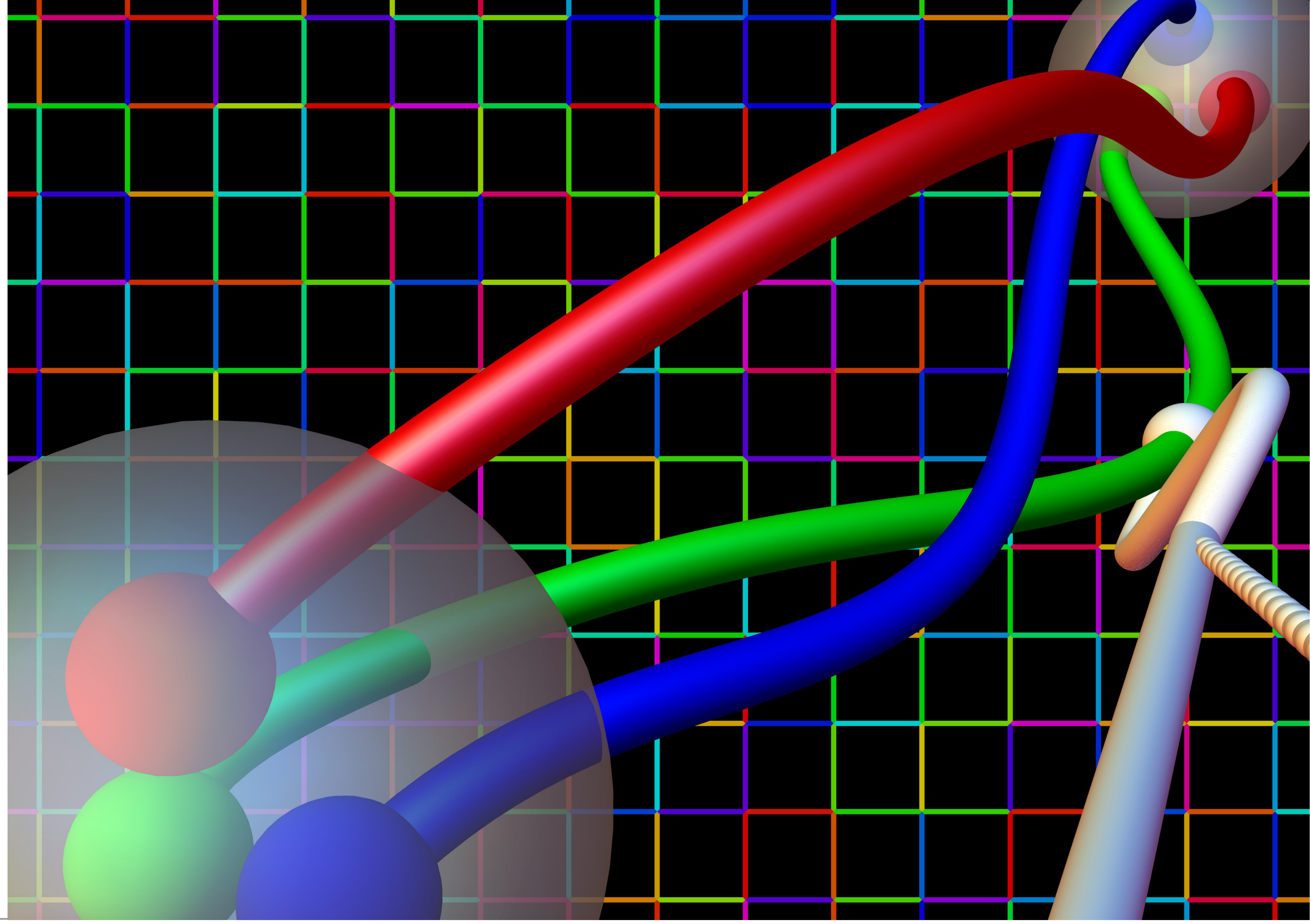
Understanding Fundamental Symmetries with Lattice QCD



Evan Berkowitz
College of Science and Mathematics
University of the Virgin Islands

UT Knoxville Colloquium
2025 January 30

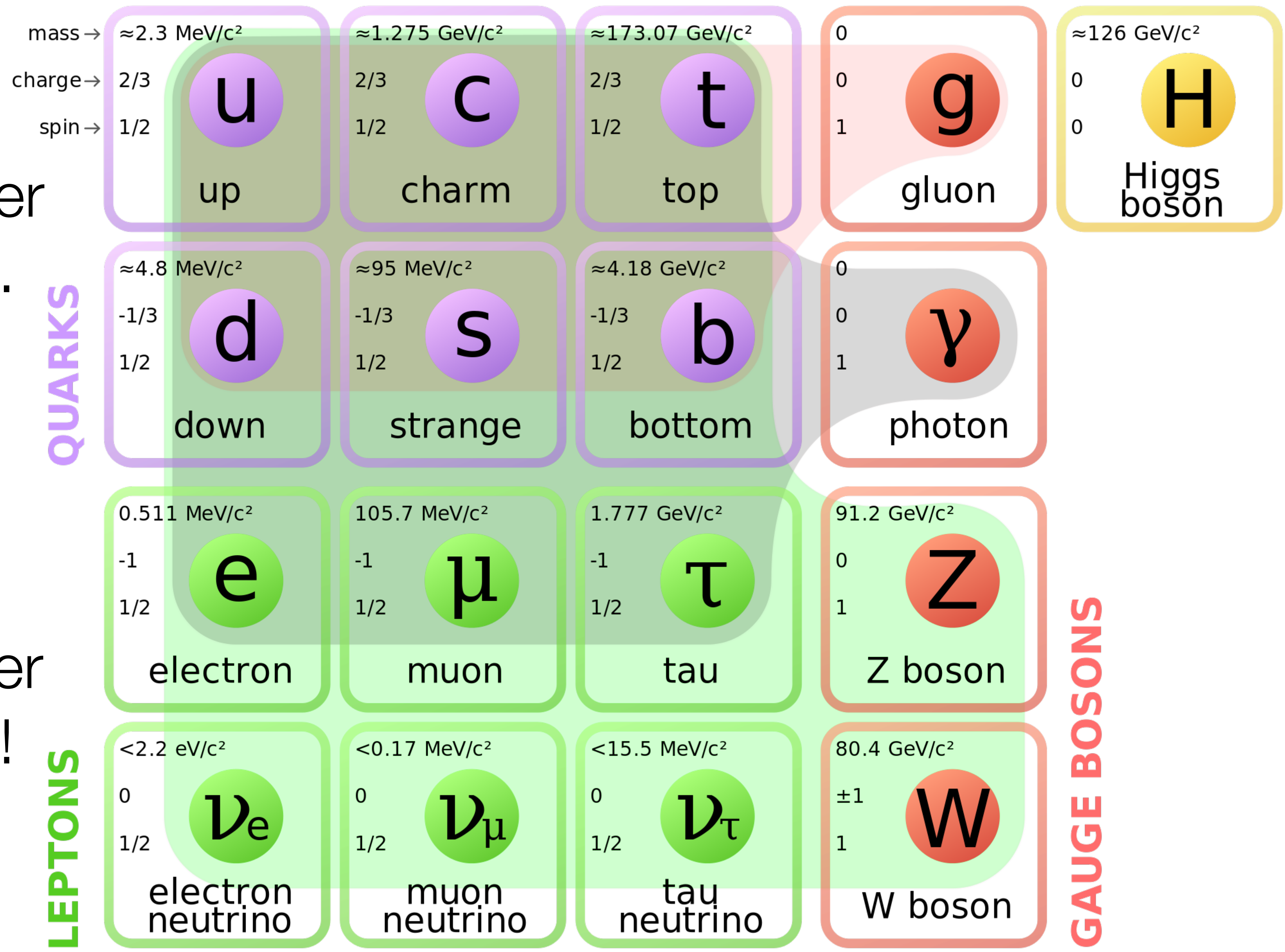
Fundamental Symmetries

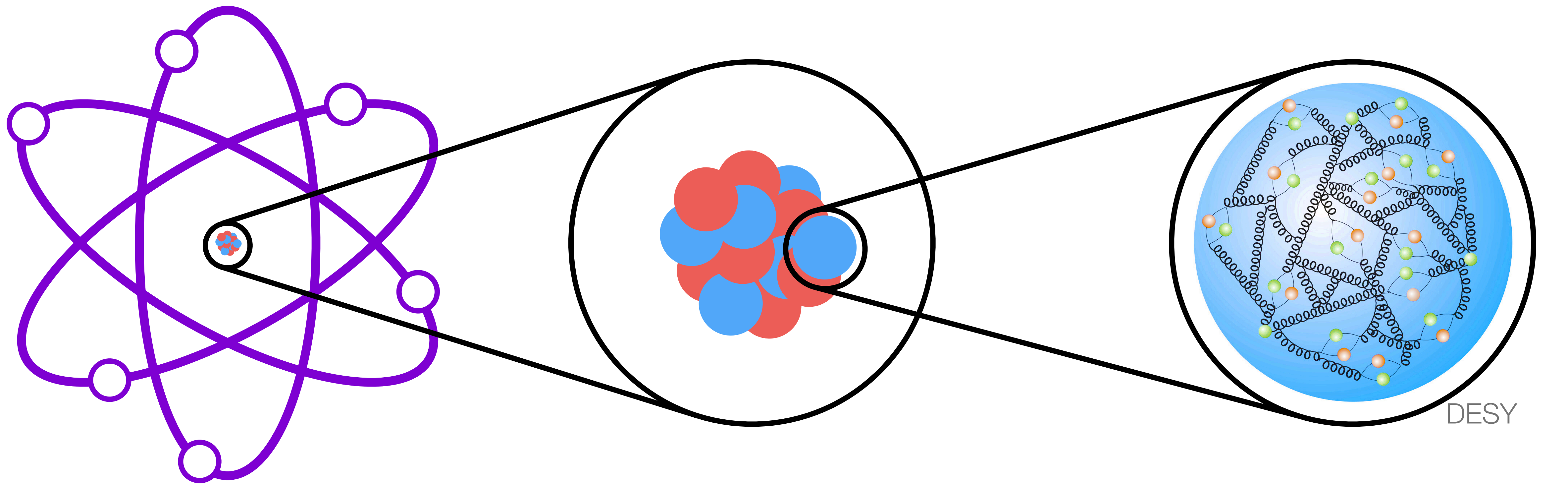
The Standard Model

- A *quantum field theory* with particular *symmetries.*
- No gravity, neutrino masses and oscillations, dark matter
- Otherwise, the ultimate description of every physical phenomenon thus far observed!

Baryon number is conserved.

Lepton number is conserved!



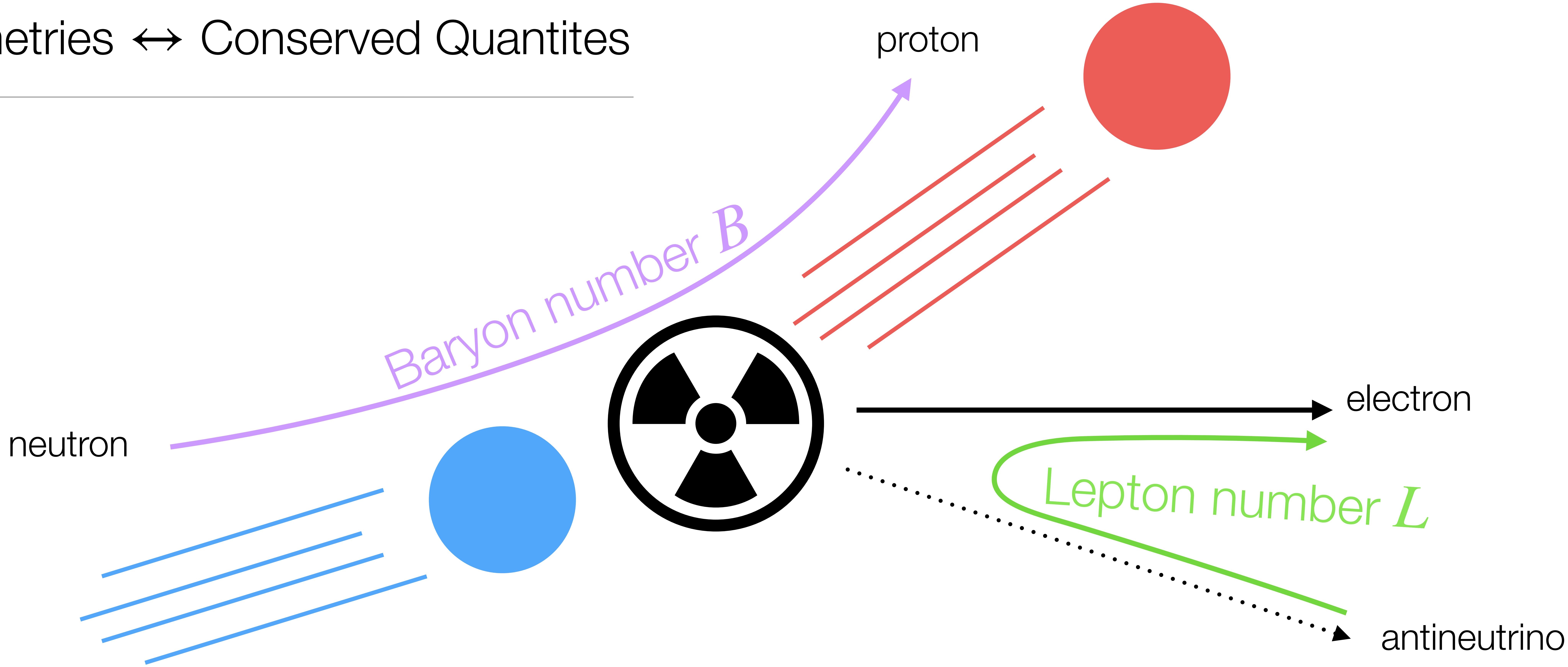


Atomic Scale
(25 to 250)×10^{-12}m

Nuclear Scale
(1 to 10)×10^{-15}m

Proton / Neutron Scale
1×10^{-15}m

Symmetries ↔ Conserved Quantites



	n	$\rightarrow$	p	+	e^-	+	$\bar{\nu}$
B	1	=	1	+	0	+	0
L	0	=	0	+	1	+	(-1)

Symmetries of the Standard Model

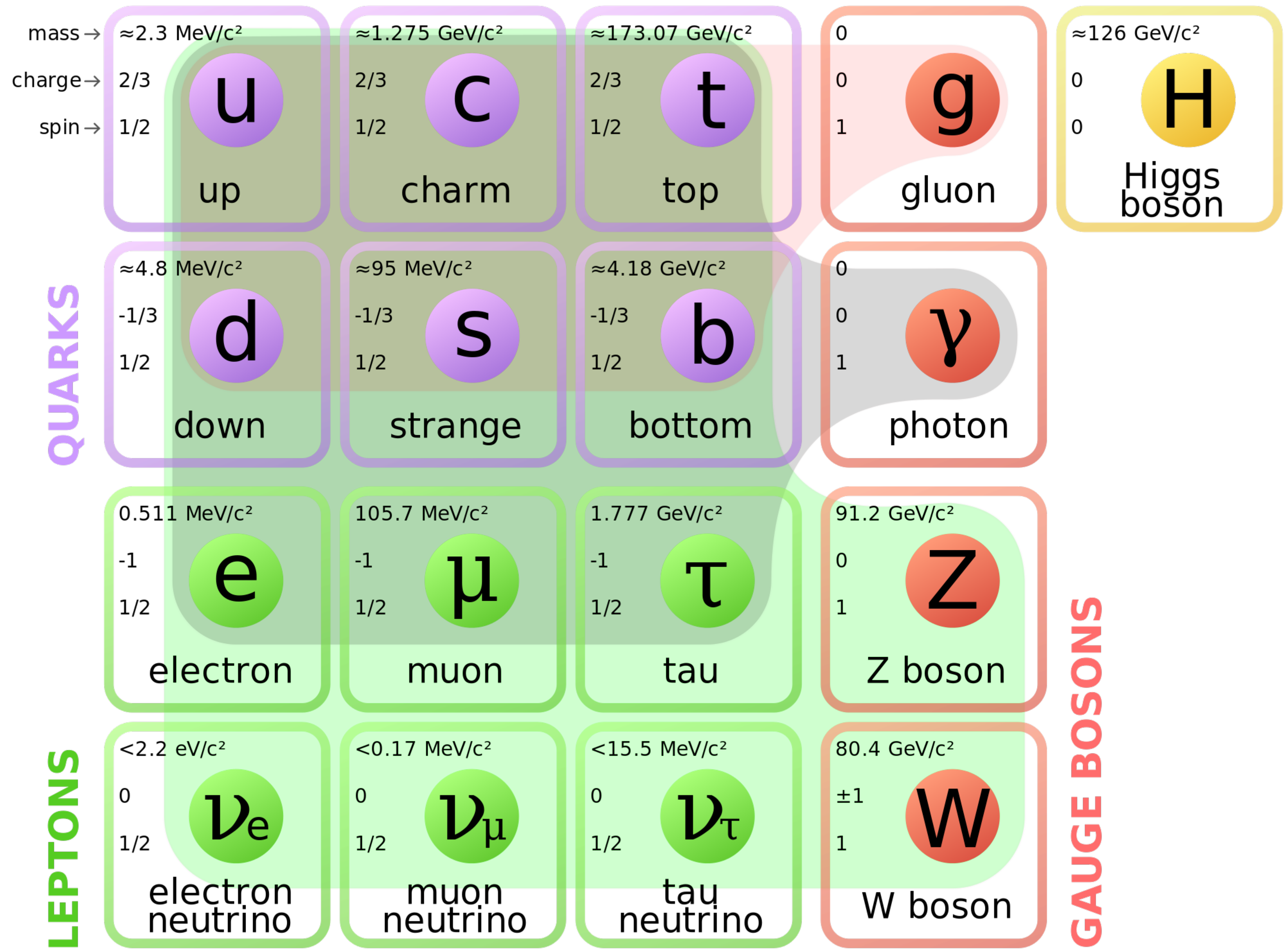
- Time invariance
- Rotational invariance
- Translational invariance

} continuous spacetime symmetries

- P: Parity
- C: Charge conjugation
- T: Time reversal

} discrete spacetime symmetries?

- $SU(3) \times SU(2) \times U(1)$ — gauge symmetry
- Baryon, Lepton number conservation — accidental symmetries?



Parity

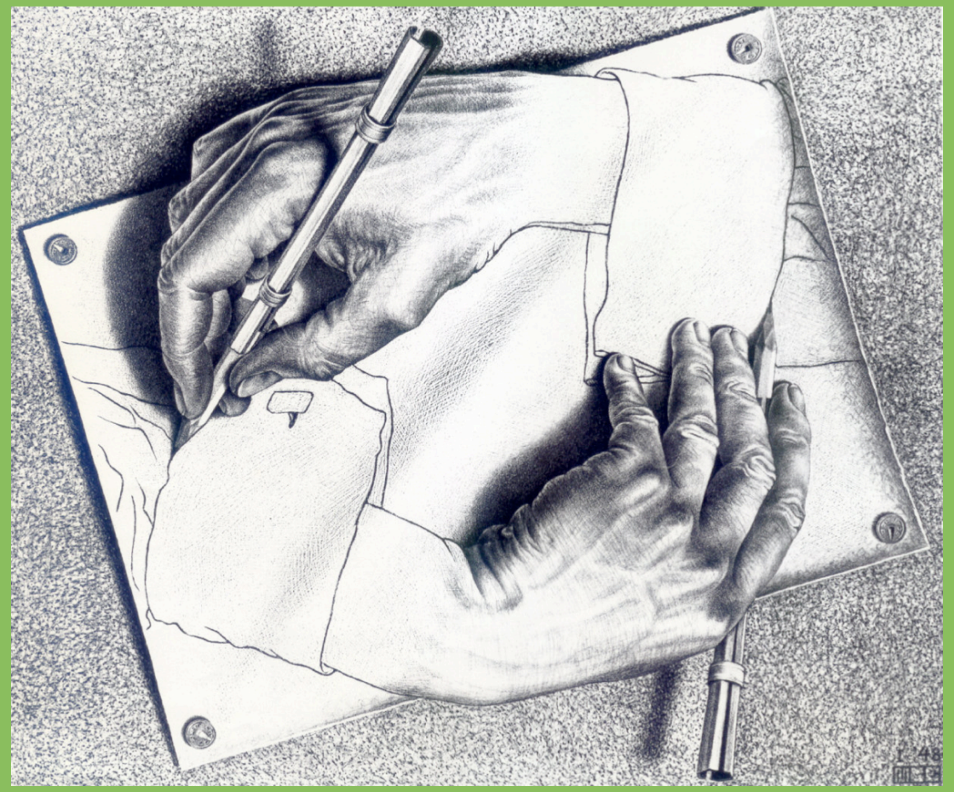
Case study: Parity (mid-1950s)

$$\theta^+ \to \pi^+ + \pi^0$$

$$\tau^+ \to \pi^+ + \pi^+ + \pi^-$$

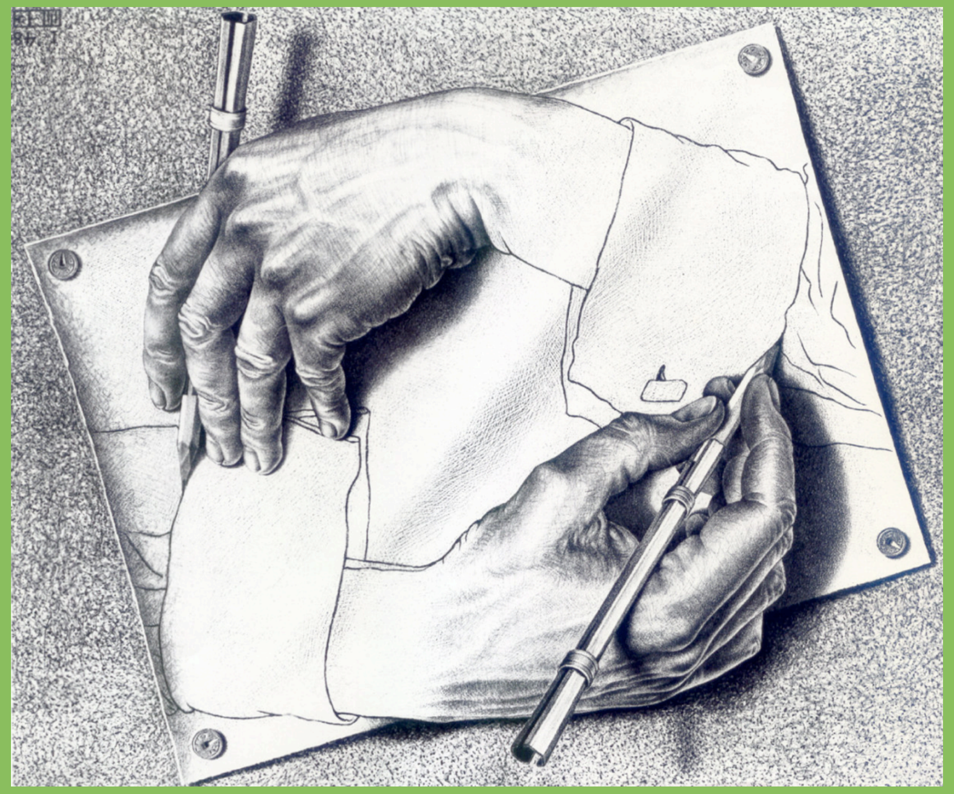
- Measurements showed θ and τ had indistinguishable mass, lifetimes, ...
- But pions π had negative parity, so θ^+ and τ^+ must have opposite parity, because parity is conserved.
- So what could explain the degeneracy?

