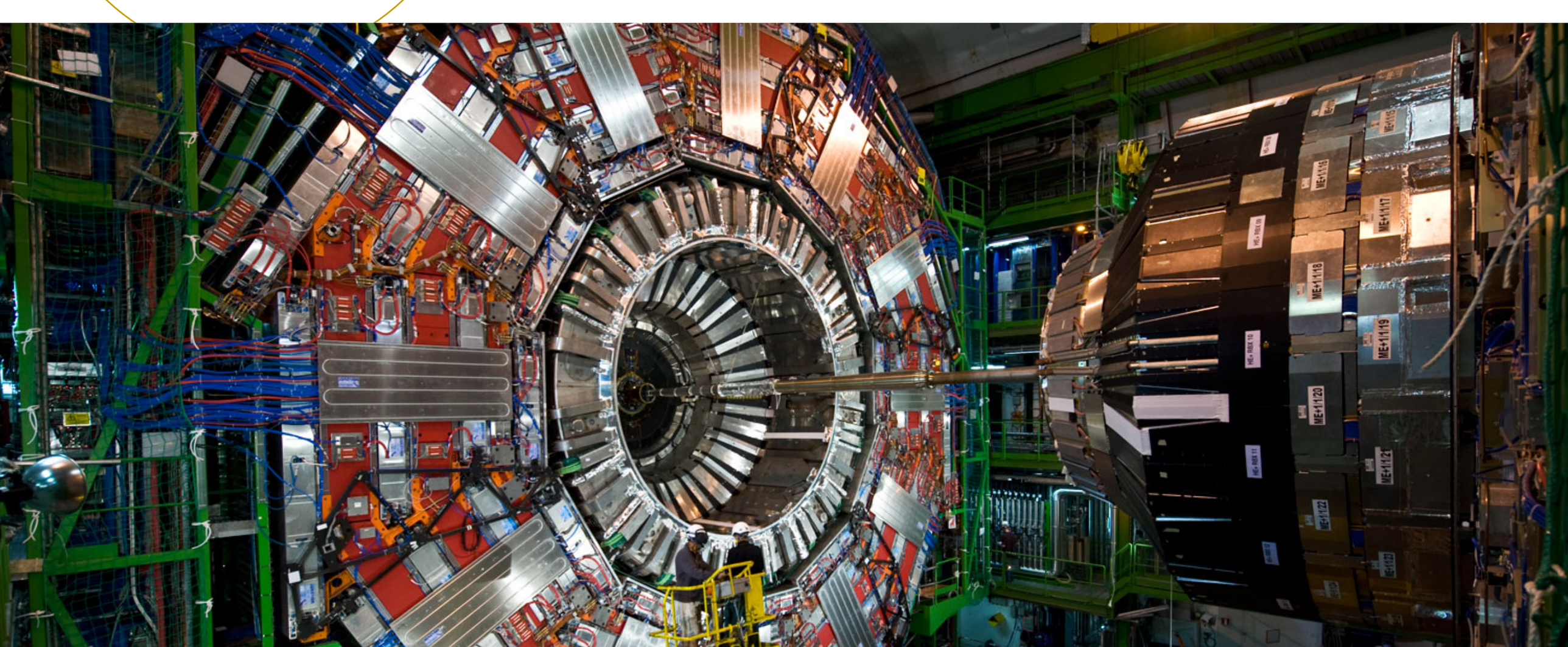
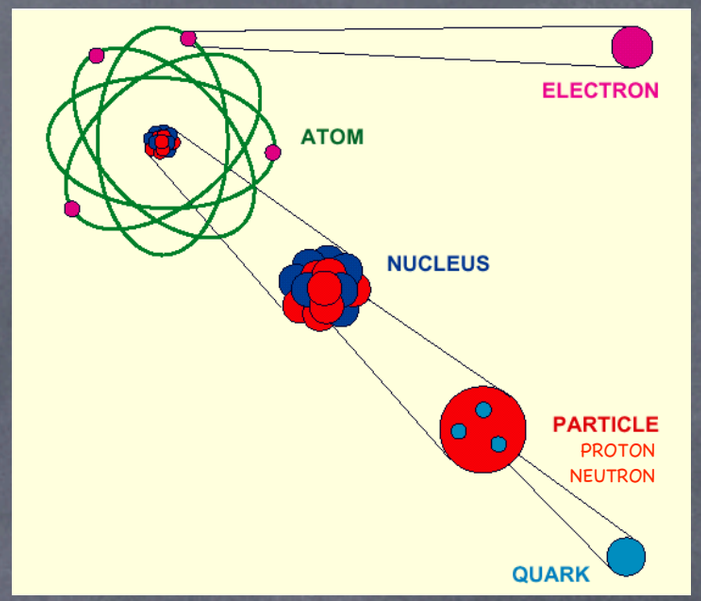
M.Nardecchia
Università Sapienza & INFN Roma
22/09/2023

