Scattering Theory & QCD Spectroscopy
Lecture 1 - Introduction

Andrew W. Jackura

William & Mary

Department of Physics

2024 Hampton University Graduate Studies (HUGS) Program

June 10th, 2024

Jefferson Lab

U.S. DEPARTMENT OF ENERGY

EXOHAD
EXOTIC HADRONS TOPICAL COLLABORATION

awjackura@wm.edu
ajackura.github.io

WILLIAM & MARY
CHARTERED 1693

About Me

Andrew Jackura

- Assistant Professor, William & Mary, 2023 - present
- Postdoctoral Research Scholar, UC Berkeley, 2023
- Postdoctoral Research Fellow, Old Dominion University, 2019 - 2023
- Ph.D., Indiana University, 2019

Research Interests

- Theoretical Hadron Spectroscopy
- Multi-particle reaction theory
- Finite-volume QFT
- Lattice QCD

$\Longrightarrow$ *Three-body reactions and resonances*
Electroweak matrix elements of multi-hadron processes

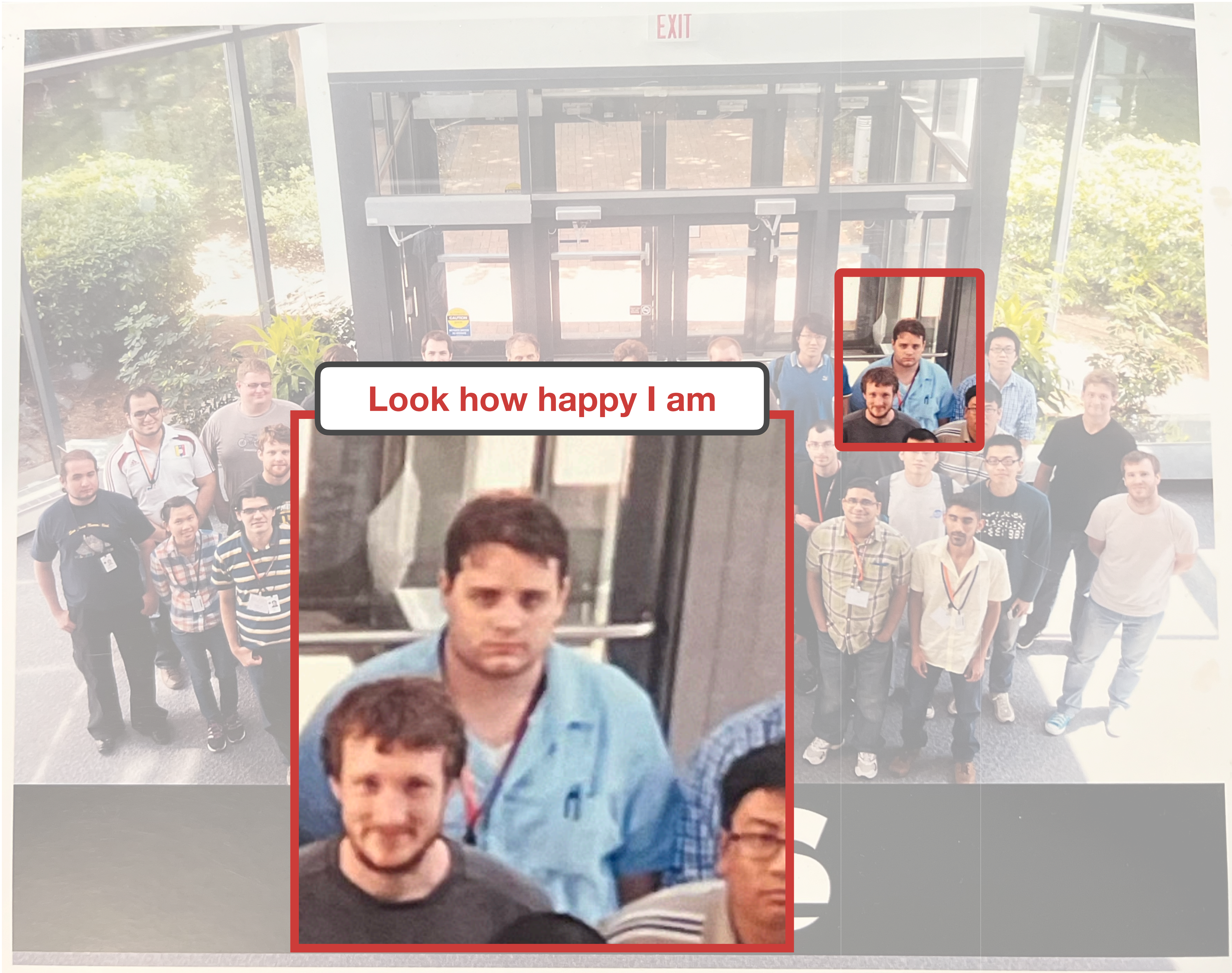
If you want to chat, contact me

awjackura@wm.edu

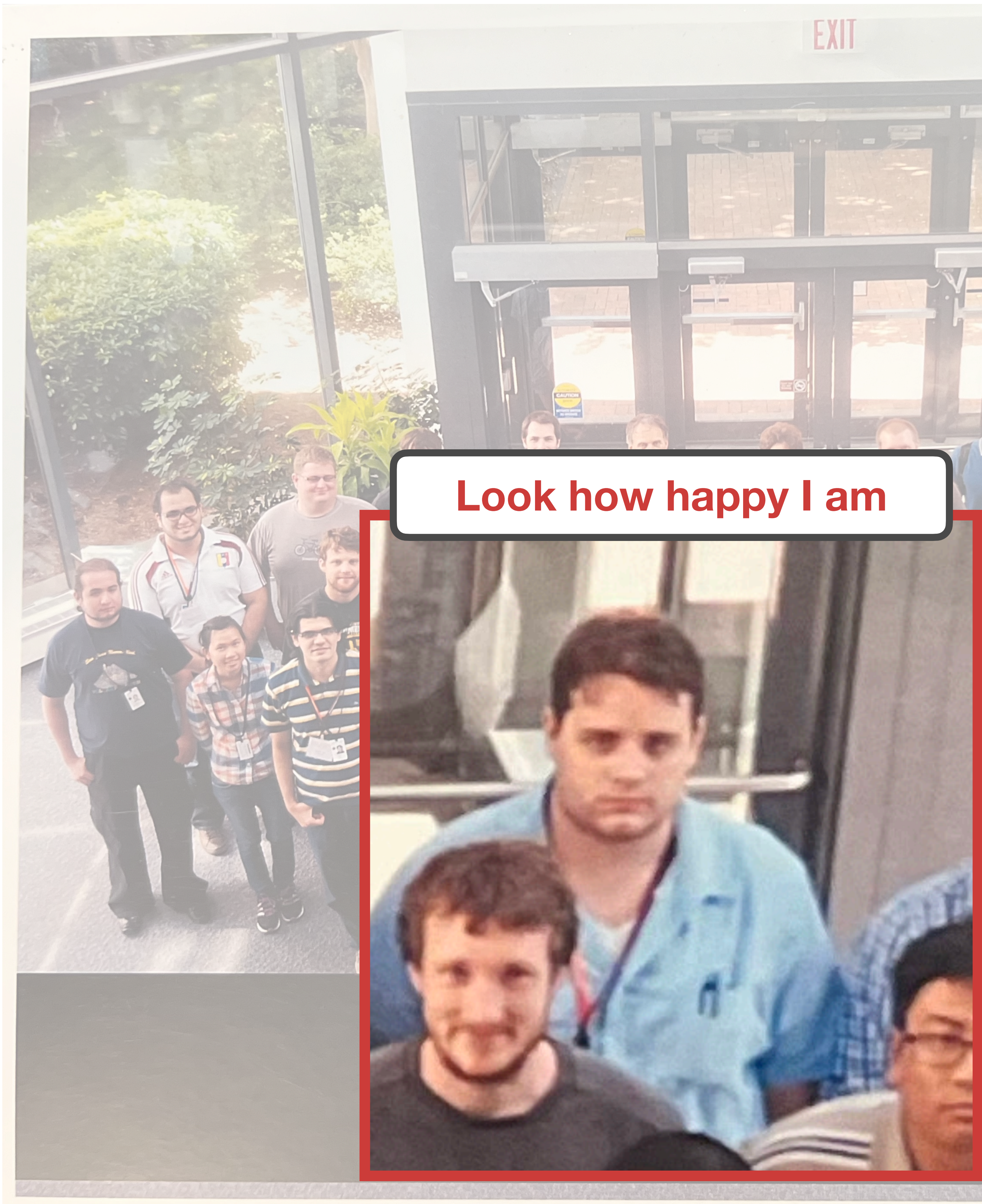
ajackura.github.io

About Me — 2014 HUGS Program

About Me — 2014 HUGS Program

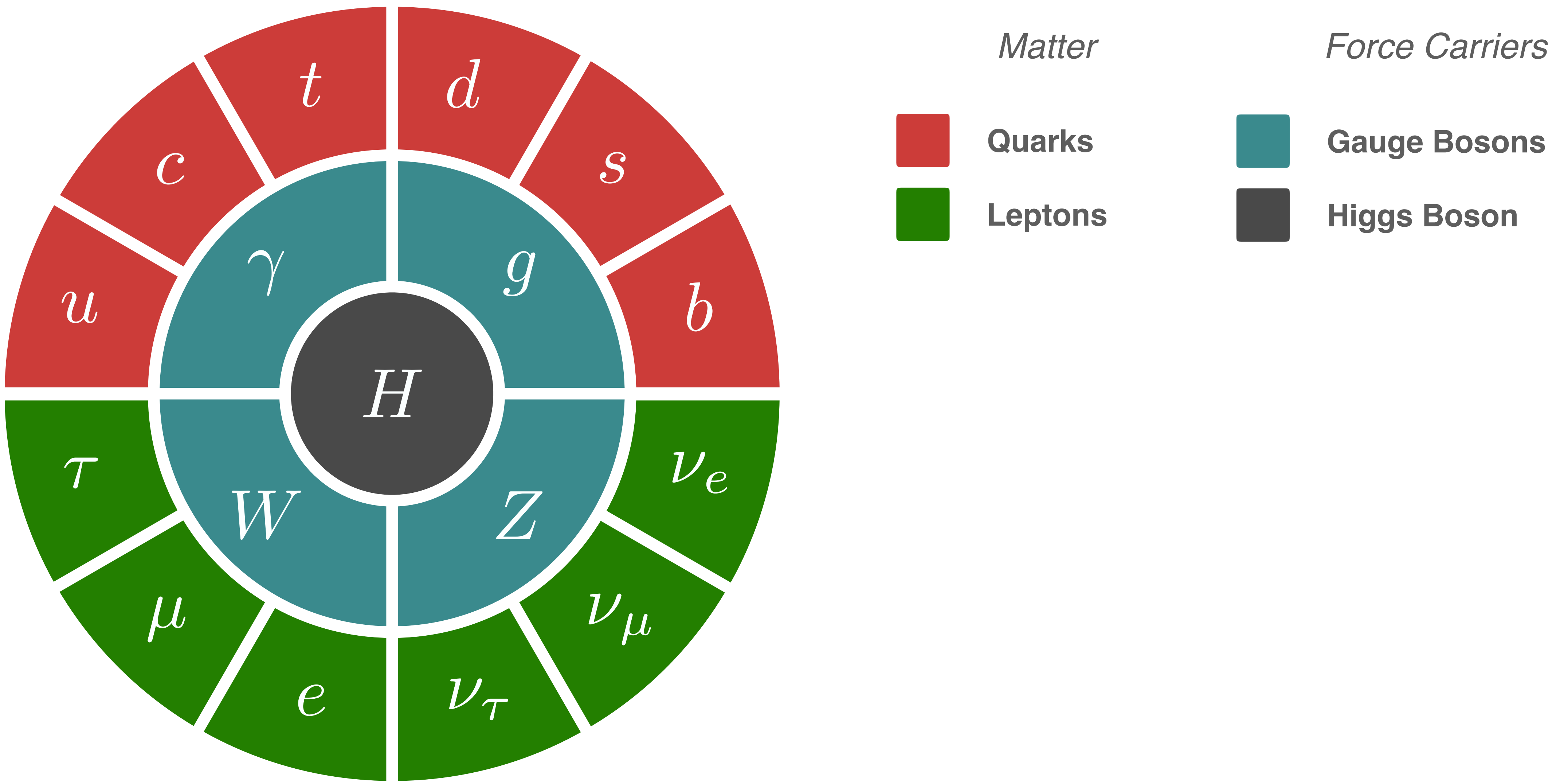


About Me — 2014 HUGS Program



The Standard Model of Particle Physics

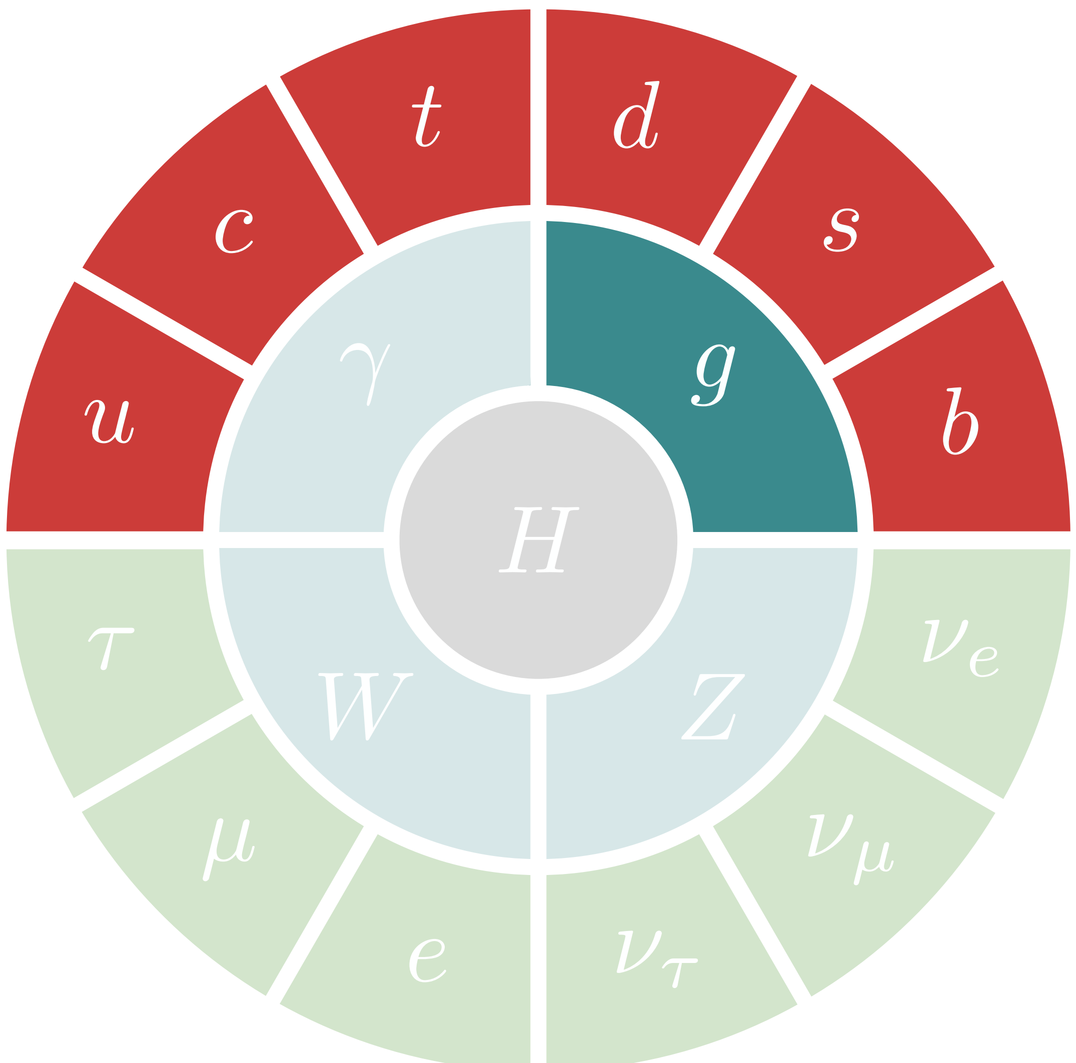
Nature can be described by a remarkably *simple** theory

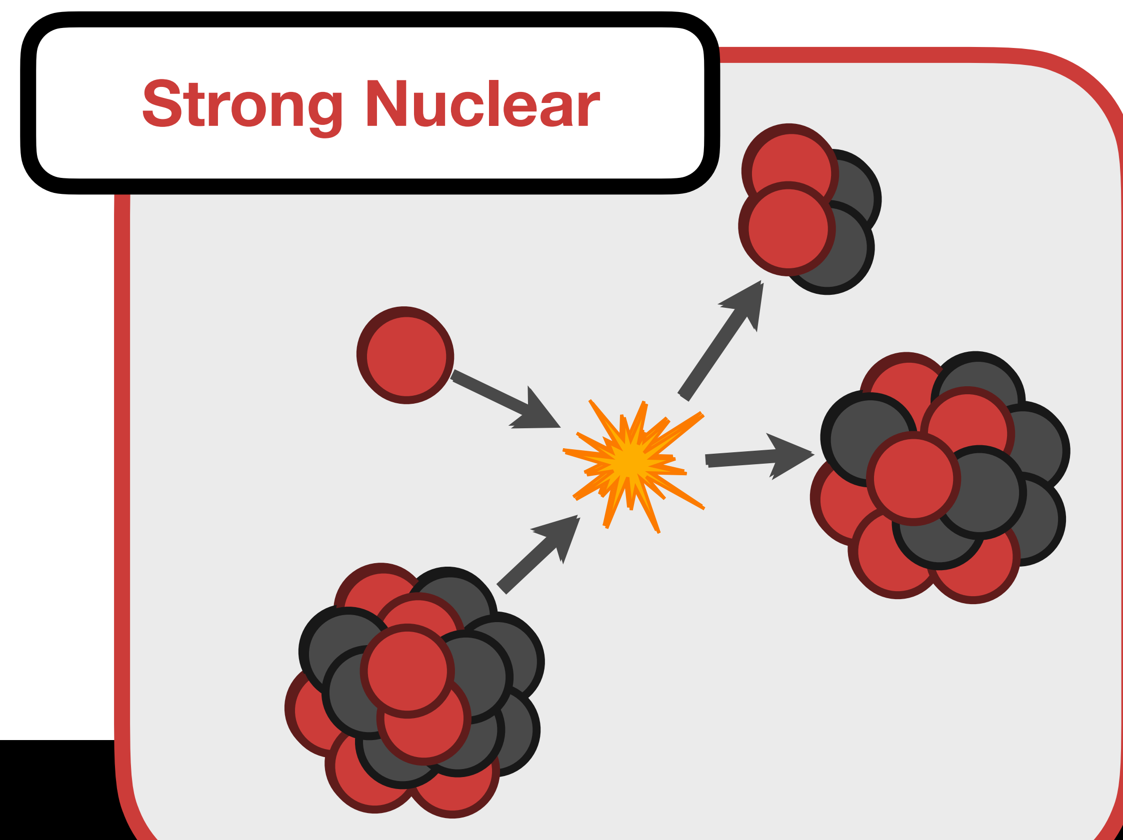


* *simple = An anomaly-free renormalizable relativistic quantum gauge field theory, invariant under the gauge group* $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ *which spontaneously breaks via a scalar field to* $SU(3)_C \otimes U(1)_Q$

