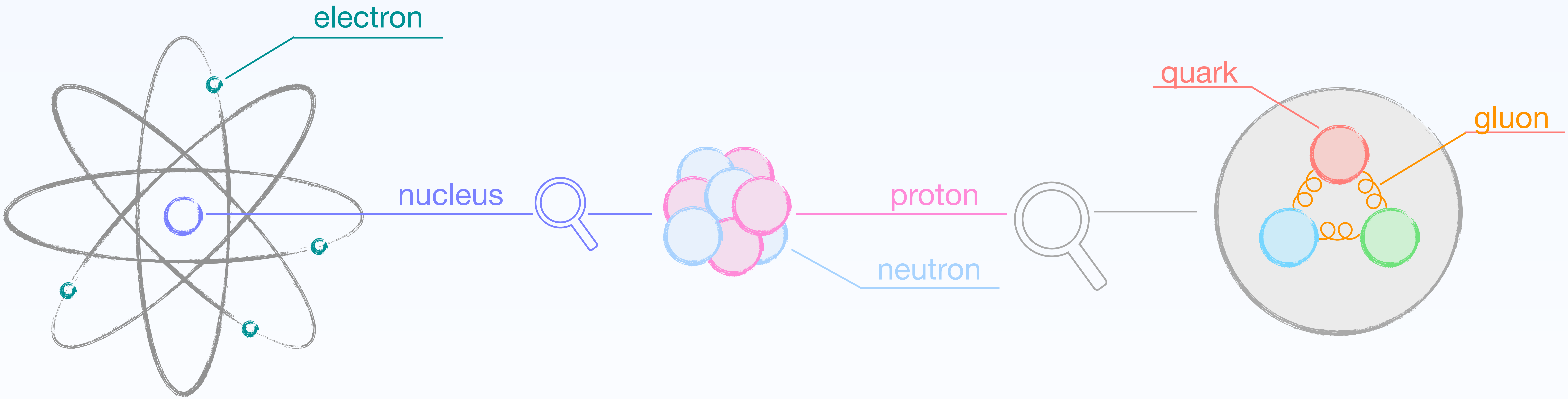
# Introduction to Hadronic Physics

## Journées de Rencontre des Jeunes Chercheurs

### Saint-Jean-De-Monts

Batoul Diab - 27/10/2023

# Building blocks of matter



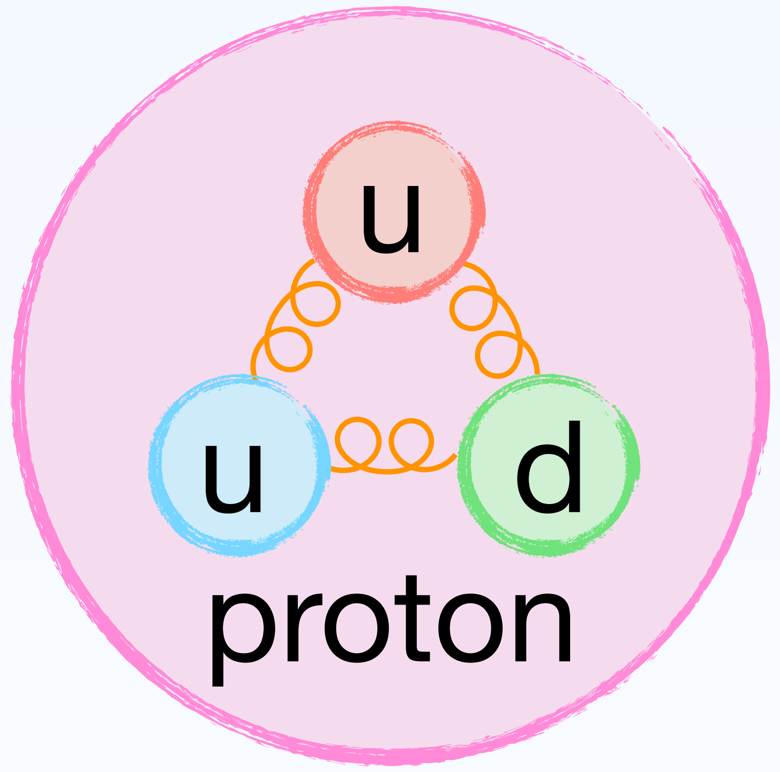

The building blocks of matter are quarks grouped in protons and neutrons

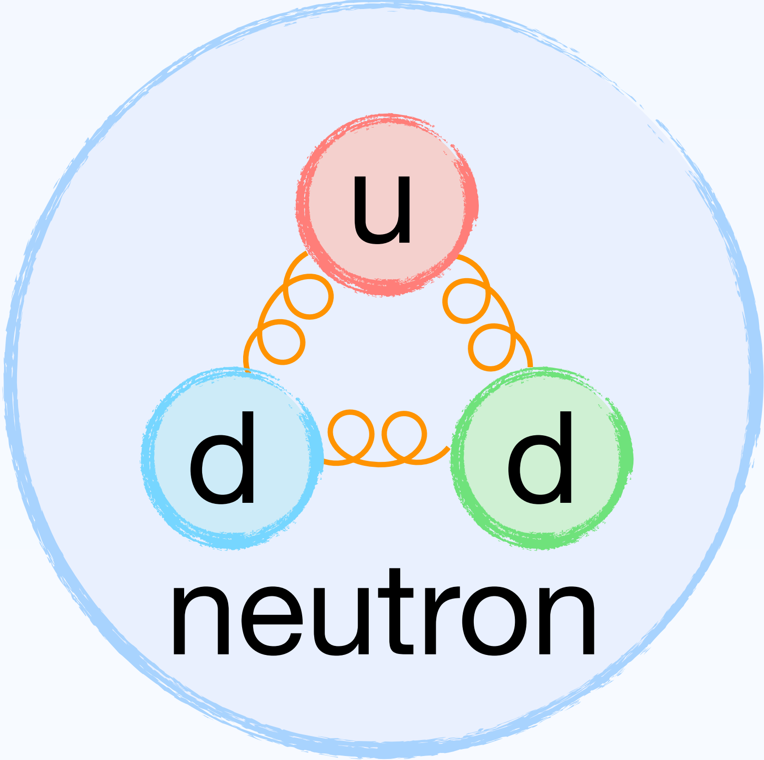

Gravity
Electromagnetic force
N
S
Weak force
Strong force

# The Strong force

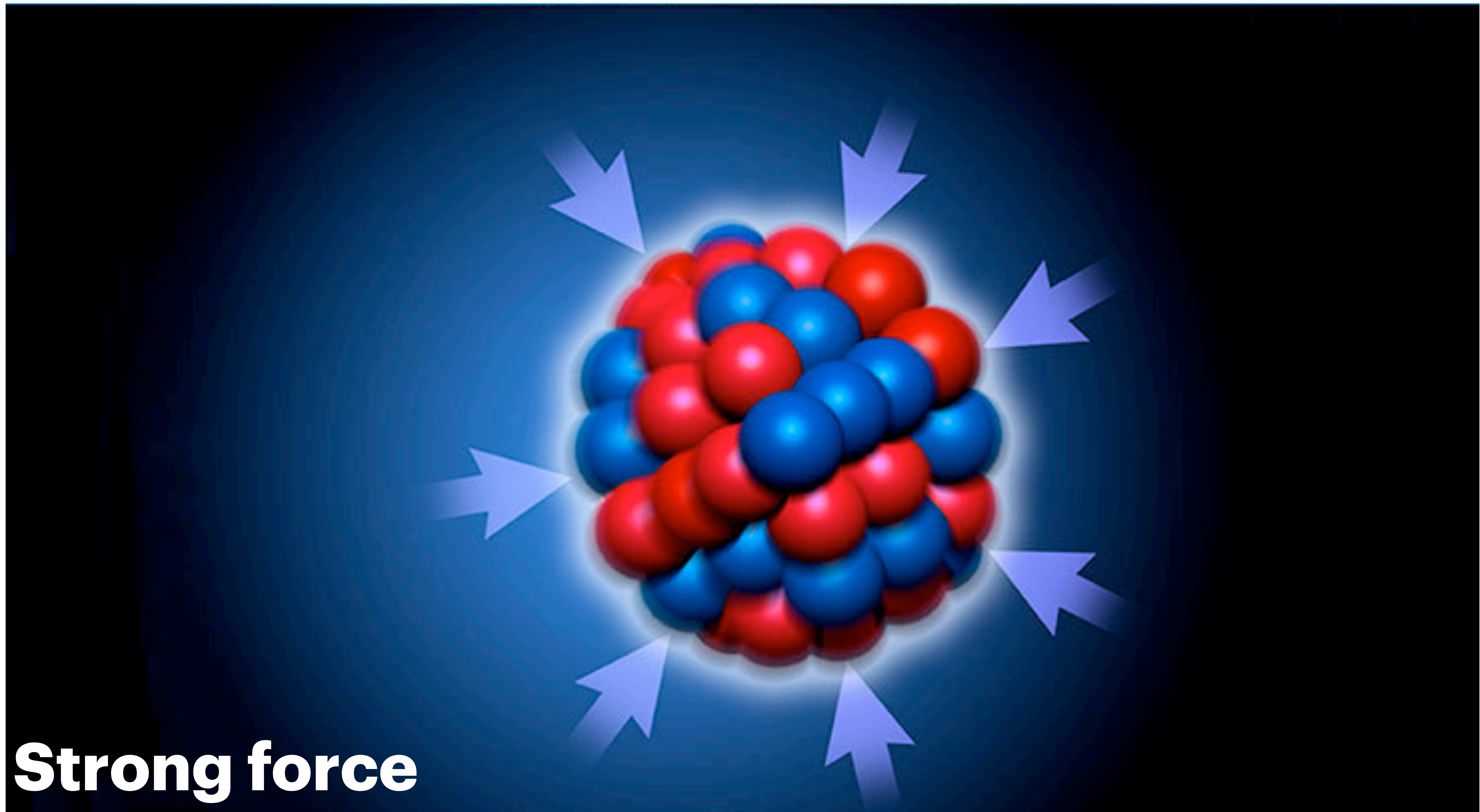
The strong force binds quarks together to form protons and neutrons

Force carriers: gluons




The residual strong force binds the nucleus



# Quantum Chromodynamics

The theory that describes the strong interaction is Quantum ChromoDynamics (QCD)

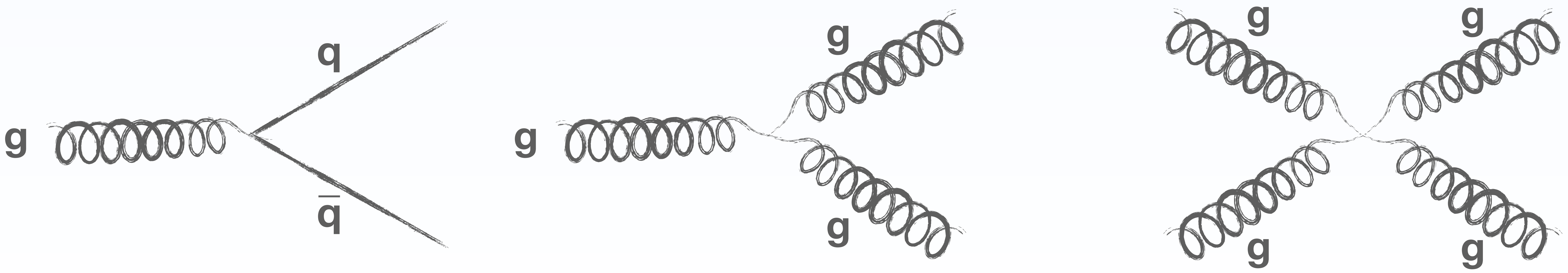
**Charge**: 3 color charges (red, green, blue)

**Mediators**: 8 gluons, massless and color charged

**Interaction with**: color charged objects (quarks, gluons)

**Range and strength**: very strong, very short

**Coupling "constant"**: $\alpha_s$, describes the strength of the interaction

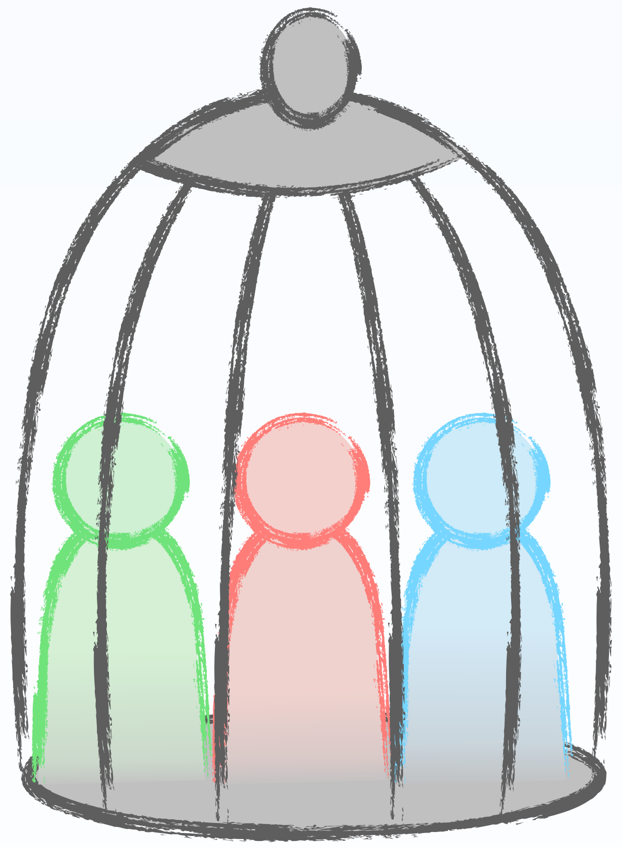


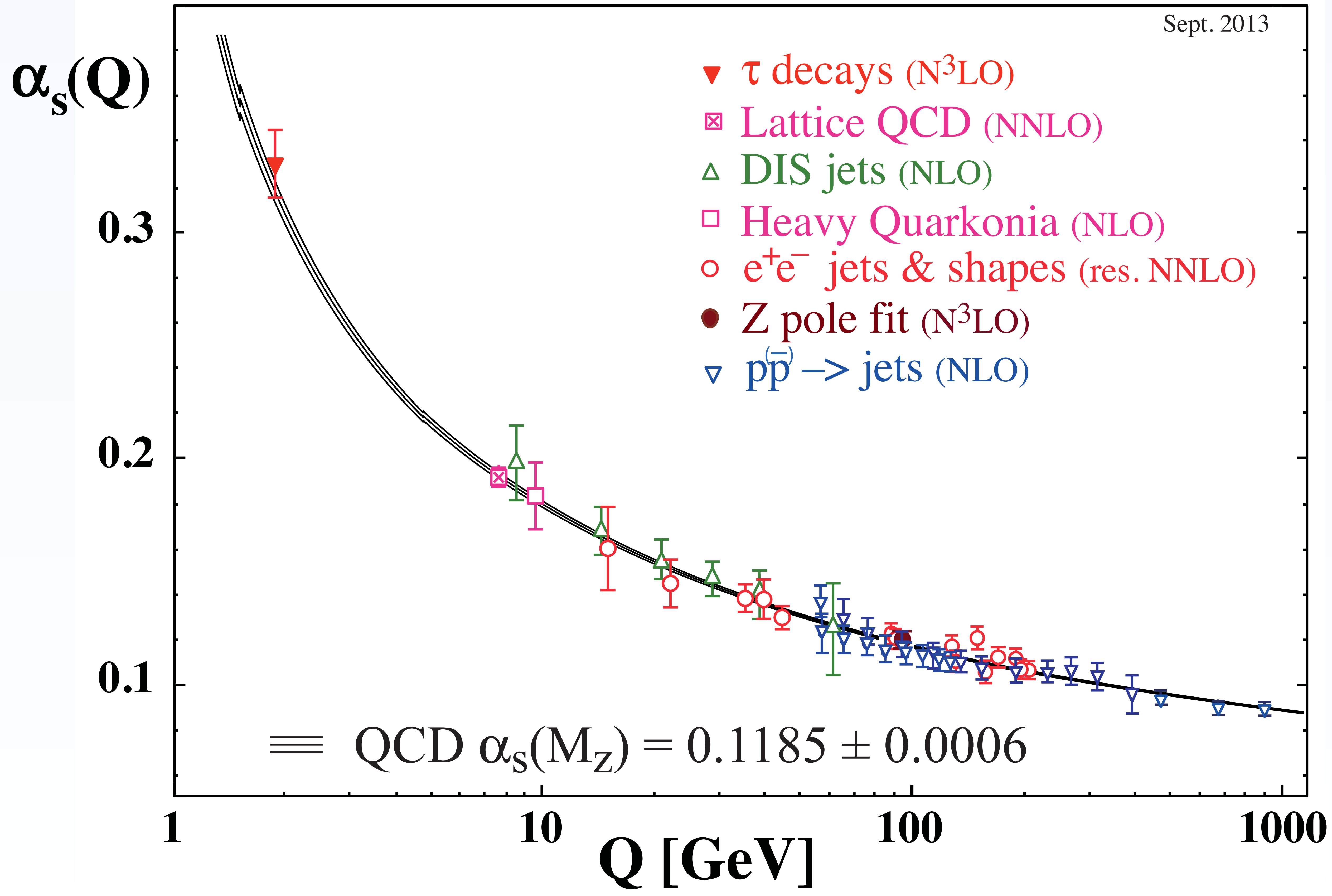
# Confinement

$\alpha_s$ varies with the energy scale

At low energy: $\alpha_s \rightarrow 1$, quarks are strongly bound

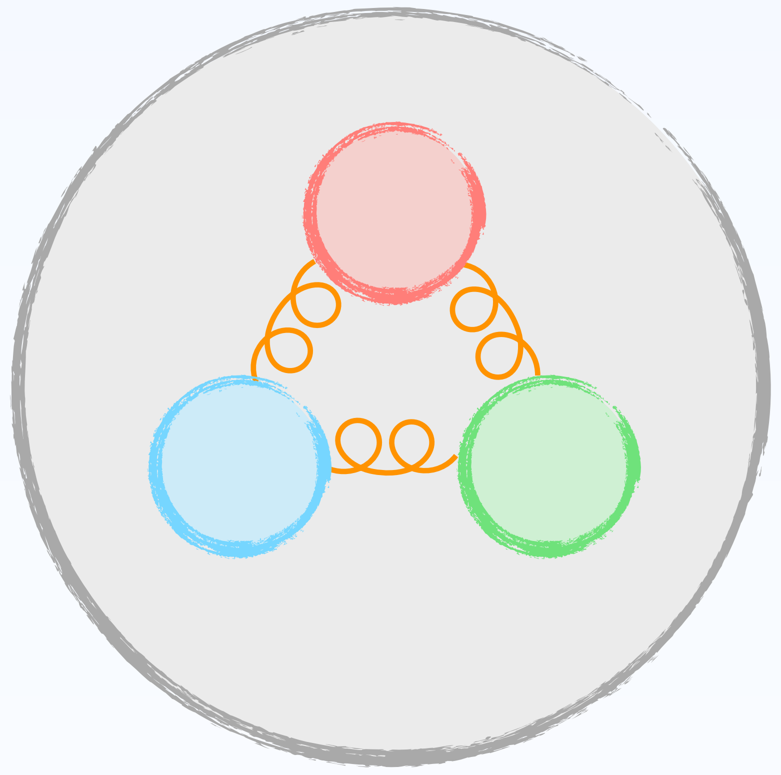
quarks are **confined** into **hadrons**





