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

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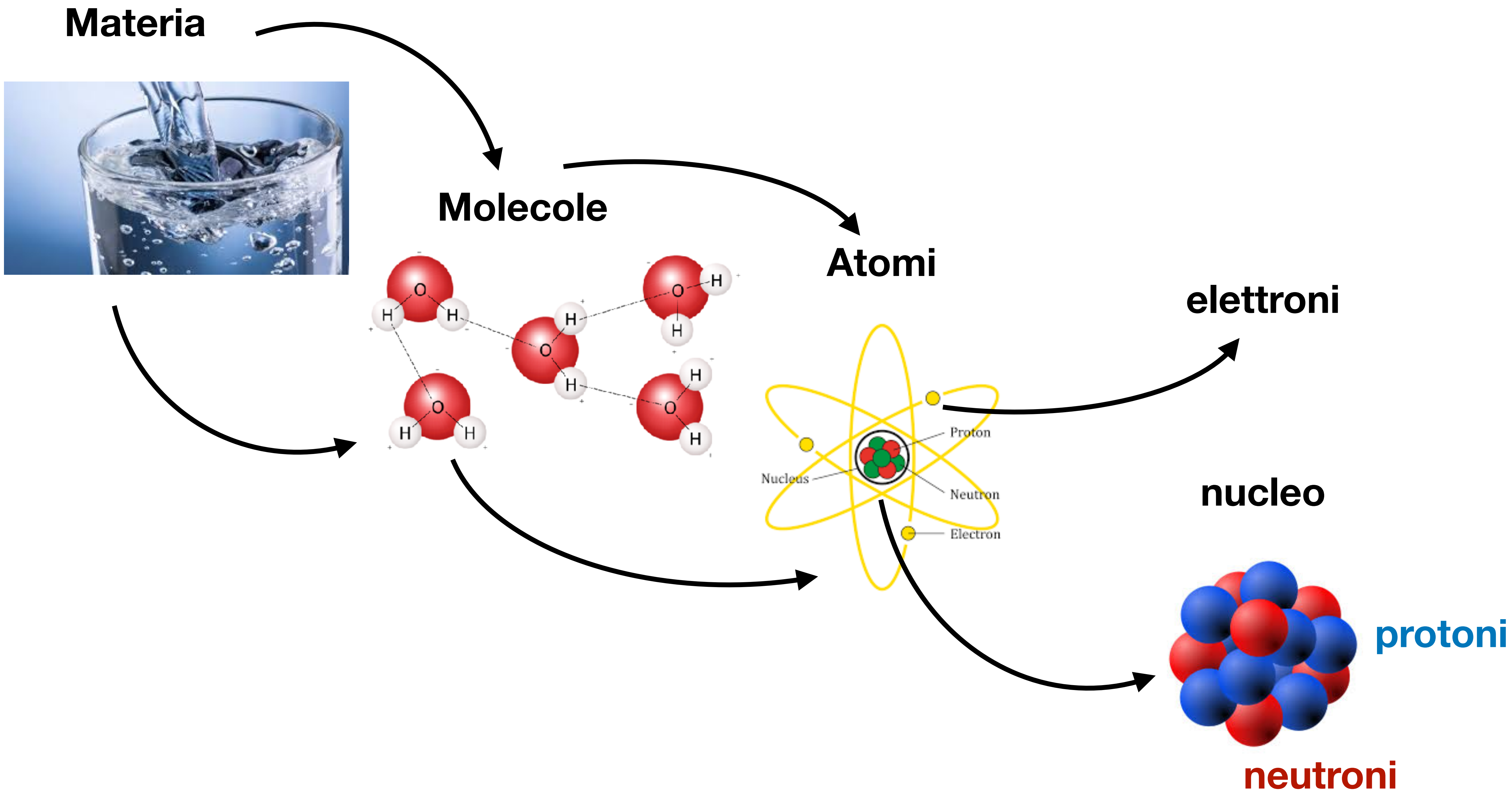


Materia

Molecole

Atomi

elettroni

nucleo

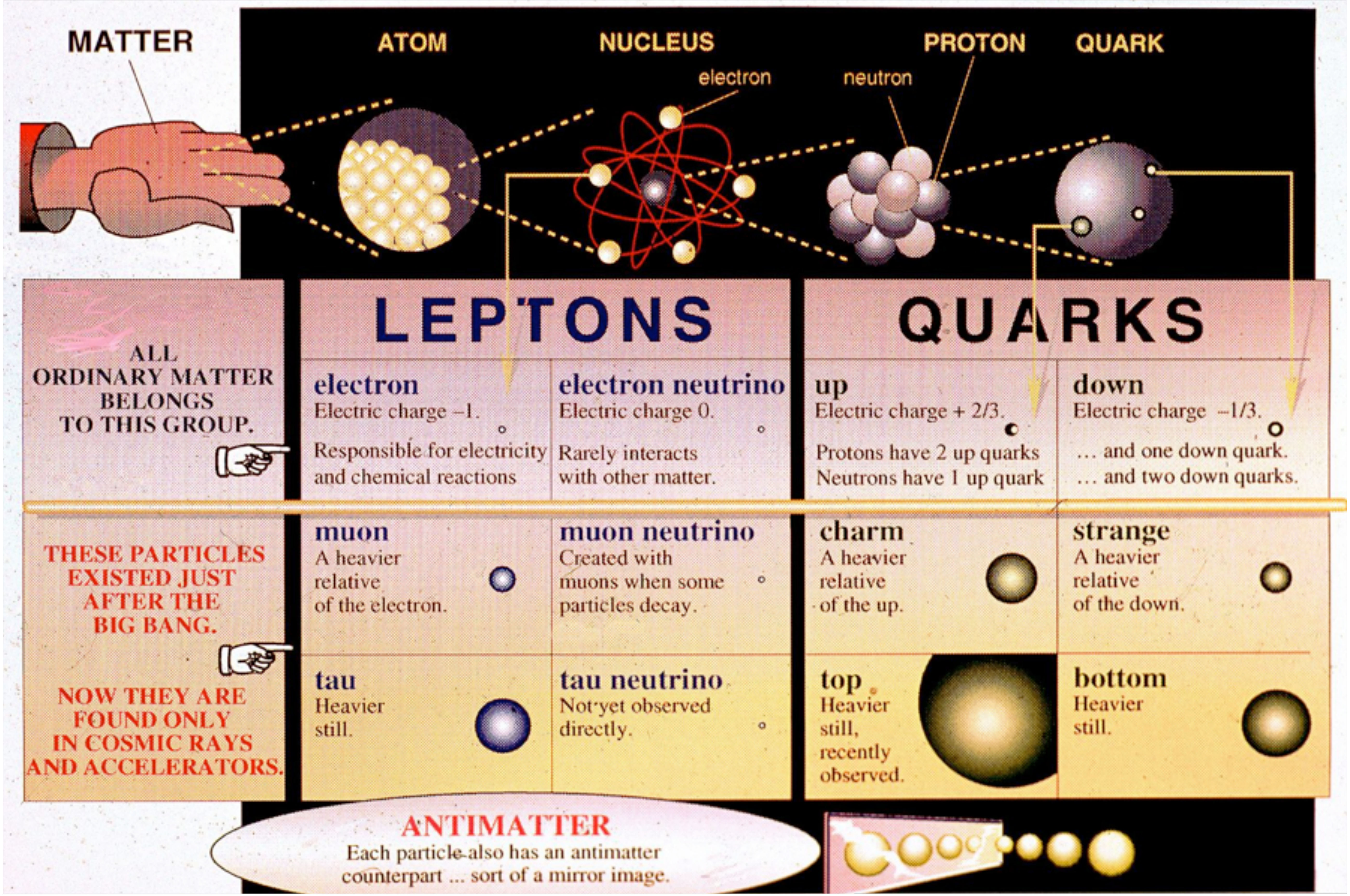
protoni

neutroni

Di cosa sono fatti elettroni, protoni, neutroni?

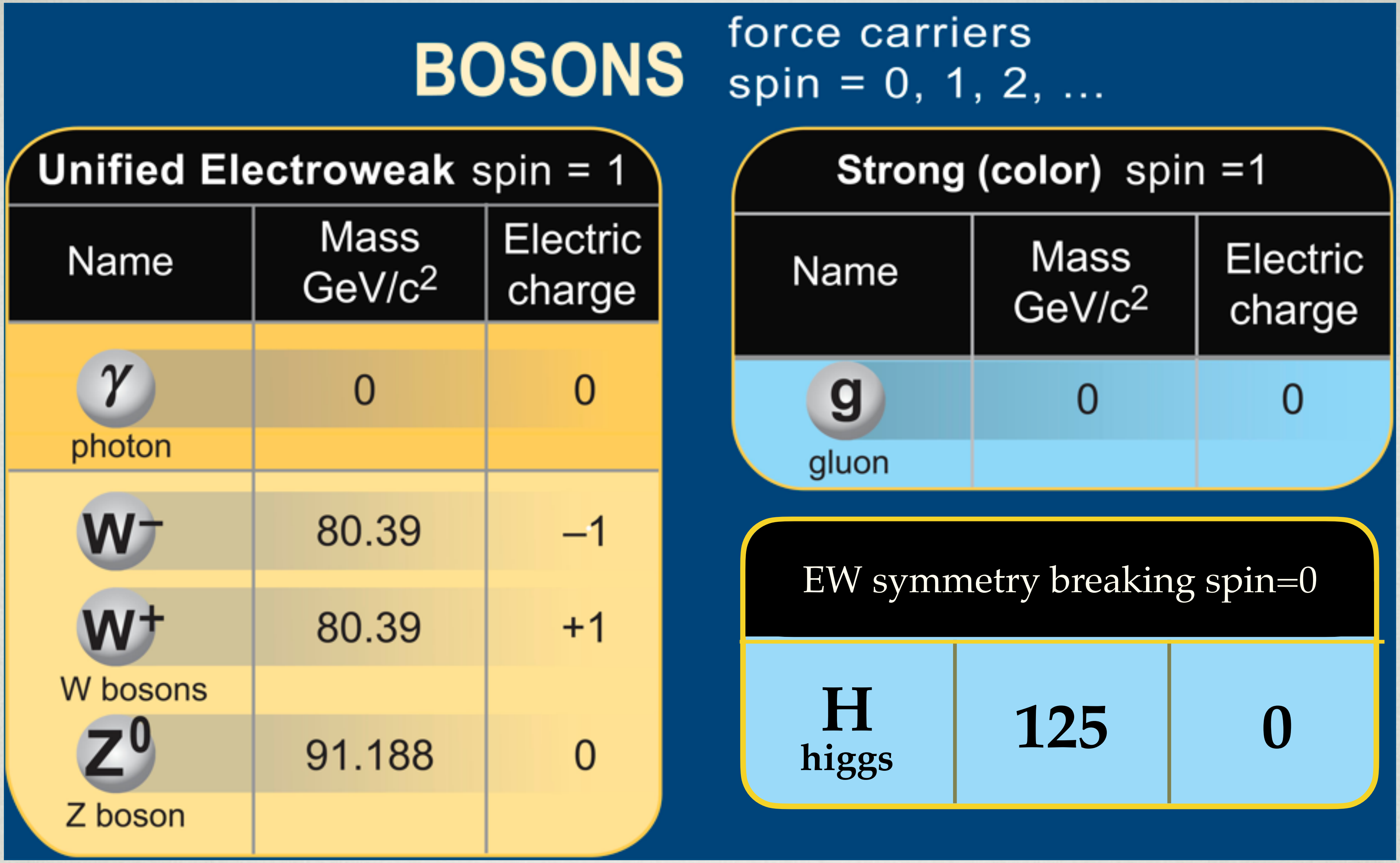
==>> FISICA DELLE PARTICELLE

Il Modello Standard



	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.	**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.
NOW THEY ARE FOUND ONLY IN COSMIC RAYS AND ACCELERATORS.	**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.



BOSONS

force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1

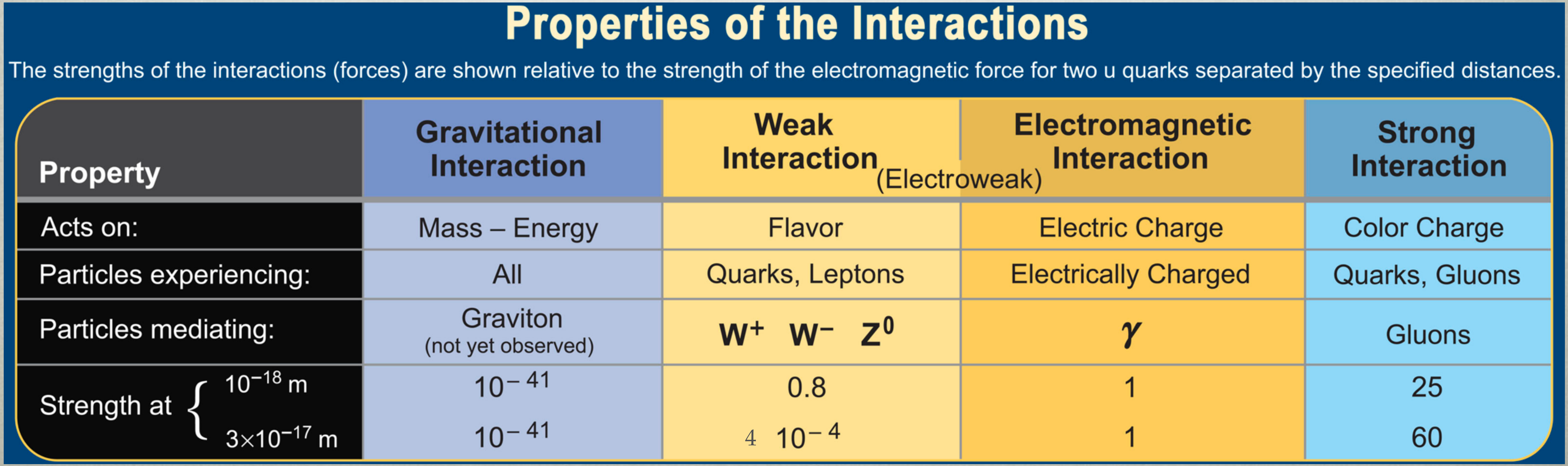
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

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

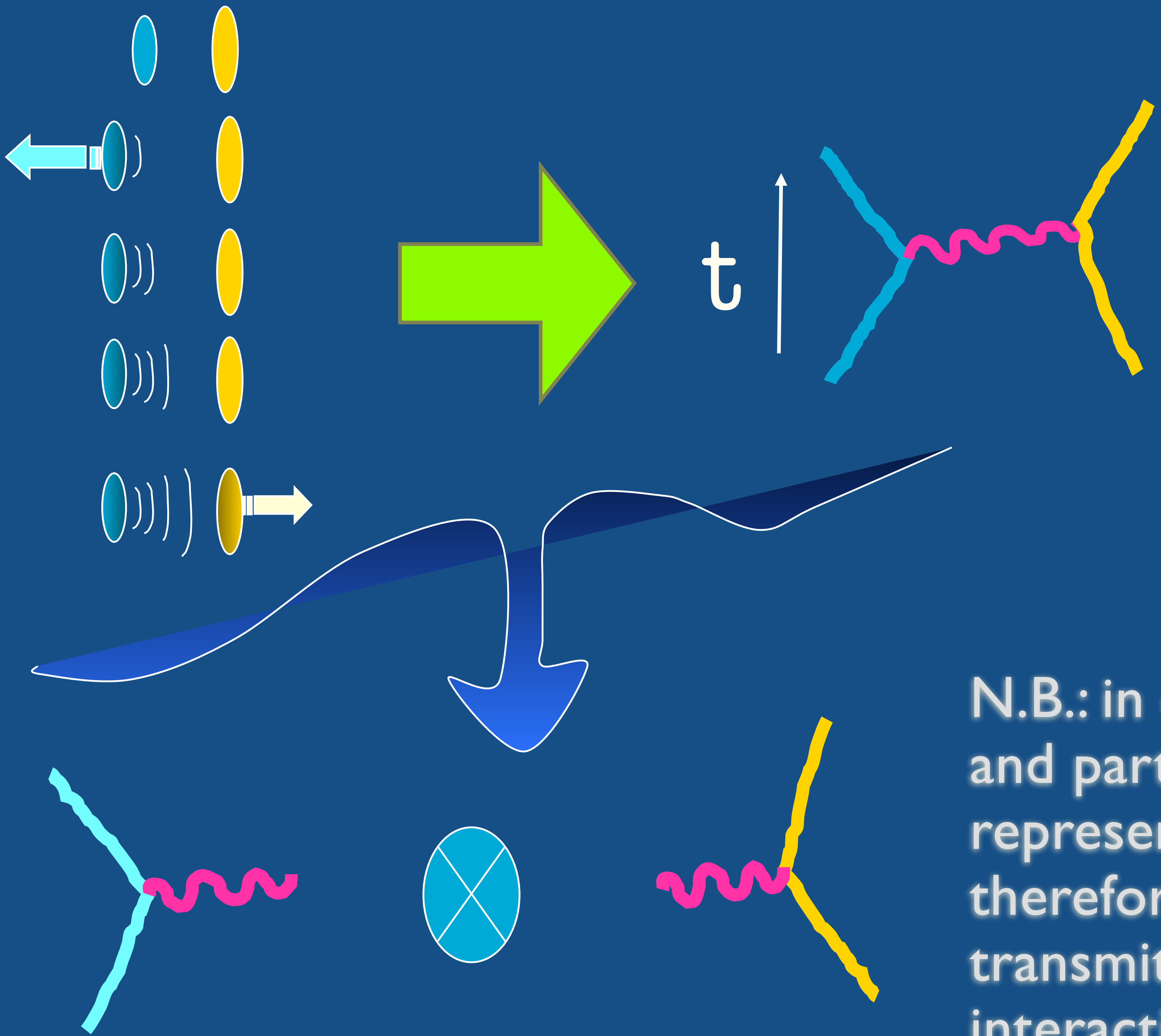
More on the role of Special Relativity

- 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

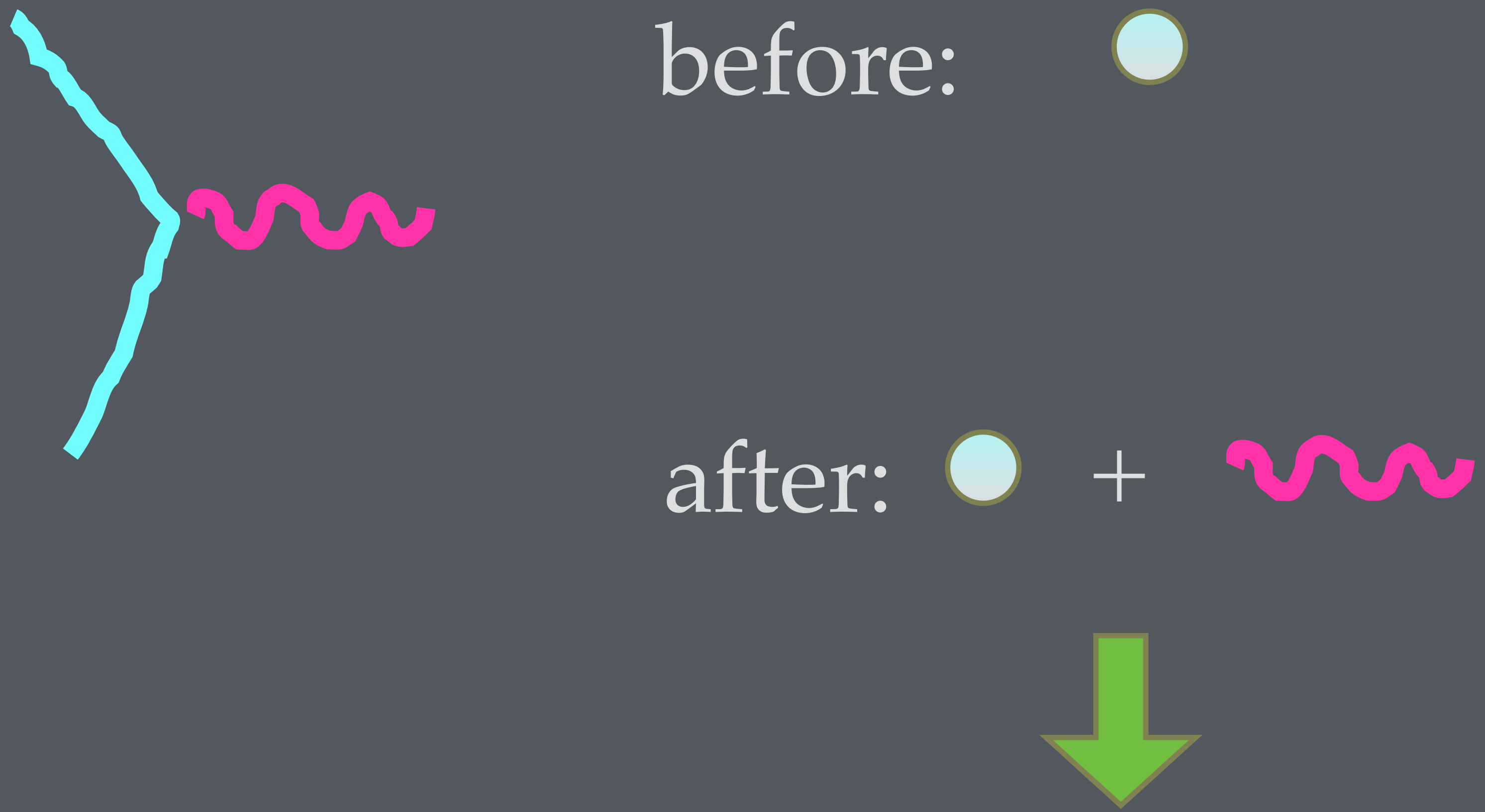


Feynman diagram

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: ● + 〰

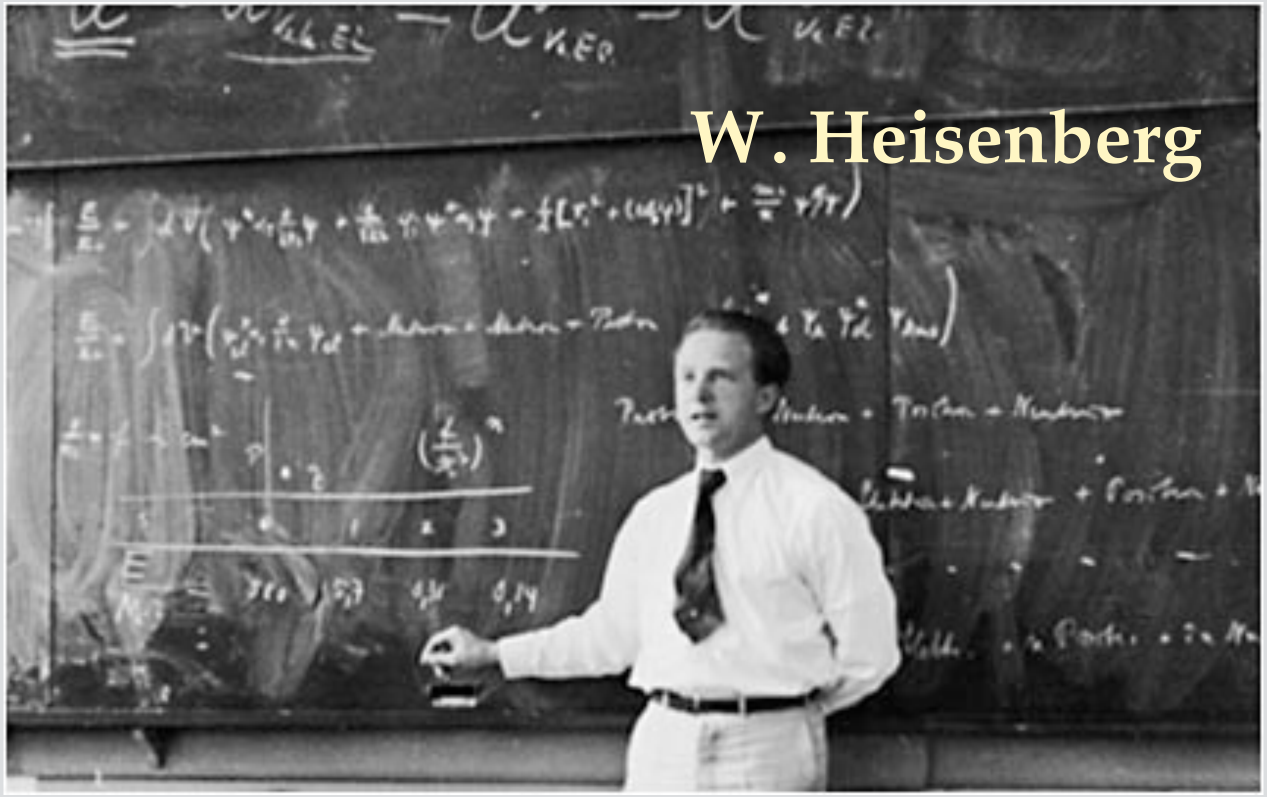
Energy(after) ≠ Energy(before)

What happens to energy conservation ?!

