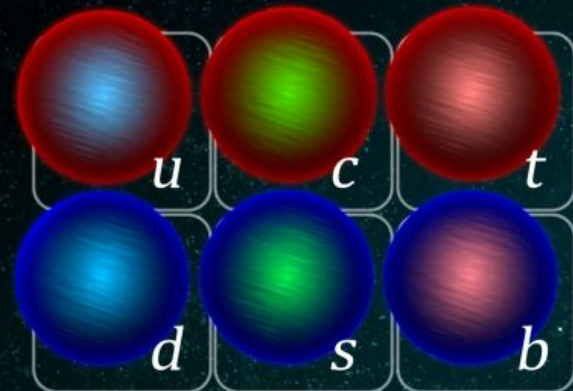
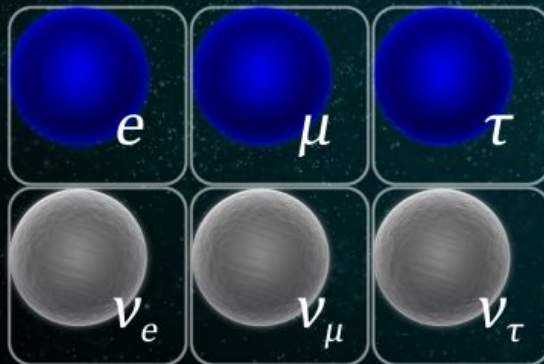


QCD AND HEAVY-ION PHYSICS

Víctor Vila
LIP Internship Program 2023
Lectures and Tutorials Week
LIP — July 4, 2023



Quarks



Leptons



Higgs boson

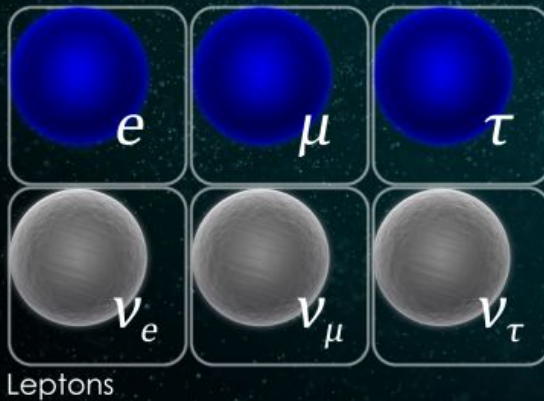
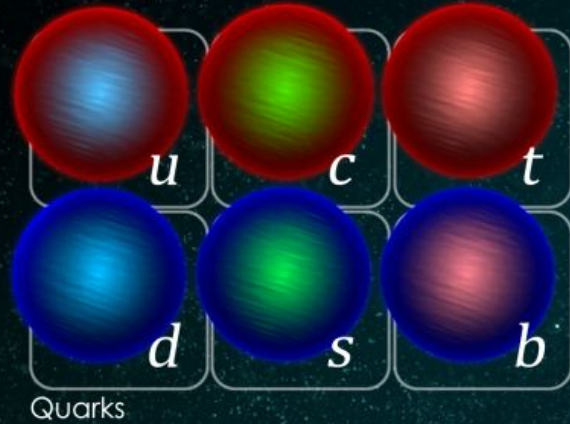


Forces



ACCELERATING SCIENCE

☼ A remarkable INSIGHT into the STRUCTURE OF MATTER.

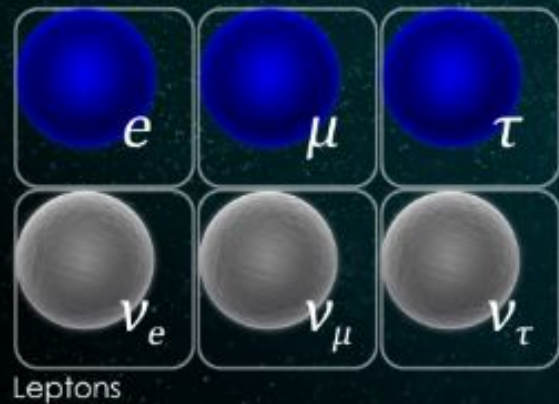
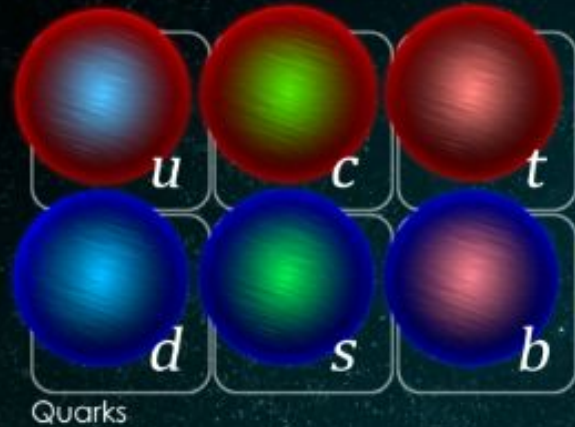


☼ EVERYTHING is made of FUNDAMENTAL PARTICLES.



☼ Governed by FOUR FUNDAMENTAL FORCES.

☼ Successfully explains EXPERIMENTAL RESULTS.

**ELEMENTARY PARTICLES****BUILDING BLOCKS**

QUARKS
LEPTONS

- ➔ Each group consists of SIX PARTICLES related in GENERATIONS.
- ➔ STABLE MATTER in the UNIVERSE is made from FIRST GEN' PARTICLES.
- ➔ QUARKS also come in different COLOURS but they form COLOURLESS objects.

FOUR FUNDAMENTAL FORCES**STRONG FORCE****EM FORCE****WEAK FORCE****GRAVITY**

- ➔ **DIFFERENT RANGES and STRENGTHS.**
- ➔ **THREE result from the EXCHANGE of FORCE-CARRIER PARTICLES: BOSONS.**
- ➔ **FITTING GRAVITY COMFORTABLY has proved to be a DIFFICULT CHALLENGE.**
- ➔ **Only when MATTER is in BULK does GRAVITY DOMINATE.**



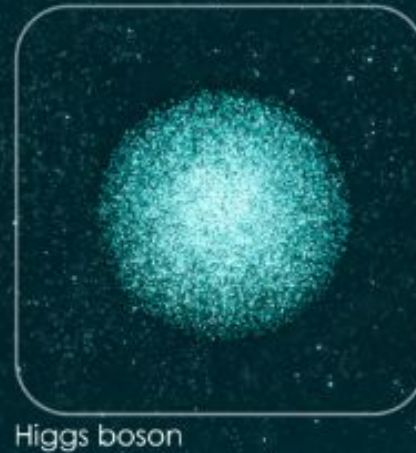
THE HIGGS BOSON

- ➔ ATLAS and CMS observed a new particle in 126 GeV.
- ➔ CONSISTENT with the HIGGS BOSON predicted by the SM.
- ➔ Understanding the ORIGIN of MASS of SUBATOMIC PARTICLES.



THE HIGGS BOSON

- ➔ ATLAS and CMS observed a new particle in 126 GeV.
- ➔ CONSISTENT with the HIGGS BOSON predicted by the SM.
- ➔ Understanding the ORIGIN of MASS of SUBATOMIC PARTICLES.



AN INCOMPLETE PICTURE

- ➔ ONLY THREE OUT OF FOUR FUNDAMENTAL FORCES.

IMPORTANT QUESTIONS

DARK MATTER
MATTER-ANTIMATTER
ASYMMETRY
MASS SCALE GAP
BETWEEN QUARKS AND
LEPTONS GEN'S.

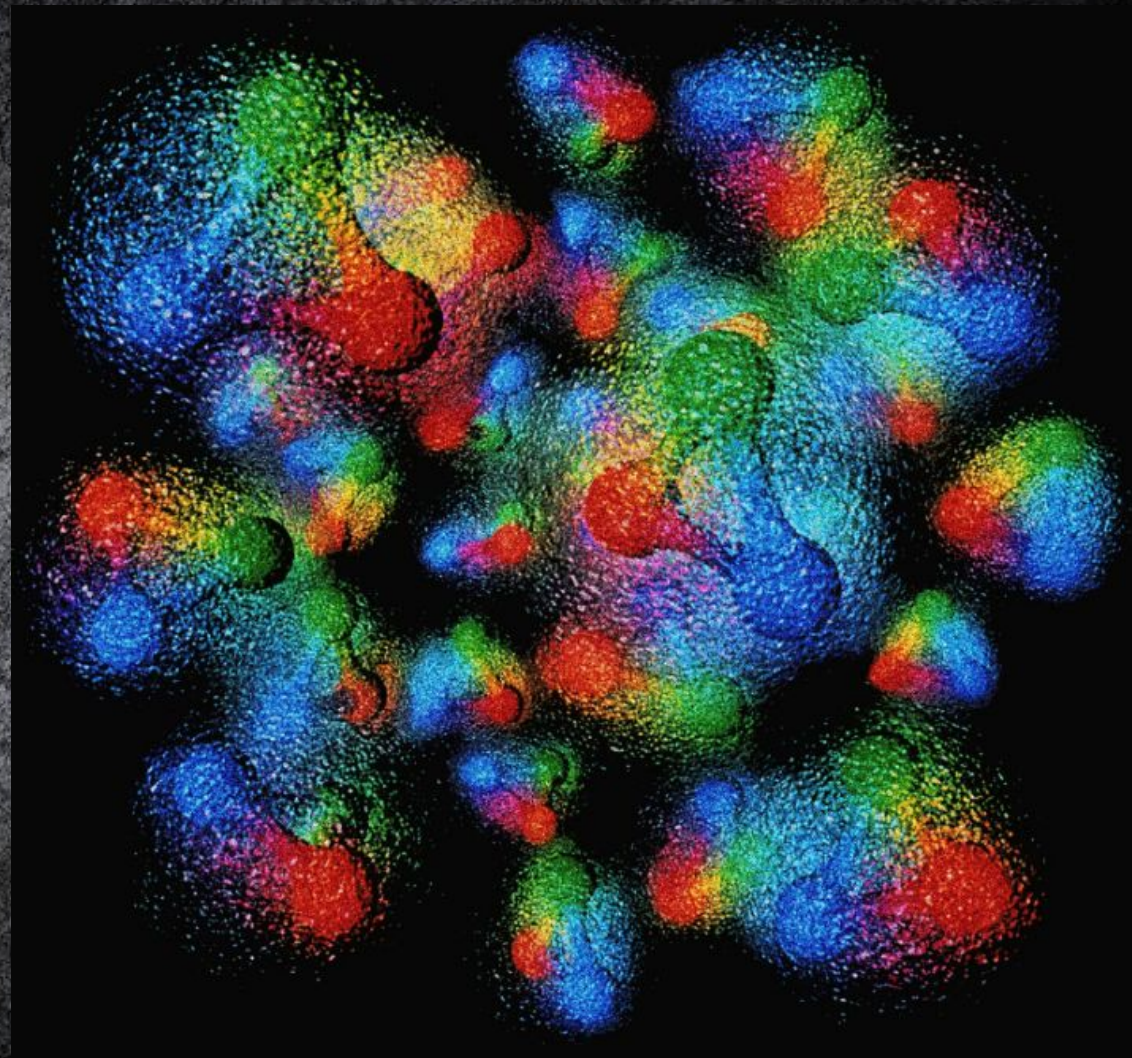
The theory of STRONG INTERACTIONS

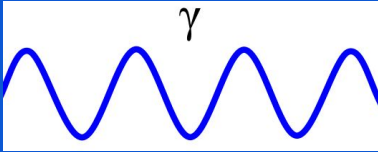
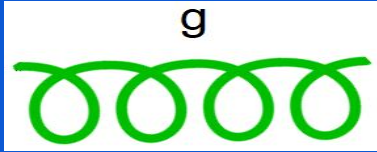
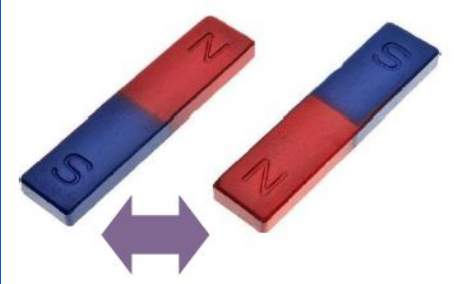

