A modern primer in particle and nuclear physics

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Why a new book on this topic

In 2015 I was asked to give an introductory course of nuclear and particle physics at undergraduate (3rd year Bachelor) level and I had to face a well-known conundrum:

At that time (generally 3rd year) the students either have a **basic background** of non-relativistic quantum mechanics and relativity or they follow these QM courses **in parallel** with it.

The limited background compared with what is needed to address quantitatively particle and nuclear physics is a **tremendous challenge for teachers.**

So, either we give a brisky tour of quantum-field-theory to introduce particle physis – leaving aside nuclear physics - (**qualitative and incomplete**!) or we reduce the course at a level the does not convey its main message: particle physics is a discipline with a solid paradigm (the Standard Model) established in the late 70s and still valid today (i.e. we give an **obsolete** course!).

Trying and trying again

At the expenses of the students ☺
(who, anyway, appreciated my efforts since the beginning, showing enthusiasm and patience for my mistakes)

Basic idea: we want to convey the contemporary view to our students:

- **Particle physics** is a well-established discipline that describes electroweak and strong forces at elementary level
- **Nuclear physics** is a difficult discipline because it represents the non perturbative regime of Quantum Chromodynamics (QCD) and (to date) can only be partially derived from QCD
- **Gravitation** is entering particle physics but the lack of a paradigm for quantum gravity makes the study of gravity at fundamental level still a major challenge

The Standard Model is presented the way it is: **the paradigm of particle physics and the foundation of nuclear physics.**

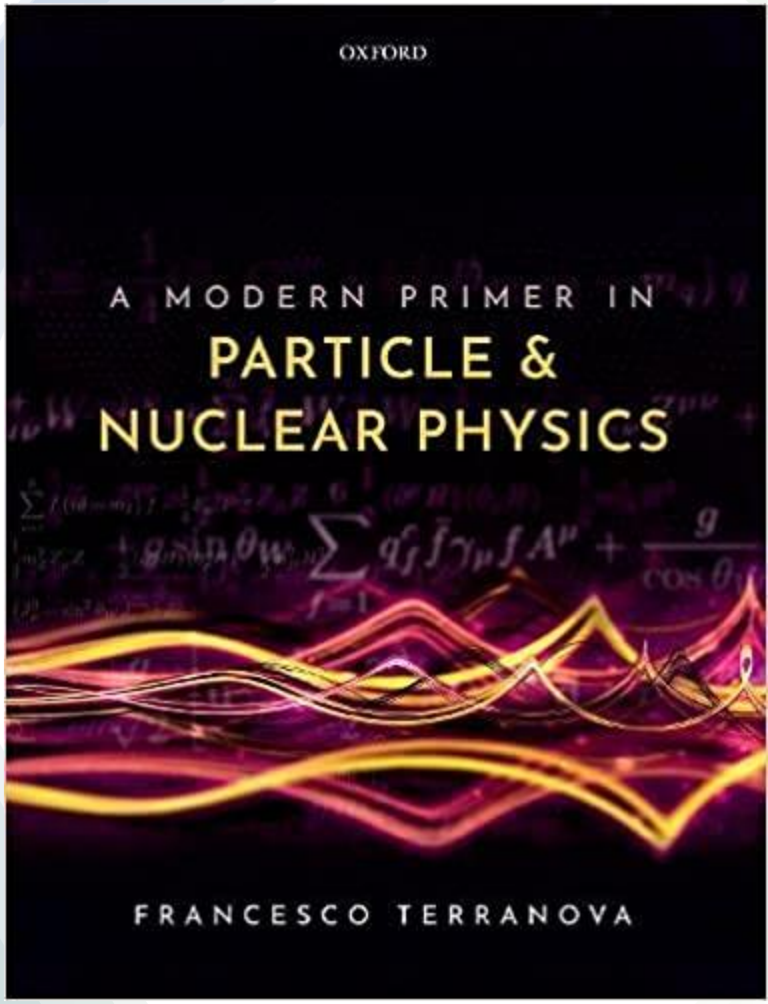
At the end of the day

It turned out that this "top-down" approach can be conveyed to **advanced undergraduate (3rd year Bachelor) and Master students**

It is a "**truly modern**" (L. Votano) approach which pave the way to more advanced (graduate level) courses on

- Advanced particle physics (including QFT and phenomenology)
- Advanced nuclear physics
- Astroparticle physics

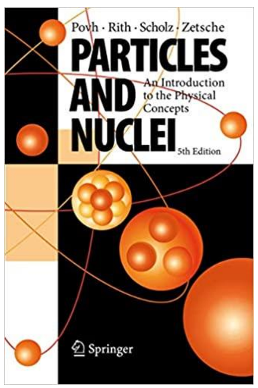
Together with Oxford University Press, we transform it in a full course, including, exercises, a companion website and all features that make this book a useful tool for students and teachers.