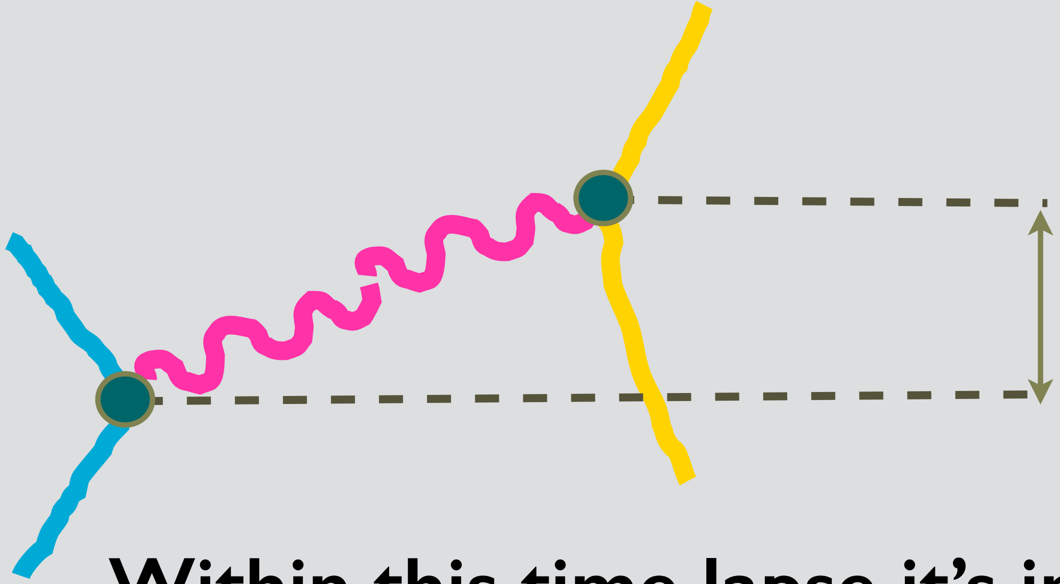
Quantum mechanics

Heisenberg uncertainty principle:

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



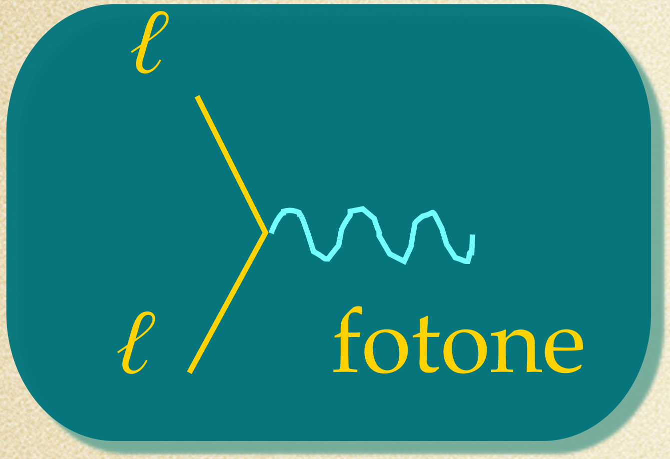
W. Heisenberg



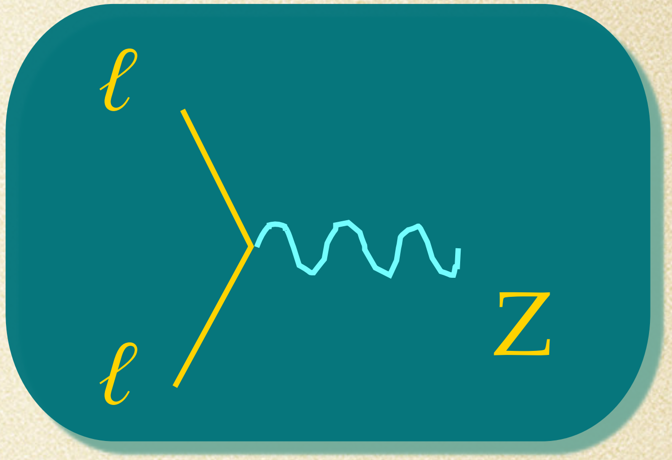
$\Delta t < 1/\Delta E$

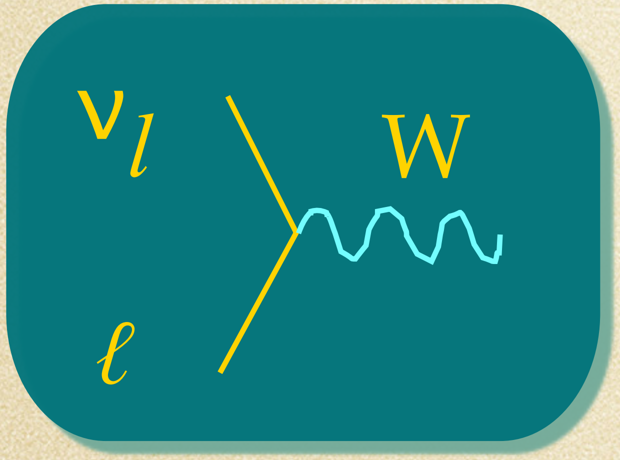
Within this time lapse it’s impossible to determine whether energy is conserved or not, since we can’t measure it accurately enough. Therefore it’s possible to “cheat” nature, and allow the exchange of energy between the two particles

