Visit of Turkey high-school students
CERN
April 8-9 2024

Why we need a future circular collider ?

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… because there are many fundamental questions in our understanding of Nature, and thus of particle physics, which cannot be answered with the current accelerators and experiments

… in particular, once we understand **how** something works, it's time to understand **why**

… and, in general, what we know and give for granted today may need revision once new evidence emerges, triggering new scientific revolutions

… therefore, we will always need a “**future**” experimental facility, to continue the endless exploration of nature at the most fundamental level

Why colliders ?

Colliders are the modern version of Demokritos thought experiment:

- *what happens if we keep slicing a piece of something, over and over again? do we ever get to the point where we can't split it anymore? If so, what is the nature of the "atom", the indivisible component of matter?*

This is one of the deepest questions that human mind was ever able to formulate in the domain of natural phenomena. As a question, it remains valid today as it was over 2000 years ago…. we just need very powerful knives!

To keep "slicing", we need to look at matter at smaller and smaller distances. Accelerators are the tools needed to extend the power of microscopes to distances much smaller than any microscope could possibly achieve

“Watching” the very small

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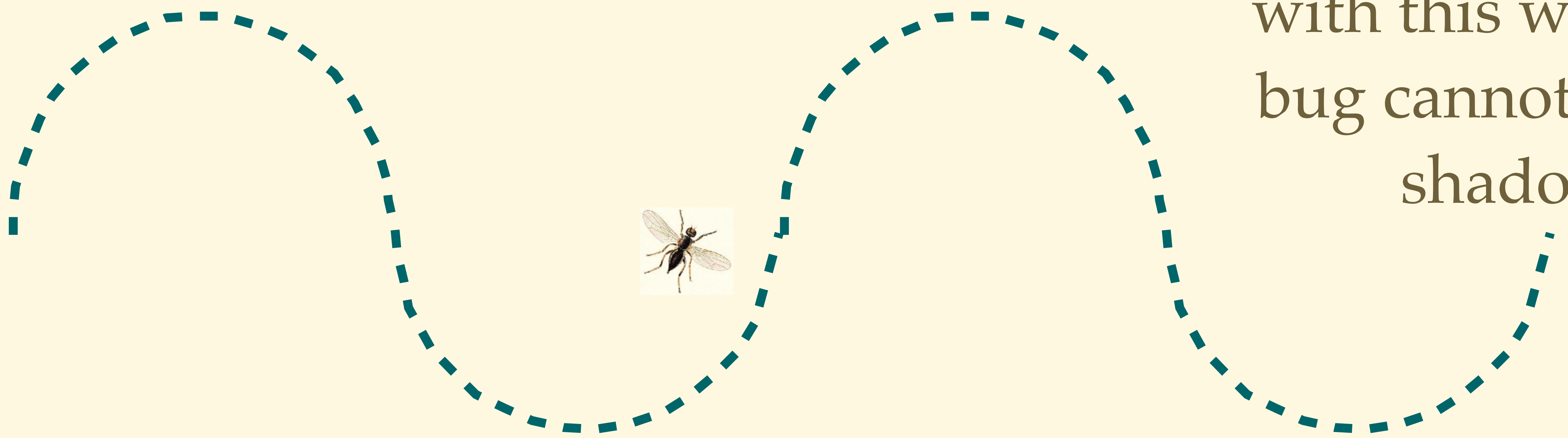

with this wave, the bug cannot leave a shadow!

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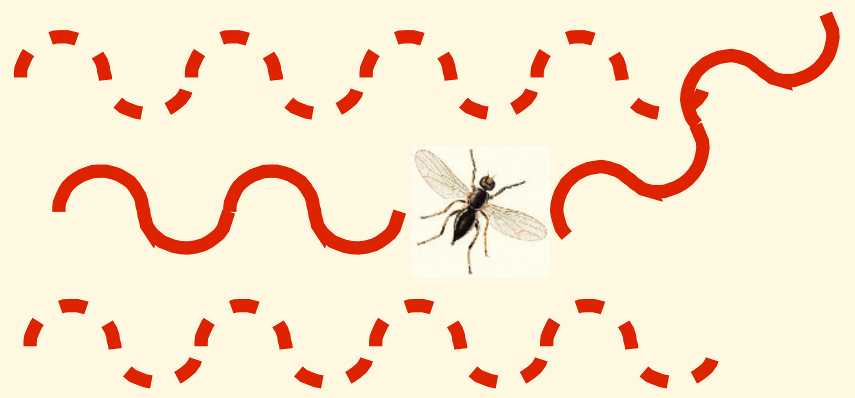

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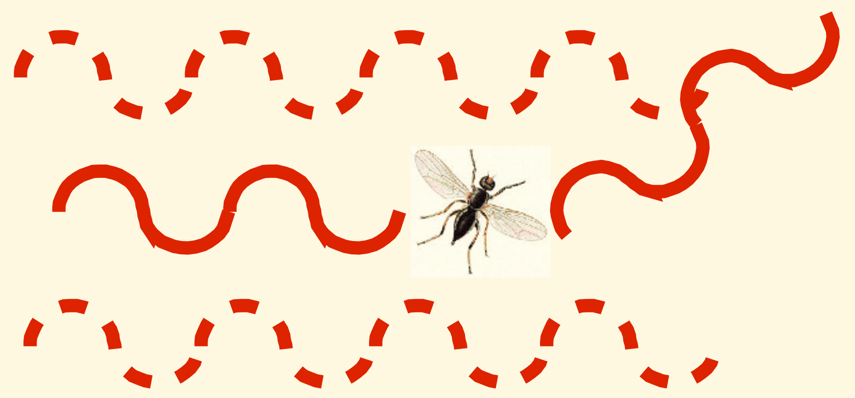

E.g.: the radar at an airport operates with a wavelength λ~30cm. It cannot resolve the presence of a single flying bird!

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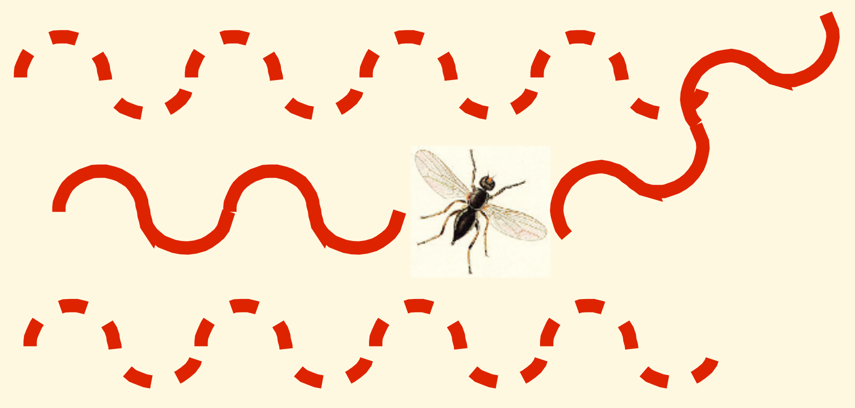

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- The smaller L, the smaller the wavelength λ
- Since E ~ frequency and frequency ~ 1/ λ ⇒
  - the smaller the object size L, the bigger the energy required to “see” it !

