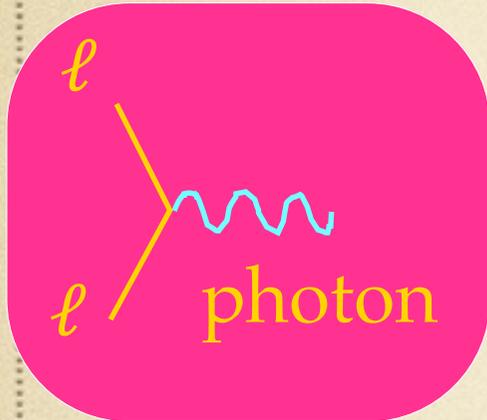
una misura di energia eseguita entro un tempo Δt puo' al piu' raggiungere una precisione $\Delta E \geq \hbar/\Delta t$



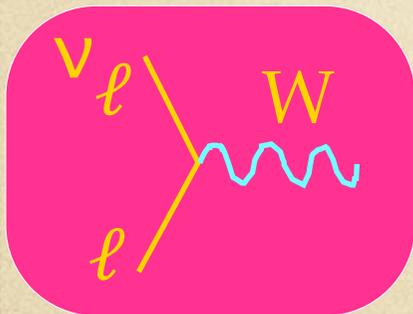
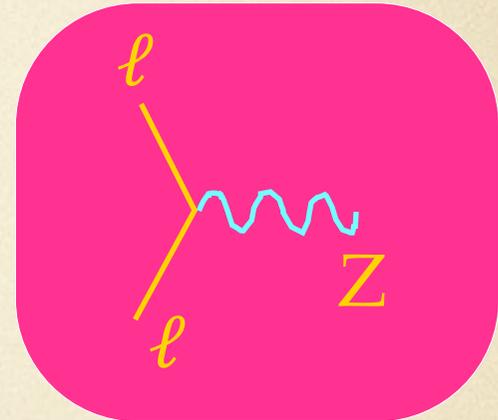
$$\Delta t < \hbar/\Delta E$$

Entro questo intervallo e' impossibile determinare se l'energia e' conservata o meno, poiche' non possiamo misurarla con sufficiente accuratezza! Dunque e' possibile "barare" con la natura, e permettere lo scambio di energia fra le due particelle, effettuandolo entro Δt

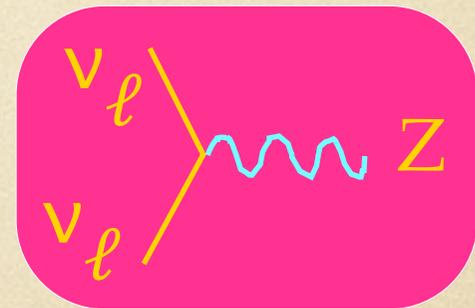
Lepton Interactions ($l=e,\mu,\tau$)



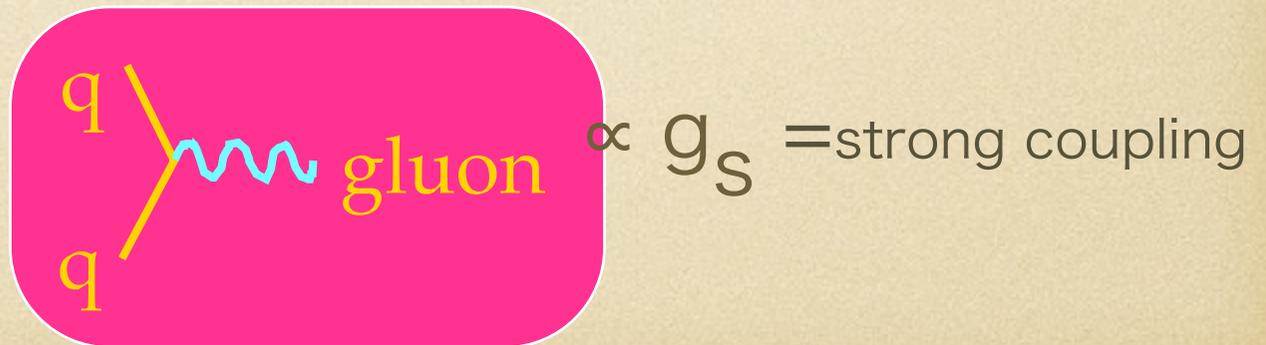
$\propto -e = \text{electric charge}$



$\propto g_W = \text{weak charge}$

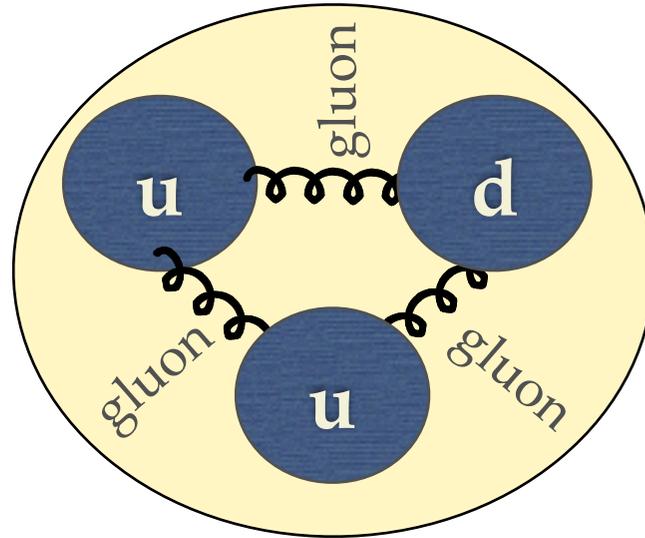


Quark Interactions



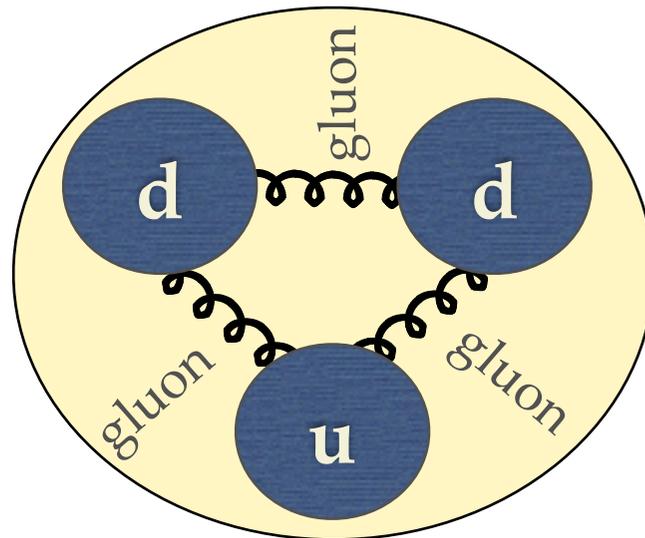
ESEMPIO

Protone



$$Q = 2/3 e + 2/3 e - 1/3 e \\ = e$$

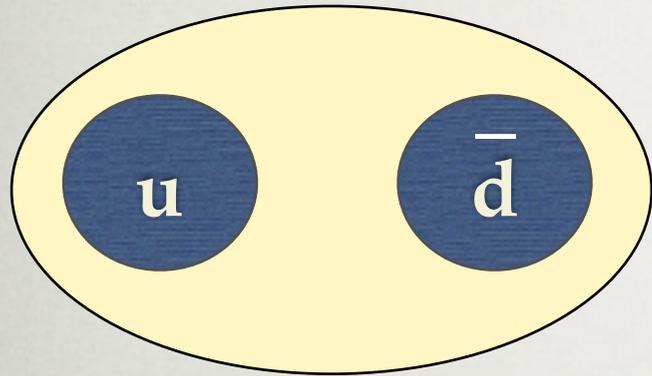
Neutrone



$$Q = 2/3 e - 1/3 e - 1/3 e \\ = 0$$

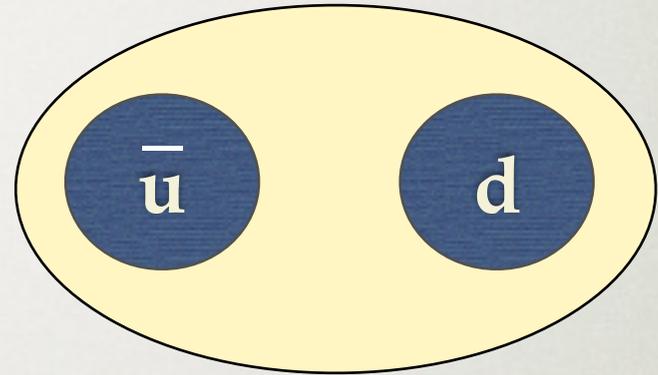
ESEMPIO, I "PIONI"

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



$$Q = 2/3 e + (-)(-1/3) e = e$$

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

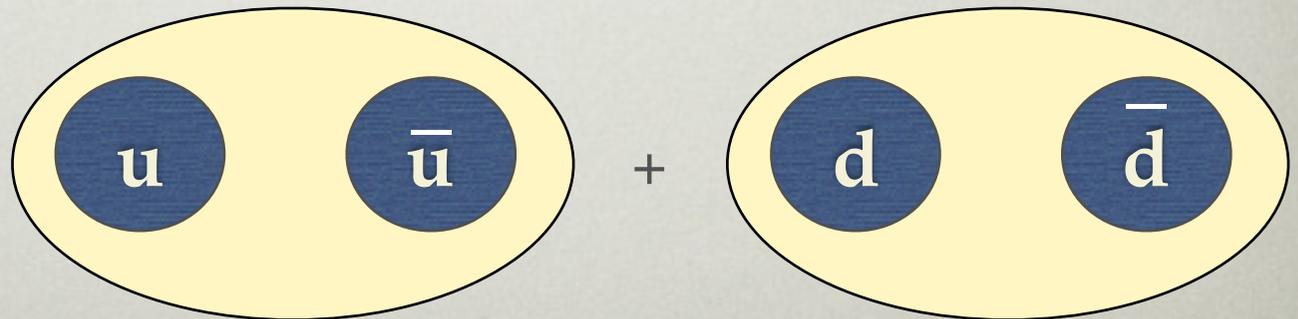


$$Q = -2/3 e + (-1/3) e = -e$$

dove \bar{q} e' l'antiquark del quark q

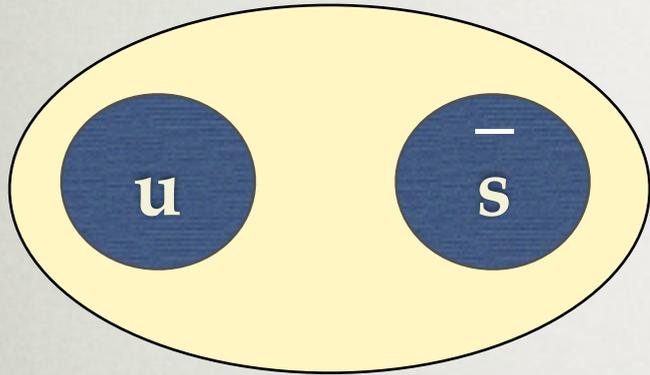
$$\pi^0 = d\bar{d} + u\bar{u}$$

$$Q = 0$$



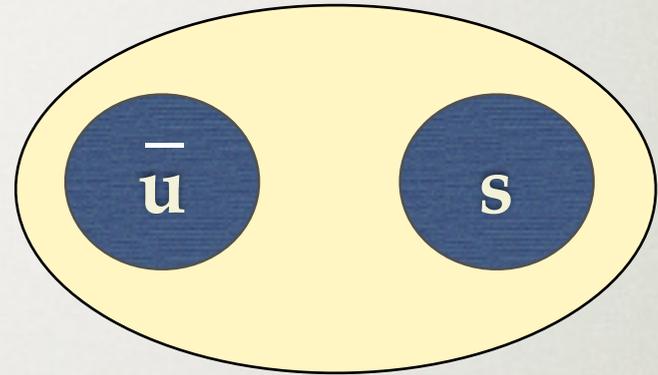
ESEMPIO, I “KAONI”