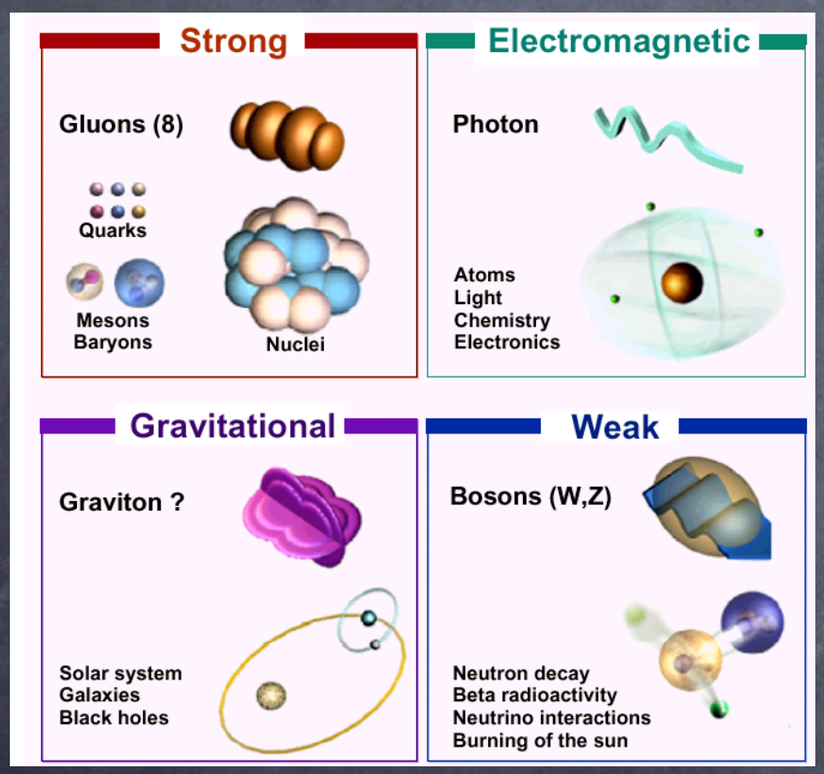
Fundamental Interactions: Theory and Experiment



"Fundamental" Physics



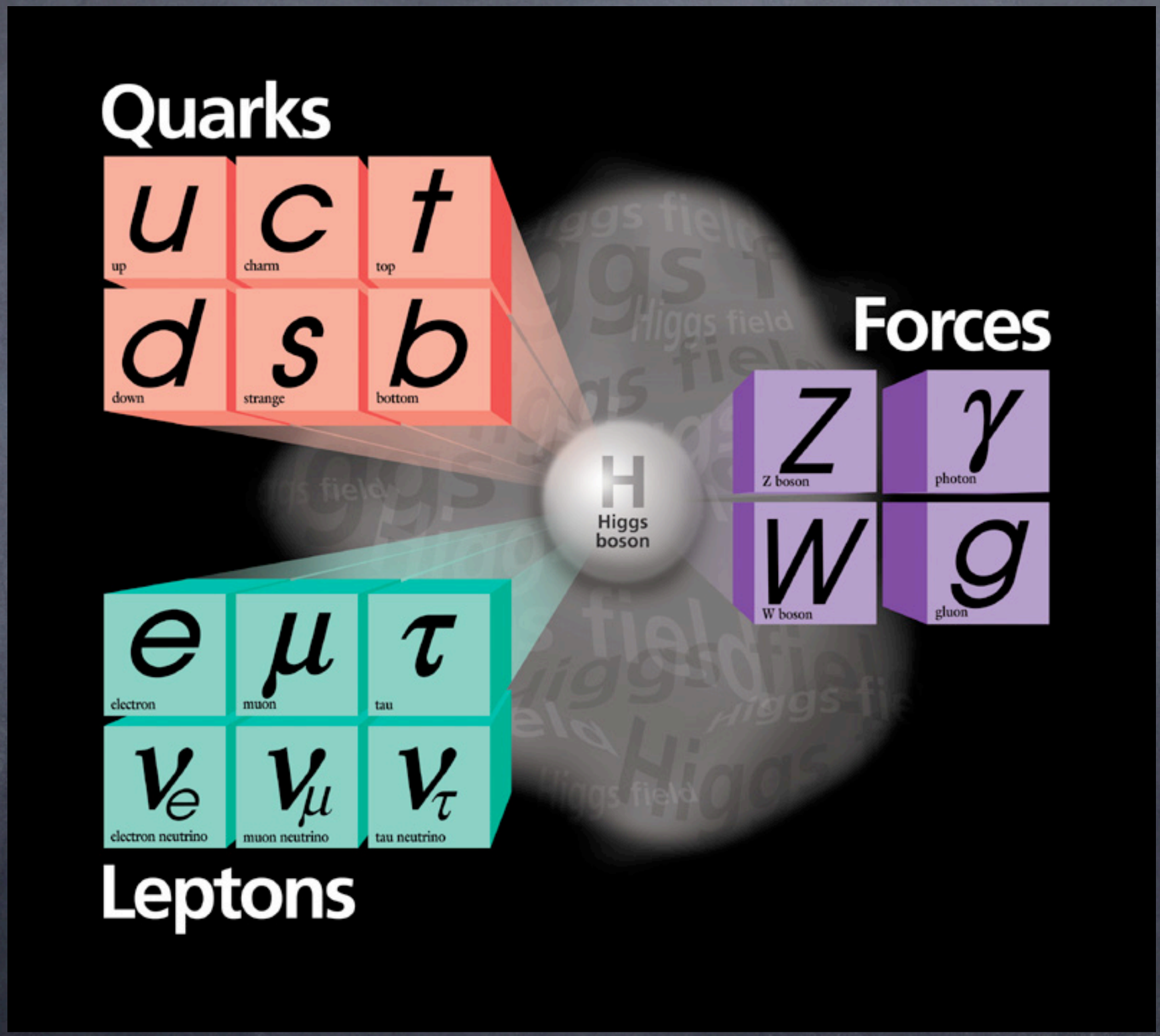
- What are the basic, elementary building blocks of matter (no inner structure, no smaller components)?



- What are the forces controlling their behaviour at the most basic level? (elementary forces)

- Can nature be understood in terms of a few basic principles, the "theory of everything"?