The Standard Model of Particle Physics

Nature can be described by a remarkably *simple** theory



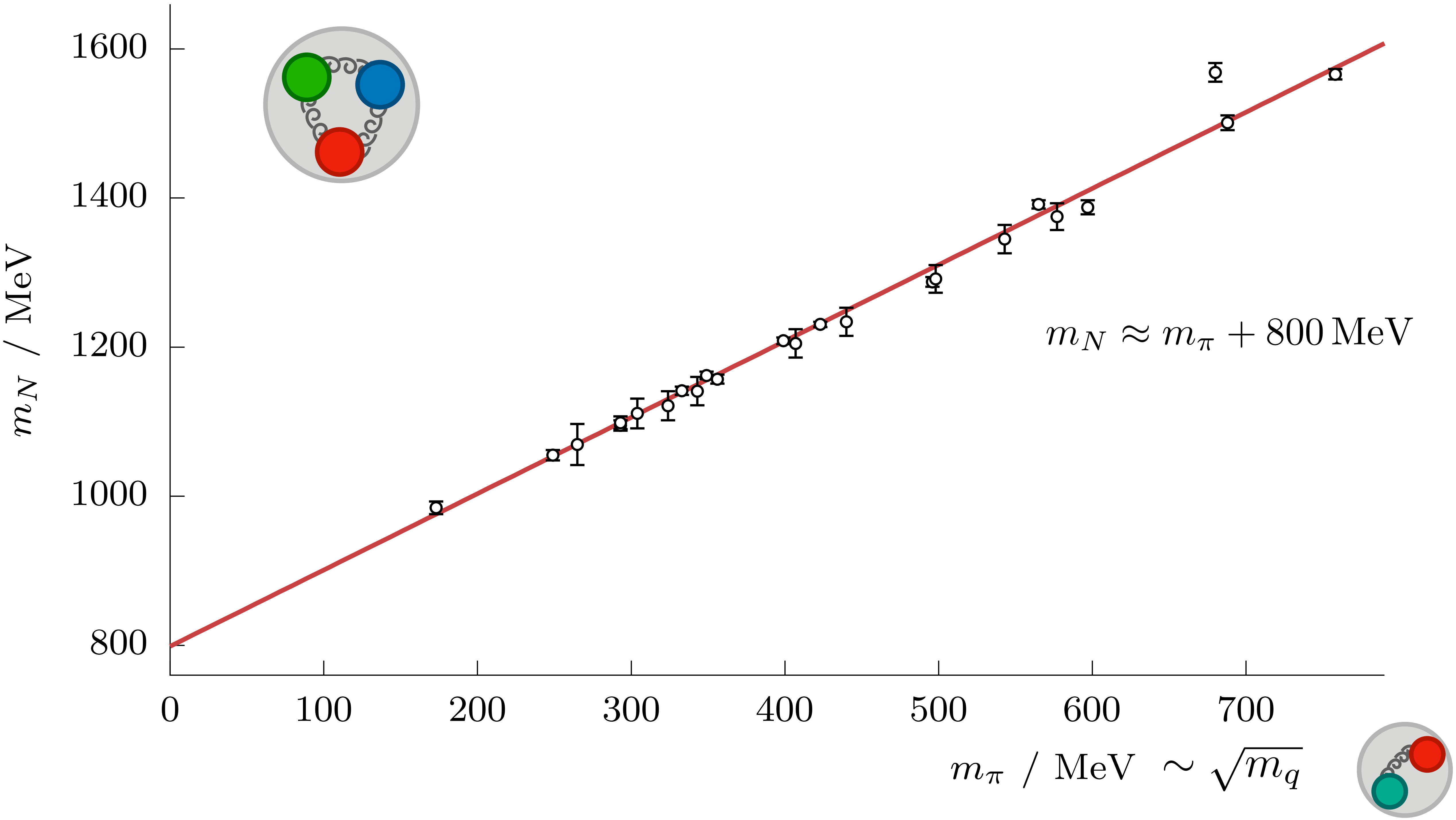


Quantum ChromoDynamics (QCD)

* *simple = An a*
invariant under the gauge group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
which spontaneously breaks via a scalar field to $SU(3)_C \otimes U(1)_Q$

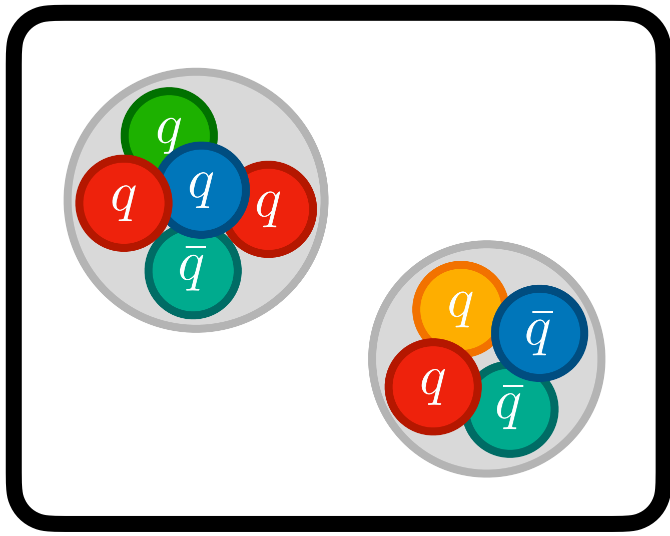
Nuclear Forces

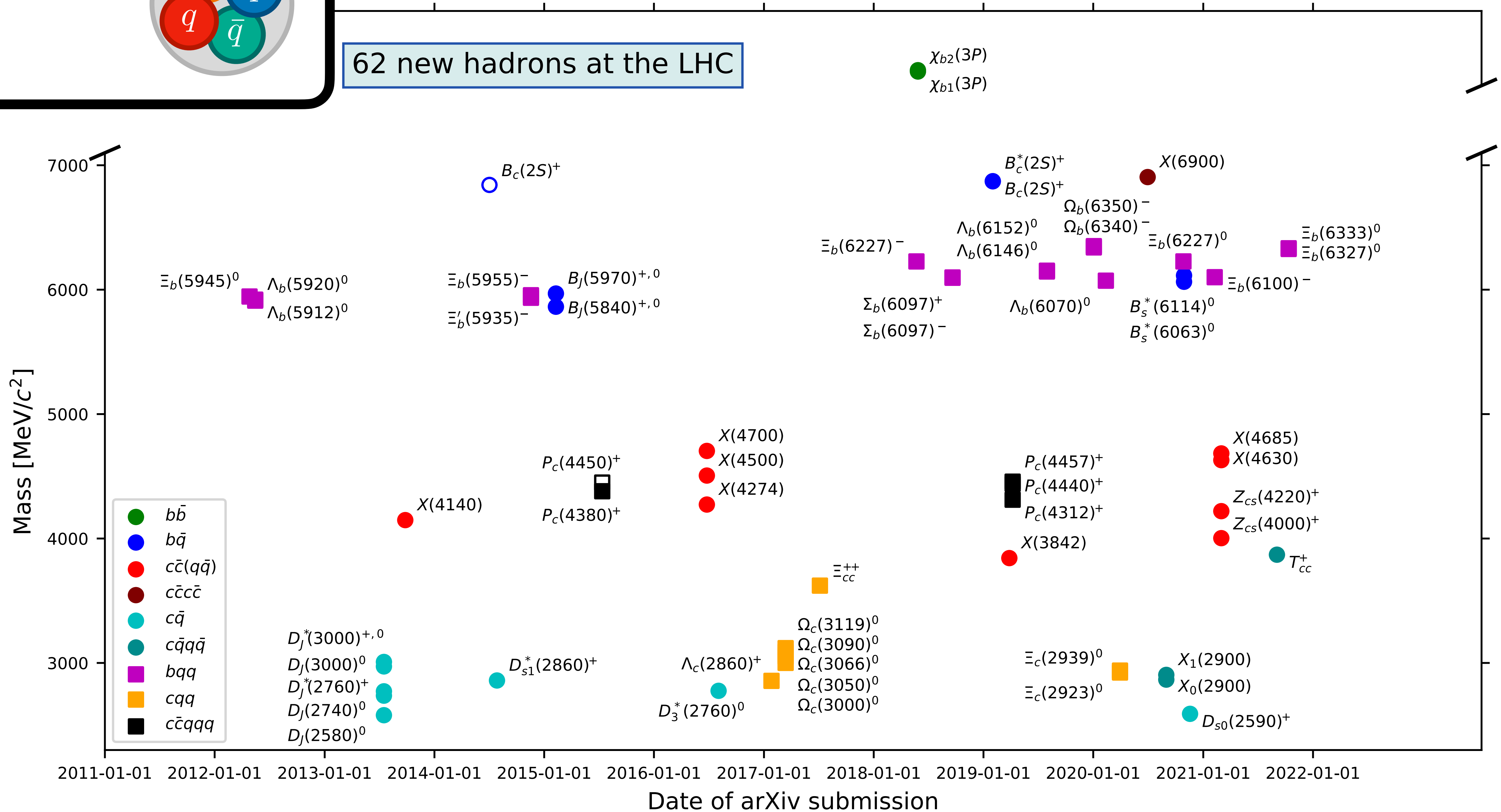
Most of our mass comes from nuclear forces!