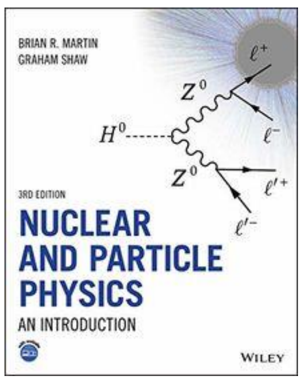


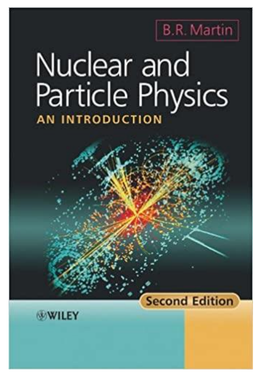
A bit of history

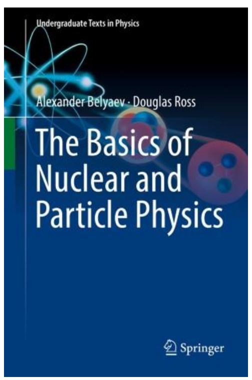
Until the 90s, all textbook followed a clear and simple approach: they introduce first nuclear physics because it can be dealt with non-relativistic quantum mechanics. Then, they introduce the discovery of "elementary" particles and **a glimpse** of the theory behind this (QED, V-A theory, a glimpse to the Standard Model)

An excellent idea that worked in the past when the Standard Model was still in the making and produced excellent textbooks!









… and many others …

Until the 90s it conveyed students exactly what was experienced by professionals. It sound now a bit old-fashioned because "Nuclear Physics" is the **most challenging environment to apply non-perturbative QCD**! Definitely not the place to start ☺

Teaching the basic of this discipline at undergraduate level is a must

- Any physicist should be aware of the fundamental forces and constituents of the universe [as they become aware of the Big Bang without mastering General Relativity]

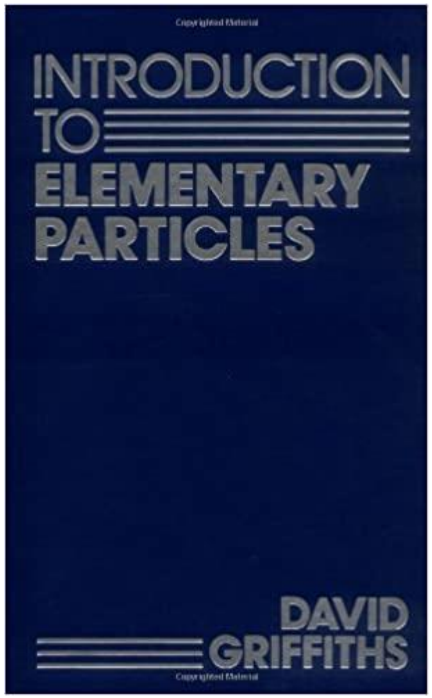
- When they enter the Master's course, they must choose a course of study (solid-state, particle, astrophysics, etc.). Their choice should be well-informed.

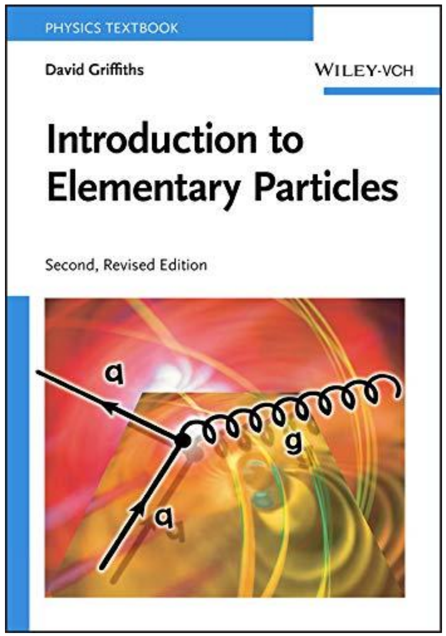
- Some of the concepts are so widespread that they are needed to nearly all physicists in their work. Common examples: radioactivity, gamma rays, fission, photon or electron scattering, etc.