In Summary


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Leptons

Is the SM the whole story?

- Experimental "problems" of the SM:
  - Gravity
  - Dark matter
  - Baryon asymmetry
- Experimental hints of physics beyond the SM
  - Neutrino masses
  - Quantum number unification
- Theoretical puzzles of the SM:
  - $\langle H \rangle \ll M_{Pl}$
  - Family replication
  - Small Yukawa couplings, pattern of masses and mixings
  - Gauge group, anomaly cancellation, charge quantization, quantum numbers
- Theoretical problems of the SM:
  - Hierarchy or Naturalness problem
  - Cosmological constant problem
  - Strong CP problem

Einstein's Field Equations

(Mathematical form of Einstein's Gravity)

General Theory of Relativity

Scalar curvature

Newton's Gravitational constant

stress energy tensor.

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}\,R + g_{\mu\nu}\,\Lambda = \frac{8\pi G}{c^4}T_{\mu\nu}$$

Ricci curvature tensor

metric tensor

cosmological constant

light speed in vacuum

Gravity & Fundamental Physics

Several of the deepest questions in fundamental physics involve gravity:

- **The nature of gravity.** Is Einstein (still) right? What building-block principles and symmetries in nature invoked by General Relativity (GR) can be challenged? Are there extra fields involved in the gravitational interaction?

- **The nature of neutron stars.** How does nuclear matter behave in the extreme conditions of the inner core of neutron stars? Does exotic physics show up in these objects?

- **The nature of black holes.** How well classical GR BHs describe observations? Do more exotic species of compact stars exist? Signatures of quantum gravity near event horizons?

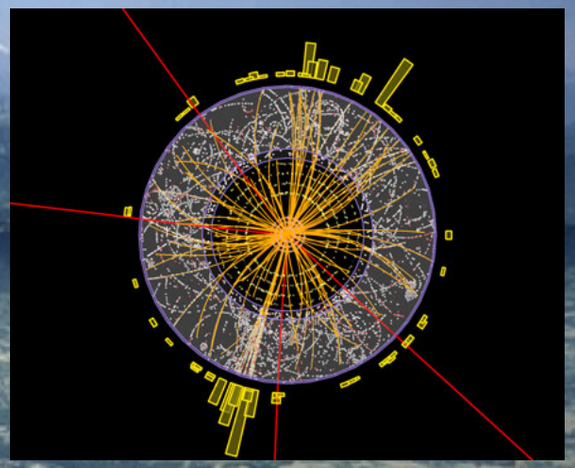
- **The nature of dark matter.** Is dark matter composed of particles, dark objects, or modified gravity? Can we detect or constrain dark matter and the early universe using GWs?

Virgo Interferometer

DarkSide @ Laboratori Nazionali del Gran Sasso

INFN
Istituto Nazionale di Fisica Nucleare

Il Large Hadron Collider (LHC): il più potente collisore di protoni



due fasci di protoni che viaggiano in senso opposto e collidono in quattro punti lungo l'anello:

circonferenza = 27 km

LHCb

ATLAS

CERN Meyrin

CERN Prévessin

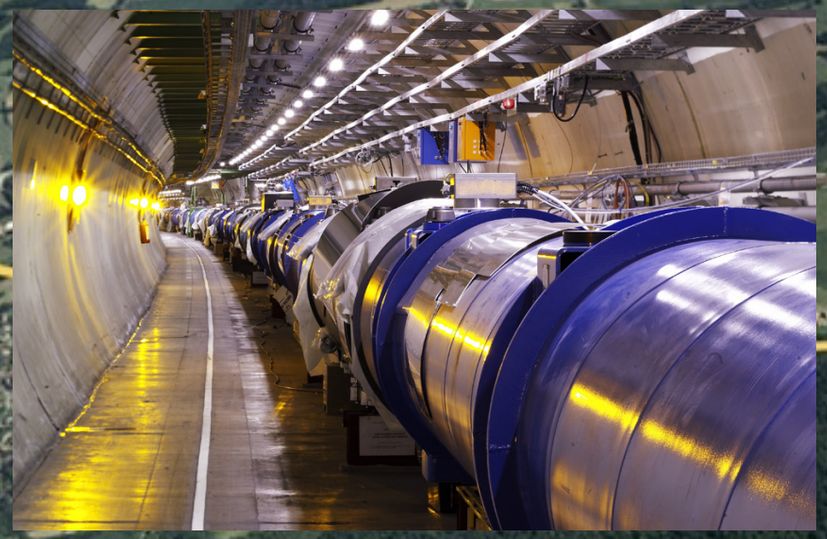
SPS 7 km

SUISSE

FRANCE

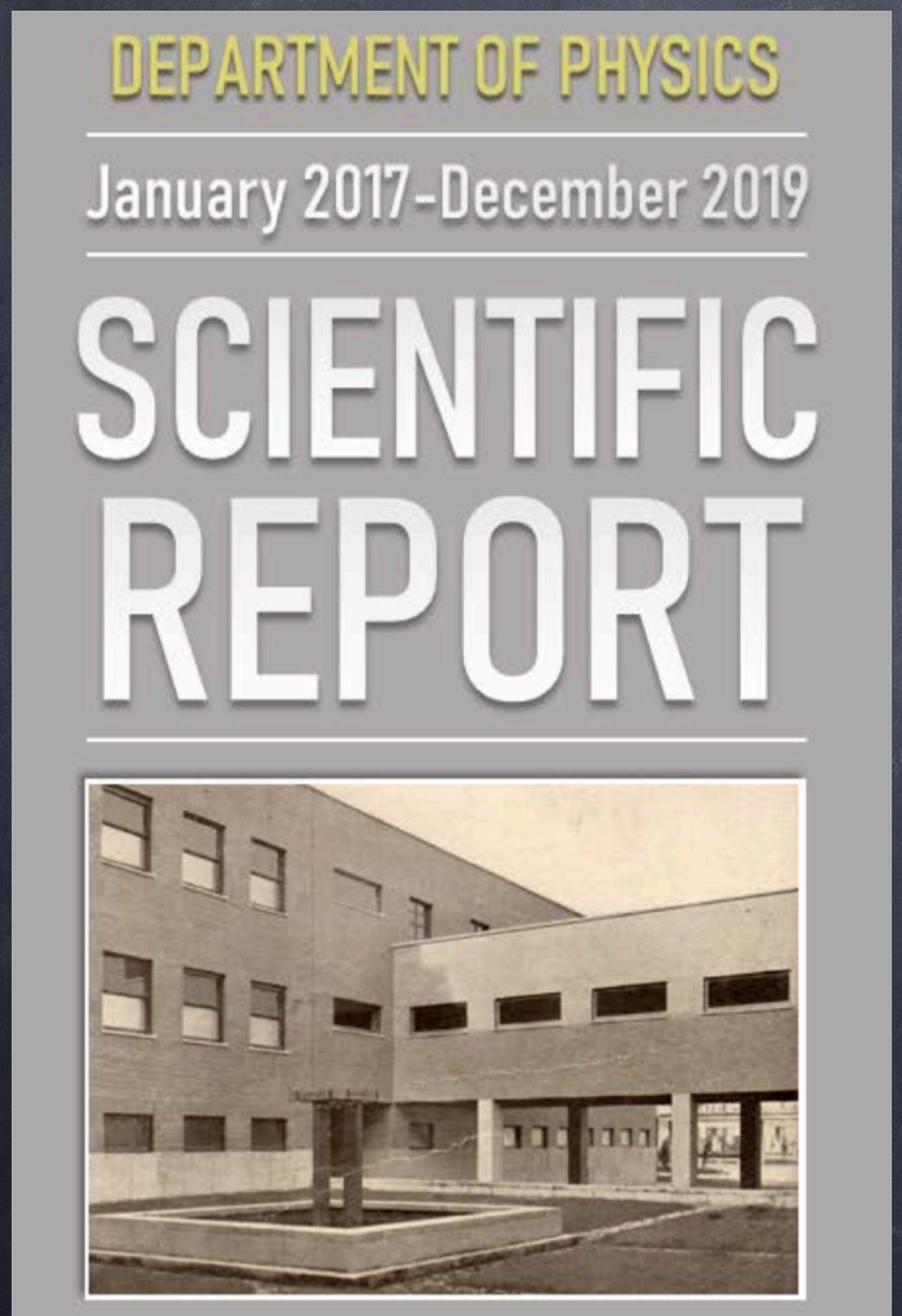
CMS

ALICE



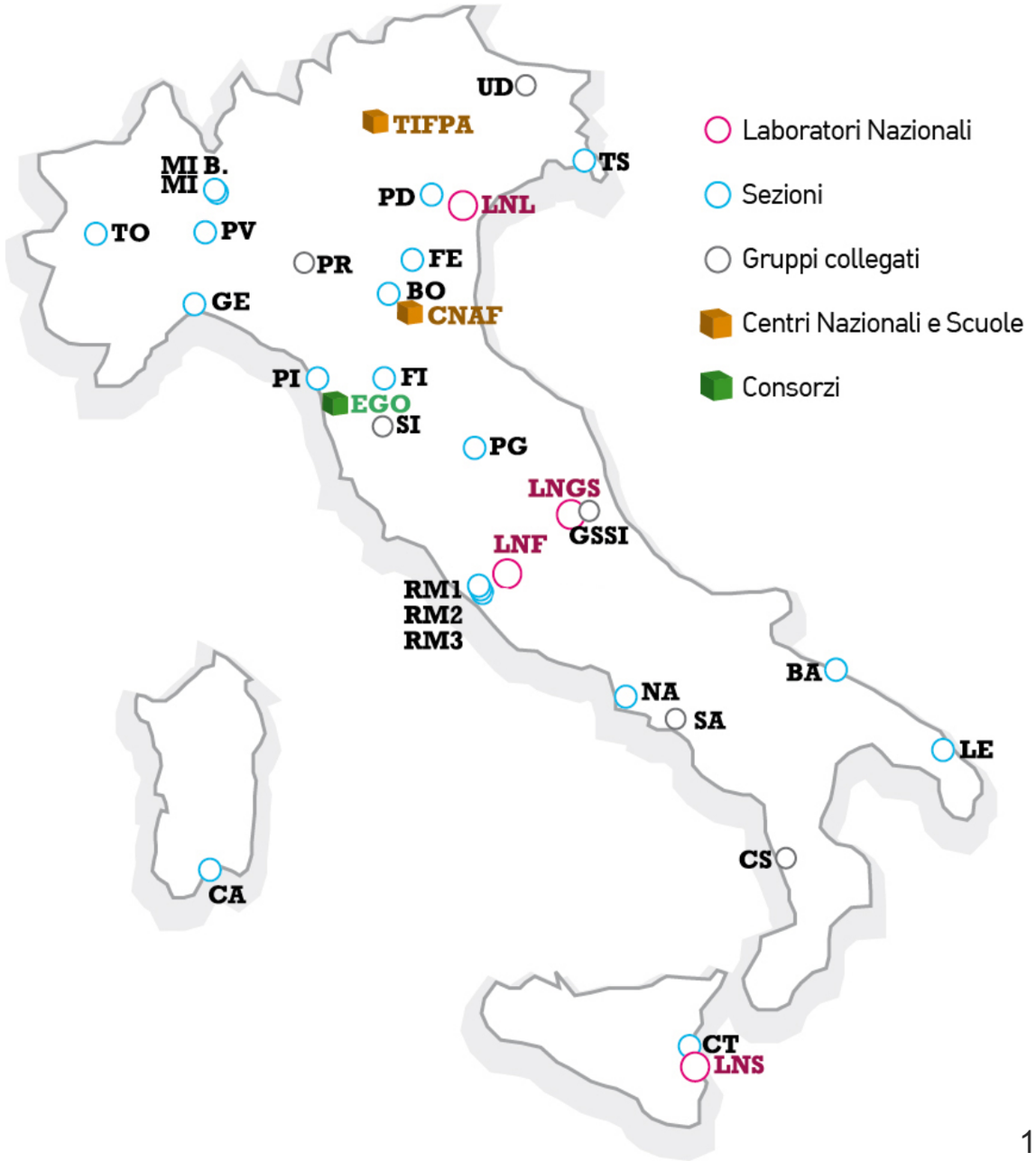
protoni accelerati ad una velocità pari al 99.999999% di quella della luce