HADRON formation

MESONS

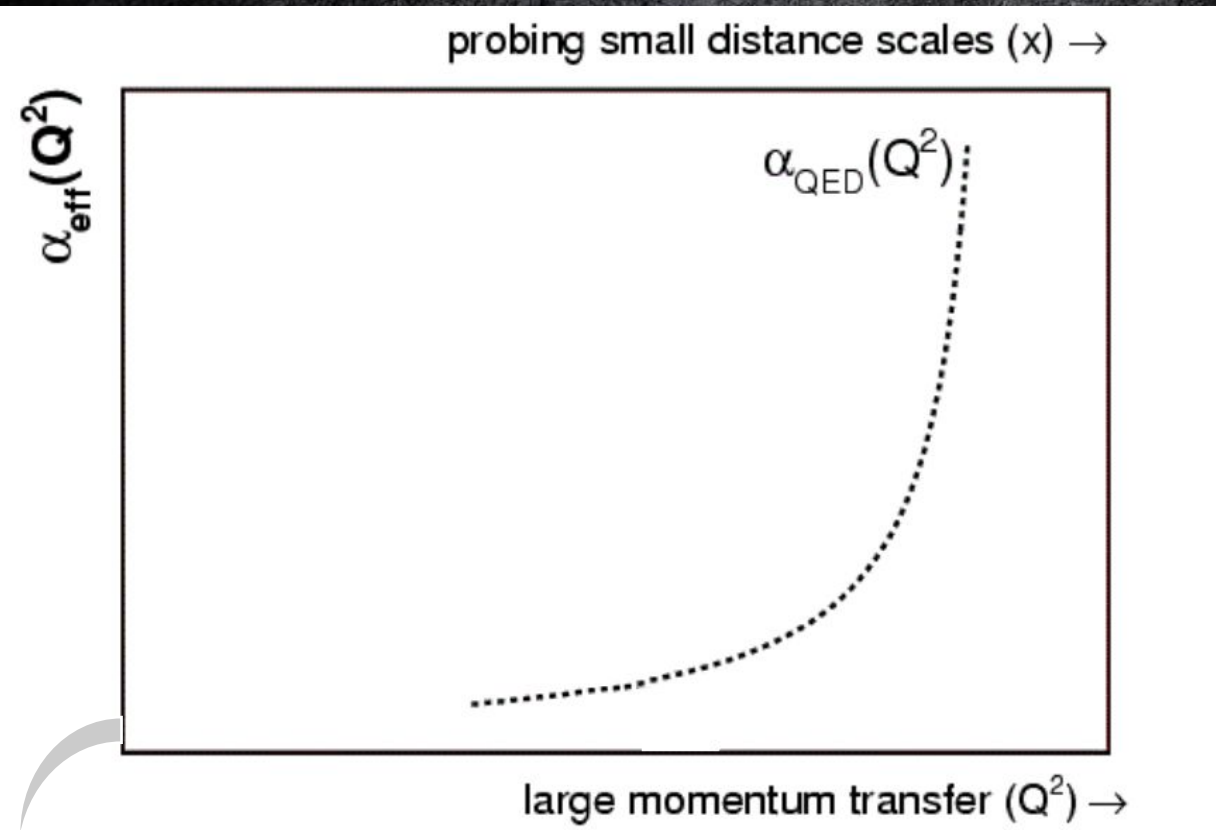
BARYONS

- QUARK INTERACTIONS take place by way of GLUON EXCHANGES.
- GLUONS are CARRIERS of a NEW QUANTUM NUMBER: **COLOR**.
- COLOR was introduced to restore PAULI'S PRINCIPLE.

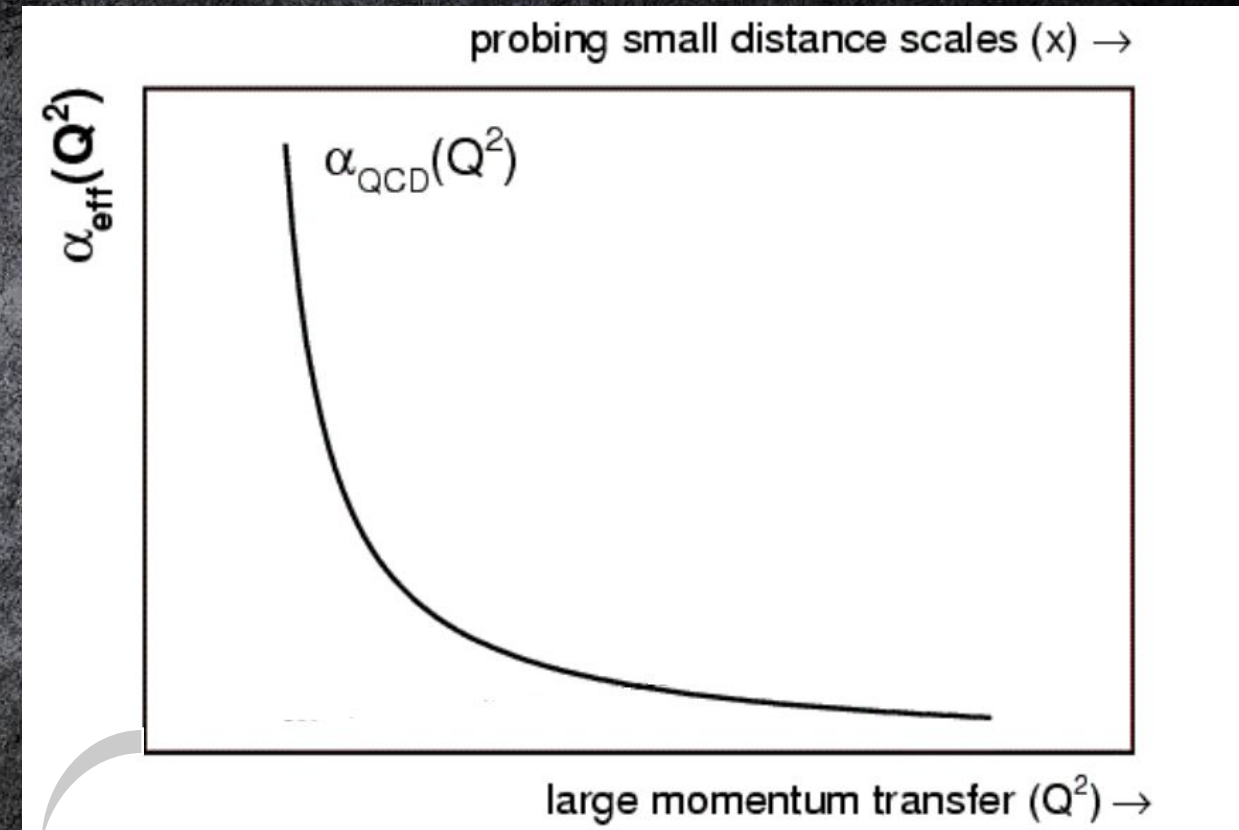


	QED	QCD
CHARGE	1 (+ / -)	3 (R / G / B)
EXCHANGES		
SELF-INTERACTION	✗	✓
RANGE		

● The **COUPLING CONSTANT** sets the **STRENGTH** of the **INTERACTIONS**.

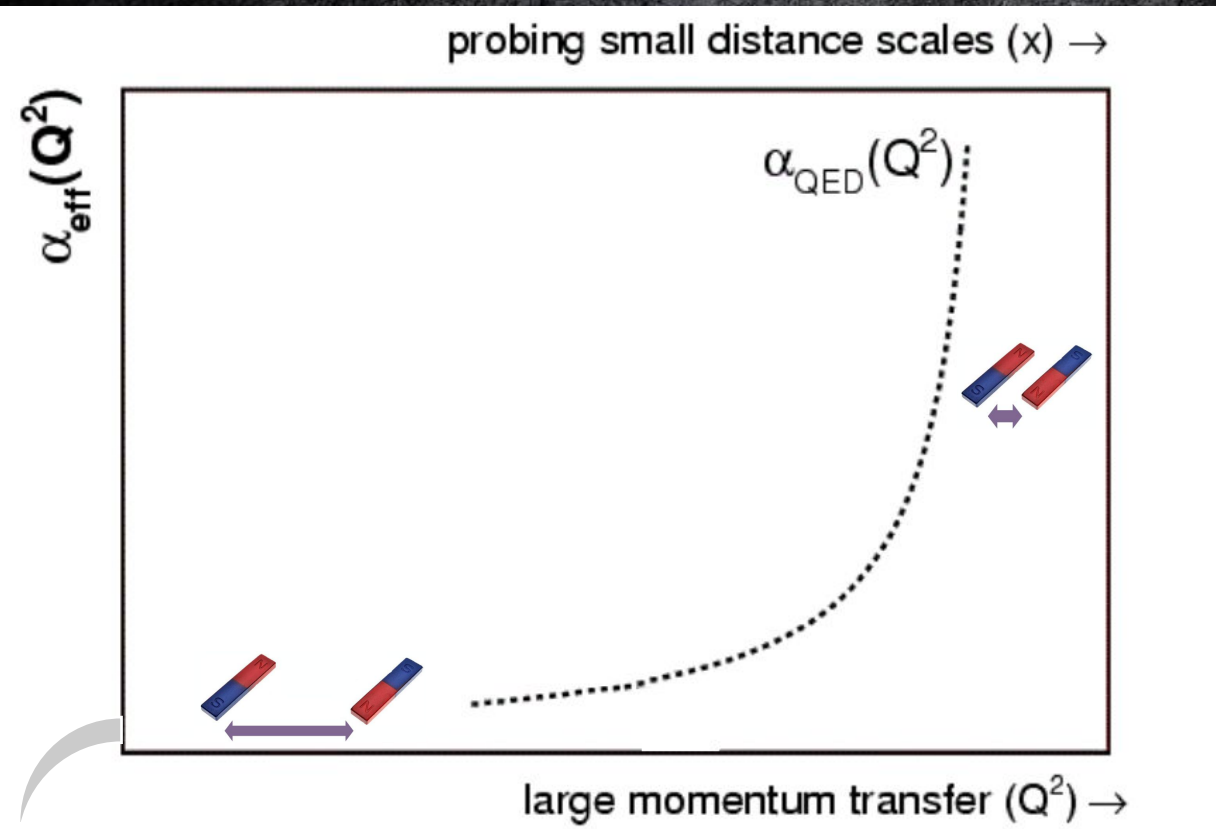


In QED **INCREASES** with increasing Q .

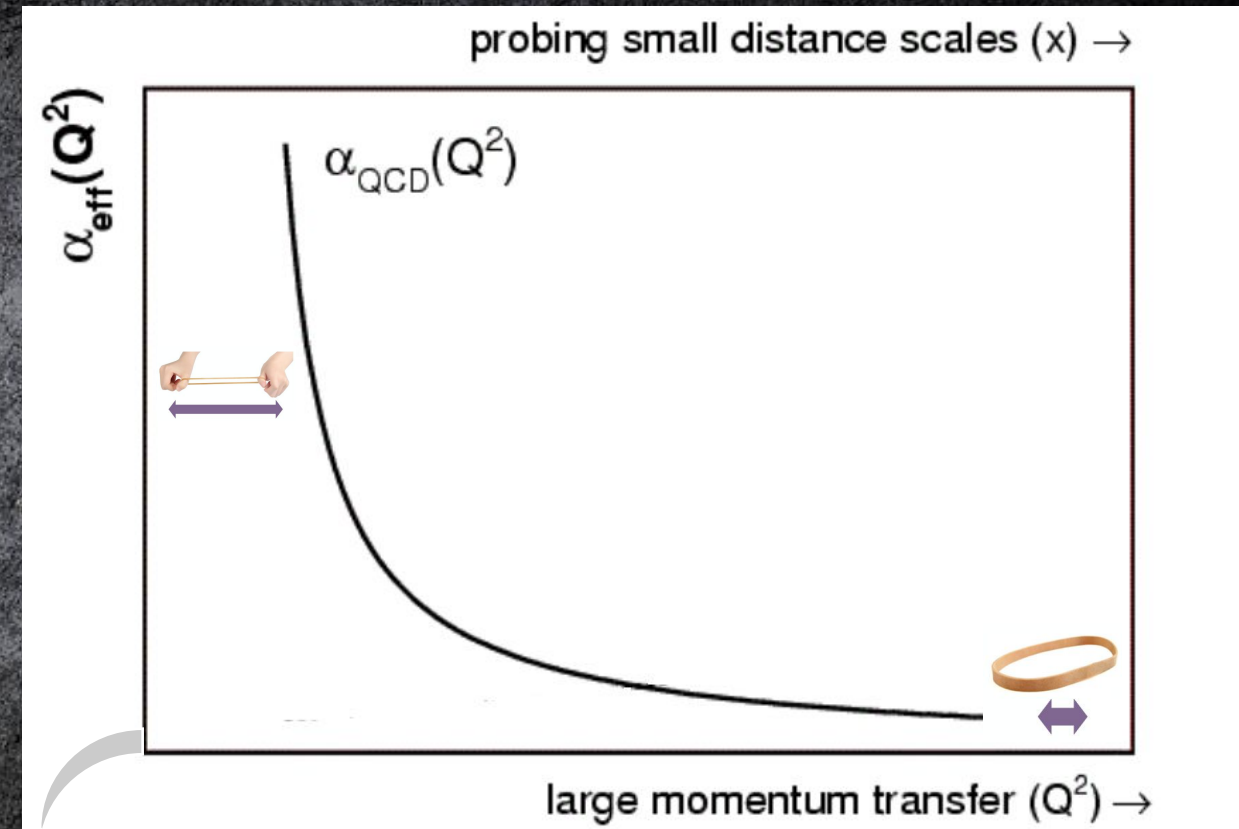


In QCD **DECREASES** with increasing Q .

