SESSION OVERVIEW: HADRONIC PHYSICS

BENJAMIN AUDURIER - JRJC - 26/11/24

HADRONIC PHYSICS

What detector's expert think we do

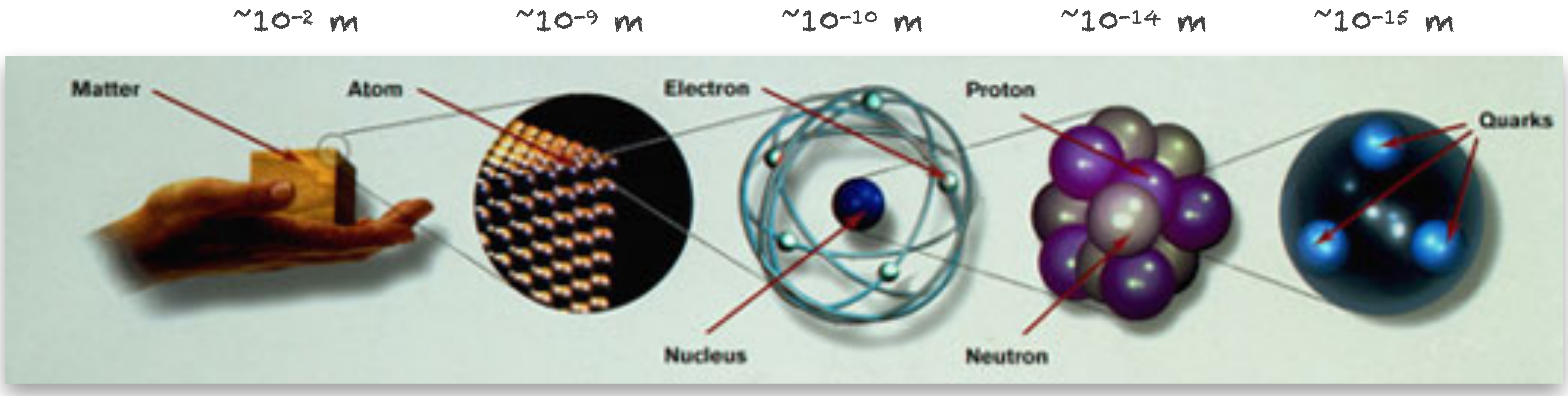
What SM physicists think we do

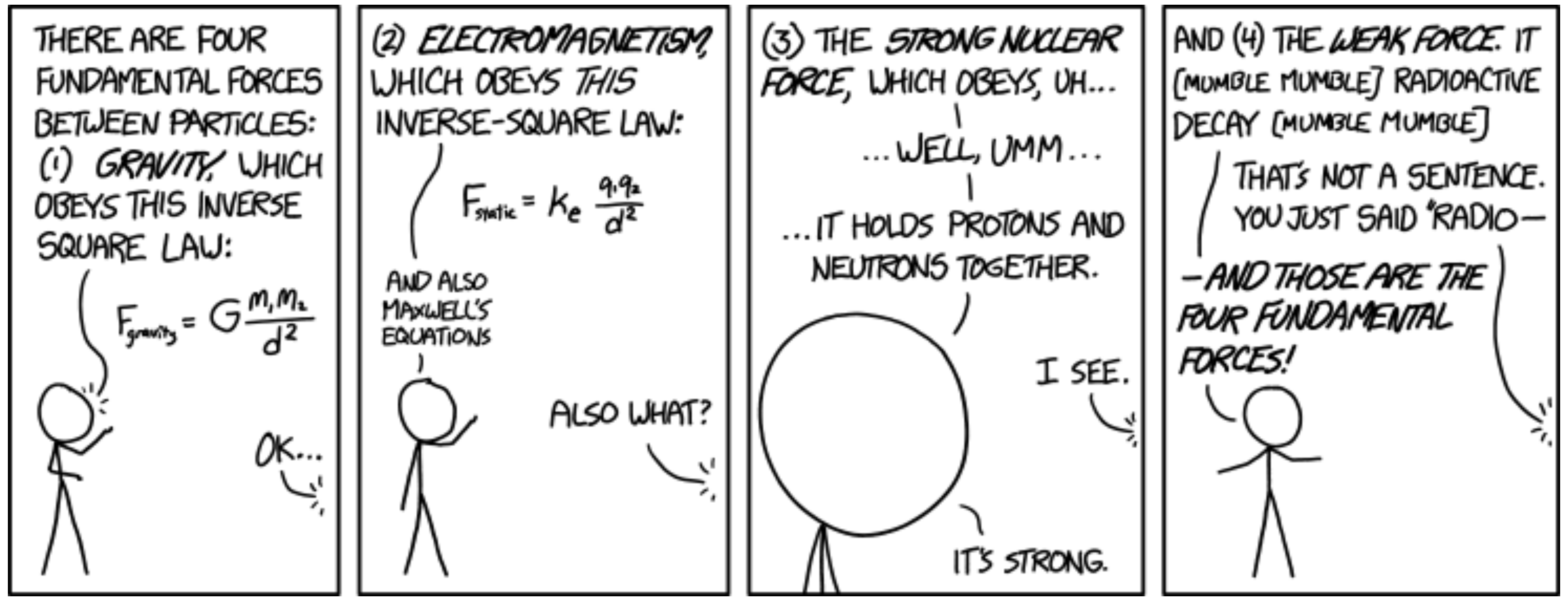
What we think we do

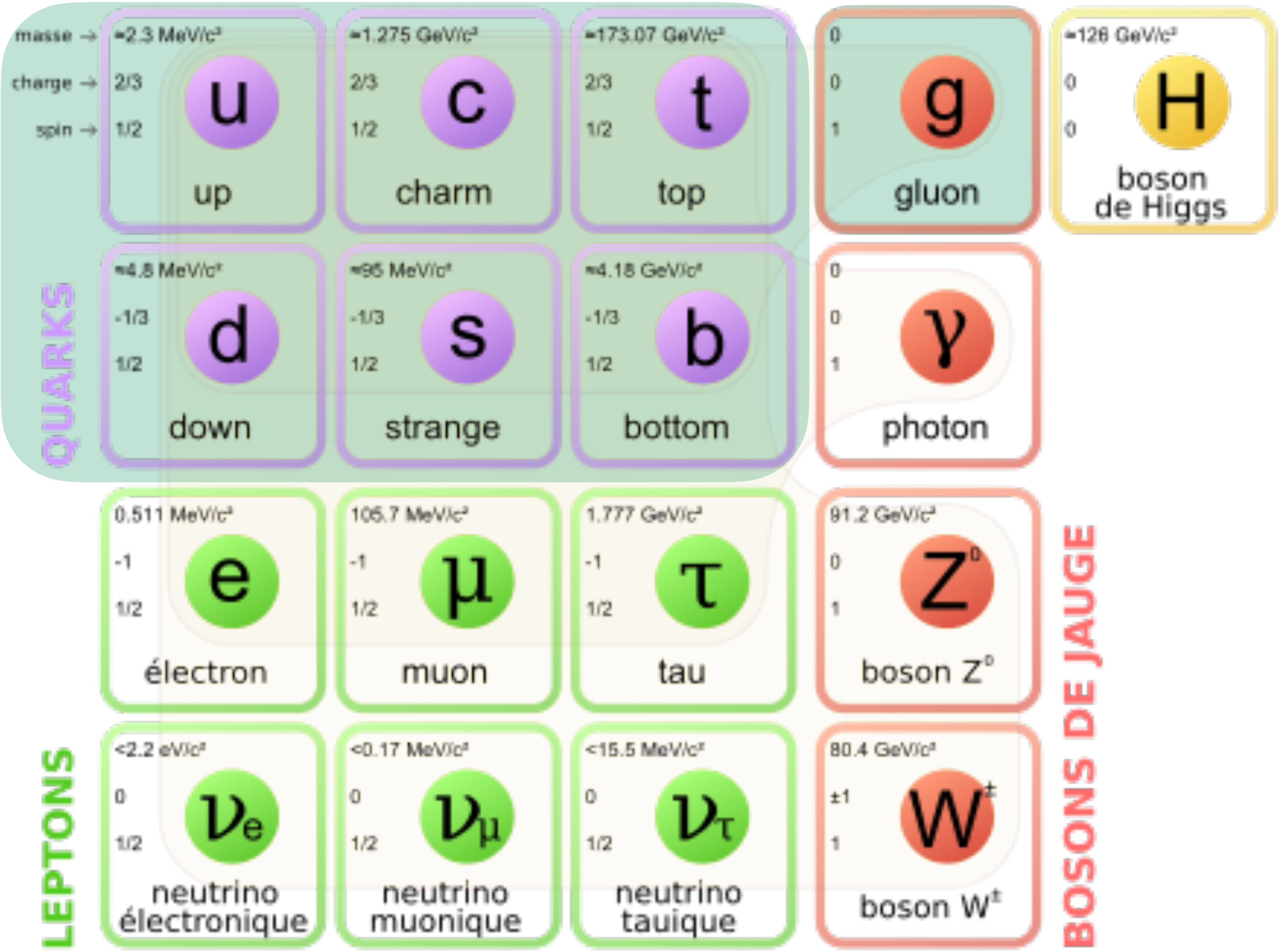
What nuclear physicists think we do

What we really do

Hadronic physics: we study hadrons



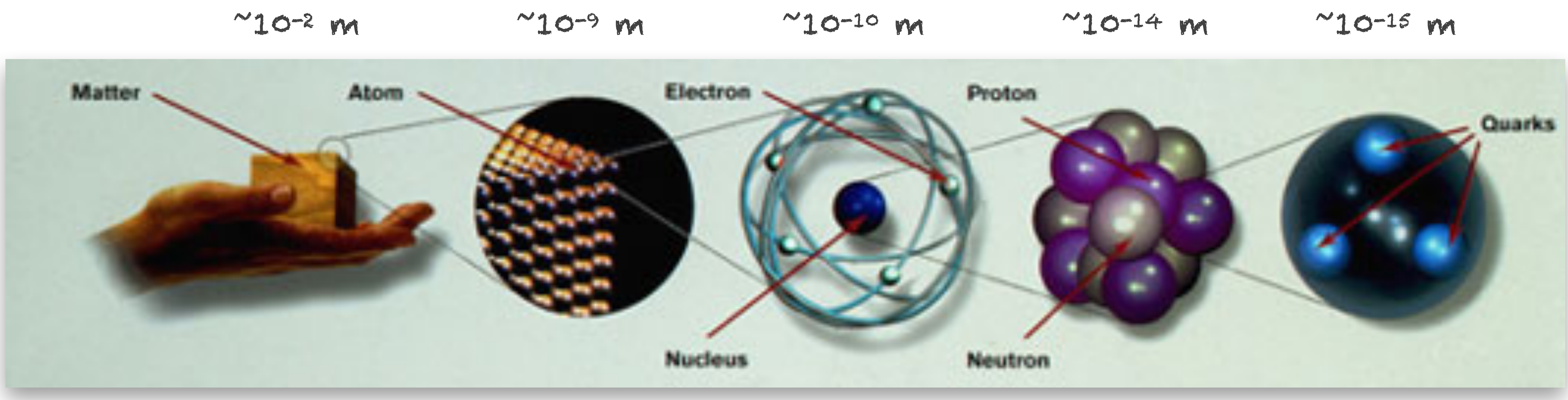


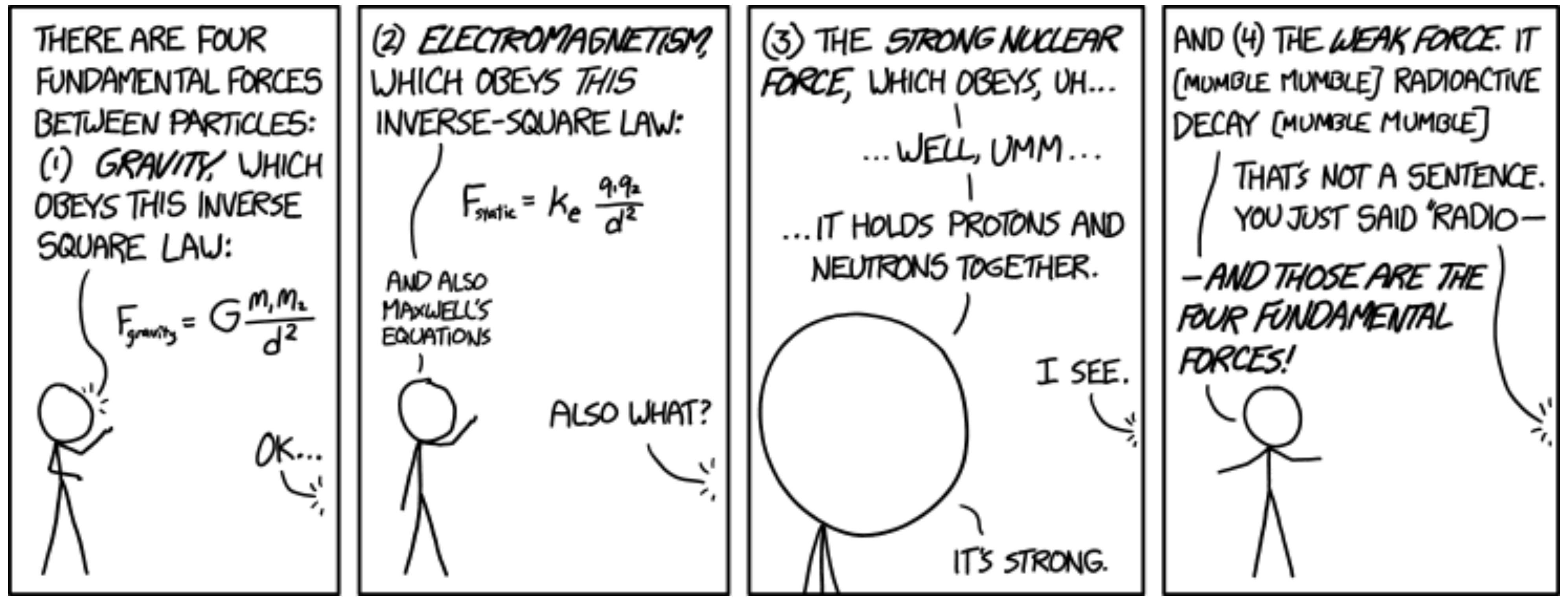


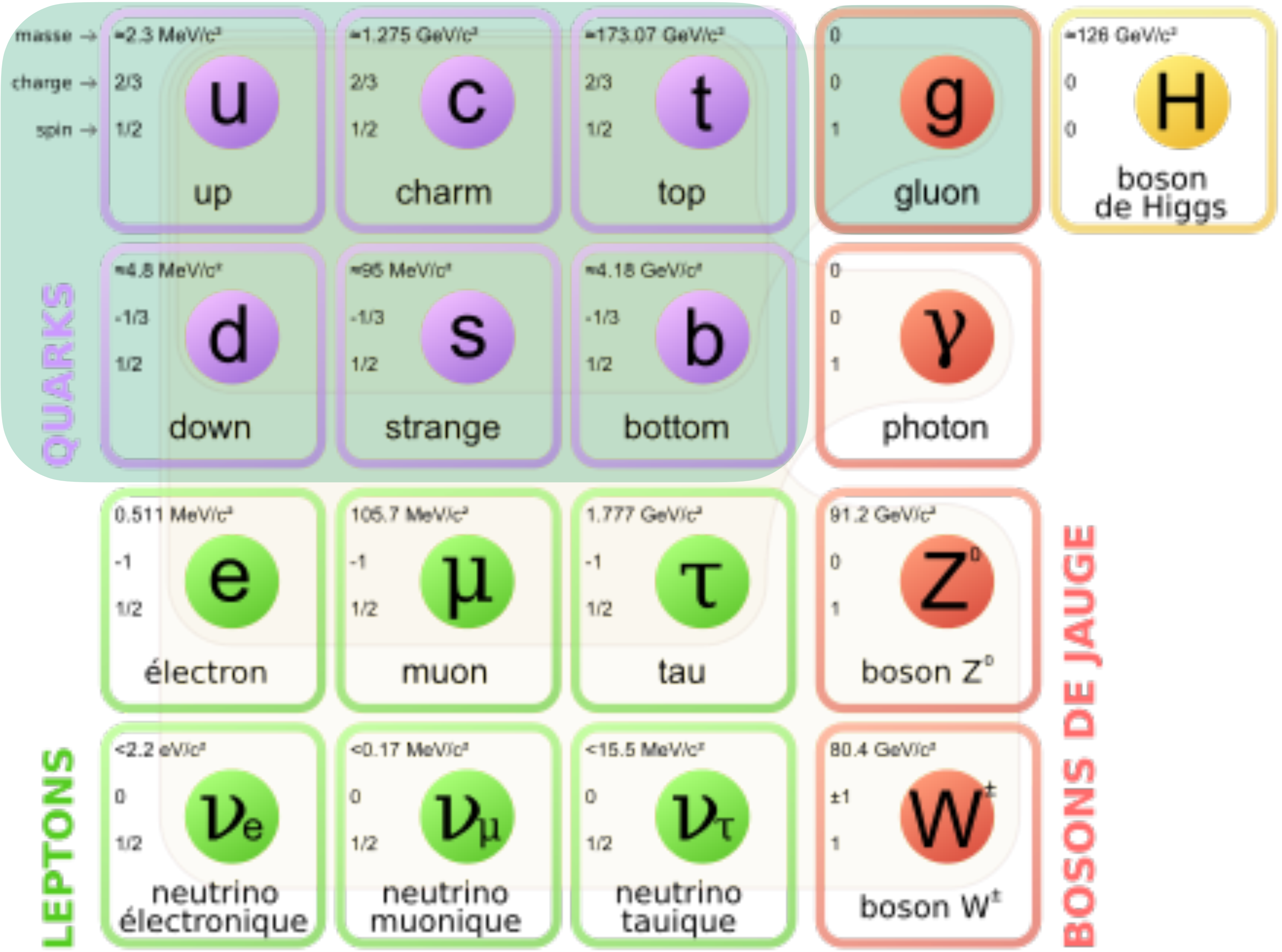
Hadrons = particles made of quarks and gluons

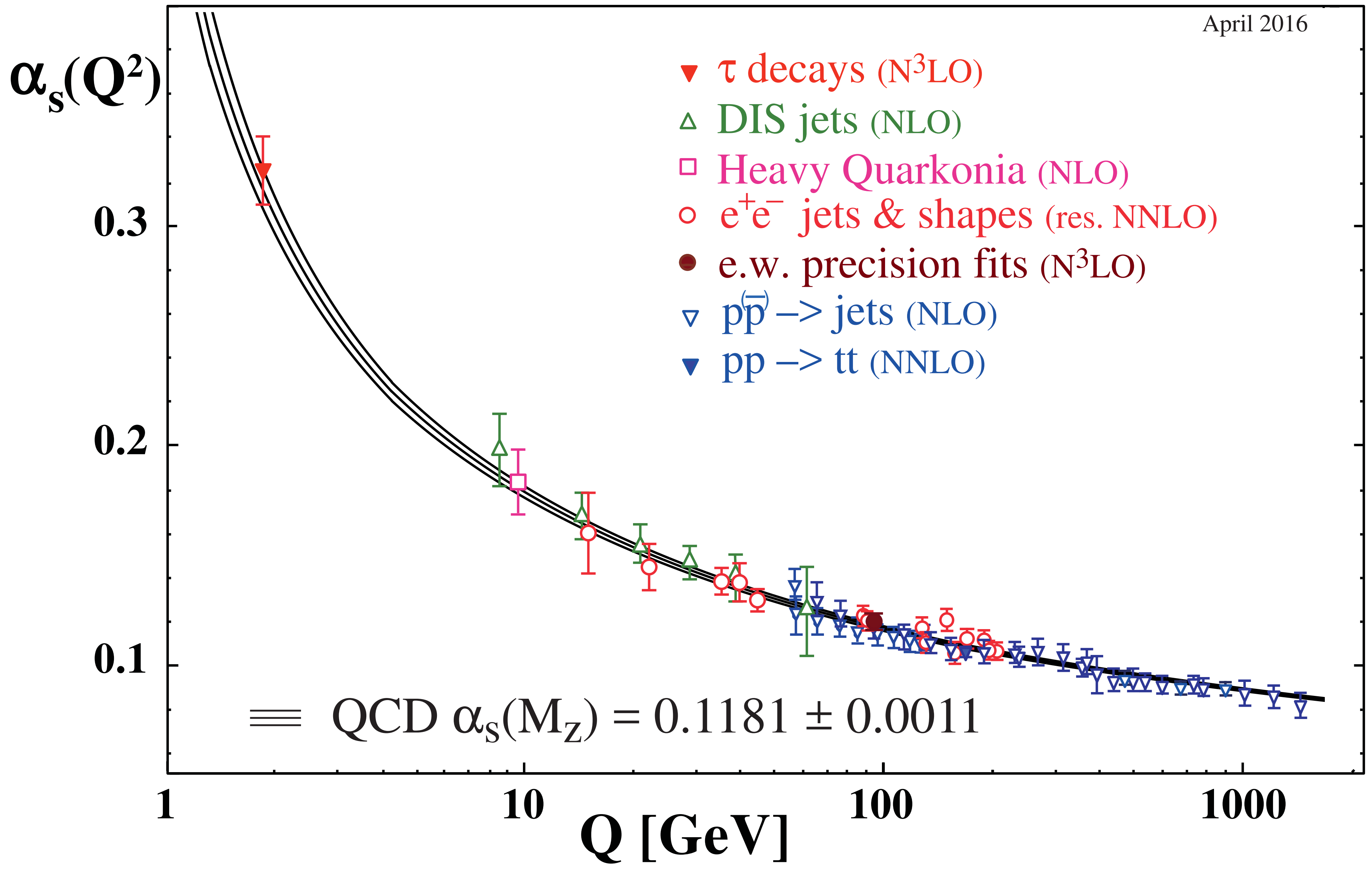
QCD running coupling constant

Hadronic physics: we study hadrons









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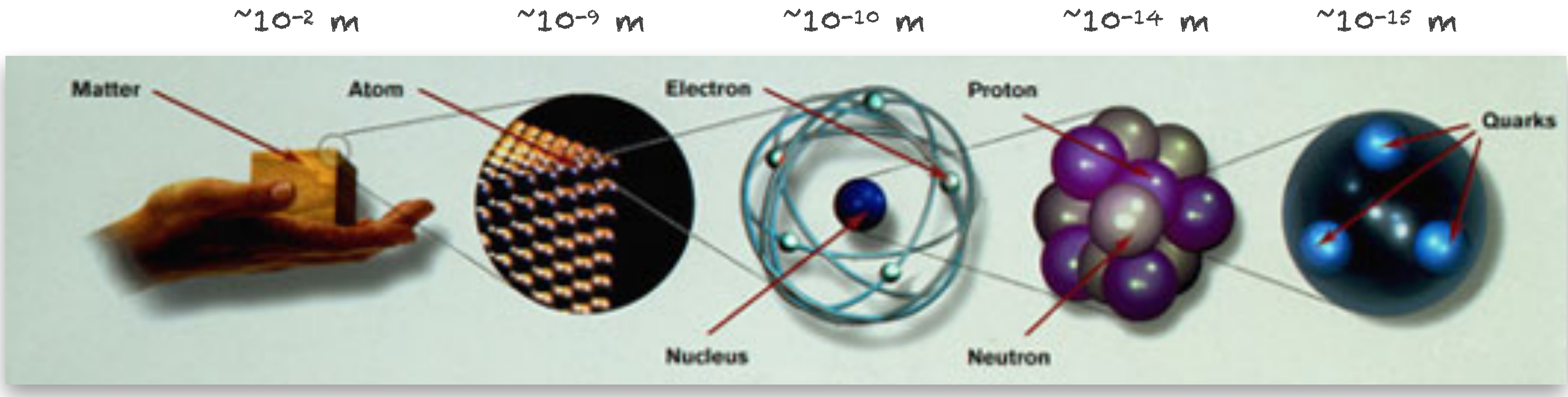
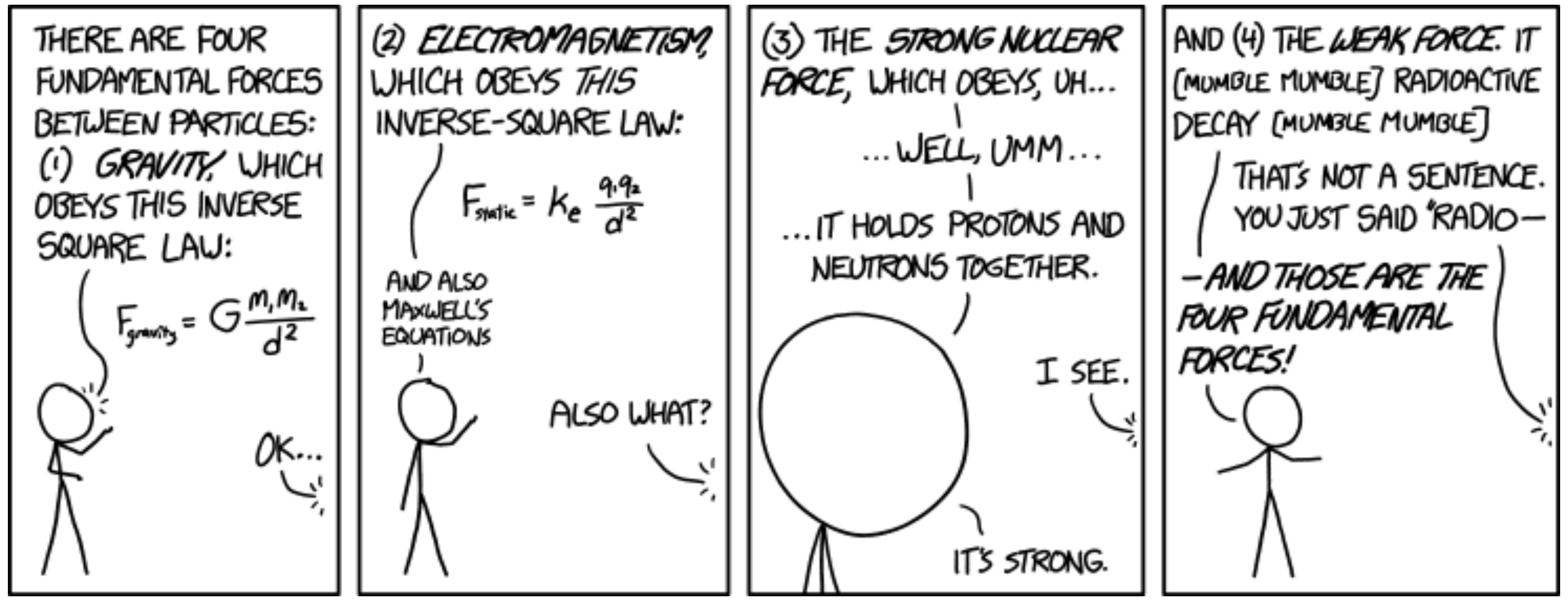
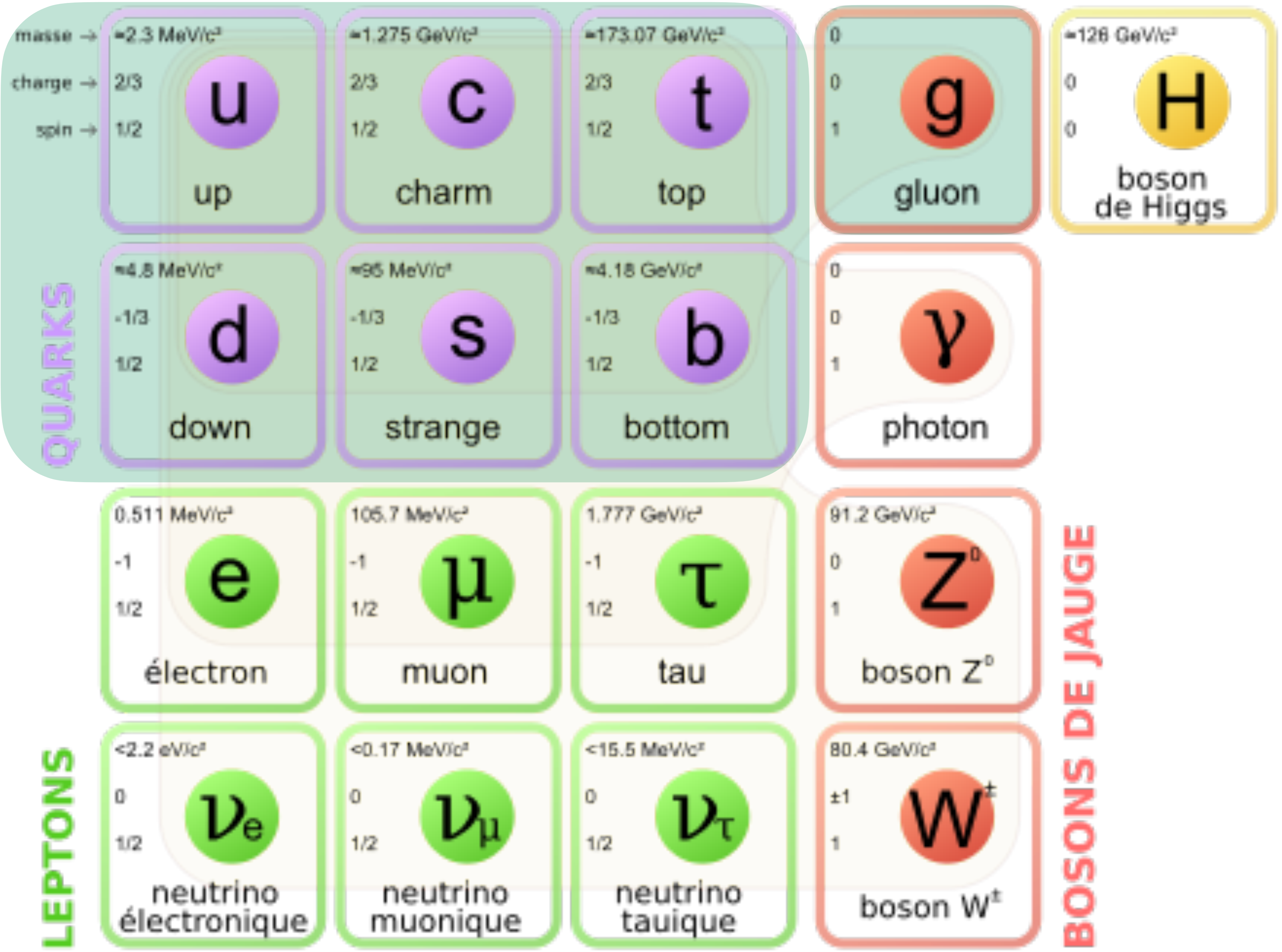
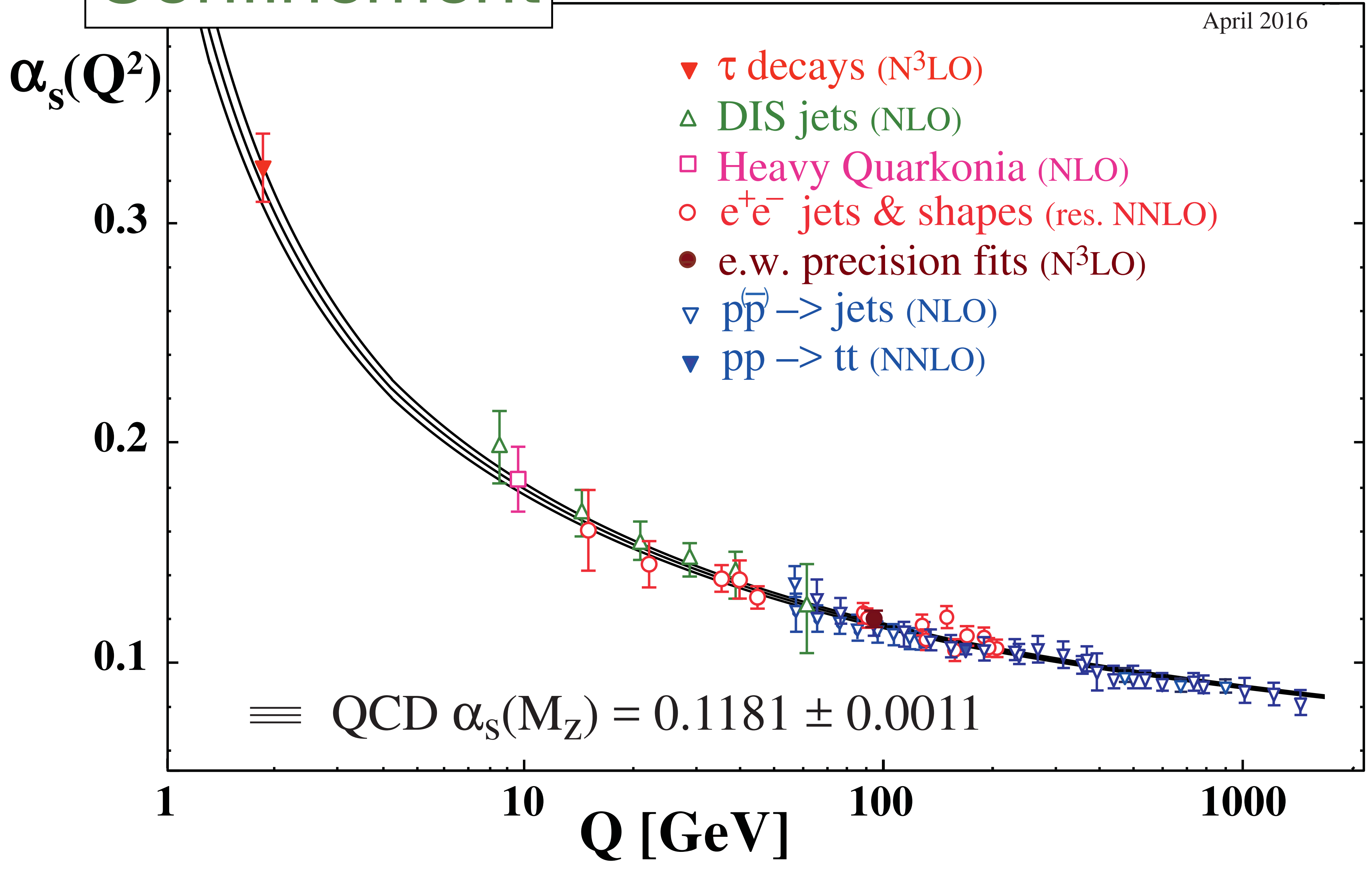






