Hadron Physics

From A to XYZ

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Mount Allison University

NSERC CRSNG

Hadrons CRC 1660 Nuclei

About Me

- PhD, 1999, University of Saskatchewan. Saskatoon, Canada. Experimental Subatomic Physics.
- Postdoc, 1999-2003, Institut für Kernphysik, Mainz, Germany.
- Professor, 2003-present, Mount Allison University, Sackville, NB, Canada.

Augustinerkeller, Mainz


CANADA
National capital
Provincial or territorial capital
Populated place
Provincial or territorial boundary
International boundary
Trans-Canada Highway
Km
0 250 500 750 1000
ARCTIC OCEAN
PACIFIC OCEAN
ATLANTIC OCEAN
RUSSIAN FEDERATION
ALASKA (United States of America)
KALAALLIT NUNAAT (Grønland) (Denmark)
UNITED STATES OF AMERICA
SAINT PIERRE ET MIQUELON (France)
Beaufort Sea
Baffin Bay
Labrador Sea
Hudson Bay
James Bay
Ungava Bay
Foxe Basin
Davis Strait
Parry Channel
YUKON
NORTHWEST TERRITORIES
NUNAVUT
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
QUEBEC
NEWFOUNDLAND AND LABRADOR
NEW BRUNSWICK
NOVA SCOTIA
Whitehorse
Yellowknife
Iqaluit
Victoria
Edmonton
Regina
Winnipeg
Toronto
Québec
Fredericton
Halifax
Charlottetown
St. John's
Ottawa
Alert
Resolute
Pond Inlet
Pangnirtung
Cambridge Bay
Baker Lake
Rankin Inlet
Old Crow
Tuktoyaktuk
Inuvik
Dawson
Délįnę
Hay River
Fort Nelson
Masset
Prince Rupert
Prince George
Vancouver
Kamloops
Calgary
Fort McMurray
La Ronge
Saskatoon
Moose Jaw
Brandon
Churchill
Thompson
Sandy Lake
Red Lake
Kenora
Thunder Bay
Attawapiskat
Timmins
Greater Sudbury
London
Windsor
Salluit
Kuujjuaq
Inukjuak
Chisasibi
Chibougamau
Val-d'Or
Montréal
Sept-Îles
Gaspé
Saint John
Yarmouth
Sydney
Nain
Cartwright
Labrador City
Corner Brook
Great Bear Lake
Great Slave Lake
Lake Athabasca
Lake Winnipeg
Lake Superior
Lake Michigan
Lake Huron
Lake Erie
Lake Ontario
Mackenzie River
Fraser River
La Grande Rivière
Saint Lawrence River
150°
120°
90°
60°
30°
The Atlas of Canada
L'Atlas du Canada
atlas.gc.ca
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Mount Allison University

New Brunswick

Population: 840,000
Area: 72,908 km^2

English and French

Lobster, Lumber, and High Tides

Mount Allison University

- 2,250 students
- Undergrads only

Sackville, NB

January 22, 2025

Bay of Fundy

Highest tides in the world — 16 m!

$\tau \approx 12.5 - 12.7$ h	$N_2 \approx 12.66$ h
Bay	Moon

Hadron Physics - Conference Talks

- Hartmut Wittig (Uni Mainz) "Low-energy puzzles and the role of lattice QCD”
- Fuminori Sakume (RIKEN) "Antikaon-Nuclear Bound States at J-PARC”
- Catalina Curceanu (INFN-LNF) "Kaonic Atom Measurements at the DAΦNE Collider”
- Gianluigi Cibinetto (U. Ferrara) "BESIII"

Full Disclosure

This talk was put together with slides from:

- Concettina Sfienti
- Harald Merkel
- Diego Bettoni
- Jianwei Qiu

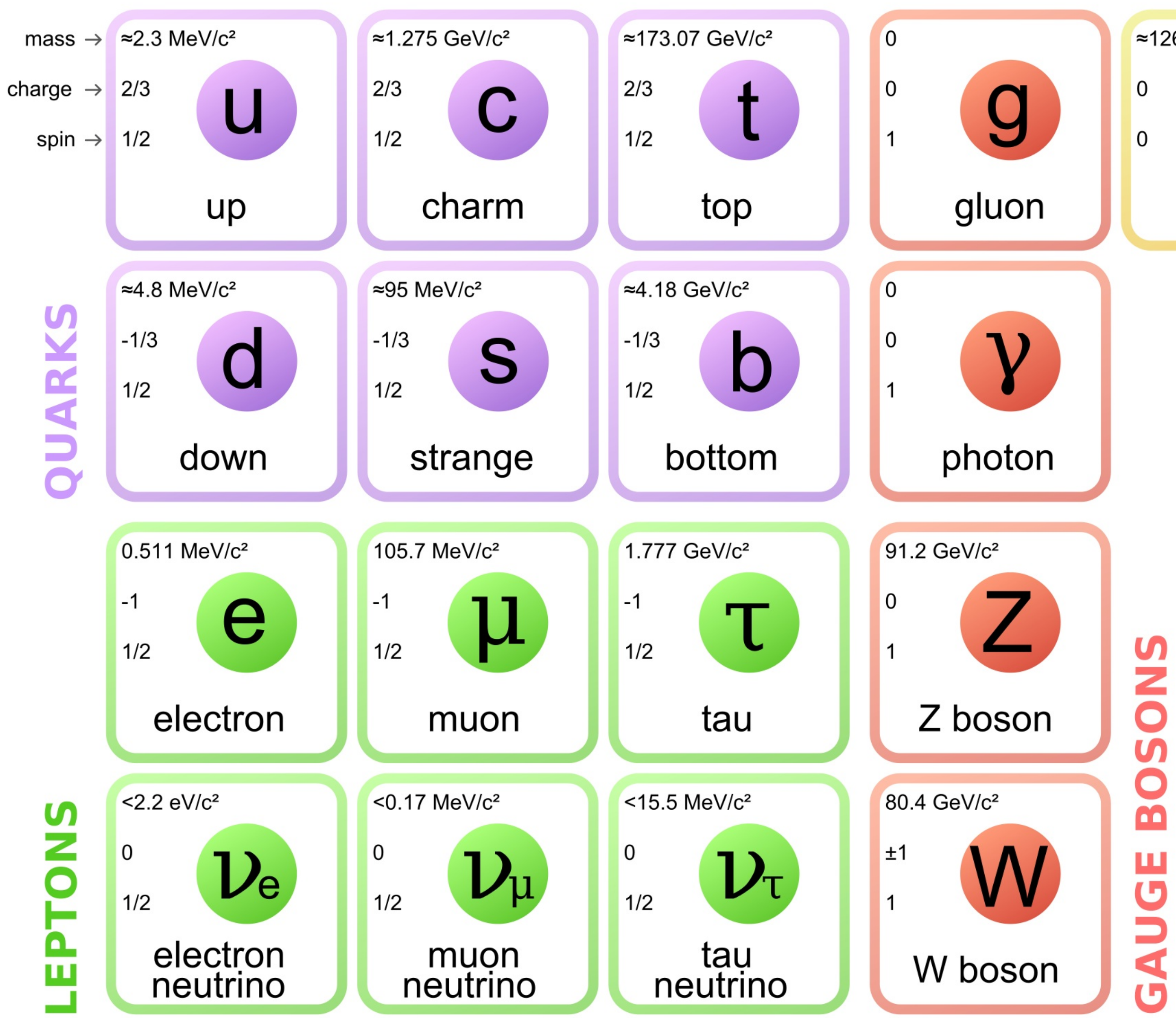
Thank you!

Hadron Physics

Where to begin…

- Introduction / History
- Experiment
- Theory
- Some Facilities / Experiments
- Outlook and Summary

Standard Model of Particle Physics



Includes strong and weak nuclear forces, and EM interaction

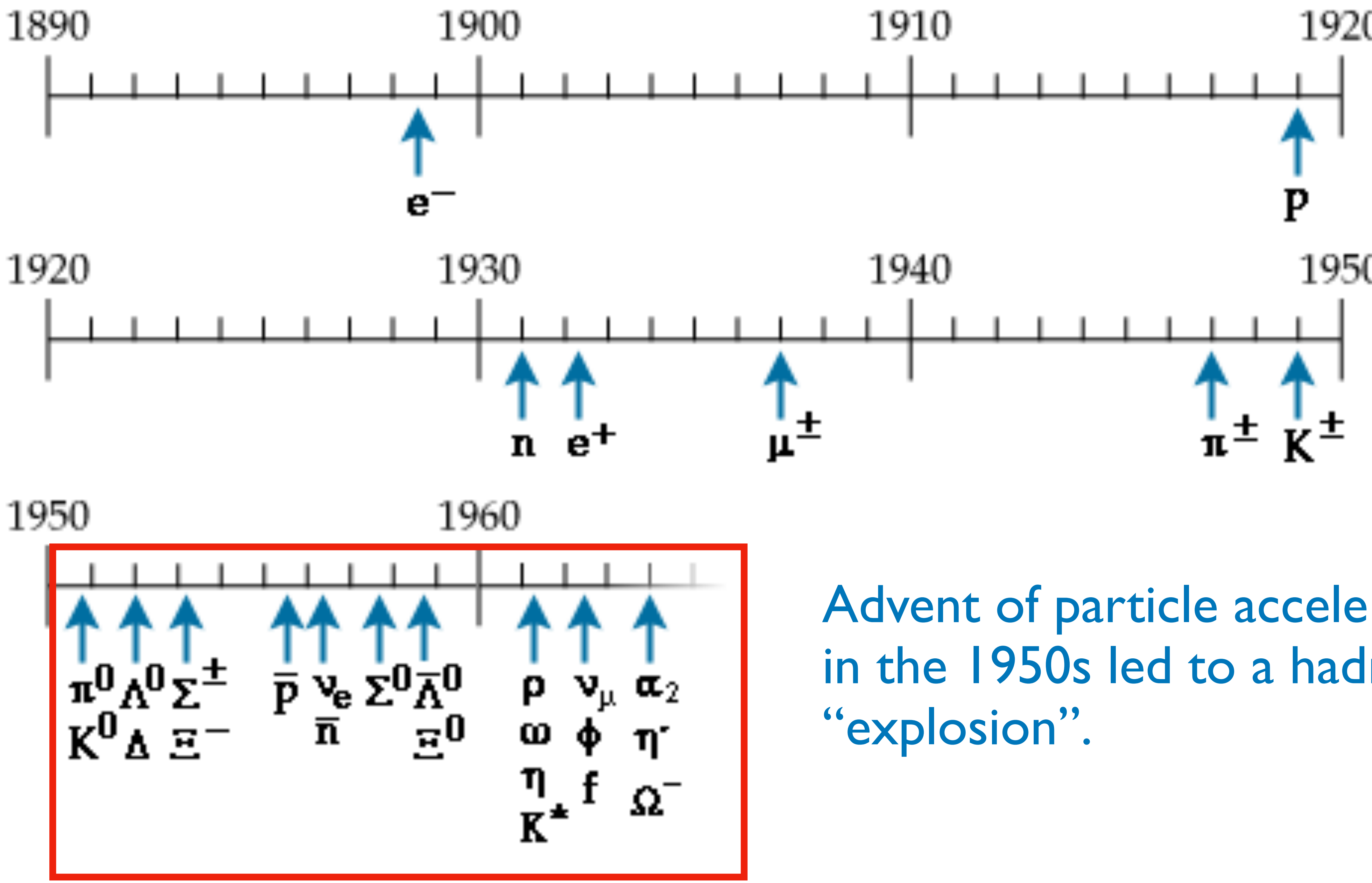
6 quarks
6 leptons
4 gauge bosons
1 Higgs boson
+ antiparticles

Still a some open questions.

