AN INTRODUCTION TO HADRONIC PHYSICS

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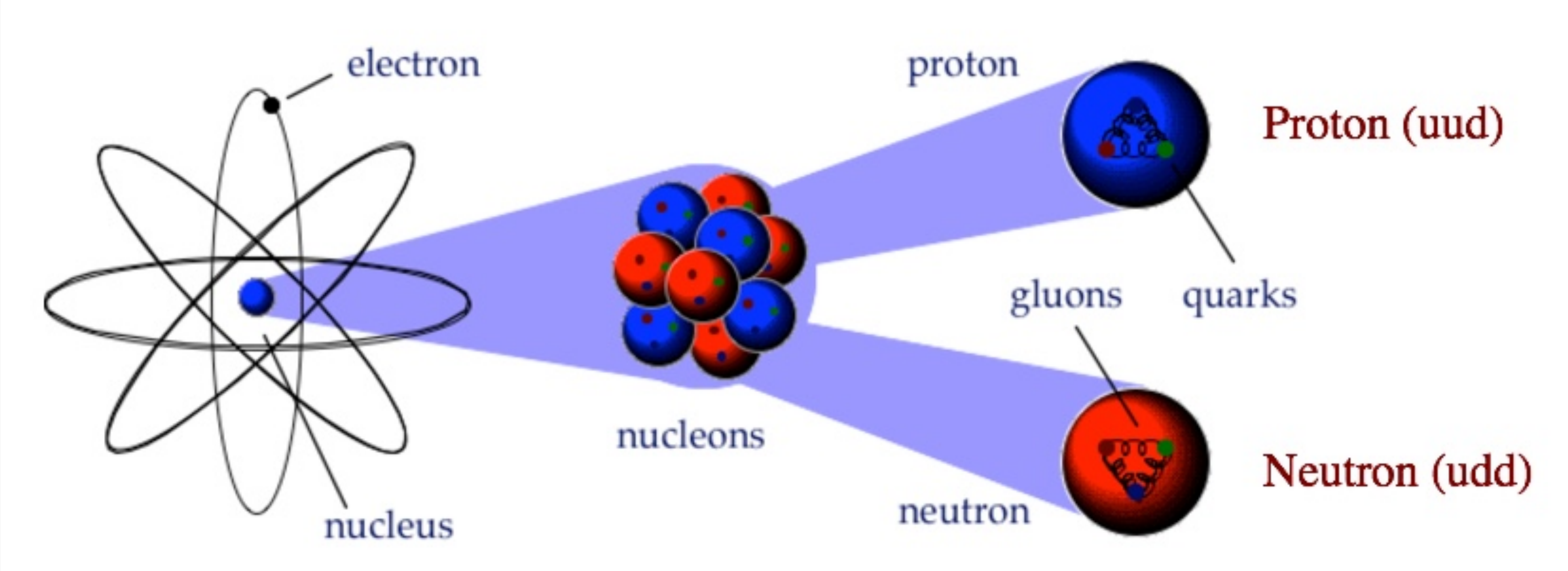
« Oysters and nuclear physics have a lot in common. When you see an oyster it looks ugly but if you open it it is beautiful. Like the beauty of nuclear physics.» – Lucia Caceres 16/10/2018

This statement also holds for hadronic physics…

QUARKS AND GLUONS : THE HEART OF MATTER

- The structure of matter :

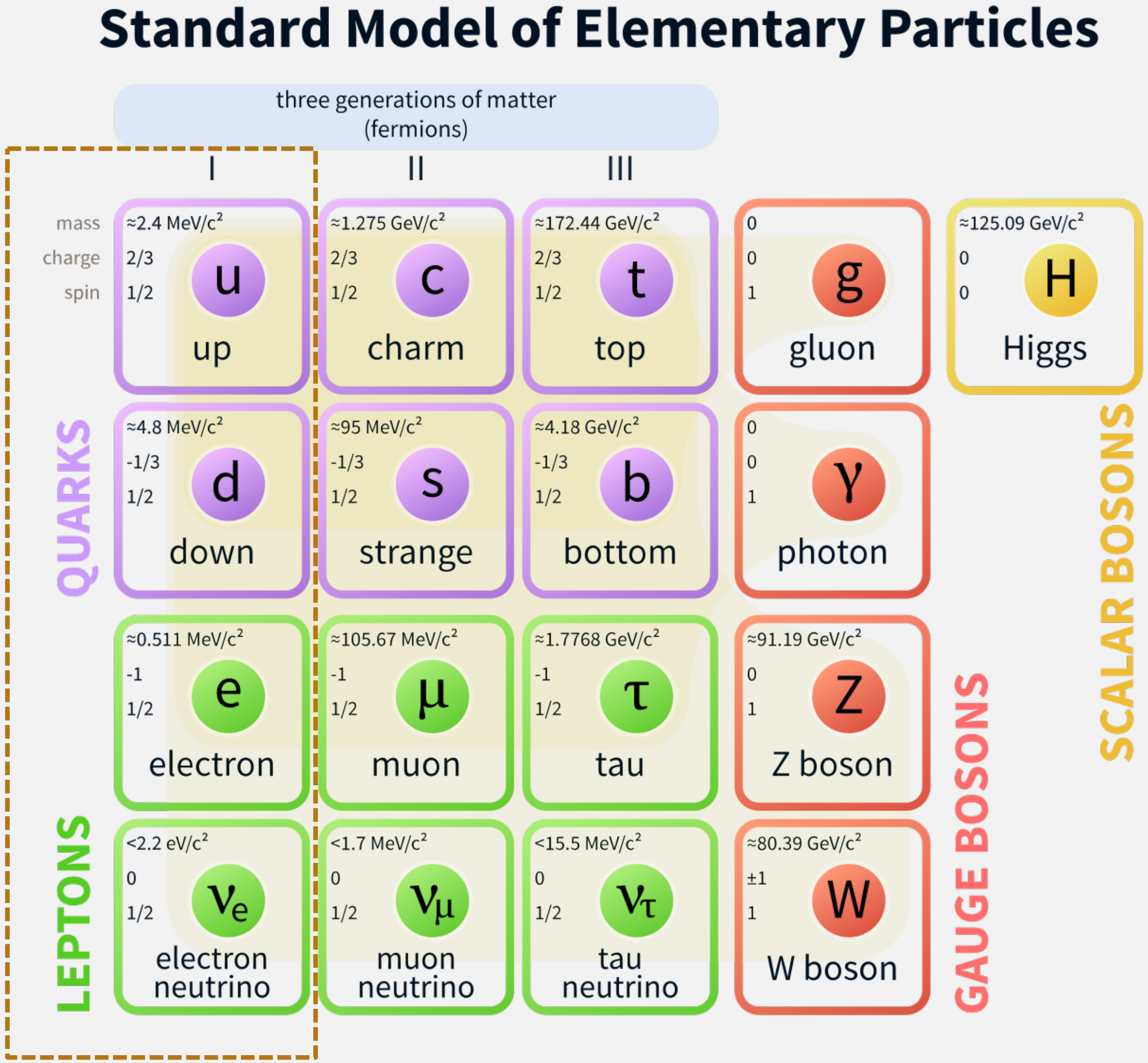


- Inside the atom : the nucleus is made up of nucleons (protons, neutrons) which are made up of quarks and gluons
- Only few percent of the proton mass comes from the mass of its constituents. The remaining mass comes from interactions.

We are not stardust, we are (virtual) gluons!

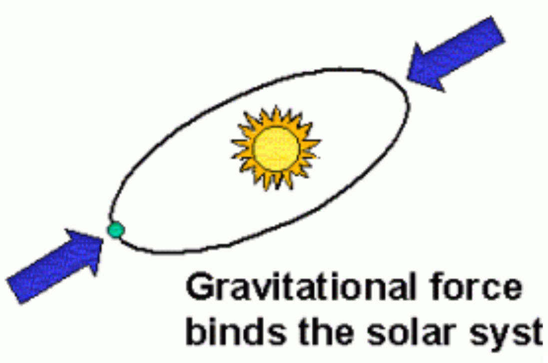
THE ELEMENTARY BUILDING BLOCKS OF MATTER

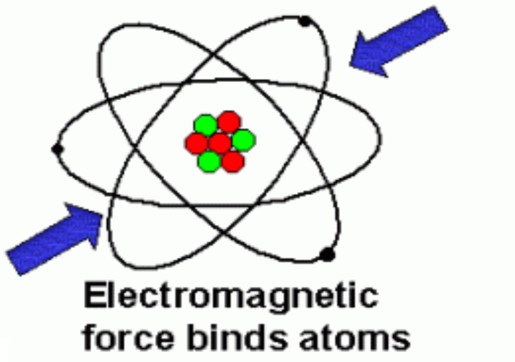
- Fermions (spin ½)
  - Divided into three generations of:
    - quarks
    - leptons
  - First generation : lightest and most stable particles → the constituents of all stable matter in the universe
- Gauge Bosons (spin 1) → the force carriers
- Higgs boson (spin 0)→ gives mass to elementary particles of the standard model
- Antiparticles : same mass as particle but opposite charge
- Hadrons are built from the elementary blocks of matters:
  - Mesons : 1 quark + antiquark (eg. pion)
  - Baryons : 3 quarks (eg. proton, neutron)



THE FOUR FUNDAMENTAL FORCES AND THEIR CARRIERS

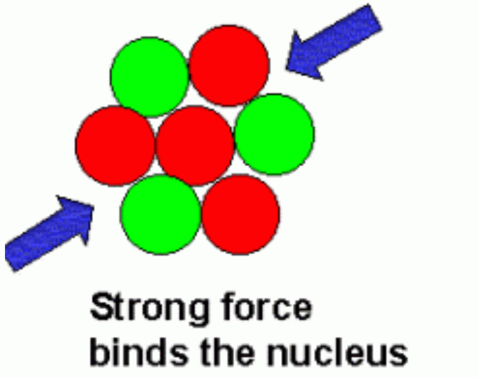
Gravitational interaction	
Acts on	Mass-Energy
Particles experiencing	All
Particles mediating	Graviton (not yet observed)
Strenght at ~ 10^{-17}m	10^{-41}



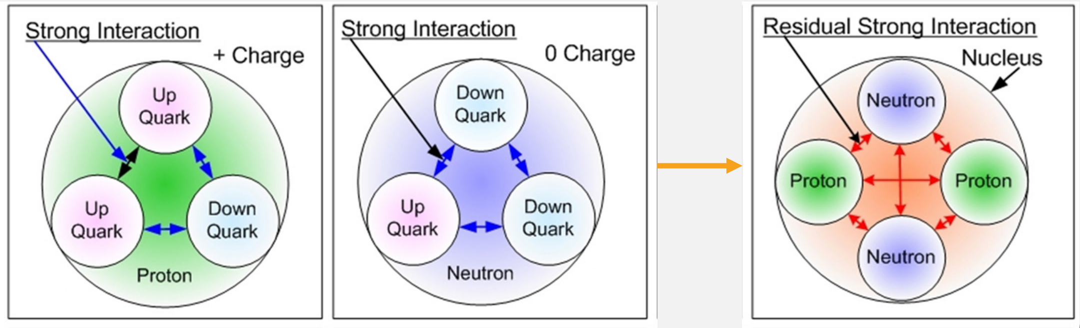


Electromagnetic interaction	
Acts on	Electric charge
Particles experiencing	Electrically charged
Particles mediating	Photon
Strenght at ~ 10^{-17}m	1

