La fisica delle particelle e la ricerca delle leggi fondamentali della natura

Visita studenti Università di Pisa
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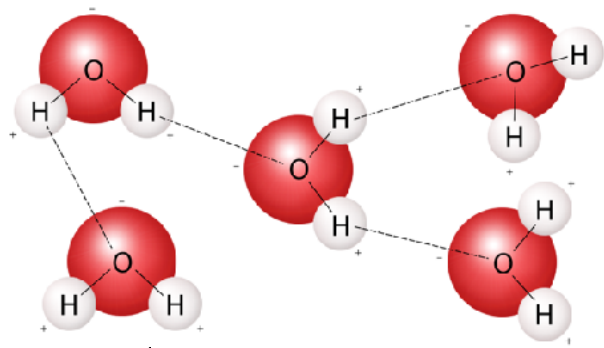
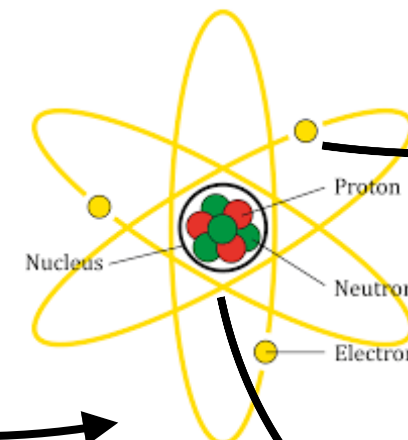
Materia

Molecole

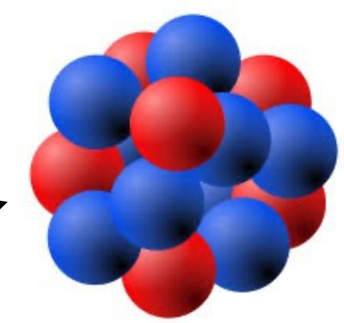


Atomi



elettroni

nucleo



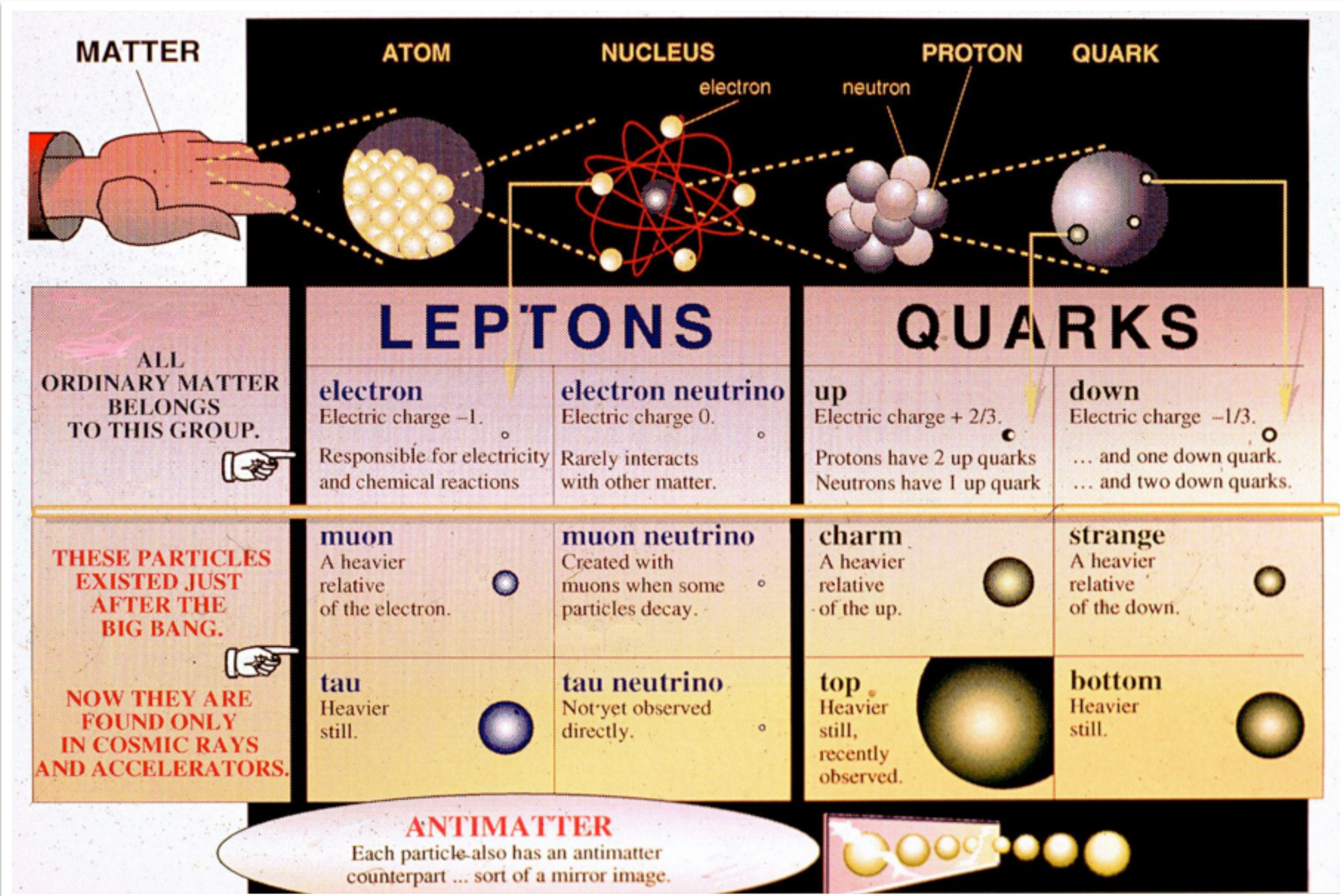
protoni

neutroni

Di cosa sono fatti elettroni, protoni, neutroni?

==>> FISICA DELLE PARTICELLE

Il Modello Standard



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^+ W bosons	80.39	+1
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 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	4 10^{-4}	1	60

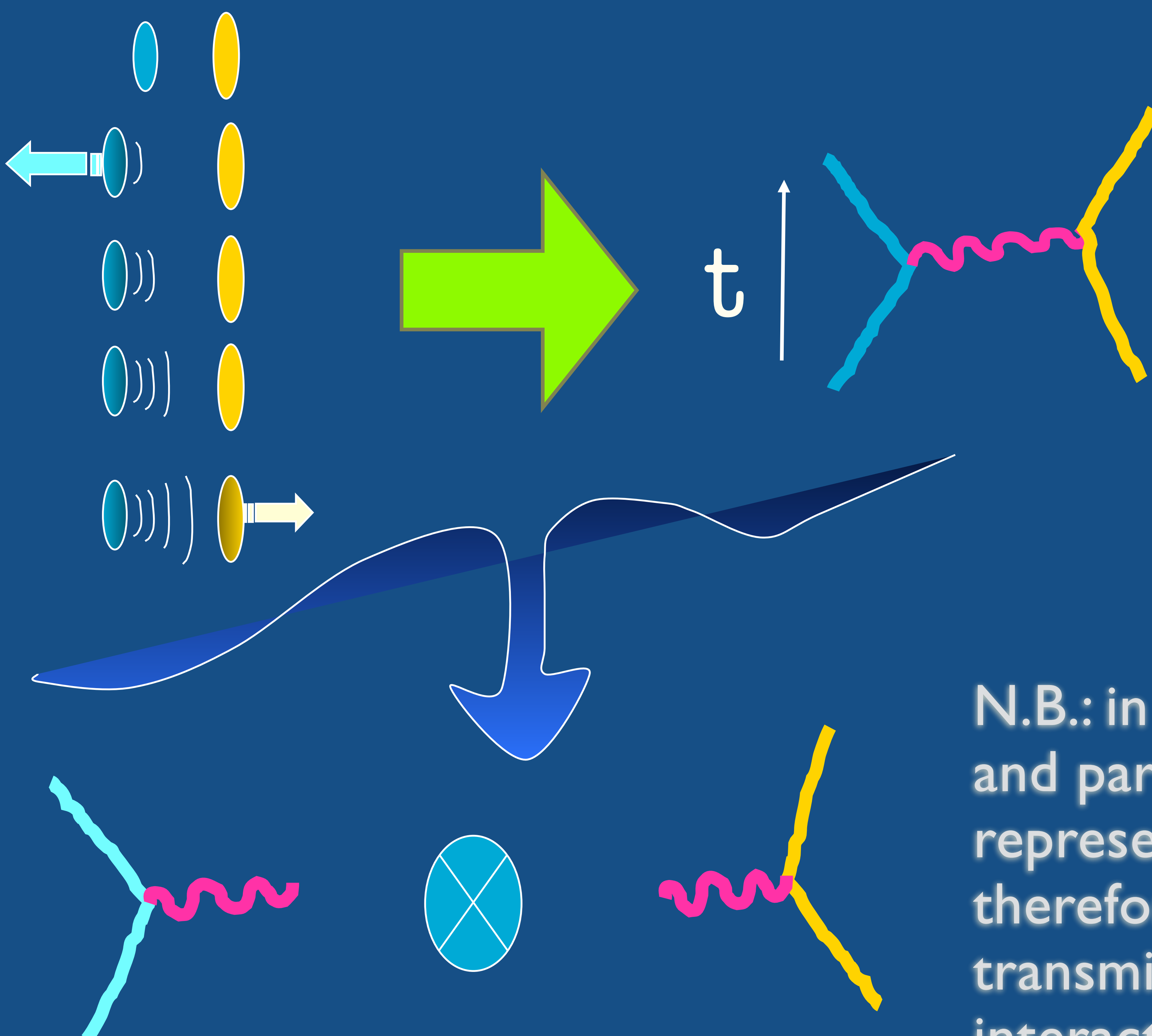
More on the role of Special Relativity

- Elementary particles have very tiny masses, and the forces present in the accelerators, as well as in the Universe, can easily accelerate them to speeds close to the speed of light.

- **Relativistic effects are therefore essential**, and the description of the behavior of elementary particles should be consistent with the laws of special relativity.

- In particular, any model of interactions should fulfill the principle that forces cannot be transmitted over distances instantaneously

The representation of interactions

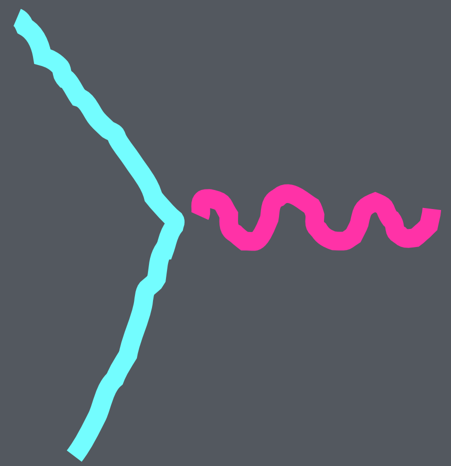


Feynman diagram

Locality

N.B.: in quantum mechanics waves and particles are different representations of the same object; therefore to the wave which transmits the signal of the interaction we should associate a particle.

Simple ... but subtle!