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⇒ to study physics at the shortest distances, we need small probes, of the highest energies

$$E = \frac{M\ C^2}{\sqrt{1 - \frac{V^2}{C^2}}}$$

$$E = mc^2$$

$$\frac{E}{C^2} = M$$

$M >> 2\,m$

$$\frac{E}{c^2} = M$$

$M \gg 2\,m$

$$\frac{E}{c^2} = M$$

Large energies not only allow to probe short distances, but give the possibility to create new, heavier particles !!

LHC

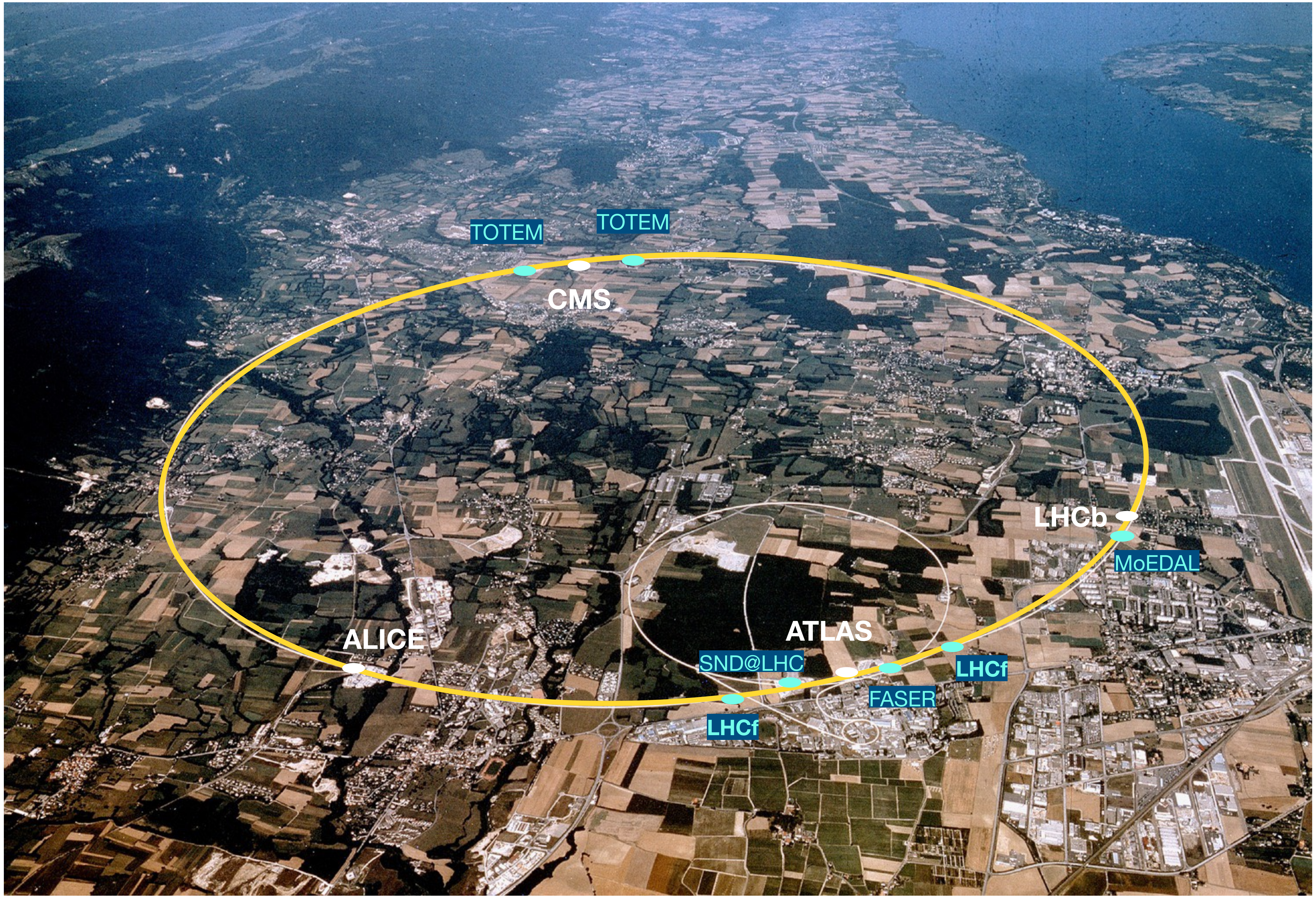
- 27 km tunnel, instrumented with NbTi magnets with B up to ~9T, to steer protons up to E=7 TeV
- proton-proton, proton-ion and ion-ion collisions, up to ECM(pp) = 14 TeV

Experiments:

ATLAS, CMS
O(3000) physicists; general purpose, optimized for high-pt physics

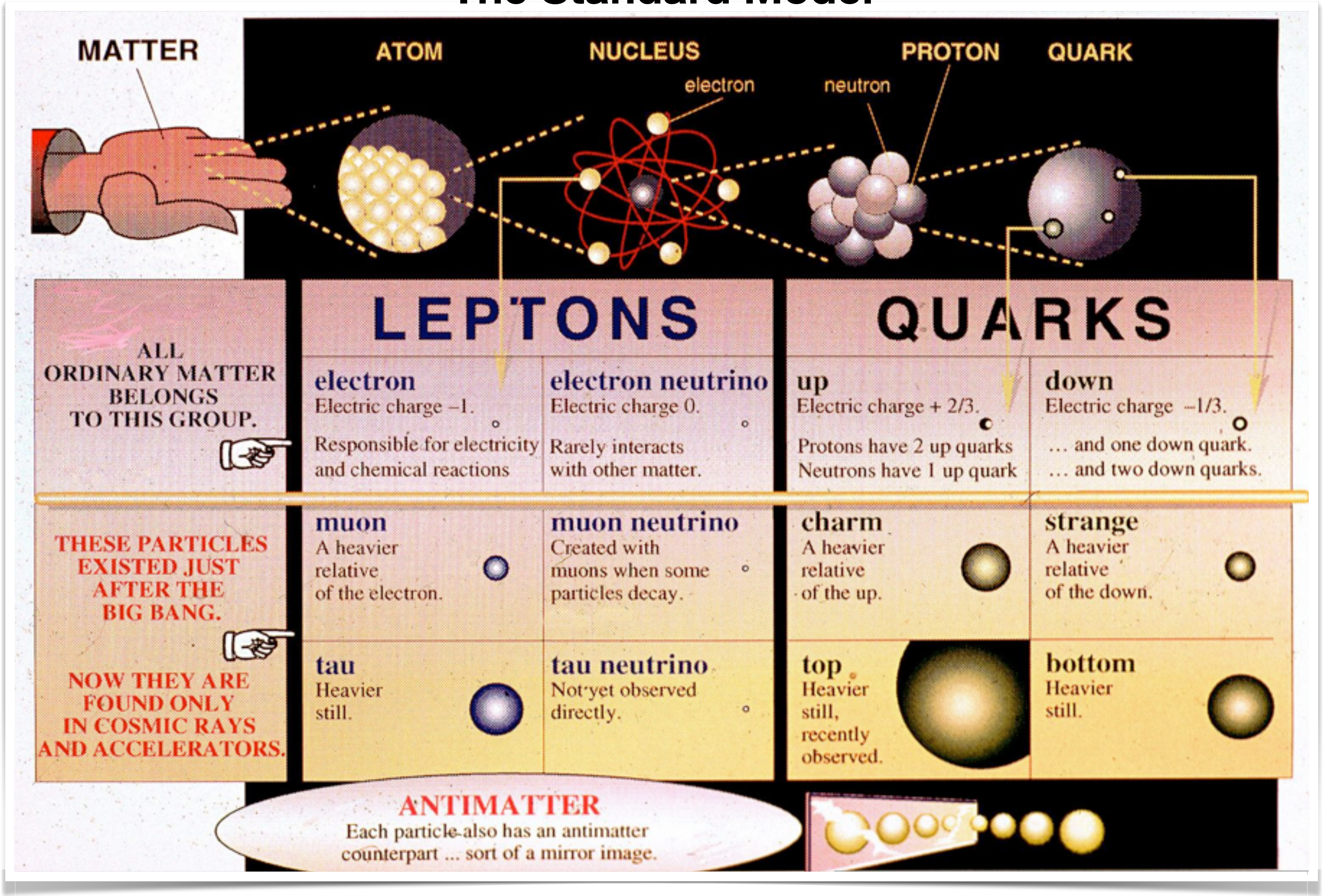
ALICE, LHCb
O(1000) physicists; general purpose, optimized for heavy ion collisions and flavour physics, resp)

