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LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

Phenomenology of the strong interaction

Grigorios Chachamis, LIP Lisbon,
9th mini-school on Particle and Astroparticle physics, Oeiras, Portugal, 5 Feb 2024

How many of you

- Have had a course on Quantum mechanics?
- Have had a course on field theory?
- Know what is the Large Hadron Collider (LHC)?
- Know what are gluons, quarks, pions, hadrons, baryons, mesons?
- Have applied some form of perturbation theory?

Even more fundamental, how many of you

- Know what particle physics is about?
- Understand the distinction between theory, experiment and the place of phenomenology?
- Are aware of this: having a theory to describe some phenomena, doesn't necessarily mean that you can use it to compute whatever you want?
- See the importance of what we call "physical observable" and the way such a notion influences a physical theory?

What this talk is not about

- It is not an introduction to Quantum chromodynamics (QCD)
- It will not cover in depth the different sub-fields of QCD theory, experiment and phenomenology of the strong interaction

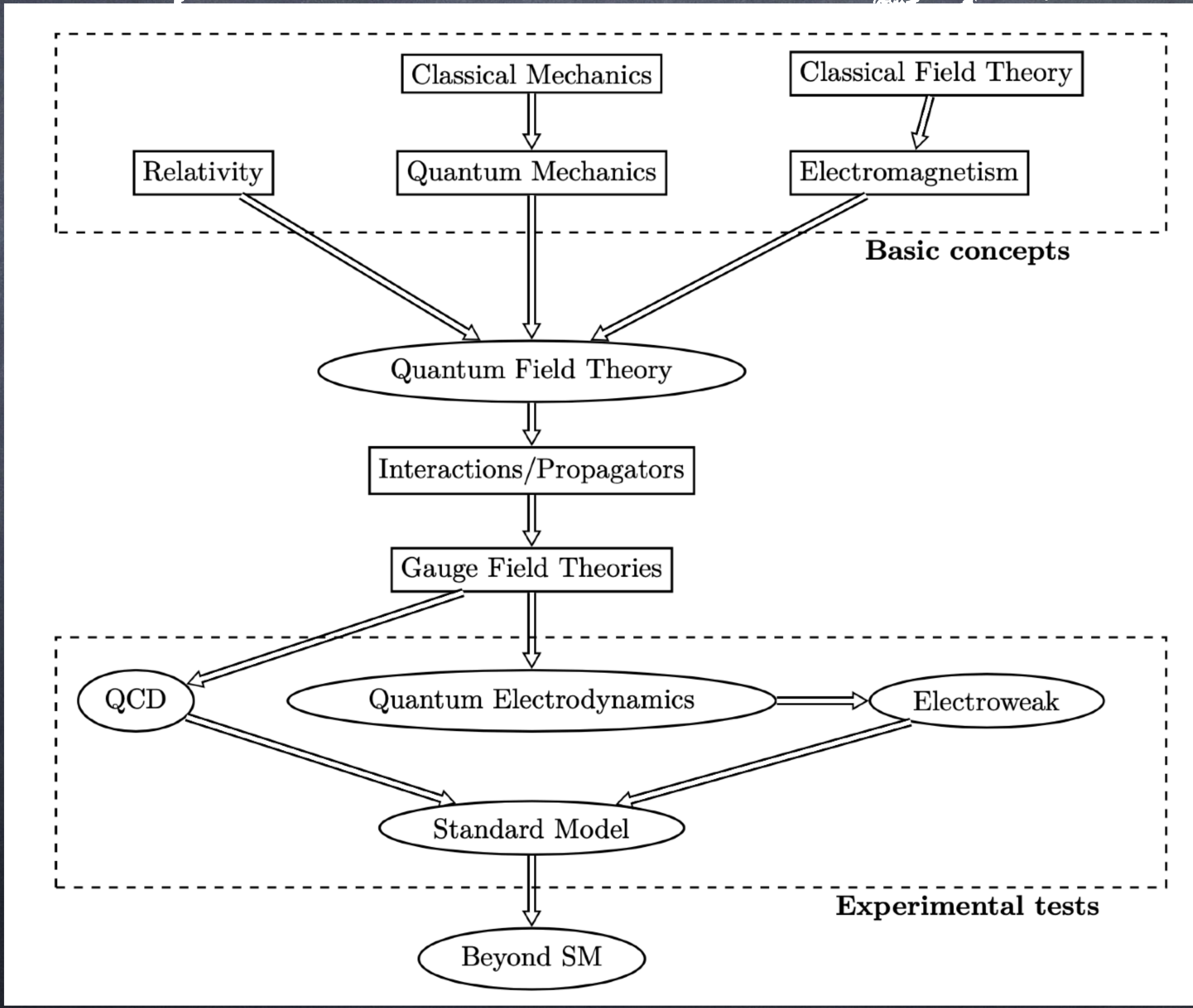
What this talk is about?

- You will get an idea of the main characteristics of QCD
- You will get an overview of the main sub-fields within QCD phenomenology
- I hope you will get a feeling of the continuity of ideas in particle physics and the paradigm shifts occurred in the phenomenology of the strong interaction but this will depend on what questions you ask

Particle phenomenology

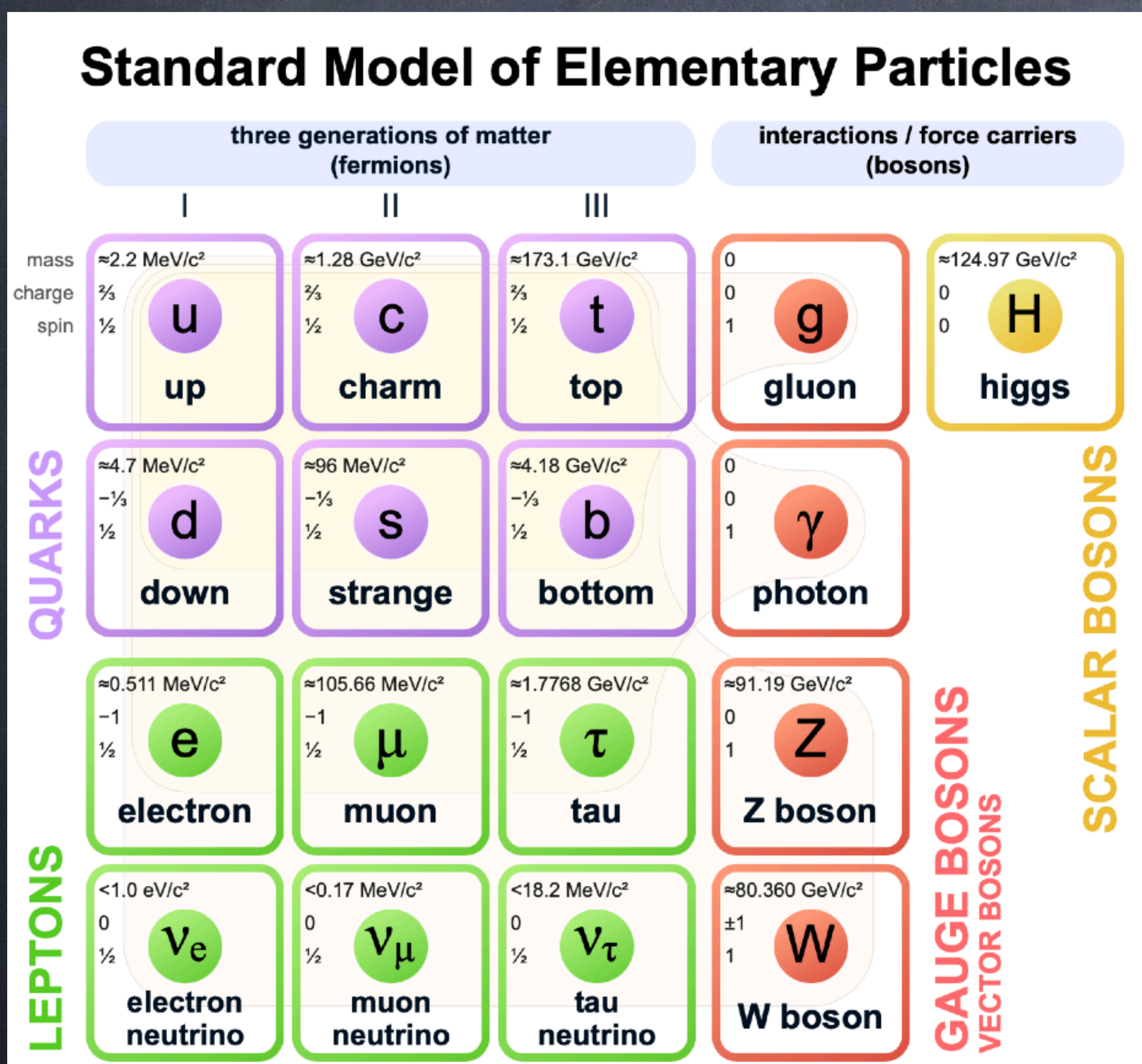
- Particle physics phenomenology is a subfield of physics that involves both theoretical and experimental aspects. It aims to connect the mathematical models of theoretical physics with the experimental data from high-energy particle experiments.
- Phenomenologists use theoretical tools to make predictions and interpret observations, as well as experimental methods to test hypotheses and measure parameters.
- In science, key experiments are often the spark for new theoretical developments.
- In particle physics lots of examples where theoretical developments guided new experimental discoveries.
- A good phenomenologist needs to know both sides really well

Cornerstones in modern particle physics (phenomenology?)