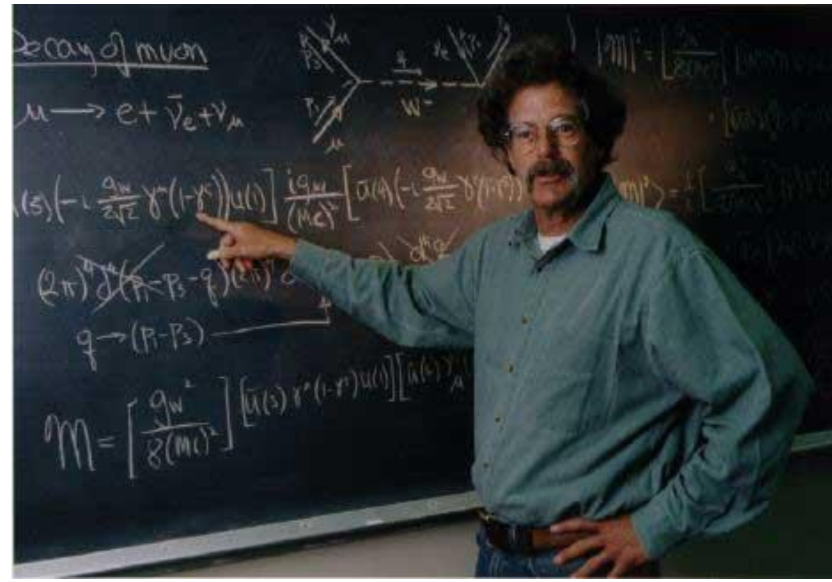
Saying "you cannot fully understand particle and nuclear physics yet, but you will learn it later" won't work!

Straight to the point

In 1987 D.J. Griffith published “the first quantitative treatment of elementary particle theory that is accessible to undergraduates”





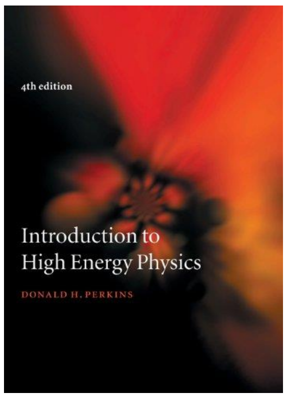


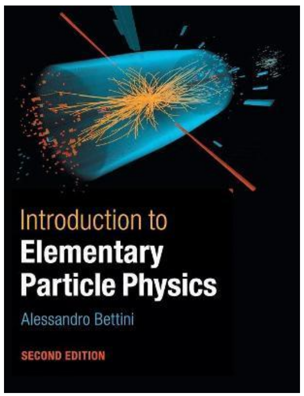
After a short historical introduction, he gives the basic of QFT and introduce the Standard Model. Nuclear physics is left to other courses.

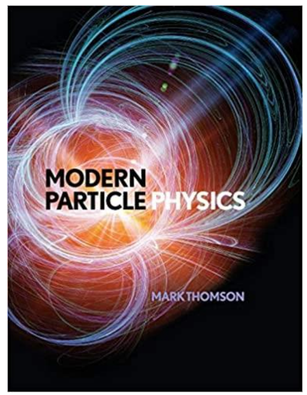
without overlooking the experimental foundation

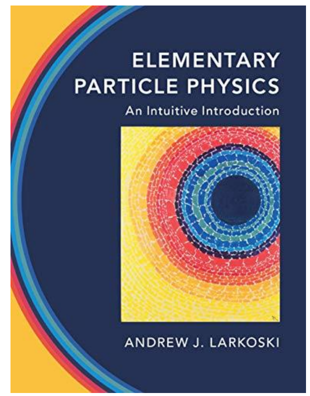
The "particle driven" approach. Put emphasis on Particle Physics and strong interactions leaving Nuclear Physics to other courses

It is a reasonable compromise that produced excellent textbooks and the most successful to date









… and many other great textbooks!

.. but two important drawbacks: it produces textbook that tend to be too advanced for undergraduates (they are rated "advanced undergraduate") and give away a unified view of fundamental physics

Setting the stage

The opening chapter of my book replaces Griffith's historical introduction with an overview of the state of the art and summarizes the goals of the book:

- What are the elementary particles?
- What are the fundamental forces
- How we describe them.