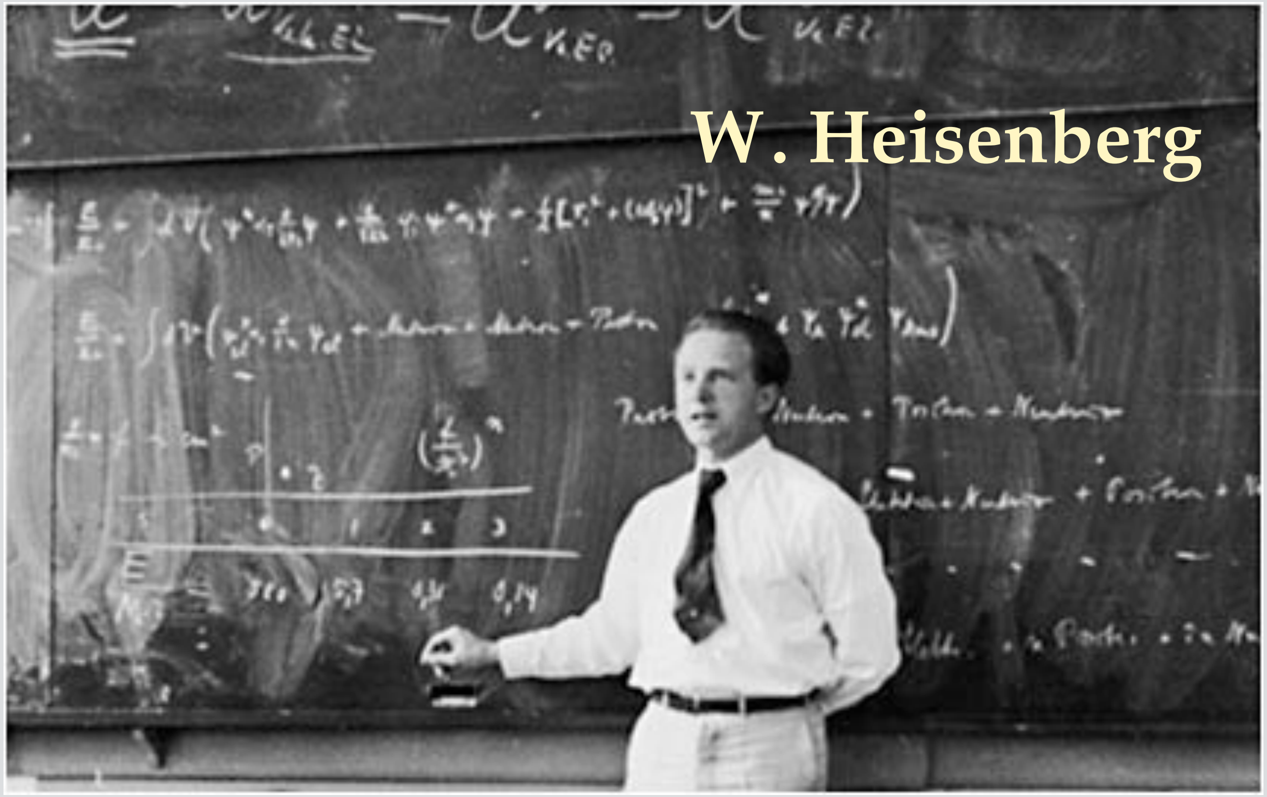
before:

after: +

$$\text{Energy(after)} \neq \text{Energy(before)}$$

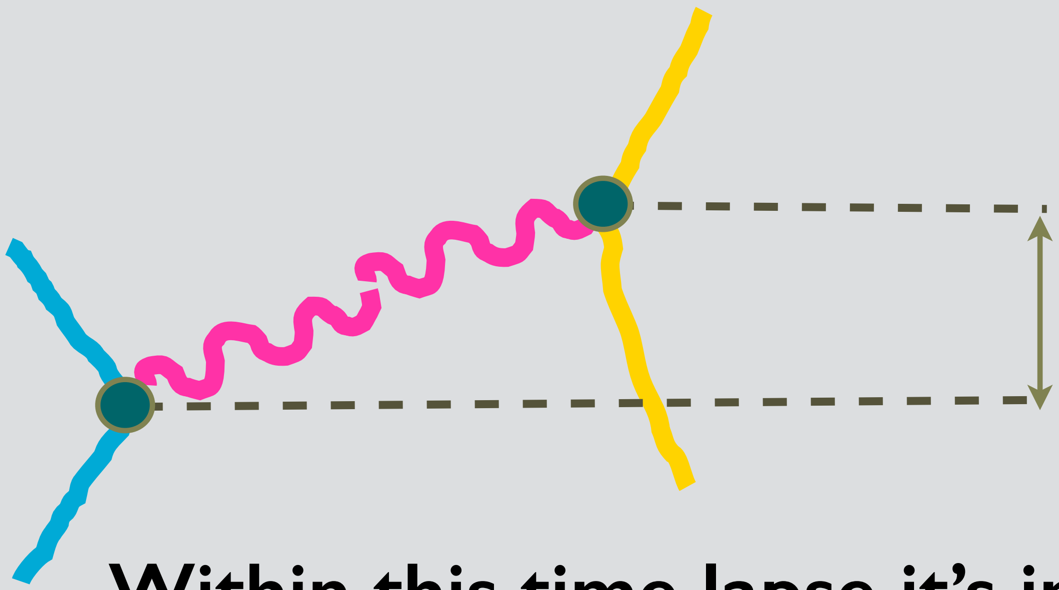
What happens to energy conservation ?!

Quantum mechanics



Heisenberg uncertainty principle:

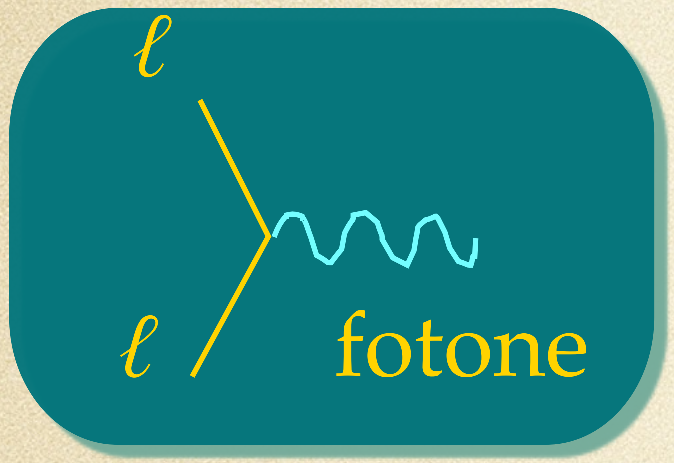
an energy measurement performed within a short time Δt can at best reach a precision $\Delta E \geq 1/\Delta t$



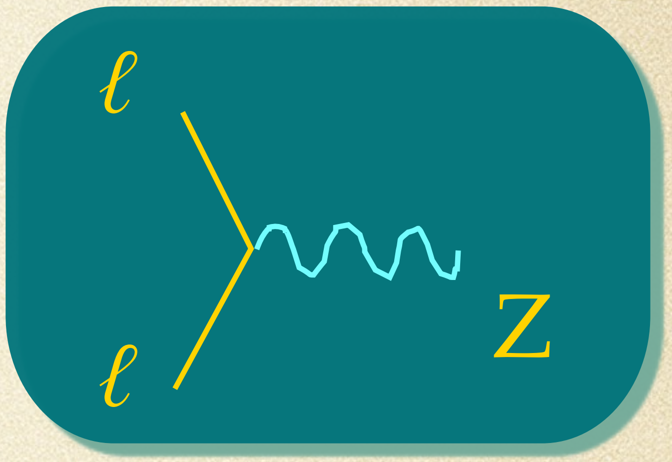
$\Delta t < 1/\Delta E$

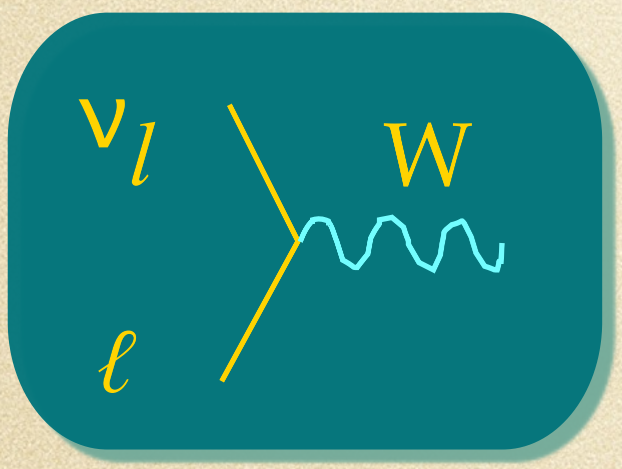
Within this time lapse it's impossible to determine whether energy is conserved or not, since we can't measure it accurately enough. Therefore it's possible to "cheat" nature, and allow the exchange of energy between the two particles

Interazioni dei leptoni ($\ell = e, \mu, \tau$)