Confinement



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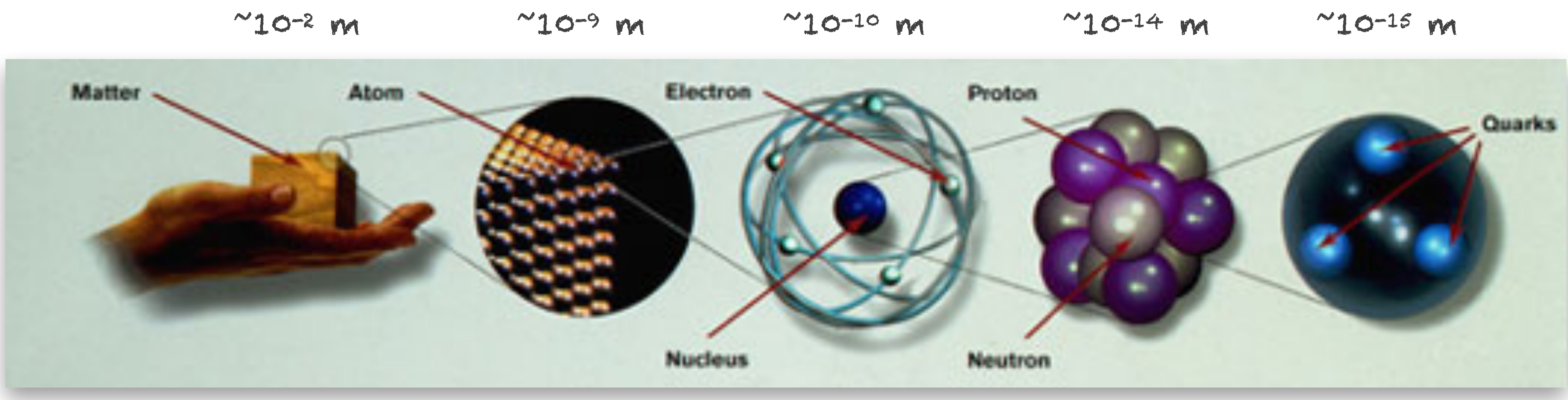

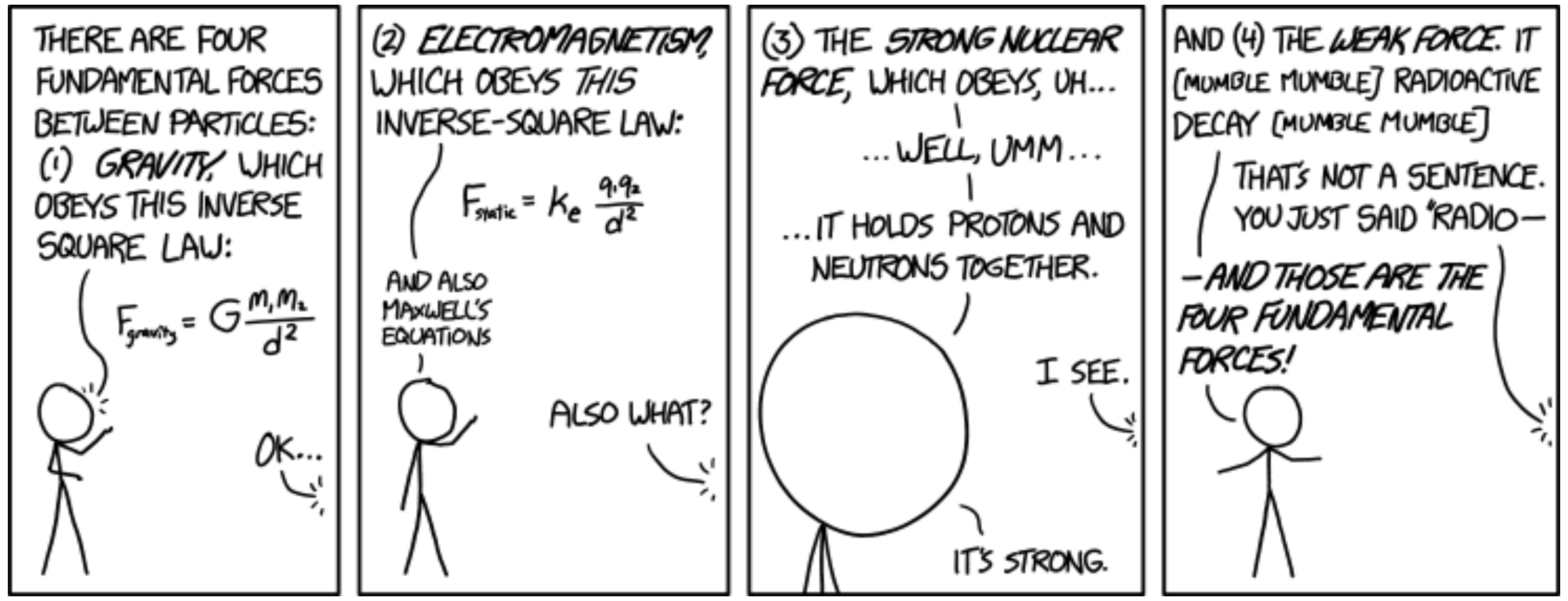

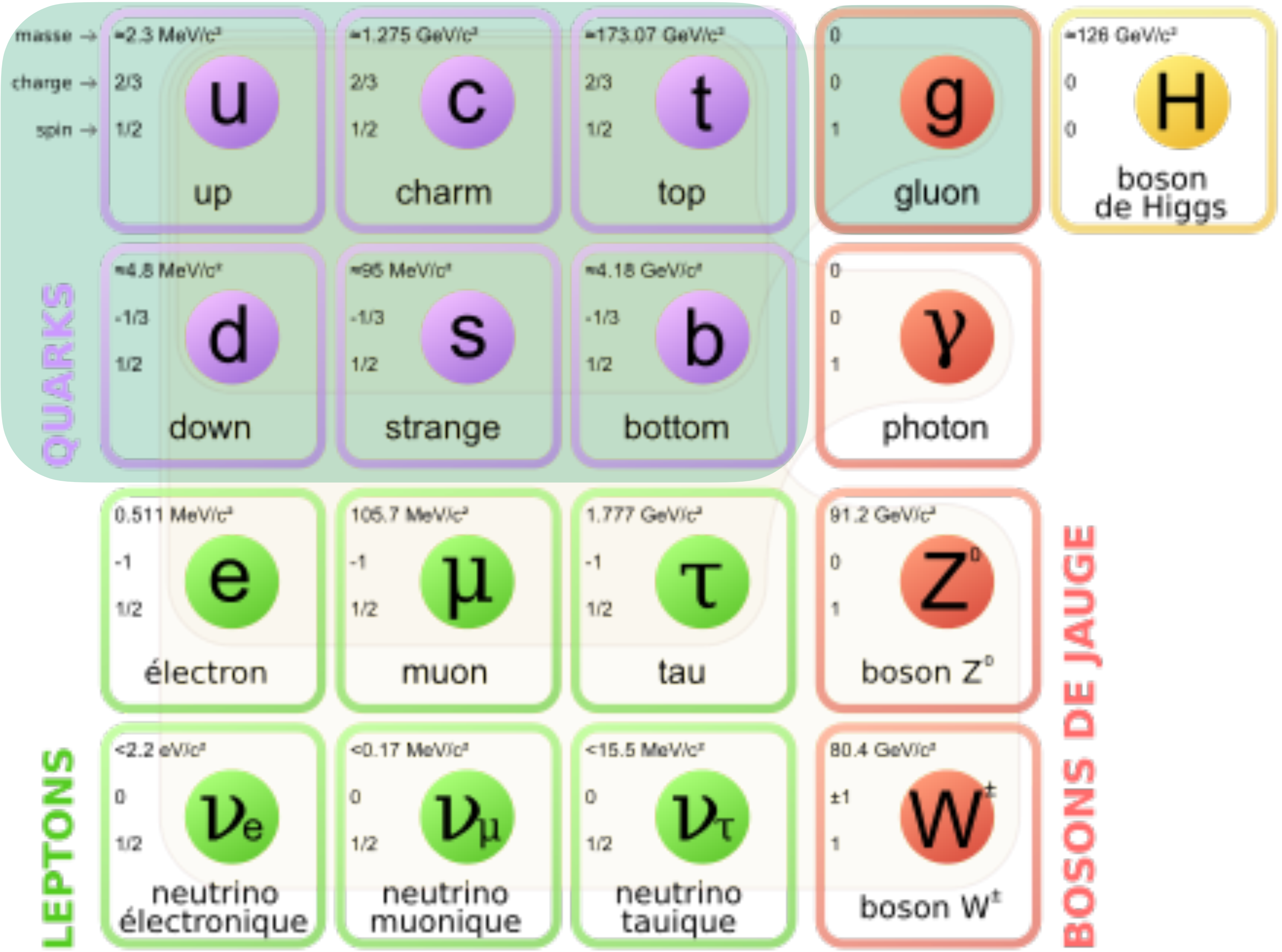

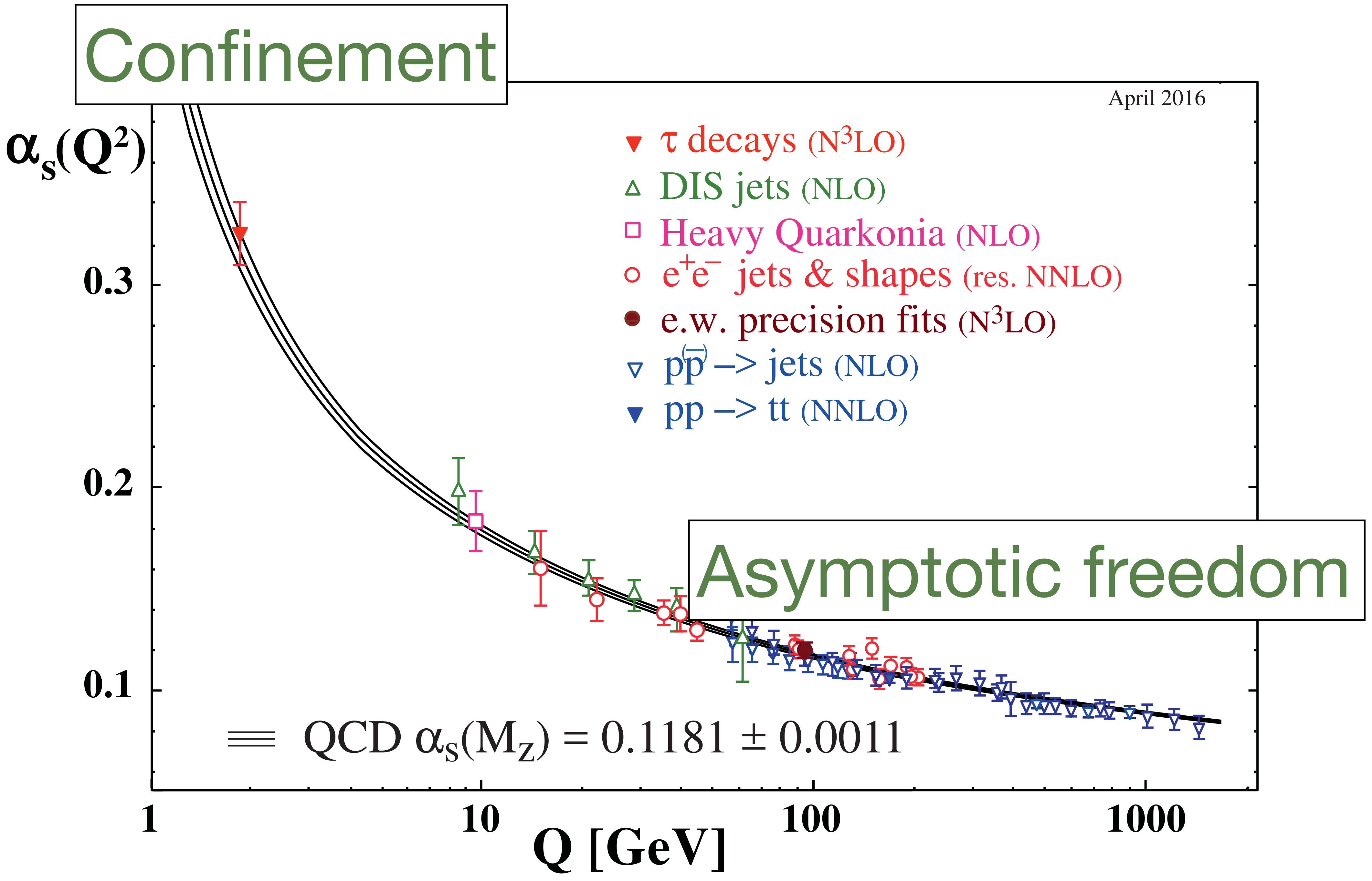

Hadrons = particles made of quarks and gluons

QCD running coupling constant

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).
- Goal: understanding of QCD to qualitatively describe a wide array of hadronic phenomena.
- 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 ?
  - Can we determine **precisely the parameters of QCD**? (Λ_{QCD}, QCD vacuum parameter, mass of quarks)
  - What is the **origin and dynamics of confinement?**
  - What are the roles of quarks and gluons in nuclei and **matter under extreme condition**?

Hadronic physics in the landscape of physics

Energy per nucleon

Few keV-MeV

GeV to TeV

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Energy per nucleon

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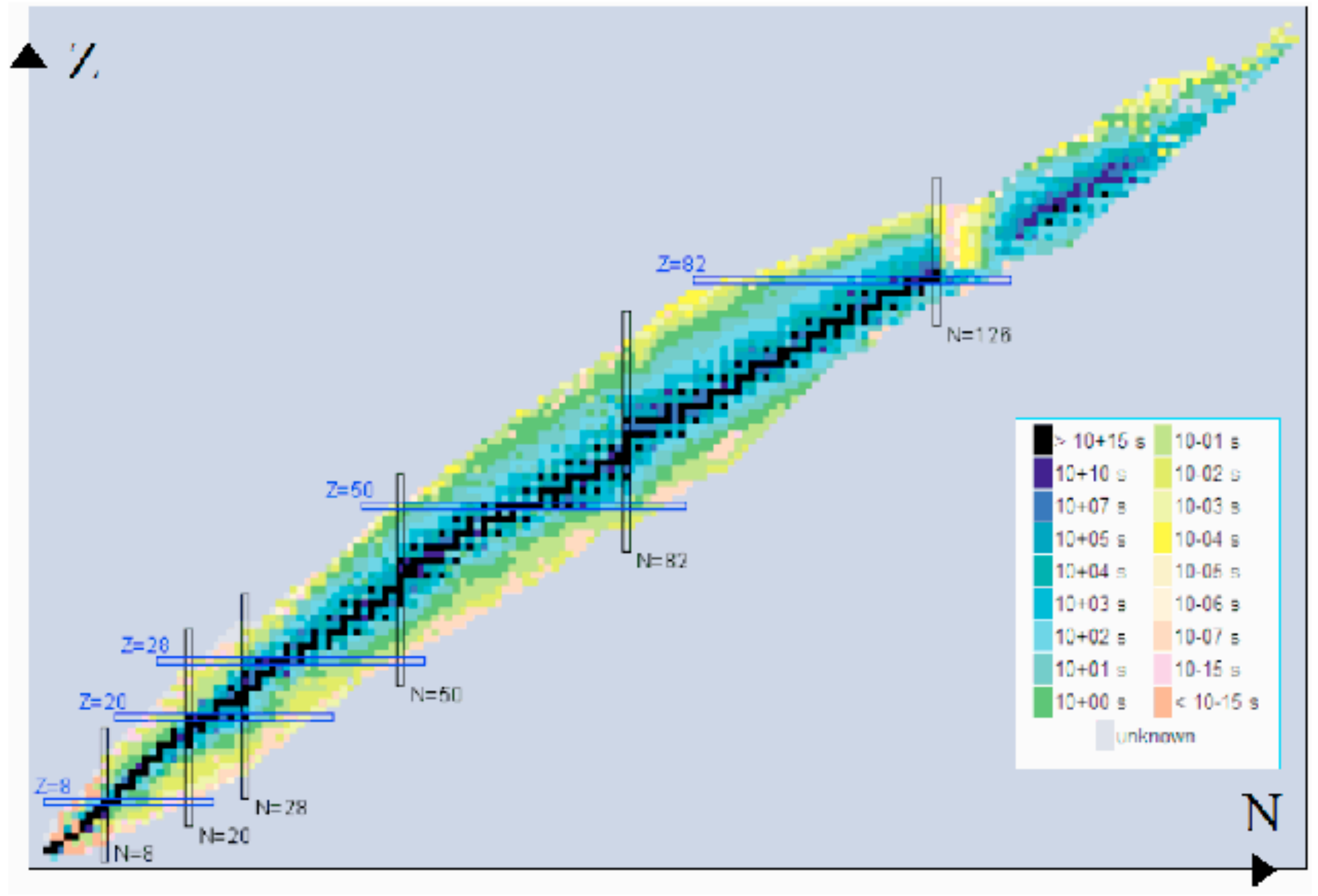
GeV to TeV

Nuclear physics



- Few keV to MeV per nucleons.
- Study nuclei as a whole.
- Typical research fields:
  - New stable states.
  - Excited states.
  - Krampouz resonance.

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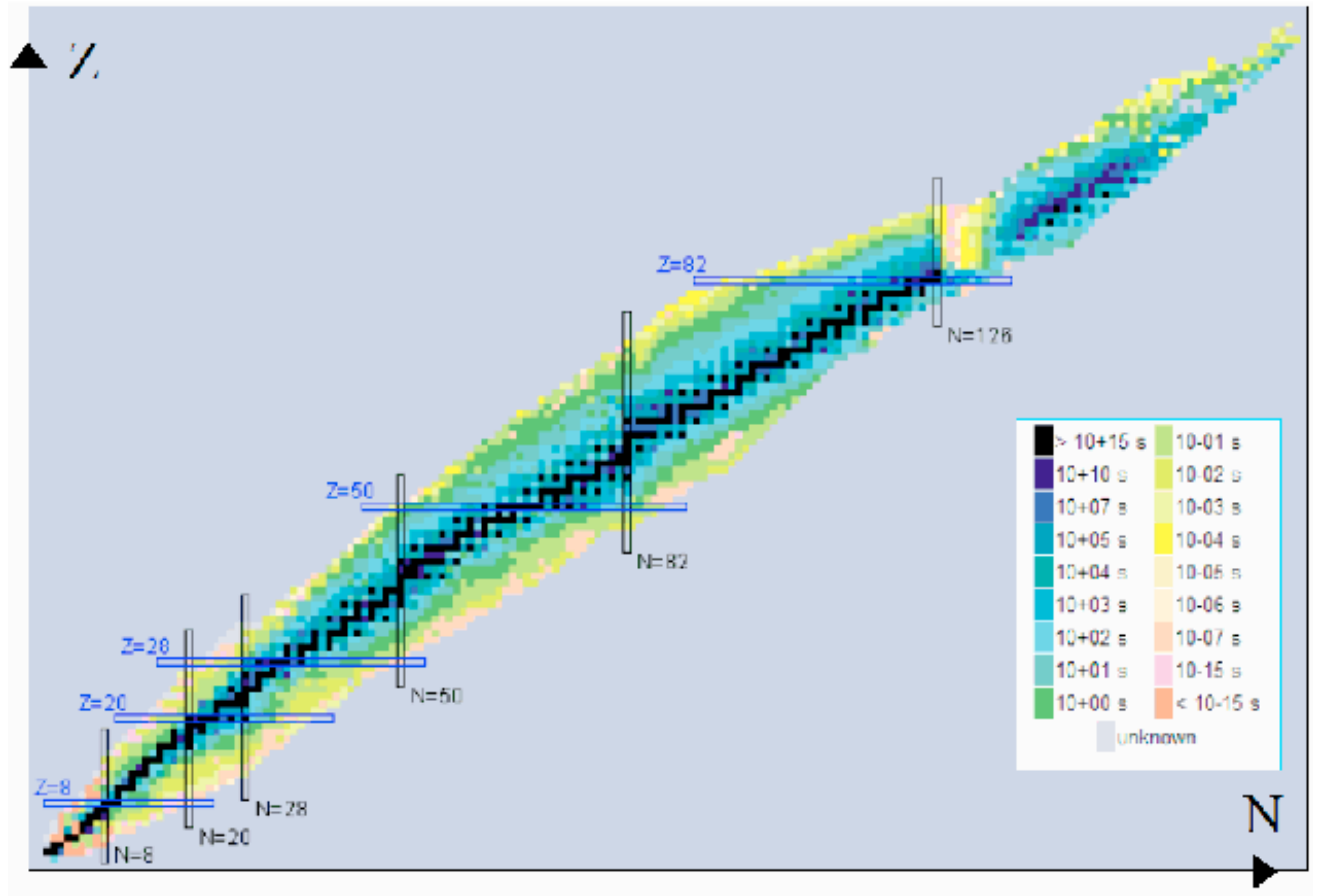

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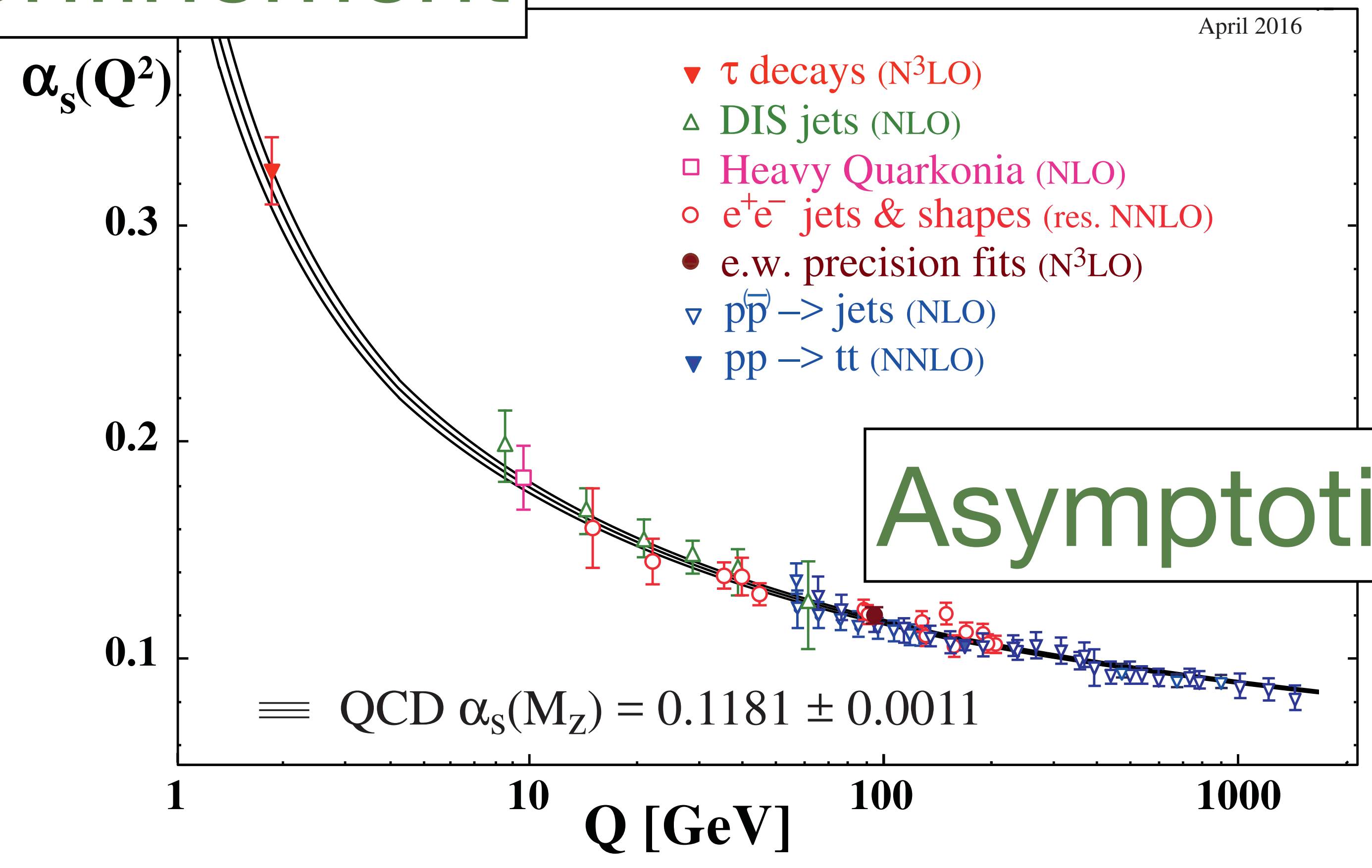