Free parameters, gravity, dark matter, dark energy, matter-antimatter asymmetry.

How did we get here?

A Brief History of Subatomic Particles



Advent of particle accelerators in the 1950s led to a hadron "explosion".

WTF?! Who ordered these? Unsatisfactory situation…

A Brief History of Subatomic Particles

Nucleons cannot be point like spin-1/2 Dirac particles

1933: Proton magnetic moment

Otto Stern
Nobel Prize 1943

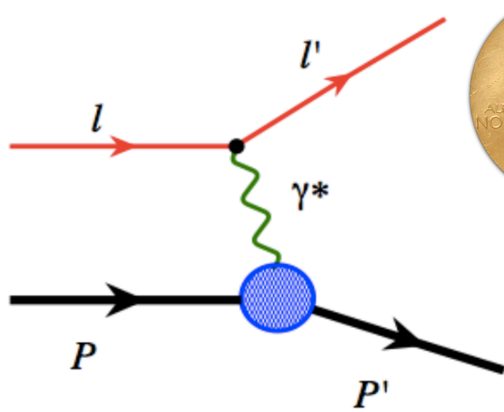
$$\mu_p = g_p \left(\frac{e\hbar}{2m_p}\right)$$

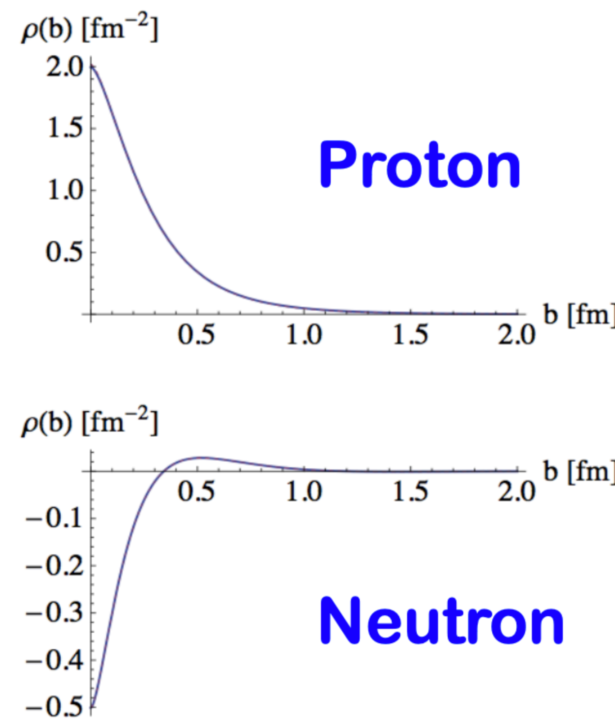