A. Rubbia, "Phenomenology of Particle Physics"

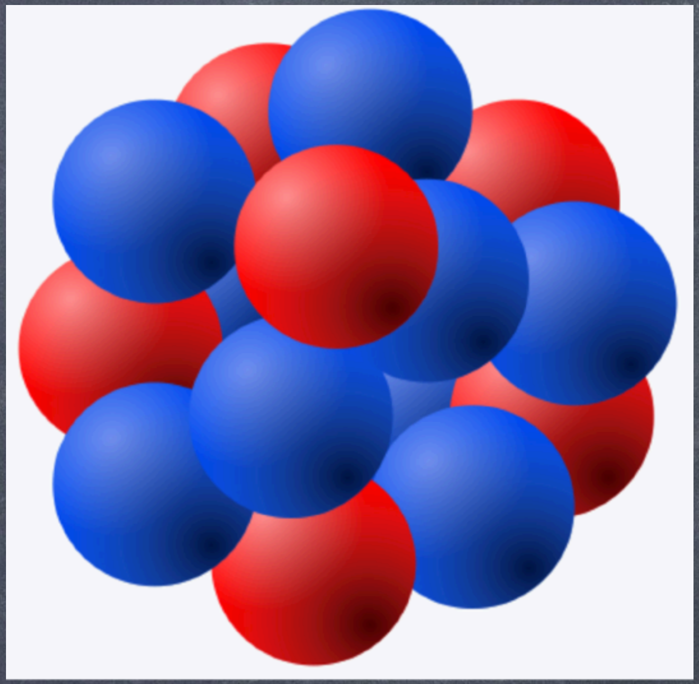
The Standard Model (SM)



$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi + h.c. \\
& + \psi_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

The strong interaction

- The Strong interaction binds together protons and neutrons in the atomic nuclei
- Back to 1930s: what holds the nucleus together? After all, the positively charged protons should repel one another violently. There must be some other force, more powerful than the force of electrical repulsion, that binds the protons (and neutrons) together. The new force was labeled the strong force



Yukawa: a first attempt at a theory of the strong force, with a new quanta, the meson. The "screened Coulomb potential":

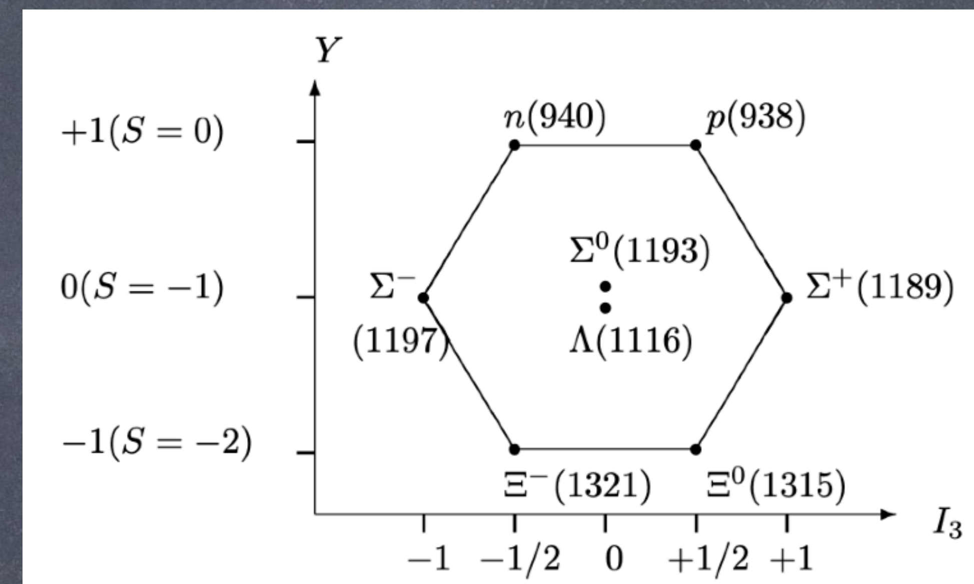
$$U(r) \sim g^2 \frac{e^{-\lambda r}}{r}$$

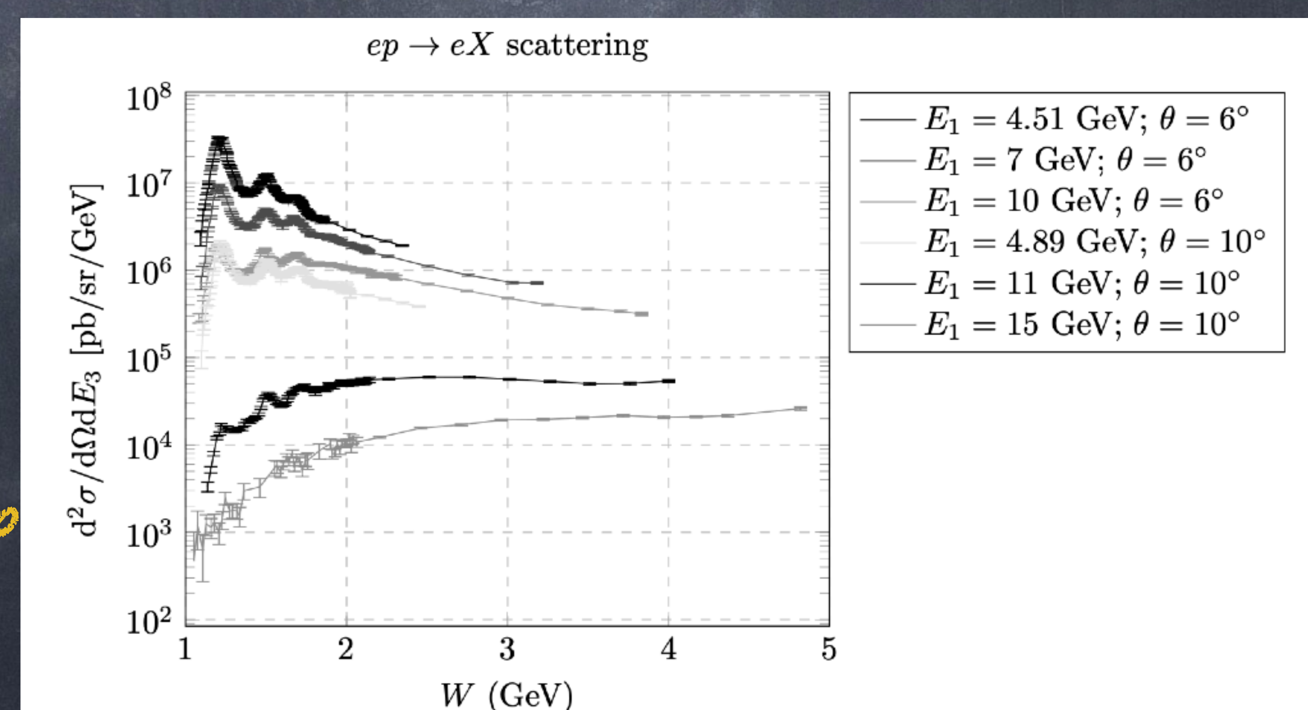
The strong interaction – early attempts

- In the 1950s and 1960s, lots of new hadrons were discovered, that is, particles that feel the strong interaction.
- Various theoretical attempts to describe the interactions of hadrons:
- S-matrix theory: A framework that focused on the scattering amplitudes of particles, without specifying the underlying dynamics or fields. Unitarity, analyticity, and symmetry.
- Regge theory: A method that used complex angular momentum to analyze the high-energy behavior of scattering processes. It predicted the existence of families of particles, called Regge trajectories, that have linear relationships between their spin and mass squared.
- Bootstrap theory: This was a hypothesis that all hadrons are composed of each other, and that there are no elementary constituents. All particles are resonances of each other.