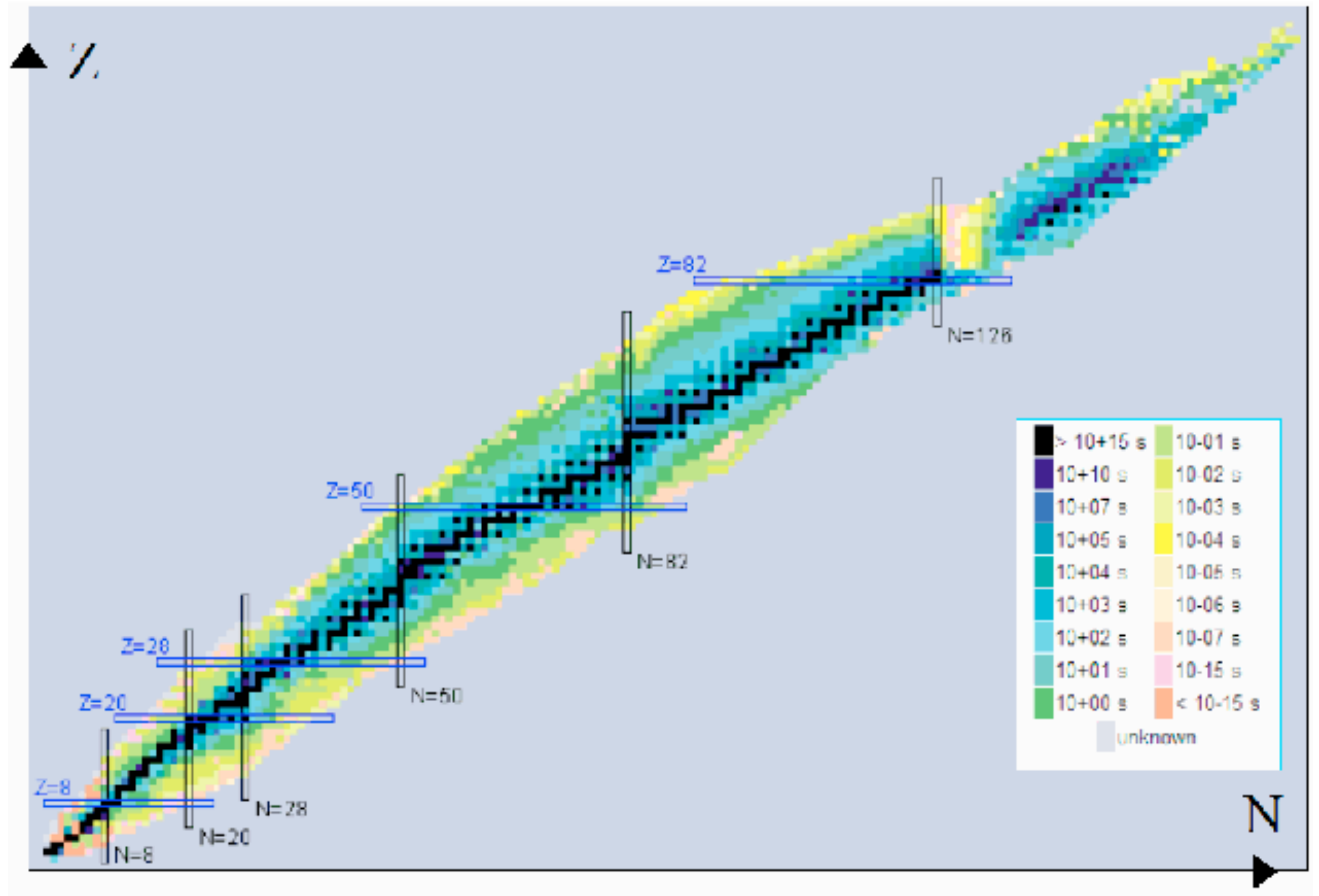
Asymptotic freedom

Hadronic physics in the landscape of physics

Energy per nucleon

Few keV-MeV — GeV to TeV

Nuclear physics



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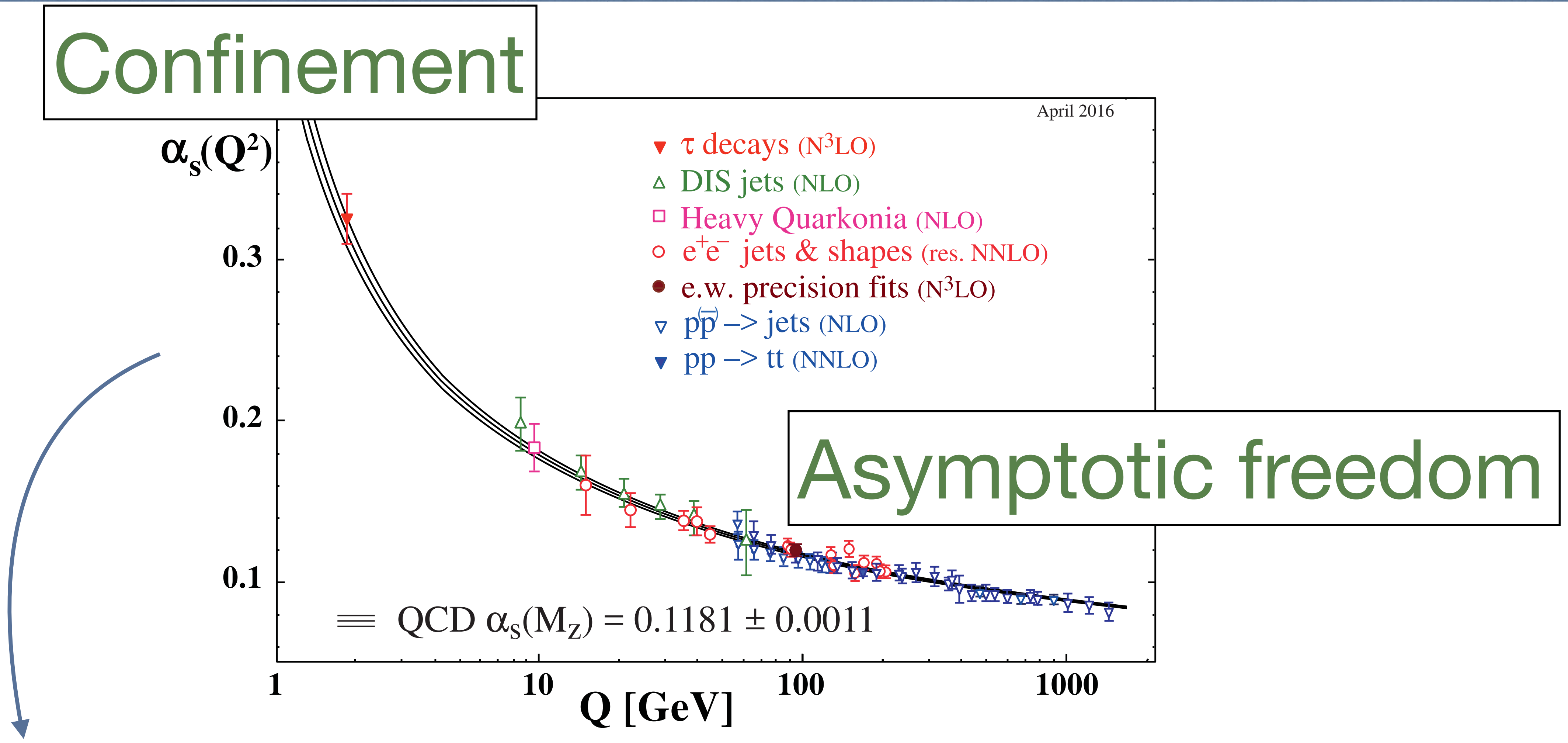
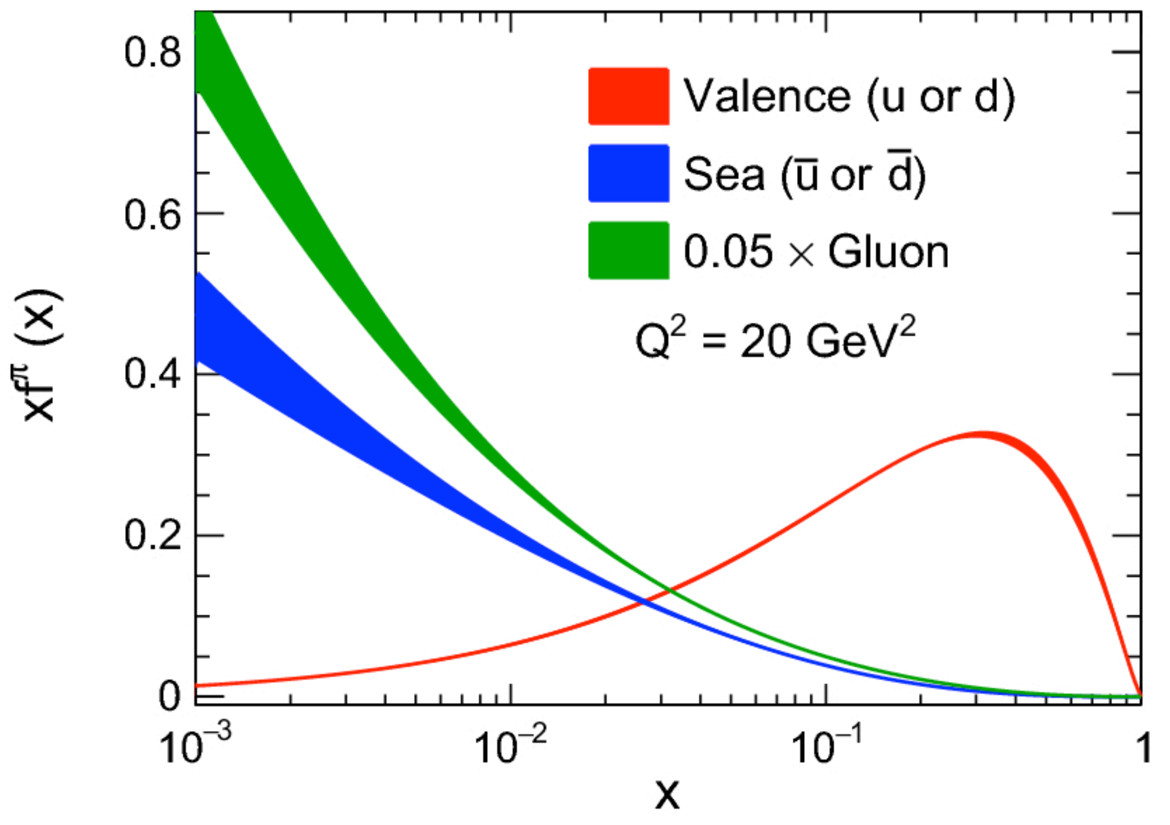


Hadronic structure



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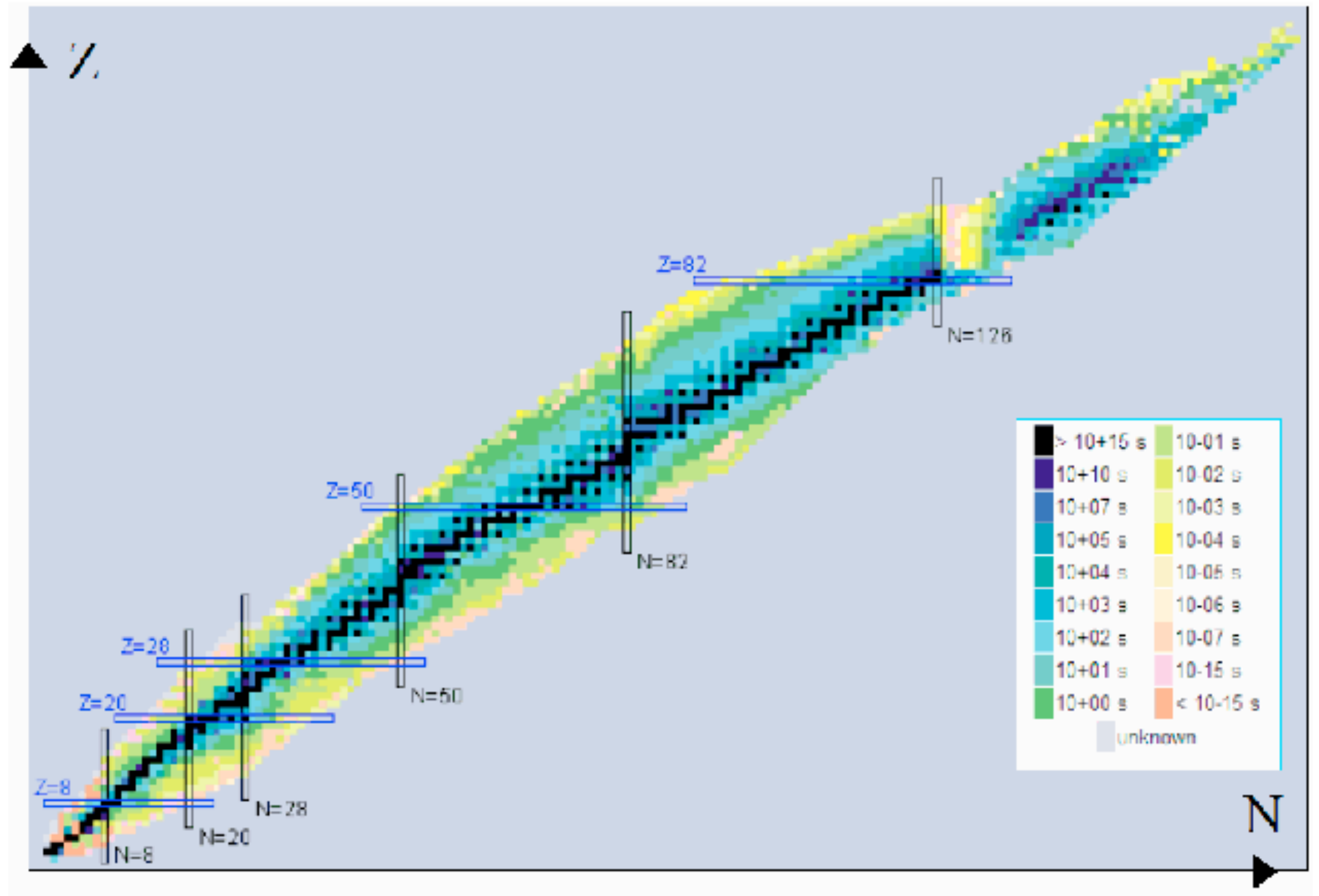

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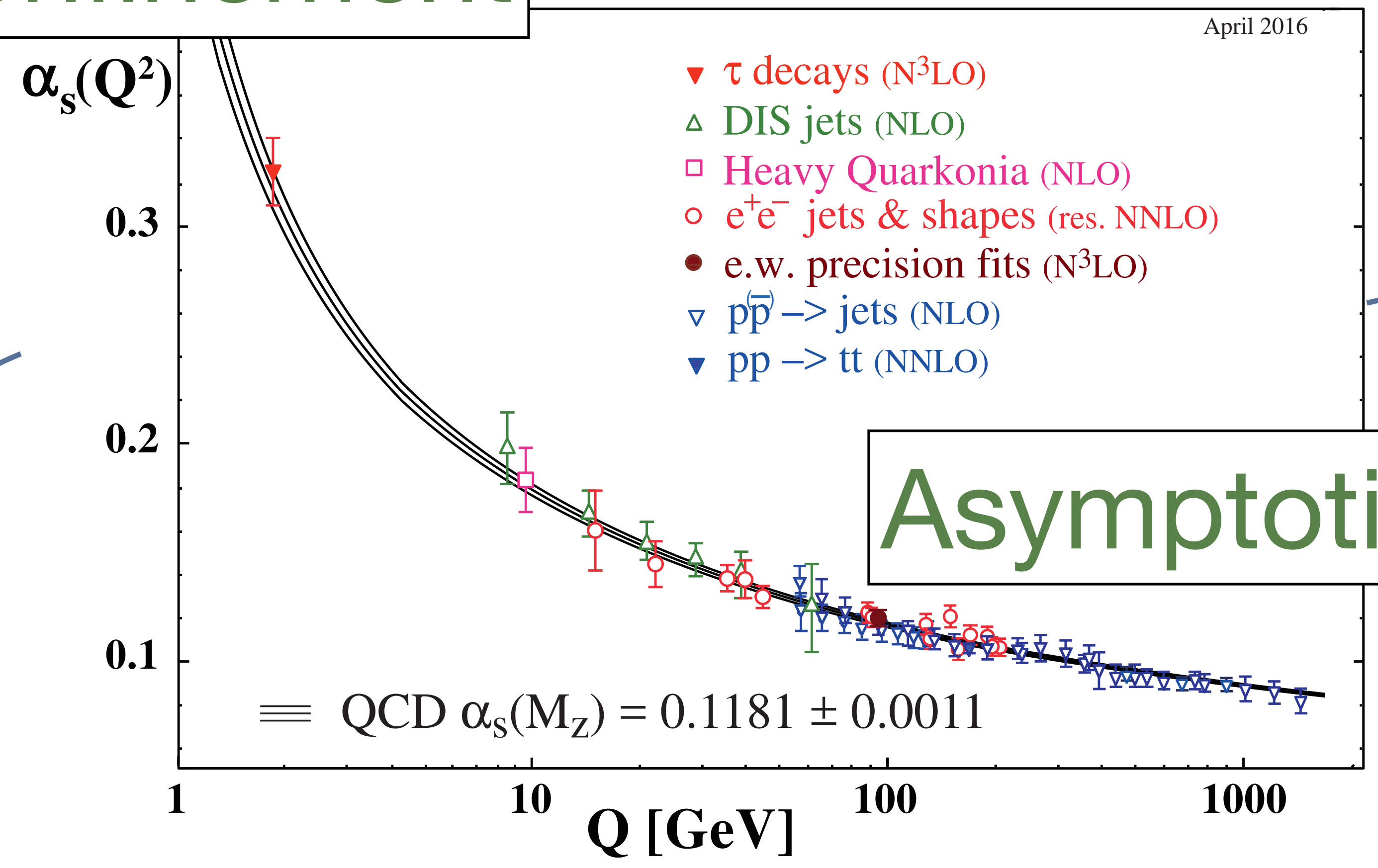

Asymptotic freedom

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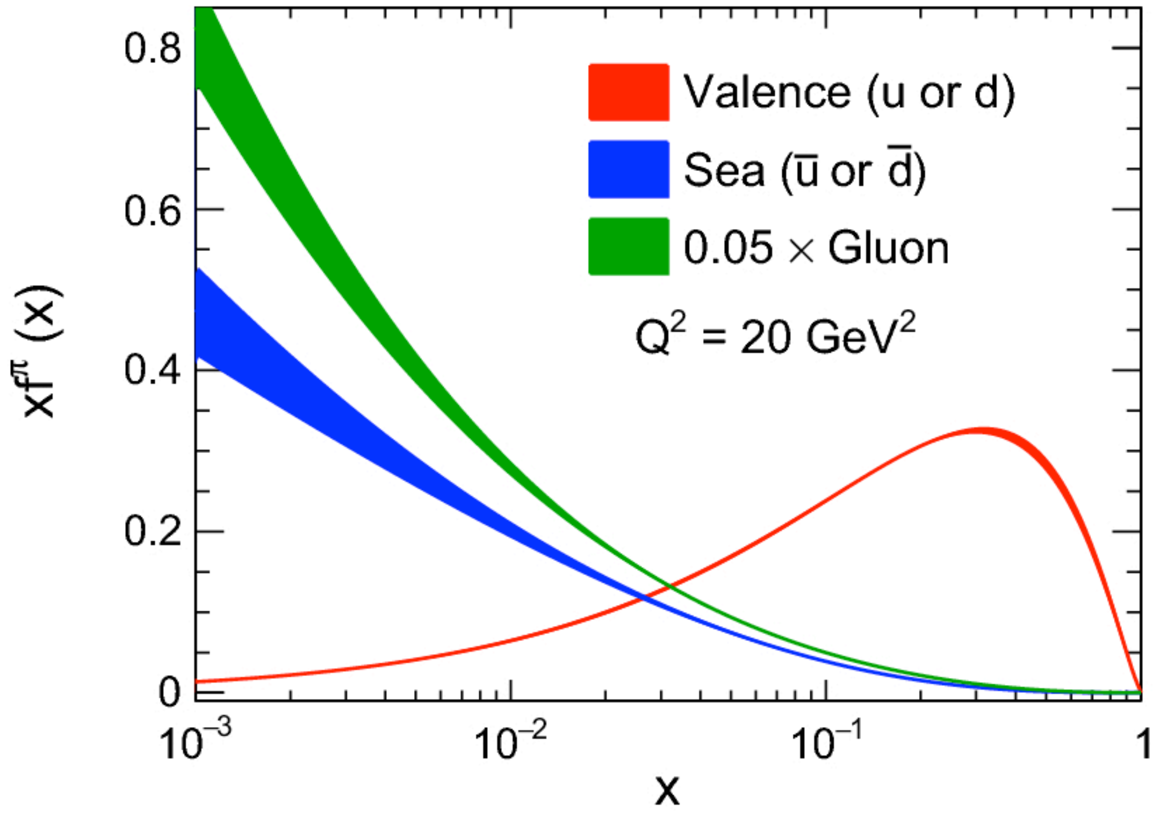
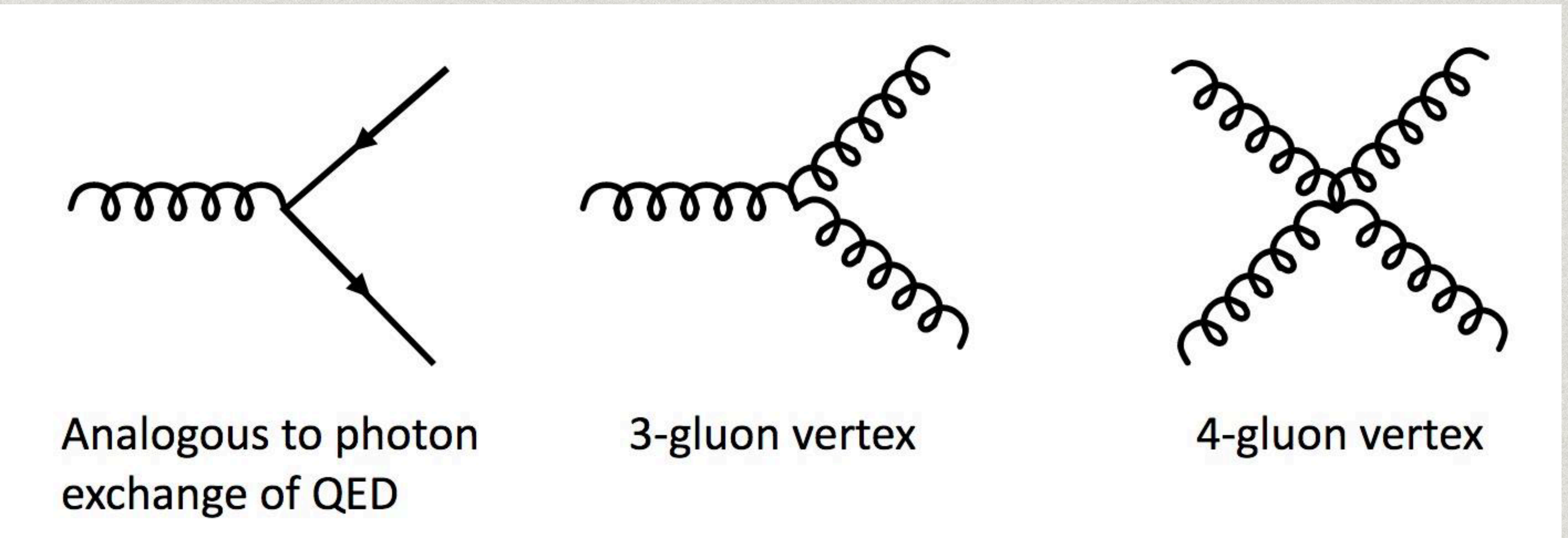


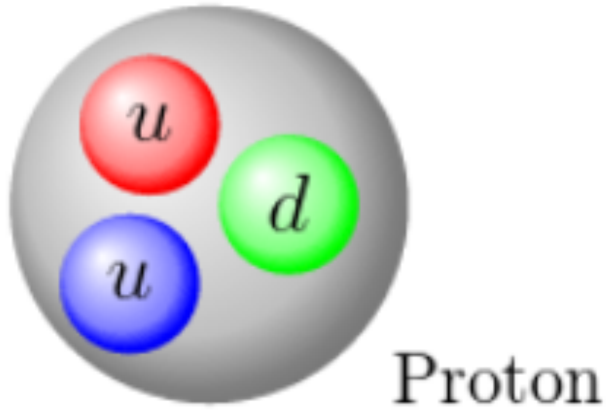
Quark-Gluon plasma

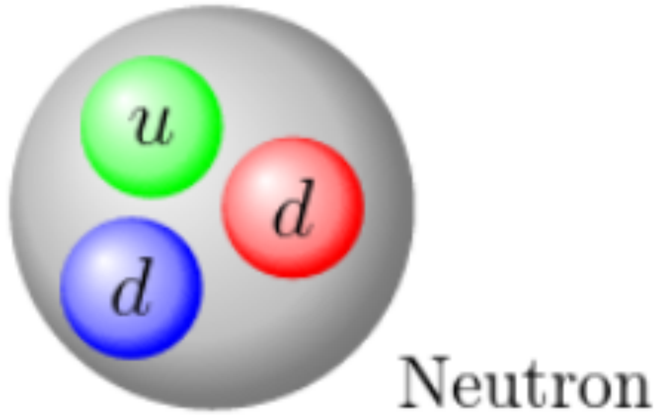


« A theory which is not renormalizable (QCD) is garbage anyway »

-My PhD director the first day of my PhD

Composition of a proton





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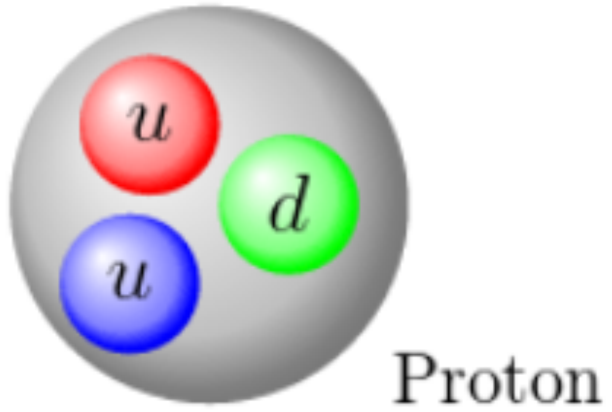