Weak interaction	
Acts on	flavours
Particles experiencing	Quarks, leptons
Particles mediating	$W^{+/-}$, Z
Strenght at ~ 10^{-17}m	10^{-4}



Strong interaction	
Acts on	Color charge
Particles experiencing	Quarks, gluons
Particles mediating	Gluons (8)
Strenght at ~ 10^{-17}m	60



THE FOUR FUNDAMENTAL FORCES AND THEIR CARRIERS

Gravitational interaction	
Acts on	Mass-Energy
Particles e	
Particles	
Strenght	

Electromagnetic interaction	
Acts on	Electric charge
	ctrically
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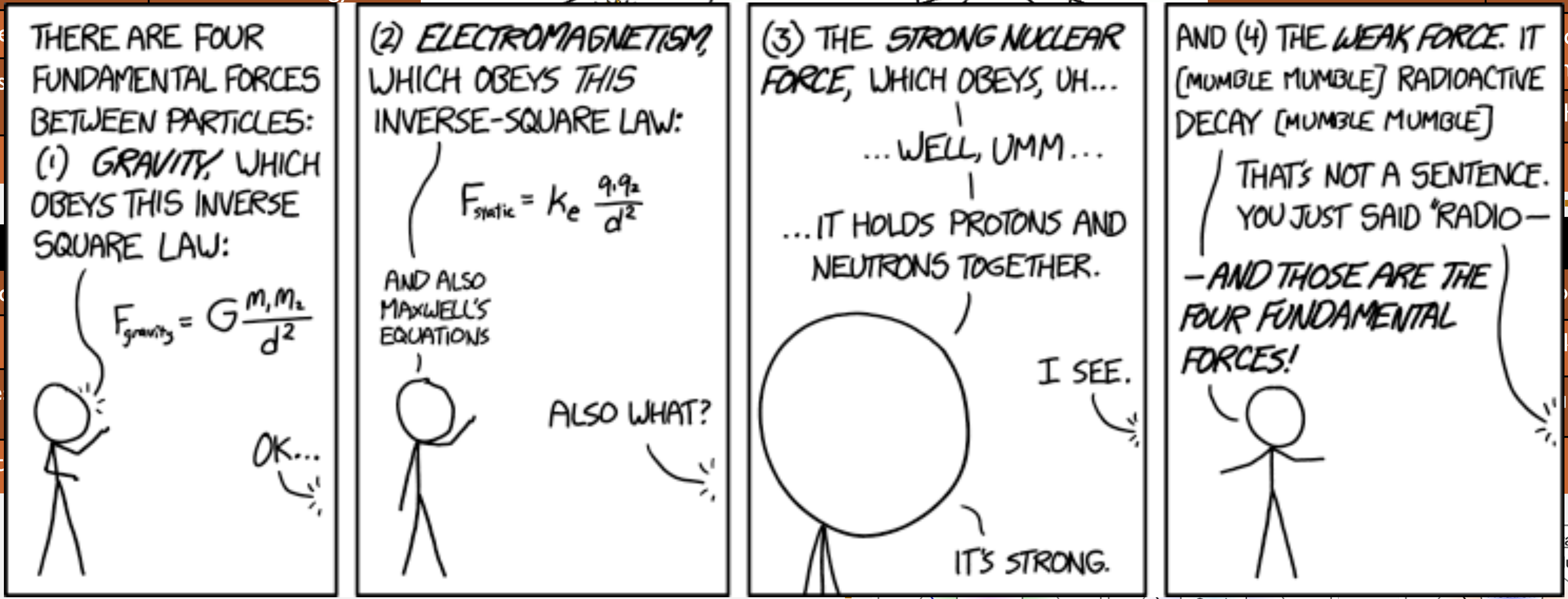
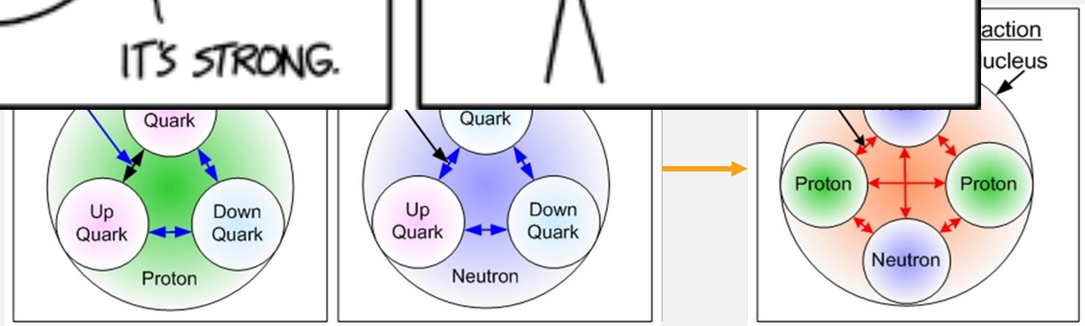
	1

Ac	r charge
Particles	ks, gluons
Particle	ons (8)
Strenght	60





HADRONIC PHYSICS: FROM QUARKS TO HADRONS

- Hadronic physics studies the structure, the properties and the interactions of the hadrons in terms of quarks and gluons
- The underlying theory is Quantum ChromoDynamics (QCD) : the theory of strong interaction between quarks and gluons
- The goal is to use our understanding of QCD to qualitatively describe a wide array of hadronic phenomena, ranging from terrestrial nuclear physics to the behaviour of matter in the early universe

- A (non exhaustive) list of few key open issues in hadronic physics :
  - How does the proton mass arise from its constituents?
  - How does the proton spin arise from its constituents ?

    More generally, understand the quark and gluon structure of hadrons based on QCD
  - What is our degree of understanding of QCD?
    - Can we determine precisely the parameters of QCD? (Λ_{QCD}, QCD vaccuum parameter, mass of quarks)
    - What is the origin and dynamics of confinement?
    - What is the origin and dynamics of chiral symmetry breaking?
    - What are the roles of quarks and gluons in nuclei and matter under extreme condition?

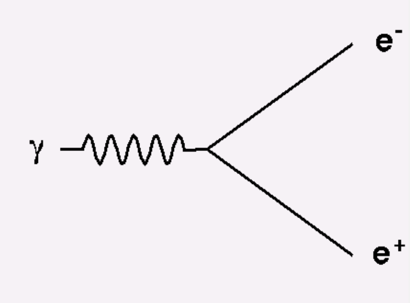
      → From the modification of the quark gluon structure of a nucleon when it is immersed in a nuclear medium within a nucleus to the novel phases and behavior of matter in neutron stars or the early universe

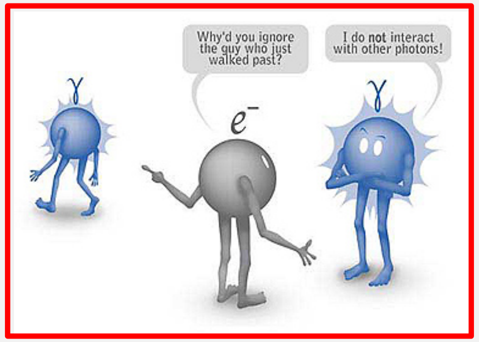
THE BASICS OF QUANTUM CHROMODYNAMICS (QCD)

- QCD is a quantum field theory with similarity and differences with respect to Quantum ElecroDynamics (QED) describing the electromagnetism interaction

	QED	versus		QCD
Charge types	+, -		Charge types	3 color charges (red, green, blue)
Mediator properties	photon, massless, neutral		Mediator properties	8 gluons , massless, color charged
Interaction with	electrically charged objects		Interaction with	color charged objects (quarks, gluons)
Range and strenght of interaction	weaker and infinite range		Range and strenght of interaction	stronger and short range

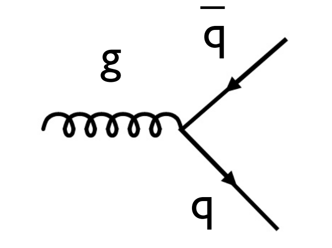
Fundamental vertices



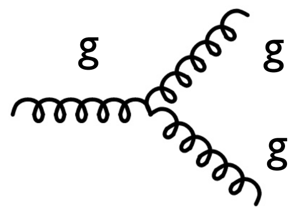


Coupling constant $\alpha = e^2/4\pi = 1/137$

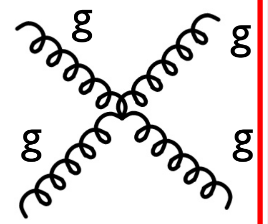
Fundamental vertices



Analogous to photon exchange of QED



3-gluon vertex



4-gluon vertex

$\alpha_s = g_s^2/4\pi \sim 1$

Strong consequences on the theory

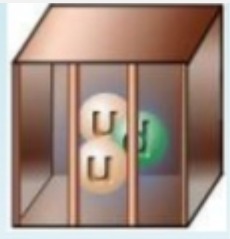
IMPORTANT FEATURES OF QCD

What is color?

- The fundamental « charge » of QCD
- A conserved quantum number
- Three colors r, g, b (and three anti-colors $\bar{r}, \bar{g}, \bar{b}$)
- Gluons carry color charges (naively expect 9 gluons → but 8 realised by nature (coulor octet + singlet))
- Leptons and other gauge bosons (γ, W, Z) → no color charge → don't participate to strong interaction
- Emission/Absorption of gluons by quarks changes color of quarks : $q_i \rightarrow g_{ij} + q_j$

Color blindness and confinement

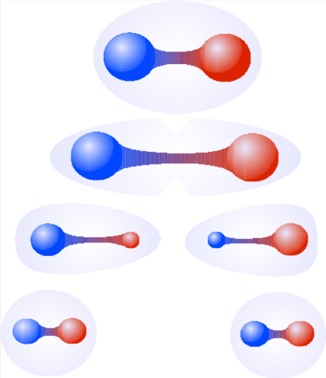
- Experimental evidence :
  - We don't observe free quarks in nature
  - Quarks are confined within hadrons (color neutral objects)



→ Direct consequence of gluon self-interaction

- What happens if you try to separate a $q\bar{q}$ pair?
  - Gluon tube between quarks elongates
  - Strong force get stronger with the distance
  - As soon as there is enough energy in the system a new quark-antiquark pair will be created

