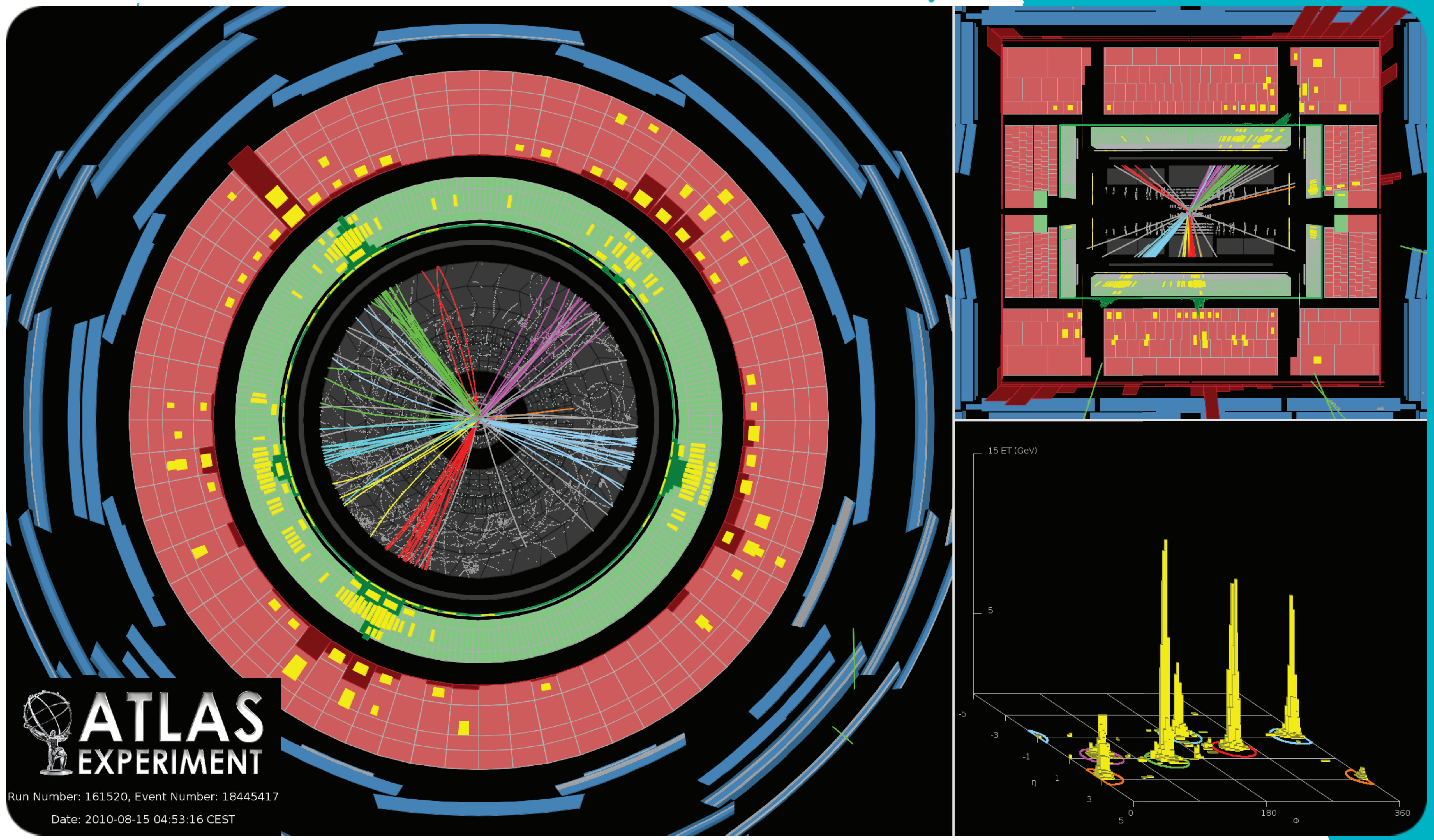
Nikhef

INTRODUCTION TO QUANTUM CHROMODYNAMICS



PARTICLE PHYSICS 2

Panos Christakoglou

BRIEFLY ABOUT ME…

PhD in 2007 from NKUA, Greece

2003-2010: At CERN (fellow)

2008-2010: Postdoc at UU (stationed at CERN)

2010 - Today: Senior scientist at Nikhef, Amsterdam

2015 - Today: Guest professor at UU and TU-Delft

Since 2024: Professor at University of Maastricht

E-mail address

- Panos.Christakoglou@nikhef.nl
- Panos.Christakoglou@cern.ch

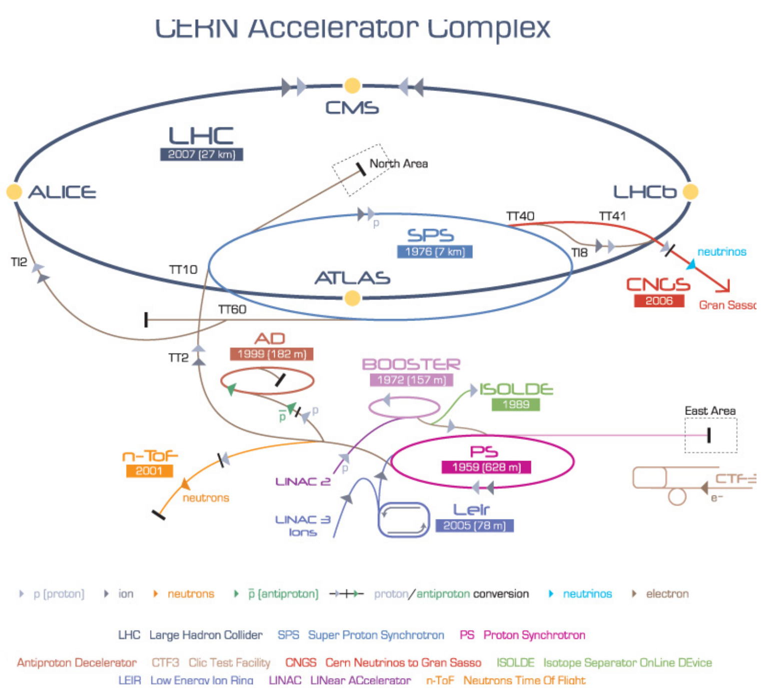
Where can you find me

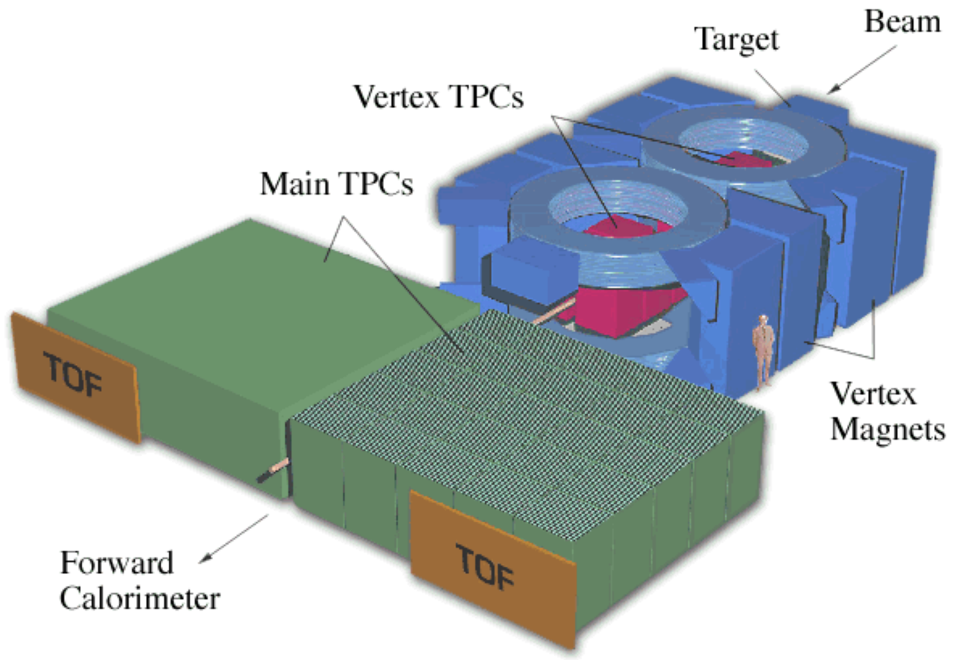
- Nikhef, Office N325, Science Park 105 Amsterdam

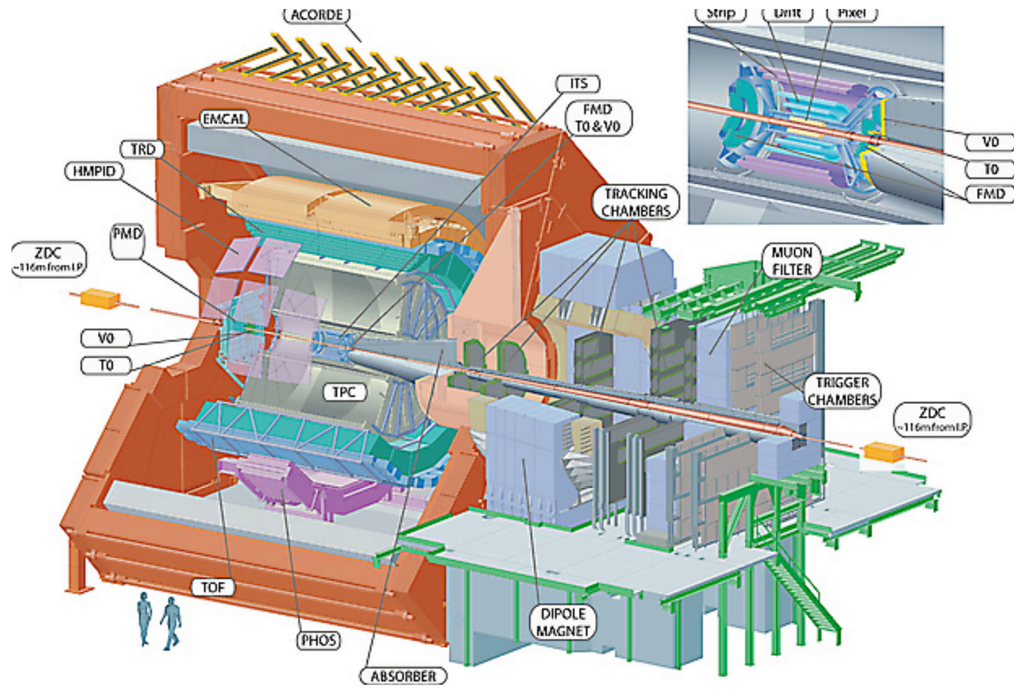
BRIEFLY ABOUT ME…

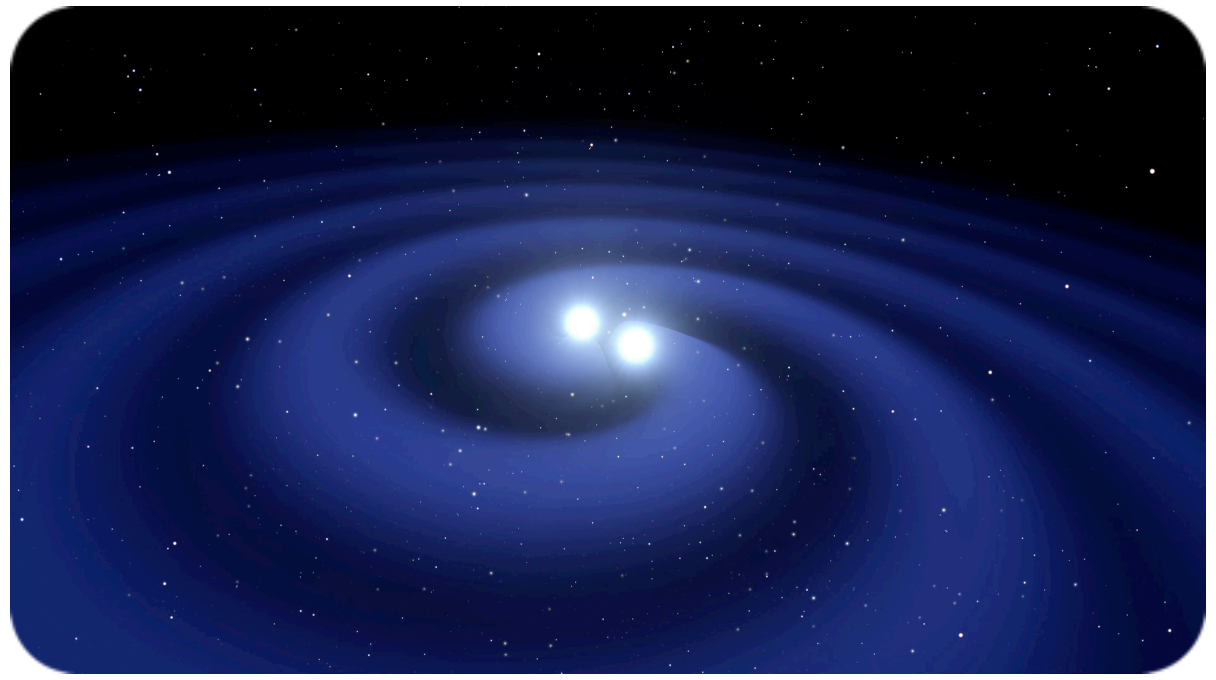
Research interest

- Quantum chromodynamics (QCD)
- Heavy-ion physics Alice @ LHC
- Connection with NS EoS



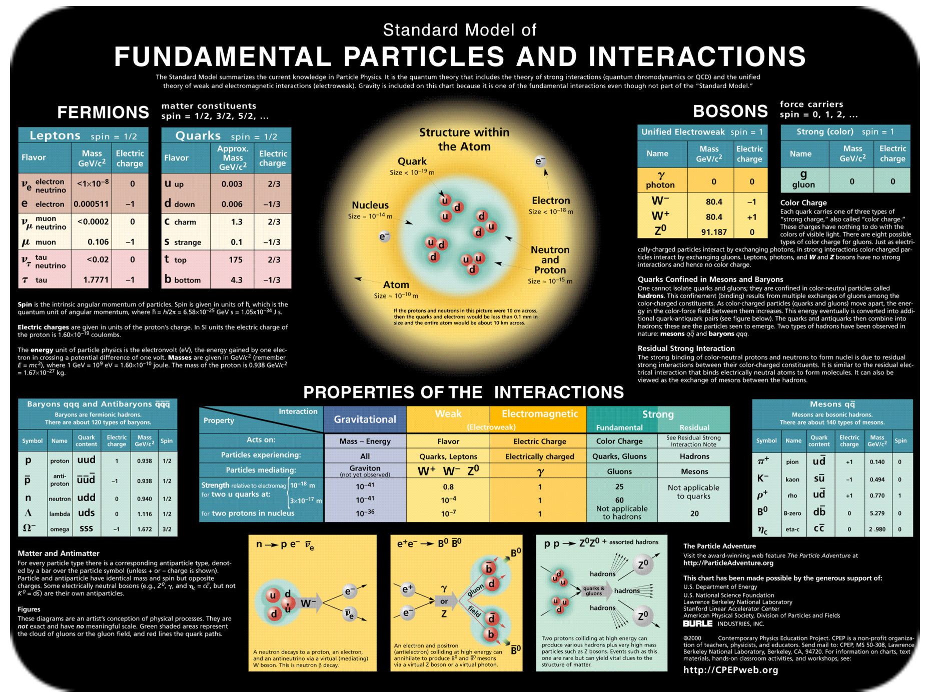


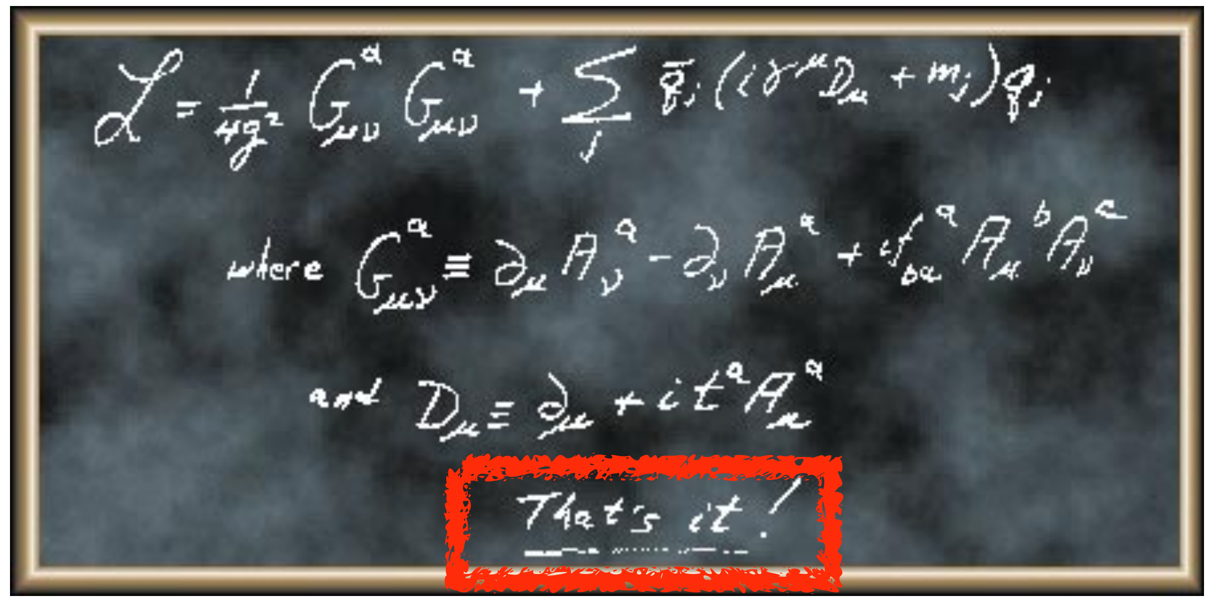




Teaching

- Introduction to elementary particle physics (1st year bachelor)
- Special relativity (1st year bachelor)
- Subatomic physics (3rd year bachelor)
- Particle physics 2 - QCD (MSc)





PRACTICAL MATTERS

COMMUNICATION

All communication from our side is done through the mailing list pp2course-msc@nikhef.nl

List populated using the lists we got from the coordinators of your programs

If you have not received a mail or if you know a case, contact me!!!

- Panos.Christakoglou@nikhef.nl

TEACHING ASSISTANTS

QCD LECTURES

Noor Koster

noor.koster@nikhef.nl

ABOUT YOUR HOMEWORK

Can be sent as a pdf file

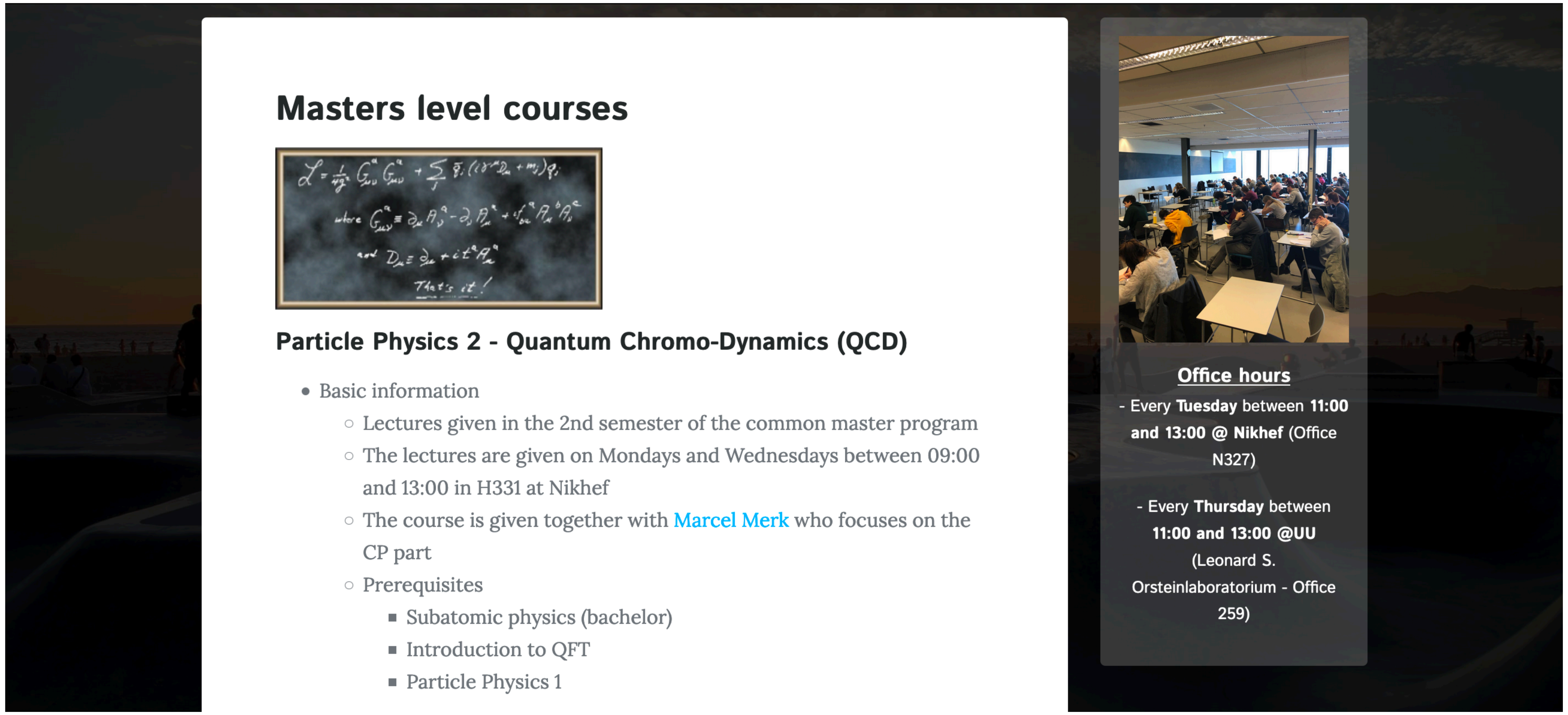
- Reasonable file size (less than 5 MB)
- Readable
- Deadline 1 week after the homework is given.

Hand in, either:

- By mail to the TAs
- At the start of tutorial/exercise class in person

MATERIAL

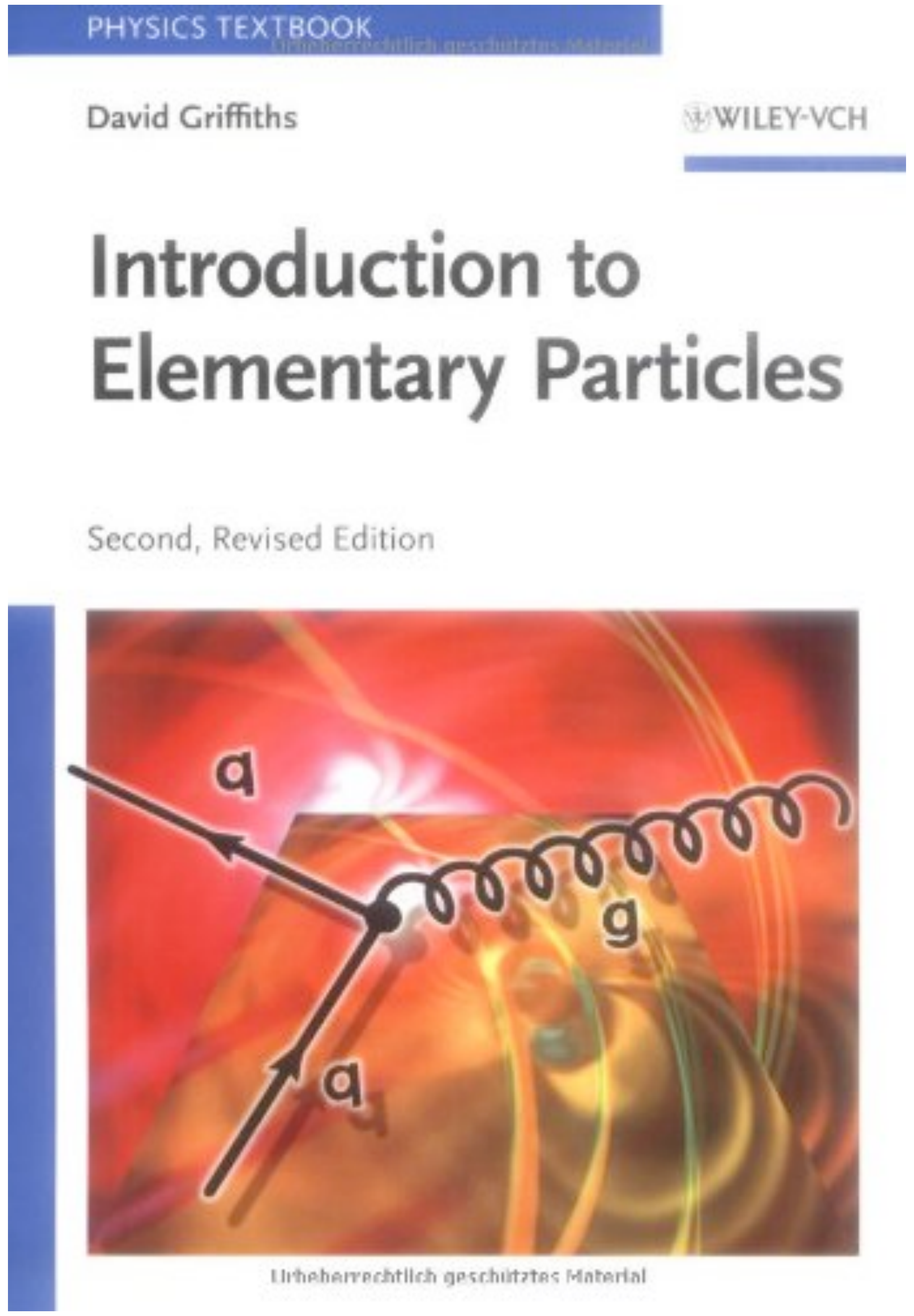
QCD material also posted on
my web page

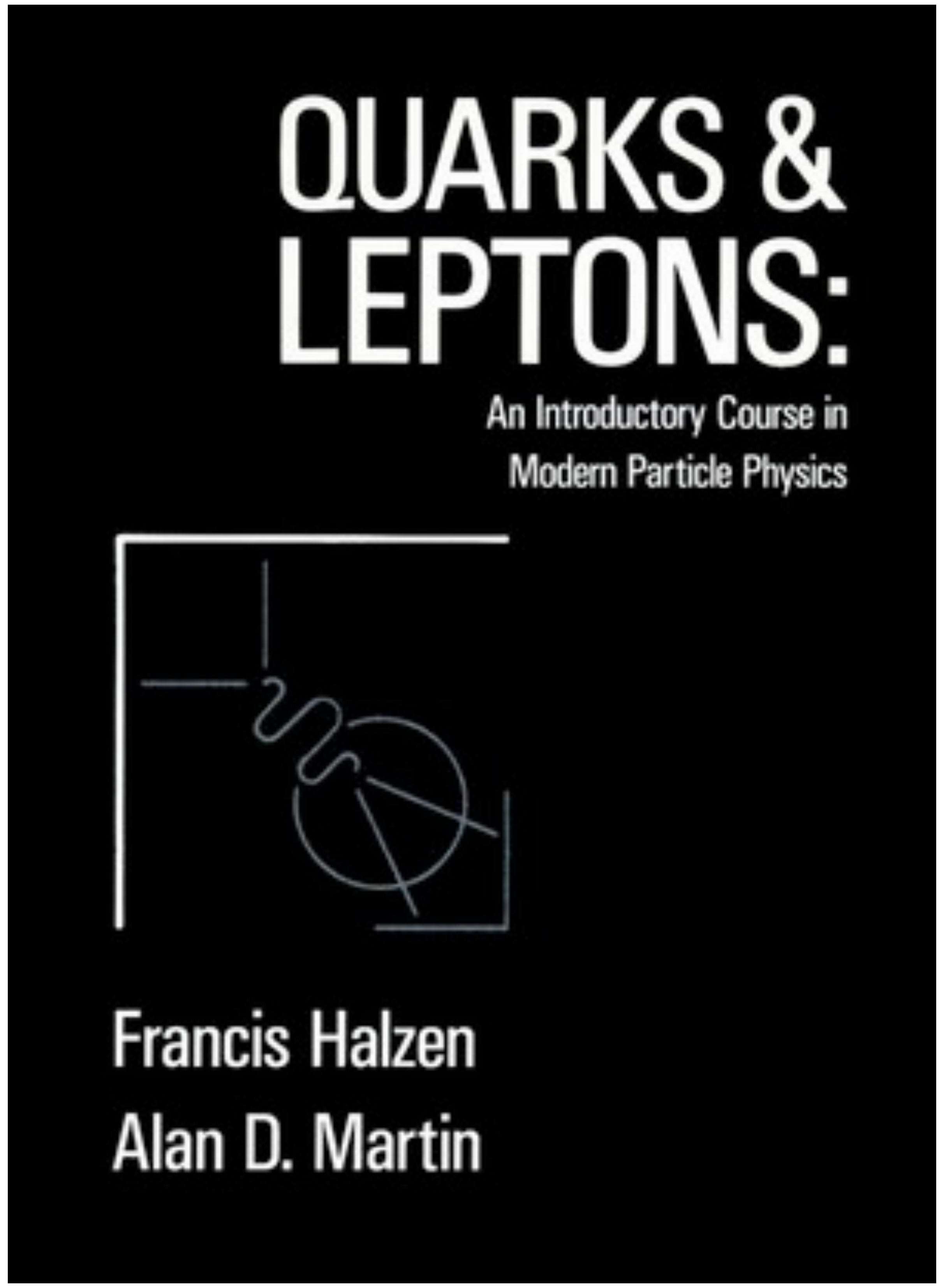


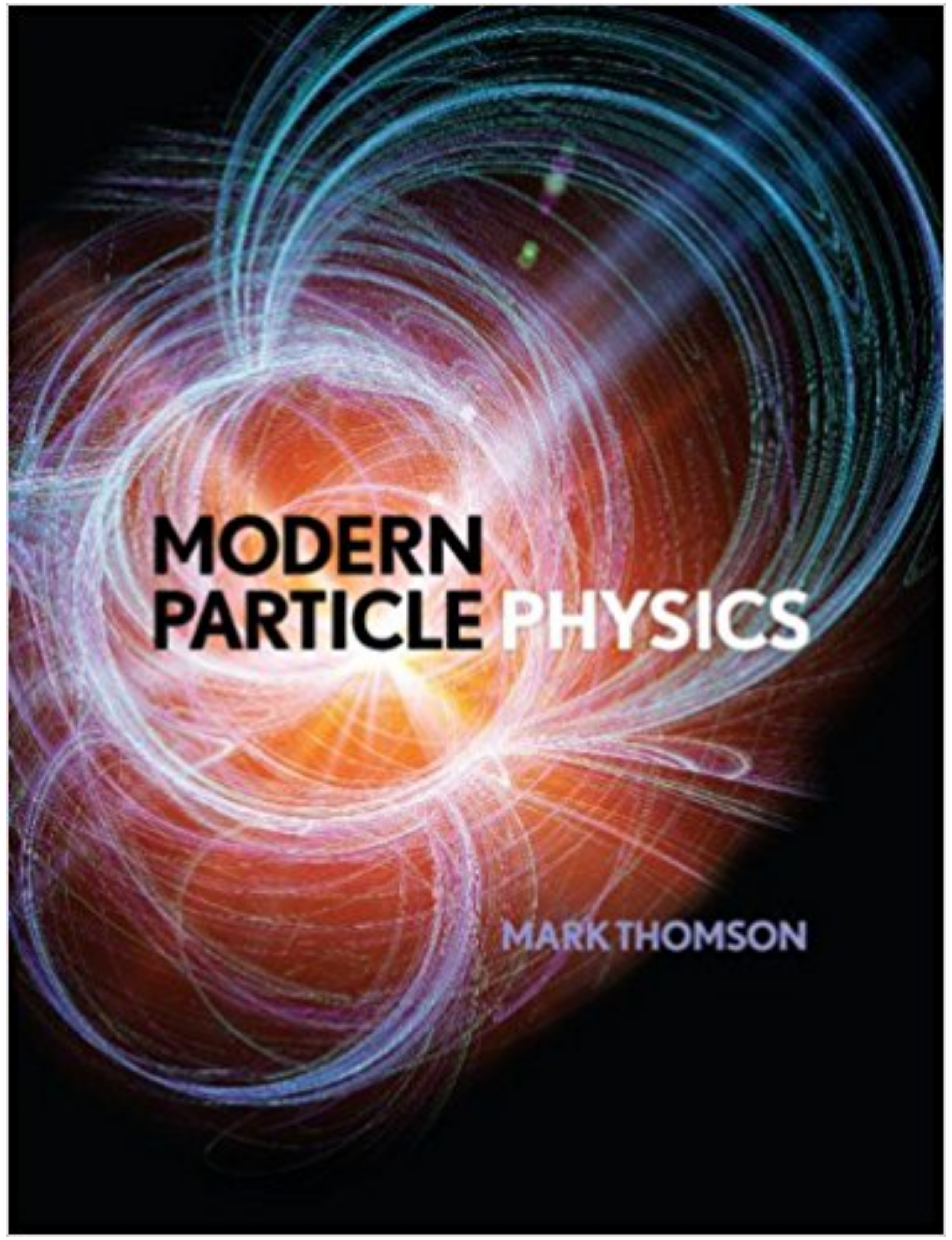
QCD syllabus

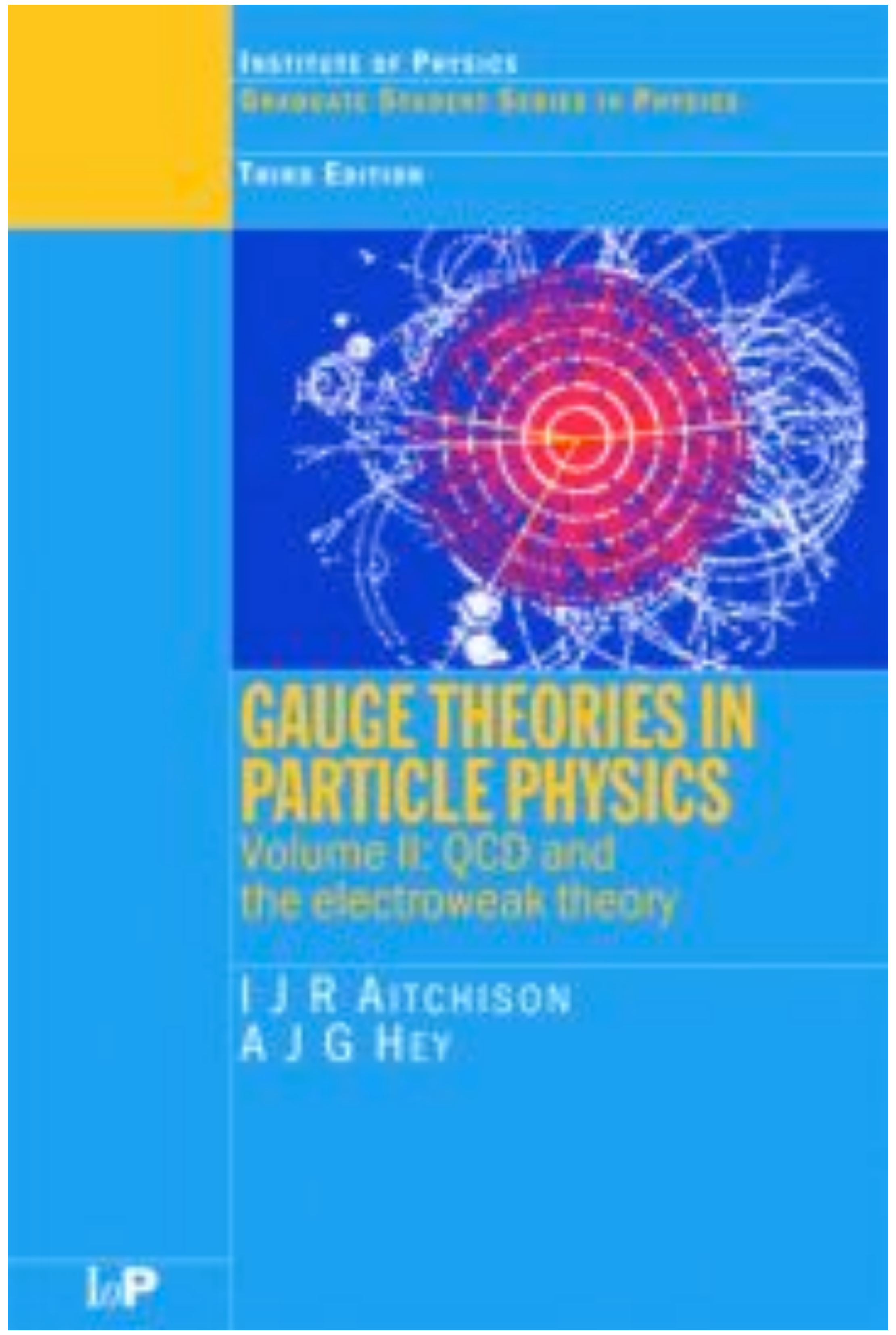
LITERATURE

The lecture notes use material mainly from these books



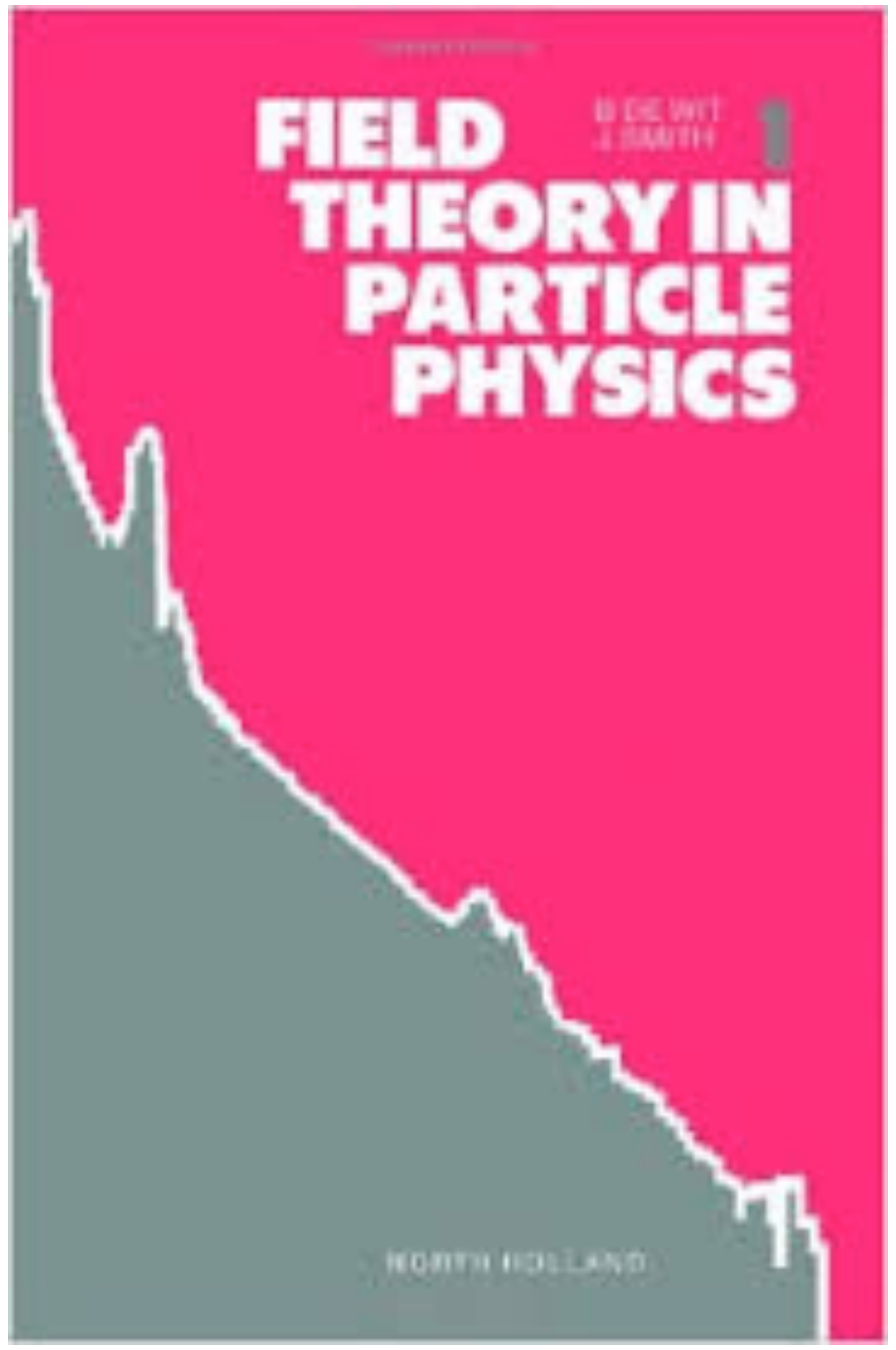


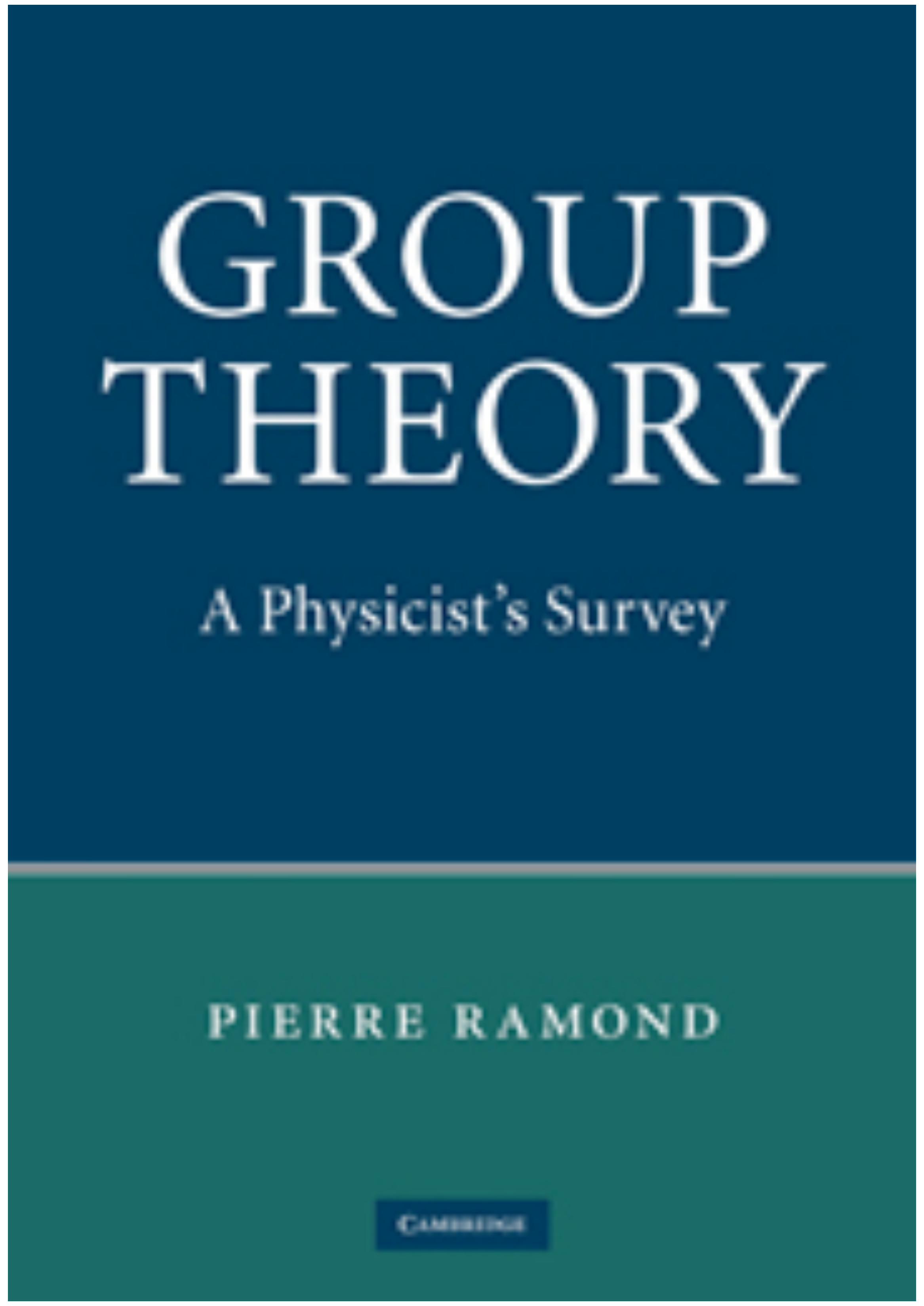


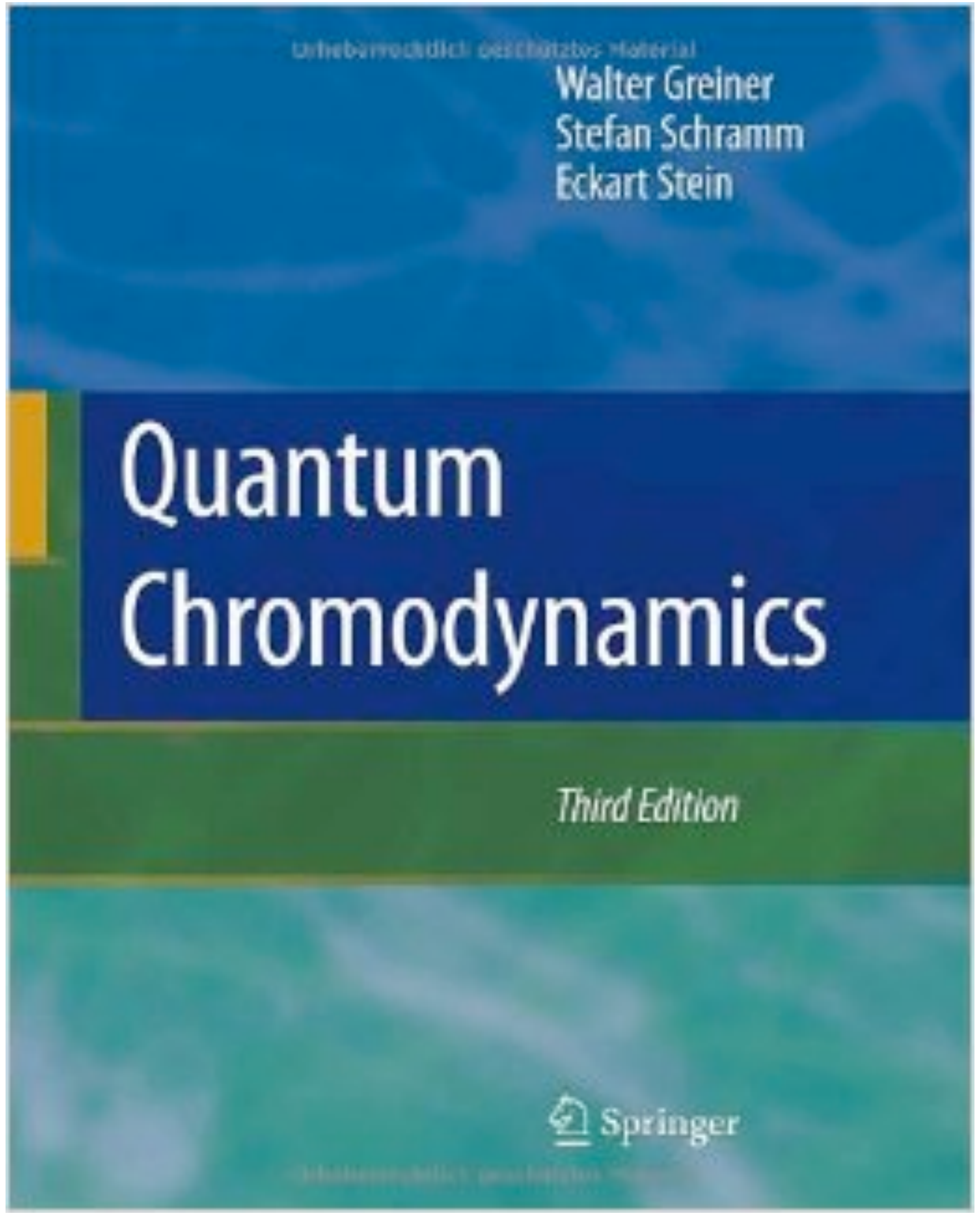


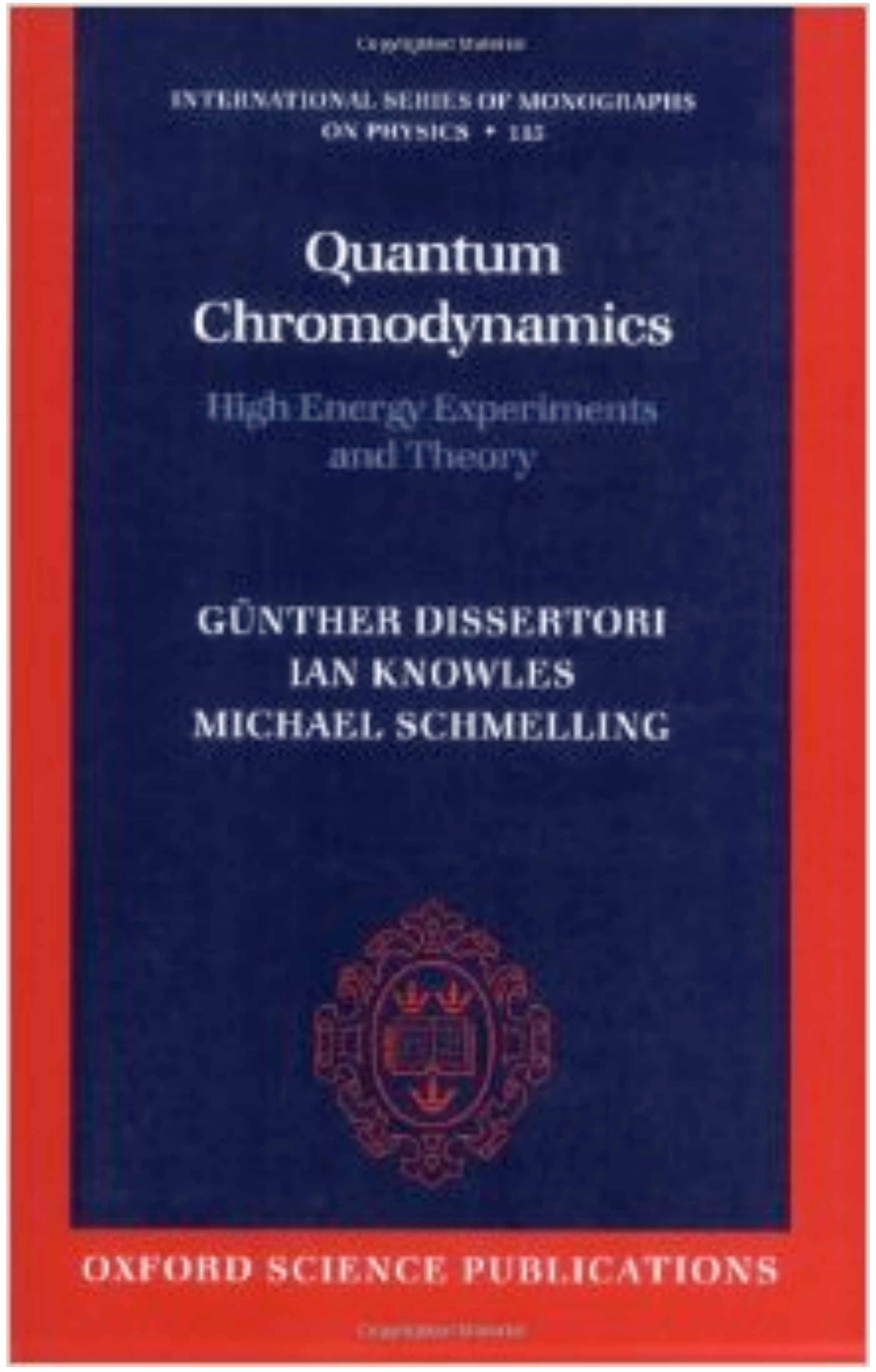
LITERATURE

The lecture notes use material mainly from these books



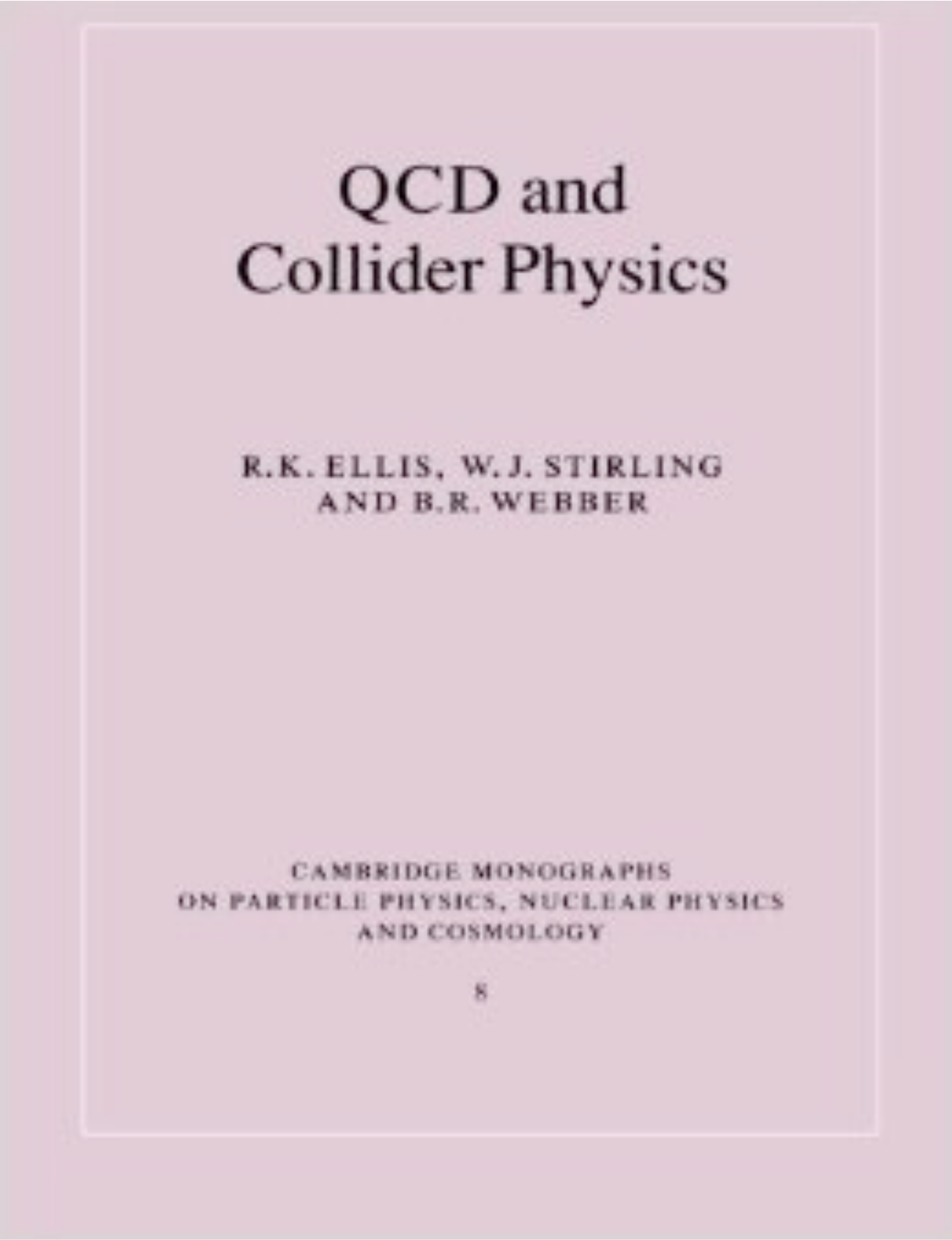


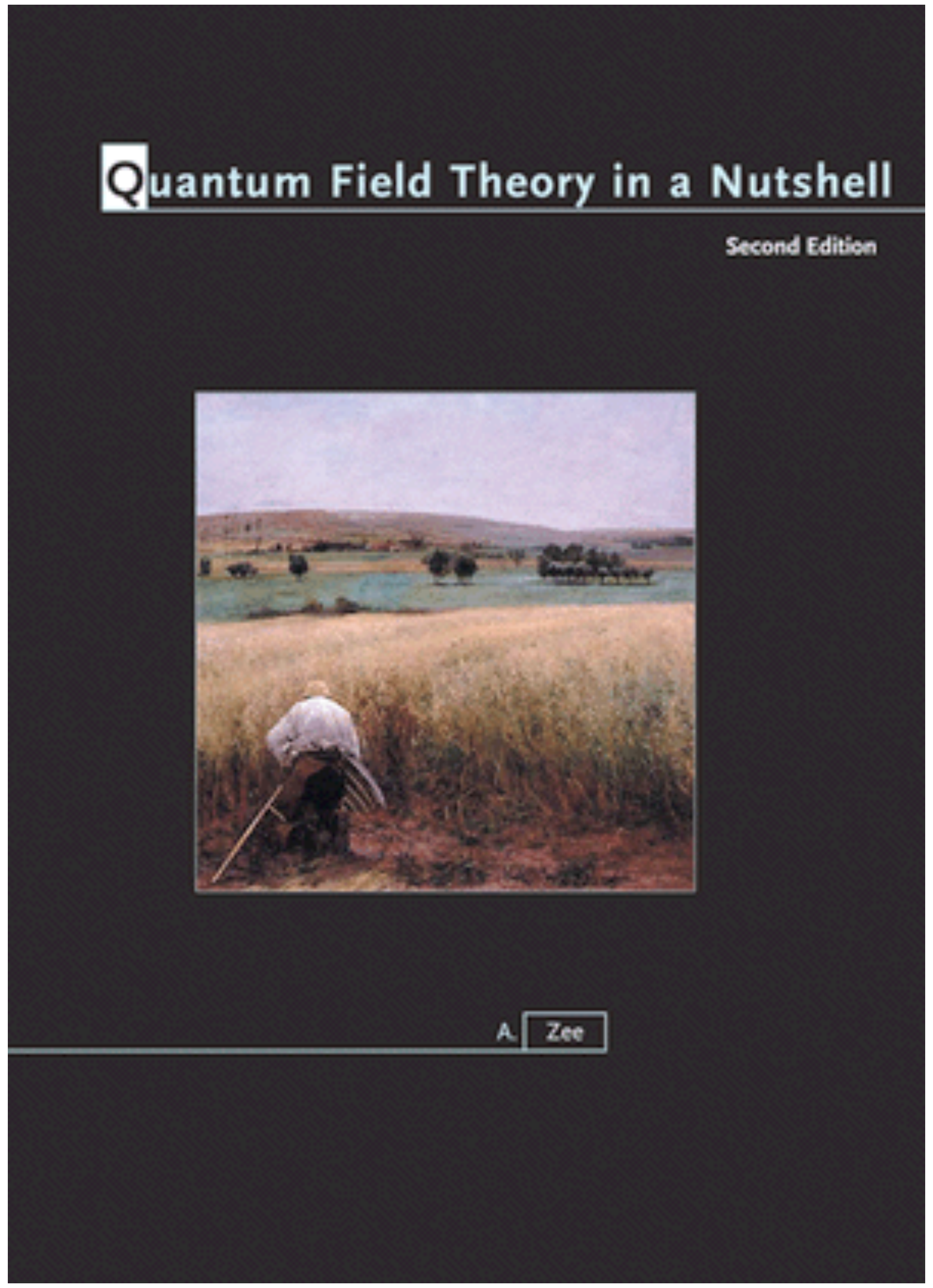


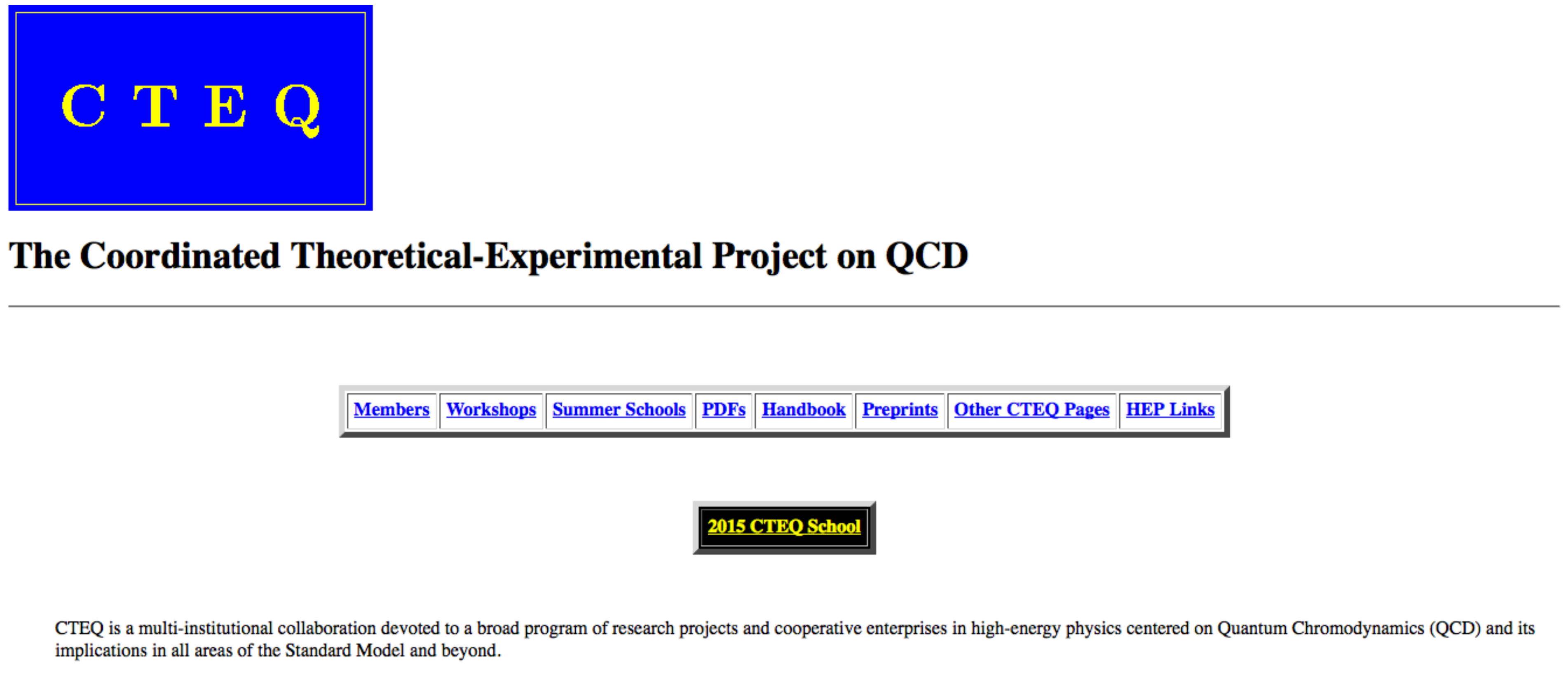


LITERATURE

The lecture notes use some, limited material also from these sources







OFFICE HOURS

You have questions or comments about the lectures?

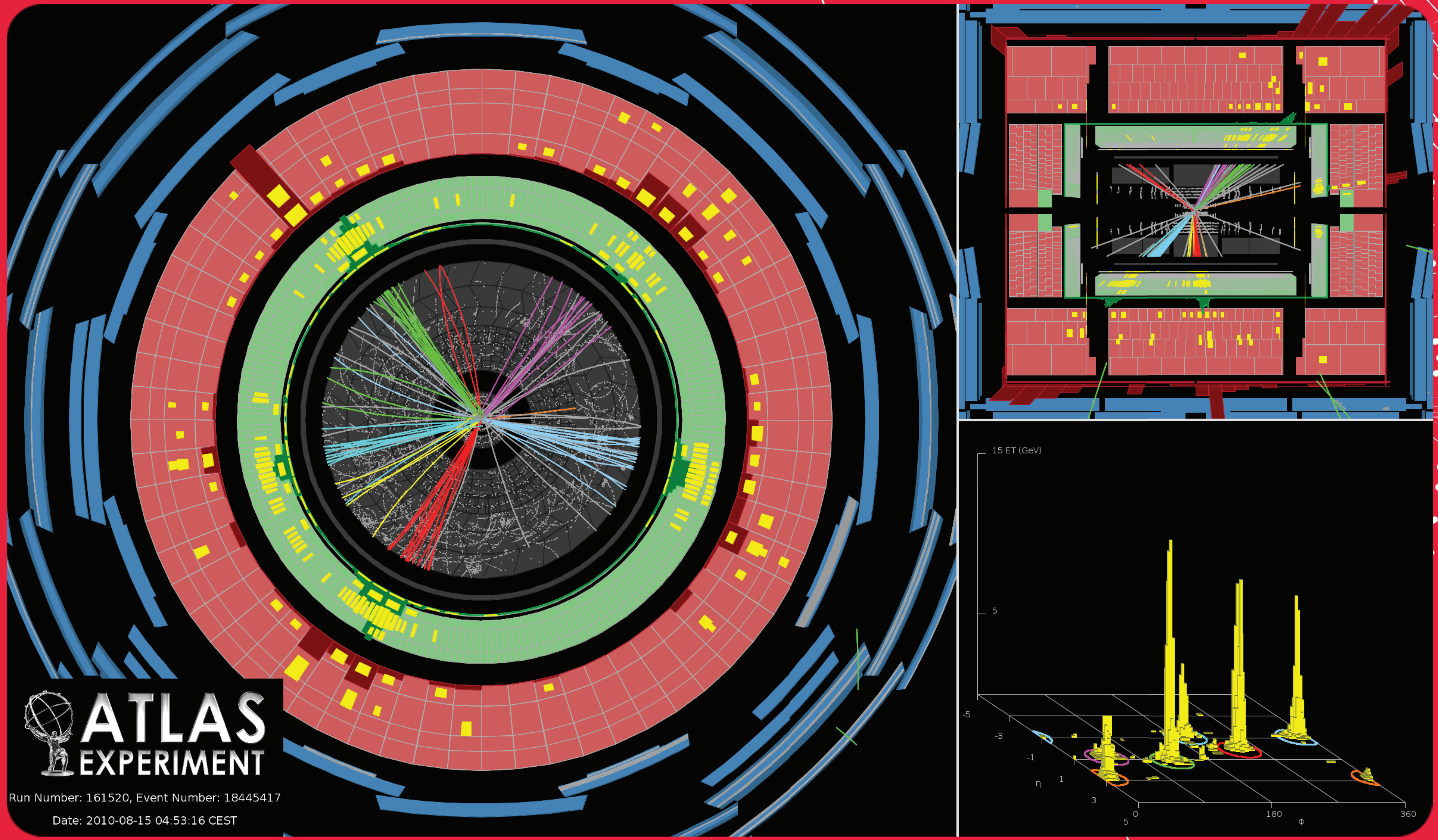
- I reserved two hours **every Tuesday, between 12:00 and 14:00**
- Address: Nikhef, Science Park 105, Room N325 or my zoom room
- Readjusted if needed e.g. everybody shows up at the same time

You could also send a mail

- I promise to try to answer as fast as possible
  - Note my teaching duties
  - Also other responsibilities e.g. research (ALICE @ LHC), committees, BSc/MSc/PhD supervision,…, and maybe a life

I will be more than glad to receive your comments, suggestions and ideas on how to improve the course!

COURSE CONTENT



INTRODUCTION TO QCD

QCD ANNIVERSARY

50 Years of Quantum Chromodynamics

11–15 Sept 2023
Luskin Conference Center
US/Pacific timezone

Enter your search term

- Overview
- Timetable
- Contribution List
- Registration
- Conference venue
- Accommodation and travel info
- Code of Conduct
- QCD@50 Poster

Conference Admin

mparedes@physics.ucla...

BIRTH OF PARTICLE PHYSICS

The list of elementary particles has changed many times over time

- The electron was the only particle that was always in that list!
- The first elementary particle to be ever identified
  - Discovered by Sir Joseph John Thomson in 1887
    - Thomson was awarded the Nobel prize for this discovery but also for his work on the conduction of electricity in gases
    - This discovery was done while Thomson investigated whether or not particle rays could be deflected by an electric field

J. J. Thomson (1856-1940)

SUBNUCLEAR STRUCTURE

In 1932 Chadwick discovered the neutron and it became clear that the nucleus consisted of protons and neutrons

Soon more particles started popping up from experiments

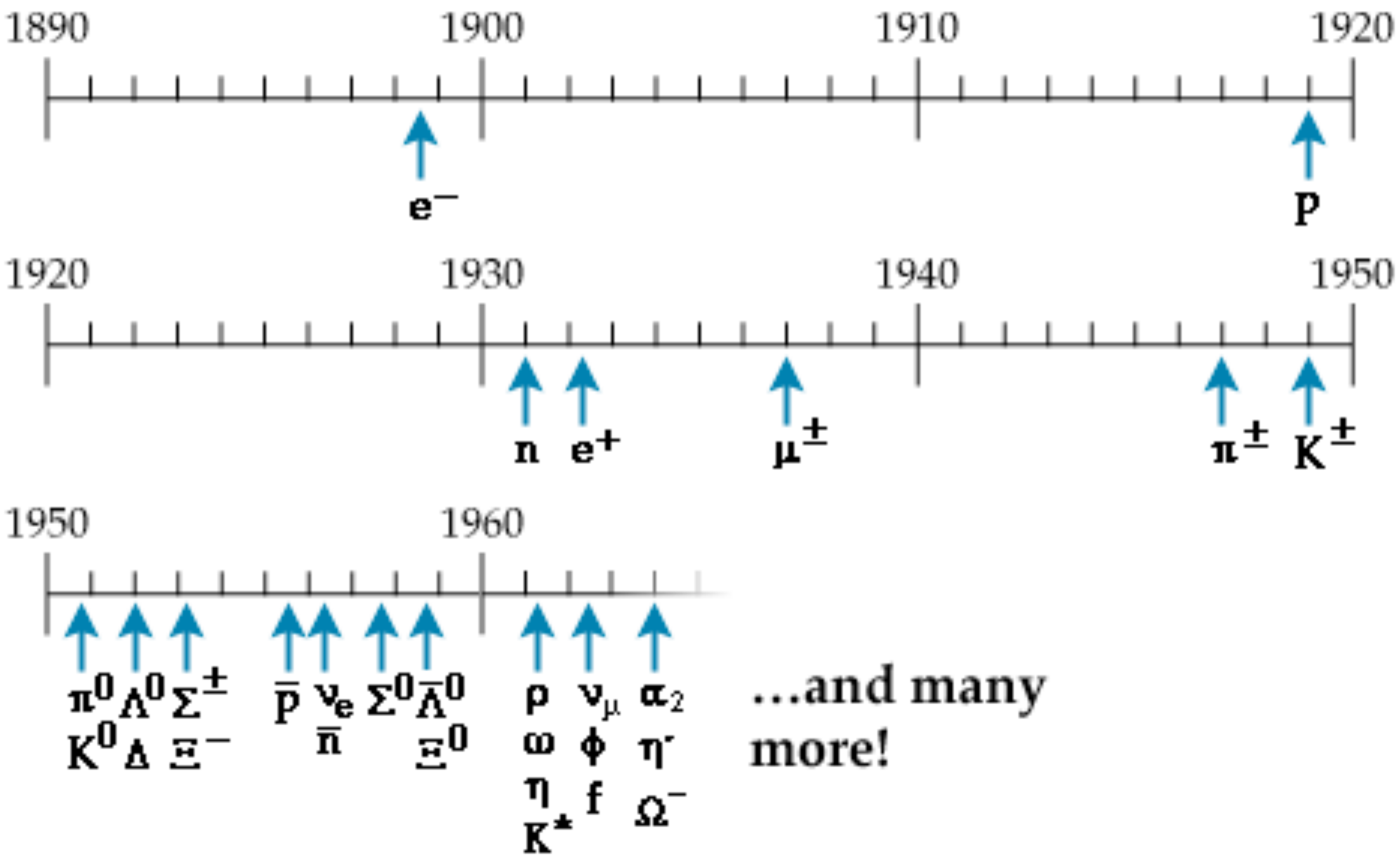
James Chadwick (1891 - 1974)

The Nobel Prize in Physics 1935

Photo from the Nobel Foundation archive.