Case study: Parity



MC Escher

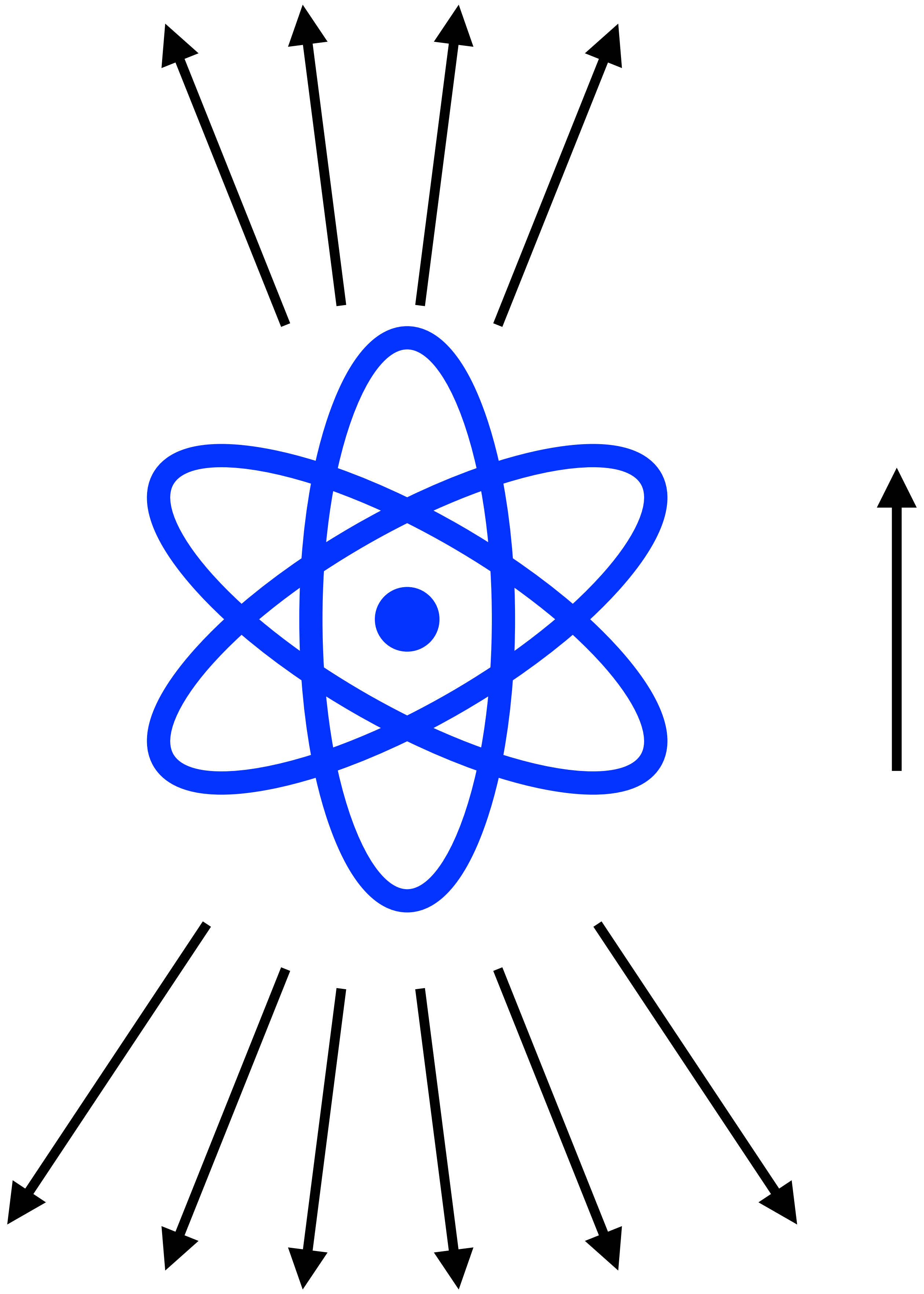
P ≠ q



Chien-shiung Wu (1912-1997)
Smithsonian Institution

Case study: Parity

^{60}Co



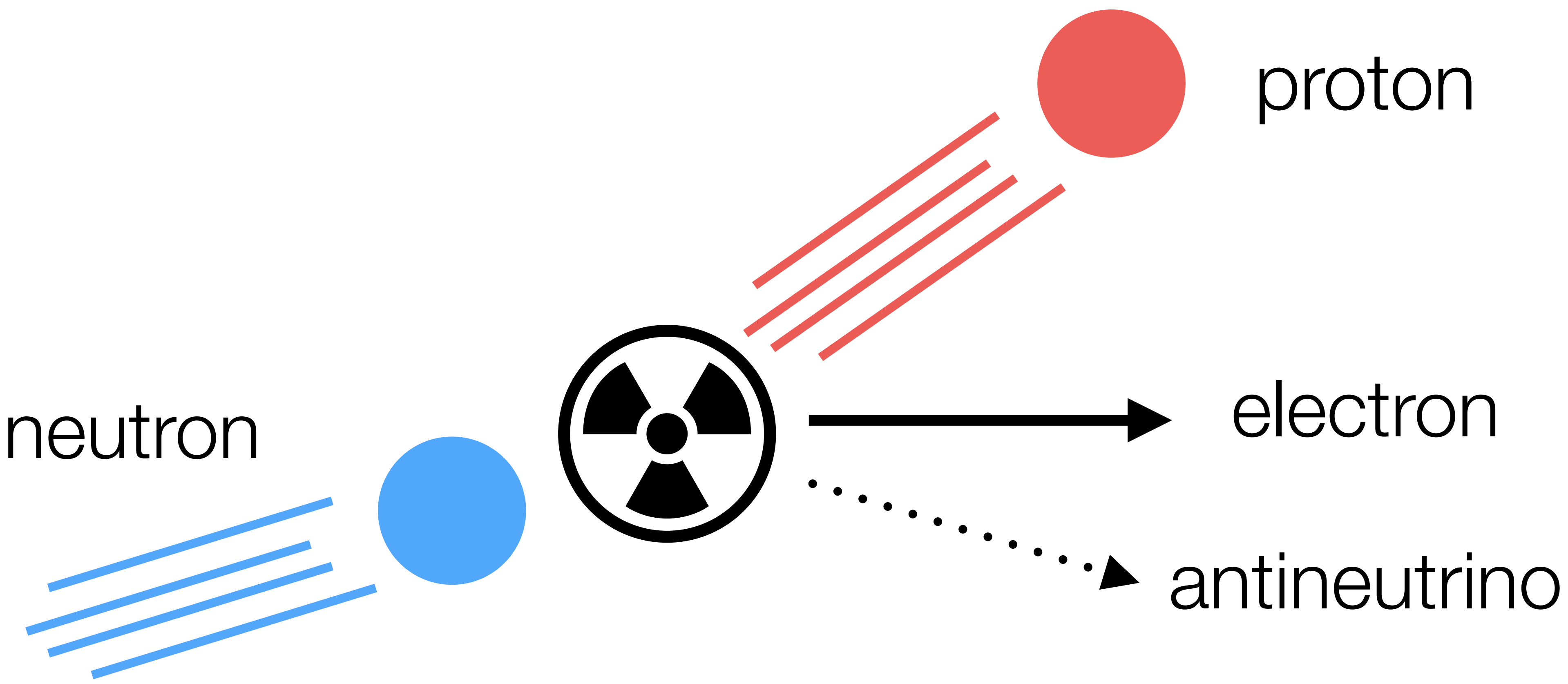
$\vec{J} \sim \vec{r} \times \vec{p}$

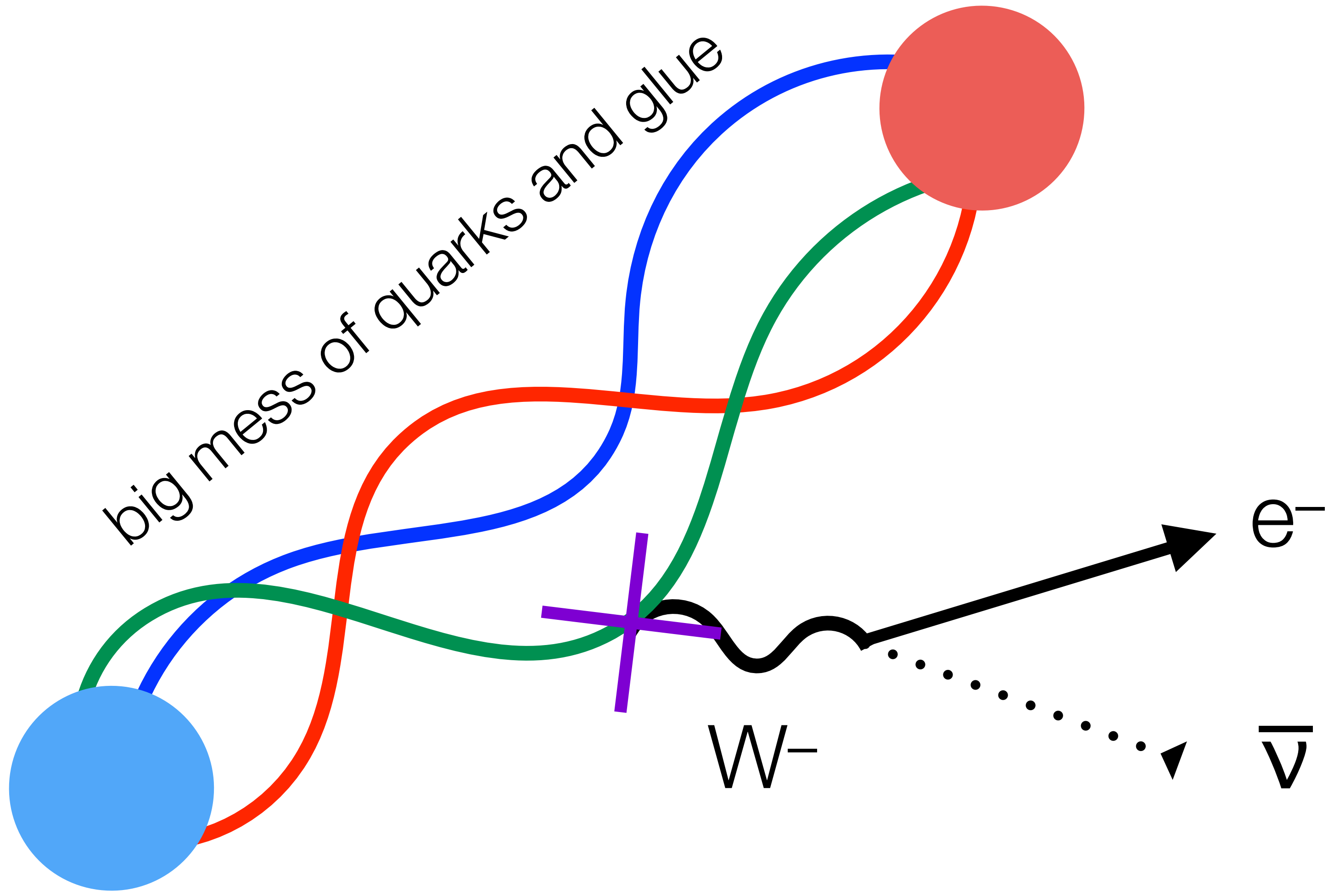
e⁻ preferentially come out away from $\vec{J}$

Chien-shiung Wu (1912-1997)
Smithsonian Institution

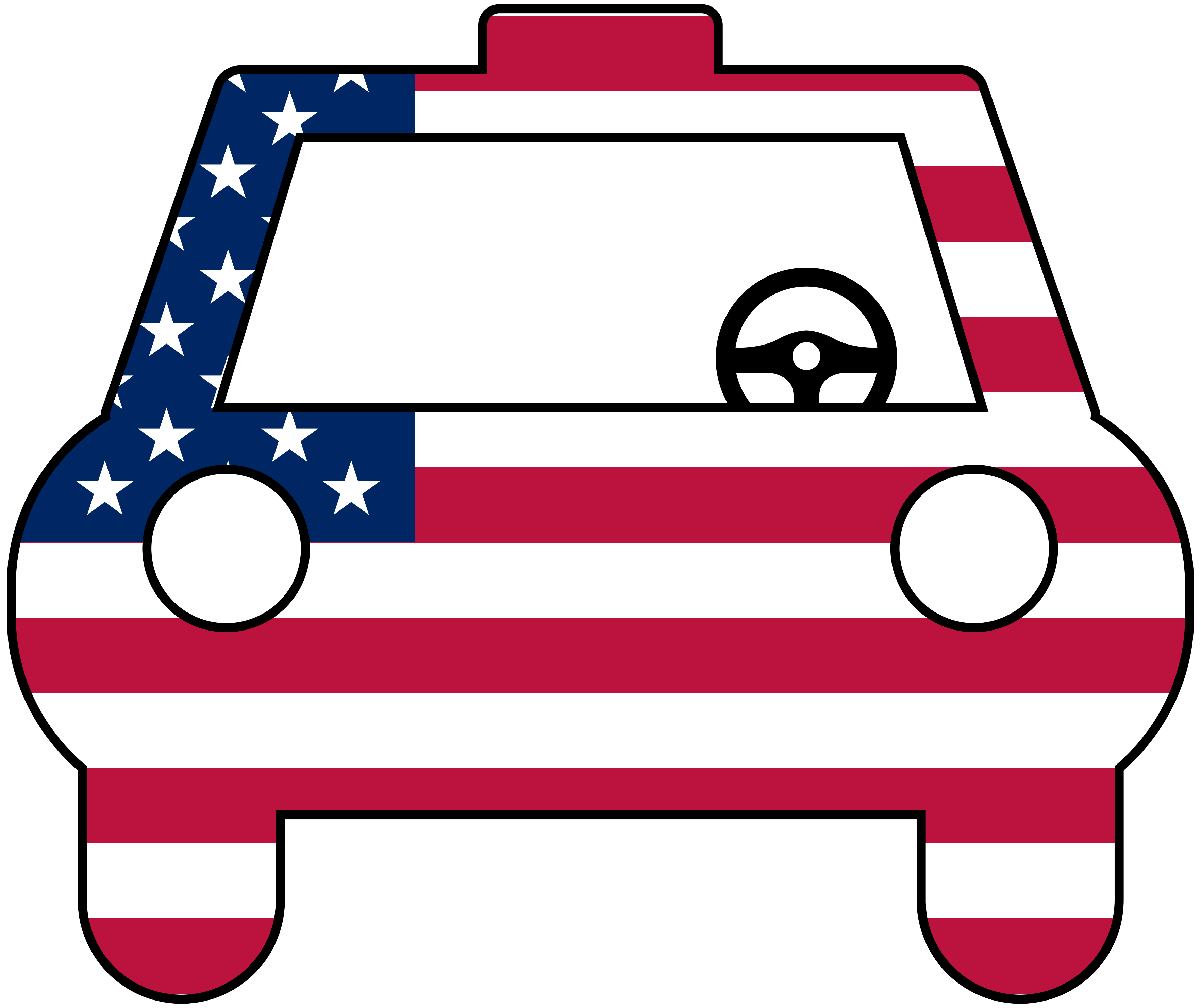
Left is alright

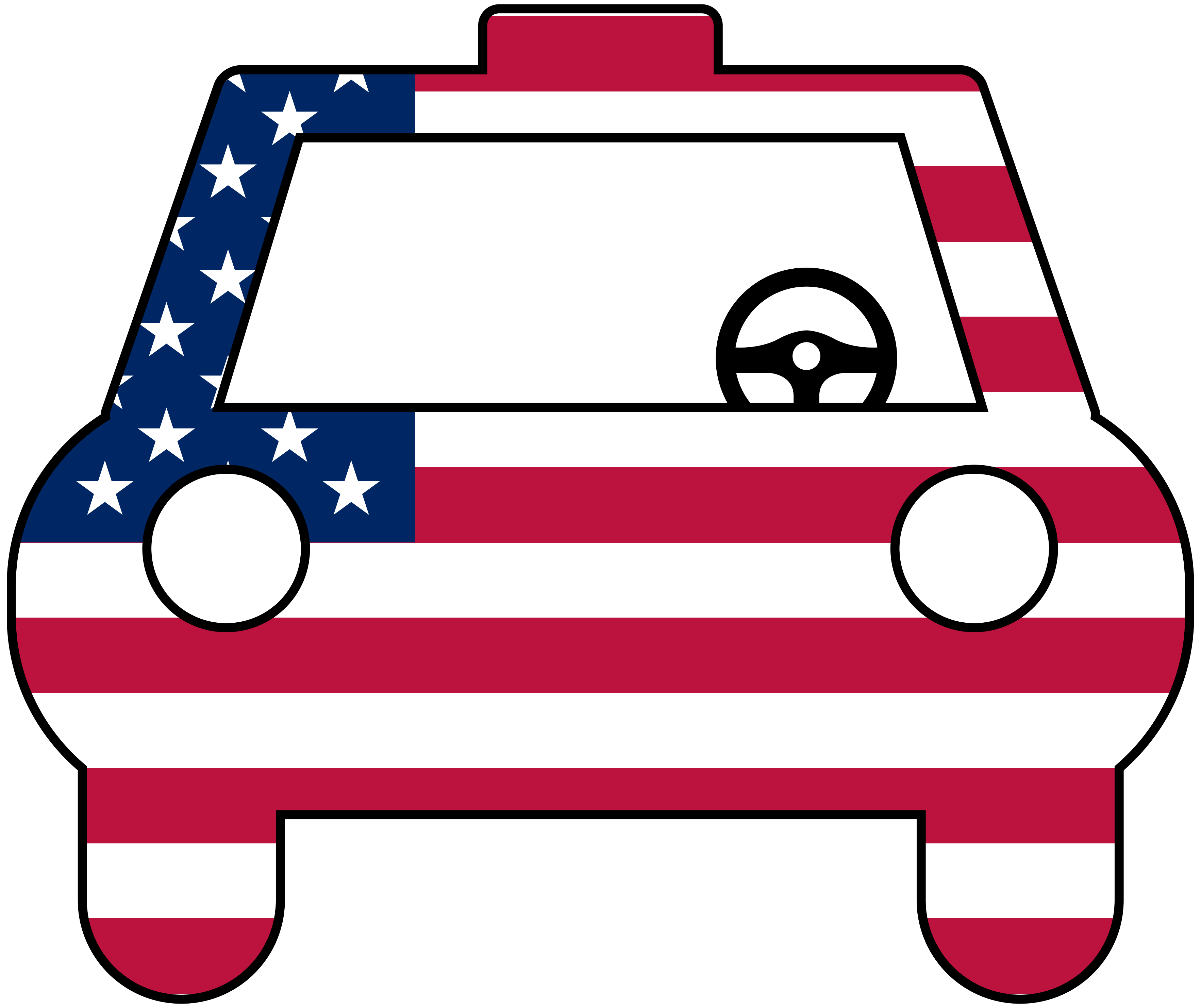
GoToStCroix.com

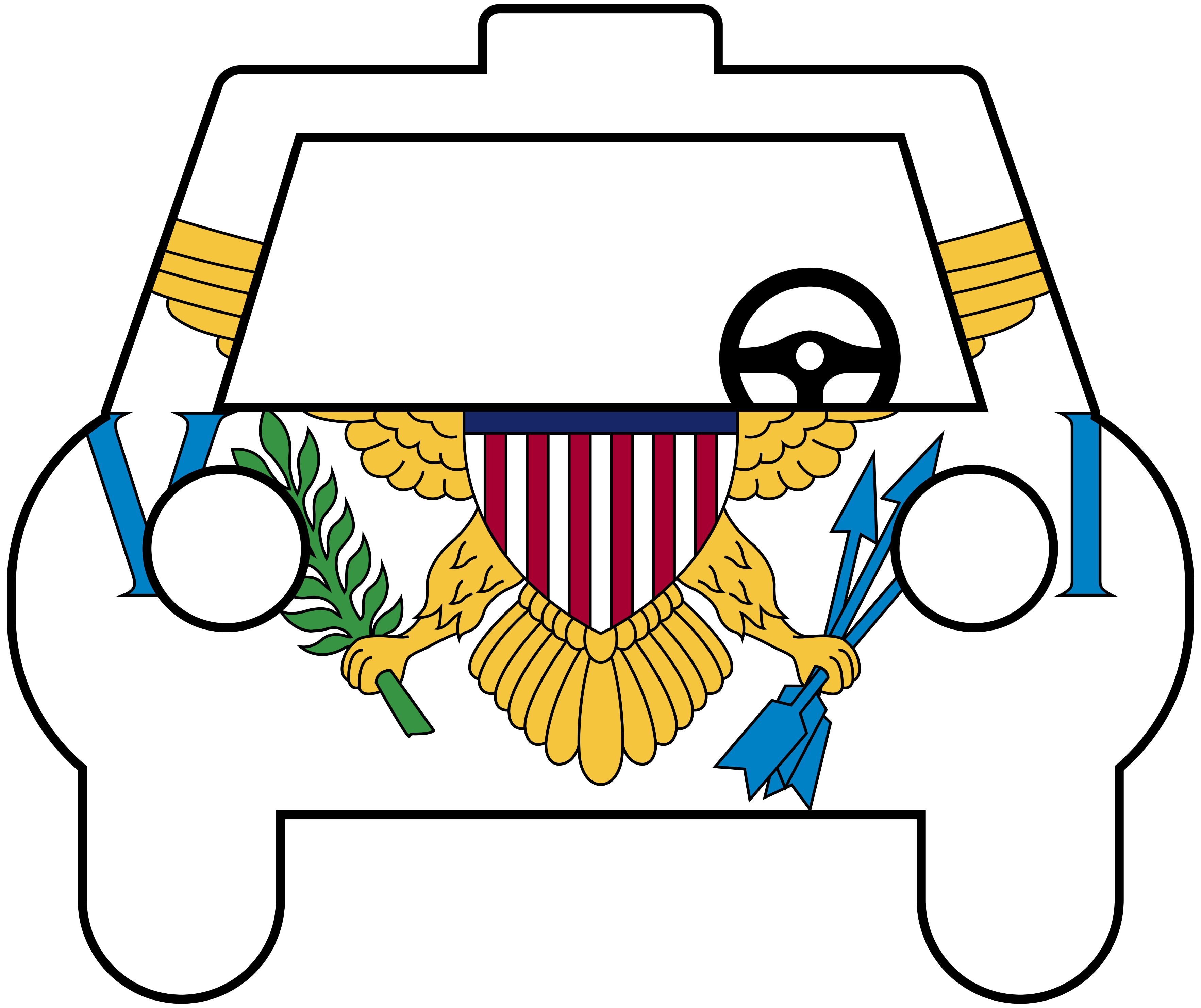




The weak force only talks to left-handed fermions!

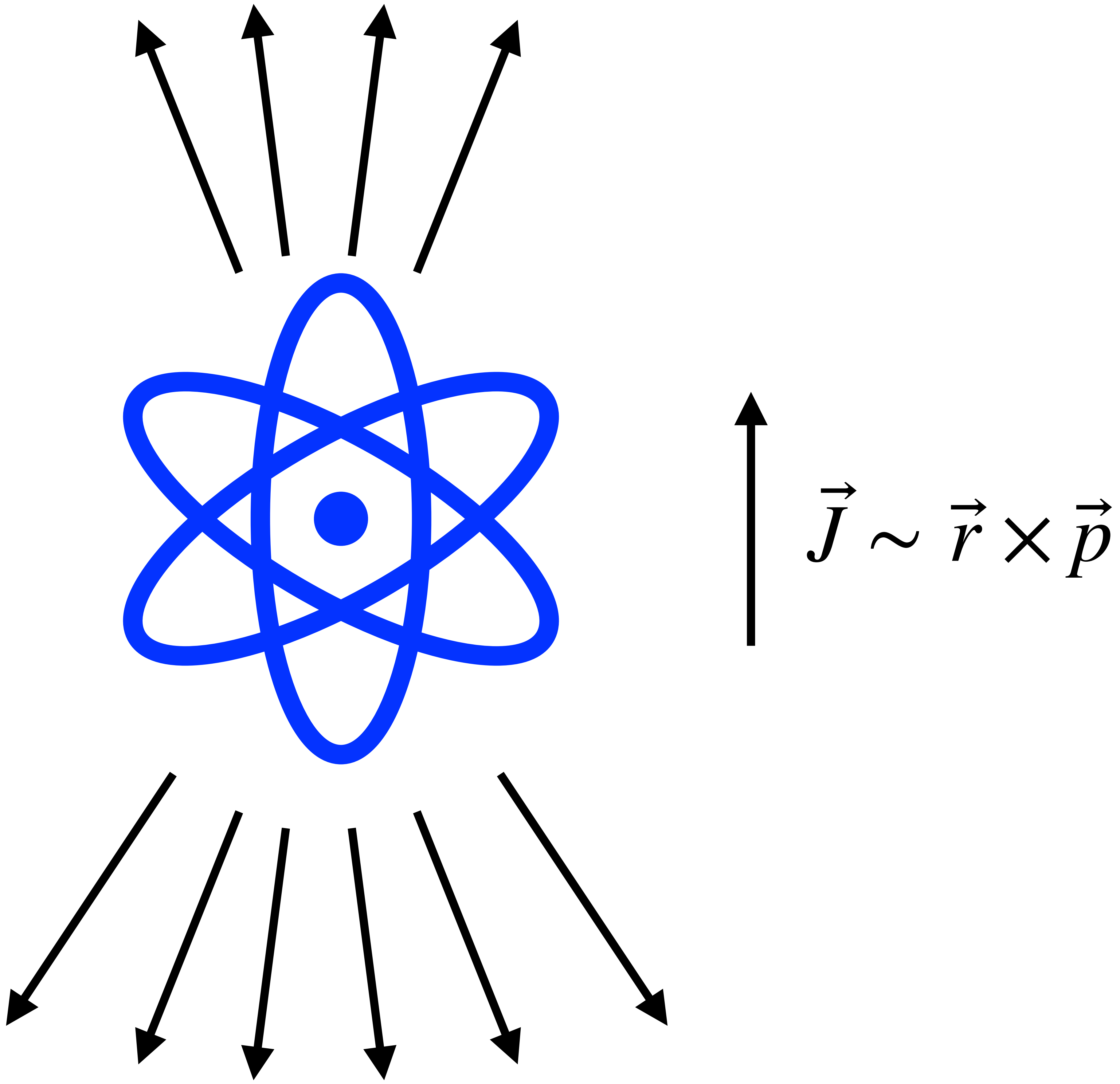





V
I

Case study: Parity

^{60}Co



e⁻ preferentially come out away from $\vec{J}$

Chien-shiung Wu (1912-1997)
Smithsonian Institution

"All the News That's Fit to Print"

The New York Times.

LATE CITY EDITION
Condensation of U. S. Weather Bureau forecast: Snow this morning, clearing in the afternoon. Fair, cold tomorrow.
Temperature range today: 22—10.
Temperature range yesterday: 18—3.1.
Full U. S. Weather Bureau Report, Page 62.

VOL. CVI . . No. 36,152. Entered as Second-Class Matter, Post Office, New York, N. Y. NEW YORK, WEDNESDAY, JANUARY 16, 1957. Times Square, New York 36, N. Y. Telephone LAckawanna 4-1000 FIVE CENTS

PRESIDENT SEEKS 76 MILLION FUND TO FIGHT DROUGHT

Assures Wichita Conference U. S. Will Have Other Plans and Will Solve Problem

ENDS GREAT PLAINS TOUR

Strongly Backs Long-Range Research With the Aim of Resisting Dry Cycles

Text of Eisenhower statement is printed on Page 18.

By DONALD JANSON
Special to The New York Times.

WICHITA, Kan., Jan. 15—President Eisenhower ended his tour of parched Great Plains states today with a pledge to seek $76,000,000 in Federal funds for emergency drought relief.

The President also gave strong

Basic Concept in Physics Is Reported Upset in Tests

Conservation of Parity Law in Nuclear Theory Challenged by Scientists at Columbia and Princeton Institute

By HAROLD M. SCHMECK Jr.

Experiments shattering a fundamental concept of nuclear physics were reported yesterday by Columbia University.

The concept called the "principle of conservation of parity,"

The text of Columbia report will be found on Page 24.

has been accepted for thirty years. It must now be discarded, according to the Columbia scientists.

The principle of parity states that two sets of phenomena, one of which is an exact mirror of the other, behave in an identical fashion except for the mirror image effect.

The principle might be explained this way:

Assume that one motion picture camera is photographing a given set of actions and that another camera simultaneously is photographing the same set of actions as reflected in a mirror.

If the two films are later screened, a viewer would have no way, according to the principle of parity, of telling which of the two was the mirror image. The recently completed experiments indicate that there is a way of determining which of the two images is the mirror image.

In communicating with people in an intelligent civilization on another world, the Columbia report explained, it would be impossible, with the principle of parity in effect, to tell whether or not they and we meant the same thing by right-handed or left-handed. This could be true and still the basic physical laws in both worlds would behave ex-

Continued on Page 24, Column 3

MACMILLAN GETS EISENHOWER WISH FOR ALL SUCCESS

Briton Responds With Equal Warmth to Greetings on His Appointment

By DREW MIDDLETON
Special to The New York Times.

LONDON, Jan. 15—President Eisenhower has warmly congratulated Harold Macmillan on his appointment as Prime Minister, wishing him "every success" in his new post.

Mr. Macmillan, in his reply, has pledged his cooperation with the President in furthering friendship between the United States and Britain.

The exchange of letters was made public today by the Prime Minister's office. Mr. Macmillan also received similar messages of congratulation from Secretary of State Dulles and Secretary of the Treasury George M. Humphrey.

Regarded as Rebuttal

Associated Press Radiophoto

DELAYING ACTION IN EGYPT: Israeli soldiers setting up a road block yesterday between El Arish and Rafa during their withdrawal in the Sinai Peninsula. Yugoslav mem-

EGYPT TAKES OVER ASSETS OF BANKS OF BRITISH, FRENCH

Insurance Concerns Affected Also by Nasser Regime's 'Egyptianization' Decrees

NATIVE OWNERSHIP AIM

Other Foreigners' Financial Institutions Get 5 Years Before Control Changes

By OSGOOD CARUTHERS
Special to The New York Times.

CAIRO, Jan. 15—The Government announced today the "Egyptianization" of all British and French banks and insurance companies in Egypt.

All other foreign banks and insurance companies were given five years before they too would be "Egyptianized."

Under decrees to become effective tomorrow, the first anniversary of the promulgation of

The New York Times
Times Machine, Wednesday, January 16, 1957

THEORY IN PHYSICS IS REPORTED UPSET

Continued From Page 1

actly alike. The recent experiments indicate that this is not the case for some weak interactions of sub-atomic particles.

The idea that destroyed this principle originated with two theoretical physicists, Dr. Tsung Dao Lee of Columbia and Dr. Chen Ning Yang of the Institute for Advanced Study at Princeton, N. J. They suggested certain definitive experiments in papers on the subject: "Is Parity Conserved in Weak Interactions?"

The generally accepted belief, which had been a part of nuclear physics since 1925, was that parity should be conserved.

Two sets of experiments suggested by the two theorists showed that this parity was not conserved. A team of four Columbia physicists in collaboration with a member of the Institute for Advanced Study and a team at the National Bureau of Standards carried out the work.

The meeting that released the results of the experiments was held at 2 P. M. yesterday in Columbia's Pupin Physics Laboratories at 119th Street and Broadway. The chairman of the meeting was Dr. I. I. Rabi, Columbia's Nobel Prize-winning physicist.

"In a certain sense," Dr. Rabi commented on the development," a rather complete theoretical structure has been shattered at the base and we are not sure how the pieces will be put together."

Physicists present at the meeting indicated that it might take a long time to evolve a new concept on the basis of the recently achieved results. One scientist said that nuclear physics, in a sense, had been battering for years at a closed door only to find that it is not a door at all but a likeness of a door painted on the wall. Now science is at least in a position to hunt for the true door again, he observed.