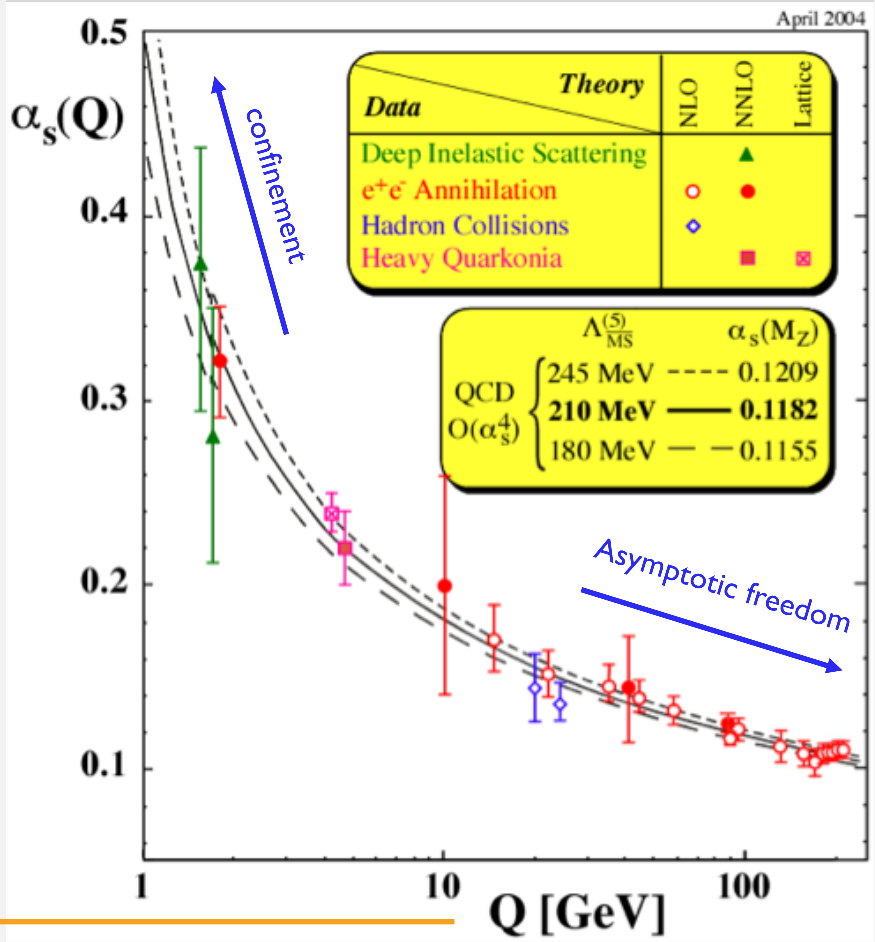
$$V_{QCD}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$



IMPORTANT FEATURES OF QCD

❑ Confinement and asymptotic freedom

Coupling constant



Energy scale

Distance

Large distance

Short distance

❖ Confinement :

- For $Q^2 < 1$ GeV
- For Distance ~ 1fm (typical size of hadrons)
- Particle we observe in nature are in the regime of non-perturbative QCD

❖ Asymptotic freedom :

- At short distances the effective coupling between quarks decreases logarithmically
- Under such conditions quarks and gluons appear to be quasi-free
- Perturbative QCD regime $Q^2 >> 1$ GeV

ELEMENTS OF QCD : THEORETICAL TOOLS

❑ Perturbative QCD (pQCD)

- **In the high-energy (high momentum transfer) regime, perturbative approach is applicable to QCD**
  → good predicting power for yields, cross sections, kinematic distributions
- Order by order expansion in α_s with $\alpha_s << 1$, observable f can be written:

$$f = f_1\alpha_s + f_2\alpha_s^2 + f_3\alpha_s^3 + \ \dots$$

- Where only the first, two or three terms are calculated and the others are assumed to be negligible
- The f factors are calculated via Feynman diagrams

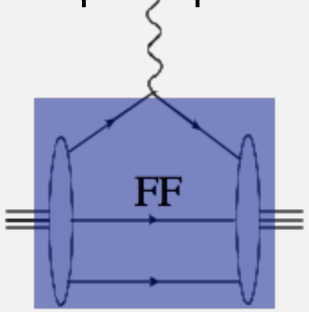
❑ Factorisation theorem and pQCD

- Factorisation of a process : hard part ⊗ soft part
- hard part = calculable with perturbative QCD
- Soft part = « universal » distributions (FF, PDF, GPD…)

→ Importance of precise experimental measurements of the universal distributions
Ex: determine PDFs in lepton-proton collisions and use them to compute proton-proton cross sections at LHC

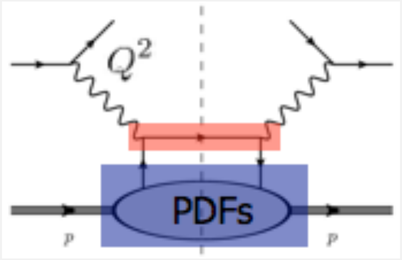
Examples for the proton case

Elastic diffusion
ep → e'p'



Form factor

Deep Inelastic Scattering
ep → e'X



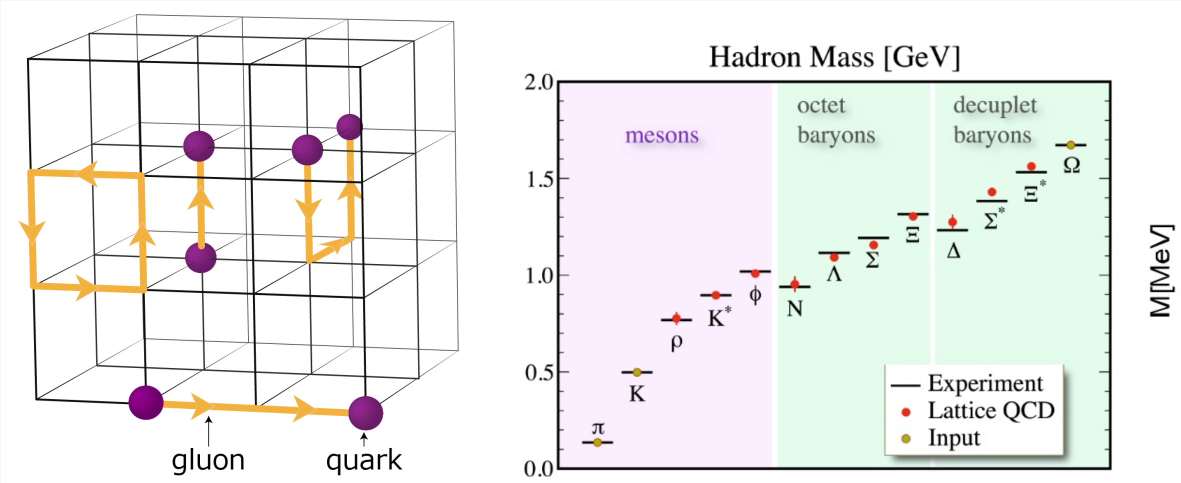
Parton distributions

ELEMENTS OF QCD : THEORETICAL TOOLS

In the low-energy (low momentum transfer) regime, various approaches to non-perturbative QCD are possible

❑ Lattice QCD

- ❖ Quarks and gluons are studied on a discrete space-time lattice
- ❖ Fields representing quarks are defined at lattice sites, while gluon fields are links connecting sites
- ❖ Only nearest neighbour interactions considered
- ❖ For infinitely large lattice and infinitesimally sites close to each other → QCD vacuum recovered
- ❖ Great predictive power: hadron masses, temperature of deconfinement, …



Phys. Rev. D79 034504 (2008)

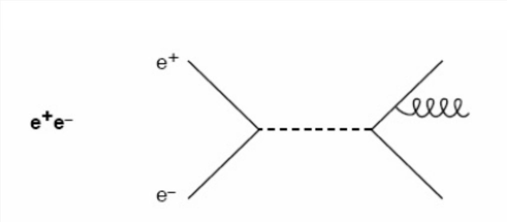
❑ Effective theories

- ❖ Approximation to an underlying physical theory at a chosen energy scale. Use of effective Lagrangians equivalent to QCD one. Ex : Chiral perturbation theory : interaction of hadrons with pions and kaons (Goldstone bosons of spontaneous chiral symmetry breaking)

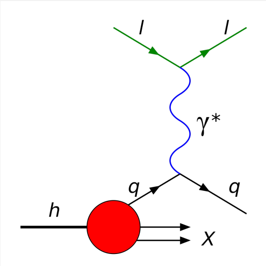
→ Jan Maelger « Introduction à Curci-Ferrari : Résultats et questions ouvertes »

ELEMENTS OF QCD : EXPERIMENTAL TOOLS

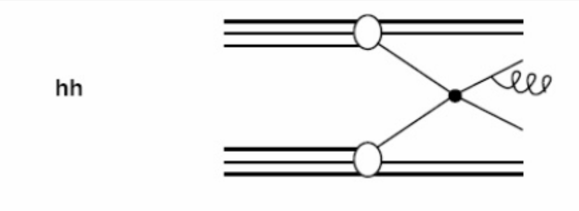
- Test of QCD can be done with different processes:
  - Electron-Positron annihilation :
    - No hadrons in initial state
    - Production of multi-jets → discovery of the gluon, gluon self-coupling



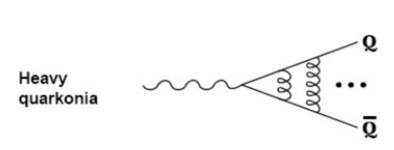
  - Deep inelastic scattering :
    - Probe the insides of hadrons using electrons, muons and neutrinos
    - One hadron in the initial state
    - First convincing evidence of the existence of quarks



  - Hadron-Hadron collisions :
    - Two hadrons in initial state
    - Rich variety of quantum states available for particle production → spectroscopy of hadrons, hadron properties

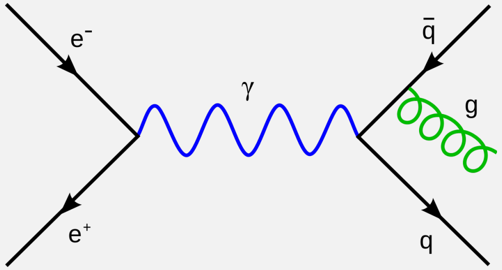


  - Heavy quarkonia : ratios of hadronic over radiative decay proportional to α_s



EXPERIMENTAL VALIDATIONS OF QCD: EVIDENCE FOR GLUONS AND GLUON SELF-COUPLING

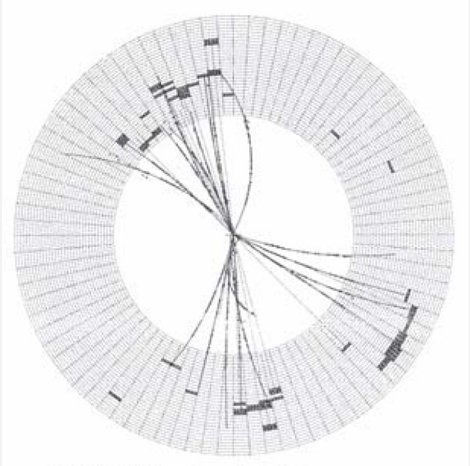
❑ With Electron-Positron annihilation



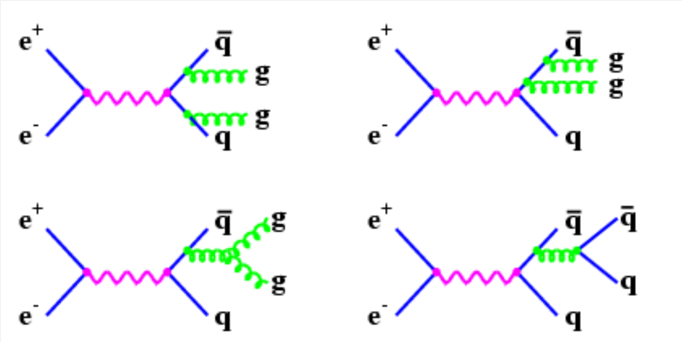
- ❖ Quarks radiate gluons
- ❖ Because of confinement, fragments hadronises into jets
- ❖ Leading order correction to the process $e^+e^- \rightarrow q\overline{q}$ (two-jet final state)
- ❖ Experimental signature: 3-jets in the final state