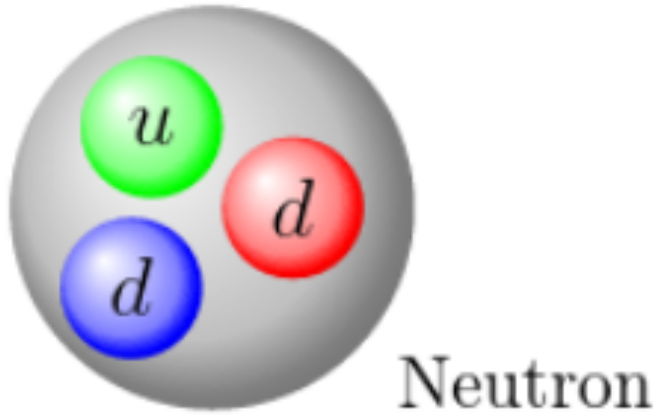

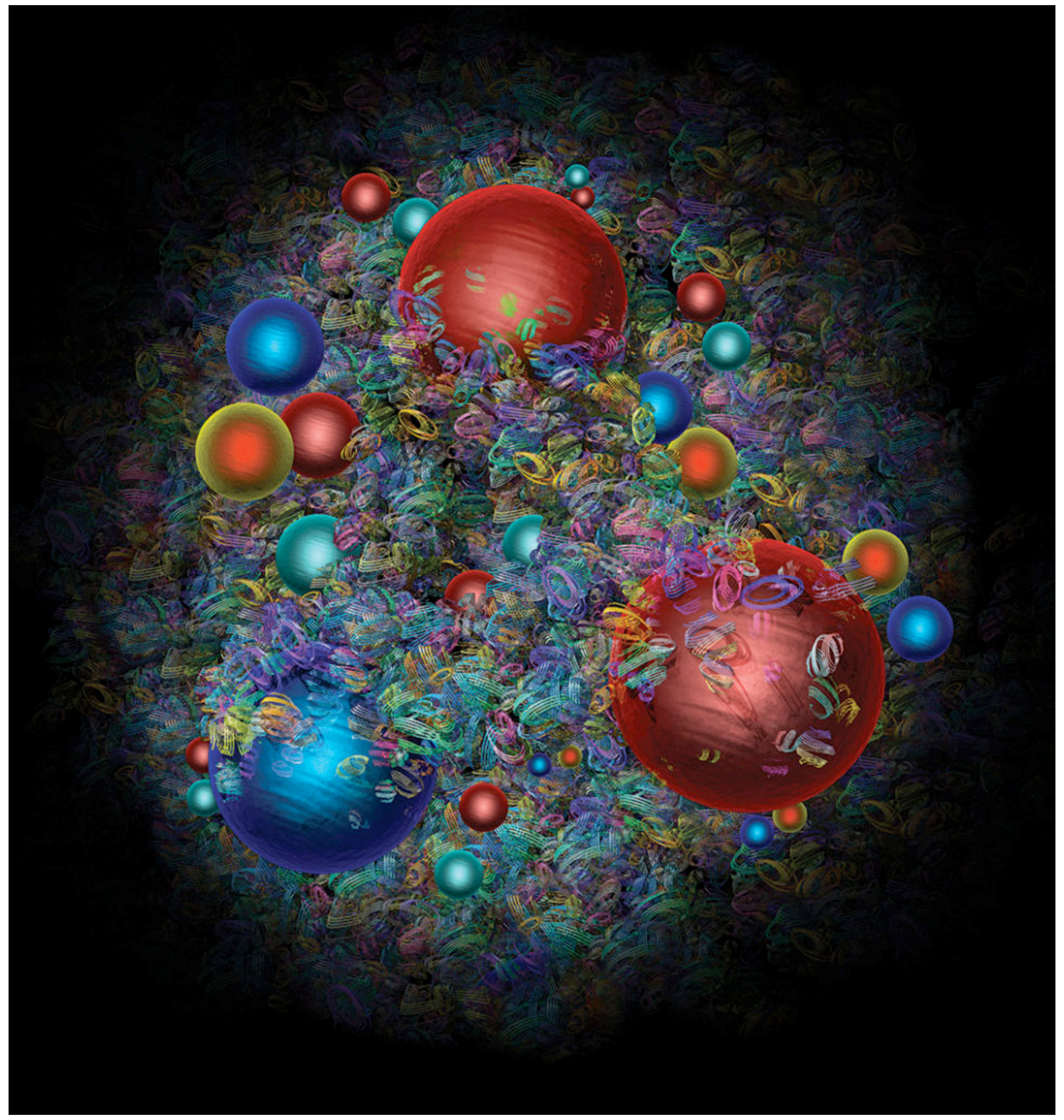

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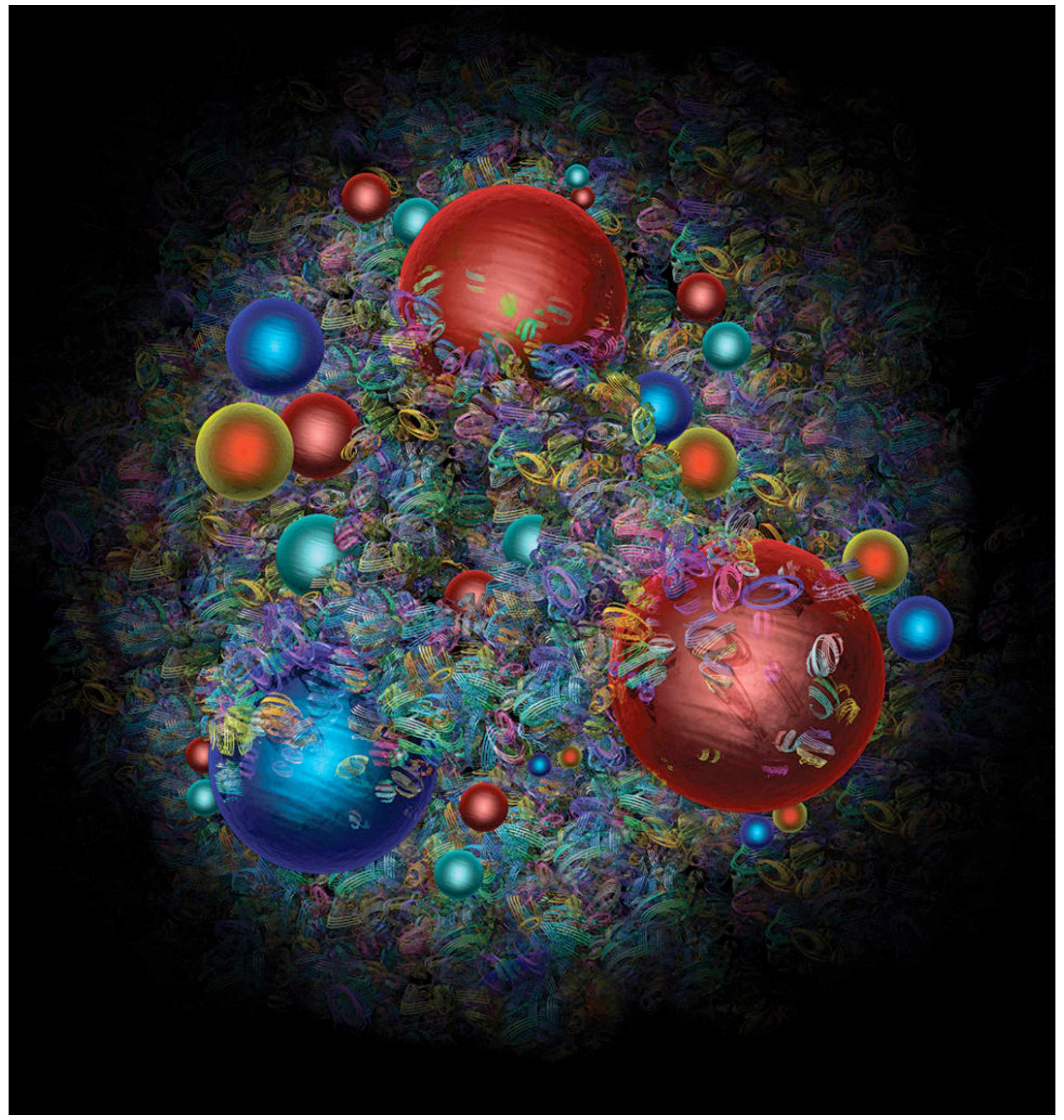
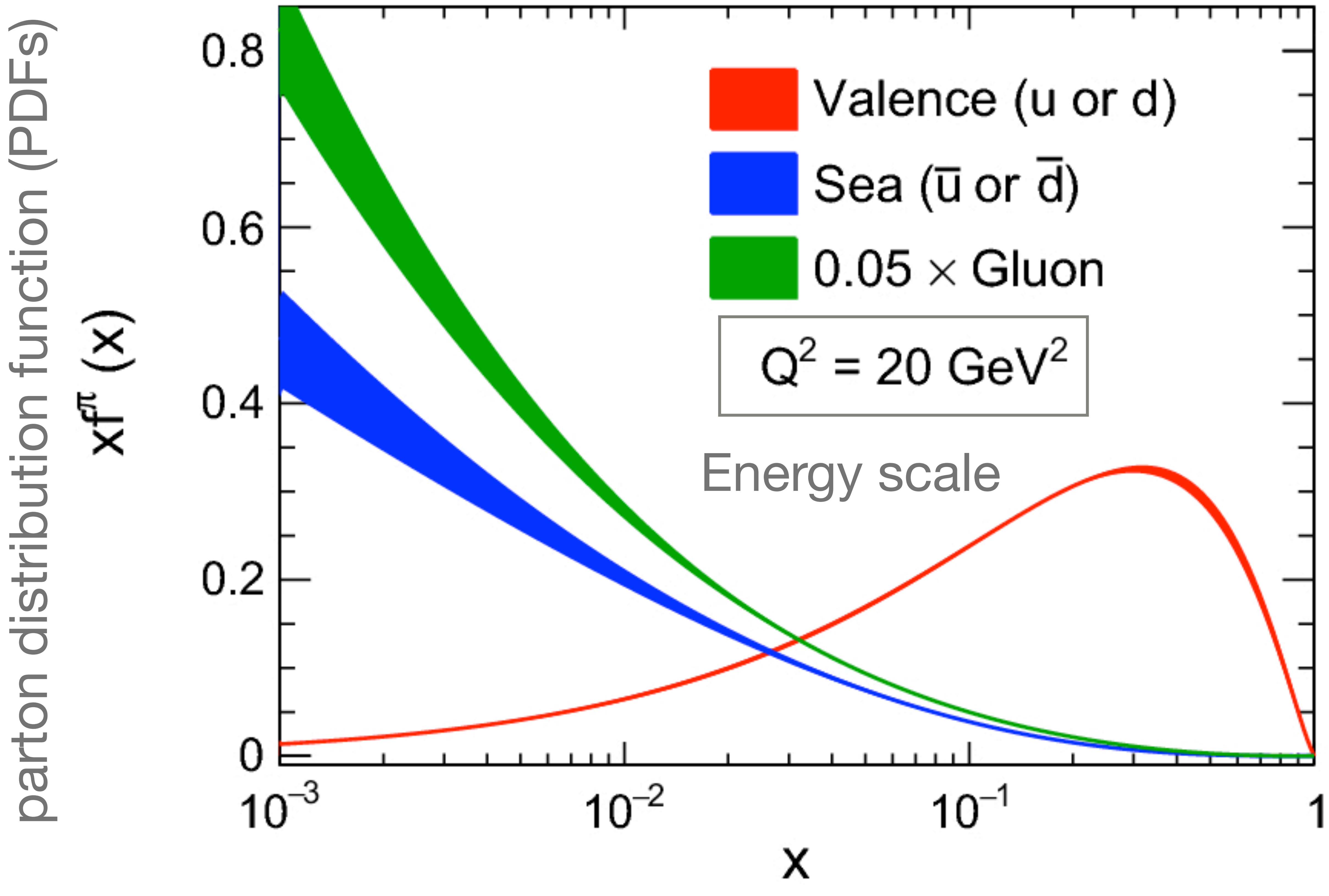
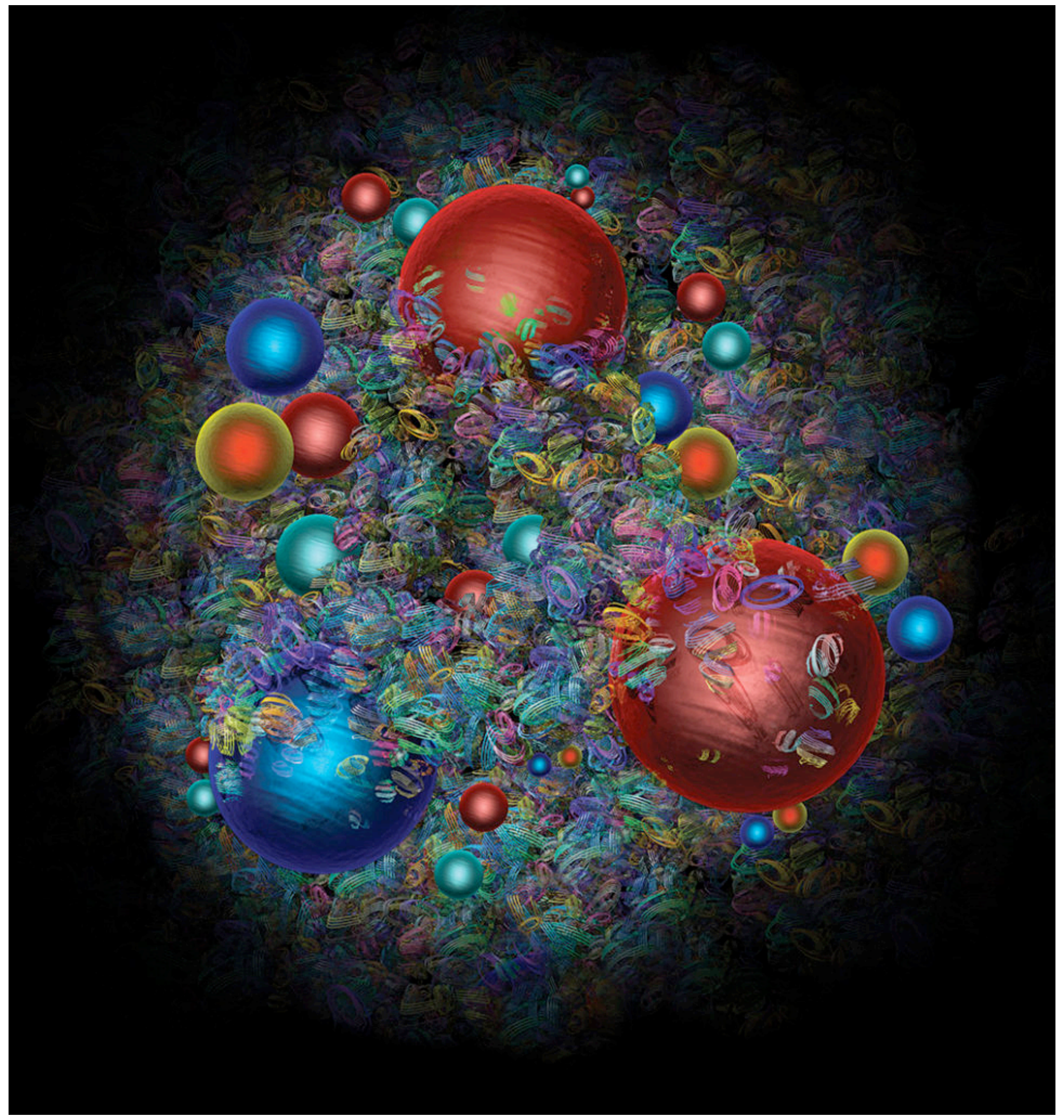
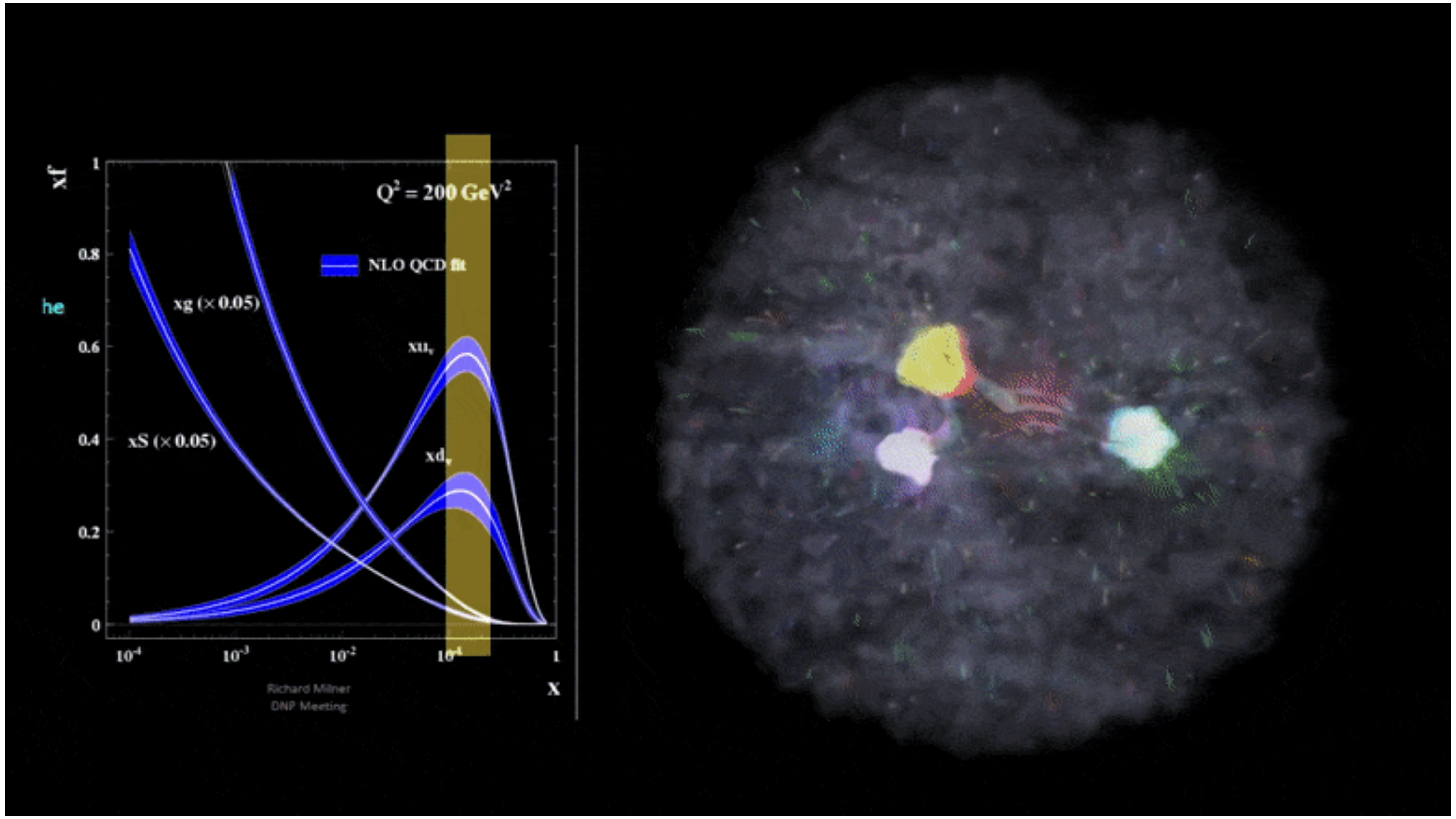




$x = P_{parton} / P_{hadron}$

Composition of a proton





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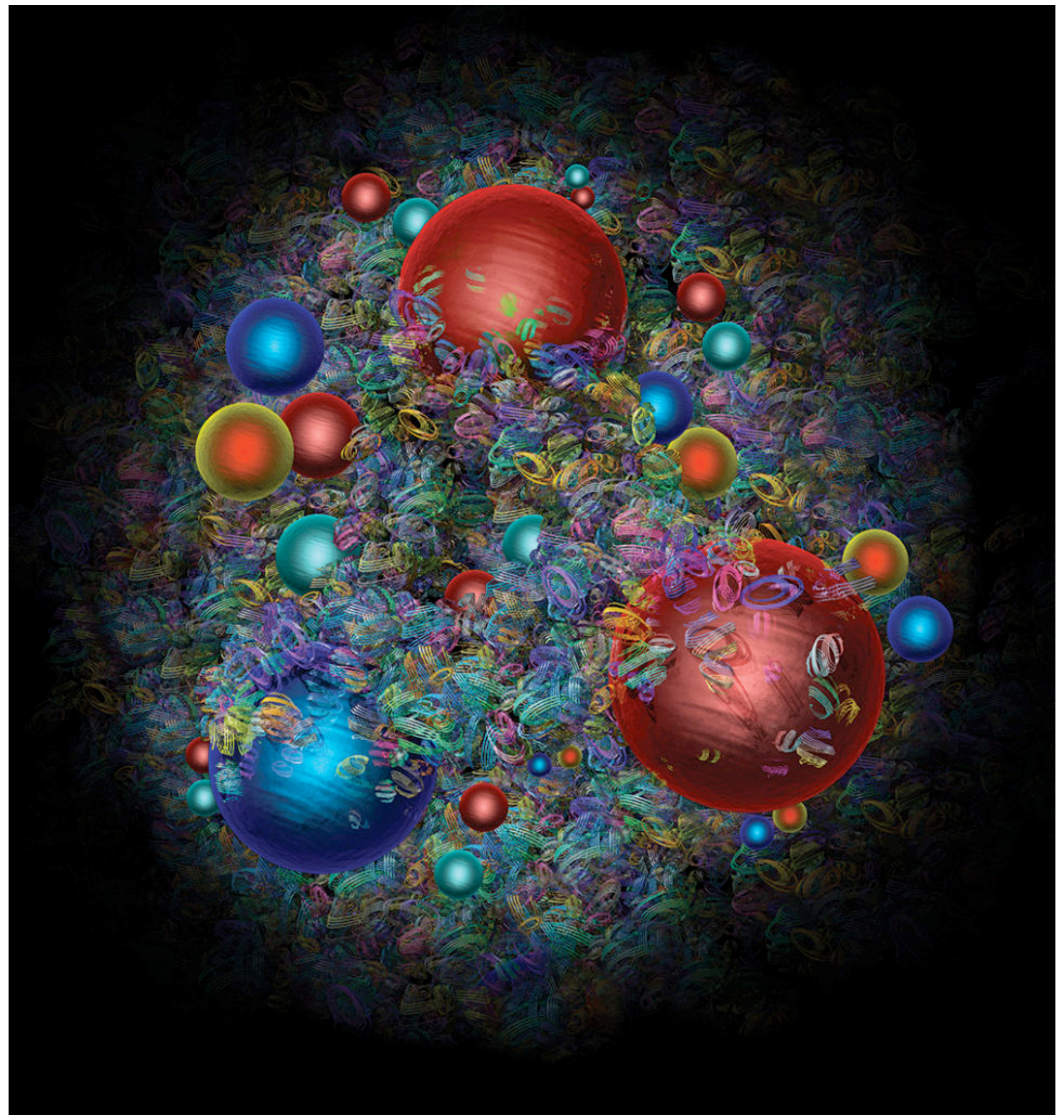
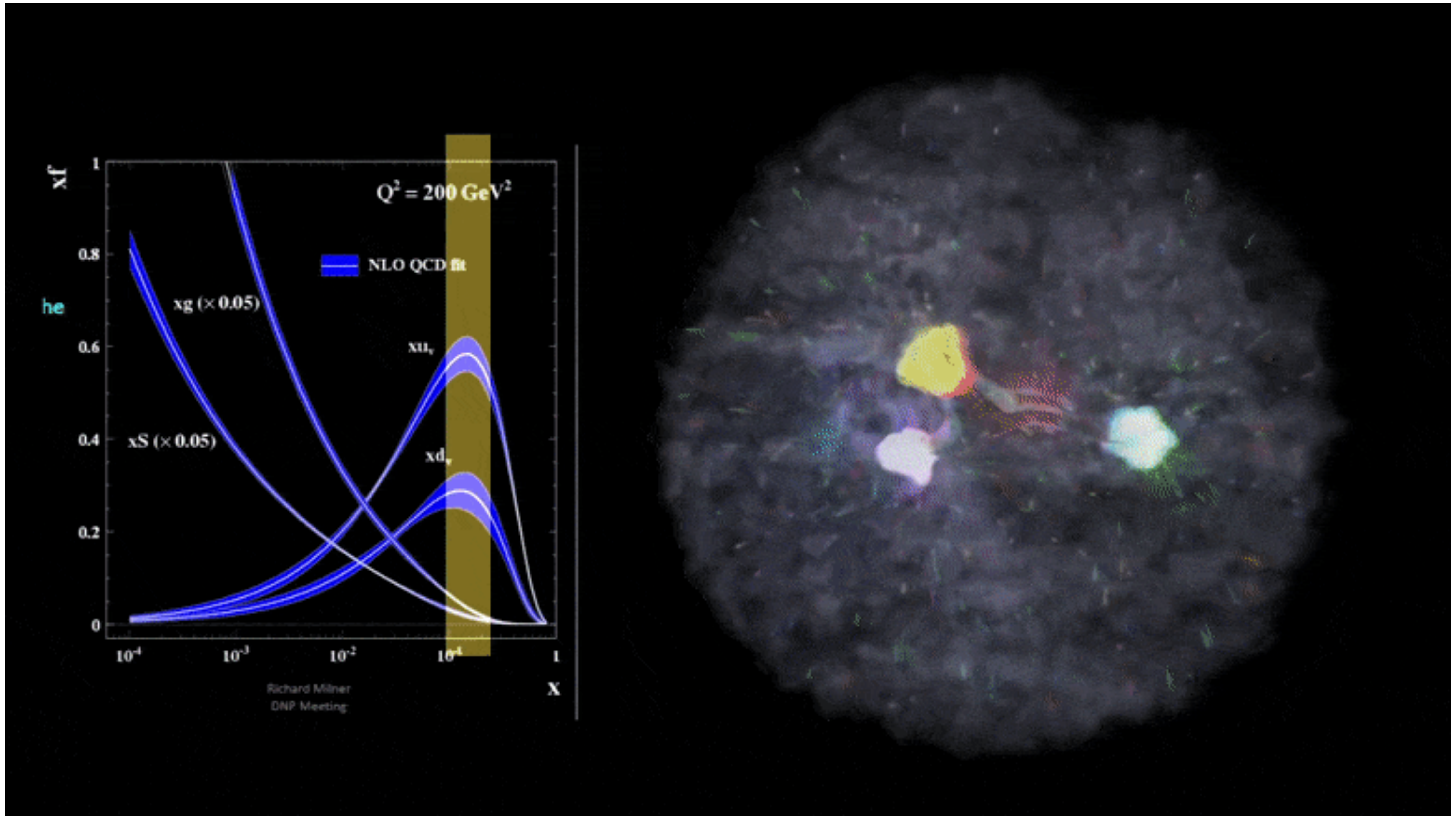
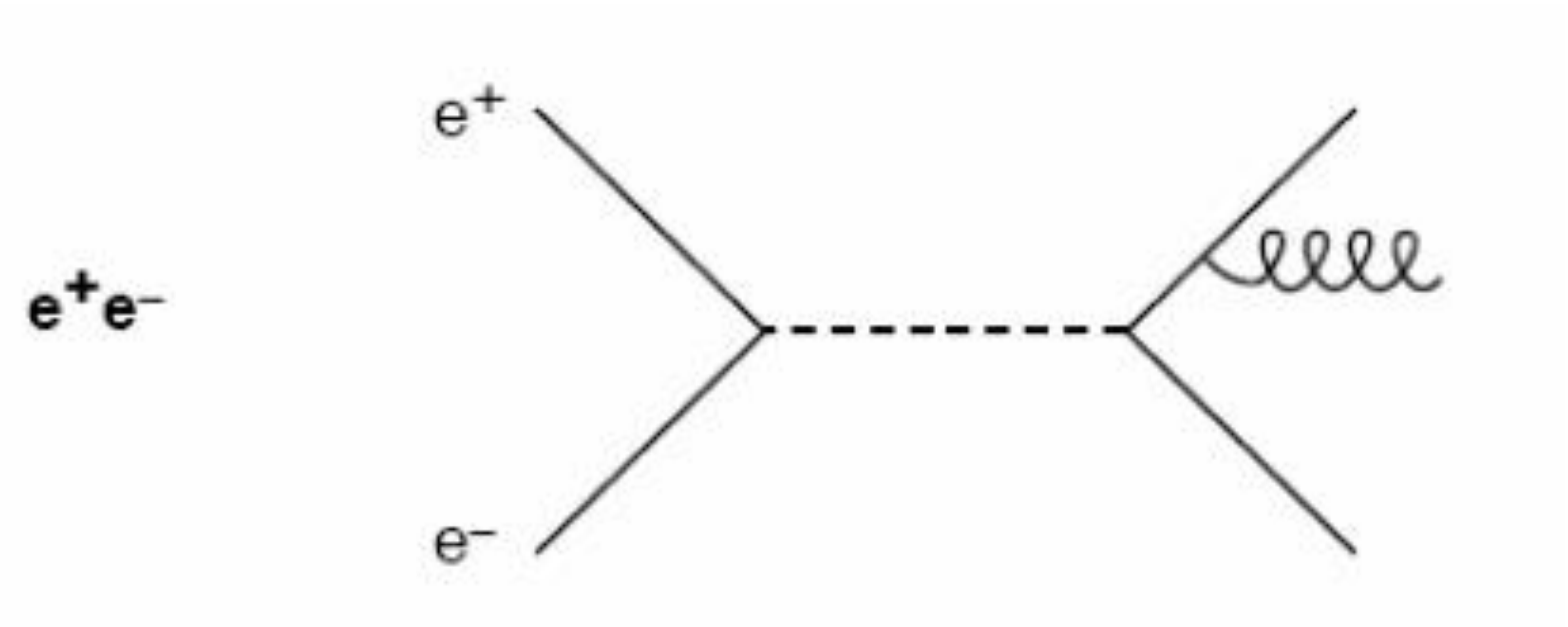




How do we measure that ?

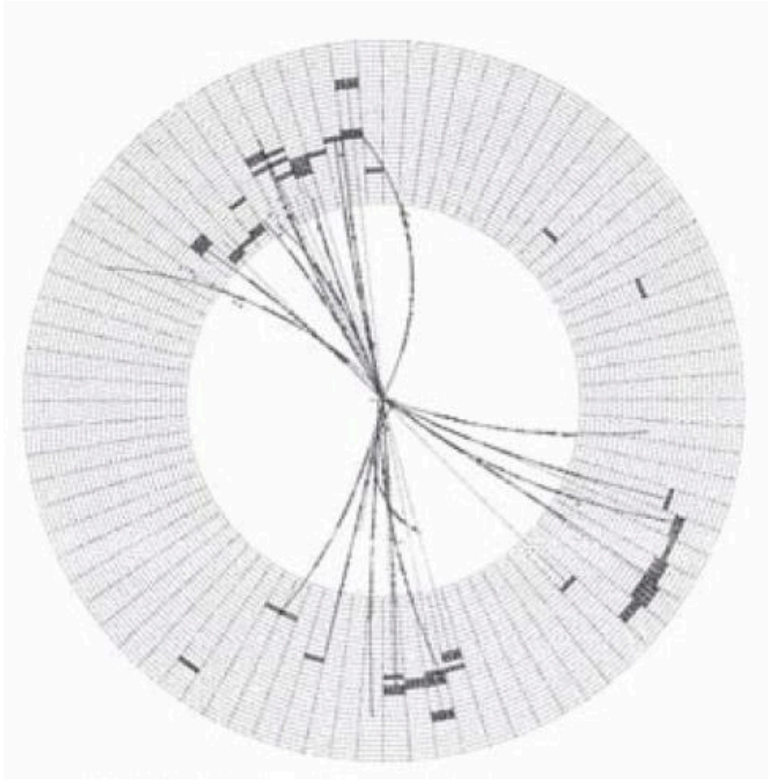
Many means for the same goal

e^+-e^- collisions



- No hadrons in initial state
- Production of multi-jets discovery of the gluon, gluon self-coupling

e+e- collider, √s = 12-47 GeV
3-jet event, JADE detector at PETRA, DESY (1977)



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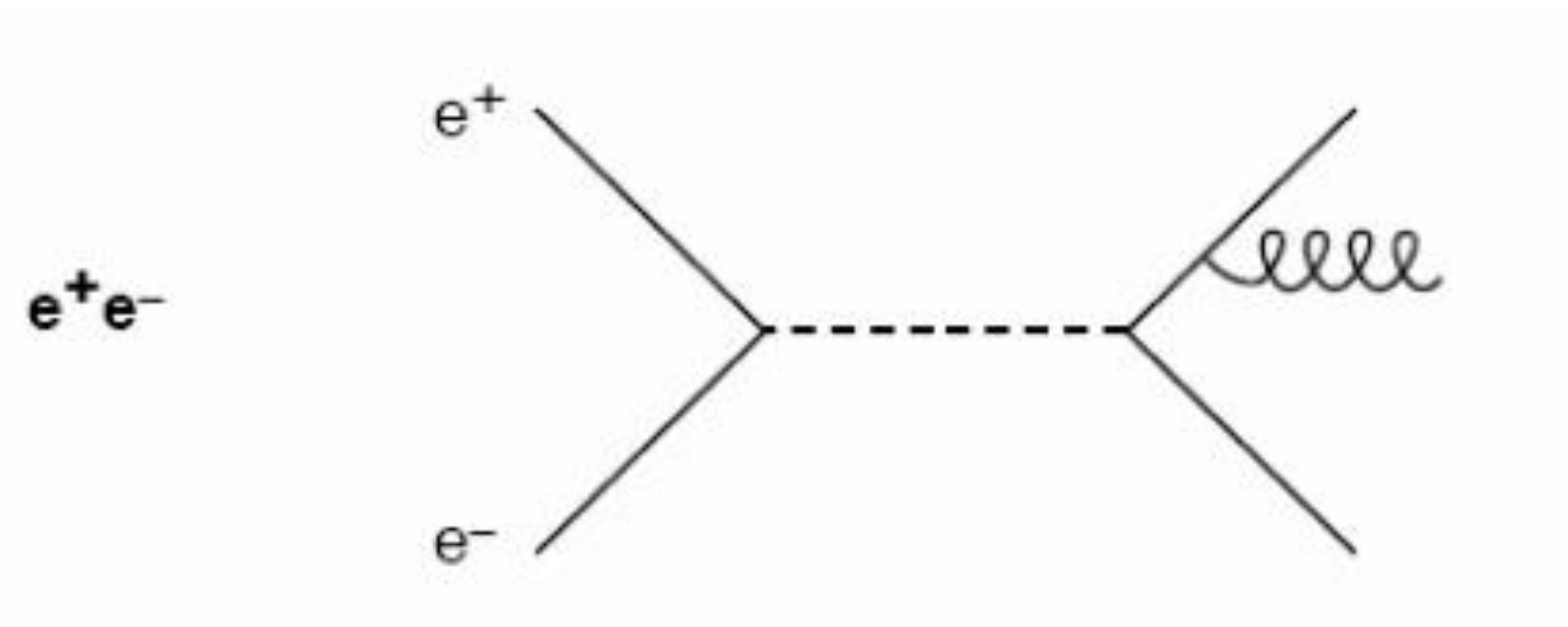