K Mesons Led to Doubts

The Columbia theorists were led to doubt the principle of parity because, during the last few years, phenomena had been described in high energy physics that could not be explained by existing theories. This was particularly true of the patterns by which certain sub-atomic particles called K mesons decayed. Nobody was able to formulate a theory to account for both of the two methods of decay that they followed.

Dr. Lee and Dr. Yang suggested that perhaps it would be necessary to give up the principle of parity to gain an explanation of the sub-atomic interactions. They found that certain experiments dealing with particles better known than the K mesons could resolve the puzzle.

One set of experiments, done in a low temperature physics laboratory of the Bureau of Standards, showed that disintegrating nuclei of radioactive

Text of Columbia Report on Physics Experiments

Following is the text of the Columbia report on physics research released yesterday:

I. Introduction

The Department of Physics of Columbia University announces a development of very profound importance uncovered in very recent experiments in the subject of the physics of elementary particles. These experiments are:

(1) The beta-decay of oriented nuclei—Prof. C. S. Wu of Columbia University in collaboration with Ernest Ambler, R. W. Hayward, D. D. Hoppes and R. P. Hudson of the National Bureau of Standards.

(2) The angular asymmetry in electron decay of mu mesons—Dr. Richard L. Garwin, Prof. Leon M. Lederman and Mr. Marcel Weinrich of Columbia University. (Note: Dr. Garwin is also a senior staff member of the I. B. M. [International Business Machines] Watson Scientific Laboratory at Columbia.)

II. Significance

Both of the above experiments (described in more detail below) were suggested by two theoretical physicists, Prof. T. D. Lee of Columbia University and Prof. C. N. Yang of the Institute for Advanced Study, Princeton, N. J. The first of a series of three papers on the subject was entitled "Is Parity Conserved in Weak Interactions?" The experiments designed to answer this question give a decisive answer—parity is not conserved—thus destroying one of the basic laws built into all physical theories of the past thirty years.

Parity

The concept of parity, although actually significant only in the realm of microscopic (atoms and particles) physics, has a well defined every-day definition. One way of describing this is as follows:

Suppose we are in communication with an intelligent civilization on another world and wish to determine whether their clocks run in the same sense as ours do—or again whether they mean the same thing by left-handed and right-handed as we do. We have always believed that communication of this idea, in the spirit of this analogy, is impossible. There was no absolute, universal sense to "Handedness." However, the stranger's laws of physics are perfectly good—even if his definition is opposite to ours for, say, a left-hand screw and a right-hand screw.

The statement that the two worlds, one based upon a left-handed system and one based upon a right-handed system, have the same laws in physics is known as an "invariance principle," i. e., the laws of physics are said to be invariant or unchanged, if the

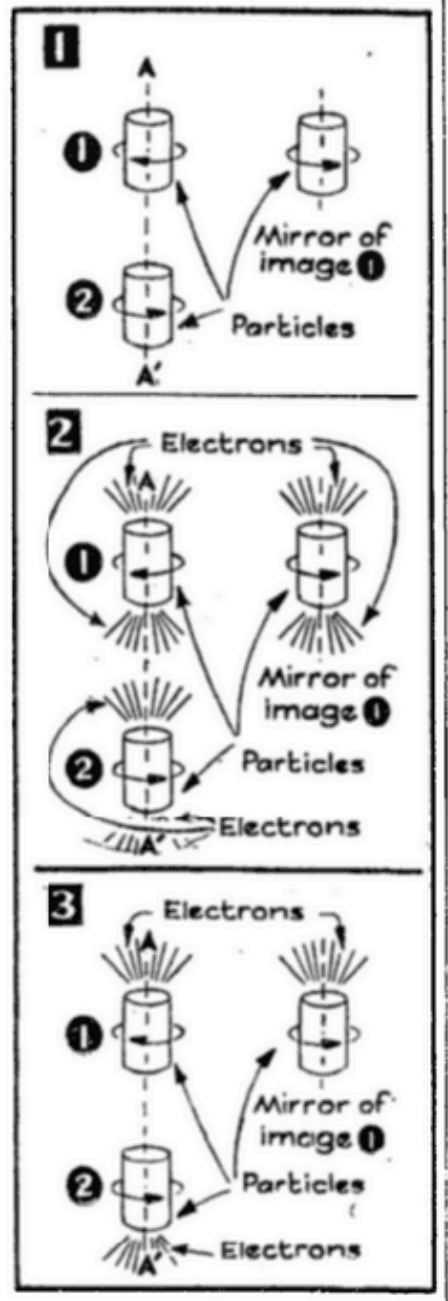
The Meaning of Parity

(Mirror Symmetry)

The parity law of physics states that for any atomic or nuclear system no new physical consequence or law should result from the construction of a new system, differing from the original by being a mirror twin.

Consider Particle 1, spinning about a direction AA'. Now construct or find Particle 2, which is chosen to be identical to the mirror image of 1. The parity law says that there should be no observable difference between the two particles, 1 and 2, which may be detected by measurements made along direction AA'. This law permits one to make predictions: suppose 1 is radioactive, disintegrating into electrons. The parity law predicts that equal numbers will be emitted toward A and A', as in Figure 2. Why? Consider the alternative. If 1 emits more electrons towards A, 2 must emit more towards A' since 1 becomes identical to 2 simply by turning it upside down. But, now 2 is no longer the same as the mirror image of 1. The physicist observing 2 would make one decision about the relation between the direction of favored electron emission and the spin sense; the physicist in the mirror world would obtain a different answer. Parity law would have been violated.

For the past thirty years, the special conditions predicted by the philosophically pleasing idea of mirror symmetry have borne fruit, consistently making successful predictions about atomic and nuclear processes. However, a general theory of the structure of matter eluded us. Then, in the new subject of "strange particles," the K-mesons studied at Brookhaven



and Berkeley, the first parity puzzle appeared. This led to the Lee-Yang proposal. The preferential emission of electrons toward one direction of its spin is the observation that disproved the parity law.

ning) particle with a spinning bullet. If the shape of the bullet were a perfect cylinder, there would be no screw defined, or no "handedness," since the two ends of the bullet are identical.

The new concept of particles is now in analogy with a normal bullet (pointed nose) which differentiates one end of the spin from the other. Particles which "point" in one direction relative to the sense of rotation are called right-handed, etc. The fact that such particles exist on this world and on the other world now permits an absolute identification of right and left hard between the two worlds, in violent disagreement with previous concepts. No theory which has included the parity idea would have been successful. These experiments, brilliantly proposed by Lee and Yang, now at last open the way to a correct and unifying theory of elementary particles. Lee and Yang also point out that the over-all symmetry of the universe may still be preserved by assuming that, if our galaxy is essentially right-handed, some distant galaxy may be in turn left-handed. It may be that this assumed distant galaxy is identical to the hypothetical anti-matter, now a subject of intense speculation. This would represent an enormous simplification in our theoretical attack on the structure of the universe.

III. Theoretical Background

The proposal that the parity law may not be true was made by Lee and Yang last summer. This was in an attempt to reconcile data obtained with the super-atom smashers, the Brookhaven Cosmotron and the Berkeley Bevatron. The data consisted of the study of the properties of the unstable Kmesons, particles which were only recently discovered (1952-53). One aspect of Kmeson disintegration seemed to violate the parity law. So deeply rooted was this law, that the entire world of physics was completely baffled by the K-meson puzzle, the general feeling being that the Kmesons, being newly discovered, were just not well enough understood. Lee and Yang boldly made the break and, in their now historic paper, they re-examined the consequences of removing the parity law for radioactive disintegrations of nuclei and particles. They found, to their surprise, that none of the existing data would be in contradiction and that certain crucial experiments, dealing with more well-known particles, would give decisive answers.

IV. The Experiment

Oriented Nuclei

To detect the "handedness" of particles, the radioactive nucleus Cobalt 60 was cooled to a temperature of 0.01° above absolute zero [—273.1 Centigrade]. At this temperature, all thermal motions are reduced to extremely small values. The application of a magnetic field will cause most of the cobalt nuclei, which are known to be spinning, to align themselves, like small magnets, parallel to the applied magnetic field. The radioactive cobalt nuclei disintegrate, giving off electrons. The crucial point is the comparison of the number of electrons emitted along the direction of spin to the number going in the opposite direction. The very fact that these numbers are different indicates the favoring of a direction associated with the spin, that is, a "handedness" in the sense of a screw. Moreover, the magnitude of the difference was sufficiently large to indicate a violation of charge conjugation invariance.

The technical aspects were quite difficult. At the request of and in collaboration with Professor Wu, the National Bureau of Standards Low Temperature Physics Group undertook experiments to verify the theoretical considerations. This group assisted by National Bureau of Standards specialists in radioactive measurements provided the techniques and experience for completing the project successfully. Scintillation counters had to be installed within the complex vacuum and cooling system and extreme care had to be taken to eliminate spurious effects. This work was partially supported by the Atomic Energy Commission.

Meson Decays

In this experiment two parity violations were detected as well as the violation of "charge-conjugation-invariance." It was discovered that when the familiar pi meson (well known since 1947, and now known to be principally responsible for the force that holds nuclei together) disintegrates into a mu meson and a neutrino the mu meson always spins in the direction of its motion. Here again, the mu advances as if it were a screw and demonstrates the parity-violating "handedness." The alignment of mu spins was detected by counting the end products of the radioactive mu meson decay, again electrons, which were found to favor one direction of spin of the parent mu meson over the other, in their direction of emission.

As a by-product of this experiment, the strength of the small "magnet" carried by the mu meson (called a magnetic moment) was measured to a precision of 5 per cent. Magnetic moments of electrons are known to precisions of 0.005 per cent (P. Kusch, Nobel prize) but the number of particles available is 10^{14}, whereas in this experiment less than 50,000 particles were counted. Oriented mu mesons are extremely sensitive to weak magnetic fields and this technique will prove a powerful tool in probing the magnetic fields inside nuclei and atoms and between atoms.

The latter experiment was carried out at Columbia's Nevis Cyclotron Laboratories in Irvington-on-Hudson, N. Y., operated under the joint program of the Office of Naval Research and the Atomic Energy Commission.

Personnae

Tsung Dao Lee, Professor of Physics, Columbia University.

Chen Ning Yang, Professor of Physics, Institute for Advanced Study, Princeton, N. J.

Chien Shiung Wu, Associate Professor of Physics, Columbia University.

Ernest Ambler, Physicist, physicist, National Bureau of Standards, Washington.

R. W. Hayward, physicist, National Bureau of Standards, Washington.

D. D. Hoppes, assistant, National Bureau of Standards, Washington.

R. P. Hudson, section chief, National Bureau of Standards, Washington.

Leon M. Lederman, Associate Professor of Physics, Columbia University.

Richard L. Garwin, Associate, Columbia University and senior staff member, I. B. M. Watson Scientific Laboratories.

Marcel Weinrich, graduate research assistant, Columbia University.

Symmetries of the Standard Model

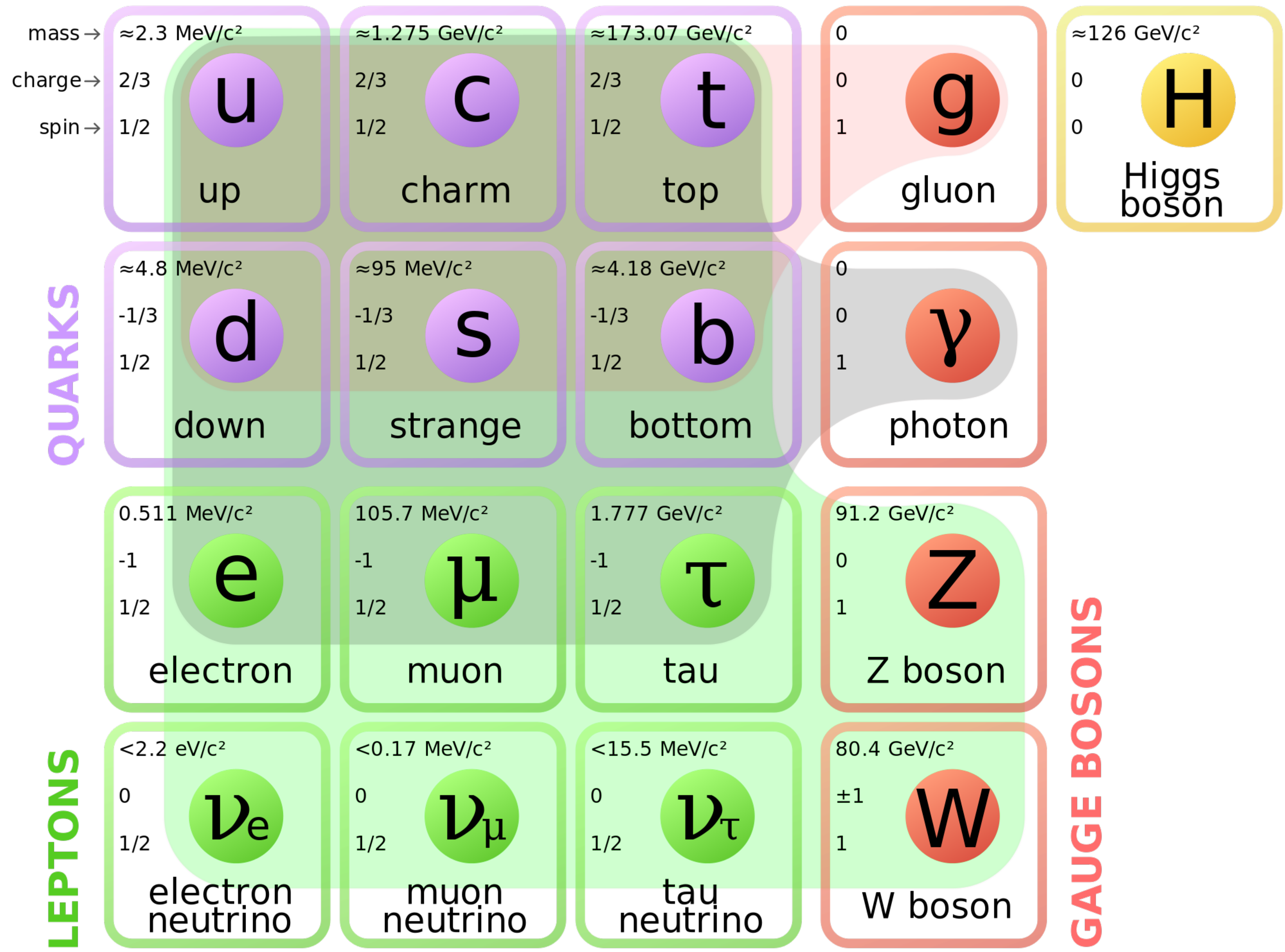
- Time invariance
- Rotational invariance
- Translational invariance
- Parity
- C: Charge conjugation
- T: Time reversal
- $SU(3) \times SU(2) \times U(1)$
- Baryon, Lepton number conservation

spacetime symmetries

discrete symmetries?

gauge symmetry

accidental symmetries?

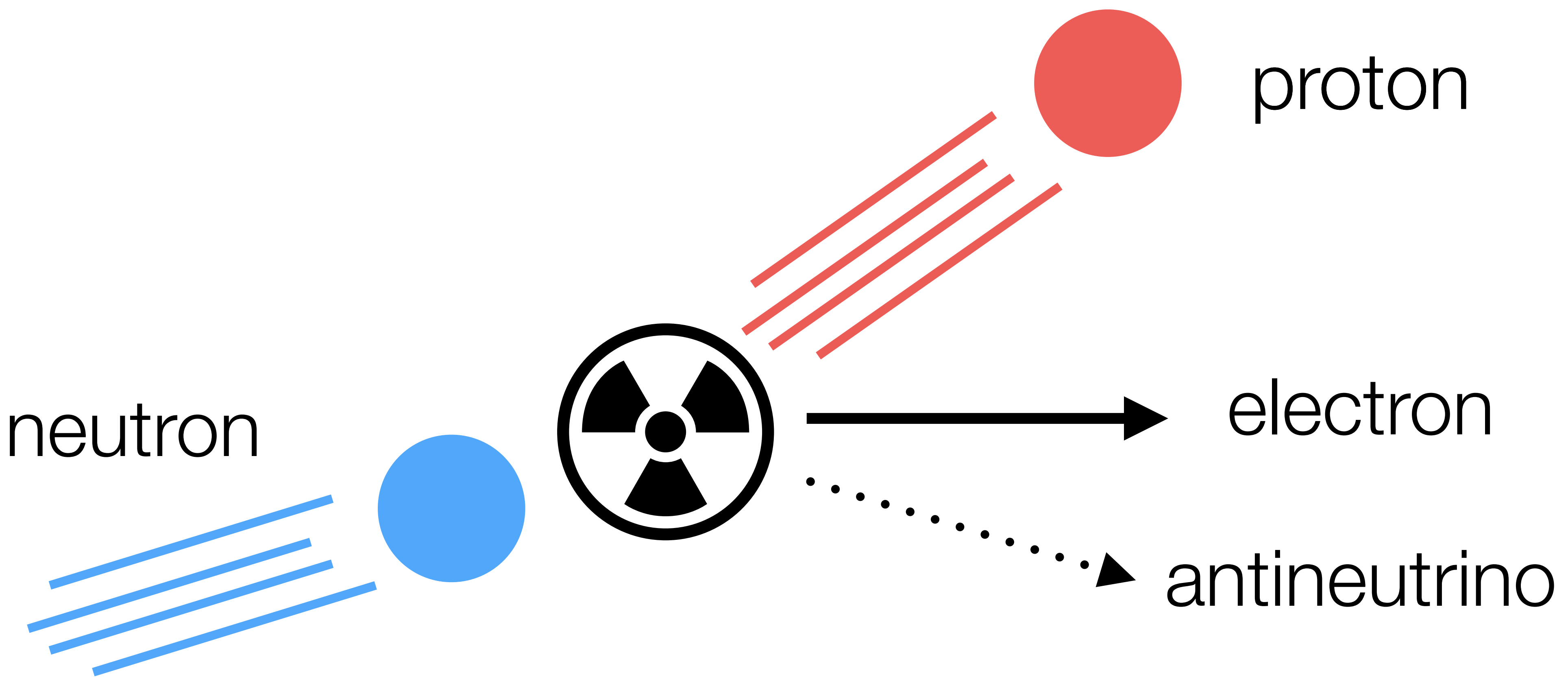


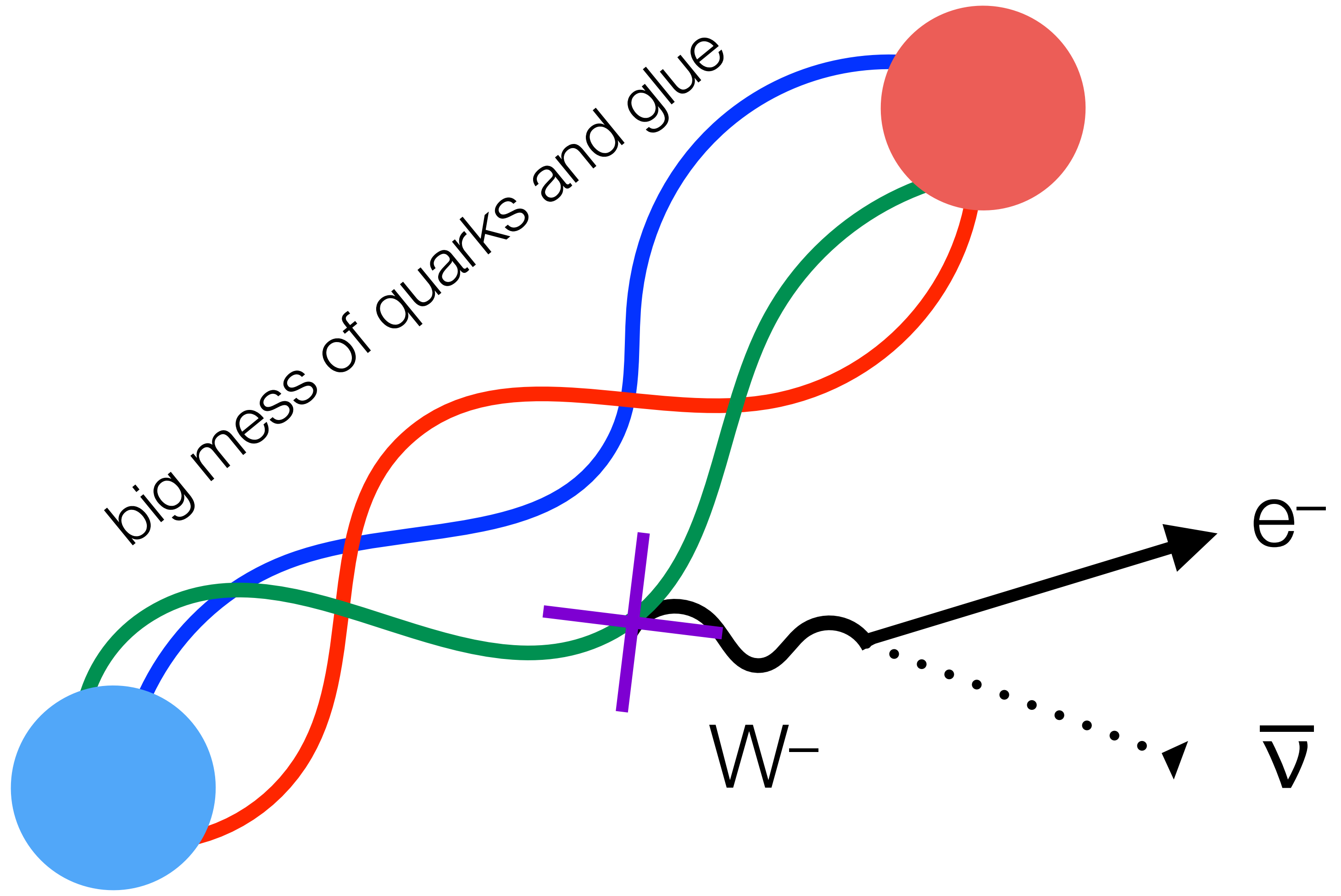
Mysterious Mesons

		Electromagnetism	Weak	Strong
C	Charge	✓	✗	✓
P	Parity	✓	✗ θ-τ	✓
T	Time Reversal	✓	✗ $K\bar{K}$	✓
L	Lepton number	✓	✓	
B	Baryon number	✓	✓	✓

Left is alright

GoToStCroix.com

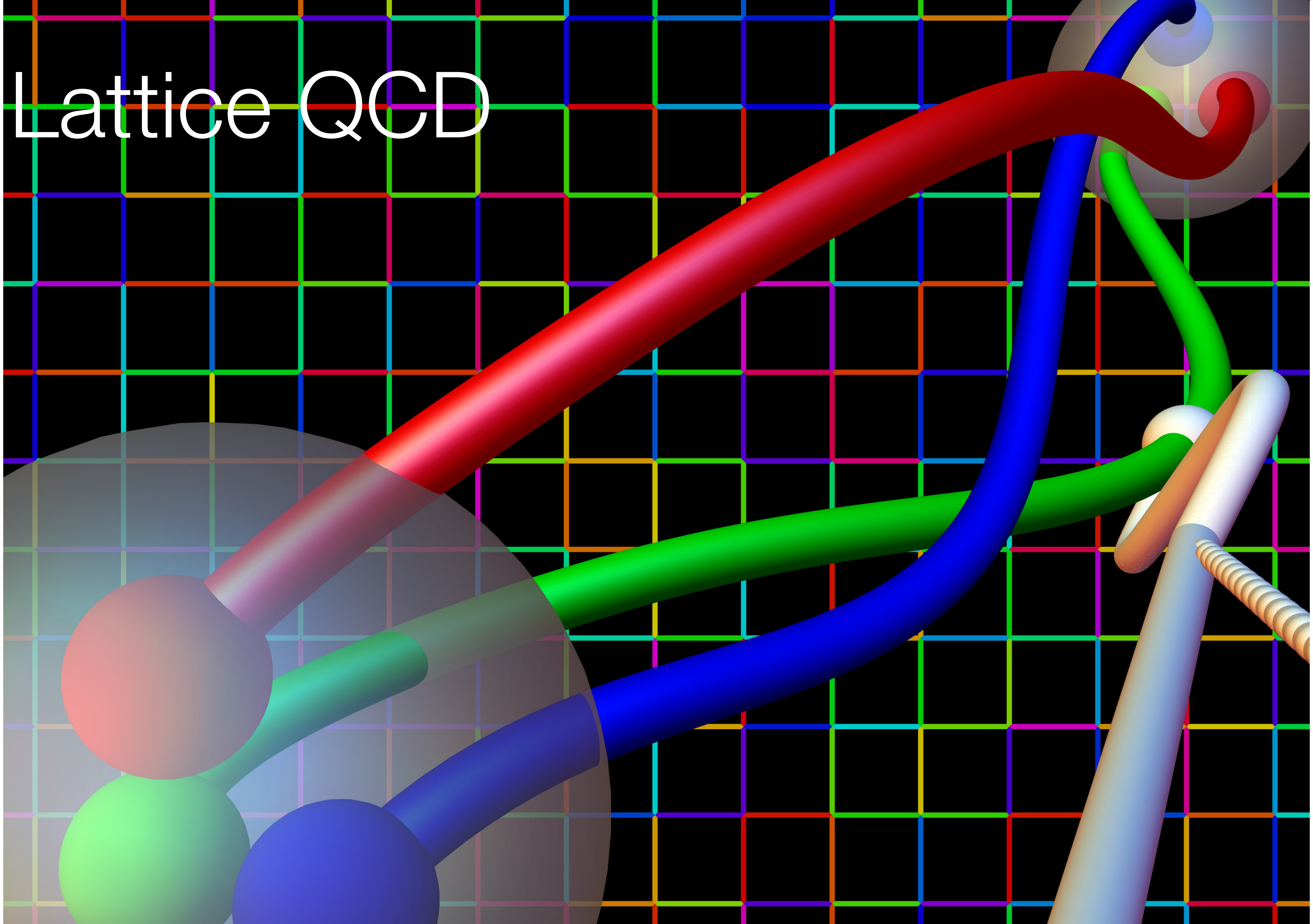




Measure g_A experimentally

Compute g_A from the SM

Lattice QCD



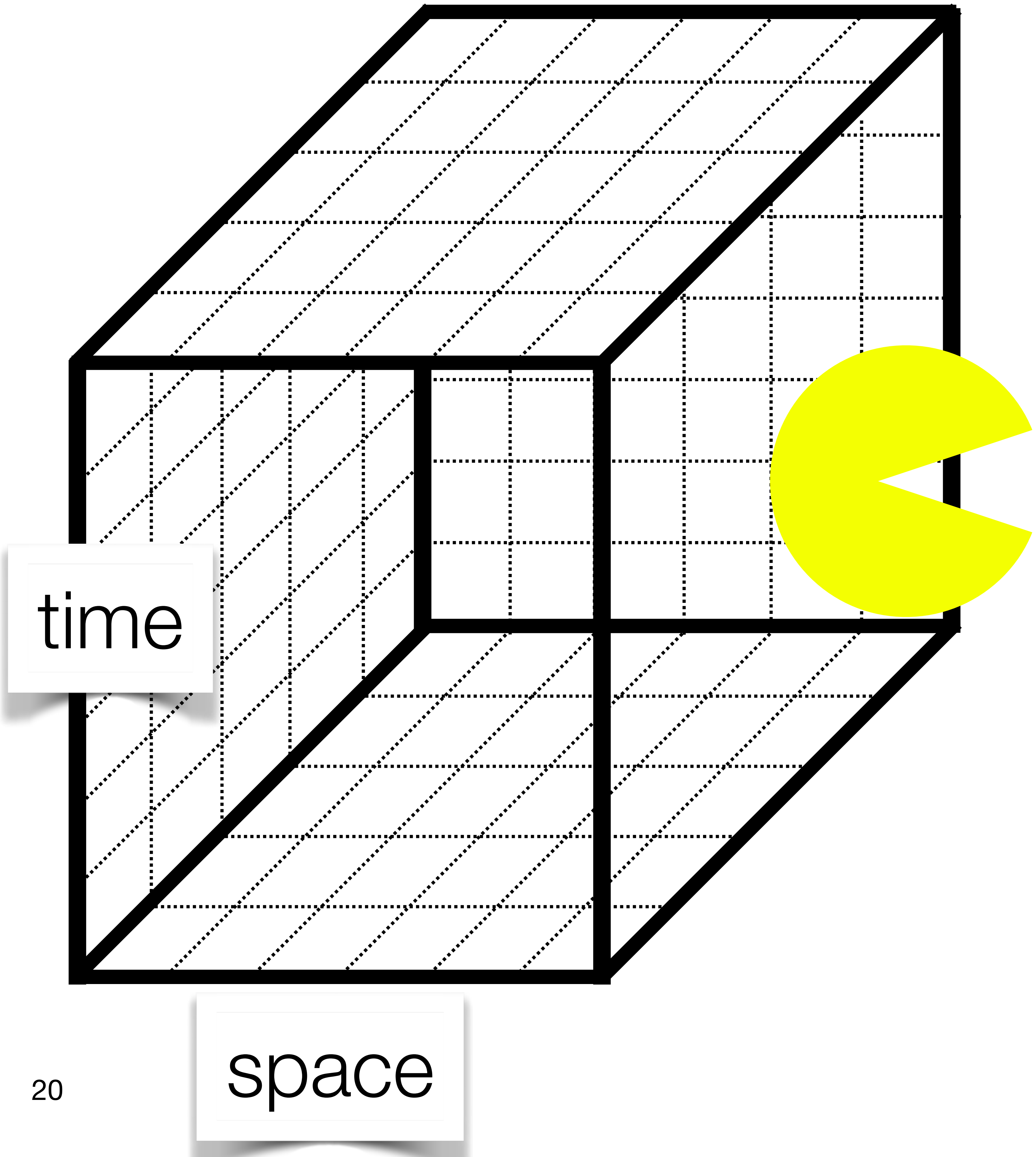
Lattice QCD

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4}F^2 + \bar{\psi}(i\not{D} + m)\psi$$