The strong interaction – towards QCD

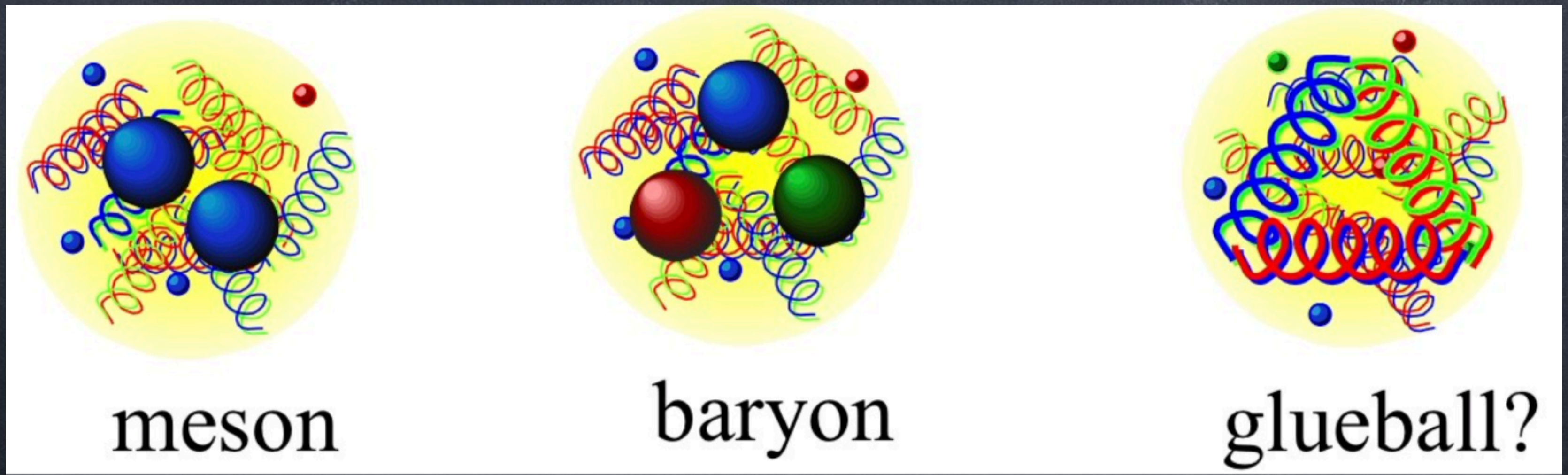
- In the 1950s and 1960s, lots of new hadrons were discovered, that is, particles that feel the strong interaction.
- Attempts to classify these into families were very successful (Eightfold Way) and led to the conclusion that hadrons (protons, neutrons, pions, kaons etc) were not fundamental particles.
- Instead, they are composite, their constituents were named quarks (partons). Another indication of their compositeness were results from deep inelastic e-p scattering experiments





The strong interaction – the advent of QCD

- In the early 1970s, QCD was formulated as a non-Abelian gauge field theory of quarks that interact by the exchange of spin-1 massless gluons
- QCD is in many aspects similar to Quantum electrodynamics (QED). The QED vertex couples a spin-1 photon with zero rest mass to an electrically charged fermion. In QCD, the strong force is mediated by eight (massless) spin-1 gluons. Quarks carry the "color charge," which comes in three types called R(ed), G(reen) and B(lue).
- Since gluons are colored and therefore carry a strong charge, they interact with other gluons or "self-couple" via QCD vertices involving three or four gluons (non-Abelian).

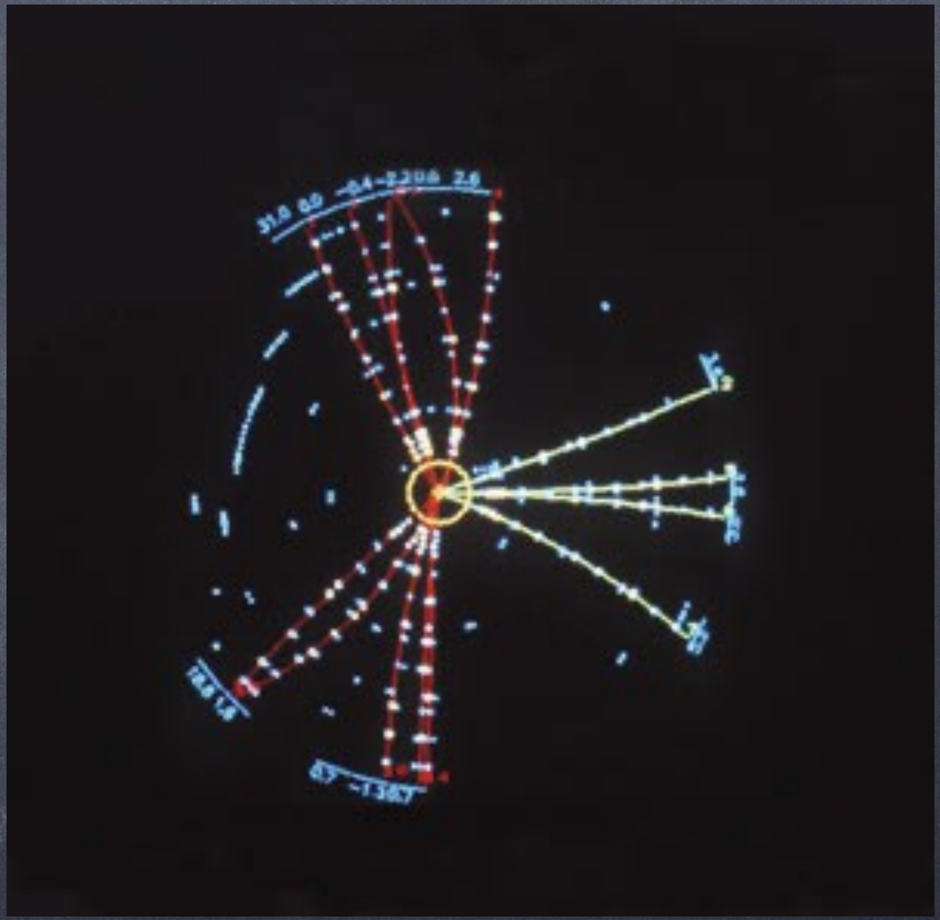


The advent of QCD, two key theoretical achievements

- 't Hooft & Veltman, showed in 1971 that "non-abelian" gauge theories are renormalizable, a type of quantum field theory that can be made free of infinities by a finite number of redefinitions of the parameters and fields.
- Asymptotic freedom in QCD was discovered in 1973 by David Gross and Frank Wilczek, and independently by David Politzer in the same year. The interactions between quarks and gluons become weaker as the energy scale increases and the distance scale decreases. At low energies, we have confinement: the interactions become stronger and quarks and gluons are confined within hadrons, such as protons and neutrons.

First evidence of the gluon

- In 1979, experiments at the DESY laboratory in Germany provided the first direct proof of the existence of gluons – the carriers of the strong force that "glue" quarks into protons, neutrons and the other particles known collectively as hadrons. This discovery was a milestone in the history of particle physics, as it helped establish QCD as the theory of the strong interaction.
- "The results followed from an idea that struck theorist John Ellis while walking in CERN's corridors in 1976. As Ellis recounts, he was walking over the bridge from the CERN cafeteria back to his office, turning the corner by the library, when it occurred to him that "the simplest experimental situation to search directly for the gluon would be through production via bremsstrahlung in electron-positron annihilation". In this process, an electron and a positron (the electron's antiparticle) would annihilate and would occasionally produce three "jets" of particles, one of which being generated by a gluon radiated by a quark-antiquark pair." CERN News, 18 JUNE, 2019