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

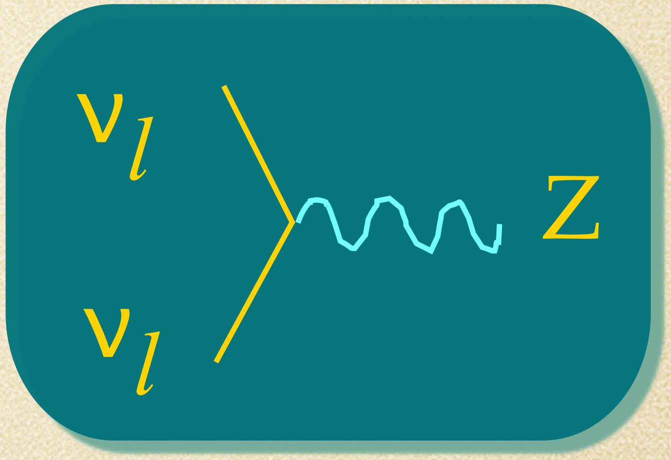


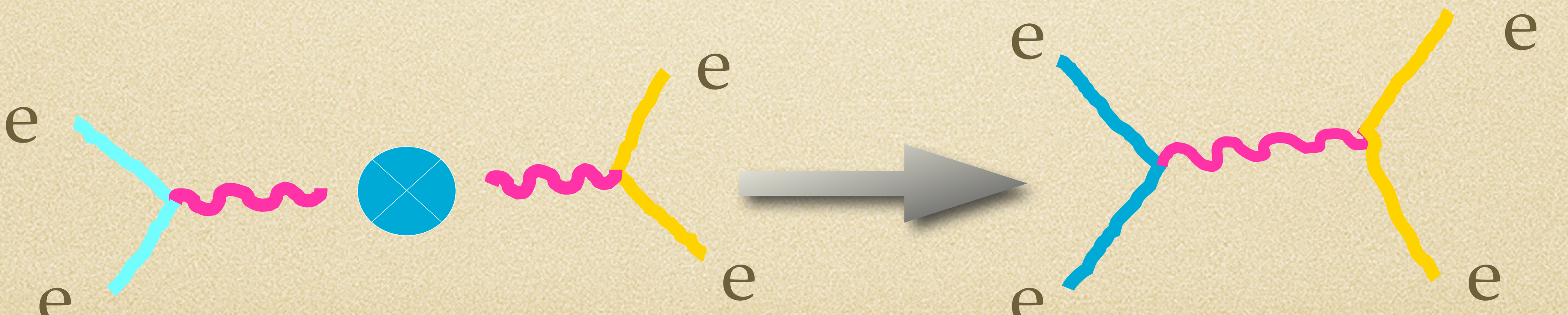
$\propto -e=$ electric charge





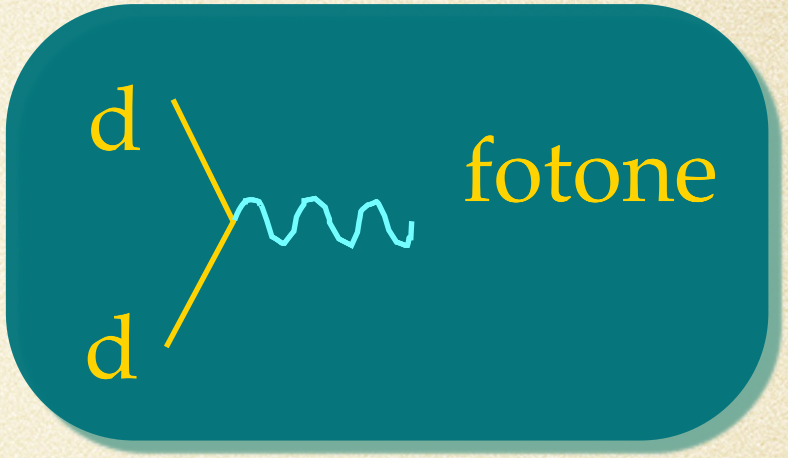
$\propto g_W=$ weak charge



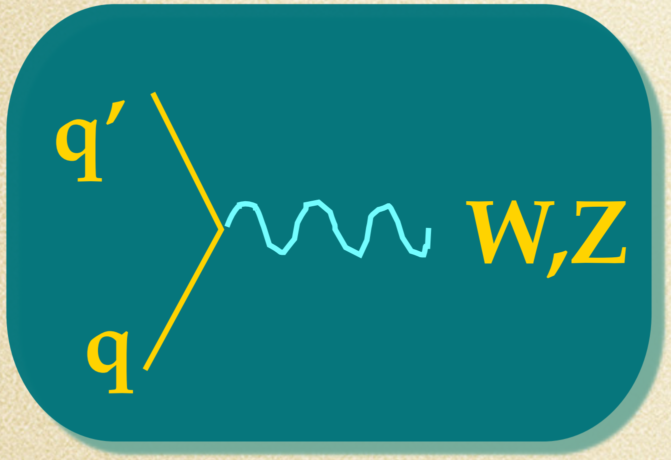


Interazioni dei quarks

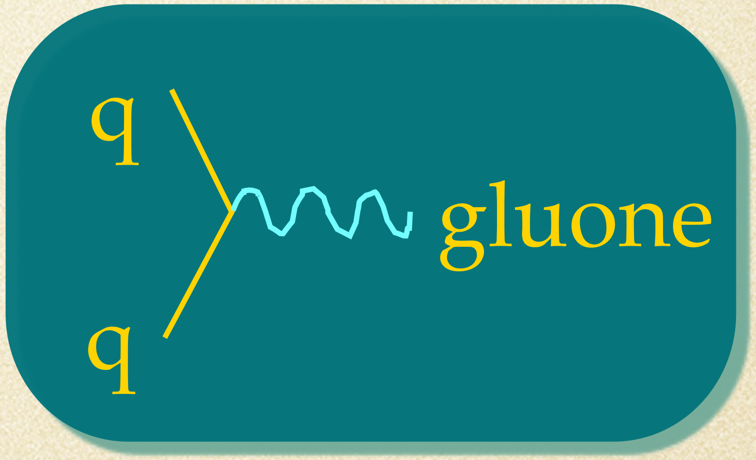
$\propto 2/3\ e$



$\propto -1/3\ e$

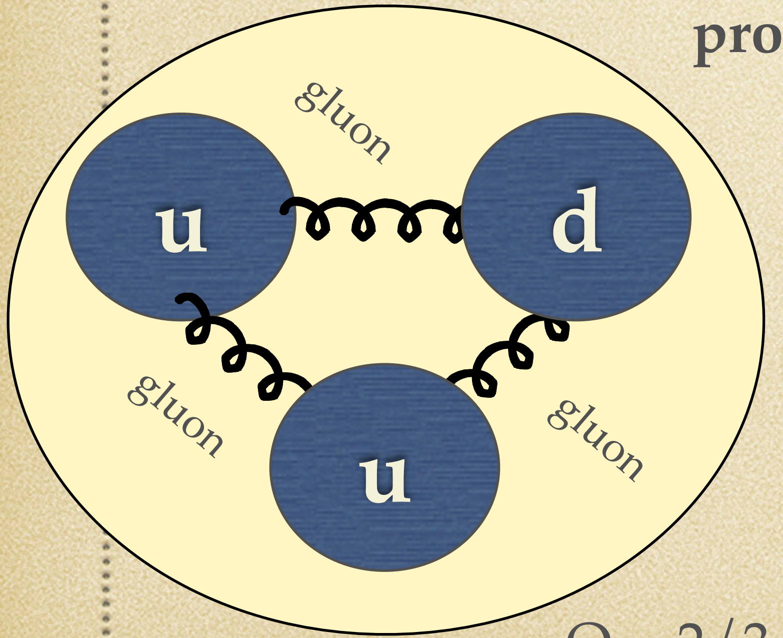


$\propto g_W$



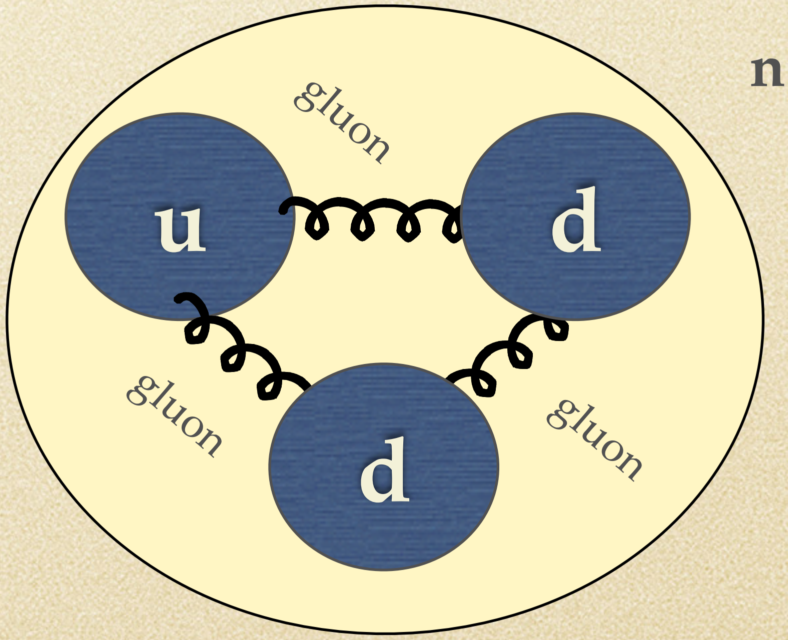
$\propto g_S$

protone



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

neutrone

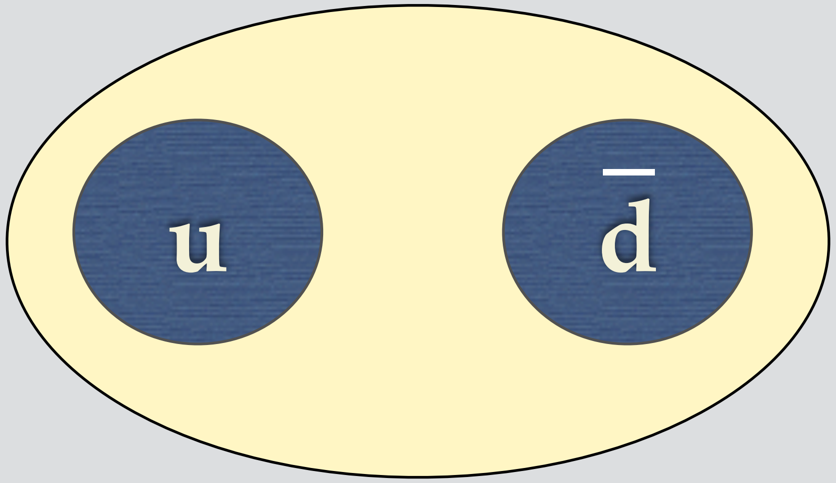


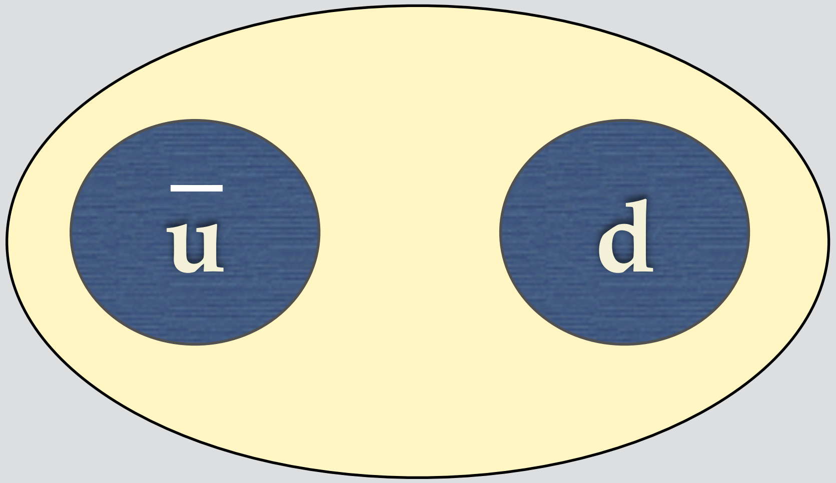
$Q = 2/3\ e - 1/3\ e - 1/3\ e = 0$

PIONS

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

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



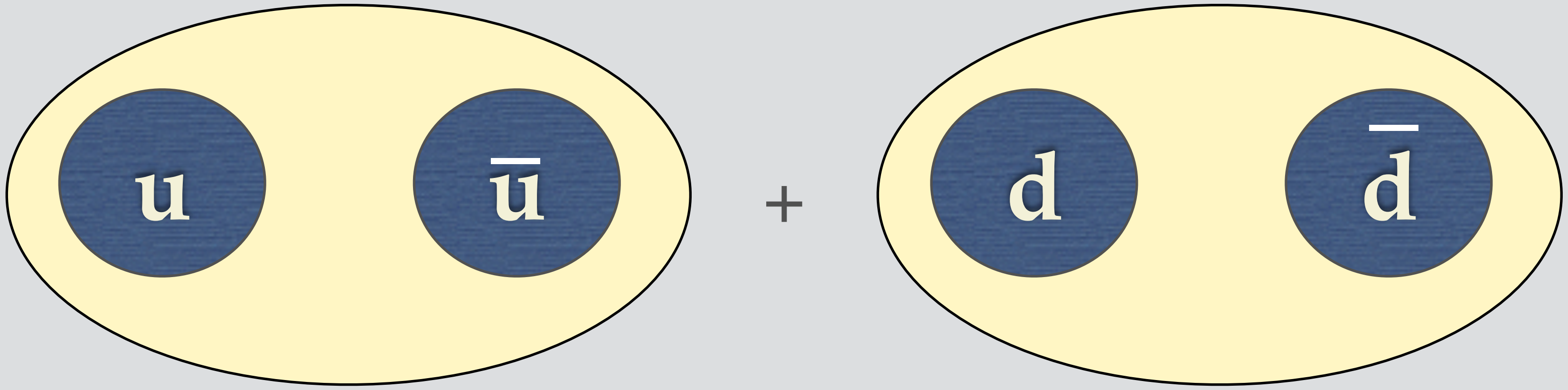


$Q = 2/3\ e + (-)(-1/3)\ e = e$

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

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

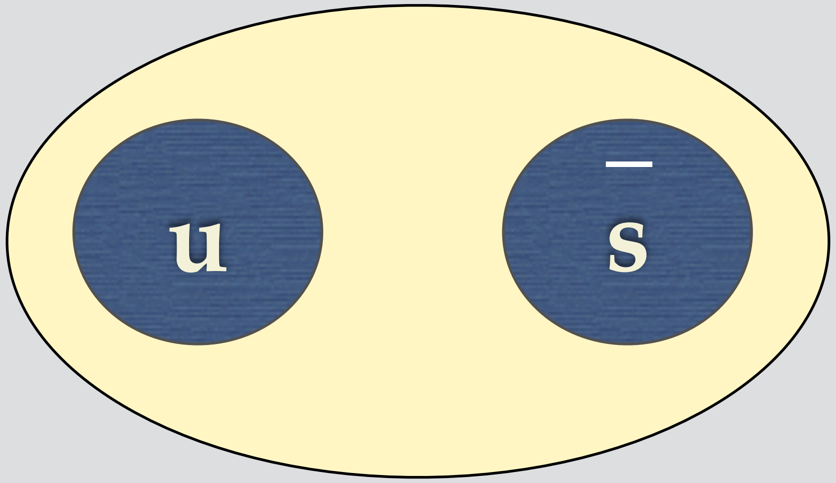
$\pi^{0} = d\,\bar{d} + u\,\bar{u}$



$Q = 0$

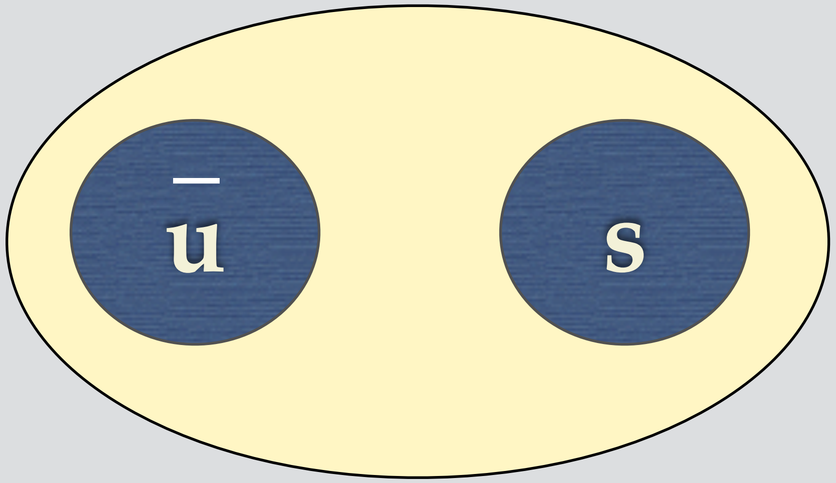
KAONS

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



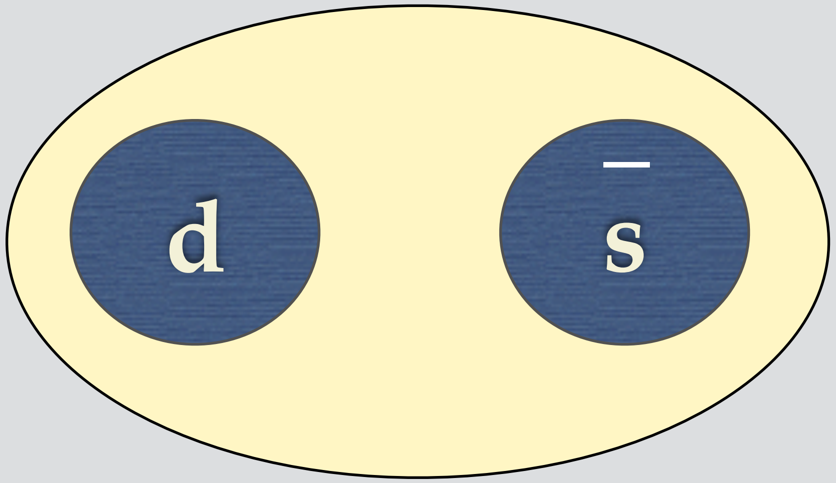
$Q = 2/3\ e + (-)(-1/3)\ e = e$

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



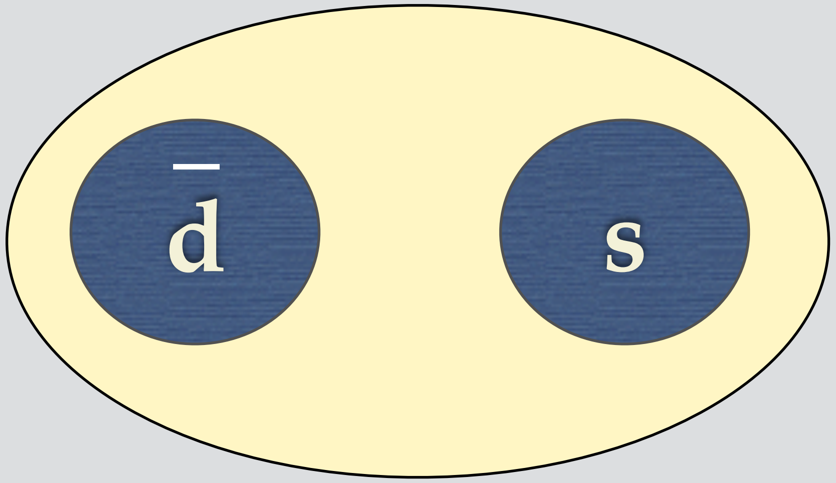
$Q = -\,2/3\ e + (-1/3)\ e = -\,e$

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



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

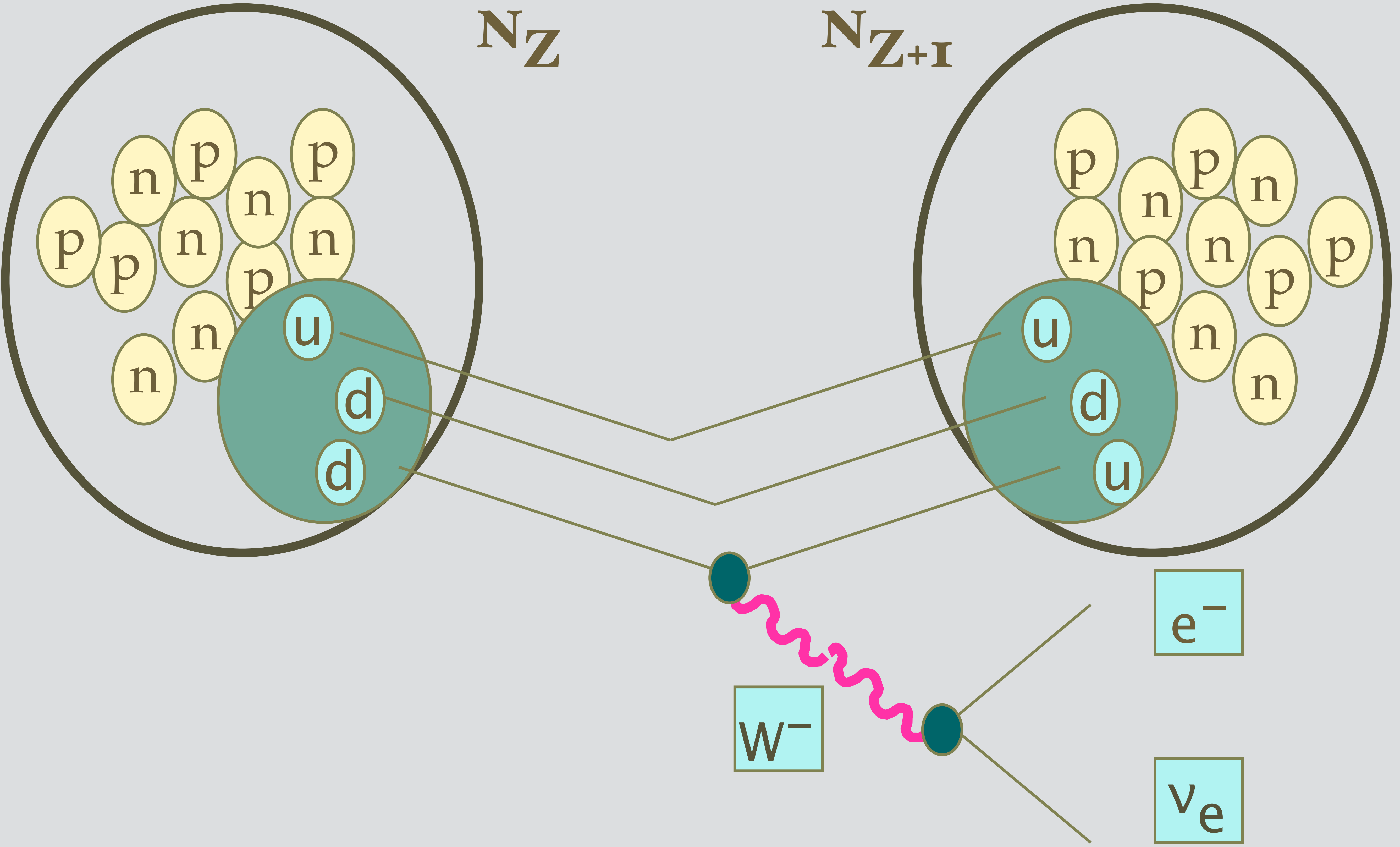
$K^0 = \bar{d}s$



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

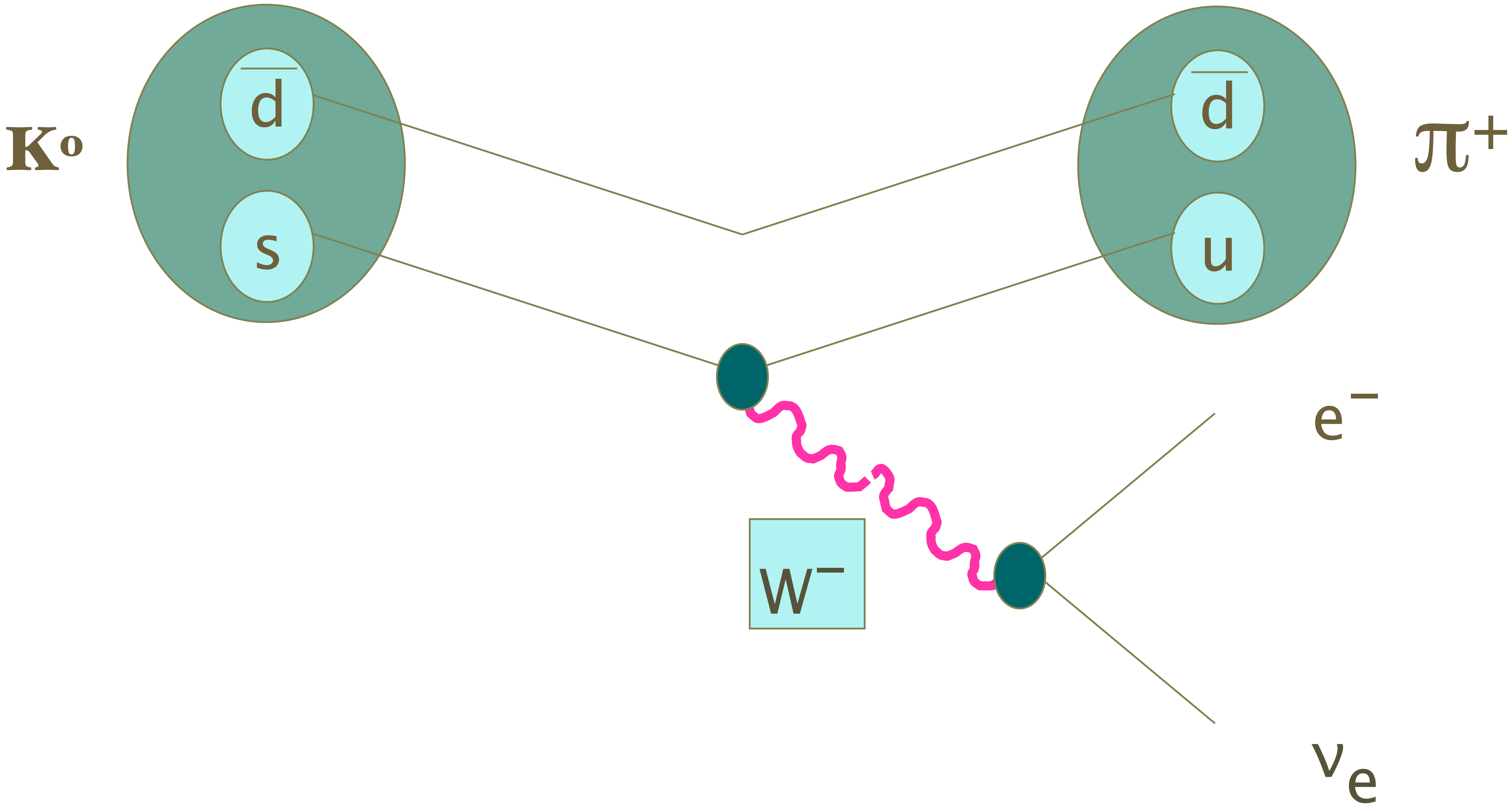
Example: radioactivity

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



…. kaon decay

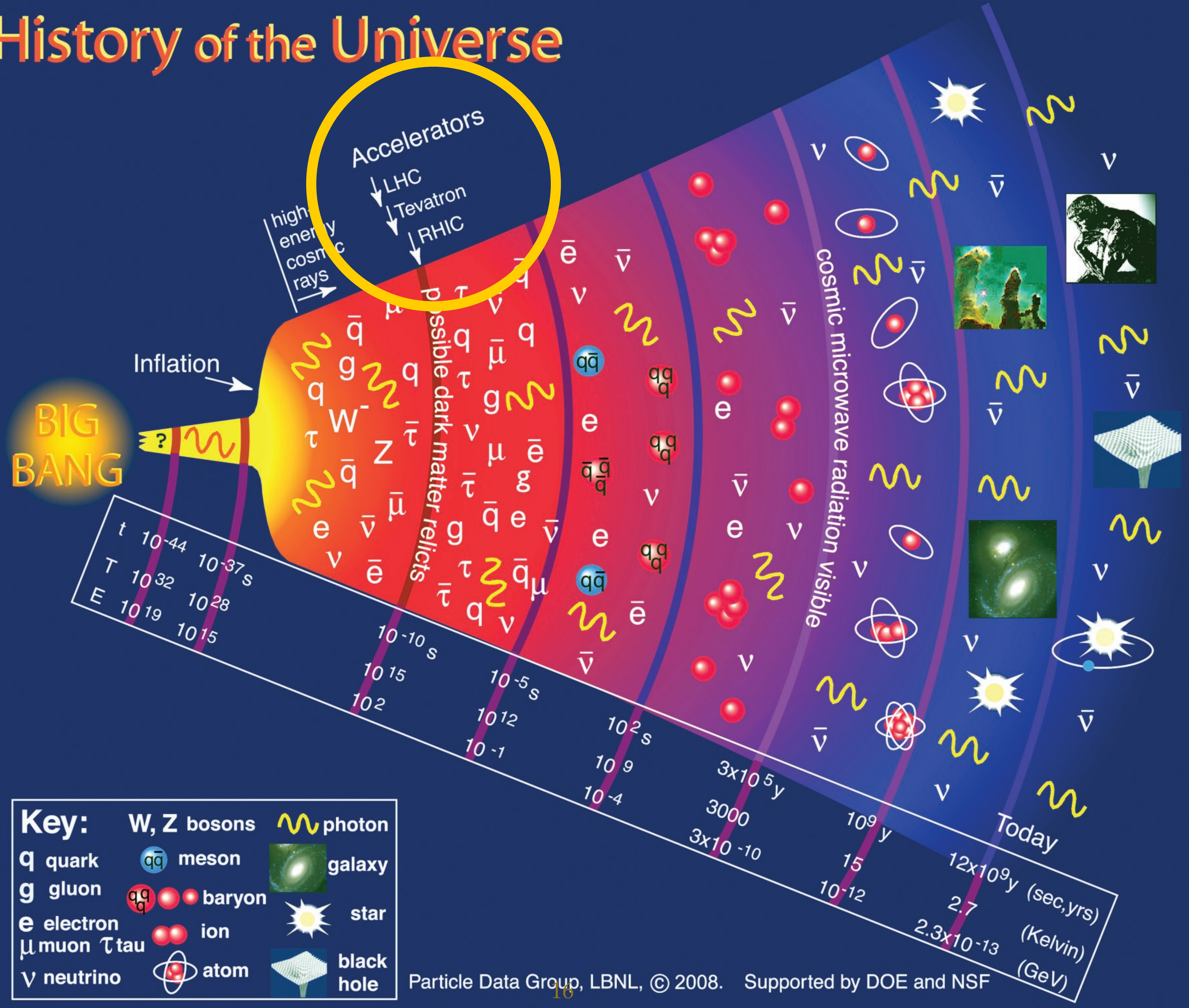
$K^o \rightarrow \pi^+ e \nu$



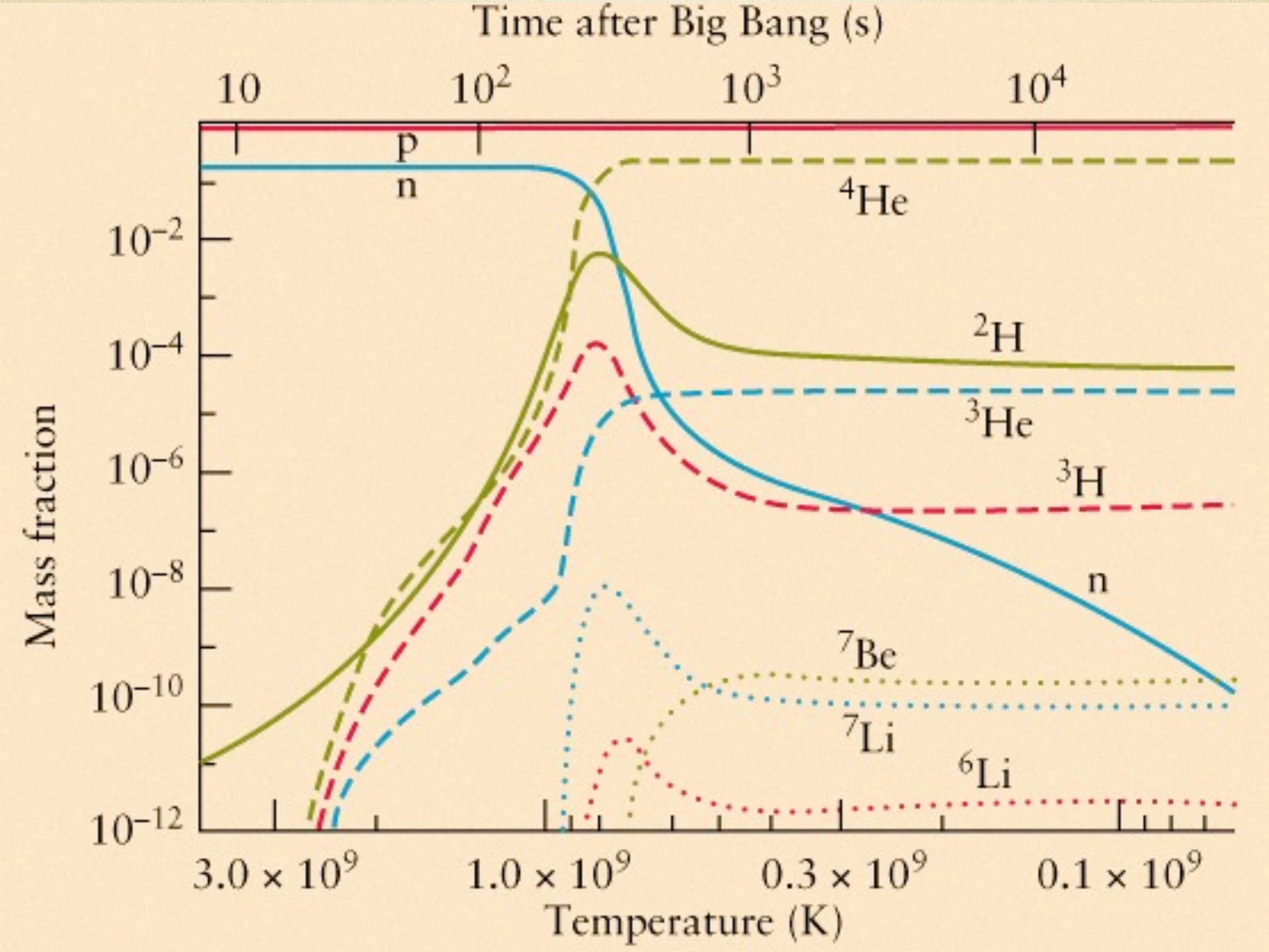
Trasformazioni come questa, in cui protoni e neutroni si trasformano gli uni negli altri con emissione di elettroni e neutrini, sono alla base del funzionamento delle stelle

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.

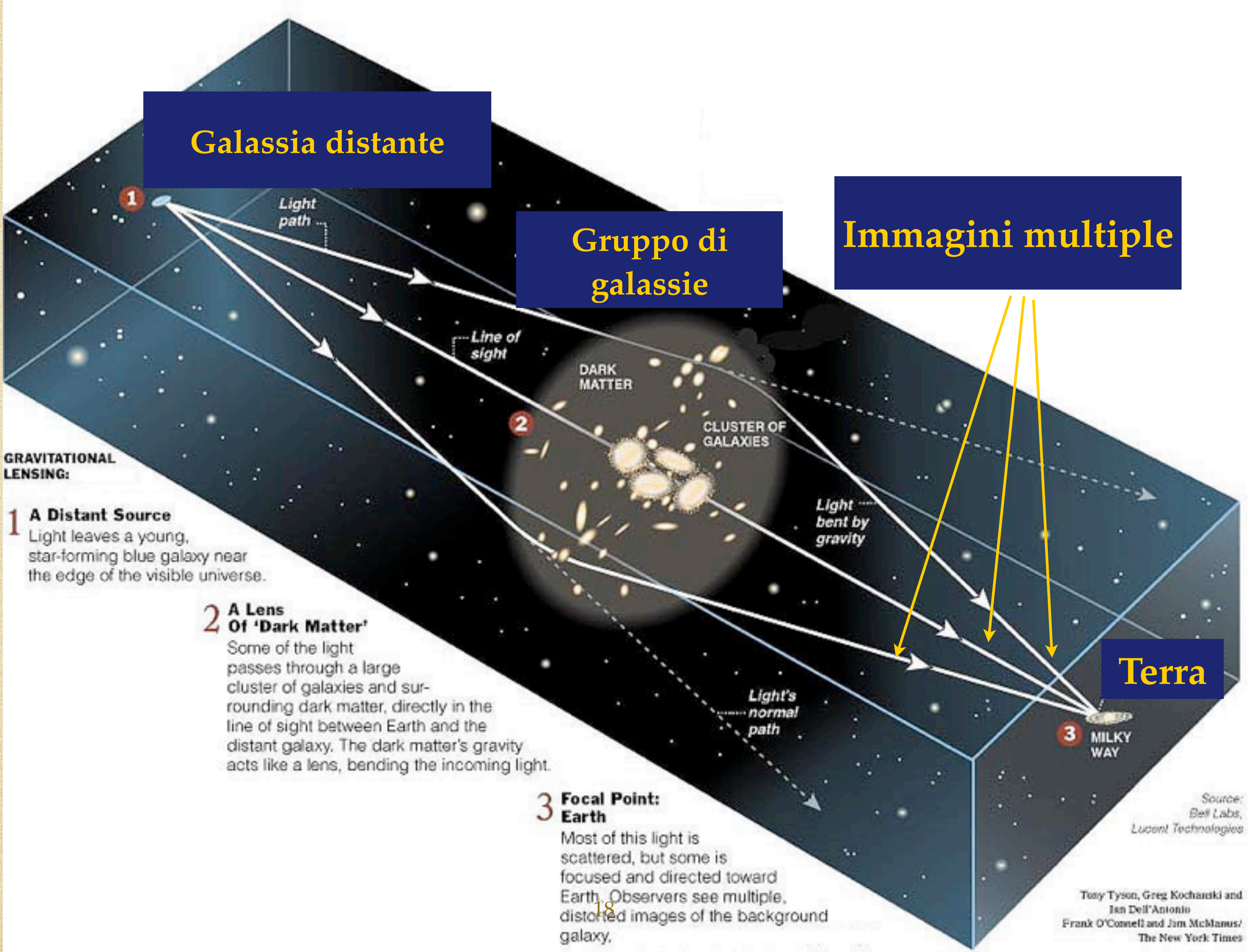
History of the Universe



Particle Data Group, LBNL, © 2008. Supported by DOE and NSF


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

Lenti gravitazionali



Galassia distante

Gruppo di galassie

Immagini multiple

Terra

GRAVITATIONAL LENSING:

1 **A Distant Source**
Light leaves a young, star-forming blue galaxy near the edge of the visible universe.

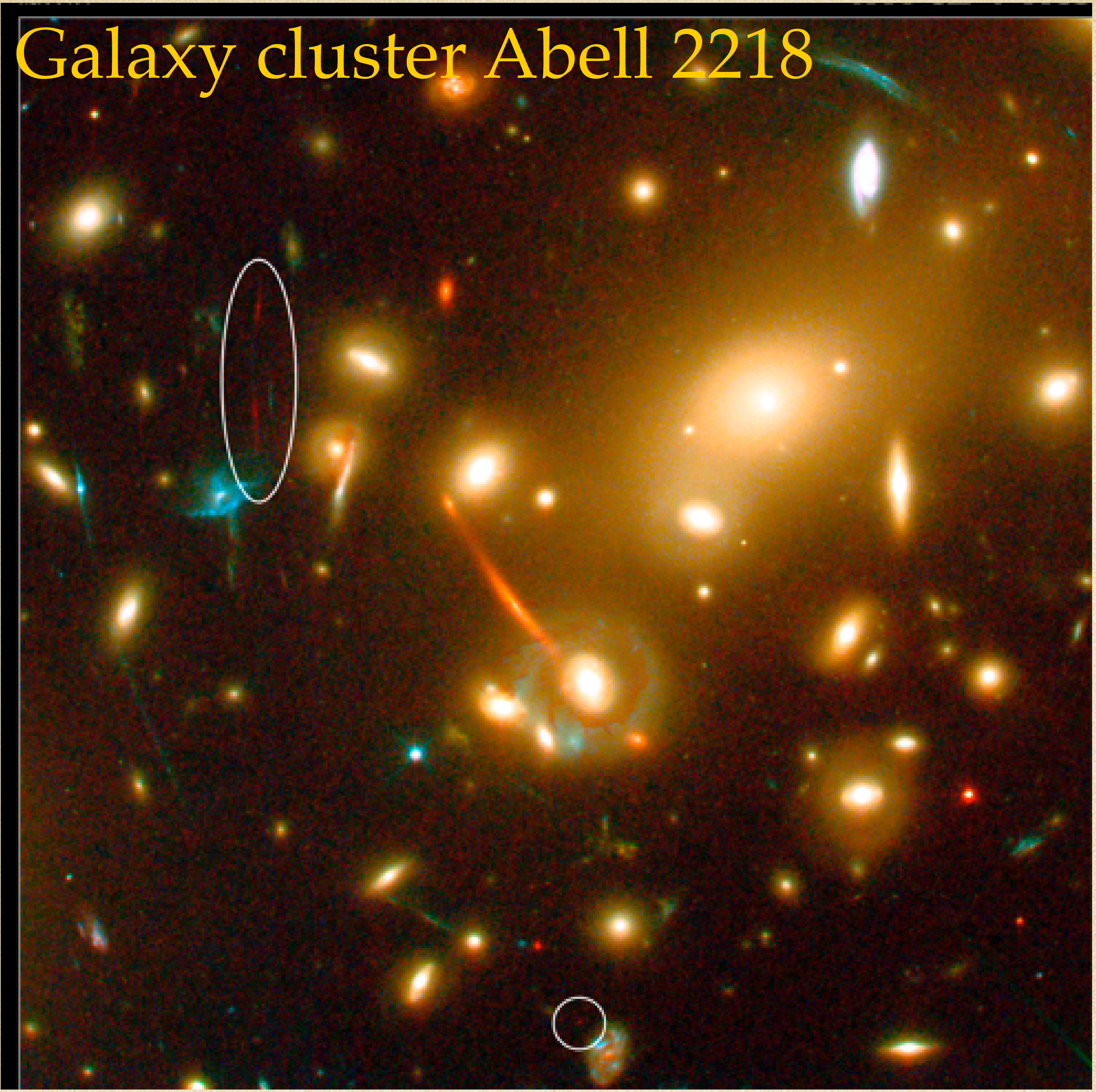
2 **A Lens Of 'Dark Matter'**
Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.

3 **Focal Point: Earth**
Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.