$$\mathcal{Z} = \int \mathcal{D}\psi\, \mathcal{D}\bar{\psi}\, \mathcal{D}U e^{-S[\bar{\psi},\psi,U]}$$

$$= \int \mathcal{D}U \det(\not{D}[U] + m) e^{-S[U]}$$

lattice
finite volume



Lattice QCD

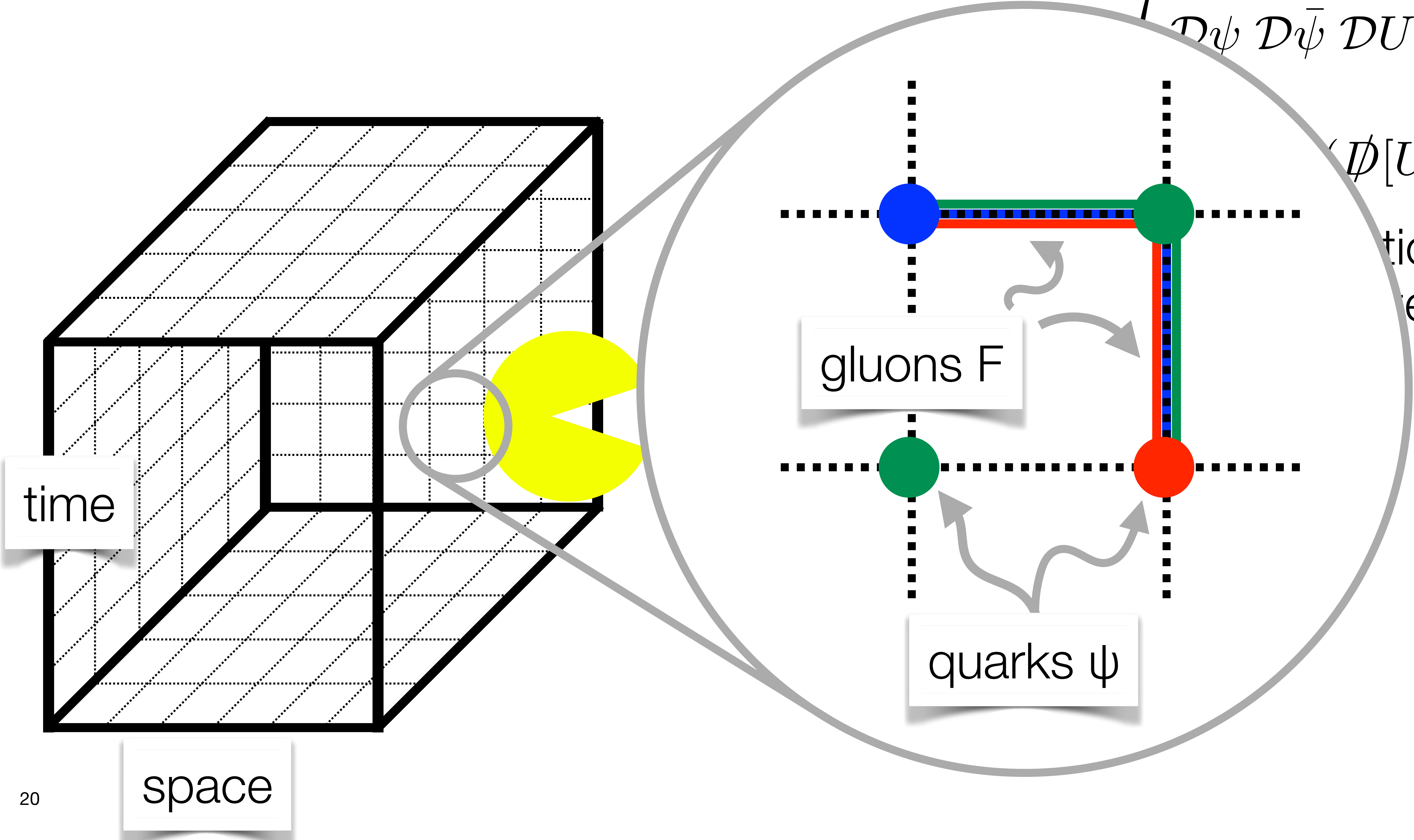
$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4}F^2 + \bar{\psi}(i\not{D} + m)\psi$$

$$\int \mathcal{D}\psi\, \mathcal{D}\bar{\psi}\, \mathcal{D}U e^{-S[\bar{\psi},\psi,U]}$$

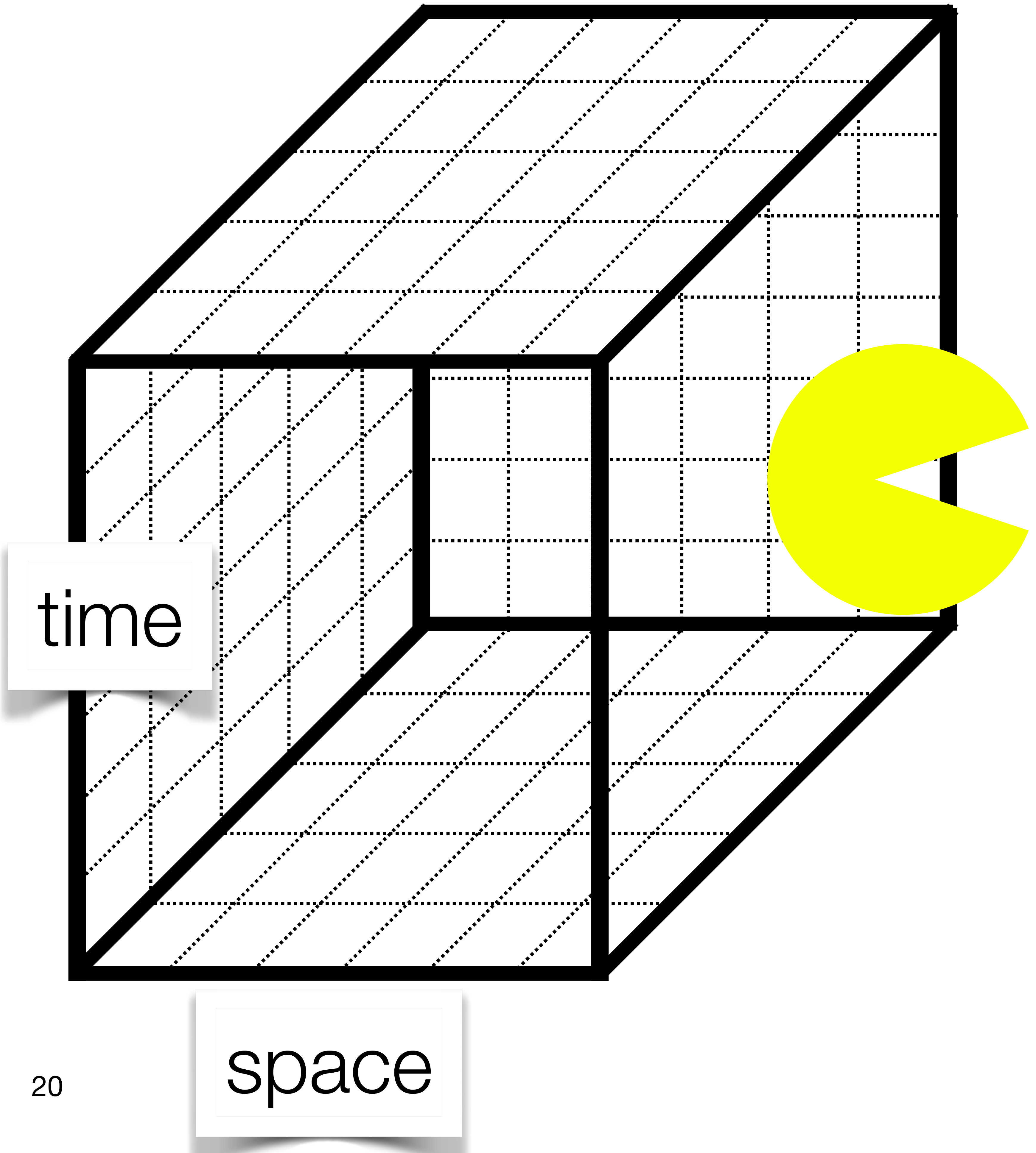
$$(\not{D}[U] + m)e^{-S[U]}$$

tice

e volume



Lattice QCD



$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4}F^2 + \bar{\psi}(i\not{D} + m)\psi$$

$$\mathcal{Z} = \int \mathcal{D}\psi\, \mathcal{D}\bar{\psi}\, \mathcal{D}U e^{-S[\bar{\psi},\psi,U]}$$

$$= \int \mathcal{D}U \underbrace{\det(\not{D}[U] + m)e^{-S[U]}}_{\text{Probability}}$$

$$\{U_1, U_2, U_3, \ldots, U_N\}$$

Markov Chain Monte Carlo

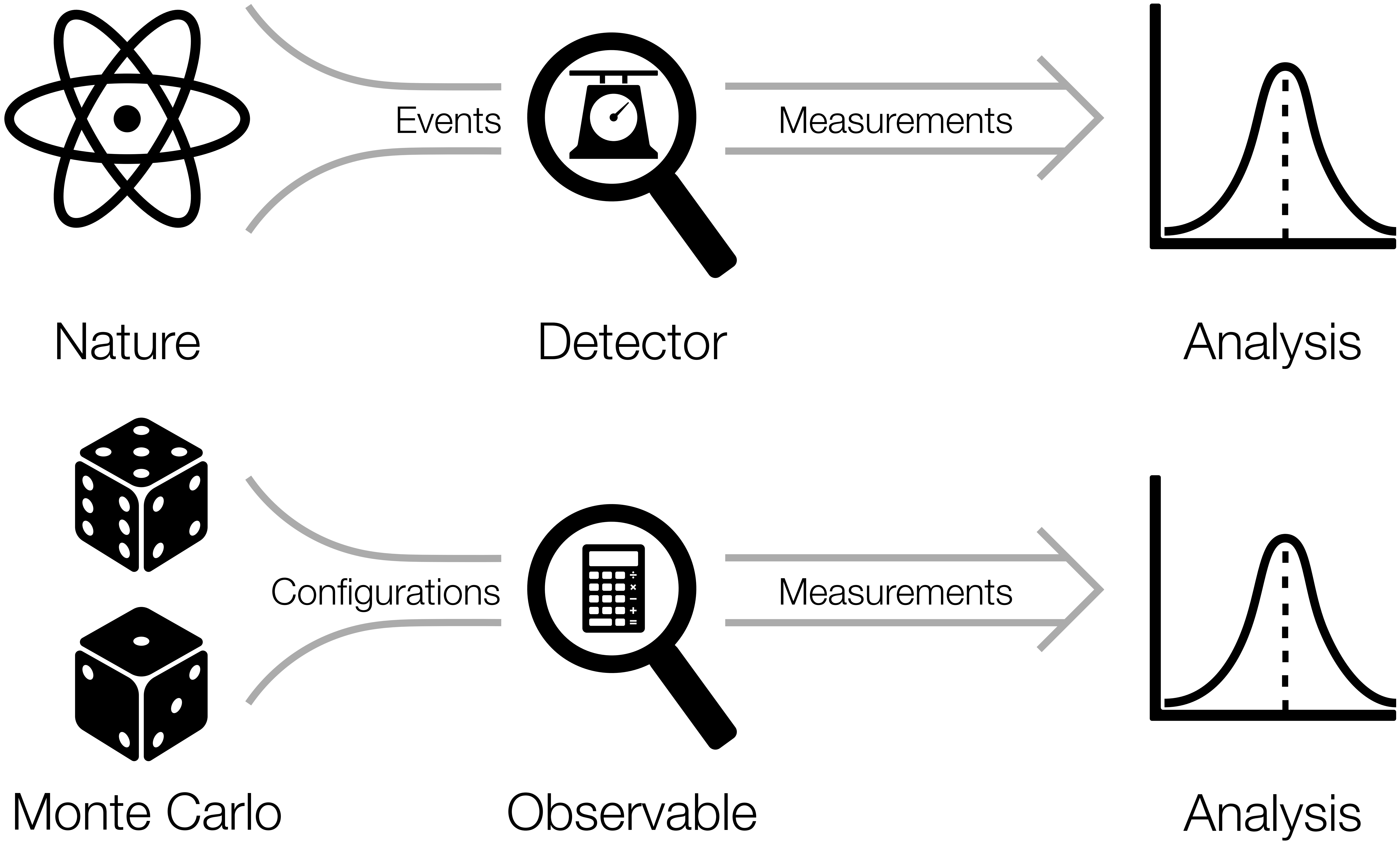
$$\langle \mathcal{O} \rangle = \frac{1}{\mathcal{Z}} \int d\mathcal{Z}\, \mathcal{O}[U]$$

$$\approx \frac{1}{N} \sum_{i=1}^{N} \mathcal{O}[U_i]$$

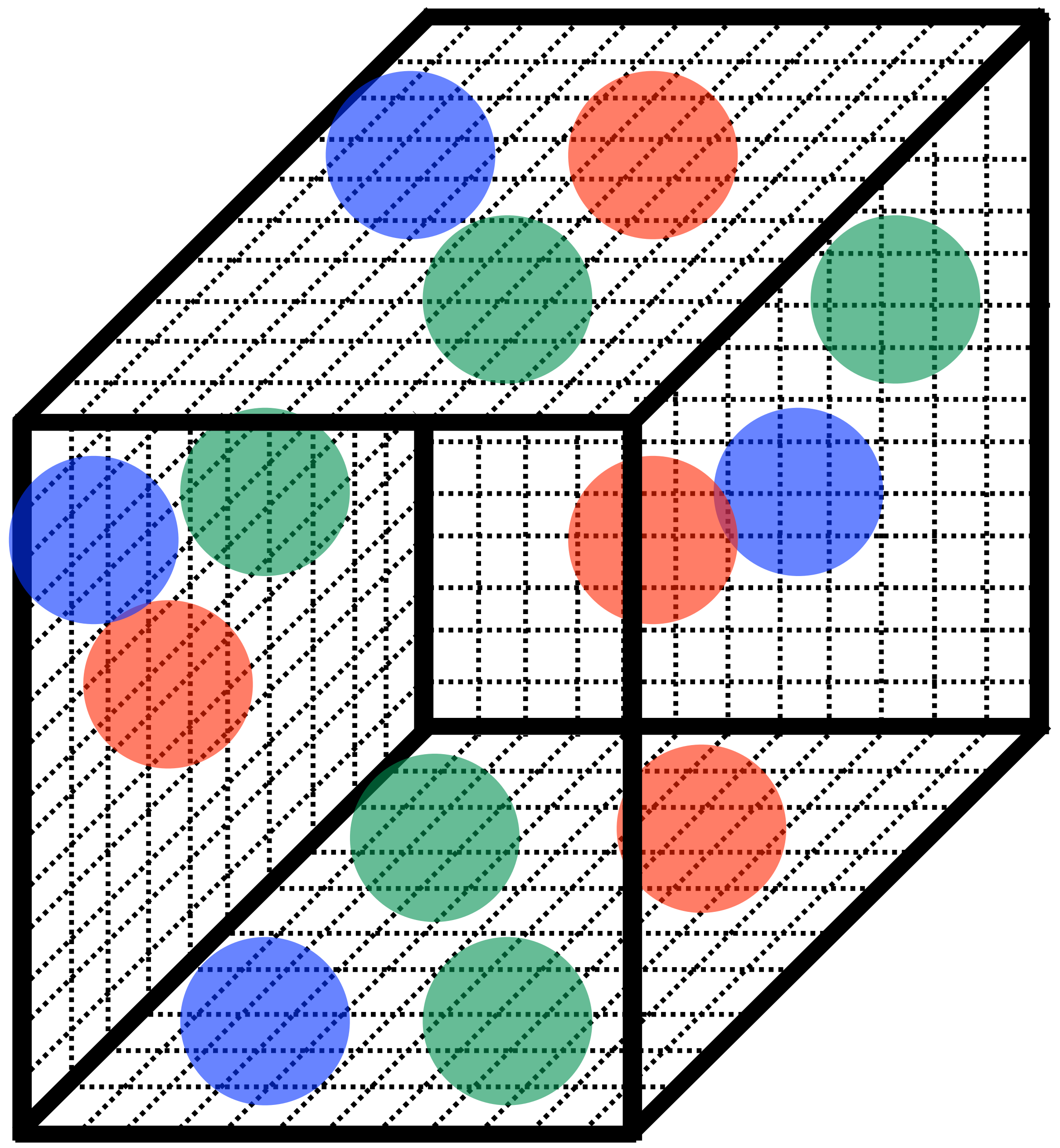
with uncertainties scaling like $\frac{1}{\sqrt{N}}$

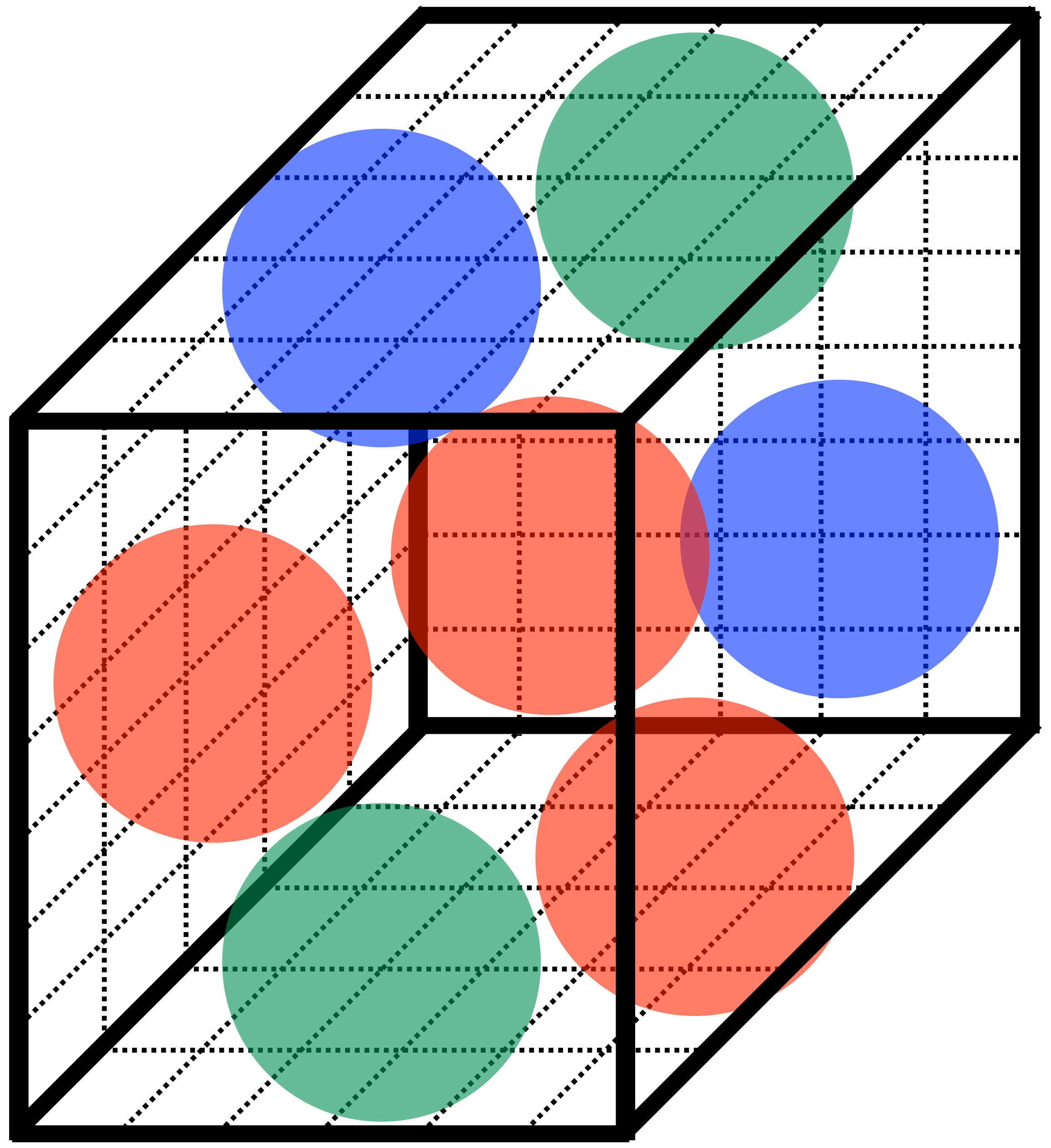
Analogy with Experiment

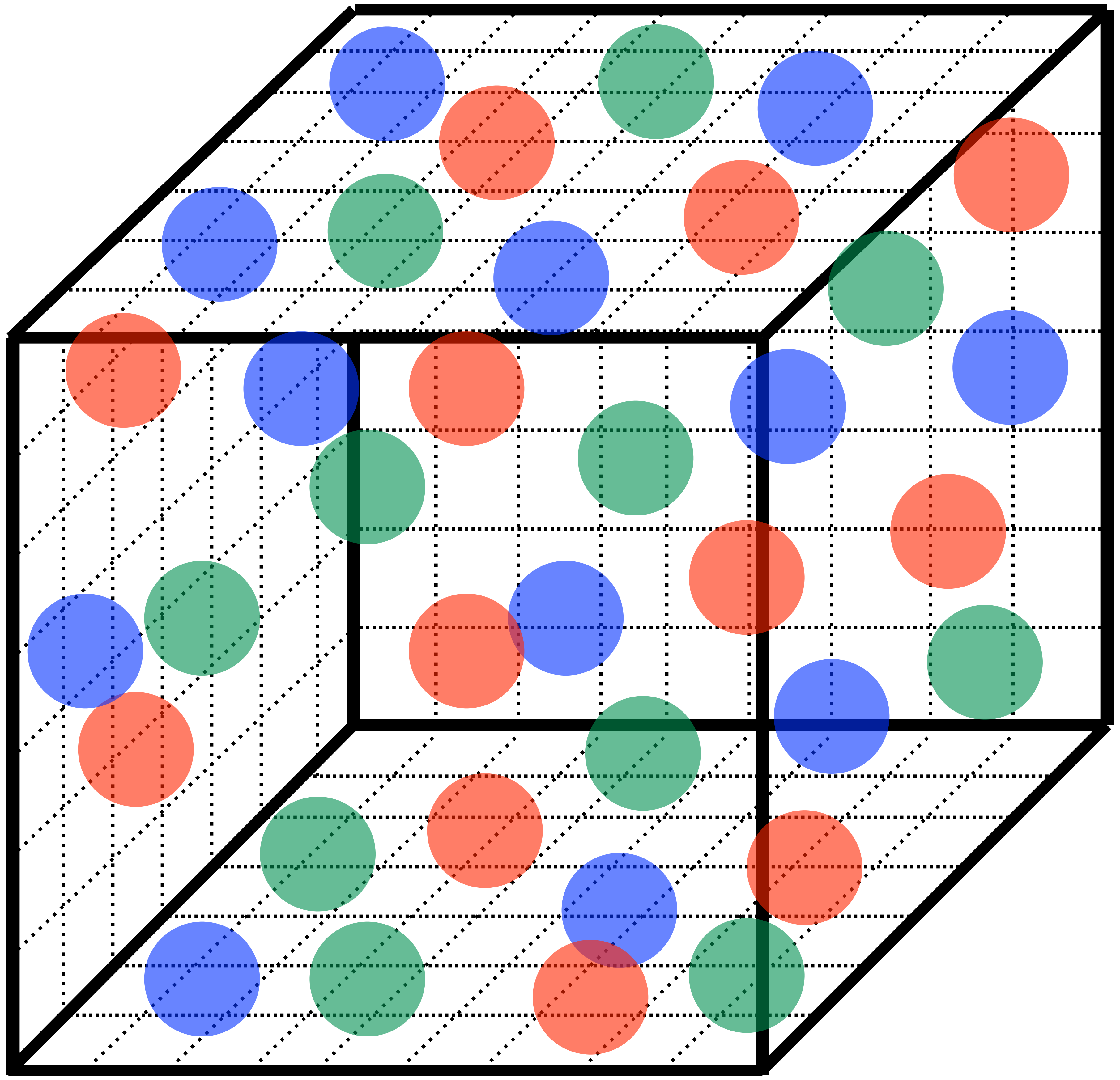
- ✓ Statistical errors are improved with run time (budget)
- ✓ Systematic errors are understood + controlled



LQCD Systematics



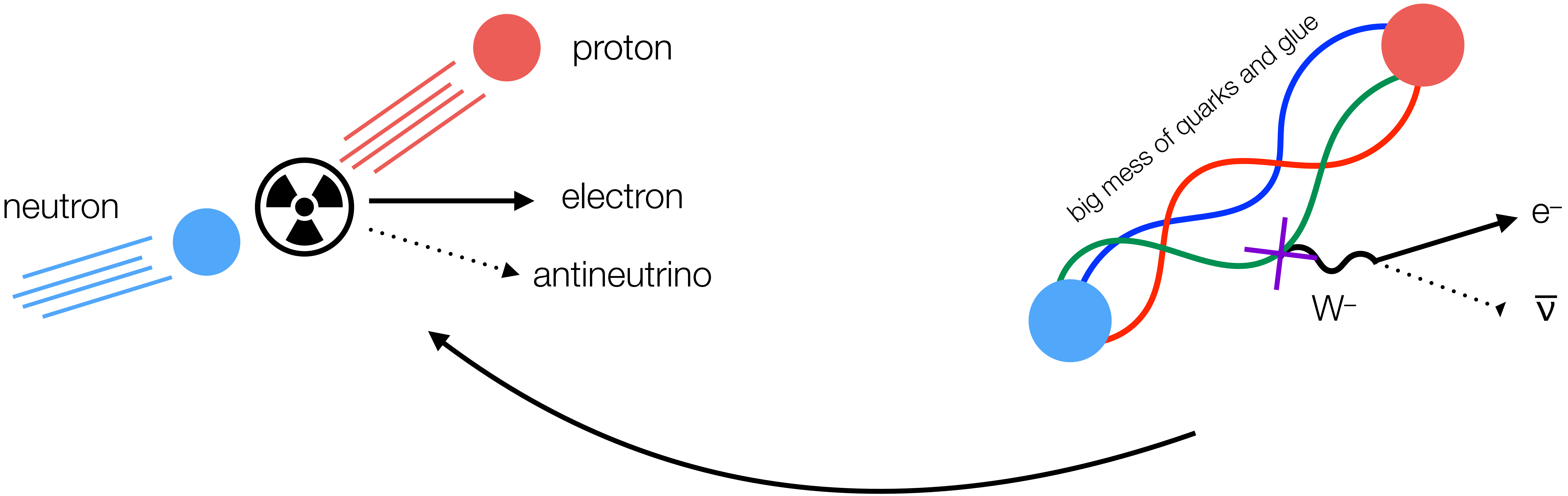




continuum limit physical quark masses infinite volume limit

High performance computing to the rescue!