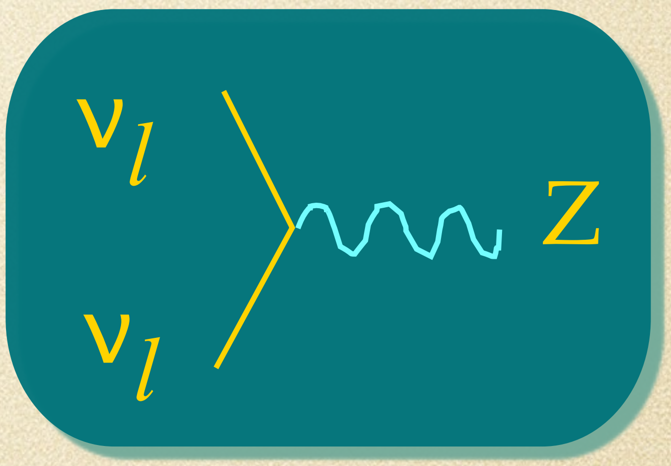


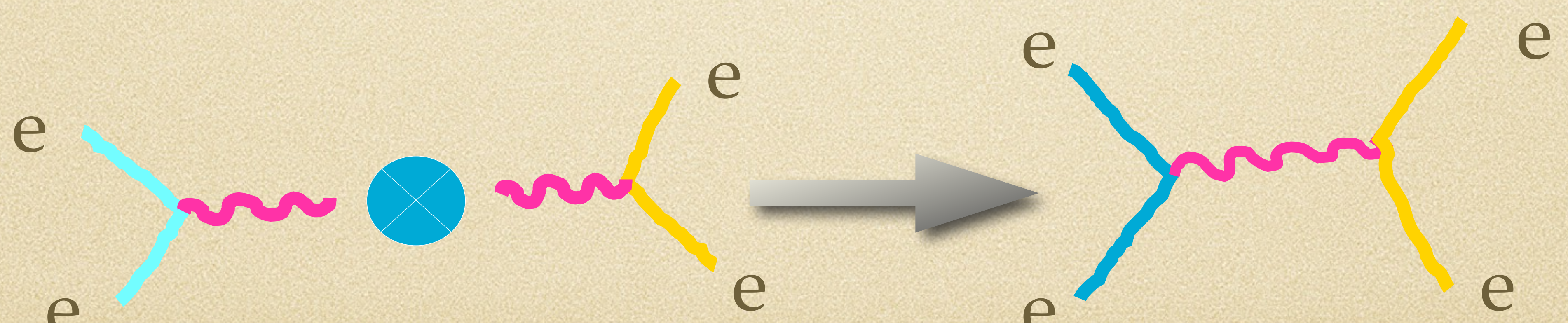
$\propto -e$ = electric charge





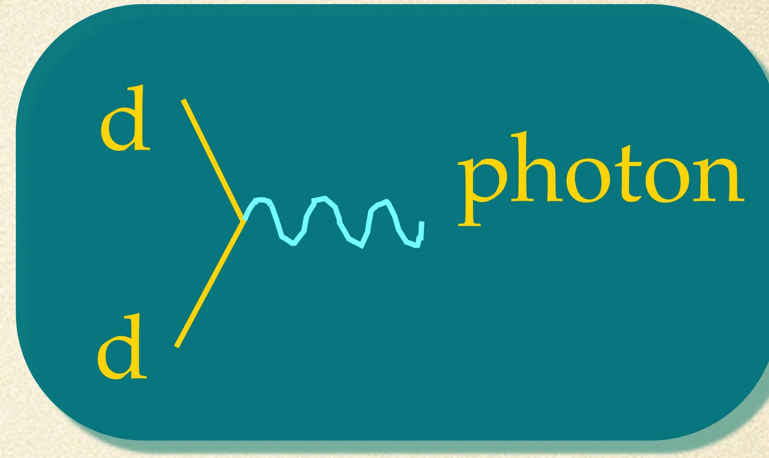
$\propto g_W$ = weak charge



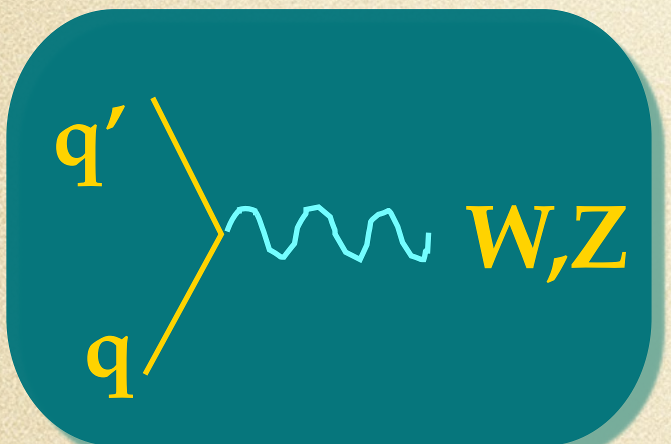


Interazioni dei quarks

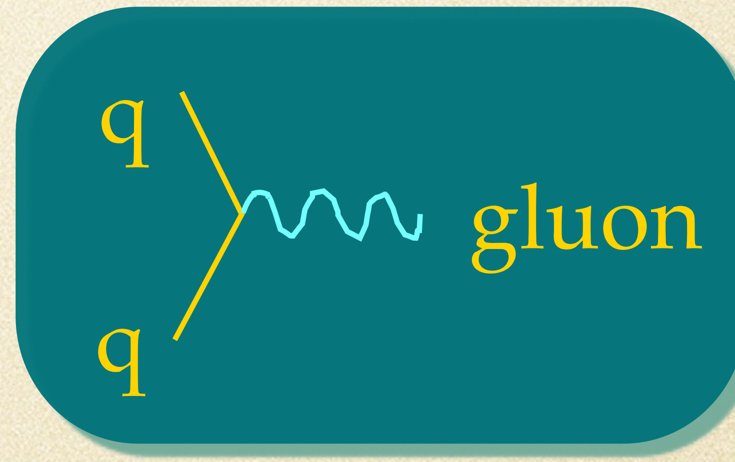
$\propto 2/3\ e$



$\propto -1/3\ e$

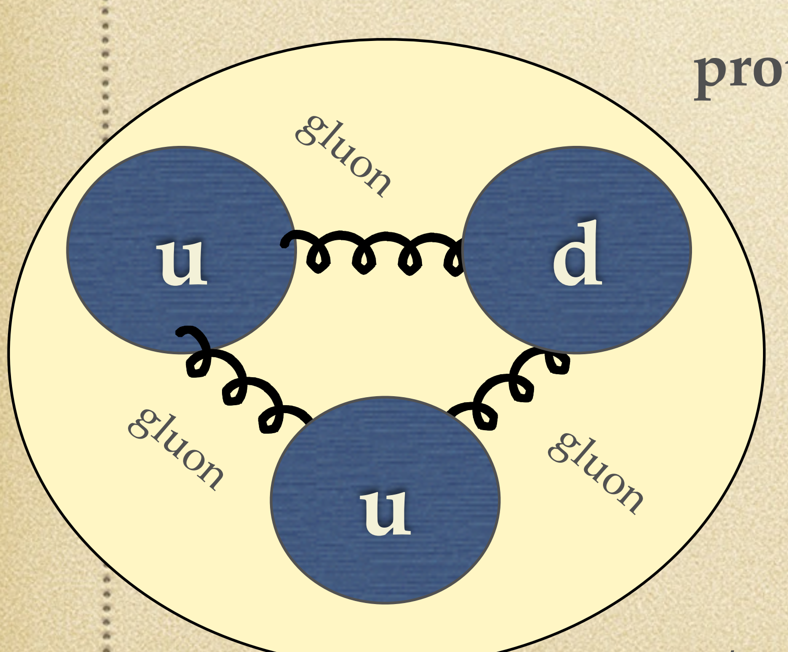


$\propto g_W$



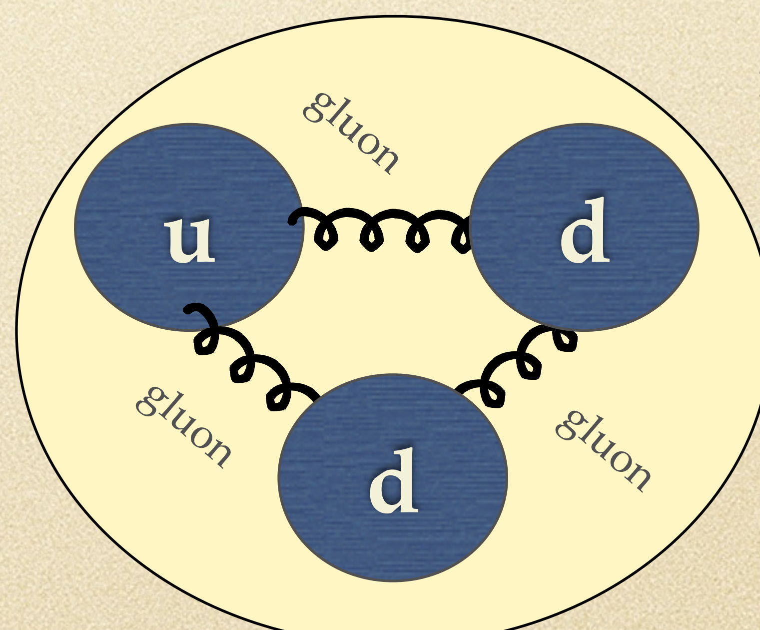
$\propto g_S$

protone



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

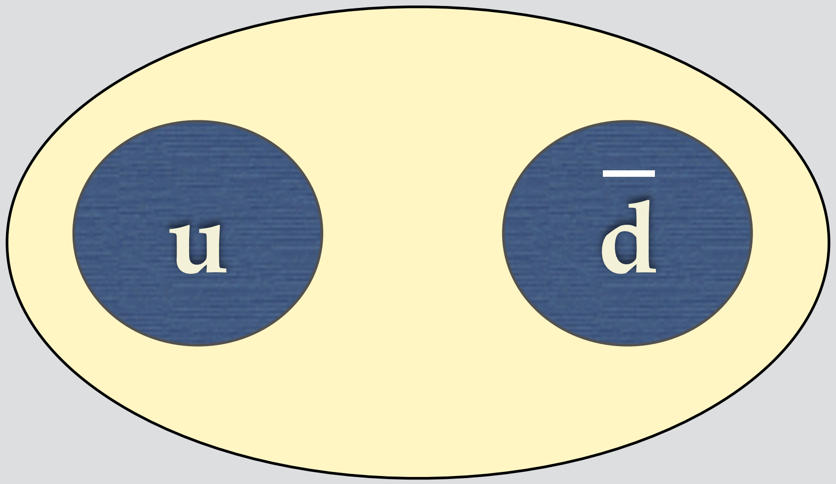
neutrone



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

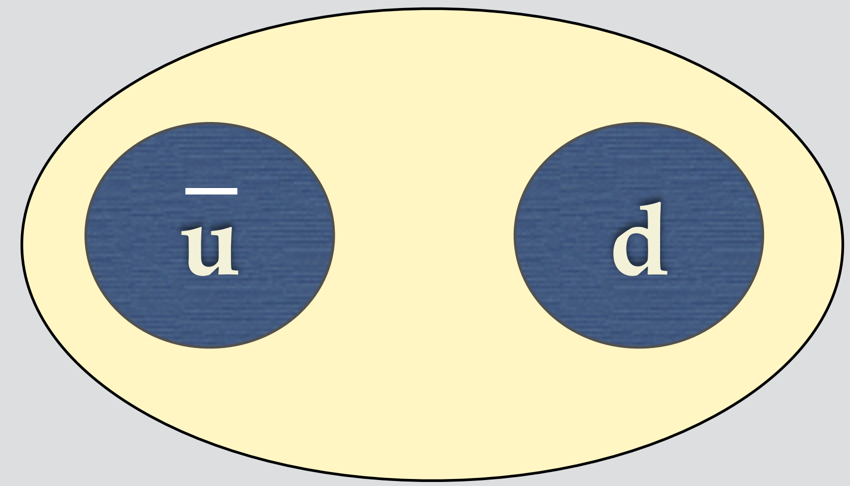
Pions