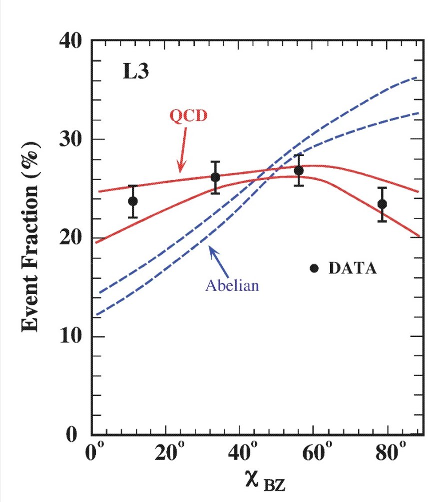
$$\frac{\#3-\text{jet events}}{\#2-\text{jet events}} \approx 0.15 \sim \alpha_s$$

e^+e^- collider, $\sqrt{s}$ = 12-47 GeV
3-jet event, JADE detector at PETRA, DESY (1977)

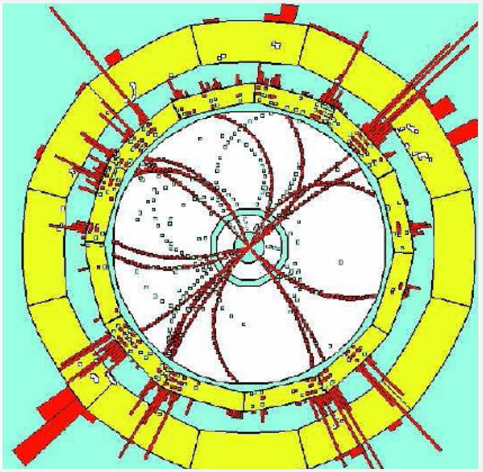


❖ 4-jet events allow to test the existence of gluon self coupling





e^+e^- collider, $\sqrt{s} \rightarrow$ 200 GeV
4-jet event, ALEPH detector at LEP-I



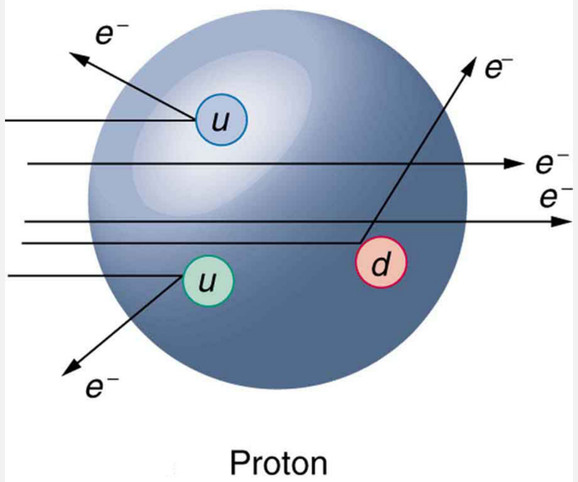
EXPERIMENTAL VALIDATIONS OF QCD: EVIDENCE FOR QUARKS

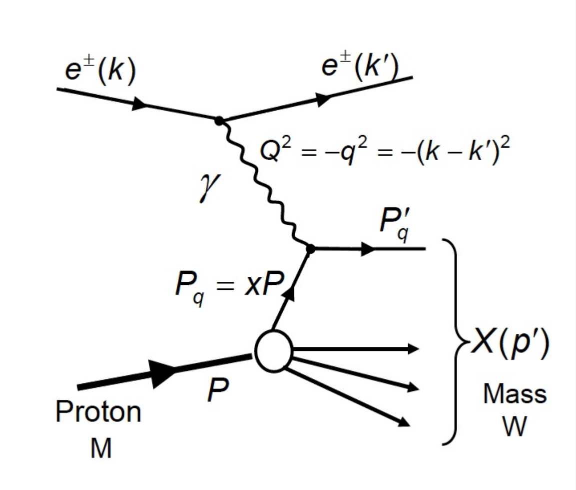
↳ proton breaks up

- With Deep Inelastic Scattering:

↳ high Q^2

- Simple idea : look inside the proton using an electron « microscope »





x = fractional momentum of struck quark

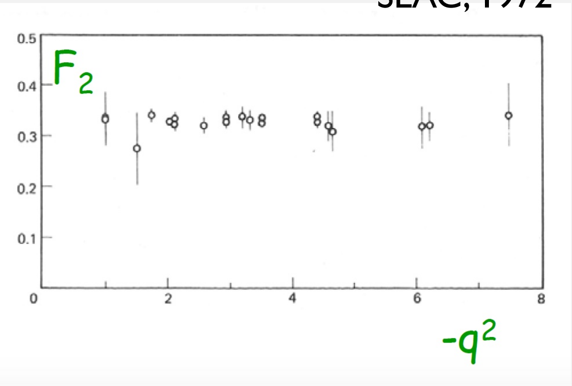
y = Pq/Pk = elasticity, fractional energy transfer in proton rest frame

ν = E - E′ = energy transfer in lab

$Q^2 = sxy$ s = CMS energy

$x = \frac{Q^2}{2M\nu}$ (Bjorken x)

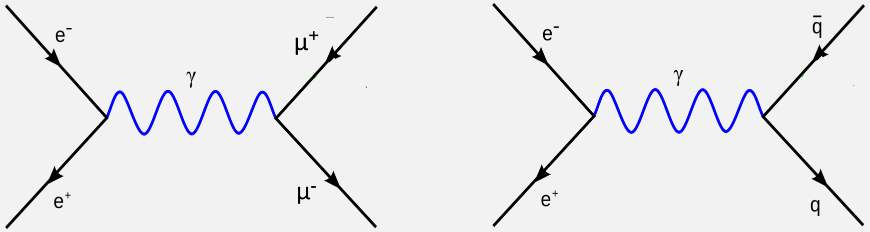
SLAC, 1972



- Scattering described by two independent variables (x, Q^2)
- F_2 → proton structure function gives the probability of finding a quark carrying fraction x of proton momentum (weighted by electric charge of quark)
- $F_2(x)$ depends on x but not on q^2 → scale invariance
  → indicates evidence for point like particles inside proton

EXPERIMENTAL VALIDATIONS OF QCD: EVIDENCE FOR COLOR

- With Electron-Positron annihilation



For a single quark flavour

No color

$$R_q = \frac{\sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \frac{Q_q^2}{Q_\mu^2} = Q_q^2$$

With 3 colors

$$R_q = \frac{\sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_C Q_q^2 = 3Q_q^2$$

But, we measure $e^+e^- \to$ hadrons not $e^+e^- \to q\bar{q}$

$$\boxed{R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3\sum_q Q_q^2}$$

Sum over all quarks flavours (accessible at a given $\sqrt{s}$)

$$R(\sqrt{s} > 2m_s \sim 1\,\text{GeV}) = 3\left(\left(\frac{2}{3}\right)^2 + \left(\frac{-1}{3}\right)^2 + \left(\frac{-1}{3}\right)^2\right) = 2 \qquad u,d,s$$

$$R(\sqrt{s} > 2m_c \sim 3\,\text{GeV}) = 3\left(\left(\frac{2}{3}\right)^2 + \left(\frac{-1}{3}\right)^2 + \left(\frac{-1}{3}\right)^2 + \left(\frac{2}{3}\right)^2\right) = \frac{10}{3} \qquad u,d,s,c$$

$$R(\sqrt{s} > 2m_b \sim 10\,\text{GeV}) = 3\left(\left(\frac{2}{3}\right)^2 + \left(\frac{-1}{3}\right)^2 + \left(\frac{-1}{3}\right)^2 + \left(\frac{2}{3}\right)^2 + \left(\frac{-1}{3}\right)^2\right) = \frac{11}{3} \qquad u,d,s,c,b$$

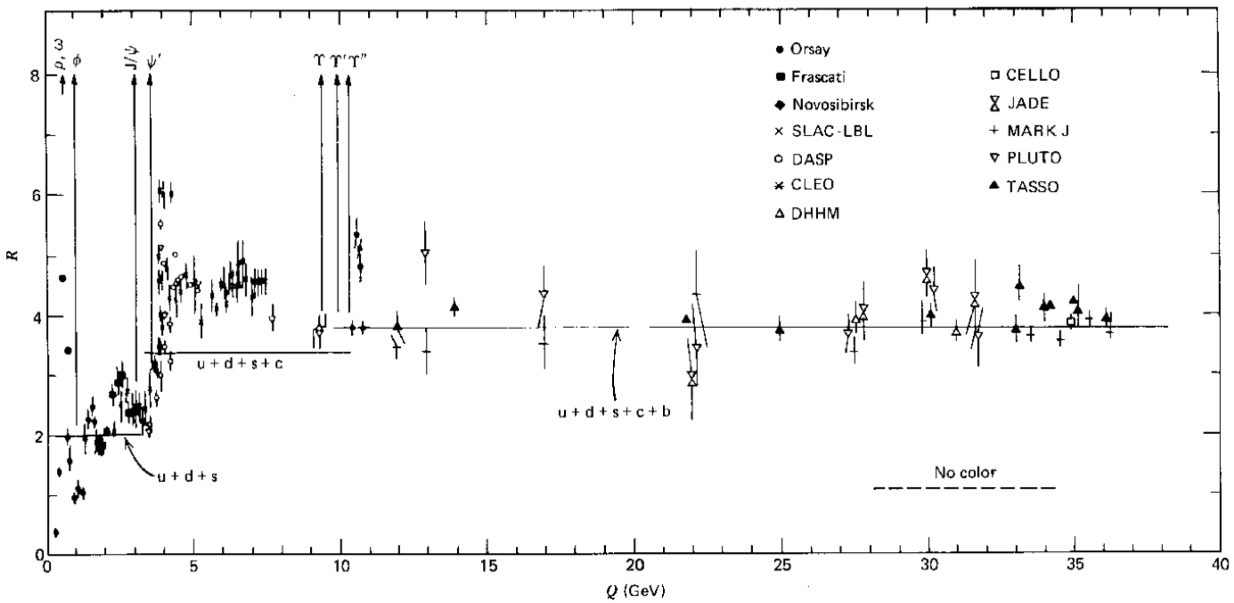
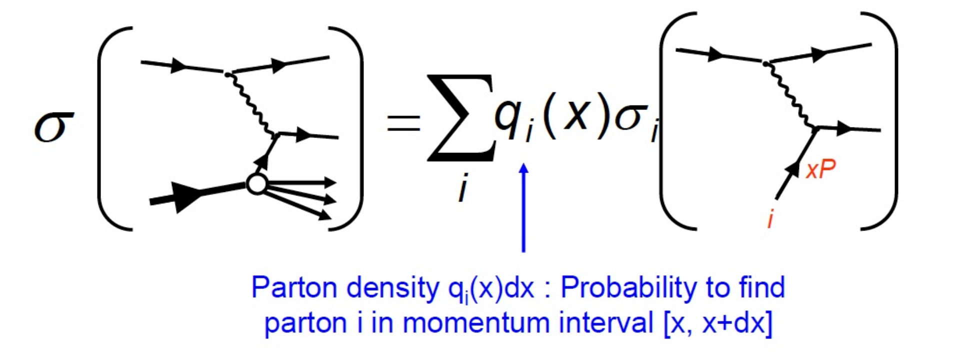


Fig. 11.3 Ratio R of (11.6) as a function of the total e^-e^+ center-of-mass energy. (The sharp peaks correspond to the production of narrow 1^- resonances just below or near the flavor thresholds.)