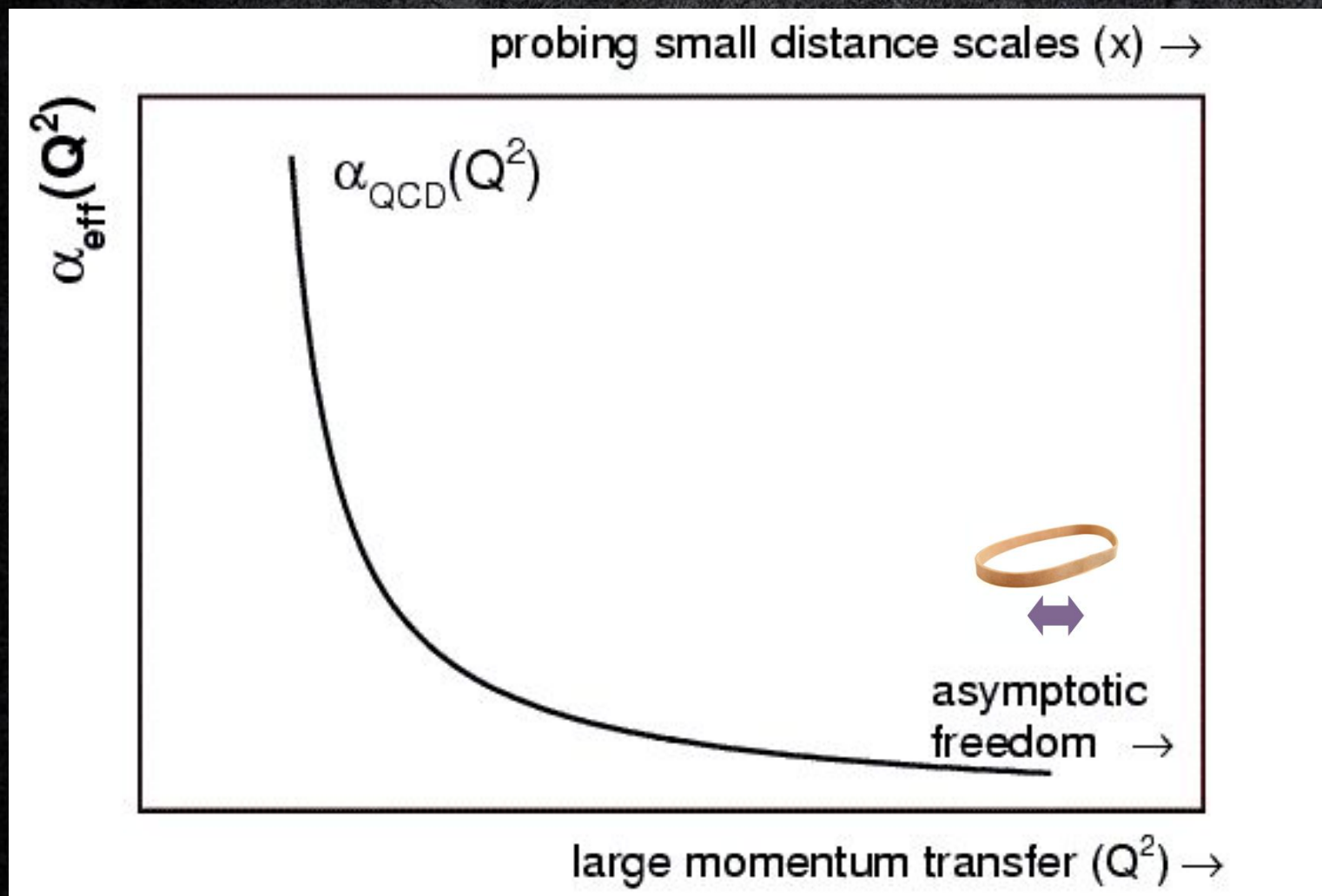
☁ The **COUPLING CONSTANT** sets the **STRENGTH** of the **INTERACTIONS**.



Force becomes **WEAKER** as the **DISTANCE** between **TWO CHARGES** **INCREASES**.



QCD embodies the **SHORT-RANGE** **NATURE** of the **STRONG** **FORCE**.



ASYMPTOTIC FREEDOM

- \rightarrow The **STRONG COUPLING** becomes **SMALL** at **SHORT** distances.
- \rightarrow **QUARKS** inside hadrons behave more or less as **FREE PARTICLES**.

PERTURBATIVE REGIME OF QCD

$$\mathcal{L} = \frac{1}{4g^2} G_{\mu\nu}^a G_{\mu\nu}^a + \sum_j \bar{\psi}_j (i \gamma^\mu D_\mu + m_j) \psi_j$$

where $G_{\mu\nu}^a \equiv \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + gf_{abc} A_\mu^b A_\nu^c$
and $D_\mu \equiv \partial_\mu + it^a A_\mu^a$
That's it!

The QCD LAGRANGIAN
(Fritz, Gell-Mann and
Leutwyler, 1973)