Source: Bell Labs, Lucent Technologies

Tony Tyson, Greg Kochanski and Ian Dell'Antonio
Frank O'Connell and Jim McManus/
The New York Times

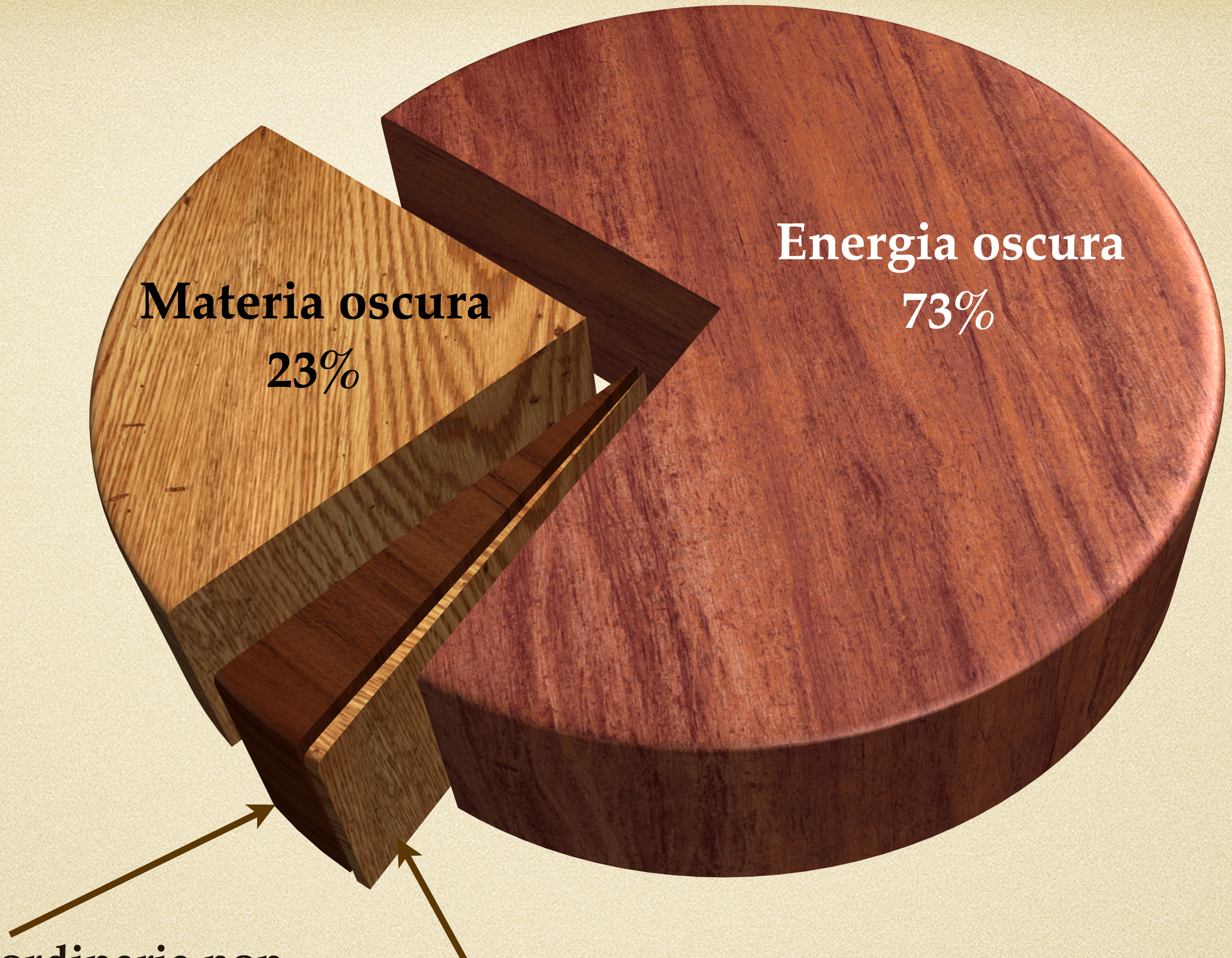
Galaxy cluster Abell 2218



Credits: *European Space Agency, NASA, J.-P. Kneib (Observatoire Midi-Pyrénées) and R. Ellis (Caltech)*

Forma ed intensita’ delle immagini multiple indicano la presenza di una quantita’ di materia 5 volte maggiore di quella visibile nelle galassie dell’ammasso!

→ **Materia oscura**



materia ordinaria non luminosa (pianeti, stelle morte, polvere, asteroidi, buchi neri, …), ~4%

materia luminosa (stelle, gas)
~0.5%

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?*
- ….

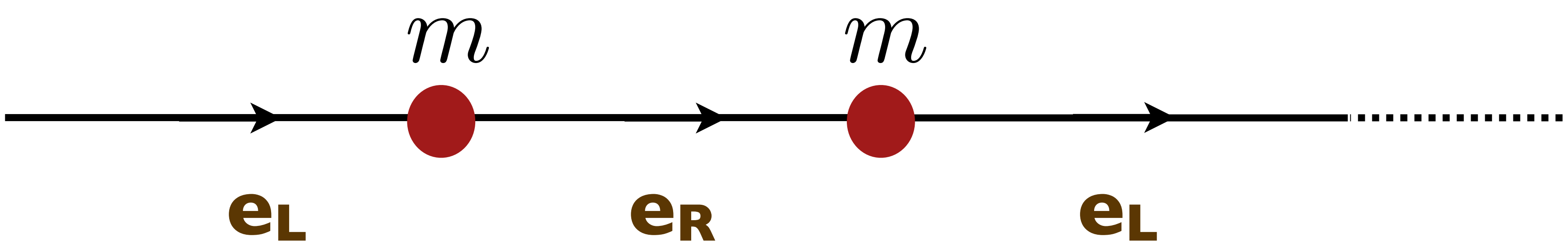
Perche’ ci vuole “un” bosone di Higgs per dare massa alle particelle?

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

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

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

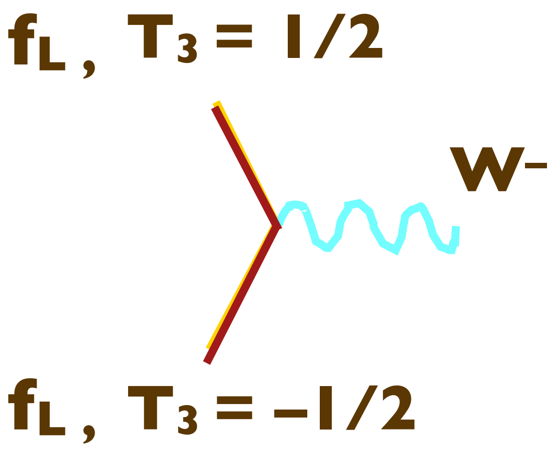


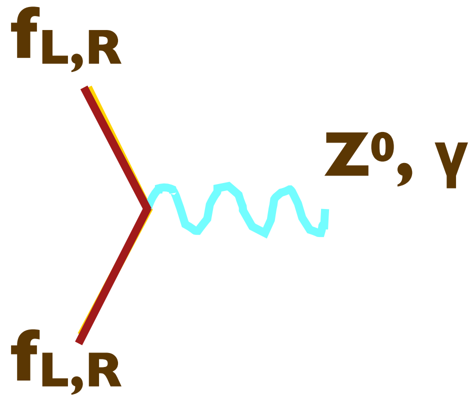
For a massive particle, chirality does not commute with the Hamiltonian, so it cannot be conserved

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

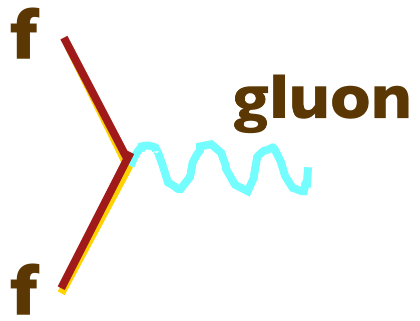
Nothing wrong with that in principle .... unless chirality is associated to a conserved charge!

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





SU(3)



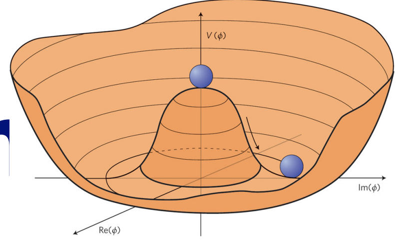
L-chirality	R-chirality
$\begin{pmatrix} u_{2/3} \\ d_{-1/3} \end{pmatrix}^{i=1,2,3}_{L}$	$u^i{}_R$, $d^i{}_R$
$\begin{pmatrix} \nu \\ e^- \end{pmatrix}_{L}$	e^-_R

+ 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 <u>new degrees of freedom</u>

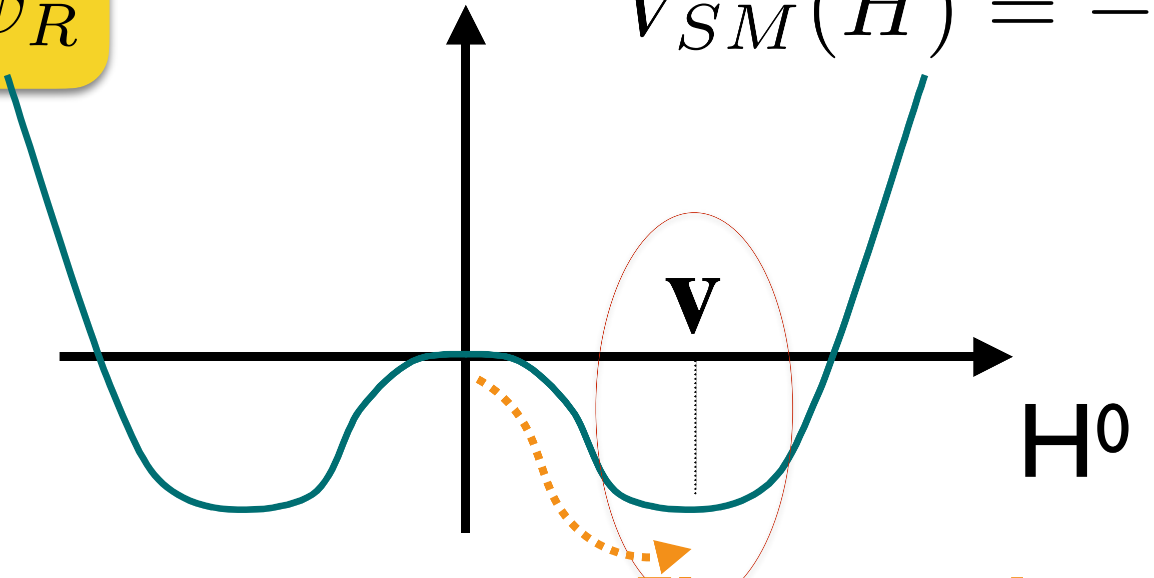
The SM solution: Higgs mechanism



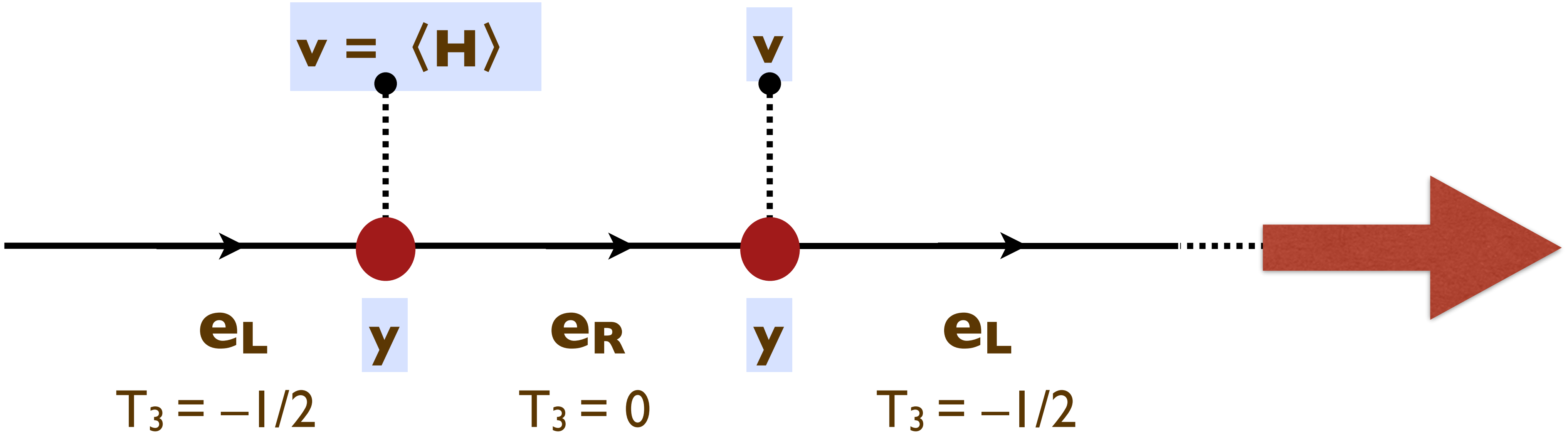
$$m\,\overline{\psi_L}\,\psi_R \rightarrow \lambda H\,\overline{\psi_L}\,\psi_R$$

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

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



Electroweak symmetry breaking (EWSB)



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

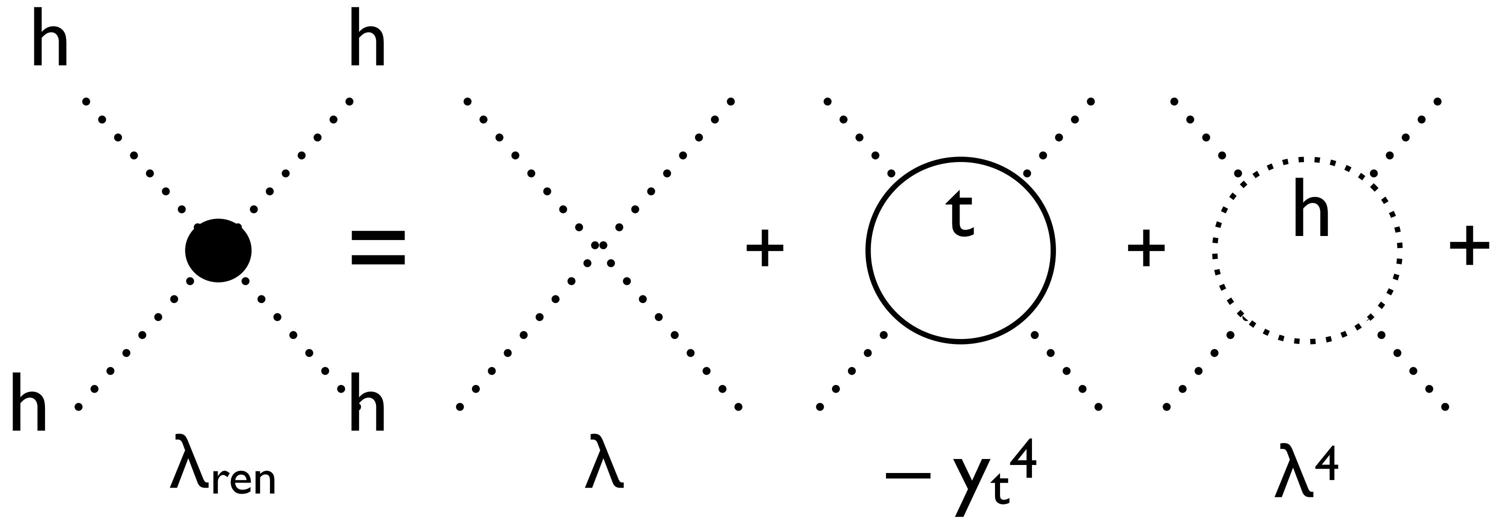
- **BCS-like**: the Higgs is a composite object
- **Supersymmetry**: the Higgs is a fundamental field and
  - $\lambda^2 \sim g^2+g'^2$, it is not arbitrary (MSSM, w/out susy breaking, has one parameter less than SM!)
  - potential is fixed by susy & gauge symmetry
  - EW symmetry breaking (and thus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

Other important open issues on the Higgs sector

- 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 **<u>same</u>** Higgs field?
  - Do $I_3=1/2$ fermions (up-type quarks) get their mass from the **<u>same</u>** Higgs field as $I_3=-1/2$ fermions (down-type quarks and charged leptons)?
  - Do Higgs couplings conserve flavour? $H\to\mu\tau$? $H\to e\tau$? $t\to Hc$?
- Is there a deep reason for the apparent metastability of the Higgs vacuum?

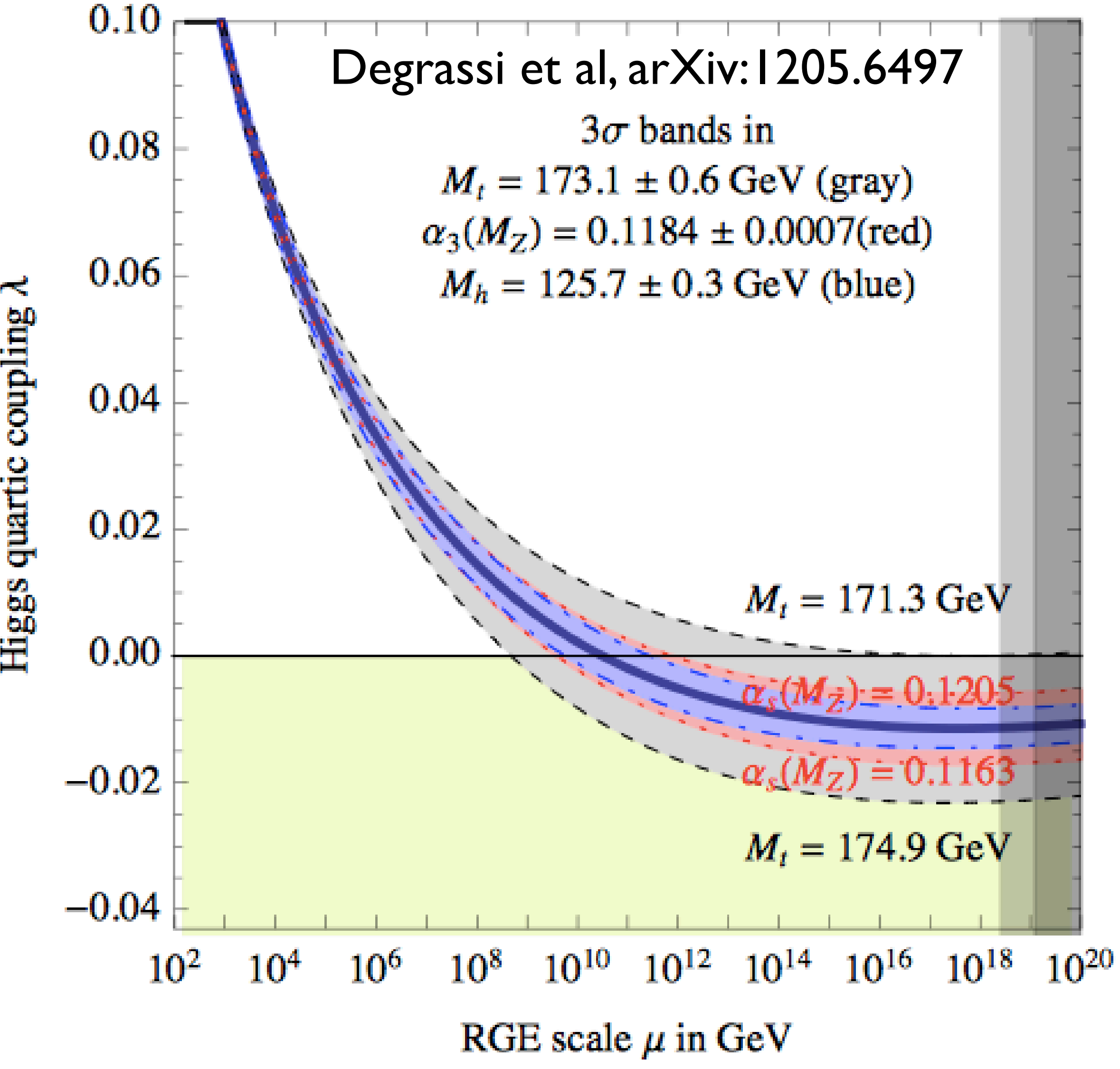
(meta)Stability of the Higgs potential

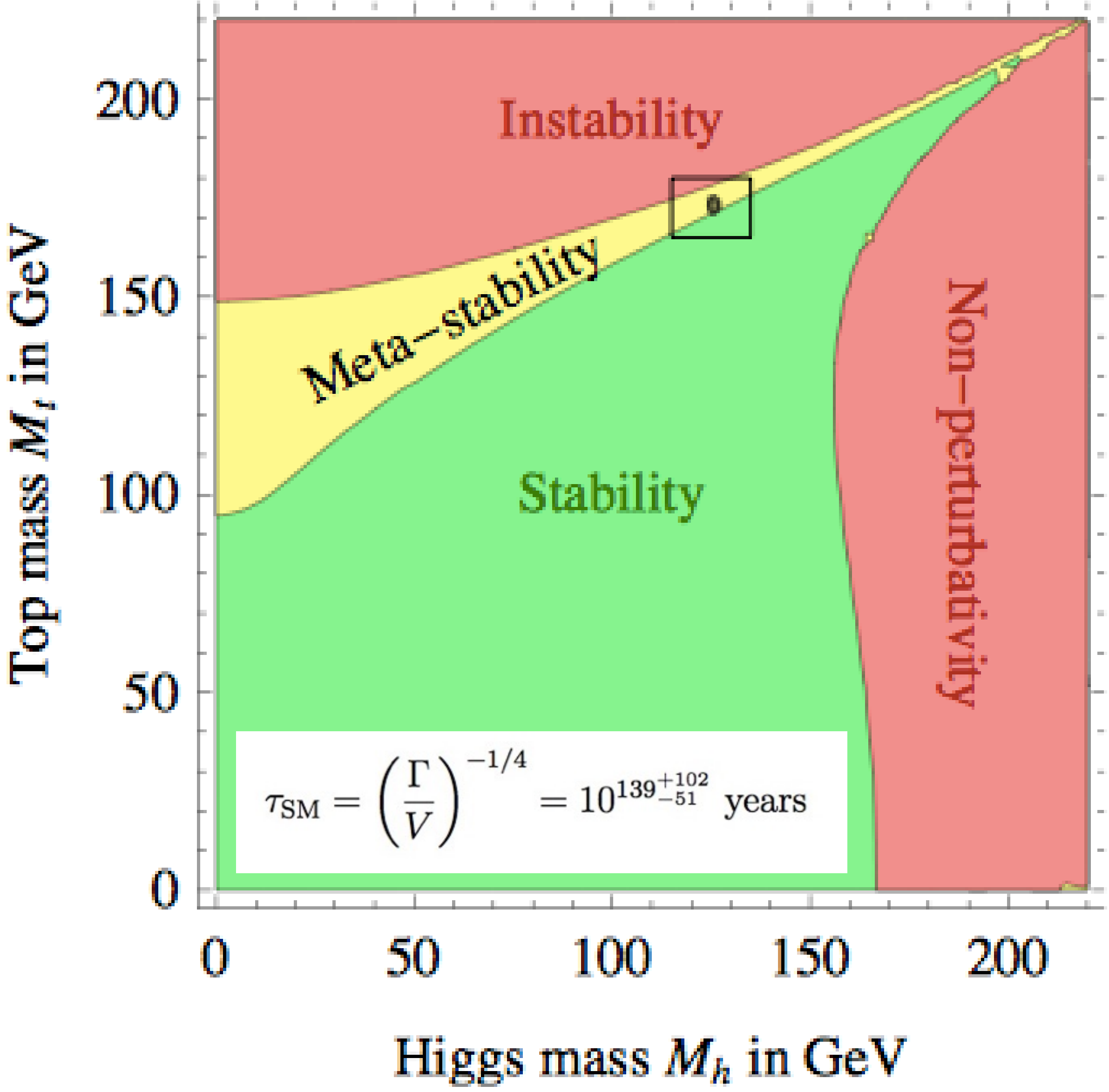
Higgs selfcoupling and coupling to the top are the key elements to define the stability of the Higgs potential



$$\Longrightarrow \frac{d\lambda}{d\log\mu} \propto \lambda^4 - y_t^4$$

$$\propto a\, m_H^4 - b\, m_t^4$$





Not an issue of concern for the human race…. but the closeness of mtop to the critical value where the Higgs selfcoupling becomes 0 at M_{Planck} (namely 171.3 GeV) might be telling us something fundamental about the origin of EWSB … incidentally, y_{top}=1 (?!)