How do the weak interactions trickle up?



Use the Standard Model to *predict* the nucleon axial coupling g_A

so measurements can tell us if there's something more.

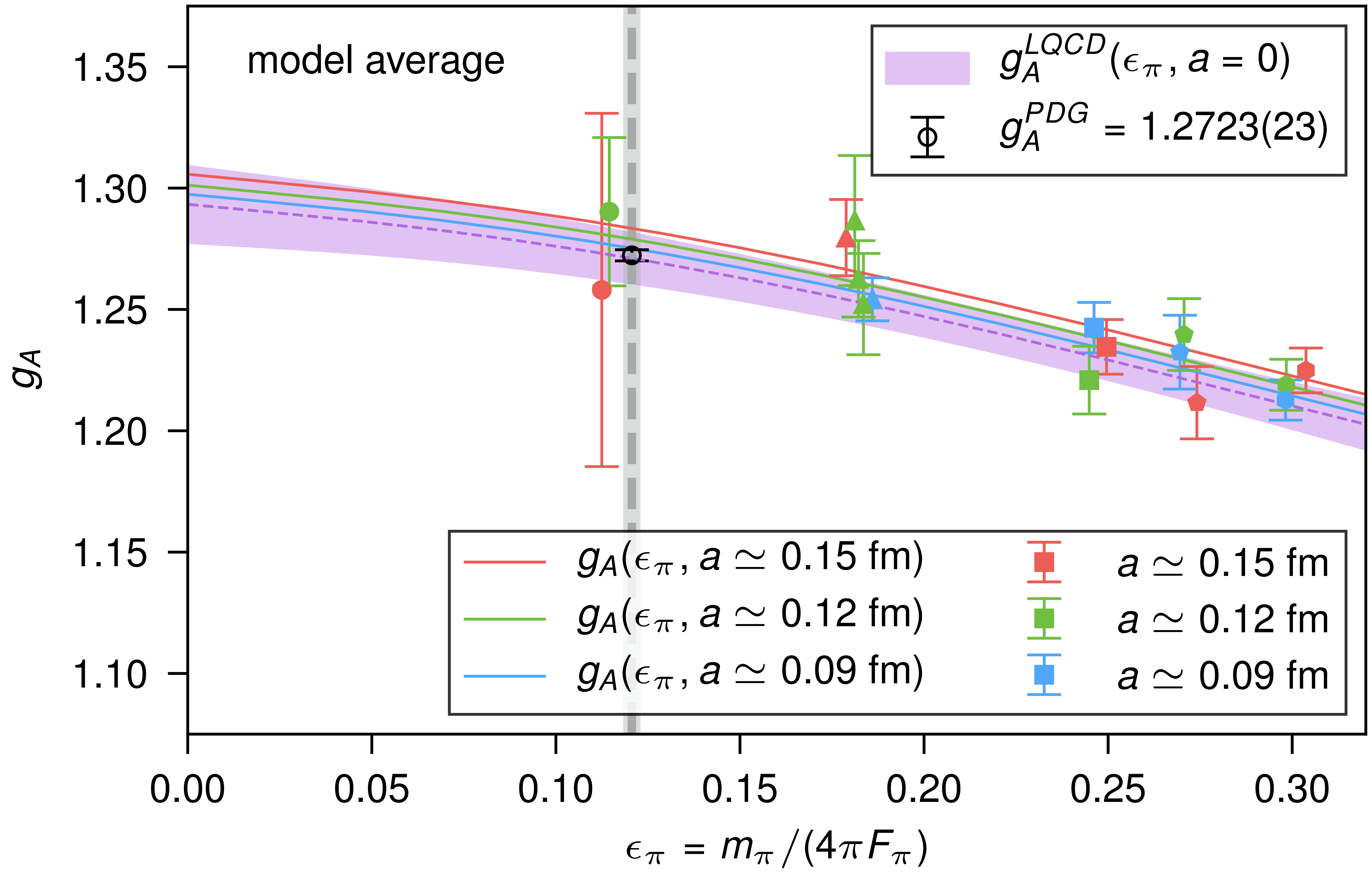
g_A^{QCD} = 1.271(13)

Nature 558:91-94, 2018 arXiv:1805.12130

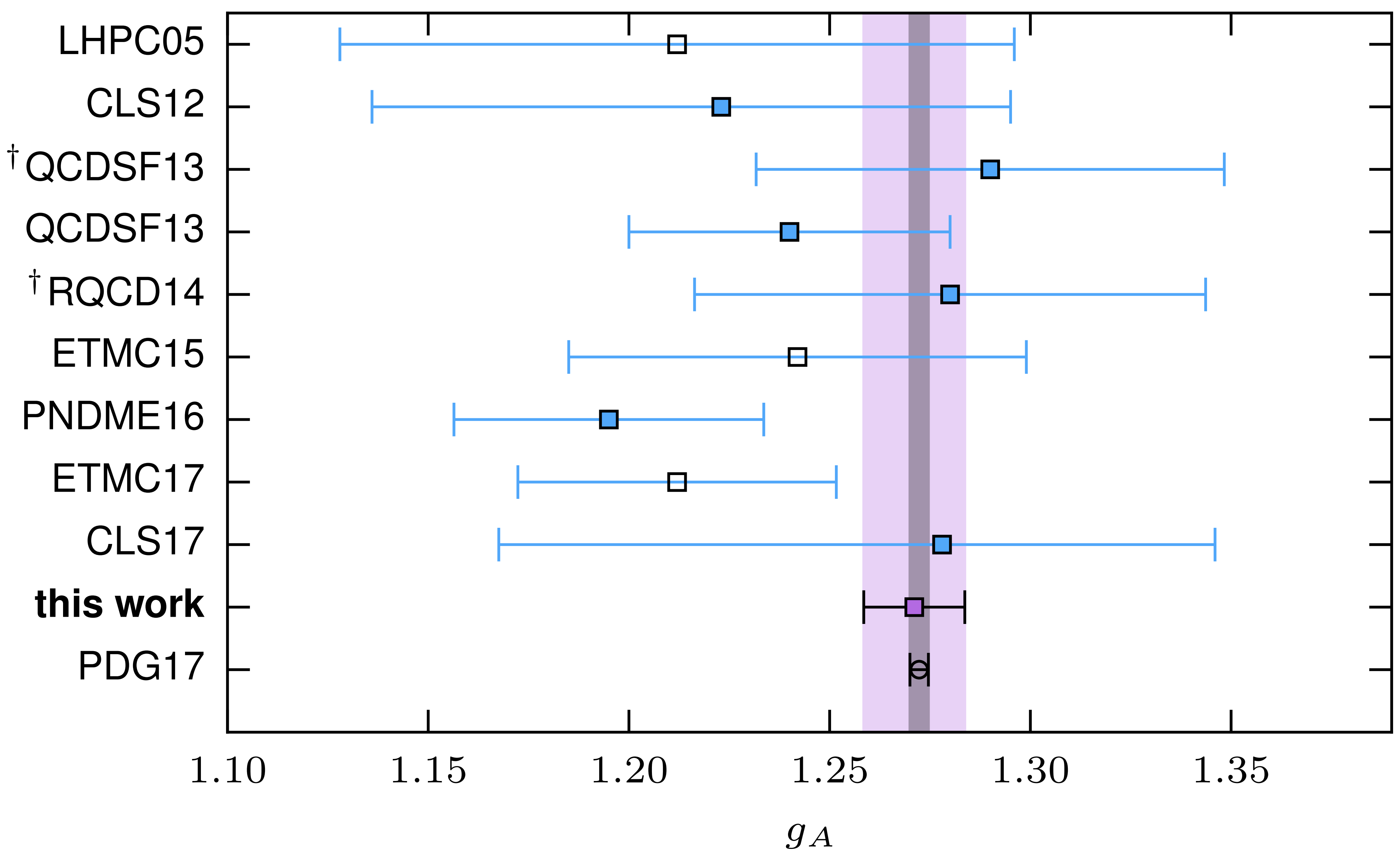
LETTER
https://doi.org/10.1038/s41586-018-0161-8

A per-cent-level determination of the nucleon axial coupling from quantum chromodynamics

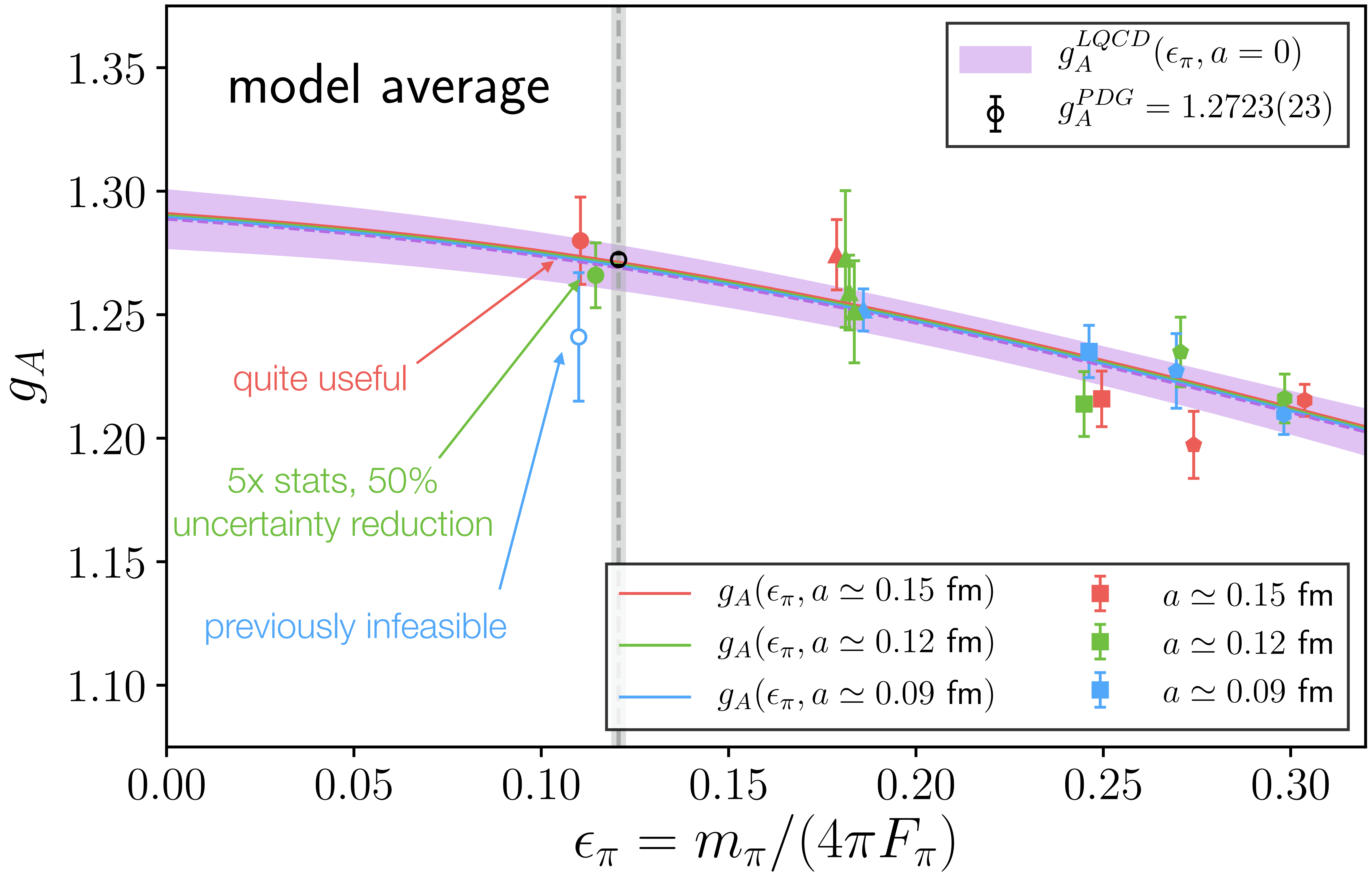
C. C. Chang[1,2], A. N. Nicholson[1,3,4], E. Rinaldi[1,5,6], E. Berkowitz[6,7], N. Garron[8], D. A. Brantley[1,6,9], H. Monge-Camacho[1,9], C. J. Monahan[10,11], C. Bouchard[9,12], M. A. Clark[13], B. Joó[14], T. Kurth[1,15], K. Orginos[9,16], P. Vranas[1,6] & A. Walker-Loud[1,6*]



- New methods
- Performant code
- Cutting-edge supercomputers



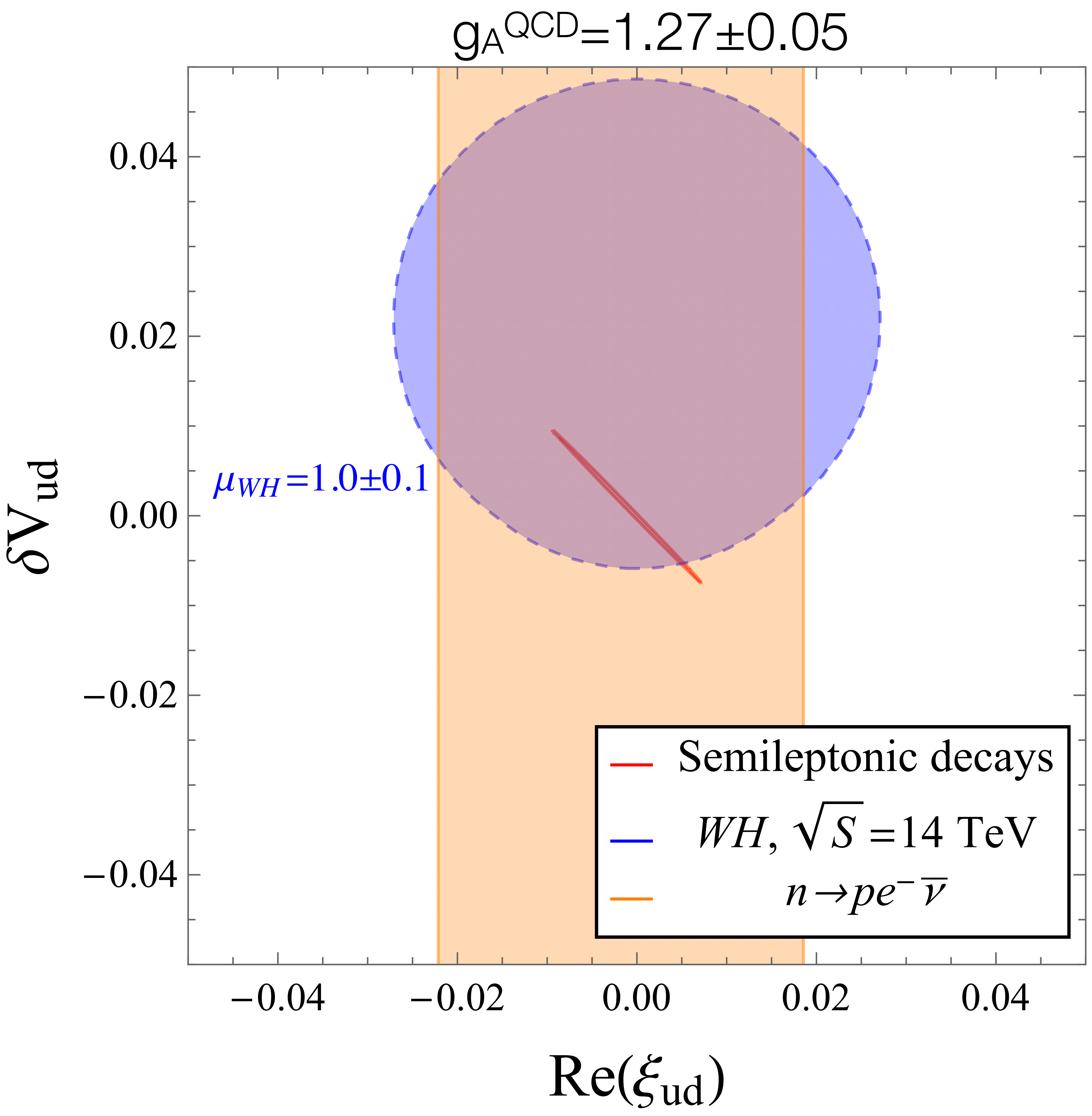
Better, faster, stronger

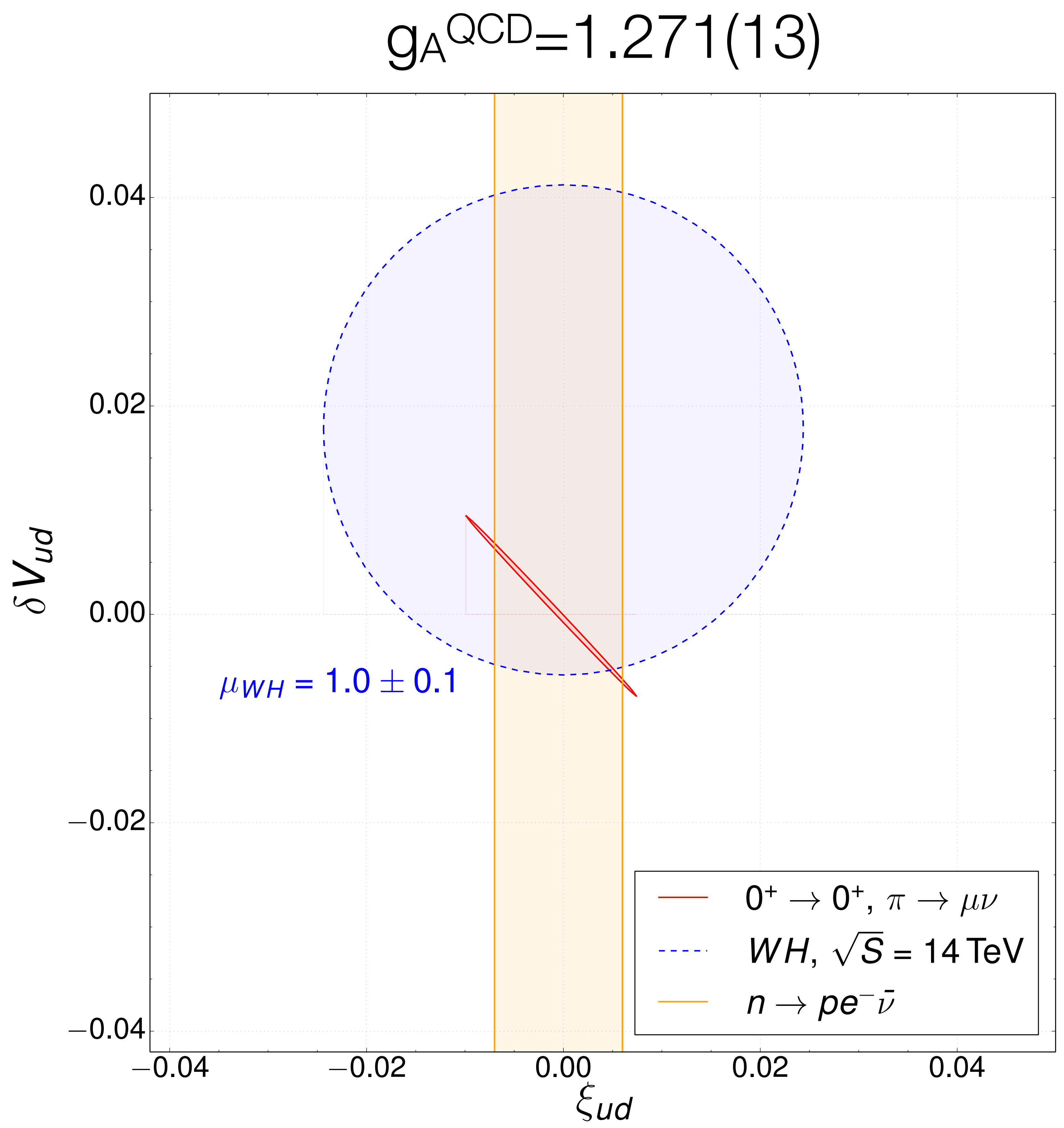


- In 2.5 weekends on Sierra we accomplished more than 5 times as much as a year on Titan
- New machines are **disruptively faster**.
- The golden age of lattice QCD is ~~just around the corner~~ here!

The hunt for new physics

Alioli, Cirigliano, Dekens, de Vries, Mereghetti JHEP 1705 (2017) 086 arXiv:1703.04751





New CKM-like physics

New right-handed currents

Fundamental Symmetries

		Electromagnetism	Weak	Strong
C	Charge	✓	✗	✓
P	Parity	✓	✗ θ-τ	✓
T	Time Reversal	✓	✗ $K\bar{K}$	✓
L	Lepton number	✓	✓	
B	Baryon number	✓	✓	✓

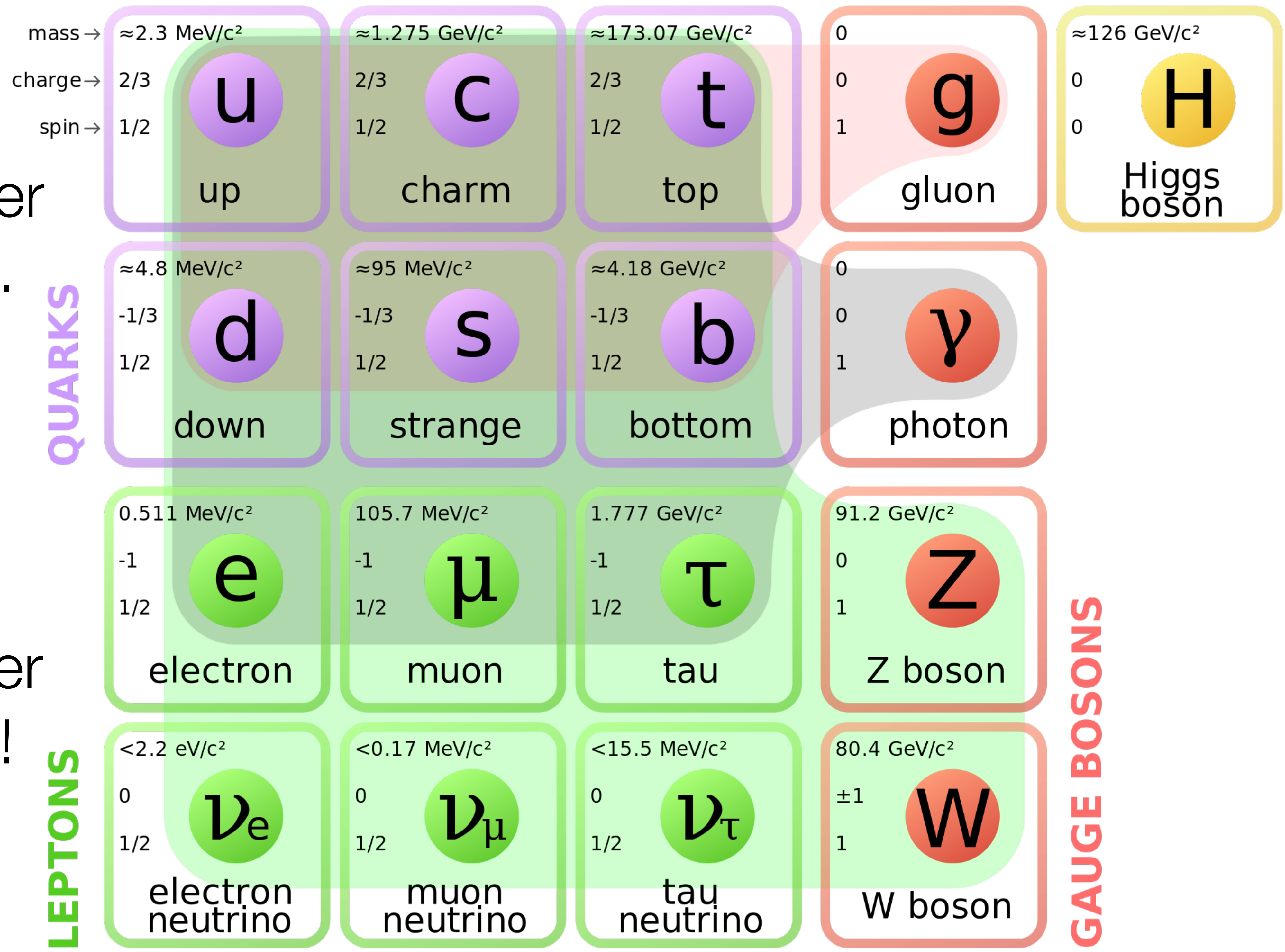
EFTs + Fundamental Symmetry

The Standard Model

- A *quantum field theory* with particular *symmetries.*
- No gravity, **neutrino masses + oscillations**, **dark matter**
- Otherwise, the ultimate description of every physical phenomenon **thus far observed**!

Baryon number is conserved.

Lepton number is conserved!



But what comes next?

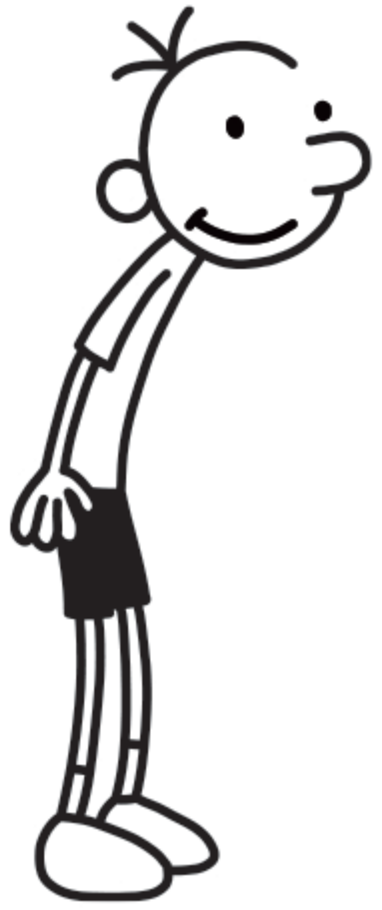
Beyond the Standard Model?