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



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

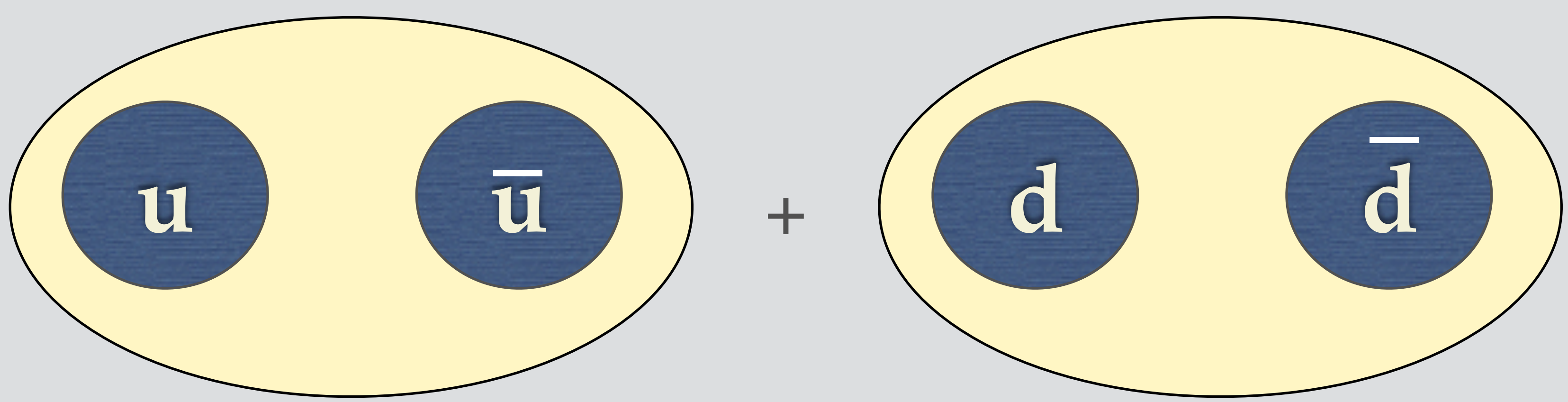
$\pi^{-} = \bar{u}d$



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

where $\bar{\mathbf{q}}$ is the **antiquark** of the quark **q**

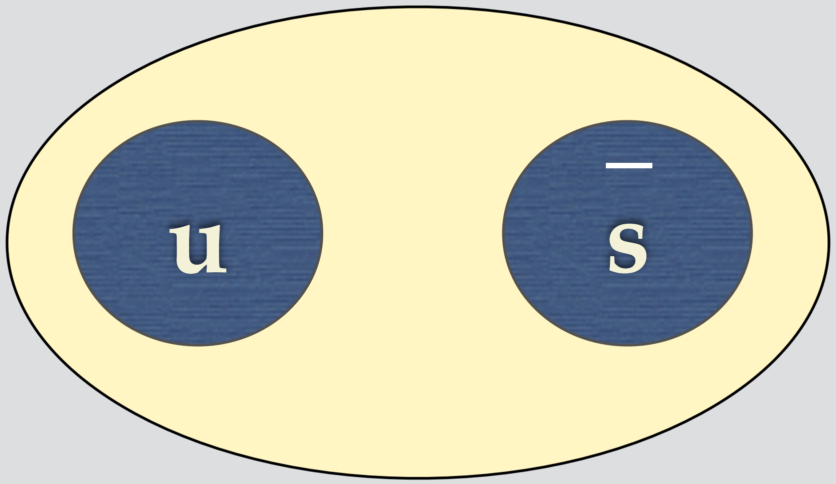
$\pi^{0} = d\,\bar{d} + u\,\bar{u}$



$Q = 0$

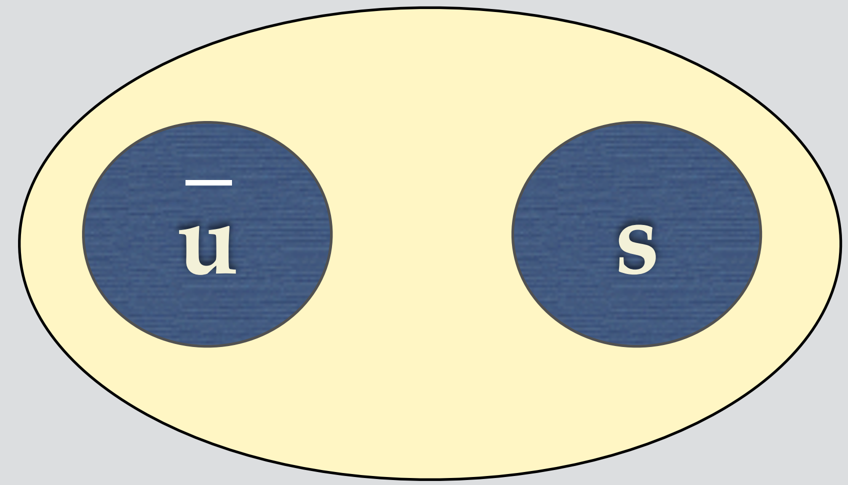
Kaons

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



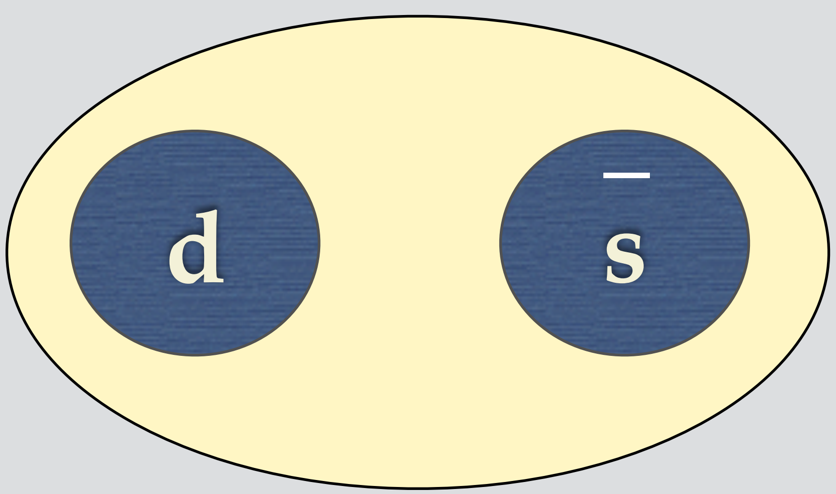
$Q = 2/3\,e + (-)(-1/3)\,e = e$

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



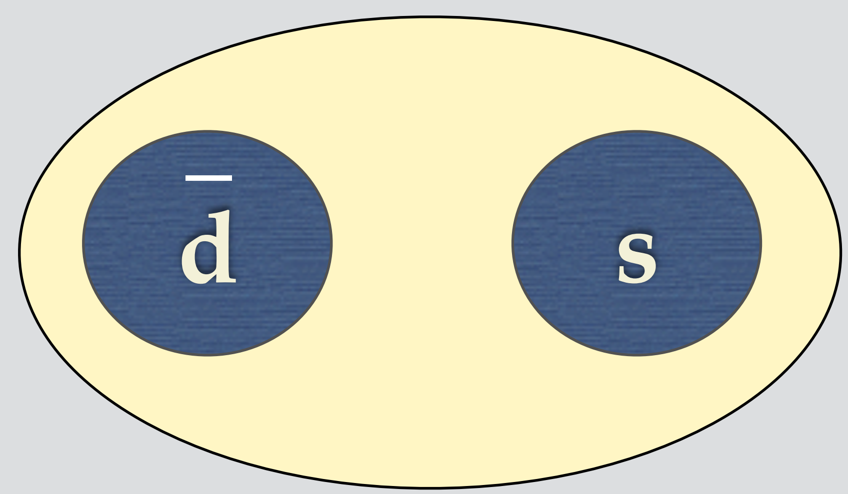
$Q = -\,2/3\,e + (-1/3)\,e = -\,e$