TASSO detector at DESY

The QCD Lagrangian

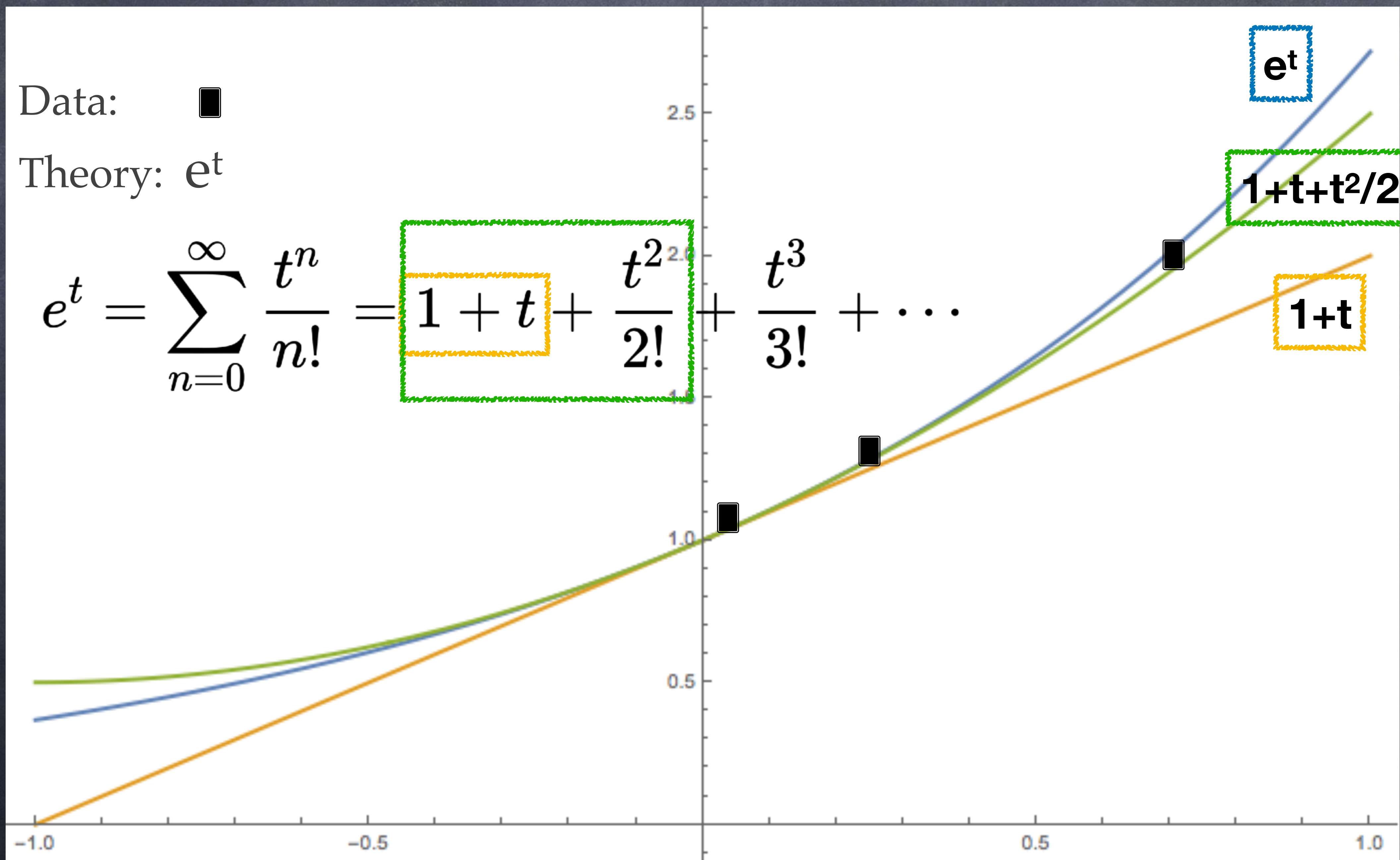
$$\mathcal{L}_{QCD} = \sum_q \left(\bar{\psi}_{qi} i\gamma^\mu \left[\delta_{ij}\partial_\mu + ig\left(G_\mu^\alpha t_\alpha\right)_{ij} \right] \psi_{qj} - m_q \bar{\psi}_{qi}\psi_{qi} \right) - \frac{1}{4} G_{\mu\nu}^\alpha G_\alpha^{\mu\nu}$$

$$\boxed{\mathcal{L}_{QED} = \bar{\psi}_e i\gamma^\mu \left[\partial_\mu + ieA_\mu \right] \psi_e - m_e \bar{\psi}_e \psi_e - \frac{1}{4} F_{\mu\nu}F^{\mu\nu}}$$

- $G_\alpha^{\mu\nu} = \partial^\mu G_\alpha^\nu - \partial^\nu G_\alpha^\mu - g f^{\alpha\beta\gamma} G_\beta^\mu G_\gamma^\nu$ color fields tensor
- G_α^μ four potential of the gluon fields (α=1,..8)
- t_α 3x3 Gell-Mann matrices; generators of the SU(3) color group
- $f^{\alpha\beta\gamma}$ structure constants of the SU(3) color group
- ψ_i Dirac spinor of the quark field (*i* represents color)
- $g = \sqrt{4\pi\alpha_s}$ $(\hbar = c = 1)$ color charge (strong coupling constant)

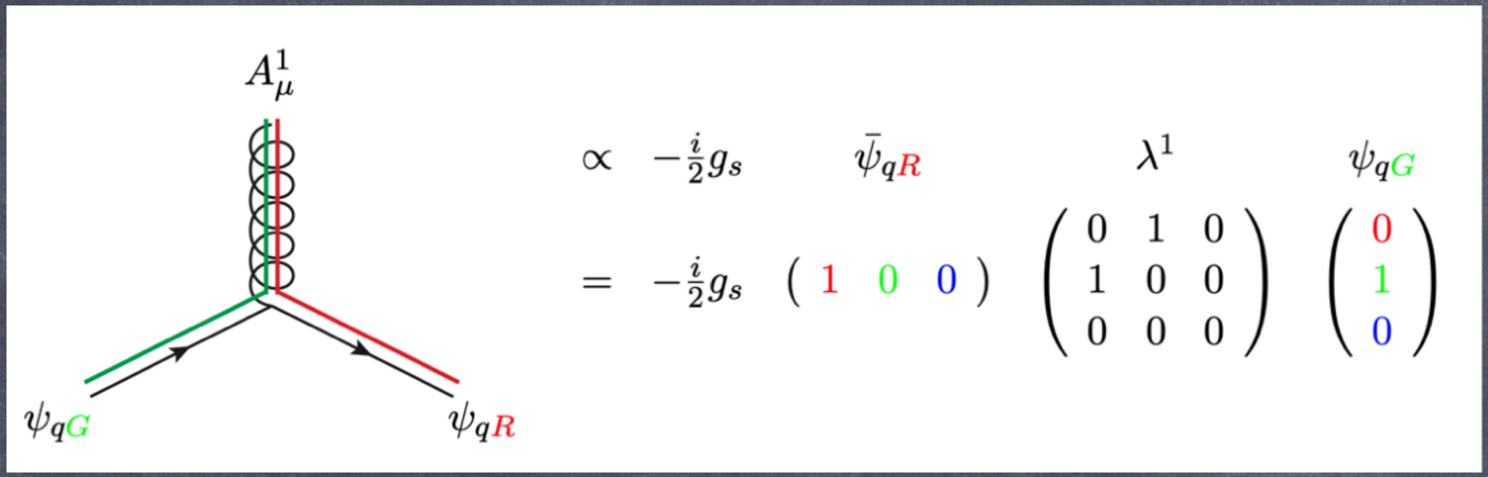
WITOLD NAZAREWICZ webpage

Perturbation theory

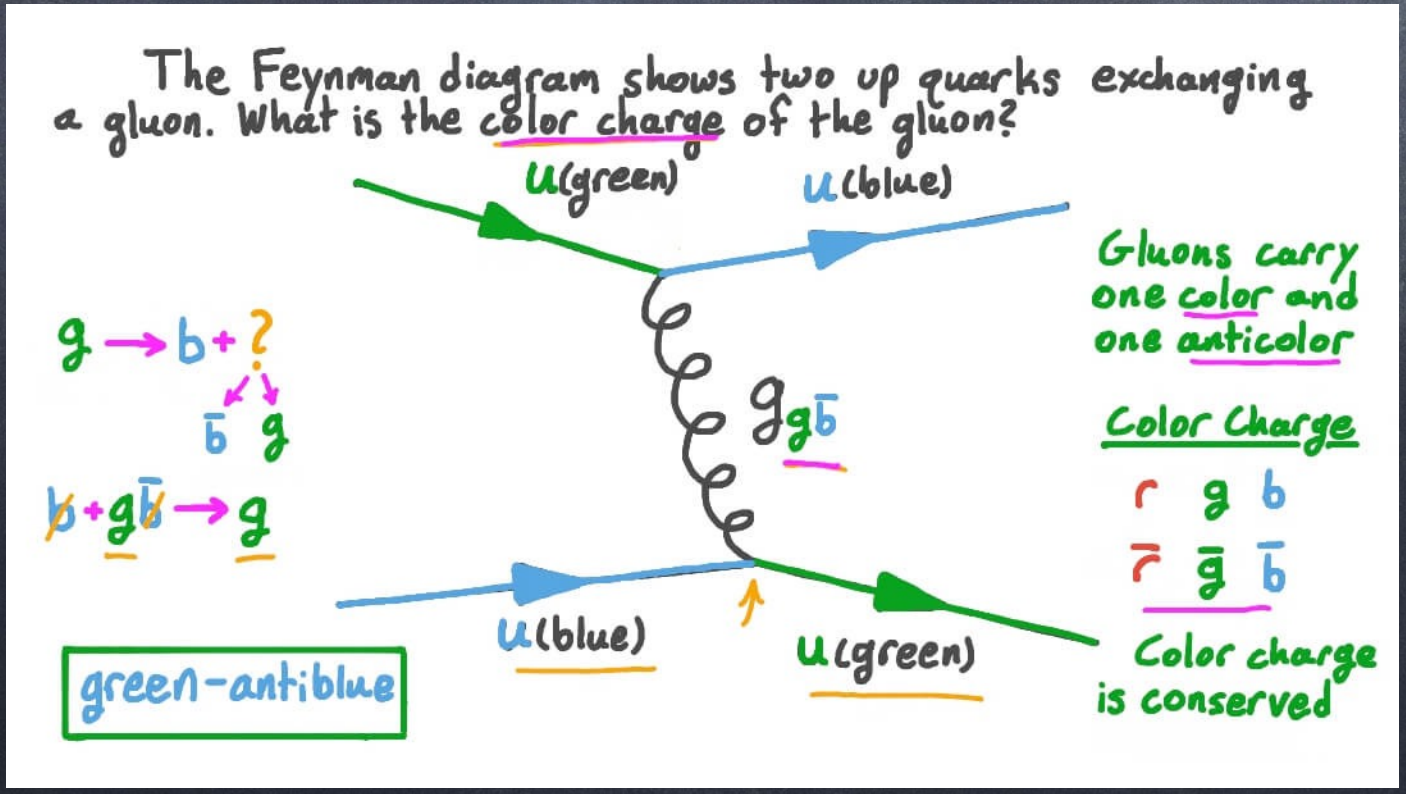


$$e^t = \sum_{n=0}^{\infty} \frac{t^n}{n!} = 1 + t + \frac{t^2}{2!} + \frac{t^3}{3!} + \cdots$$