$$K^+ = u\bar{s}$$



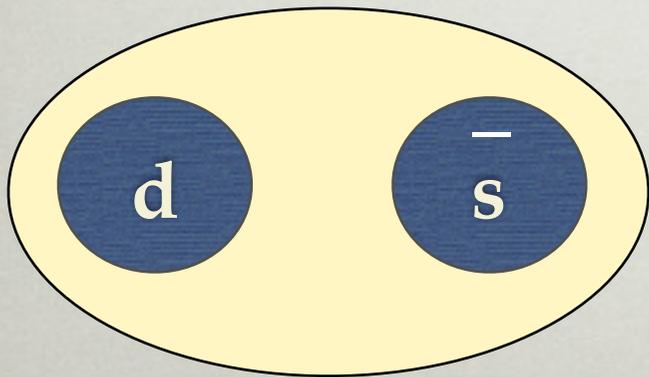
$$Q = 2/3 e + (-)(-1/3) e = e$$

$$K^- = \bar{u}s$$



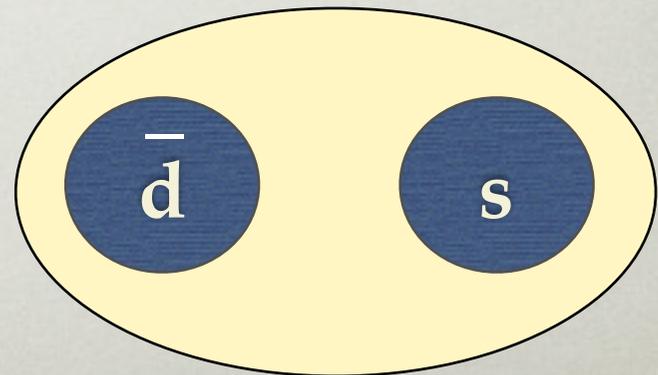
$$Q = -2/3 e + (-1/3) e = -e$$

$$\bar{K}^0 = d\bar{s}$$



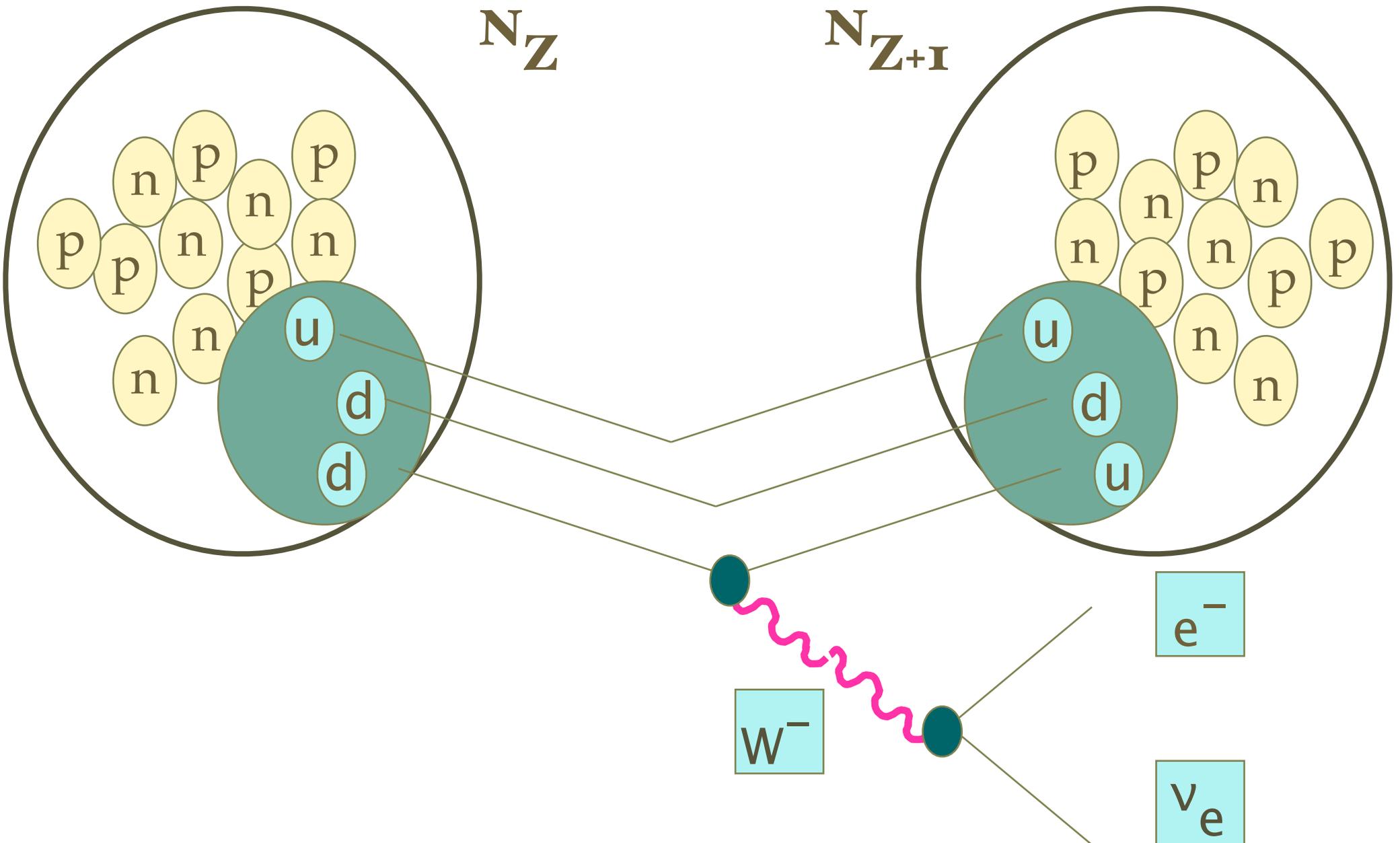
$$Q = -1/3 e + (-)(-1/3) e = 0$$

$$K^0 = \bar{d}s$$



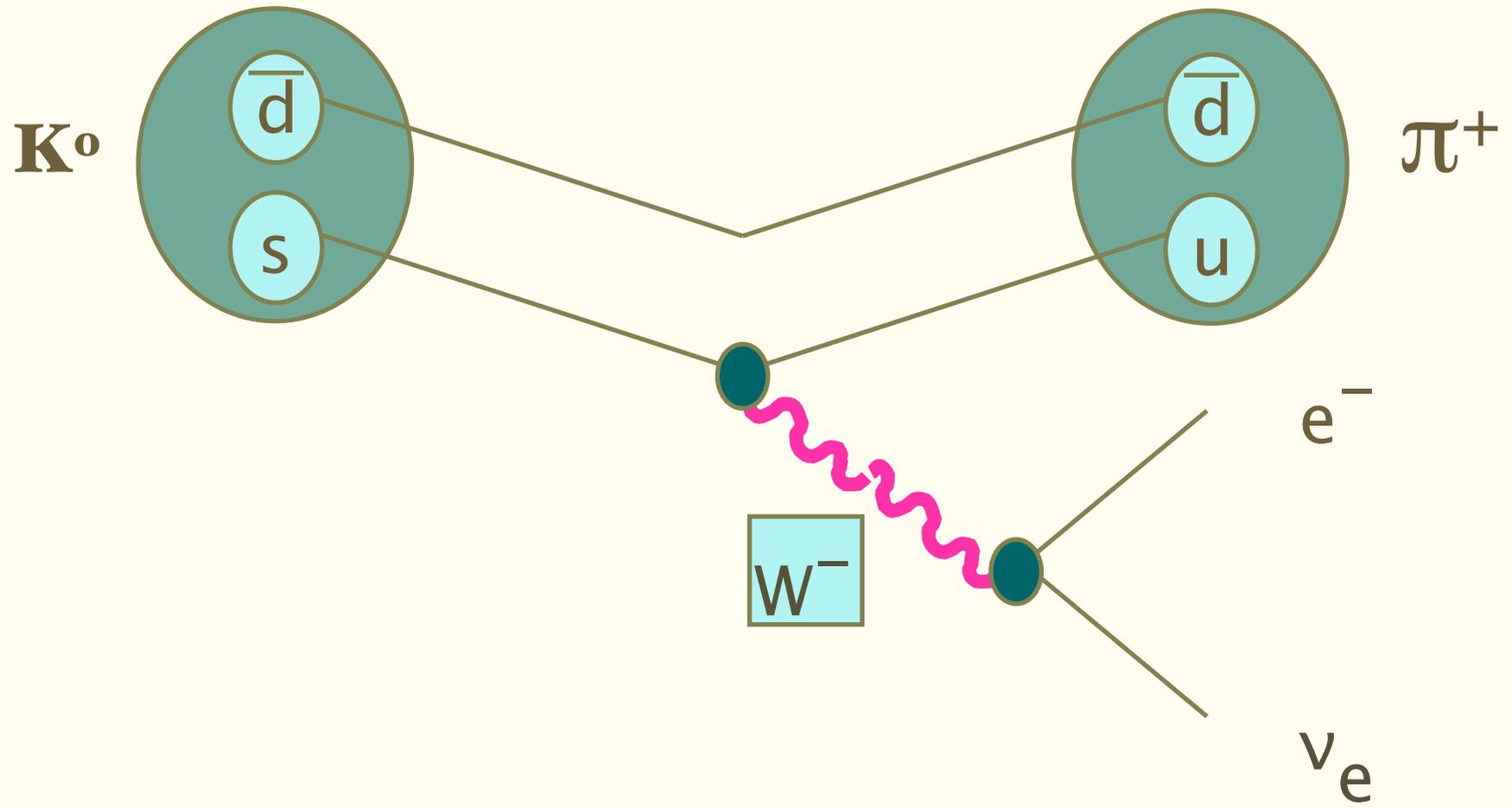
$$Q = (-)(-1/3) e + (-1/3) e = 0$$

Esempio: la radioattività'