New discoveries in Nuclear Physics

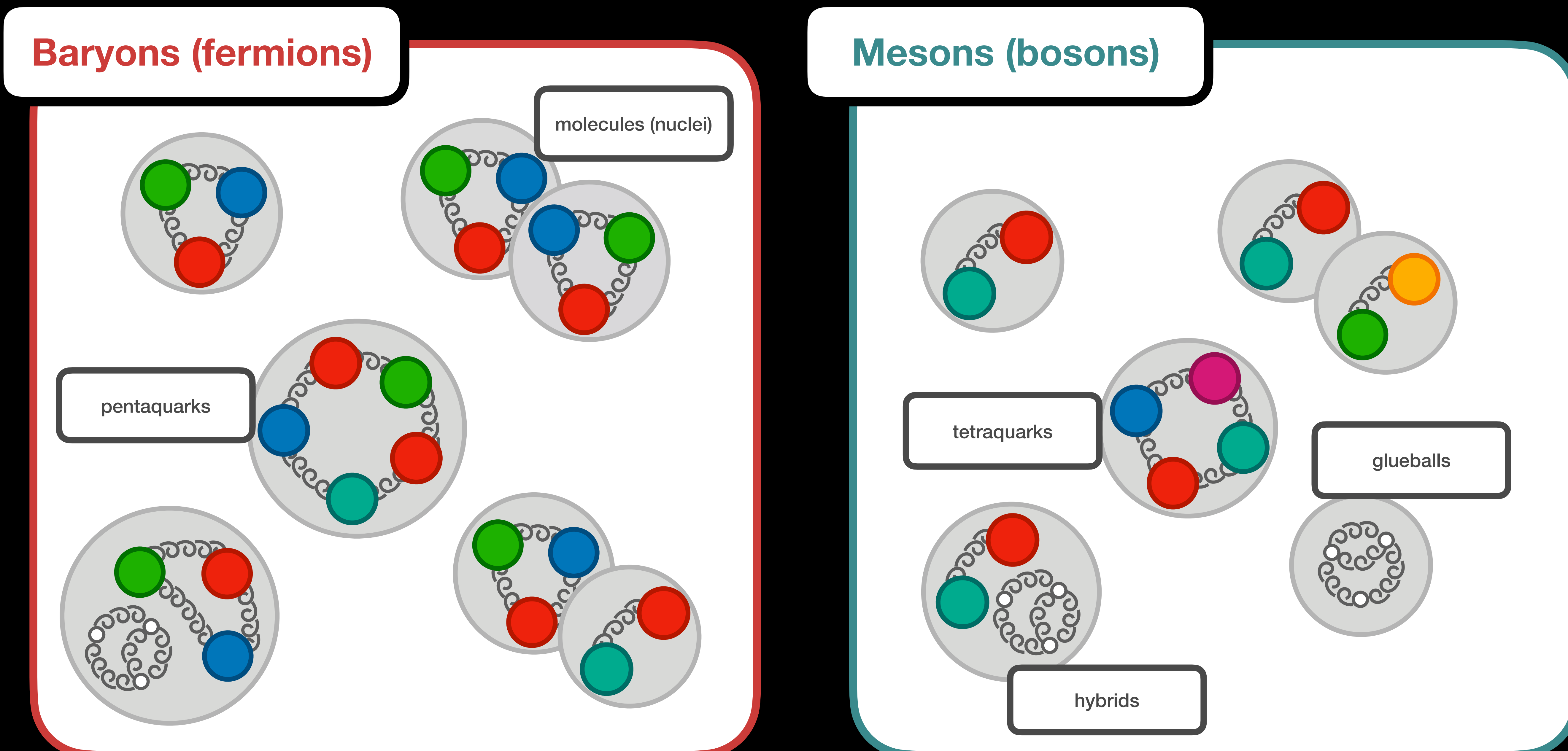
Zoo of ***exotic*** quark configurations discovered





Many types of nuclear particles

A zoo of particles — How to understand?



Observing Hadrons

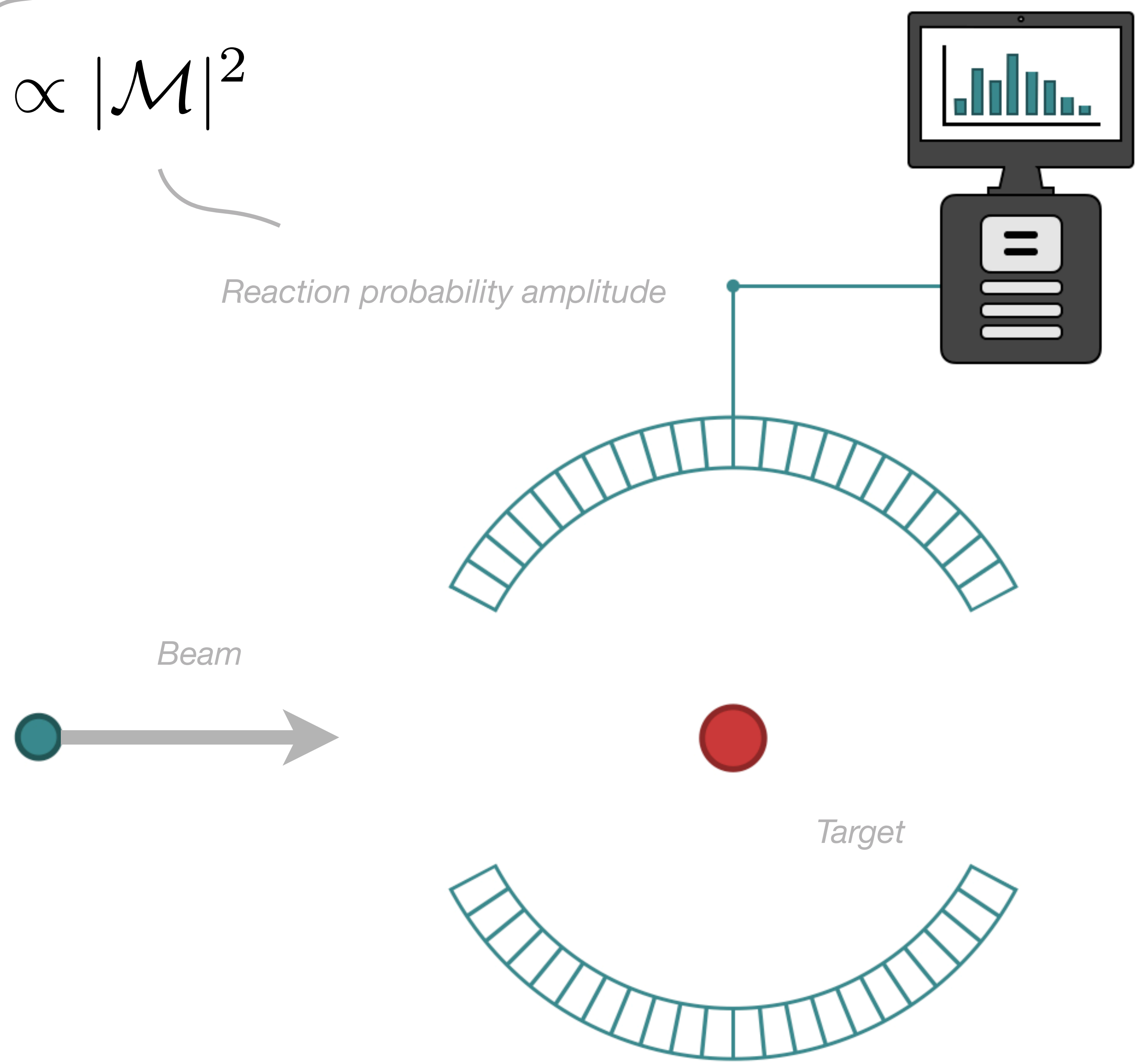
We observe strongly interacting hadrons through reactions in accelerators/colliders