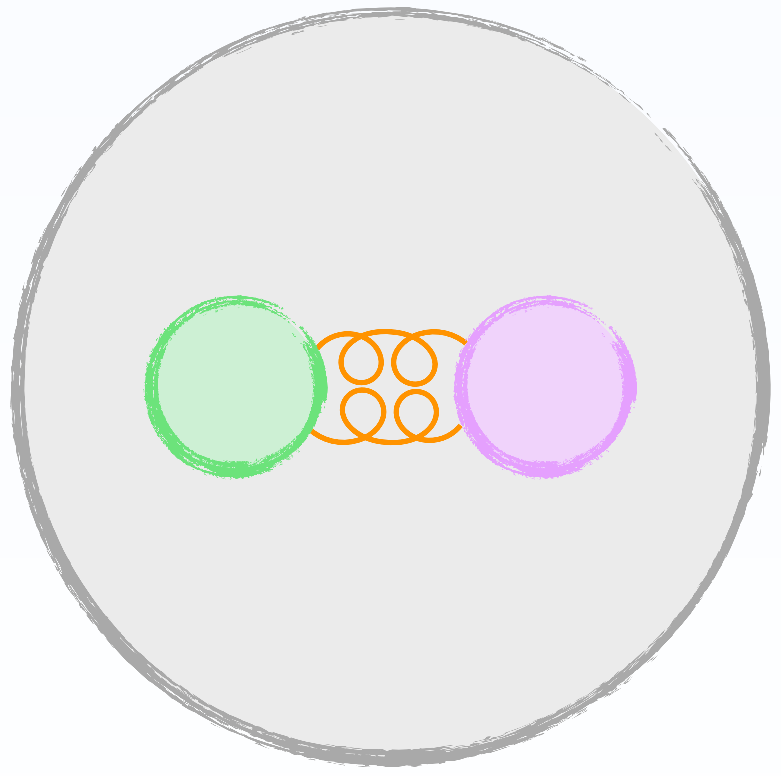
# Mesons and Baryons

**Hadrons are colorless objects**



Baryons

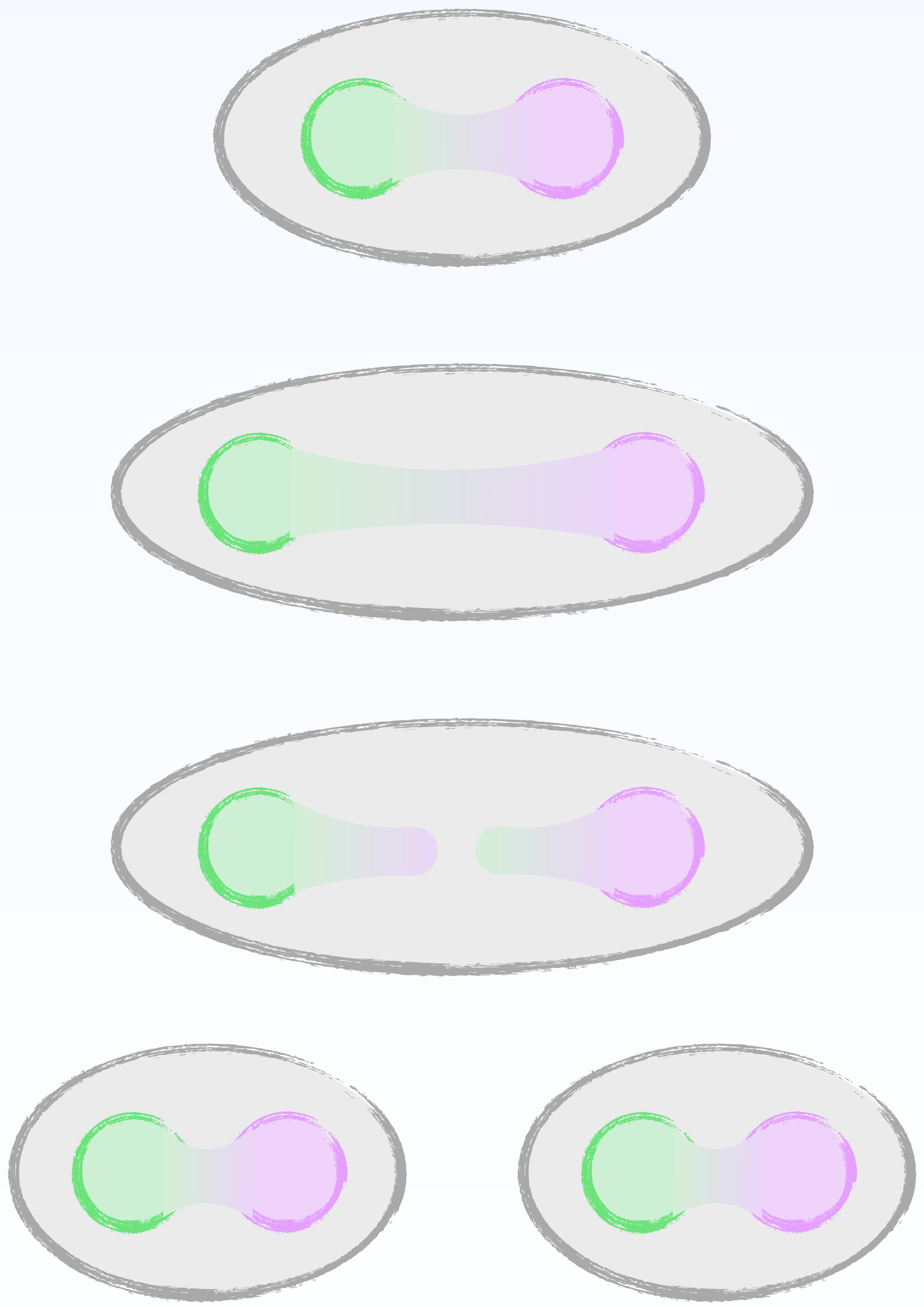
Charge: red + blue + green



Mesons

Charge: color + anti-color

**What happens if we try to separate a $q\bar{q}$ pair?**



Gluon tube between quarks elongates

Strong force gets stronger with the distance

new quark-antiquark pairs are created

# Lattice QCD

Imagine you have this QCD Lagrangian:

$$\mathcal{L} = -\frac{1}{2}\mathrm{Tr}[F_{\mu\nu}F^{\mu\nu}] + \sum_{i=1}^{N_f} \bar{\psi}_i(x)(\mathcal{D} + m_i)\psi_i(x)\ ,\ \mathcal{D} = \gamma^m u[\partial_\mu - igA_\mu(x)]$$

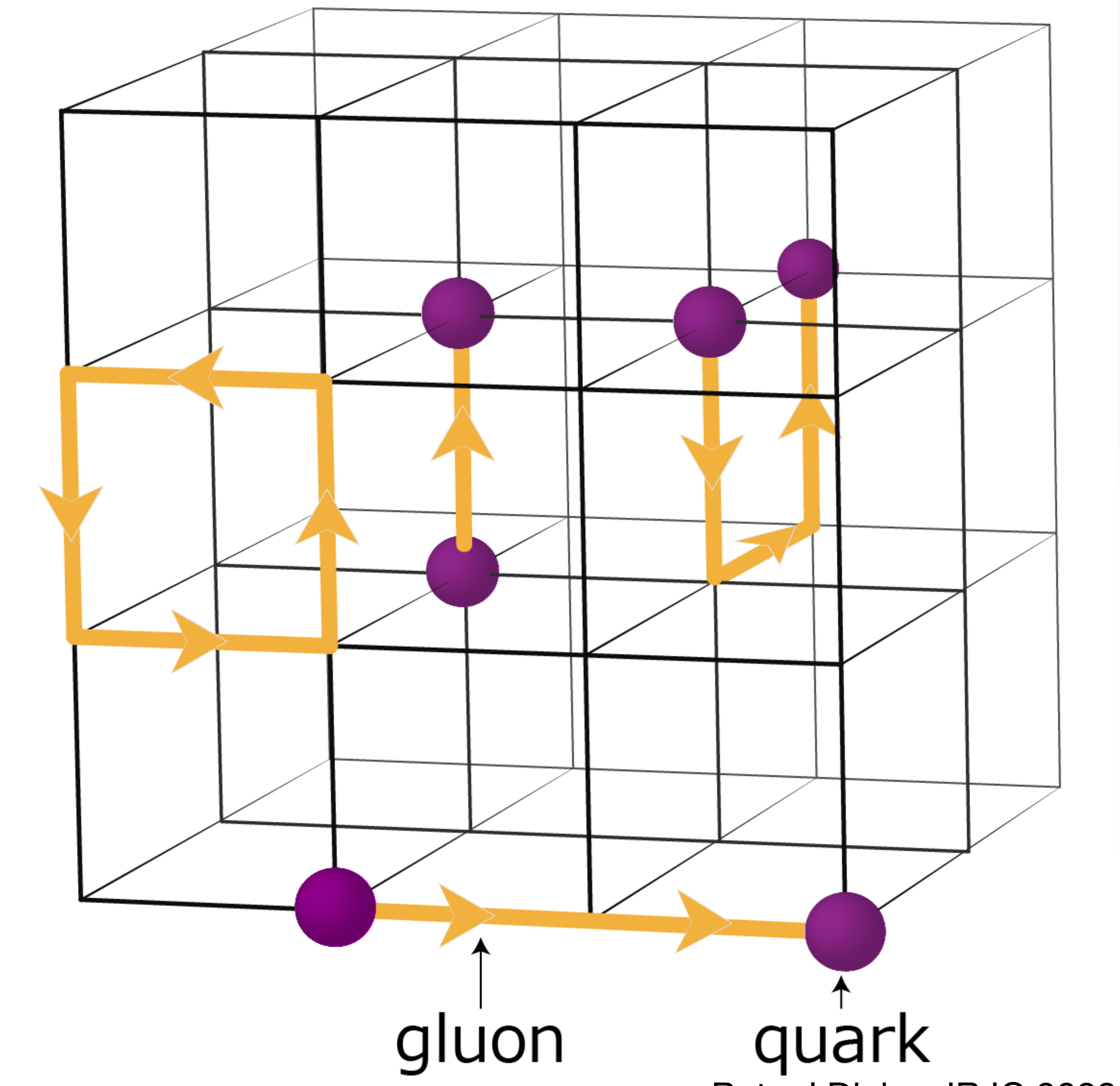
**Lattice QCD** breaks up spacetime into a grid:

Quarks are lattice sites

Gluons are links connecting sites

Only considers nearest-neighbor interactions

Continuum: infinitely large lattice of infinitely close sites

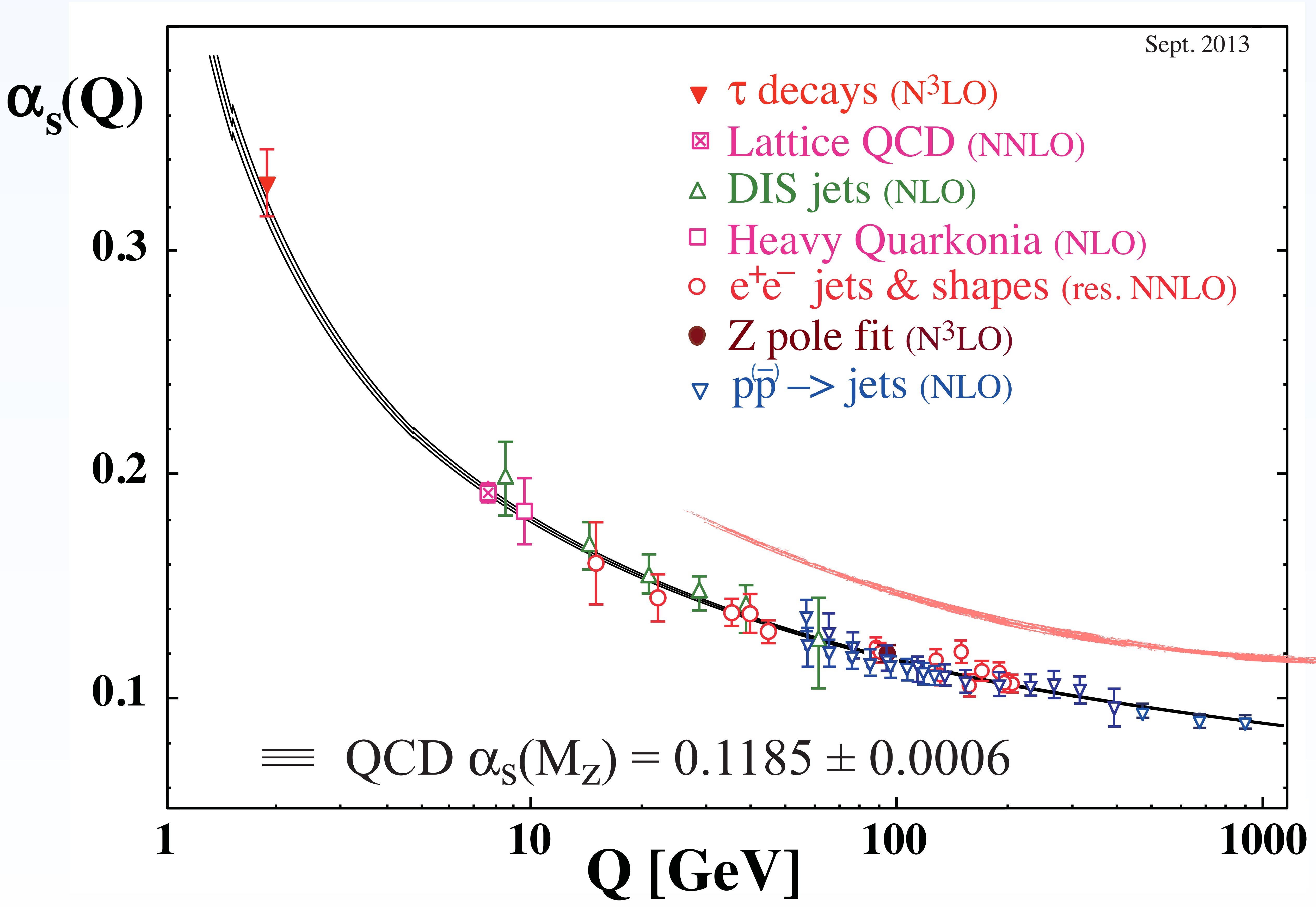



| Advantages | Disadvantages |
|---|---|
| Great predictive power | Need supercomputers |
| Rigorous calculation | Gives numbers |
| systematically improved | |

# Asymptotic freedom

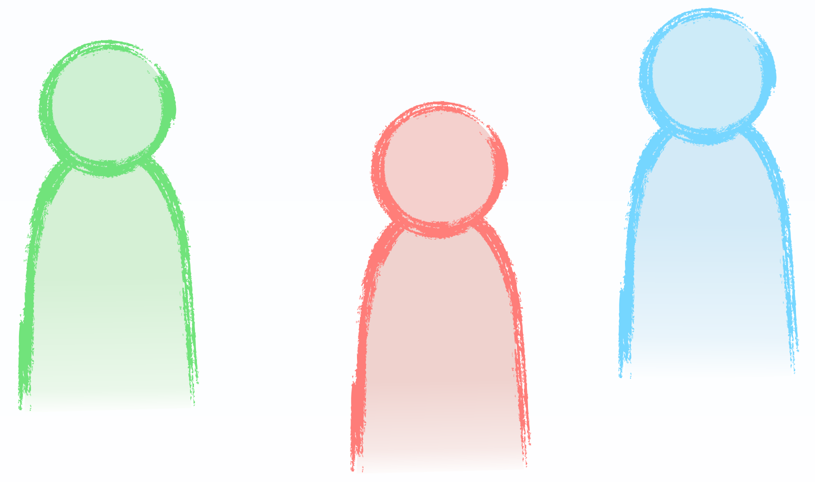
$\alpha_s$ varies with the energy scale

At high energy: $\alpha_s \rightarrow 0$, quarks are weakly coupled




quarks are seen as individuals

**Asymptotic freedom**



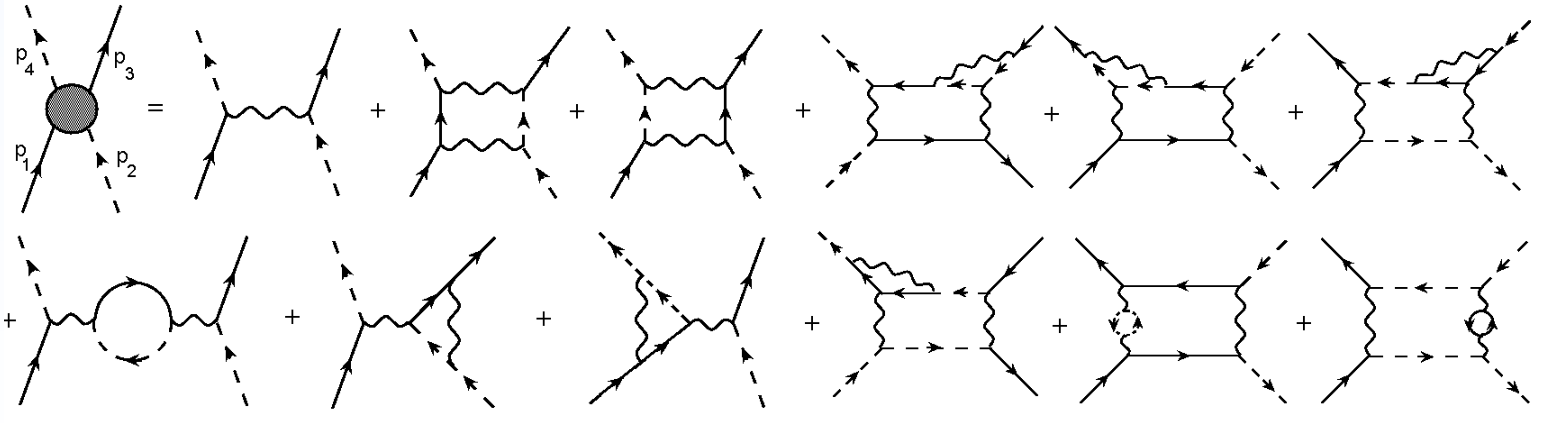
# Perturbative QCD

Perturbative expansion in $\alpha_s$ of an observable $f$ can be written as:

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

In high-energy regimes, $\alpha_s \ll 1$

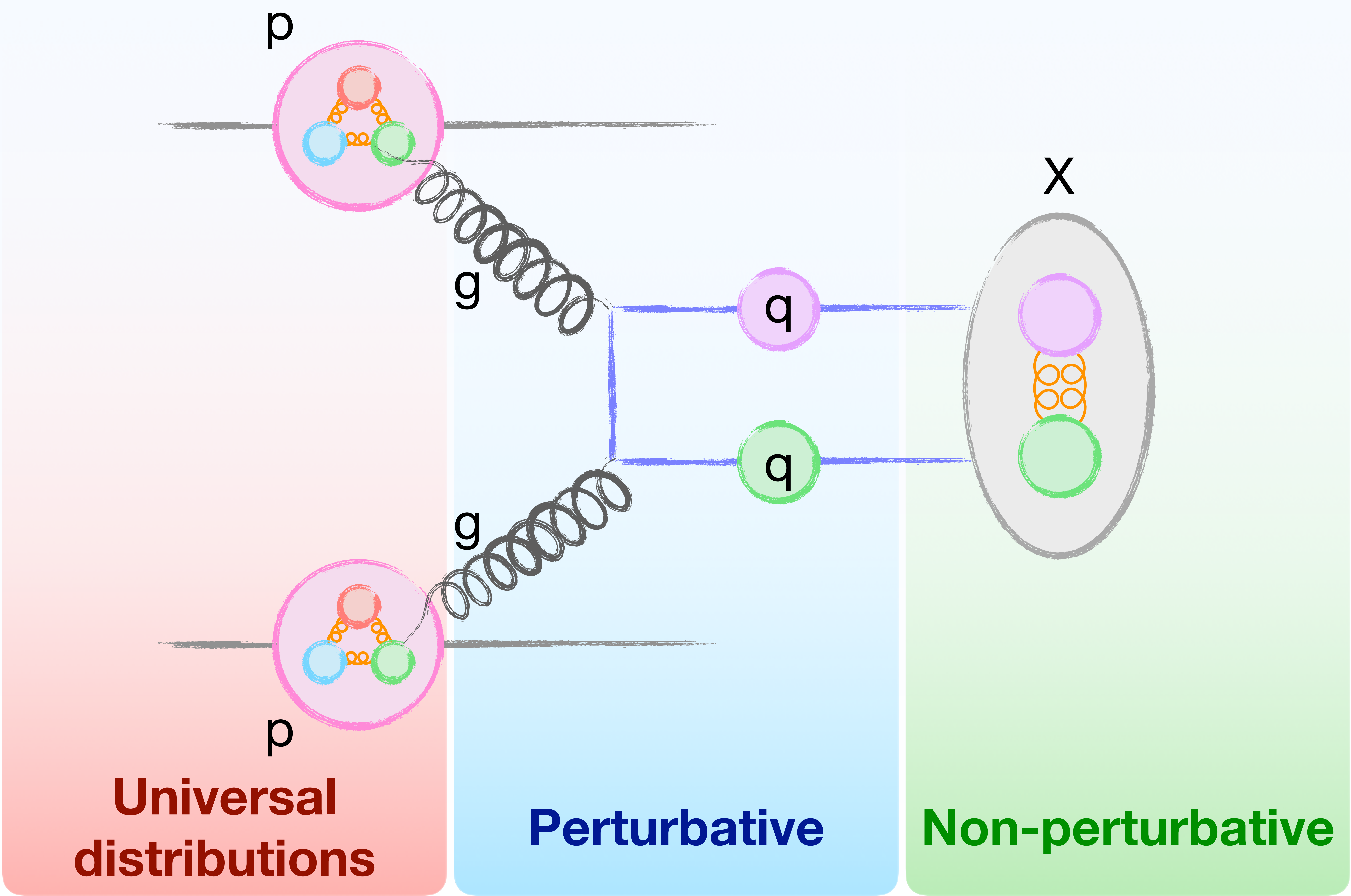
Only the first, two or three terms are calculated
The others are assumed to be negligible



# Factorization theorem

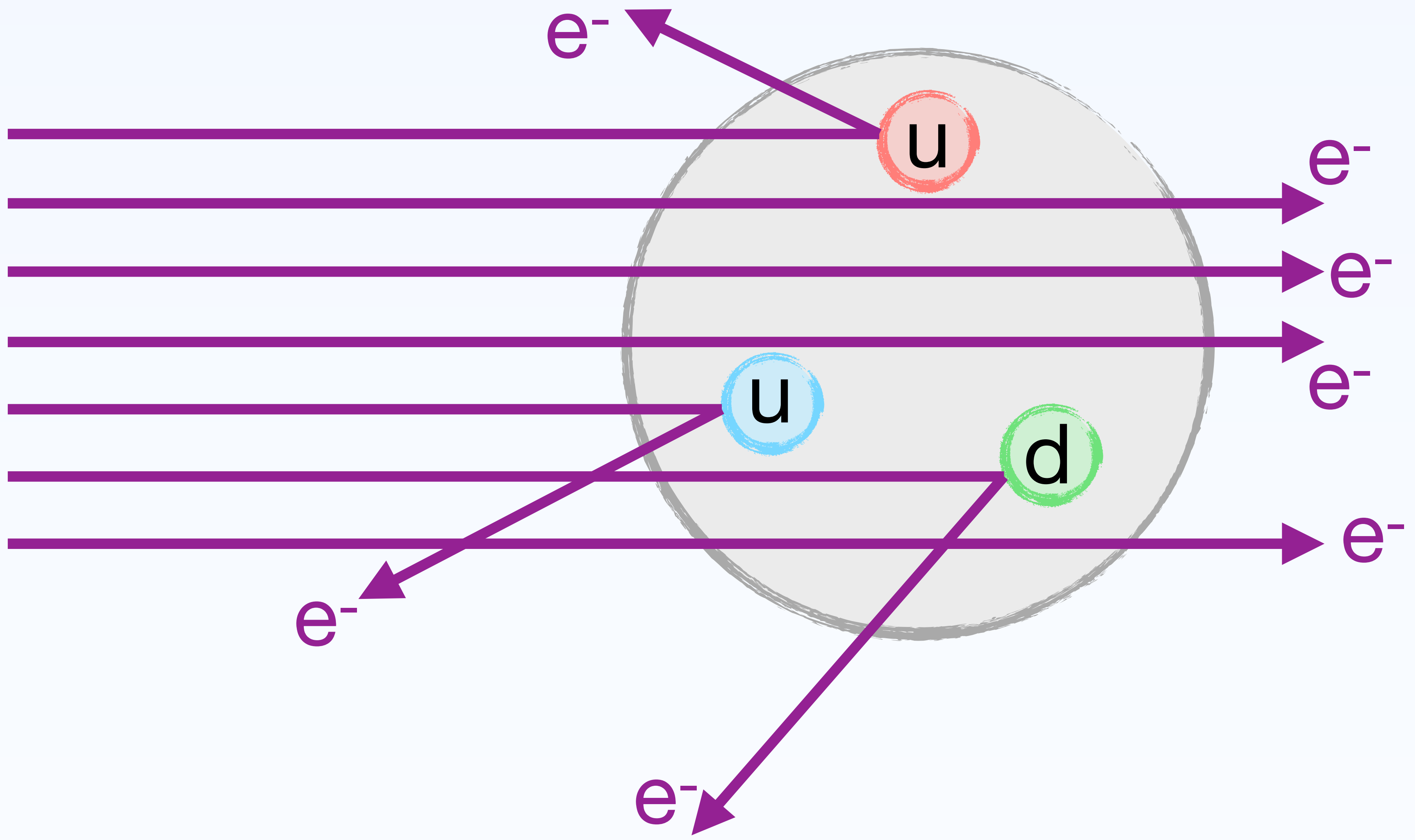
Cross section of a generic final state $X$ in pp collisions: $\sigma_{pp\to X} = \sum_{i,j} \int dx_1 dx_2 f_i(x_1) f_j(x_2) \hat{\sigma}_{ij\to X}(x_1, x_2)$

The Factorization theorem separates the perturbative and non-perturbative parts of a process:

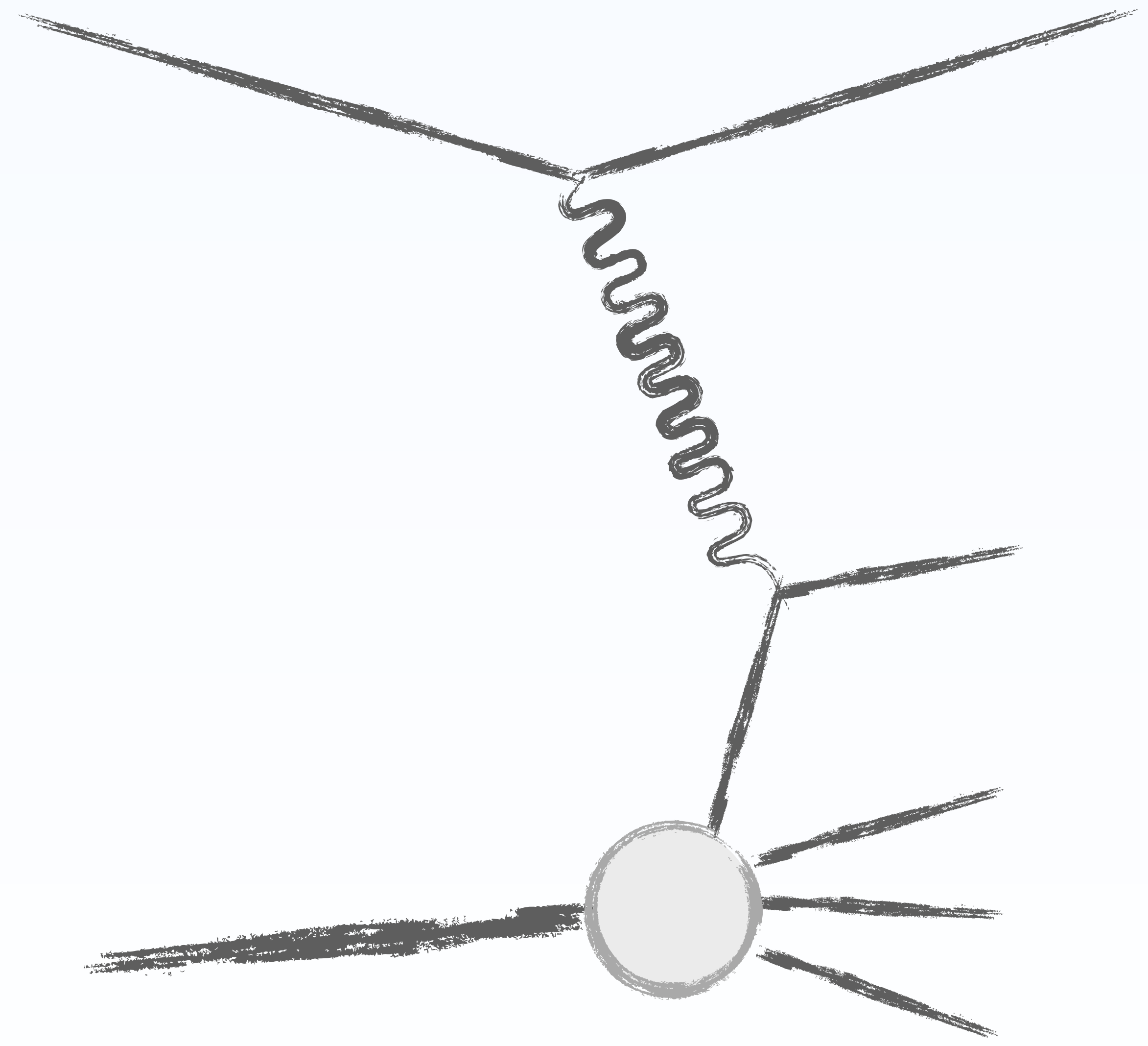


# Evidence for quarks

Let's fire electrons at protons and observed how the electrons bounced off:




**Deep inelastic scattering**

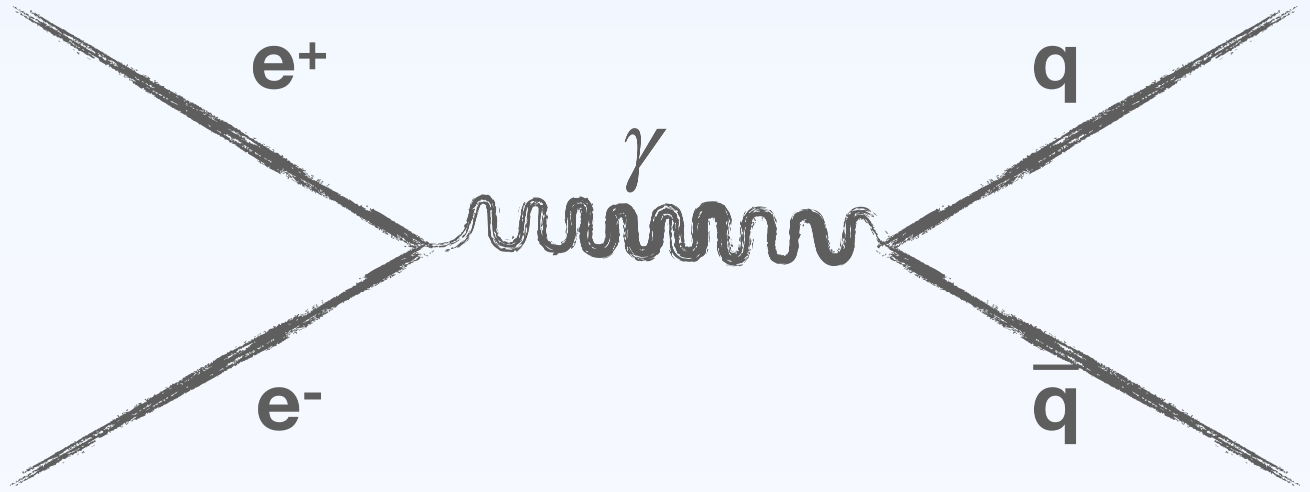


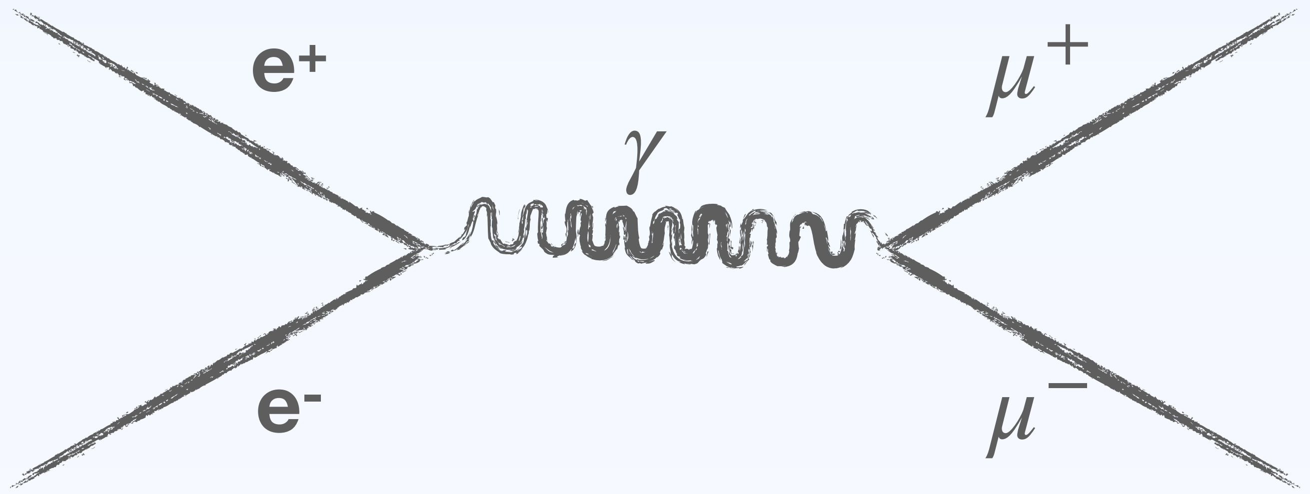
Observation:
If an electron comes closer than a femtometer, the electron bounces off or passes through the proton

Conclusion:
**Point-like charges inside the proton**

# Evidence for color

$e^+e^-$ annihilation:

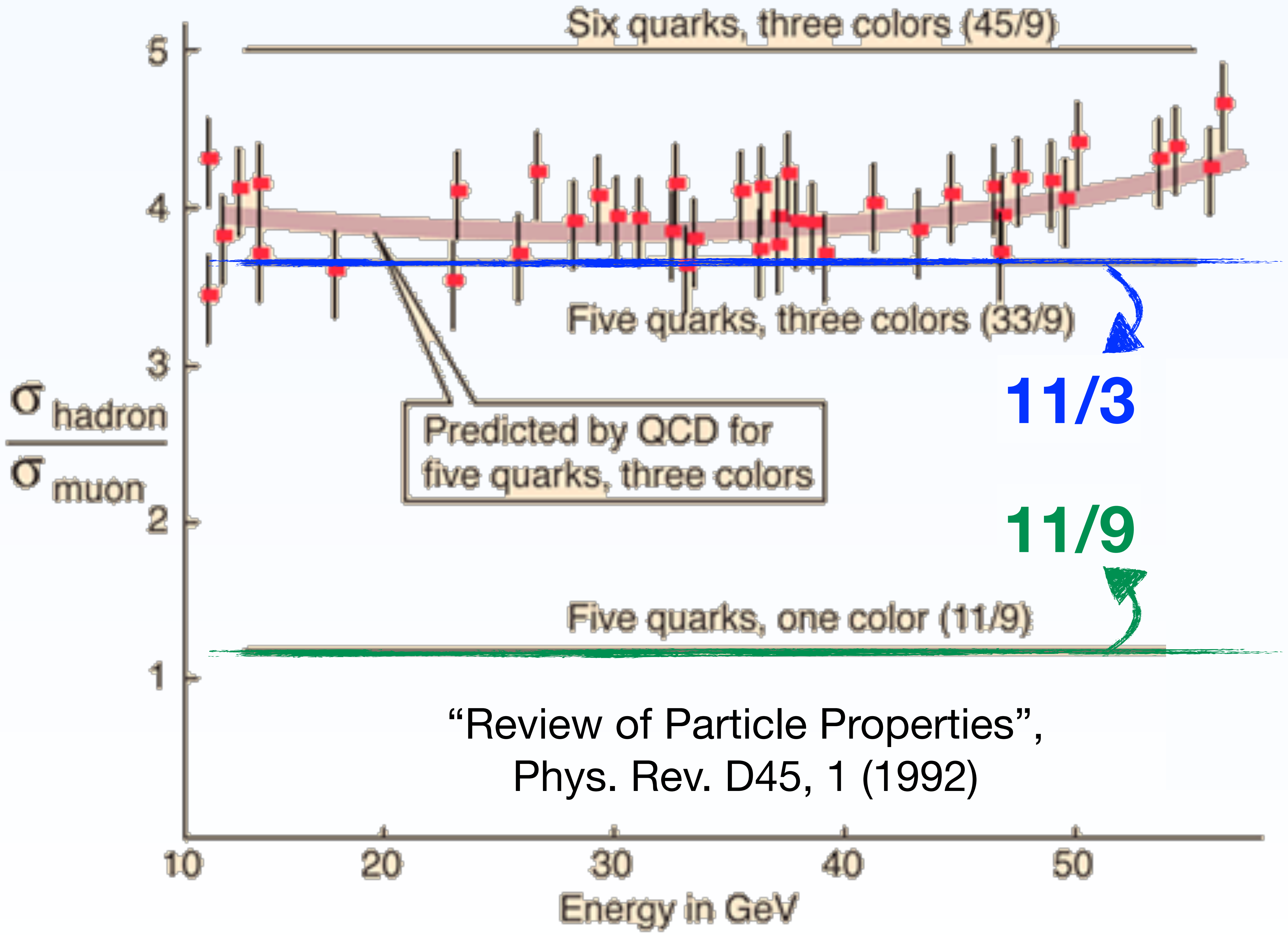



$$R = \frac{\sigma_{\text{hadrons}}}{\sigma_{\text{muons}}} = \frac{\sum \sigma_{q\bar{q}}}{\sigma_{\text{muons}}} = \sum \left(\frac{q_q}{e}\right)^2$$

The flavor production depends on the energy, for $\sqrt{s} > 2m_b \sim 10$ GeV, $u, d, s, c$ and $b$ are produced:

$$R = 3\left[\left(\frac{2}{3}\right)^2 + \left(\frac{-1}{3}\right)^2 + \left(\frac{-1}{3}\right)^2 + \left(\frac{2}{3}\right)^2 + \left(\frac{-1}{3}\right)^2\right] = \frac{11}{3}$$