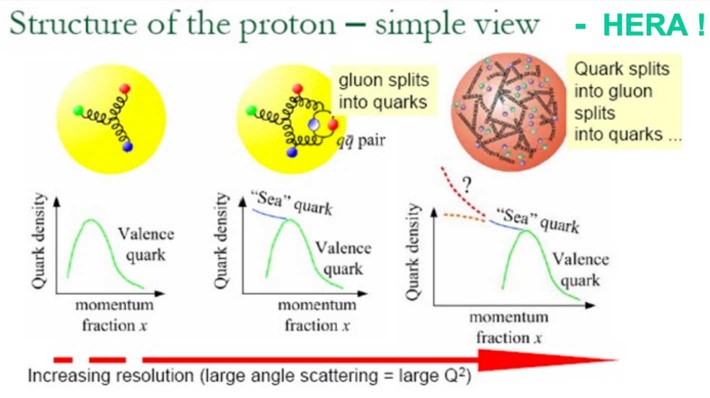
MEASURING « UNIVERSAL » DISTRIBUTIONS

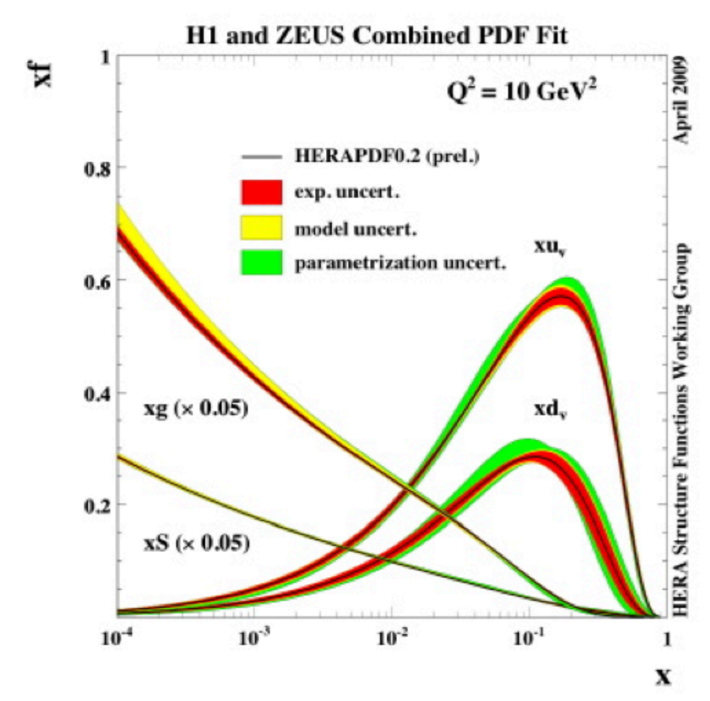
- Example : Measure pdf with Deep Inelastic Scattering:

❖ Factorisation hypothesis



❖ 15 years of measurements at HERA (DESY)
❖ Good precisions for u, d quarks, gluons
❖ But still many unknown:
  - parton distributions at very low x
  - modification of pdf in nuclear matter
  - generalised descriptions (GPDs, TMDs)



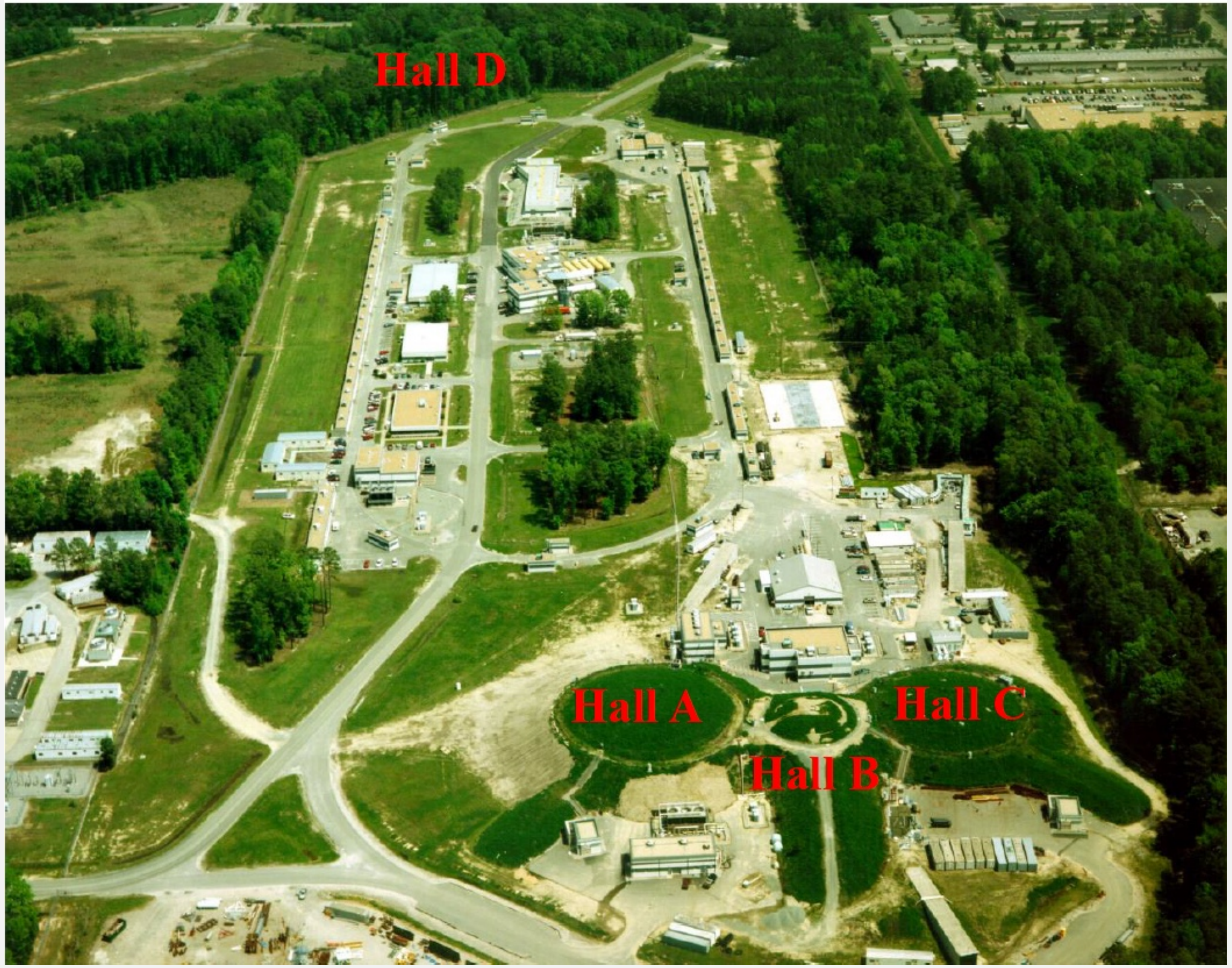


Small x
Gluons, sea quarks

Large x
Valence quarks

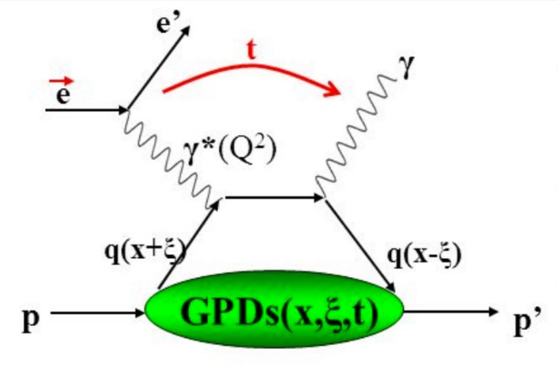
DEEPER IN THE UNDERSTANDING OF THE NUCLEON STRUCTURE

- The example of the experiments conducted at Jefferson Lab (USA)



- e^- beam at 12 GeV (4 experimental hall A, B, C, D)

- 3D spatial maps of the nucleons :
  - With Generalised parton distributions (GPDs)
  - Accessed through Deeply Virtual Compton Scattering (DVCS) : ep → e'p'γ