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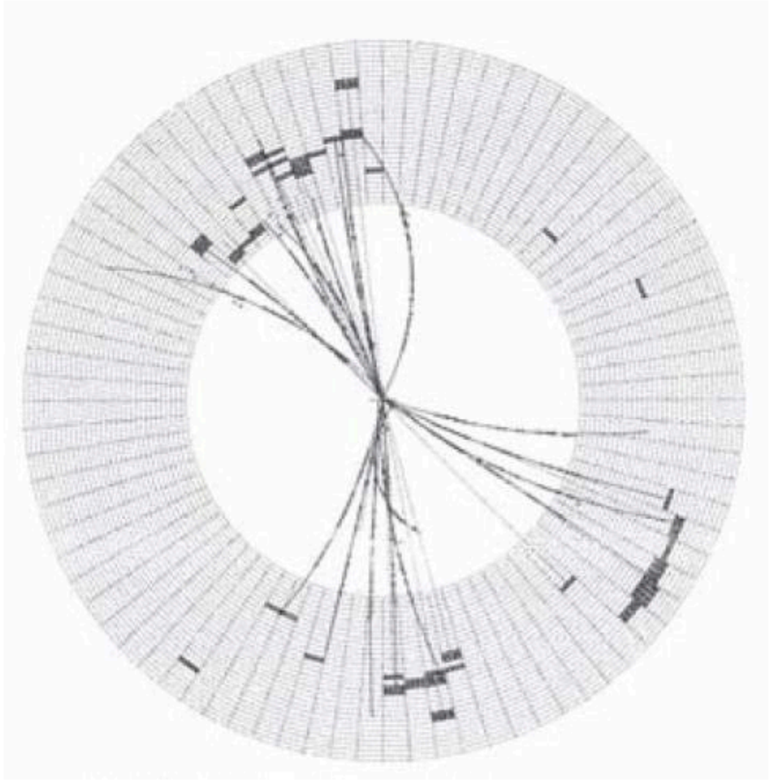
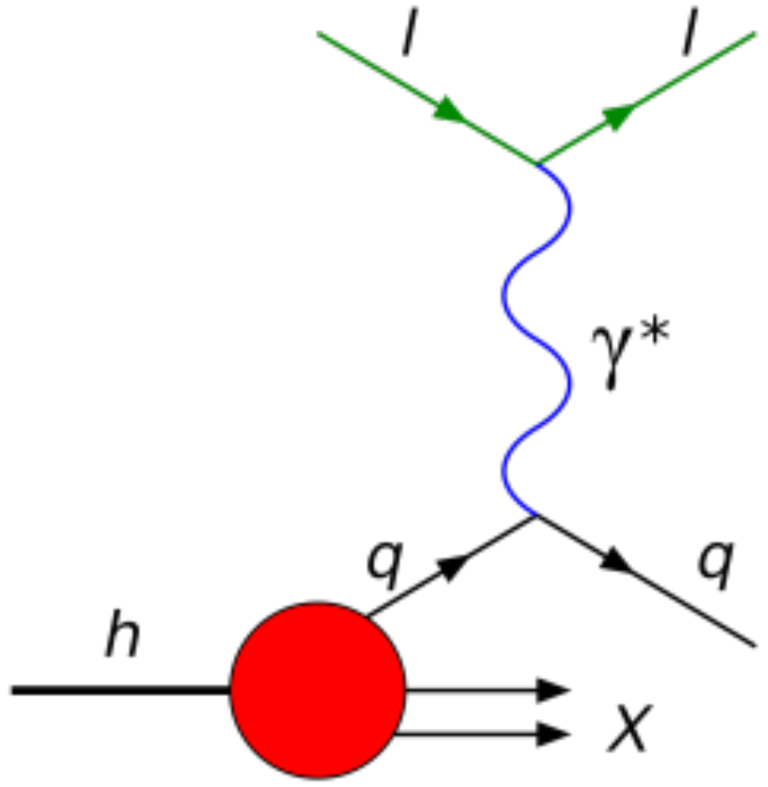


e-p/A collisions



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

Many means for the same goal

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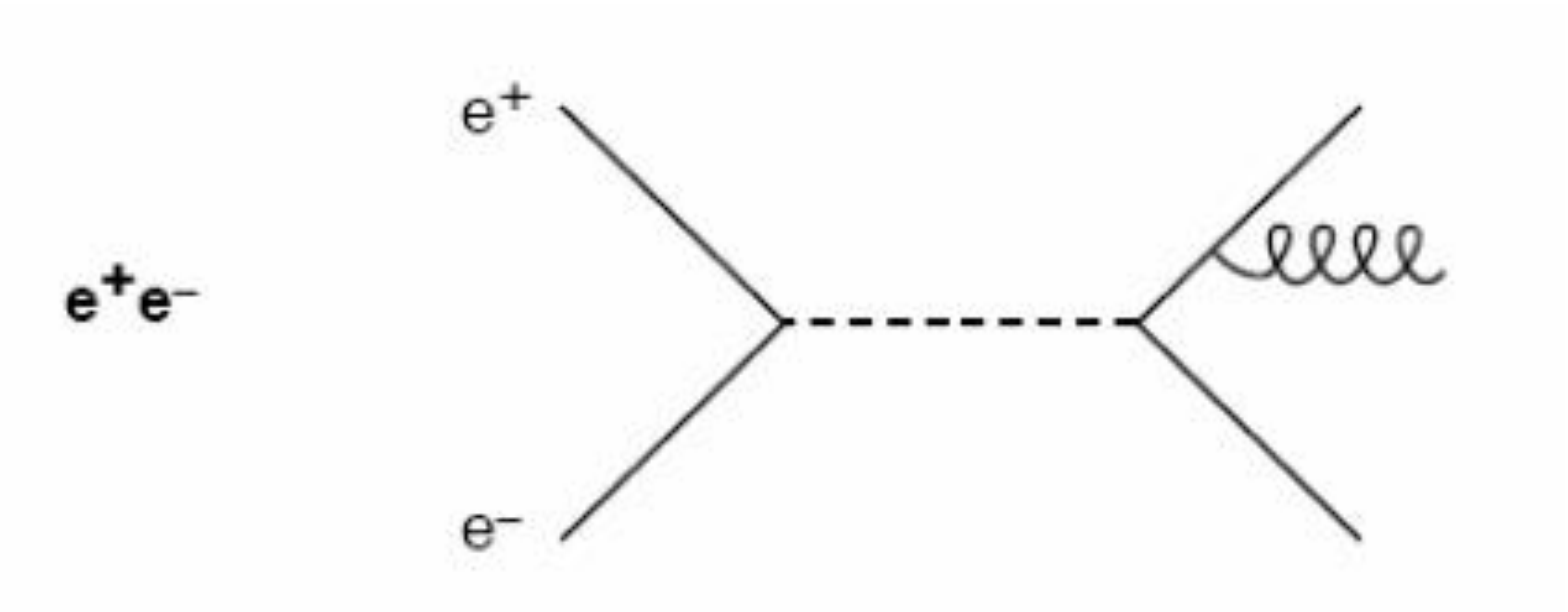

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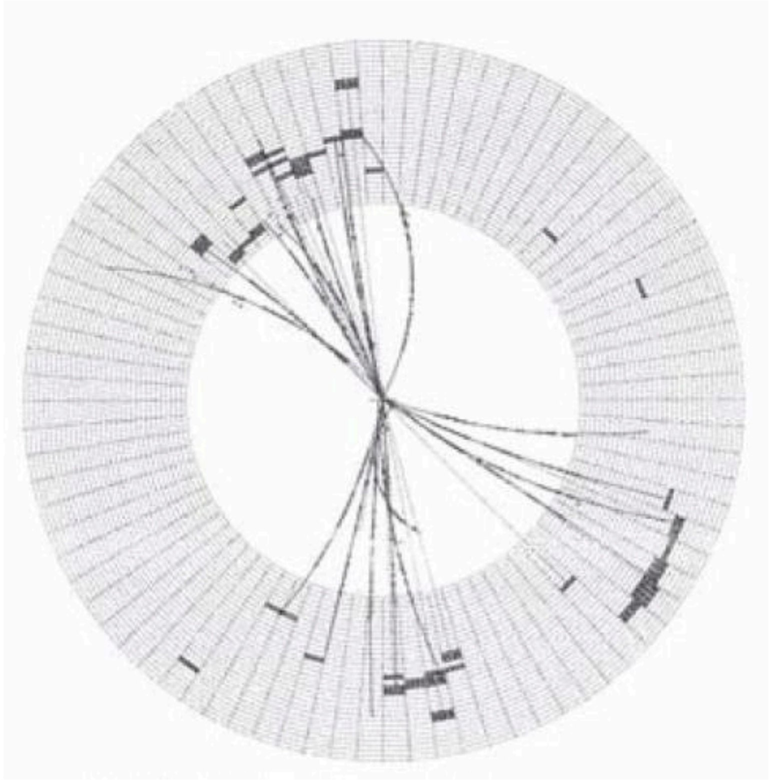

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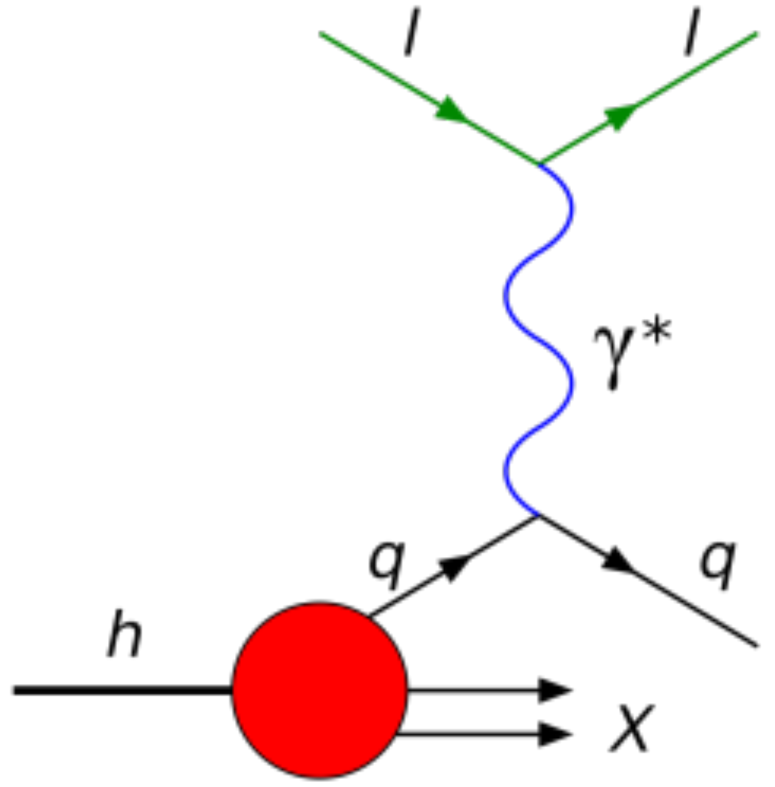

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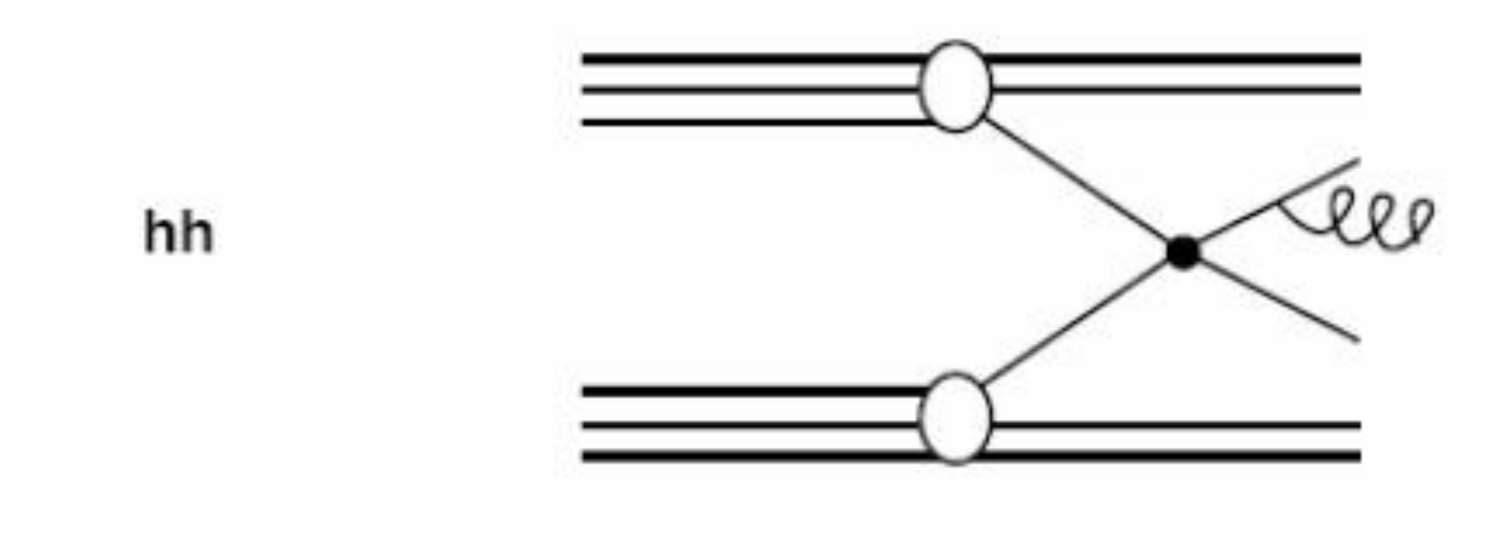
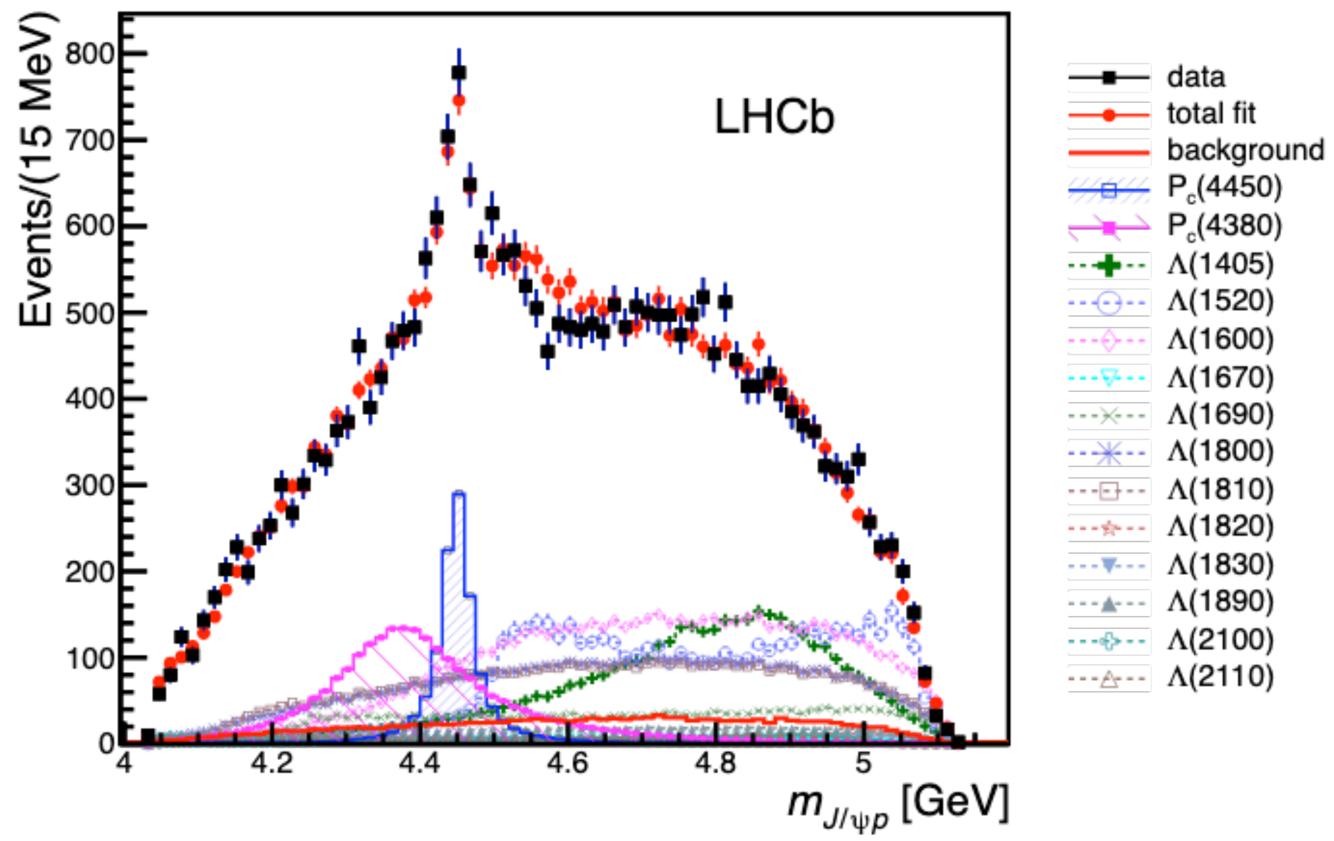
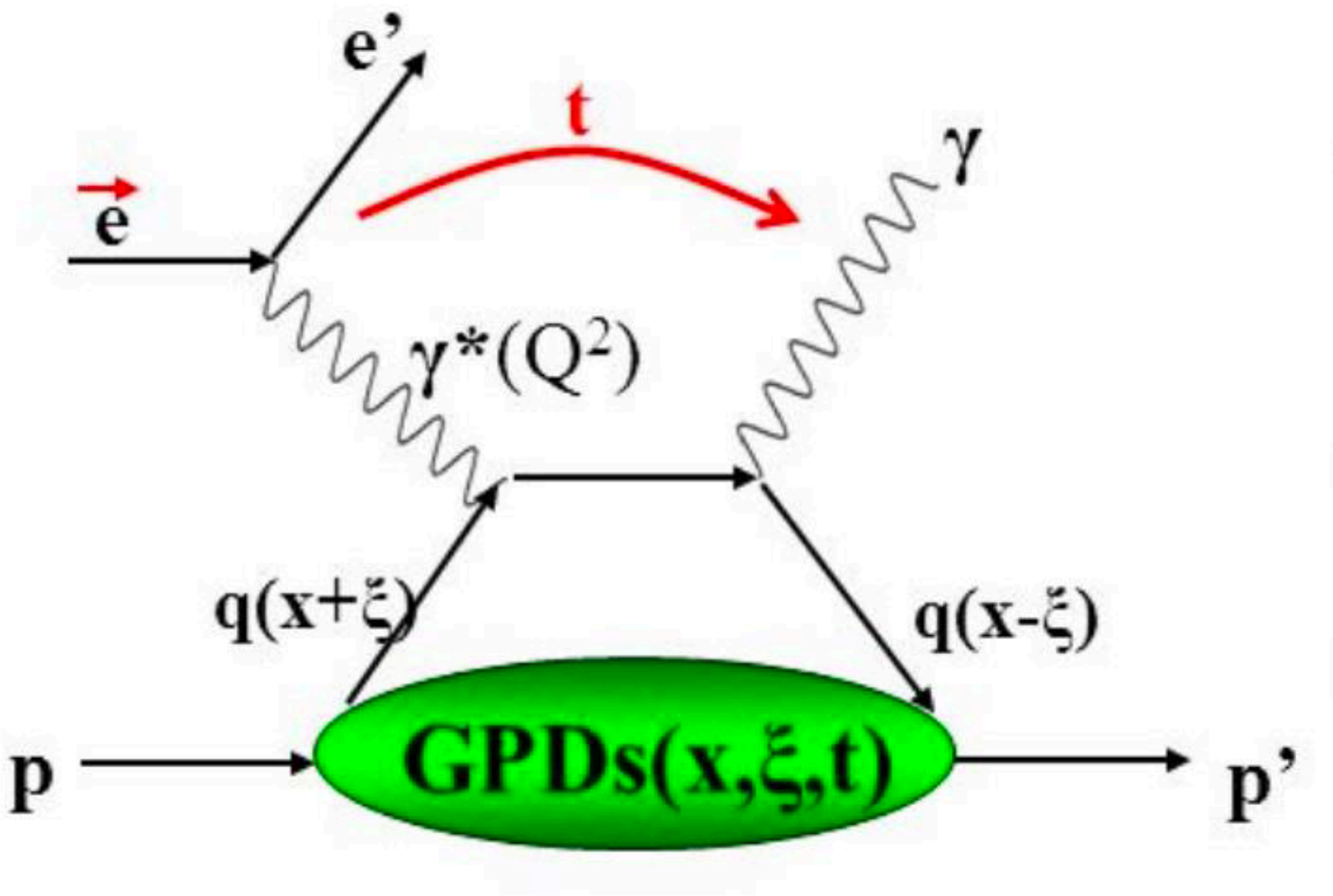


- Two hadrons in initial state
- Rich variety of quantum states available for particle production → spectroscopy of hadrons, hadron properties.



Where it gets messy

Deeply Virtual Compton Scattering (DVCS)



Factorization theorem

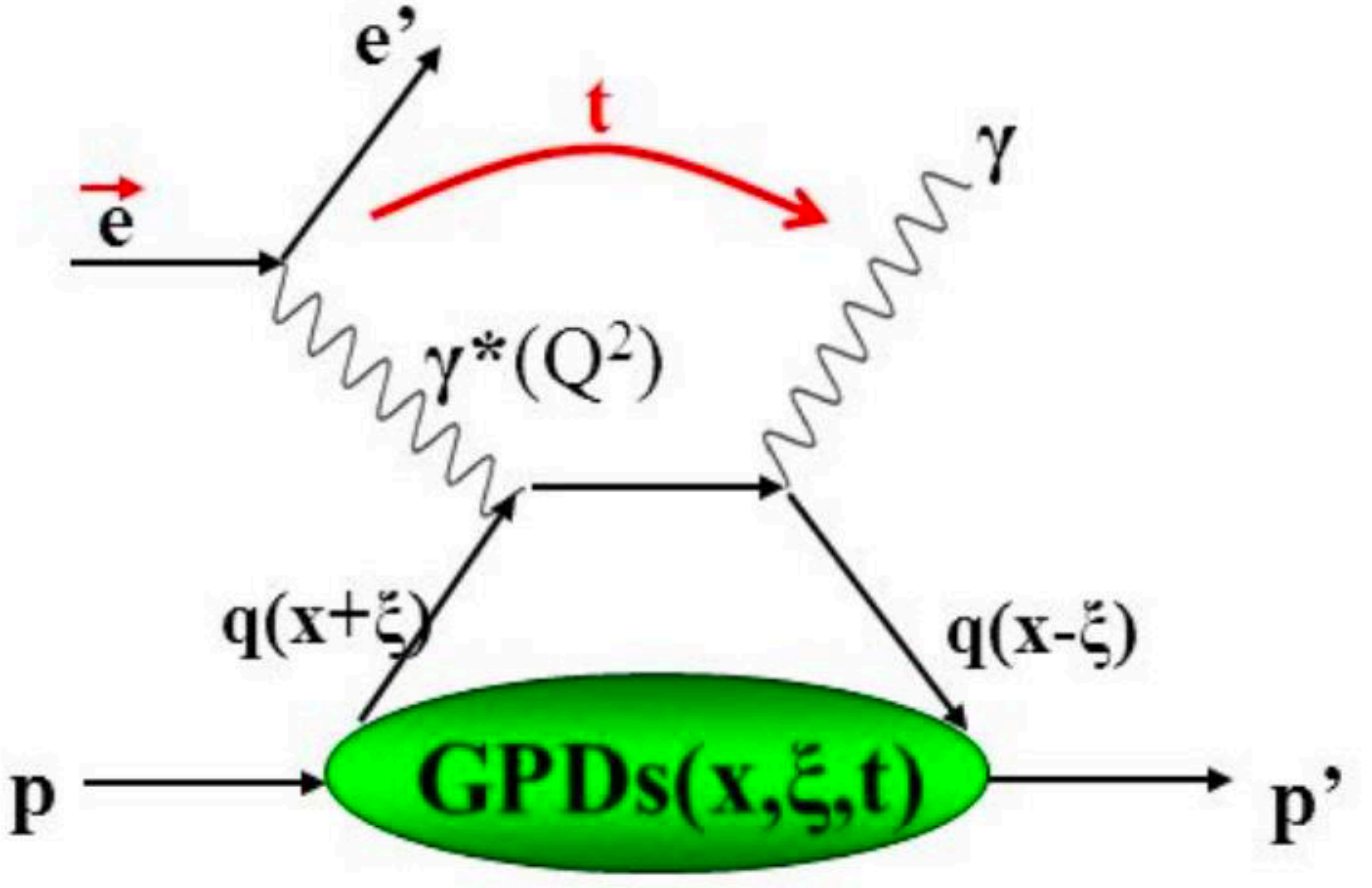
$$\Gamma \propto \int \mathrm{GPDs} \otimes \sigma(e^- + q \rightarrow e^- + q + \gamma)$$

- GPD = General Parton Distributions Functions
- Yes, MANY implementation of the parton distribution functions exist.

See next talk !

Where it gets messy

Deeply Virtual Compton Scattering (DVCS)



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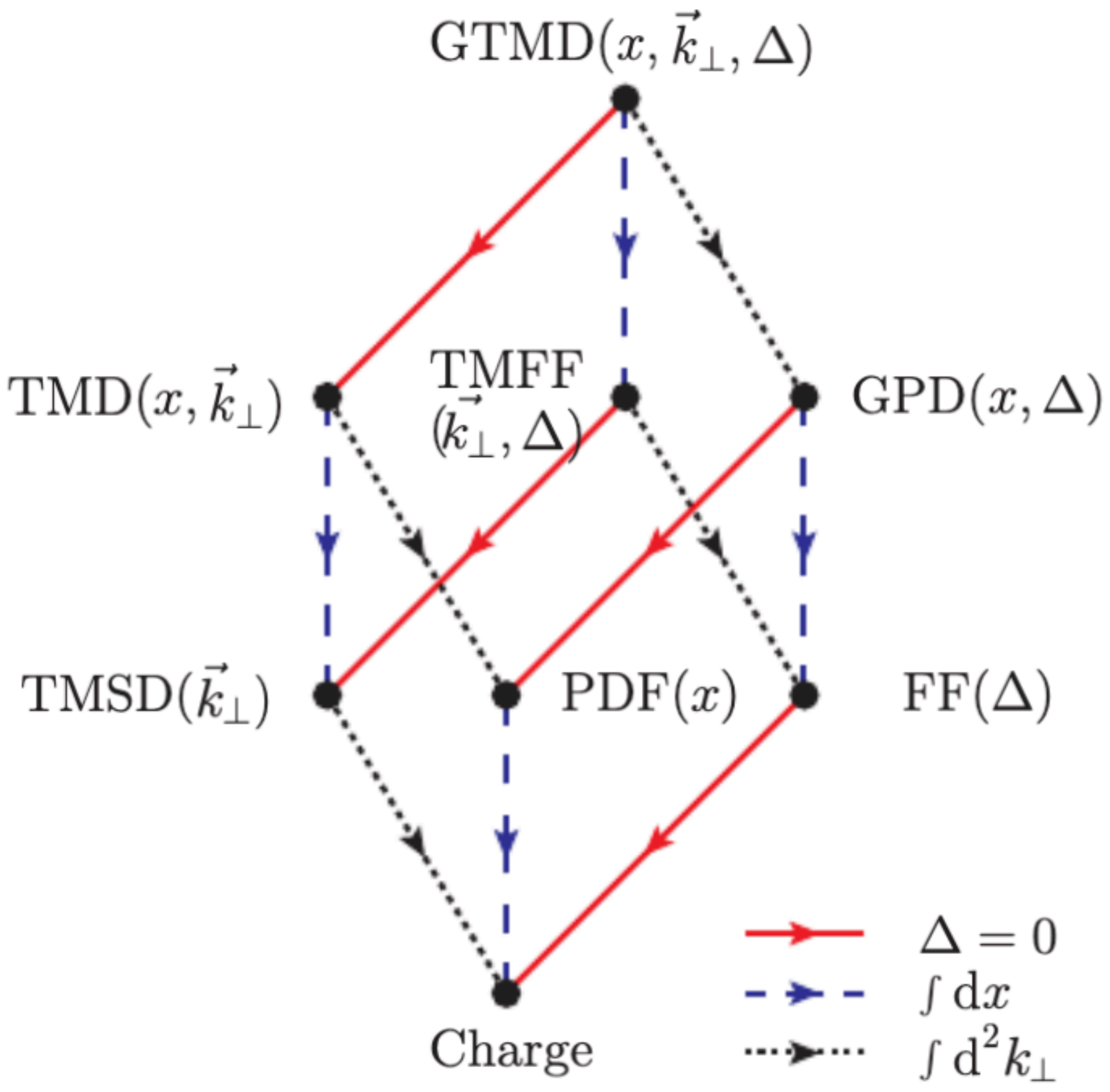
See next talk !

One cube to rule them all



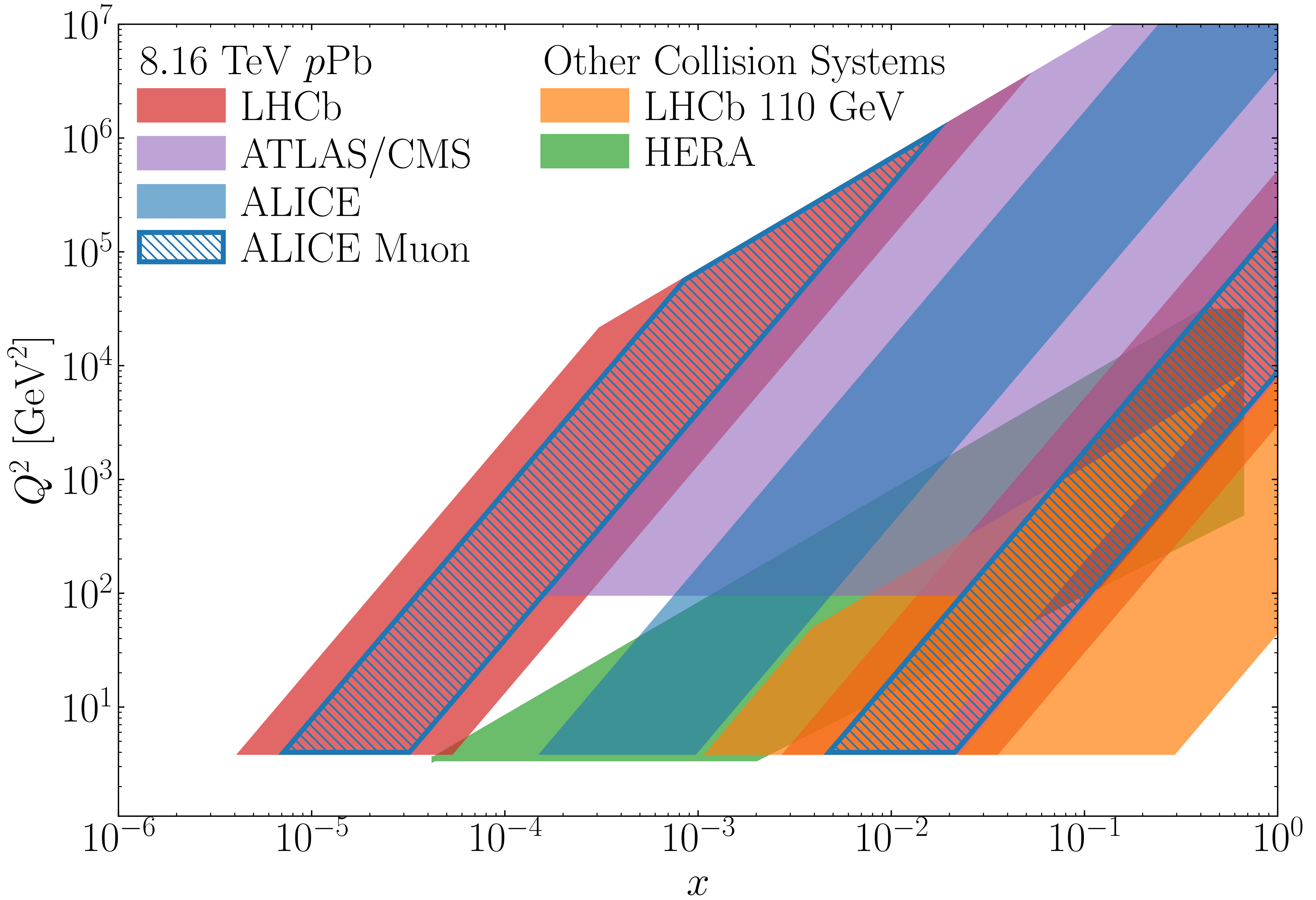
- Depends on what kinematic variables available experimentally.
- … and I pass the question of polarization or nuclear PDFs!