James Chadwick

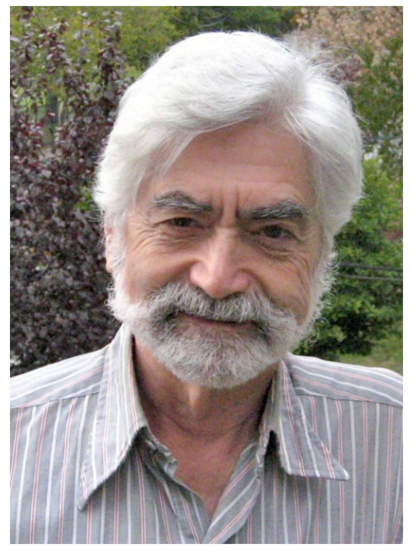
Prize share: 1/1



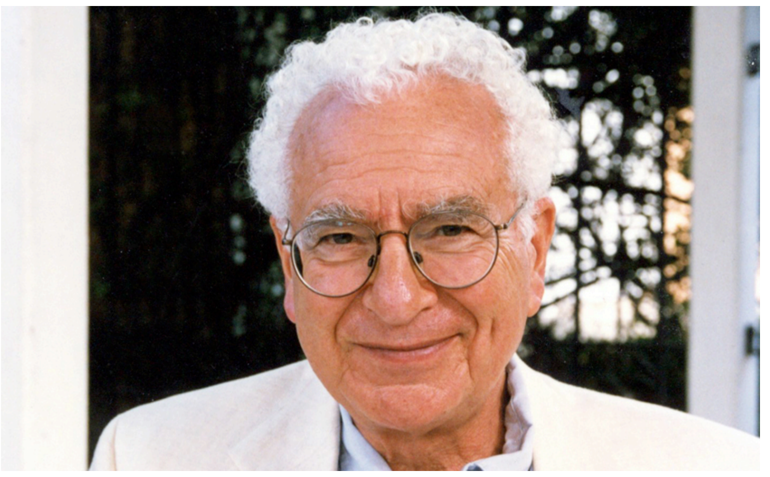
Who ordered these? What are their properties? Are there any patterns?

GELL-MANN'S QUARK MODEL

George Zweig



Murray Gell-Mann



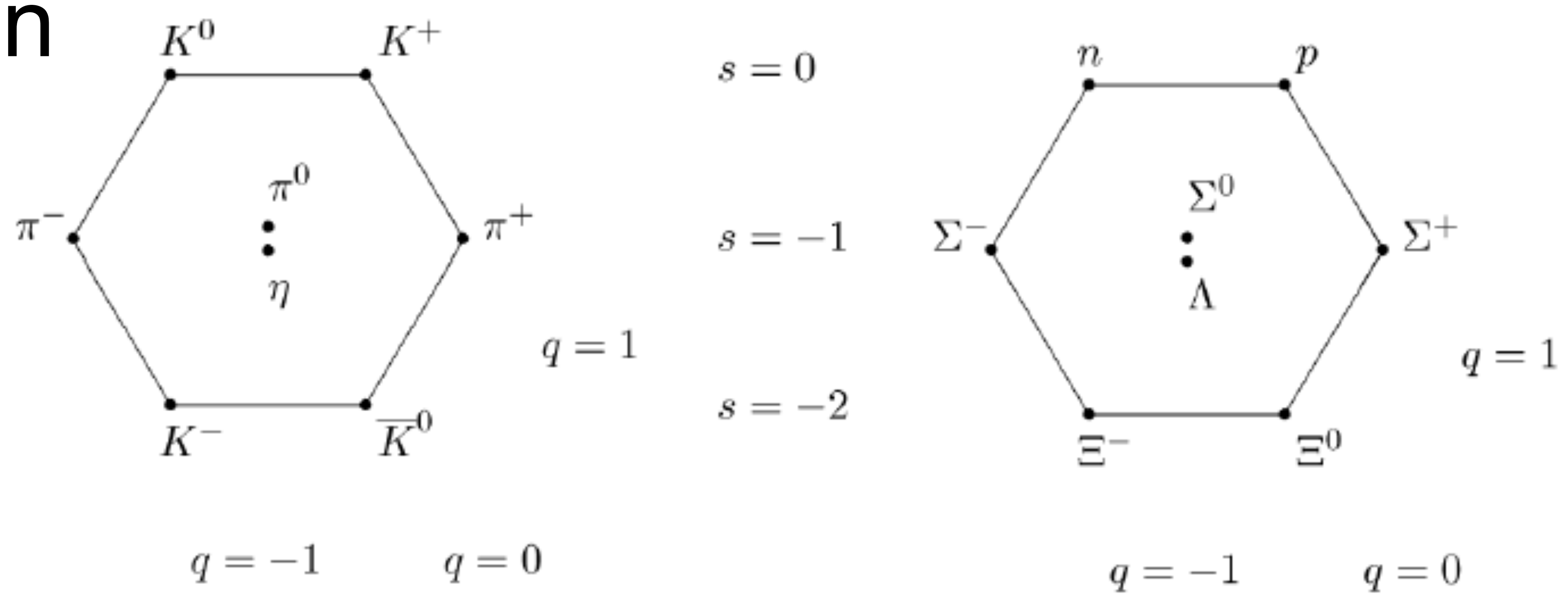


Fig. 1.4: The meson (left) and the baryon (right) octets.

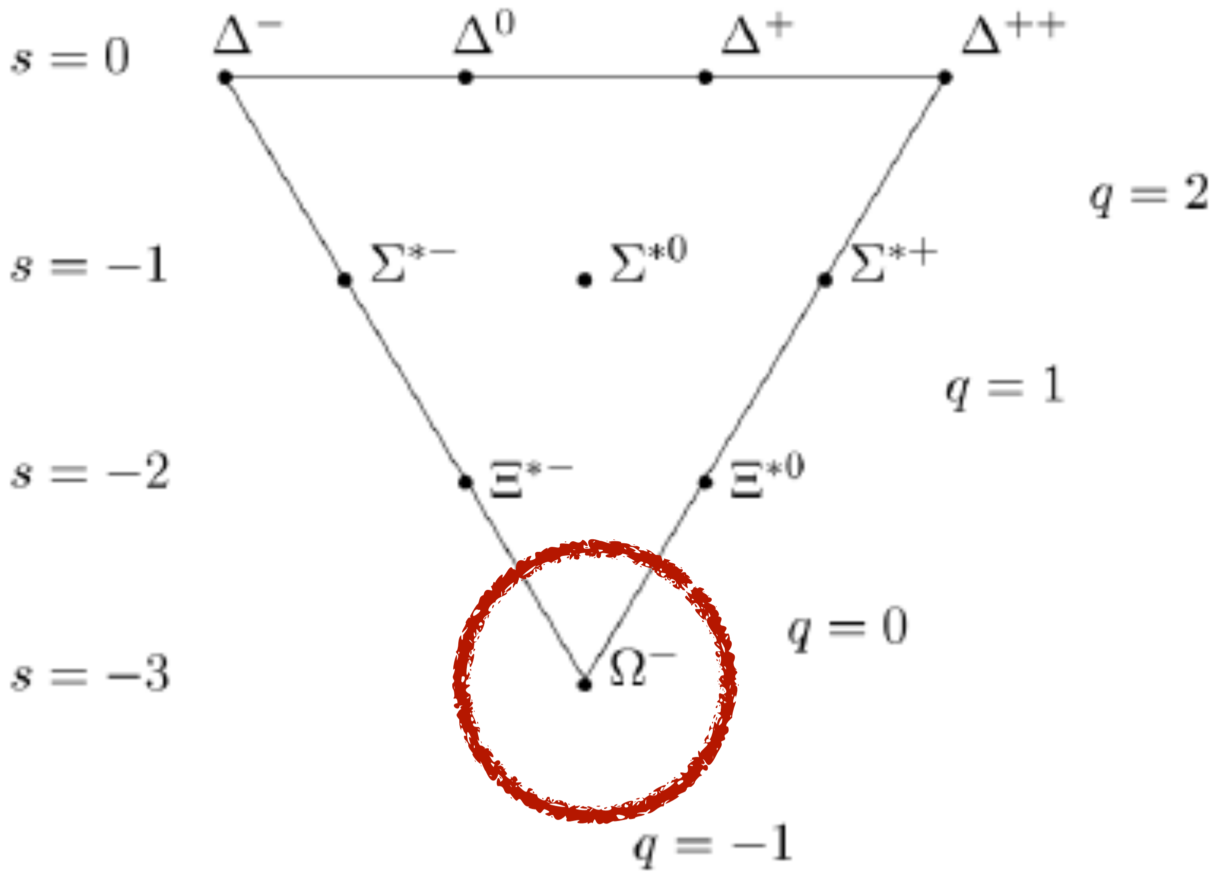
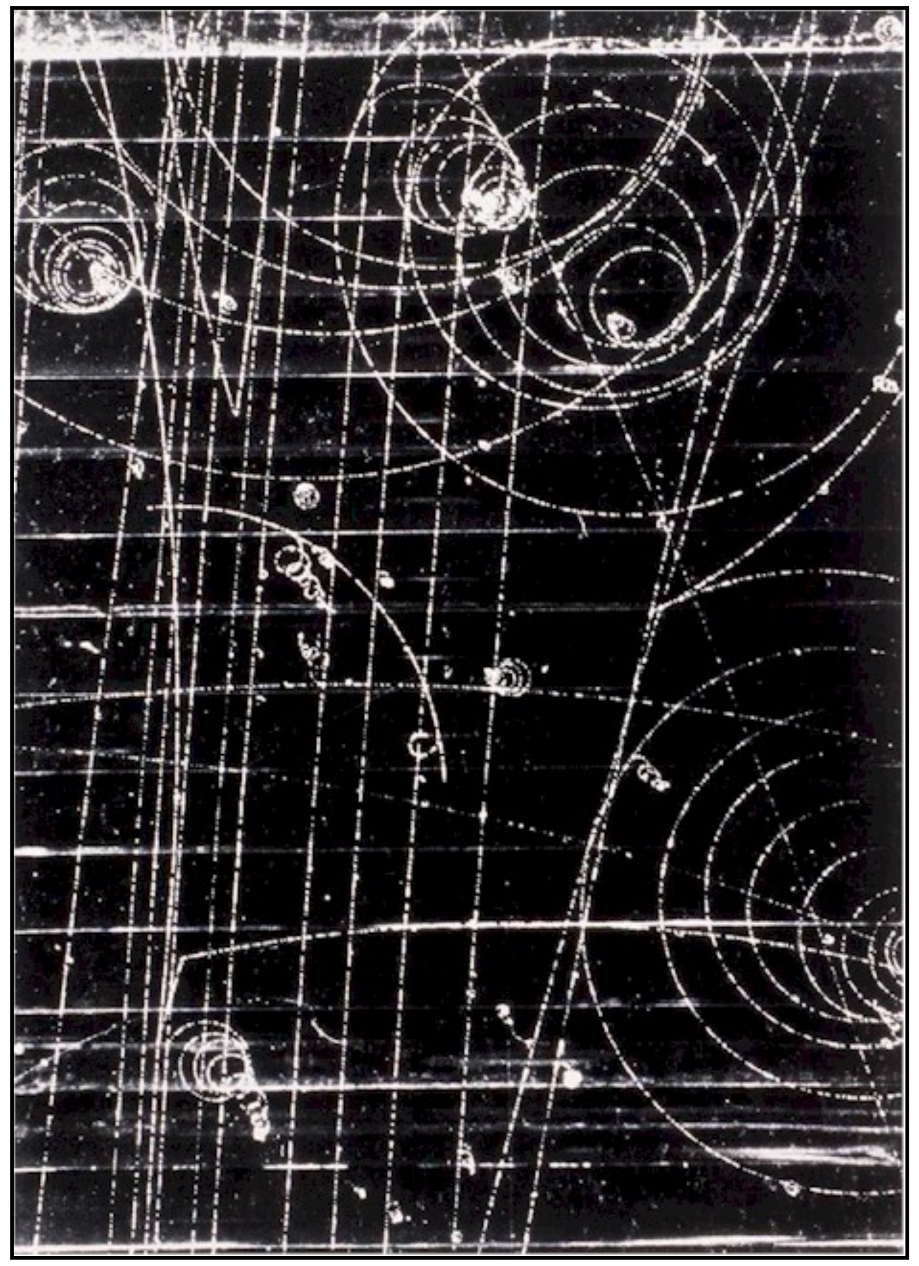


Fig. 1.5: The baryon octet (left) and decuplet (right).



The Nobel Prize in Physics 1969
Murray Gell-Mann

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The Nobel Prize in Physics 1969

Murray Gell-Mann
Prize share: 1/1

The Nobel Prize in Physics 1969 was awarded to Murray Gell-Mann *"for his contributions and discoveries concerning the classification of elementary particles and their interactions".*

Hint for quark fractional charge and a new quantum number → colour(?)

EVIDENCE OF COLOUR

$$R = \frac{\sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_c z_q^2$$

$$R = N_c z_q^2 \left(1 + \frac{\alpha_s(Q^2)}{\pi}\right)$$

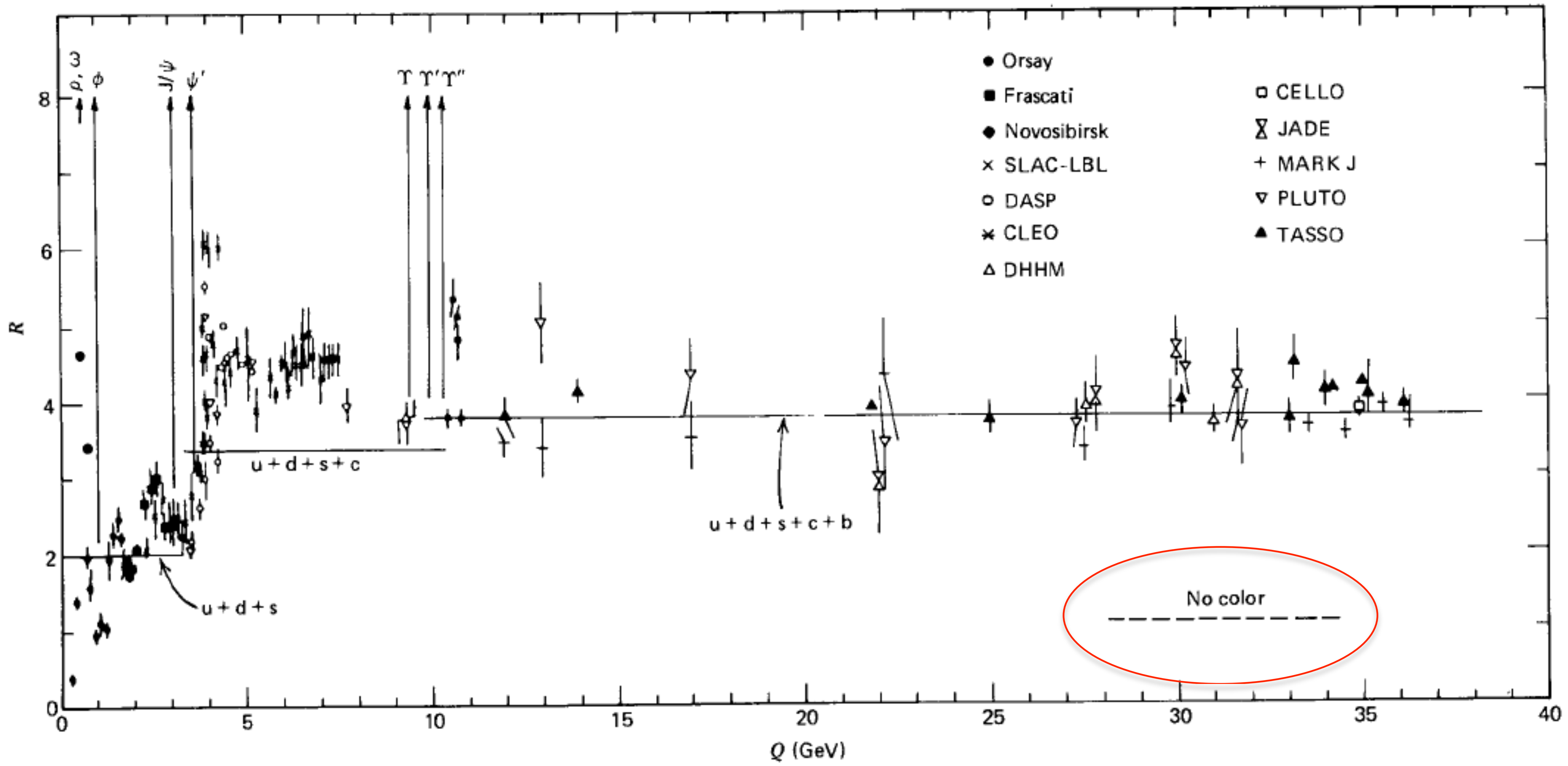
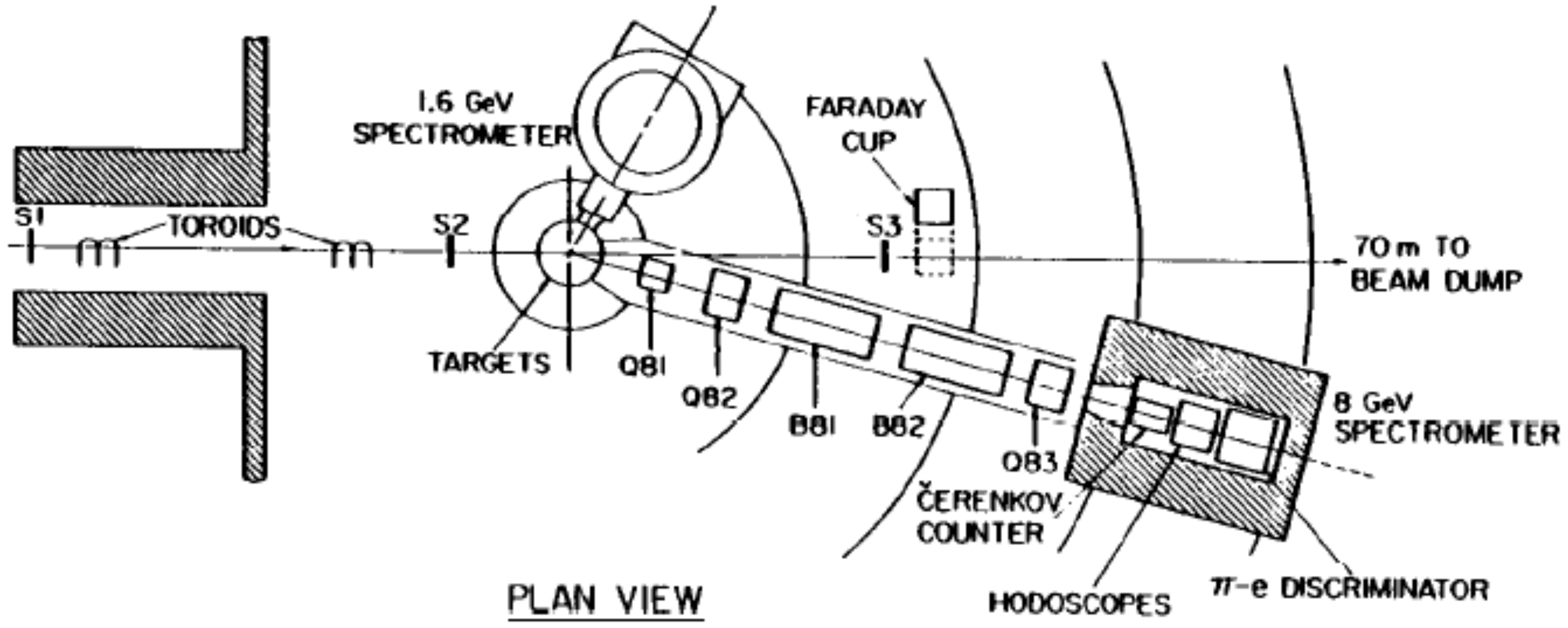


Fig. 11.3 Ratio R of (11.6) as a function of the total e^-e^+ center-of-mass energy. (The sharp peaks correspond to the production of narrow 1^- resonances just below or near the flavor thresholds.)

ARE NUCLEONS ELEMENTARY?

e-p scattering: Repeat similar experiment as Rutherford did in ~1909



The Nobel Prize in Physics 1961
Robert Hofstadter, Rudolf Mössbauer

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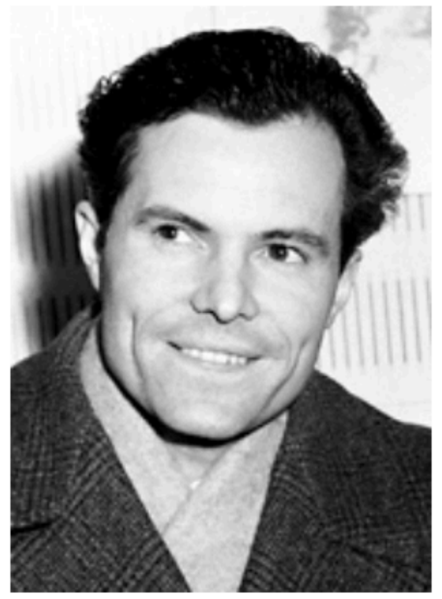
The Nobel Prize in Physics 1961

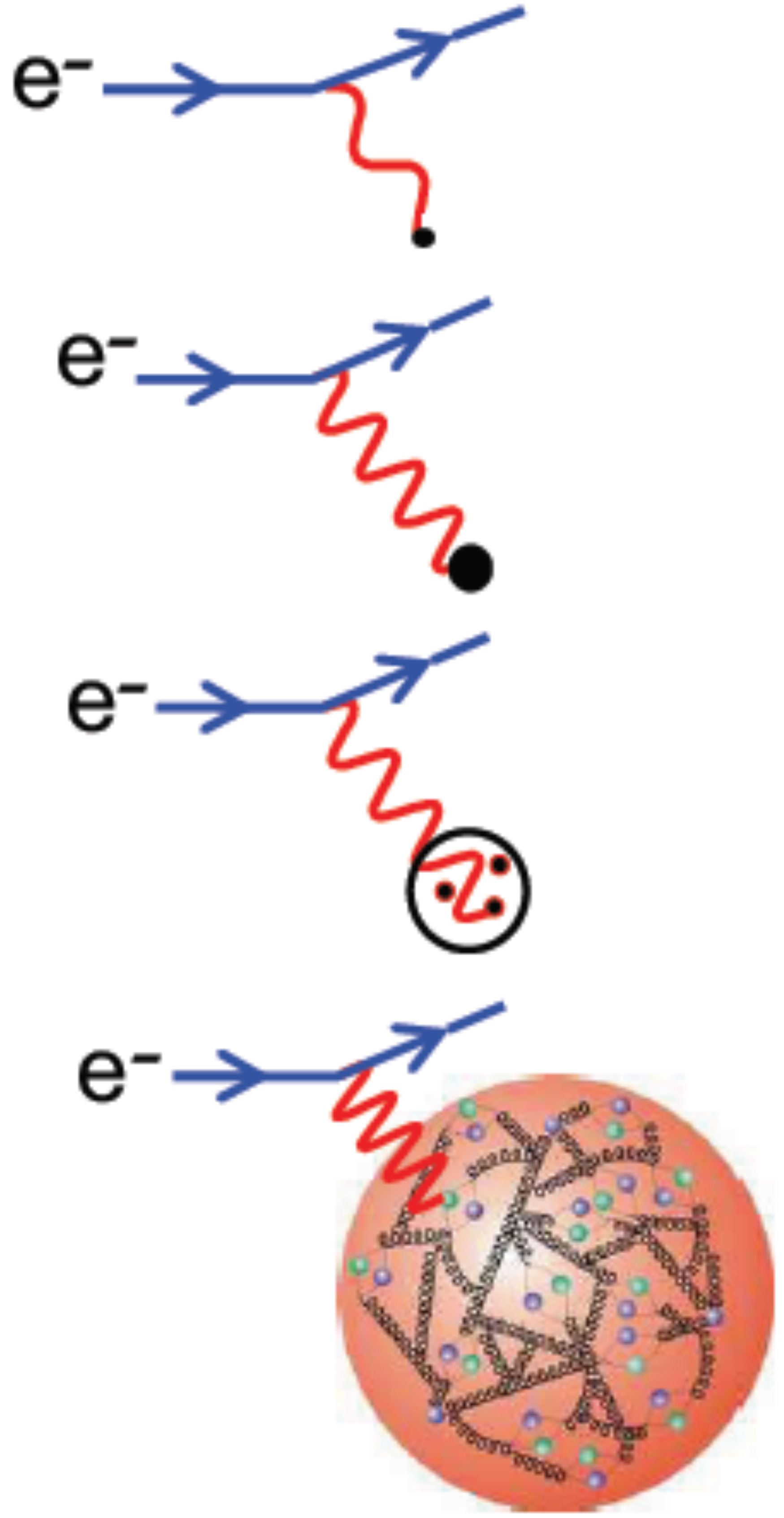
Robert Hofstadter
Prize share: 1/2



Rudolf Ludwig Mössbauer
Prize share: 1/2

The Nobel Prize in Physics 1961 was divided equally between Robert Hofstadter *"for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons"* and Rudolf Ludwig Mössbauer *"for his researches concerning the resonance absorption of gamma radiation and his discovery in this connection of the effect which bears his name".*

ARE NUCLEONS ELEMENTARY?



SLAC-MIT experiment

The Nobel Prize in Physics 1990
Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor

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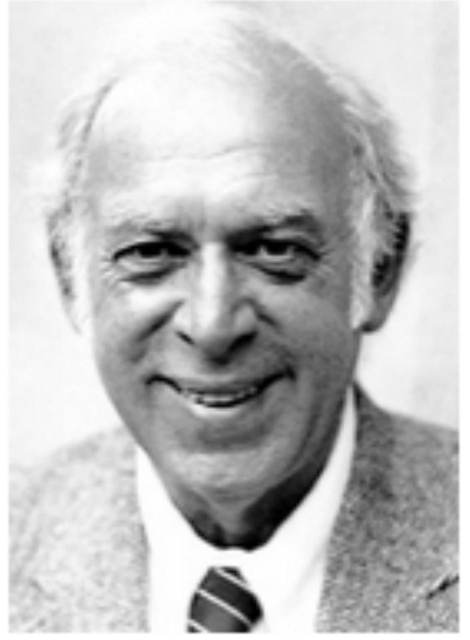
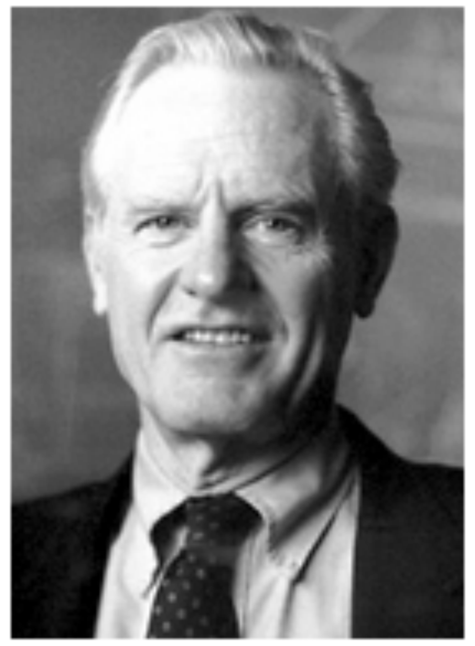
The Nobel Prize in Physics 1990



Jerome I. Friedman
Prize share: 1/3



Henry W. Kendall
Prize share: 1/3

Photo: T. Nakashima
Richard E. Taylor
Prize share: 1/3

The Nobel Prize in Physics 1990 was awarded jointly to Jerome I. Friedman, Henry W. Kendall and Richard E. Taylor *"for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics".*

DEEP INELASTIC SCATTERING

Bjorken's scaling hypothesis

- if scattering is caused by point-like constituents, then the structure functions should be independent of Q^2

James Bjorken

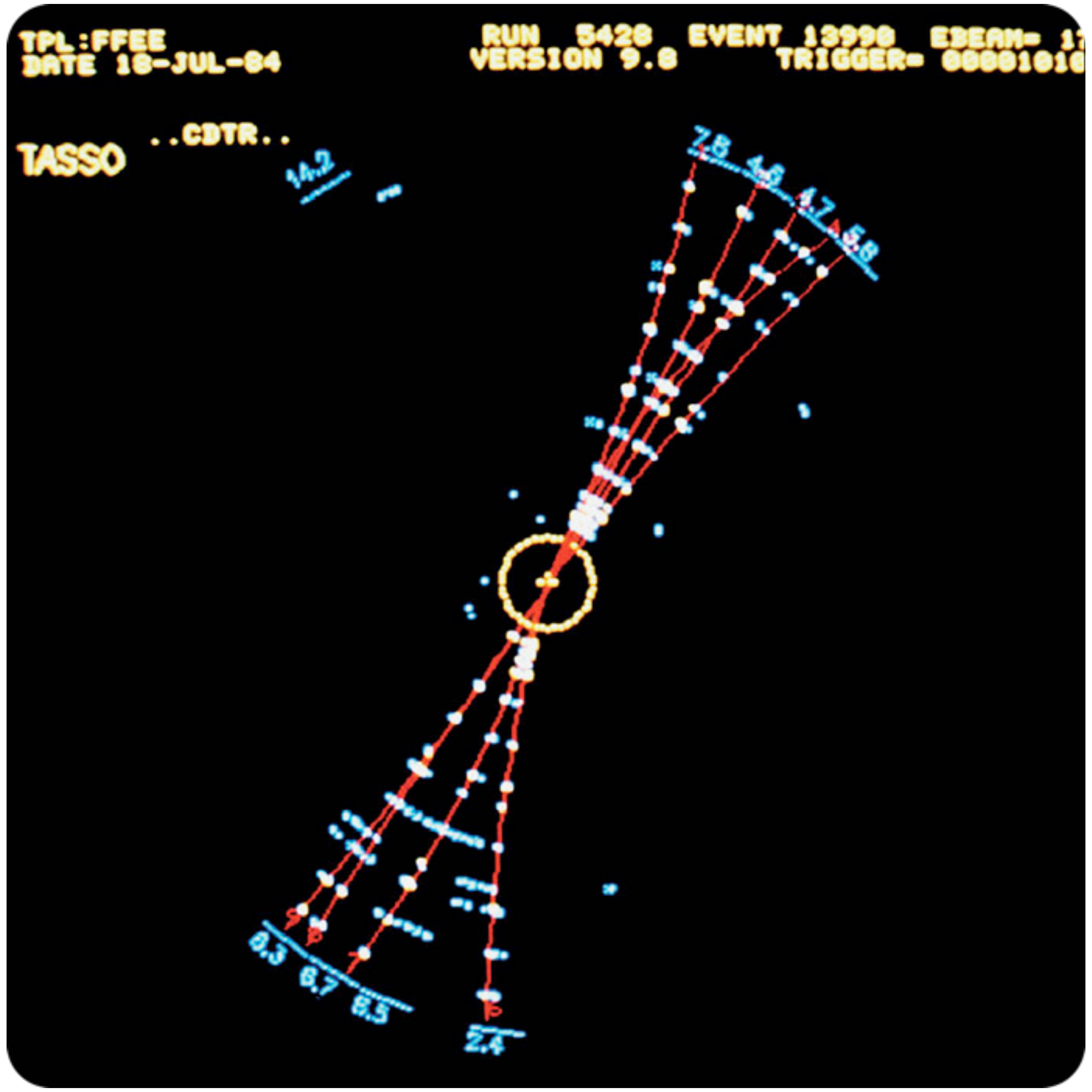
Feynman's parton model

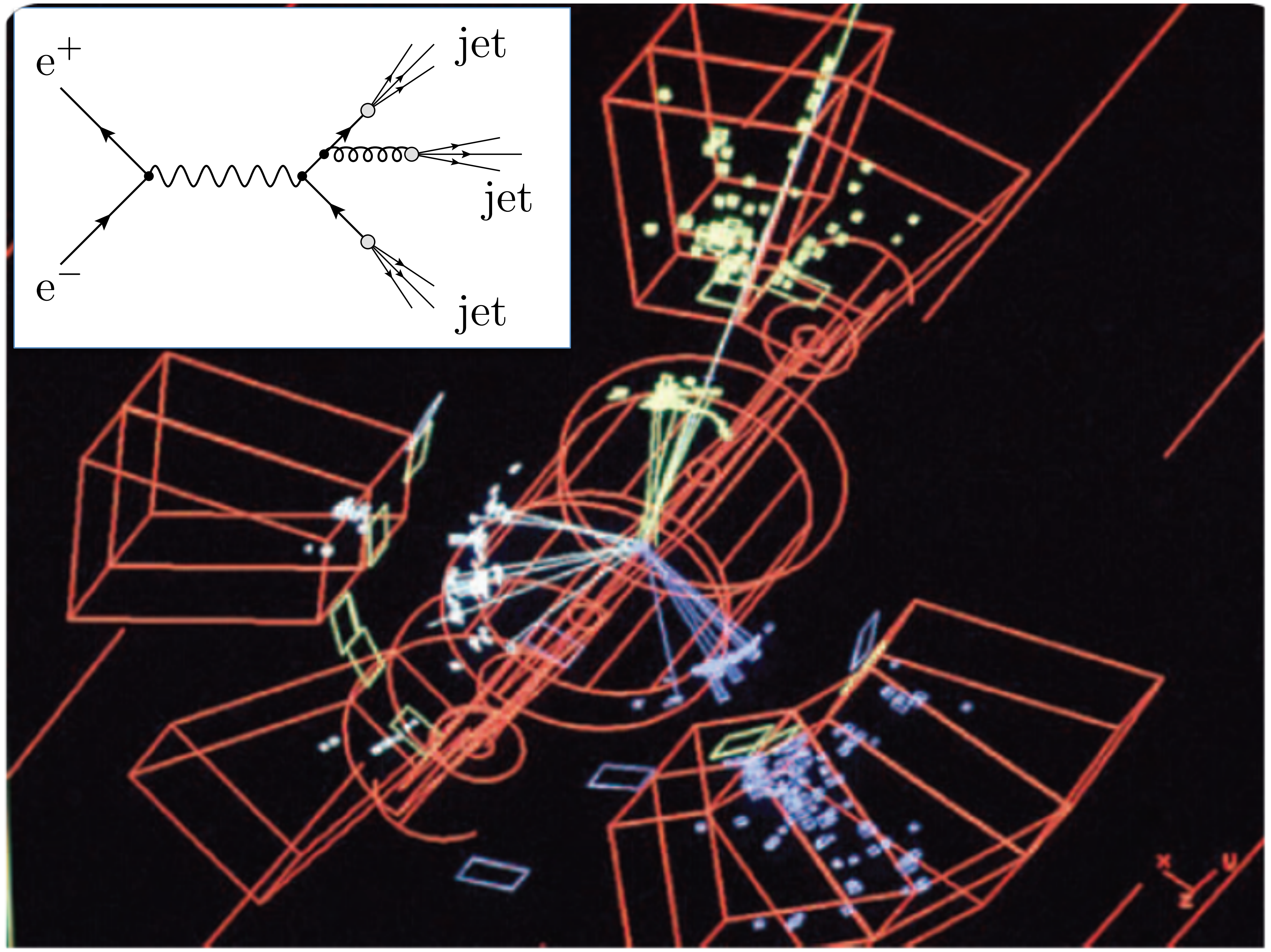
- a proton consists of constituents
- the term "parton" was used by Feynman at the early stages of his formulation and stands until our days
  - Physicists were reluctant to talk about quarks at that stage, let alone about gluons

Richard Feynman (1918-1988)

DISCOVERY OF QUARKS AND GLUONS

Positron-Electron Tandem Ring Accelerator: electron-positron collisions between 1978 and 1986	TASSO experiment @ PETRA @ DESY