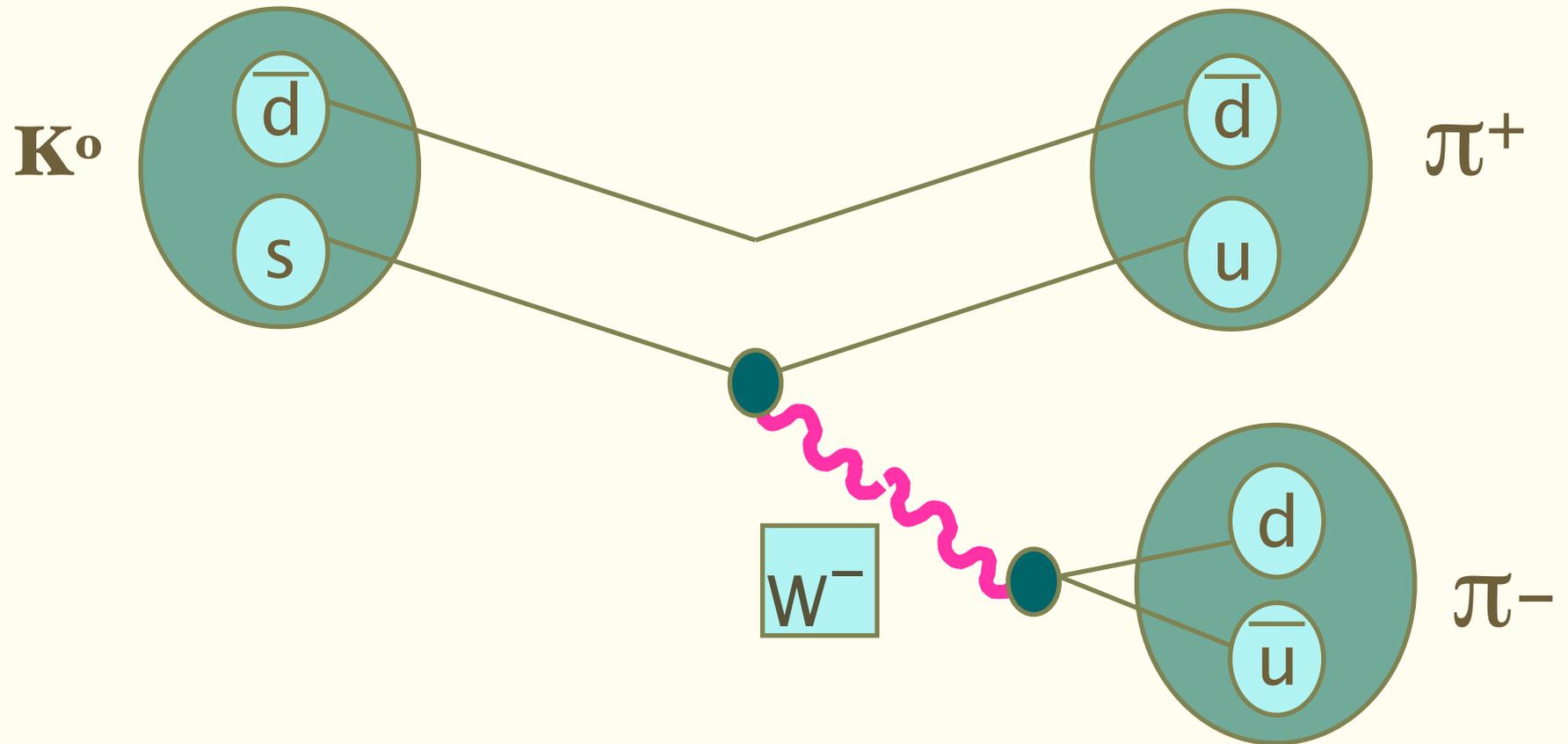
Esempio: decadimento dei kaoni

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



Esempio: decadimento dei kaoni

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



Trasformazioni come questa, in cui protoni e neutroni si trasformano gli uni negli altri con emissione di elettroni e neutrini, sono alla base del funzionamento delle stelle

Esse generano l'energia prodotta dalle stelle, ne trasformano il contenuto, fino all'esaurimento del loro potenziale energetico. Per le stelle piu' grandi, alla fine della loro vita, l'energia gravitazionale induce un collasso finale, ed ad un ultimo ciclo di trasformazioni nucleari, da cui emergono, in una catastrofica esplosione, nuclei piu' pesanti come silicio, ferro, oro, uranio, che, disperdendosi nello spazio, ed unendosi a nubi di gas in procinto di formare nuove stelle e sistemi solari, danno origine a stelle come il sole, e pianeti come la terra.

Observables and fundamental quantities

■ *Mass:*

- Composite particles -> dynamical origin, calculable: $M=E/c^2$, $E=T+U$
- Fundamental particles -> assigned parameter; origin ???
- Measurement:
 - in decays: $P=\sum p_i$, $M^2=P^2$
 - in production: M =minimum energy necessary for creation

■ *Charge:*

- Which type (electric, weak, strong)?
- Are there other charges?? What is the origin of charge??
- Measurement: interaction strength
 - lifetime of a particle before its decay
 - reaction probabilities (rate counting)

■ *Spin* (intrinsic angular momentum):

- Integer-> bosons, Semi-integer -> fermions
- Origin??
- Pauli principle (two identical fermions cannot occupy the same quantum state) at the origin of matter stability and diversity
- Measurement: angular distributions in scattering or decay processes

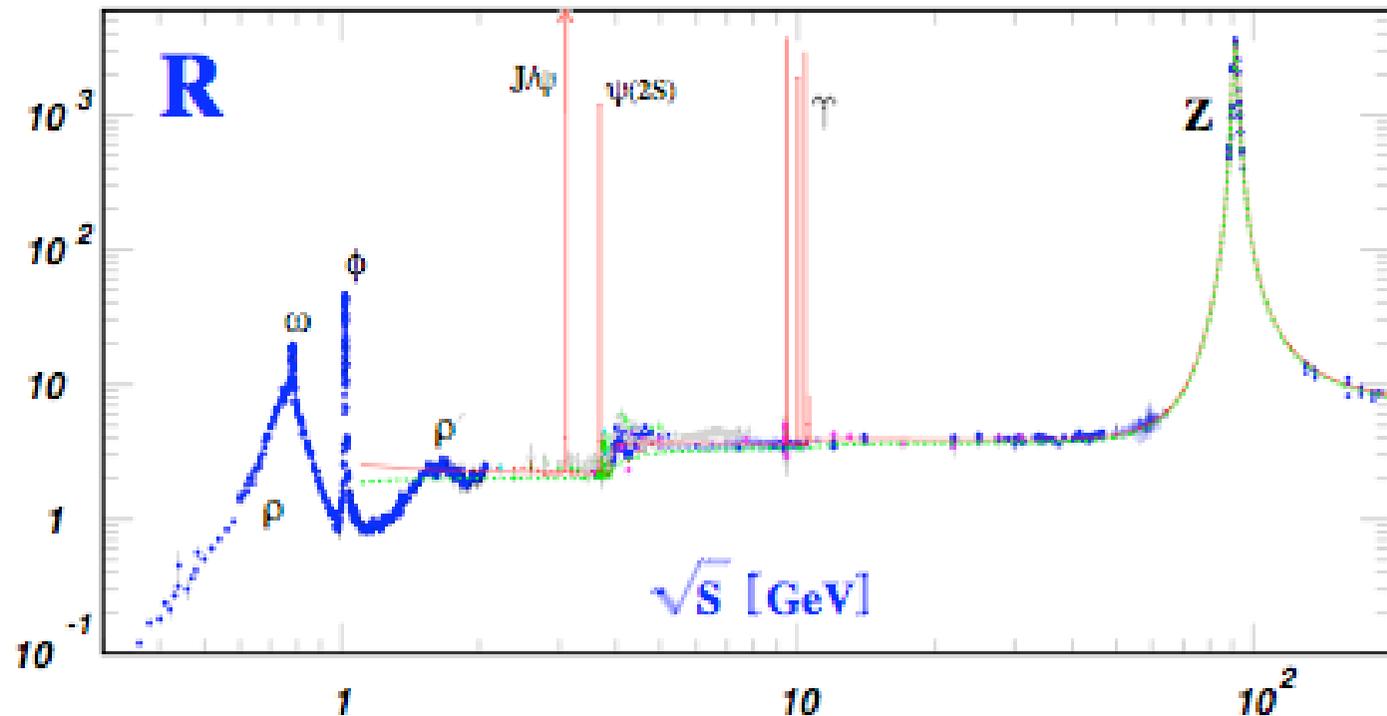
Examples of mass determination:

$M =$ energy at production threshold

Production rate for $e^+e^- \rightarrow$ hadrons, as a function of the center of mass energy



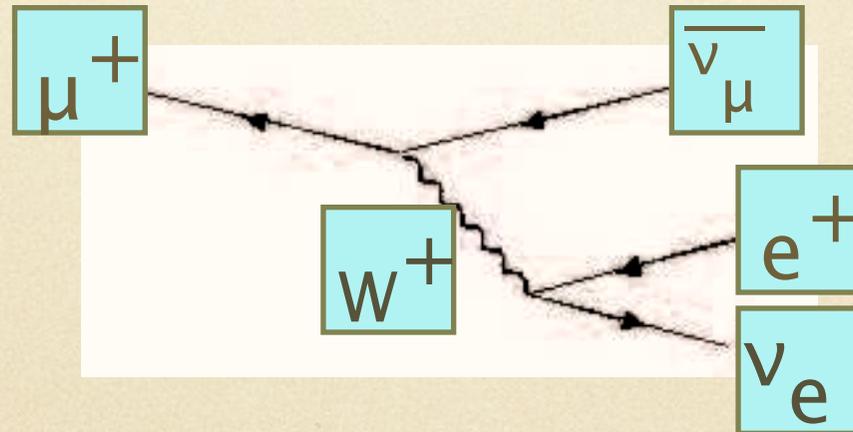
The peaks represent the appearance of a new possible final state, made it possible by having enough CM energy to create it. It appears as a "resonance" in a "spectrum".



Decays and lifetimes

- If the couplings of a particle \mathbf{A} allow it to transform itself into a series of particles $\mathbf{B}_1, \dots, \mathbf{B}_n$, and if $m_A > m_{B_1} + \dots + m_{B_n}$, \mathbf{A} decays into $\mathbf{B}_1 + \dots + \mathbf{B}_n$. Only particles for which no decay channel is open can be stable. As of today, we only know of three such examples: the electron, the lightest neutrino and the proton (although there are theories in which the proton is predicted to decay with a lifetime of about 10^{34} years, as well as theories in which stable heavy particles explain the origin of dark matter).