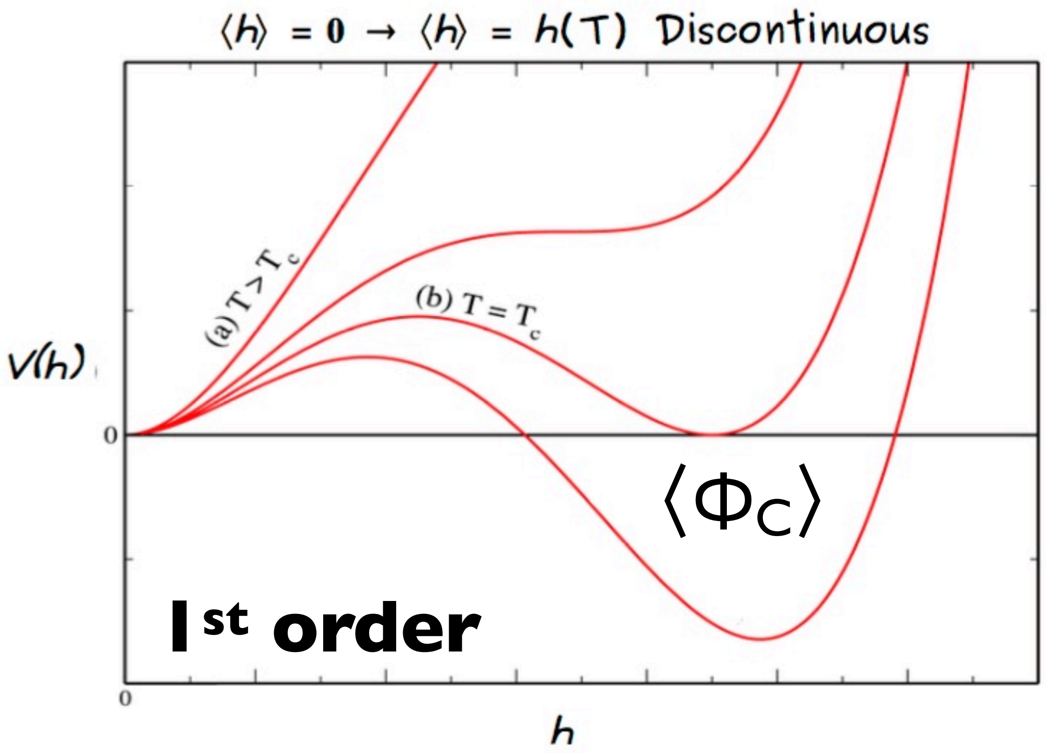
Other important open issues on the Higgs sector

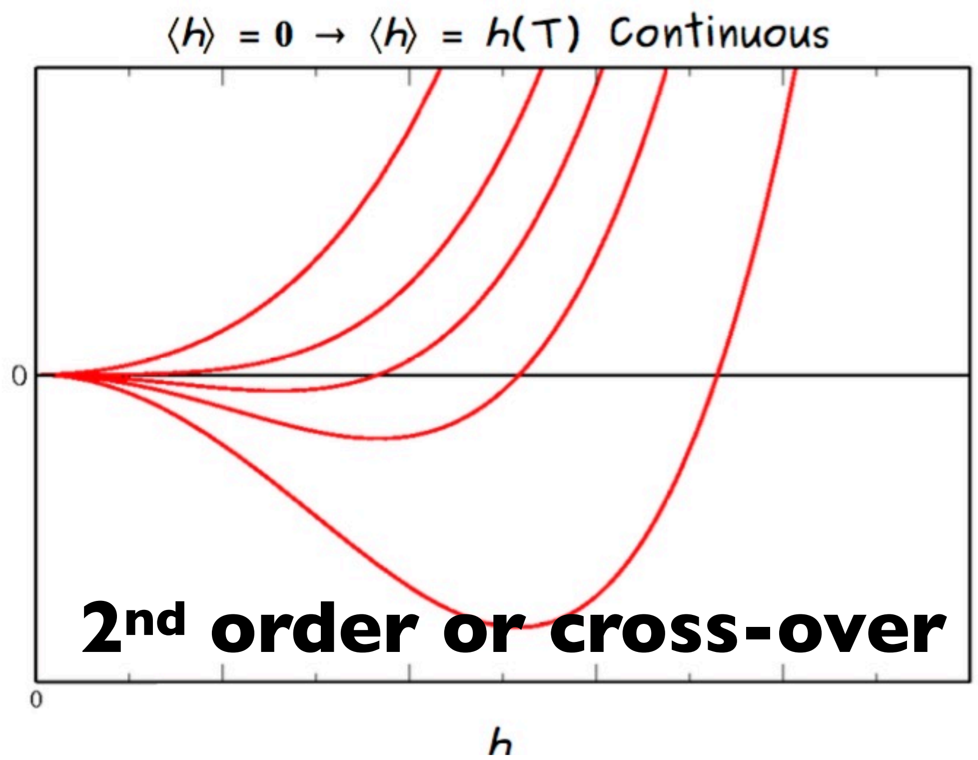
- Is the Higgs the only (fundamental?) scalar field, or are there other Higgs-like states (e.g. $H^\pm$, A^0, $H^{\pm\pm}$, ... , EW-singlets, ...) ?
  - Do all SM families get their mass from the **same** Higgs field?
  - Do I_3=1/2 fermions (up-type quarks) get their mass from the **same** Higgs field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

- Is there a deep reason for the apparent metastability of the Higgs vacuum?

- 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?

The nature of the EW phase transition





Strong 1st order phase transition is required to induce and sustain the out of equilibrium generation of a baryon asymmetry during EW symmetry breaking

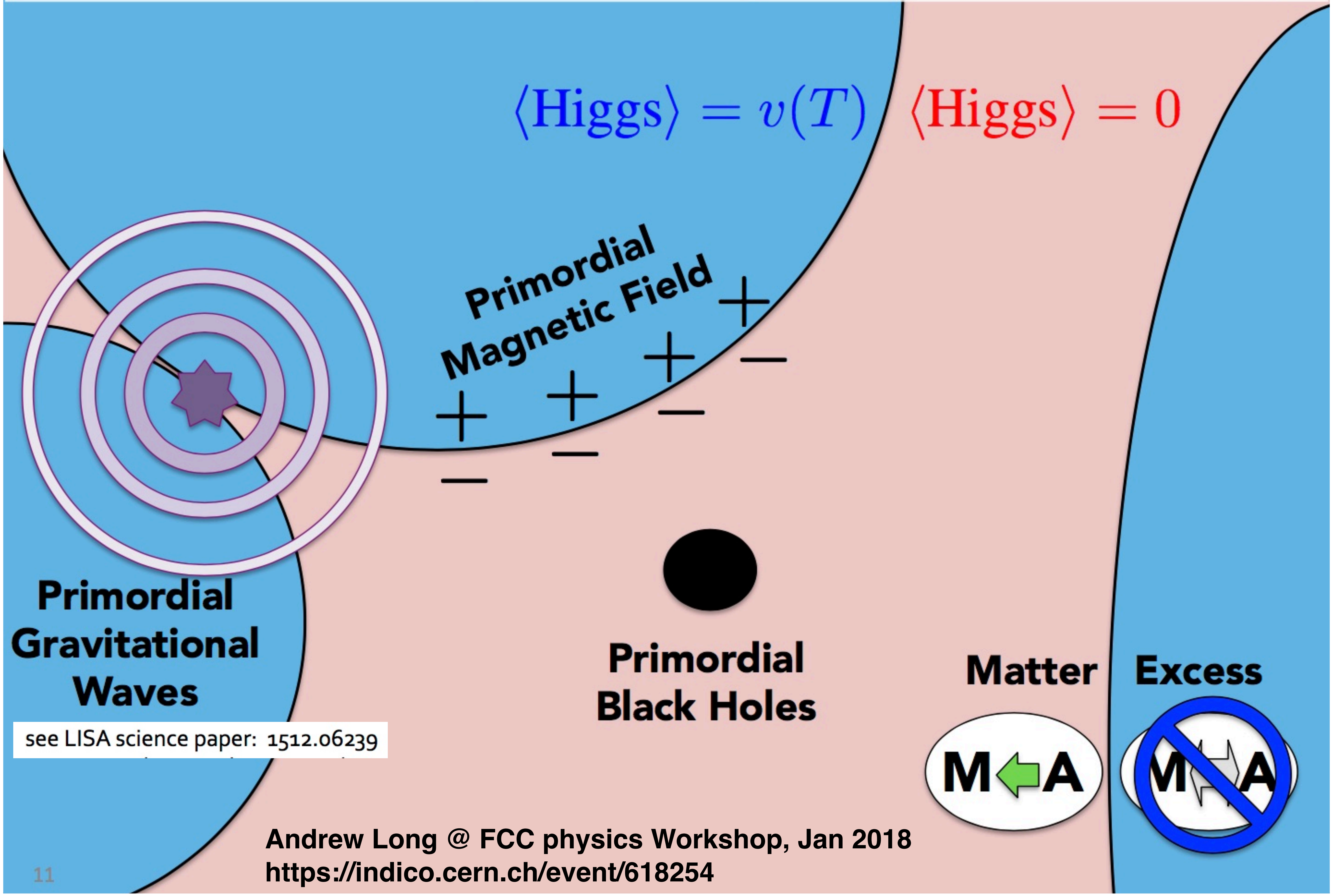
Strong 1st order phase transition ⇒ $\langle \Phi_C \rangle > T_C$

In the SM this requires $m_H \lesssim$ 80 GeV, else transition is a smooth crossover.

Since m_H = 125 GeV, **new physics**, coupling to the Higgs and effective at **scales O(TeV)**, must modify the Higgs potential to make this possible

- **Probe higher-order terms of the Higgs potential (selfcouplings)**
- **Probe the existence of other particles coupled to the Higgs**

1st Order EWPT has profound implications for cosmology



Primordial Magnetic Field

Primordial Gravitational Waves

see LISA science paper: 1512.06239

Primordial Black Holes

Matter Excess

Andrew Long @ FCC physics Workshop, Jan 2018
https://indico.cern.ch/event/618254

Other important open issues in the Higgs sector

- 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? $H\to\mu\tau$? $H\to e\tau$? $t\to Hc$?

- Is there a deep reason for the apparent metastability of the Higgs vacuum?

- 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!

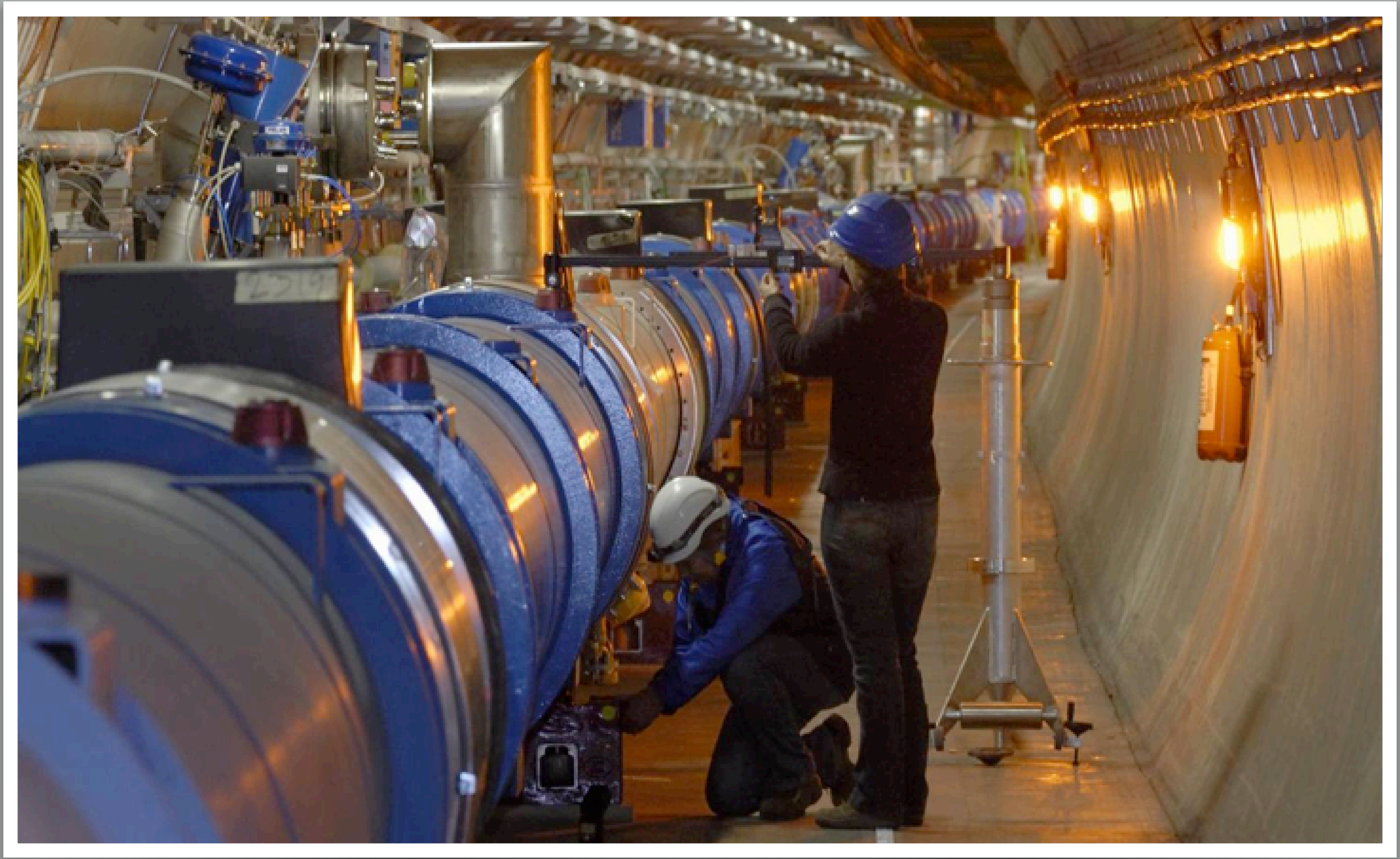
La produzione e rivelazione del bosone di Higgs

Come ogni altro mezzo continuo, il campo di Higgs puó 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 dualità onda-corpuscolo della meccanica quantistica.

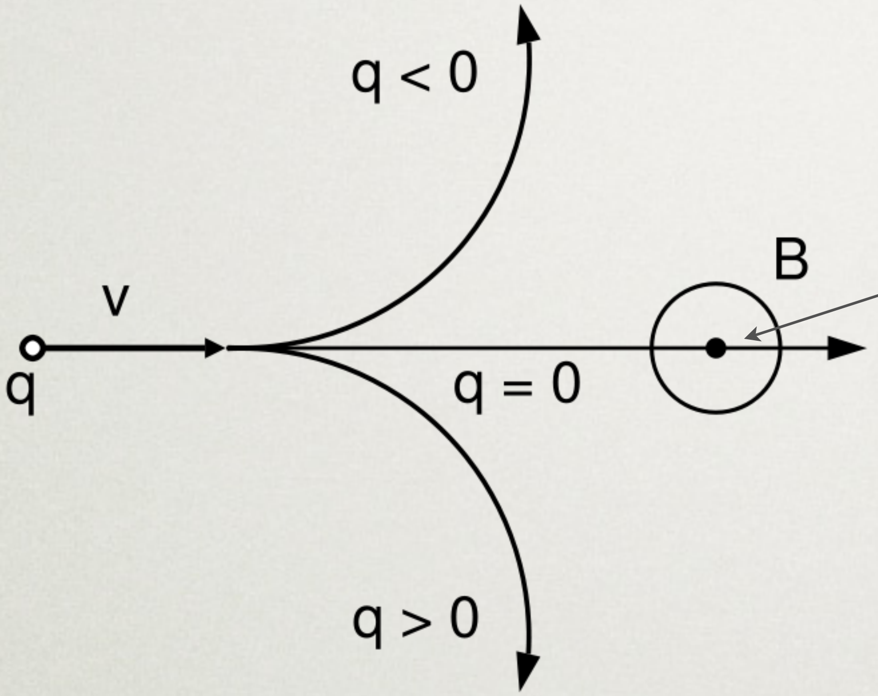
Far ciò richiede concentrare in un piccolo volume particelle di massa grande (per avere una forte interazione col campo di Higgs) e con sufficiente energia

⇒ LHC !!!

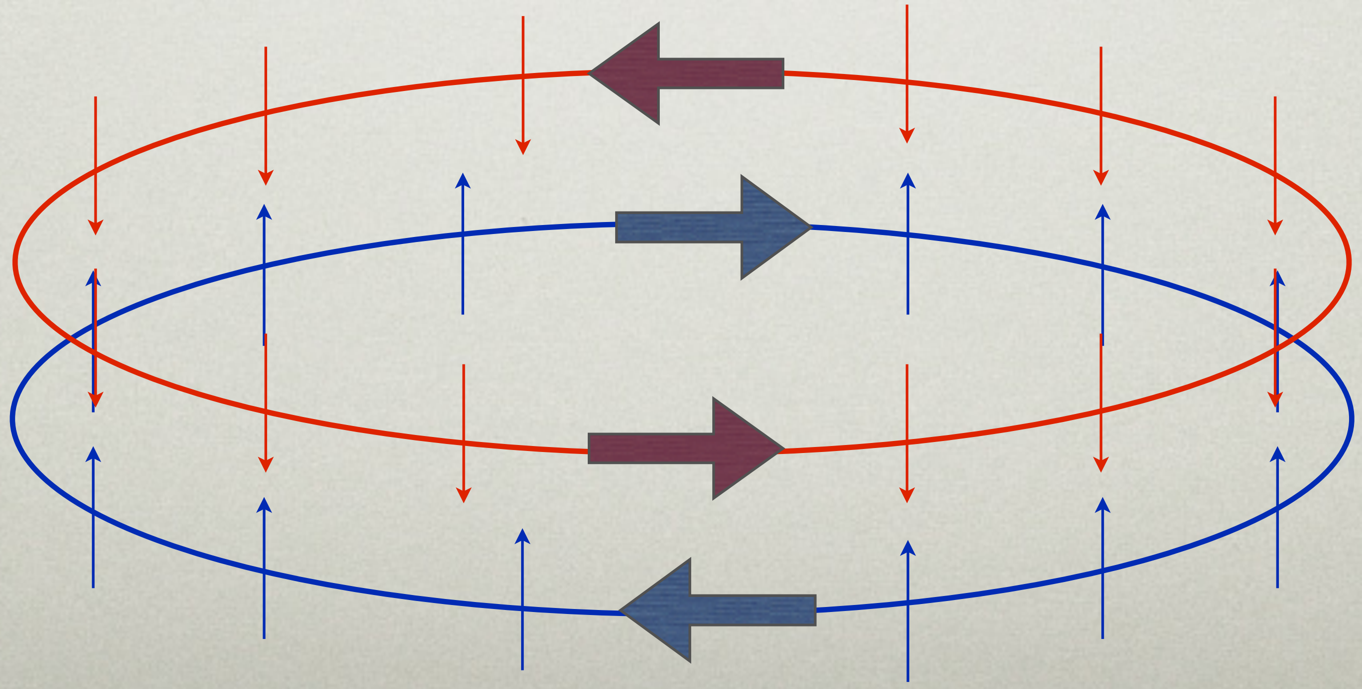
IL LARGE HADRON COLLIDER (LHC)



STEERING PROTONS



B: Magnetic field line perpendicular to the screen

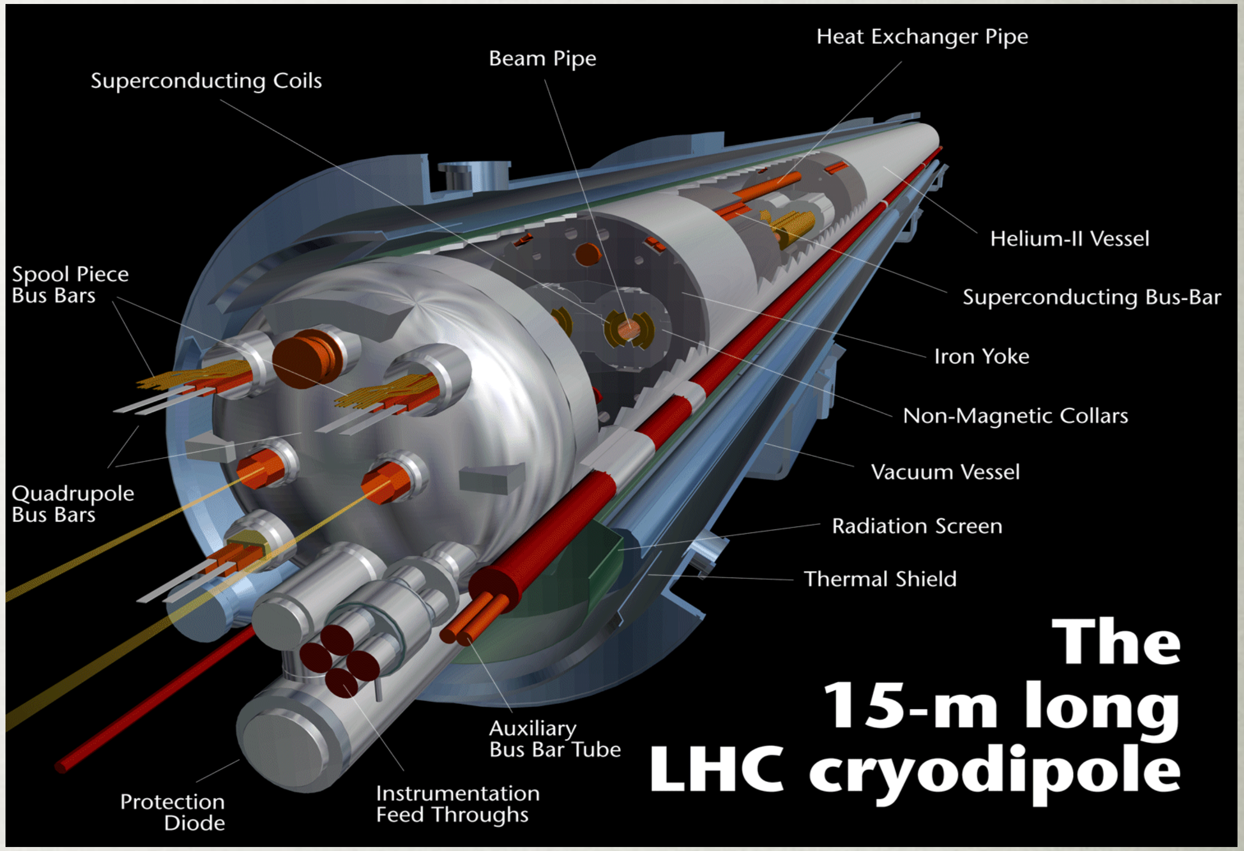


The LHC dipole

- B field = 83,000 Gauss
  - Ni Ti SC cable

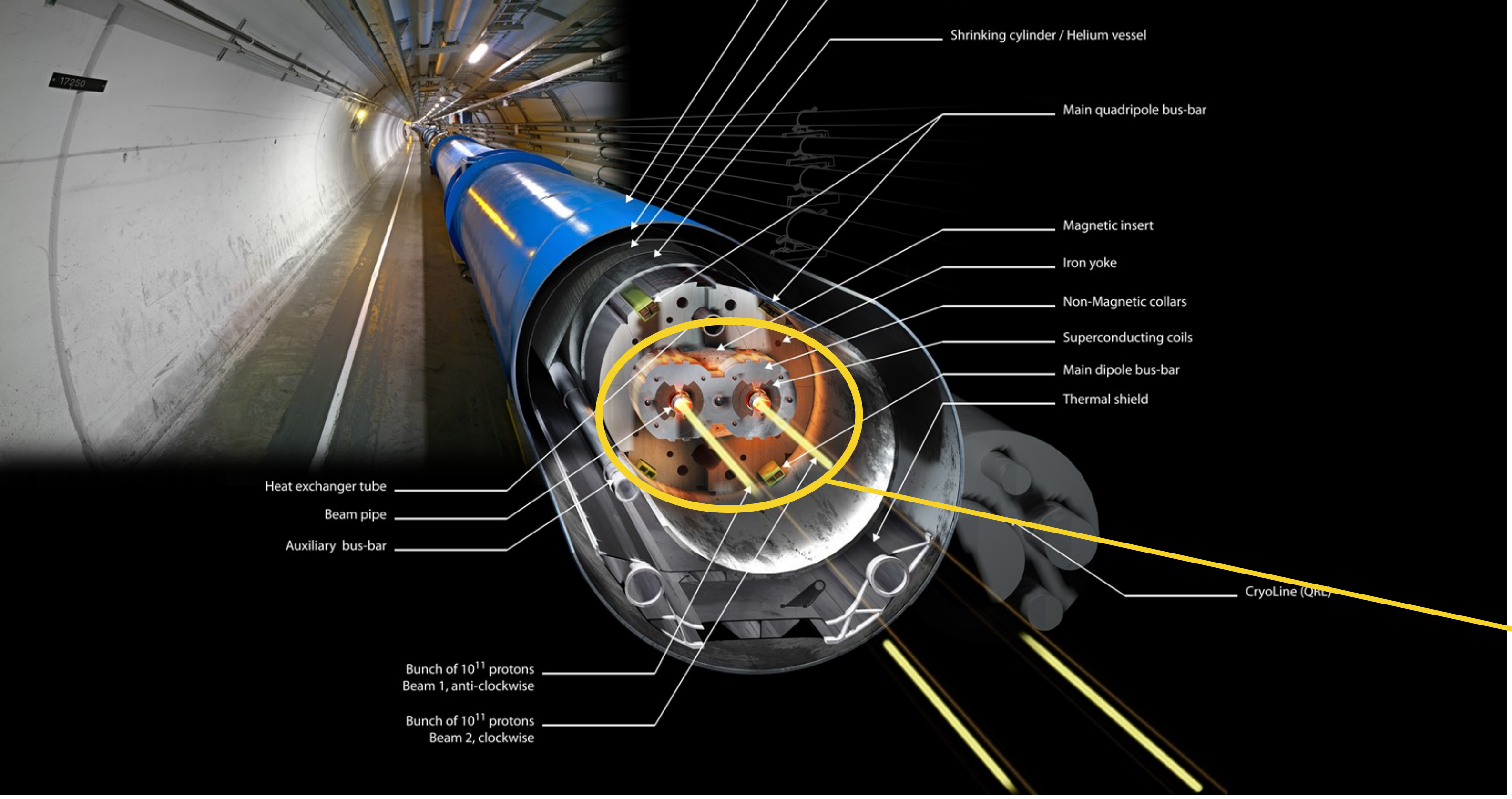
(Earth's field ~ 0.5 Gauss)