Question		Refs
Why does each particle have an antiparticle?	Yes	Chap. 4
Why are weak interactions weak?	Yes	Chap. 12
Why are strong interactions strong?	Yes	Chap. 8
Why are the mass of the fermions so different?	No	Chap. 13
Why are neutrinos so light?	No	Chap. 11
Why can't quarks be seen as free particles?	Yes	Chap. 8
Why is the charge quantized in units of $e/3$	No	–
Why have the leptons no color charge?	No	–
Why has the SM three families?	No	Chap. 12

The language of modern physics: covariance

Even if students do not know relativistic quantum mechanics, they do know special relativity and non-relativistic quantum physics (*). We can get rid of the issue of using nuclear physics as a bridge between classical and relativistic physics introducing **the language of covariance**

The concept of covariance can be introduced on a general ground to cope with SR, General Relativity, and quantum gravity and can be restricted to SR in all cases of interest for this book.

Covariance is a prescription on the form of the physical laws that ensures compliance with the axioms of relativity:
(A1) The physical laws retain the same functional form in all inertial frames.
(A2) The speed of light in vacuum is the same for all inertial observers.

(*) In my book, two appendices recall the basics of these topics

Filling the gap: the Dirac equation

To go beyond non-relativistic quantum mechanics without introducing QFT, we use two techniques:

- **We generalize the Fermi golden rule a la Dirac using the covariant formalism only**

The **relativistic golden rule** for the decays is then:

$$\Gamma_{i\to f} = \frac{1}{2E_a}\int \prod_{i=1}^{n} \frac{d^4 p_i}{(2\pi)^4}\,|\mathcal{M}|^2\,(2\pi)^4\,\delta^4\left(p_a - \sum_{i=1}^{n} p_i\right) \times (2\pi)\,\delta(p_i^2 - m^2) \tag{2.88}$$

The product:

$$\prod_{i=1}^{N} \frac{d^3\mathbf{p}_i}{(2\pi)^3 2E_i} = \prod_{i=1}^{N} \frac{d^4 p_i}{(2\pi)^4}\,(2\pi)\,\delta(p_i^2 - m^2) \tag{2.89}$$

is called the **Lorentz invariant phase-space** and is the relativistic version of $\rho(E)$ in eqn 2.73.

- **We introduce the Dirac equation in chap.5 together with P and C symmetries.** From Chap.5 on, we provide an intuitive explanation of the concept and we deepen each of it using the Dirac equation (*)

(*) The book is self-consistent even if the teacher wants to postpone the Dirac equation to advanced courses.

General strategy

- Introduce the concept (e.g. parity violation – Chap.5) using symmetries, the covariant formalism and non relativistic quantum mechanics
- Provide a solid experimental ground about the concept (e.g. discovery of parity violation in 60Co – Chap.10)
- Exploit the Dirac equation and classical relativistic field theory to provide a rigorous derivation of the concept (e.g. from parity violation to the V-A theory, Chap.10)
- Present the corresponding Standard Model interpretation through classical field (e.g. P violation in the electroweak theory - Chap.12)
- Postpone the full QFT treatment to more advanced course giving a glimpse in the final chapter

We used this strategy for the most important ideas/achievements in particle and nuclear physics integrating the experimental finding with the theory explanation (*)

(*) I was astonished to see that it works very week! When I realized it (AY2019-20) I decided to publish the book ☺.

An example: antimatter

The discovery of the positron naturally arises from the study of particle interaction in matter

Introducing antimatter from Anderson experiment instead of Dirac equation turned out to be very effective

Another example: from theory (QCD) to experiments

It would be great to take a movie of student reactions when I explain 7.6 (quarks, colors, gluons…)

And the eagerness to hear the lecture on “Do quark exist?”