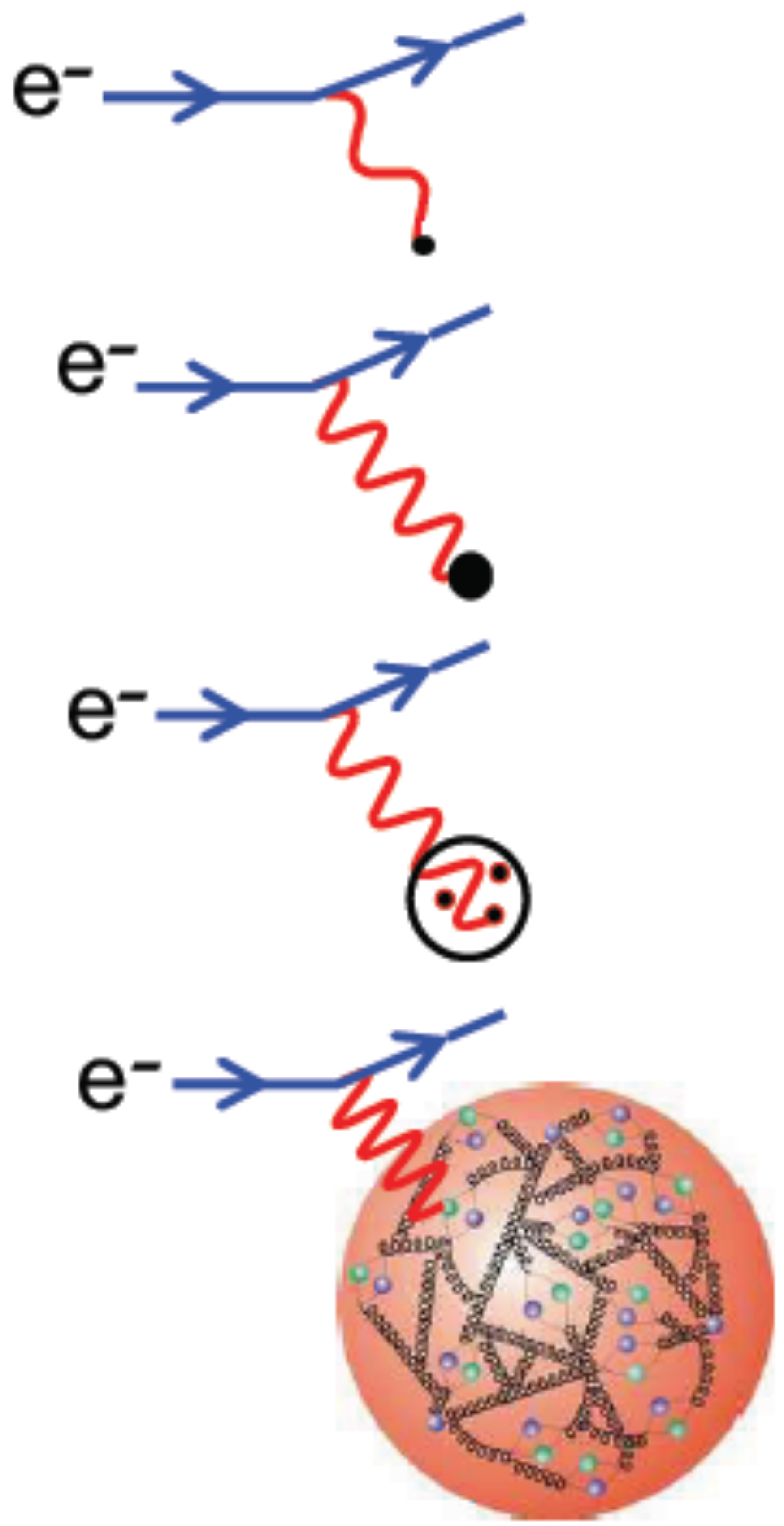


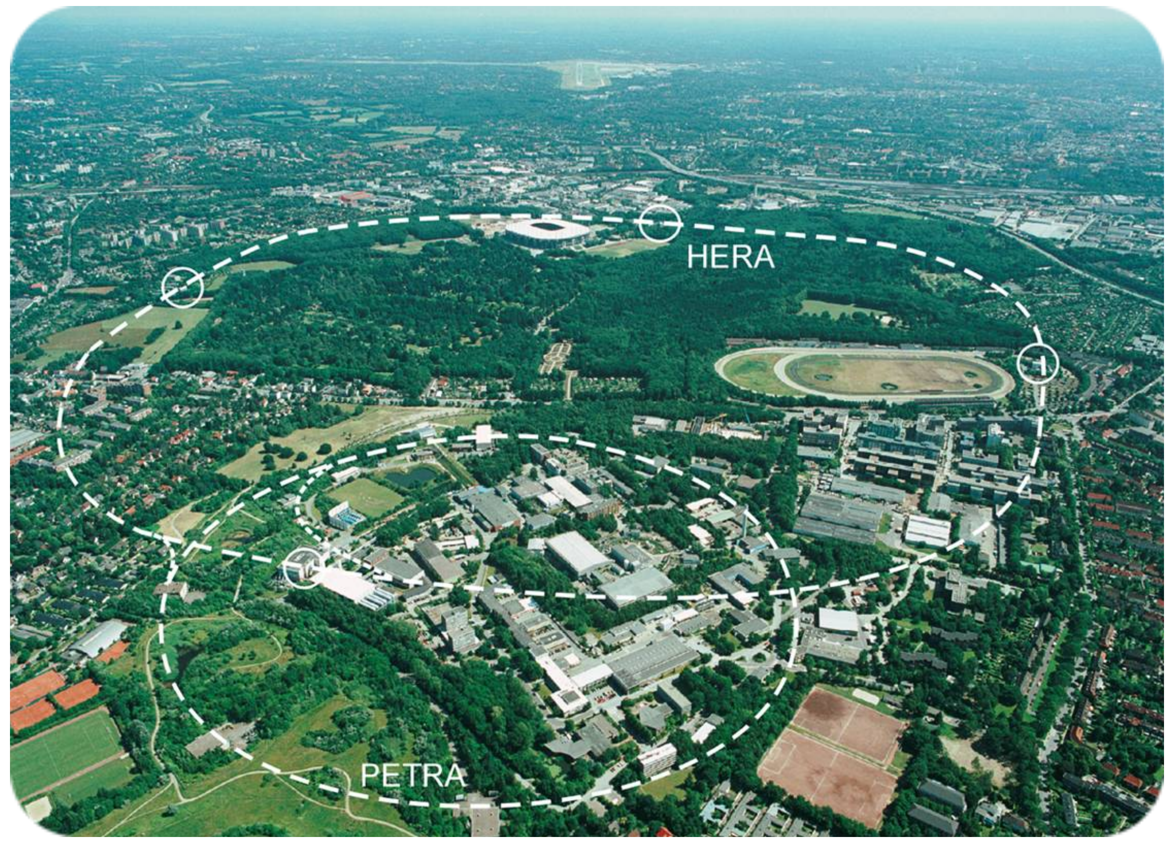


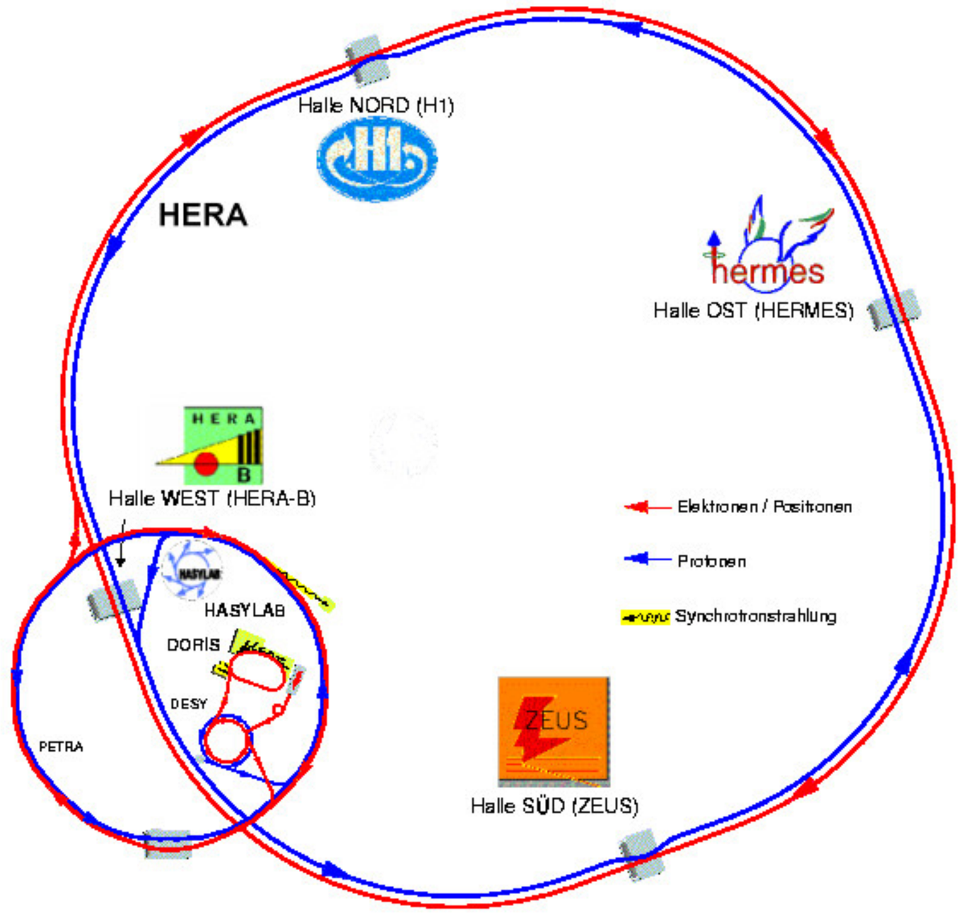
DIS EXPERIMENTS

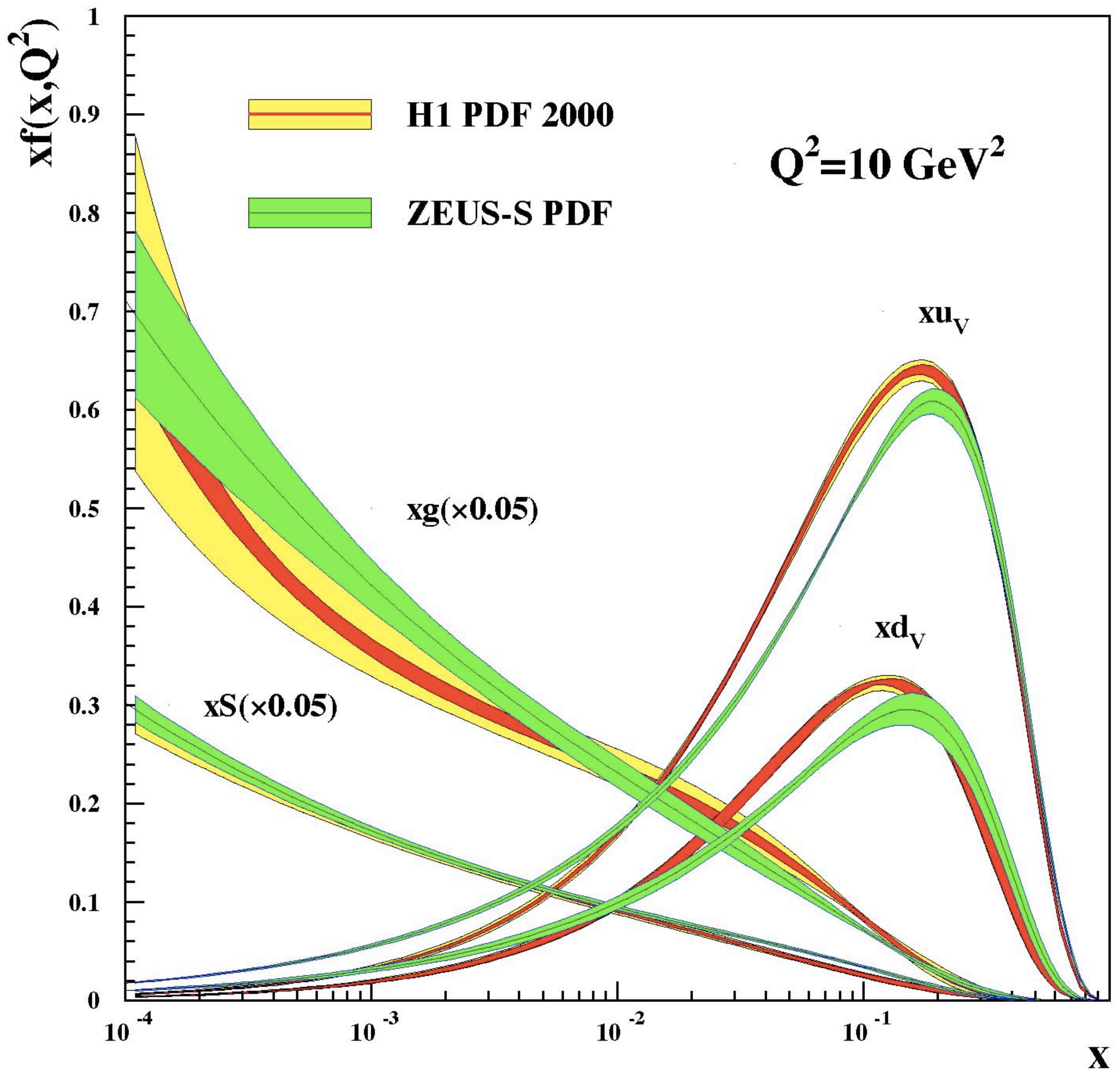
DESY (Deutsches Elektronen-Synchroton) Laboratory, Hamburg, (1992-2007)

$e^{\pm}$ 27.5 GeV → ← 920 GeV p $\sqrt{s}$~318 GeV

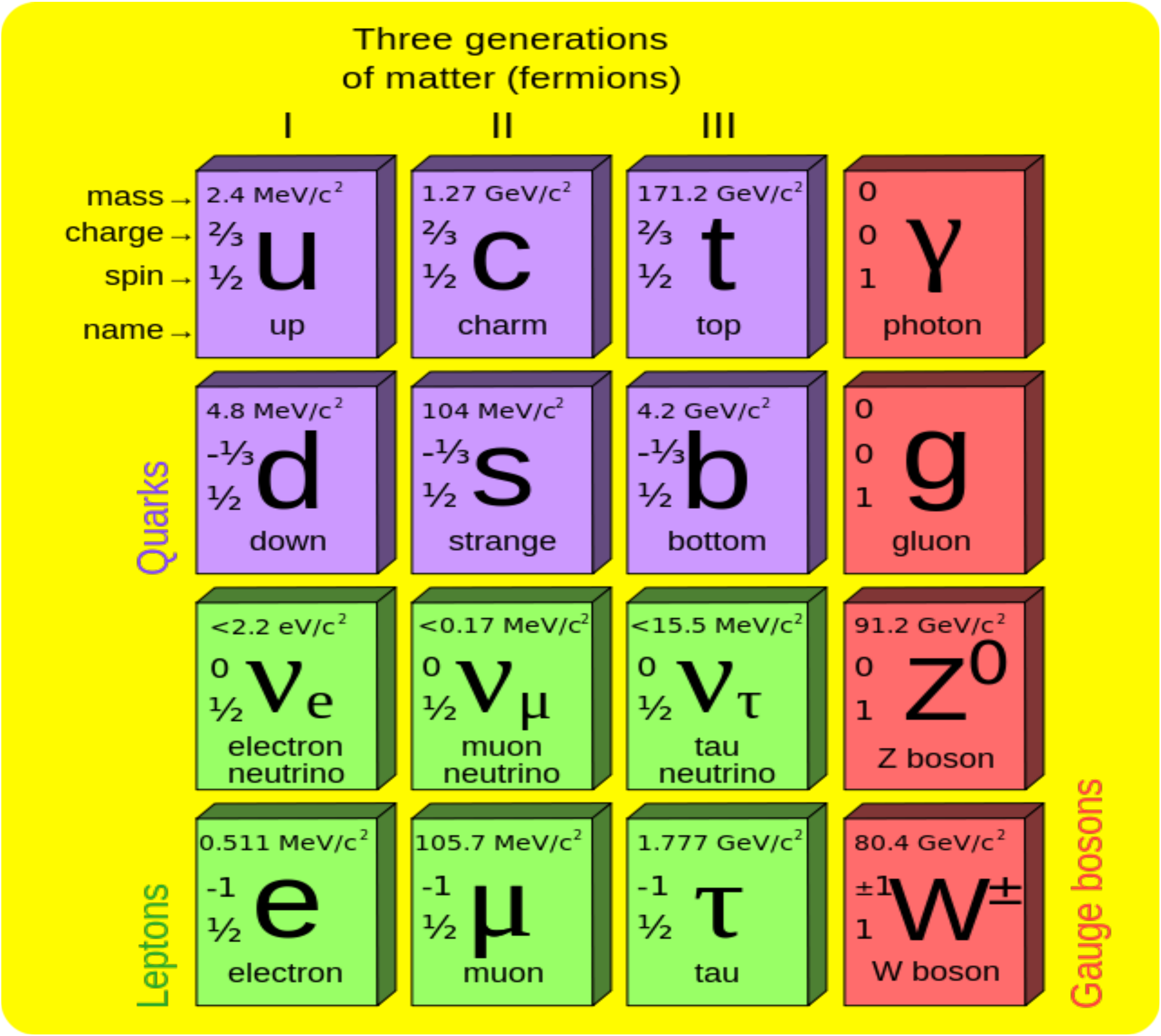








PERIODIC TABLE OF PARTICLE PHYSICS



FORCES AND MEDIATORS

Developing QFTs that describe the interactions between these elementary particles

THE STANDARD MODEL

Quantum ElectroDynamics (QED)

The Nobel Prize in Physics 1965
Sin-Itiro Tomonaga, Julian Schwinger, Richard P. Feynman

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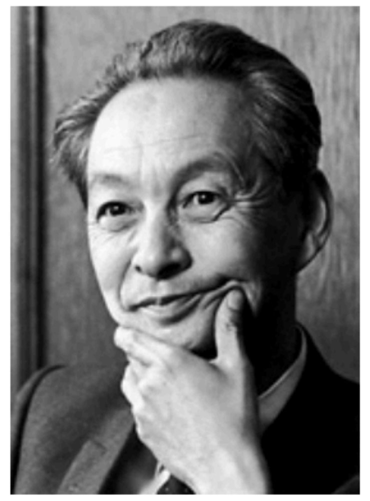
The Nobel Prize in Physics 1965



Sin-Itiro Tomonaga
Prize share: 1/3

Julian Schwinger
Prize share: 1/3

Richard P. Feynman
Prize share: 1/3

The Nobel Prize in Physics 1965 was awarded jointly to Sin-Itiro Tomonaga, Julian Schwinger and Richard P. Feynman *"for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles"*.

Electroweak Unification (GSW)

The Nobel Prize in Physics 1979
Sheldon Glashow, Abdus Salam, Steven Weinberg

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The Nobel Prize in Physics 1979

Sheldon Lee Glashow
Prize share: 1/3

Abdus Salam
Prize share: 1/3

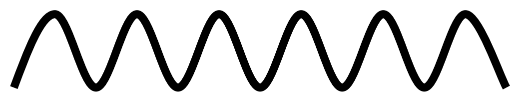
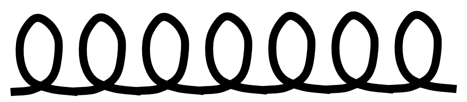
Steven Weinberg
Prize share: 1/3

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg *"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"*.

Strong interactions

?

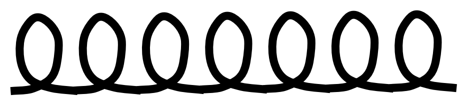
SYMMETRIES AND GAUGE TRANSFORMATIONS

	Conserved quantities	Gauge transformation	Symmetry group	Field
QED	(Hyper)charge: Q	$\Psi \rightarrow \Psi' = e^{ig\Lambda}\Psi$	U(1)	A_μ (1 photon) 
Weak	Weak isospin $\Psi = \begin{pmatrix} e \\ \nu_e \end{pmatrix}$ $\Psi = \begin{pmatrix} u \\ d \end{pmatrix}$	$\Psi \rightarrow \Psi' = e^{\frac{ig\tau^j\Lambda^j}{2}}\Psi$	SU(2)	A_μ (3 bosons, $W^\pm$, Z^0) 
QCD	Colour $\Psi = \begin{pmatrix} \Psi_R \\ \Psi_B \\ \Psi_G \end{pmatrix}$	$\Psi \rightarrow \Psi' = e^{\frac{ig\lambda^\alpha\Lambda^\alpha}{2}}\Psi$	SU(3)	A_μ (8 gluons, g) 

Nikhef

FOCUS ON STRONG INTERACTIONS

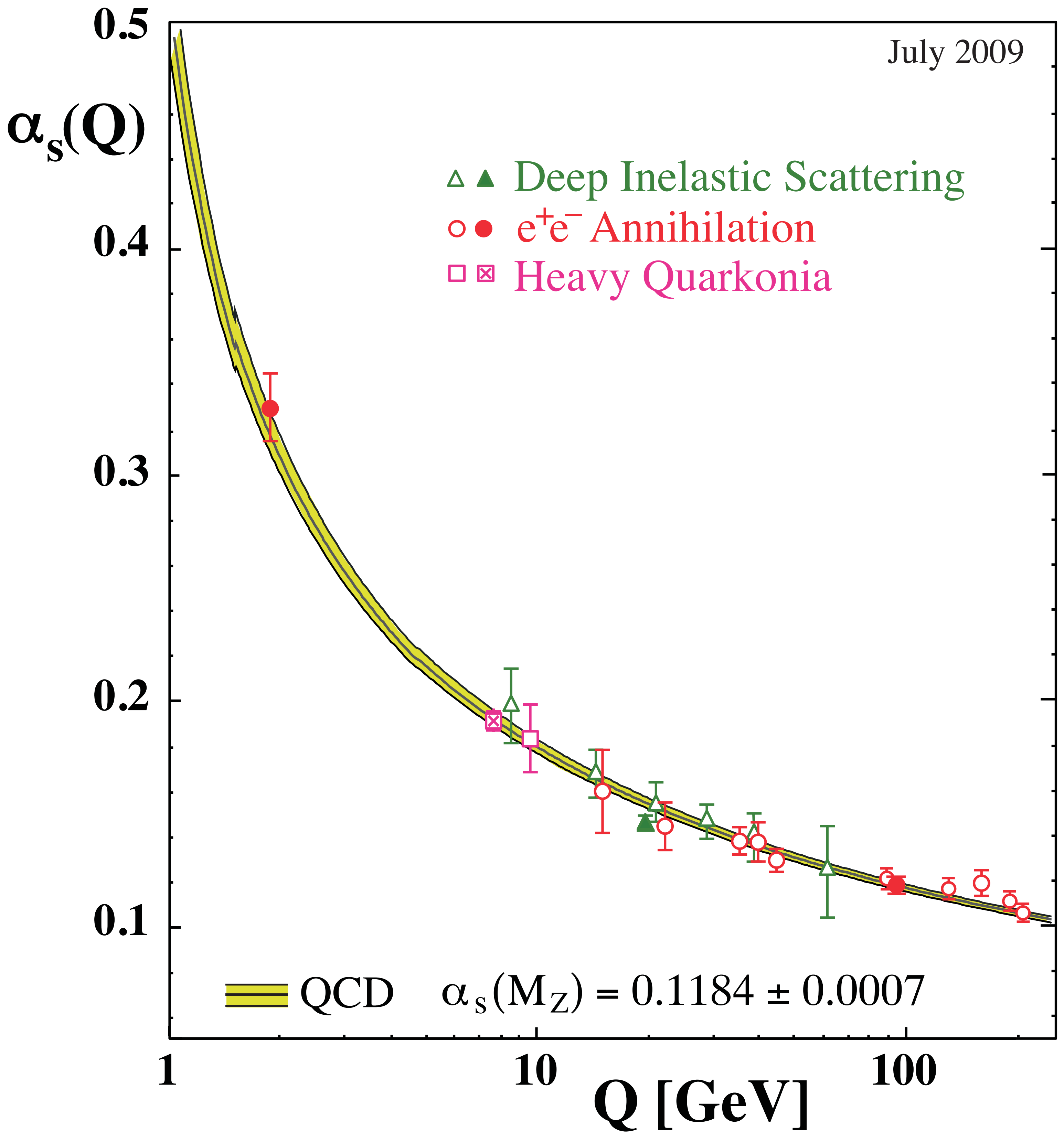
	Conserved quantities	Gauge transformation	Symmetry group	Field
QCD	Colour $\Psi = \begin{pmatrix} \Psi_R \\ \Psi_B \\ \Psi_G \end{pmatrix}$	$\Psi \to \Psi' = e^{\frac{ig\lambda^\alpha \Lambda^\alpha}{2}} \Psi$	SU(3)	A_μ (8 gluons, g)



ASYMPTOTIC FREEDOM

The coupling constant is denoted by α_S and as in the case of QED is not a constant

- In contrast to QED though, we will see that the strong coupling constant changes quite rapidly as a function of the distance between the interacting particles
  - At short distances a_S becomes quite small, allowing the quarks e.g. within a proton to move freely without interacting much with their neighbouring quarks.
    - This phenomenon is called asymptotic freedom
    - Its existence was postulated in 1973 by Frank Wilczek, David Gross, and independently by David Politzer the same year. All three shared the Nobel Prize in physics in 2004



THE BIRTH OF QCD

The Nobel Prize in Physics 2004
David J. Gross, H. David Politzer, Frank Wilczek

The Nobel Prize in Physics 2004


David J. Gross


H. David Politzer


Frank Wilczek

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek *"for the discovery of asymptotic freedom in the theory of the strong interaction"*.

VOLUME 30, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 1973

[14] Y. Nambu and G. Jona-Lasino, Phys. Rev. 122, 345 (1961); S. Coleman and E. Weinberg, Phys. Rev. D 7, 1888 (1973).
[15] K. Symanzik (to be published) has recently suggested that one consider a $\lambda\varphi^4$ theory with a negative λ to achieve UV stability at $\lambda = 0$. However, one can show, using the renormalization-group equations, that in such theory the ground-state energy is unbounded from below (S. Coleman, private communication).
[16] W. A. Bardeen, H. Fritzsch, and M. Gell-Mann, CERN Report No. CERN-TH-1538, 1972 (to be published).
[17] H. Georgi and S. L. Glashow, Phys. Rev. Lett. 28, 1494 (1972); S. Weinberg, Phys. Rev. D 5, 1962 (1972).
[18] For a review of this program, see S. L. Adler, in Proceedings of the Sixteenth International Conference on High Energy Physics, National Accelerator Laboratory, Batavia, Illinois, 1972 (to be published).

Reliable Perturbative Results for Strong Interactions?*

H. David Politzer
Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138
(Received 3 May 1973)

An explicit calculation shows perturbation theory to be arbitrarily good for the deep Euclidean Green's functions of any Yang-Mills theory and of many Yang-Mills theories with fermions. Under the hypothesis that spontaneous symmetry breakdown is of dynamical origin, these symmetric Green's functions are the asymptotic forms of the physically significant spontaneously broken solution, whose coupling could be strong.

VOLUME 30, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 1973

Ultraviolet Behavior of Non-Abelian Gauge Theories*

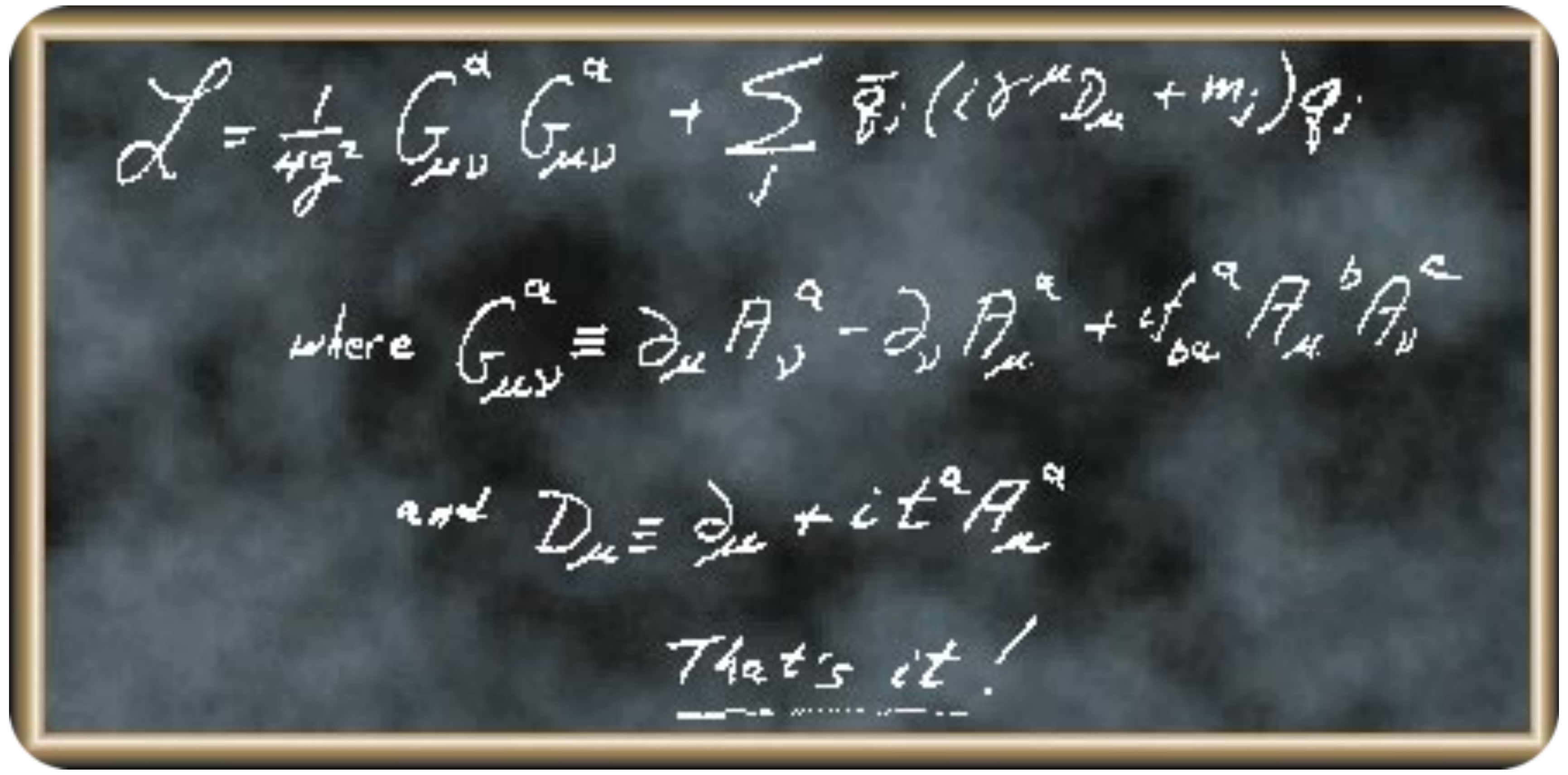
David J. Gross† and Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 27 April 1973)

It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field–theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.

Non-Abelian gauge theories have received much attention recently as a means of constructing unified and renormalizable theories of the weak and electromagnetic interactions.[1] In this note we report on an investigation of the ultraviolet (UV) asymptotic behavior of such theories. We have found that they possess the remarkable feature, perhaps unique among renormalizable theories, of asymptotically approaching free-field theory. Such asymptotically free theories will exhibit, for matrix elements of currents between on-mass-shell states, Bjorken scaling. We therefore suggest that one should look to a non-Abelian gauge theory of the strong interactions to provide the explanation for Bjorken scaling, which has so far eluded field-theoretic understanding.

The UV behavior of renormalizable field theories can be discussed using the renormalization-group equations,[2,3] which for a theory involving one field (say $g\varphi^4$) are

$$[m\partial/\partial m + \beta(g)\partial/\partial g - n\gamma(g)]\Gamma_{\text{asy}}^{(n)}(g; P_1, \ldots, P_n) = 0. \quad (1)$$



THE STANDARD MODEL

Quantum ElectroDynamics (QED)

The Nobel Prize in Physics 1965
Sin-Itiro Tomonaga, Julian Schwinger, Richard P. Feynman

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The Nobel Prize in Physics 1965

Sin-Itiro Tomonaga
Prize share: 1/3

Julian Schwinger
Prize share: 1/3

Richard P. Feynman
Prize share: 1/3

The Nobel Prize in Physics 1965 was awarded jointly to Sin-Itiro Tomonaga, Julian Schwinger and Richard P. Feynman *"for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles"*.

Electroweak Unification (GSW)

The Nobel Prize in Physics 1979
Sheldon Glashow, Abdus Salam, Steven Weinberg

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The Nobel Prize in Physics 1979

Sheldon Lee Glashow
Prize share: 1/3

Abdus Salam
Prize share: 1/3

Steven Weinberg
Prize share: 1/3

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg *"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"*.

Quantum ChromoDynamics (QCD)

The Nobel Prize in Physics 2004
David J. Gross, H. David Politzer, Frank Wilczek

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The Nobel Prize in Physics 2004

David J. Gross
Prize share: 1/3

H. David Politzer
Prize share: 1/3

Frank Wilczek
Prize share: 1/3

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek *"for the discovery of asymptotic freedom in the theory of the strong interaction"*.