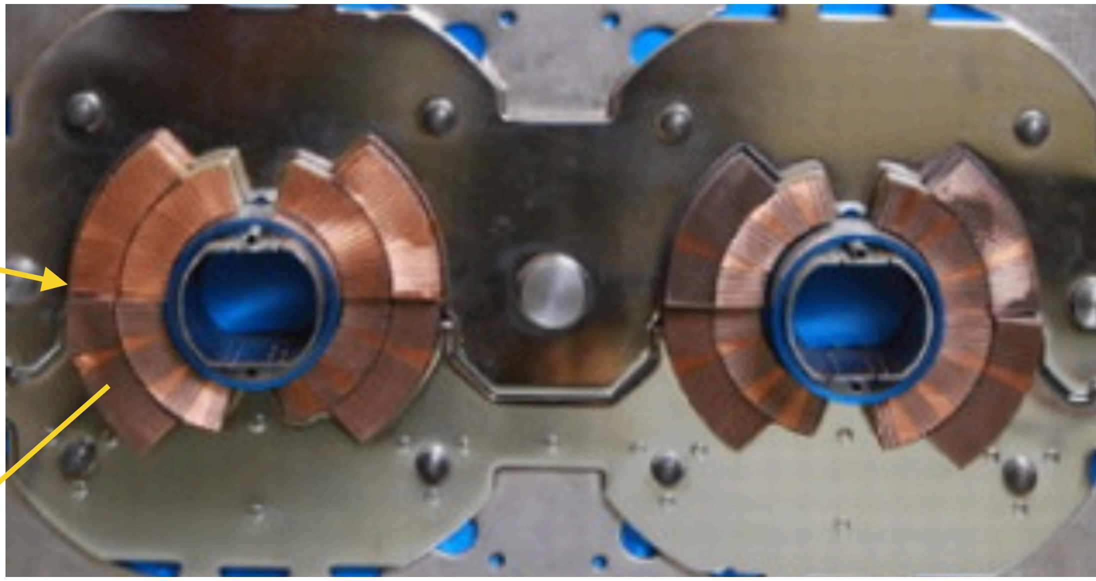
- $T = 1.9K^0 = -456$ F
  - superfluid liquid Helium
- 35 tonnes
- 50 ft long
- Stress at the collar: 150 MPa
- Stored energy: 7 MJoule

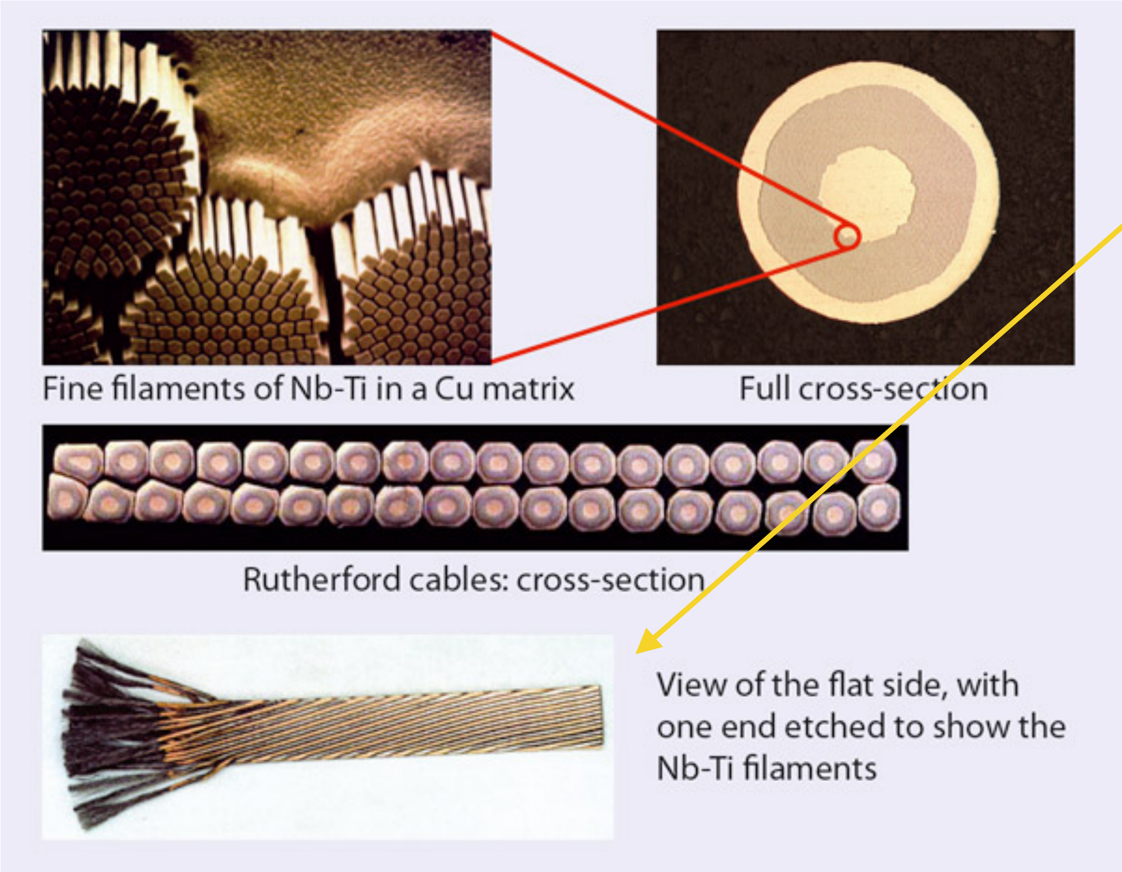


The 15-m long LHC cryodipole

- ~ 22,000 psi
- ~ 1,500 kg/cm^2





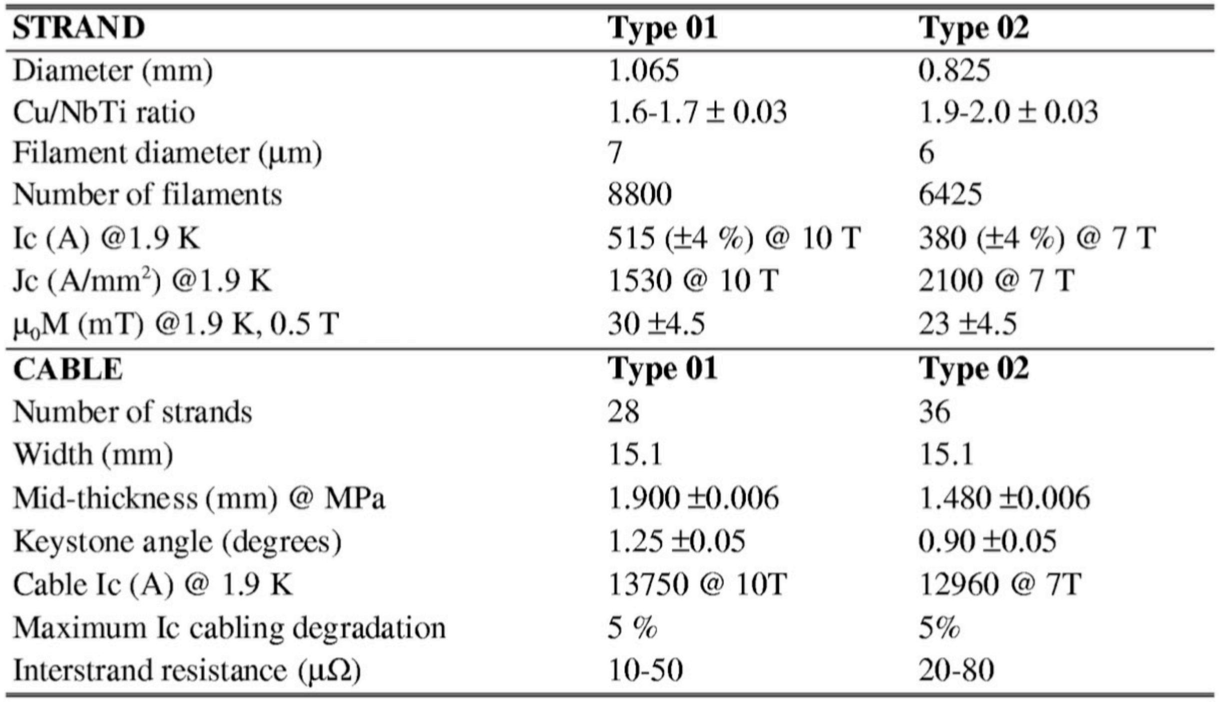


Fine filaments of Nb-Ti in a Cu matrix

Full cross-section

Rutherford cables: cross-section

View of the flat side, with one end etched to show the Nb-Ti filaments



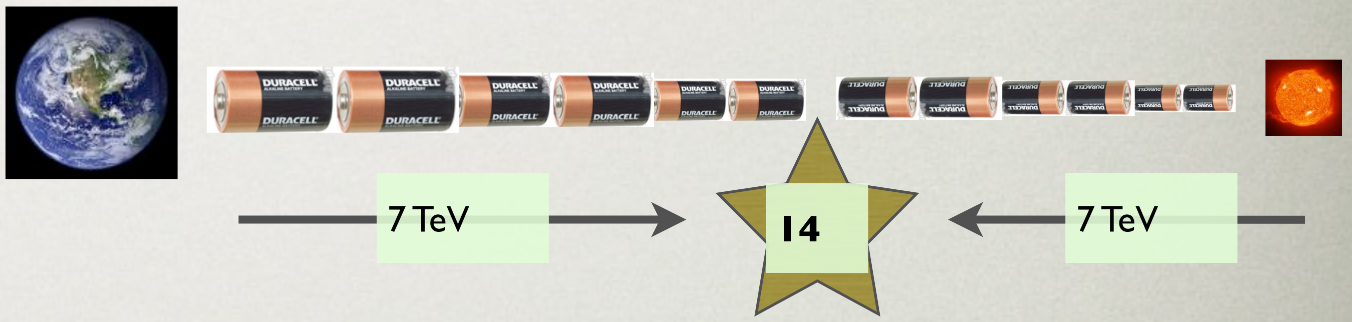
STRAND	Type 01	Type 02
Diameter (mm)	1.065	0.825
Cu/NbTi ratio	1.6-1.7 ± 0.03	1.9-2.0 ± 0.03
Filament diameter (μm)	7	6
Number of filaments	8800	6425
Ic (A) @1.9 K	515 (±4 %) @ 10 T	380 (±4 %) @ 7 T
Jc (A/mm^2) @1.9 K	1530 @ 10 T	2100 @ 7 T
μ_0M (mT) @1.9 K, 0.5 T	30 ±4.5	23 ±4.5
CABLE	**Type 01**	**Type 02**
Number of strands	28	36
Width (mm)	15.1	15.1
Mid-thickness (mm) @ MPa	1.900 ±0.006	1.480 ±0.006
Keystone angle (degrees)	1.25 ±0.05	0.90 ±0.05
Cable Ic (A) @ 1.9 K	13750 @ 10T	12960 @ 7T
Maximum Ic cabling degradation	5 %	5%
Interstrand resistance (μΩ)	10-50	20-80

THE LHC ACCELERATOR

- 1232 LHC dipoles, plus ~600 other smaller magnets

- E_{beam} = 7000 GeV ~ 7×10^{12} eV ~ 5 trillions 1.5V batteries

~ 100 M km of batteries, about d[Earth-Sun]

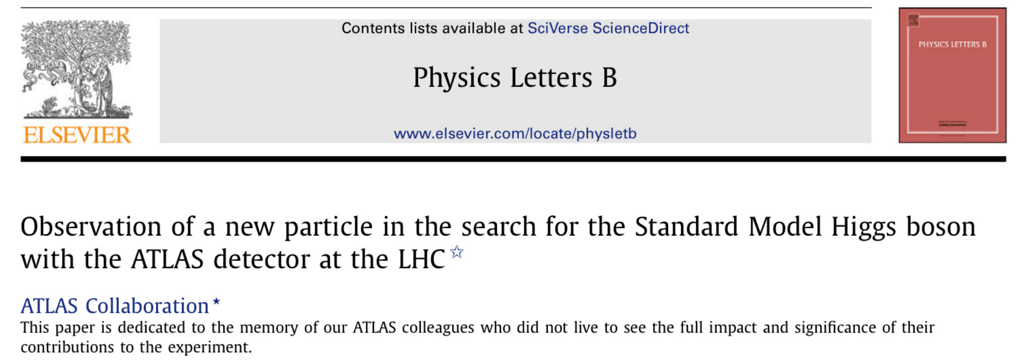


- E_{beam} = 7000 GeV ~ 7500 $m_{proton} c^2$
  - $E = mc^2 / \sqrt{[1 - v^2/c^2]}$ ⇨ v = 0.999 999 99 c

- N_{proton} ~ 10^{11}/bunch x 2800 bunches/beam x 2 beams ~ 10^{14}

- Energy stored ~ 350 MJ ~ 200 lb of TNT ~ Train running full speed

2012



Contents lists available at SciVerse ScienceDirect

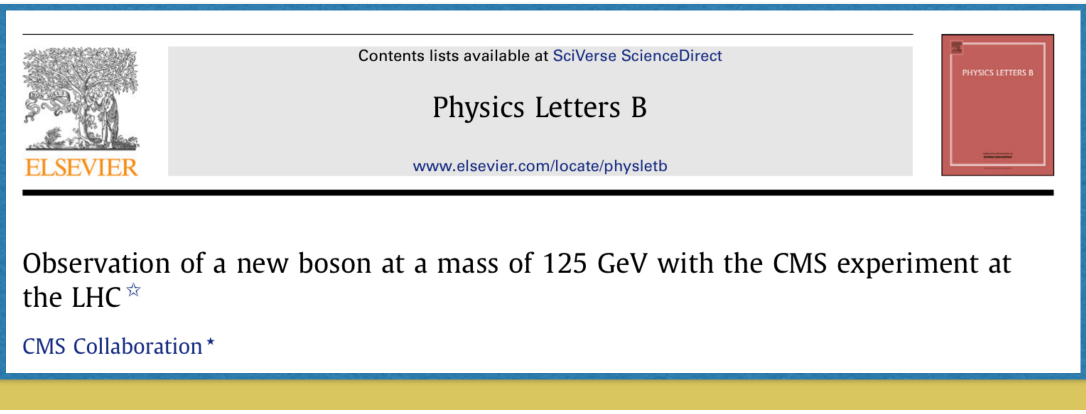
Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.



Contents lists available at SciVerse ScienceDirect

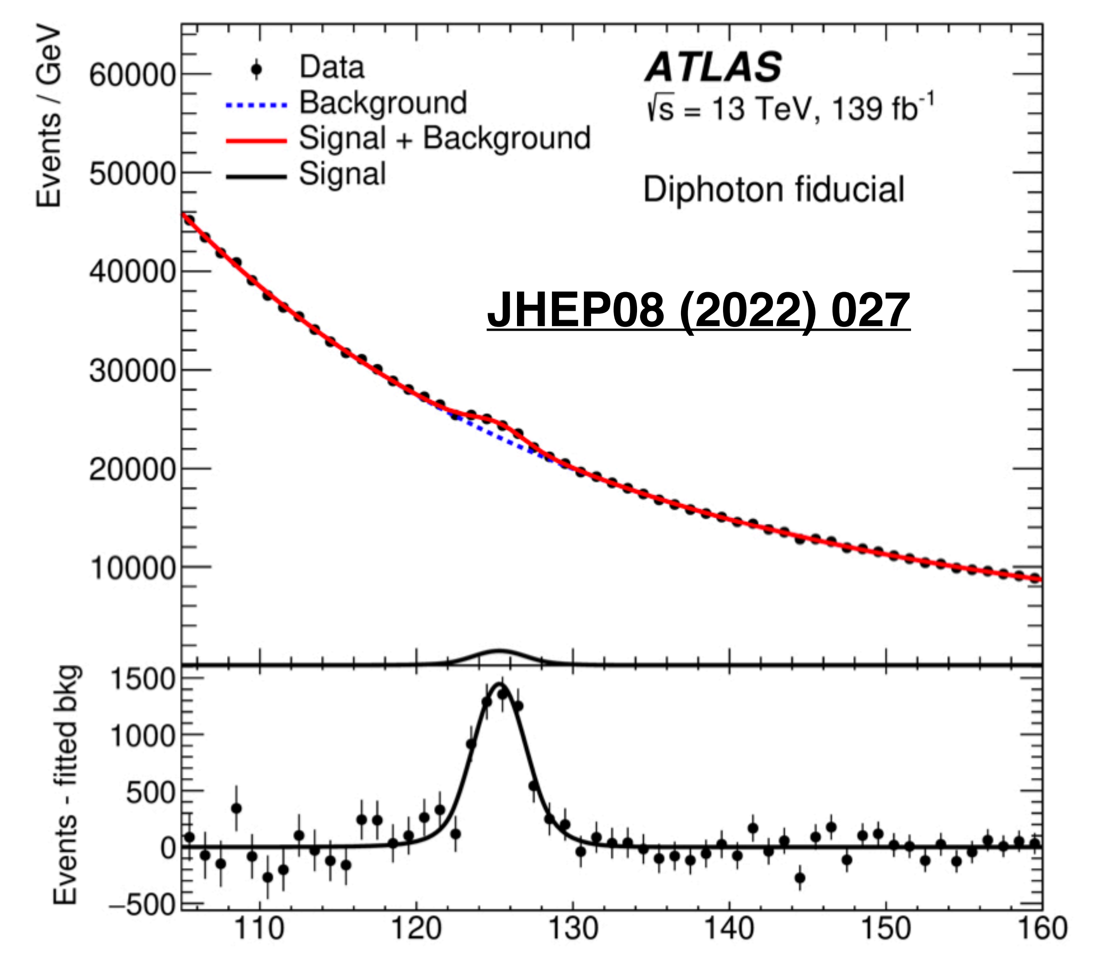
Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