$$g_p = 2.792847356(23) \neq 2!$$

$$\mu_n = -1.913 \left(\frac{e\hbar}{2m_p}\right) \neq 0!$$

1960: Elastic e-p scattering

Robert Hofstadter
Nobel Prize 1961



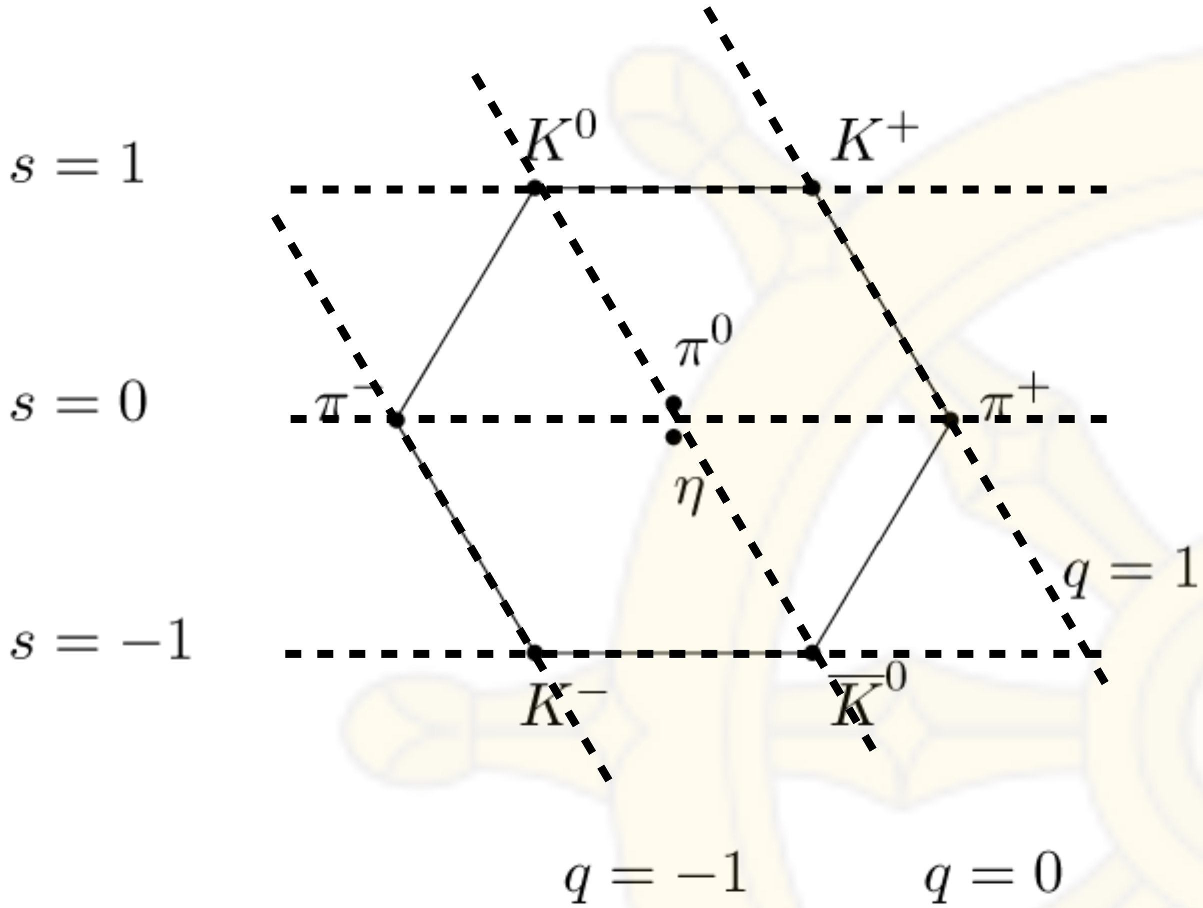


Proton EM Charge Radius!

Form Factors $F(Q^2) \rightarrow \rho(r)$ Electric Charge Distribution

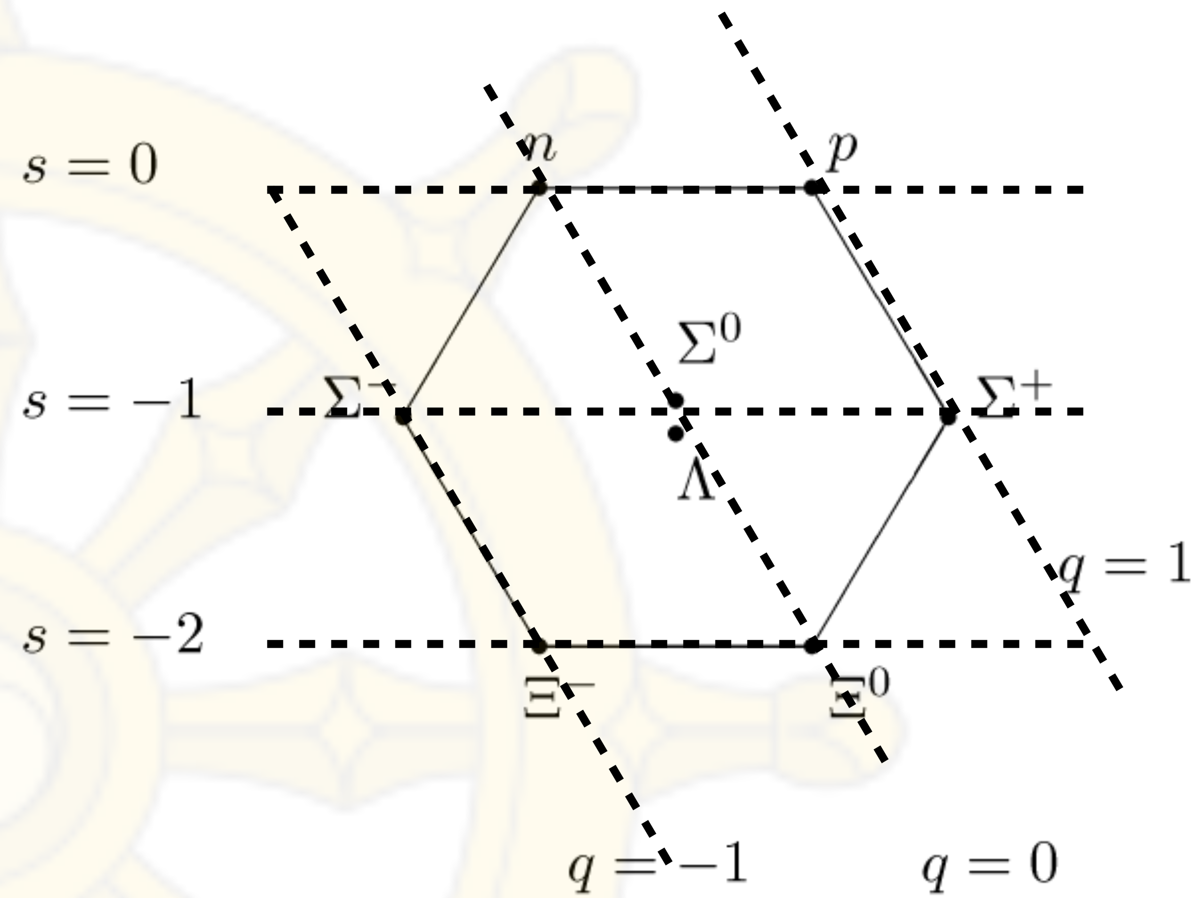
Eightfold Way

Proposed by Gell-Mann in 1961, independently by Ne'eman.



Meson Octet

Spin 0



Baryon Octet

Spin 1/2

Arranged baryons and mesons into weird geometrical patterns, according to charge q and strangeness s.