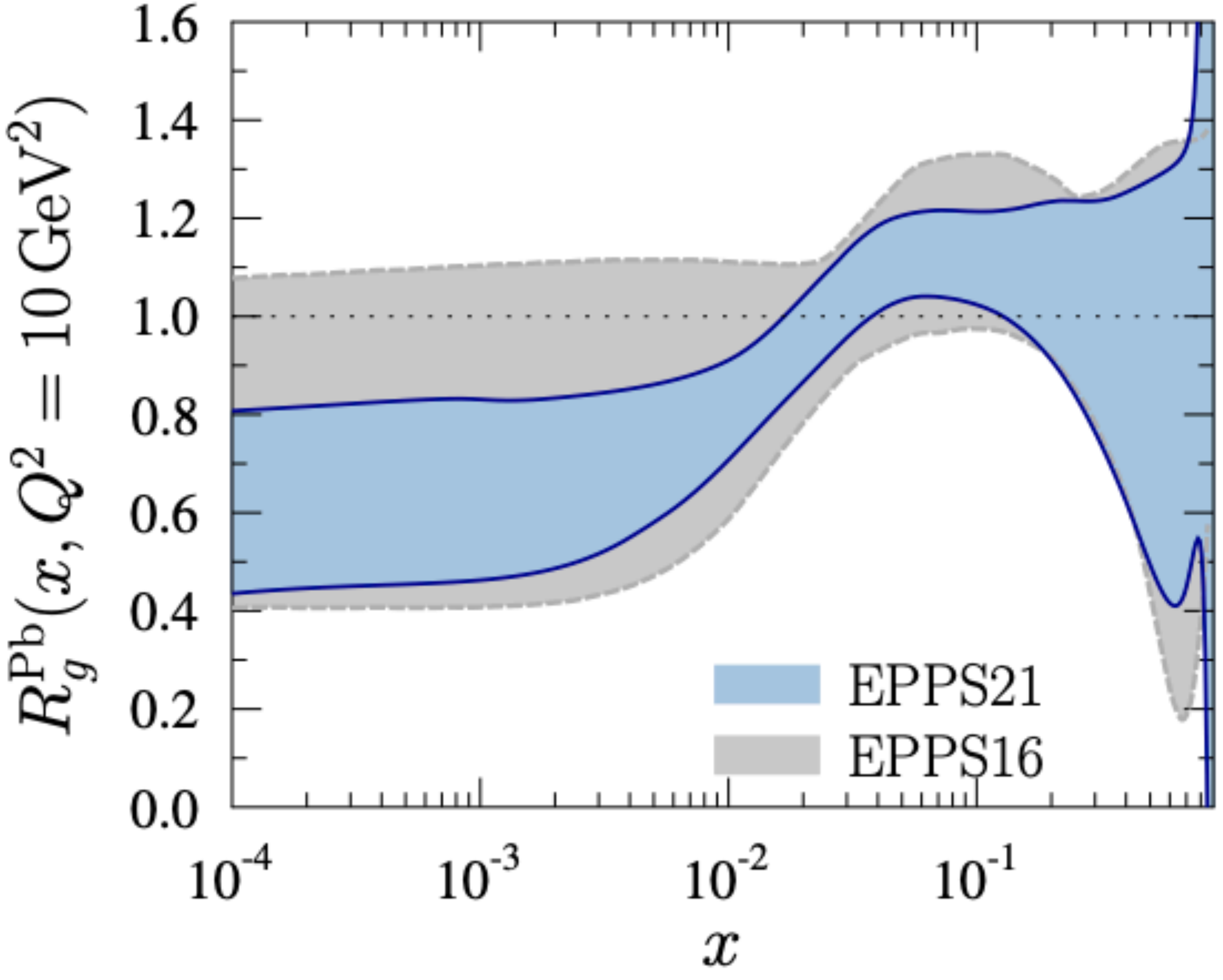
… or not: pA collisions !

- Cold nuclear matter effects (CNM) : *relate the fact that a nucleus is not a simple superposition of protons and neutrons.*

$$R_g^{pPb}(x, Q^2) = \frac{f_g^{nPDF}(x, Q^2)}{f_g^{PDF}(x, Q^2)}$$

- Usually considered CNM effects :
  - Modification of the PDF (*nPDF*).



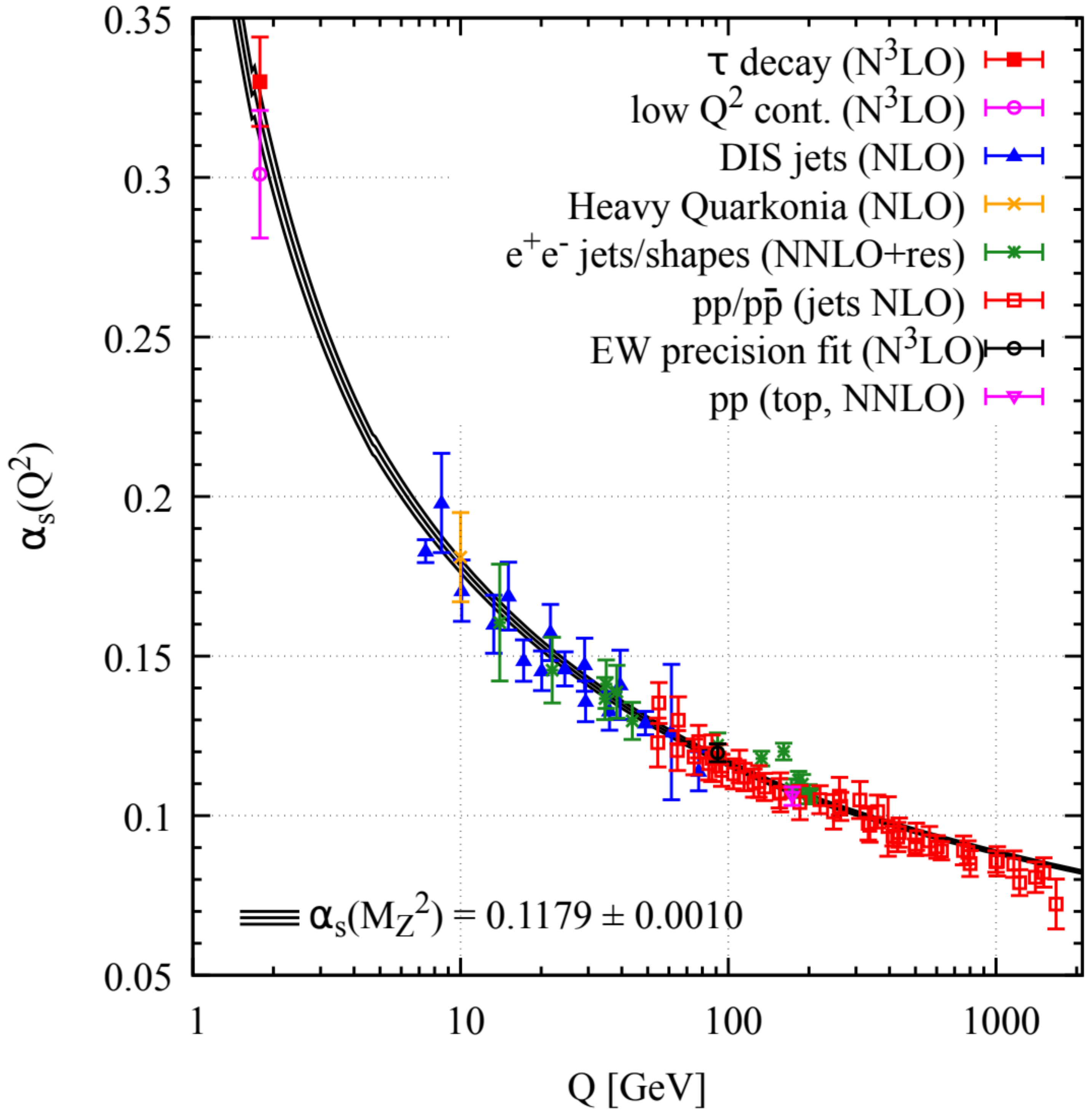


« A constant that varies, we already dealt with that in the past, no big deal. »

-A colleague at a coffee break in a workshop three weeks ago

The best of two worlds

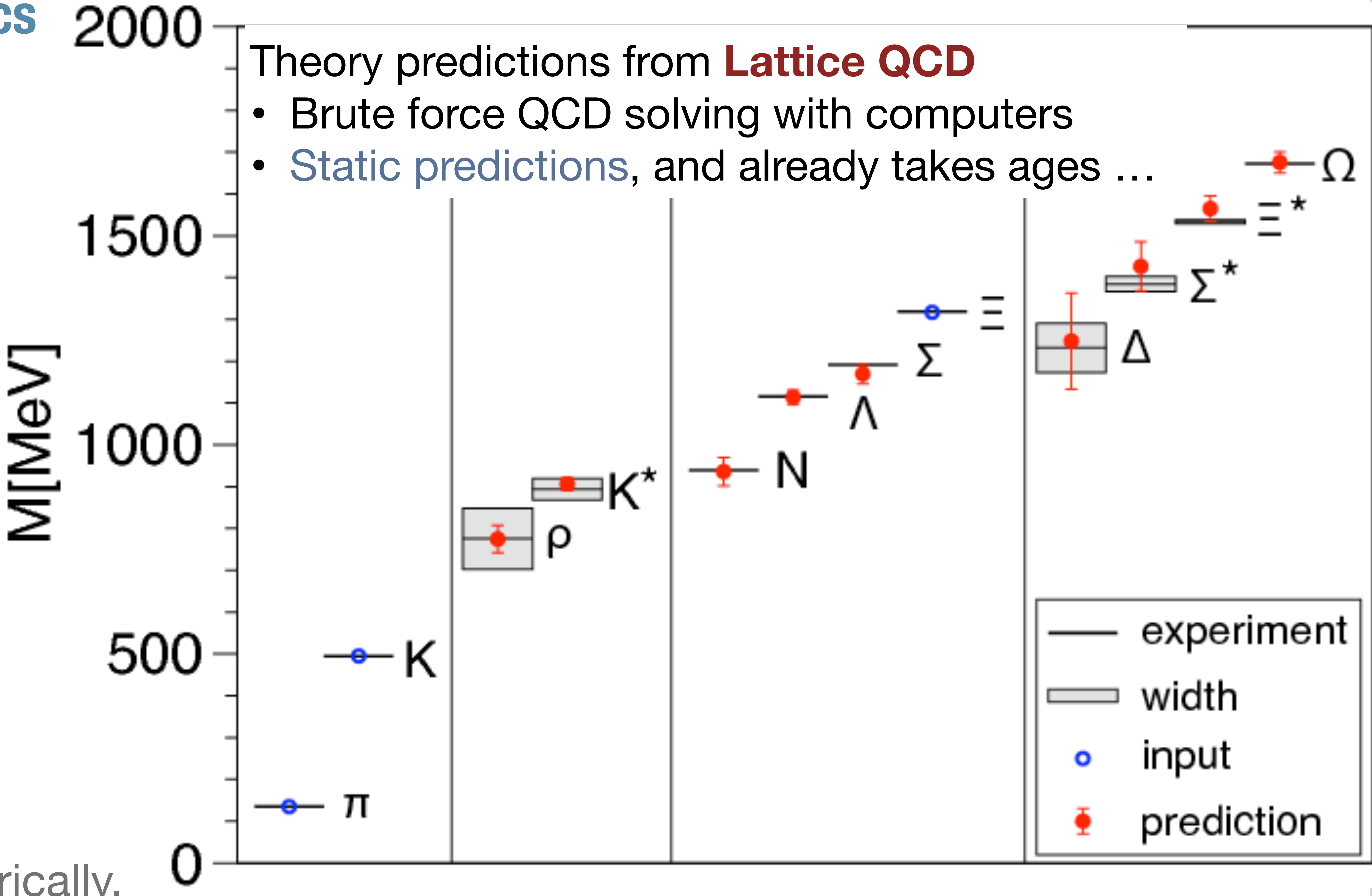
Quantum Chromodynamics



- Non-re-normalizable.
- Headache to solve numerically.

Theory predictions from **Lattice QCD**

- Brute force QCD solving with computers
- Static predictions, and already takes ages …



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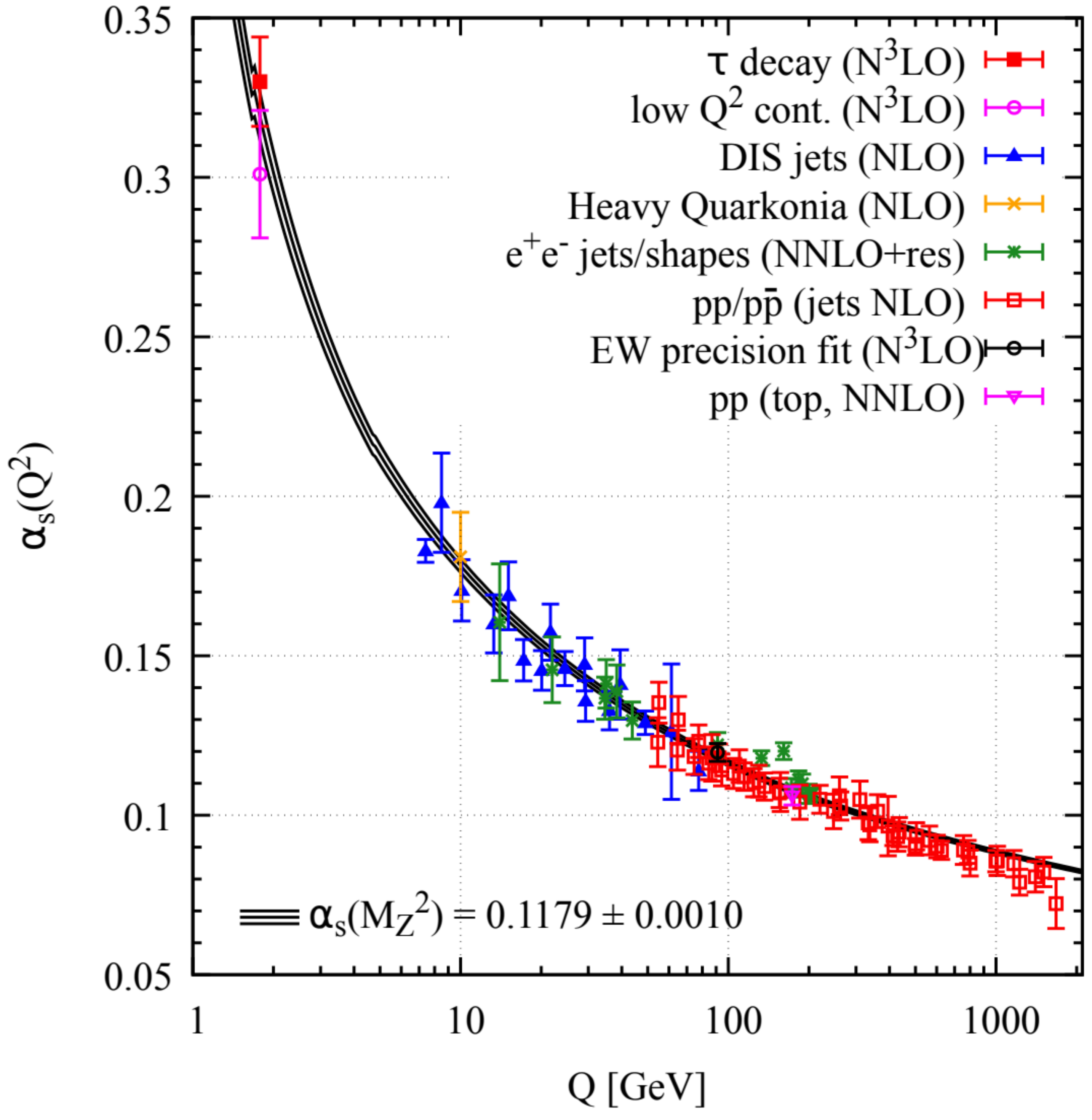

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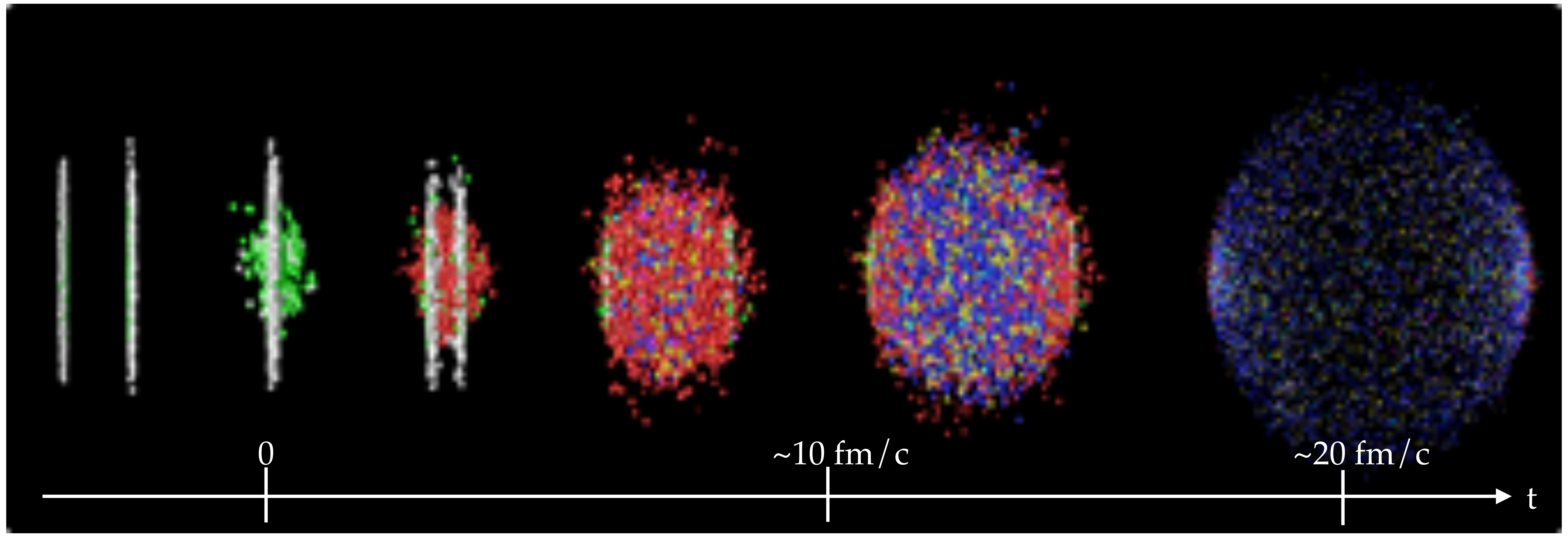
Dynamic colliding nuclear medium



- Initial conditions are different from proton-proton collisions.
- Expending medium in the collision.

The best of two worlds

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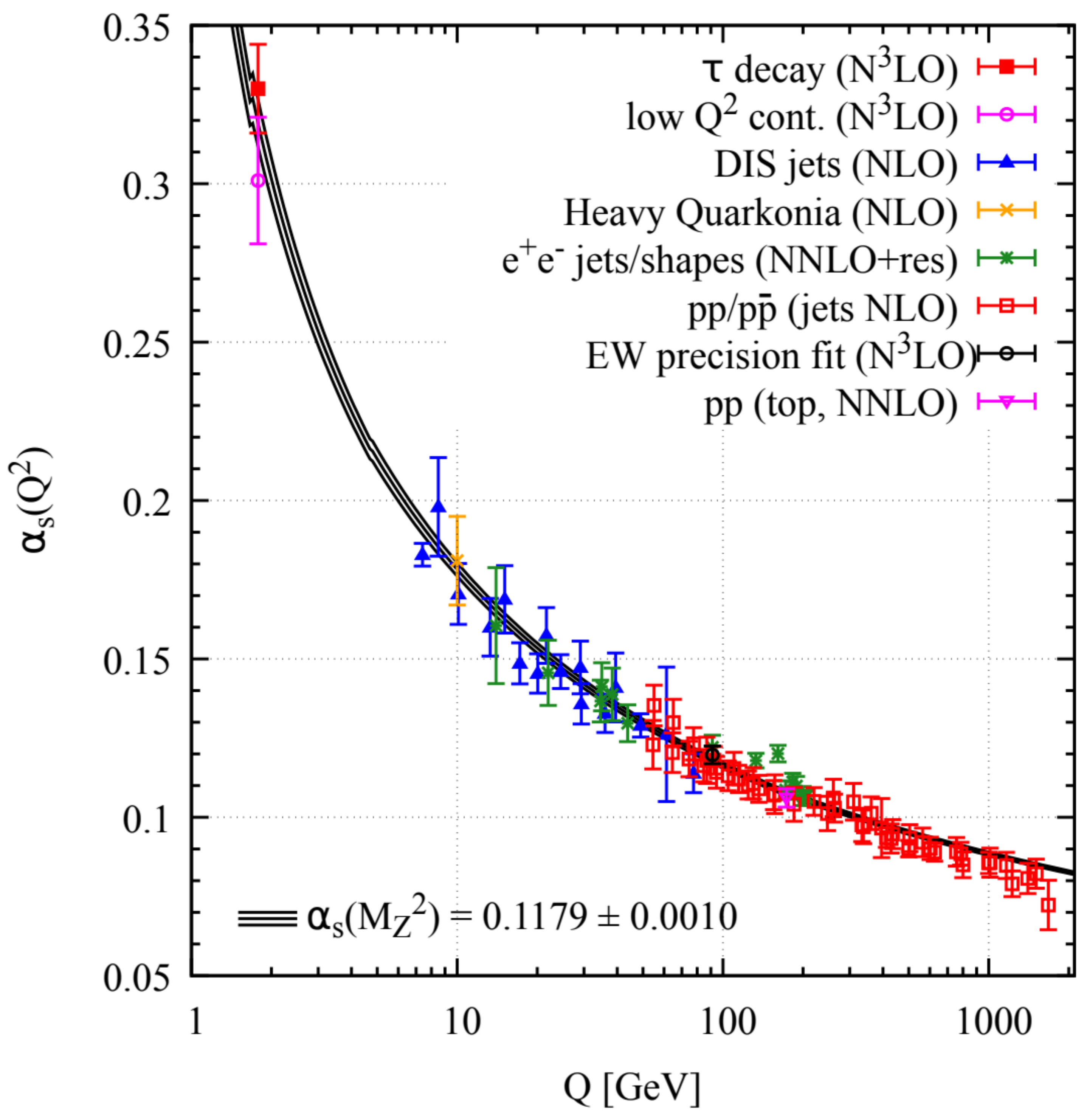

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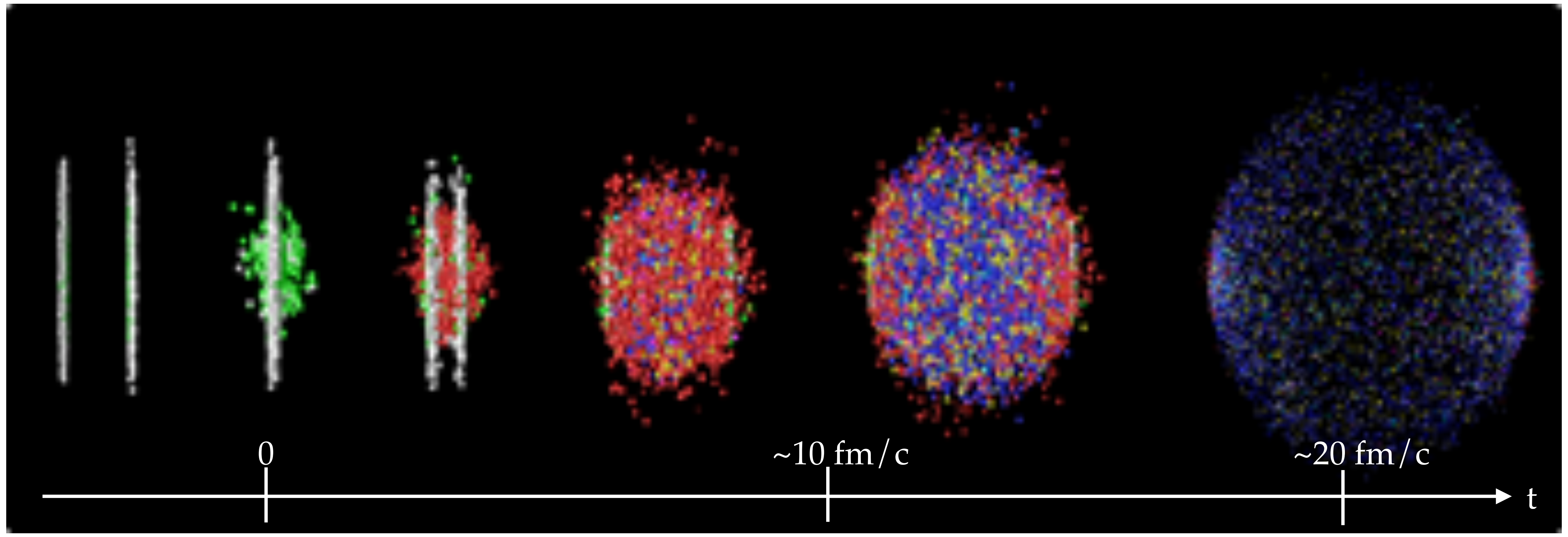

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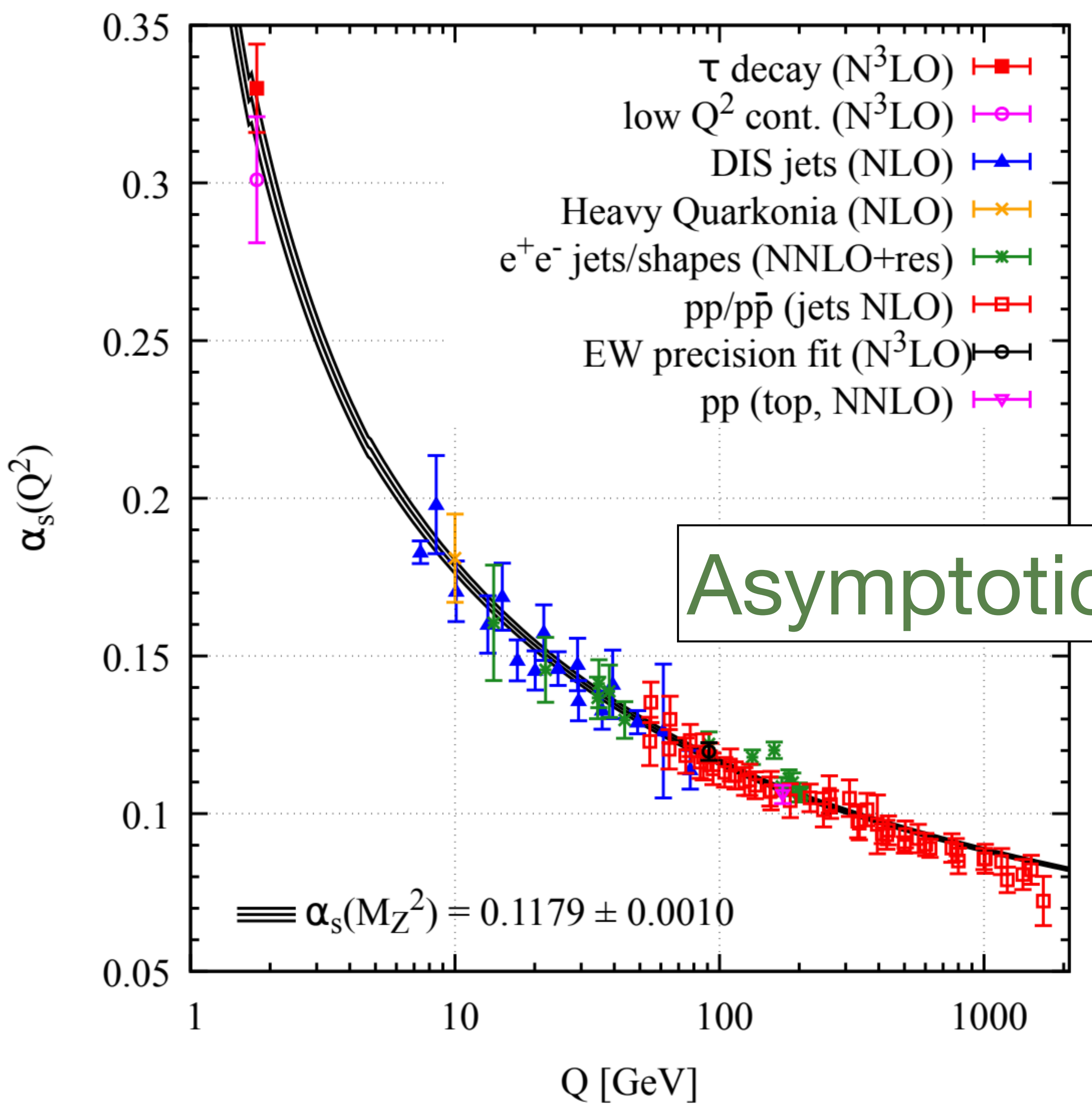
Heavy-ion physics: interface between effective theory, modeling and phenomenology