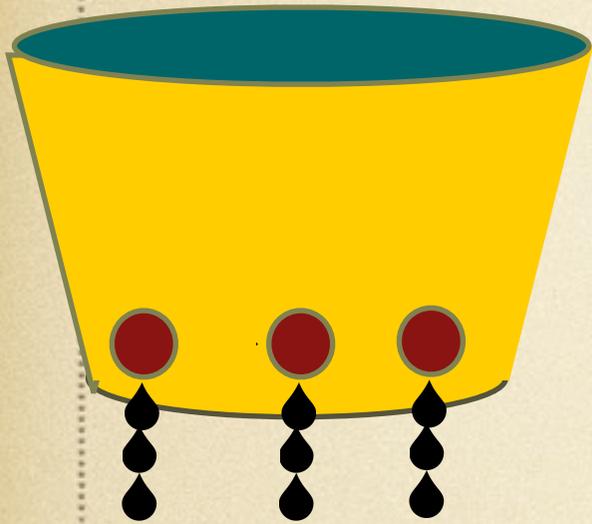
- Example:



- The stronger the couplings, and the larger the mass difference, the faster the decay:

$$N(t) = N(0) e^{-t/\tau} \quad \text{where } \tau = \tau(M, g) \text{ is the } \mathbf{life\ time}$$

Example: counting the number of neutrinos

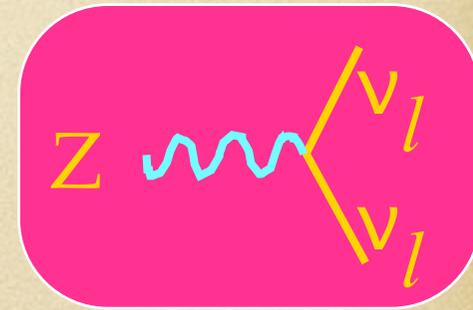
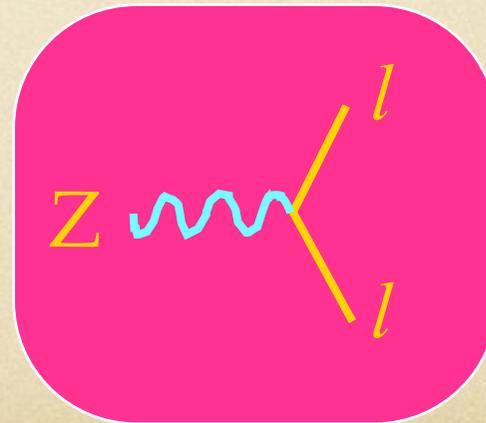


$$\tau \propto 1/(\text{number of holes}) \sim 1/(\text{number of decay channels})$$



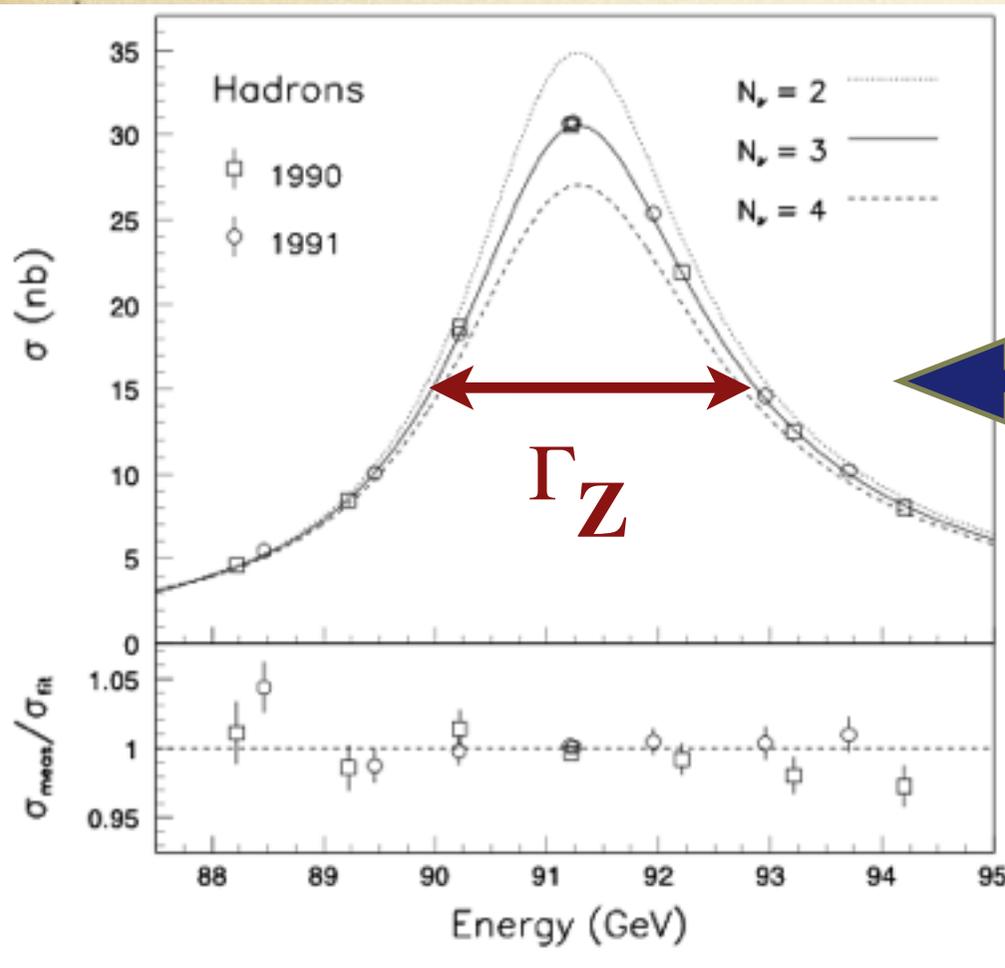
$$\tau(Z) = 1 / \Gamma(Z) \propto 1/\text{number of decay channels}$$

$$\Gamma(Z) = \sum_{q \setminus m_q < m_Z/2} \Gamma(Z \rightarrow q\bar{q}) + \sum_{\ell \setminus m_\ell < m_Z/2} \Gamma(Z \rightarrow \ell^+\ell^-) + \sum_{\nu \setminus m_\nu < m_Z/2} \Gamma(Z \rightarrow \nu\bar{\nu})$$



$$N_{\text{events}}(e^+e^- \rightarrow Z^0) \propto \left[(S - M_Z^2)^2 + M_Z^2 \Gamma_Z^2 \right]^{-1}$$

$\sqrt{S} = \text{Energy}(e^+e^-)$



LEP $e^+e^- \rightarrow Z^0$ data, showing that the number of neutrino species $N_\nu = 3$

The measurement of a width can tell us something about what is not directly seen! It's like knowing that there is a leak in your tank if your car runs out of petrol while sitting in the parking lot!

More in general, the measurement of a width will give us the strength of the coupling of the decaying particle to the decay products. The width (lifetime) itself is therefore not an "intrinsic" property of a particle, but is a consequence of its mass and of its interactions with other particles.

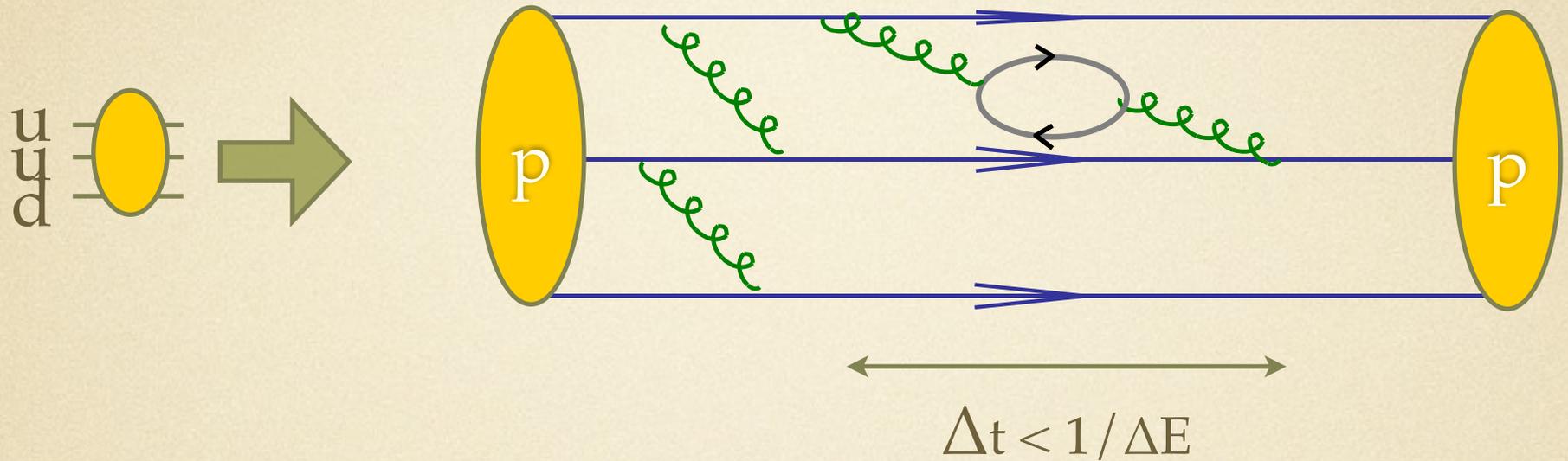
Level-I questions: Why?

- Why 3 families of quarks and leptons?
- Why some particles have mass?
- Why $m(\text{neutrino}) \sim 10^{-7} m(e)$?
- Why is there a matter-antimatter asymmetry in the Universe?
- Why $F_{\text{gravity}} \sim 10^{-40} F_{\text{electric}}$?
- Are particles really pointlike? Strings?? Membranes?
- Why $D=3+1$?
-
- Why something instead of nothing?

The goals of the LHC

- To firmly establish the “what”:
 - discover the crucial missing element of the Standard Model, namely the **Higgs boson => done !**
 - search for possible **new fundamental interactions**, too weak to have been observed so far
 - search for possible **new generations** of quarks or leptons
 - confirm / disprove the **elementary nature** of quarks / leptons
 - discover direct evidence for the particle responsible for the **Dark Matter** in the Universe
- To firmly establish the “how”: the observation of the Higgs boson, and the determination of its properties, will complete the dynamical picture of the Standard Model, confirming (hopefully!) our presumed understanding of “how” **particles acquire a mass.**
- To seek new elements which can help us shed light on the most difficult question, namely **WHY?**

The structure of the proton



Inside the proton we can find, in addition to the component **uud** quarks, also **gluons** as well as **quark-antiquark** pairs

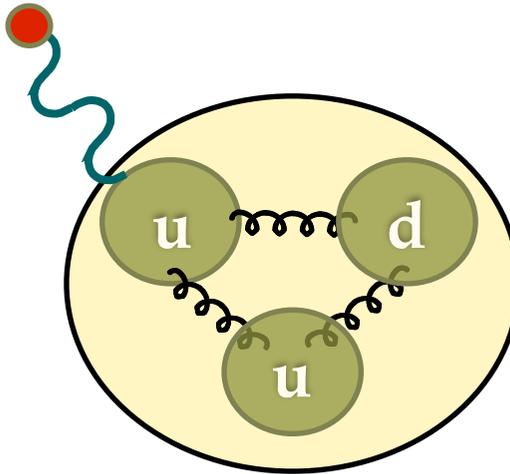
If we probe the proton at energies high enough, we take a picture of the proton with a very sharp time resolution, and we can “detect” the presence of these additional components. In particular, the gluons and antiquarks present inside will participate in the reactions involving proton.

Notice that, if Δt is small enough, even pairs of quark-antiquark belonging to the heavier generations (e.g. s - \bar{s} , c - \bar{c}) can appear!!
The proton can contain quarks heavier than itself!!