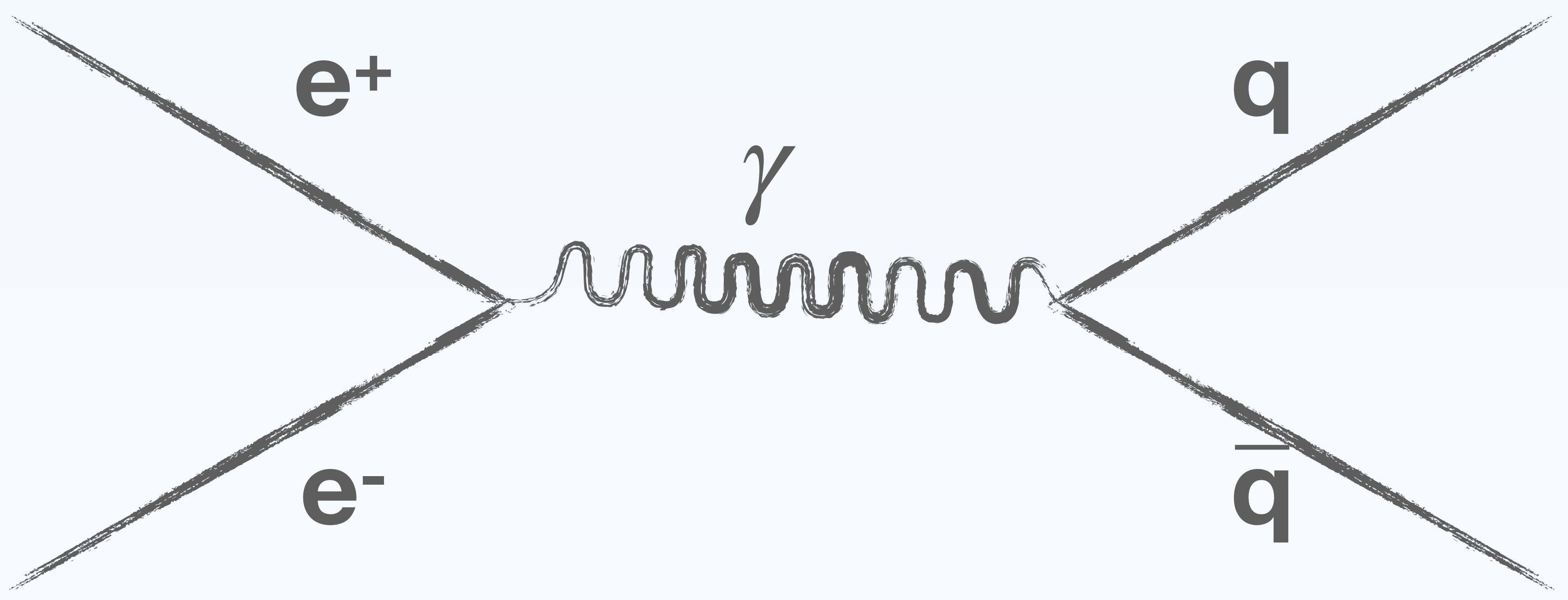

"Review of Particle Properties", Phys. Rev. D45, 1 (1992)

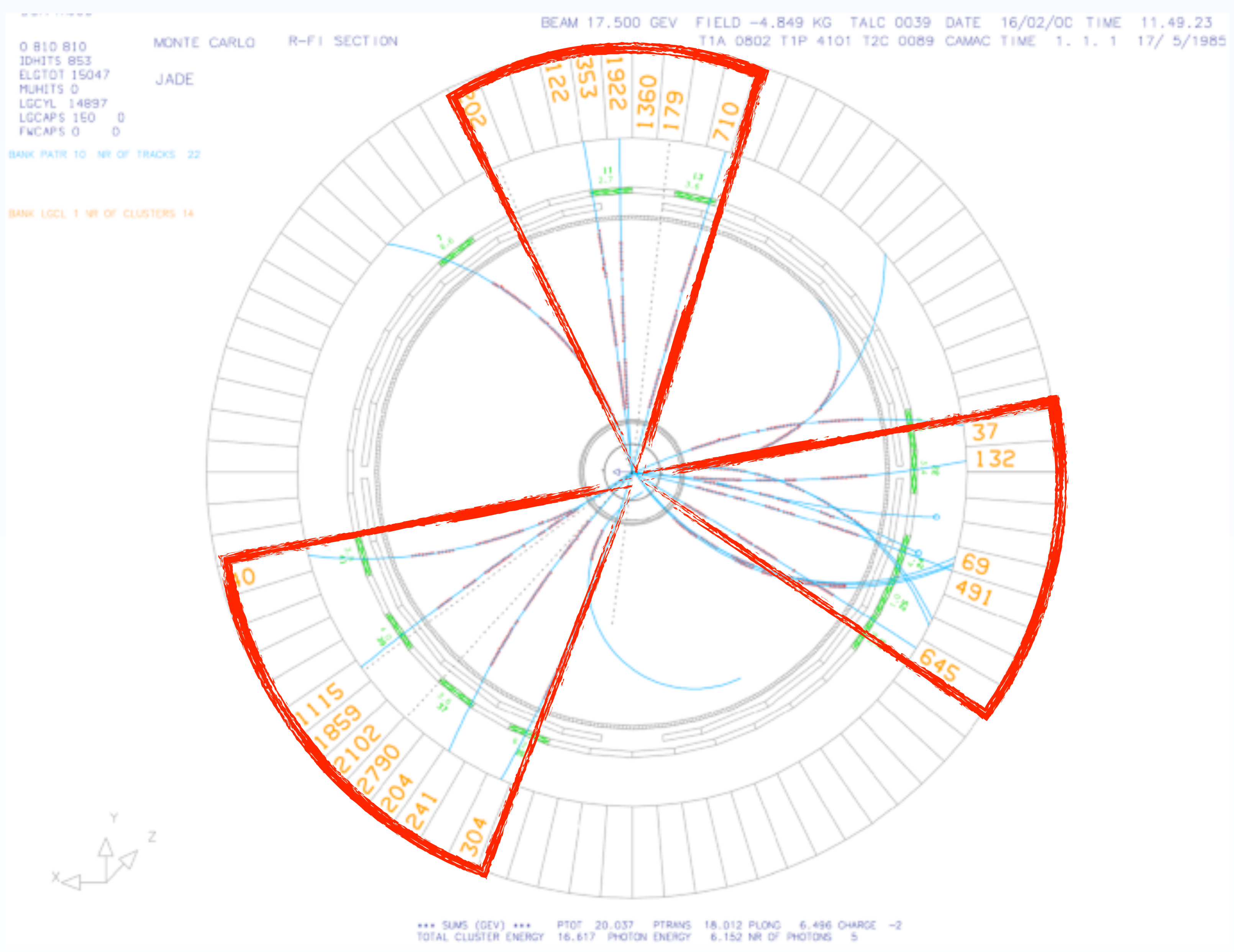
# Evidence for gluons

$e^+e^-$ are perfect tools:

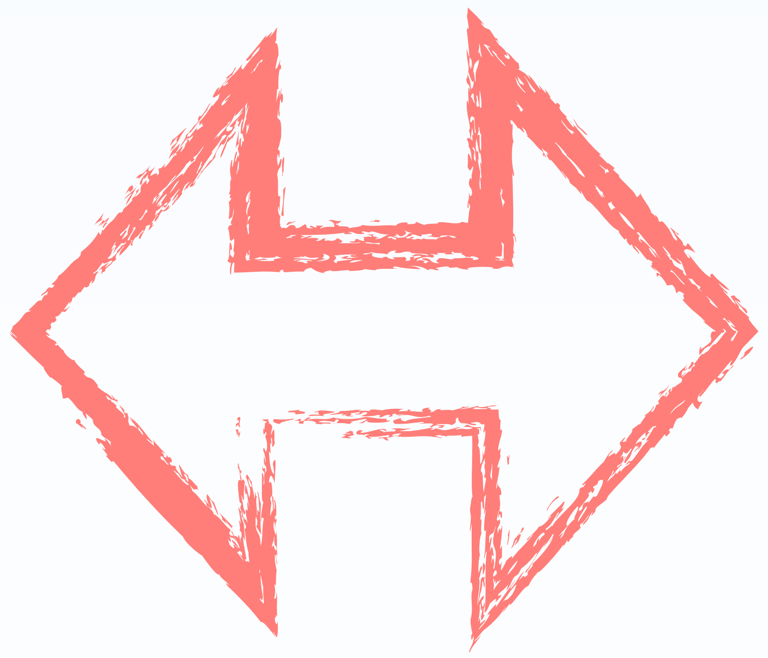
no hadron in the initial state → very clear environment

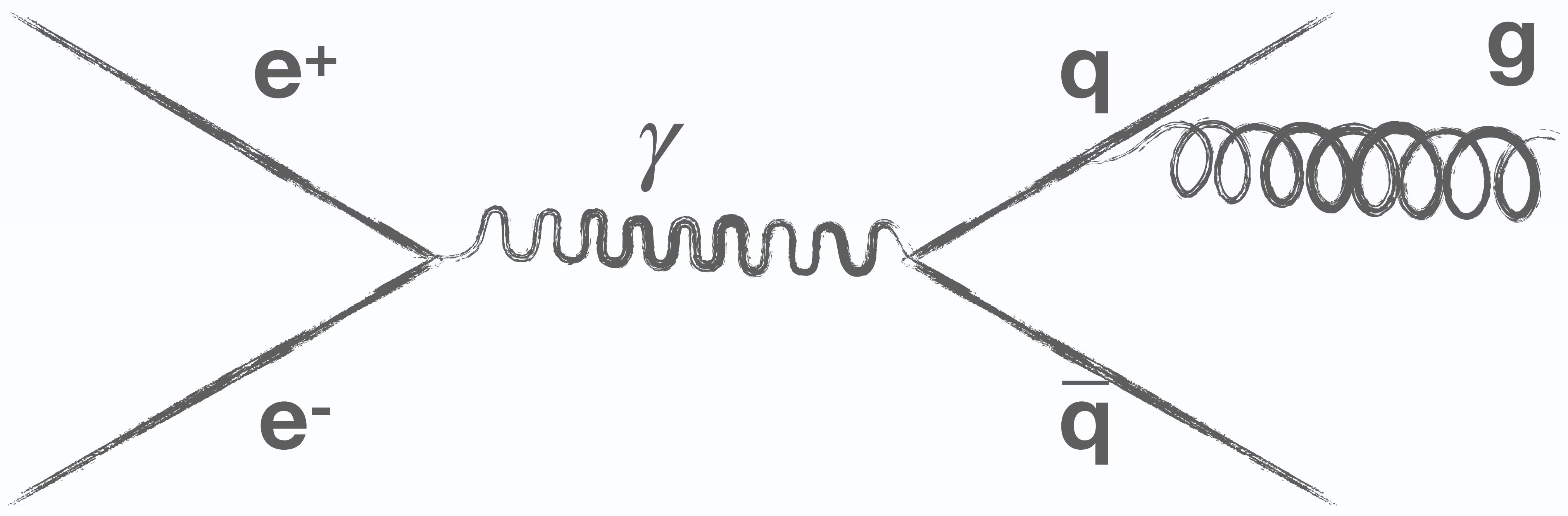
Main process: $e^+e^- \rightarrow Z^0/\gamma^* \rightarrow q\bar{q}$




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



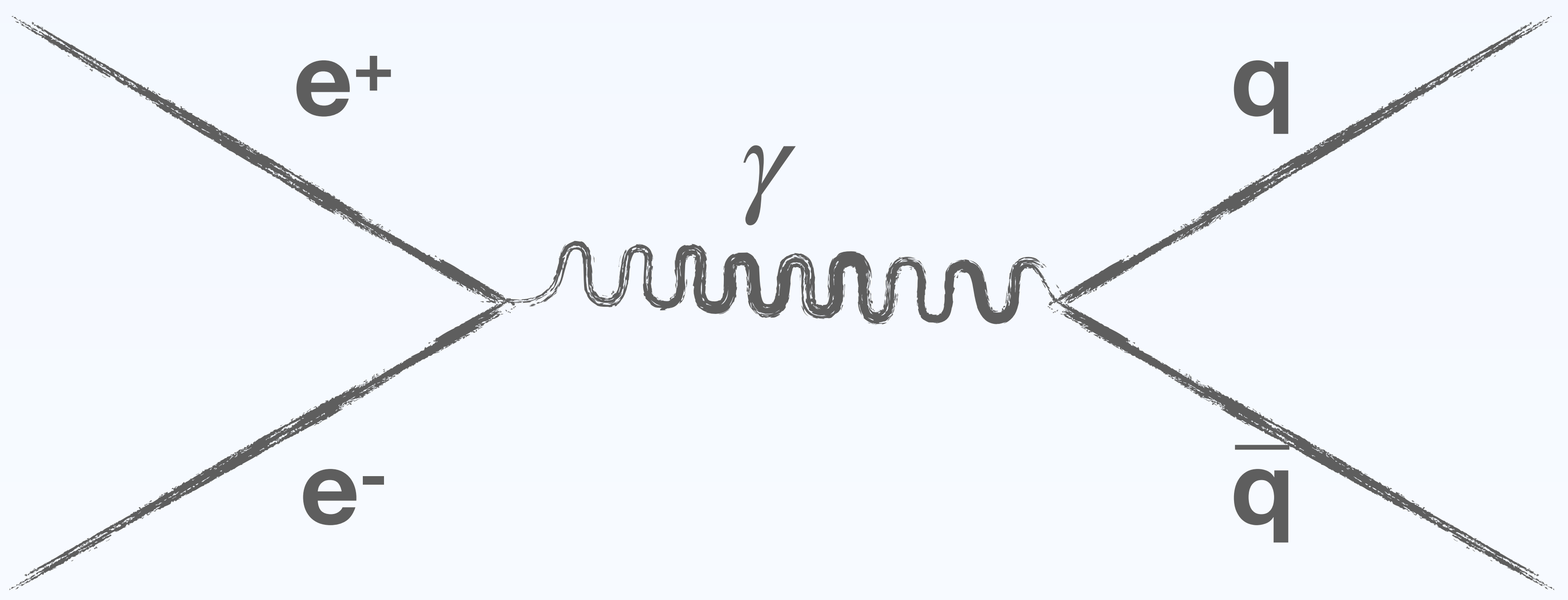


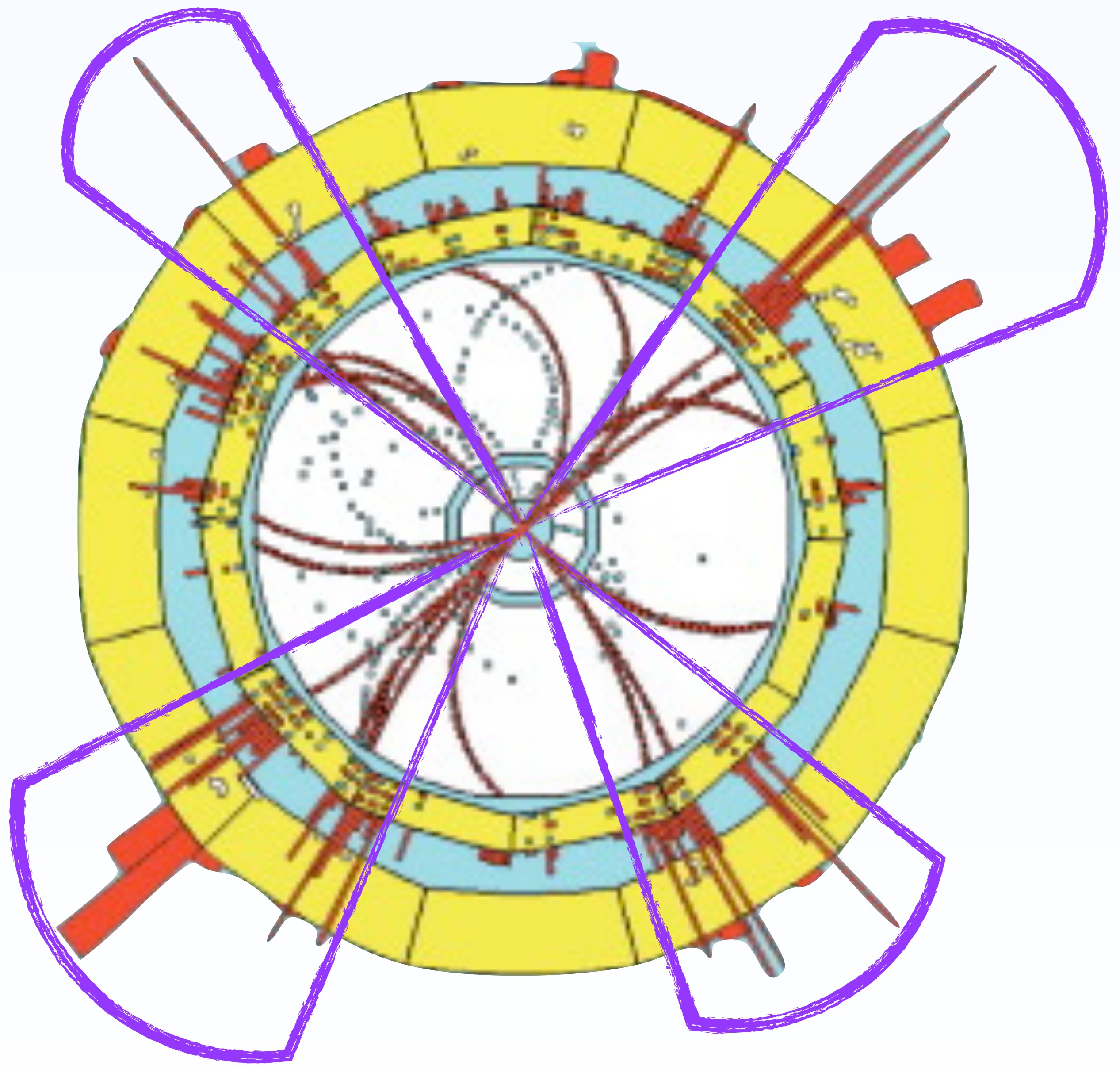
# Evidence for gluon coupling

$e^+e^-$ are perfect tools:

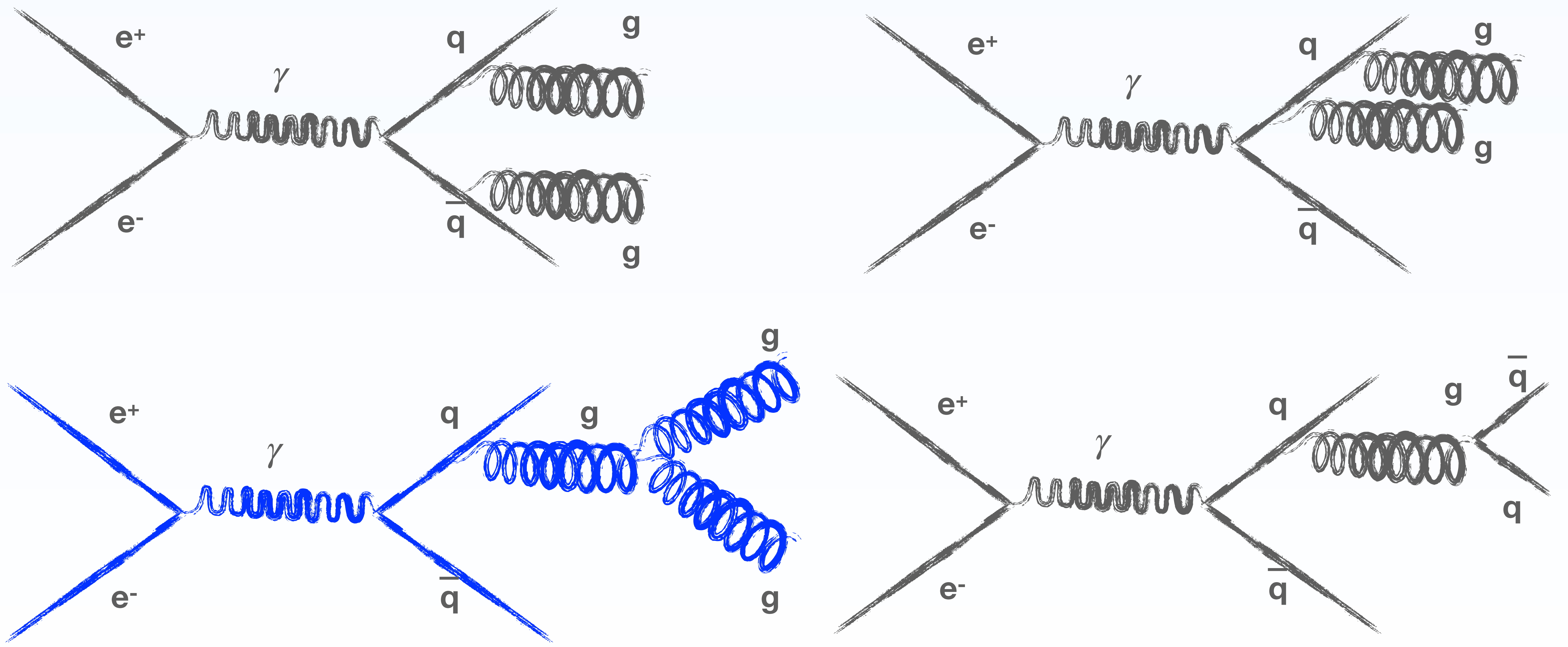
no hadron in the initial state → very clear environment