Smaller (O(100) physicists):
TOTEM, LHCf (hadronic forward physics, modeling of cosmic ray showers),
MoEDAL (magnetic monopole and highly-ionizing particle searches),
FASER, SND@LHC (neutrino interactions and searches for long-lived weakly interacting particles)



What have we learned so far ?

The Standard Model



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

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
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EW symmetry breaking spin=0

H higgs	**125**	**0**

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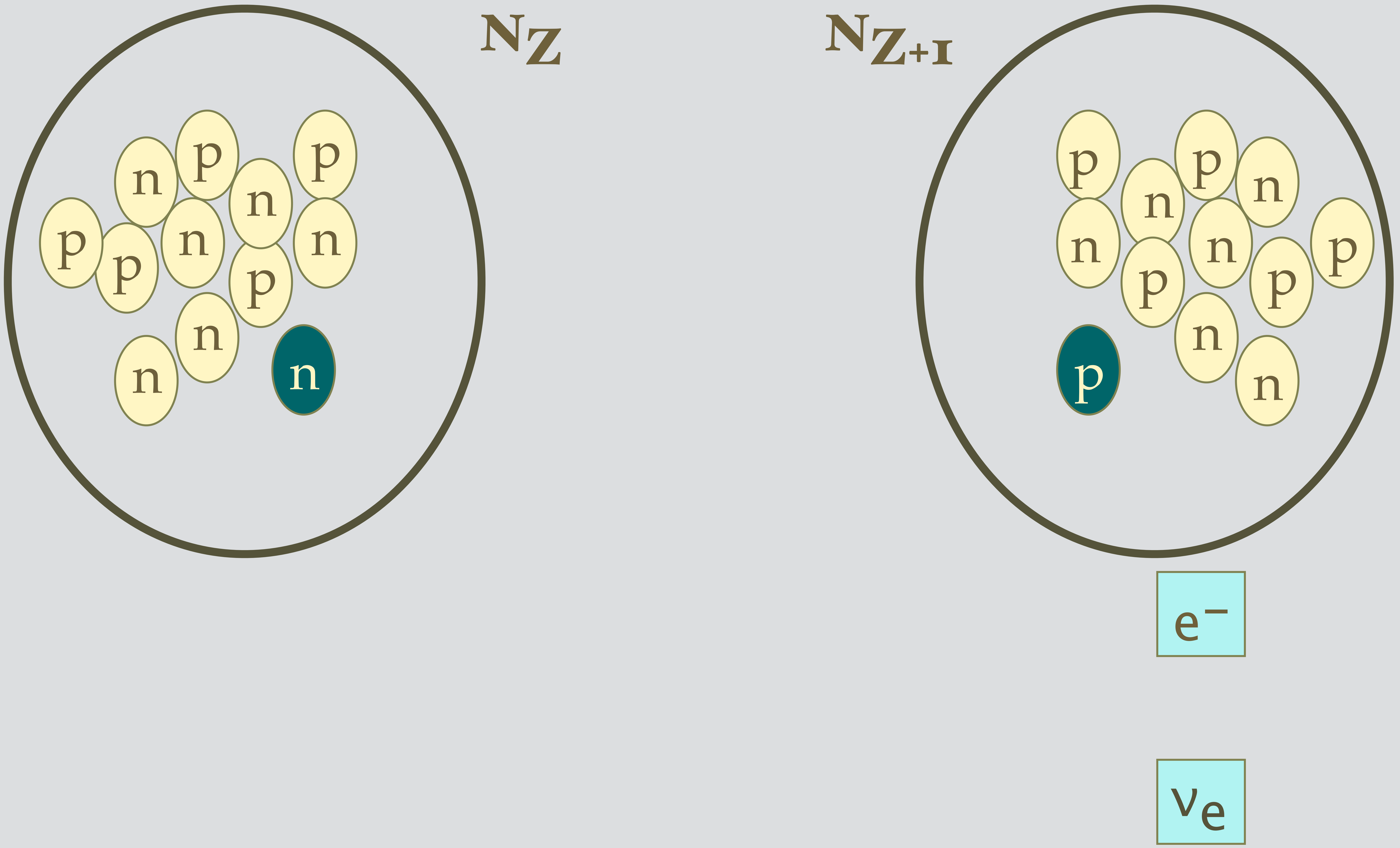