Hard part: photon-quark interaction and re-emission of real photon

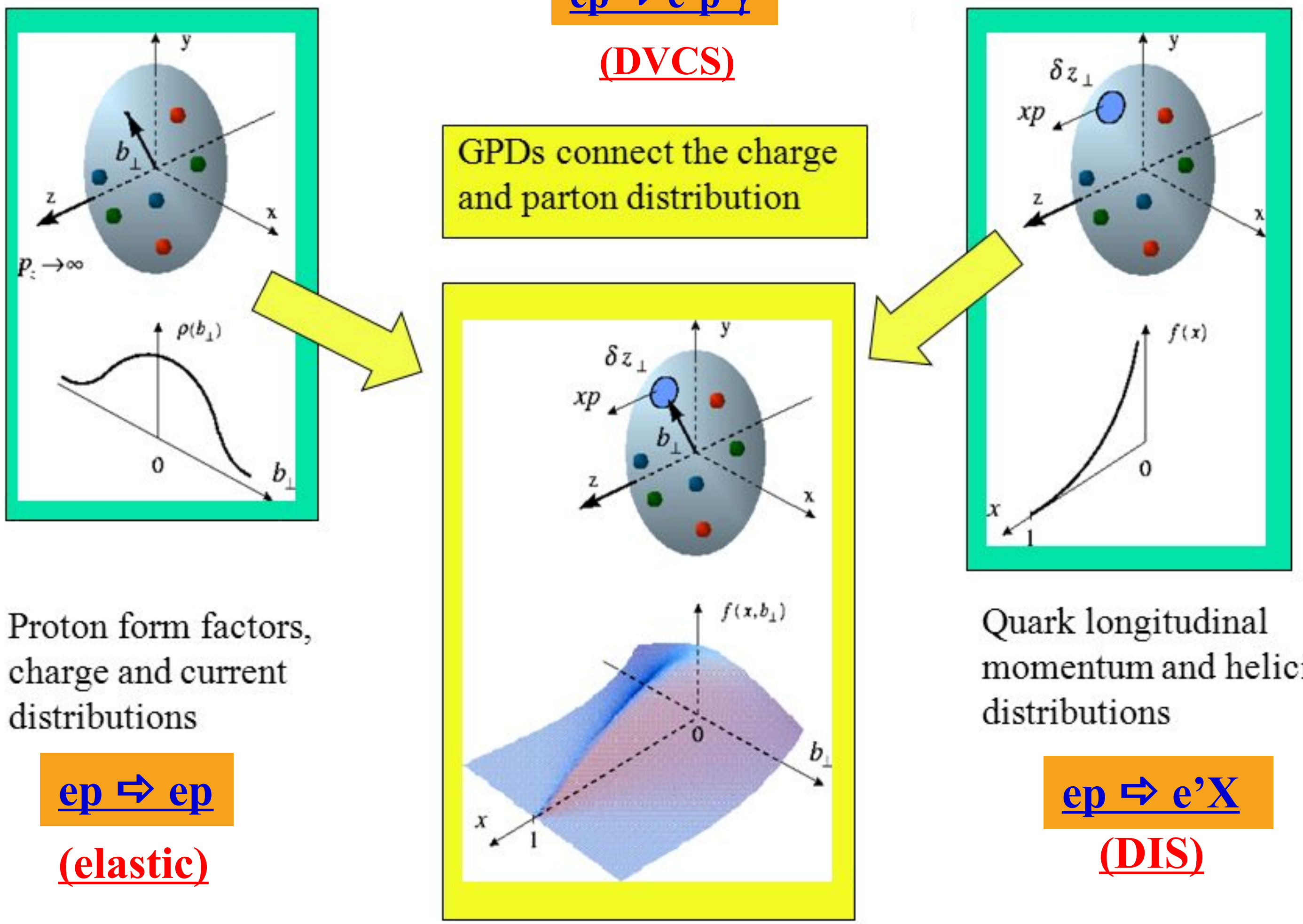
Soft part: GPDs

3D SPATIAL MAPS OF THE NUCLEONS: THE GPDs

ep ⇨ e'p'γ

(DVCS)

GPDs connect the charge and parton distribution



Proton form factors, charge and current distributions

ep ⇨ ep

(elastic)

Quark longitudinal momentum and helicity distributions

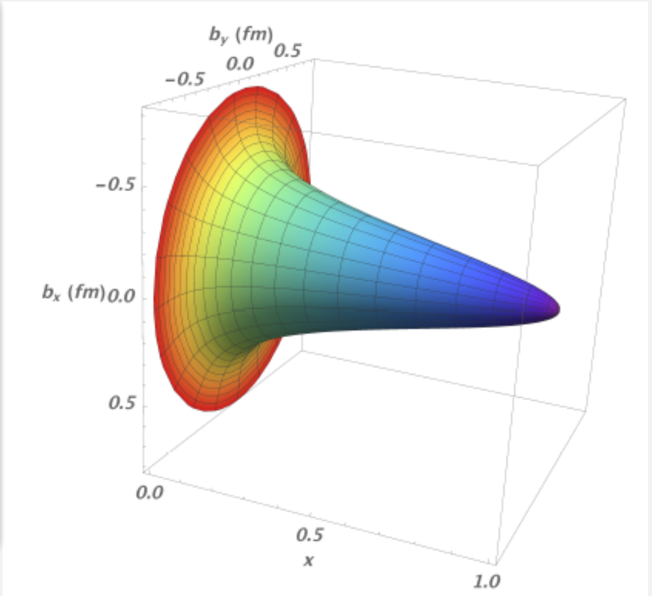
ep ⇨ e'X

(DIS)

Proton tomography

Faster quarks (valence) at the core of the nucleon. Slower quarks (sea) at its periphery