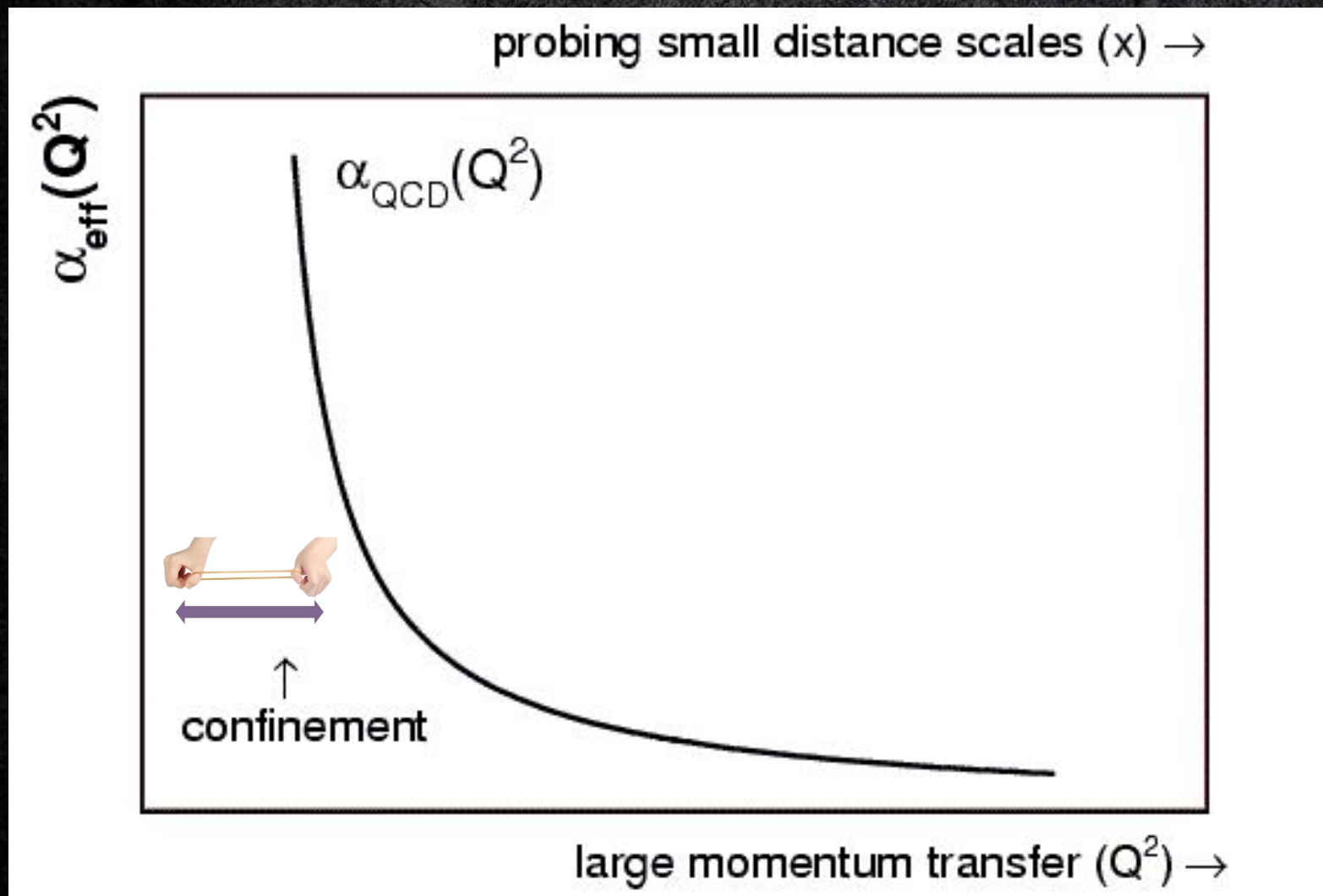
**STRONG
COUPLING SMALL**

**PERTURBATION THEORY
TECHNIQUES**

**SMALL EXPANSION
PARAMETER**

$$\sum_{n=0}^{\infty} C_n x^n = C_0 x^0 + C_1 x^1 + C_2 x^2 + C_3 x^3 + \dots$$



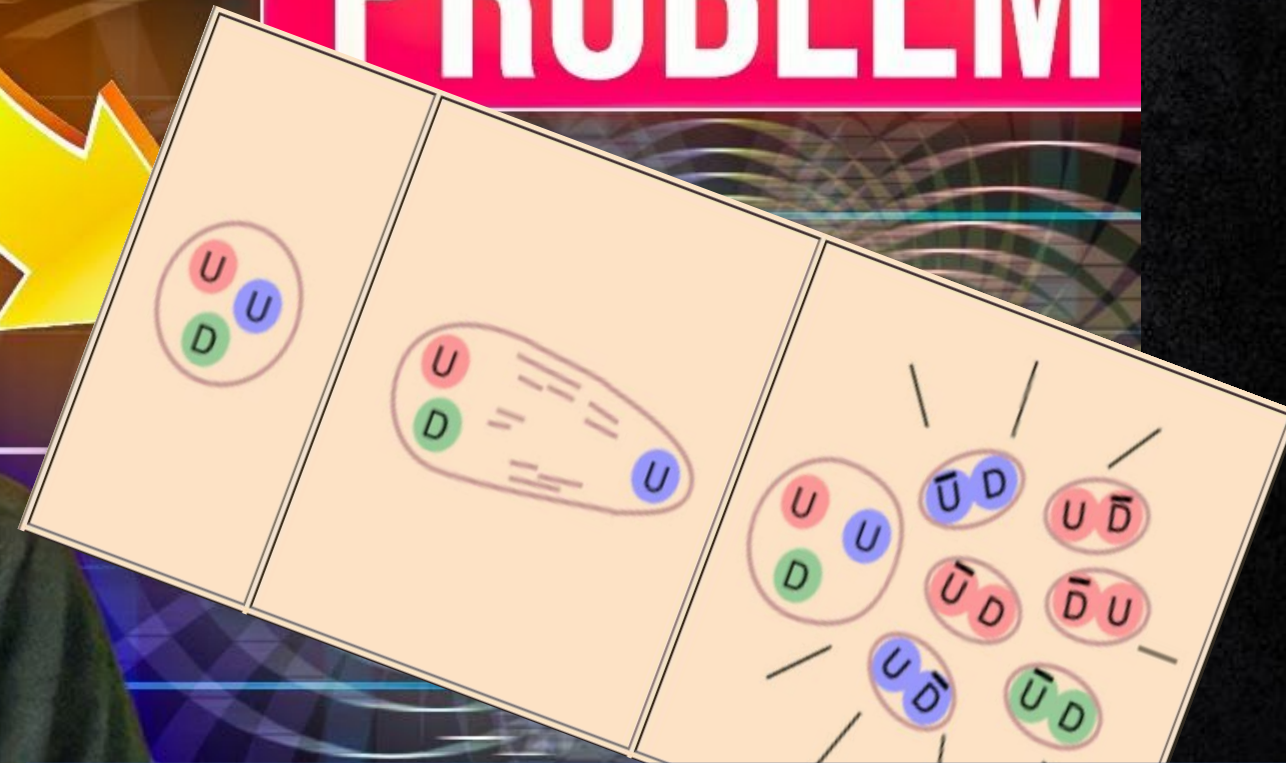


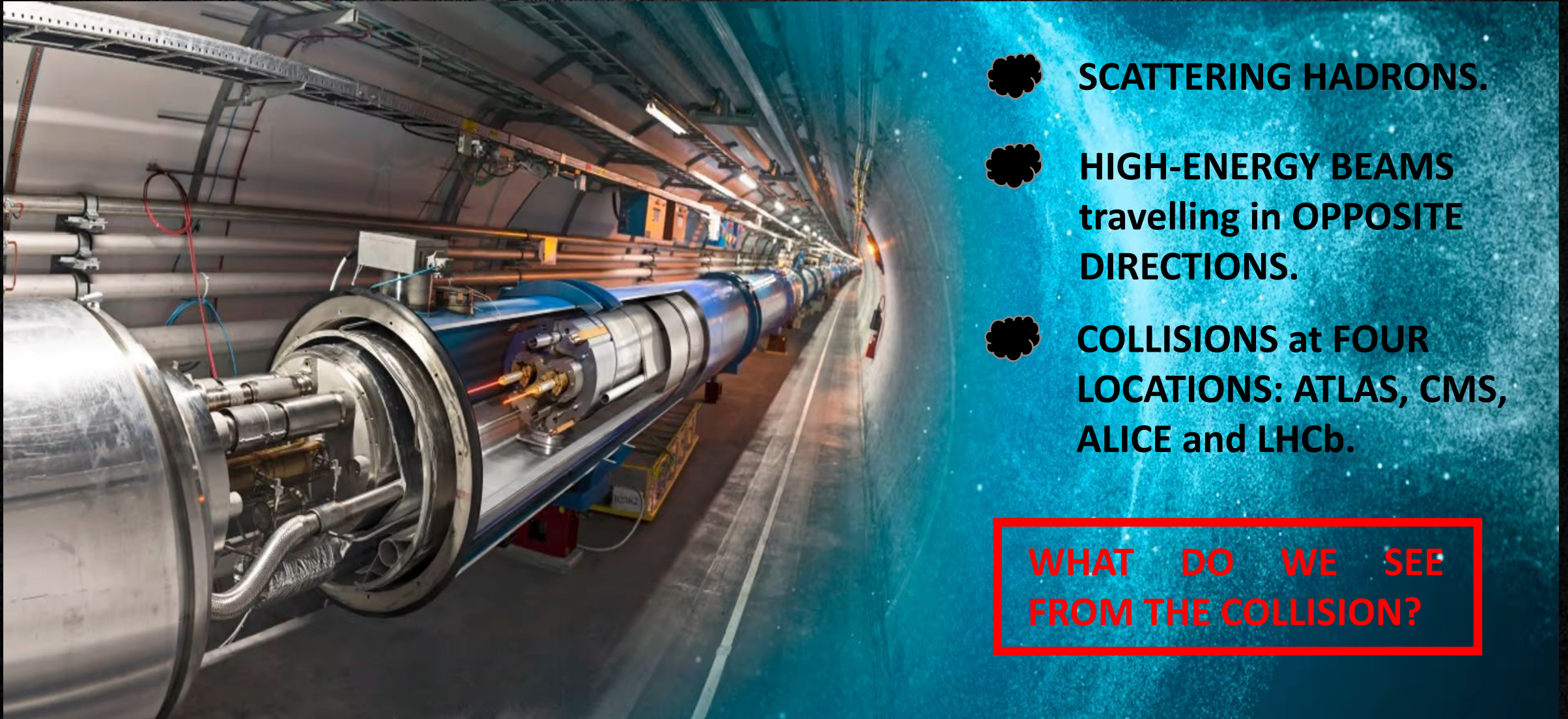
CONFINEMENT

\rightarrow At INCREASING DISTANCE the COUPLING becomes so STRONG that it is IMPOSSIBLE to ISOLATE a QUARK from a HADRON.

NOT ACCESSIBLE BY PERTURBATIVE QCD

MILLION DOLLAR PROBLEM



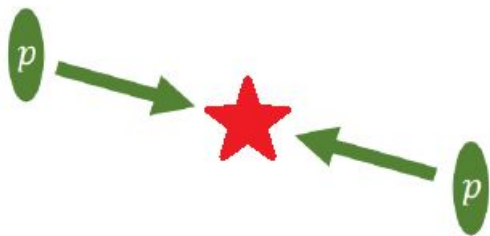
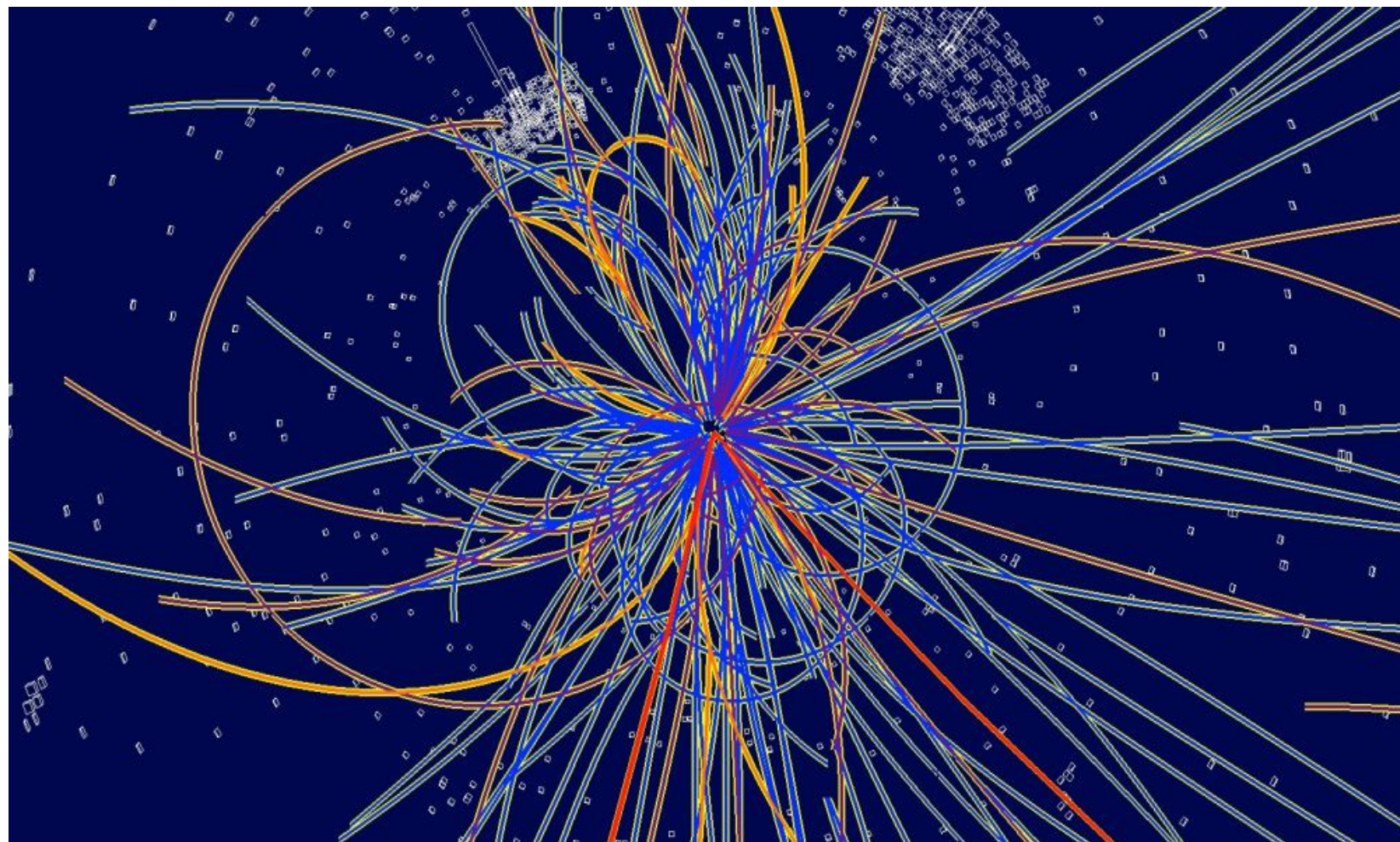


- ❁ SCATTERING HADRONS.
- ❁ HIGH-ENERGY BEAMS travelling in OPPOSITE DIRECTIONS.
- ❁ COLLISIONS at FOUR LOCATIONS: ATLAS, CMS, ALICE and LHCb.

WHAT DO WE SEE FROM THE COLLISION?

COLLIDING PARTICLES

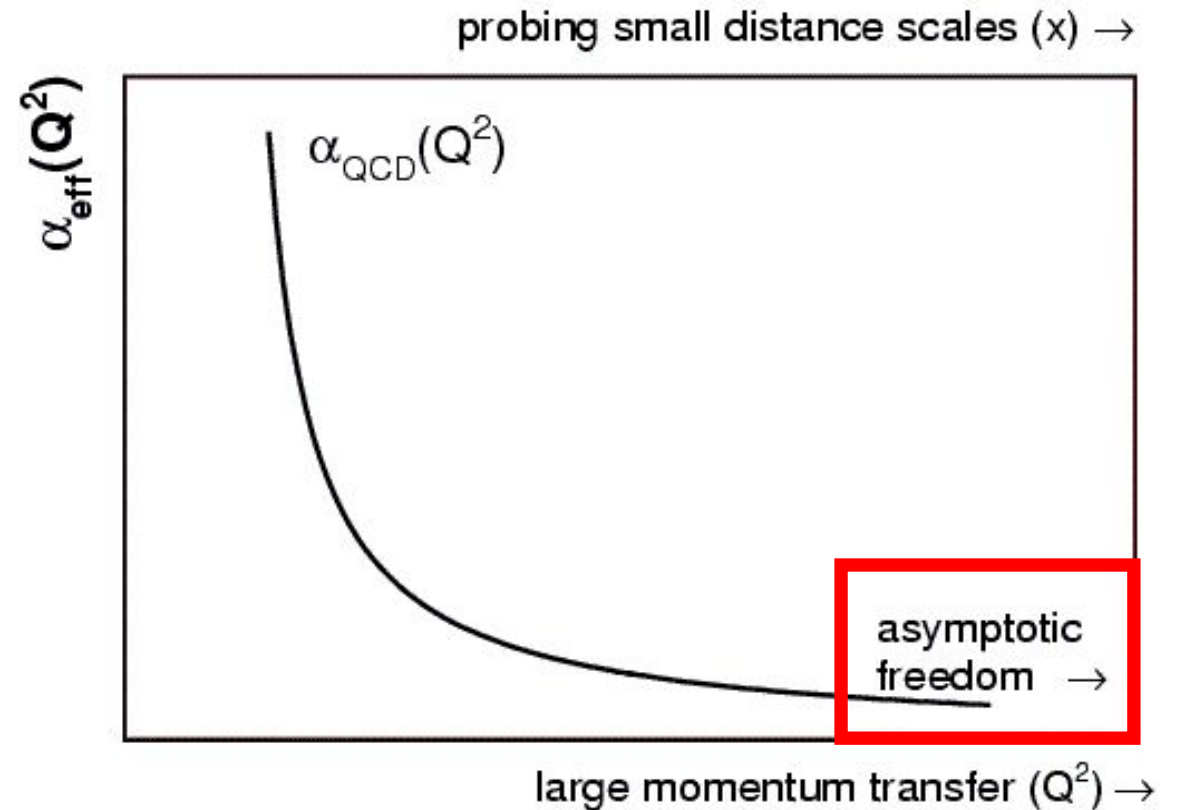
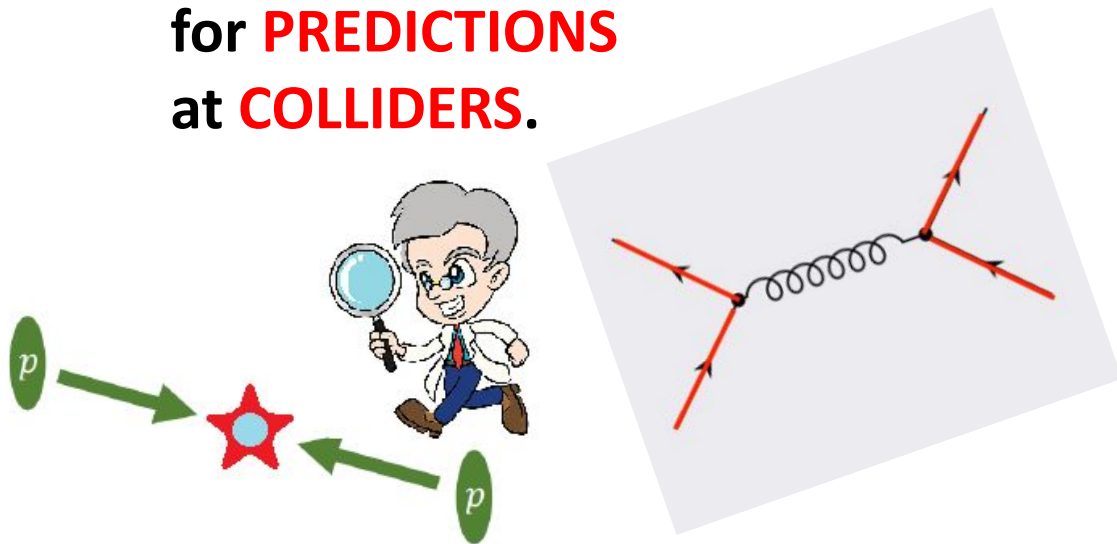
- LHC works with PROTONS and LEAD NUCLEUS.
- Energetic particles COLLIDE at the CENTER of the DETECTORS.
- NEW PARTICLES are CREATED.