…AND ITS MISSING PIECE

The Higgs mechanism

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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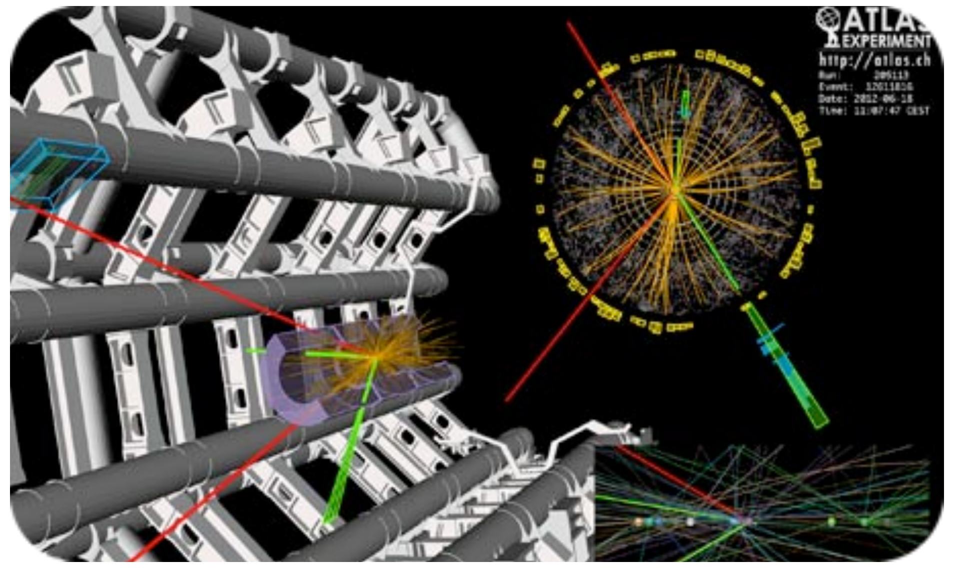
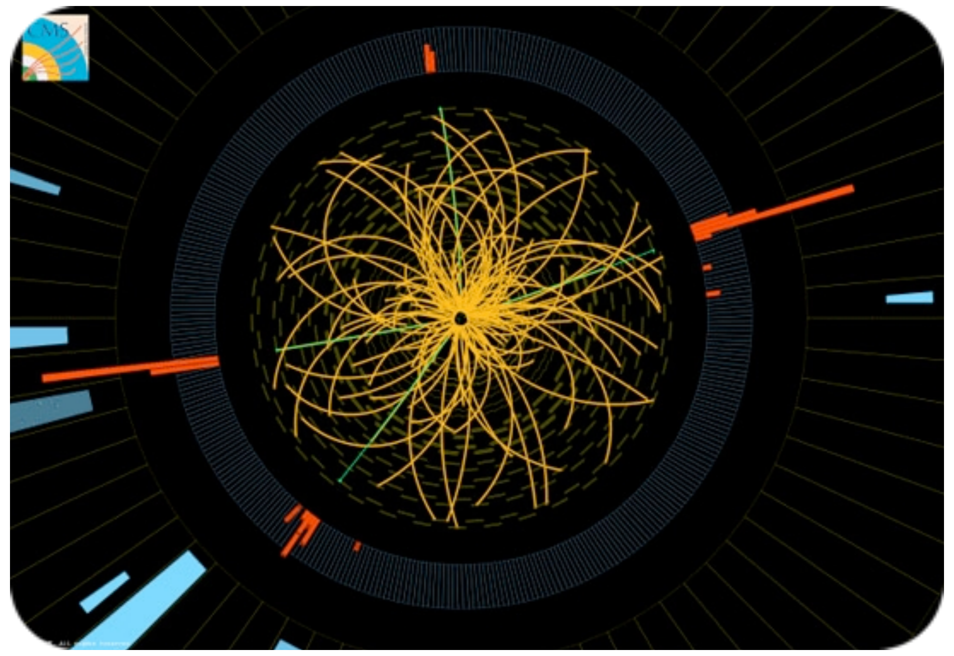
The Nobel Prize in Physics 2013

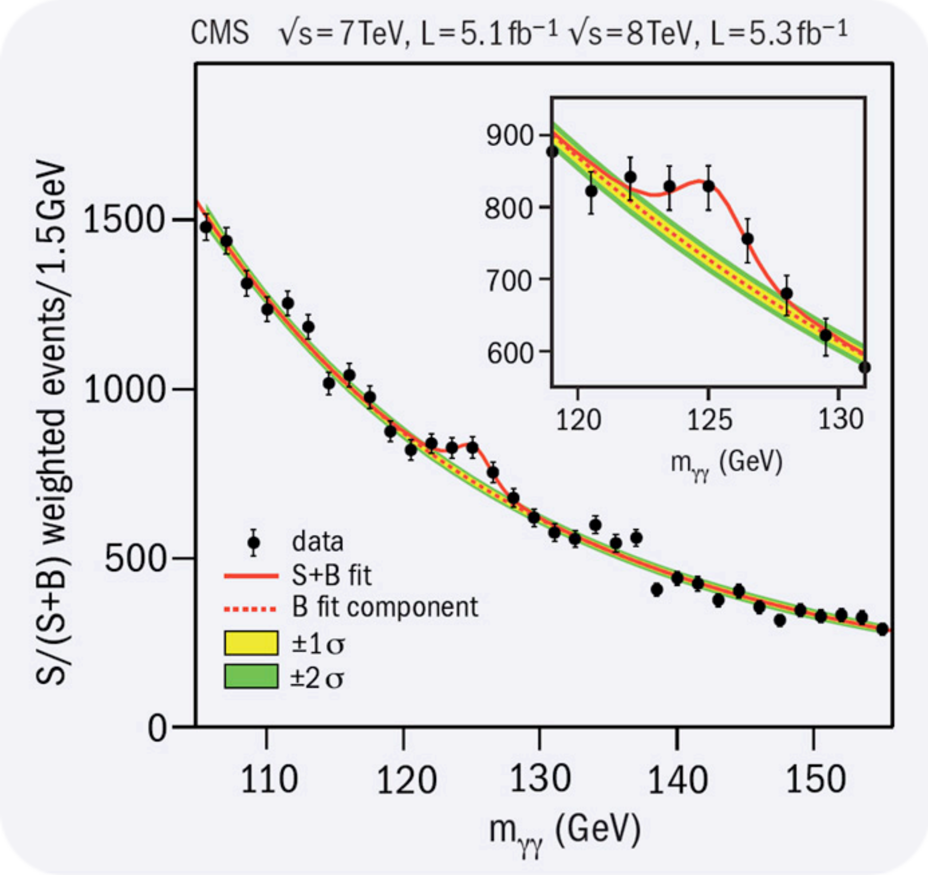
Photo: A. Mahmoud
François Englert
Prize share: 1/2

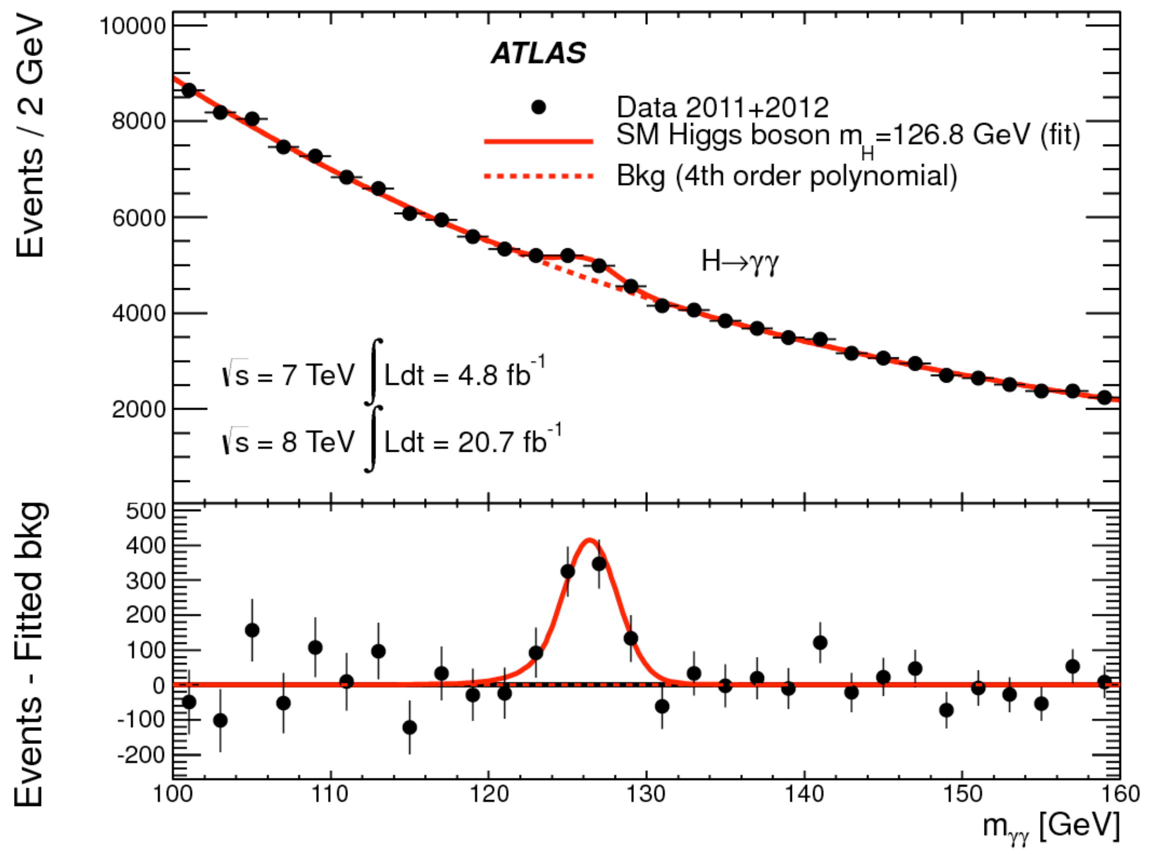
Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

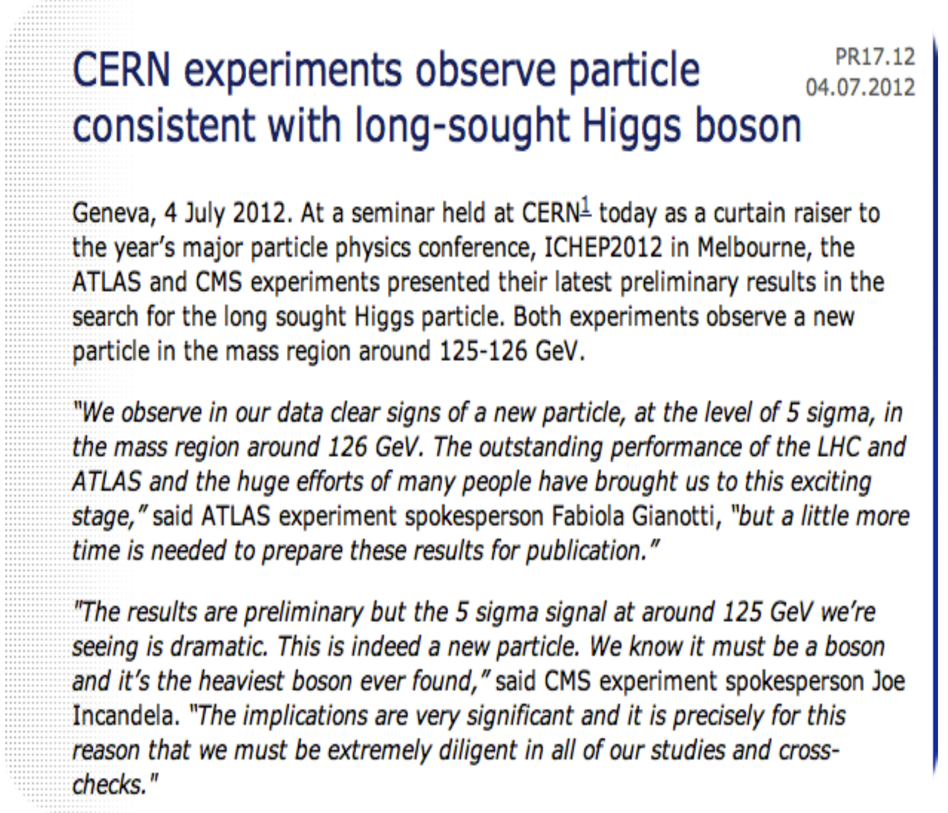
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*











CERN experiments observe particle consistent with long-sought Higgs boson

PR17.12
04.07.2012

Geneva, 4 July 2012. At a seminar held at CERN[1] today as a curtain raiser to the year's major particle physics conference, ICHEP2012 in Melbourne, the ATLAS and CMS experiments presented their latest preliminary results in the search for the long sought Higgs particle. Both experiments observe a new particle in the mass region around 125-126 GeV.

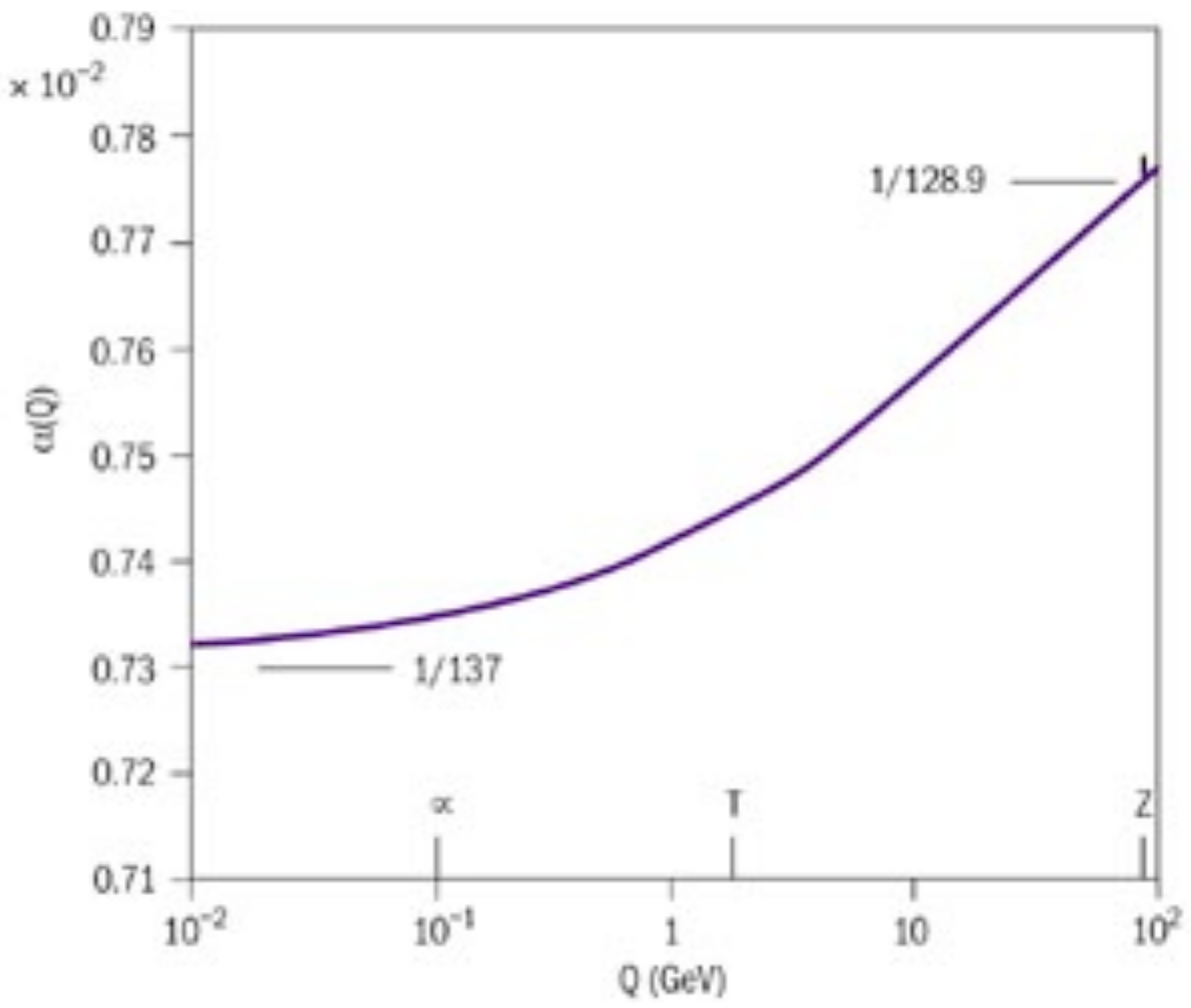
"We observe in our data clear signs of a new particle, at the level of 5 sigma, in the mass region around 126 GeV. The outstanding performance of the LHC and ATLAS and the huge efforts of many people have brought us to this exciting stage," said ATLAS experiment spokesperson Fabiola Gianotti, "but a little more time is needed to prepare these results for publication."

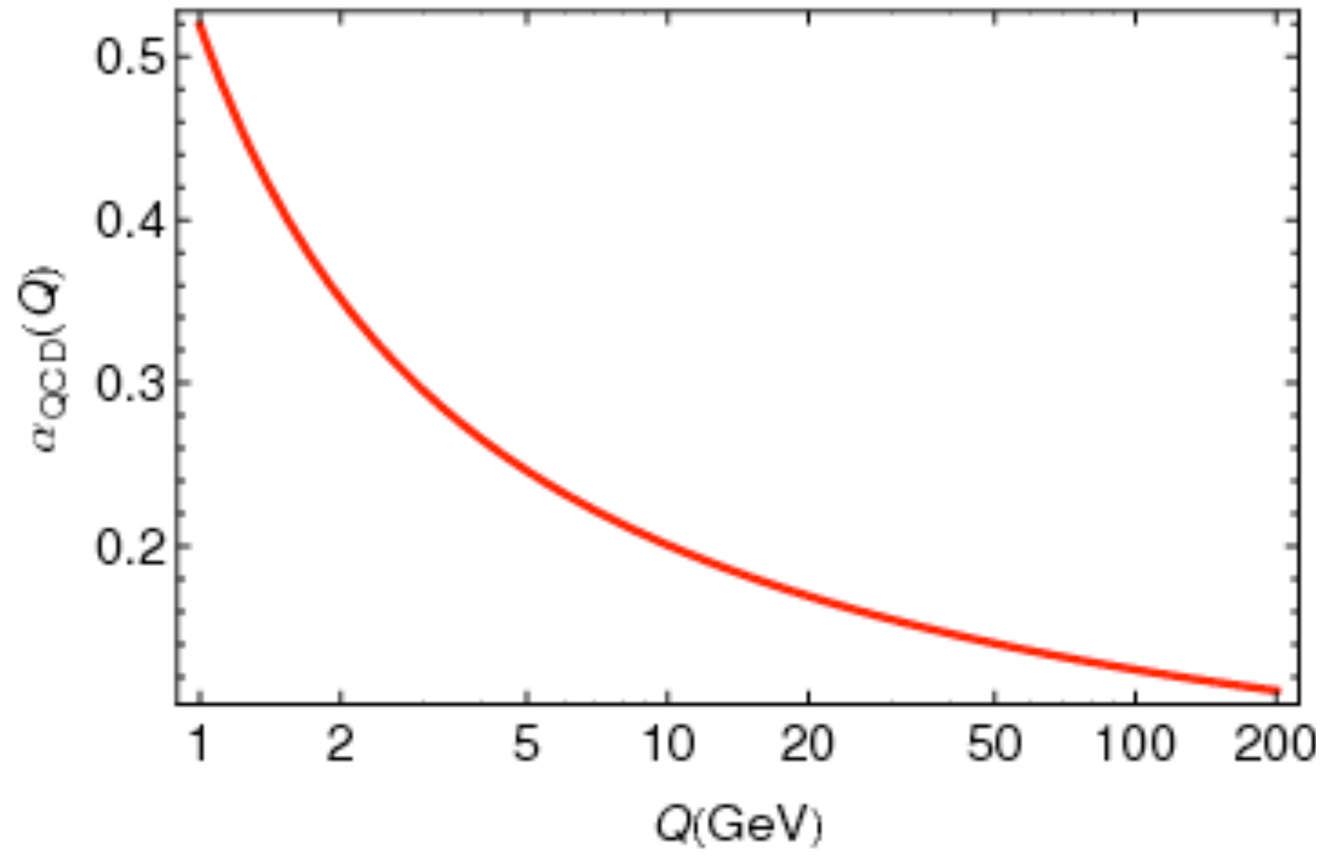
"The results are preliminary but the 5 sigma signal at around 125 GeV we're seeing is dramatic. This is indeed a new particle. We know it must be a boson and it's the heaviest boson ever found," said CMS experiment spokesperson Joe Incandela. "The implications are very significant and it is precisely for this reason that we must be extremely diligent in all of our studies and cross-checks."

QCD VS QED

Similar formulation between QED and QCD but with fundamental differences

- in QED there is one charge (i.e. electric charge) in QCD we have three (i.e. colour)
  - There are three kind of colours in QCD,: red (R), green (G) and blue (B).
  - Gluons have two colours, carrying one unit of color and one of anticolor.
  - There are 3x3 = 9 possibilities for the gluons but as we will see later there are only 8.
  - Since the gluons carry color, they can also couple directly to other gluons making the existence of gluon-gluon vertices possible.
- Another difference comes from the fact that particles decaying strongly have typical lifetimes of 10^{-23}sec
- Finally, the coupling strength…





QUANTUM CHROMODYNAMICS - QCD

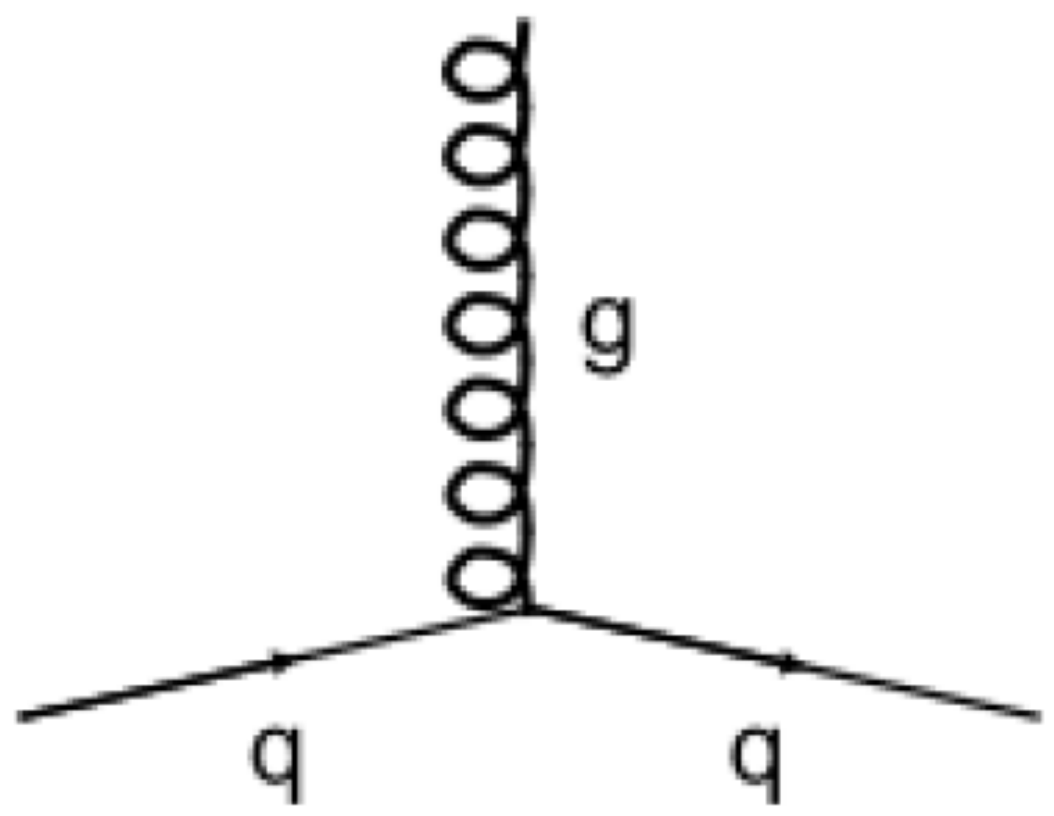


Fig. 1.14: The basic diagram that represents the most elementary process in QCD.

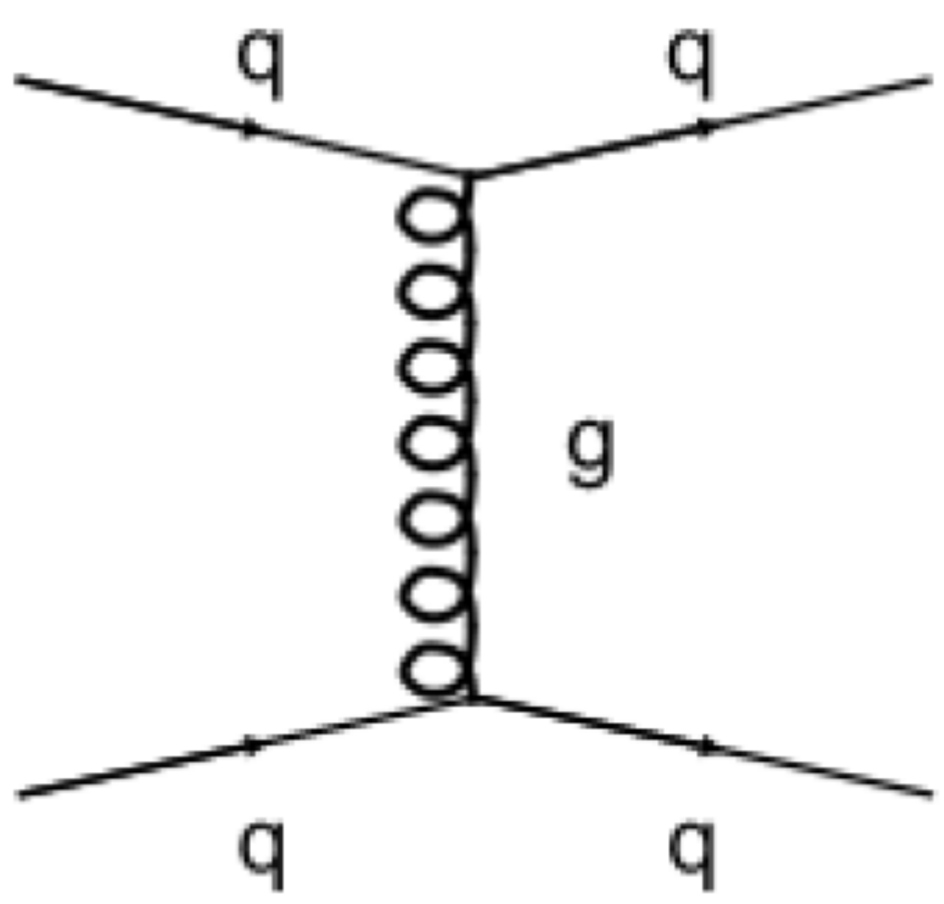


Fig. 1.15: The lower order diagram that describes the interaction between two quarks.

FEYNMAN RULES OF QCD

- **Labeling:** We label every external line with the ingoing and outgoing momenta $\mathbf{P_1}, \ldots, \mathbf{P_n}$, adding also an arrow indicating whether a particle is approaching or moving away from the vertex. If the diagram includes antiparticles, we still label them as particles but with the reverse direction of the arrow. We then label the 4-momenta for all internal lines $\mathbf{q_1}, \ldots, \mathbf{q_j}$ and we give an arbitrary direction to the relevant arrow.
- **External lines:** Each external line contribute the following factors:

$$\text{Incoming quark} \to u^s \cdot c$$
$$\text{Outgoing quark} \to \overline{u}^s \cdot c^\dagger$$

$$\text{Incoming anti-quark} \to \overline{v}^s \cdot c^\dagger$$
$$\text{Outgoing anti-quark} \to v \cdot c$$

$$\text{Incoming gluon} \to \varepsilon_\mu \cdot a^\alpha$$
$$\text{Outgoing gluon} \to \varepsilon_\mu^* \cdot a^{\alpha *}$$

where u and v are the relevant Dirac spinors. In the previous c are the matrices that represent the colour:

$$\begin{pmatrix}1\\0\\0\end{pmatrix} \text{ for R, } \begin{pmatrix}0\\1\\0\end{pmatrix} \text{ for G, } \begin{pmatrix}0\\0\\1\end{pmatrix} \text{ for B}$$

and a are the 8-element column matrices, one for each gluon state (i.e. α goes from 1 to 8):

$$|1\rangle \equiv \begin{pmatrix}1\\0\\0\\0\\0\\0\\0\\0\end{pmatrix}, |2\rangle \equiv \begin{pmatrix}0\\1\\0\\0\\0\\0\\0\\0\end{pmatrix}, |3\rangle \equiv \begin{pmatrix}0\\0\\1\\0\\0\\0\\0\\0\end{pmatrix}, |4\rangle \equiv \begin{pmatrix}0\\0\\0\\1\\0\\0\\0\\0\end{pmatrix}, |5\rangle \equiv \begin{pmatrix}0\\0\\0\\0\\1\\0\\0\\0\end{pmatrix}, |6\rangle \equiv \begin{pmatrix}0\\0\\0\\0\\0\\1\\0\\0\end{pmatrix}, |7\rangle \equiv \begin{pmatrix}0\\0\\0\\0\\0\\0\\1\\0\end{pmatrix}, |8\rangle \equiv \begin{pmatrix}0\\0\\0\\0\\0\\0\\0\\1\end{pmatrix}$$

- **Vertices:** For each vertex we note down in the diagram the coupling constant factor $\approx g_s$. This factor is connected to the coupling constant via the equation

$$g_s = \sqrt{4\pi\alpha_s}$$

For a quark-gluon vertex (see fig. 3.4) the factor is of the form:

$$\frac{-ig_s}{2}\lambda^\alpha \gamma^\mu$$

where the parameters λ^α are the Gell-Man λ-matrices of SU(3).

For a 3-gluon vertex (see fig. 3.4) the factor is of the form:

$$-g_s f^{\alpha\beta\gamma}\left[g_{\mu\nu}(\mathbf{k_1}-\mathbf{k_2})_\rho + g_{\nu\rho}(\mathbf{k_2}-\mathbf{k_3})_\mu + g_{\rho\mu}(\mathbf{k_3}-\mathbf{k_1})_\nu\right]$$

,

where the factors $f^{\alpha\beta\gamma}$ are the structure constants of SU(3) and $\mathbf{k}_i$ are the 4-momenta of each internal line (with $i = 1,2,3$).

Finally, for a 4-gluon vertex (see fig. 3.4) the factor is of the form:

$$-ig_s^2\left[f^{\alpha\beta\eta}f^{\gamma\delta\eta}(g_{\mu\sigma}g_{\nu\rho}-g_{\mu\rho}g_{\nu\sigma}) + f^{\alpha\delta\eta}f^{\beta\gamma\eta}(g_{\mu\nu}g_{\sigma\rho}-g_{\mu\sigma}g_{\nu\rho}) + f^{\alpha\gamma\eta}f^{\delta\beta\eta}(g_{\mu\rho}g_{\nu\sigma}-g_{\mu\nu}g_{\sigma\rho})\right]$$

- **Propagators:** For each internal line, we give a factor of

$$q-\overline{q}: \frac{i(\not{q}+m)}{\mathbf{q}^2-m^2}$$

$$\text{gluon}: -ig_{\mu\nu}\delta^{\alpha\beta}$$

where $\not{q} \equiv \gamma_\nu q^\nu$.

- **δ-functions and integration:** The remaining steps are identical as in the general rules described before.

Figure 3.4 presents the lines for the basic particles and anti-particles but also the propagators for the strong interactions.

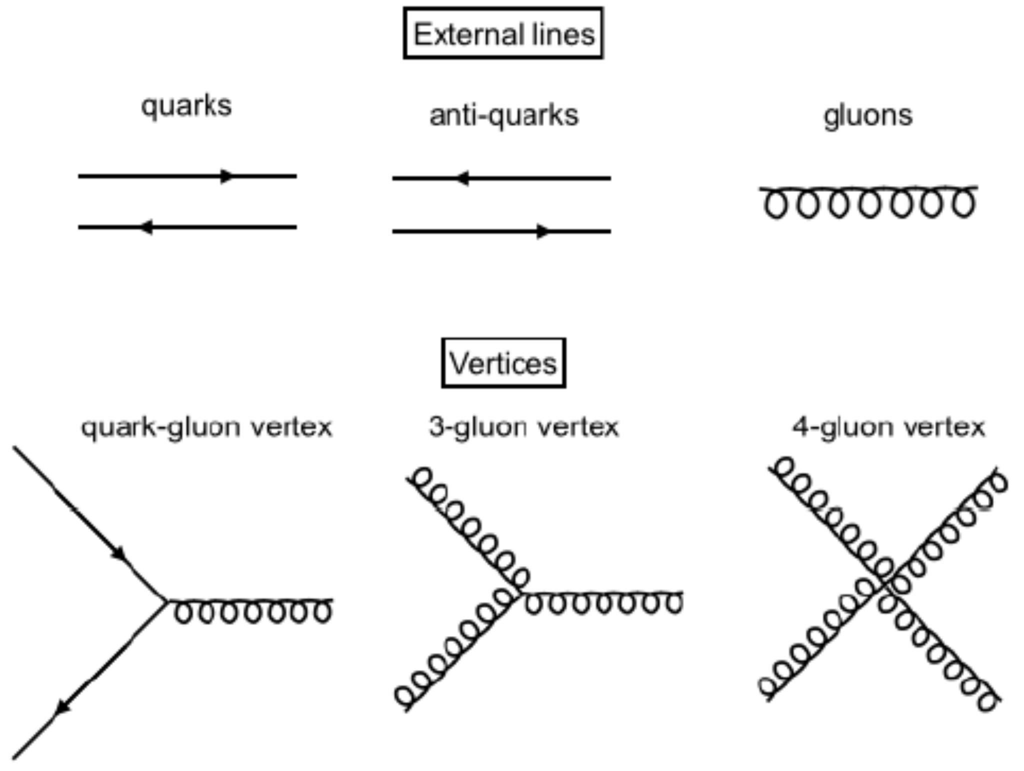


Fig. 3.4: The most characteristic lines for the Feynman diagrams in strong interactions.

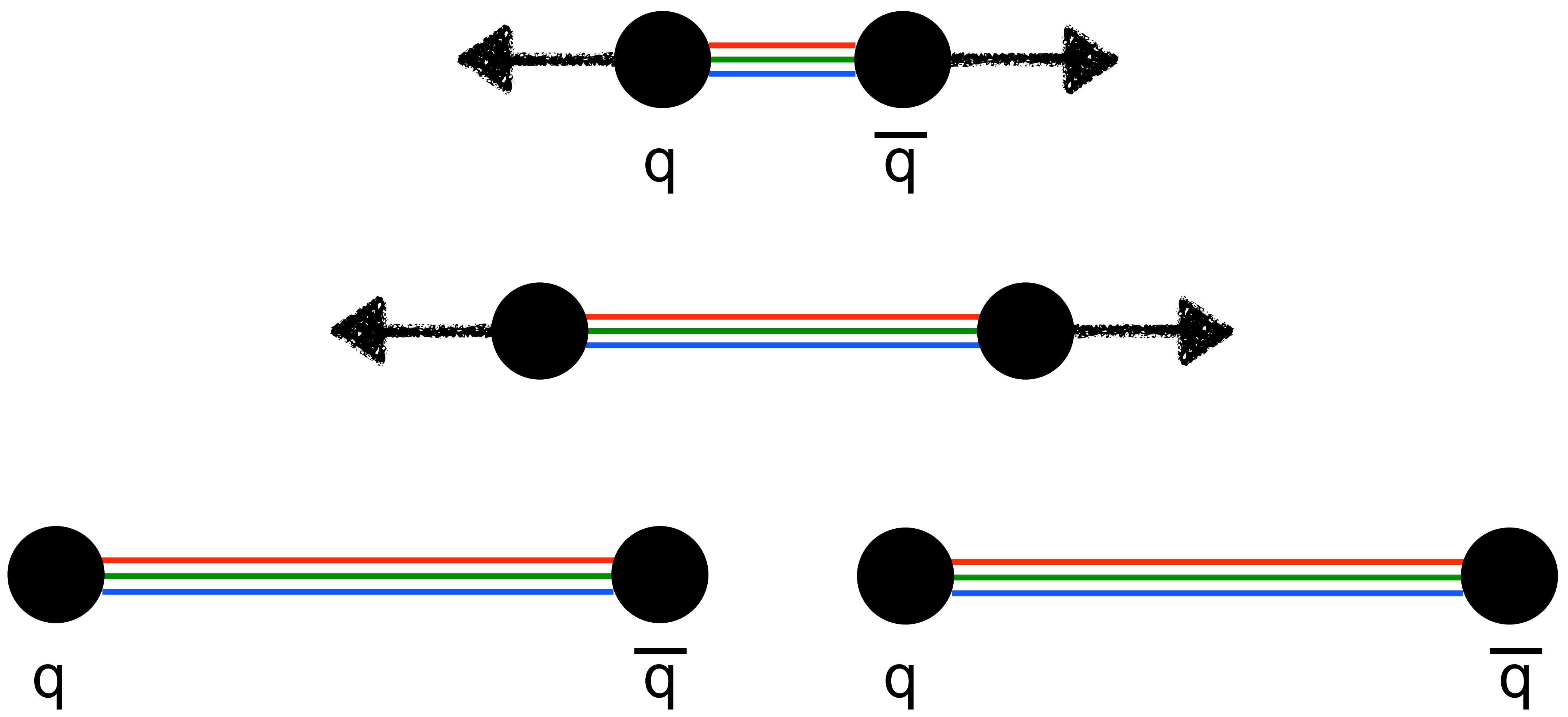
CONFINEMENT

For small values of momentum transfer, large spatial range, the strong interactions are exceptionally strong

- Quarks are bound together within hadrons

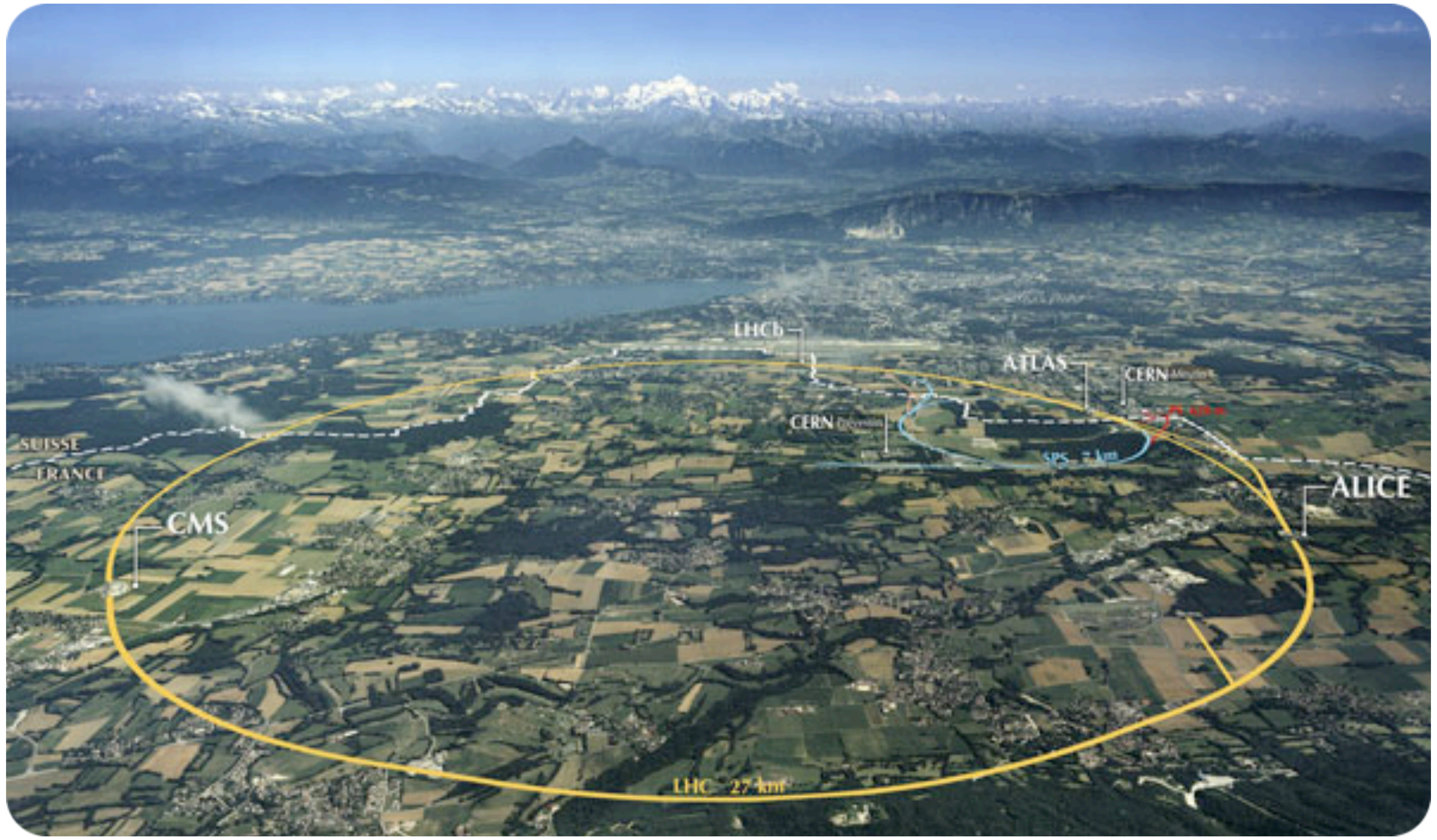
Breaking the colour string between a quark-antiquark pair is not easy