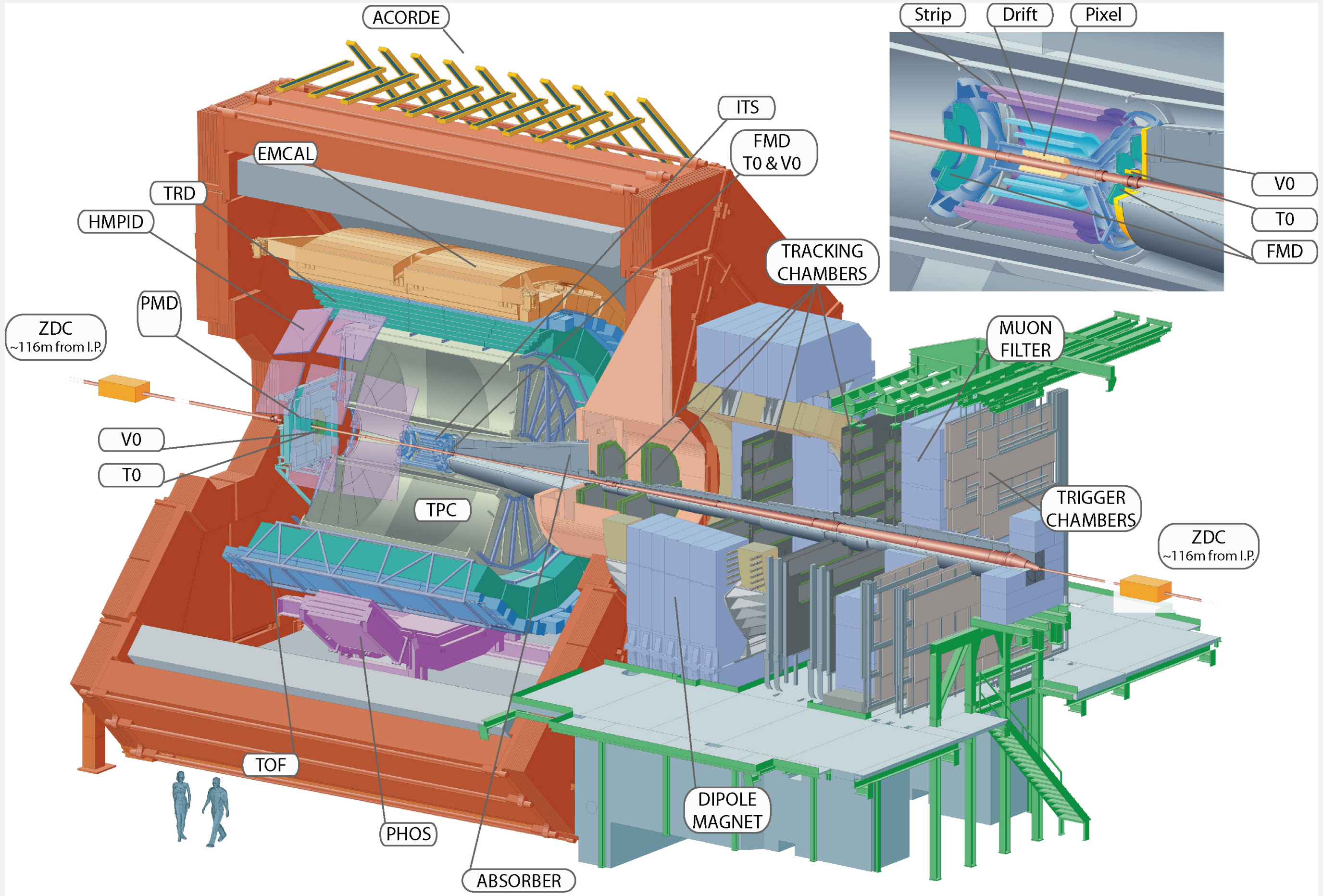
Transverse position



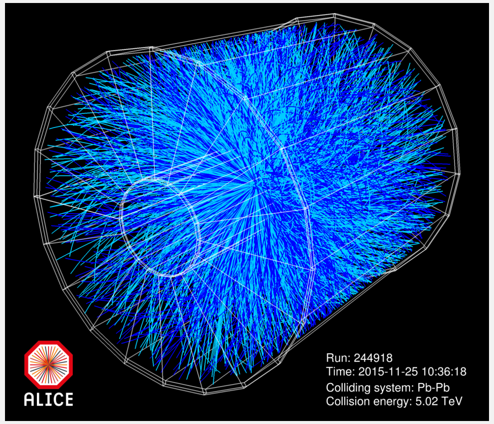
Quark longitudinal momentum

STUDY QCD UNDER EXTREME CONDITIONS WITH ULTRA-RELATIVISTIC HEAVY ION COLLISIONS

- ❑ The example of the ALICE experiment at CERN

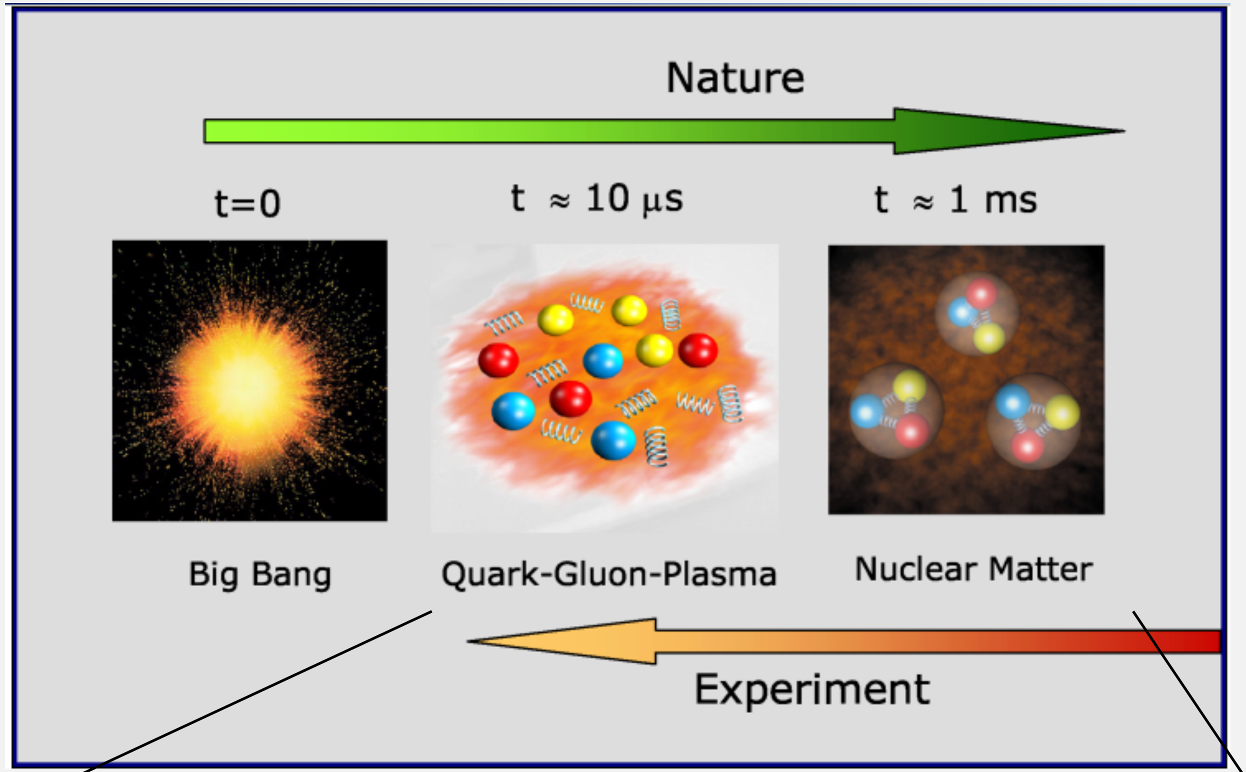


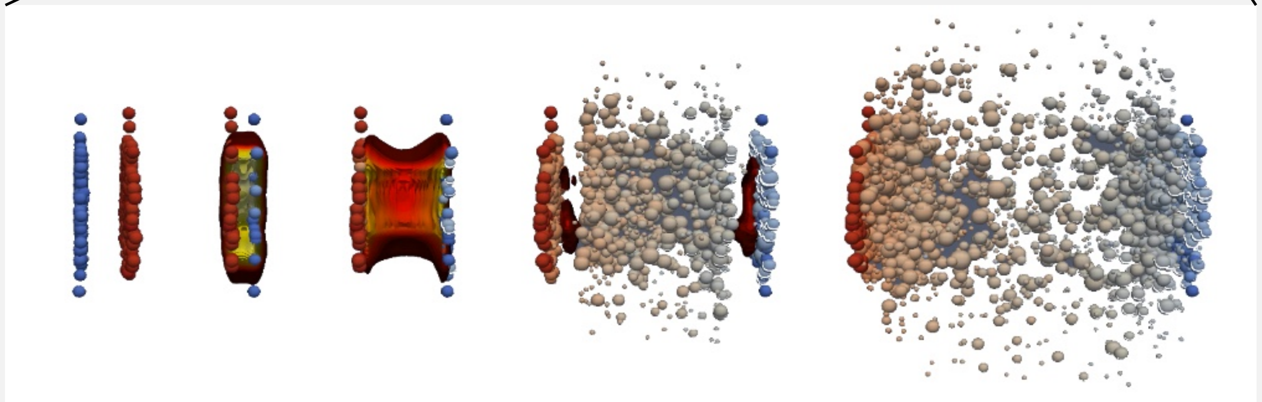
- ❖ Study of the Quark Gluon Plasma (GQP) in Pb-Pb collisions



- ❖ QGP : Deconfined state of nuclear matter
  → quarks and gluons evolve freely during a short amount of time
- ❖ High temperature and pressure needed!
- ❖ Conditions similar to the early universe

ULTRA-RELATIVISTIC HI COLLISIONS TO RECREATE THE CONDITIONS OF THE EARLY UNIVERSE





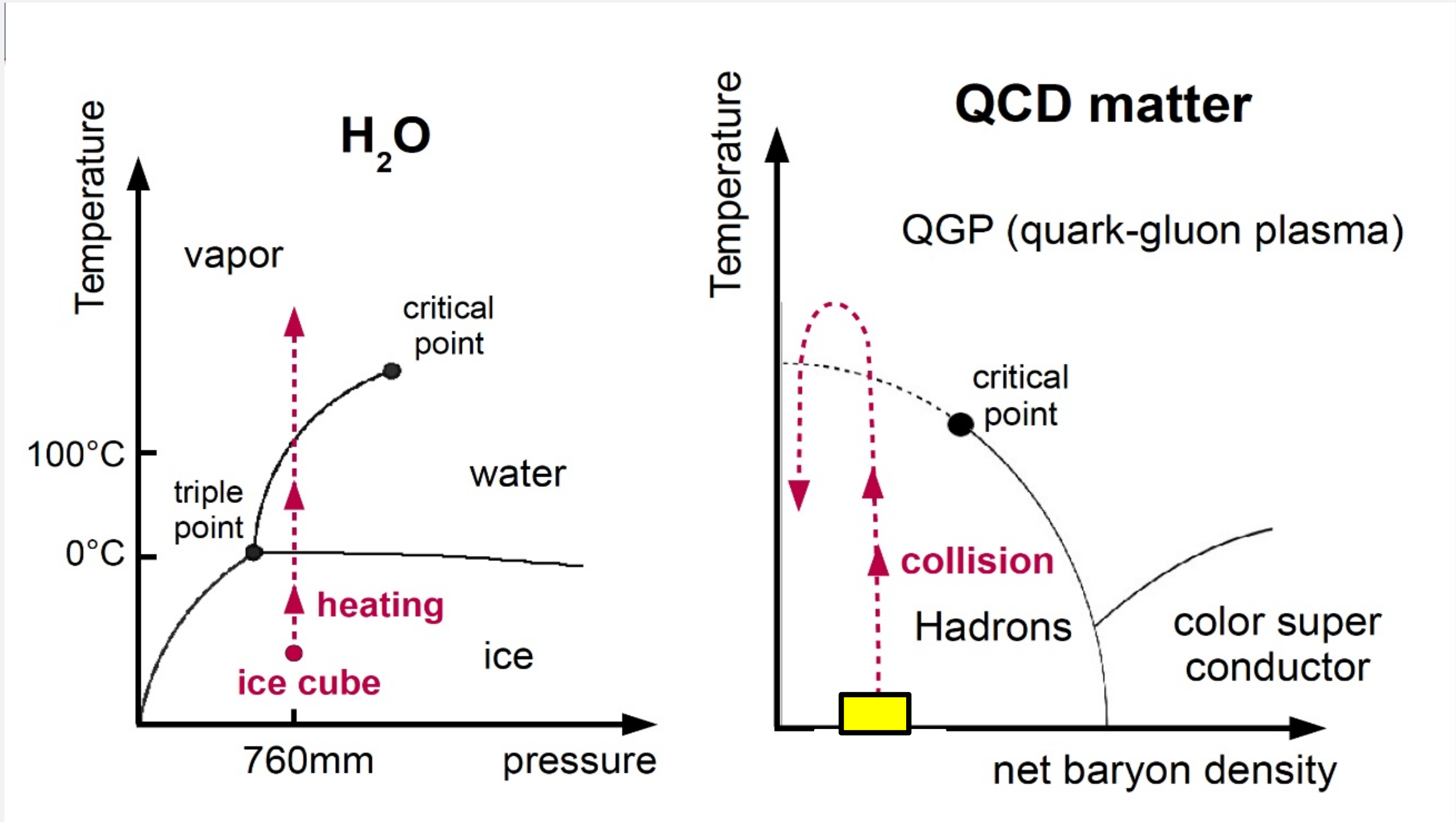
- In the early stages of the Universe (few μs after Big Bang), quarks and gluons were evolving freely due to the large temperature and energy density
- As the universe cooled down, they were confined inside the hadrons
- To study confinement → recreate this stage of matter in the lab
- From lattice QCD → T_c ~ 170 MeV (10^5 times t° inside sun)
  → ε_c ~ 1 GeV/fm^3 (5 times ordinary matter)

How to reach those conditions in lab?

Collisions of High-Energy Ultra-Relativistic Heavy Nuclei
→ Vary type of nuclei and energy to explore different regions of the phase diagramme of nuclear matter

THE PHASE DIAGRAMME OF NUCLEAR MATTER

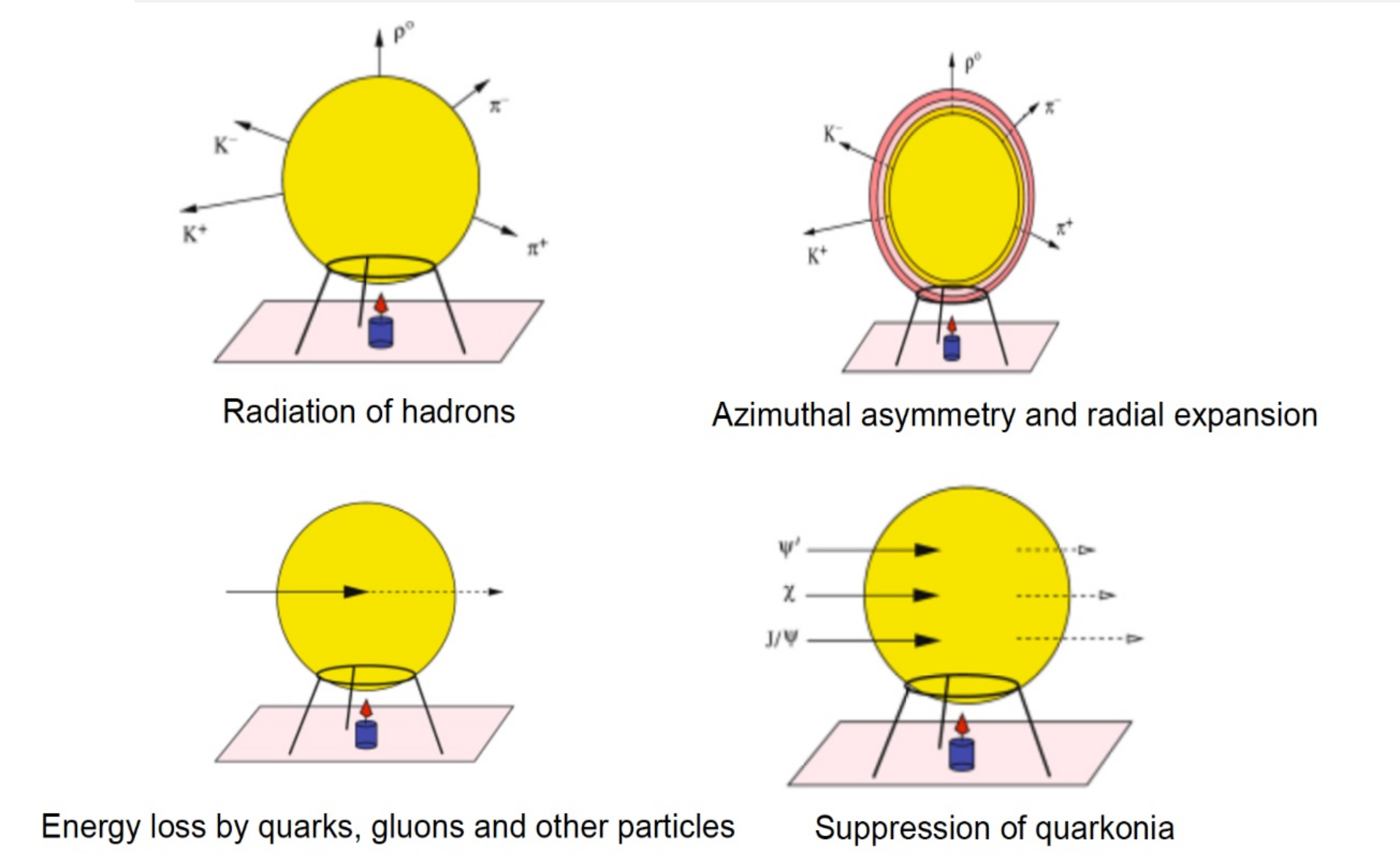
- ❖ What is the state of QCD matter under specific conditions of temperature and baryon density?
- ❖ What is the nature of the phase transition? Is there a critical point?
- ❖ Can we write down the EoS of nuclear matter? → interesting for astrophysics