One medium to rule them all

Quantum Chromodynamics

Confinement



Asymptotic freedom

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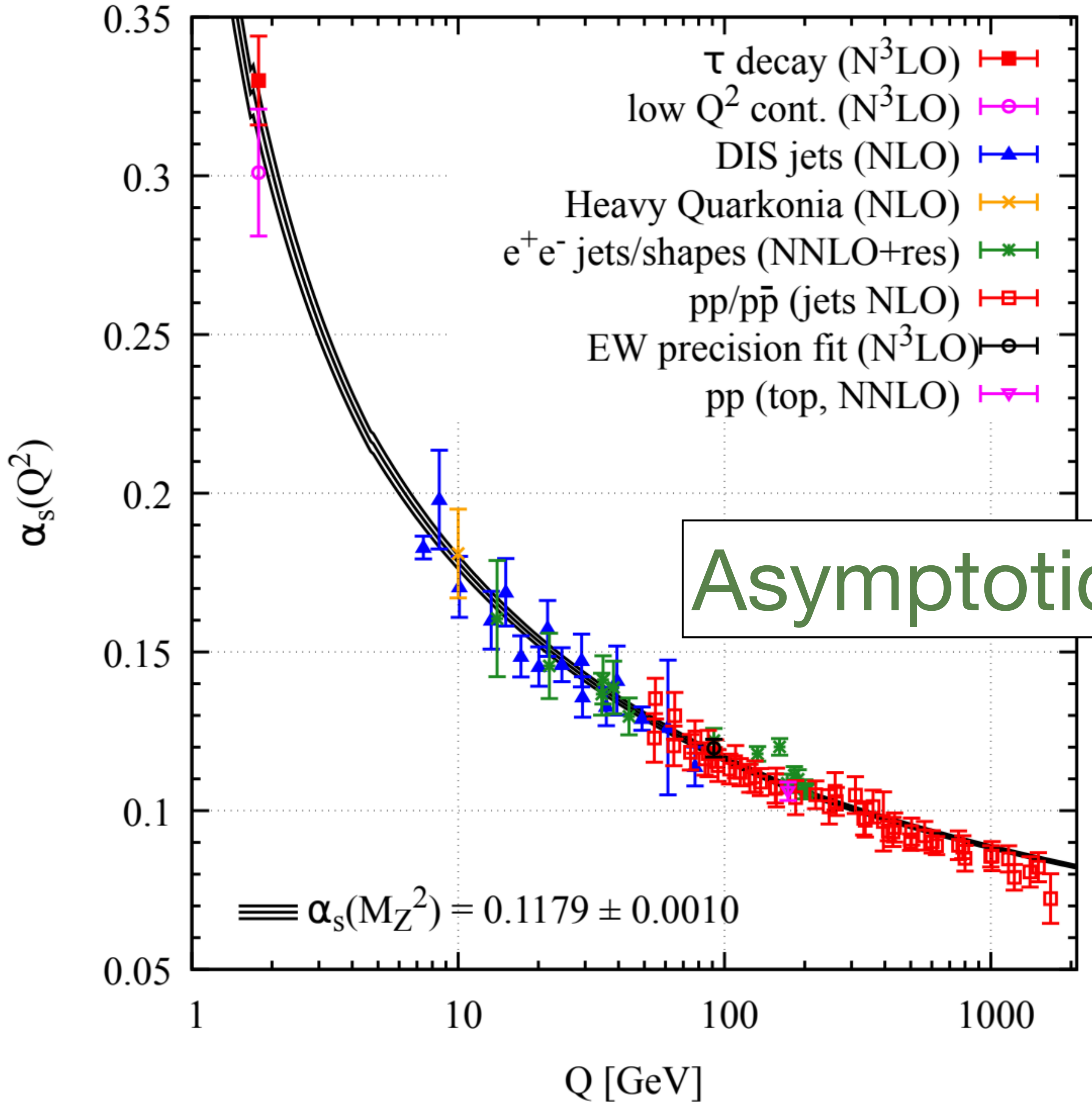
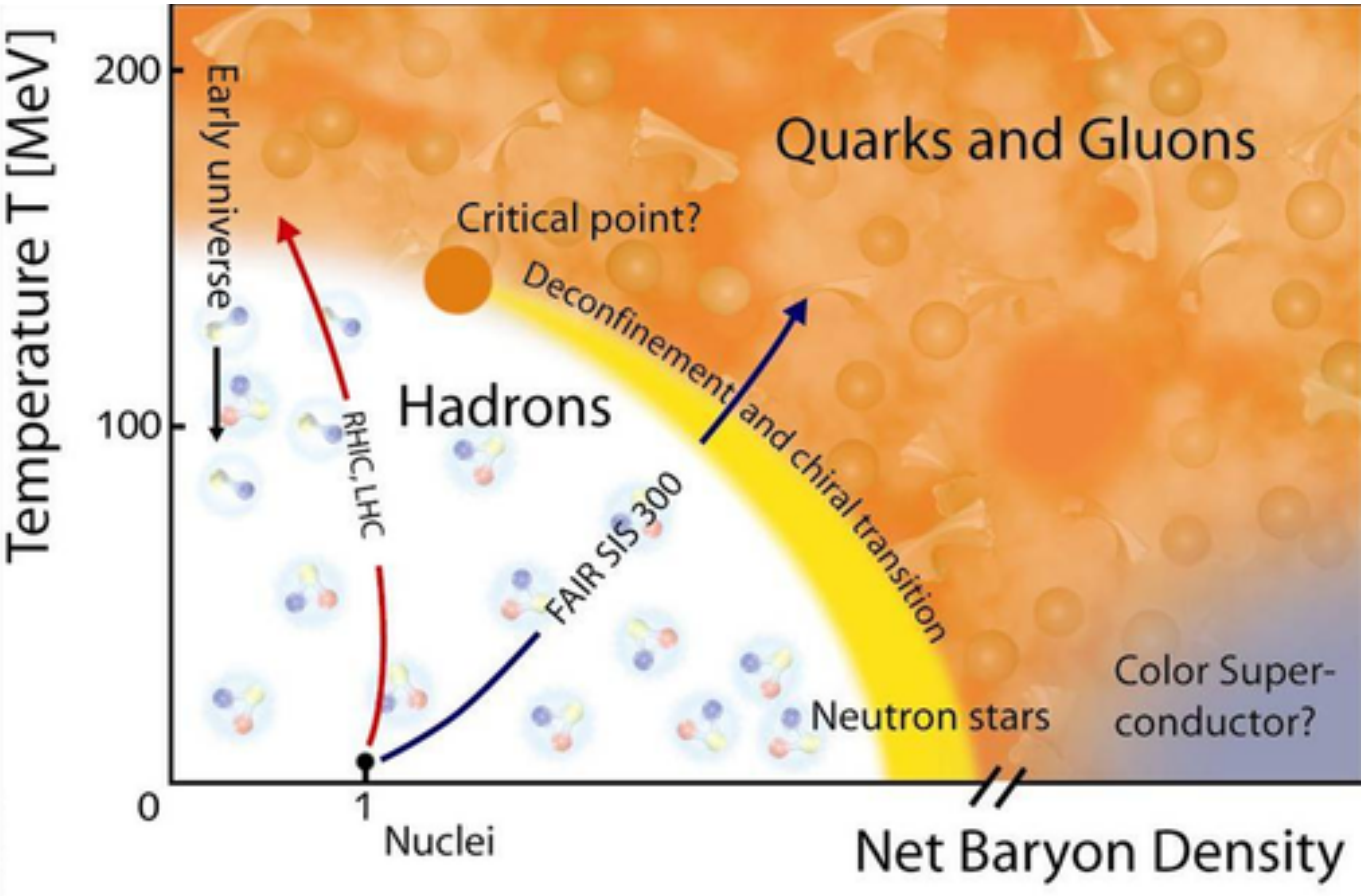


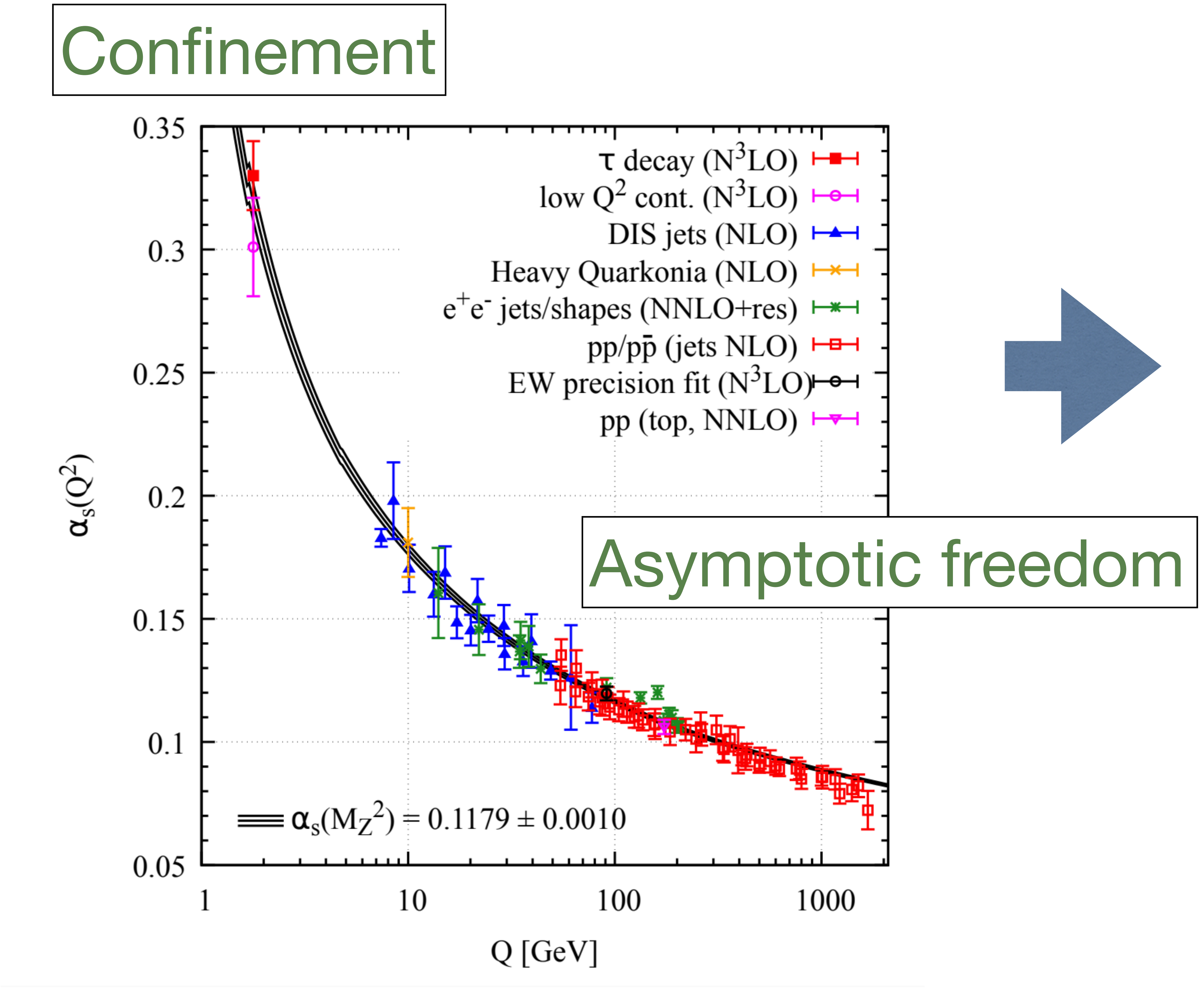
Asymptotic freedom

Phase diagram of hadronic matter

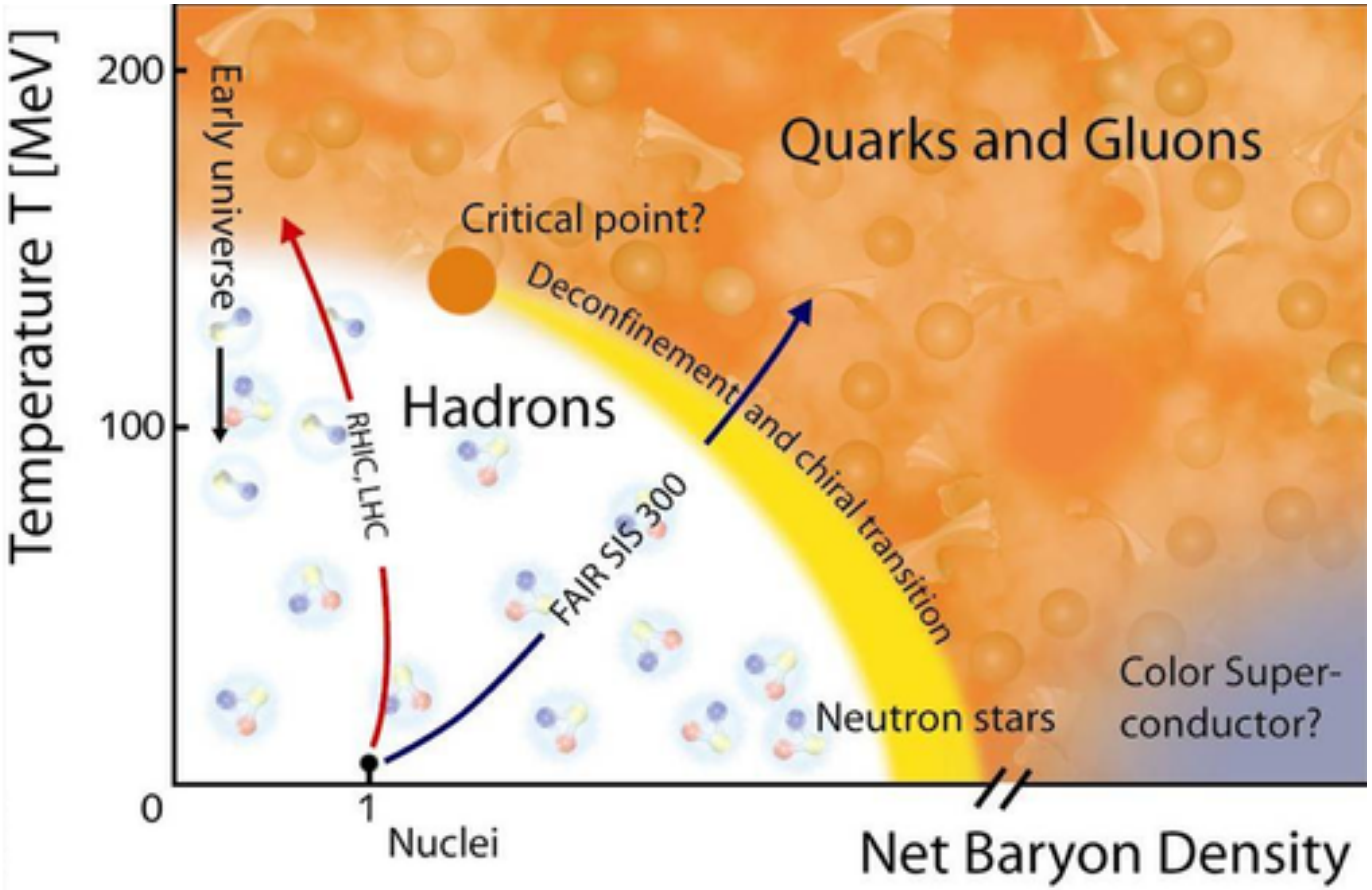


One medium to rule them all

Quantum Chromodynamics

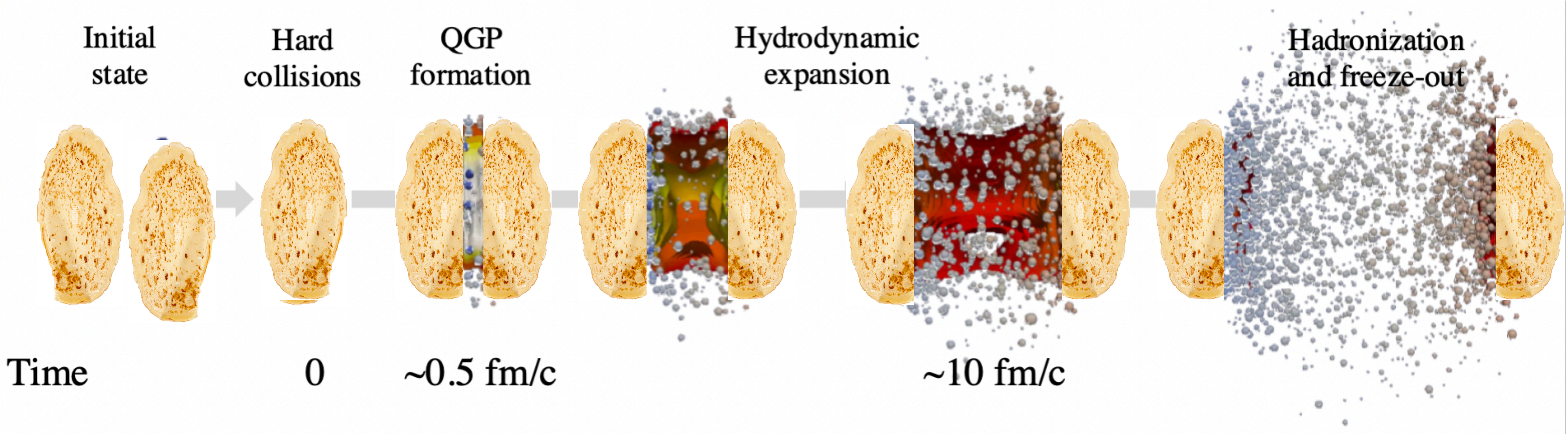


Phase diagram of hadronic matter



High temperature/density: formation of the Quark-Gluon Plasma

Why study the QGP?



Visualization by J.E. Bernhard, arXiv:1804.06469

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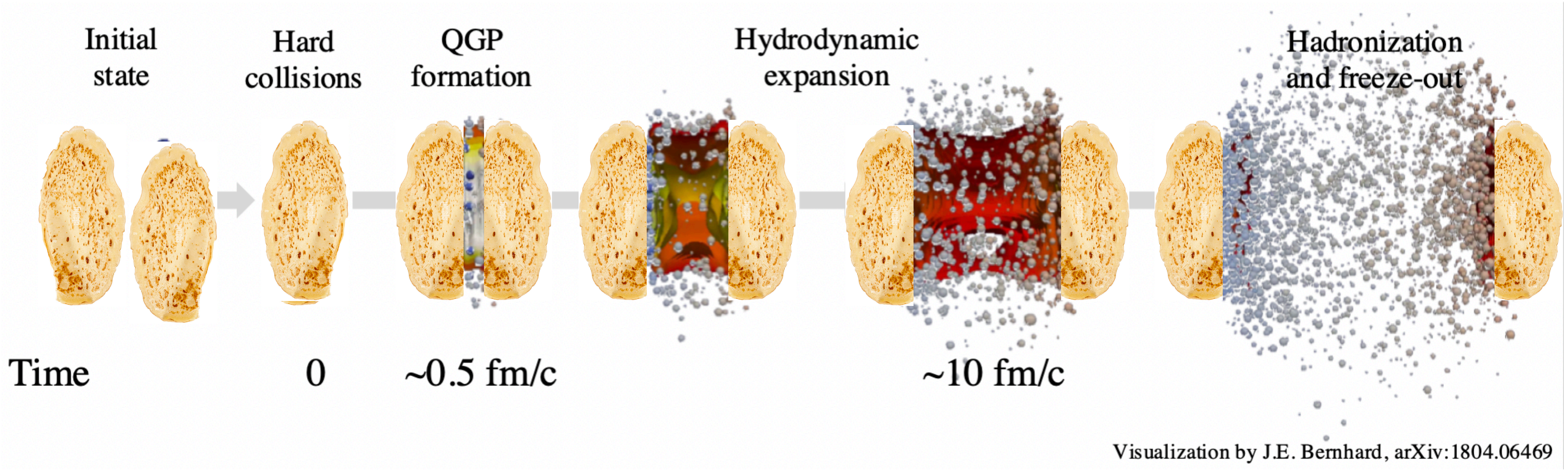

- QGP studies at CERN:

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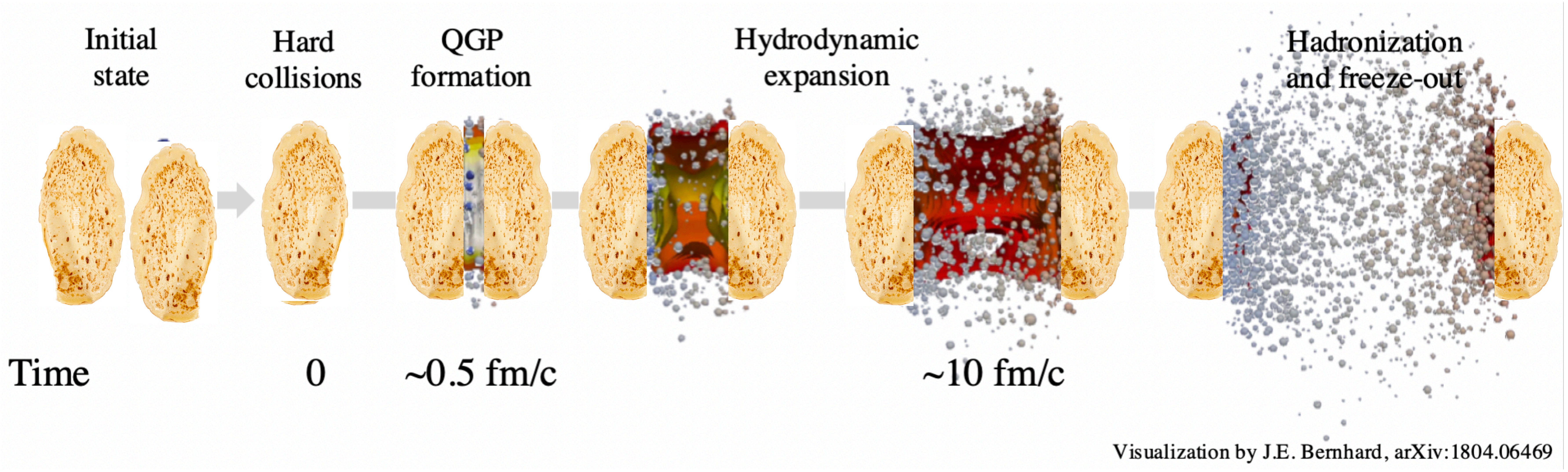

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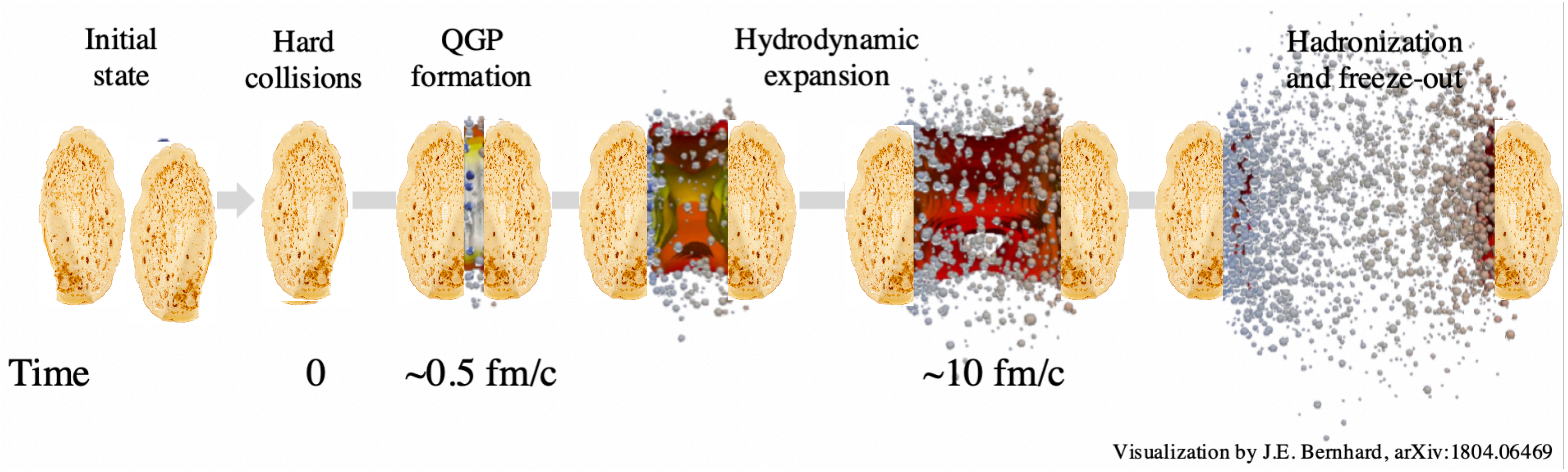

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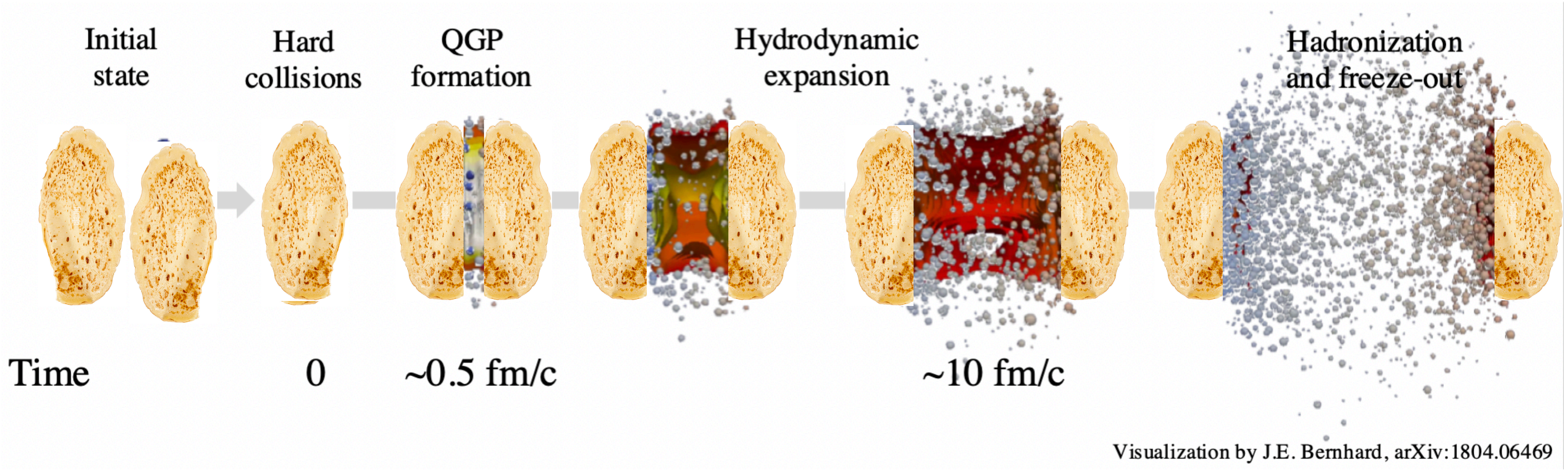

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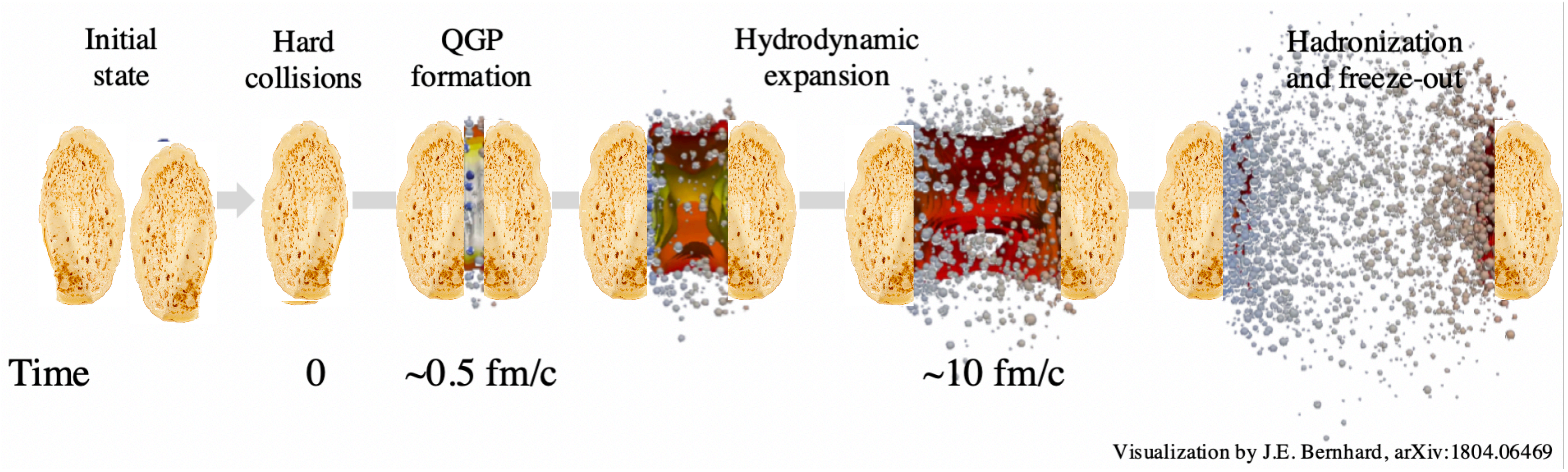

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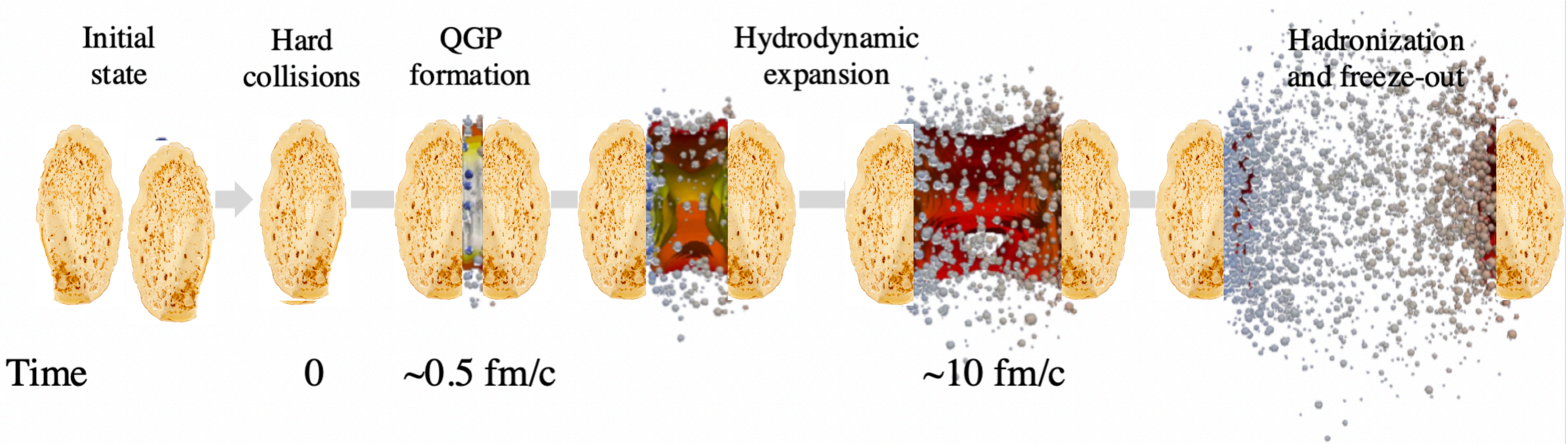

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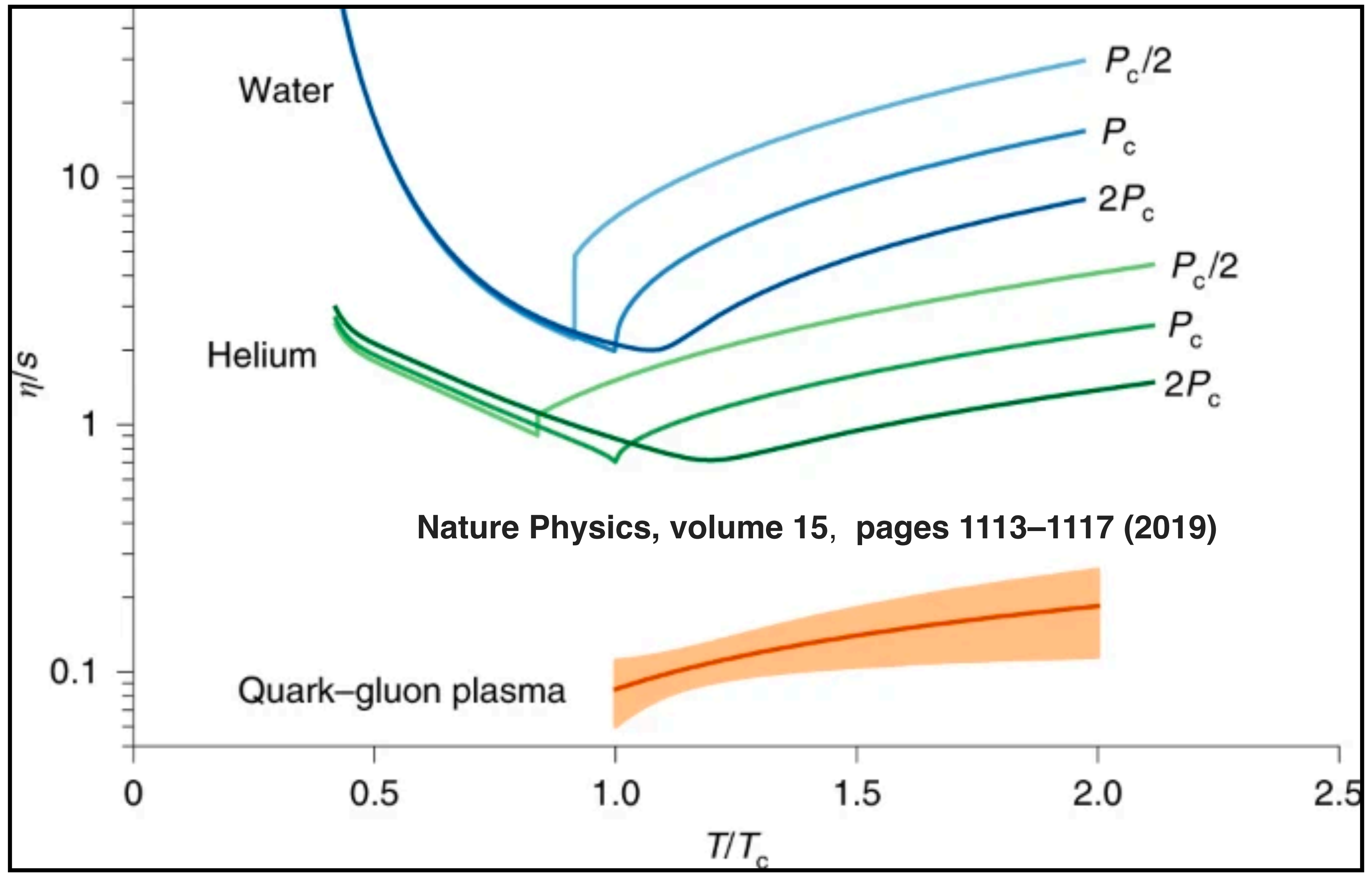


Nature Physics, volume 15, pages 1113–1117 (2019)

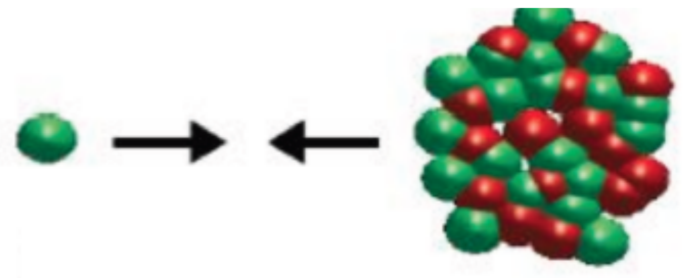
QGP = perfect build

Where it gets messy

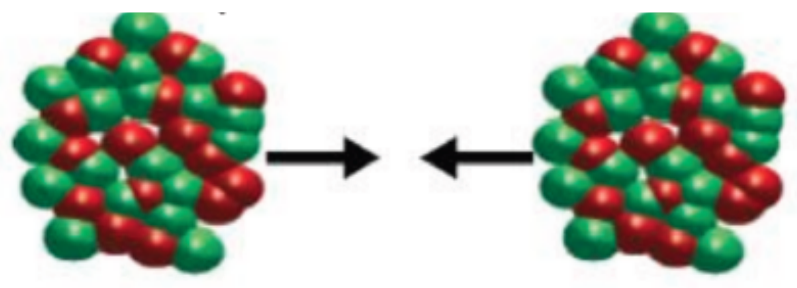
Where it gets messy

The orthodoxe approach

- The QCD ‘vacuum’.