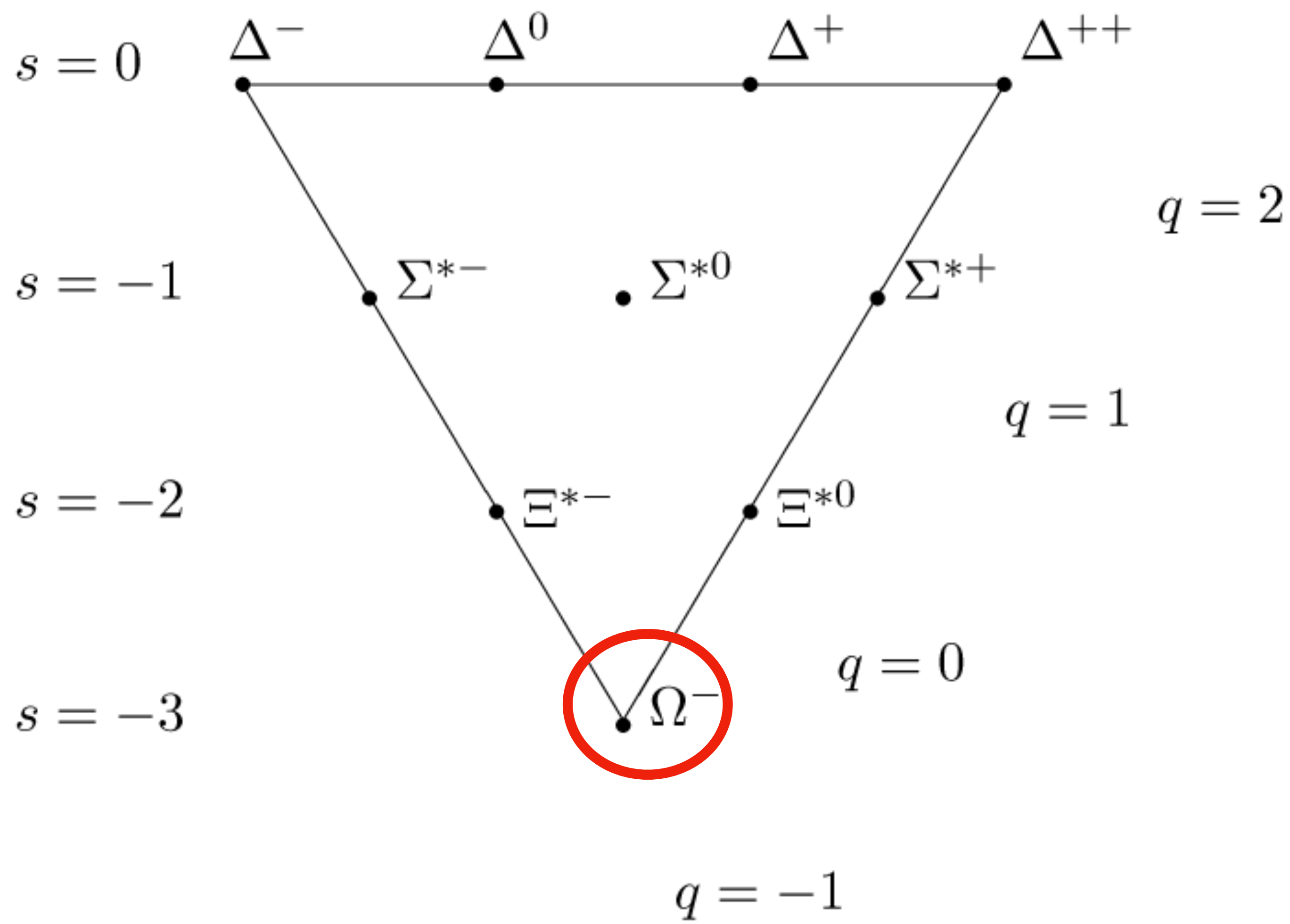
Hinted at substructure, the same way the periodic table did.

Gell-Mann was the Mendeleev of the subatomic particle zoo…

Eightfold Way

Baryon Decuplet

Spin 3/2



9 of the particles were known experimentally, but the Ω^- was not.

Gell-Mann predicted it, and in 1964 it was discovered!

SUCCESS!

Over the next 10 years, every new hadron found a place in one of the Eightfold Way supermultiplets.

This begs the question, though, why the patterns?

Constituent Quark Model

In1964 Gell-Mann and Zweig proposed (independently) that all hadrons are composed of even more fundamental constituents, which Gell-Mann called **quarks**.