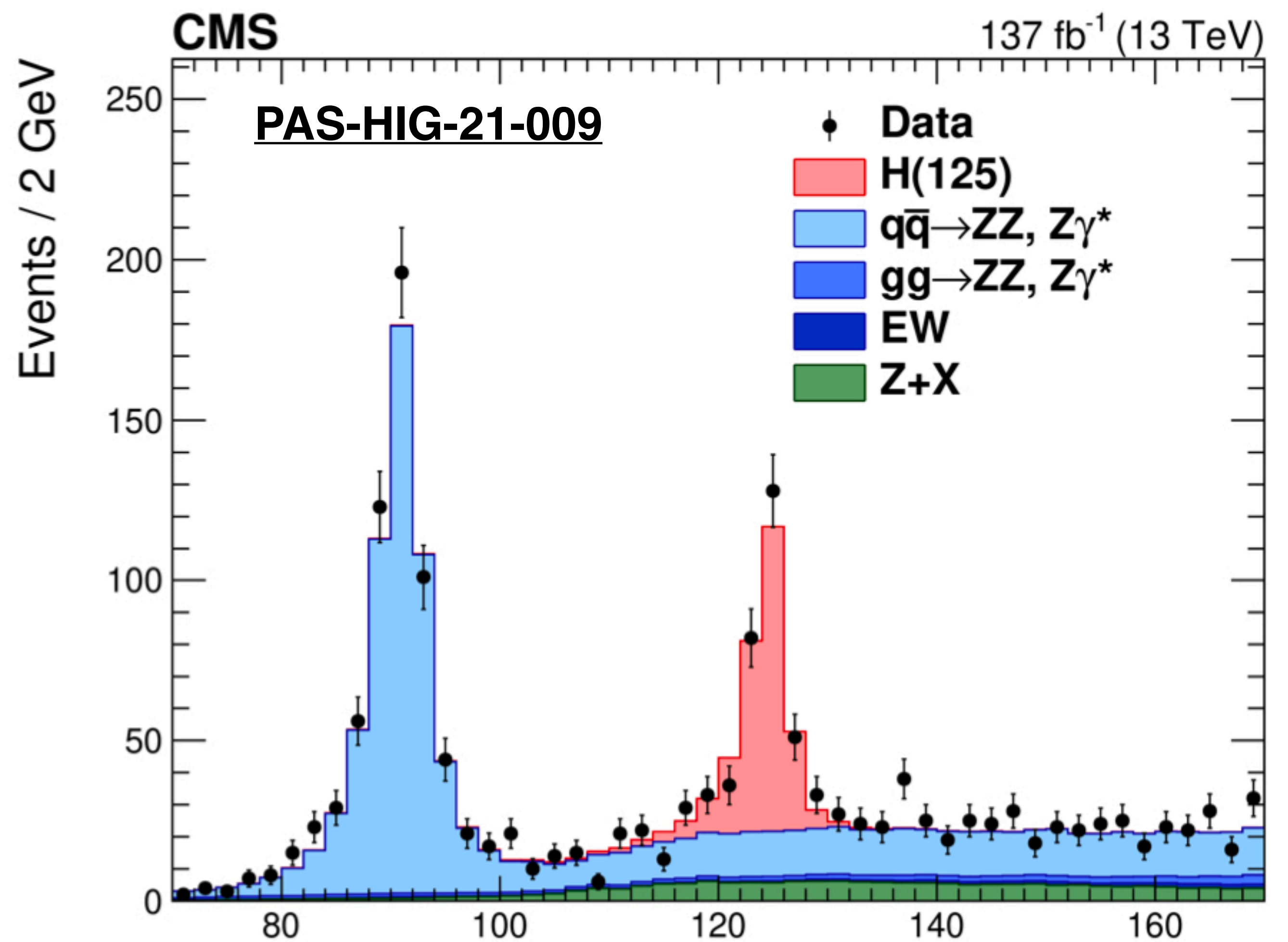
CMS Collaboration *

2023



JHEP08 (2022) 027

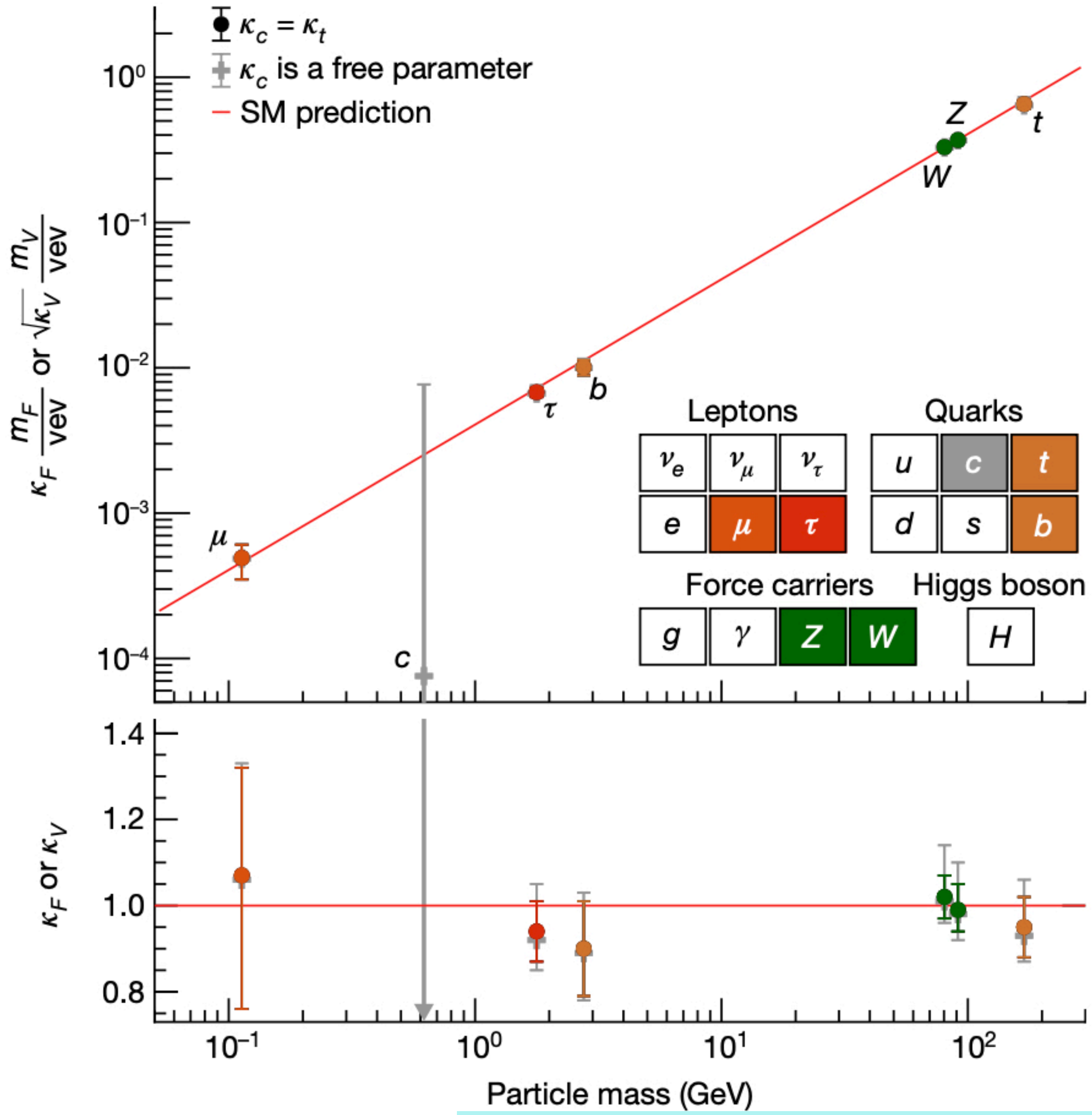
$H \to \gamma\gamma$

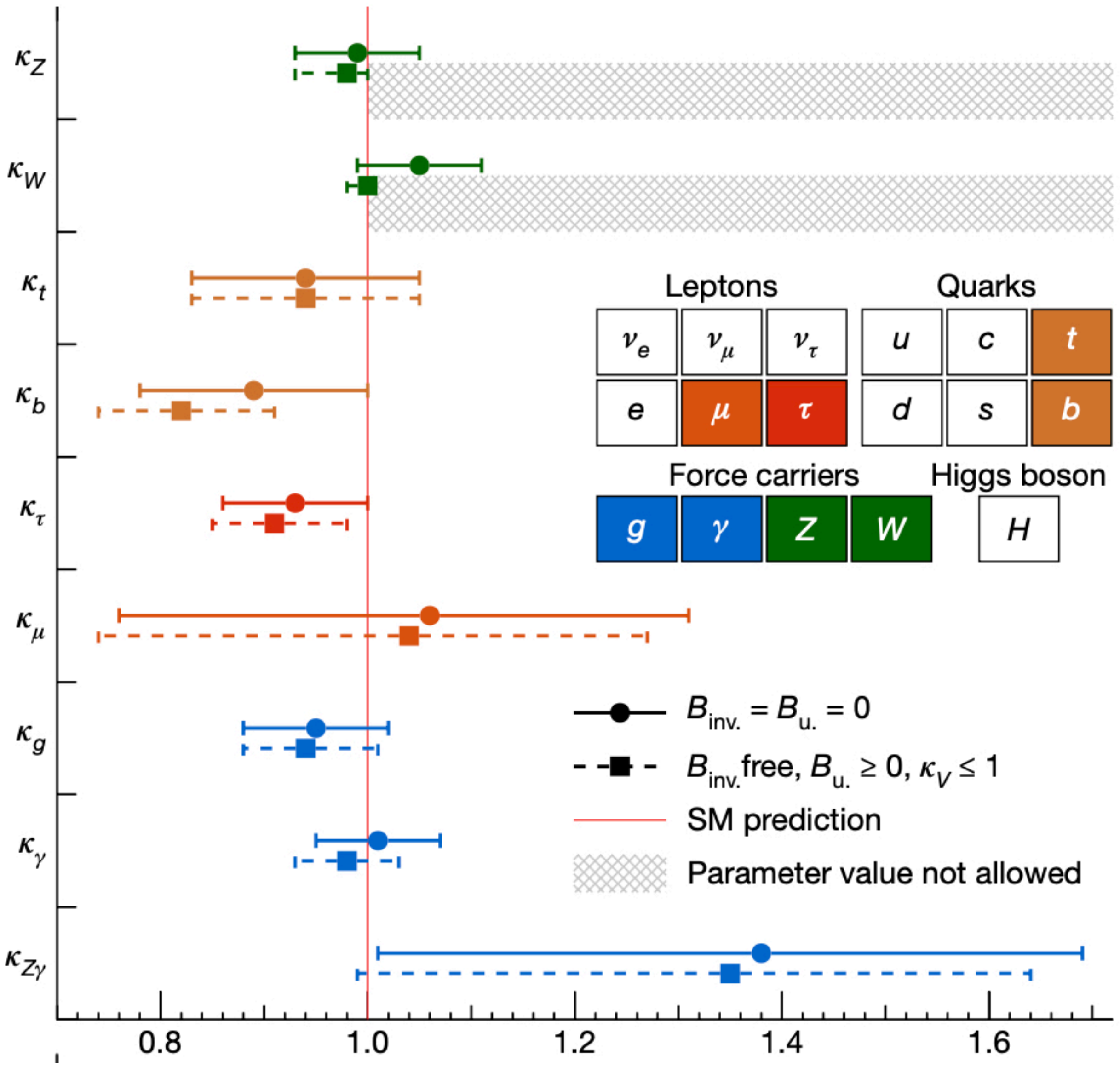


PAS-HIG-21-009

$H \to$ 4 leptons

General properties and couplings: OK



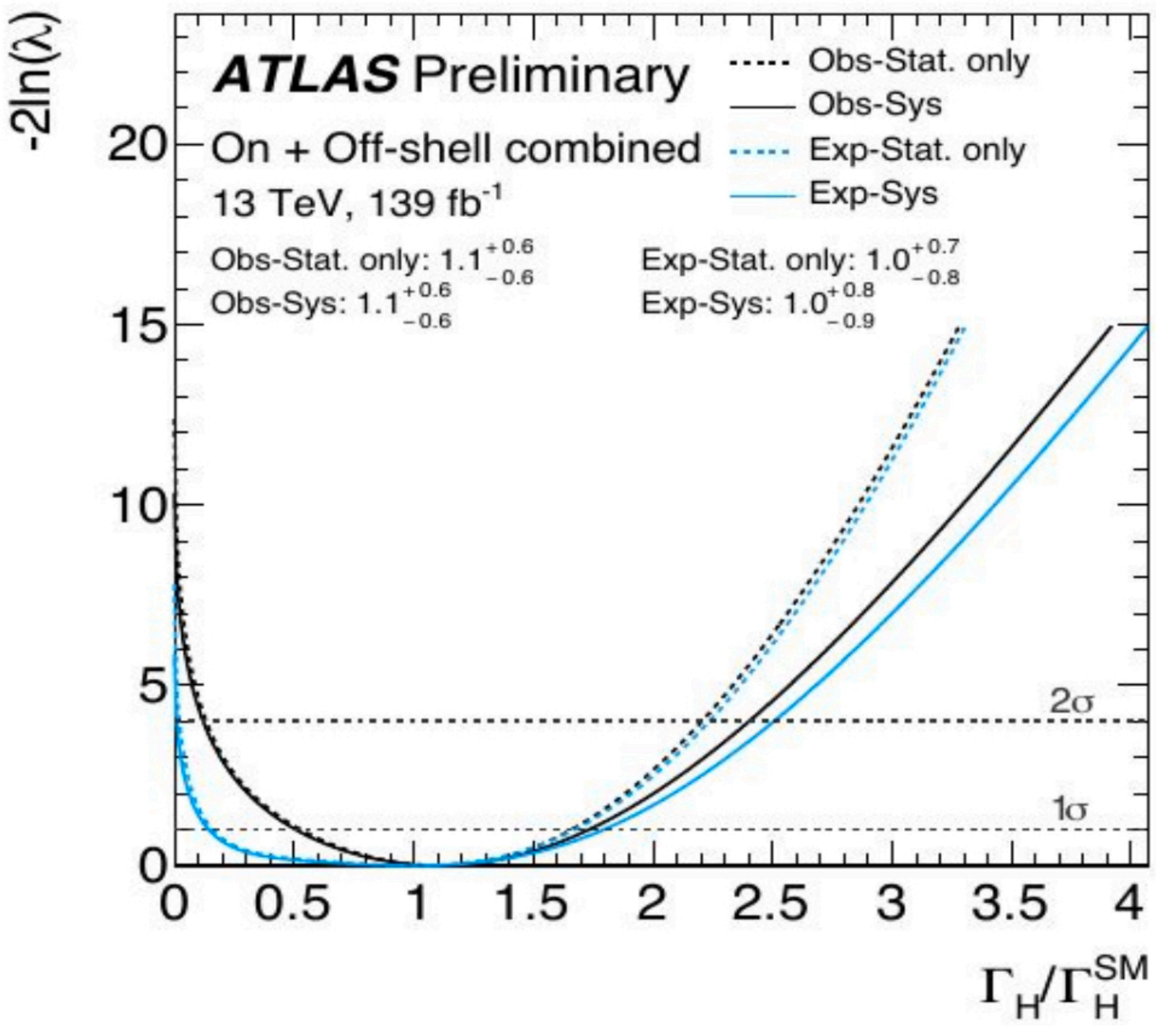


The ATLAS Collaboration Nature, 607, 52–59 (2022) , The CMS Collaboration Nature, 607, 60–68 (2022)

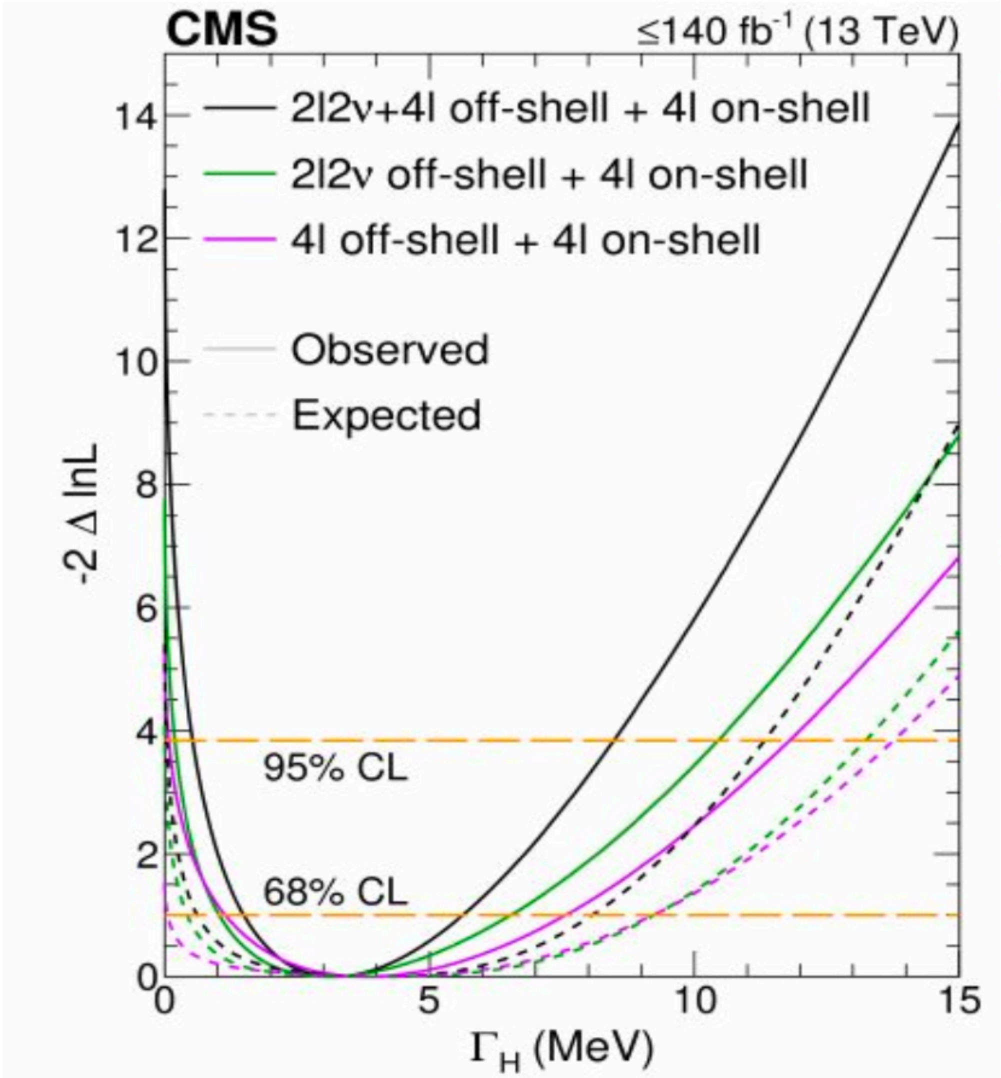
The Higgs width (SM: 4.1 MeV) **: OK**

$$\sigma^{\text{on-shell}}_{gg\to H\to VV} \sim \frac{g^2_{\text{ggH}}g^2_{\text{HZZ}}}{m_H\Gamma_H} \qquad \sigma^{\text{off-shell}}_{gg\to H\to VV} \sim \frac{g^2_{\text{ggH}}g^2_{\text{HZZ}}}{m^2_{ZZ}}$$

ATLAS-CONF-2022-068



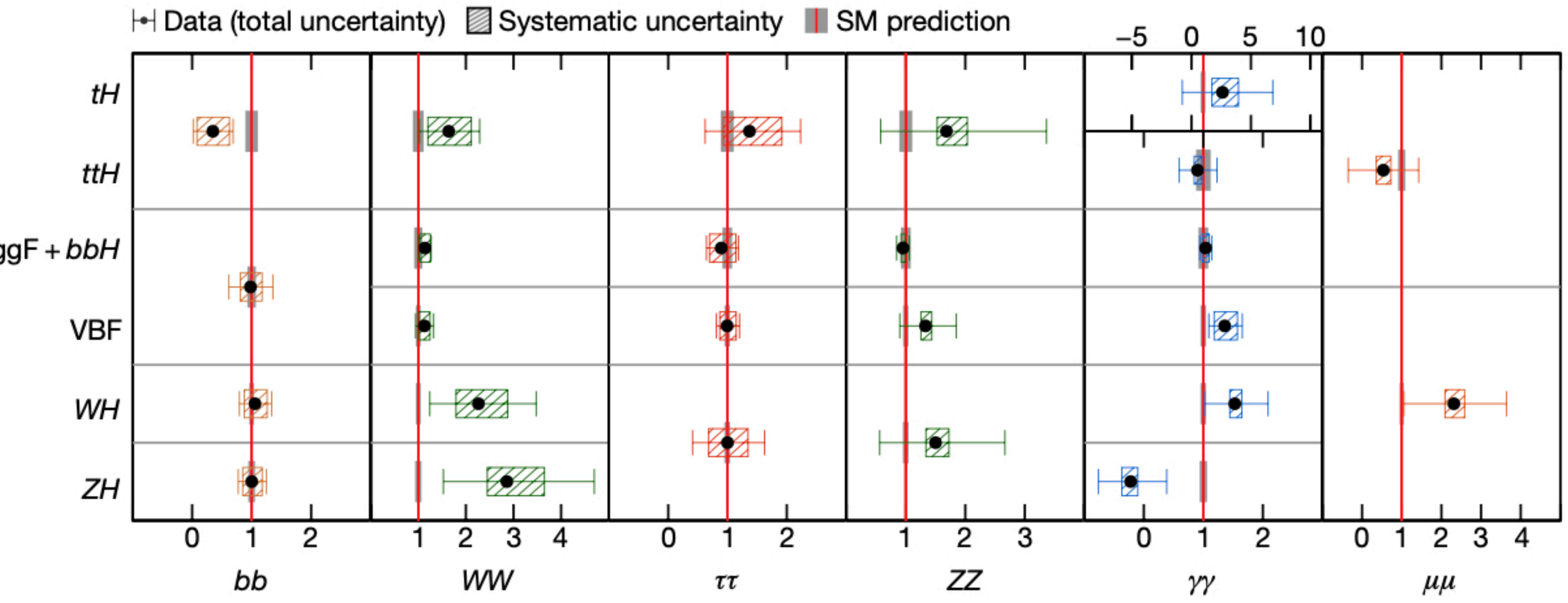
$$\Gamma_H = 4.6^{+2.6}_{-2.5}\ \text{MeV at } 68\,\%\ CL$$

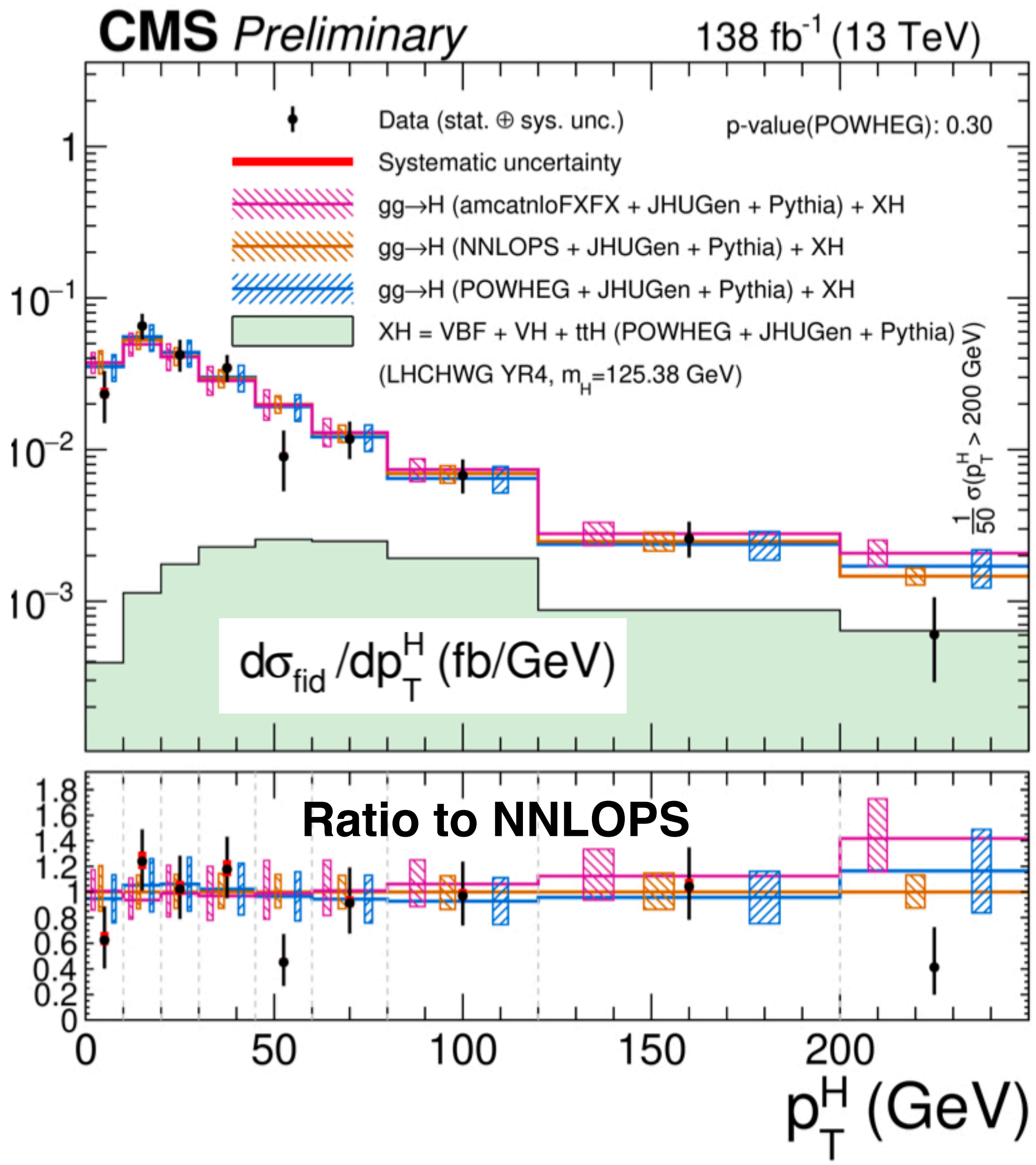


Nat. Phys. 18 (2022) 1329

$$\Gamma_H = 3.2^{+2.4}_{-1.7}\ \text{MeV at } 68\,\%\ CL$$

Production properties: OK





The LHC experiments have been exploring a vast multitude of scenarios of physics beyond the Standard Model

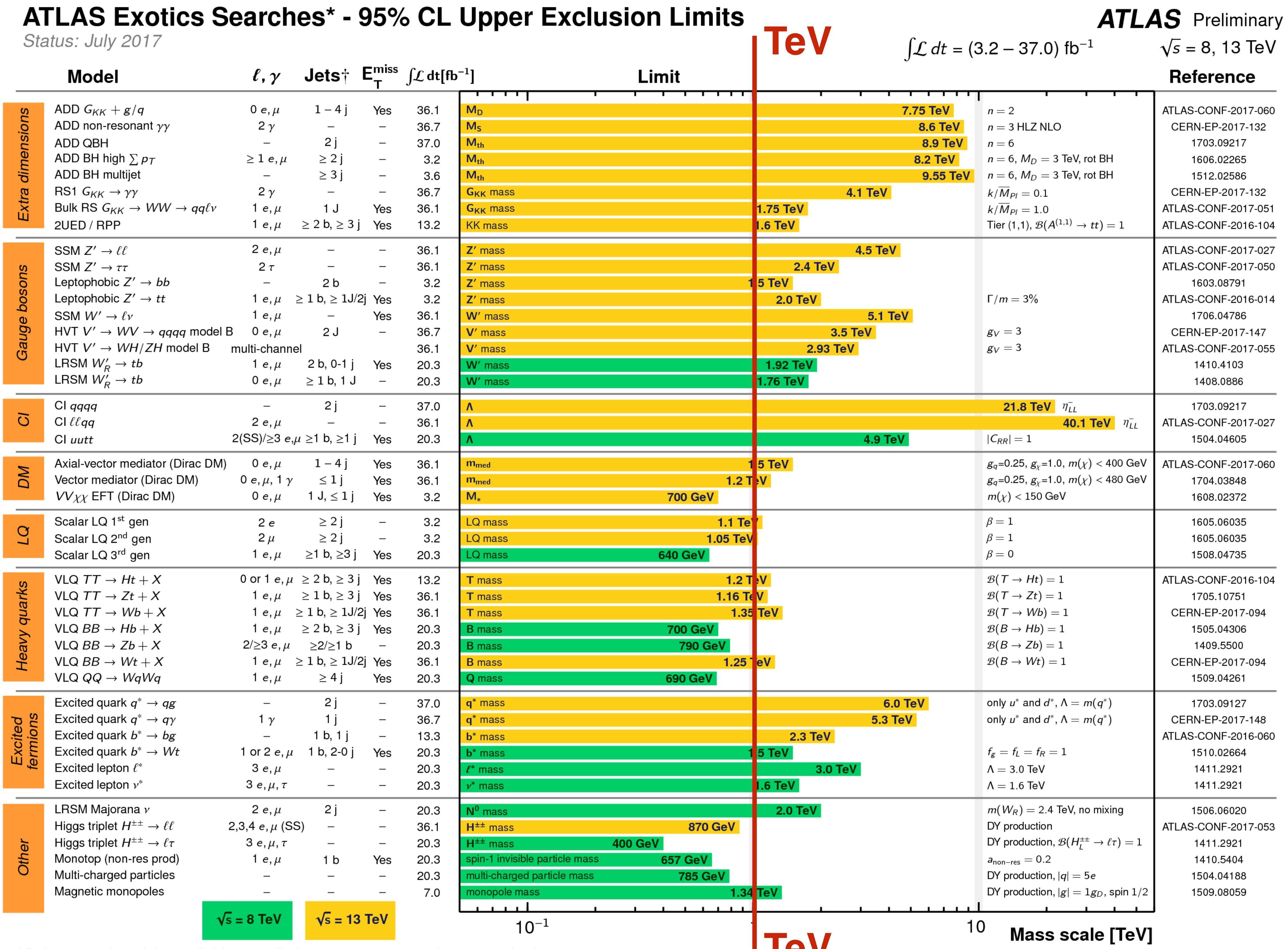
In search of the origin of known departures from the SM

- Dark matter, long lived particles
- Neutrino masses
- Matter/antimatter asymmetry of the universe

To explore alternative extensions of the SM

- New gauge interactions (Z’, W’) or extra Higgs bosons
- Additional fermionic partners of quarks and leptons, leptoquarks, …
- Composite nature of quarks and leptons
- Supersymmetry, in a variety of twists (minimal, constrained, natural, RPV, …)
- Extra dimensions
- New flavour phenomena
- unanticipated surprises …

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



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 37.0)\ \mathrm{fb}^{-1}$

$\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	🟨 M_D	7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	🟨 M_S	8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	2 j	–	37.0	🟨 M_{th}	8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	🟨 M_{th}	8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th}	9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	🟨 G_{KK} mass	4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	36.1	🟨 G_{KK} mass	1.75 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	🟨 KK mass	1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	🟨 Z' mass	4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	🟨 Z' mass	2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	🟨 Z' mass	1.5 TeV		1603.08791
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	3.2	🟨 Z' mass	2.0 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	36.1	🟨 W' mass	5.1 TeV		1706.04786
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	36.7	🟨 V' mass	3.5 TeV	$g_V = 3$	CERN-EP-2017-147
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	🟨 V' mass	2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055
	LRSM $W'_R \to tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	🟩 W' mass	1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	🟩 W' mass	1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ	21.8 TeV	η^-_{LL}	1703.09217
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	🟨 Λ	40.1 TeV	η^-_{LL}	ATLAS-CONF-2017-027
	CI $uutt$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	20.3	🟩 Λ	4.9 TeV	$\lvert C_{RR} \rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	🟨 m_{med}	1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 400$ GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	0 e, μ, 1 γ	≤ 1 j	Yes	36.1	🟨 m_{med}	1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 480$ GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	🟨 M_*	700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	🟨 LQ mass	1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	🟨 LQ mass	1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	$\geq$1 b, $\geq$3 j	Yes	20.3	🟩 LQ mass	640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	0 or 1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	🟨 T mass	1.2 TeV	$\mathcal{B}(T \to Ht) = 1$	ATLAS-CONF-2016-104
	VLQ $TT \to Zt + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	36.1	🟨 T mass	1.16 TeV	$\mathcal{B}(T \to Zt) = 1$	1705.10751
	VLQ $TT \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 T mass	1.35 TeV	$\mathcal{B}(T \to Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 B mass	700 GeV	$\mathcal{B}(B \to Hb) = 1$	1505.04306
	VLQ $BB \to Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	🟩 B mass	790 GeV	$\mathcal{B}(B \to Zb) = 1$	1409.5500
	VLQ $BB \to Wt + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 B mass	1.25 TeV	$\mathcal{B}(B \to Wt) = 1$	CERN-EP-2017-094
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	🟩 Q mass	690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	🟨 q^* mass	6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	🟨 q^* mass	5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	13.3	🟨 b^* mass	2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	🟩 b^* mass	1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	🟩 ℓ^* mass	3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	🟩 ν^* mass	1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LRSM Majorana ν	2 e, μ	2 j	–	20.3	🟩 N^0 mass	2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	🟨 $H^{\pm\pm}$ mass	870 GeV	DY production	ATLAS-CONF-2017-053
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	🟩 $H^{\pm\pm}$ mass	400 GeV	DY production, $\mathcal{B}(H^{\pm\pm}_L \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	🟩 spin-1 invisible particle mass	657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass	785 GeV	DY production, $\lvert q \rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass	1.34 TeV	DY production, $\lvert g \rvert = 1 g_D$, spin 1/2	1509.08059

🟩 $\sqrt{s}$ = 8 TeV

🟨 $\sqrt{s}$ = 13 TeV

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Given no clear sign of BSM is there, is there anything else interesting?