Colgate-Palmolive

DC Comics

Francisco de Goya

Technicolor Group



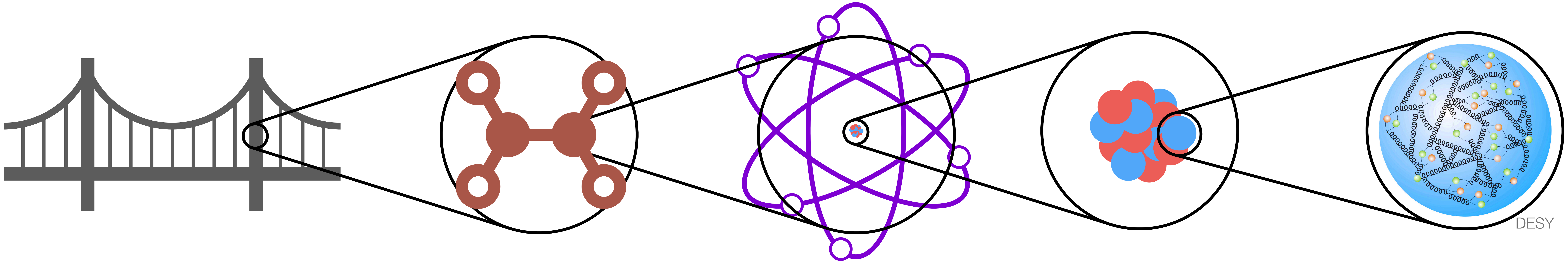
Jeff Kinney

Getty Images iStock / Alexandrum 79

Standard Model as an EFT

- We can *summarize* BSM models by the effects they have on the Standard Model
- The most obvious new effects will be ones where 'fundamental' symmetries are violated!
- Experiments search for these + can't get confused because the SM background is 0!

'Separation of scales'



Materials Scale
Human Scale

Molecular Scale

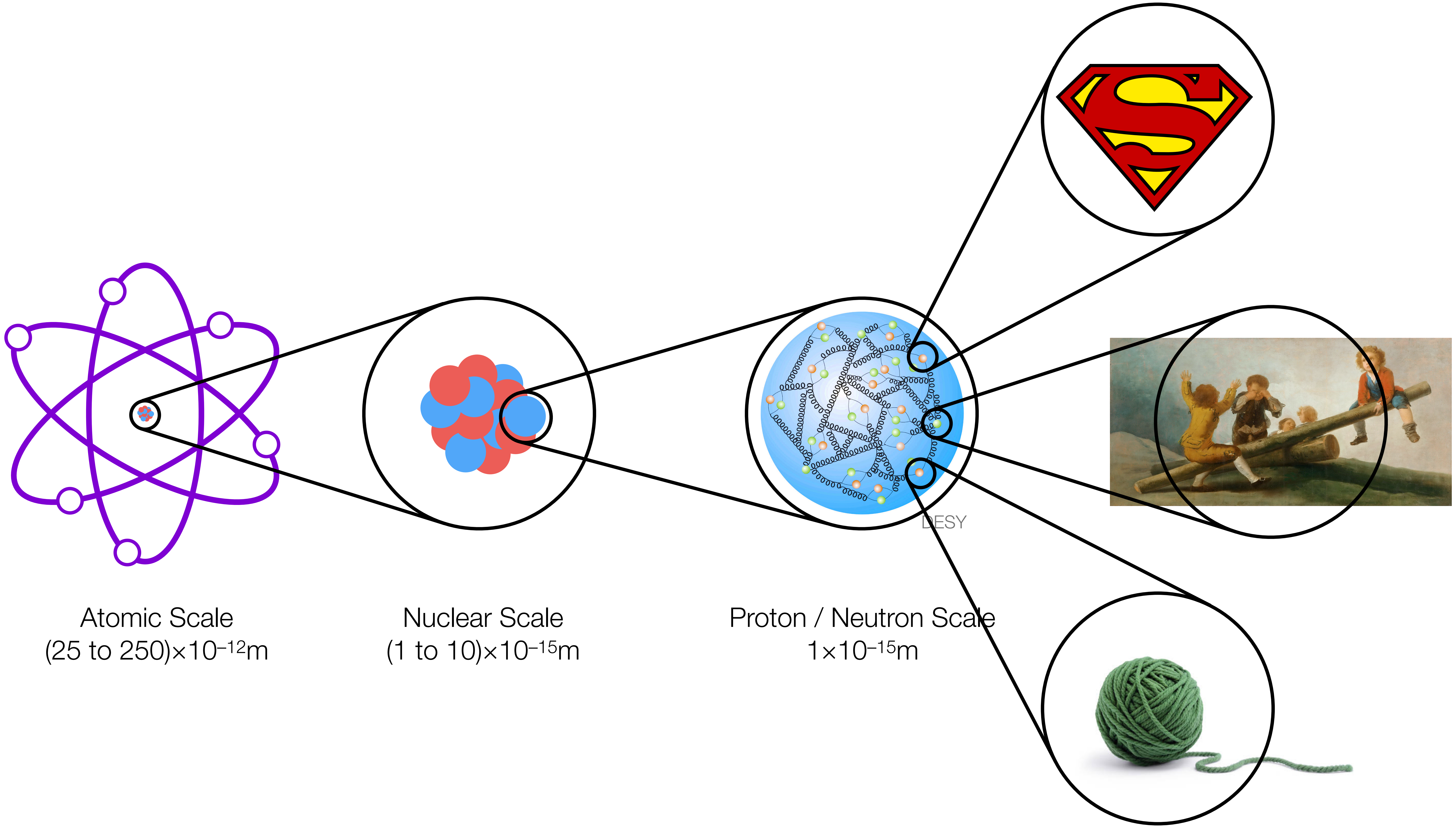
Atomic Scale
(25 to 250)$\times 10^{-12}$m

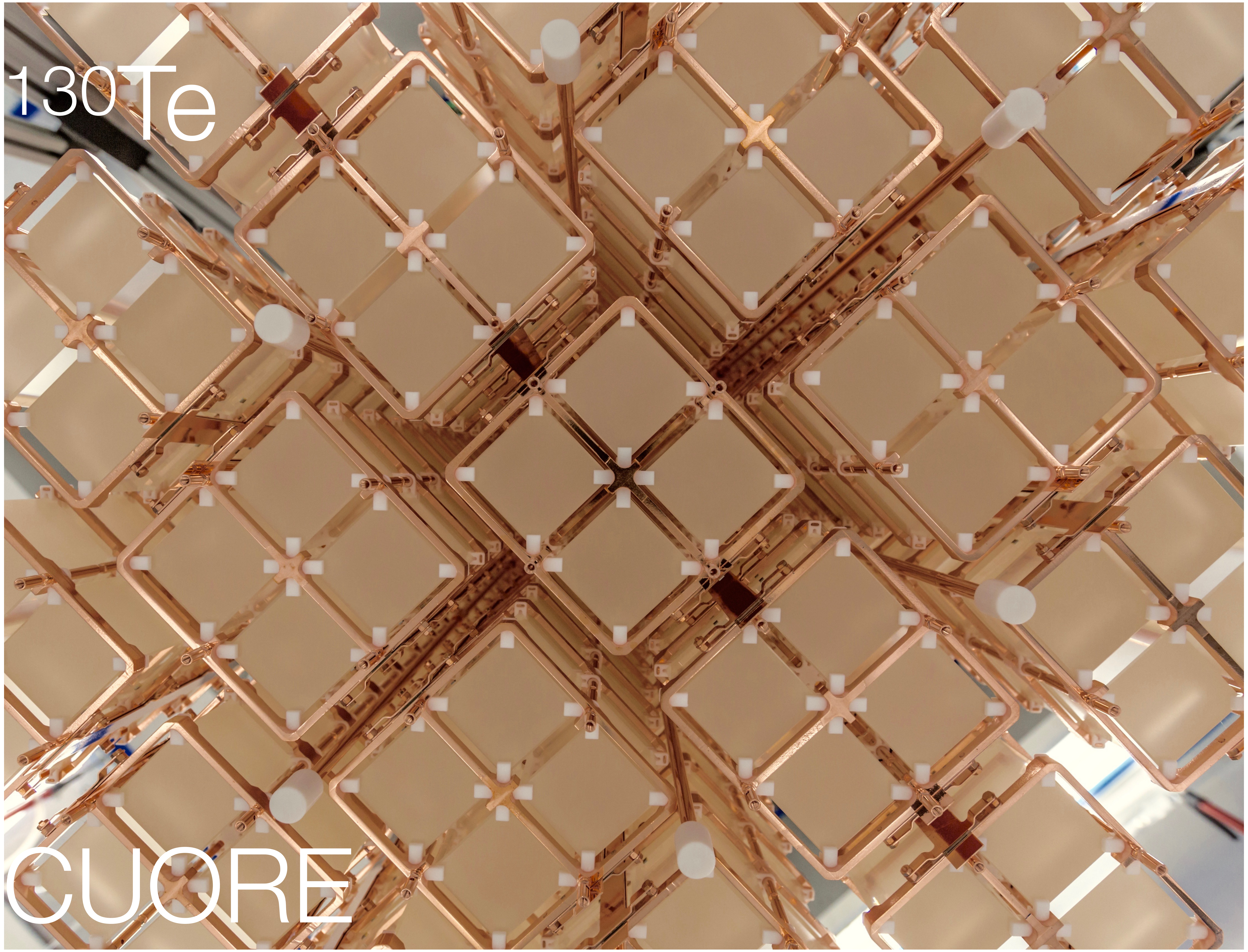
Nuclear Scale
(1 to 10)$\times 10^{-15}$m

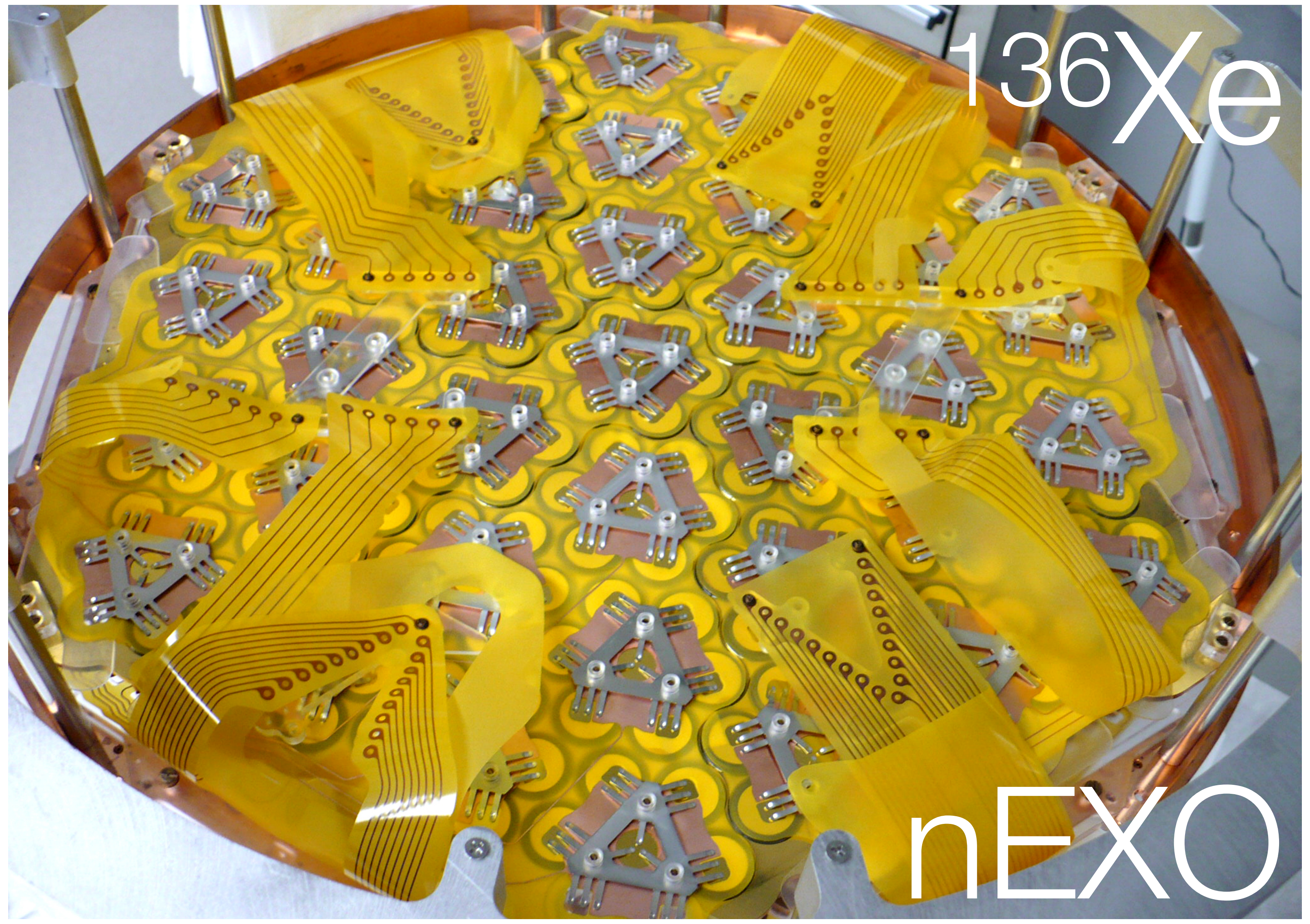
Proton / Neutron Scale
1×10^{-15}m

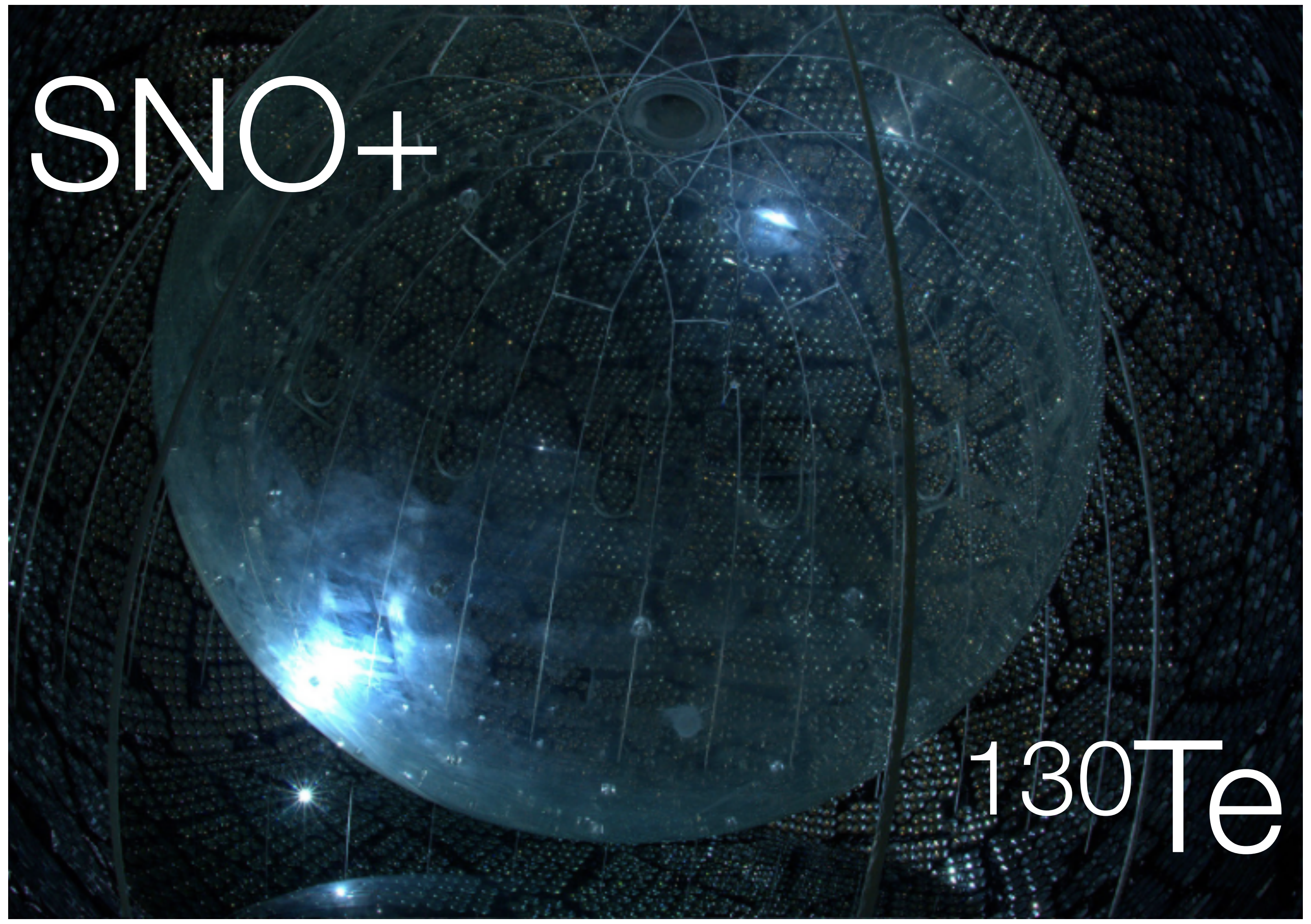
Standard Model as an EFT

What if...?