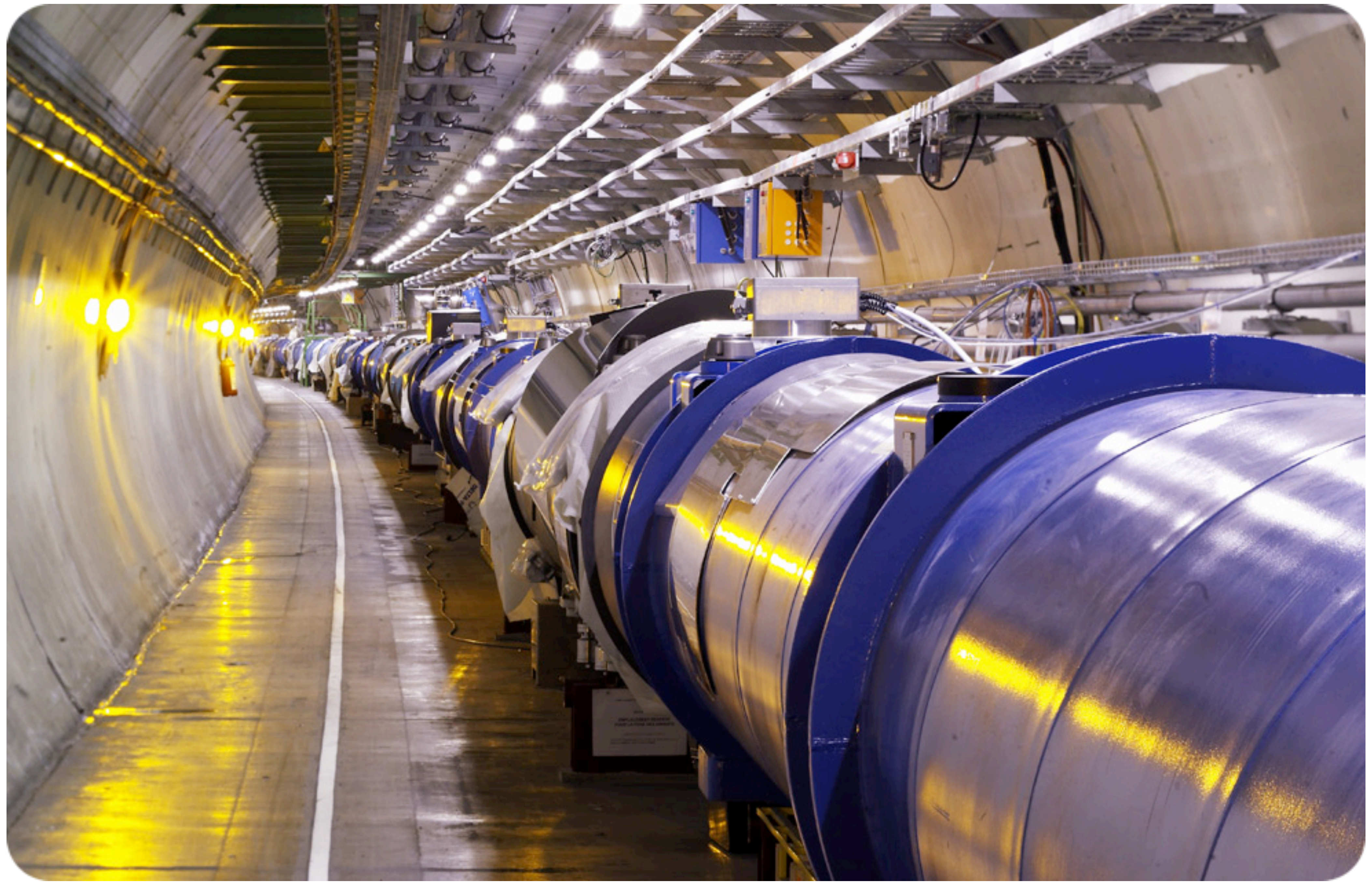
- At some point, it is energetically more favourable to create a new pair of quarks and antiquarks
  - Quarks and gluons can not move freely