Perturbation theory – Feynman diagrams



P. Skands, arXiv:1207.2389



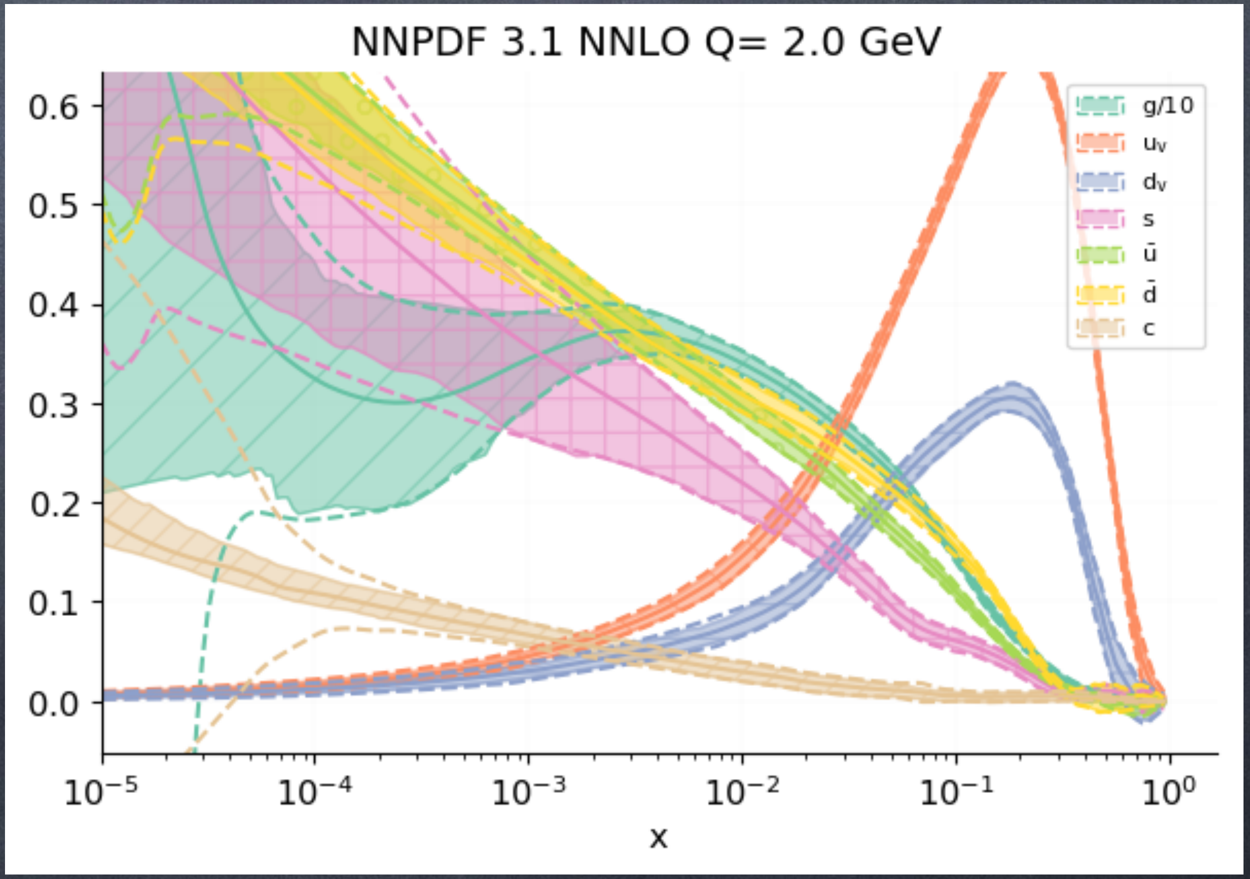
QCD phenomenology

- Nowadays, QCD is the established theory of the strong interaction. It describes how quarks and gluons interact to form hadrons, such as protons and neutrons and how hadrons interact with each other.
- QCD phenomenology is the study of the observable consequences of QCD, such as the production and decay of hadrons, the structure of nucleons, and the properties of nuclear matter. Most of the work within QCD phenomenology is connected to collider experiments.

QCD phenomenology

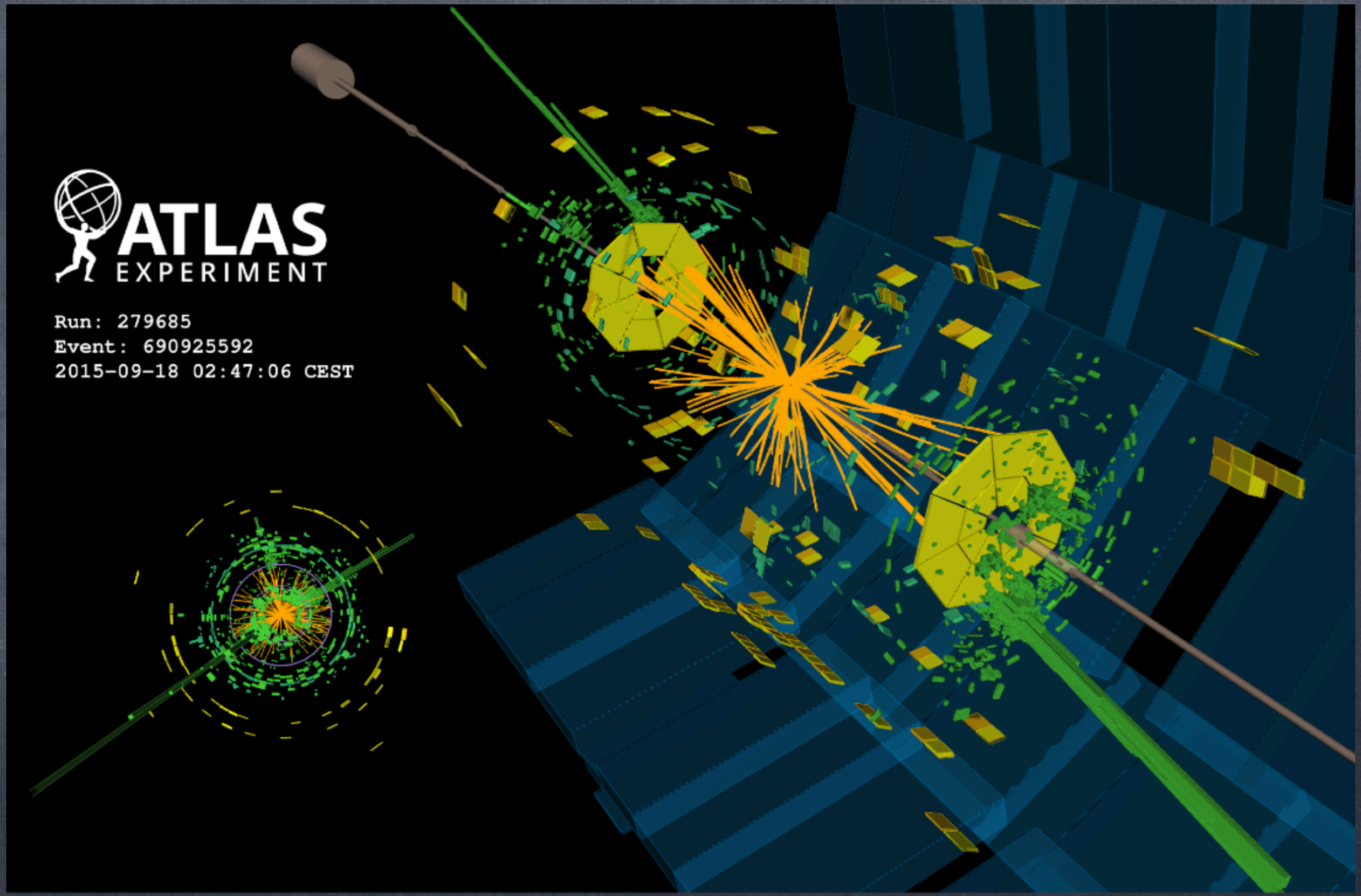
- Some of the main areas of QCD phenomenology are:

- Parton distribution functions (PDFs): These are the probability densities of finding a quark or a gluon with a given fraction of the momentum of a hadron, such as a proton or a neutron. PDFs are essential for predicting the cross sections of hard processes involving hadrons at high energies, such as deep inelastic scattering or hadron collisions.