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 3000 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) →μμ
- D mixing and CP violation in the D system
- Measurement of the γ angle, CPV phase ϕs, …
- Lepton flavour universality in charge- and neutral-current semileptonic B decays => possible anomalies ?

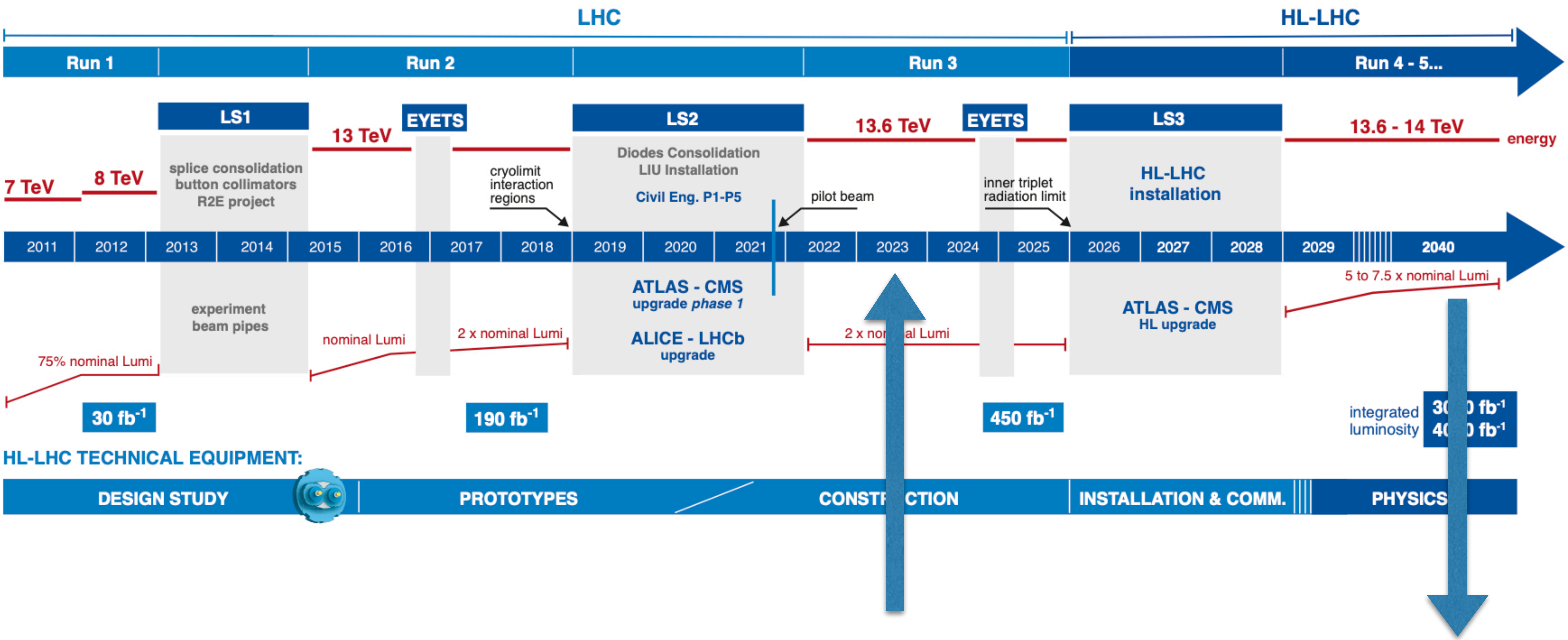
QCD dynamics

- 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, …)

LHC / HL-LHC Plan



oggi - ▶ 2043

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 ?

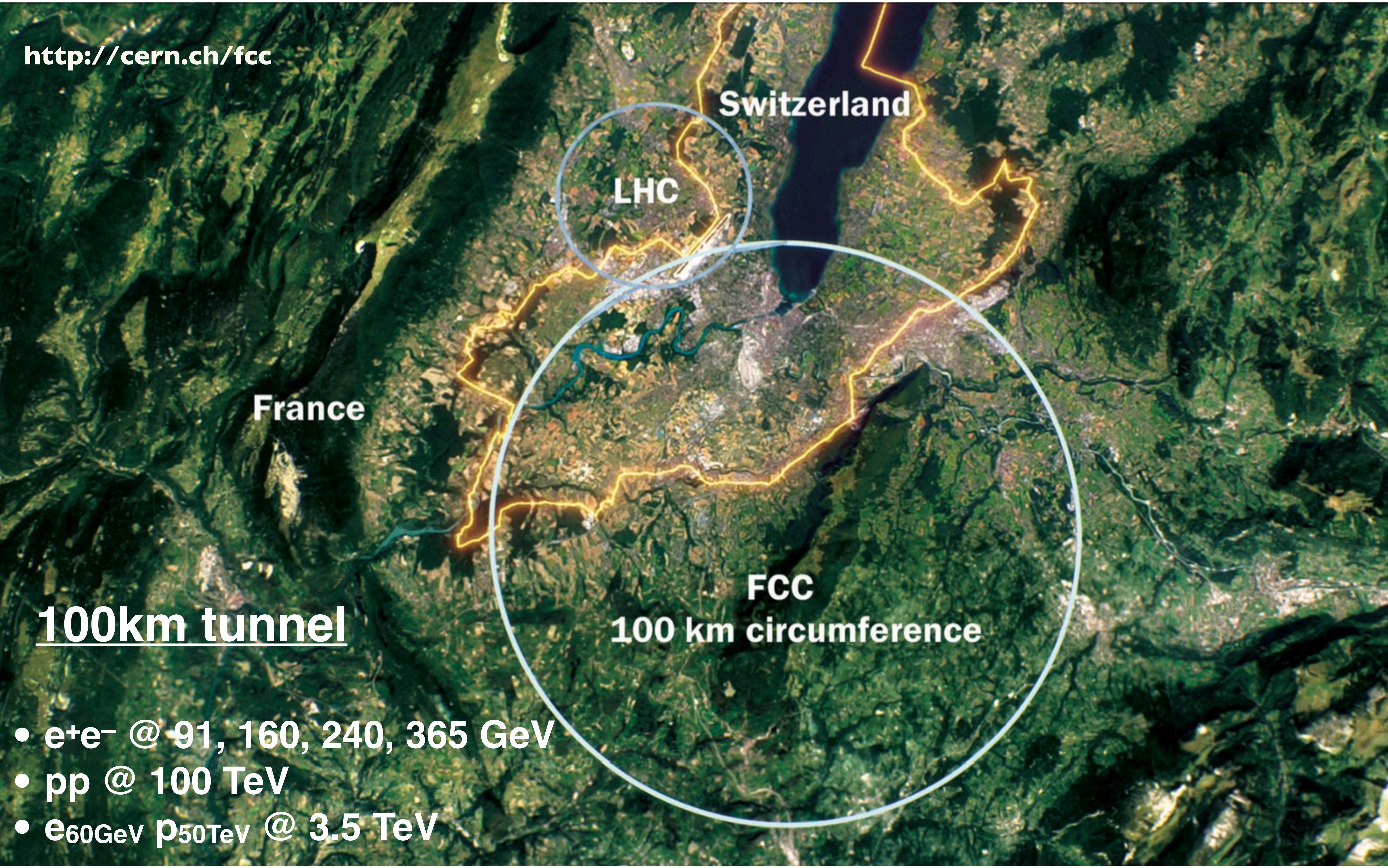
- **Is the mass scale beyond the LHC reach ?**
- **Is the mass scale within LHC's reach, but final states are elusive to the direct search ?**

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



http://cern.ch/fcc

100km tunnel

- e^+e^- @ 91, 160, 240, 365 GeV
- pp @ 100 TeV
- $e_{60\mathrm{GeV}}\ p_{50\mathrm{TeV}}$ @ 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	$\tau(\leftarrow Z)$	$b(\leftarrow Z)$	$c(\leftarrow Z)$
	10^6	$5\ 10^{12}$	10^8	10^6	$3\ 10^{11}$	$1.5\ 10^{12}$	10^{12}

FCC-hh	H	b	t	$W(\leftarrow t)$	$\tau(\leftarrow W \leftarrow t)$
	$2.5\ 10^{10}$	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

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

$BR(H\to\mu\mu) \sim O(10^{-4}) \Rightarrow$ **$O(10^8)$ 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

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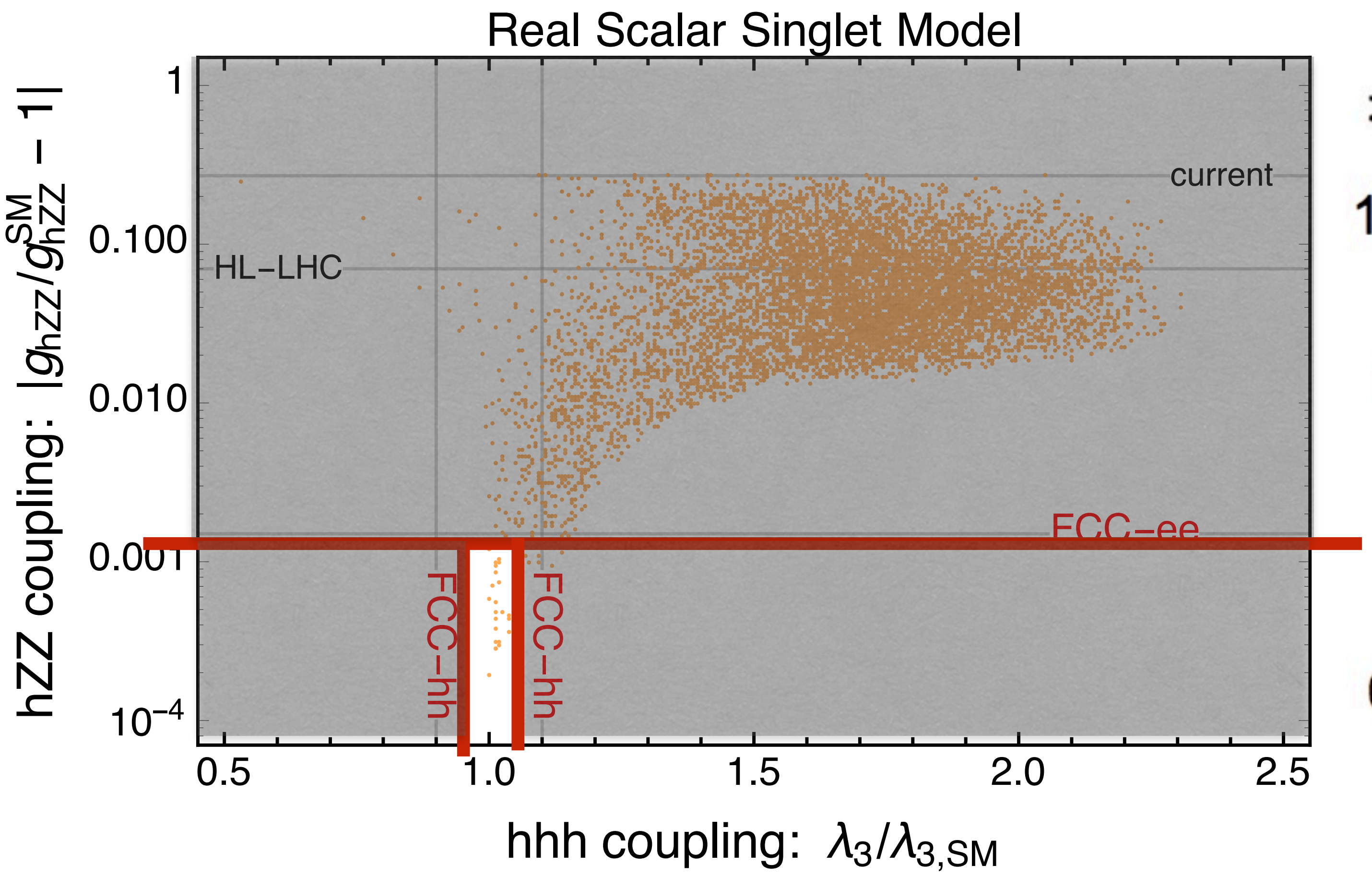
* From BR ratios wrt $B(H\to ZZ^*)$ @ FCC-ee

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

Constraints on models with 1st order phase transition at the FCC

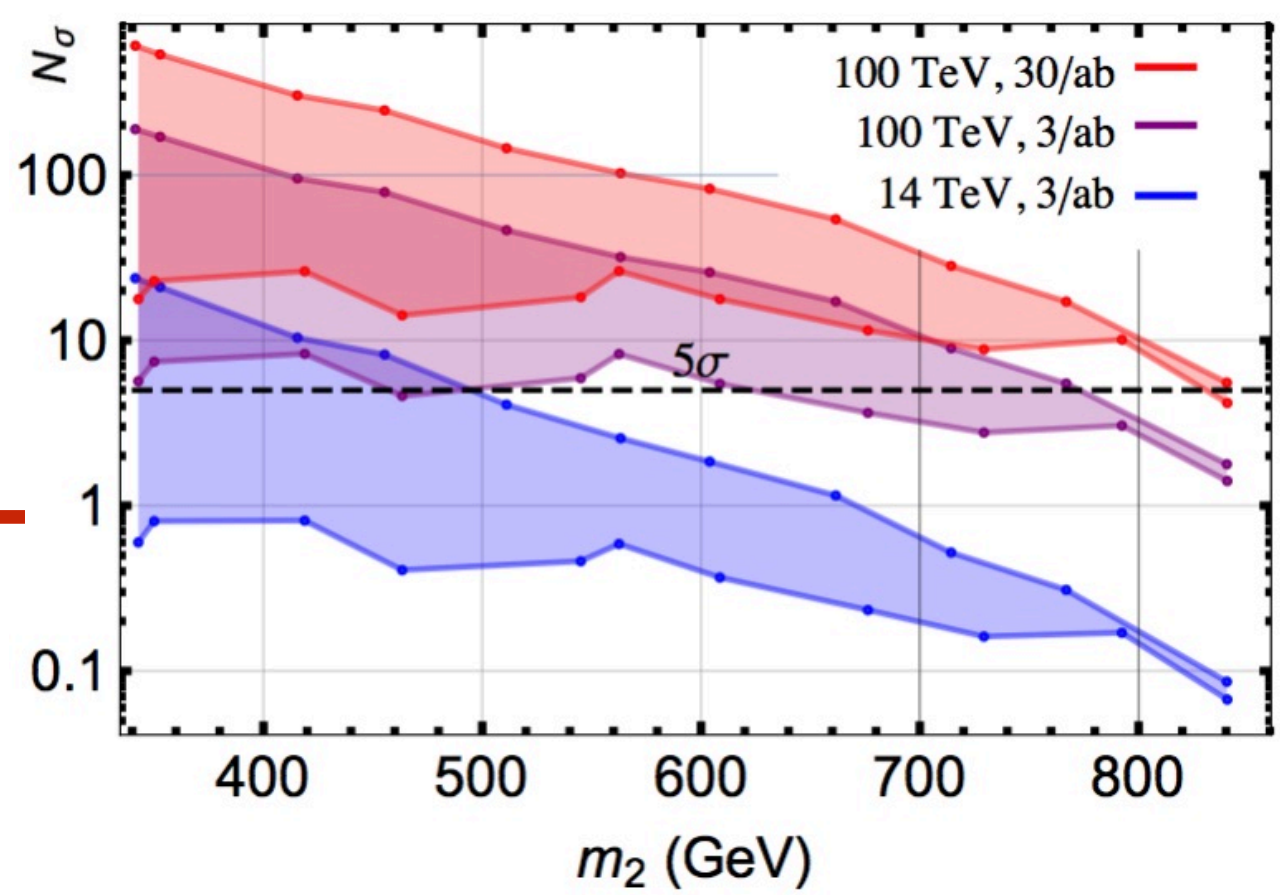
$$V(H,S) = -\mu^2 \left(H^\dagger H\right) + \lambda \left(H^\dagger H\right)^2 + \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4 .$$

Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh



Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

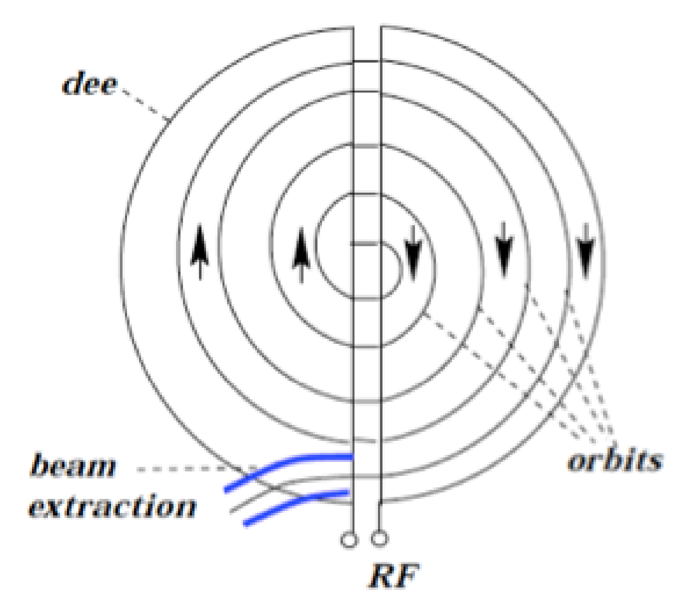
Direct detection of extra Higgs states at FCC-hh



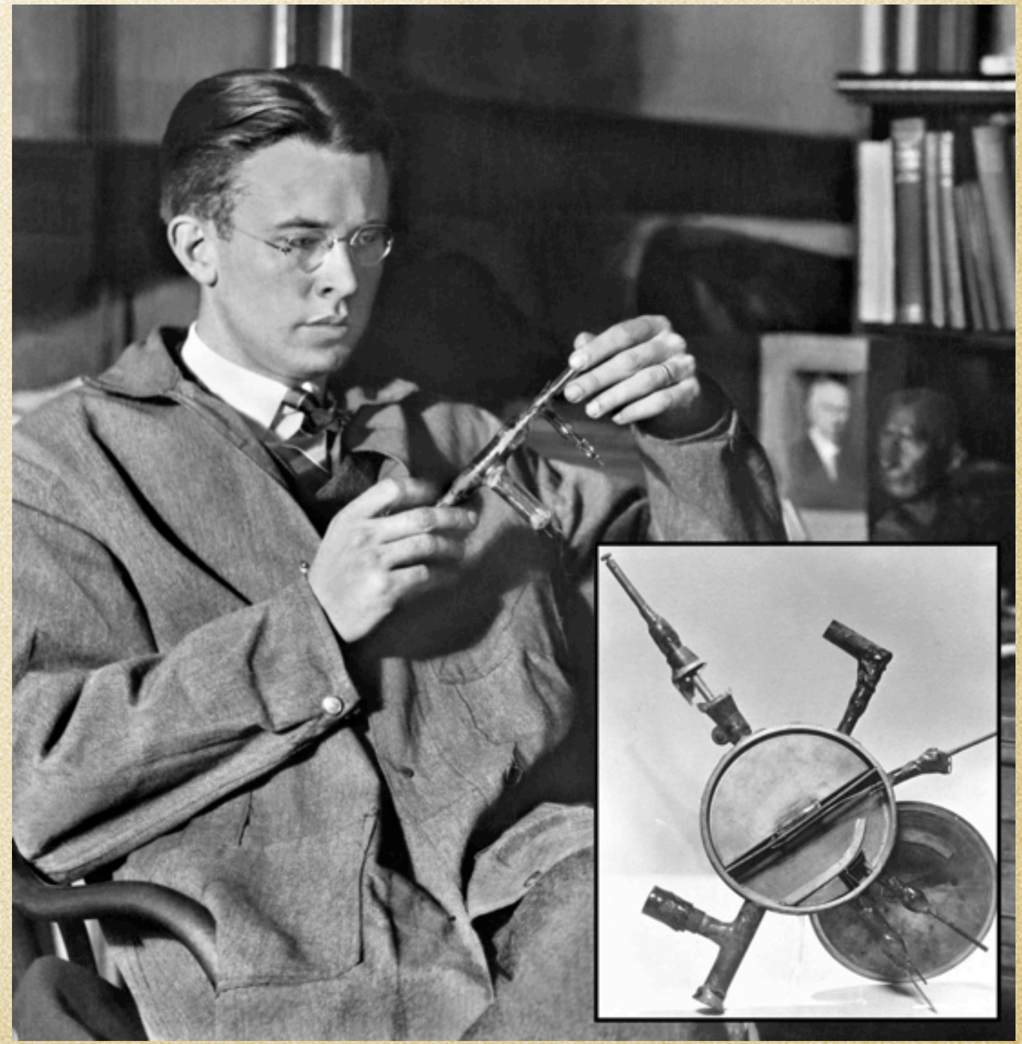
$h_2 \to h_1 h_1$ ($b\bar{b}\gamma\gamma$ + 4τ)

($h_2 \sim S$, $h_1 \sim H$)

Un acceleratore van de Graaf
da 1 MeV (1931)



E. Lawrence, Premio Nobel 1939 per l’invenzione (1931) del ciclotrone, il primo acceleratore circolare di particelle (80 keV, tenuto da lui in mano qui nella foto)



Additional material: recent reports on future projects

- **ILC:** Physics Case for the 250 GeV Stage, K. Fujii et al, arxiv:1710.07621
- **CLIC:** Potential for New Physics, J. de Blas et al,, arxiv:1812.02093
- **HL/HE-LHC** Physics Workshop reports
  - P. Azzi, et al, Standard Model Physics at the HL-LHC and HE-LHC, CERN-LPCC-2018-03, CERN, Geneva, 2018. https://cds.cern.ch/record/2650160.
  - M. Cepeda, et al, Higgs Physics at the HL-LHC and HE-LHC, CERN-LPCC-2018-04, CERN, Geneva, 2018. https://cds.cern.ch/record/2650162.
  - X. Cid-Vidal, et al, Beyond the Standard Model Physics at the HL-LHC and HE-LHC, CERN-LPCC-2018-05, CERN, Geneva, 2018. https://cds.cern.ch/record/2650173.
  - A. Cerri, et al, Flavour Physics at the HL-LHC and HE-LHC, CERN-LPCC-2018-06, CERN, Geneva, 2018. https://cds.cern.ch/record/2650175.
  - Z. Citron,et al, Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams, CERN-LPCC-2018-07, CERN, Geneva, 2018. arXiv:1812.06772 [hep-ph]. https://cds.cern.ch/record/2650176.
- **FCC CDR**:
  - Vol.1: Physics Opportunities (CERN-ACC-2018-0056) http://cern.ch/go/Nqx7
  - Vol.2: The Lepton Machine (CERN-ACC-2018-0057) http://cern.ch/go/7DH9
  - Vol.3: The Hadron Machine (CERN-ACC-2018-0058), http://cern.ch/go/Xrg6
  - Vol.4: High-Energy LHC (CERN-ACC-2018-0059) http://cern.ch/go/S9Gq
- **"Physics at 100 TeV"**, CERN Yellow Report: https://arxiv.org/abs/1710.06353
- **CEPC CDR**: Physics and Detectors
- **Muon Collider** Collaboration, J. de Blas et al., “The physics case of a 3 TeV muon collider stage,” arXiv:2203.07261
- **Physics Briefing Book: Input for the European Strategy for Particle Physics Update 2020,** arXiv:1910.11775