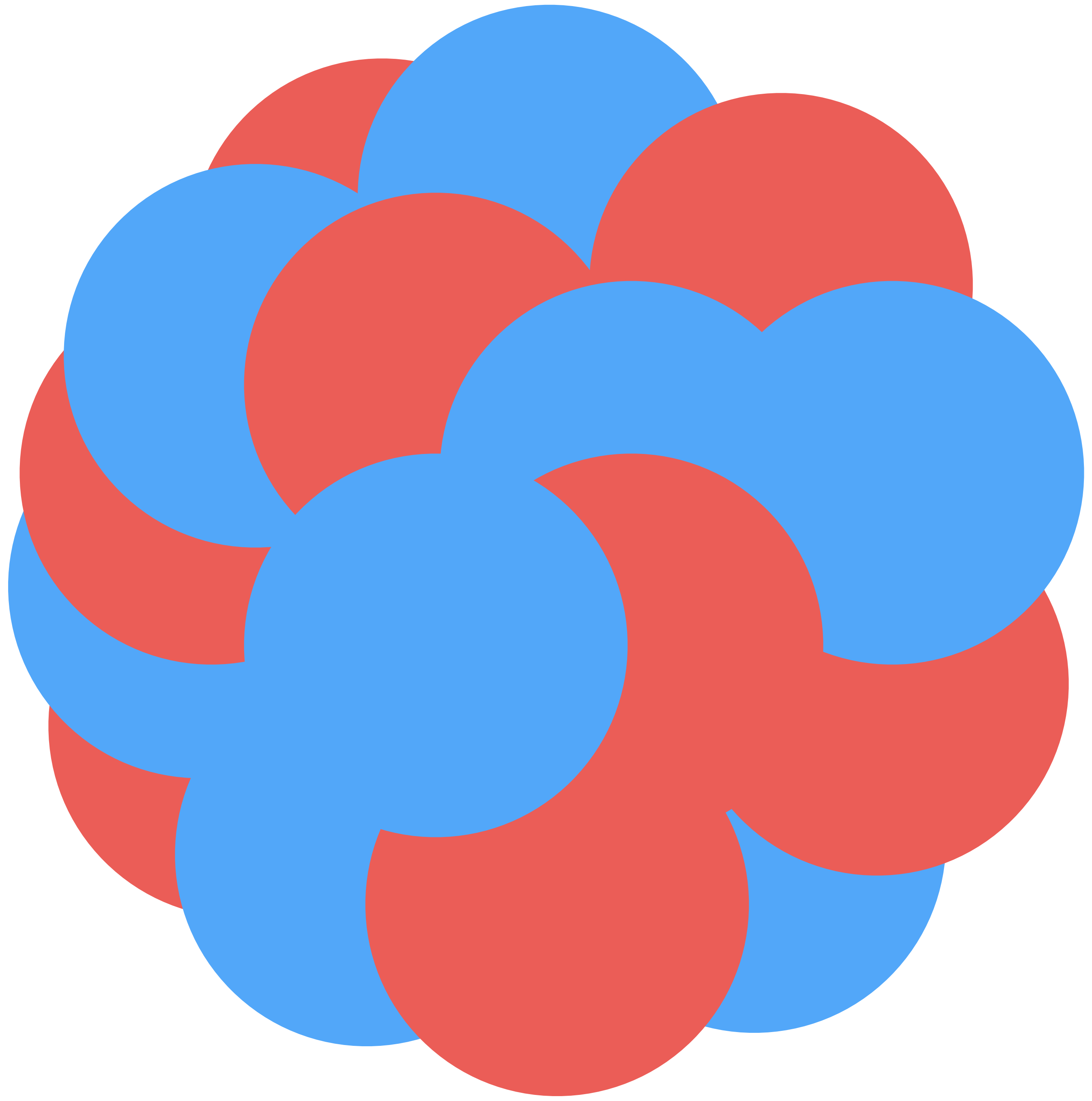


Hunting Lepton Number Violation

Double β Decay and Lepton Number Violation

nobelprize.org

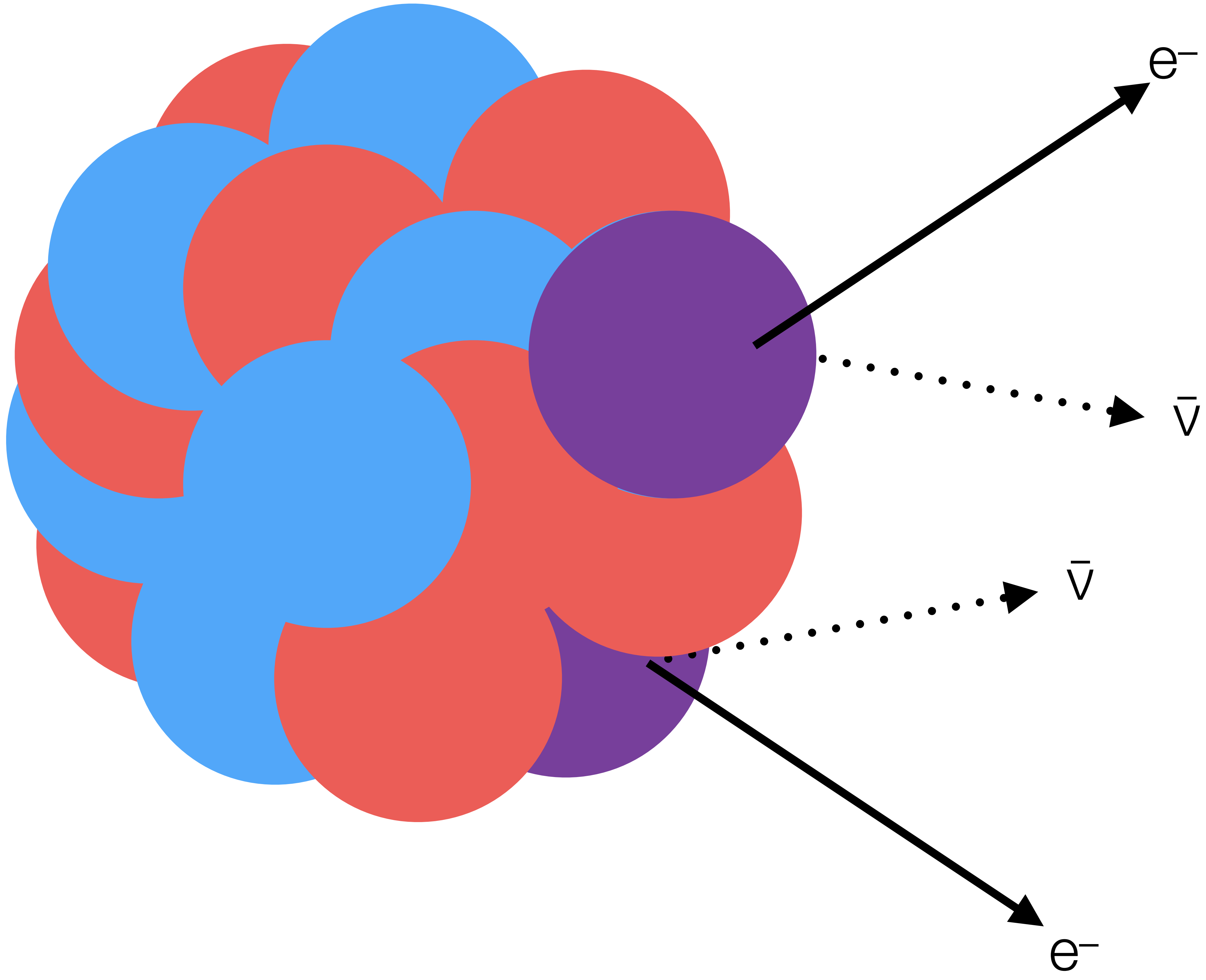
Goeppert Mayer 1935



Double β Decay and Lepton Number Violation


nobelprize.org

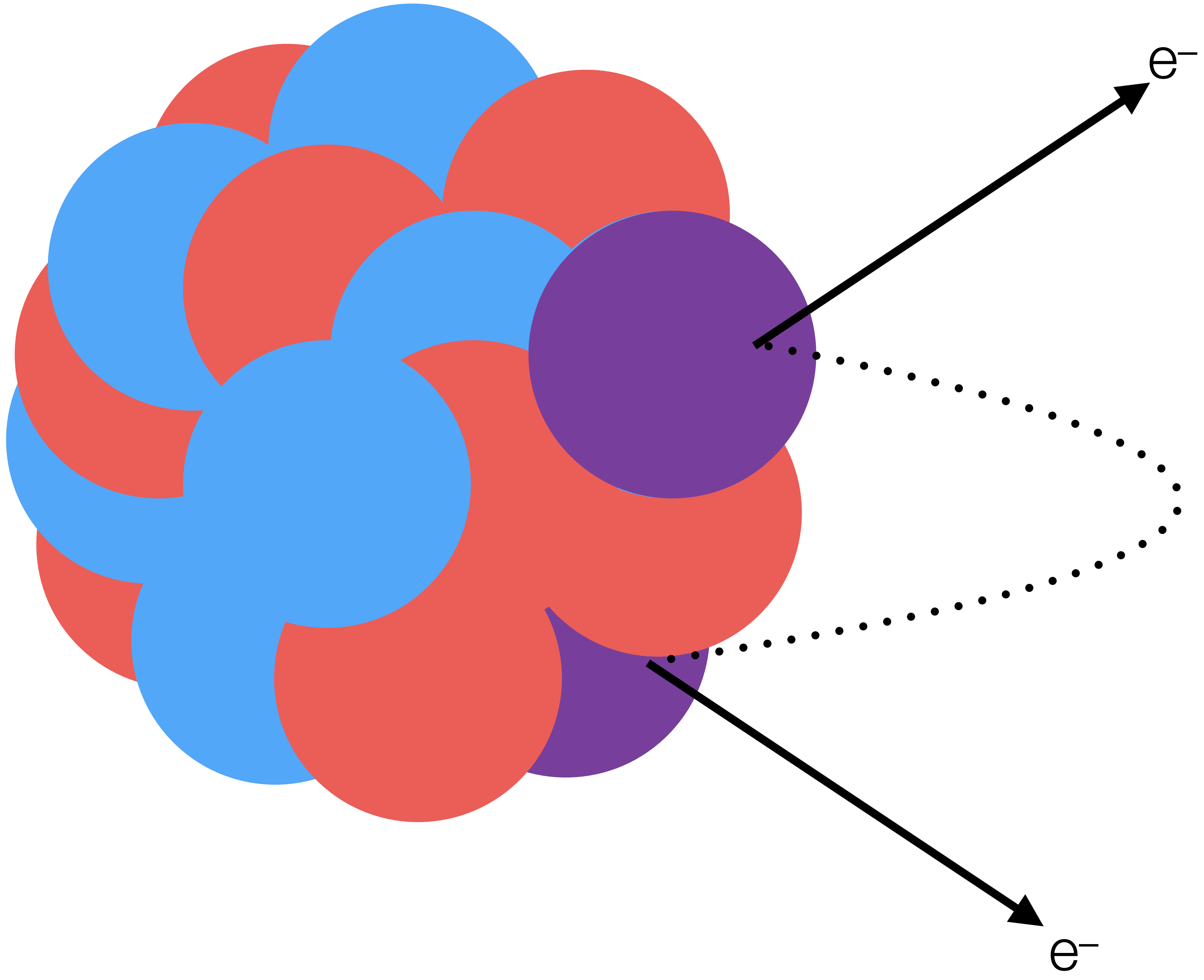
Goeppert Mayer 1935

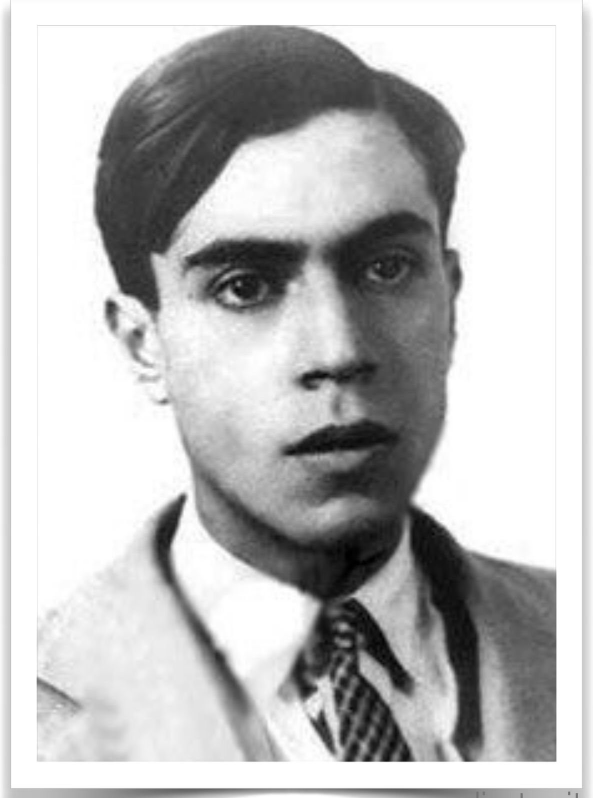


Double β Decay and Lepton Number Violation

nobelprize.org

Goeppert Mayer 1935





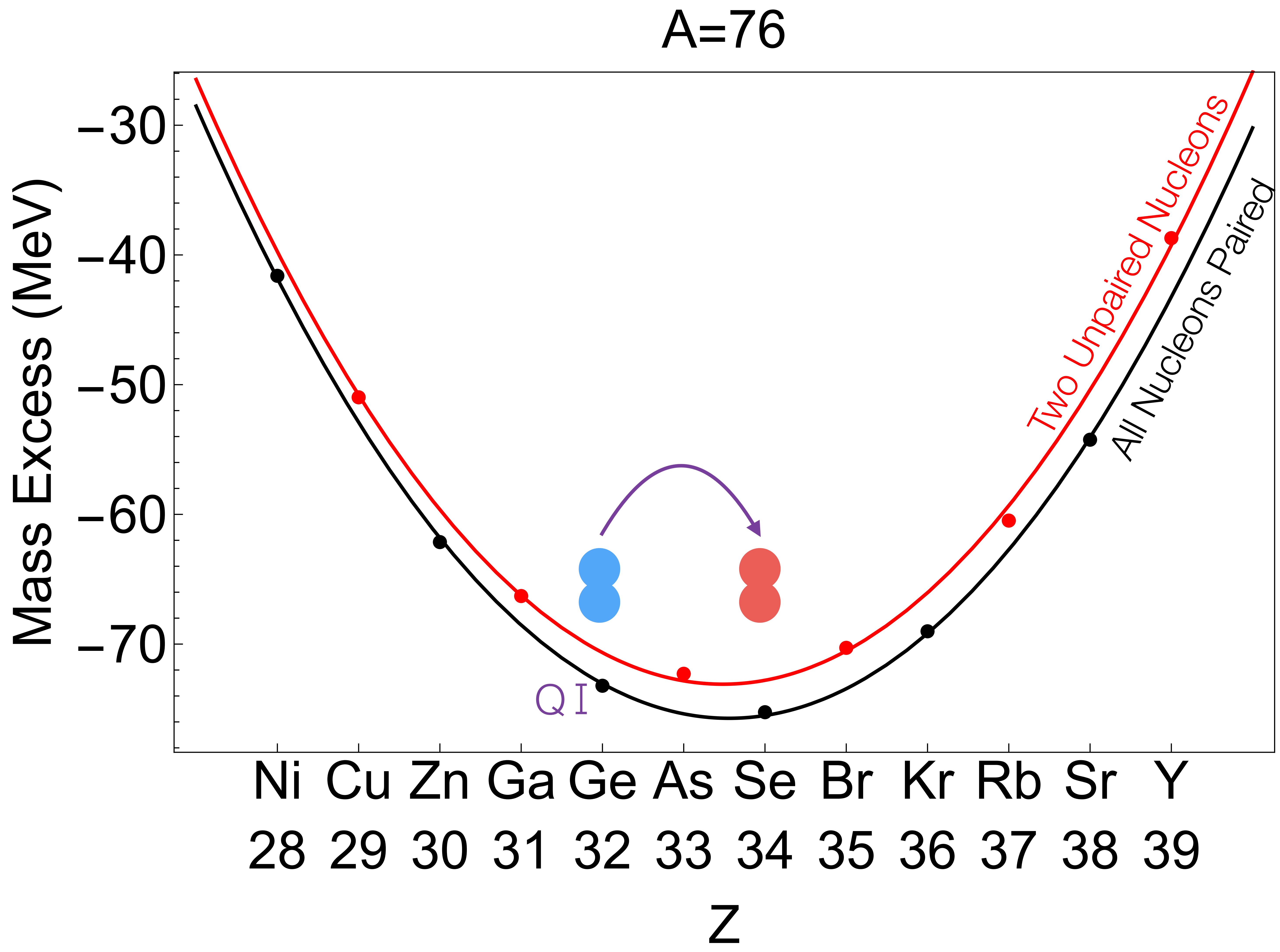
radiortm.it

Majorana 1937

alchetron.com

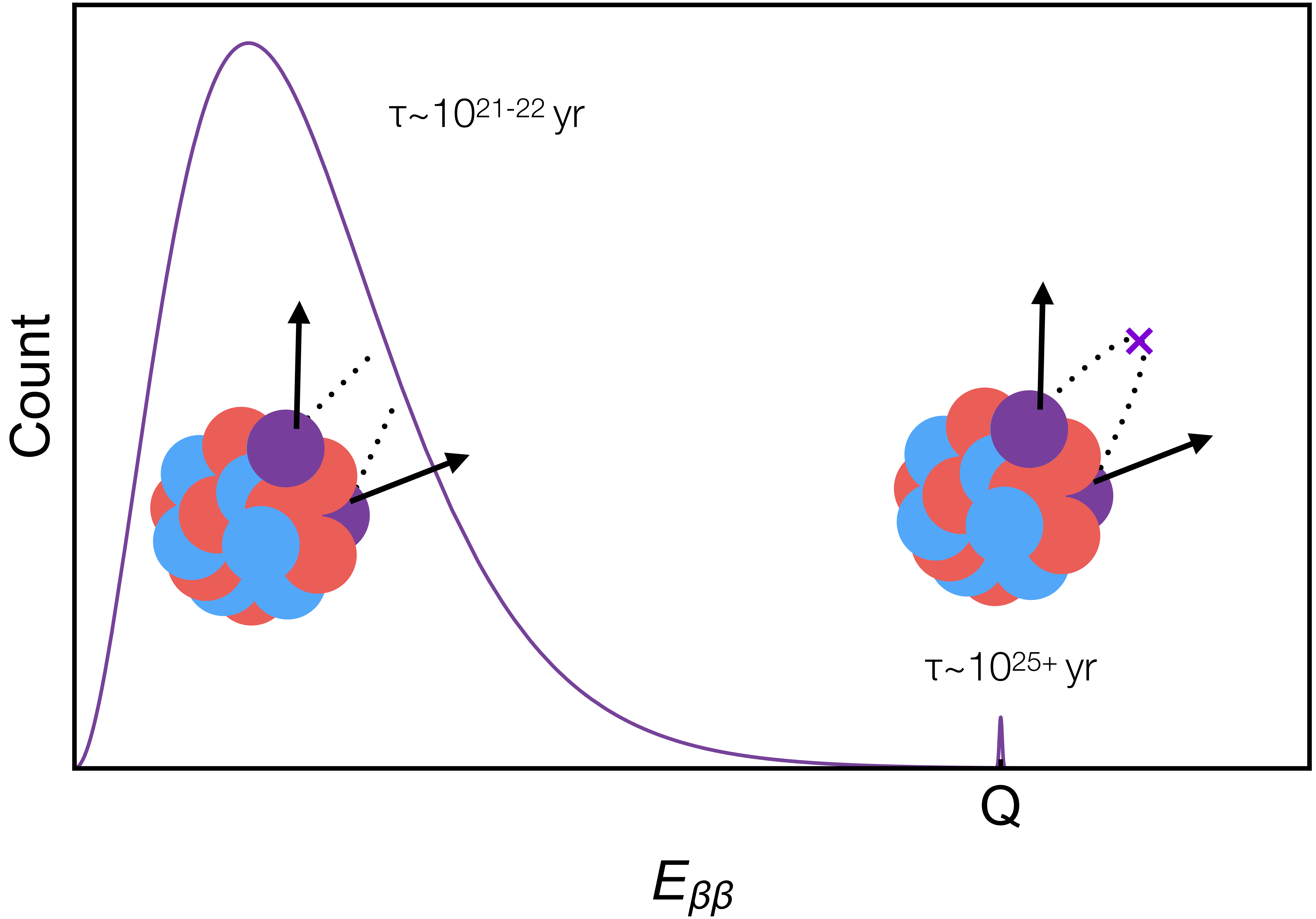
Furry 1939

Nuclear Laboratory

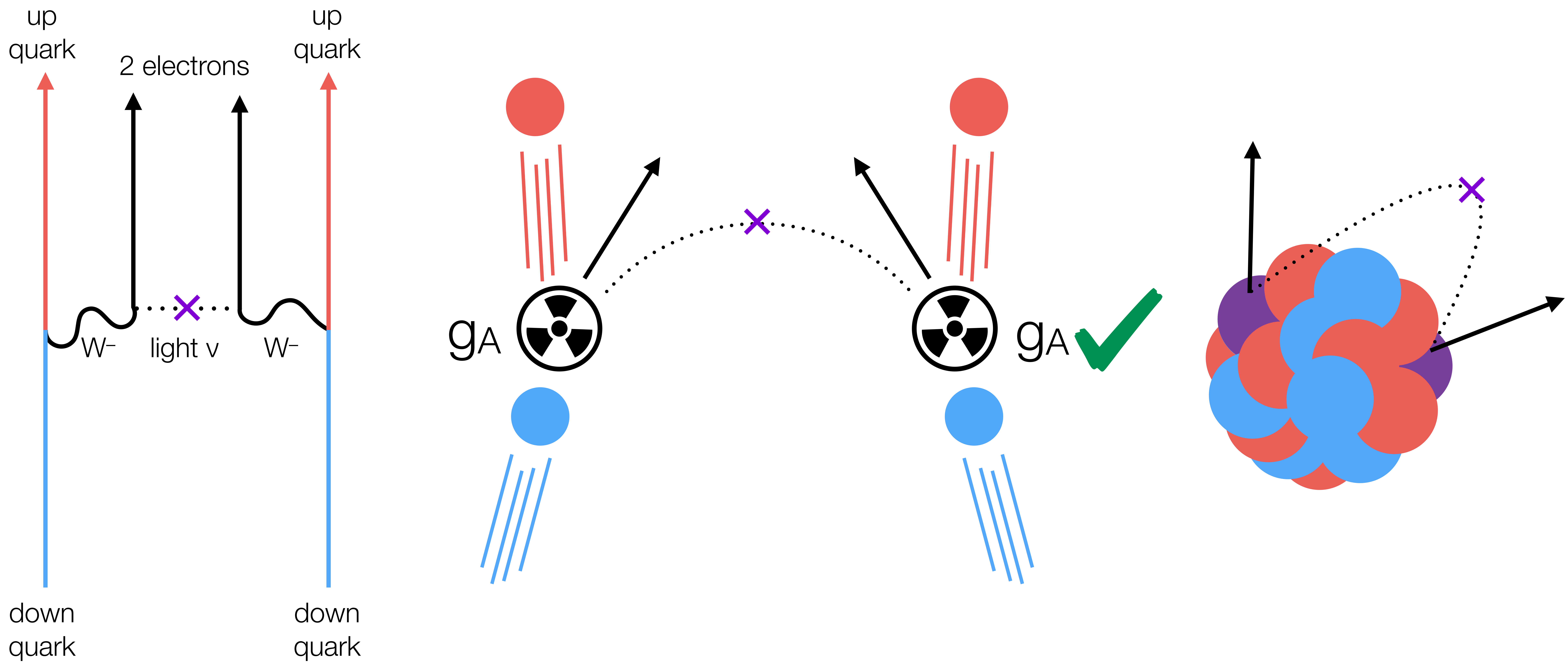


- Energetically impossible to have a single decay, but possible to have two simultaneous decays.
- Energy of the leptons sums to Q.