Dipartimento di Fisica
-> Ricerca
-> Scientific Report



Istituto Nazionale di Fisica Nucleare (INFN)

- INFN is the Italian research agency dedicated to the study of the fundamental constituents of matter and their interactions.
- The research activities presented here are mainly founded by INFN.
  Research groups include both University and INFN staff.
- INFN divisions are located in the Physics Departments
  (web site of Rome division).
- Availability of master thesis in national/ international laboratories and in international collaborations.
- PhD school on Accelerator Physics



INFN Scolarship

Istituto Nazionale di Fisica Nucleare

CONCORSO PER IL CONFERIMENTO

DI N. 5 BORSE DI STUDIO PER ATTIVITA' DI FORMAZIONE SCIENTIFICA

PER STUDENTI UNIVERSITARI

https://jobs.dsi.infn.it

Fundamental Interactions curriculum, practical guide

Curriculum Fundamental Interactions : Theory and Experiment							
N.	**Insegnamenti**	**CFU**	**anno**	**sem.**	**SSD**	**eng**	**ambito**
1	Introduction to Quantum Field Theory	6	1	1	FIS/02	Y	caratt.
2	Condensed Matter Physics	6	1	1	FIS/03	Y	caratt.
3	Physics Laboratory I (propedeutic teaching to Physics Laboratory II)	6	1	1	FIS/01	Y	caratt.
4	Group Theory in Mathematical Physics	6	1	1	MAT/07	Y	aff.-int.
5	Theory of Fundamental Interactions	6	1	2	FIS/02	Y	caratt.
6	Particle Physics	6	1	2	FIS/04	Y	caratt.
7	Physics Laboratory II	9	1	2	FIS/01	Y	caratt
8	English language	4	1	2		Y	AAF
9	Elective (within group A)	6	1/2	1/2	FIS/01	Y	caratt.
10	Elective (within group B)	6	1/2	1/2	FIS/02-05	Y	aff..-int.
11	Elective (within group C)	6	1/2	1/2		Y	aff.-int.
12	Elective (free choice)	6	1/2	1/2		Y	
13	Elective (free choice)	6	1/2	1/2		Y	
14	Internship	3	2	1		Y	AAF
15	Thesis Project	38	2	2		Y	AAF

CFU = number of credits

SSD: Settore Scientifico Disciplinare

- FIS: Physics course
  - FIS/01: experimental physics
  - FIS/02: theoretical physics
  - FIS/03: condensed matter physics
  - FIS/04: nuclear and subnuclear physics
  - FIS/05: astronomy and astrophysics
- MAT: Mathematics course

Three semesters.
Seven compulsory courses + five optional courses.

Mandatory courses

Compalsury courses of the curriculum

YEAR	SEMESTER	COURSE	SSD
1	1	Introduction to Quantum Field Theory (R. Bonciani or A. Polosa)	FIS/02
1	1	Condensed Matter Physics (S. Caprara or A.Polimeni)	FIS/03
1	1	Physics Laboratory I (G. Cavoto)	FIS/01
1	1	Group Theory in Mathematical Phyiscs (G. Panati)	MAT/07
1	2	Theory of Fundamental Interactions (A. Urbano)	FIS/02
1	2	Particle Physics (S. Rahatlou)	FIS/04
1	2	Physics Laboratory II (G. Cavoto	FIS/01

The real thing: the SM in one Table...

$G = SU(3)_C \times SU(2)_L \times U(1)_Y$

	SU(3)	SU(2)	U(1)
L_i	1	2	-1/2
e^c_i	1	1	1
Q_i	3	2	1/6
u^c_i	3^*	1	1/3
d^c_i	3^*	1	-2/3

...and 3 lines

Y

$$\bar{\Psi}_i i\sigma^\mu D_\mu \Psi_i - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} \qquad \text{gauge}$$

$$\mathcal{L}^{\text{ren}}_{\text{SM}} = \qquad +|D_\mu H|^2 - V(H) \qquad \text{symmetry breaking}$$

$$+\lambda_{ij} \Psi_i \Psi_j H + \text{h.c.} \qquad \text{flavor}$$

Theory of Fundamental Interactions (A. Urbano)