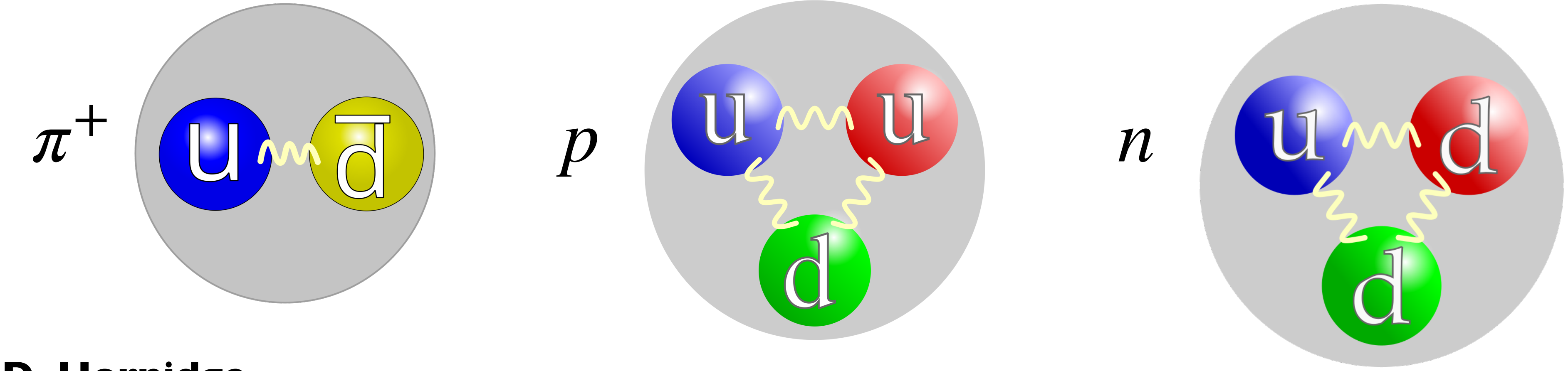
"—Three quarks for Muster Mark!" James Joyce in Finnegan's Wake.

Three fundamental building blocks

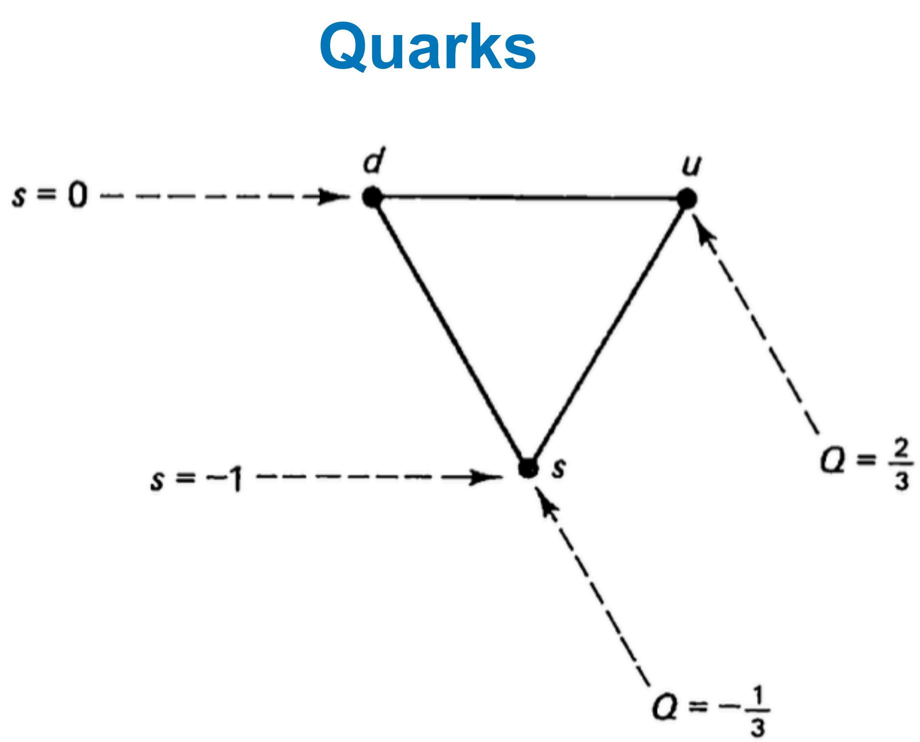
1960s $(p, n, \Lambda) \Rightarrow$ 1970s (u, d, s)

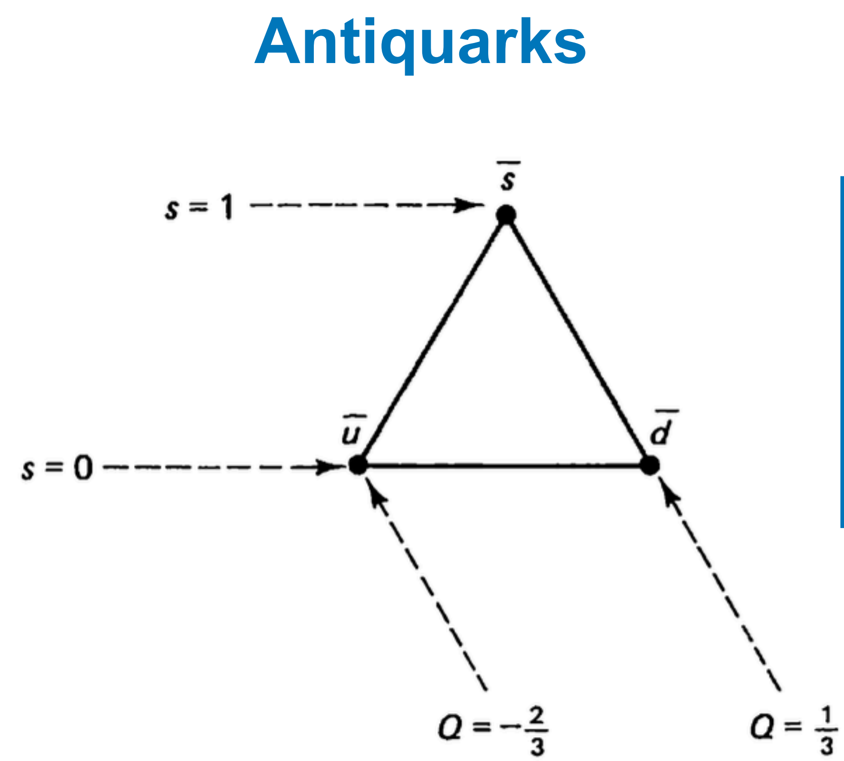
Murray Gell-Mann
Nobel Prize 1969

- **Meson**, made of 2 quarks: $q\bar{q}$
- **Baryon**, made of 3 quarks: qqq or $\bar{q}\bar{q}\bar{q}$