Probing the proton structure

If the energy with which we probe the proton is small, the proton holds together, and it simply bounces off

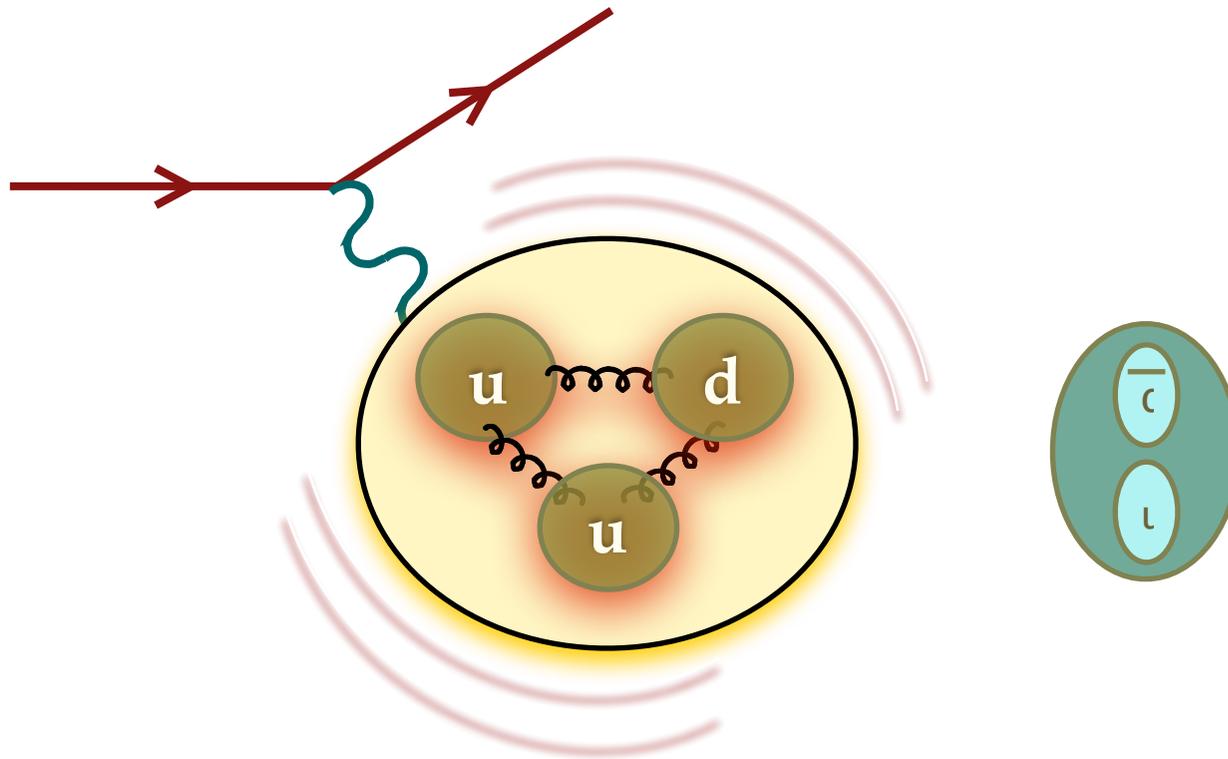
electron



From the detailed experimental study of this process, we learned that the proton behaves like an extended object, with a charge radius of $O(10^{-12} \text{ cm})$

Probing the proton structure

If the energy transferred by the probe is large enough, we can excite the proton, giving rise to a baryonic “resonance”

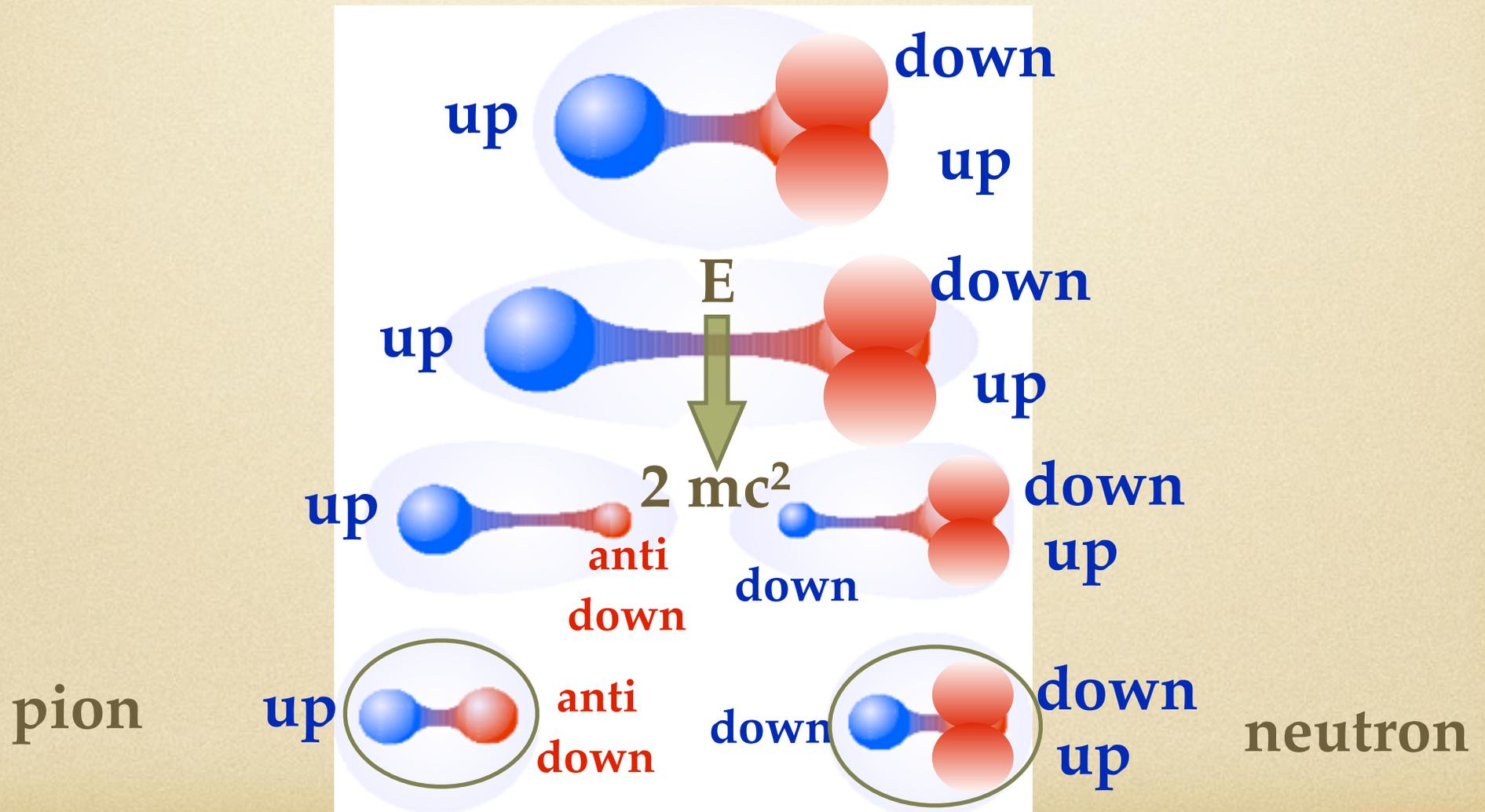


The study of this process helped understanding the nature of the forces that hold together quarks

.... which decays to a proton and a pion

Quarks inside a proton:

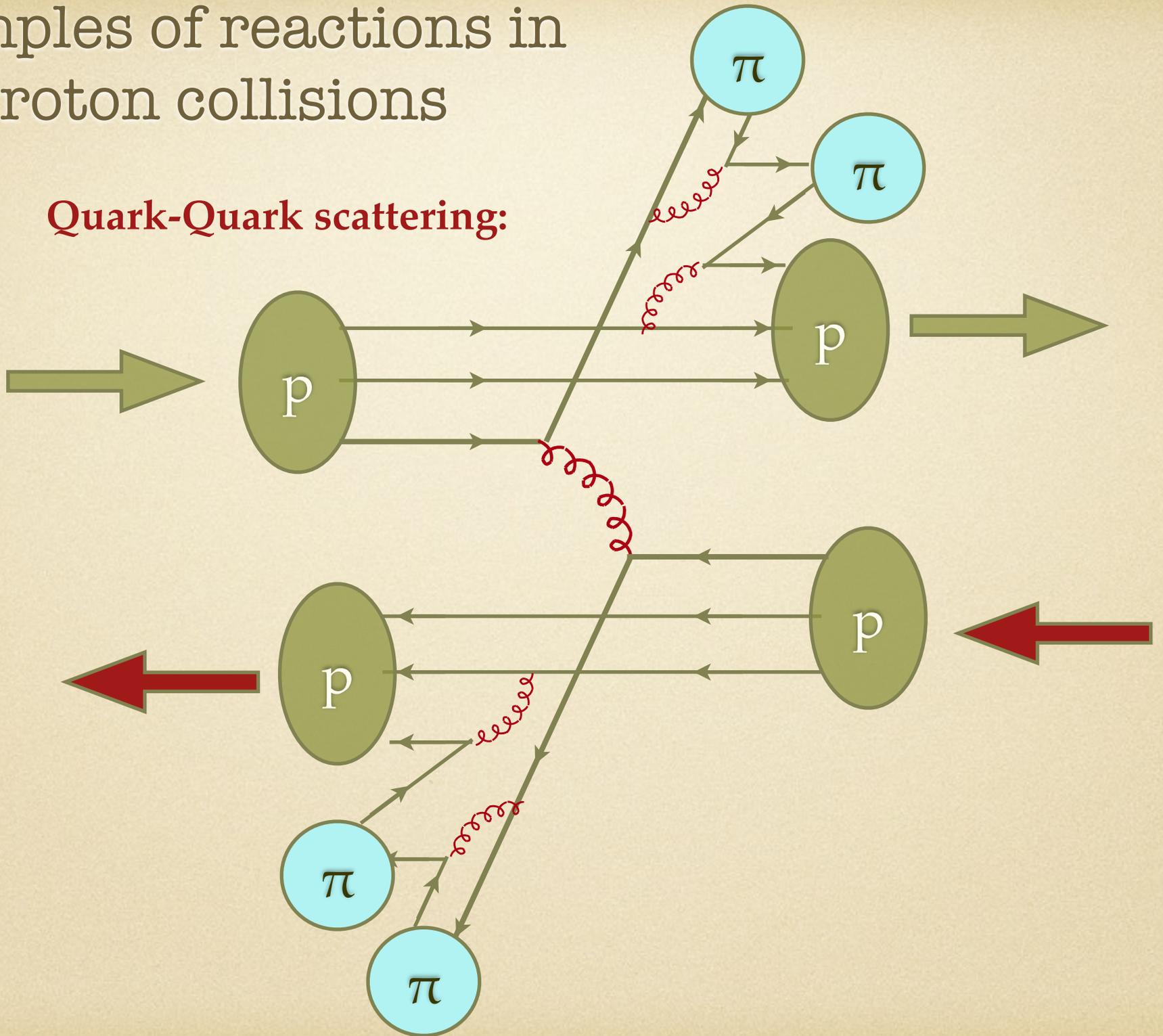
they can't be separated nor extracted from it. If we try, the energy we need to inject in the system is transformed into a new quark-antiquark pair, which screens the individual quark