**LHC: A SUPER MICROSCOPE**

THE HARD SCATTERING

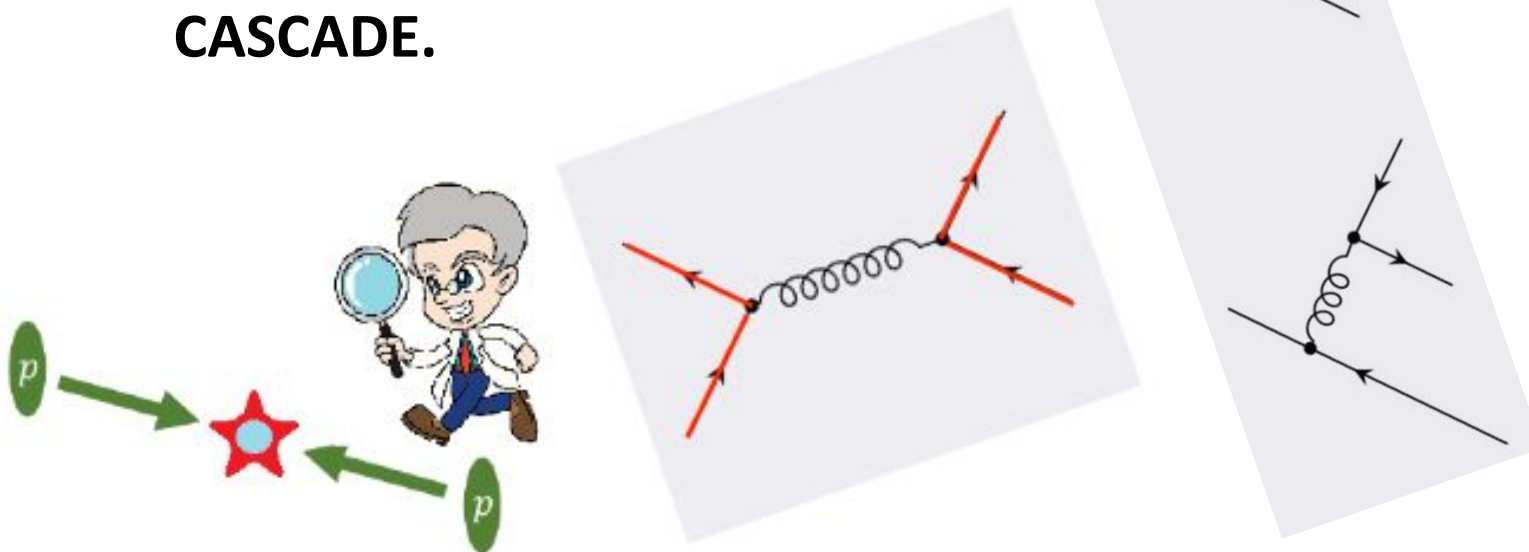
Very **ENERGETIC QUARKS** and **GLUONS** are produced through **HARD SCATTERING PROCESSES**.

We compute **SCATTERING AMPLITUDES**, which are essential for **PREDICTIONS** at **COLLIDERS**.



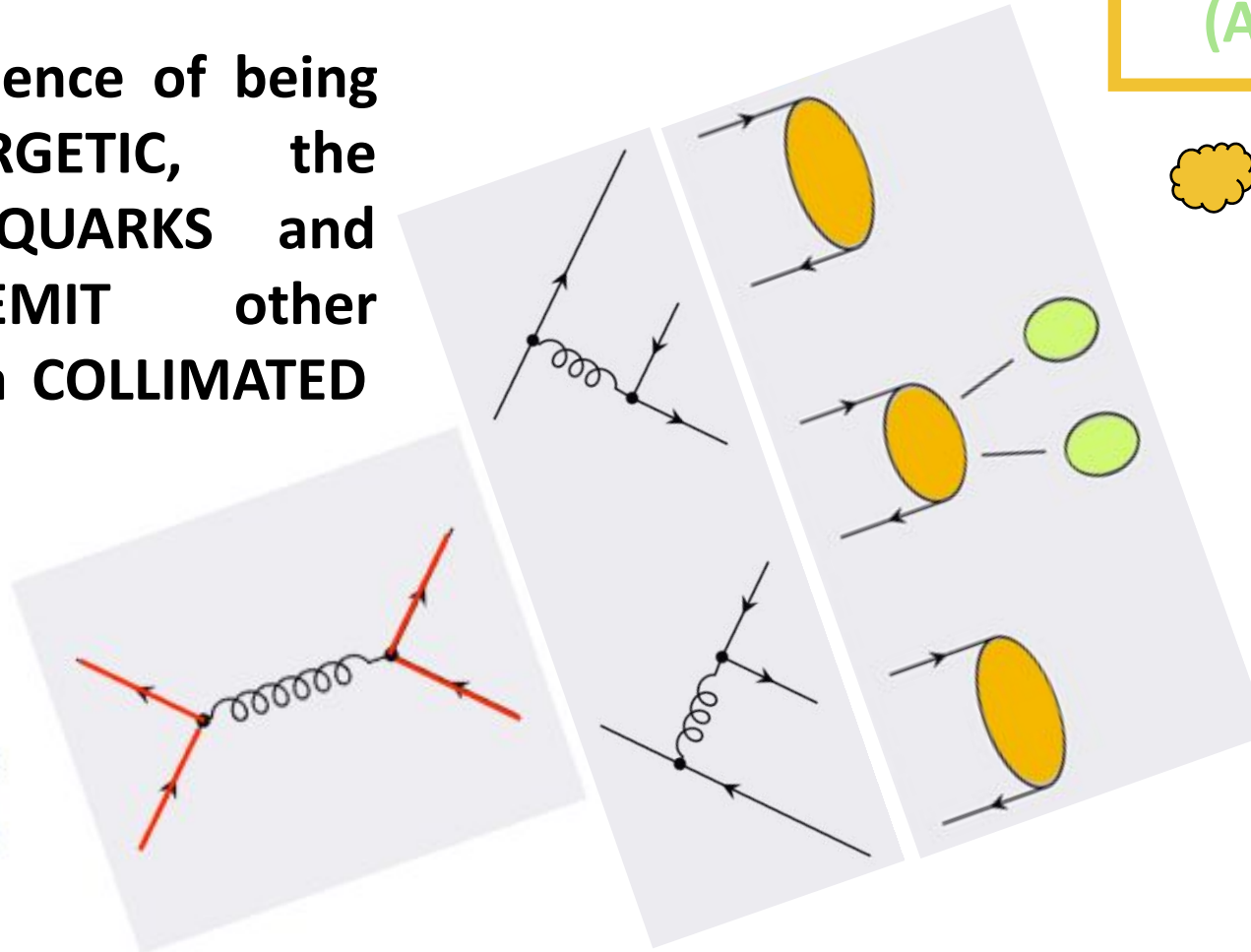
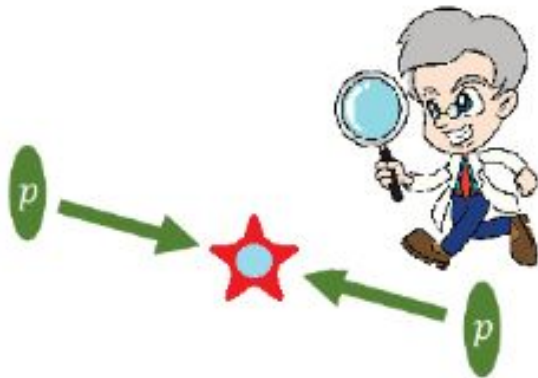
THE PARTON SHOWER

- As a consequence of being
VERY ENERGETIC, the
PRODUCED QUARKS and
GLUONS EMIT other
PARTONS in a COLLIMATED
CASCADE.**