Nuclear physics as an emergent phenomenon

Nuclear physics is introduced in a very unconventional way:

- Perturbative QCD provides the UV regime of strong interaction
- Non-perturbative QCD is a (nearly) intractable regime dealt with:
  - Numerical methods (lattice QCD)
  - Approximate symmetries (flavor symmetries in the quark model
- Nuclear physics is the regime where no flavors but u and d can be produced (F=2, $SU(2)_F$ symmetry)
- The treatment of nuclear bound states (decays, reactions, etc.) is thus handled by
  - Classification of isobaric states in analogy with quark model
  - Semi-empirical models: from QCD-inspired (isomultiplets, shell model) to semiclassical (Fermi gas, liquid drop, SME formula) models

We cannot introduce lattice QCD but we can still present the nuclear model in a modern perspective

Preserve the uniqueness of Nuclear Physics

Nuclear physics is not a "corollary" of QCD and QCD has limited predictive power here (yet). But:

- The student can appreciate that QCD and color symmetry is the fundamental theory of Nuclear physics
- They become aware that lattice QCD is a candidate nuclear physics tool like the isospin symmetry. **In my book, they have the same status (approximate methods)!**
- We use the Standard Model to introduce radioactive decays instead of re-explaining them in later chapters
- Astroparticle physics appears in Chap.11 as a natural follow up of particle and nuclear physics

There is no shame in using approximate methods in nuclear physics because **this is the real state-of-the-art, and not a student-friendly simplification**.

A bridge toward graduate courses

The book can be used in Master courses selecting Chap.4-13 and removing the chapters on nuclear physics, if needed.

Pros:

- It contains what needed for an introductory course in particle physics at master level, including the electroweak theory (Chap.12), the Higgs mechanism (Chap.13), lepton and quark mixing ("the Yukawa sector")
- It promotes a critical attitude toward the limitation of the Standard Model, the interface with Cosmology and the physics of gravitation

But (cons)

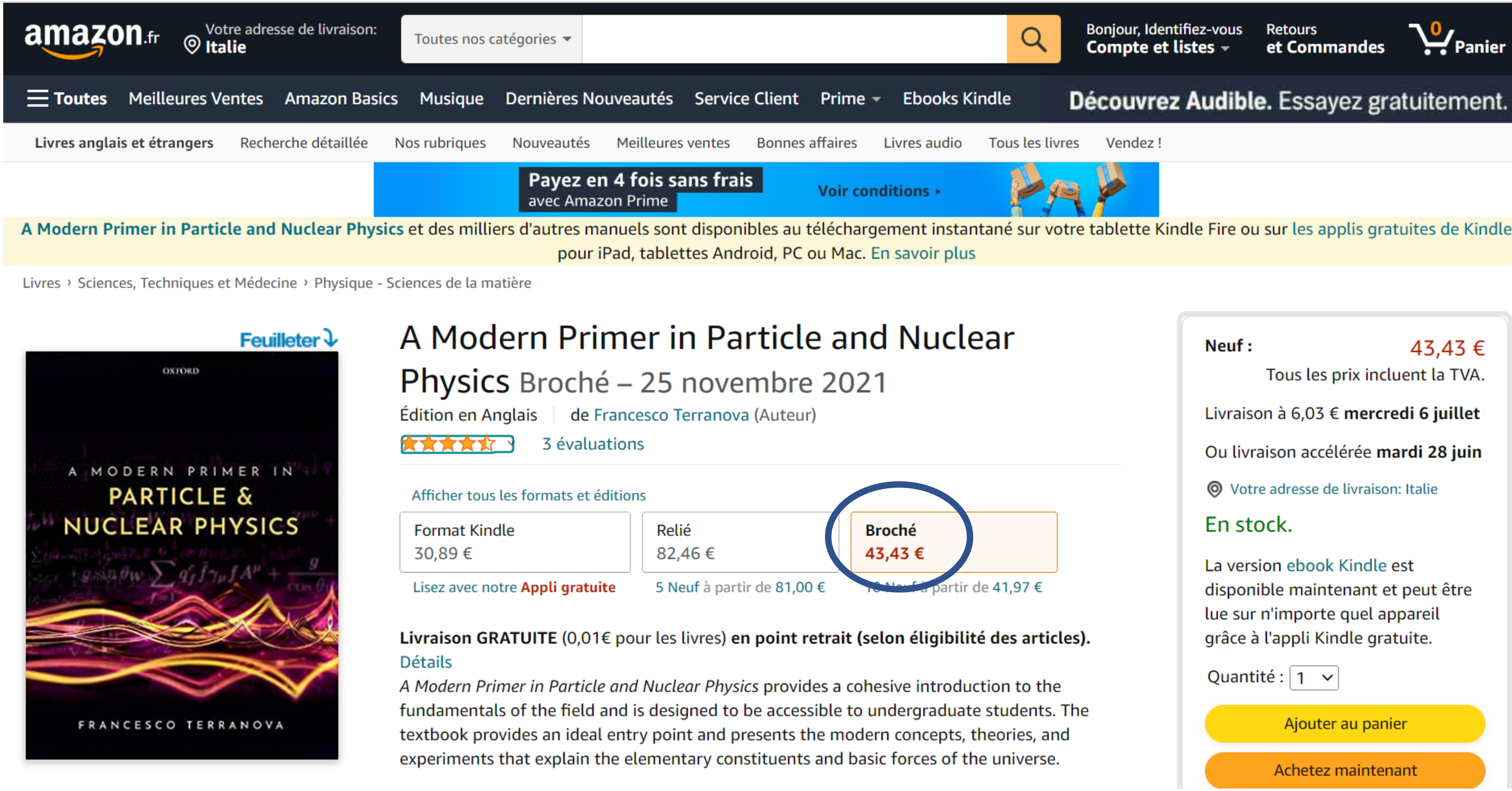
- It does not provide students the tools to compute cross sections and decay rates (computation of Feynman diagrams)
- It does not cover advanced topics in nuclear physics and astrophysics