As the energy put into the system becomes larger and larger (w.r.t. the quark masses), it is possible to form multiple quark-antiquark pairs, and the proton breaks up into a multitude of particles

Examples of reactions in proton collisions

Quark-Quark scattering:

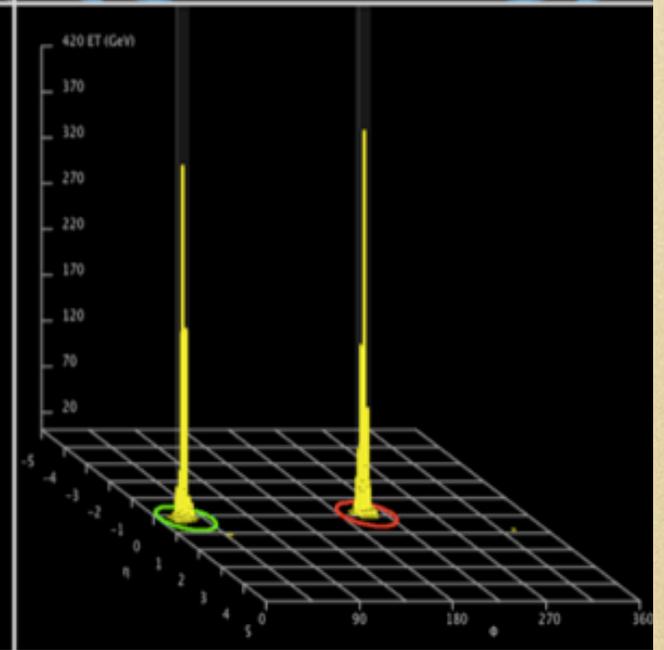
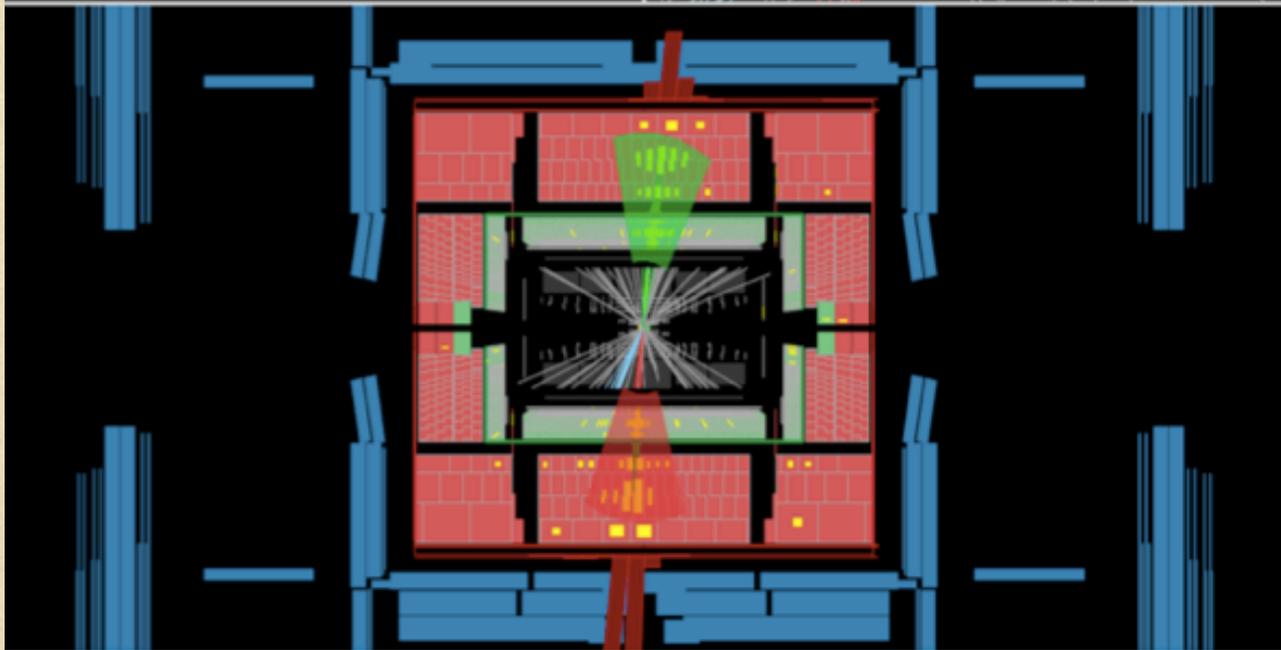
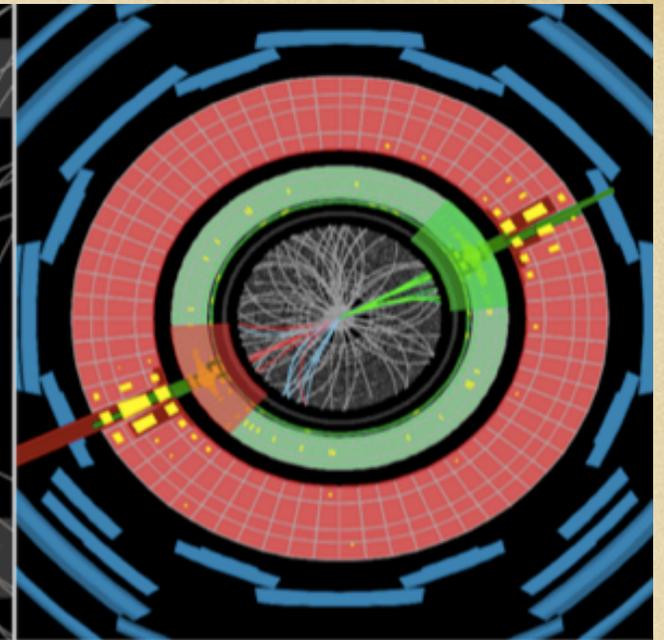
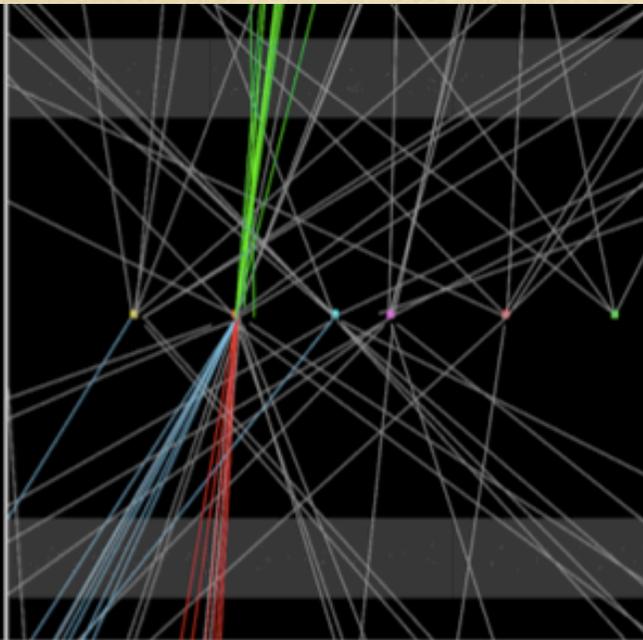




ATLAS EXPERIMENT

Run Number: 201006, Event Number: 55422459

Date: 2012-04-09 14:07:47 UTC



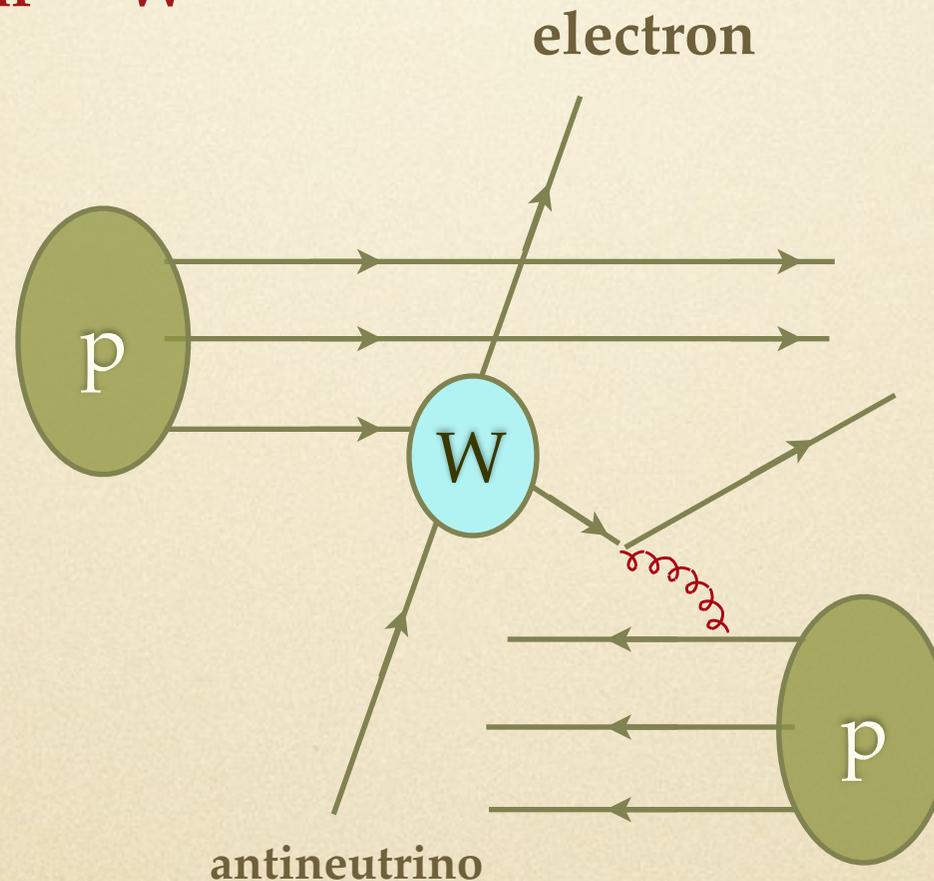
Leading jets 1.96 & 1.65 TeV. Invariant mass 3.81 TeV