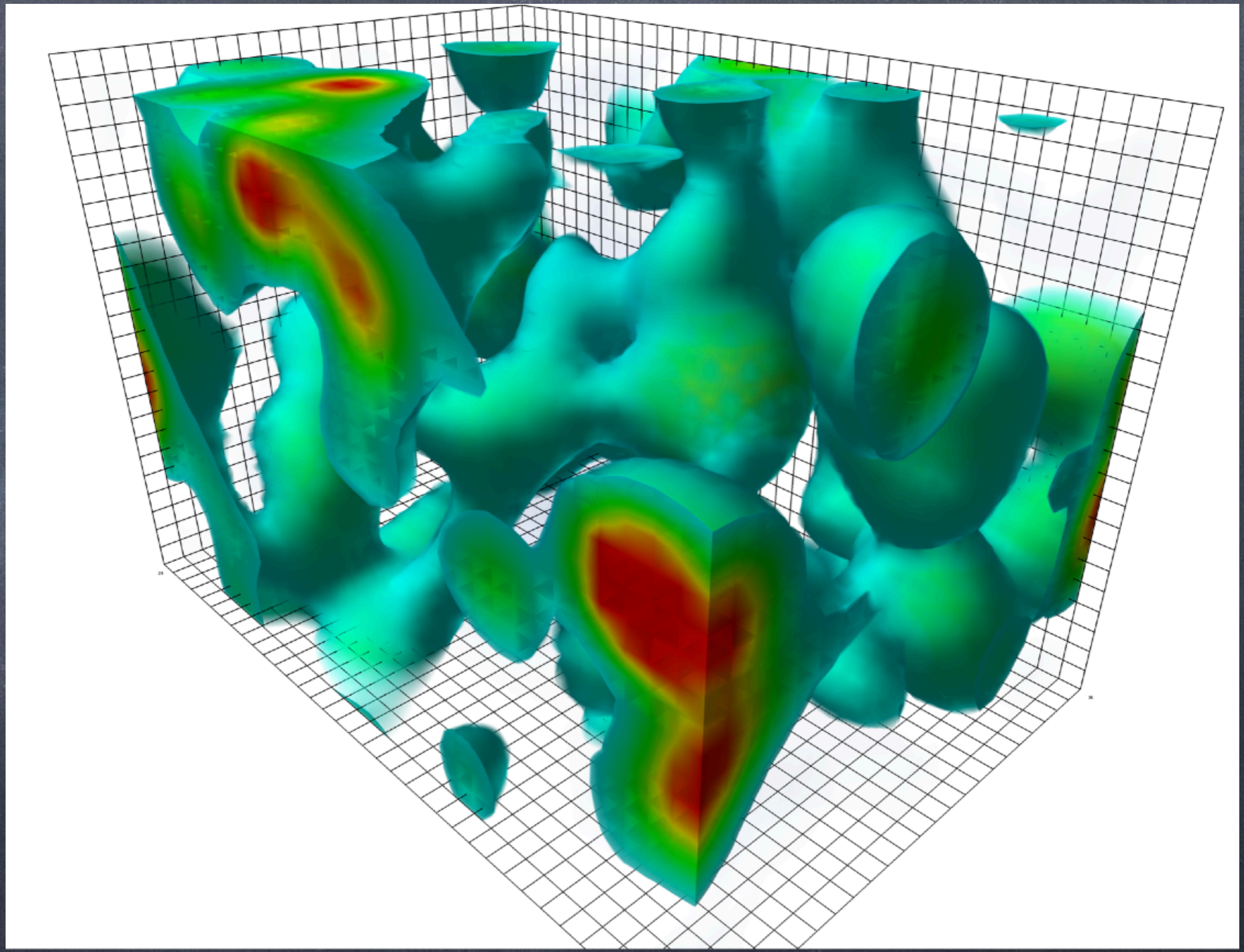
QCD phenomenology

- Some of the main areas of QCD phenomenology are:
- Jet physics: Jets are collimated sprays of hadrons that originate from the fragmentation and hadronization of high-energy quarks and gluons. Jet physics is important for testing the perturbative aspects of QCD and for probing the structure of the proton and the nucleus.



QCD phenomenology

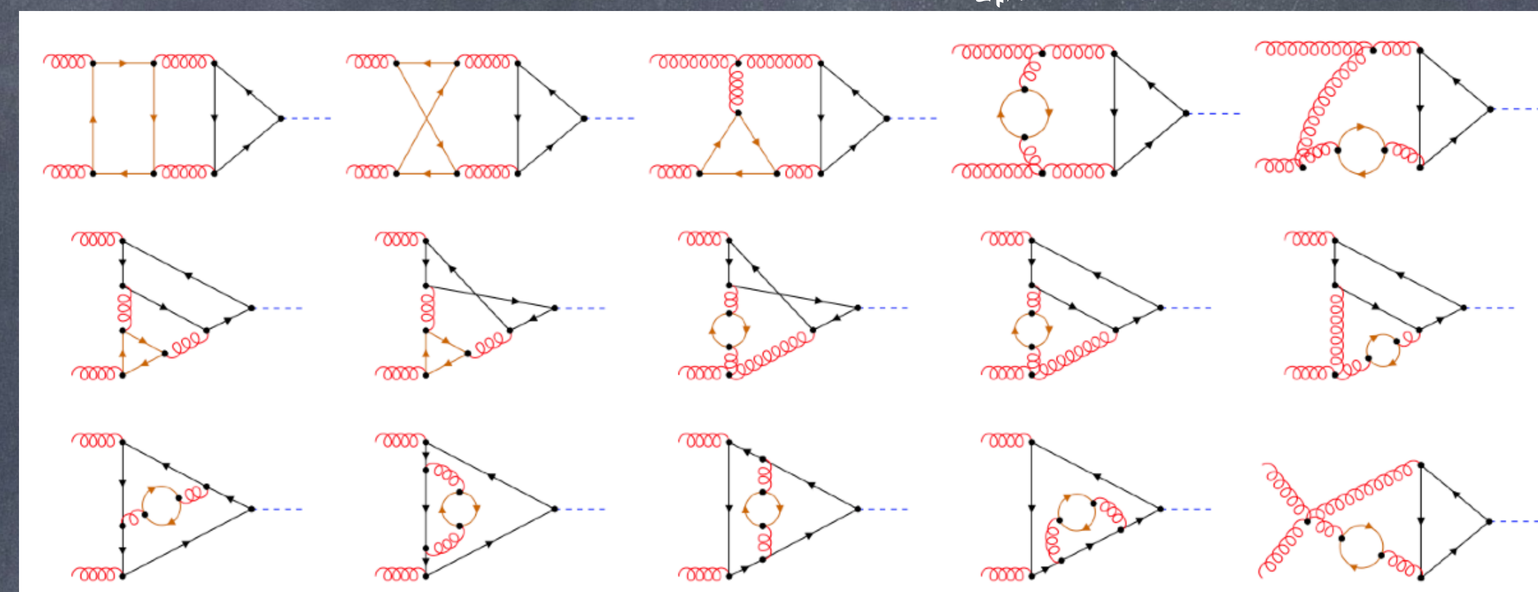
- Some of the main areas of QCD phenomenology are:
- Lattice QCD: Lattice QCD is a numerical method for solving the QCD equations of motion on a discrete space-time grid. Lattice QCD allows for the non-perturbative calculation of various QCD observables, such as hadron masses, decay constants, form factors, and phase transitions.

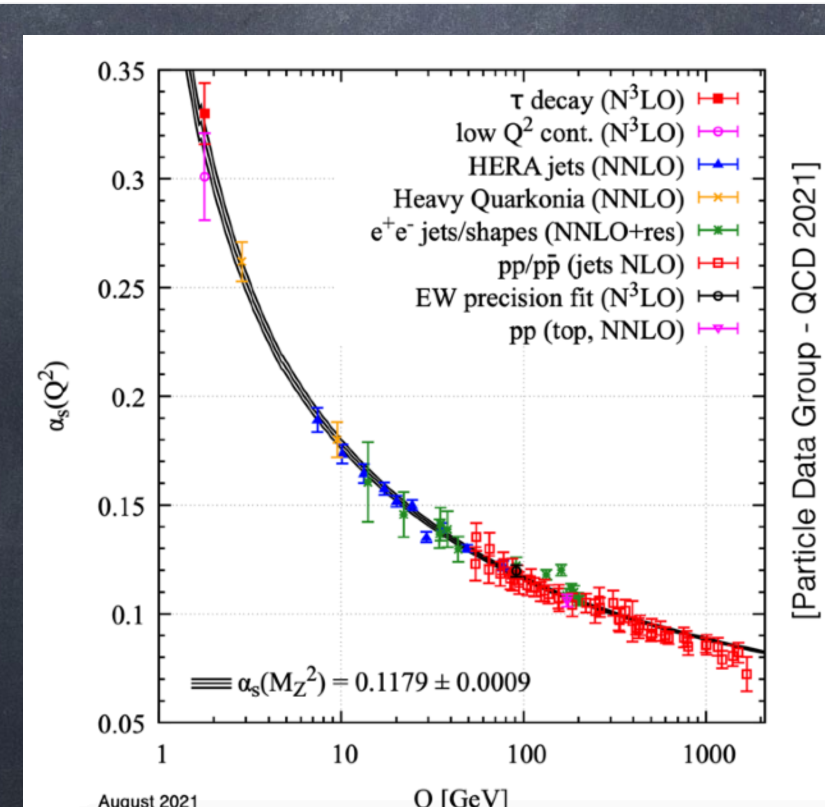


http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/ImprovedOperators/index.html