Main process: $e^+e^- \to Z^0/\gamma^* \to q\bar{q}$



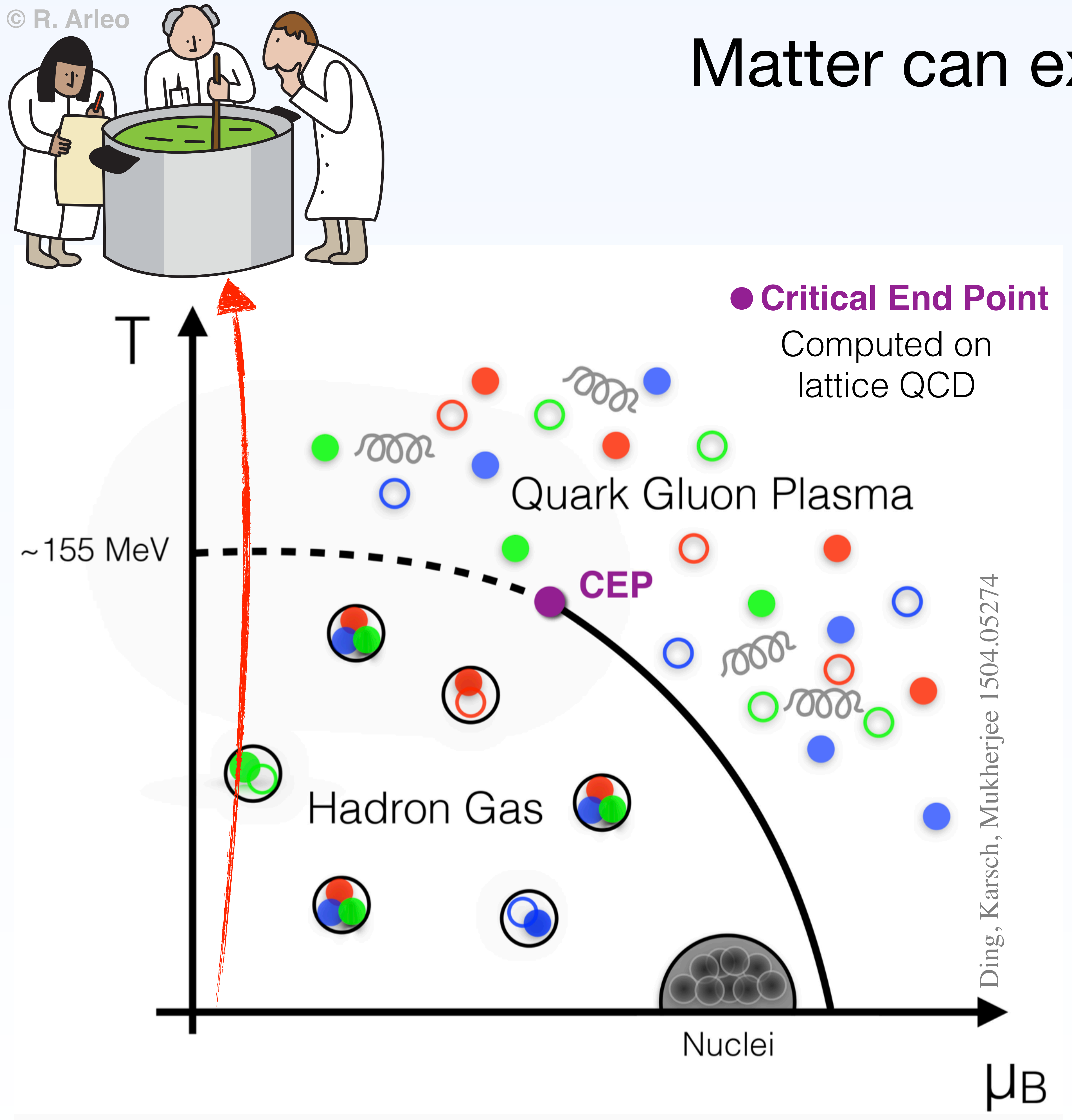



e+e- collider, √s = 200 GeV
4-jet event, ALEPH detector at LEP-I



# Phase transition: Quark Gluon Plasma

Matter can exist in different forms

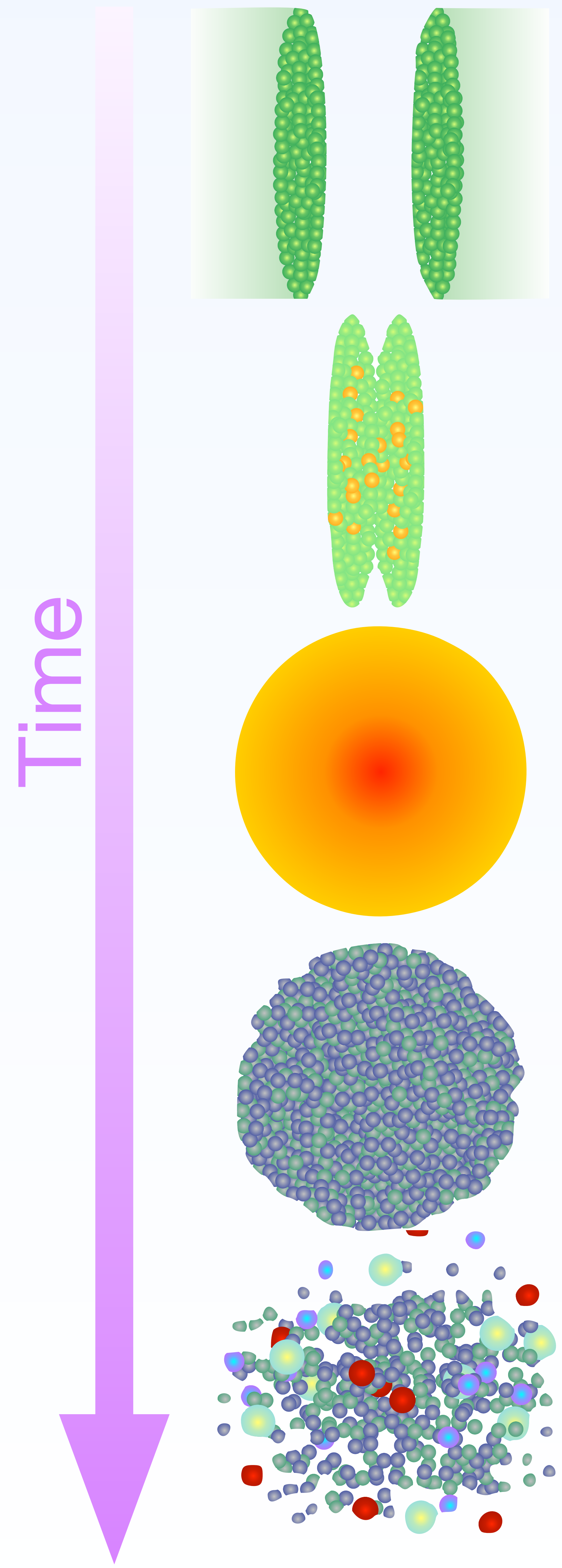



Low temperature and density → hadronic matter

High temperature and/or density → Quark Gluon Plasma

Reproduced at colliders with heavy-ion collisions

# Heavy-ion collisions




Ultra-relativistic heavy nuclei

Initial nucleon-nucleon collisions

Quark Gluon Plasma

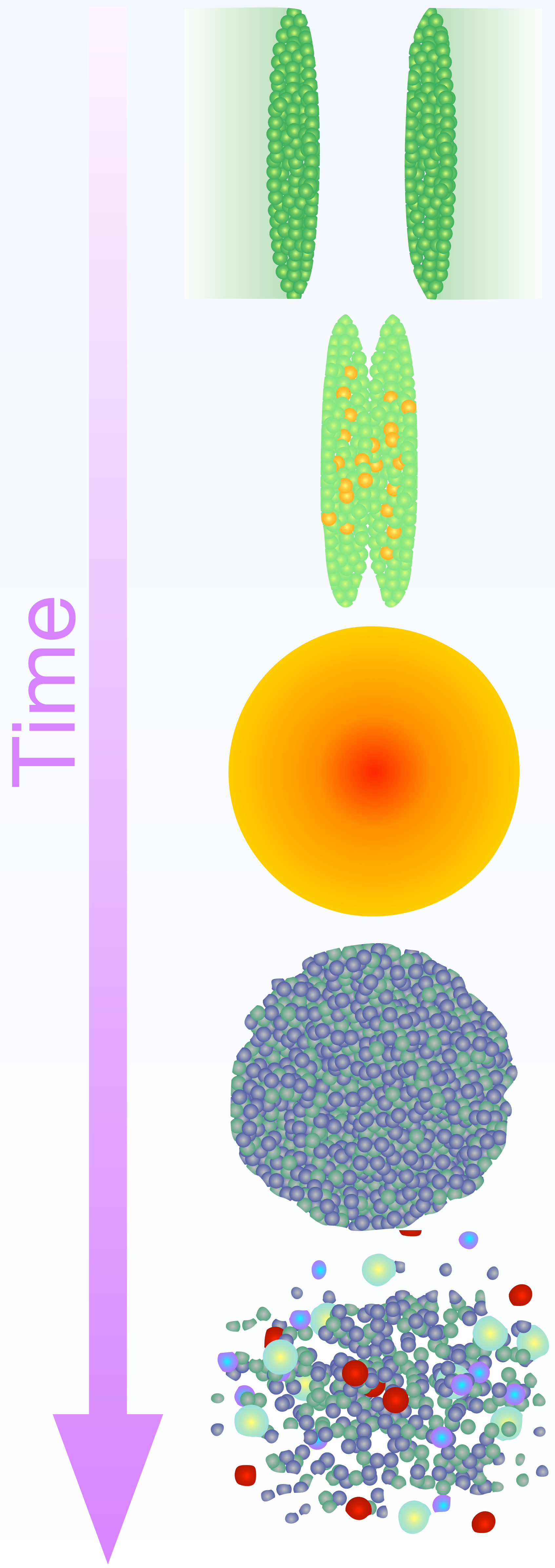
Hadronization

Kinetic freeze-out

Initial nucleon-nucleon collisions

Heavy flavor production