Real-life example of jets produced at the LHC

Examples of reactions in proton collisions

Quark-Antiquark annihilation:

$$u \bar{d} \rightarrow W$$

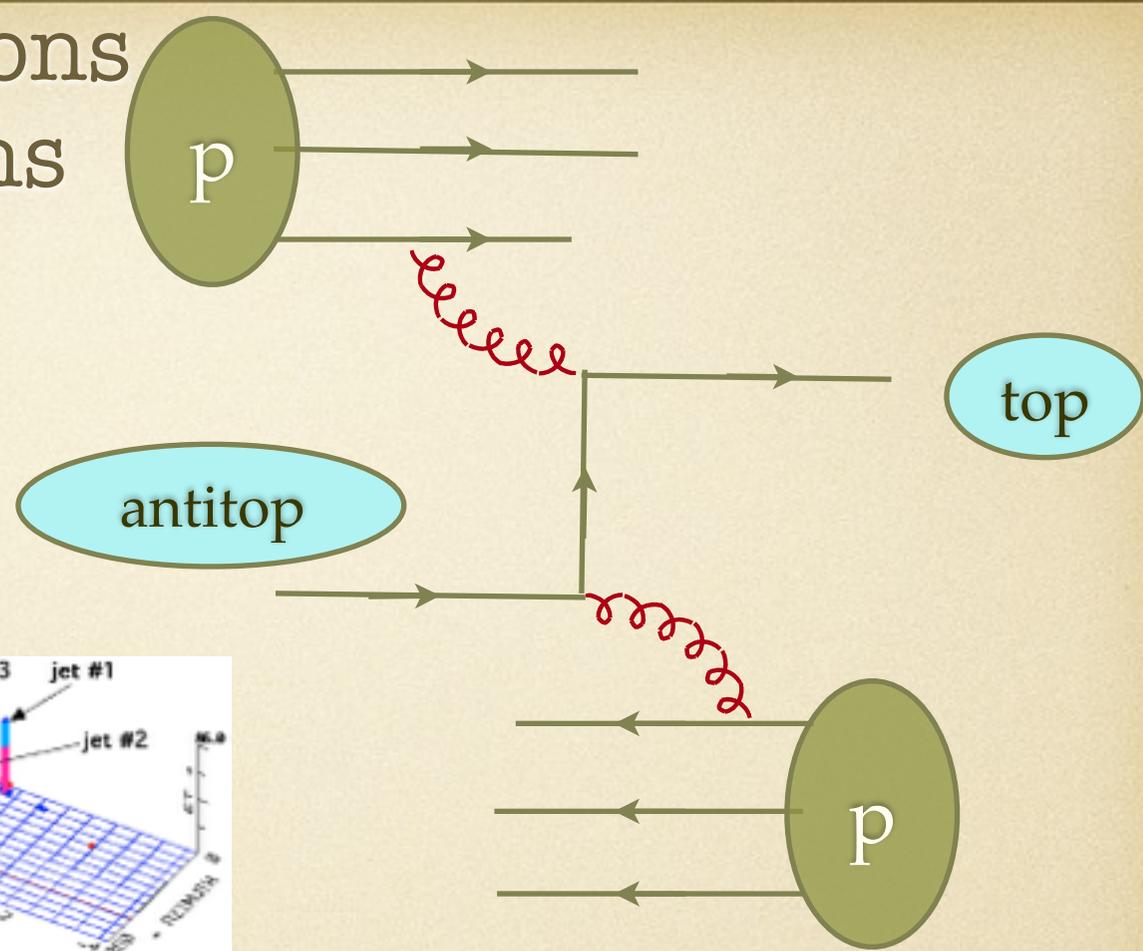


In principle the “force carrier” of new interactions could be created in the same way, provided their mass is not too large

Examples of reactions in proton collisions

gluon-gluon reactions:

$gg \rightarrow \text{top antitop}$



e + 4 jet event

40758_44414

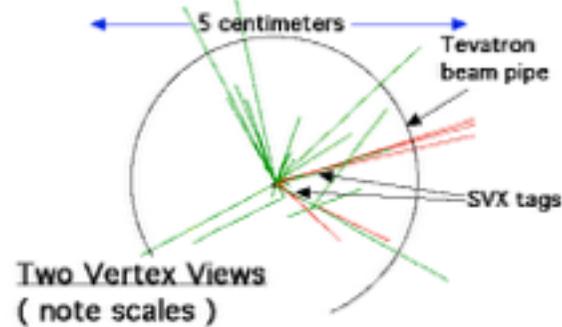
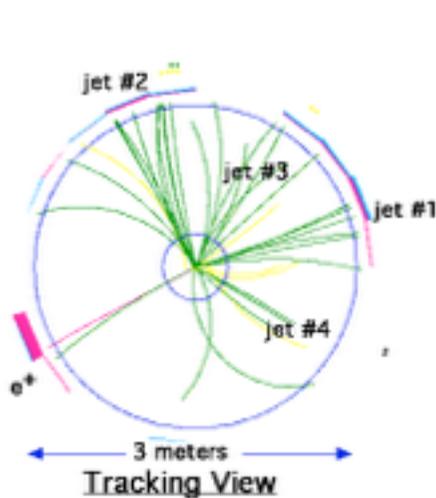
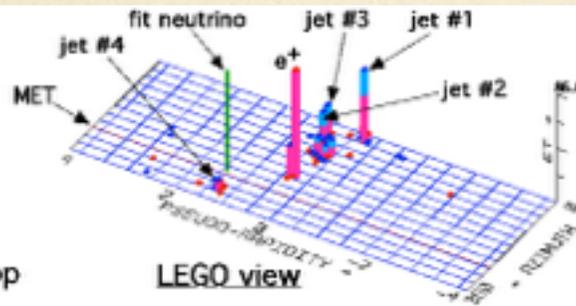
24-September, 1992

TWO jets tagged by SVX

fit top mass is 170 ± 10 GeV

e^+ , Missing E_T , jet #4 from top

jets 1,2,3 from top (2&3 from W)



The Higgs boson

La massa delle particelle elementari

$m = E/c^2 \Rightarrow$ per un sistema composto, la massa e' ottenuta risolvendo le equazioni della dinamica dello stato legato, con

$$E = (\text{energia cinetica}) + (\text{energia potenziale})$$

Dunque $m_p = 938 \text{ MeV}$ richiede di capire un "come", non un "perche'"

Diverse le cose per particelle elementari: infatti
elementare \Rightarrow nessuna dinamica interna



Occorre sviluppare una teoria che spieghi cosa sia la massa per particelle elementari, e che ne determini il valore particella per particella

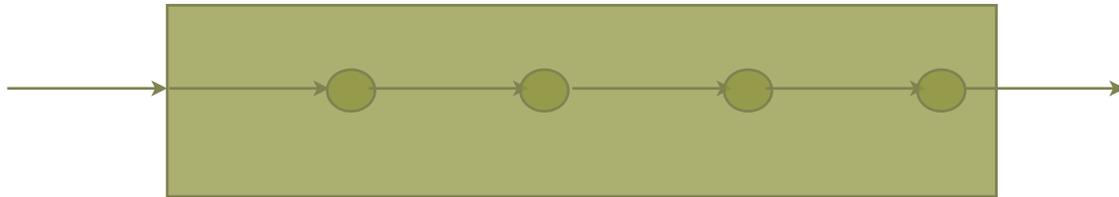
Il vuoto ed il campo di HIGGS

Il “vuoto” , cioè lo stato di riposo di ogni volume di spazio nell’universo, e’ occupato da una densita’ costante del campo di una particella, il bosone di Higgs”, che permea l’universo come un etere

Le interazioni delle particelle con questo campo di fondo, determinano, fra le altre cose, la loro massa

Il bosone di Higgs e la massa delle particelle elementari

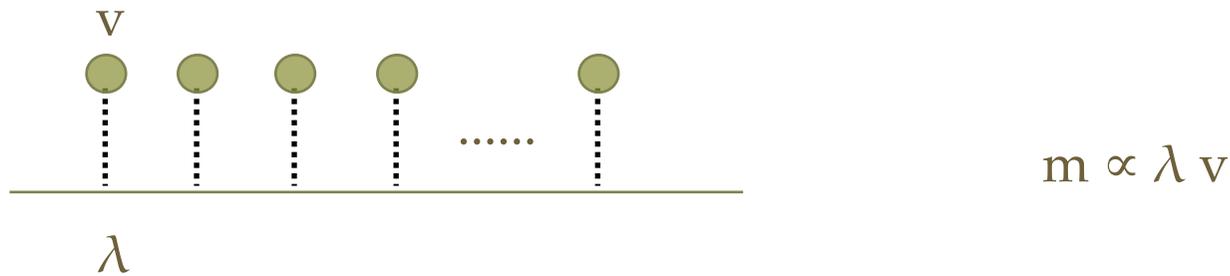
La luce che si propaga in un mezzo “rallenta” a causa delle continue interazioni col mezzo stesso



Il tempo necessario per attraversare il mezzo e' maggiore che se la luce attraversasse il vuoto

$$\Rightarrow c_{\text{medium}} < c_{\text{vacuum}}$$

Il campo di Higgs e' un mezzo continuo in cui l'universo e' immerso. Le particelle, interagendo con esso, acquistano l'inerzia caratteristica delle particelle con massa.



La quantità “ v ” è una proprietà universale dello stato del campo di Higgs che permea l’universo.

La quantità “ λ ” è caratteristica della particella.

Grande λ vuol dire grande massa, con $m \propto \lambda v$

Ora la domanda “**perché una certa particella ha massa m ?**” è rimpiazzata da “**perché una certa particella si accoppia al campo di Higgs con intensità $\lambda \propto m / v$?**”

Tuttavia almeno ora abbiamo un modello matematico per capire **come** le particelle acquistino massa

Note on “the mass of the Universe”

- proton's mass arises from QCD dynamics, not from the mass of its constituent quarks. Half of it is kinetic energy of the tightly bound relativistic quarks, the other half is binding energy ($M=Ec^2$, $E=K+U$, virial theorem....)

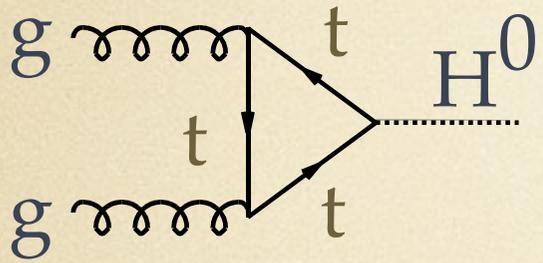
- the mass of particles composing Dark Matter does not need to arise from the coupling with the Higgs. E.g. in Supersymmetry models it could mostly come from the breaking of supersymmetry, nothing to do with the Higgs

La produzione e rivelazione del bosone di Higgs

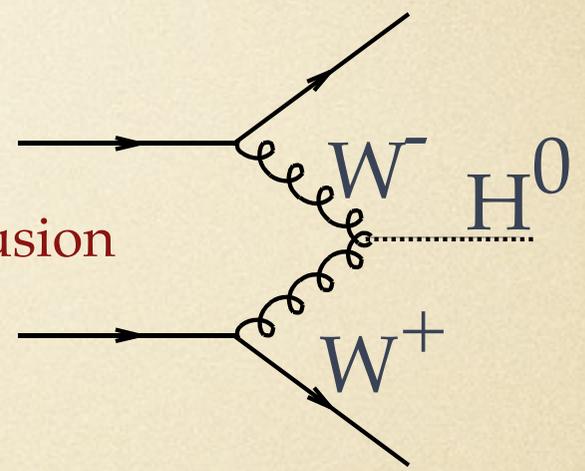
Come ogni altro mezzo continuo, il campo di Higgs puo' essere perturbato. Come succede quando colpiamo un tavolo con un martello, creando onde sonore, se riusciamo a scuotere il campo di Higgs possiamo creare "onde di Higgs". Queste "onde" si manifestano come "particelle", il bosone di Higgs per l'appunto, secondo il solito principio di dualita' onda-corpuscolo della meccanica quantistica.