Cross-section

$$N \propto \sigma \propto |\mathcal{M}|^2$$

Events experimentally measured

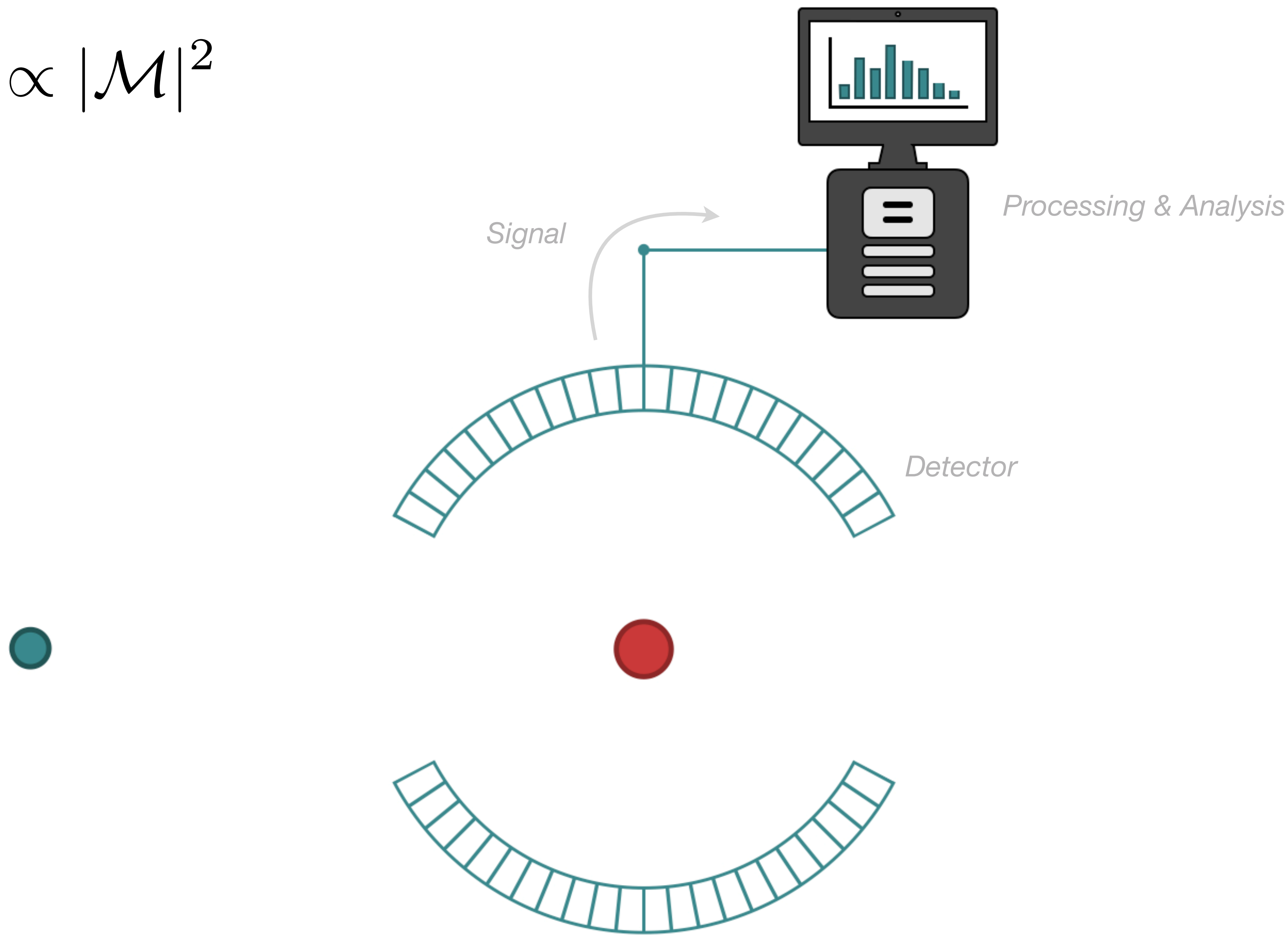
Reaction probability amplitude



Observing Hadrons

We observe strongly interacting hadrons through reactions in accelerators/colliders

$$N \propto \sigma \propto |\mathcal{M}|^2$$



Observing Hadrons

We observe strongly interacting hadrons through reactions in accelerators/colliders

- If the interaction is sufficiently attractive, particles can form a ***resonance***

Observing Hadrons

We observe strongly interacting hadrons through reactions in accelerators/colliders

- If the interaction is sufficiently attractive, particles can form a ***resonance***