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



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

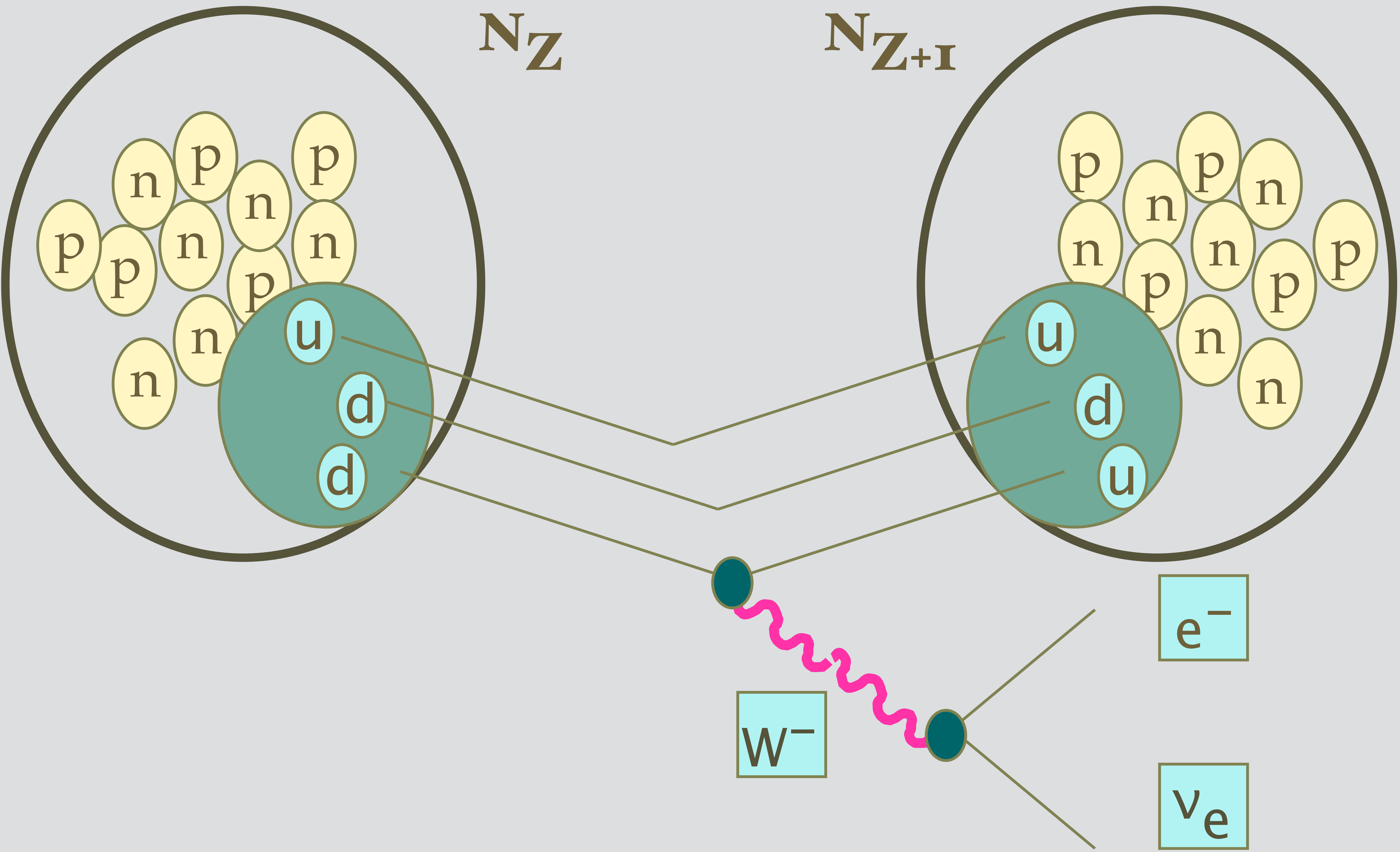
$K^{0} = \bar{d}s$



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

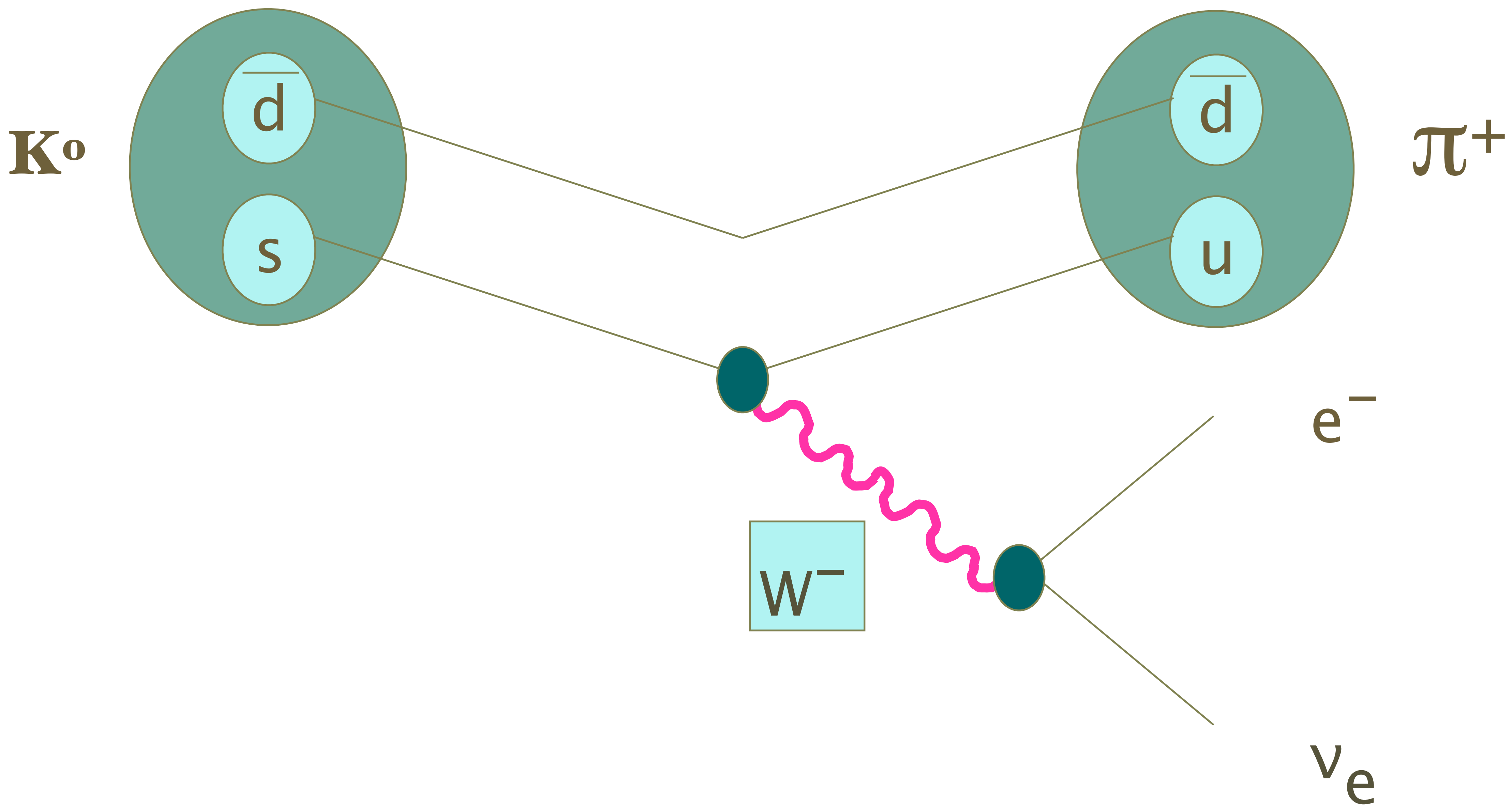
Example: radioactivity

$N_Z \to N_{Z+1}\ e\ \nu$



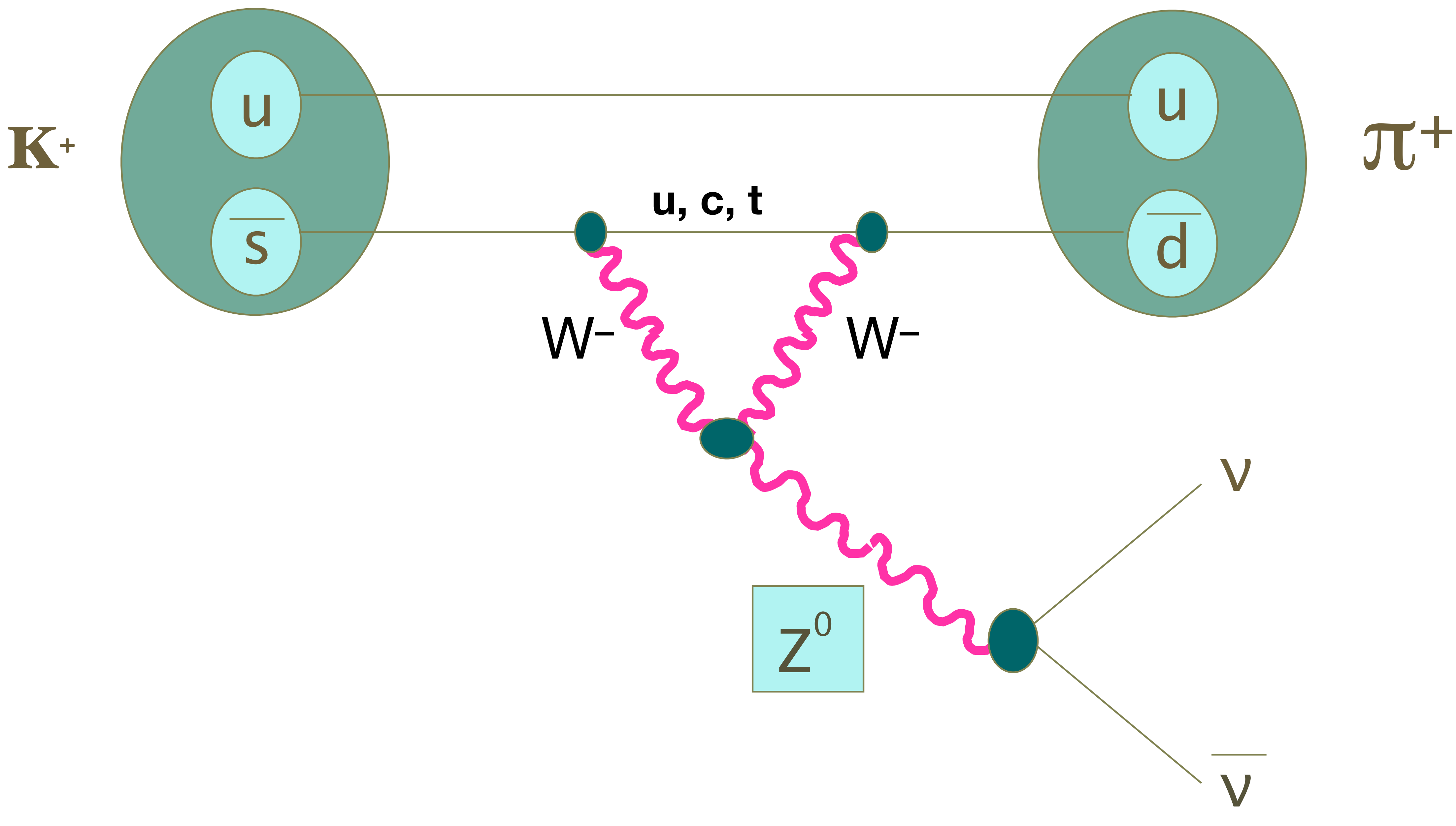
.... kaon decay

$K^o \rightarrow \pi^+ e \nu$



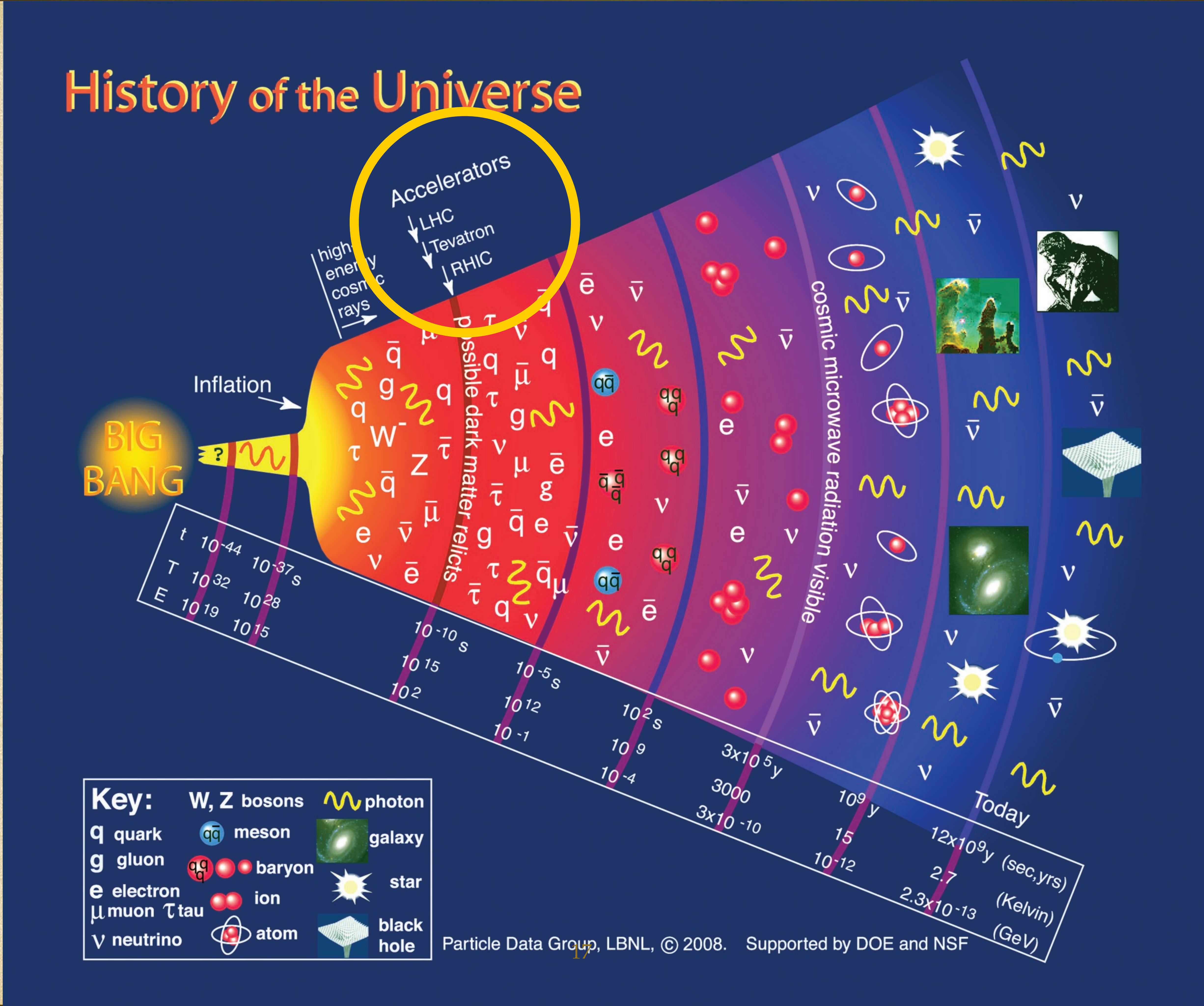
.... rare kaon decay in NA62

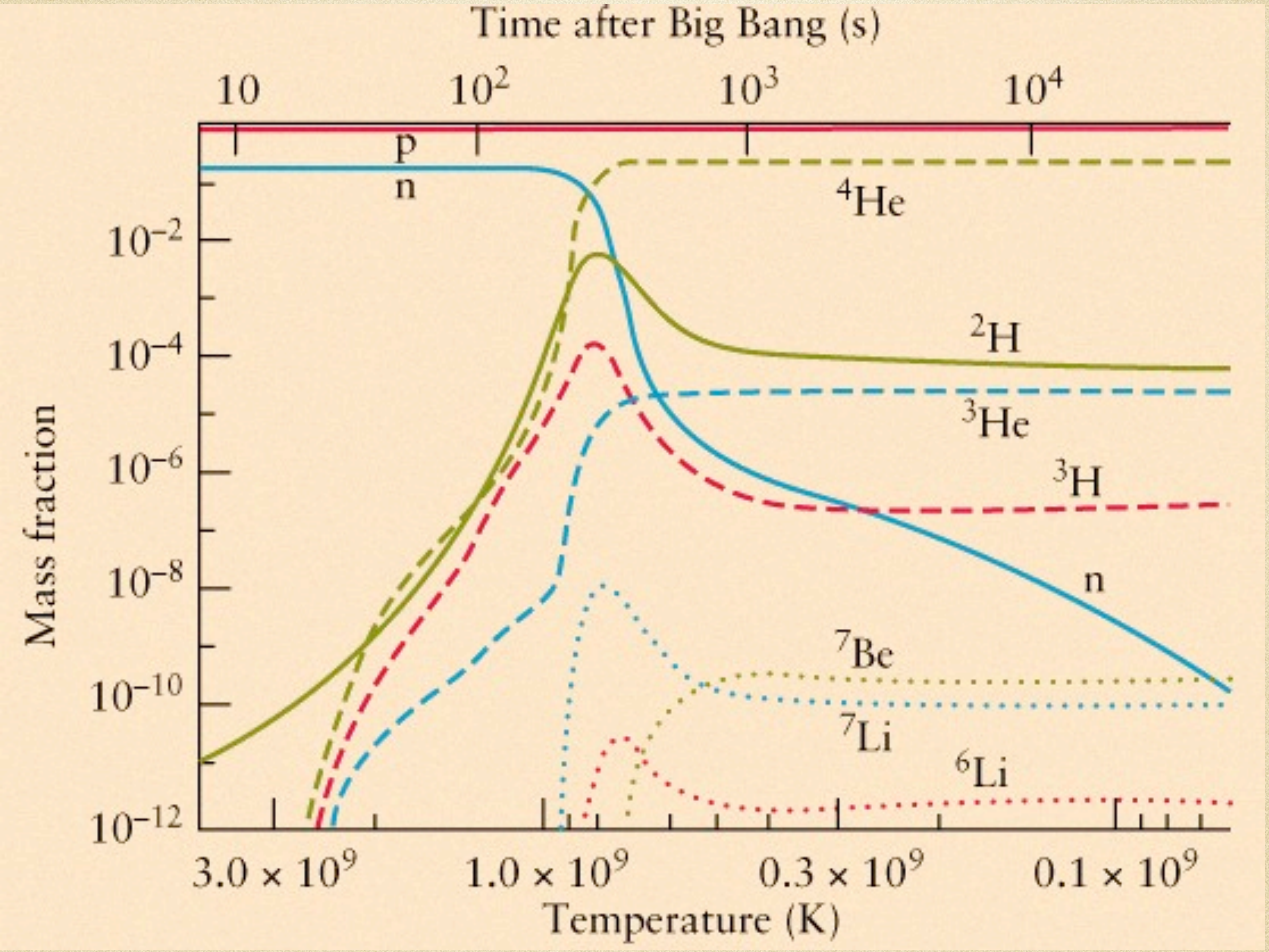
$K^+ \to \pi^+ \nu \bar{\nu}$



Trasformazioni dovute alle interazioni deboli, 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.