Far ciò richiede concentrare in un piccolo volume particelle di massa grande (per avere una forte interazione col campo di Higgs) e con sufficiente energia ⇒ LHC !!!

Higgs: Four main production mechanisms



Gluon-gluon fusion

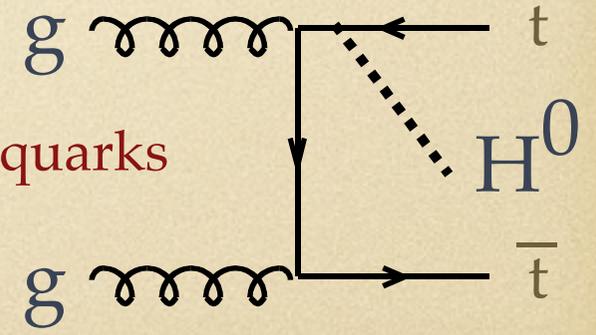


Vector boson fusion

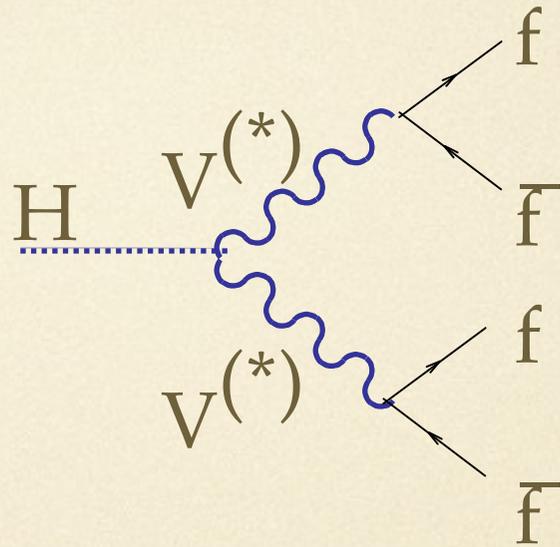
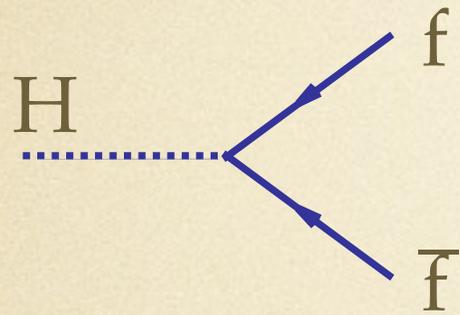


Radiation from vector bosons

Radiation from top quarks

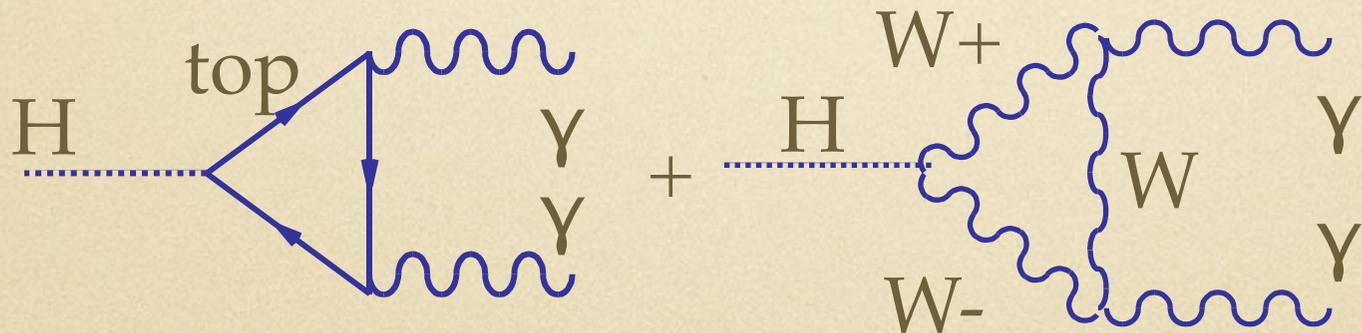


Higgs decays



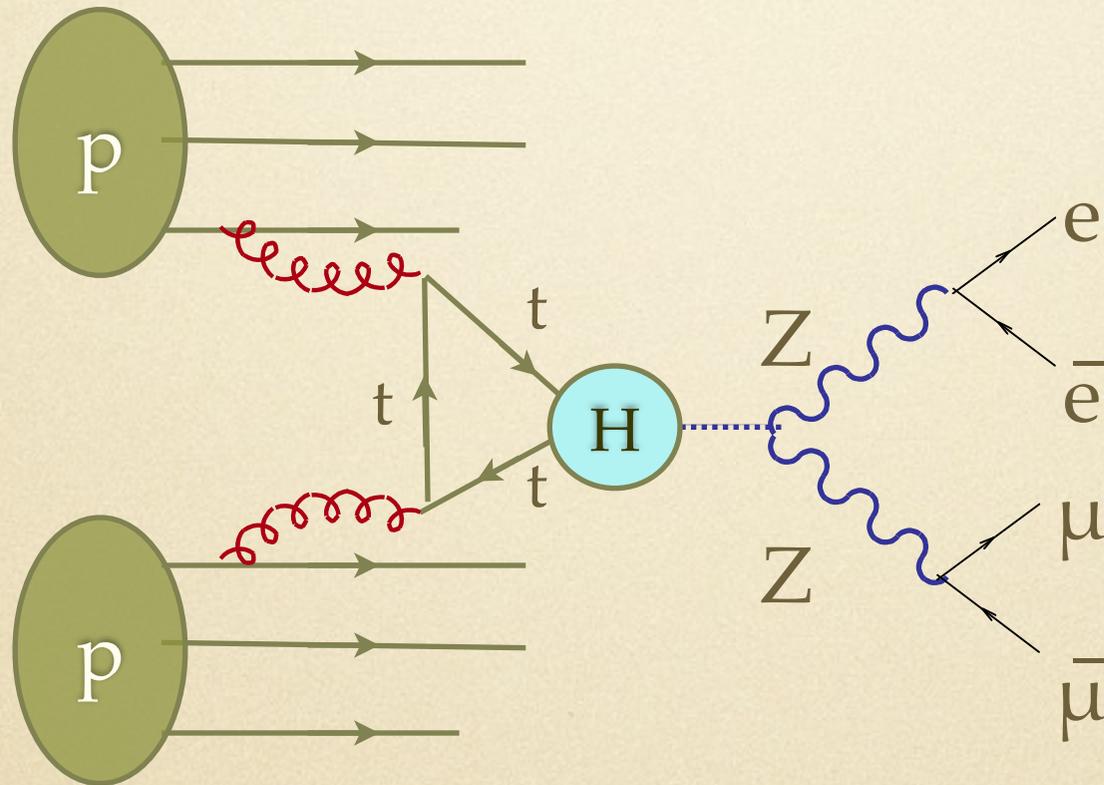
f = quarks or leptons

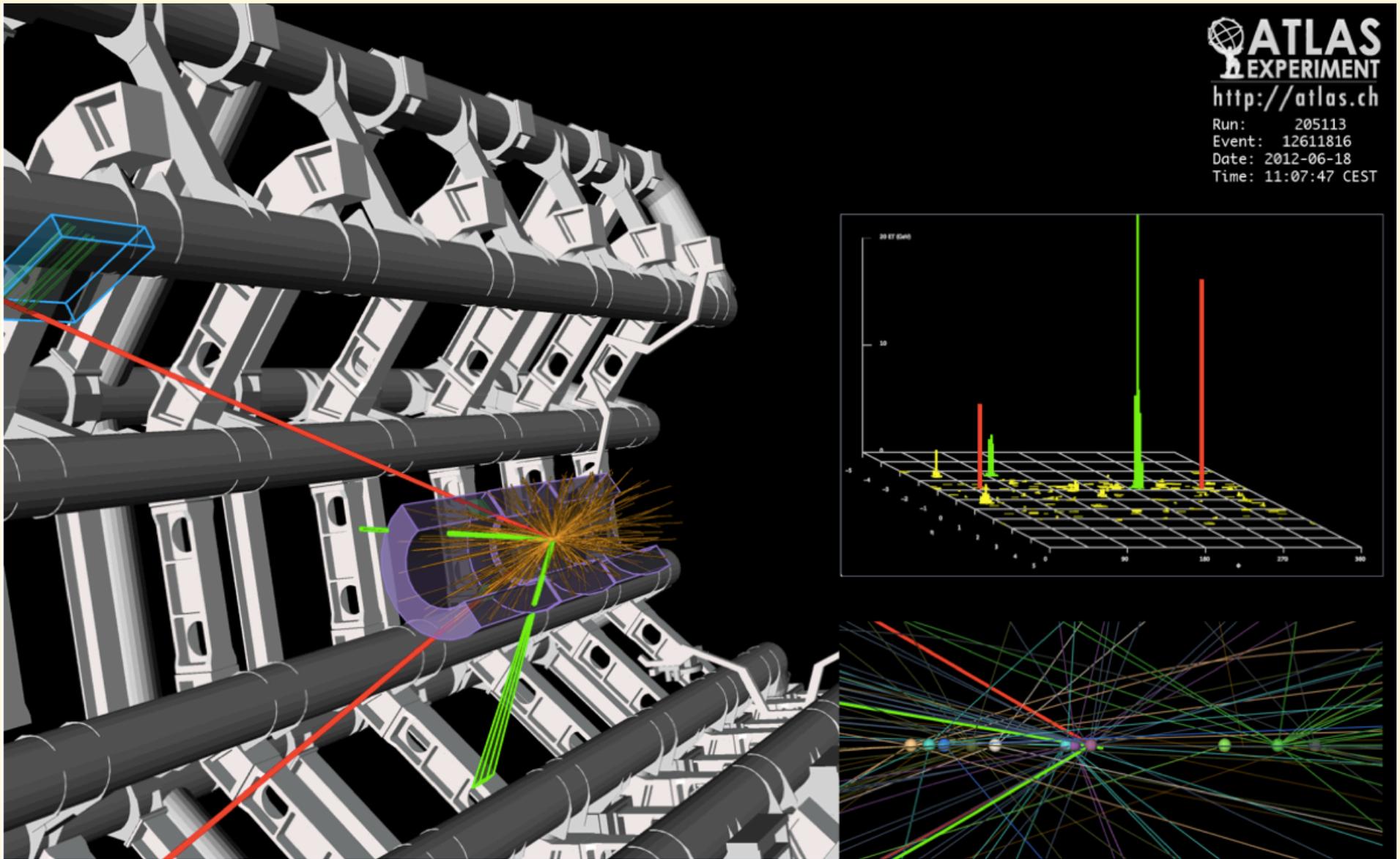
V = W or Z



Examples of reactions in proton collisions

Produzione di Higgs





Higgs candidate event, in ATLAS, with $H \rightarrow ZZ^* \rightarrow \mu^+ \mu^- e^+ e^-$

The things I didn't talk about

- Supersymmetry
- Superstrings
- Dark energy
- Matter-antimatter asymmetry of the Universe
- Quark-gluon plasma