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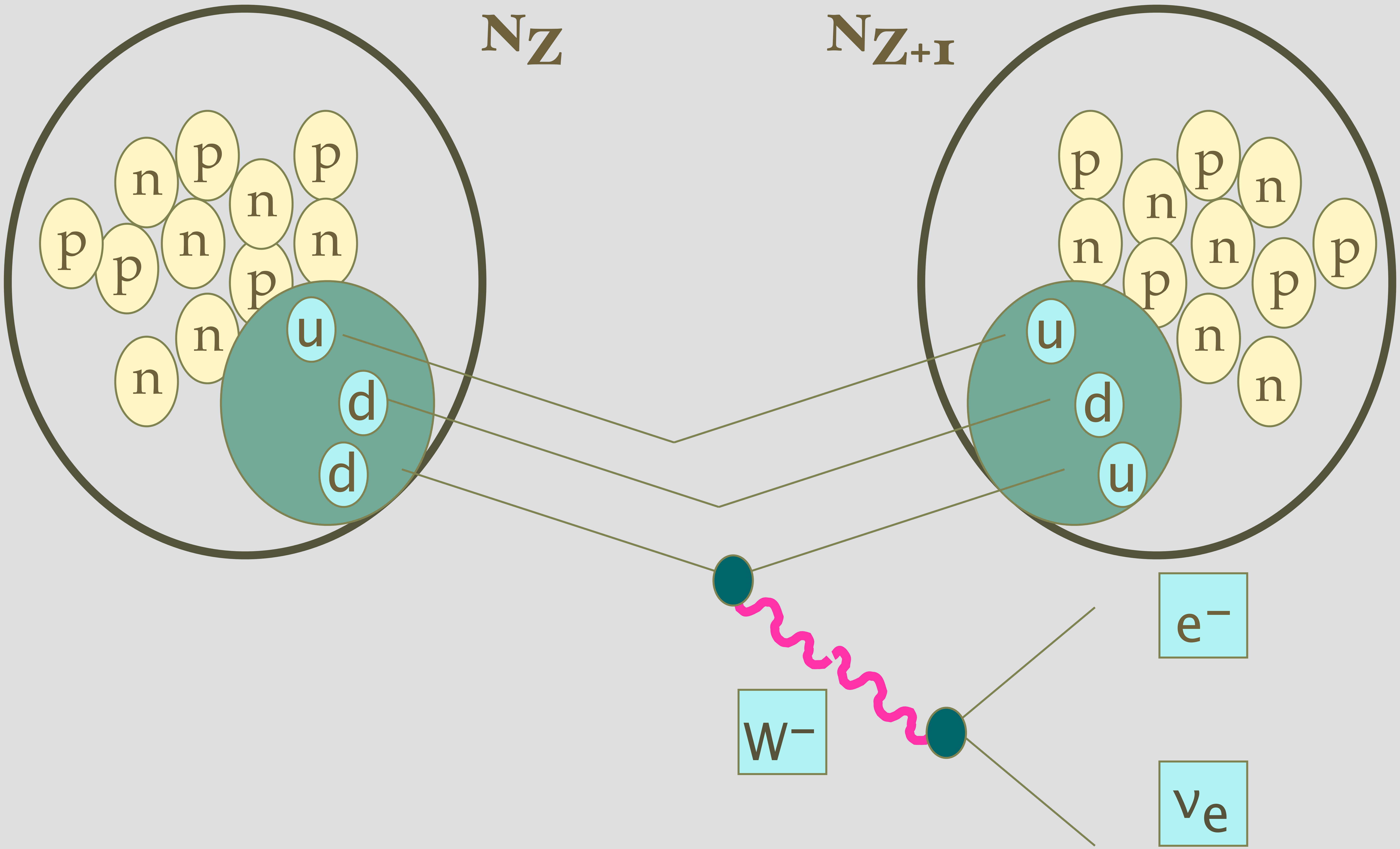
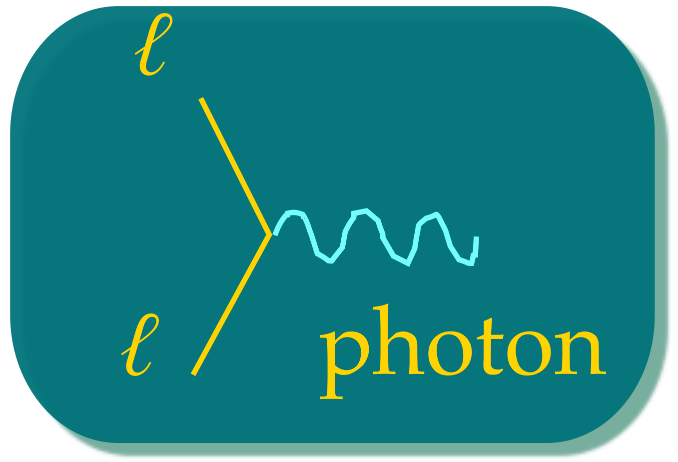
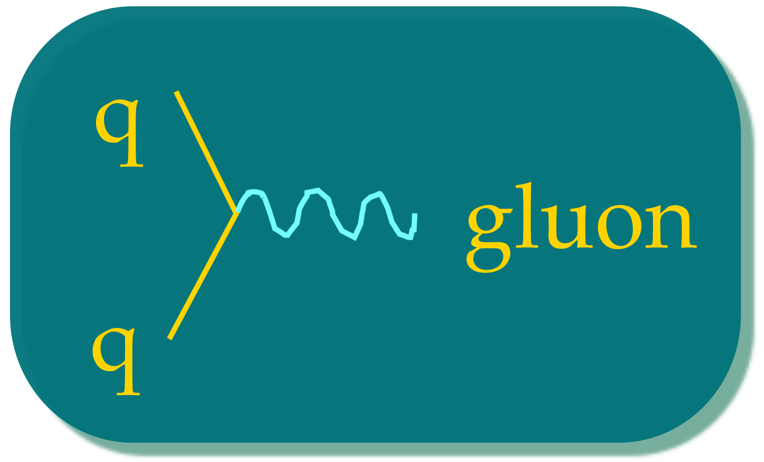


Fundamental interactions

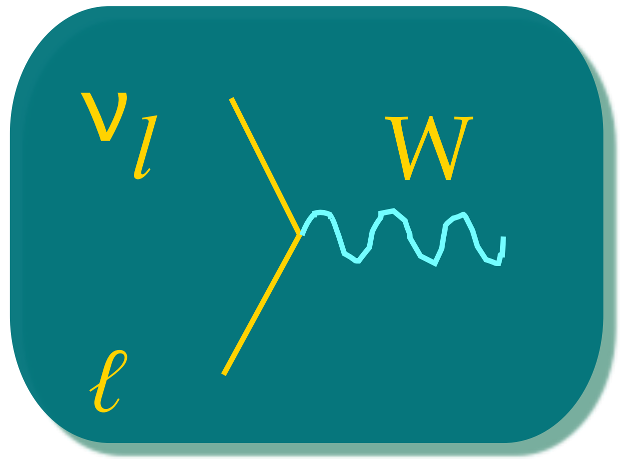


∝ -e=electric charge

∝ 2/3 e



∝ g_s



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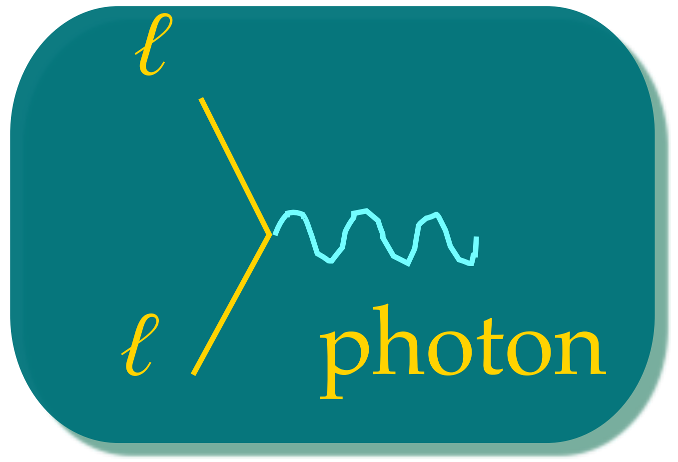