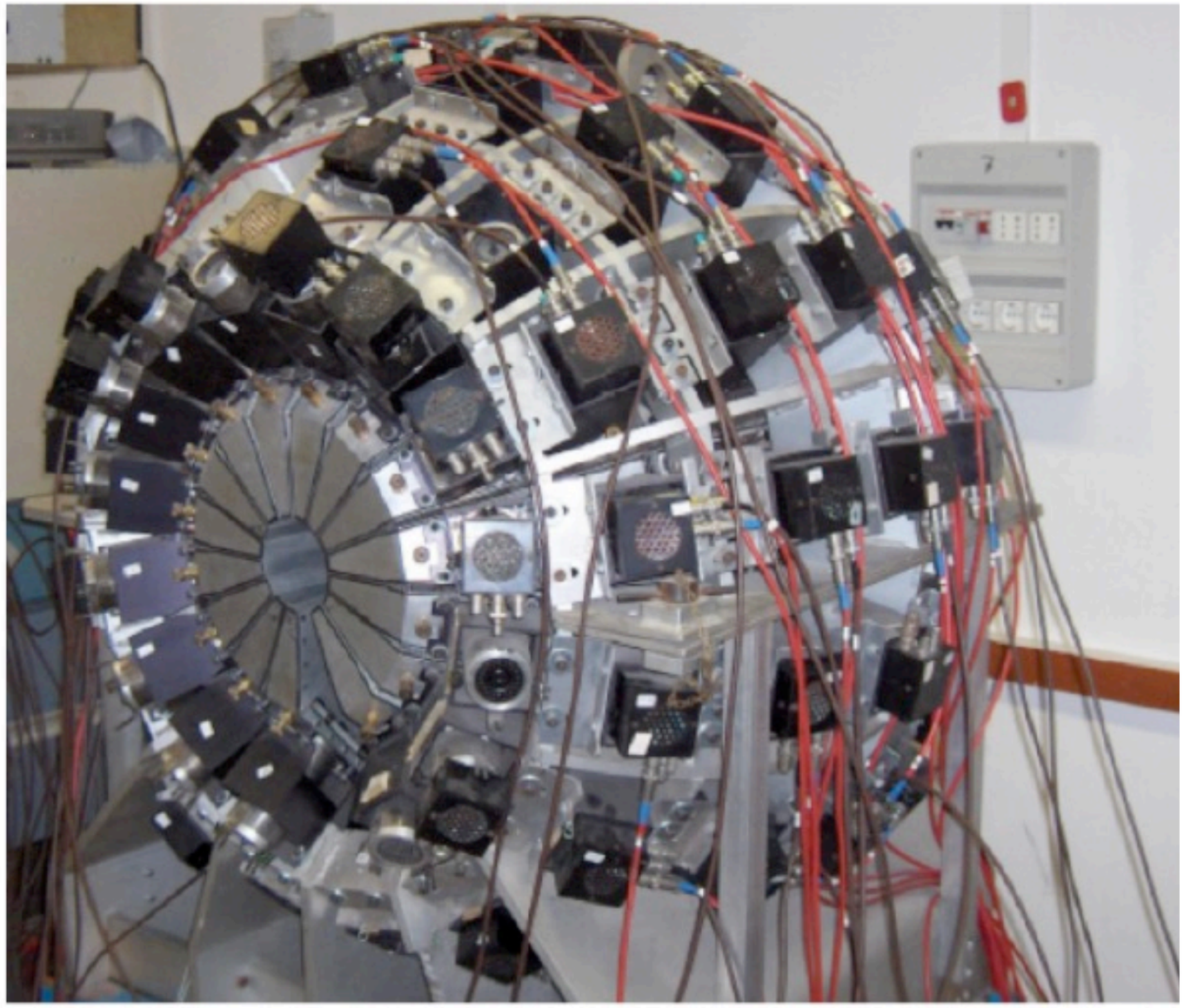
Particle Physics (S. Rahatlou)

▾ Obiettivi

Lo scopo del corso è l'apprendimento delle evidenze sperimentali e delle metodologie che hanno condotto alla formulazione del Modello Standard (SM) della fisica delle particelle elementari, dall'inizio della disciplina negli anni 30 e 40 del secolo scorso fino alla formulazione dello SM. Il corso è strettamente legato ai corsi teorici del primo semestre e a quello annuale di Laboratorio.

Physics Laboratory I and II

- Physics Lab. I is propedeutic to Physics Lab. II. Both mandatories.
- Content of the course:
  - Interaction of radiation with matter
  - Gas, semiconductor, scintillation detectors
  - Spectrometers, calorimeters, Cherenkov counters
  - Signal formation & electronics
  - Statistics for data analysis
- In Physics Lab. II:
  - Realization of a small scale experiment in groups of few students.