QCD phenomenology

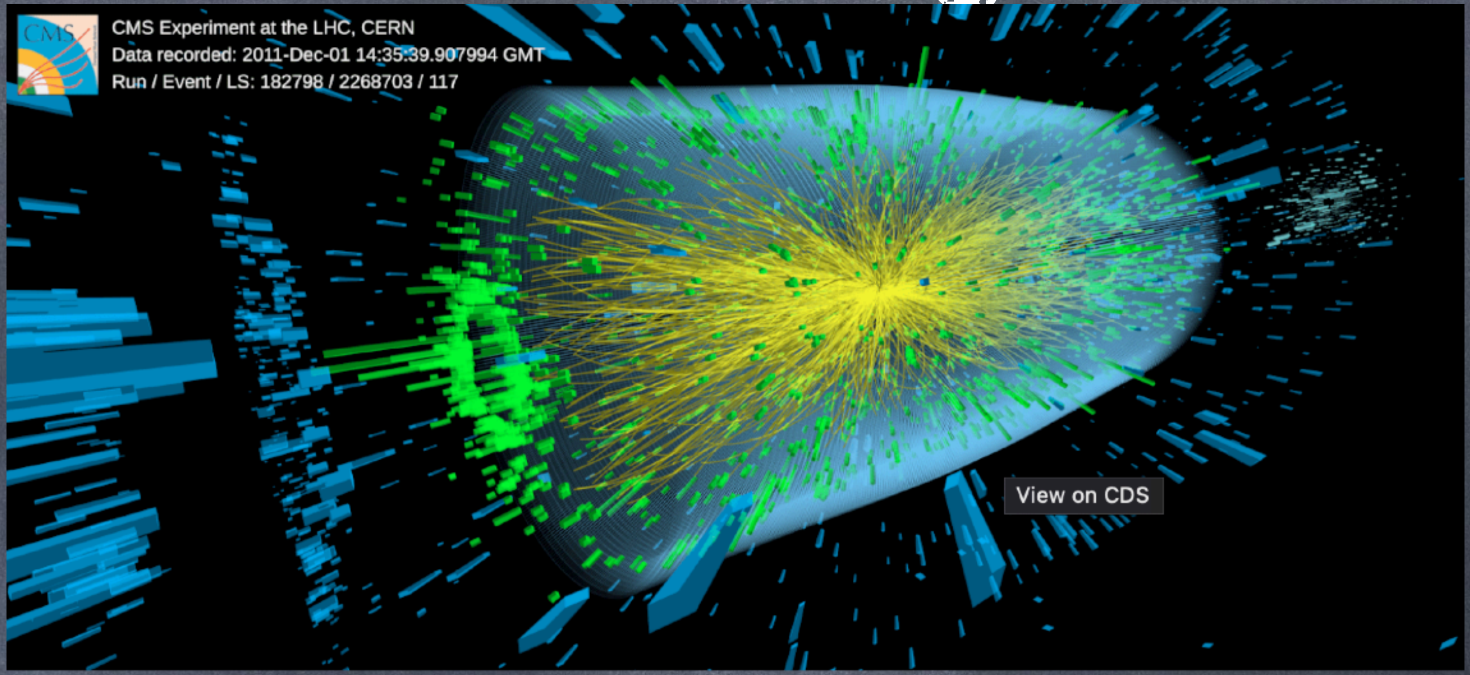
- Some of the main areas of QCD phenomenology are:
- <u>Precision physics</u>: the study of the effects of quantum corrections and higher-order processes on the observables measured at high-energy particle colliders. Main goal the improvement of the theoretical predictions and experimental measurements of the strong interactions, such as the strong coupling constant, the parton distribution functions, the jet cross sections. This can reduce the uncertainties and enhance the sensitivity of the collider searches and analyses.

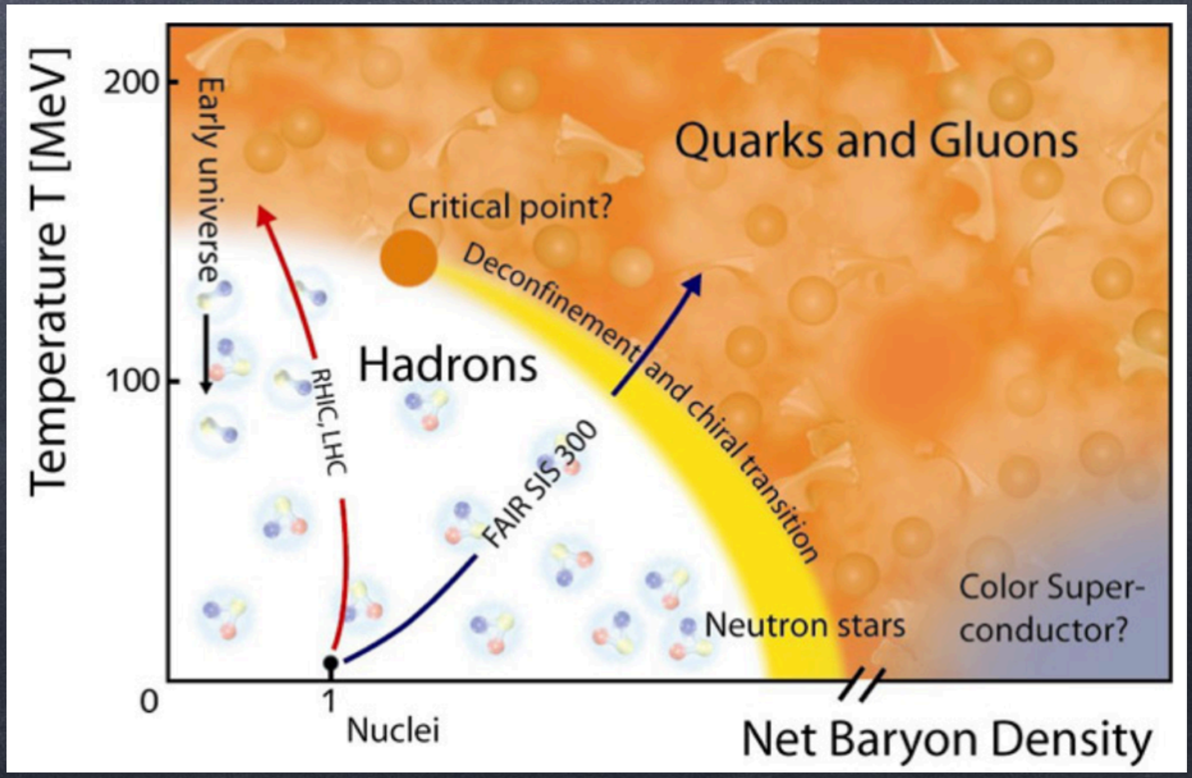




QCD phenomenology

- Some of the main areas of QCD phenomenology are:
- Heavy ion collisions physics: explores the phase diagram of QCD matter and the formation of a new state of matter called quark-gluon plasma, which is believed to exist at extremely high temperatures and densities





QCD phenomenology

- And there are many other areas, such as soft and hard diffraction and Forward physics, exclusive processes, spin physics, QCD at finite temperature and density, and QCD in strong magnetic fields.
- QCD phenomenology is a rich and active field of research that aims to understand the fundamental nature of the strong force and its manifestations in nature.
- It is one of the most exciting and demanding fields of research in particle physics.