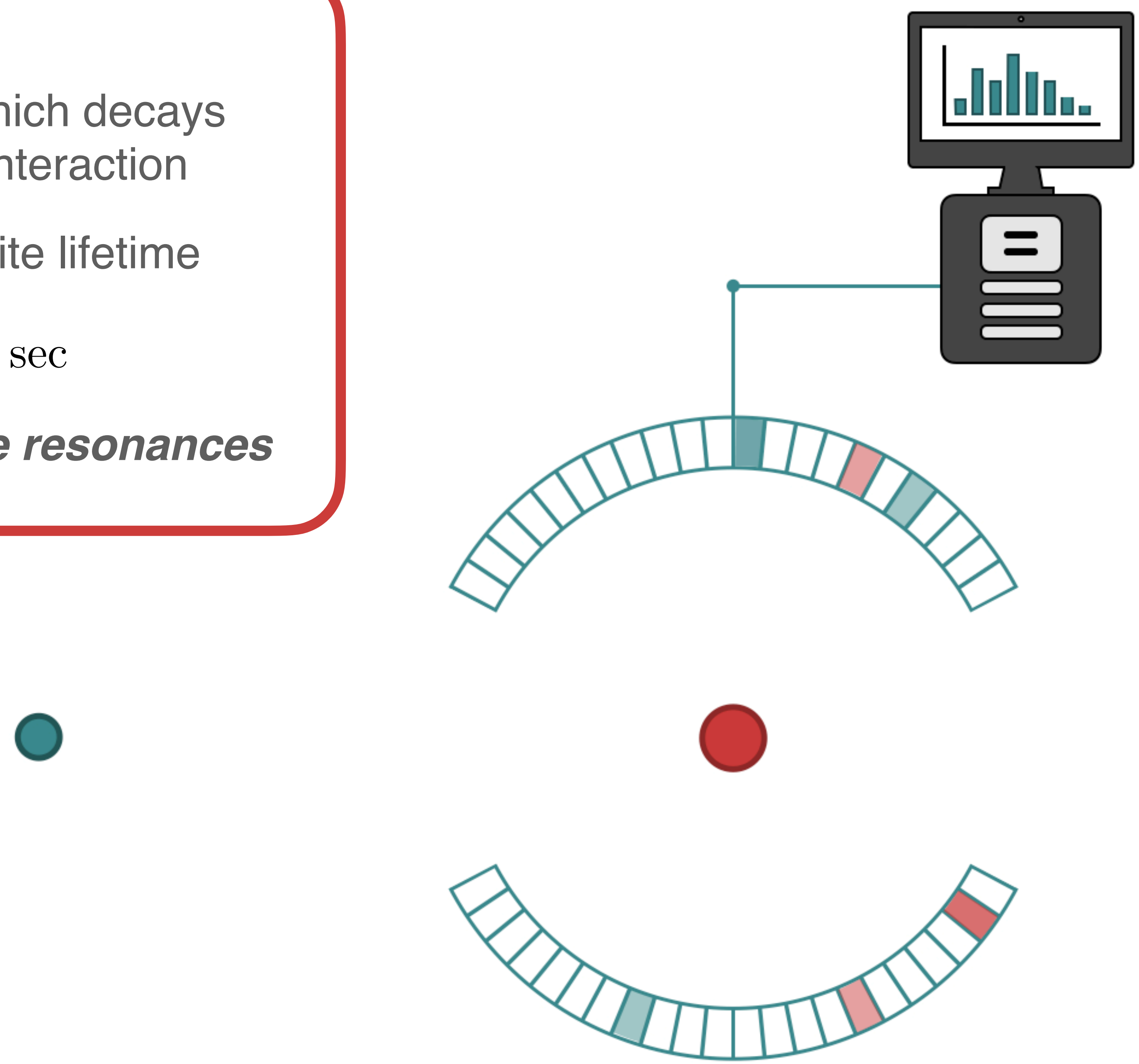
Resonance

Unstable hadron which decays via strong nuclear interaction

Has a mass *and* finite lifetime

$$\tau \sim 10^{-23}\,\mathrm{sec}$$

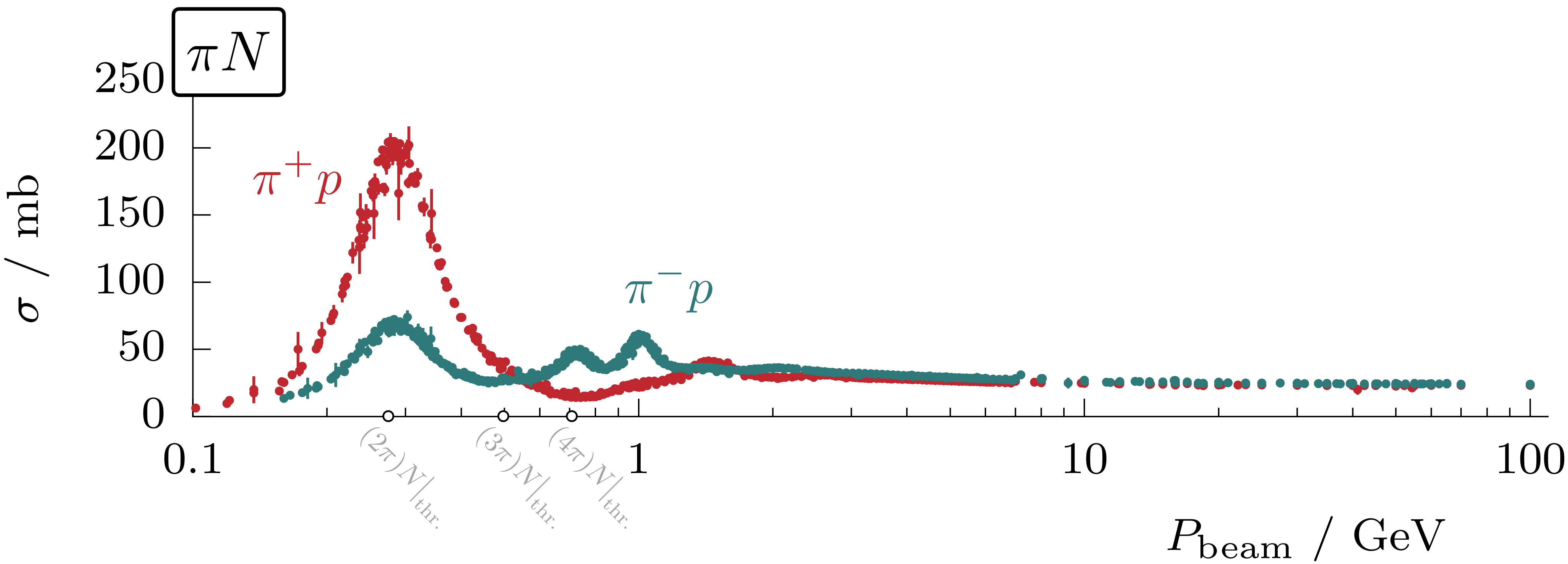
Most hadrons are resonances



Observing Hadrons

We observe strongly interacting hadrons through reactions in accelerators/colliders

- If the interaction is sufficiently attractive, particles can form a ***resonance***
- Resonances can appear as enhancements in the cross-section / amplitude

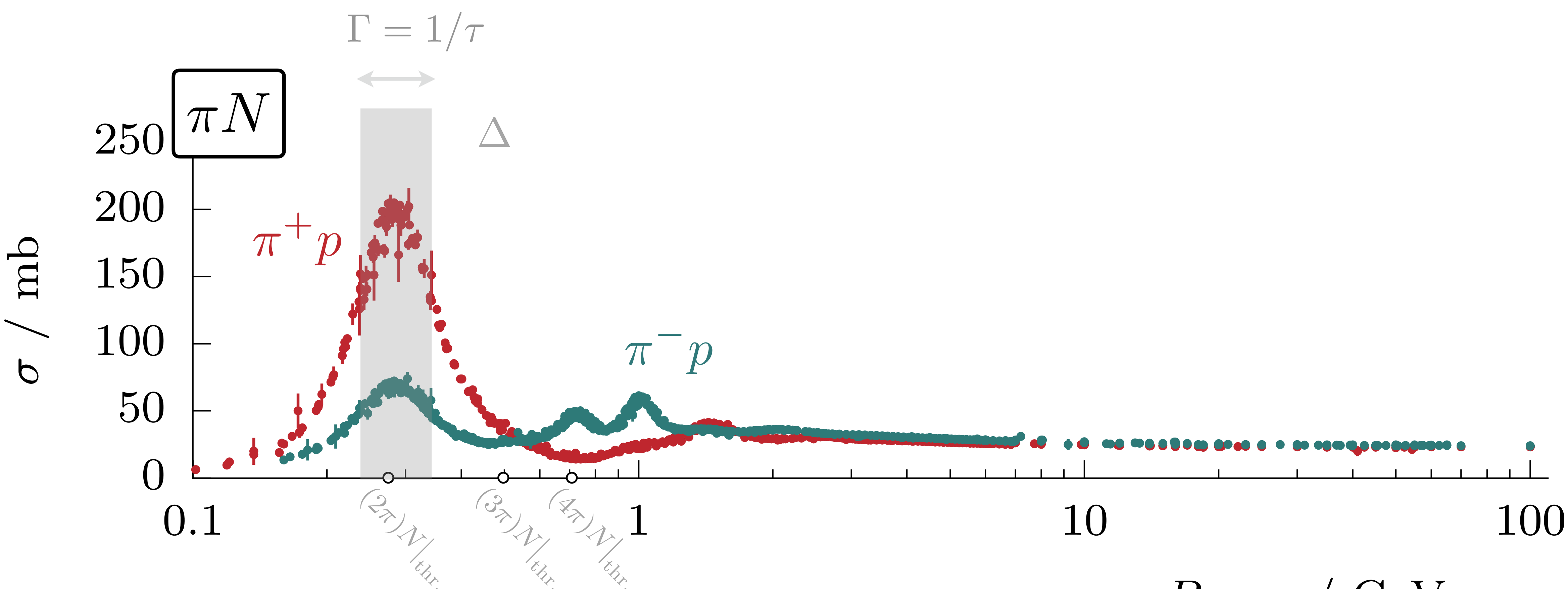


Particle Data Group (PDG)
The Review of Particle Physics (RPP)

Observing Hadrons

We observe strongly interacting hadrons through reactions in accelerators/colliders

- If the interaction is sufficiently attractive, particles can form a ***resonance***
- Resonances can appear as enhancements in the cross-section / amplitude

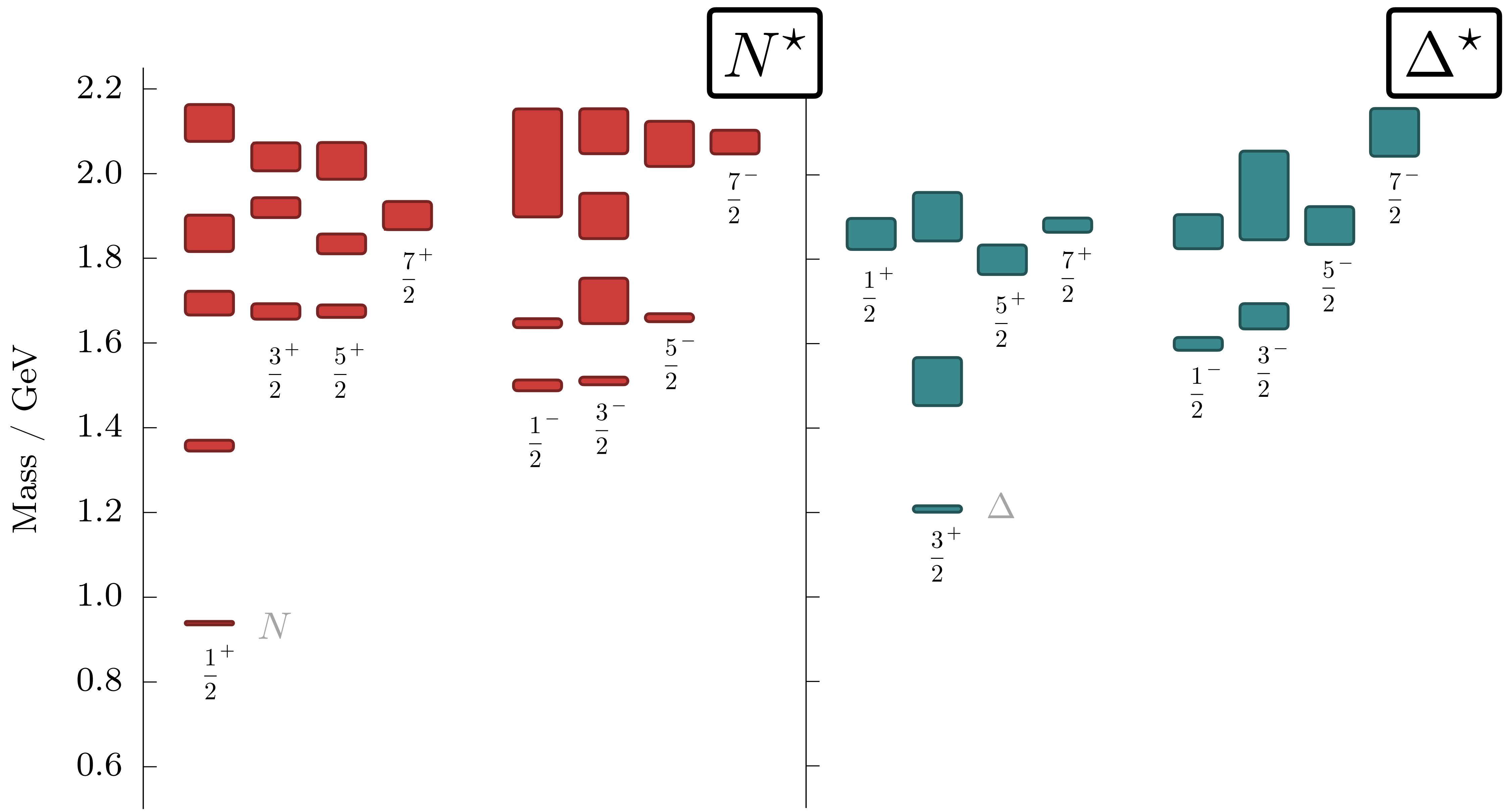


Particle Data Group (PDG)
The Review of Particle Physics (RPP)