History of the Universe
Accelerators
LHC
Tevatron
RHIC
high energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s 10^-10 s 10^-5 s 10^2 s 3x10^5 y 10^9 y 12x10^9 y (sec,yrs)
T 10^32 10^28 10^15 10^12 10^9 3000 15 2.7 (Kelvin)
E 10^19 10^15 10^2 10^-1 10^-4 3x10^-10 10^-12 2.3x10^-13 (GeV)
Today
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
μ muon τ tau
black hole
ν neutrino
atom
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF


Time after Big Bang (s)
10
10^2
10^3
10^4
p
n
^{4}He
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
Mass fraction
^{2}H
^{3}He
^{3}H
n
^{7}Be
^{7}Li
^{6}Li
3.0×10^9
1.0×10^9
0.3×10^9
0.1×10^9
Temperature (K)

Lo scopo odierno della fisica delle particelle è di continuare l'esplorazione delle leggi fisiche e delle componenti fondamentali della materia a distanze sempre più piccole, per svelare i fenomeni che hanno avuto luogo all'inizio della storia dell'universo, e che ne hanno modellato l'evoluzione fino ad oggi

Le domande aperte

- *esistono altre* ***interazioni fondamentali****, troppo deboli per essere state osservate finora?*
- *esistono nuove* ***generazioni*** *di quarks o leptoni?*
- *quarks e leptoni: sono* ***elementari****, o anch'essi composti di particelle ancora piú elementari?*
- *da dove origina* ***l'asimmetria*** *fra materia ed antimateria?*
- *qual'è l'origine della* ***Materia oscura*** *nell' Universo?*
- *qual'è l'origine dell'* ***Energia oscura*** *nell' Universo?*
- *qual'e' l'origine della* ***massa dei neutrini****?*
- *il bosone di* ***Higgs****: funziona esattamente come previsto dal Modello Standard? Ne esistono altri? Qual'e' l'****origine*** *del bosone di Higgs?*
- ….

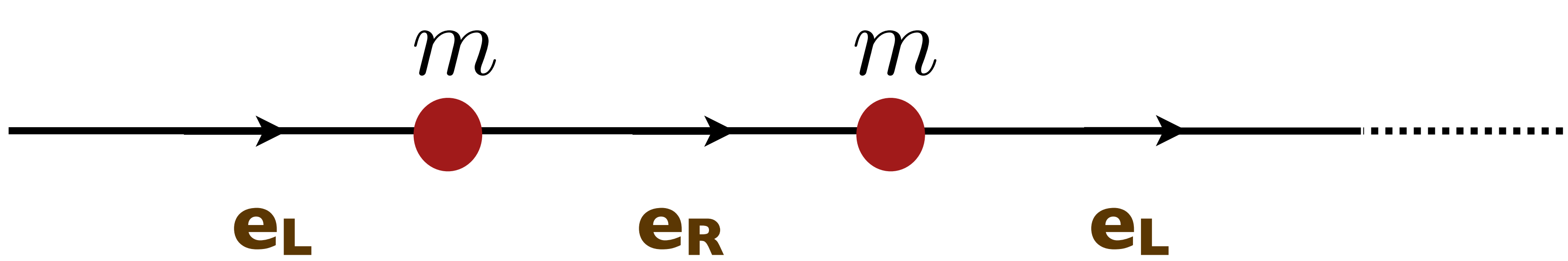
Perche' ci vuole "un" bosone di Higgs per dare massa alle particelle?

Parity asymmetry* and mass for spin-1/2 particles

* T.D Lee C.N.Yang, https://journals.aps.org/pr/abstract/10.1103/PhysRev.104.254 => 1957 Nobel Prize

$$\gamma_5 \, \psi_{L,R} = \pm \, \psi_{L,R}$$

$$H \propto i\overline{\psi_L}\,\partial\cdot\gamma\,\psi_L + i\overline{\psi_R}\,\partial\cdot\gamma\,\psi_R + m\,\overline{\psi_L}\,\psi_R$$

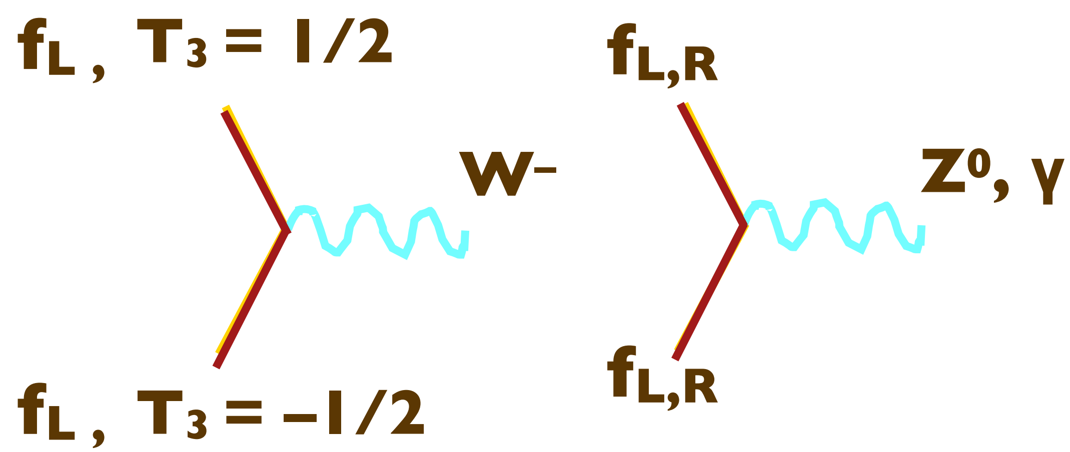


For a massive particle, chirality does not commute with the Hamiltonian, so it cannot be conserved

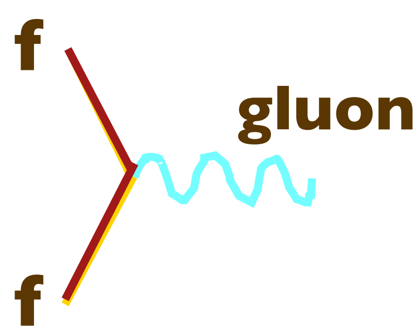
Chirality eigenstates of a massive particle cannot be Hamiltonian (physical) eigenstates

Nothing wrong with that in principle .... unless chirality is associated to a conserved charge!

$SU(2)_L \otimes U(1)$ → **Electroweak (EW) gauge symmetry**



SU(3)



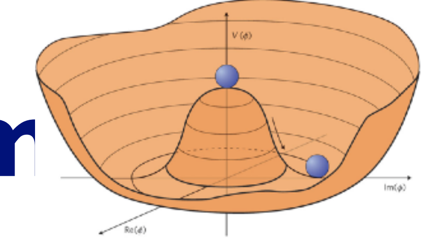
L-chirality	R-chirality
$\begin{pmatrix} u_{2/3} \\ d_{-1/3} \end{pmatrix}_L^{i=1,2,3}$	$u^i{}_R$, $d^i{}_R$
$\begin{pmatrix} \nu \\ e^- \end{pmatrix}_L$	$e^-{}_R$

+ 2 more "families" differing from the 1st one only in the mass of their elements

The symmetry associated with the conservation of the weak charge must therefore be broken for leptons and quarks to have a mass

In this process, weak gauge bosons must also acquire a mass. This needs the existence of new degrees of freedom

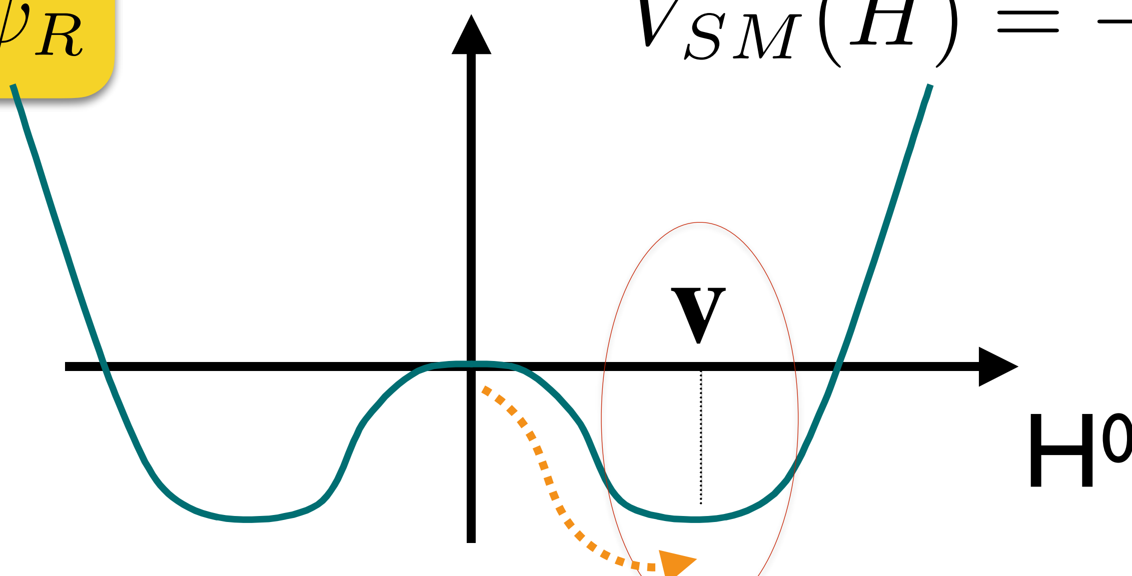
The SM solution: Higgs mechanism

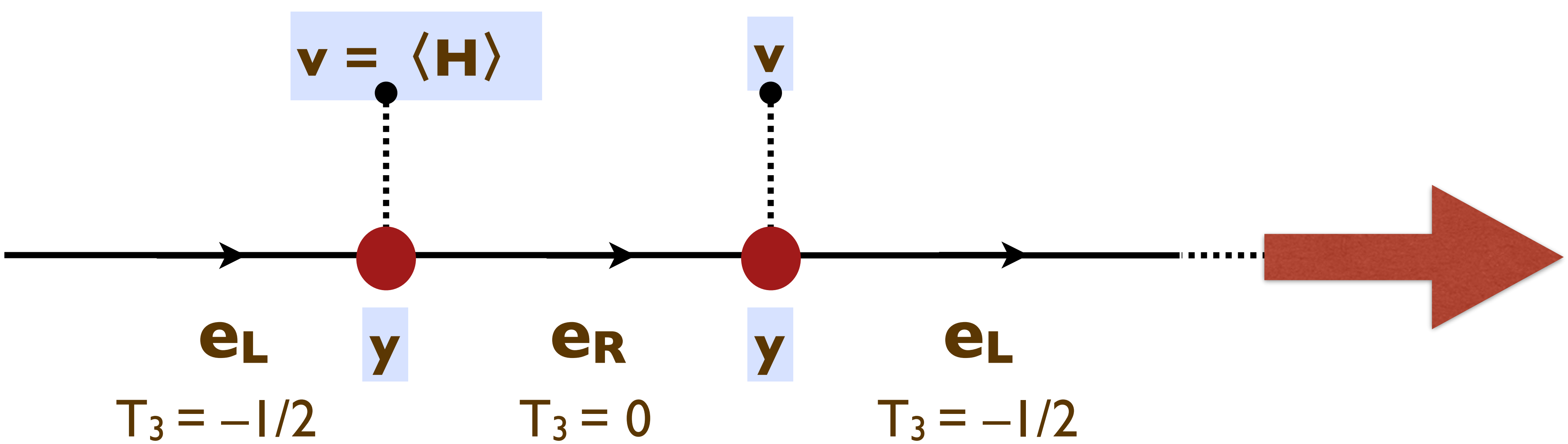


$$m\,\overline{\psi_L}\,\psi_R \rightarrow \lambda H\,\overline{\psi_L}\,\psi_R$$

$$V_{SM}(H) = -\mu^2\,|H|^2 + \lambda\,|H|^4$$

$$H = \begin{pmatrix} H^0 \\ H^- \end{pmatrix}$$





m = y v

The transition between L and R states, and the absorption of the changes in weak charge, are ensured by the interaction with a background scalar field, **H**. Its "vacuum density" provides an infinite reservoir of weak charge.