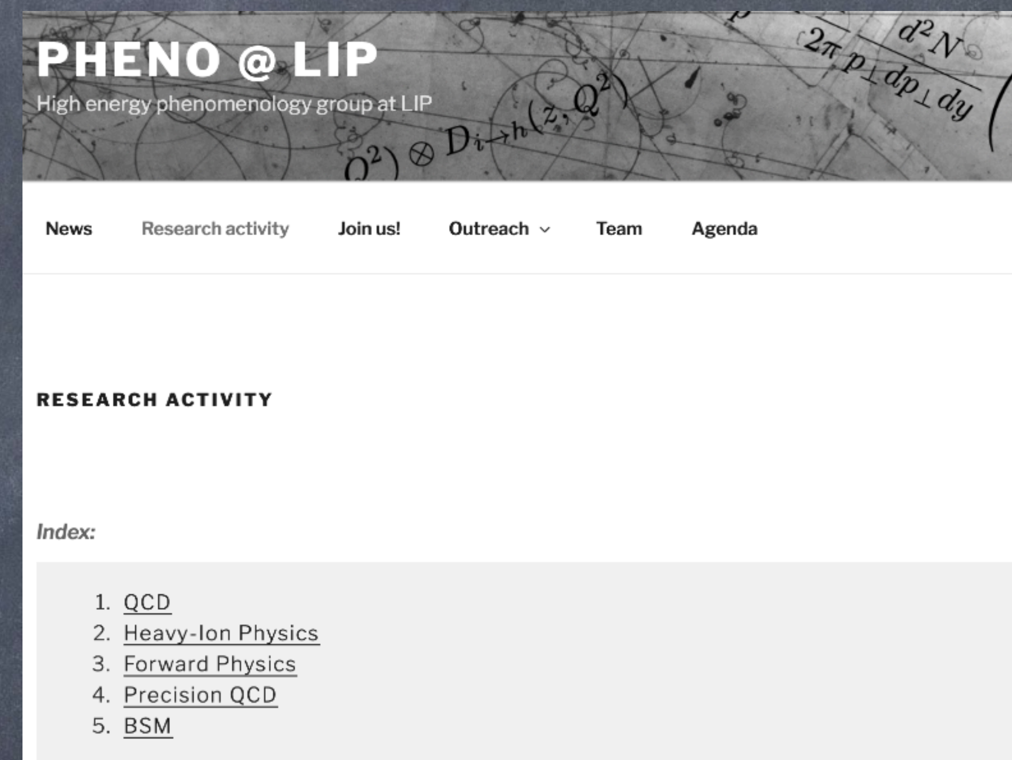
Some of the LIP Pheno Group members

Guilherme Milhano [LIP-Lisboa]
Jet Physics, QGP

Liliana Apolinário [LIP-Lisboa]
Jet Physics, QGP

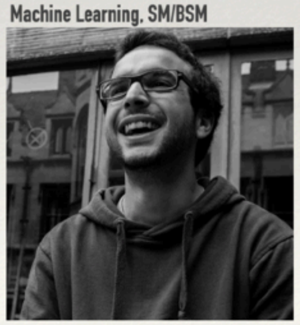
João Pires [LIP-Lisboa]
QCD precision

Grigorios Chachamis [LIP-Lisboa]
QCD precision



Nuno Castro [LIP-Minho]
SM/BSM [also ATLAS]

Miguel Romão [LIP-Minho/Lisboa]
Machine Learning, SM/BSM



Ricardo Gonçalo [LIP-Coimbra/Lisboa]
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António Onofre [LIP-Minho]
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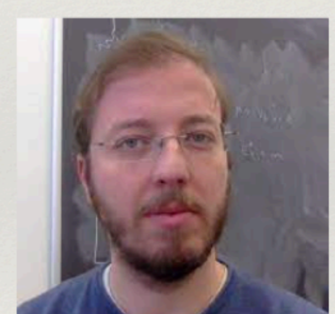
Ruben Conceição [LIP-Lisboa]
QGP, Cosmic Rays



Pietro Faccioli [LIP-Lisboa]
QCD quarkonium production

Pablo Rodriguez [LIP-Lisboa]
Jet Physics, QGP

https://pages.lip.pt/pheno/

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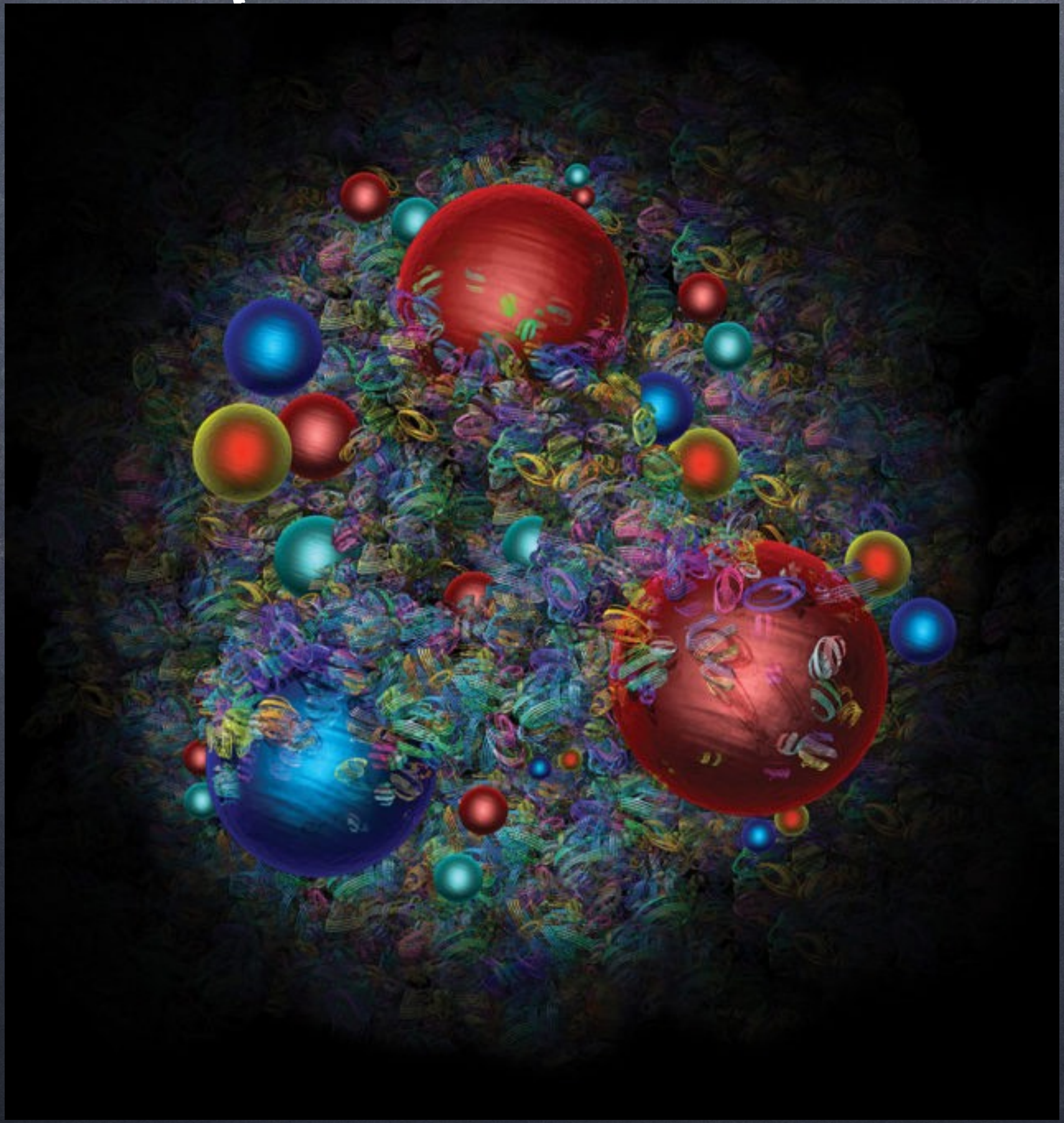
09:00 – 10:45	**Hands on Neutrinos** *Ivo Varzielas, Valentina Lozza* *Oeiras INATEL* 09:00 - 10:45	**Hands on Higgs** *Jorge Romão, Rute Pedro* *Oeiras INATEL* 09:00 - 10:45	**Hands on QCD Jets** *Mr Dario Vaccaro, Liliana Apolinário* *Oeiras INATEL* 09:00 - 10:45	**Hands on Hadrons** *Alfred Stadler, Elmar Biernat* *Oeiras INATEL* 09:00 - 10:45
10:45 – 11:30	**Coffee Break & Poster Session by PhD and MSc students** *Oeiras INATEL* 10:45 - 11:30			
11:30 – 13:30	**Hands on Neutrinos** *Ivo Varzielas, Valentina Lozza* *Oeiras INATEL* 11:30 - 13:30	**Hands on Higgs** *Jorge Romão, Rute Pedro* *Oeiras INATEL* 11:30 - 13:30	**Hands on QCD Jets** *Mr Dario Vaccaro, Liliana Apolinário* *Oeiras INATEL* 11:30 - 13:30	**Hands on Hadrons** *Alfred Stadler, Elmar Biernat* *Oeiras INATEL* 11:30 - 13:30

Back up

A graphic impression of quarks and gluons inside the proton (CERN)



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QCD phenomenology

- Some of the main areas of QCD phenomenology are:

- Heavy quark physics: Heavy quarks, such as charm, bottom, and top, have masses much larger than the typical QCD scale. Heavy quark physics explores the properties and interactions of hadrons containing heavy quarks, such as mesons and baryons, and the effects of QCD on the flavor and CP violation phenomena.

The strong interaction

	Boson	Charge	Mass (GeV/c^2)	Width (GeV/c^2)	Lifetime (sec)	Force
photon	γ	0	0	0	∞	EM
	$W^{\pm}$	± 1	80.399 ± 0.023	2.085 ± 0.042	3.14×10^{-25}	weak
	Z^0	0	91.1876 ± 0.0021	2.4952 ± 0.0023	2.64×10^{-25}	weak
gluon	g	0	"0"			strong

- Nowadays, Quantum Chromodynamics (QCD) is the theory that describes the Strong interaction that binds together protons and neutrons in the atomic nuclei