PARTICLE ACCELERATORS

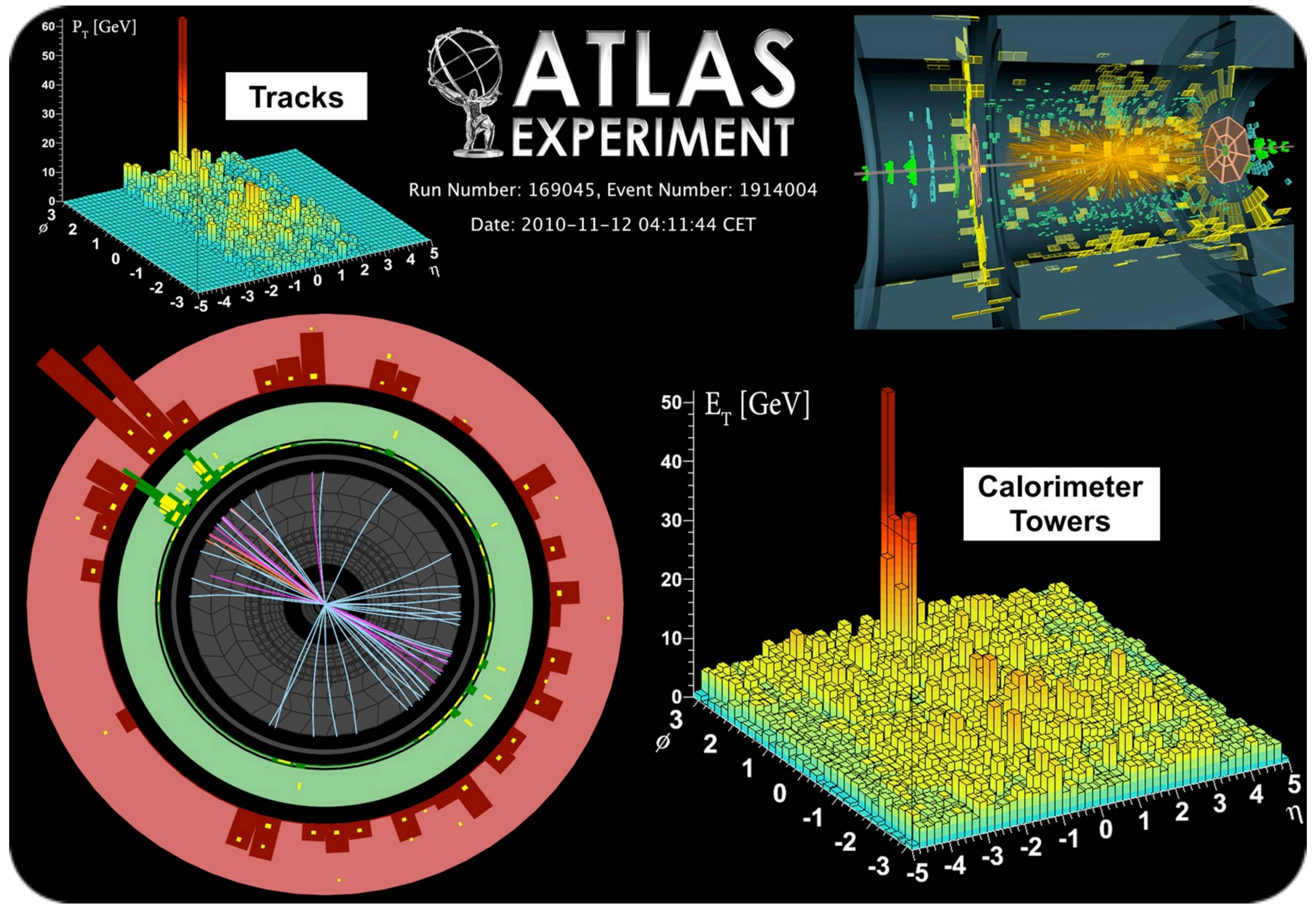
Studying QCD in the laboratory

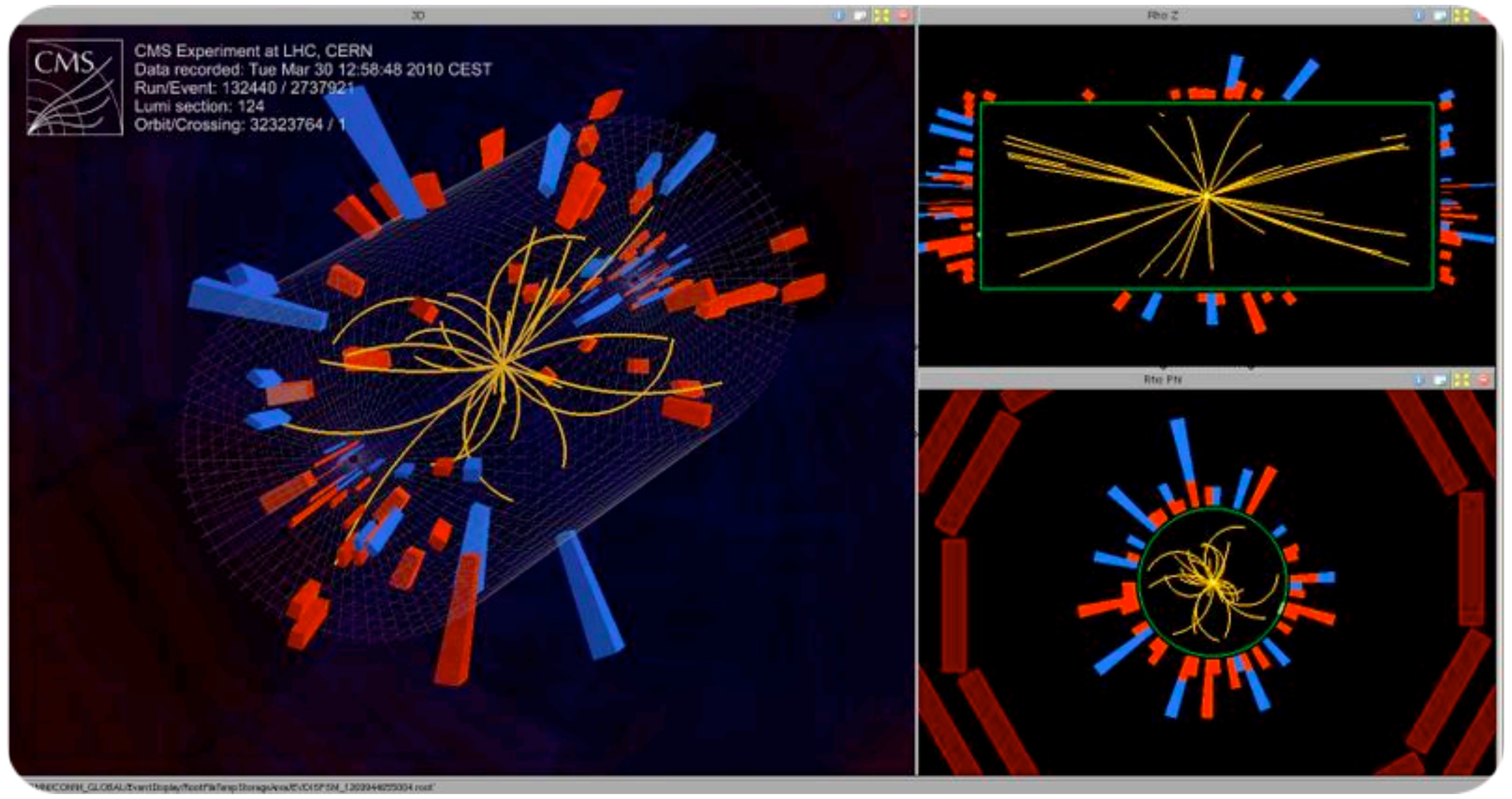


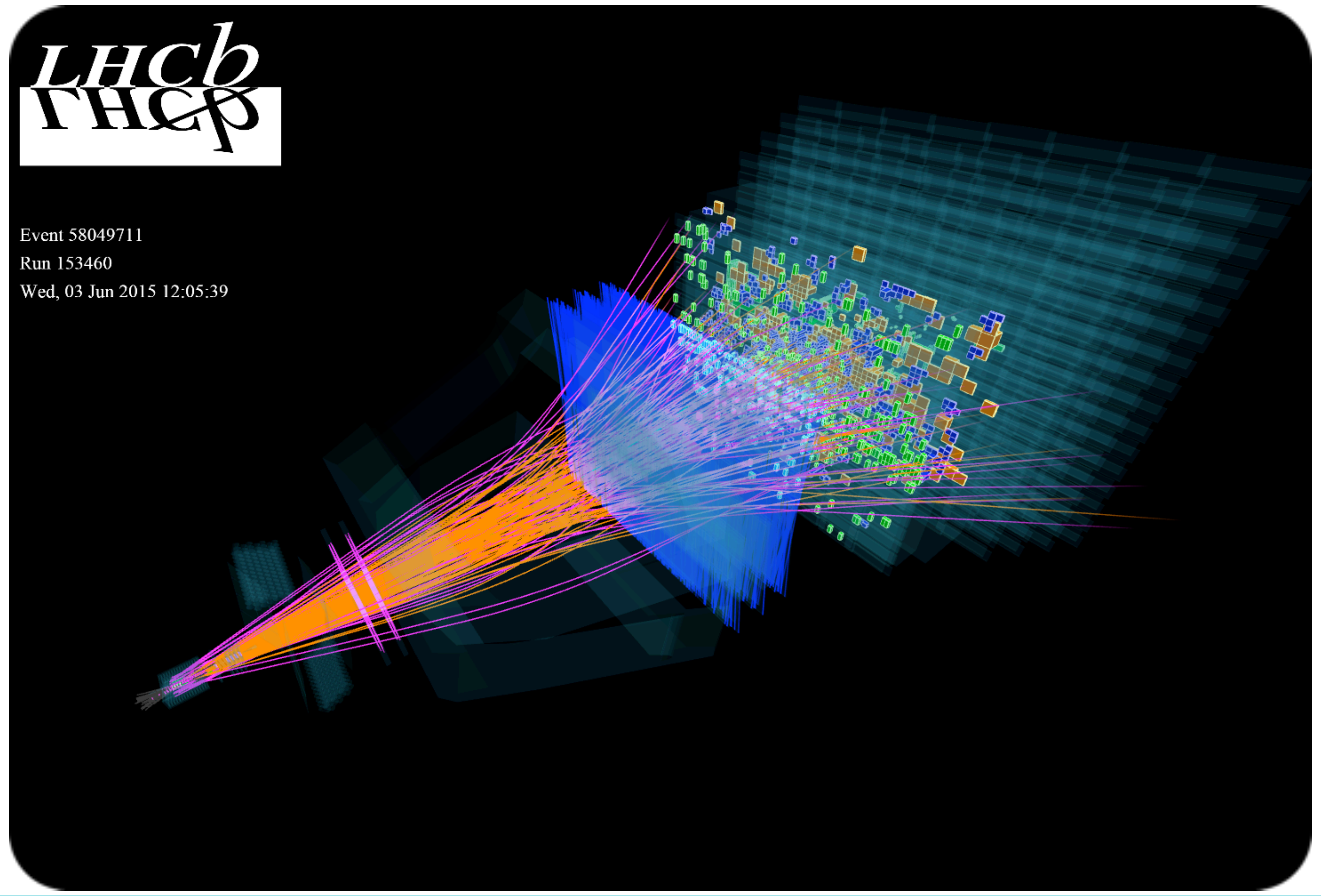


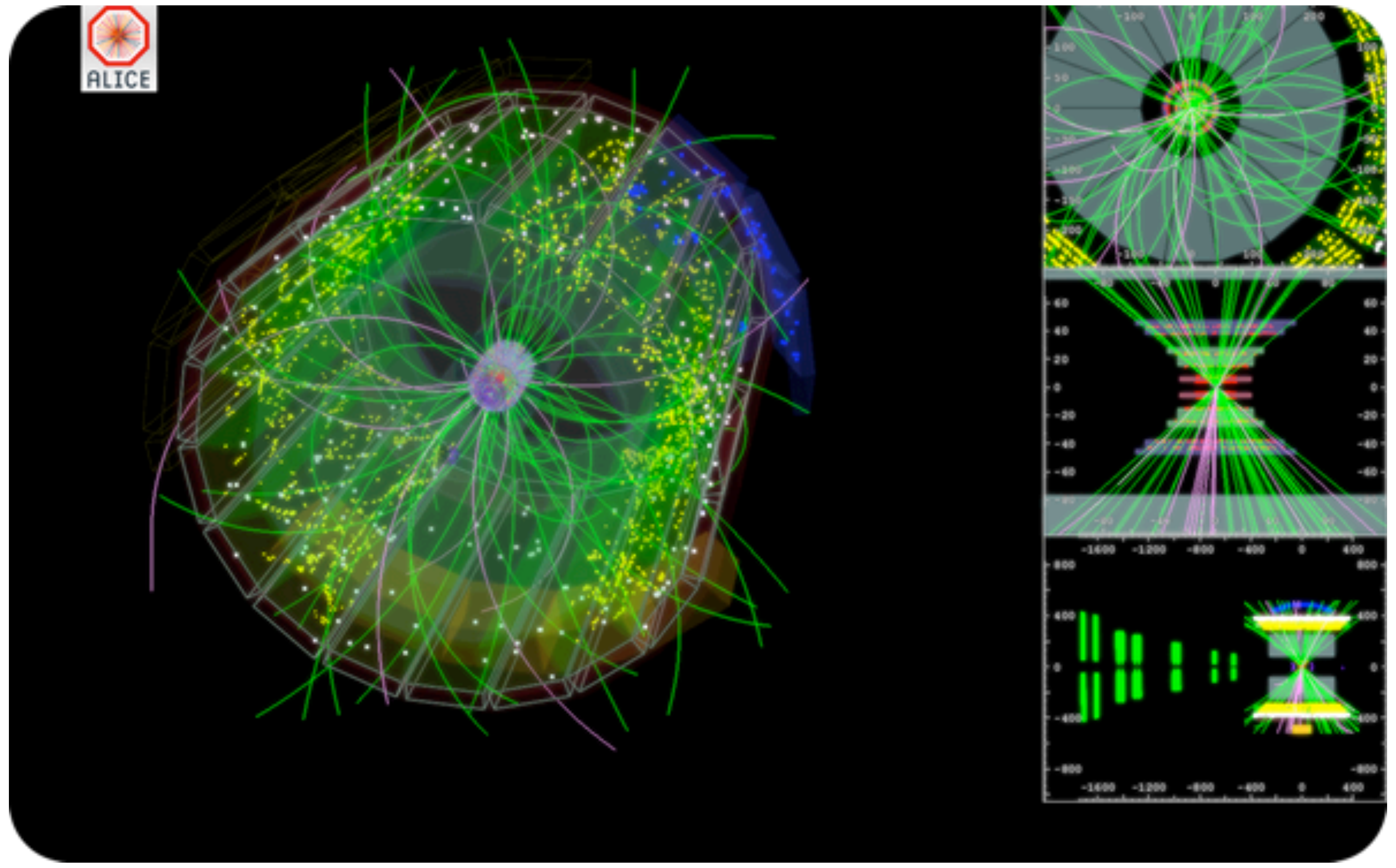
PARTICLE DETECTORS

pp collisions ➡ small number of particles

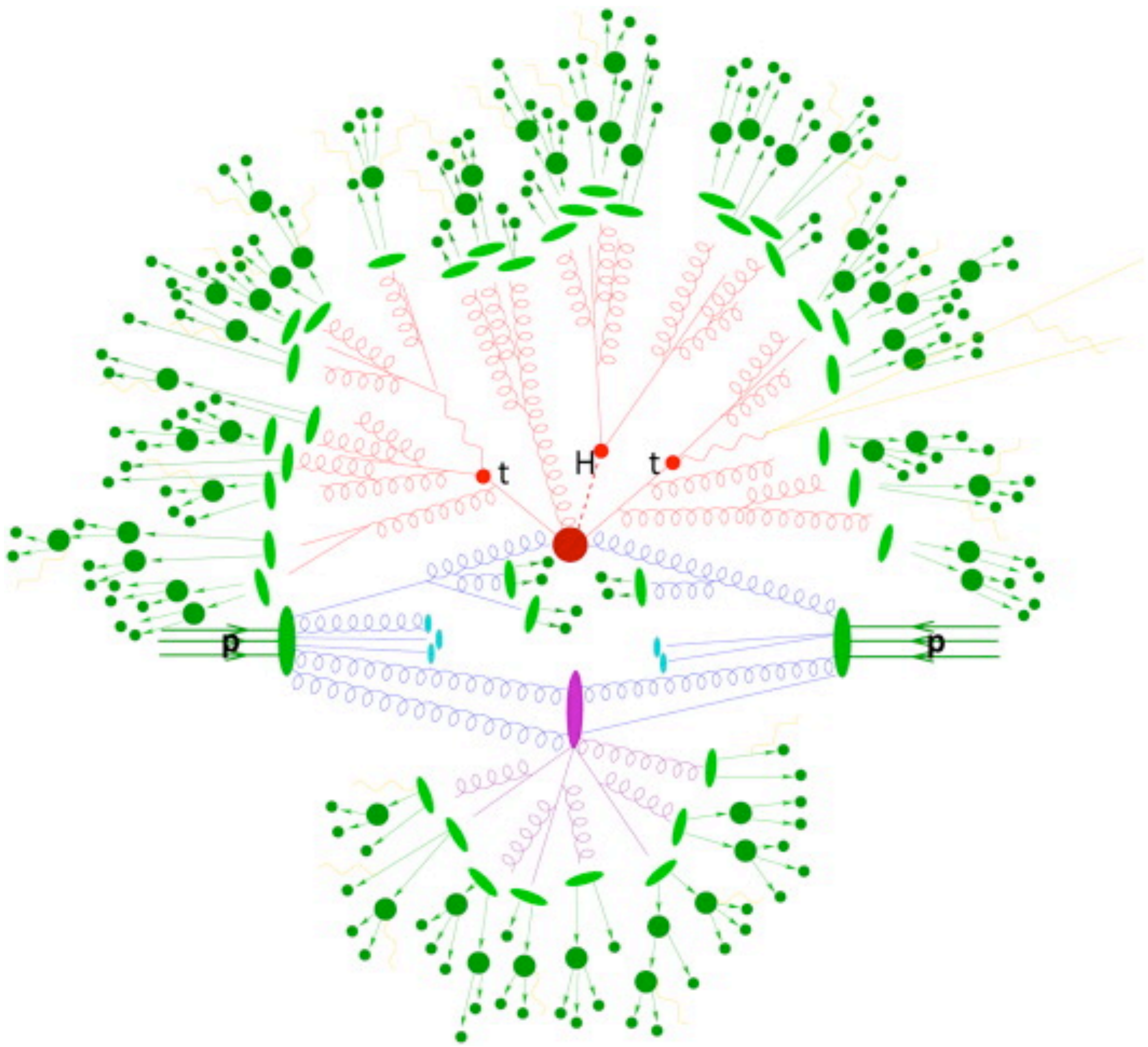


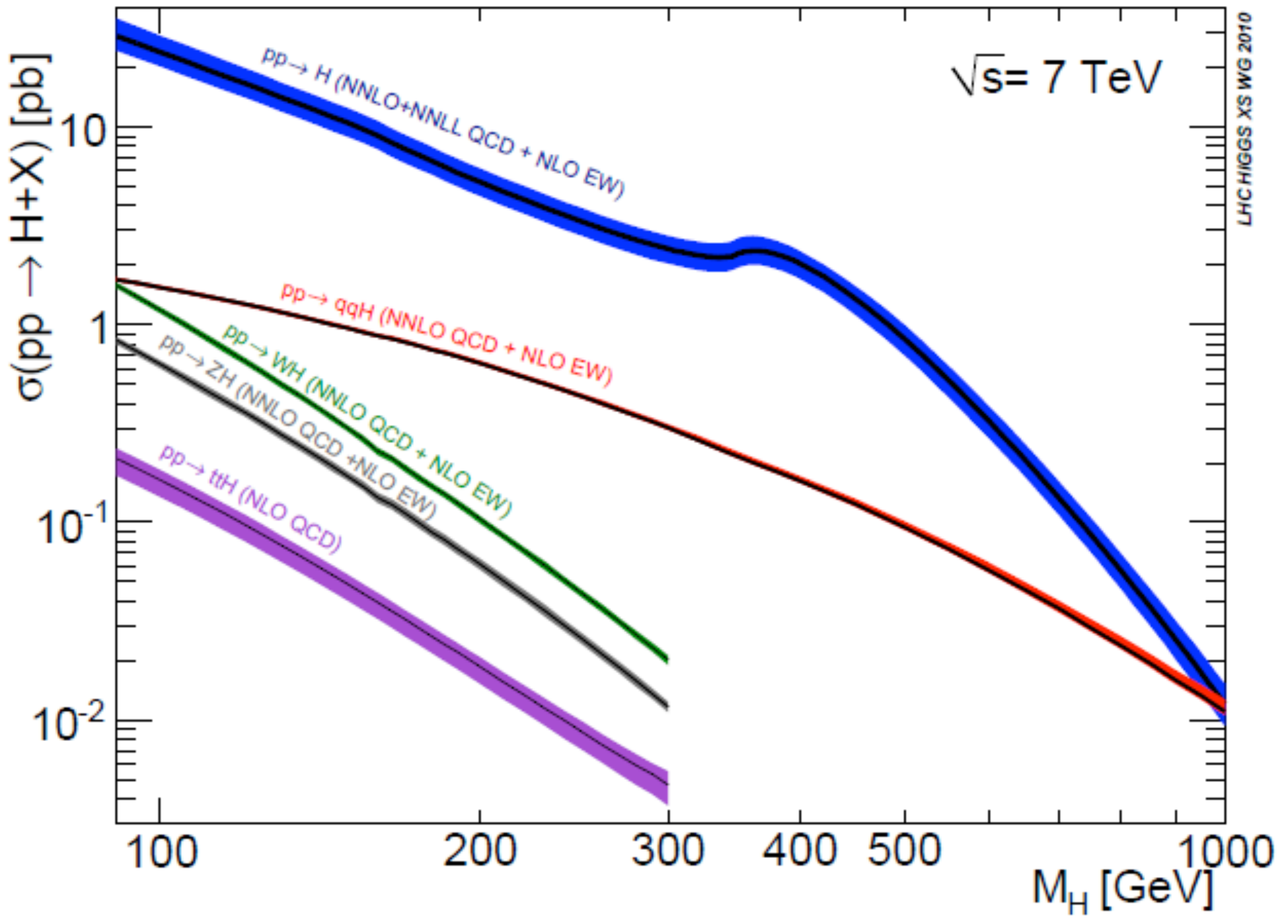


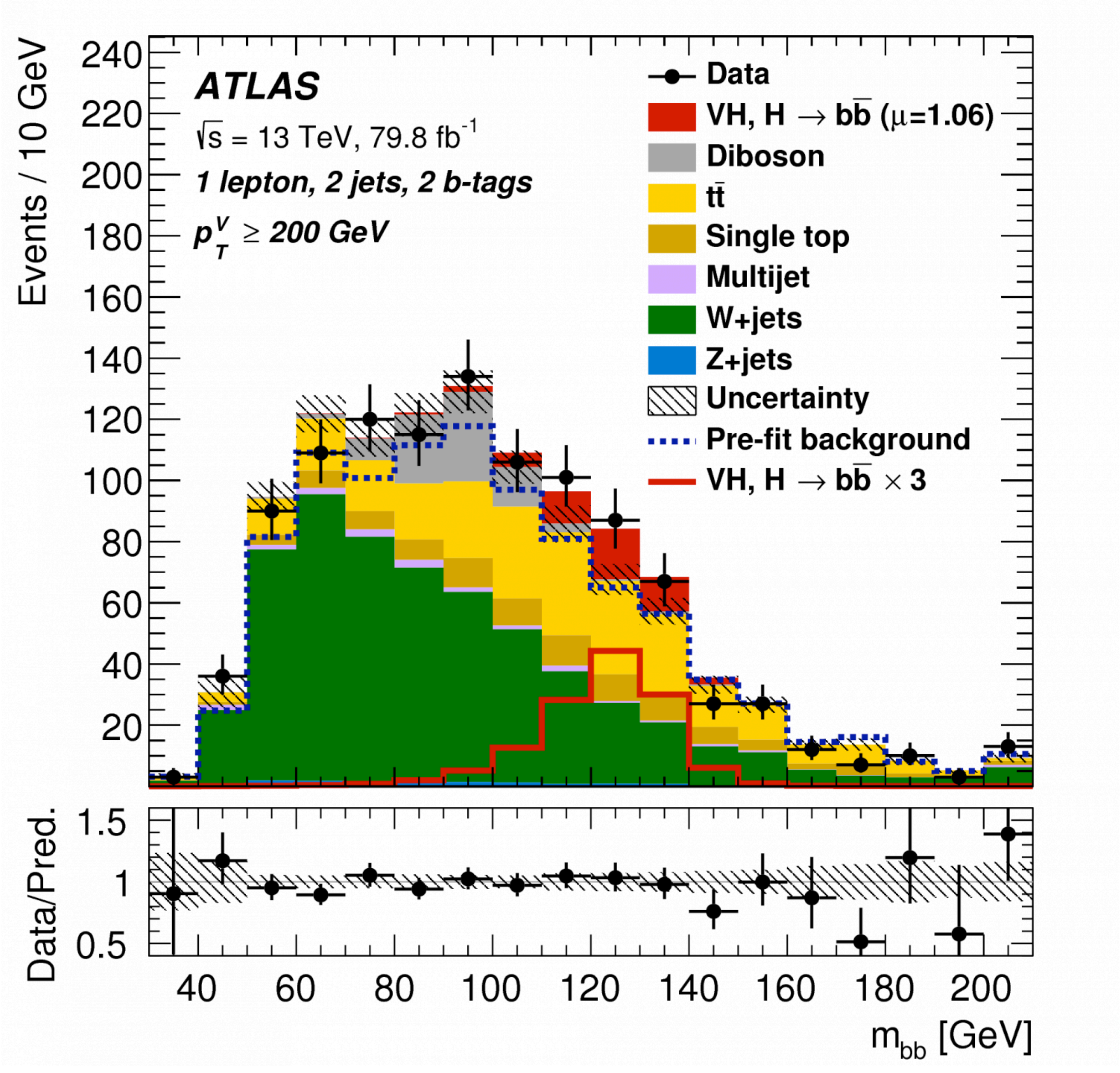


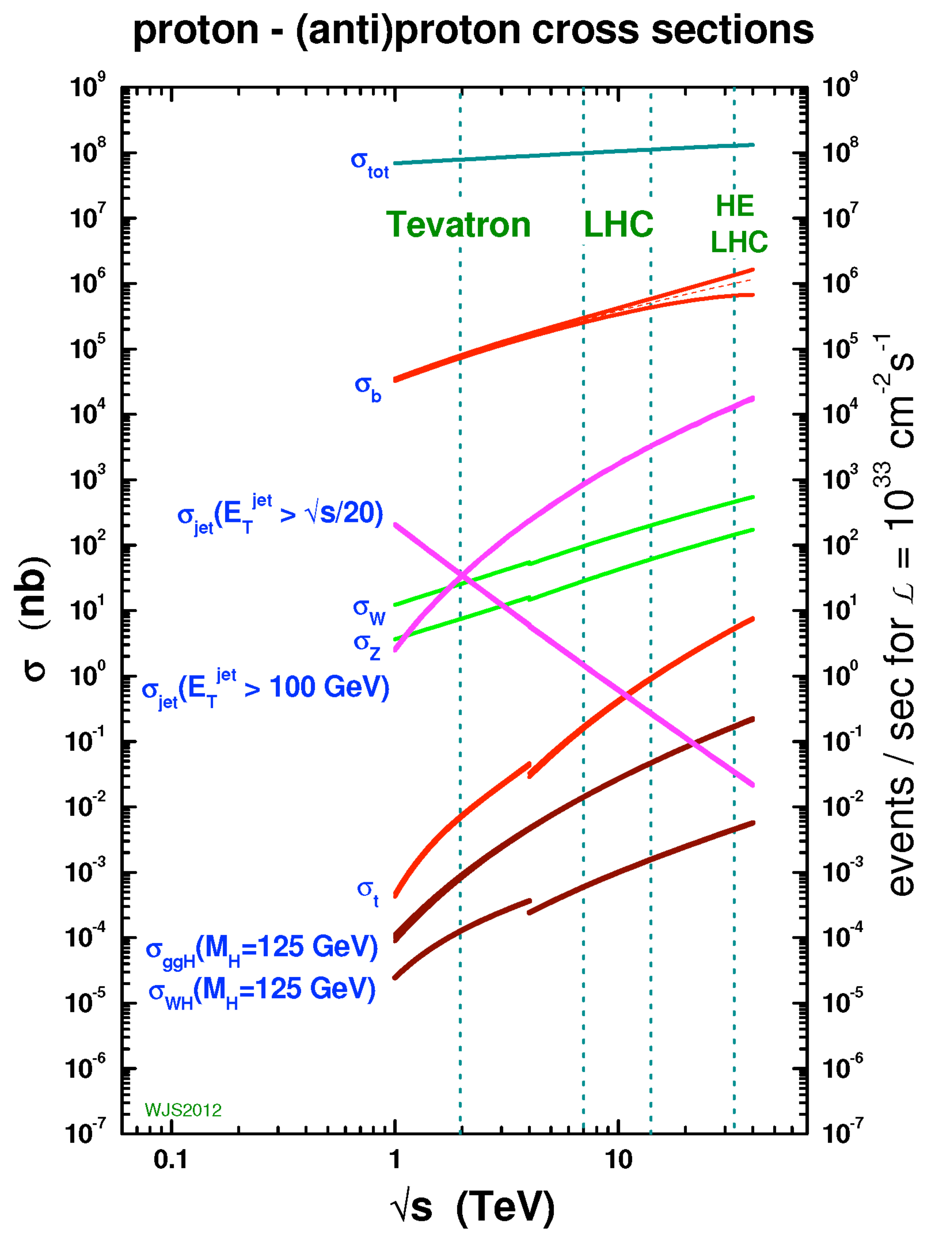


QCD: THE DOMINANT FORCE AT THE LHC





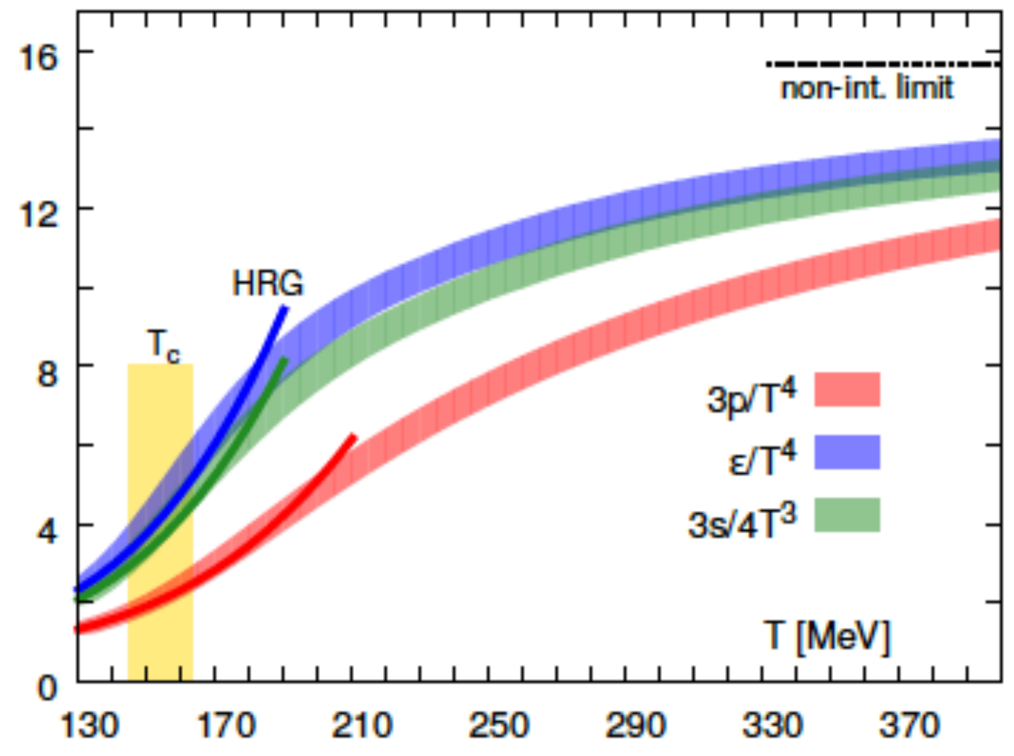


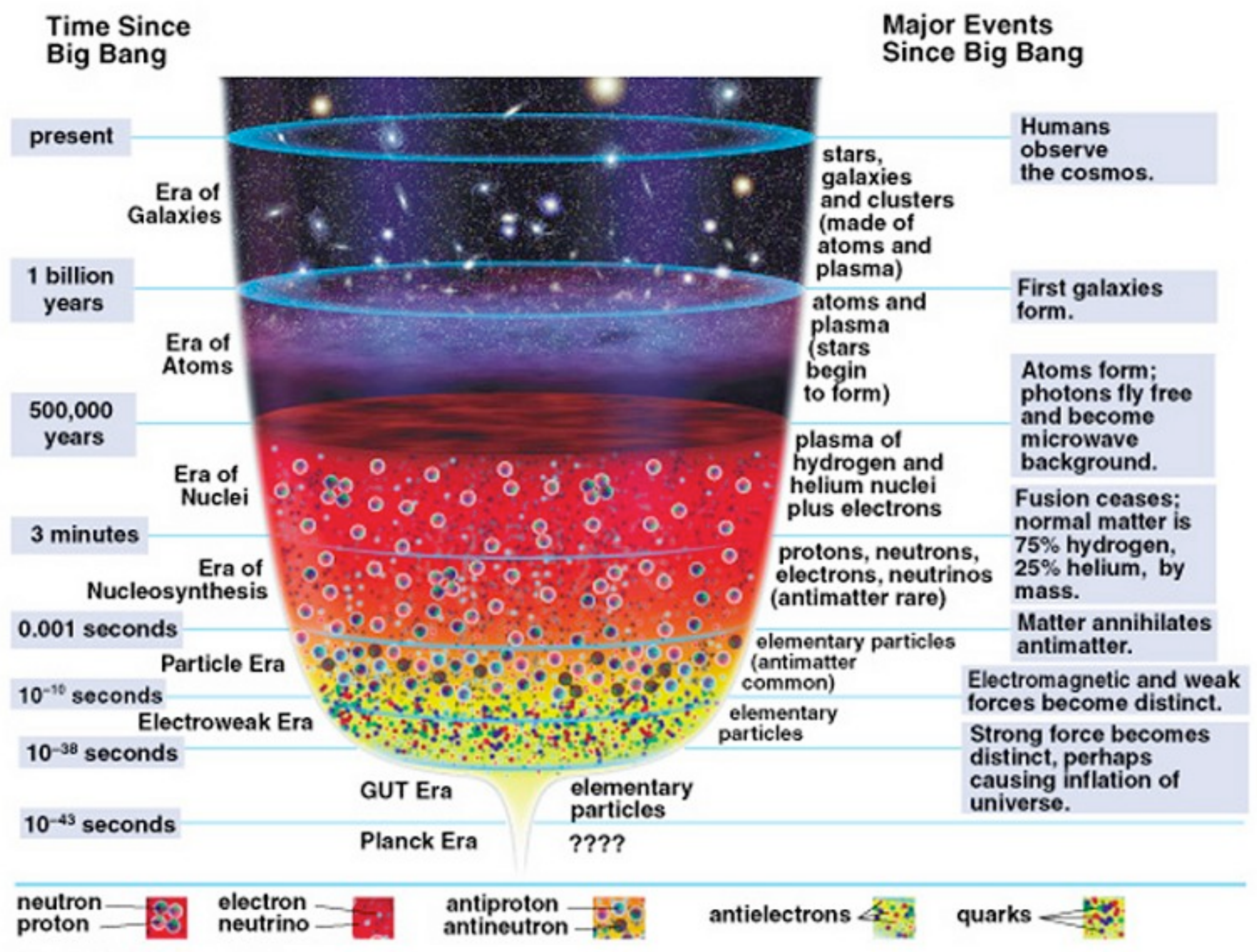


Nikhef

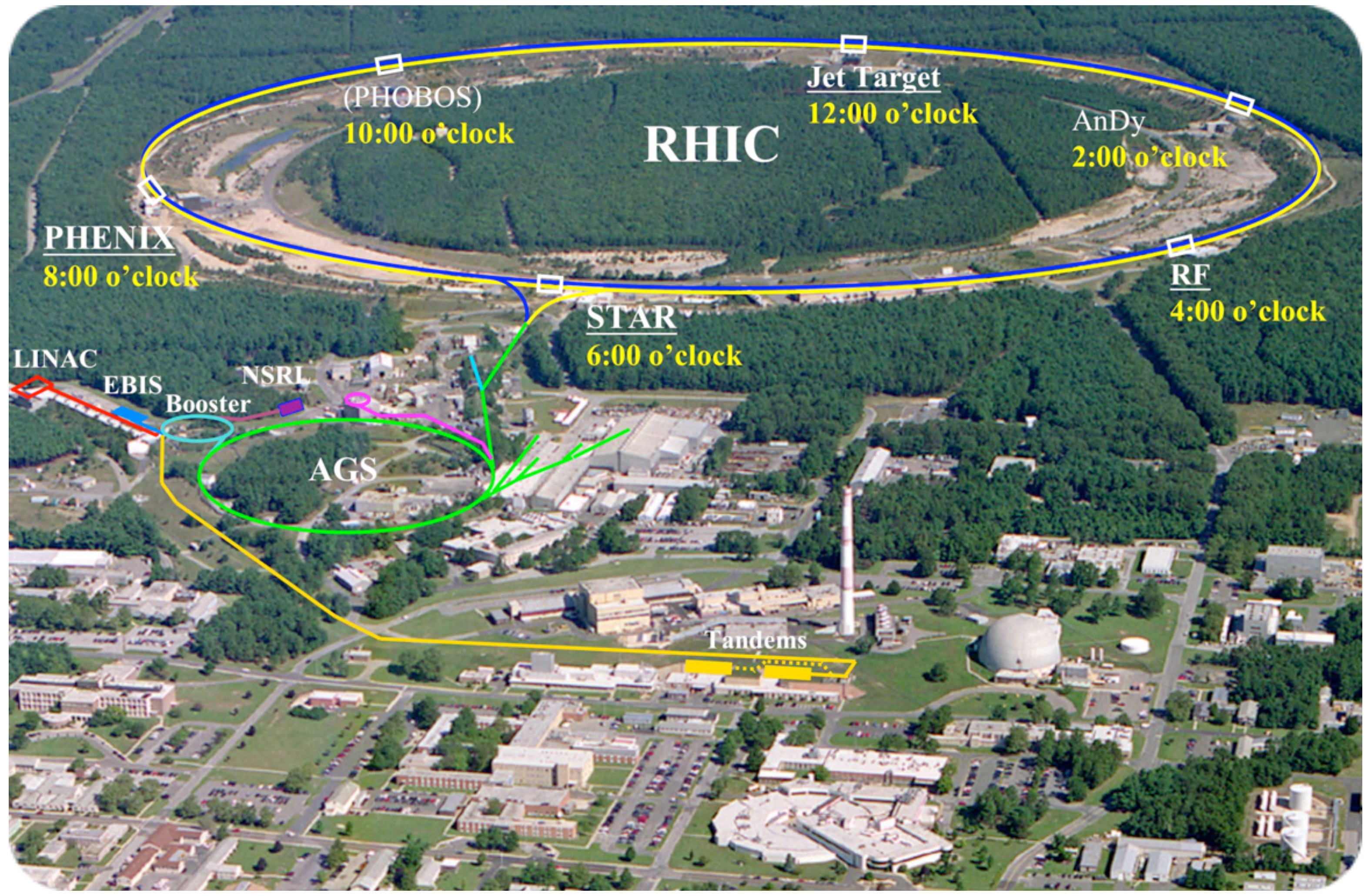
MULTIBODY FACET OF QCD

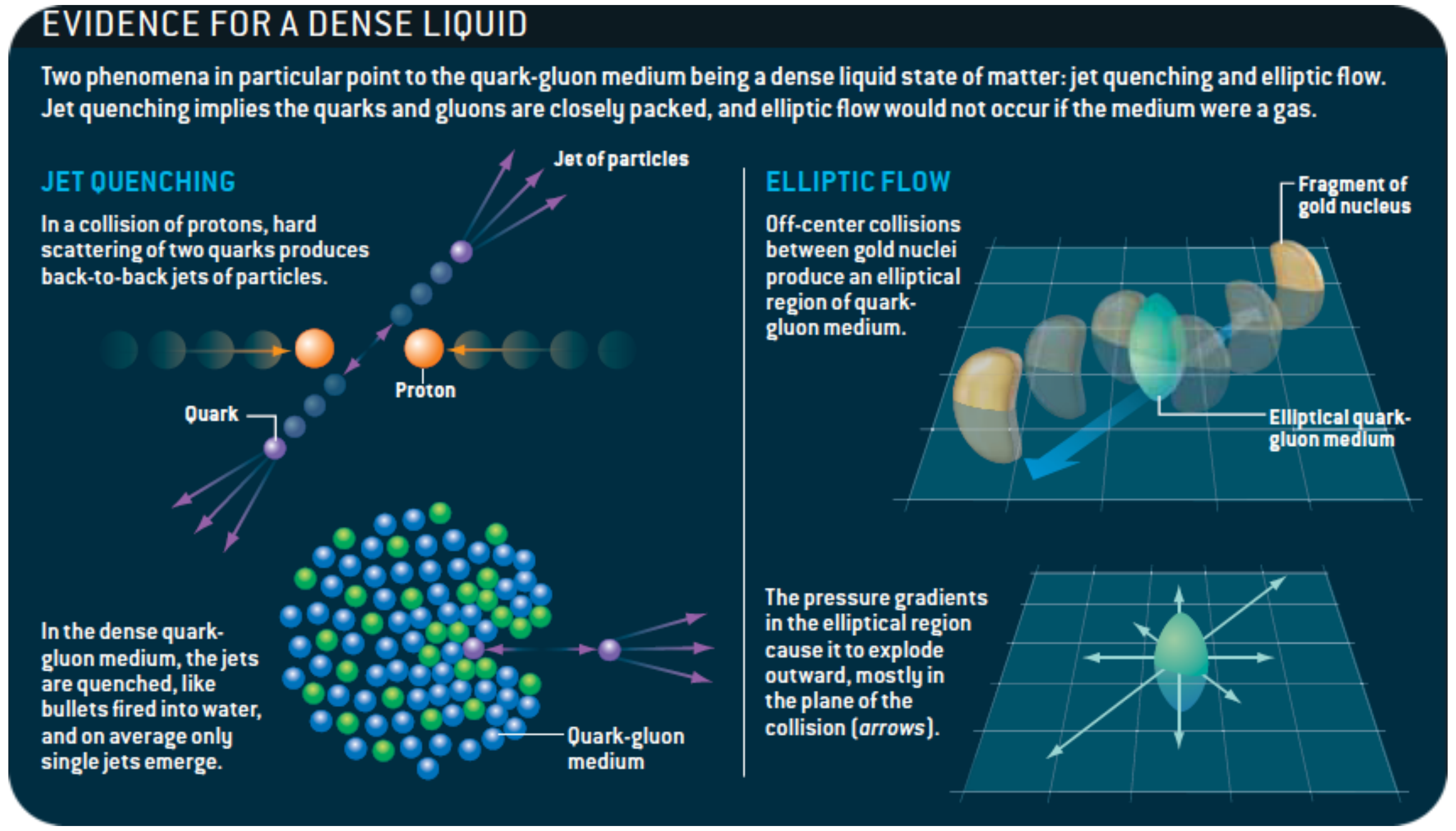
QCD phase transition

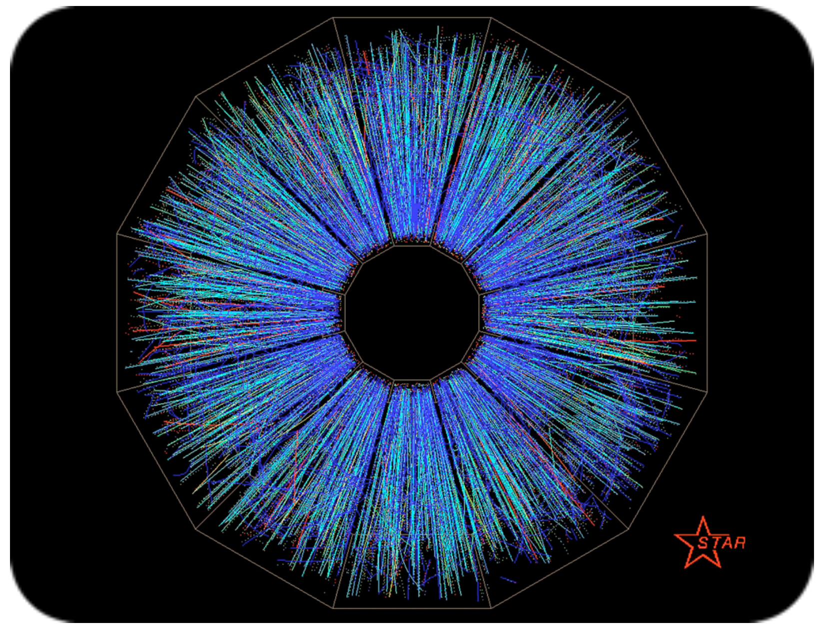




~4 decades of experimental program



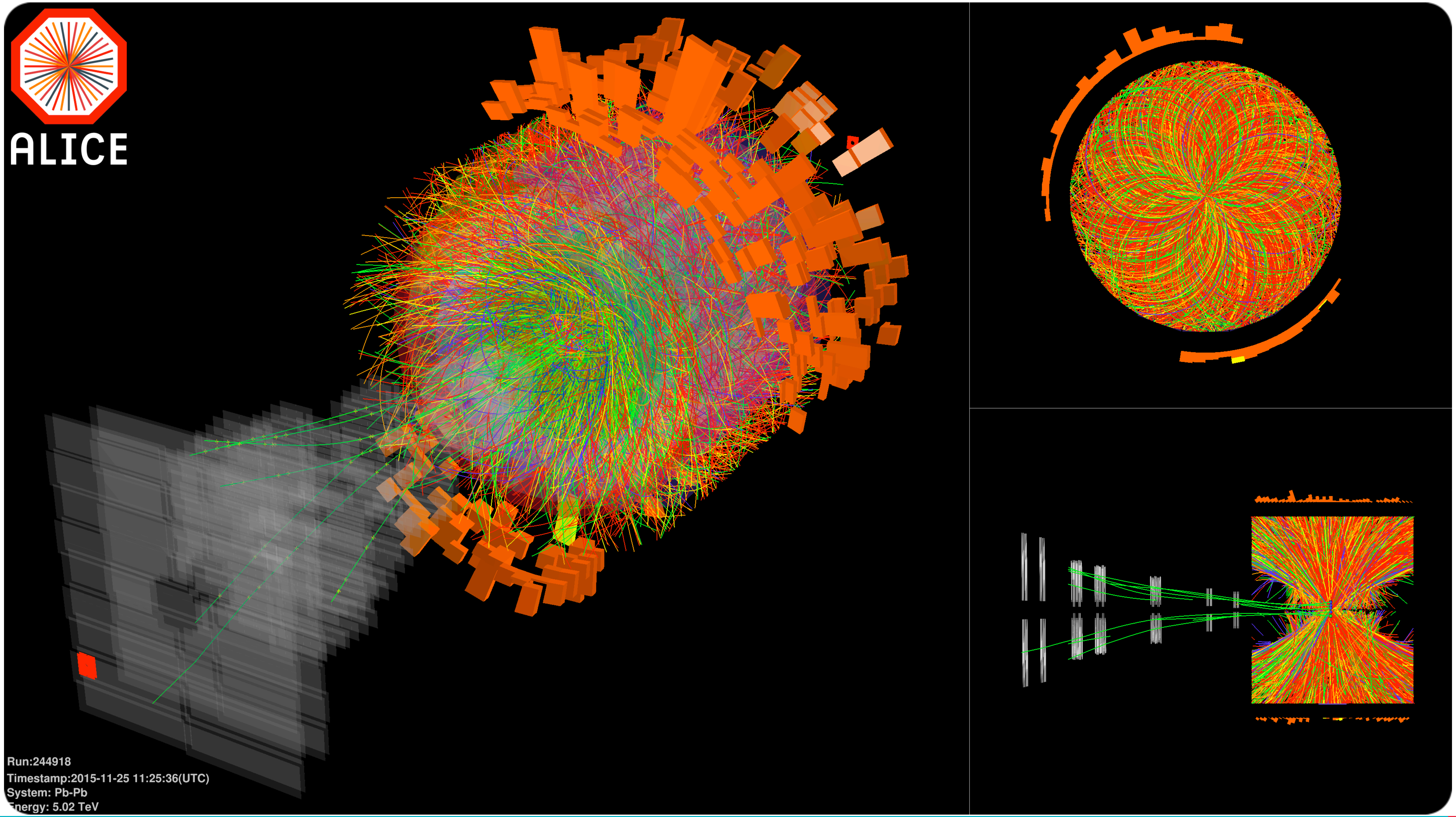




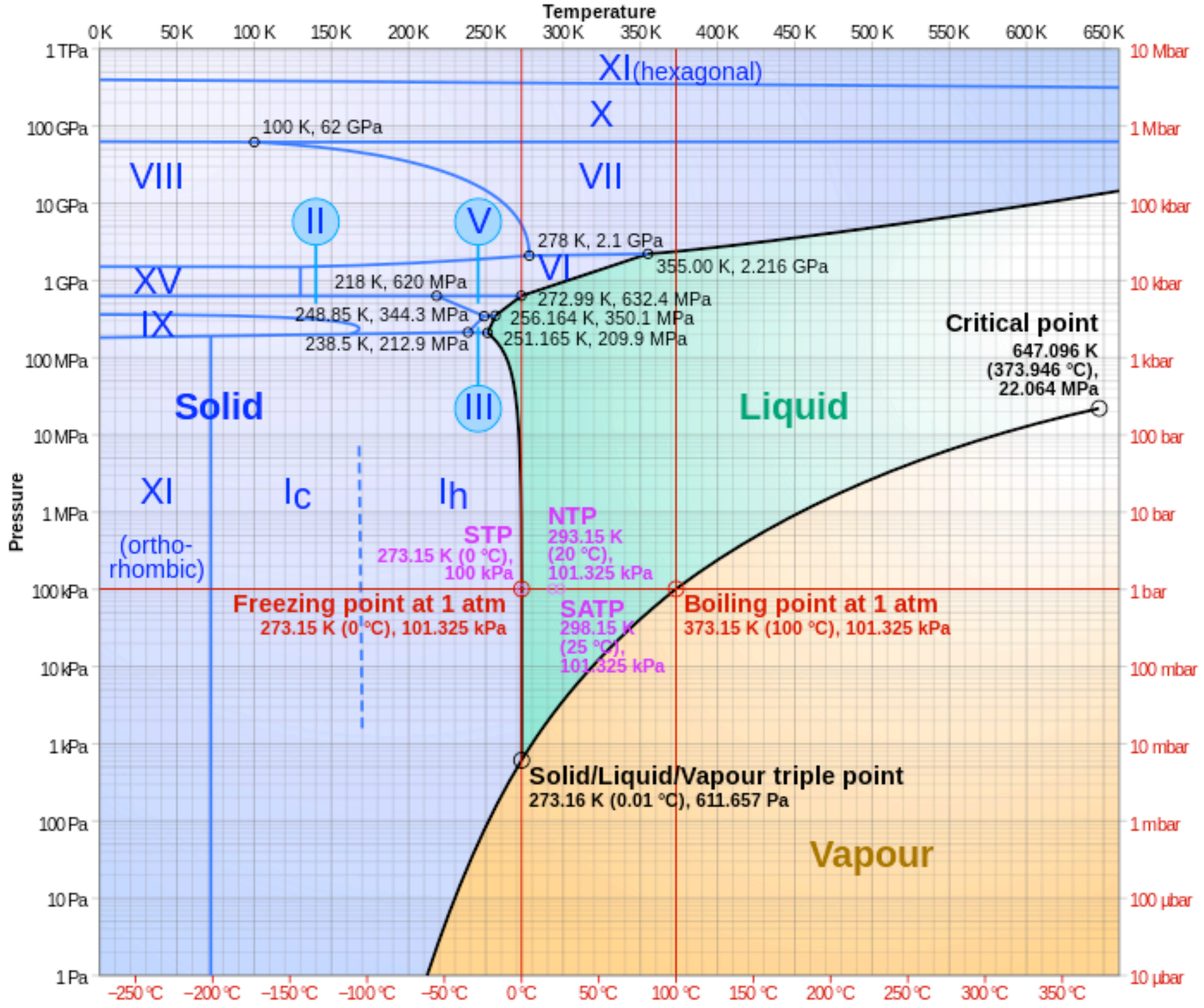
What is the nature of this primordial matter?

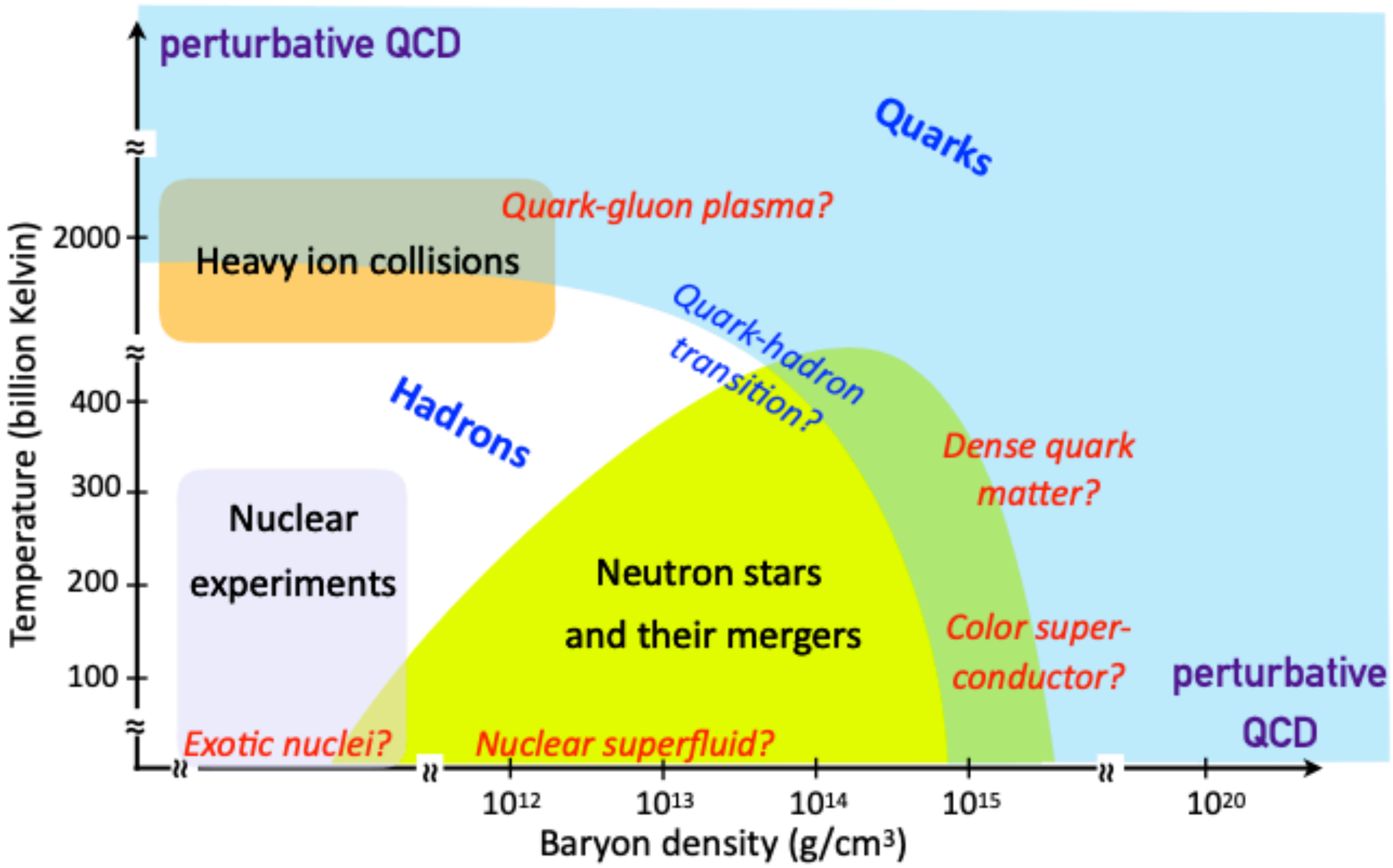
STUDYING PHASE TRANSITIONS IN THE LAB

Pb-Pb collisions ➡ large number of particles



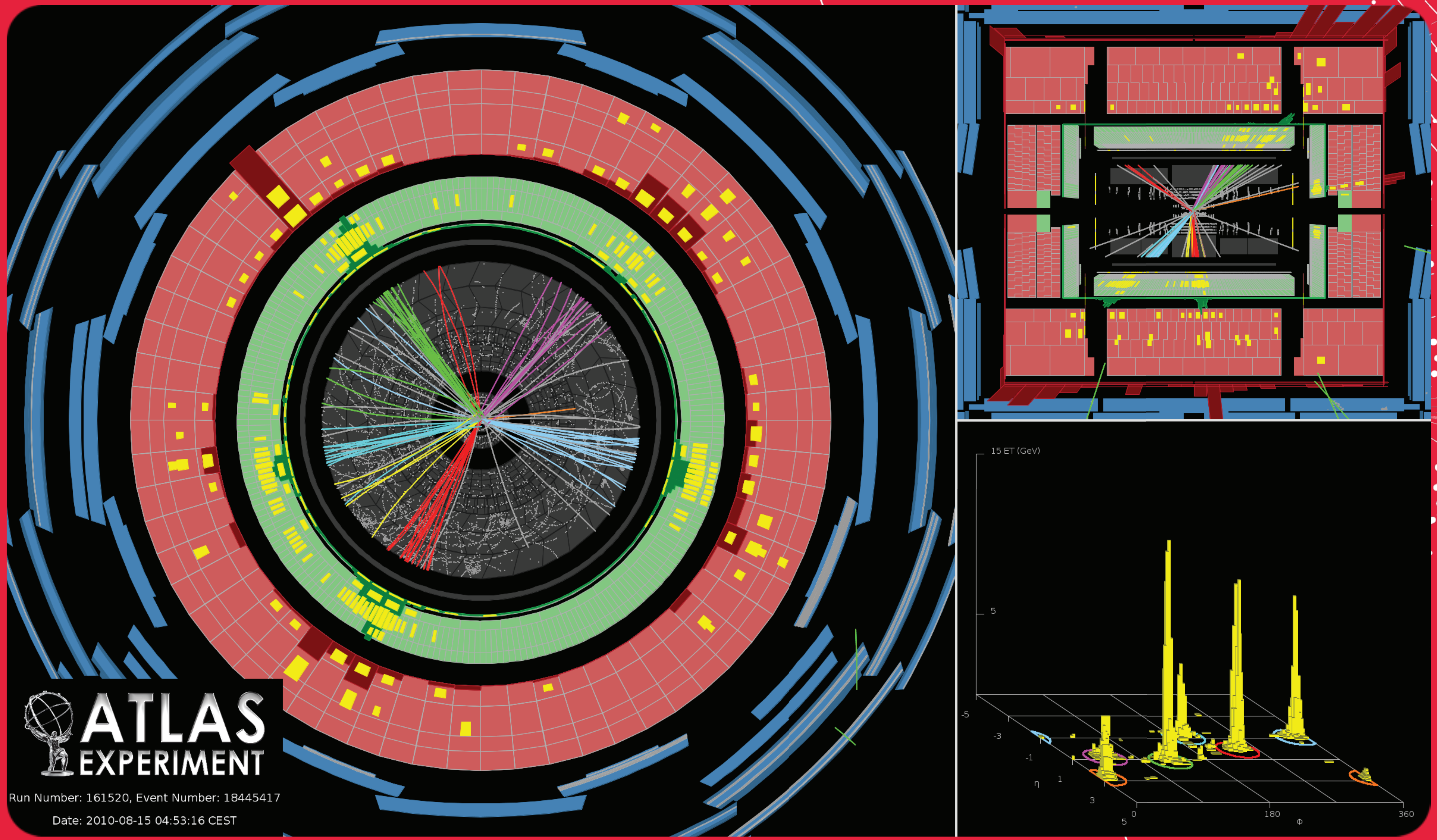
QCD PHASE DIAGRAM





Can we bring the QCD phase diagram at a textbook level version?