The SM Higgs mechanism provides the *minimal* set of *ingredients* required to enable a consistent breaking of the EW symmetry.

Where these *ingredients* come from, what possible additional infrastructure comes with them, whether their presence is due to purely anthropic or more fundamental reasons, we don't know, the SM doesn't tell us ...

a historical example: superconductivity

- The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But we would still lack a deep understanding of the relevant dynamics.

- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in both cases we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and **we must look beyond.**

examples of possible scenarios

- **BCS-like**: the Higgs is a composite object
- **Supersymmetry**: the Higgs is a fundamental field and
  - $\lambda^2 \sim g^2+g'^2$, it is not arbitrary (MSSM, w/out susy breaking, has one parameter less than SM!)
  - potential is fixed by susy & gauge symmetry
  - EW symmetry breaking (and thus m_H and λ) determined by the parameters of SUSY breaking
- …

Important questions about the Higgs sector beyond the Standard Model

- Is the Higgs the only (fundamental?) scalar field, or are there other Higgs-like states (e.g. $H^\pm$, A^0, $H^{\pm\pm}$, ... , EW-singlets, ...) ?
  - Do all SM families get their mass from the **same** Higgs field?
  - Do $I_3=1/2$ fermions (up-type quarks) get their mass from the **same** Higgs field as $I_3=-1/2$ fermions (down-type quarks and charged leptons)?
  - Do Higgs couplings conserve flavour? $H\to\mu\tau$? $H\to e\tau$? $t\to Hc$?

- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?

- Is there a relation among Higgs/EWSB, baryogenesis, Dark Matter, inflation?

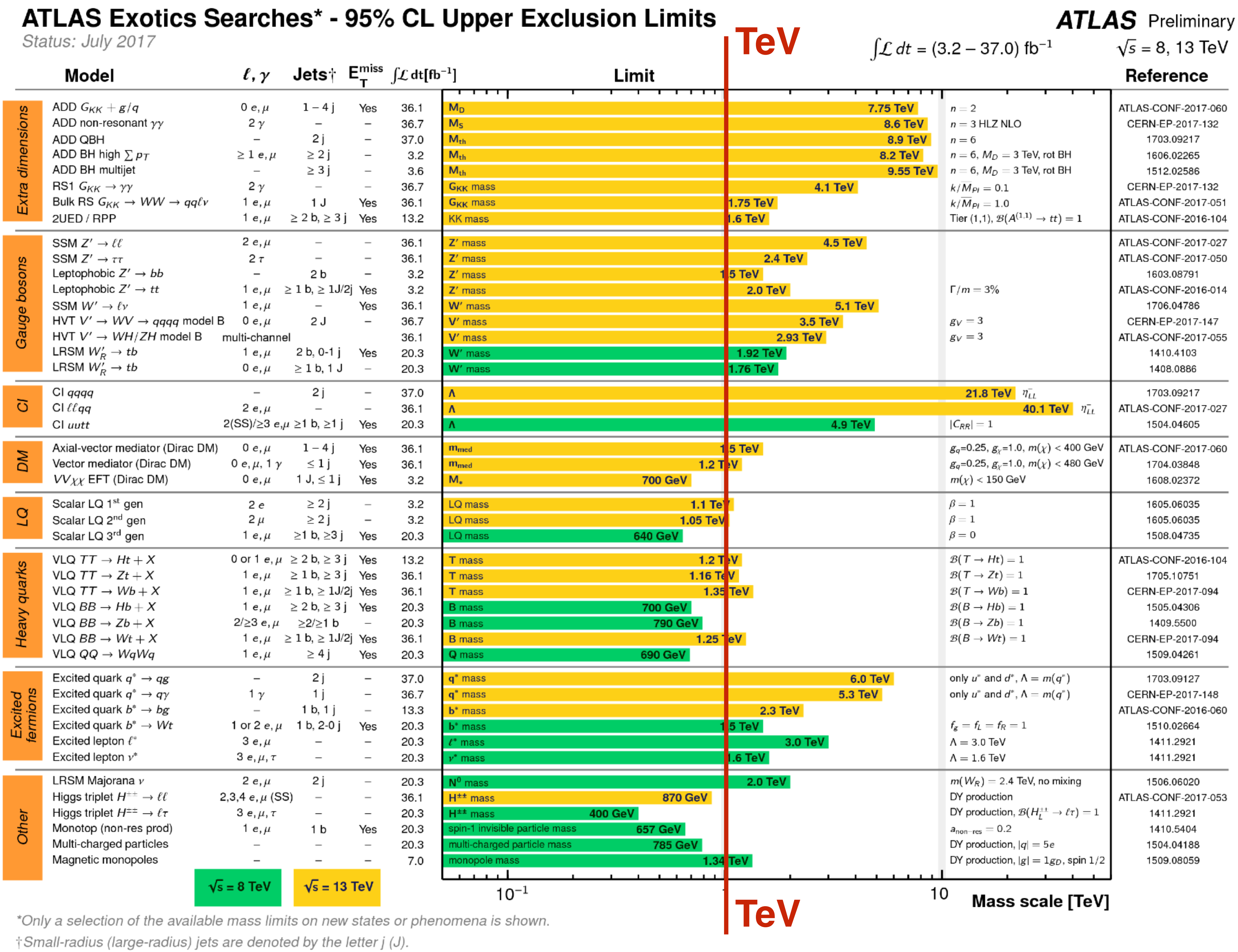
Per iniziare a rispondere a tutte queste domande sul bosone di Higgs, l'unica via e' di misurarne le proprieta' con la massima precisione, e con la maggiore ampiezza di esplorazione, possibile

L'unico strumento sperimentale adatto sono i colliders!

Tutte le proprieta' del bosone di Higgs misurate fino ad oggi all'LHC sono consistenti con le attese del Modello Standard… ma la loro precisione e' ancora limitata

Nessuna manifestazione di fisica oltre il Modello Standard, in particolare legata all'origine dell'Higgs, e' apparsa dai dati dell'LHC … ma rimane ancora parecchio spazio per manifestazioni più rare o più esotiche di quanto si sia studiato/misurato

So far, no *conclusive* signal of physics beyond the SM



Given no sign of BSM is there, precision measurements become the key tool for exploration

The serendipitous value of data: a few history lessons

- Tycho Brahe (1546-1601) spent his life measuring planets' positions more and more precisely
  - Johannes Kepler (1571-1630) used those data to extract a "phenomenological" interpretation, based on his 3 laws
  - Isaac Newton (1643-1727) discovered the underlying "theoretical" foundation of Kepler's laws … but it all started from Brahe's precision data!
- Newton's law became the new Standard Model for planetary motions. Precision measurements of the Uranus orbit, in the first half of the XIX century, showed deviations from this "SM": was it a break-down of the SM, or the signal of a new ~~particle~~ planet?
  - assuming the validity of the SM, interpreting the deviations as due to perturbations by a yet unknown planet, Neptun was discovered (1846), implicitly giving stronger support to Newton's SM
- Precision planetary measurements continued throughout the XIX century, revealing yet another SM deviation, in Mercury's motion. This time, it was indeed a beyond SM (BSM) signal: Einstein's theory of General Relativity!! Mercury's data did not motivate Einstein to formulate it, but once he had the equations, he used those precise data to confirm its validity!

- Aside from exceptional moments in the development of the field, research is not about proving a theory is right or wrong, or about making milestone Nobel-prize-worth discoveries…. it's about finding out how things work
- We do not measure Higgs couplings precisely with the **goal to find** deviations from the SM. We measure them to **know** them, while being ready to detect deviations, if any…
- LEP's success was establishing SM's amazing power, by fully confirming its predictions!
- … and who knows how important a given measurement can become, to assess the validity of a future theory?
    - the day some BSM signal is found somewhere, the available precision measurements, will be crucial to establish the nature of the signal, whether they agree or deviate from the SM

BOTTOM LINE:

- **you never know what data will lead to!**
- **there are no useless data, there is only <u>correct</u> data or <u>wrong</u> data**
- **physics progress builds on good data and powerful tools to interpret them**

LHC scientific production

Over 4000 papers published/submitted to refereed journals by the 7 experiments that operated in Run 1 and 2 (ALICE, ATLAS, CMS, LHCb, LHCf, TOTEM, MoEDAL)… and the first papers are appearing by the new experiments started in Run 3 (FASER, SND@LHC)

Of these:

~10% on Higgs (15% if ATLAS+CMS only)

~30% on searches for new physics (35% if ATLAS+CMS only)

~60% of the papers on SM measurements (jets, EW, top, b, HIs, …)

Not only Higgs and exotic searches !

Flavour physics

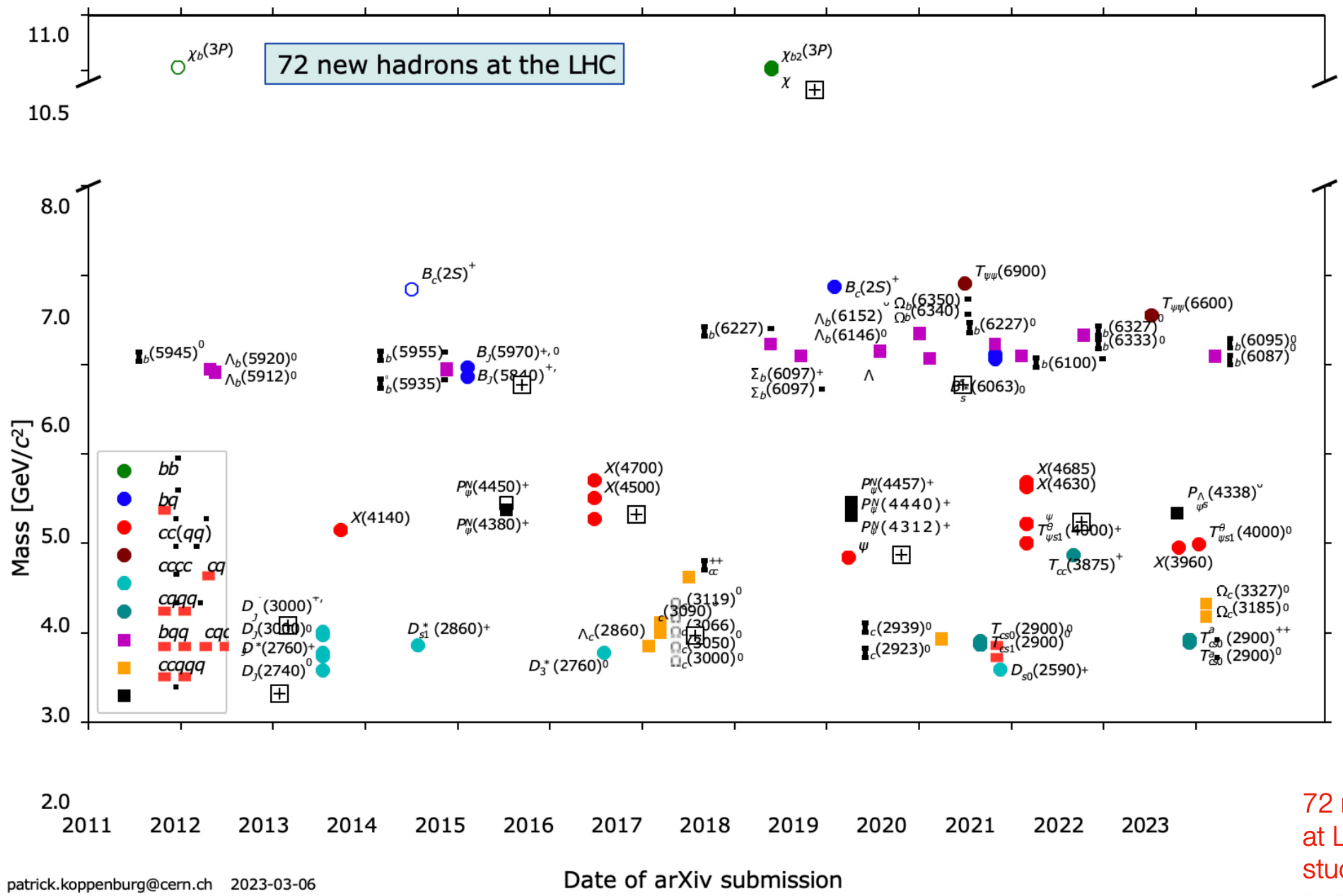
- $B_{(s)} \to \mu\mu$
- D mixing and CP violation in the D system
- Measurement of the γ angle, CPV phase ϕ_s, …
- Lepton flavour universality in charge- and neutral-current semileptonic B decays => possible anomalies ?