# Heavy-ion collisions



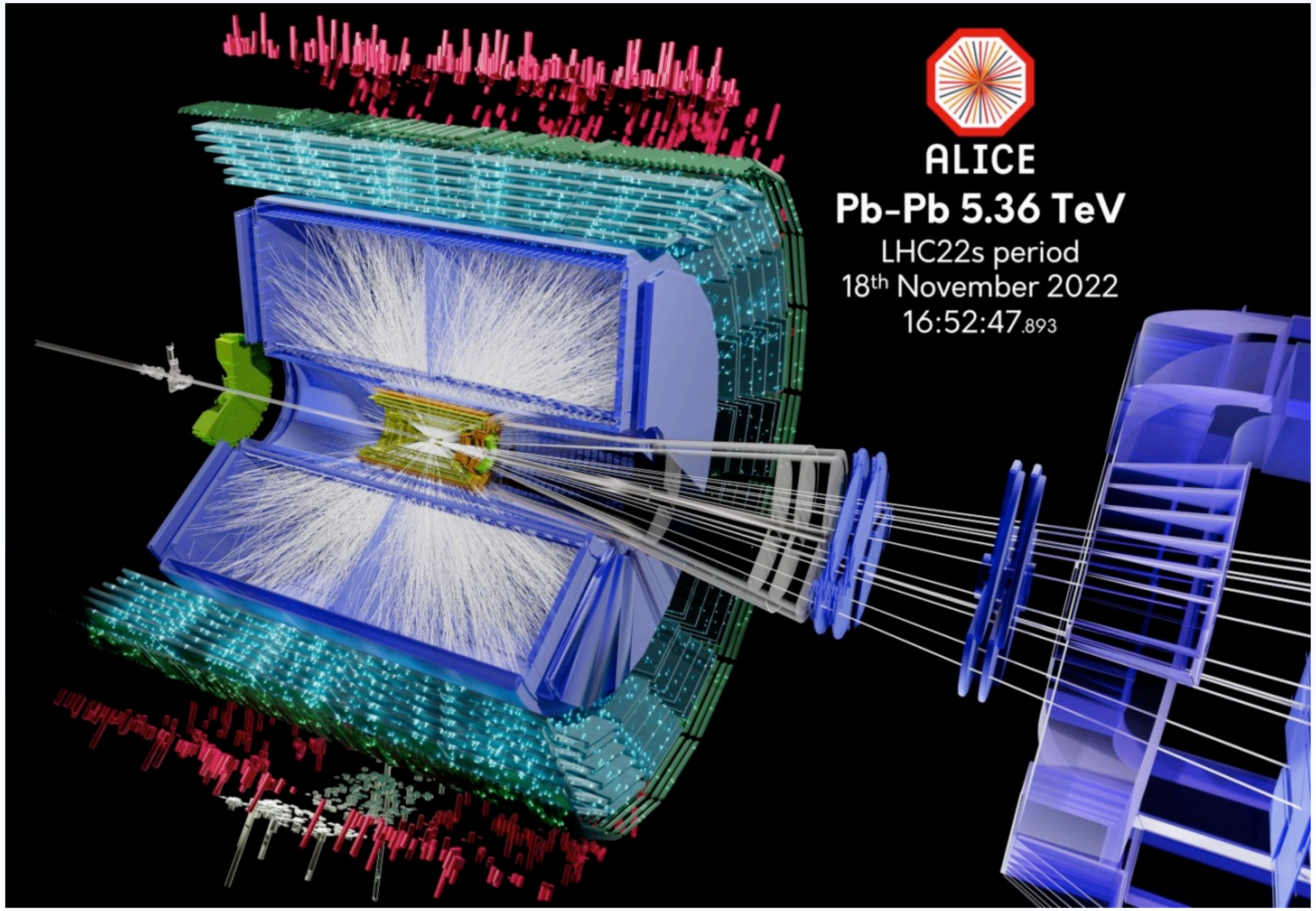

Ultra-relativistic heavy nuclei

Initial nucleon-nucleon collisions

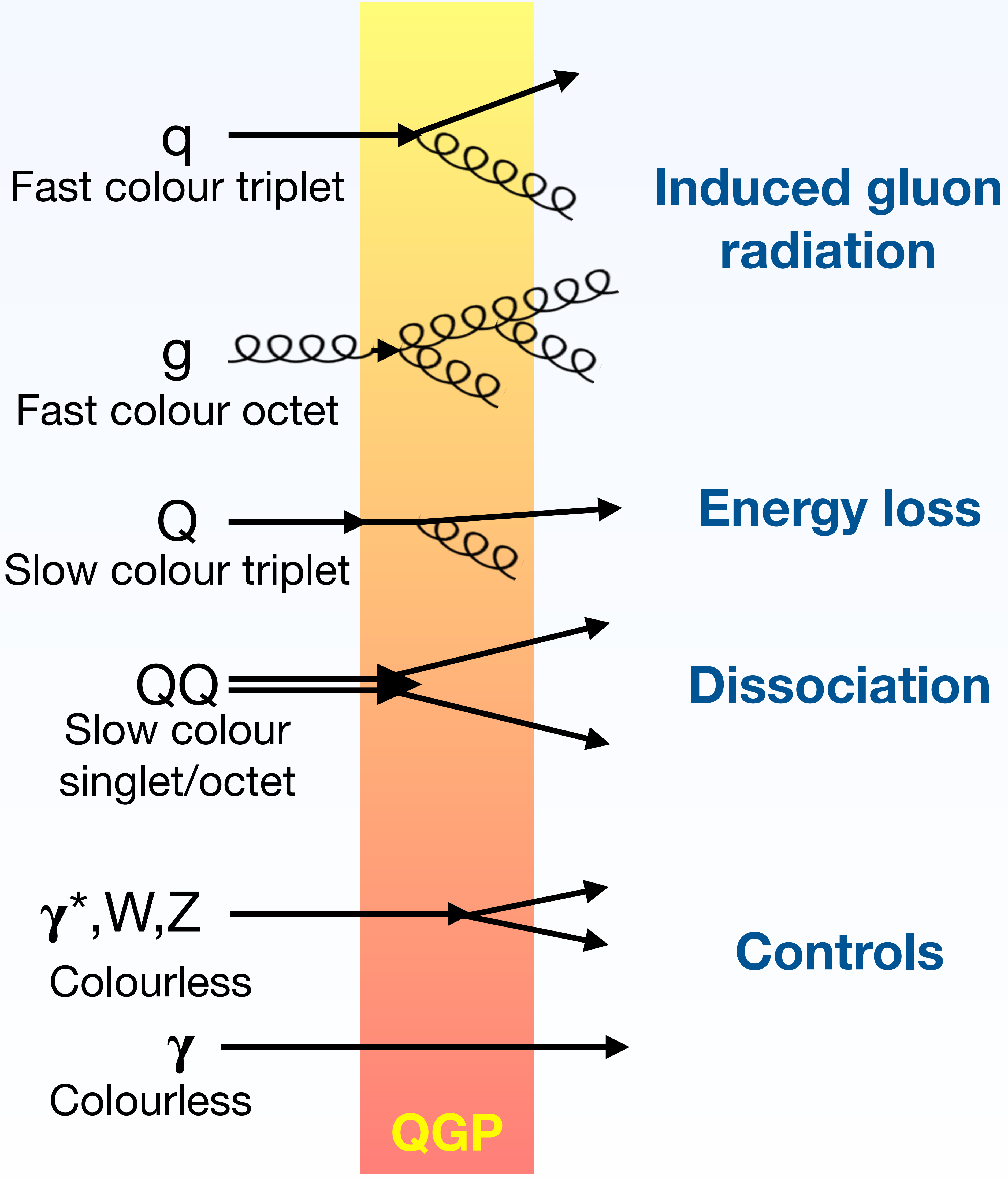
Quark Gluon Plasma

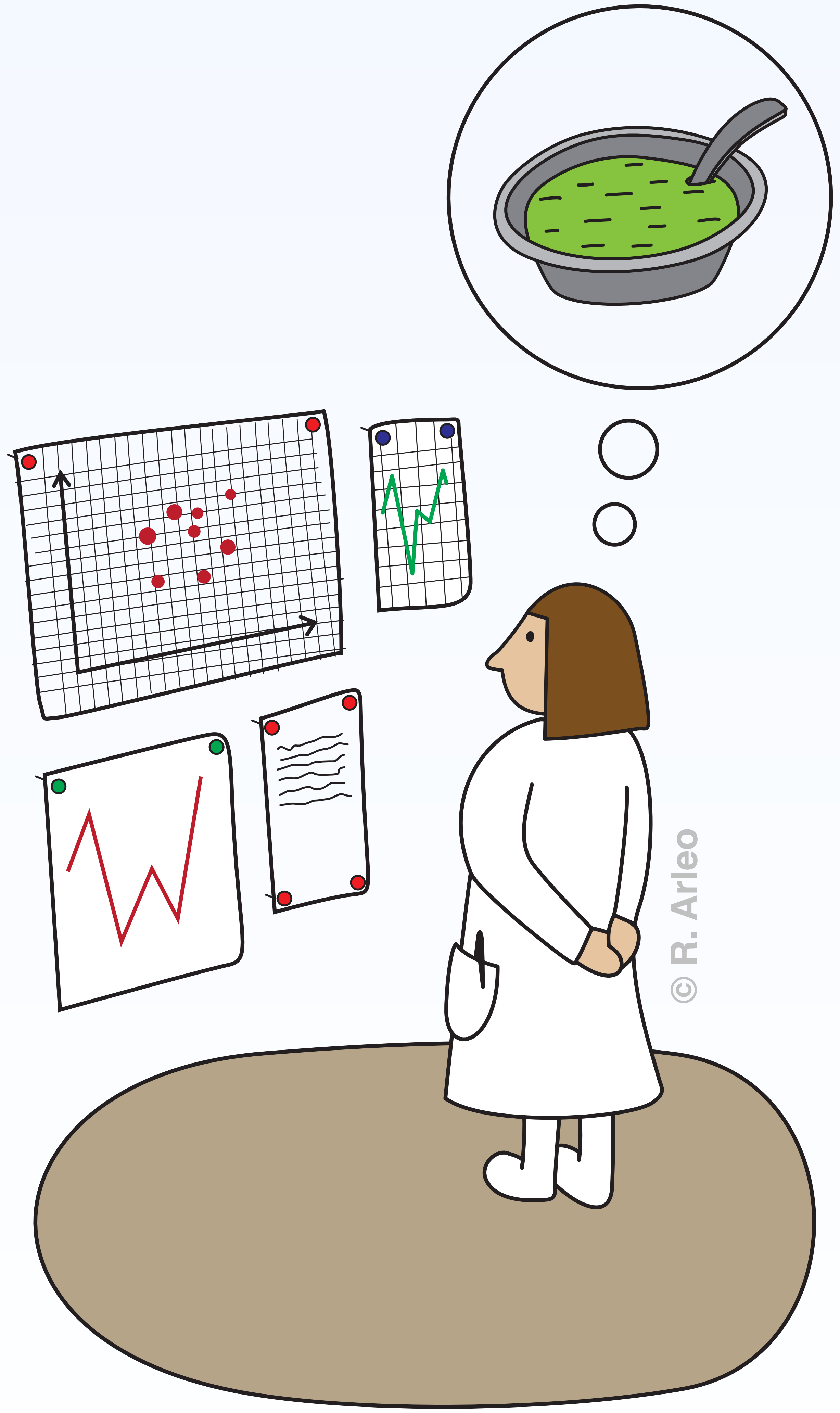
Hadronization

Kinetic freeze-out



# Probes of the QGP

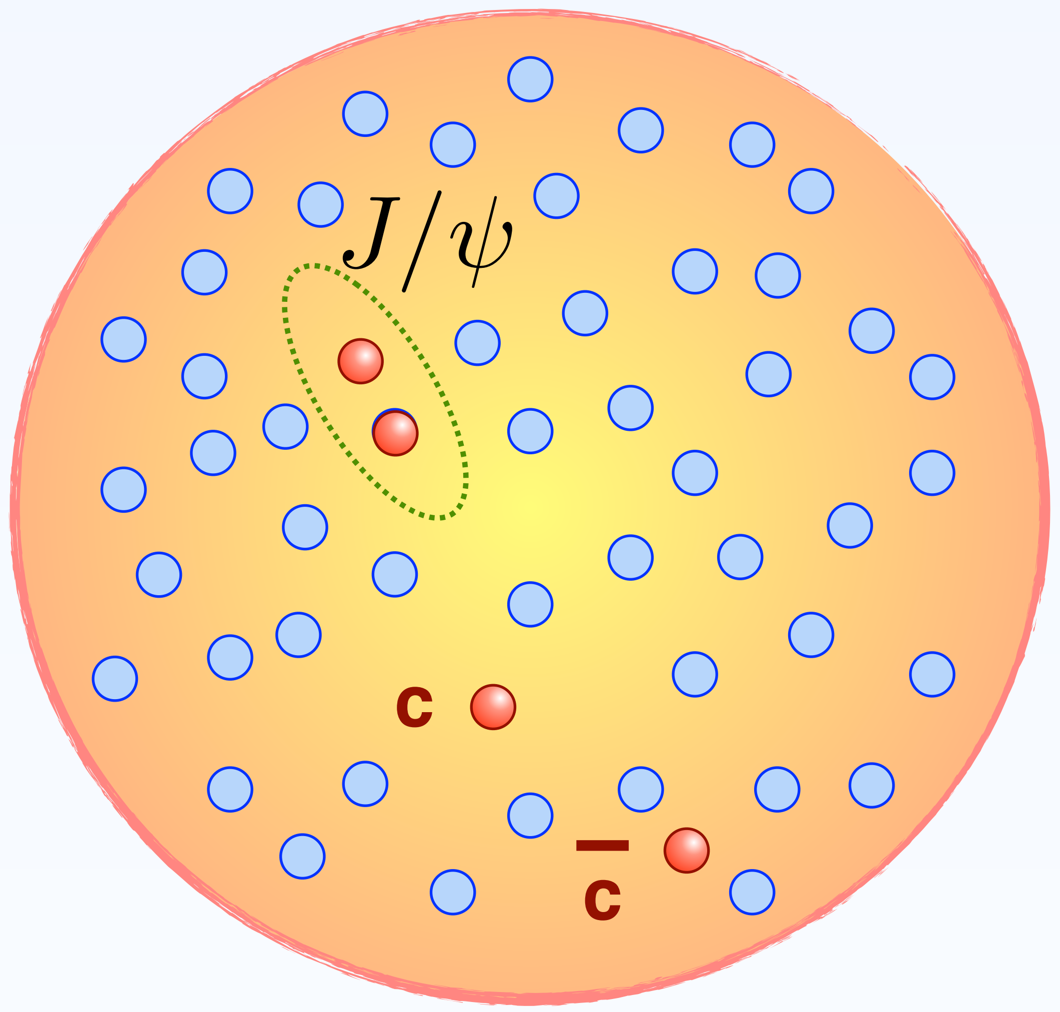


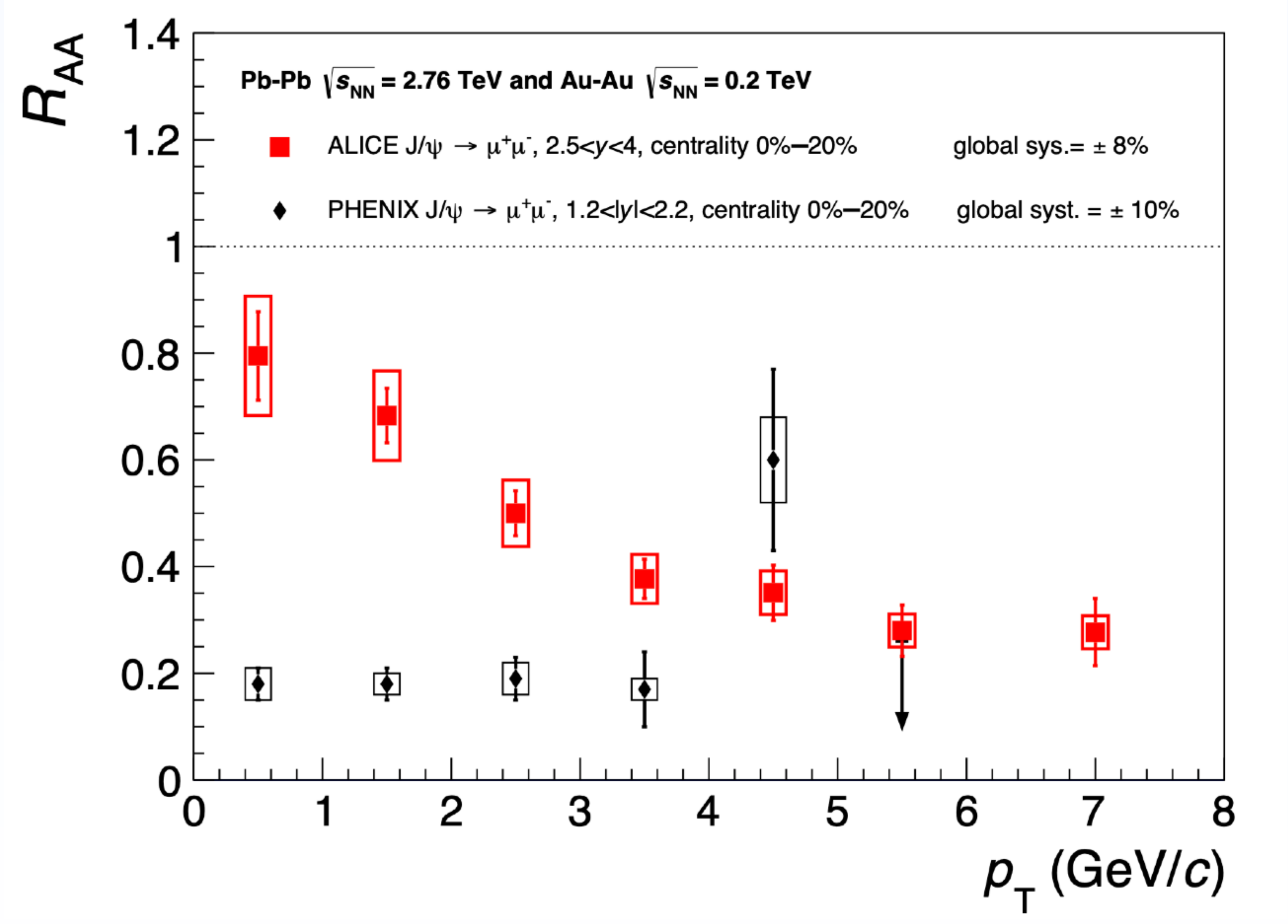



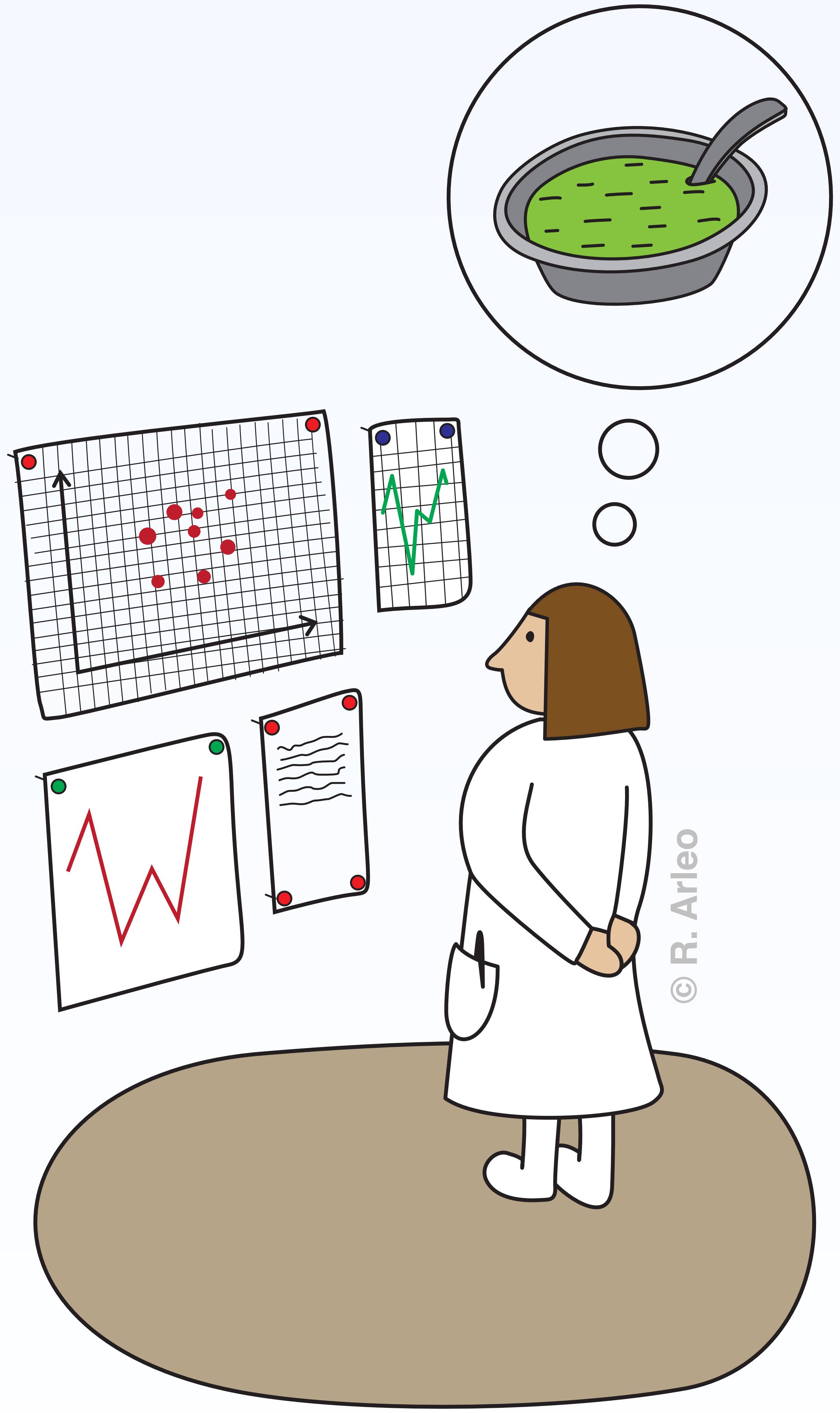

QGP not “directly” observed
(lasts only a few fm/c!)

Recipe:
Several probes
Good reference system

# Probes of the QGP: Quarkonia



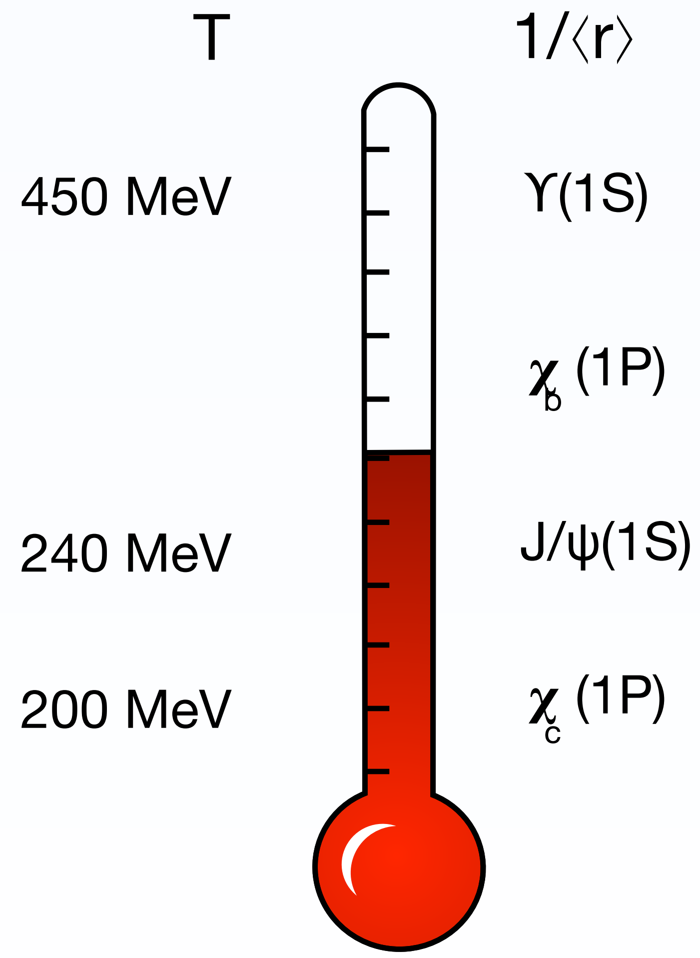




$J/\psi$ is made of $c\bar{c}$

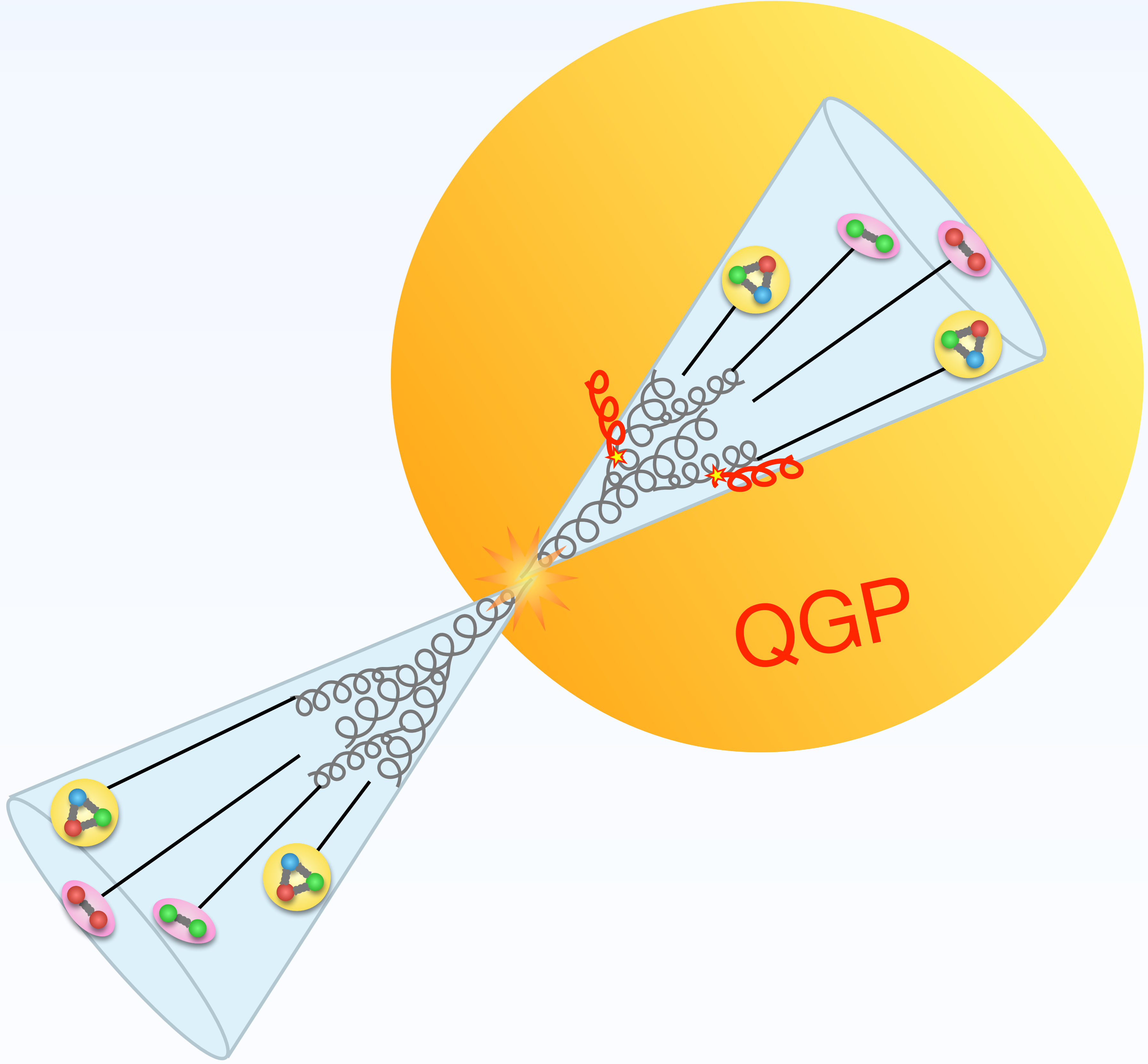
The QGP screens the interaction between the c quarks