THE PARTON SHOWER

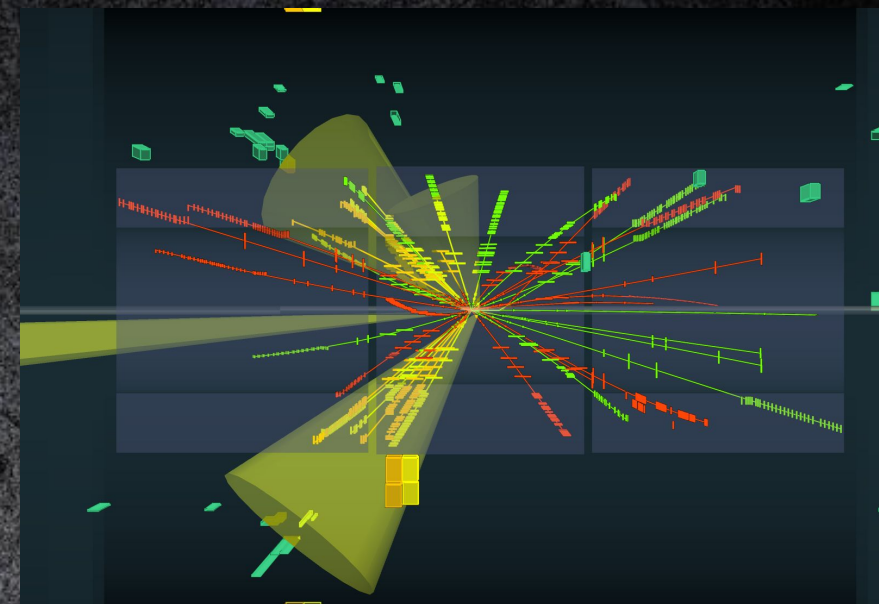
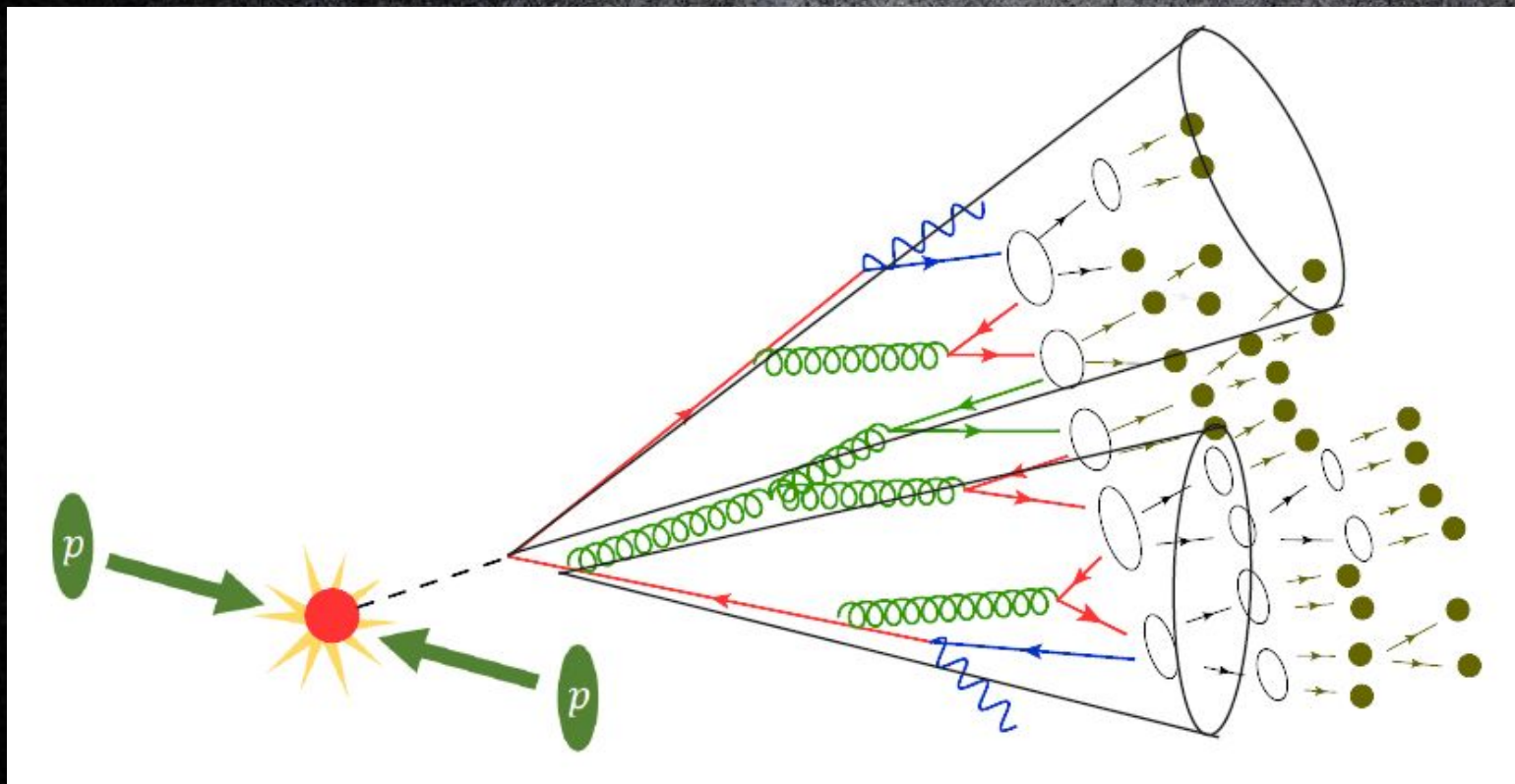
- As a consequence of being VERY ENERGETIC, the PRODUCED QUARKS and GLUONS EMIT other PARTONS in a COLLIMATED CASCADE.



HADRONIZATION (AND DECAY)

- The PARTON SHOWER KEEPS DEVELOPING until HADRONIZATION takes place, and the NEWLY formed HADRONS SPREAD until they eventually REACH the DETECTORS.

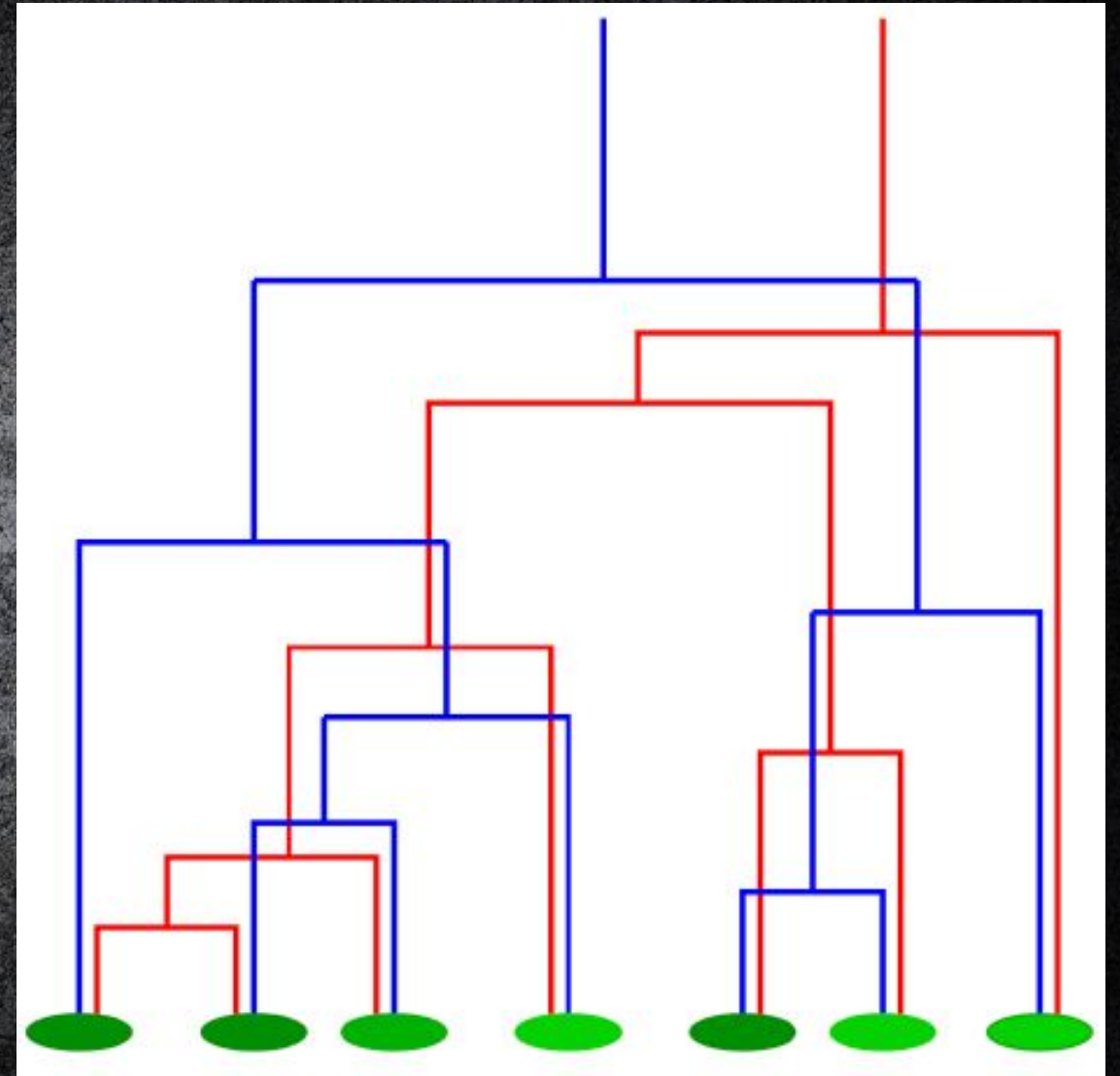
- The **COLLIMATED SIGNATURE** of the **PARTON SHOWER** is measurable since **FINAL-STATE HADRONS** are **NOT EVENLY DISTRIBUTED** in every likely direction.



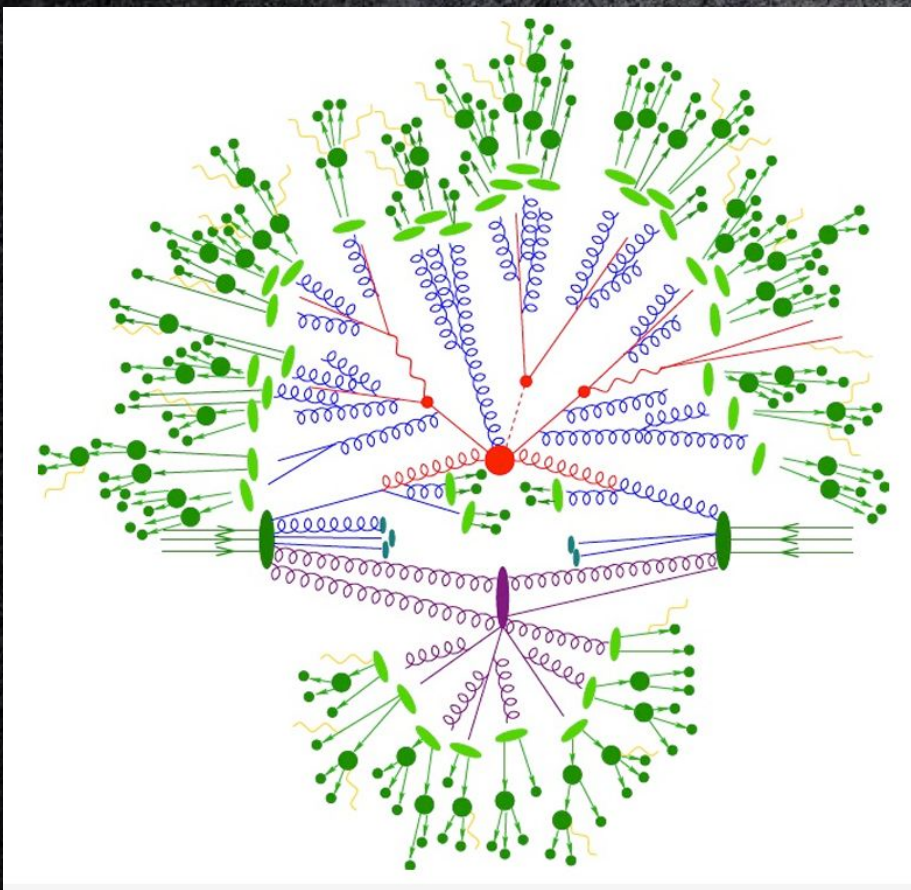
- We **MEASURE JETS**, which allows the **RECONSTRUCTION** of the **KINEMATICS** of the **ELEMENTARY QCD INTERACTIONS**.

JET ALGORITHMS: INVERTING THE PROCESS

- IDENTIFICATION of JETS is NON-TRIVIAL: JETS can partially OVERLAP.
- A JET ALGORITHM INVERTS the CASCADING PROCESS by SUCCESSIVELY RECOMBINING TWO PARTICLES INTO ONE.
- In JET SUBSTRUCTURE TECHNIQUES, JETS are organized in a HIERARCHICAL TREE where the NODES account for SUCCESSIVE SPLITTING PROCESSES.