QCD dynamics

- Countless precise measurements of hard cross sections, and improved determinations of the proton PDF
- Measurement of total, elastic, inelastic pp cross sections at different energies, new inputs for the understanding of the dominant reactions in pp collisions
- Exotic spectroscopy: discovery and study of new tetra- and penta-quarks, doubly heavy baryons, expected sensitivity to glueballs
- Discovery of QGP-like collective phenomena (long-range correlations, strange and charm enhancement, …) in "small" systems (pA and pp)

EW param's and dynamics

- m_W, m_{top} 171.77 ± 0.37 GeV, $\sin^2\theta_W$
- EW interactions at the TeV scale (DY, VV, VVV, VBS, VBF, Higgs, …)



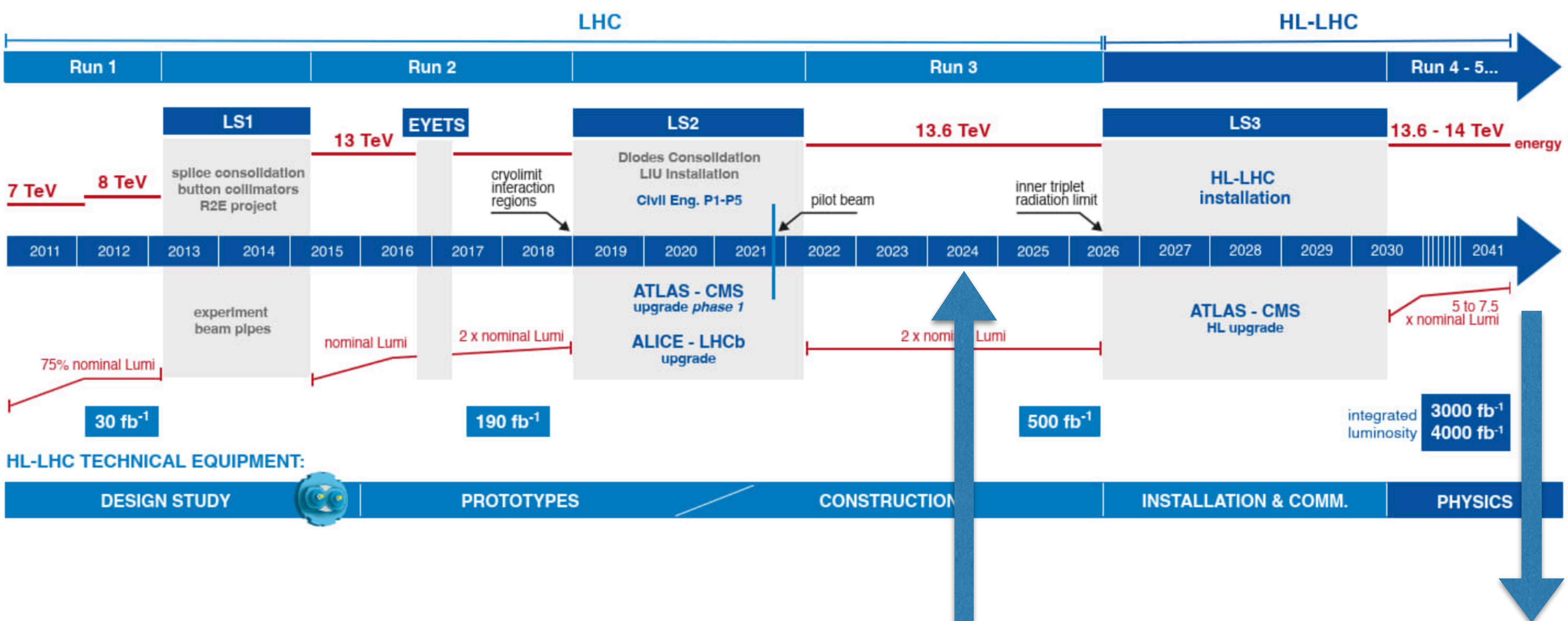
72 new hadrons discovered at LHC, opening a new era of studies of QCD non-perturbative dynamics

"***New physics***" is not just BSM particles or interactions. New physics must include SM phenomena, emerging from the data, which are unexpected, surprising, or simply poorly understood.

A discovery is everything that is not obviously predictable, or that requires deeper study to be clarified, even if it belongs to the realm of SM phenomena.

"New physics" is emerging every day at the LHC!

LHC / HL-LHC Plan



oggi → 2041

Key question for the future developments of HEP: Why don’t we see the new physics we expected to be present around the TeV scale ?

- **Is the mass scale beyond the LHC reach ?**

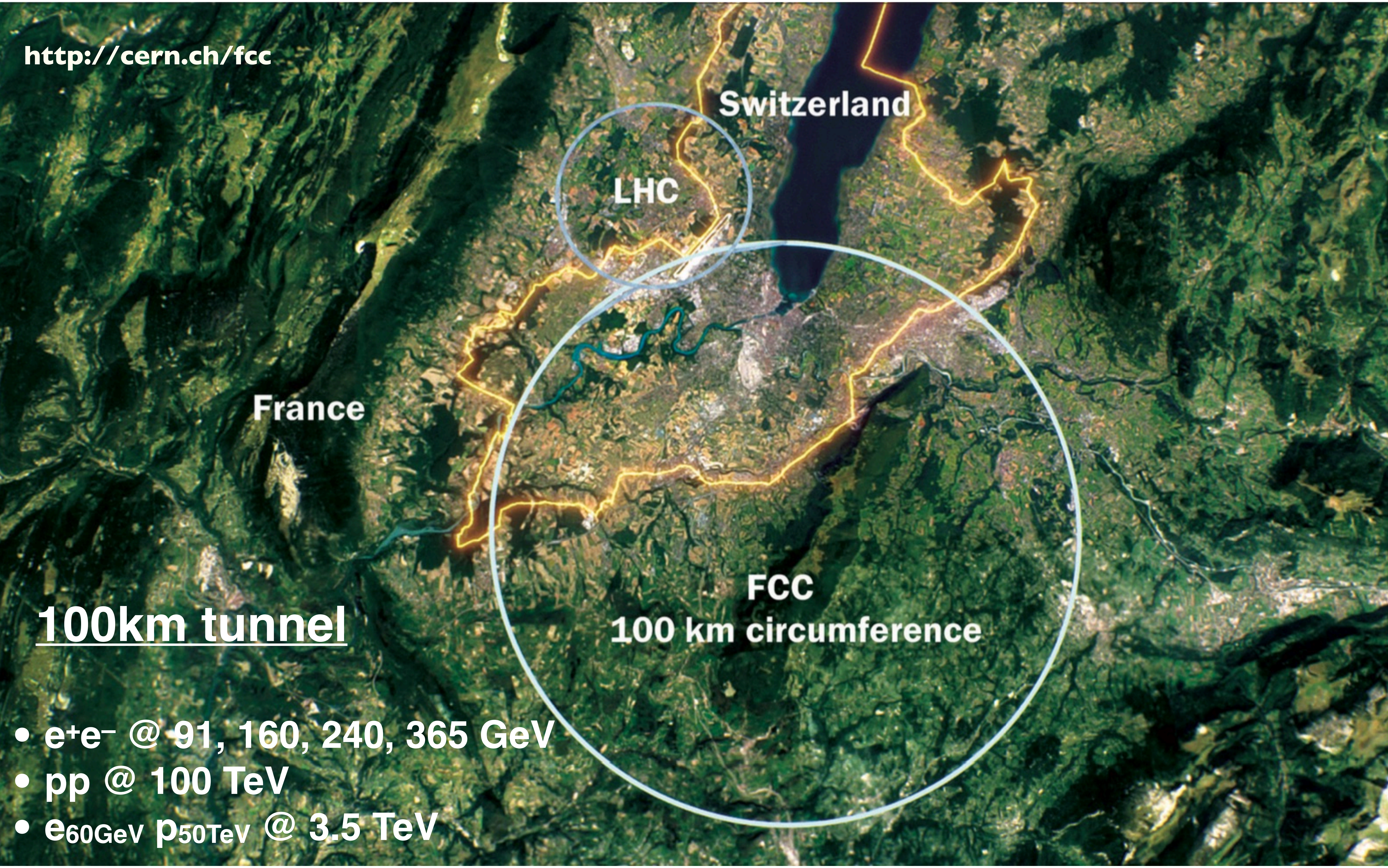
- **Is the mass scale within LHC’s reach, but final states are elusive to the direct search ?**

These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities

Readiness to address both scenarios is the best hedge for the field:

- *precision ⇒ higher statistics, better detectors and experimental conditions*
- *sensitivity (to elusive signatures) ⇒ ditto*
- ***extended energy/mass reach ⇒ higher energy***

Future Circular Collider



100km tunnel

- e^+e^- @ 91, 160, 240, 365 GeV
- pp @ 100 TeV
- e_{60GeV} p_{50TeV} @ 3.5 TeV

What a future circular collider can offer

- Guaranteed deliverables:
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with the best possible **precision and sensitivity**
- Exploration potential:
  - exploit both direct (large Q^2) and indirect (precision) probes
  - **enhanced mass reach** for direct exploration at 100 TeV
    - *E.g. match the mass scales for new physics that could be exposed via indirect precision measurements in the EW and Higgs sector*
- Provide firm Yes/No answers to questions like:
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - could the cosmological EW phase transition have been 1st order?
  - could baryogenesis have taken place during the EW phase transition?
  - could neutrino masses have their origin at the TeV scale?
  - …

Event rates: examples

FCC-ee	H	Z	W	t	τ(←Z)	b(←Z)	c(←Z)
	10^{6}	$5\ 10^{12}$	10^{8}	10^{6}	$3\ 10^{11}$	$1.5\ 10^{12}$	10^{12}

FCC-hh	H	b	t	W(←t)	τ(←W←t)
	$2.5\ 10^{10}$	10^{17}	10^{12}	10^{12}	10^{11}

FCC-eh	H	t
	$2.5\ 10^{6}$	$2\ 10^{7}$

Higgs couplings after FCC-ee / hh

	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0	**0.65 (*)**
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9	**0.4 (*)**
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	~10 (indirect)	**0.95 (**)**
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	**0.9 (*)**
$\delta g_{HHH} / g_{HHH}$ (%)	50	~44 (indirect)	**5**
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**	**$BR_{inv} < 0.025\%$**

NB

$BR(H\rightarrow Z\gamma,\gamma\gamma) \sim O(10^{-3}) \Rightarrow$ **$O(10^7)$ evts for Δ_{stat}~%**

$BR(H\rightarrow\mu\mu) \sim O(10^{-4}) \Rightarrow$ **$O(10^8)$ evts for Δ_{stat}~%**

pp collider is essential to beat the % target, since no proposed ee collider can produce more than $O(10^6)$ H's

* From BR ratios wrt $B(H\rightarrow ZZ^*)$ @ FCC-ee

** From pp→ttH / pp→ttZ, using $B(H\rightarrow bb)$ and ttZ EW coupling @ FCC-ee