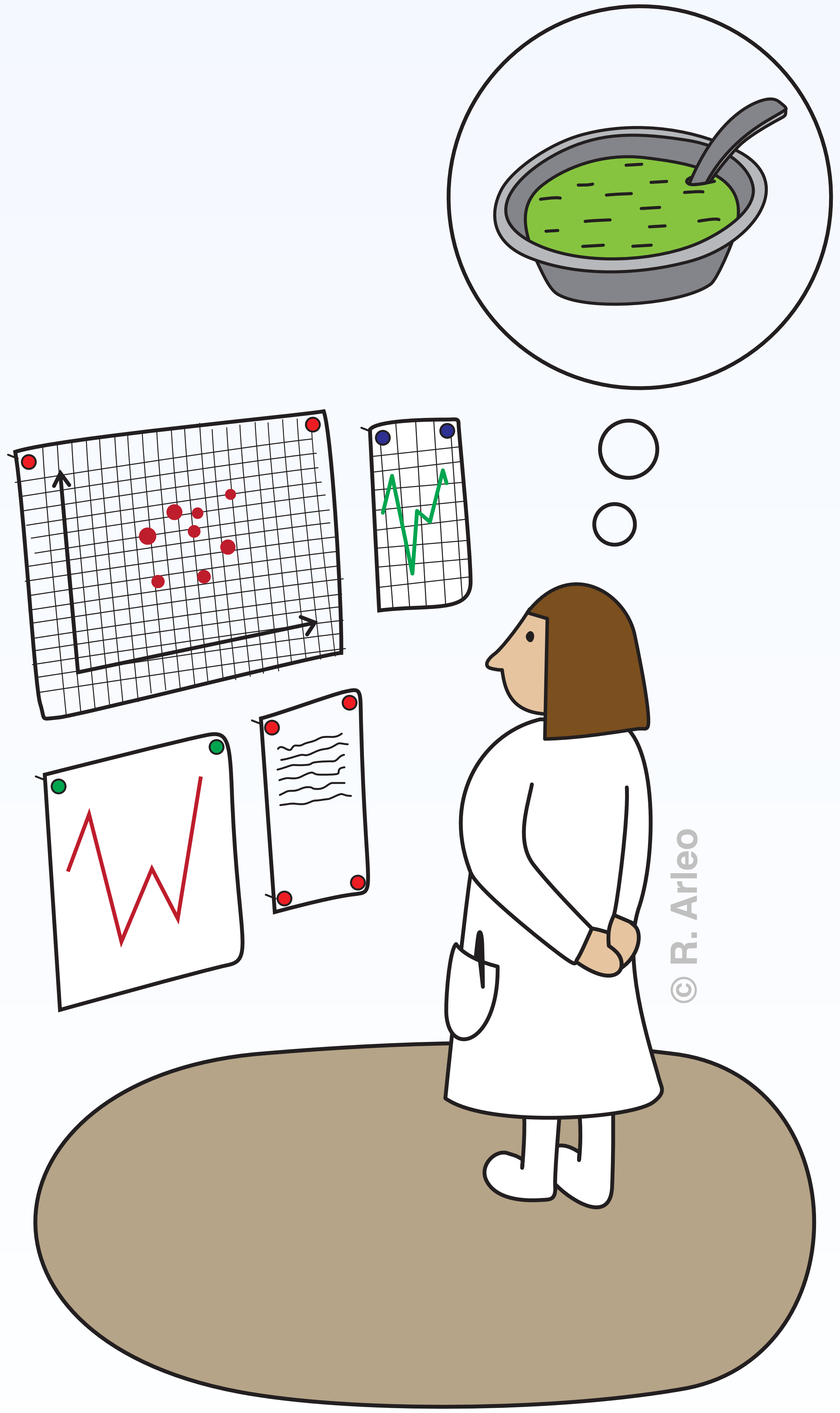
Less $J/\psi$ in PbPb than pp

**QGP thermometer!**



# Probes of the QGP: Jets



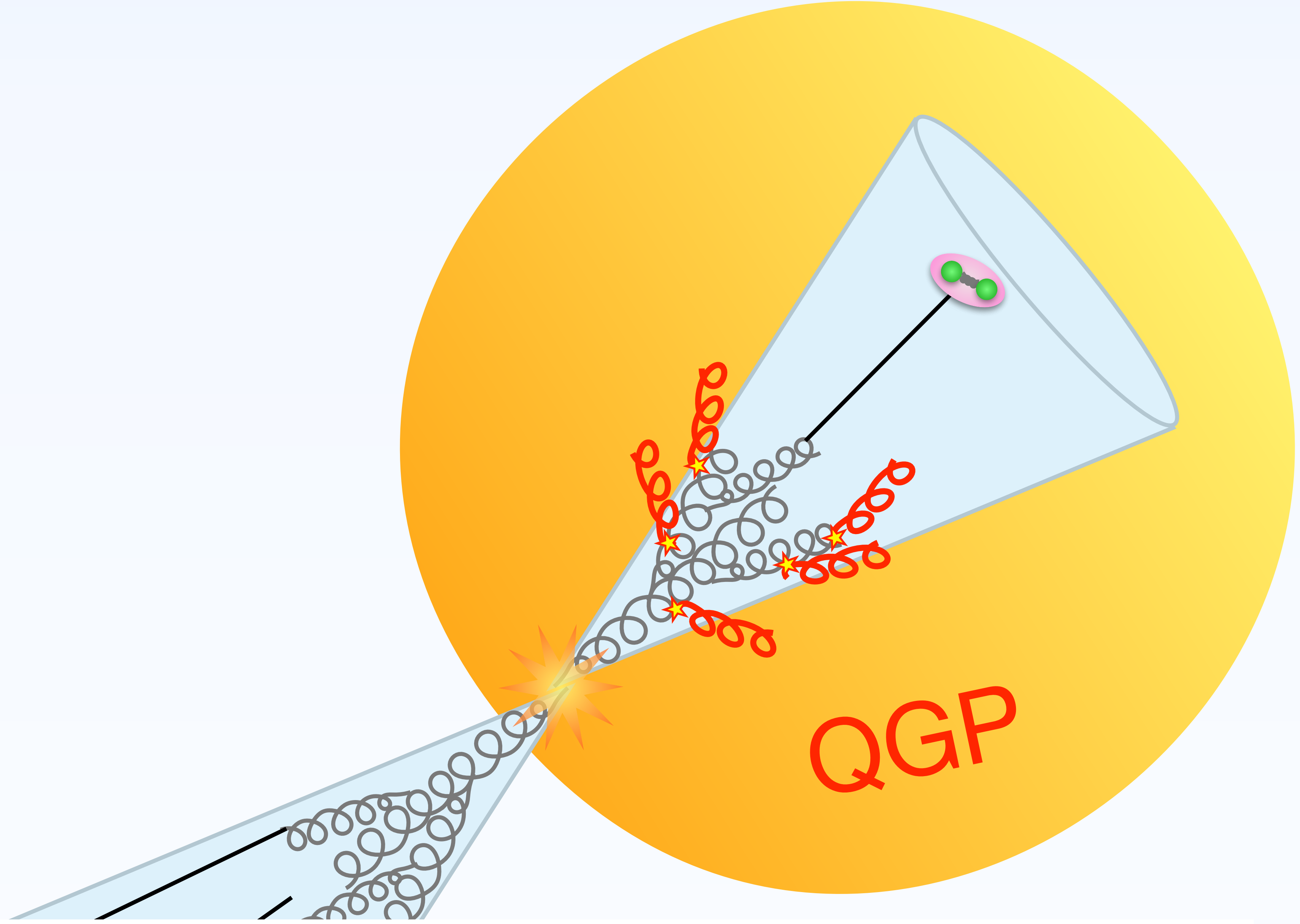



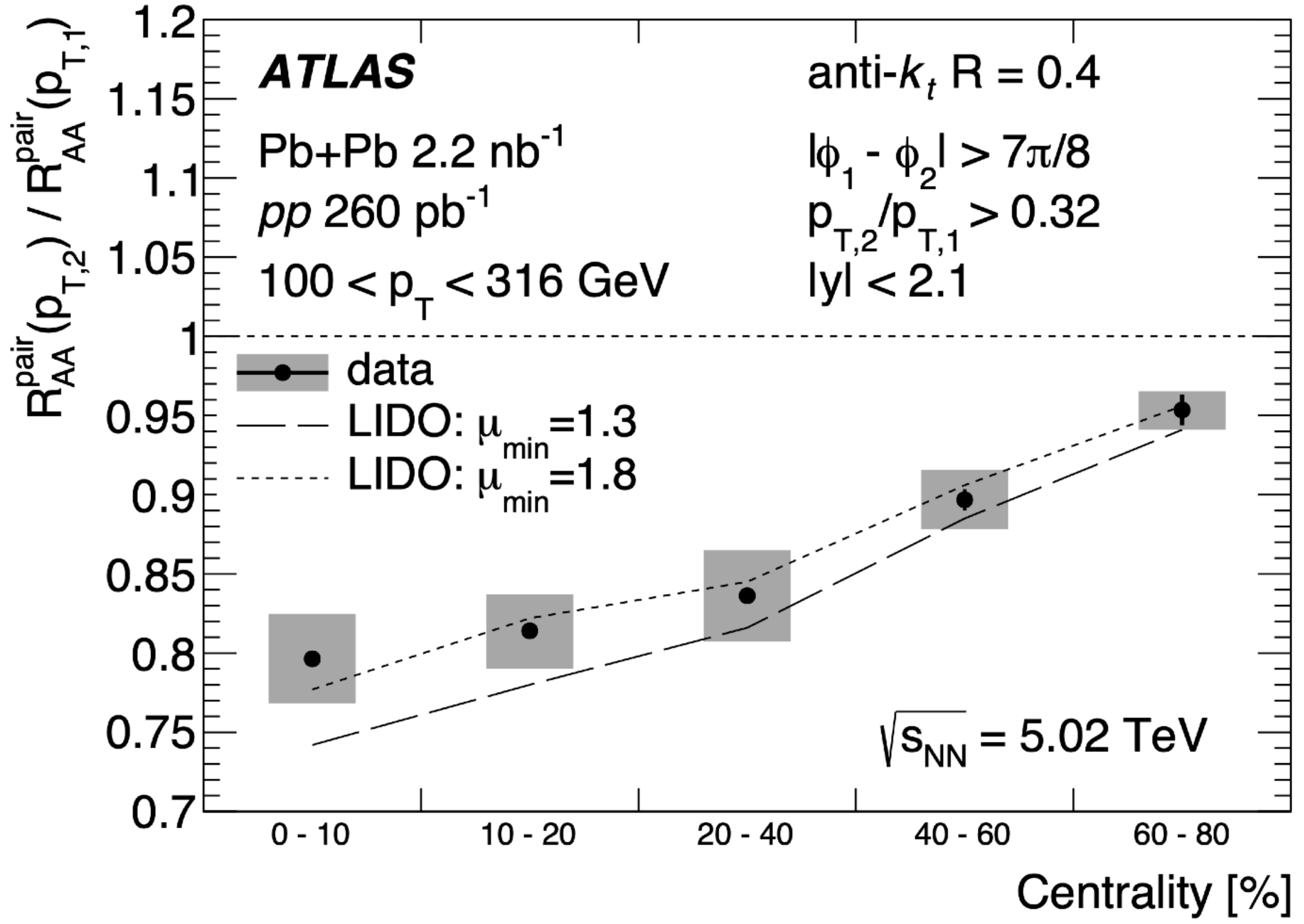

Jets are the experimental signatures of partons

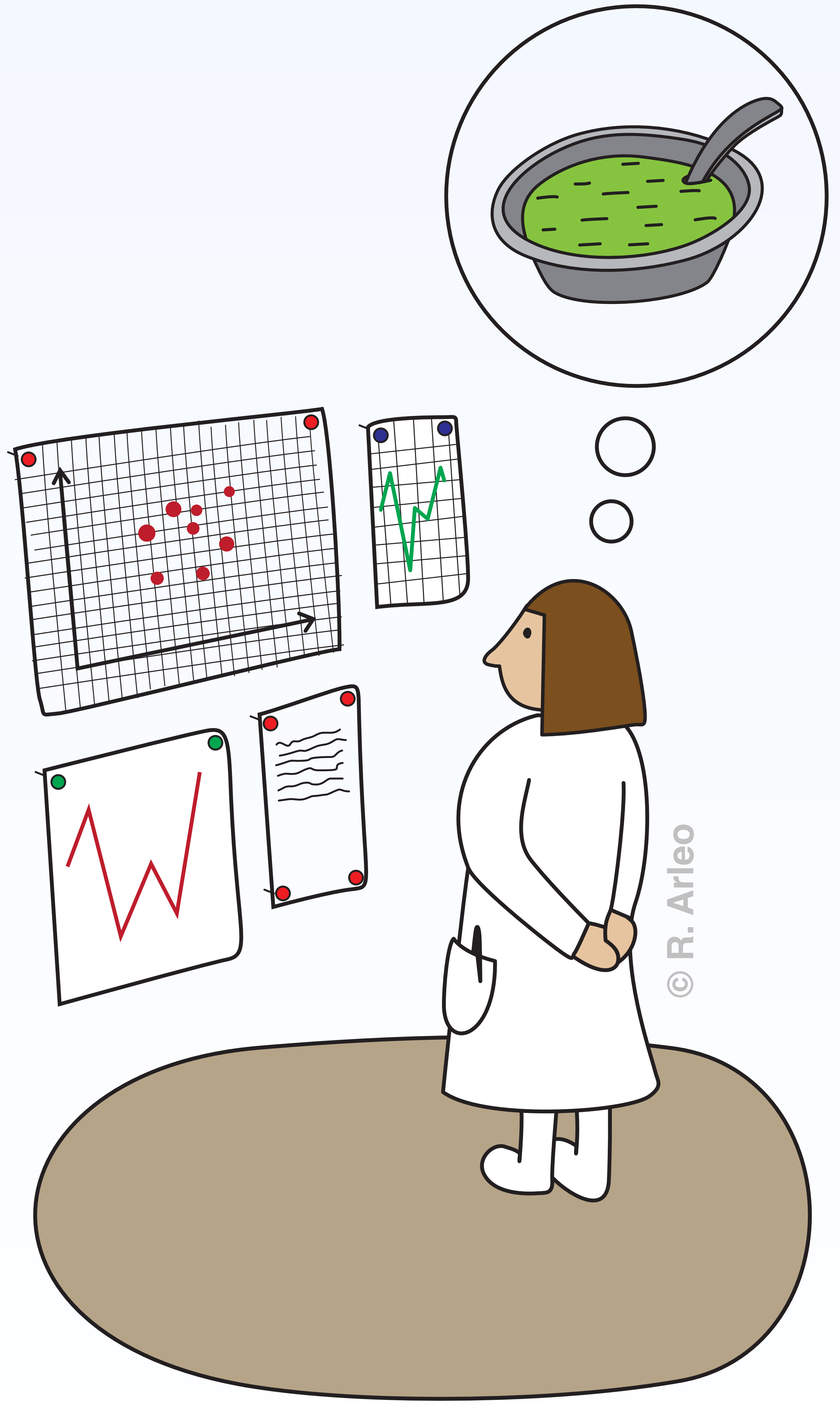
Momentum conservation
→ dijet events

In the QGP, the jets traverse different lengths

# Probes of the QGP: Jets




Jets are the experimental signatures of partons

Momentum conservation
→ dijet events

In the QGP, the jets traverse different lengths

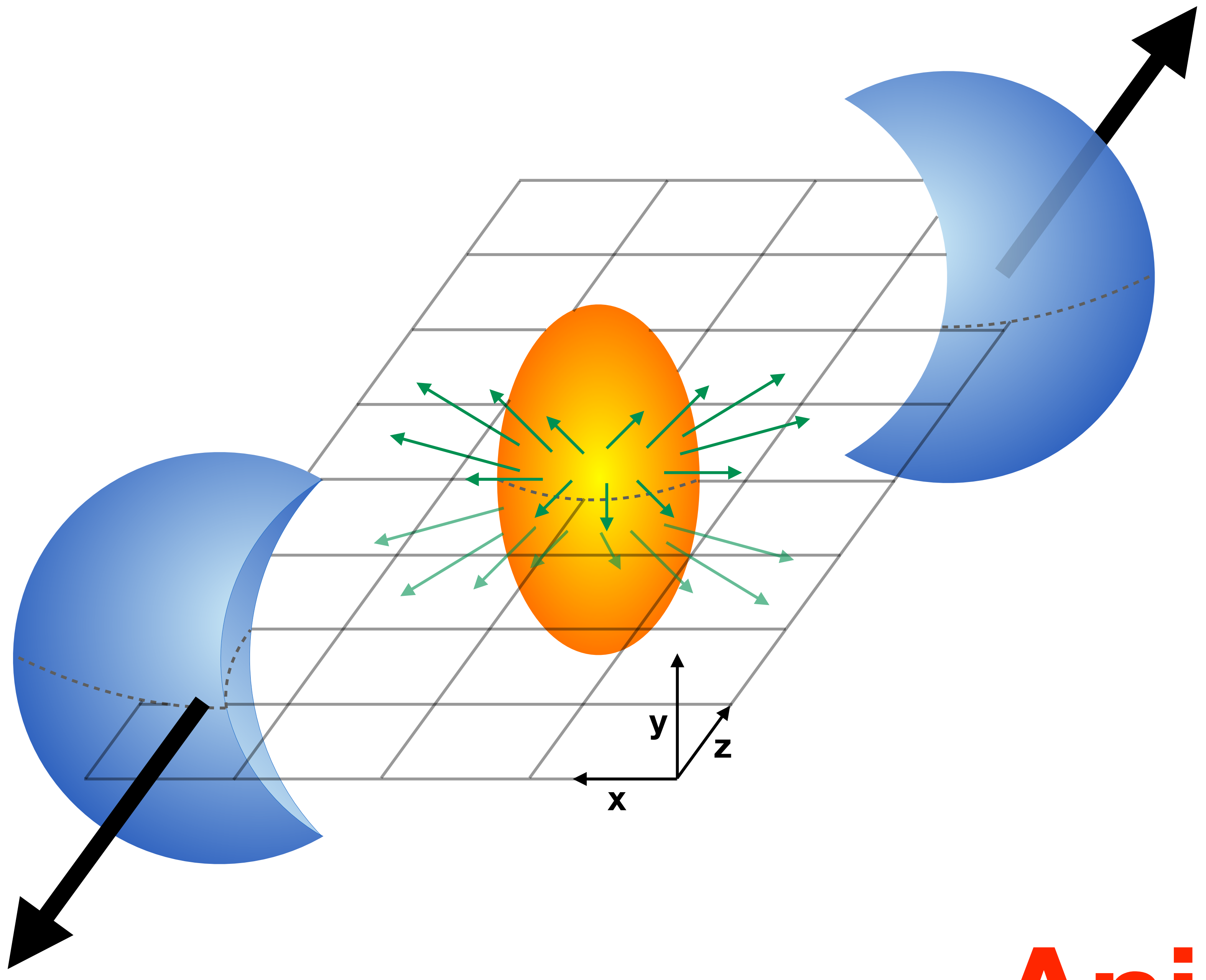
Jets lose energy when they interact with the QGP