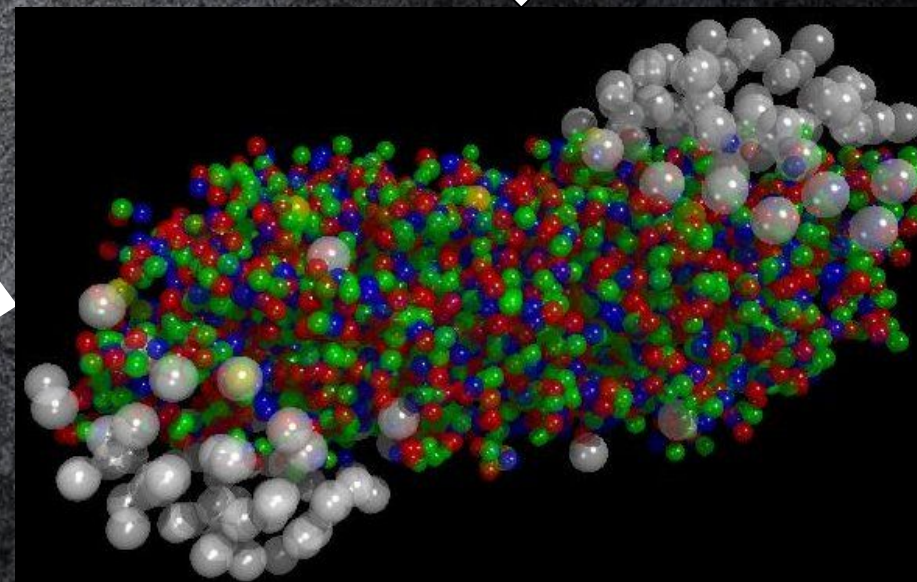
JET STUDIES IN SMALL SYSTEMS



JET STUDIES IN AA COLLISIONS



**MAIN PROBES for looking into
the QUARK GLUON PLASMA.**



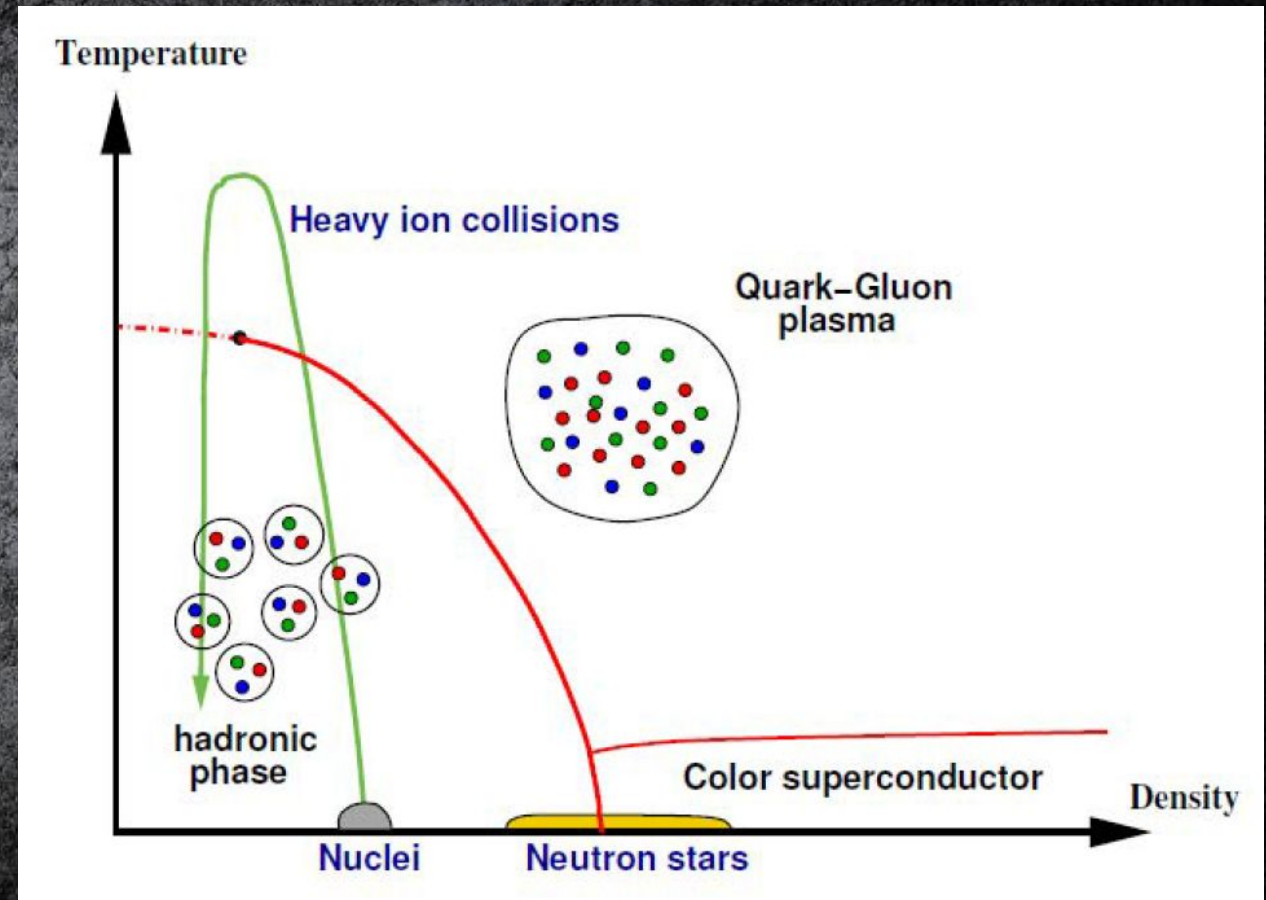
QUARK-GLUON PLASMA

HIGHLY DENSE form of NUCLEAR MATTER made up by DECONFINED QUARKS and GLUONS.

PHASE TRANSITION from a STATE OF CONFINED QUARKS AND GLUONS to DECONFINED.

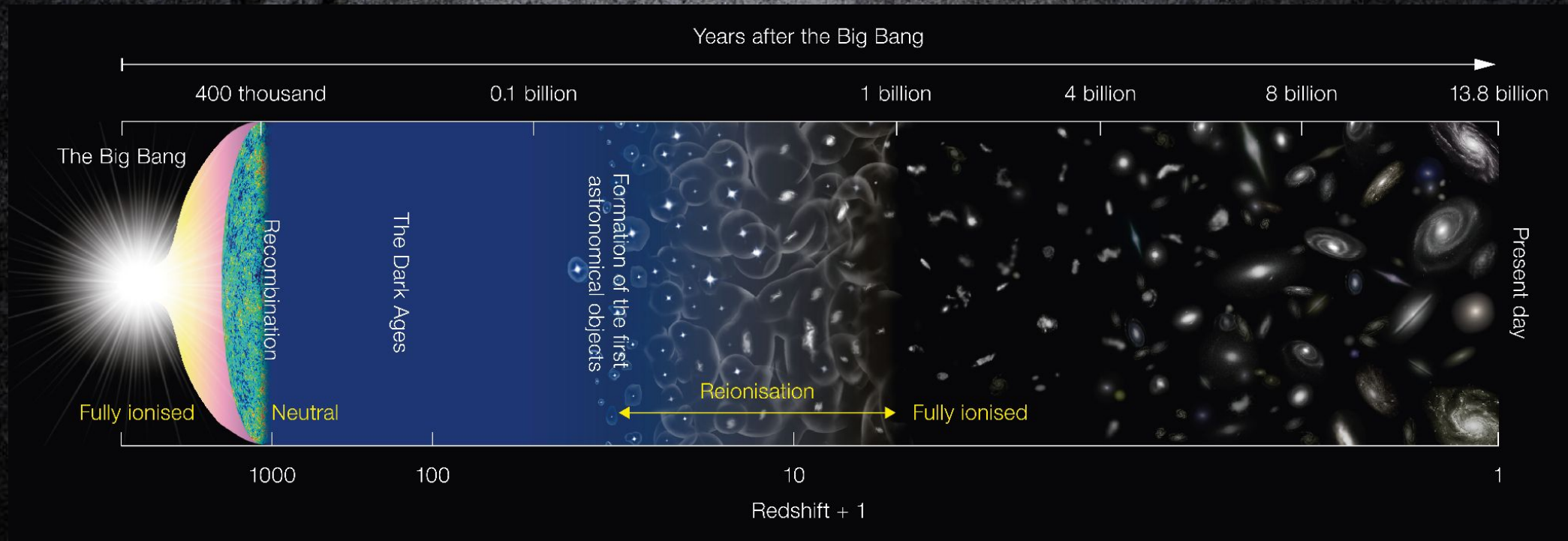
(ALMOST FREE) QGP at TEMPERATURES MUCH HIGHER than the CRITICAL TEMPERATURE.

QCD PHASE DIAGRAM



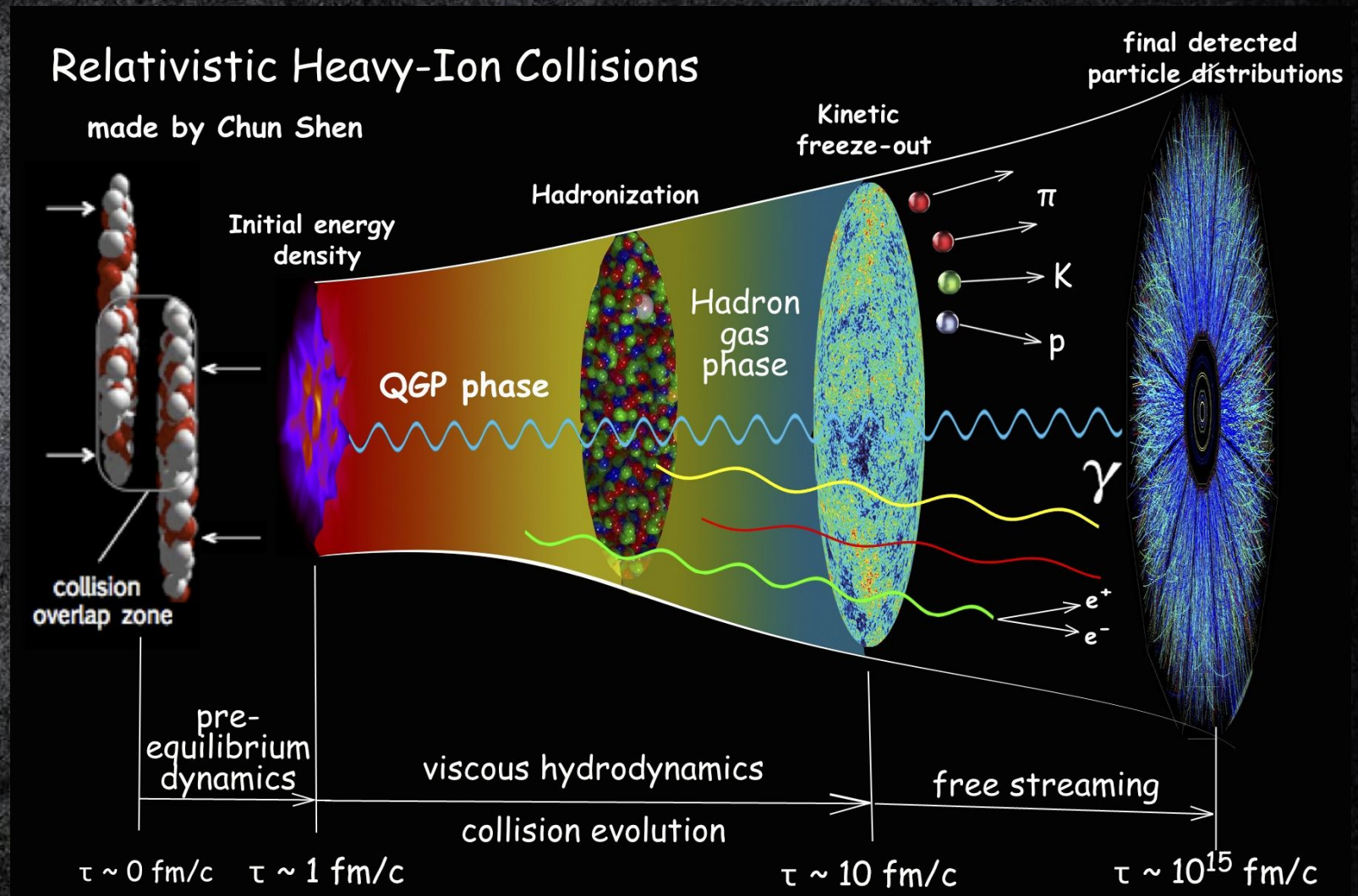
THE QUEST FOR THE QUARK-GLUON PLASMA

- QGP present during FIRST MICROSECONDS AFTER the BIG BANG.
- QGP can exist in NEUTRON STARS.
- Unique information on QUARKS AND GLUONS CONFINEMENT.