Observing Hadrons

We observe strongly interacting hadrons through reactions in accelerators/colliders

- If the interaction is sufficiently attractive, particles can form a ***resonance***
- Resonances can appear as enhancements in the cross-section / amplitude

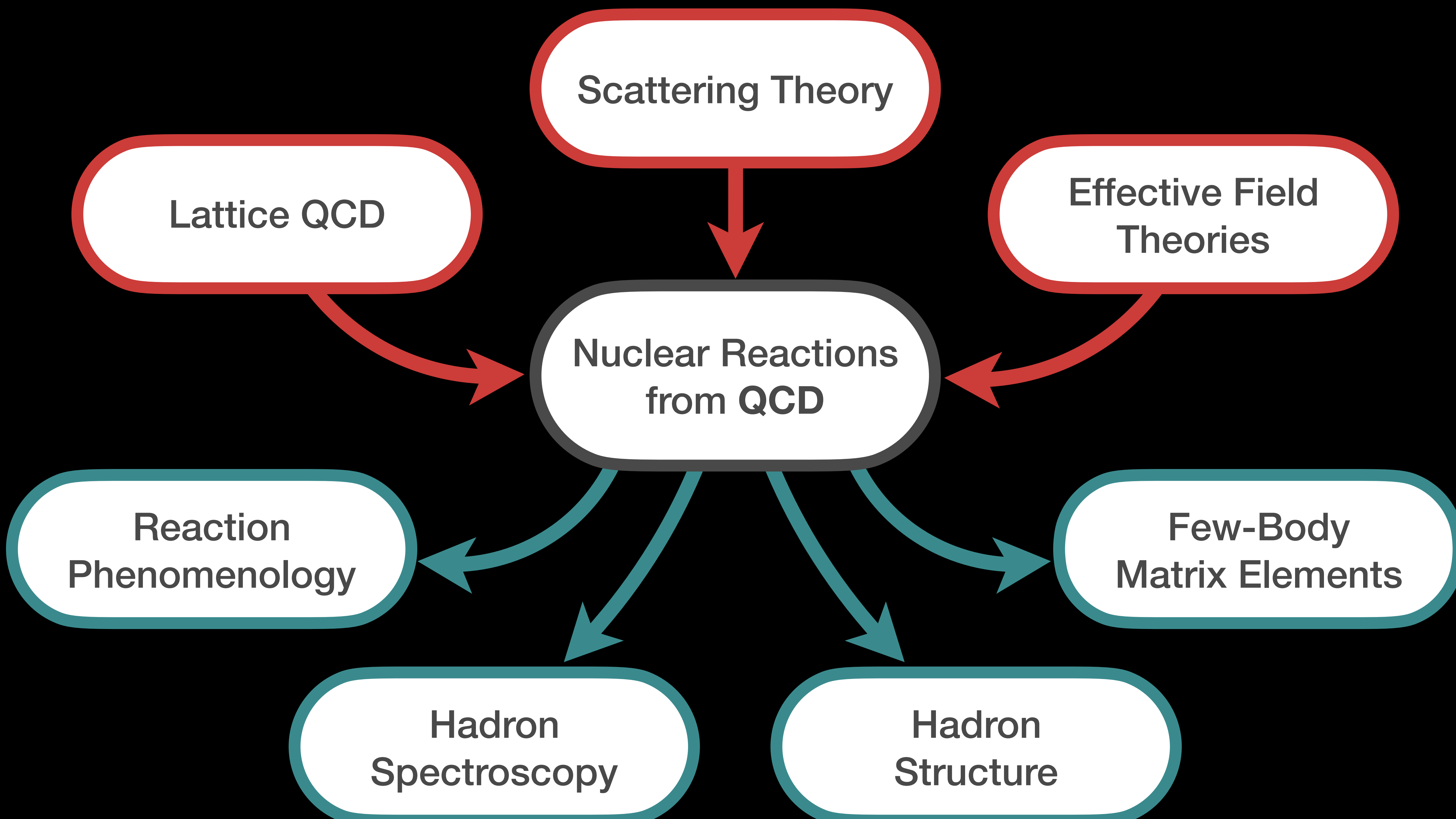


Particle Data Group (PDG)
The Review of Particle Physics (RPP)

Modern Nuclear Physics

Connect low-energy hadron & nuclear physics to **QCD**

- Quantitatively describe few-body reactions and their impact on observables



Outline

I. Scattering Theory

- Amplitudes and the *S* matrix
- Partial Wave Analysis
- Resonances & Bound States

II. Connecting QCD to Scattering Amplitudes

- Overview of Lattice QCD
- Correlators and Finite-Volume Spectra
- Lüscher Quantization Condition

I will assume you have had *some* exposure to…

particle physics (e.g., you know what a quark is)

quantum field theory (e.g., you know what a Feynman diagram is)

complex analysis (e.g., you know what a contour integral is)

$N = 4$ supersymmetric Yang-Mills Theory

Outline

I. Scattering Theory

- Amplitudes and the *S* matrix
- Partial Wave Analysis
- Resonances & Bound States

II. Connecting QCD to Scattering Amplitudes

- Overview of Lattice QCD
- Correlators and Finite-Volume Spectra
- Lüscher Quantization Condition

I will assume you have had *some* exposure to…

particle physics (e.g., you know what a quark is)

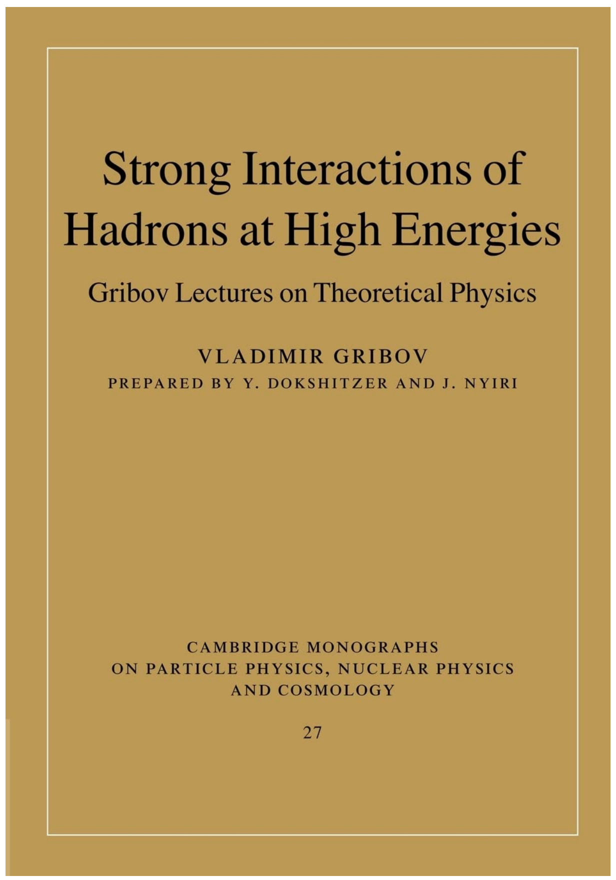
quantum field theory (e.g., you know what a Feynman diagram is)

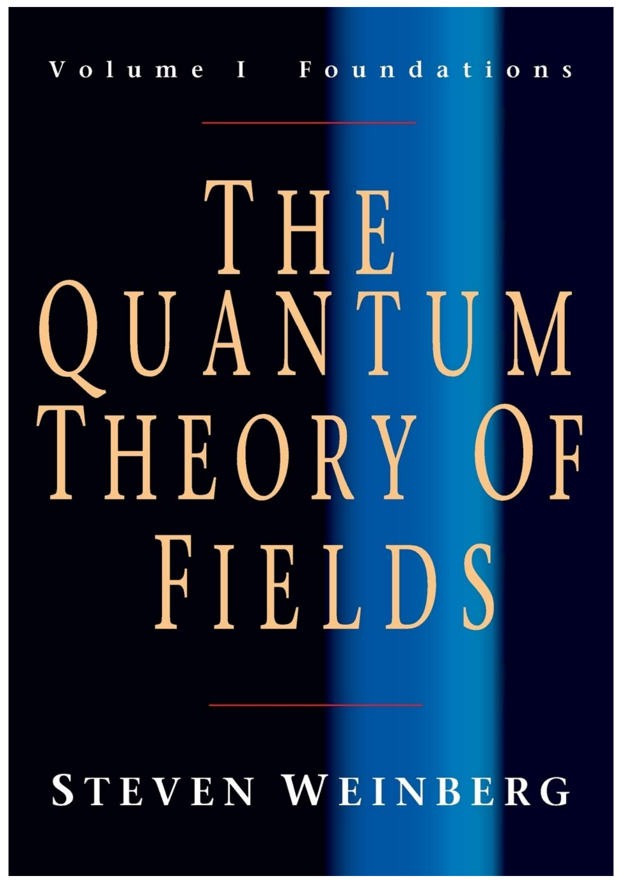
complex analysis (e.g., you know what a contour integral is)