Nikhef

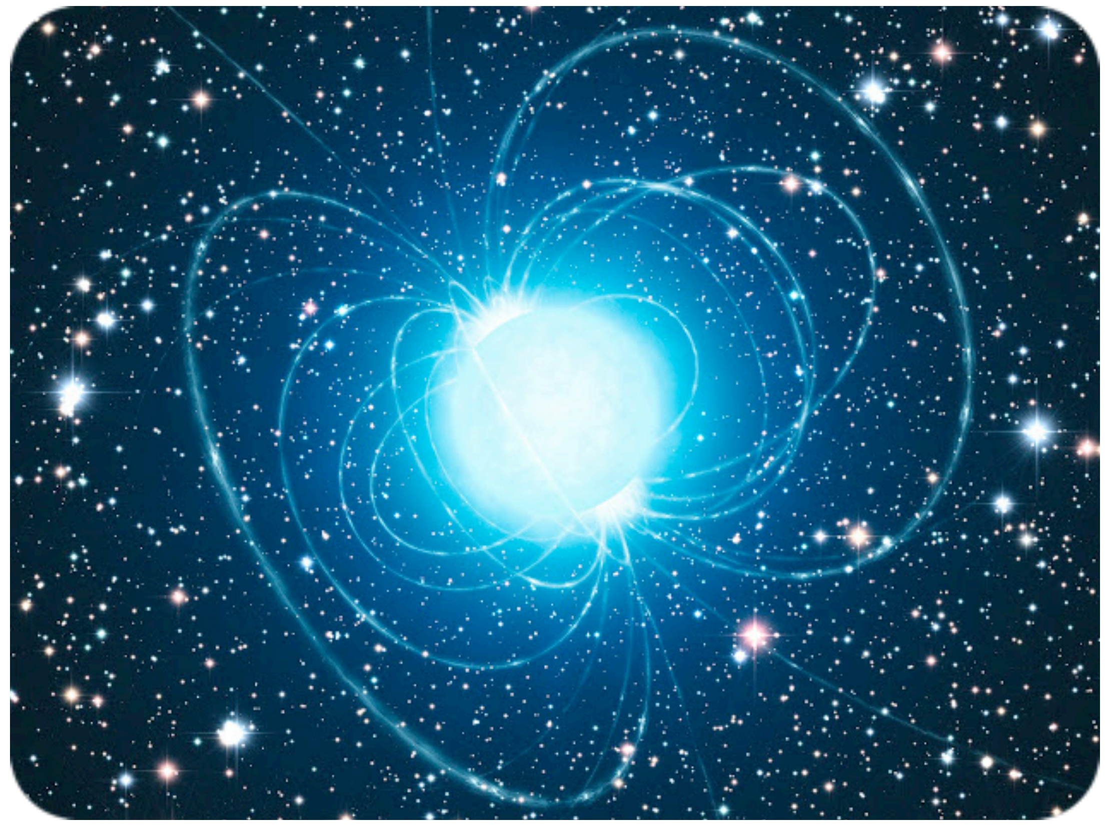


MSC PROJECTS IN ALICE

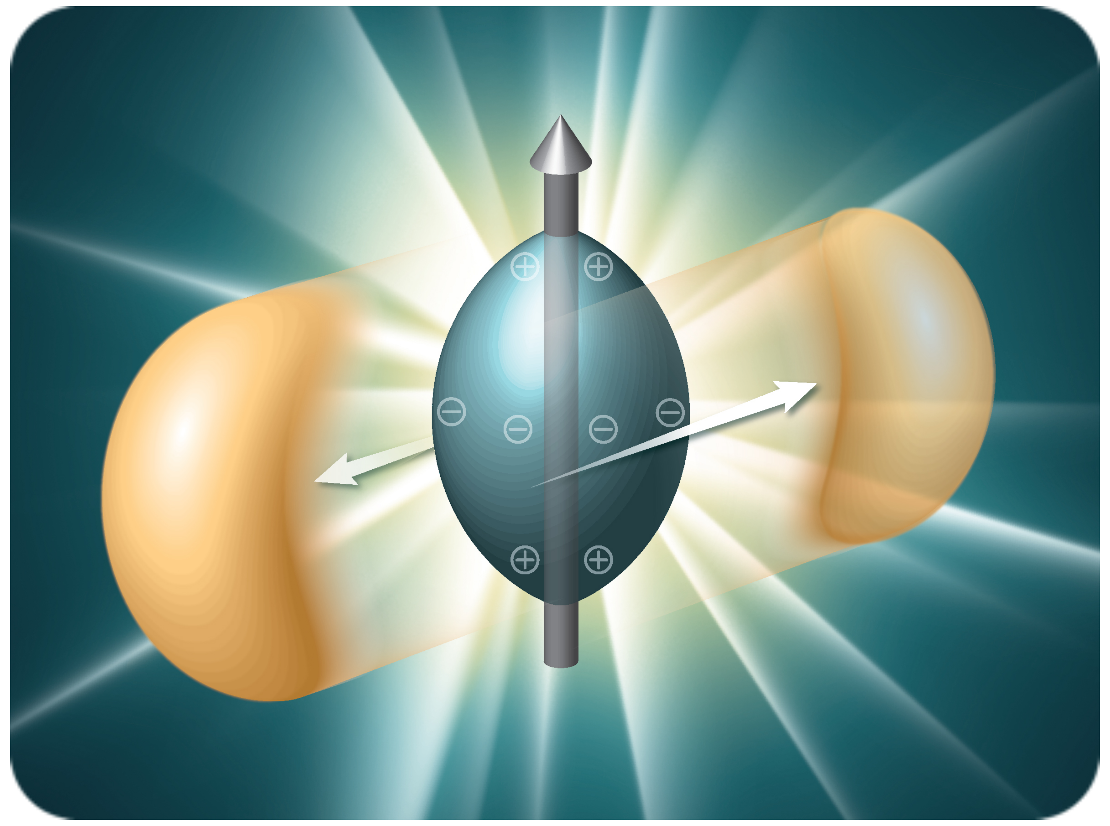
MSC PROJECTS

Search of the strongest magnetic field in the universe

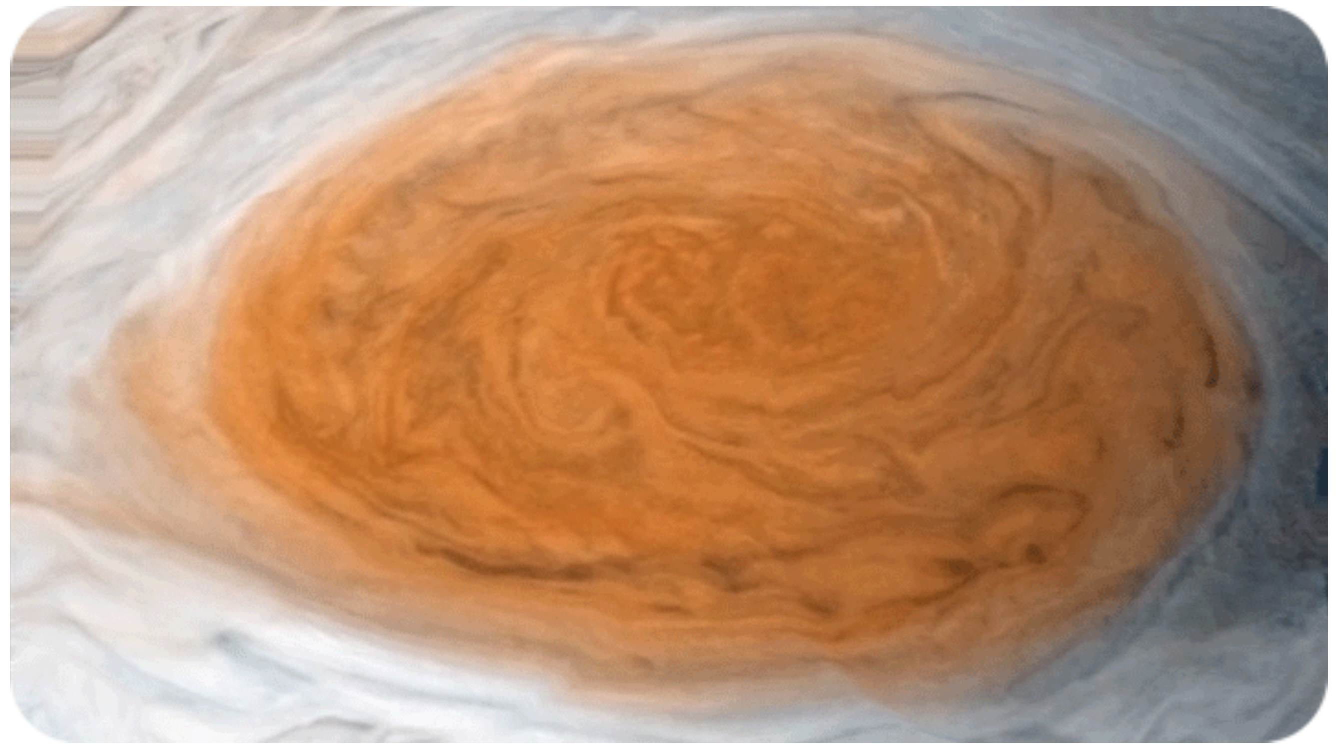
Magnetar's field: 10^{12} - 10^{15} G

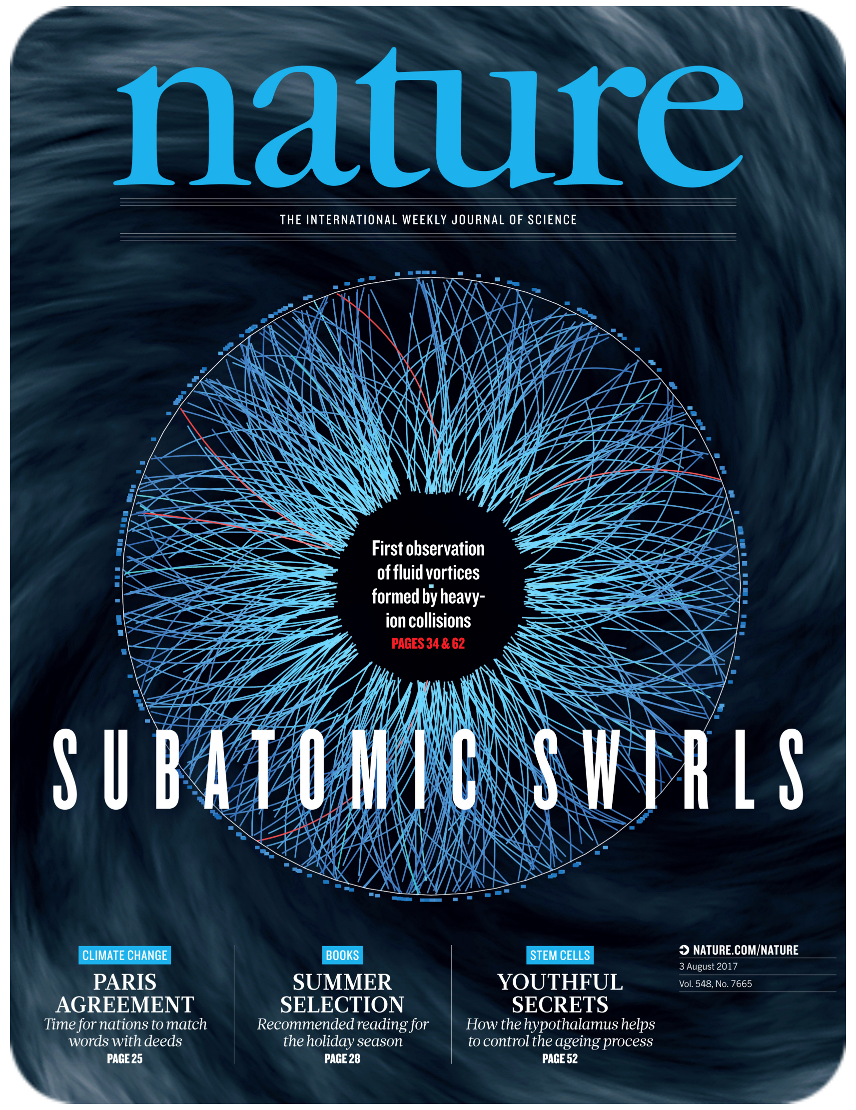


B in heavy ion collisions: 10^{19} - 10^{20} G

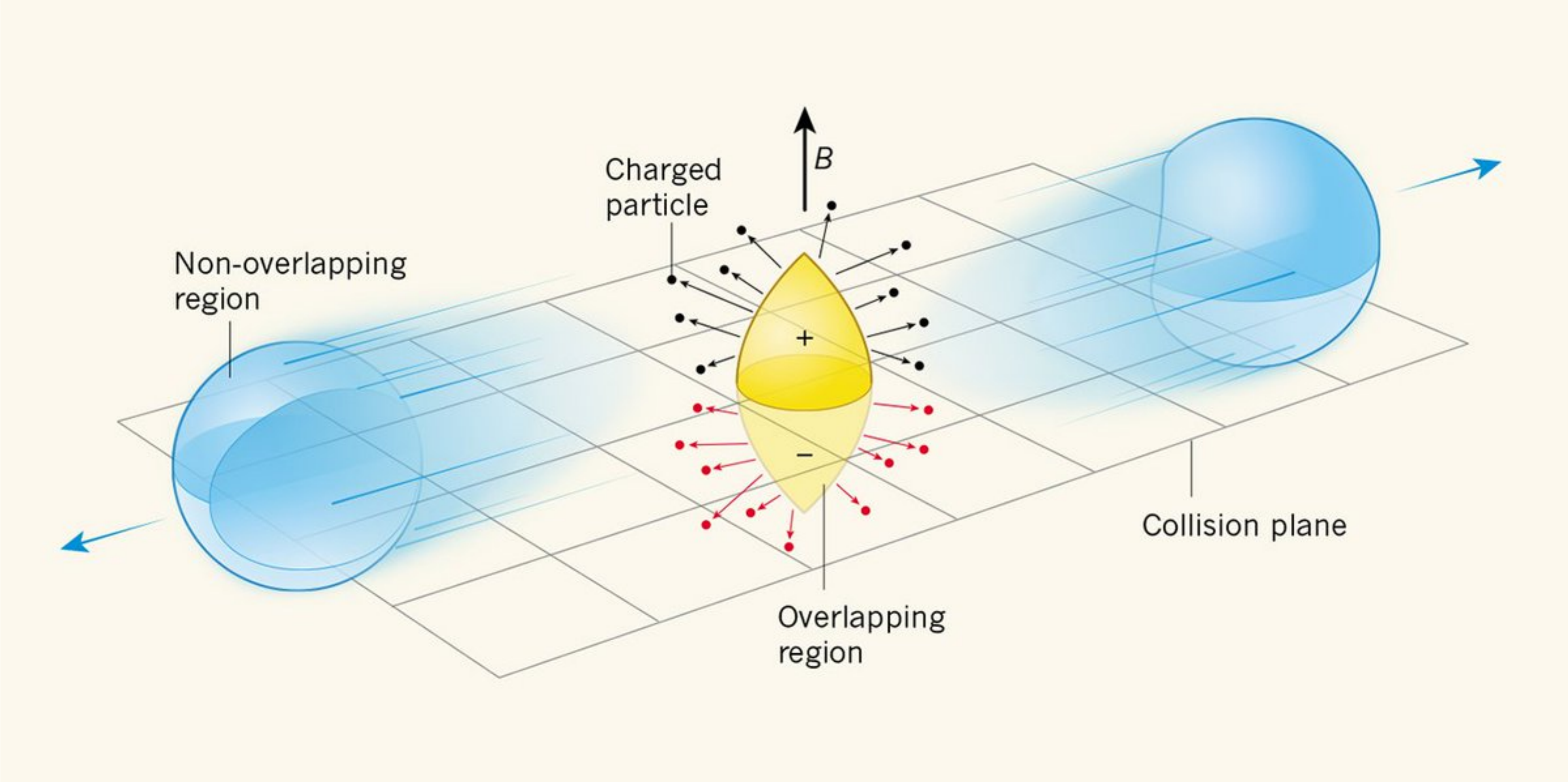


Studies of the most vortical fluid in nature

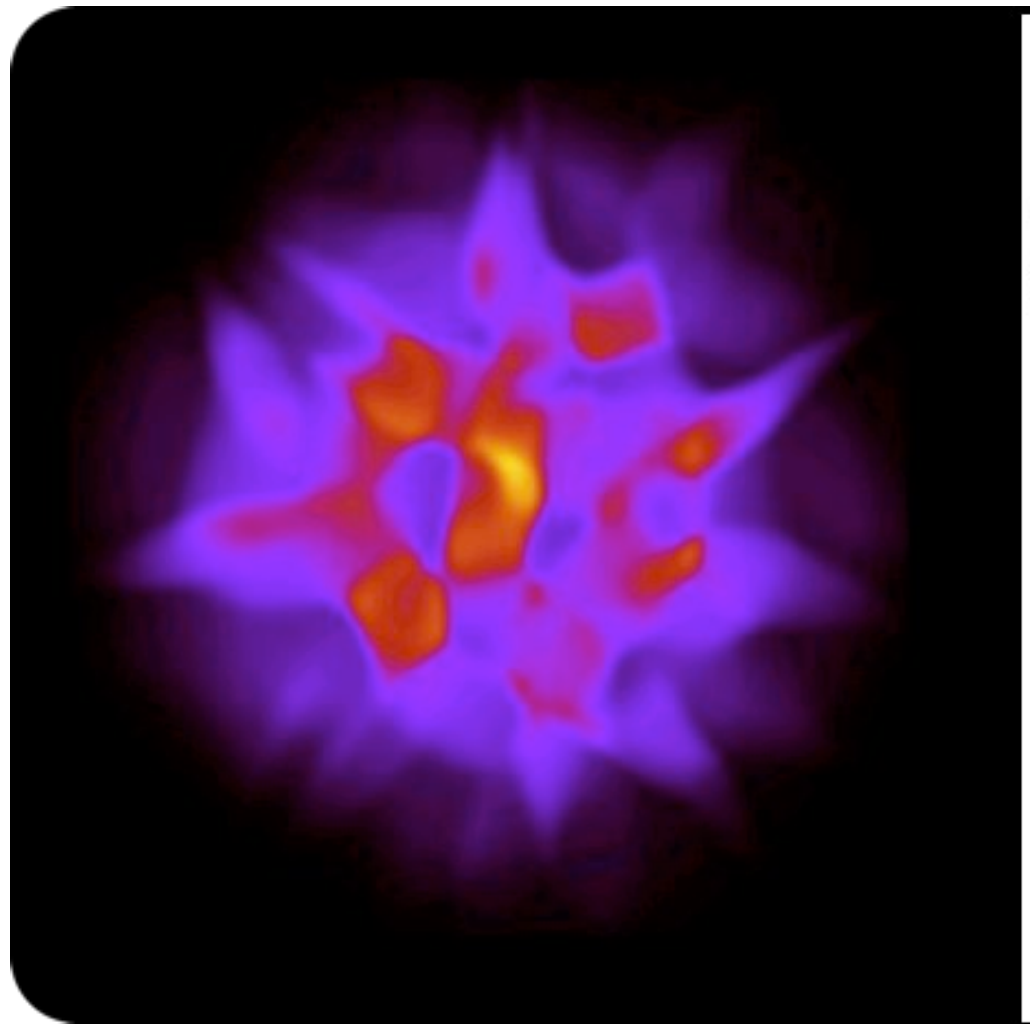


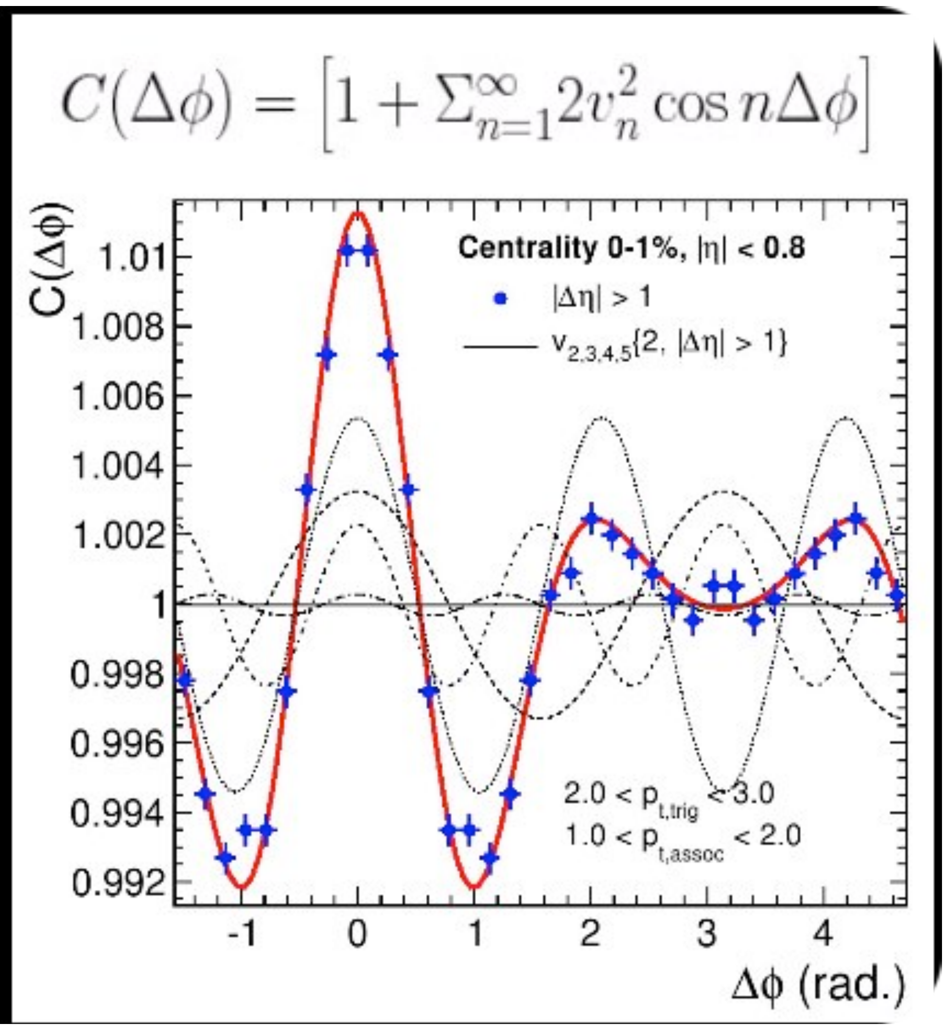


Direct searches of parity violation in QCD



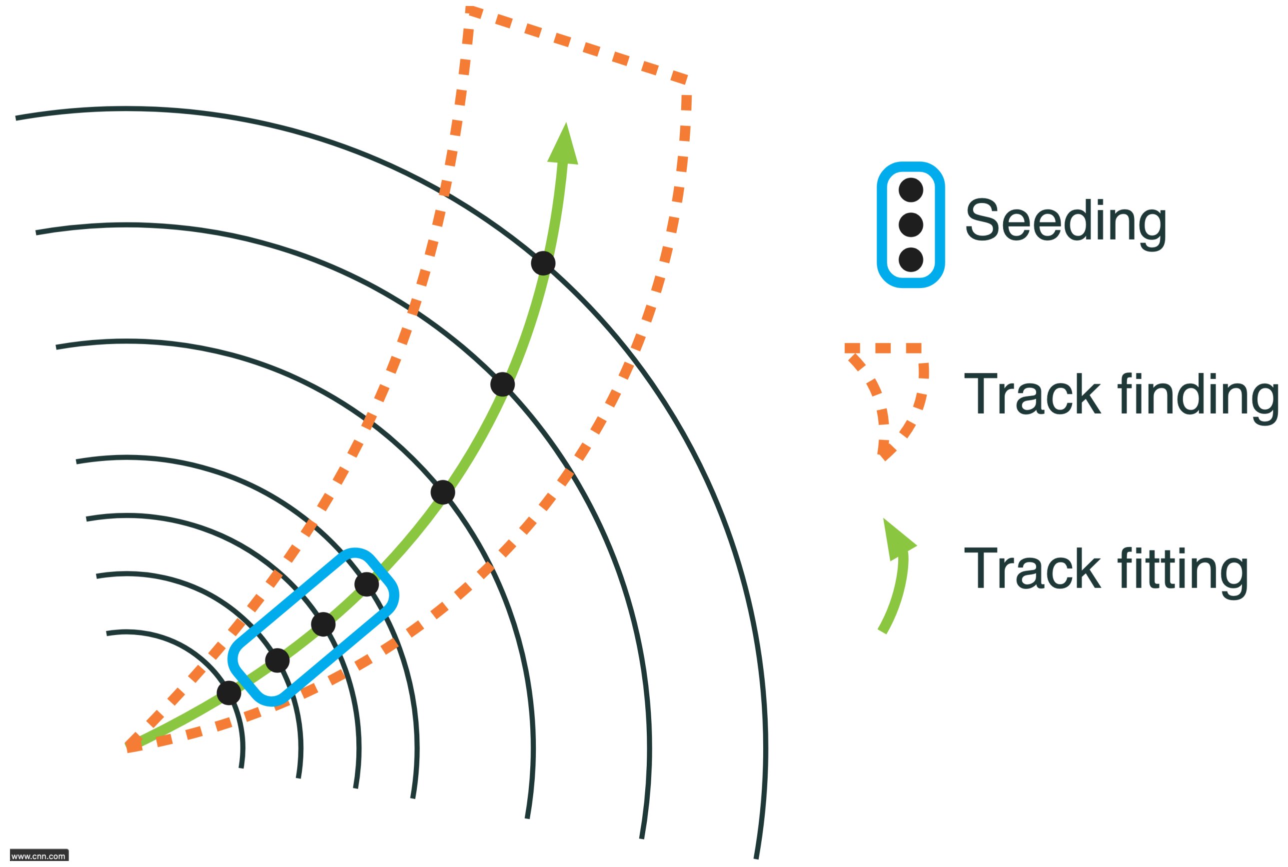
Characterising the perfect liquid

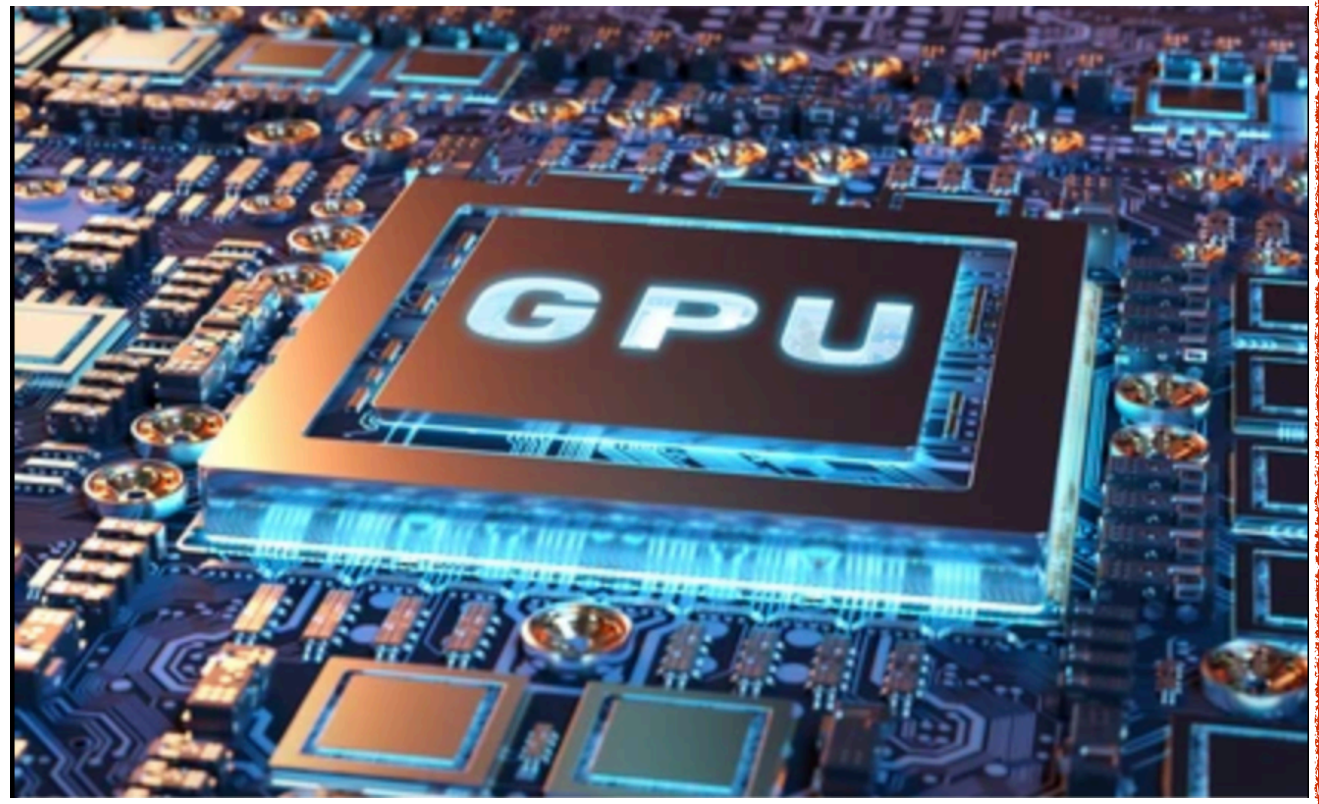




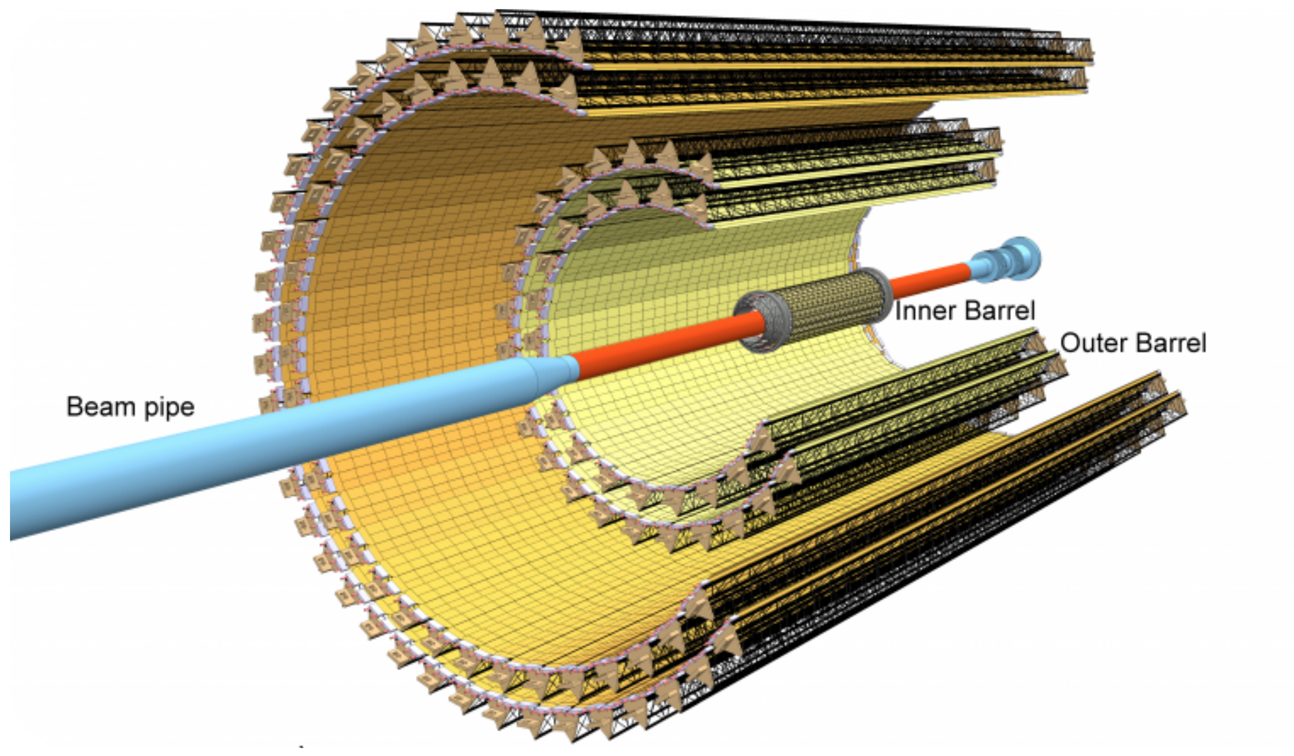
MSC PROJECTS

Computing projects (GPU + ML - Alice/PDP)

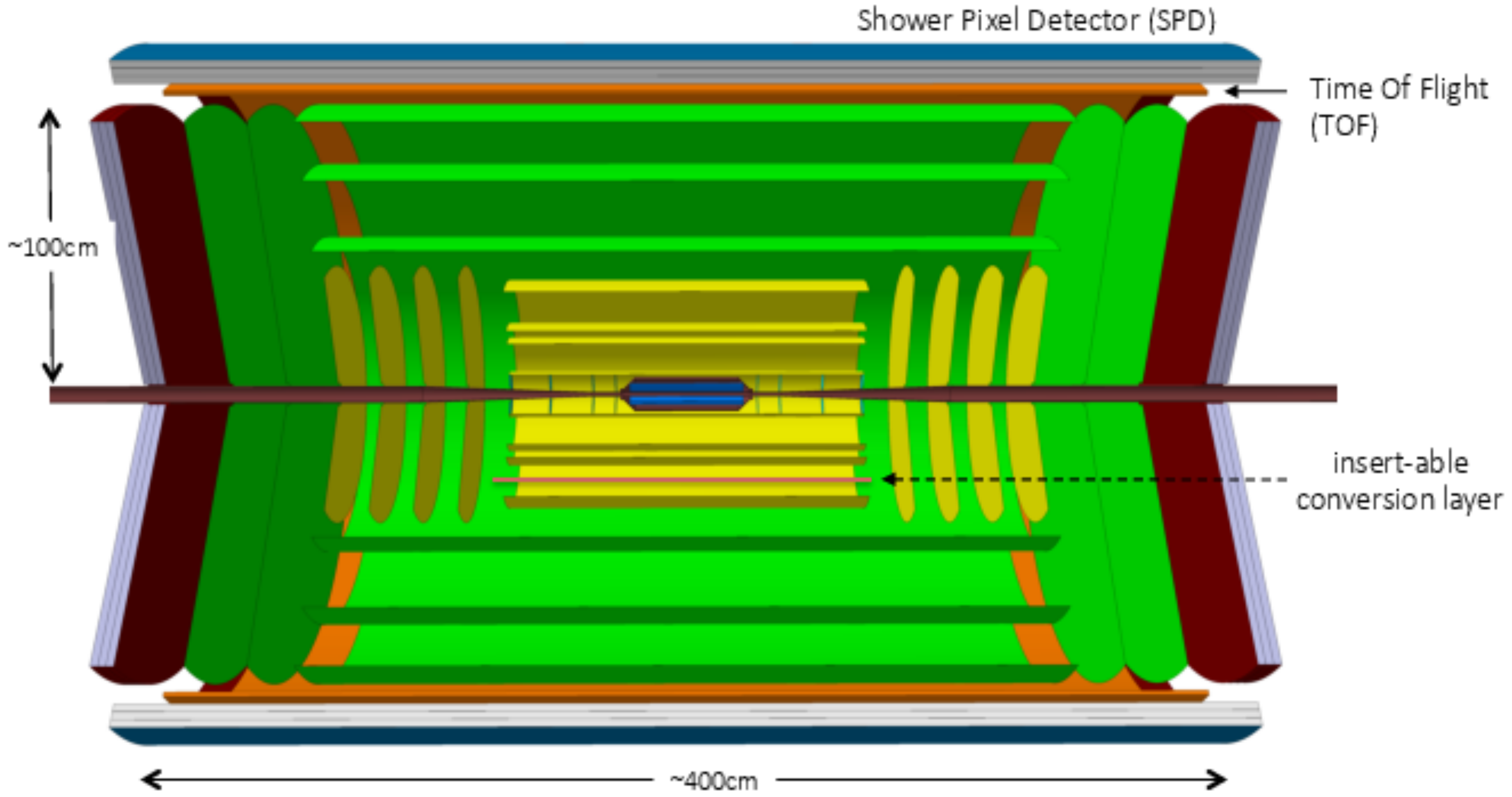




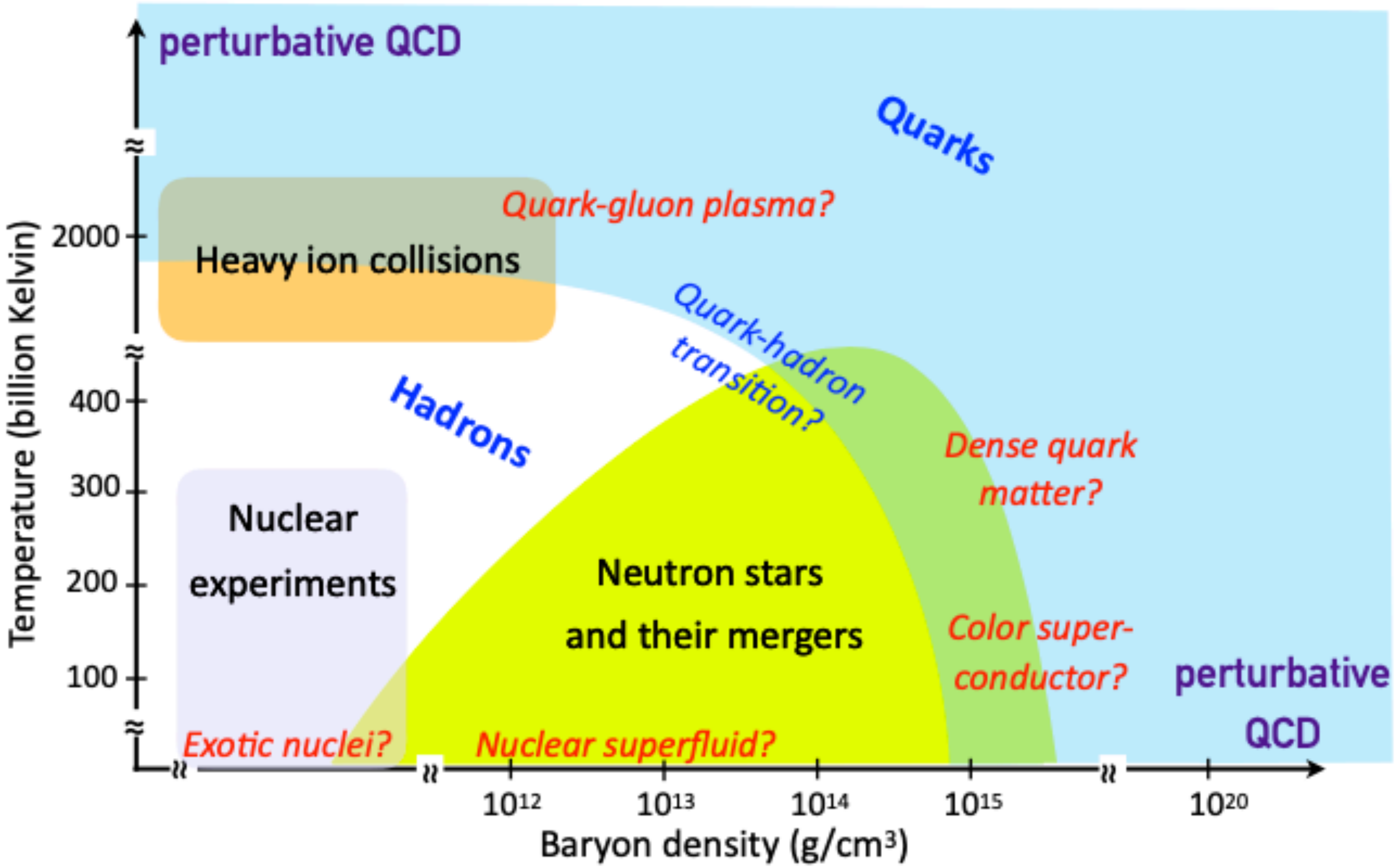
Hardware (Alice/R&D)



Simulation studies for the future HI detector



QCD PHASE DIAGRAM



Some of the topics could have (direct) connections to GW physics

Full Application - NWO Open Competition Domain Science - XL, 2021-2022

NWO Open Competition Domain Science - XL Round 2021-2022

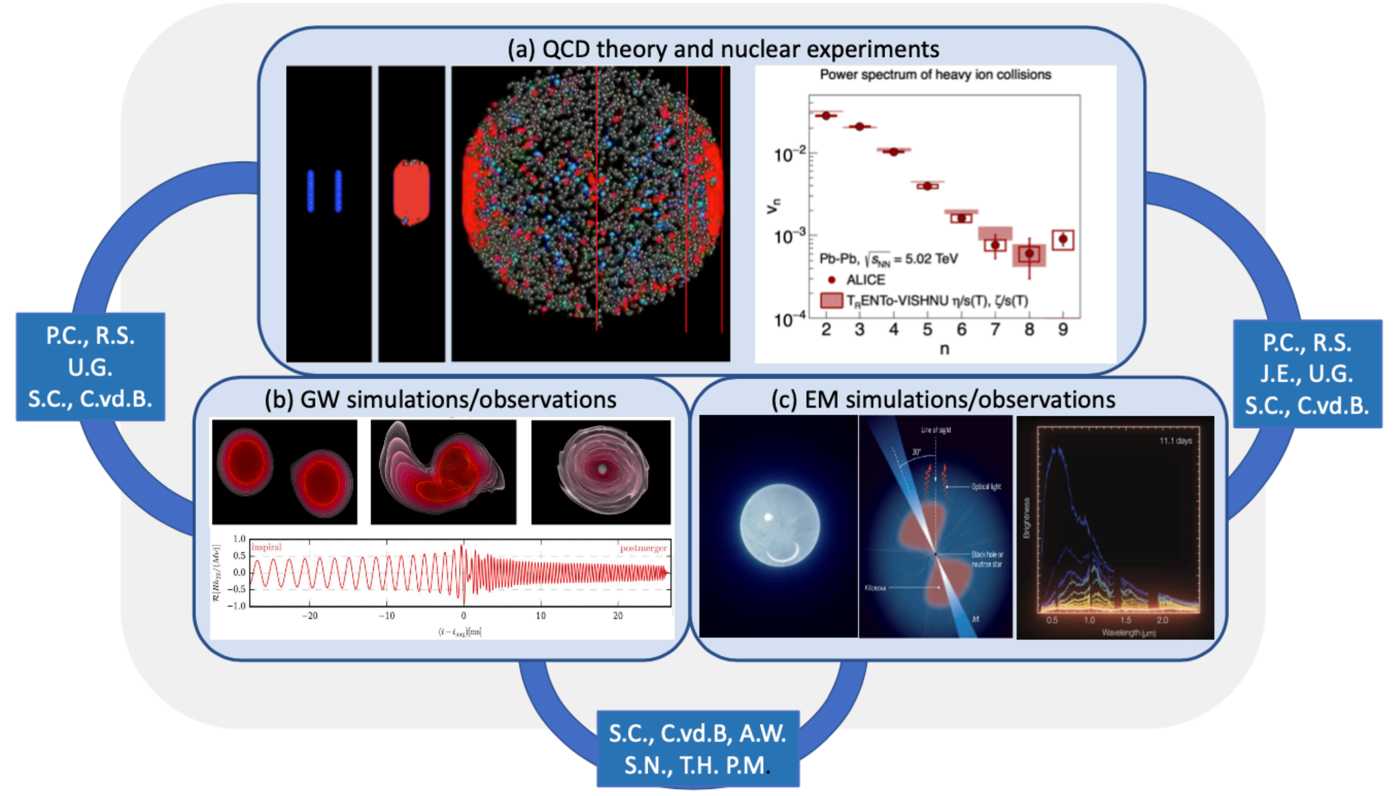
Grant application form

PART A: Scientific proposal

A.1 General information

A.1.1 Grant application title

Probing the phase diagram of quantum chromodynamics



Dutch consortium consisting of

- Experimentalists & theorists
- GW, astrophysicists, nuclear and high energy heavy-ion physicists

LAST TUTORIAL SESSION OF QCD

Tuesday, February the 27th at 13:00

Discussion about MSc projects

My experience as a MSc student

- What to expect from a MSc project (in ALICE)

The future of (our) students after their MSc

My experience as a PhD candidate

- What does it mean to do an experimental PhD?

Paul Veen

Noor Koster

Thank you for
your attention!