Constituent Quark Model





Spin 1/2

quark	charge	strangenes
u	$+2/3$	0
d	$-1/3$	0
s	$-1/3$	1

The baryon decuplet

qqq	Q	S	Baryon
uuu	2	0	Δ^{++}
uud	1	0	Δ^{+}
udd	0	0	Δ^{0}
ddd	−1	0	Δ^{-}
uus	1	−1	Σ^{*+}
uds	0	−1	Σ^{*0}
dds	−1	−1	Σ^{*-}
uss	0	−2	Ξ^{*0}
dss	−1	−2	Ξ^{*-}
sss	−1	−3	Ω^{-}

The meson nonet

$q\bar{q}$	Q	S	Meson
$u\bar{u}$	0	0	π^0
$u\bar{d}$	1	0	π^+
$d\bar{u}$	−1	0	π^-
$d\bar{d}$	0	0	η
$u\bar{s}$	1	1	K^+
$d\bar{s}$	0	1	K^0
$s\bar{u}$	−1	−1	K^-
$s\bar{d}$	0	−1	$\bar{K}^0$
$s\bar{s}$	0	0	??

Actual flavour wave function for hadrons is more complicated and is a superposition of these flavour states…

Constituent Quark Model

Mesons, made of 2 quarks: $q\bar{q}$

$$\pi^+ = u\bar{d} \quad \pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \quad \pi^- = d\bar{u}$$

$$K^+ = u\bar{s} \quad K^0 = d\bar{s} \quad \bar{K}^0 = s\bar{d} \quad K^- = s\bar{u}$$

Baryons, made of 3 quarks: qqq or $\bar{q}\bar{q}\bar{q}$

$$p = uud \quad n = udd \quad \Lambda = uds$$

$$\bar{p} = \bar{u}\bar{u}\bar{d} \quad \bar{n} = \bar{u}\bar{d}\bar{d} \quad \bar{\Lambda} = \bar{u}\bar{d}\bar{s}$$

No free quarks observed in nature, ever!

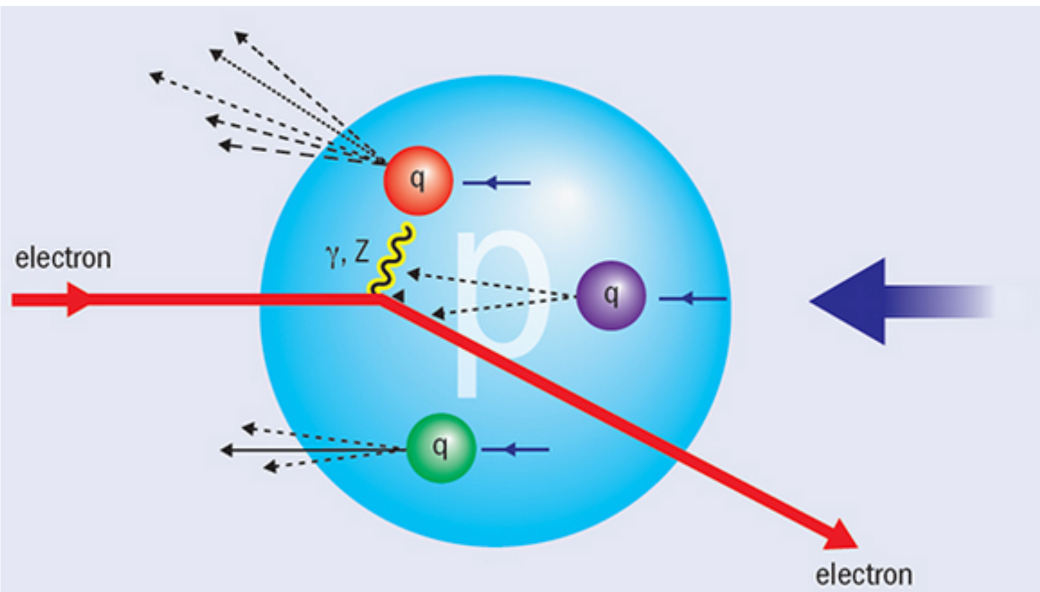
Peculiar…

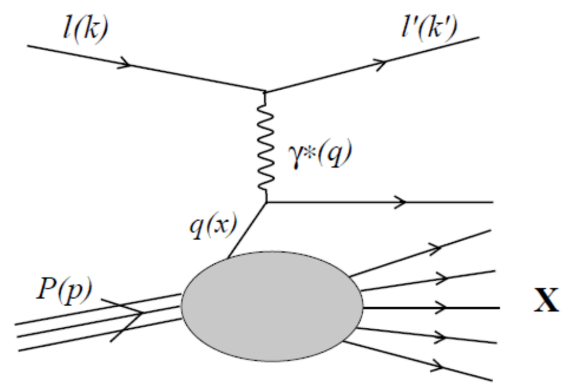
Observed indirectly in DIS experiments at SLAC in the 1970s.

Deep Inelastic Scattering at SLAC

"Modern Rutherford Experiment"

$$e(p) + h(P) \to e'(p') + X$$





Localized Probe

$$Q^2 = -(p-p')^2 \gg 1\ \mathrm{fm}^{-2}$$

$$\frac{1}{Q} \ll 1\ \mathrm{fm}$$

Two variables:

$$Q^2 = 4EE'\sin^2(\theta/2)$$

$$x_B = \frac{Q^2}{2M_N\nu}$$

$$\nu = E - E'$$

Discovery of spin-1/2 quarks and partonic structure!