- The confined matter.



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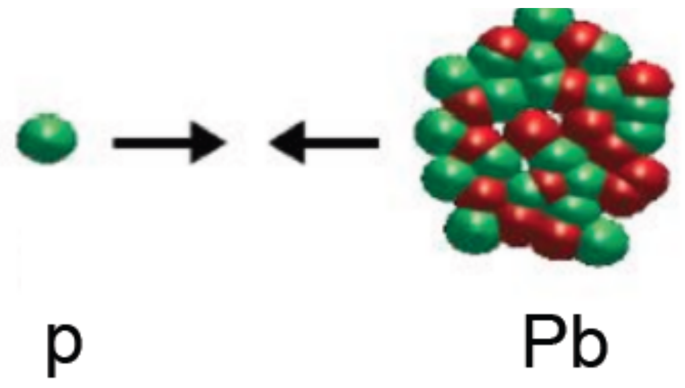

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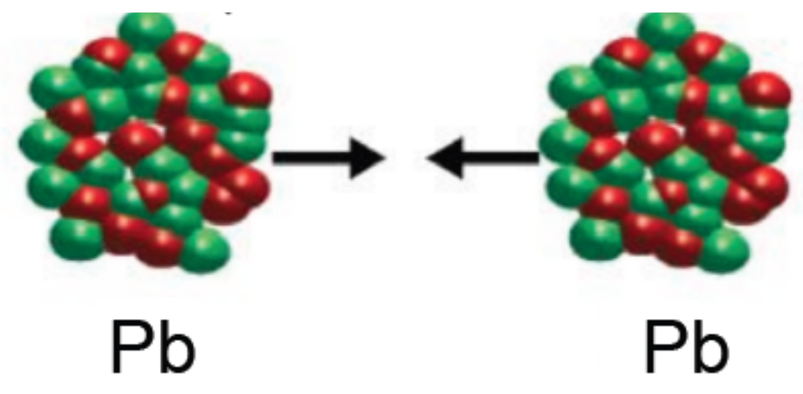

- The QGP

The probes

Hard probes

- Heavy-quark mesons, quarkonia, jets…

Soft probes

- Charged particles, light hadrons, low-mass hadrons …

Electromagnetic probes

- Drell-Yan, photons, weak bosons …

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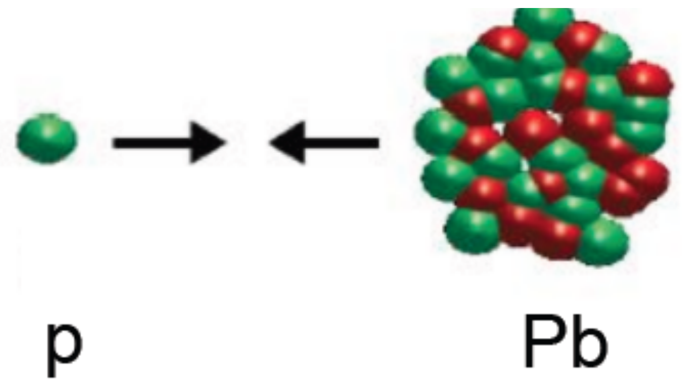

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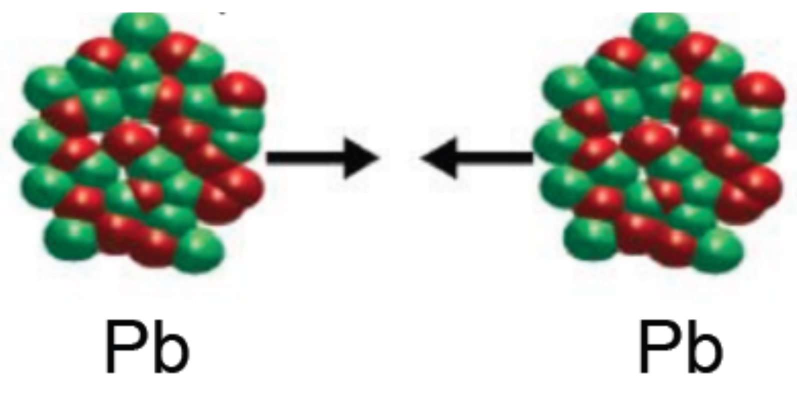

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- Multiplicity dependance, flow measurements…

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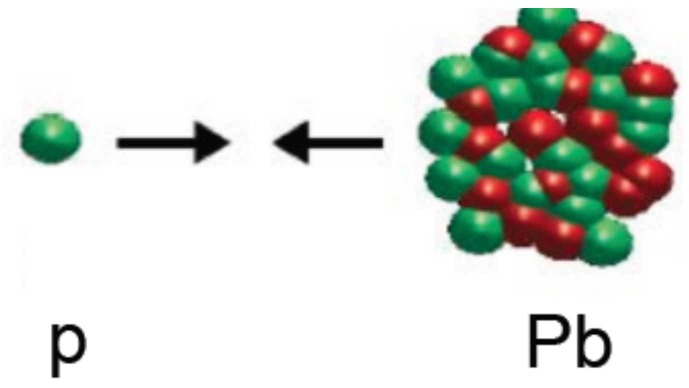

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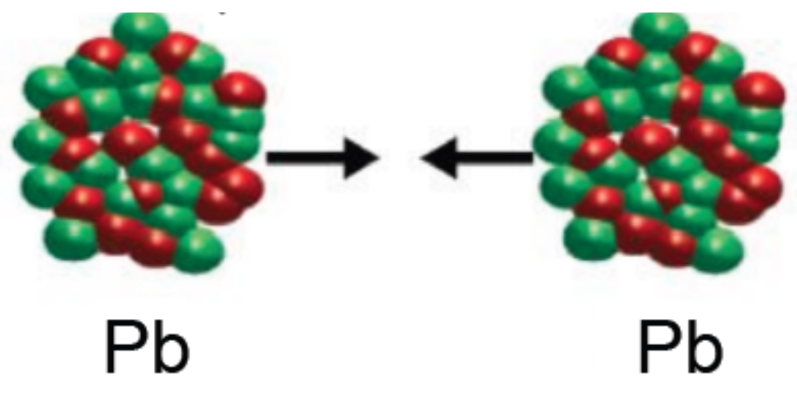

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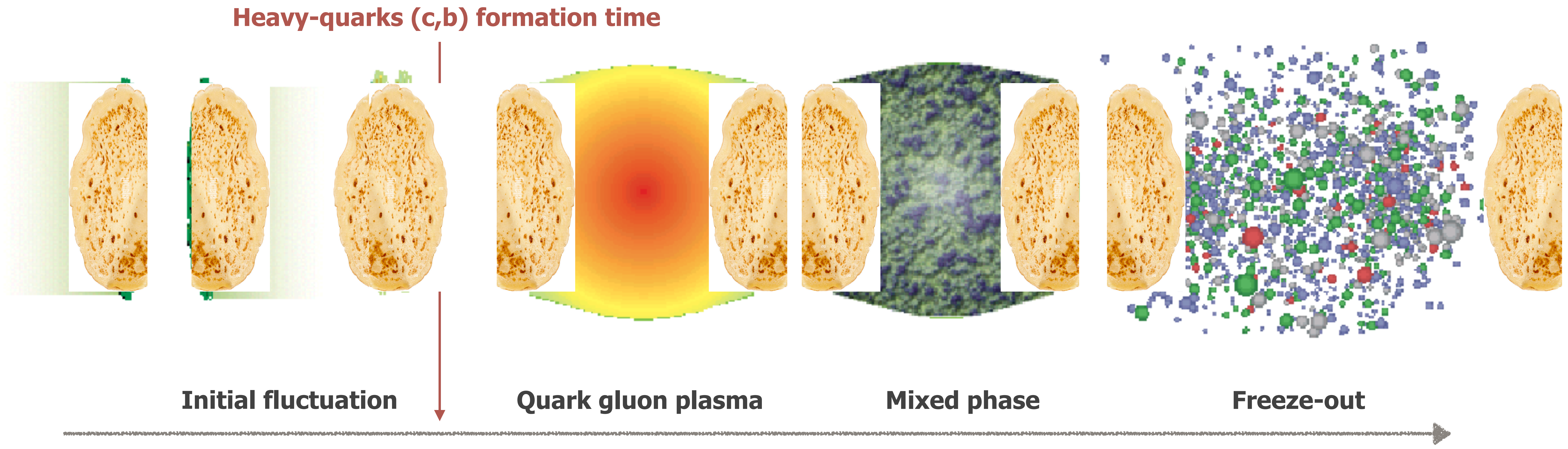
A QGP physicist should know everything about his/her favorite probs !

«Oh my god, look at that peak, it’s gorgeous !»

-Young enthusiastic me barely arriving in LHCb, looking at any charm hadron peaks.

Why heavy is good



- Heavy quarks (charm and bottom) = M >> Λ_{QCD} → *pQCD*
- Large mass = *produced at the early stage of the collision*
  - $\tau_{c\bar{c}} \sim 1/2m_c \sim 0.1$ fm << $\tau_{eq} \sim 1$ fm << τ_{hadron}
- Large mass M >> T_{medium} : *thermal modification / abundance negligible*
- Heavy-flavours = **ideal probes of the deconfined phase !**

Physics case: Λ_c^+-to-D^0 ratio

LHCB-PAPER-2021-046

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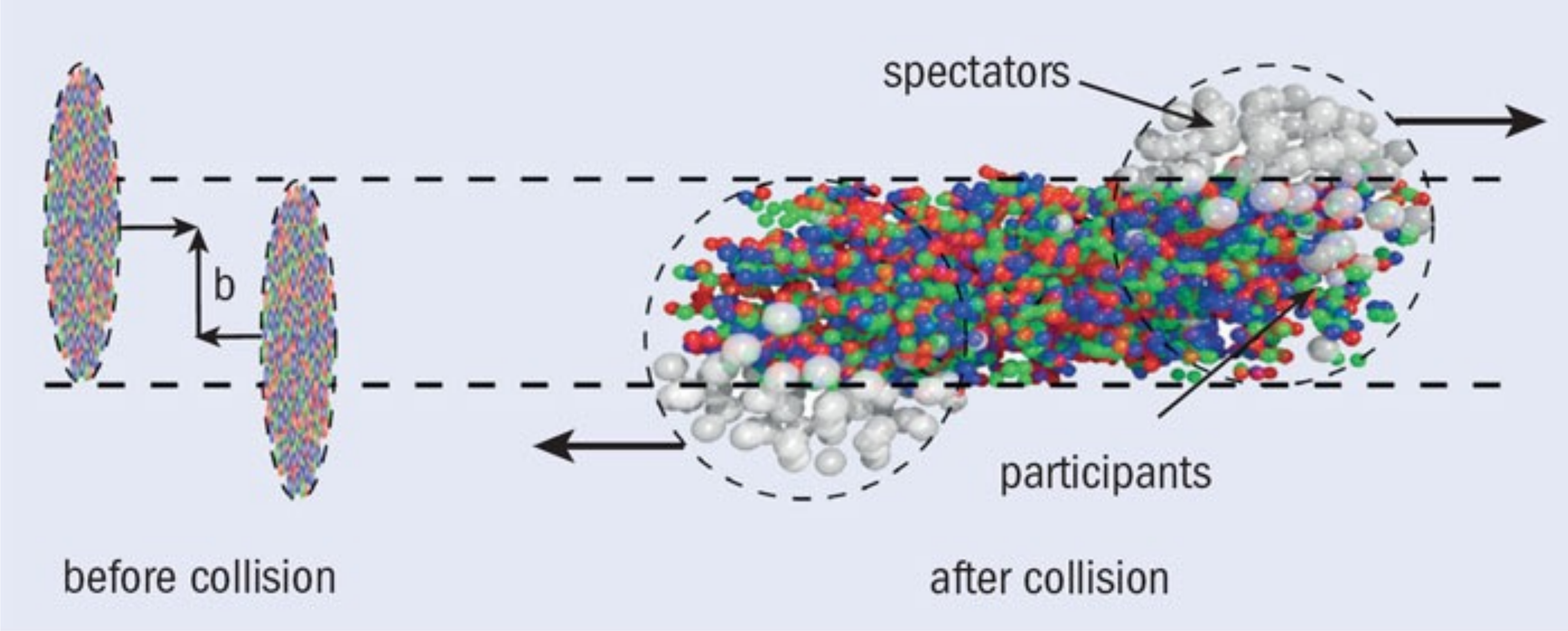
‘What is that strange variable there ?’

Small detour: centrality

- The quantity that relate if a (A-A) collision is head-on or more peripheral is called *centrality.*



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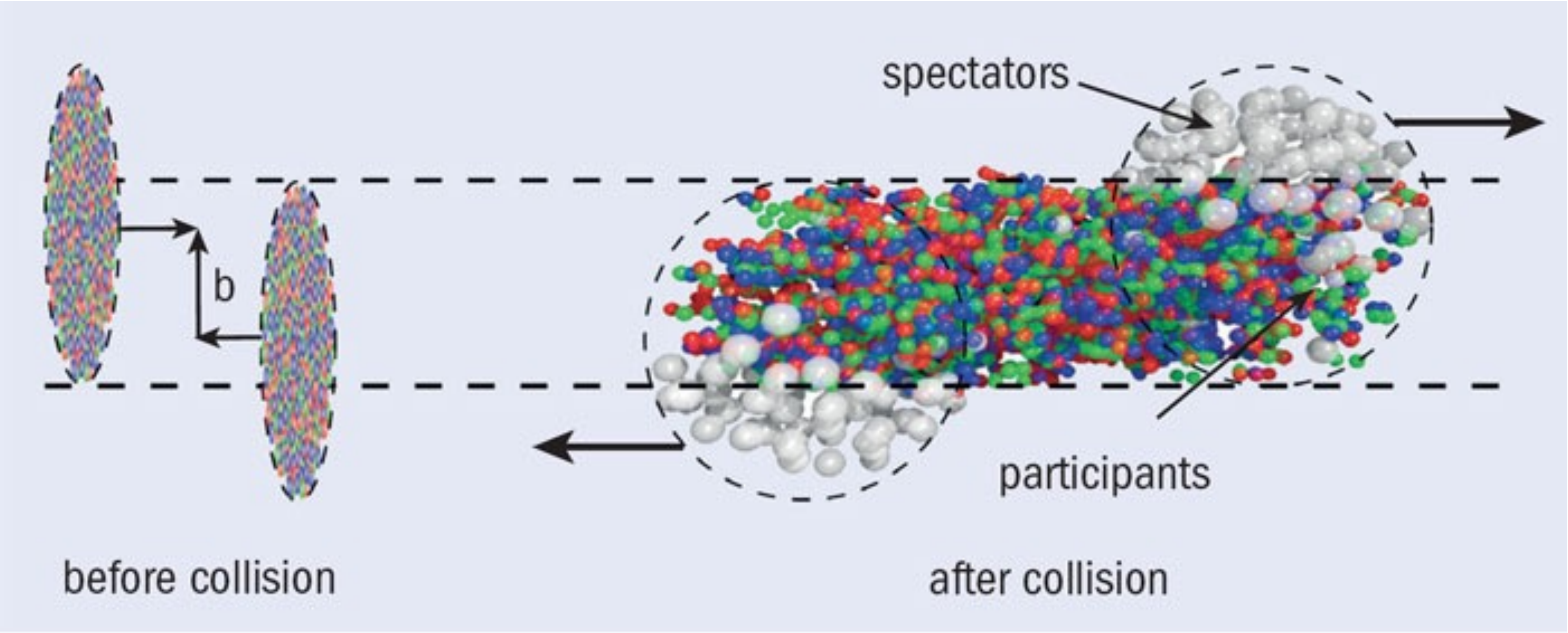


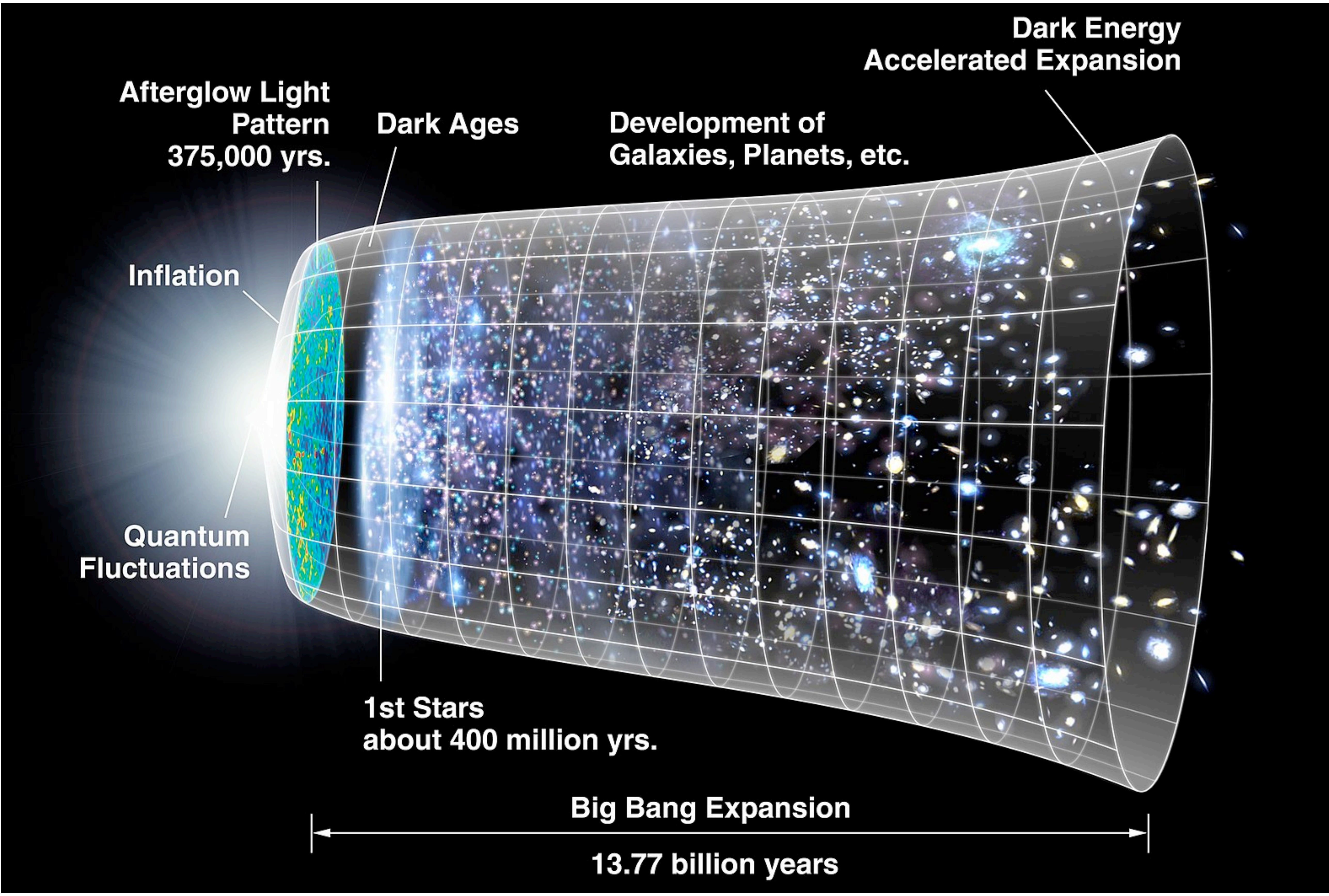
$$\frac{dN_{ch}}{d\eta} \propto (N_{part} \leftrightarrow N_{coll}) \propto b \rightarrow \text{Centrality}$$

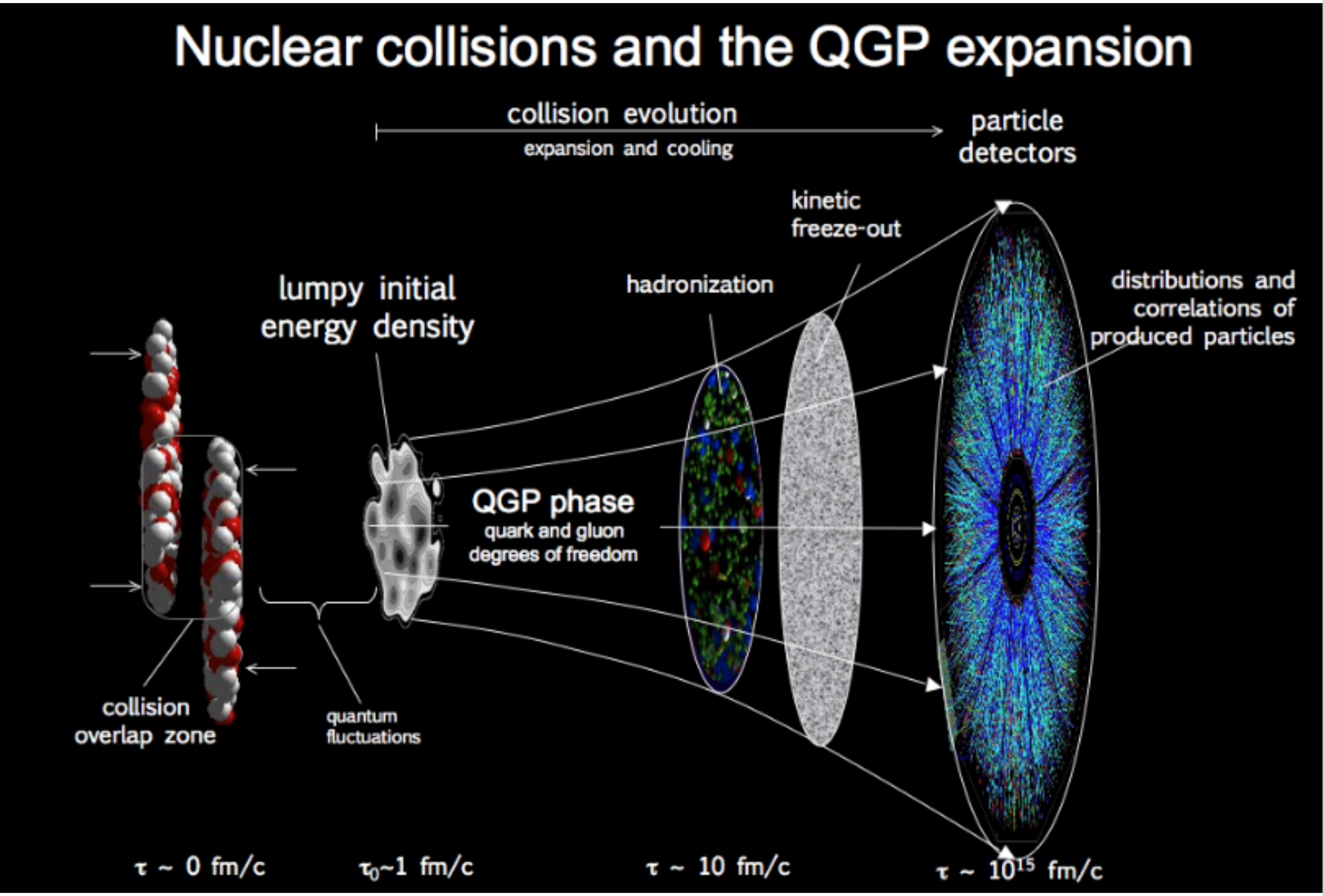
Experimental Observable

Glauber Model

What we want

The wrong by beautiful analogy

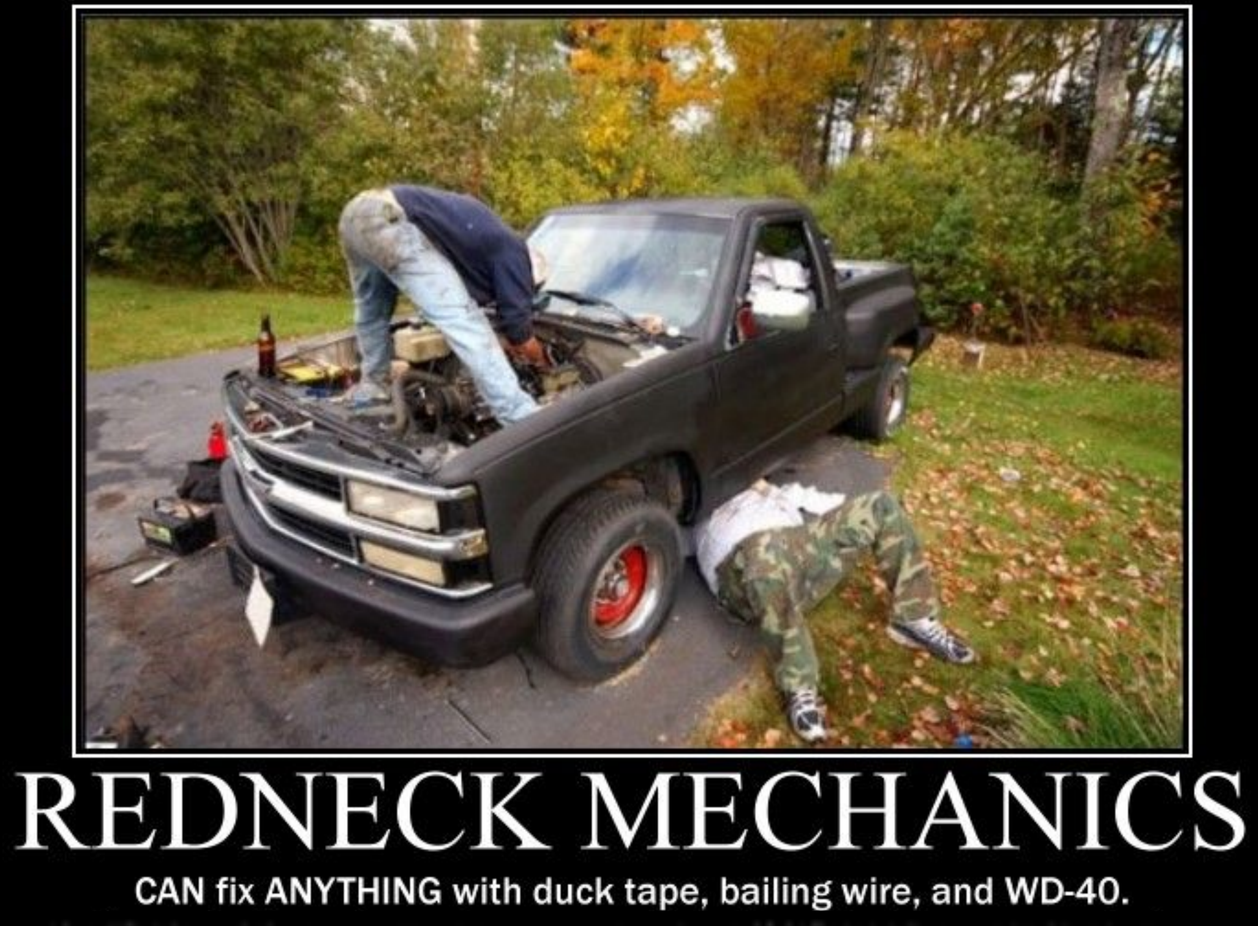




Now you can understand it !

HADRONIC PHYSICS

What detector's expert think we do



What SM physicists think we do

What we think we do

What nuclear physicists think we do

What we really do