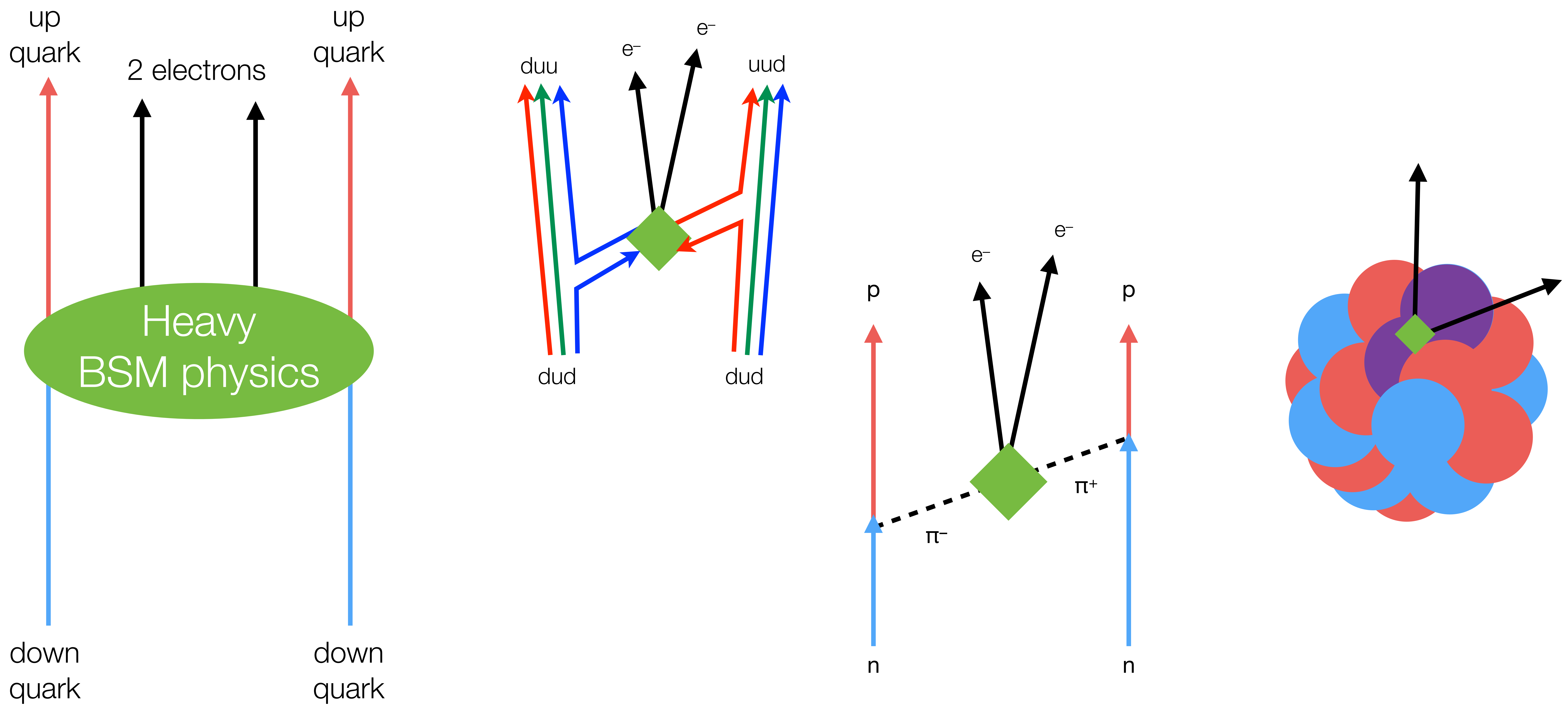
Decay Rates



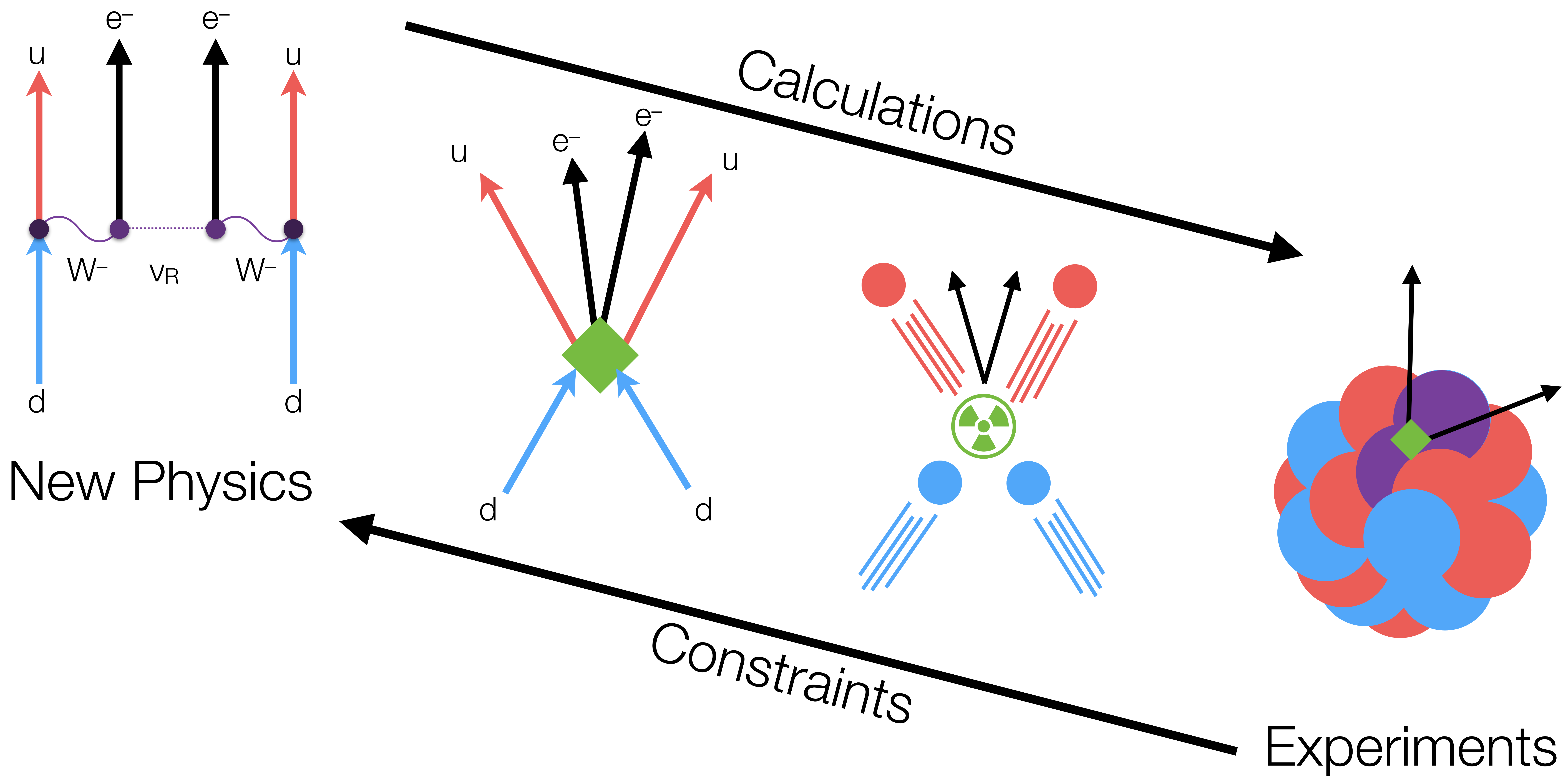
Neutrinoless Double Beta Decay 0νββ



Neutrinoless Double Beta Decay 0νββ



Nuclear Laboratories

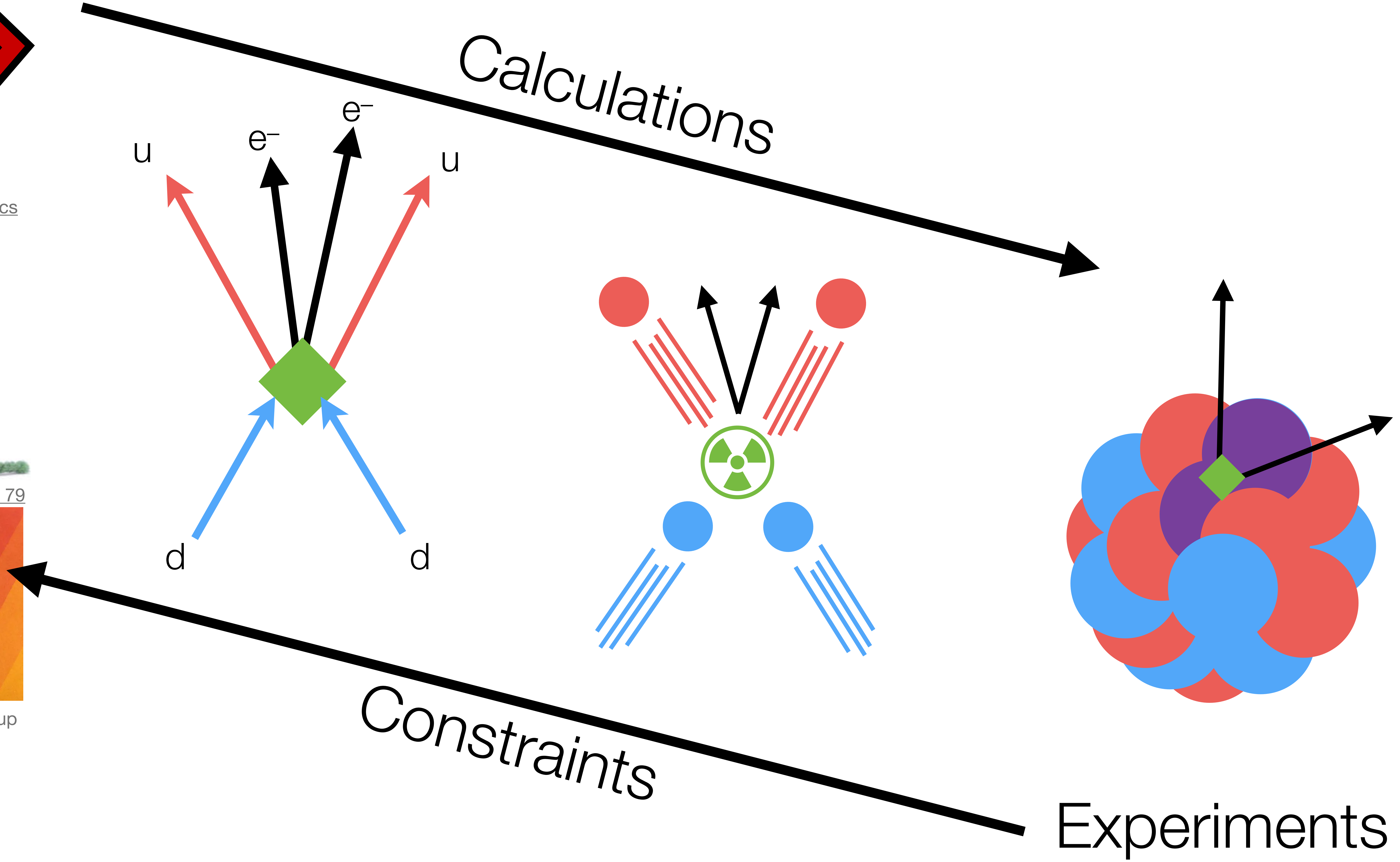


Nuclear Laboratories

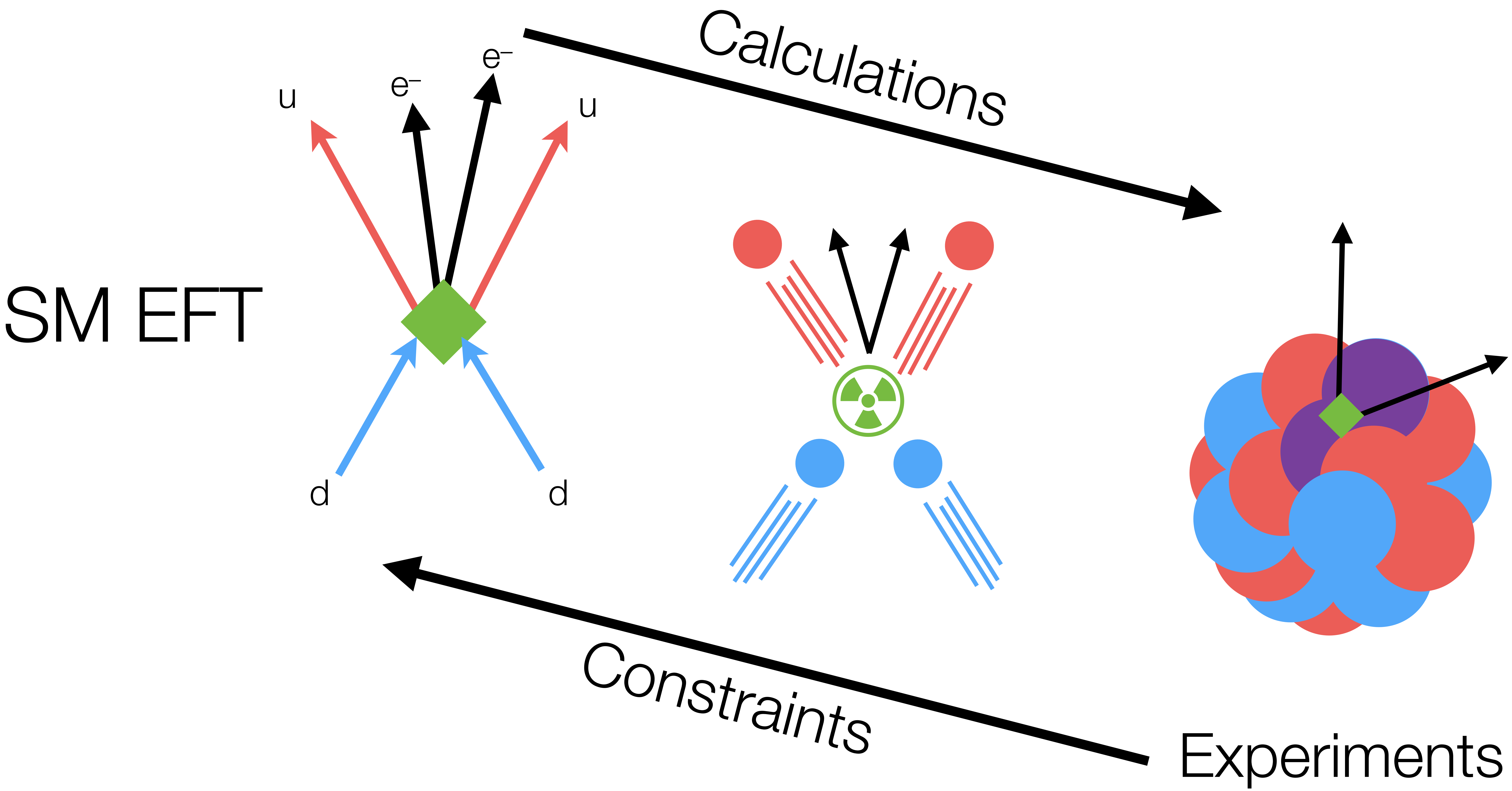
DC Comics

Getty Images iStock / Alexandrum 79

Technicolor Group

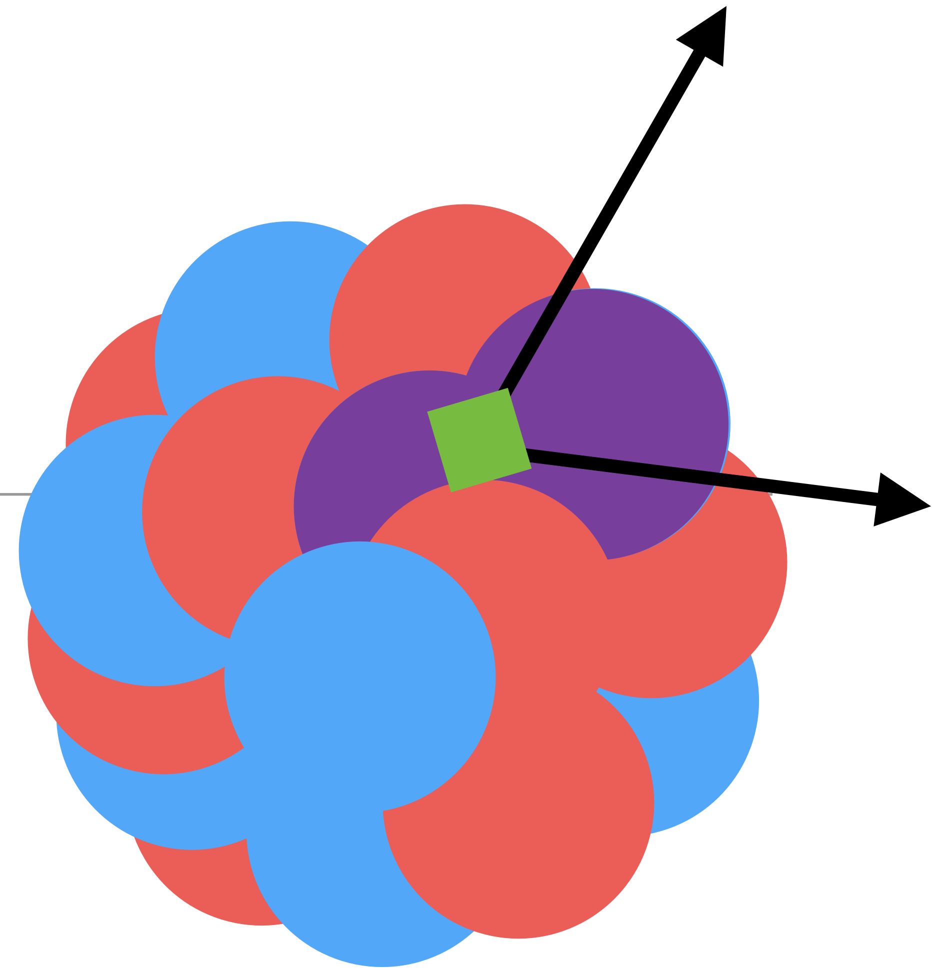


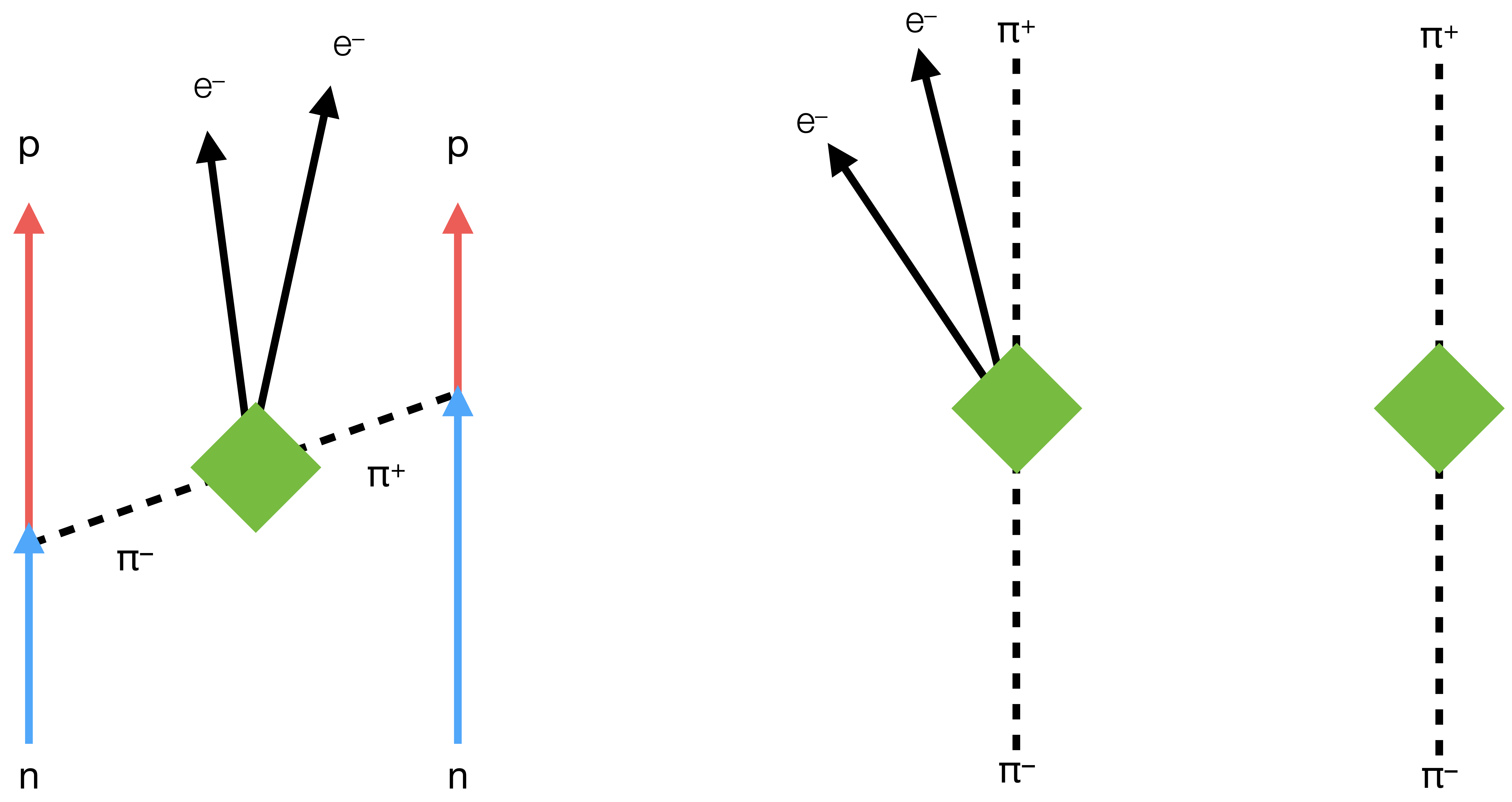
Add fundamental-symmetry-violating terms to the SM



Simplify, simplify, simplify!

Prézeau, Ramsey-Musolf, Vogel PRD68 (2003) 034016 hep-ph/0303205



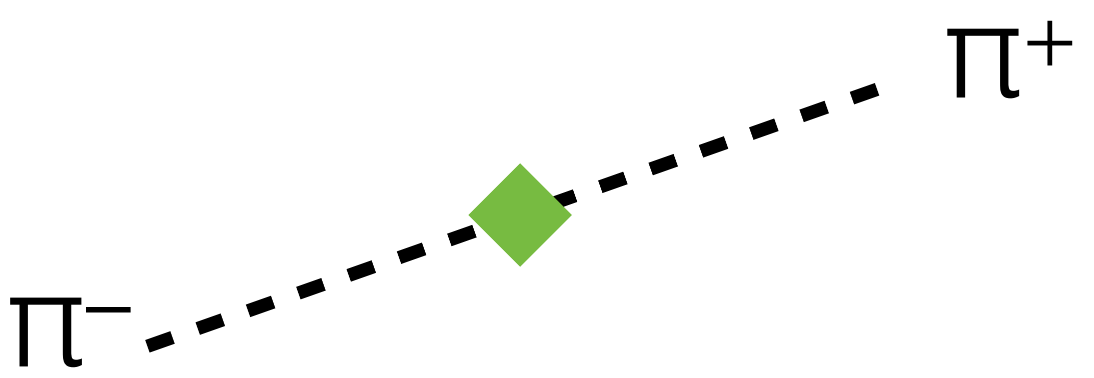


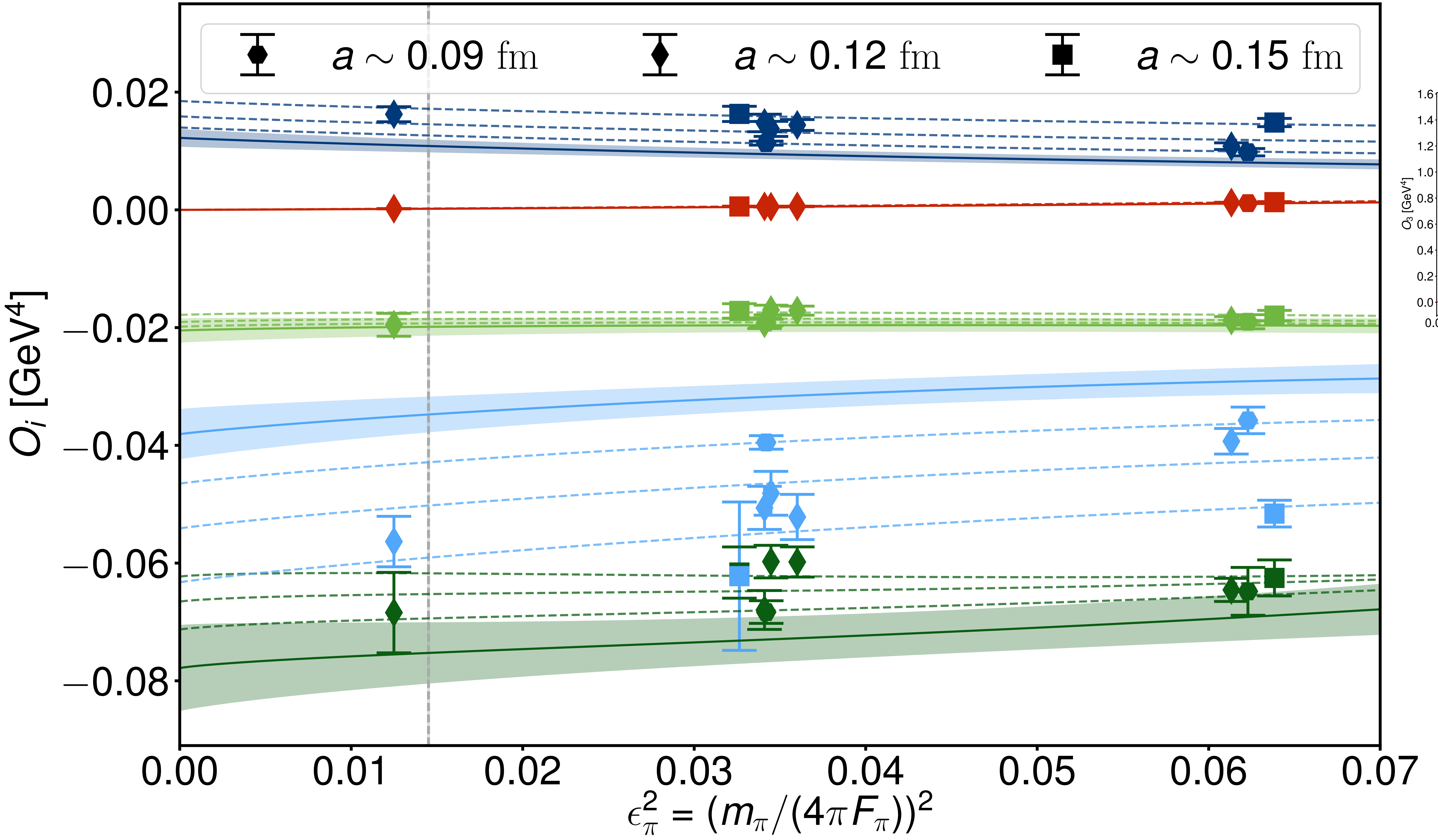
- These are *the simplest* hadronic matrix elements, computationally.
- They're also the most important for short-distance 0νββ!
- My algorithm unlocked continuum, physical-point, infinite-volume results in the very first publication!

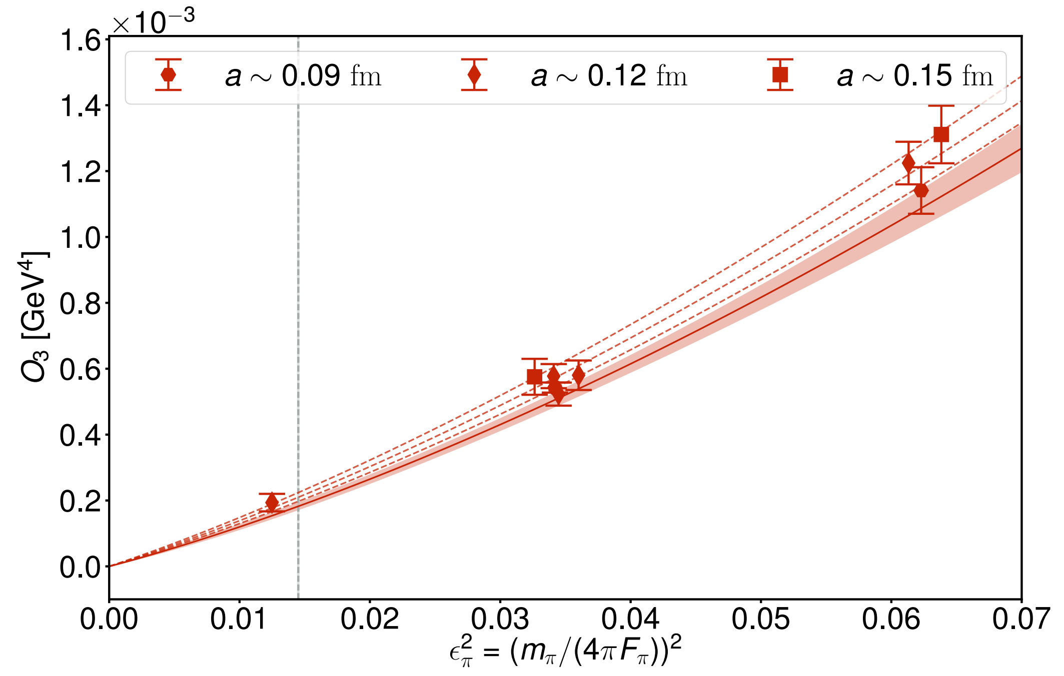
Nicholson **EB** et al., PRL 121:172501 (2018) arXiv:1805.02634

0νββ π⁻ → π⁺ ee Transition

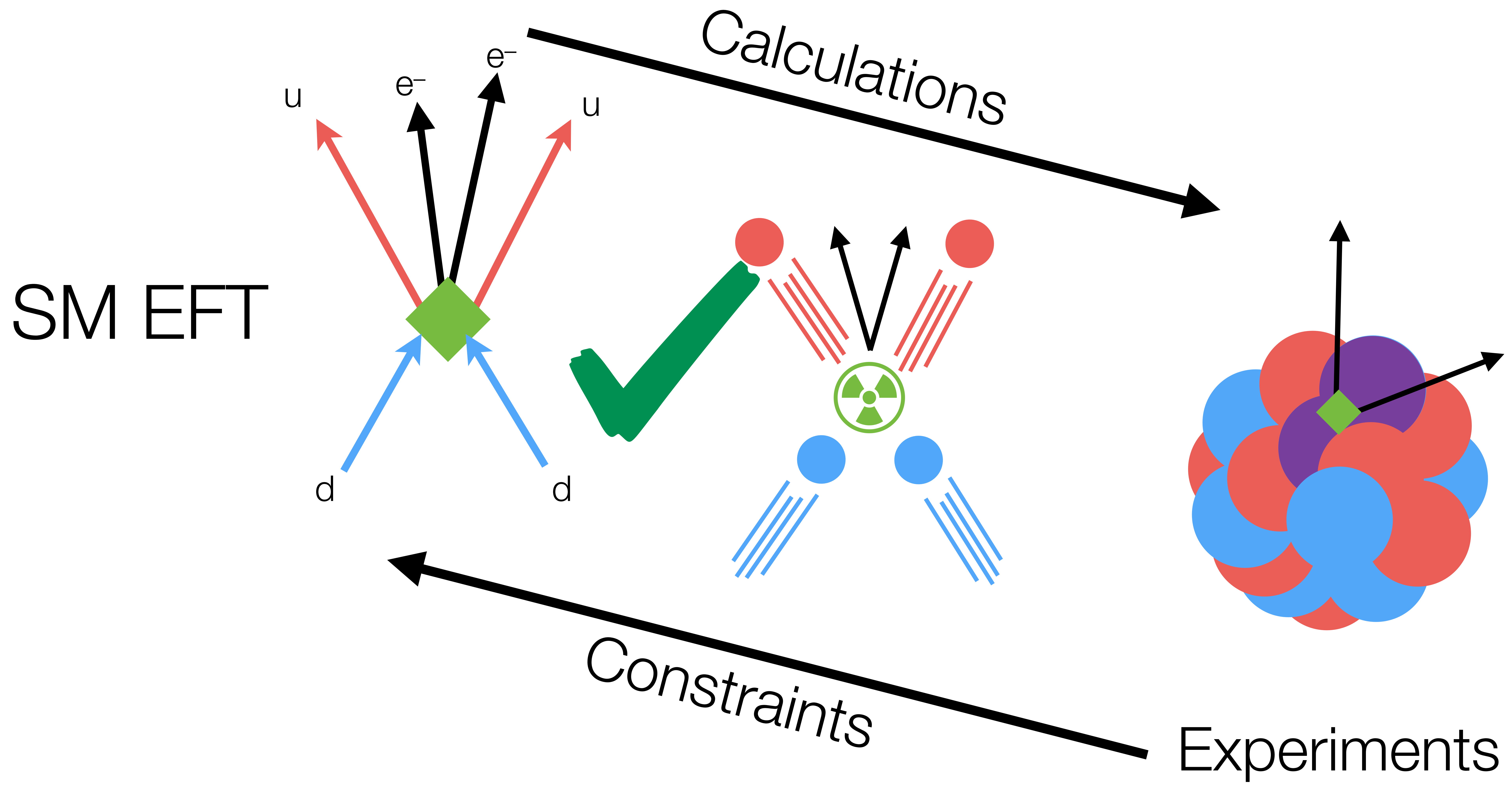
Nicholson **EB** et al., PRL 121:172501 (2018) arXiv:1805.02634







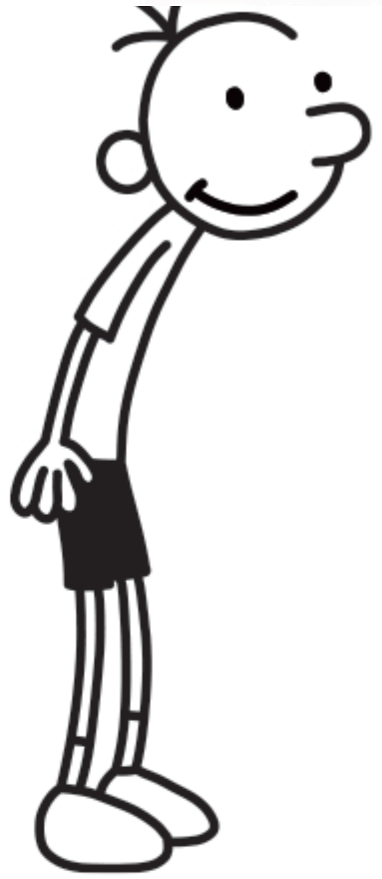
Add fundamental-symmetry-violating terms to the SM



Recap

Effective Field Theory:
include violations of 'fundamental' SM symmetries in a controlled way

Colgate-Palmolive

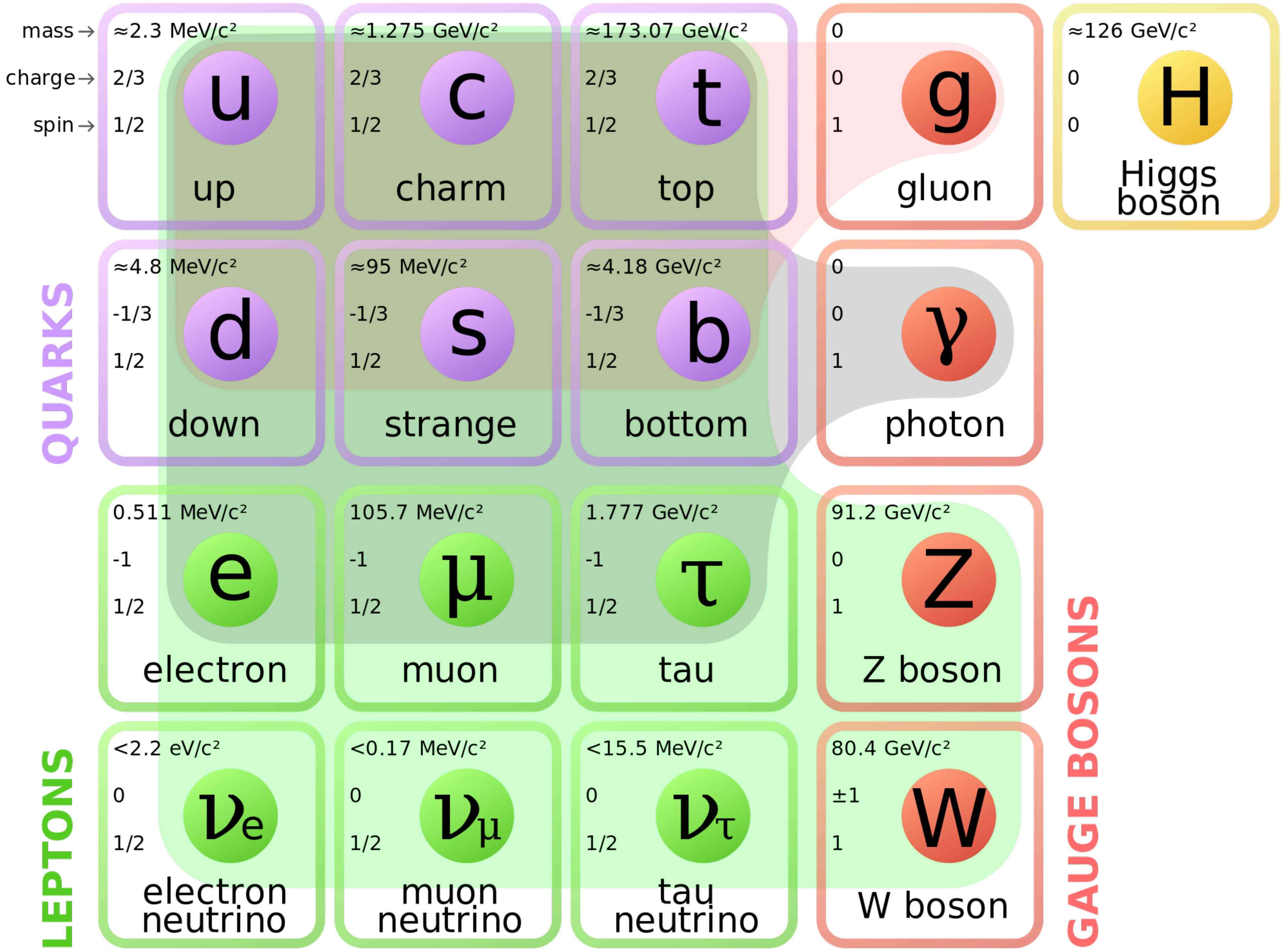


Jeff Kinney

DC Comics

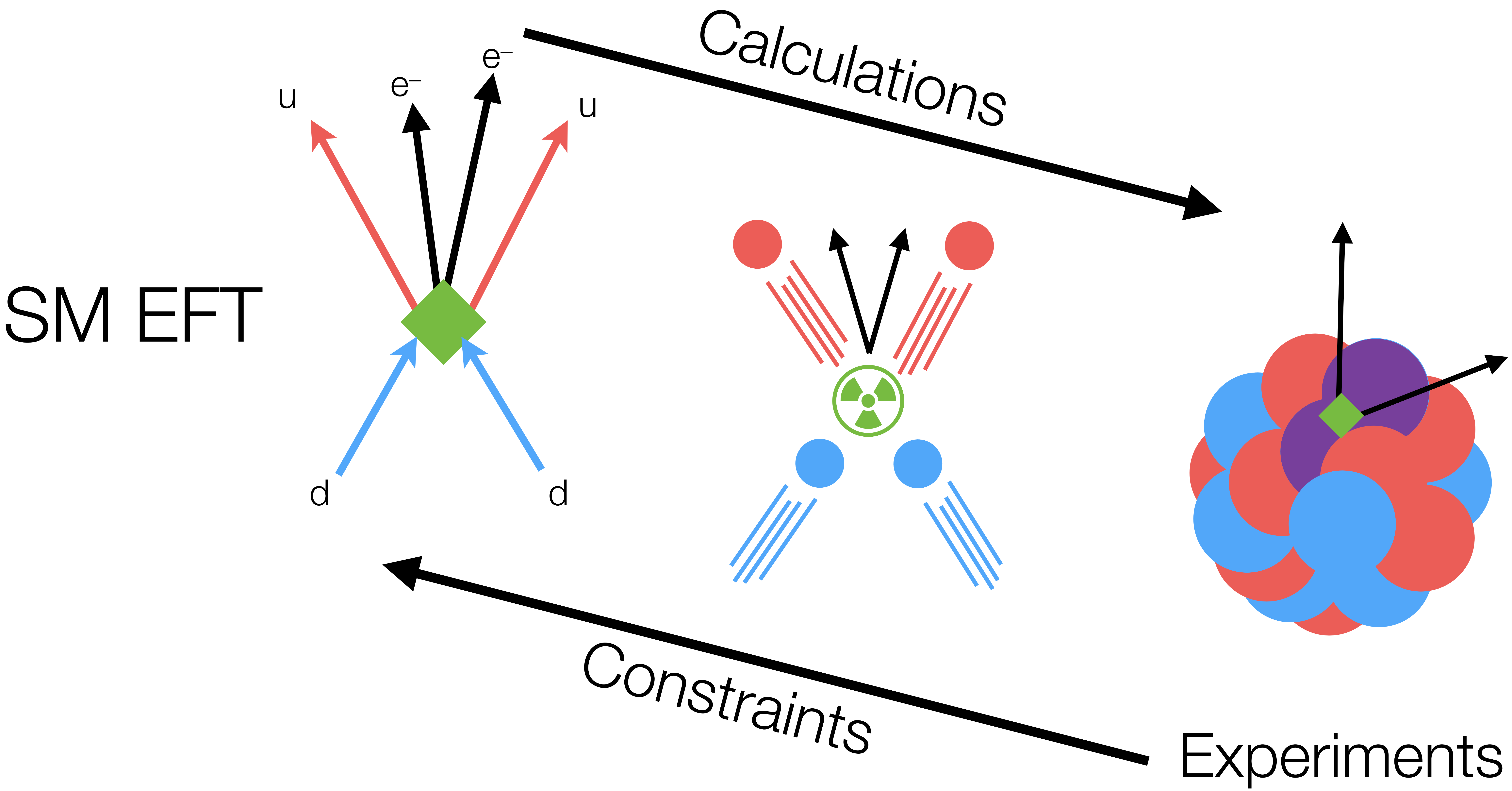
Technicolor Group

Getty Images iStock / Alexandrum 79



CC BY 3.0 Wikipedia users MissMJ, Nasfarley88, et al.

Understanding Experiments Requires Understanding the SM



Understanding the SM Requires LQCD