**Jet Quenching!**

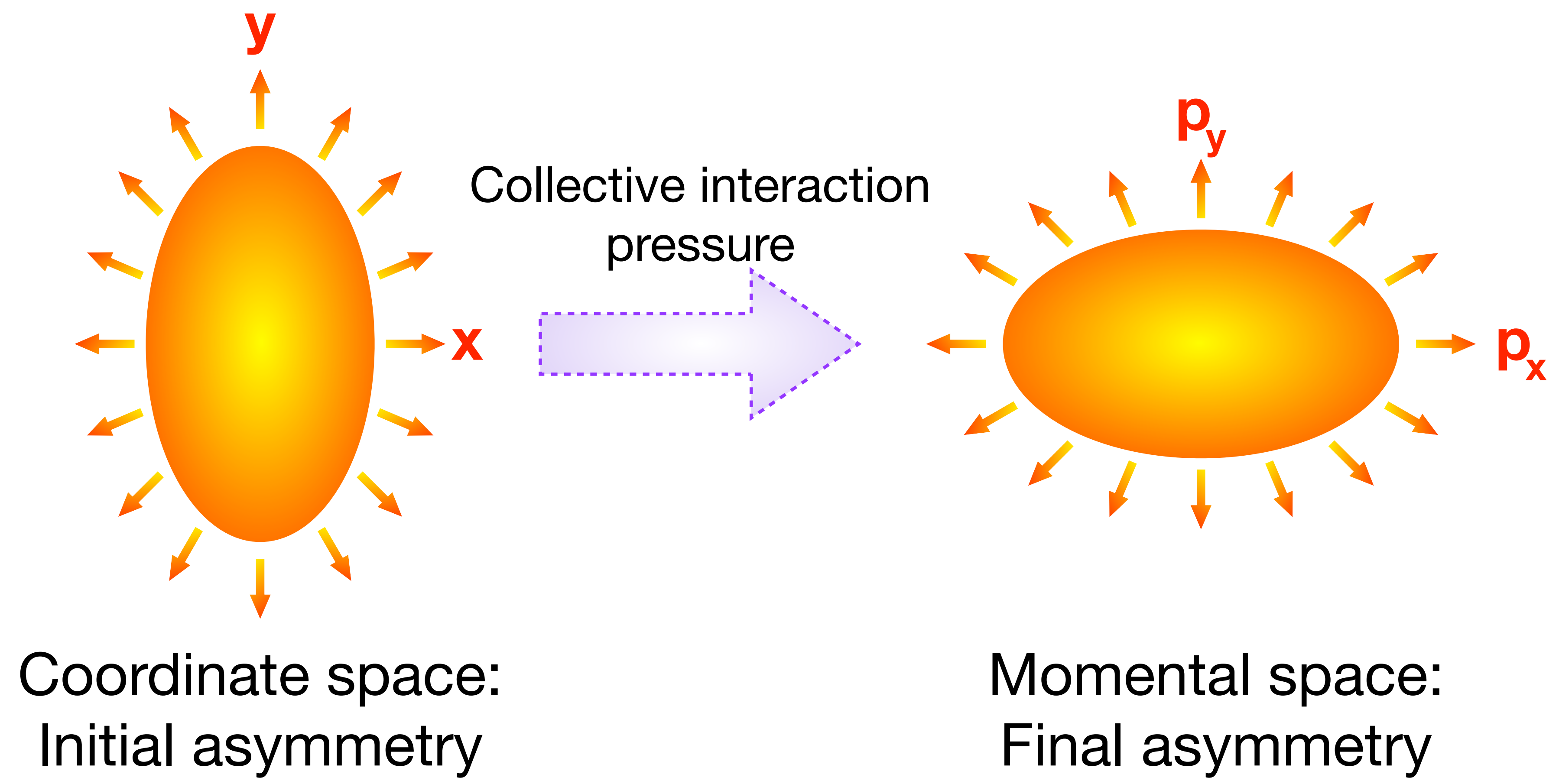
# Collectivity in HI collisions

Heavy-ion collisions produce tiny droplets of relativistic fluid

Collectivity ≡ emitted particle exhibit a common property




Larger acceleration along smaller dimension x



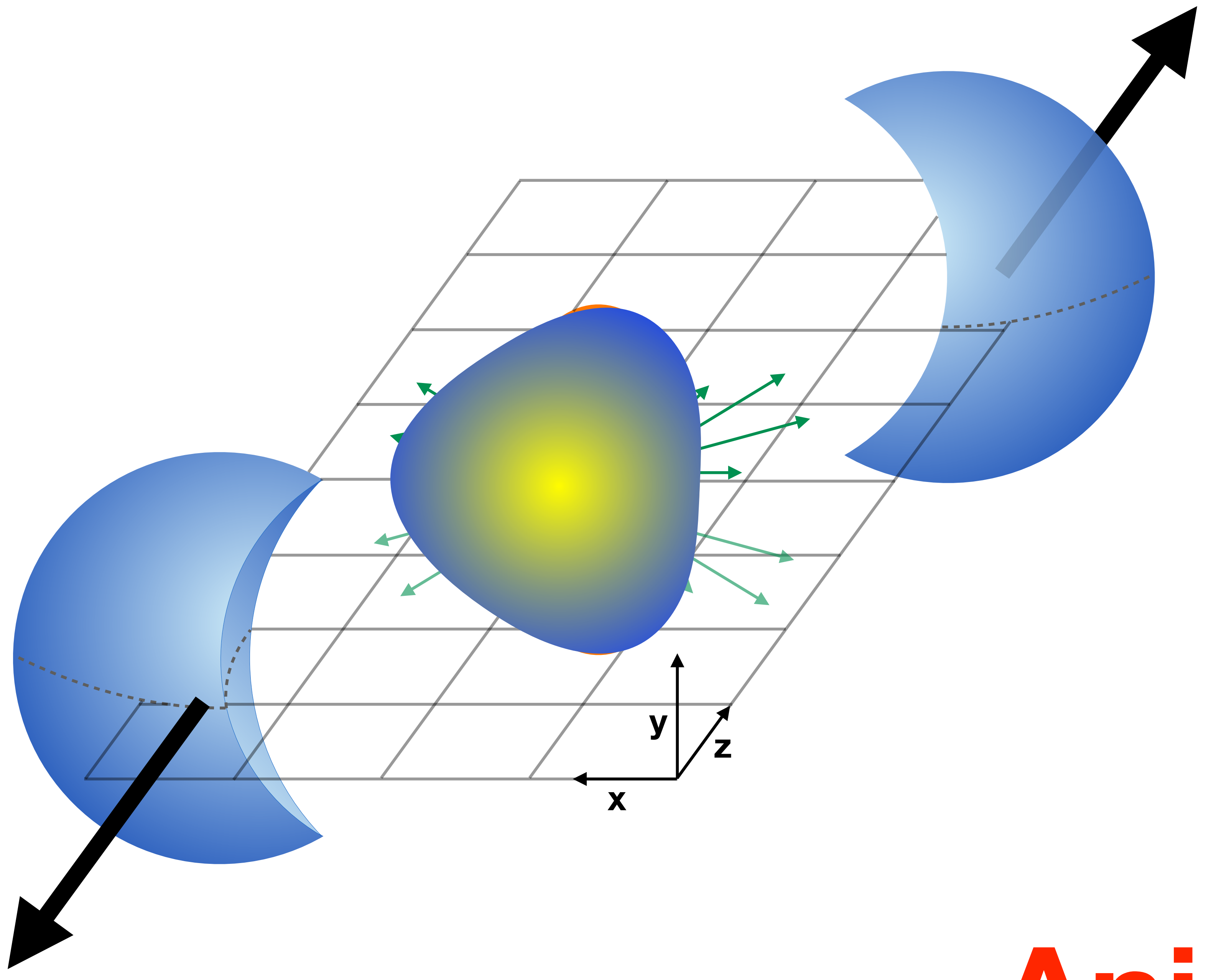

**Anisotropic flow**

Elliptic flow: $v_2$ ≡ average over all particles of $\cos(2\phi)$

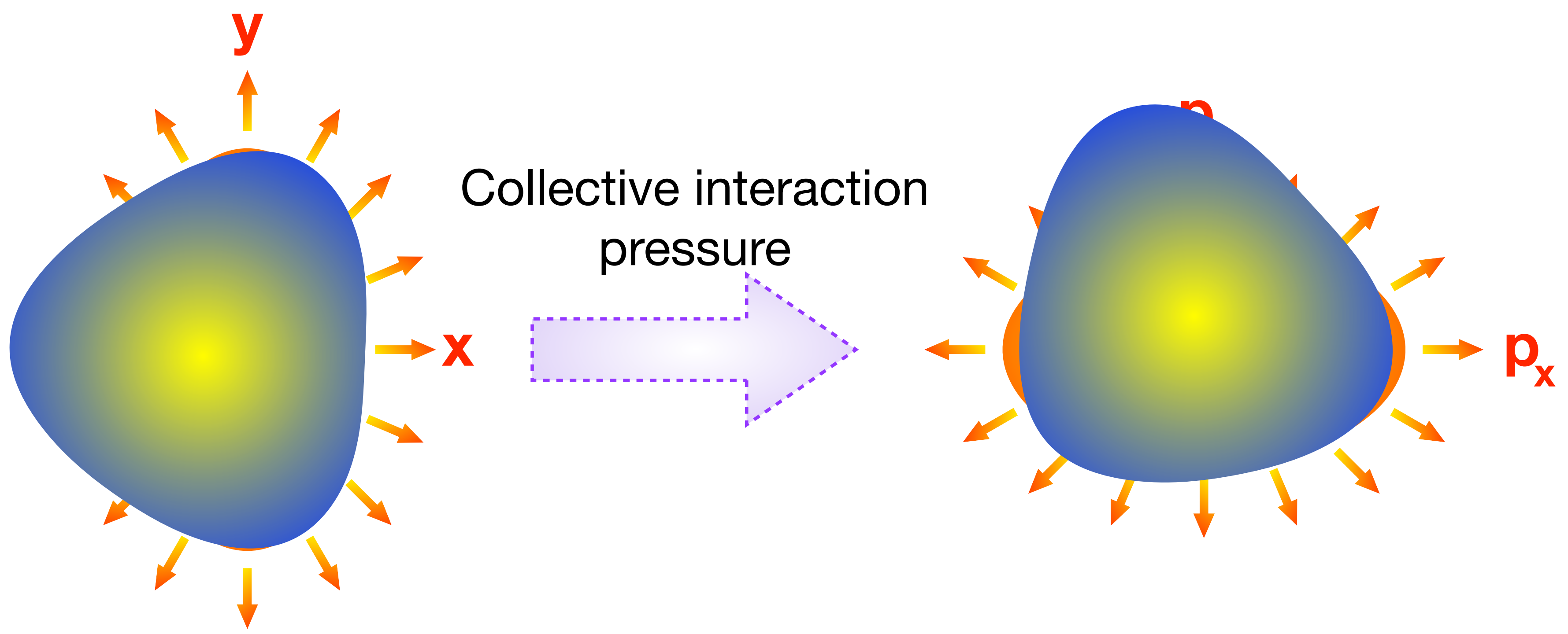
# Collectivity in HI collisions

Heavy-ion collisions produce tiny droplets of relativistic fluid

Collectivity ≡ emitted particle exhibit a common property




Larger acceleration along smaller dimension x




Coordinate space: Initial asymmetry

Momental space: Final asymmetry

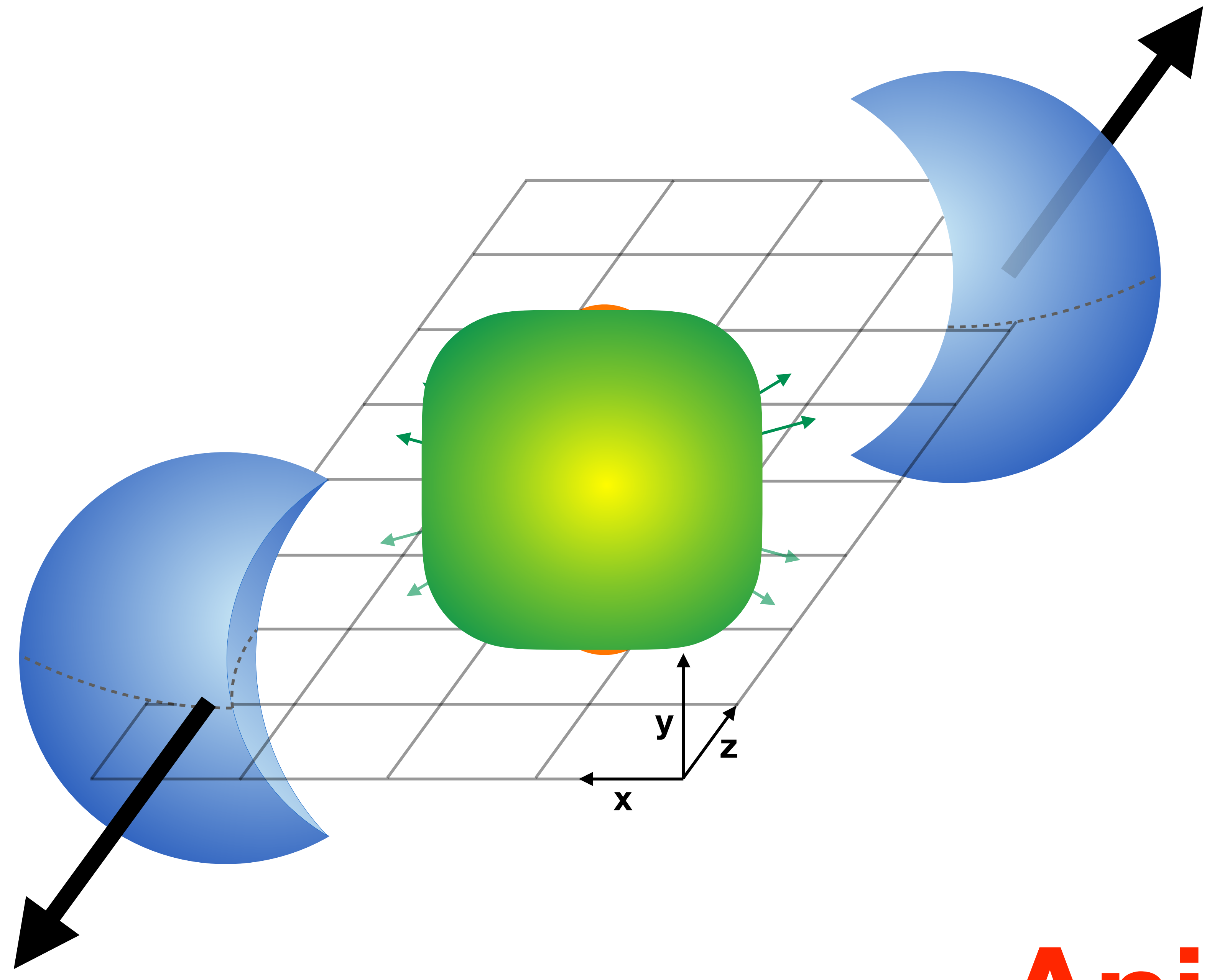
**Anisotropic flow**

Triangular flow: $v_3$ ≡ average over all particles of $\cos(3\phi)$

# Collectivity in HI collisions

Heavy-ion collisions produce tiny droplets of relativistic fluid

Collectivity ≡ emitted particle exhibit a common property

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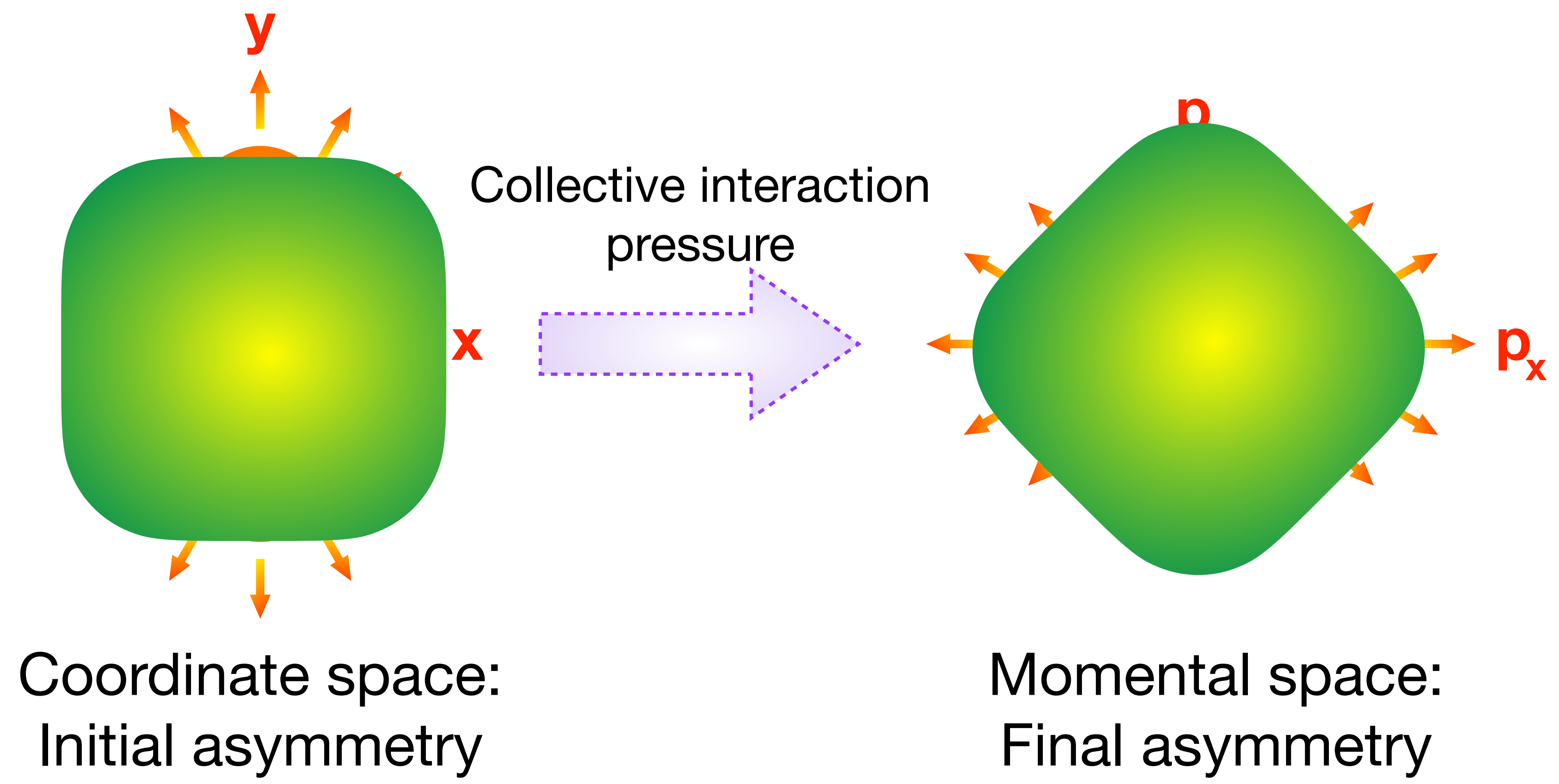


**Anisotropic flow**

Quadrangular flow: $v_4$ ≡ average over all particles of $\cos(4\phi)$

# Conclusion

Hadronic physics studies the structure, the properties and the interactions of hadrons

Vast domain : theoretical and experimental

**Fri 27/10**

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| | | | |
| --- | --- | --- | --- |
| 11:00 | **Session overview** | *Batoul Diab* | 11:00 - 11:30 |
| | **Quantum vs. semi classical description of in-medium quarkonia** | *Aoumeur Daddi Hammou* | 11:30 - 12:00 |
| 12:00 | **J/ψ flow measurements in Pb-Pb collisions with the ALICE detector at LHC Run 3** | *Victor Valencia* | 12:00 - 12:30 |