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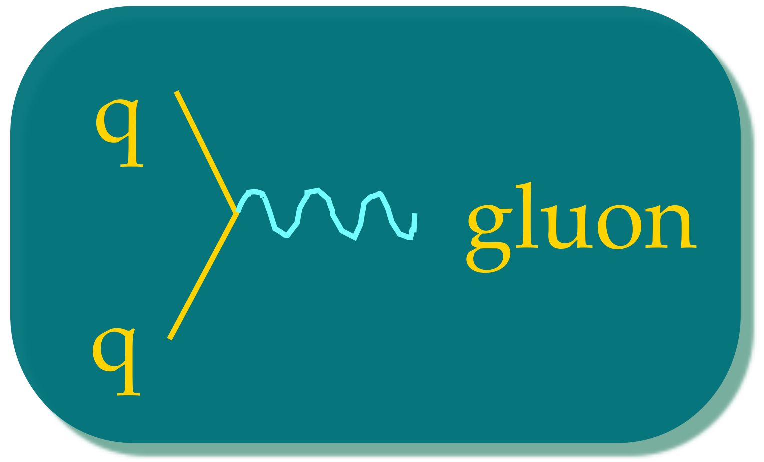

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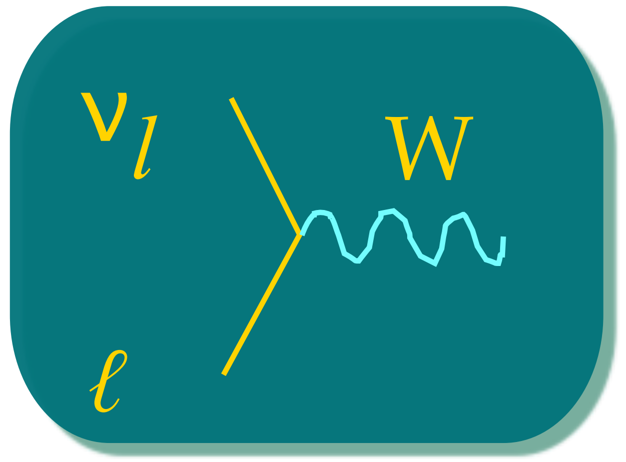

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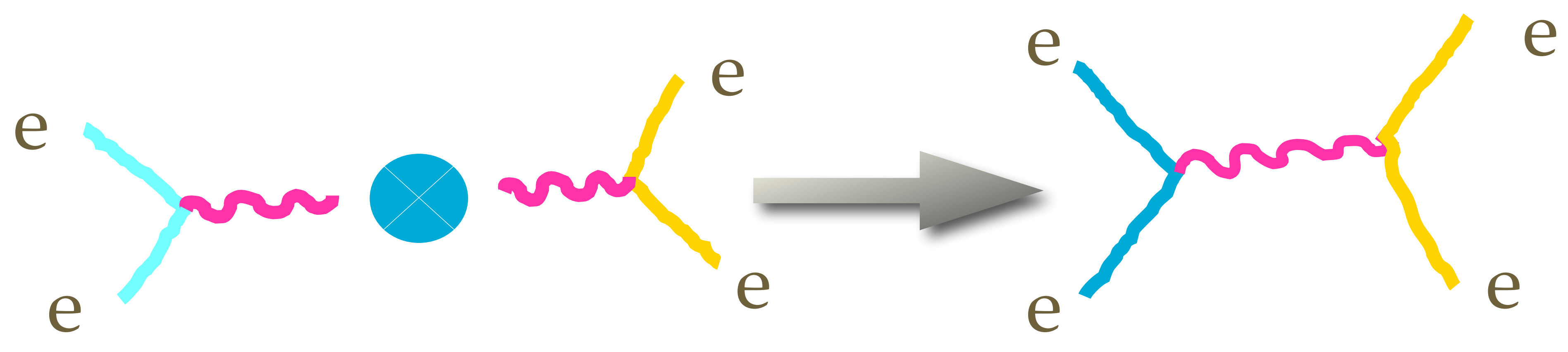
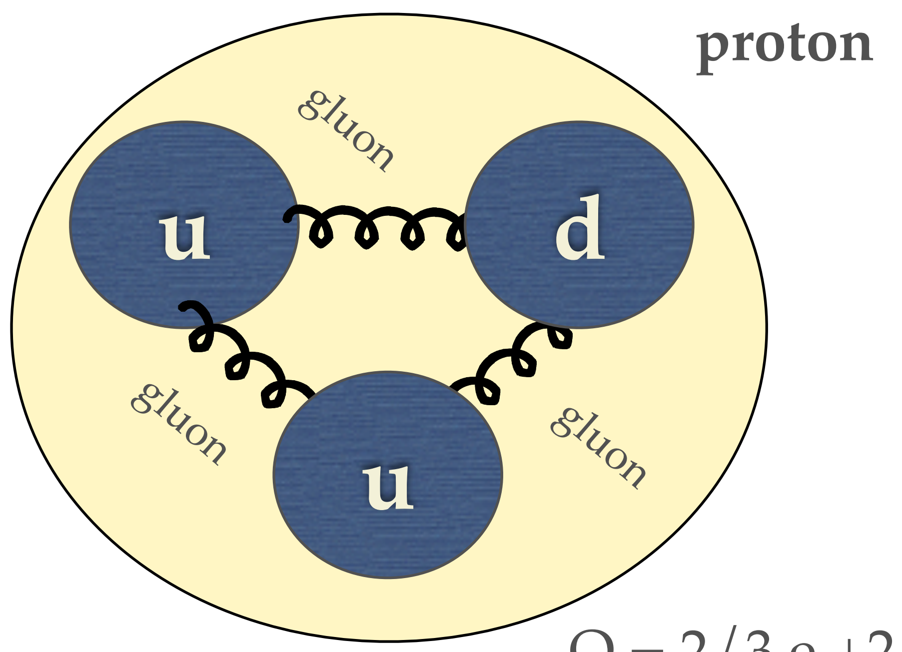
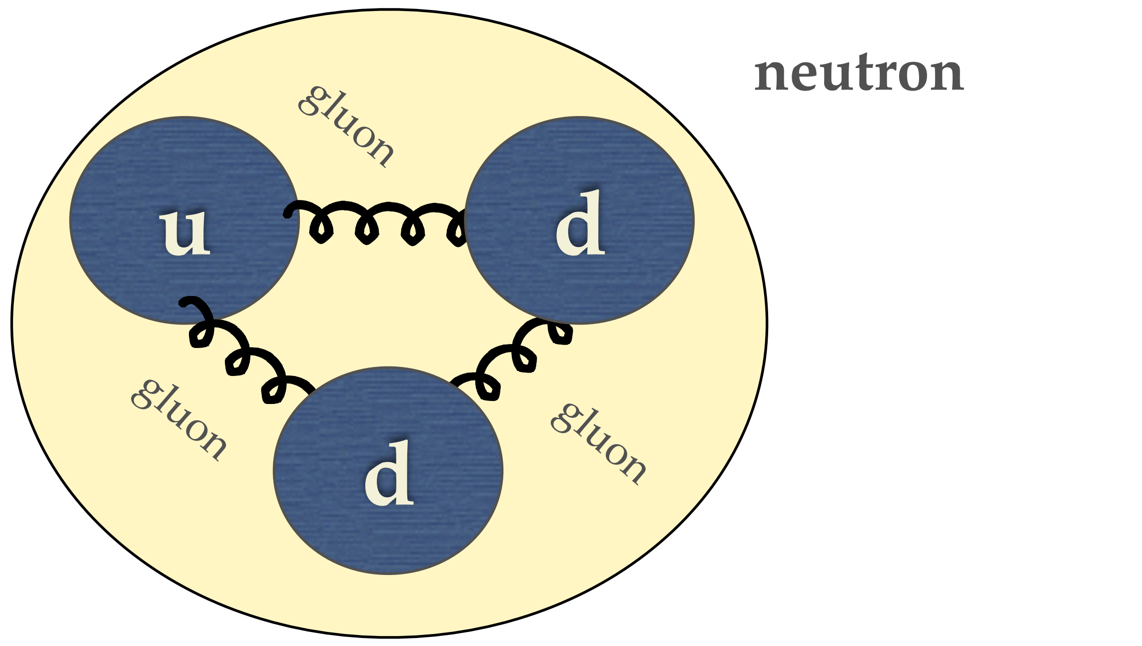