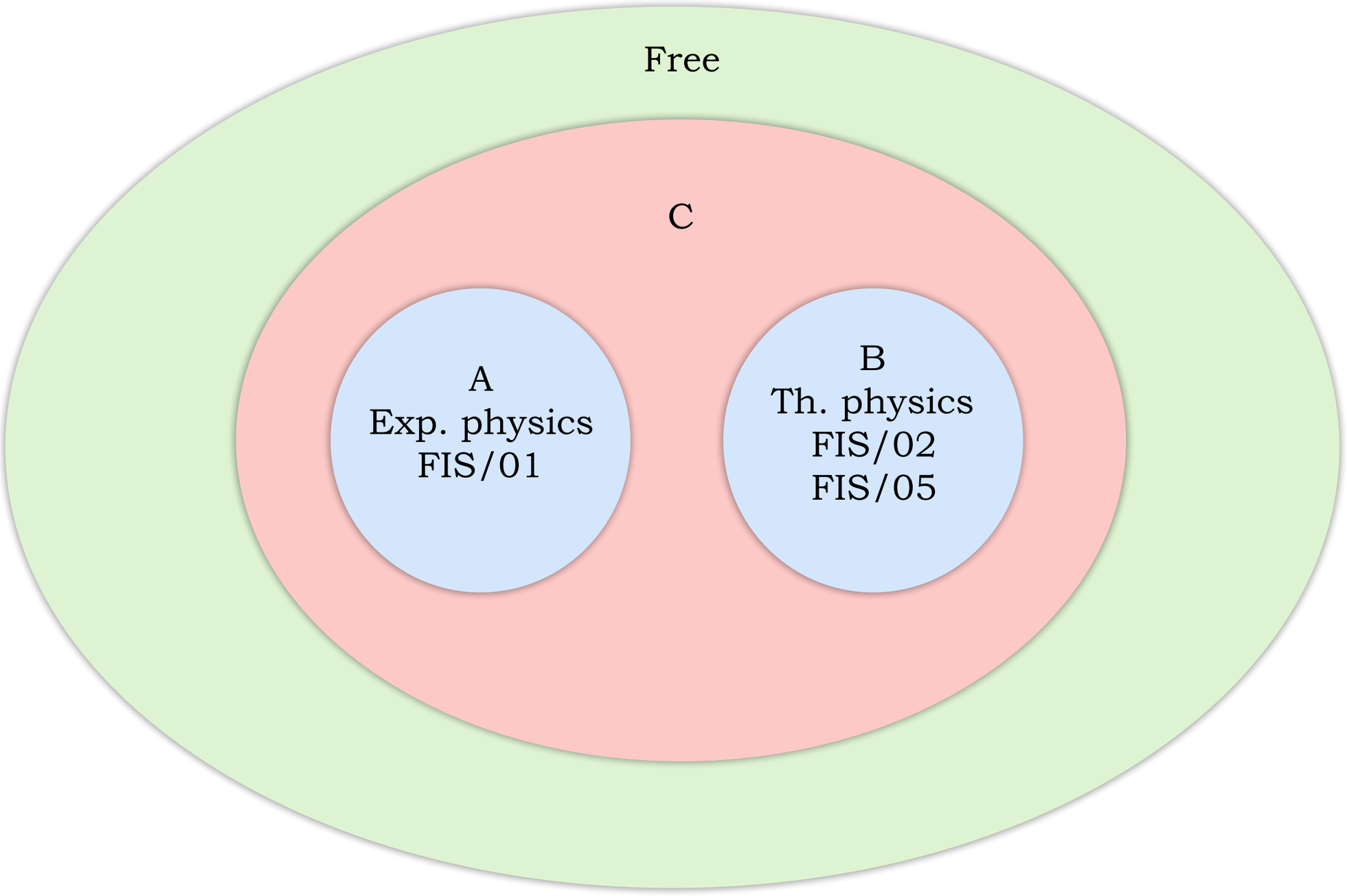
Groups A & B

Gruppo A (caratt.)							
1	Detectors and Accelerators in Particle Physics	6	1	2	FIS/01	Y	
2	Methods in Experimental Particle Physics	6	1	2	FIS/01	Y	
3	Collider Particle Physics	6	2	1	FIS/01	Y	
4	Neutrinos and Dark Matter	6	2	1	FIS/01	Y	
5	Experimental Gravitation (mutuato da LM-58)	6	2	1	FIS/01	Y	
6	Medical Applications of Physics	6	2	1	FIS/01	Y	
7	Astroparticle Physics (mutuato da LM-58)	6	2	1	FIS/01	Y	
8	Solid State Sensors	6	2	1	FIS/01	Y	
Gruppo B (aff.-int.)							
1	General Relativity (mutuato da LM-58)	6	1	1	FIS/02	Y	
2	Neural Networks	6	1	2	FIS/02	Y	
3	Gravitational Waves, Compact Stars and Black Holes	6	1	2	FIS/02	Y	
4	Physical Cosmology (mutuato da LM-58)	6	1	2	FIS/05	Y	
5	Strong Interactions and QCD	6	1	2	FIS/02	Y	
6	Quantum Field Theory	6	2	1	FIS/02	Y	
7	Phenomenology of the Standard Model	6	2	1	FIS/02	Y	

Group C

1	Computing Methods for Physics	6	1	1	INF/01	Y	
2	General Relativity (mutuato da LM-58)	6	1	1	FIS/02	Y	
3	Neural Networks	6	1	2	FIS/02	Y	
4	Advanced Machine Learning for Physics	6	1	2	INF/01	Y	
5	Computer Architecture for Physics	6	1	2	INF/01	Y	
6	Detectors and Accelerators in Particle Physics	6	1	2	FIS/01	Y	
7	Mathematical Physics	6	1	2	MAT/07	Y	
8	Methods in Experimental Particle Physics	6	1	2	FIS/01	Y	
9	Nuclear Physics	6	1	2	FIS/04	Y	
10	Gravitational Waves, Compact Stars and Black Holes	6	1	2	FIS/02	Y	
11	Physical Cosmology (mutuato da LM-58)	6	1	2	FIS/05	Y	
12	Plasma Physics and Nuclear Fusion (mutuato da LM-30)	6	1	2	FIS/01	Y	
13	Strong interactions and QCD	6	1	2	FIS/02	Y	
14	Accelerator Physics and Relativistic Electrodynamics (mutuato da LM-29)	6	1	2	FIS/01	Y	
15	Astroparticle Physics (mutuato da LM-58)	6	2	1	FIS/01	Y	
16	Collider Particle Physics	6	2	1	FIS/01	Y	
17	Experimental Gravitation (mutuato da LM-58)	6	2	1	FIS/01	Y	
18	Medical Applications of Physics	6	2	1	FIS/01	Y	
19	Neutrinos and Dark Matter	6	2	1	FIS/01	Y	
20	Quantum Field Theory	6	2	1	FIS/02	Y	
21	Solid State Sensors	6	2	1	FIS/01	Y	
22	Phenomenology of the Standard Model	6	2	1	FIS/02	Y	
23	Laser Fundamentals (mutuato da LM-29, reserved for Lascala students only)	6	1	2	FIS/01	Y	
24	Optics (mutuato da LM-29, reserved for Lascala students only)	6	1	2	FIS/01	Y	