It could have been done at the expenses of an increase of size and cost. Your feedback are needed to assess the relevance of these drawbacks

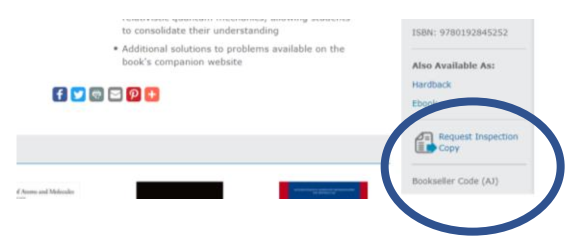
The companion website

A companion website is now available and contains **errata** and **solutions to selected problems** (30% now, 70% by sep 2022, 100% in 2023)

Is it expensive?



Request **an inspection copy**: go to the OUP website and select "paperback" (https://global.oup.com/academic/product/a-modern-primer-in-particle-and-nuclear-physics-9780192845252



Backup

How to use this book

It is hopeless to cover all material in one semester and, to my knowledge, there are no two-semester courses of this kind.

Use this material to cook your course according to your wishes and needs

Example I "junior level course":

A one semester course at third year ("junior level"), after a course on quantum mechanics. This is the standard in **Italy, Spain, and Germany**. It is common in **France, Switzerland**, **India** and **China**, too.

In depth: Chap. 2 (covariance, decay, cross sections), 3 (detection), 5 (symmetries), 9 (Nuclear physics), 10 (weak interactions) 11 (radioactivity)
Pick your favorite items: Chap. 4 (accelerator and collider), 6 (gauge principle and QED), 7 (strong interaction), 8 (Quark model)
Give a flavor of: Chap 12 (electroweak theory) Chap 13(whatever you like. I usually take neutrinos)

How to use this book

Example II ("sophomore/junior level course"):

A one semester course at second or third year ("sophomore or junior level"), in parallel with quantum mechanics. This is a common occurrence in **US** and **UK**.

In depth: Chap.1, Appendix 1 and 2 (*), Chap. 2 (covariance, decay, cross sections), 3 (detection), 5 (symmetries), 9 (Nuclear physics), 10 (weak interactions) 11 (radioactivity)
Pick your favorite items: Chap. 4 (accelerator and collider), 6 (gauge principle and QED), 7 (strong interaction), 8 (Quark model)

(*) They summarize what is needed of Special Relativity and non-relativistic Quantum Mechanics. Please use it only if they are really needed: it is likely that your students are studying these subject in parallel with your course

How to use this book

Example III (“Master’s level course”):

A one semester course at fourth year (“Master’s level course”), in parallel with quantum field theory. It is **an introductory course on Particle Physics**.

In depth: Chap. 2 (covariance, decay, cross sections), 3 (detection), 5 (symmetries), 6 (gauge principle and QED), 7 (strong interaction), 10 (Weak interactions)

Pick your favorite items: Chap. 4 (accelerator and collider), 8 (Quark model), 12 (electroweak), 13 (frontier of Standard Model)

This is the rational of having a 450 pages book: it fits the need of a large audience and can be used by students both in Bachelor and Master courses [we are going to do this in Milano Bicocca]