Q = 2/3 e +2/3 e –1/3 e = e



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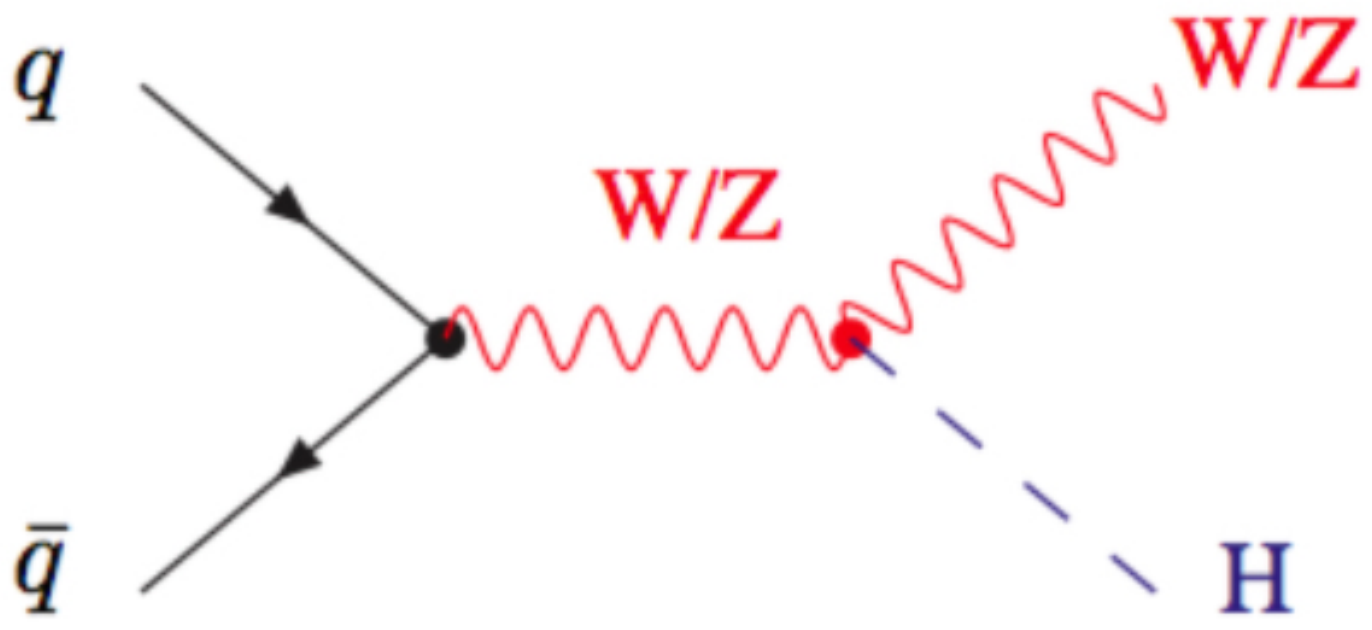

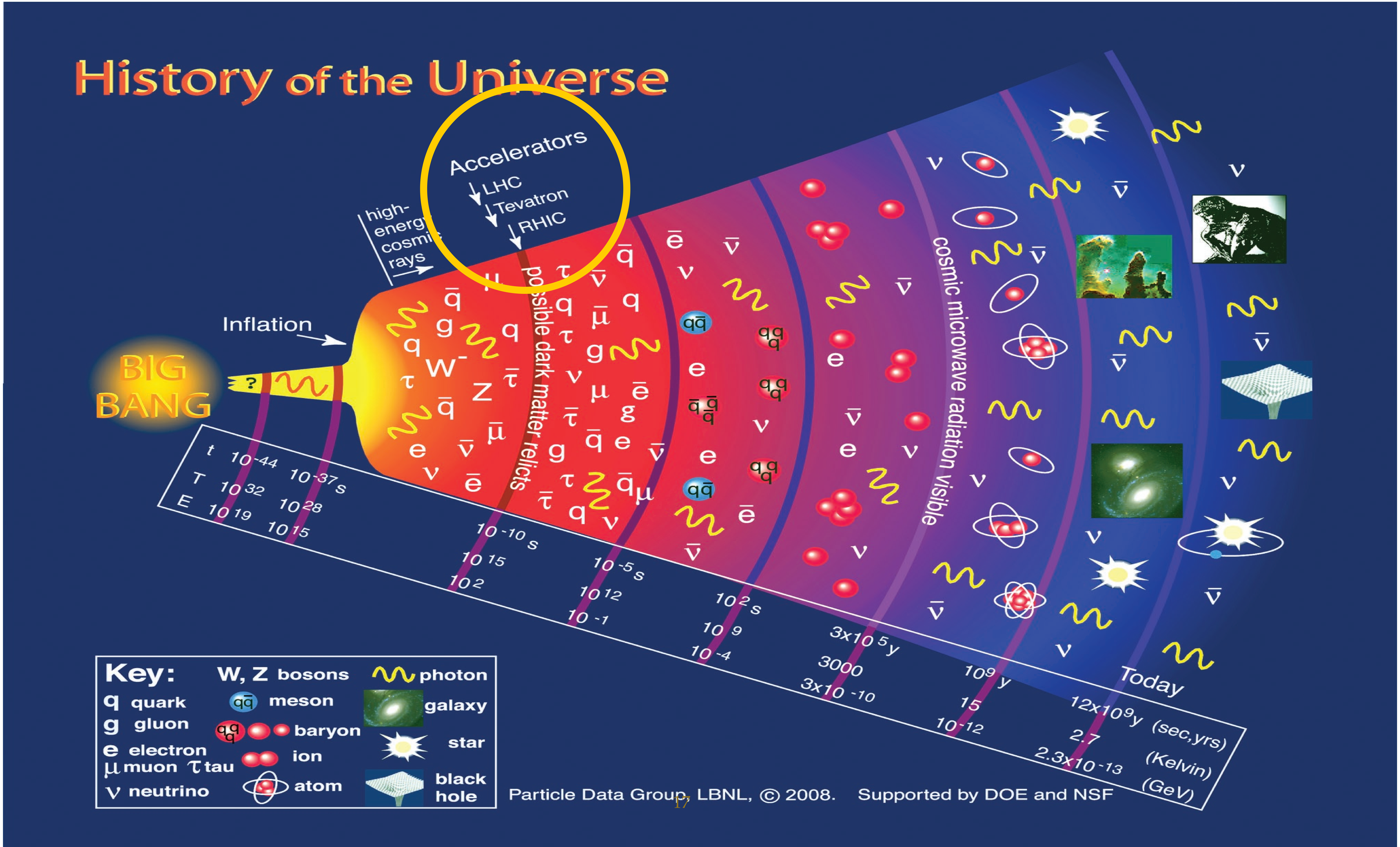
History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12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