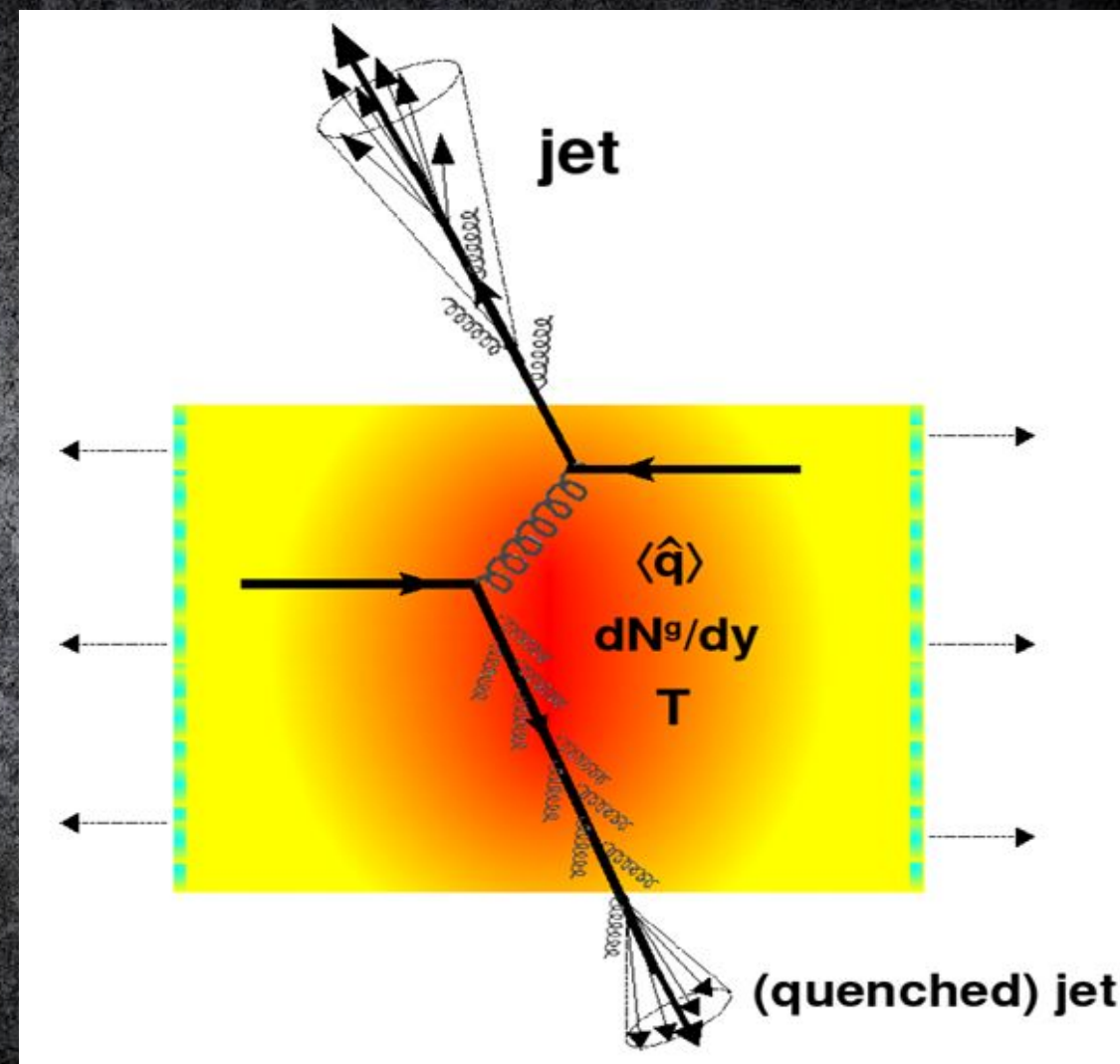
HEAVY-ION EXPERIMENTS TO ACHIEVE THE QGP

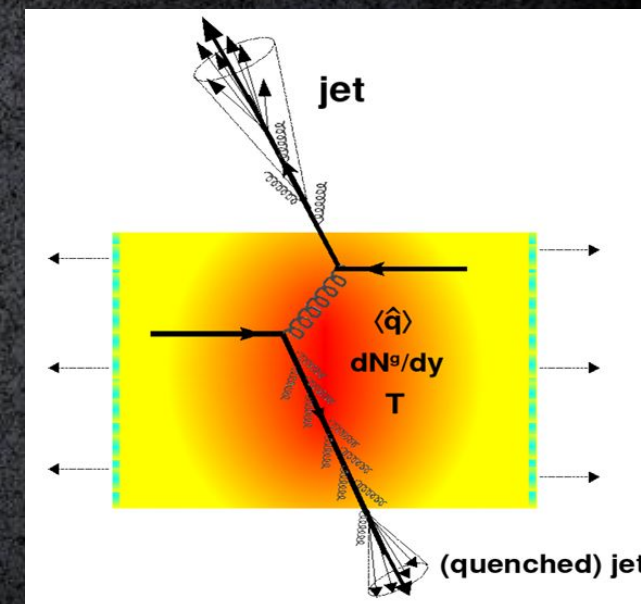
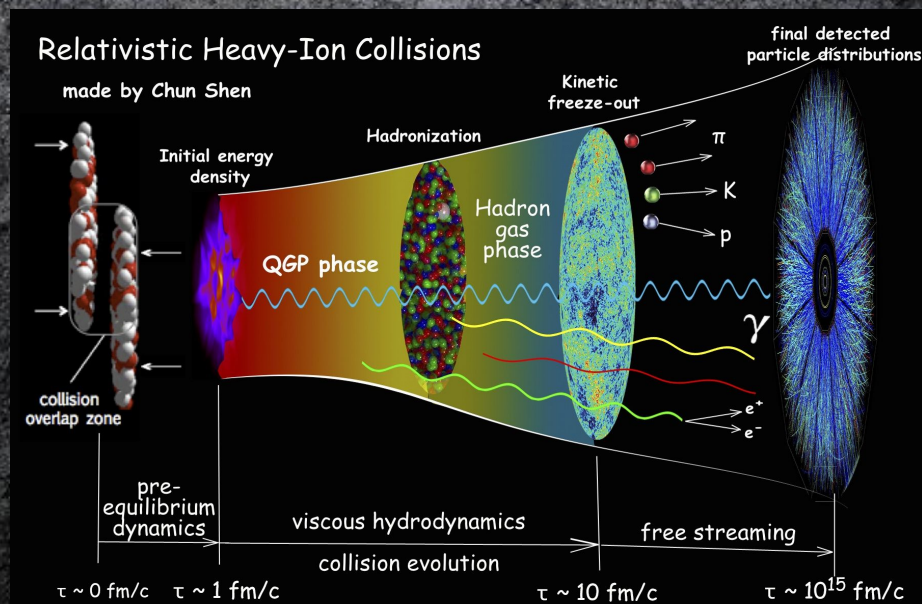
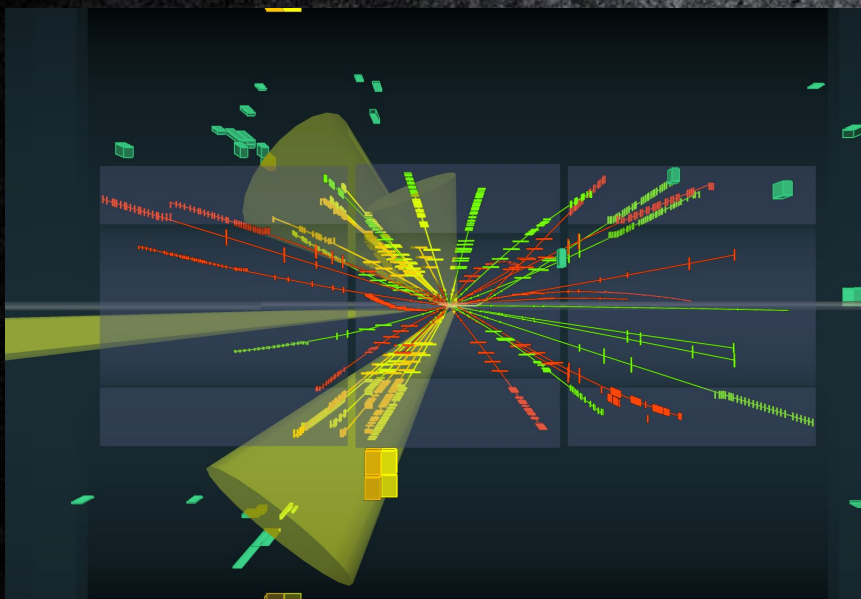
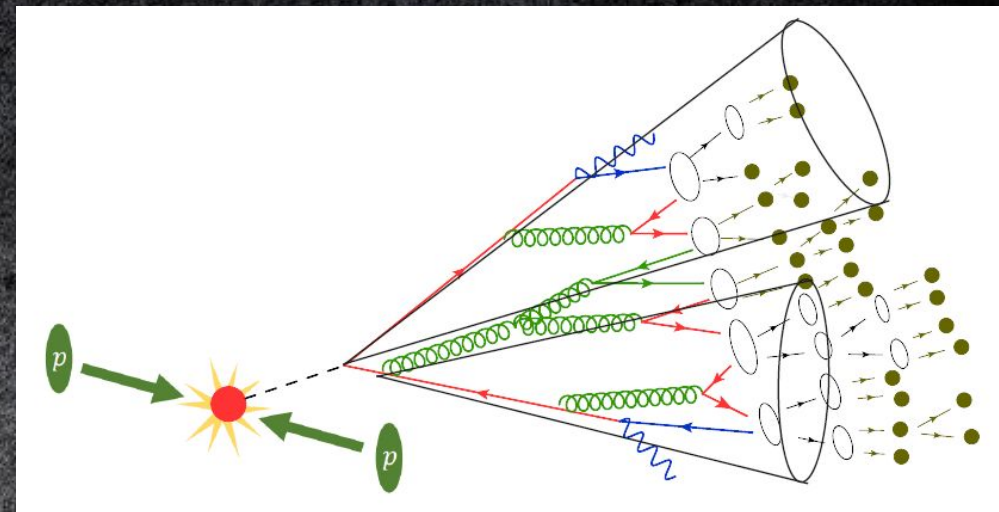
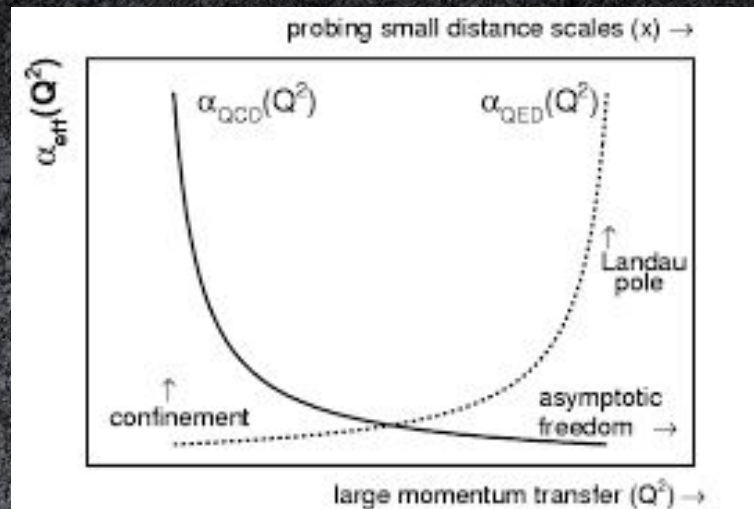
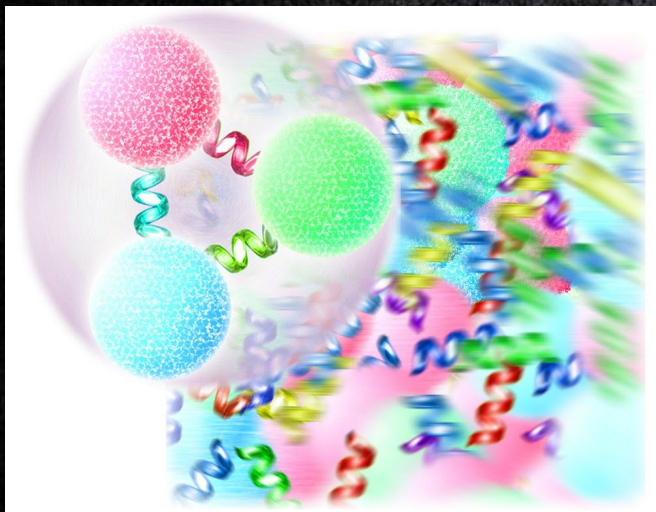
- ❁ RHIC: AuAu collisions at 200 GeV.
- ❁ LHC: PbPb collisions at 2.75 to 5.5 TeV.
- ❁ FCC: PbPb collisions at 39 TeV?



HOW TO PROBE THE QGP**HARD
PROBES**

- Created in the **EARLY STAGES** of the **COLLISION**.
- KEY PROBES** for **INFERRING** the **MEDIUM PROPERTIES**.
- JETS** are **NATURAL HARD PROBES**.

JET QUENCHING



THANK YOU VERY MUCH FOR YOUR ATTENTION!