Decision Theory



Choose in this order:
1) pick 1 from A and 1 from B
2) pick 1 from C
3) pick 2 from Free

Some suggestions..

Particle Exp. (4+5+3)

YEAR	SEMESTER	COURSE	SSD
1	1	Introduction to Quantum Field Theory	FIS/02
1	1	Condensed Matter Physics	FIS/03
1	1	Physics Laboratory I	FIS/01
1	1	Group Theory in Mathematical Phyiscs	MAT/07
1	2	Theory of Fundamental Interactions	FIS/02
1	2	Particle Physics	FIS/04
1	2	Physics Laboratory II	FIS/01
1	2	Detectors and Accelerators in Particle Physics (Gauzzi)	FIS/01
1	2	Methods in Experimental Particle Physics (Di Domenico)	FIS/01
2	1	Neutrinos and Dark Matter (Vignati)	FIS/01
2	1	Collider Particle Physics (Luci)	FIS/01
2	1	Phenomenology of the Standard Model (Contino,Nardecchia)	FIS/02

Some suggestions..

Particle Theory (5+4+3)

YEAR	SEMESTER	COURSE	SSD
1	1	Introduction to Quantum Field Theory	FIS/02
1	1	Condensed Matter Physics	FIS/03
1	1	Physics Laboratory I	FIS/01
1	1	Group Theory in Mathematical Phyiscs	MAT/07
1	1	General Relativity (Pani)	FIS/02
1	2	Theory of Fundamental Interactions	FIS/02
1	2	Particle Physics	FIS/04
1	2	Physics Laboratory II	FIS/01
1	2	Strong Interactions and QCD (Polosa)	FIS/02
2	1	Neutrinos and Dark Matter (Vignati)	FIS/01
2	1	Phenomenology of the Standard Model (Contino,Nardecchia)	FIS/02
2	1	Quantum Field Theory (Papinutto)	FIS/02

Some suggestions..

Gravity Pheno (5+4+3)

YEAR	SEMESTER	COURSE	SSD
1	1	Introduction to Quantum Field Theory	FIS/02
1	1	Condensed Matter Physics	FIS/03
1	1	Physics Laboratory I	FIS/01
1	1	Group Theory in Mathematical Phyiscs	MAT/07
1	1	General Relativity (Pani)	FIS/02
1	2	Theory of Fundamental Interactions	FIS/02
1	2	Particle Physics	FIS/04
1	2	Physics Laboratory II	FIS/01
1	2	Gravitational Waves, Compact Stars and Black Holes (Pani,Pannarale)	FIS/02
2	1	Experimental Gravitation (Leaci,Majorana)	FIS/01
2	1	Solid State Sensors (Bocci,Polimeni)	FIS/01
2	1	Astroparticle physics (Di Palma)	FIS/01

Some suggestions..

Gravity Theory (5+5+2)

YEAR	SEMESTER	COURSE	SSD
1	1	Introduction to Quantum Field Theory	FIS/02
1	1	Condensed Matter Physics	FIS/03
1	1	Physics Laboratory I	FIS/01
1	1	Group Theory in Mathematical Phyiscs	MAT/07
1	1	General Relativity (Pani)	FIS/02
1	2	Theory of Fundamental Interactions	FIS/02
1	2	Particle Physics	FIS/04
1	2	Physics Laboratory II	FIS/01
1	2	Gravitational Waves, Compact Stars and BH (Pani,Pannarale)	FIS/02
1	2	Physical Cosmology (Melchiorri)	FIS/05
2	1	Quantum Field Theory (Papinutto)	FIS/02
2	1	Experimental Gravitation (Leaci, Majorana)	FIS/01

Some suggestions..

Applied (5+5+2)

YEAR	SEMESTER	COURSE	SSD
1	1	Introduction to Quantum Field Theory	FIS/02
1	1	Condensed Matter Physics	FIS/03
1	1	Physics Laboratory I	FIS/01
1	1	Group Theory in Mathematical Phyiscs	MAT/07
1	1	Computing Methods for Physics (Pannarale)	INF/01
1	2	Theory of Fundamental Interactions	FIS/02
1	2	Particle Physics	FIS/04
1	2	Physics Laboratory II	FIS/01
1	2	Nuclear Physics (De Cecco)	FIS/04
1	2	Strong Interactions and QCD (Polosa)	FIS/02
2	1	Medical Applications of Physics (Patera, Saini)	FIS/01
2	1	Solid State Sensors (Bocci,Polimeni)	FIS/01

Few final remarks…

- More information about ongoing researches in the Scientific Report of Department of Physics (link).
  Pages 97-159 dedicated to particle and astroparticle physics.

- Practical infos about courses:
  https://corsidilaurea.uniroma1.it/it/corso/2022/30055/programmazione

Questions on the FI curriculum:

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