dark energy
73%
dark matter
23%
non-luminous atoms
(e.g. planets, dead
stars, dust, etc), ~4%
stars, neutrinos,
photons ~0.5%

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Answers to these questions imply the existence of new physics beyond the Standard Model

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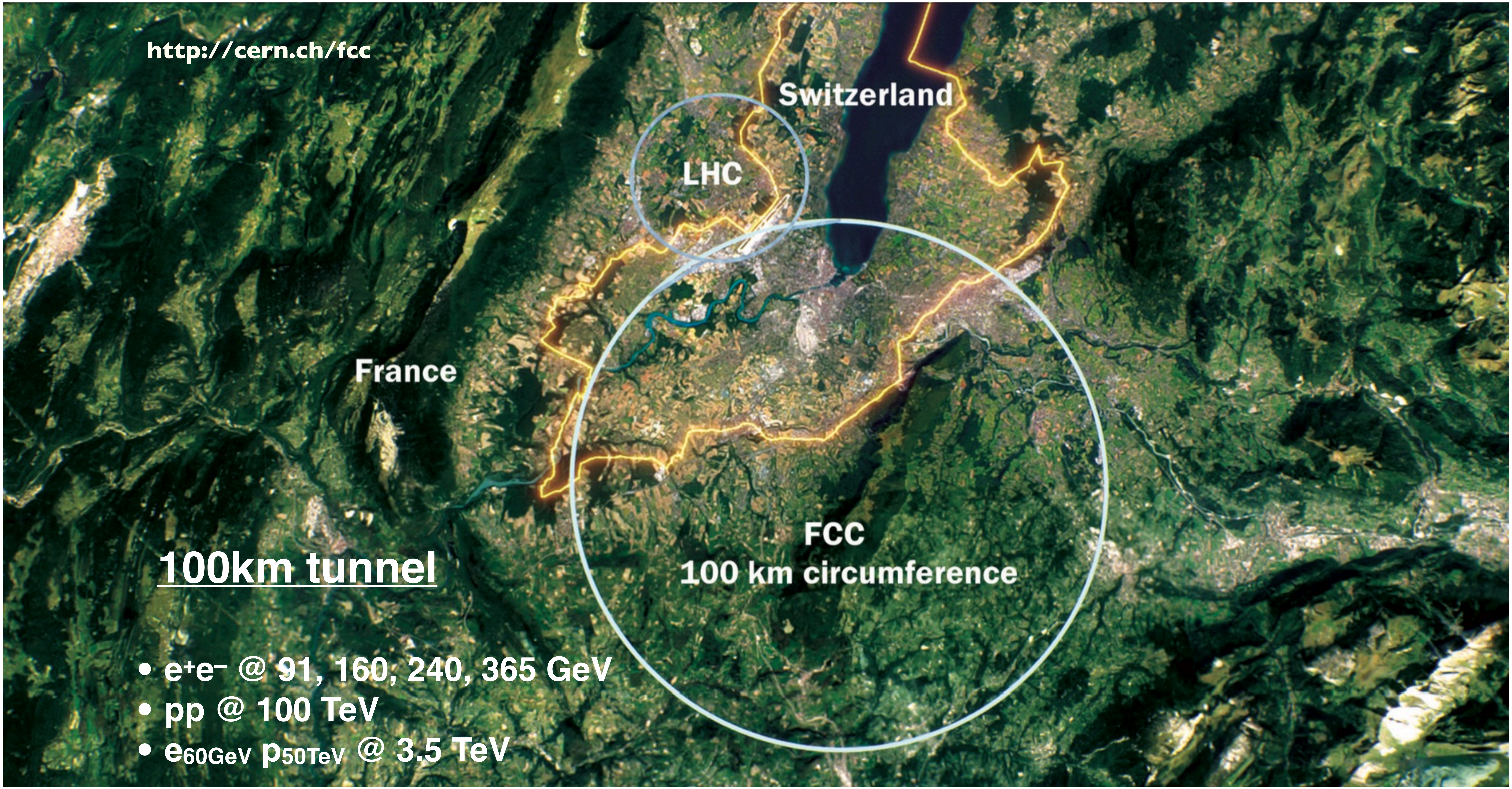
To address both possibilities, we need a future circular collider to increase the:

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

Future Circular Collider



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- 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

e+e– collisions: very clean experimental environment, every single event is recorded and later analyzed, small backgrounds, high experimental precision and small systematic uncertainties

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}

pp collisions: very high energies, very large production rates, sensitivity to extremely rare processes and potential to directly observe new partiles of very large mass

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

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

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- 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!