ordinary matter, ie where the oyster sits in the phase diagram

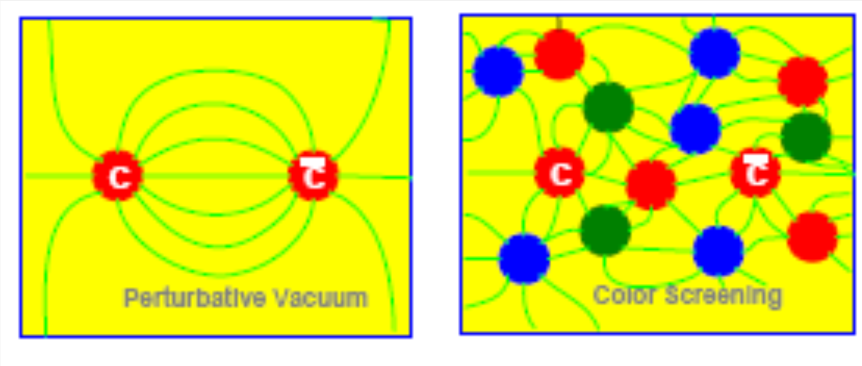
HOW TO CHARACTERISE THE QGP EXPERIMENTALLY?

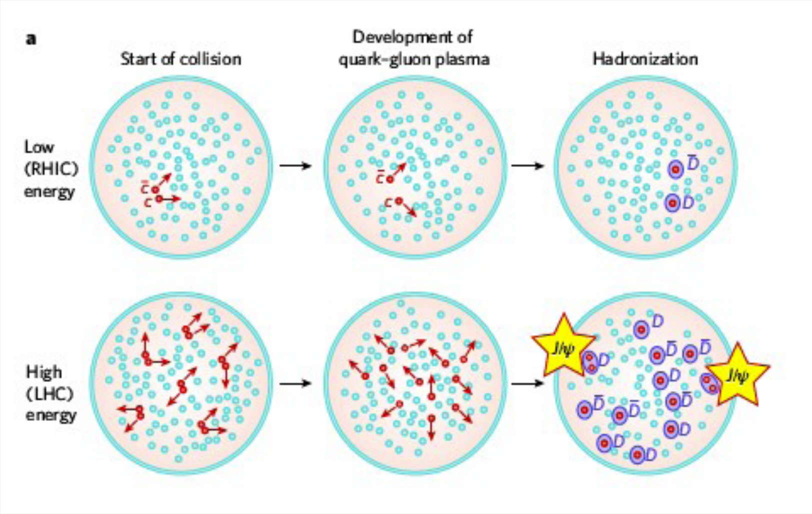
- QGP not « directly » accessible to observation (last only few fm/c!)
- Need a combination of several probes and a good reference system (without QGP formation)
- Also need probes unaffected by the QGP to serve as reference for other probes (Z, Drell-Yan)



HOW TO CHARACTERISE THE QGP EXPERIMENTALLY?
THE EXAMPLE OF CHARMONIA ($c\bar{c}$)

- ❖ Heavy quarks created early in the collision (before the QGP is formed)
- ❖ While going through the QGP (depending on its temperature) the less bound charmonia will be suppressed by color screening
- ❖ If chamonium yields in PbPb collisions are suppressed with respect to the «scaled» yield from pp collisions → evidence for QGP formation
- ❖ Unfortunatelly not so clear (other mechanisms at play → regeneration of charmonium at LHC energies)

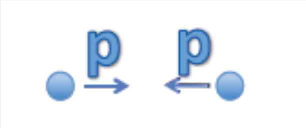




- ❖ Important to well understand charmonium formation and production rates in « simplier » systems (not so simple in fact!)

HOW TO CHARACTERISE THE QGP EXPERIMENTALLY?
THE EXAMPLE OF CHARMONIA ($c\bar{c}$)

❖ Important to well understand charmonium formation and production rates in « simplier » systems : the short story

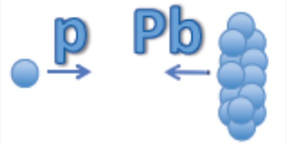


A tool to study QCD

Understand charmonium production at partonic level

Various model on the market: Color Singlet, Color Evaporation, NRQCD

Experimental tools : production cross section, charmonium polarization



A tool to study Cold Nuclear Matter Effects

Understand charmonium production rated in «normal» nuclear matter (without QGP formation)

Various CNM effects at play: gluon shadowing, coherent energy loss, nuclear absorption…

Experimental tools : nuclear modification factor (compare pPb to pp)

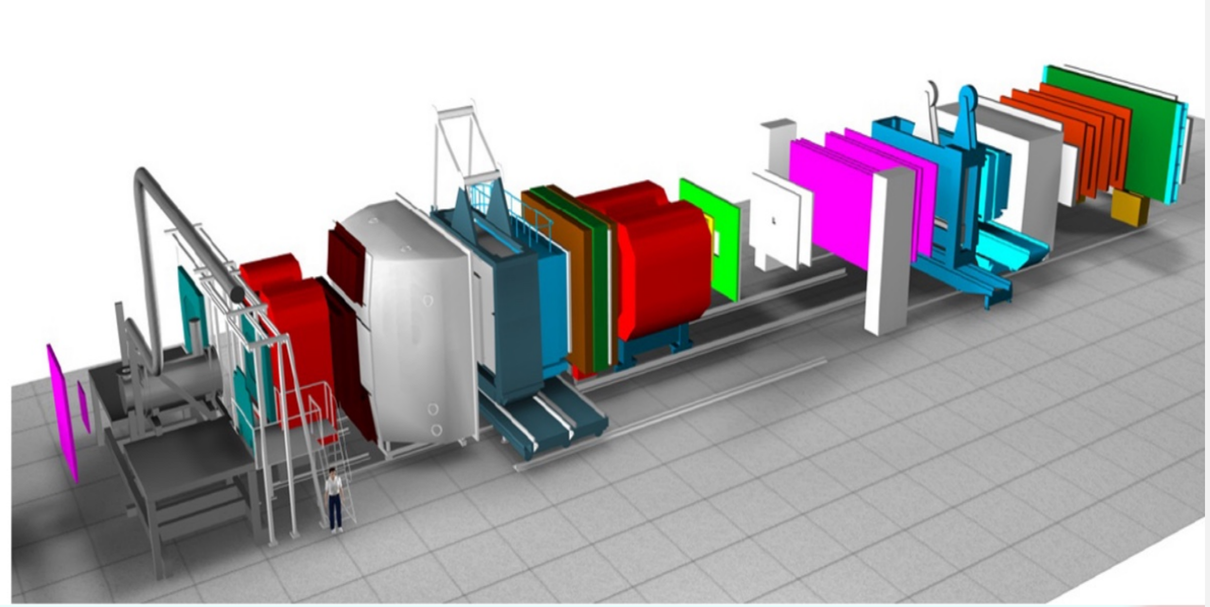
A tool to study deconfinement

Understand charmonium suppression and recombination in the QGP

Experimental tools: nuclear modification factor (compare PbPb to pp), elliptic flow…

HADRON STUCTURE AND SPECTROSCOPY : THE EXAMPLE OF THE COMPASS EXPERIMENT

- COMPASS (Common Muon Proton Apparatus for Stucture and Spectroscopy) located at SPS (CERN)
- High intensity muon and hadron beams (160 – 200 GeV) on target (target can be polarised! → spin physics measurements)
- Set of measurements to study the structure of hadrons (DVCS, SIDIS, Polarized Drell-Yan)



Artistic view of the 60 m long COMPASS two-stage spectrometer. The two dipole magnets are indicated in red.

- COMPASS can also study Cold Nuclear Matter effect at low energy with nuclear target

  → Charles-Joseph Naïm « Cold Nuclear Matter effects in Drell-Yan process and charmonium production »

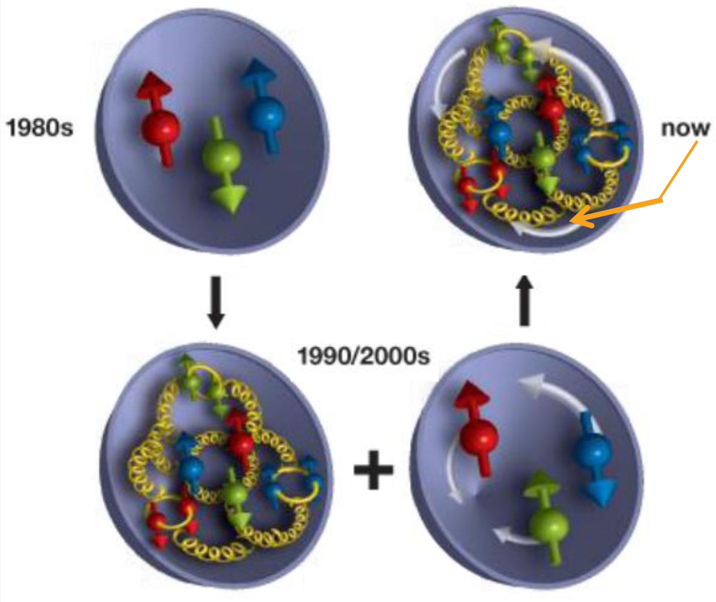
CONCLUSIONS

- ❑ Hadronic physics is a (vast!) domain which studies the structure, the properties and the interactions of the hadrons in terms of quarks and gluons
- ❑ In this afternoon session you will have a partial « aperçu » of the domain

14:00		
	Introduction à la physique hadronique *VVF Villages Lège-Cap-Ferret*	*Laure MASSACRIER* 14:30 - 15:00
15:00	**Introduction à Curci-Ferrari : Résultats et questions ouvertes** *VVF Villages Lège-Cap-Ferret*	*Jan Maelger* 15:00 - 15:30
	Coffee break *VVF Villages Lège-Cap-Ferret*	15:30 - 16:00
16:00	**Cold nuclear matter effects in Drell-Yan process and charmonium production** *VVF Villages Lège-Cap-Ferret*	*Charles-Joseph Naïm* 16:00 - 16:30

HADRON STUCTURE AND SPECTROSCOPY : THE EXAMPLE OF THE COMPASS EXPERIMENT

❖ The proton spin puzzle (quarks do not carry all the nucleon spin, in fact they carry only a small fraction)



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \underbrace{\ell_g + \ell_q}_{\text{Orbital angular momentum of quarks and gluons}}$$

Spin of quarks /antiquarks

Spin of gluons

Orbital angular momentum of quarks and gluons