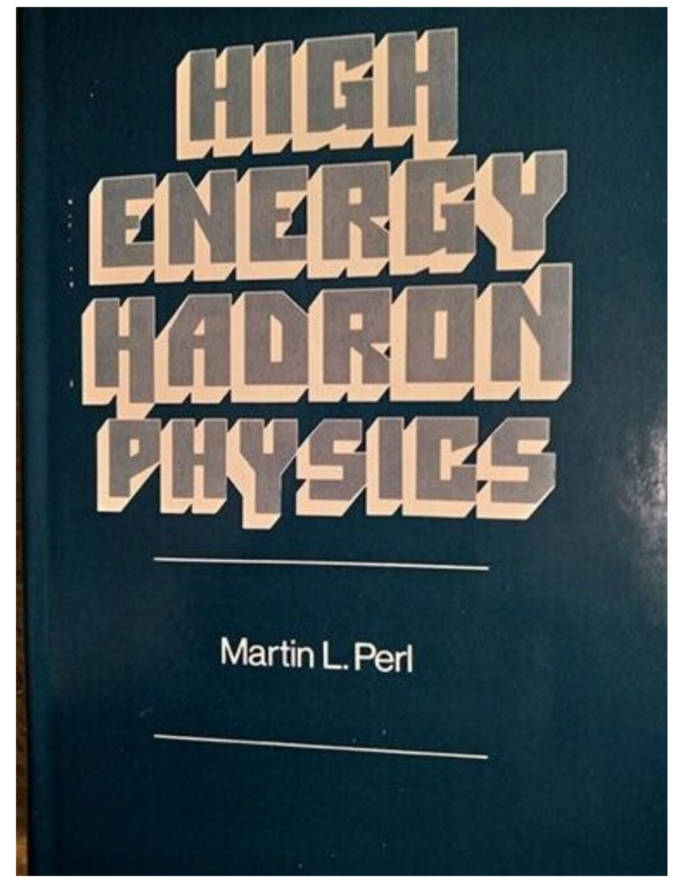
~~$N = 4$ supersymmetric Yang-Mills Theory~~

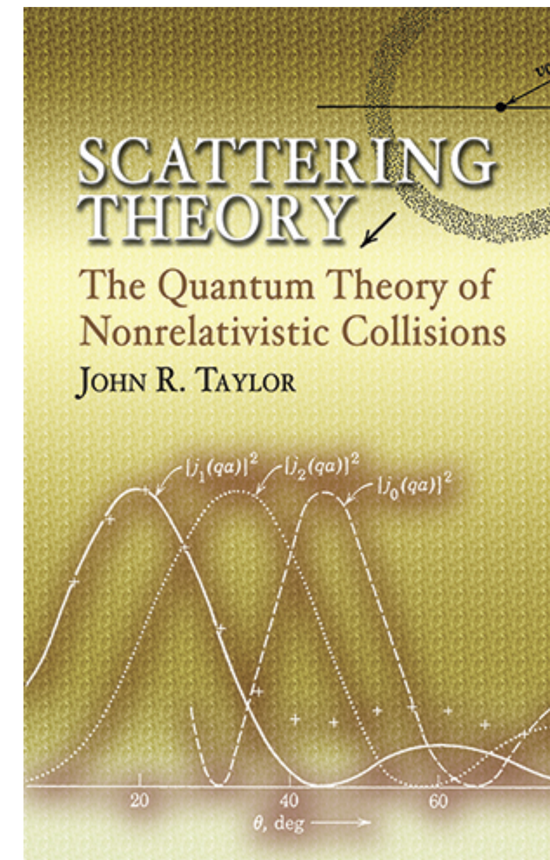
Some References (that I like)

Also see JPAC summer schools   http://jpac.nucleares.unam.mx/schools.html









Some References (that I like)

arXiv:1706.06223 (2017)

Scattering processes and resonances from lattice QCD

Raúl A. Briceño,[1,*] Jozef J. Dudek,[1,2,†] and Ross D. Young[3,‡]

[1] *Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, Newport News, Virginia 23606, USA*

[2] *Department of Physics, College of William and Mary, Williamsburg, Virginia 23187, USA*

[3] *Special Research Center for the Subatomic Structure of Matter (CSSM), Department of Physics, University of Adelaide, Adelaide 5005, Australia*

(Dated: June 21, 2017)

The vast majority of hadrons observed in nature are not stable under the strong interaction, rather they are *resonances* whose existence is deduced from enhancements in the energy dependence of scattering amplitudes. The study of hadron resonances offers a window into the workings of quantum chromodynamics (QCD) in the low-energy non-perturbative region, and in addition, many probes of the limits of the electroweak sector of the Standard Model consider processes which feature hadron resonances. From a theoretical standpoint, this is a challenging field: the same dynamics that binds quarks and gluons into hadron resonances also controls their decay into lighter hadrons, so a complete approach to QCD is required. Presently, lattice QCD is the only available tool that provides the required non-perturbative evaluation of hadron observables. In this article, we review progress in the study of few-hadron reactions in which resonances and bound-states appear using lattice QCD techniques. We describe the leading approach which takes advantage of the periodic finite spatial volume used in lattice QCD calculations to extract scattering amplitudes from the discrete spectrum of QCD eigenstates in a box. We explain how from explicit lattice QCD calculations, one can rigorously garner information about a variety of resonance properties, including their masses, widths, decay couplings, and form factors. The challenges which currently limit the field are discussed along with the steps being taken to resolve them.

CONTENTS

Some References (that I like)

arXiv:1706.06223 (2017)

Scattering processes and resonances from lattice QCD

Raúl A. Briceño,[1,*] Jozef J. Dudek,[1,2,†] and Ross D. Young[3,‡]

[1] *Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, Newport News, Virginia 23606, USA*

[2] *Department of Physics, College of William and Mary, Williamsburg, Virginia 23187, USA*

[3] *Special Research Center for the Subatomic Structure of Matter (CSSM), Department of Physics, University of Adelaide, Adelaide 5005, Australia*

(Dated: June 21, 2017)

The vast majority of hadrons observed in nature a
action, rather they are *resonances* whose existenc
the energy dependence of scattering amplitudes.
fers a window into the workings of quantum chrom
non-perturbative region, and in addition, many pr
sector of the Standard Model consider processes wh
a theoretical standpoint, this is a challenging field:
and gluons into hadron resonances also controls t
complete approach to QCD is required. Presently,
that provides the required non-perturbative evalu
article, we review progress in the study of few-hadr
bound-states appear using lattice QCD technique
which takes advantage of the periodic finite spatial
tions to extract scattering amplitudes from the disc
a box. We explain how from explicit lattice QCD
ner information about a variety of resonance prope
decay couplings, and form factors. The challenge
discussed along with the steps being taken to resol

CONTENTS

arXiv:2112.13436 (2021)

Novel approaches in Hadron Spectroscopy

Miguel Albaladejo[a,b], Łukasz Bibrzycki[c], Sebastian M. Dawid[d,e], César Fernández-Ramírez[f,g], Sergi Gonzàlez-Solís[d,e,h], Astrid N. Hiller Blin[a], Andrew W. Jackura[a,i], Vincent Mathieu[j,k], Mikhail Mikhasenko[l,m], Victor I. Mokeev[a], Emilie Passemar[a,d,e], Alessandro Pilloni[n,o,*], Arkaitz Rodas[a,p], Jorge A. Silva-Castro[f], Wyatt A. Smith[d], Adam P. Szczepaniak[a,d,e], Daniel Winney[d,e,q,r],

(Joint Physics Analysis Center)

[a] *Theory Center and Physics Division, Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA*
[b] *Instituto de Física Corpuscular (IFIC), Centro Mixto CSIC-Universidad de Valencia, E-46071 Valencia, Spain*
[c] *Pedagogical University of Krakow, 30-084 Kraków, Poland*
[d] *Department of Physics, Indiana University, Bloomington, IN 47405, USA*
[e] *Center for Exploration of Energy and Matter, Indiana University, Bloomington, IN 47403, USA*
[f] *Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Ciudad de México 04510, Mexico*
[g] *Departamento de Física Interdisciplinar, Universidad Nacional de Educación a Distancia (UNED), Madrid E-28040, Spain*
[h] *Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[i] *Department of Physics, Old Dominion University, Norfolk, VA 23529, USA*
[j] *Departament de Física Quàntica i Astrofísica and Institut de Ciències del Cosmos, Universitat de Barcelona, E-08028, Spain*
[k] *Departamento de Física Teórica, Universidad Complutense de Madrid and IPARCOS, E-28040 Madrid, Spain*
[l] *ORIGINS Excellence Cluster, 80939 Munich, Germany*
[m] *Ludwig-Maximilian University of Munich, Germany*
[n] *Dipartimento di Scienze Matematiche e Informatiche, Scienze Fisiche e Scienze della Terra, Università degli Studi di Messina, I-98122 Messina, Italy*
[o] *INFN Sezione di Catania, I-95123 Catania, Italy*
[p] *College of William & Mary, Williamsburg, VA 23187, USA*
[q] *Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter, South China Normal University, Guangzhou 510006, China*
[r] *Guangdong-Hong Kong Joint Laboratory of Quantum Matter, Southern Nuclear Science Computing Center, South China*