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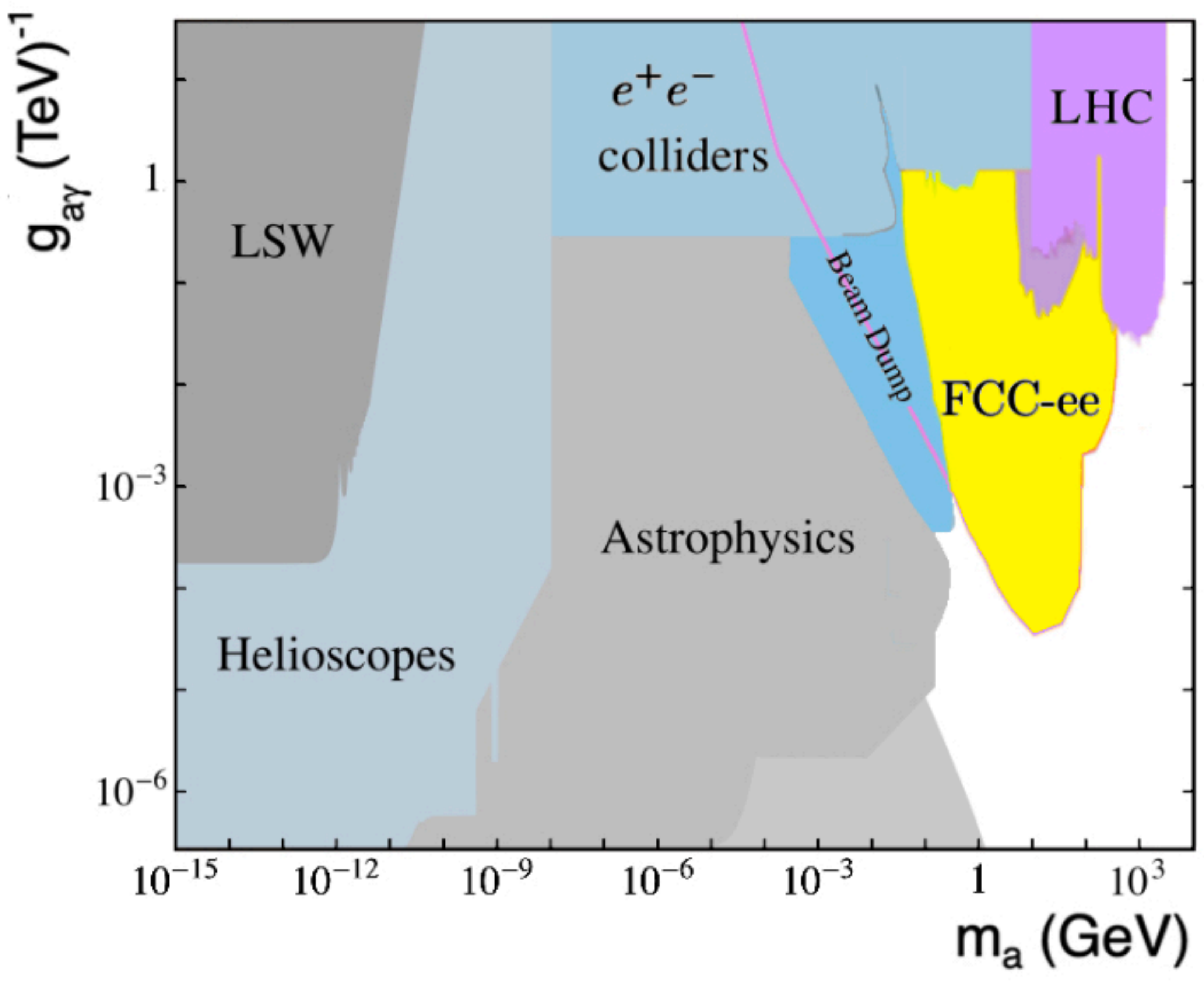
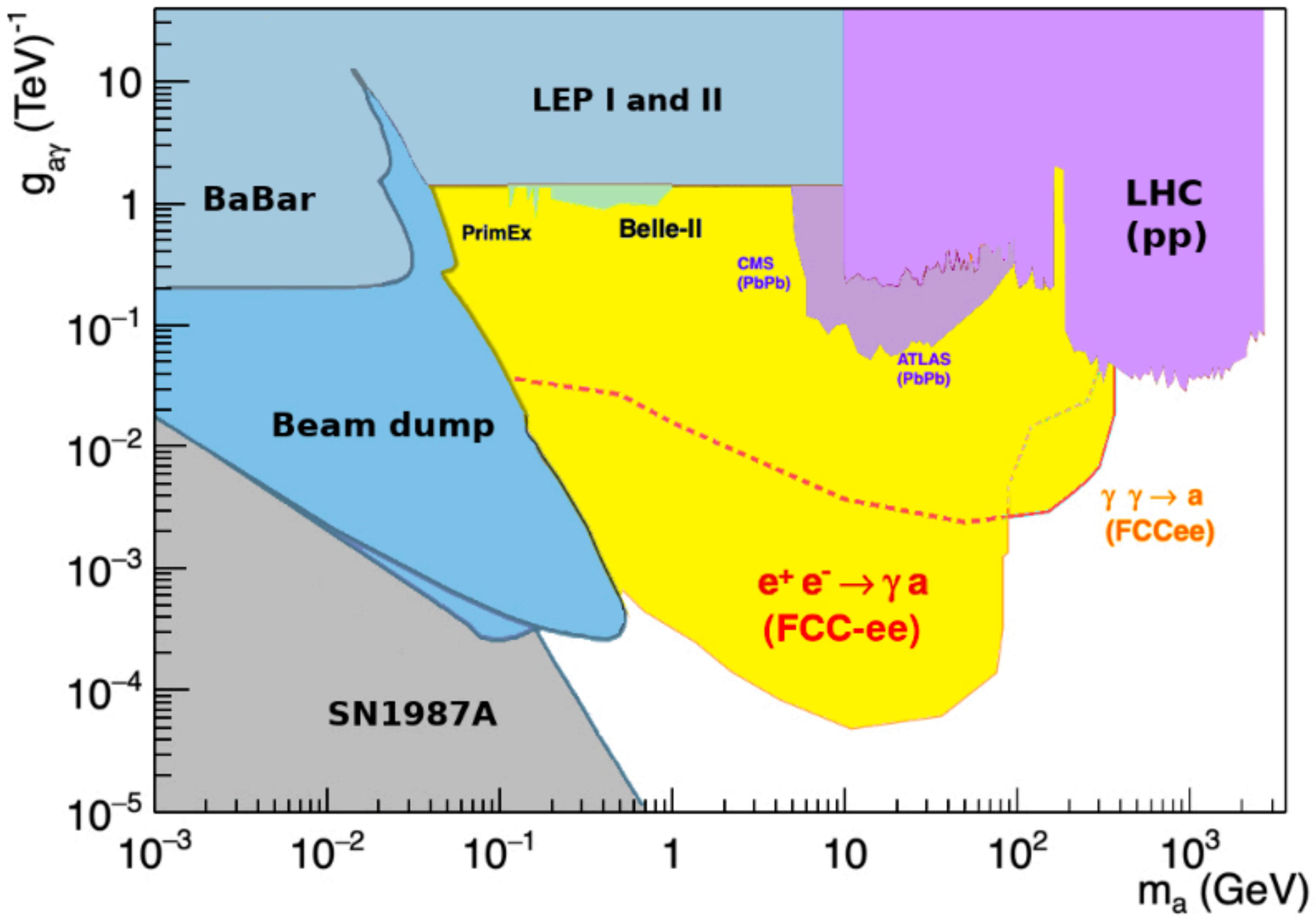
    - Eg:

$$e^+e^- \to a\gamma$$

$$e^+e^- \to e^+e^-a$$

$$a \to \gamma\gamma$$





- … and much more !!