The birth of QCD (1973)
Quark Model + Yang-Mills gauge theory

Taylor, Friedman, Kendall
Nobel Prize, 1990

Quantum Chromodynamics

PROBLEM:

The spin-3/2 Δ^{++} particle had 3 spin-1/2 u-quarks all in the same apparent state!?

Similar problems with the Δ^{-} (ddd) and the Ω^{-} (sss).

No two identical Fermions can occupy the same state.

Colour is necessary for the Pauli exclusion principle to still hold!

$$\Delta^{++} = \underbrace{|uuu>}_{\text{flavour}} \; \underbrace{|\uparrow\uparrow\uparrow>}_{\text{spin}} \; \underbrace{|\ell = 0>}_{\text{orb. } \ell} \; \boxed{\underbrace{\left| \frac{1}{\sqrt{6}} \varepsilon^{ijk} q_i q_j q_k \right\rangle}_{\text{colour d.o.f.}}}$$

Enter Quantum **Chromo**Dynamics.

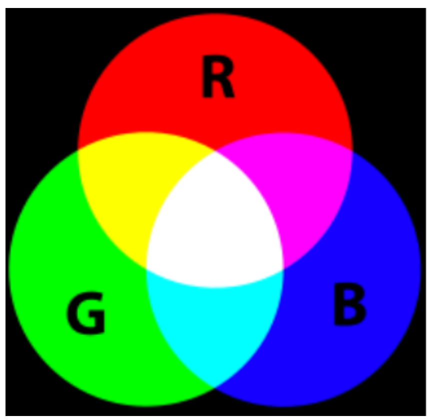
From the Greek "khroma" ($\chi\rho\mu\alpha$), meaning colour.

$$|\,qqq\rangle = \sqrt{\frac{1}{6}}(RGB - RBG + BRG - BGR + GBR - GRB)$$

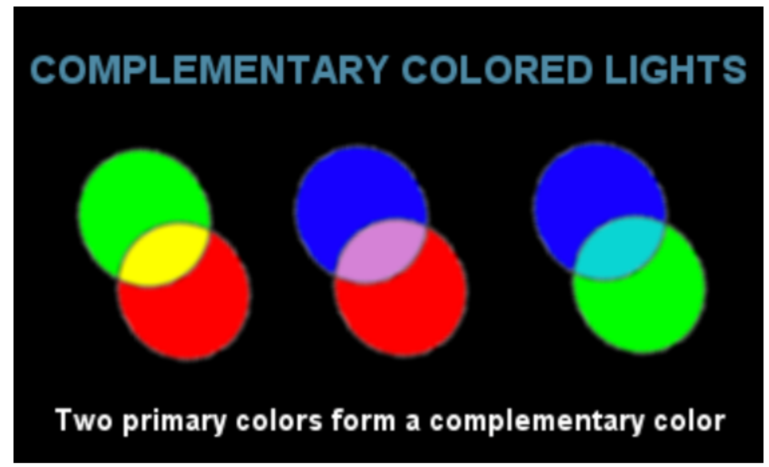
Quantum Chromodynamics

All observable particles must be white $\Rightarrow$ colour singlet.

Baryons are red-blue-green triplets.

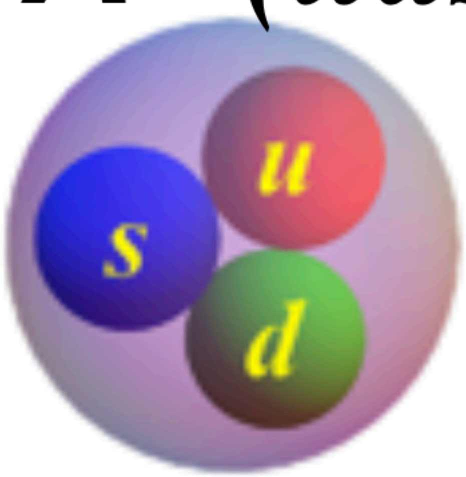


Mesons are colour-anticolour pairs.



blue-yellow
green-magenta
red-cyan

$$\Lambda = (uds)$$



3 primary colours together $\Rightarrow$ white

2 primary colours $\Rightarrow$ complementary colour

$$\pi^- = (d\bar{u})$$

QCD Lagrangian

QCD is the theory of quarks, gluons, and their interactions.
QFT based on the invariance under local gauge transformations in $SU(3)_c$

$$\mathscr{L}_{\text{QCD}} = \bar{\psi}(i\gamma_\mu \mathscr{D}^\mu - m)\psi - \frac{1}{4} G^j_{\mu\nu} G^{\mu\nu}_j$$

Covariant derivative:

$$\mathscr{D}^\mu = \partial_\mu - ig \sum_{j=1}^{8} \frac{\lambda_j}{2} \mathscr{A}^j_\mu(x)$$

Gluon field tensor:

$$G^i_{\mu\nu}(x) = \partial_\mu \mathscr{A}^i_\nu(x) - \partial_\nu \mathscr{A}^i_\mu(x) + g f_{ijk} \mathscr{A}^j_\mu(x) \mathscr{A}^k_\nu(x)$$

$\lambda_j \rightarrow$ Gell-Mann Matrices
$f_{ijk} \rightarrow$ Structure Constants
$\mathscr{A}^j_\mu \rightarrow$ Gluons
$g \rightarrow$ Coupling constant

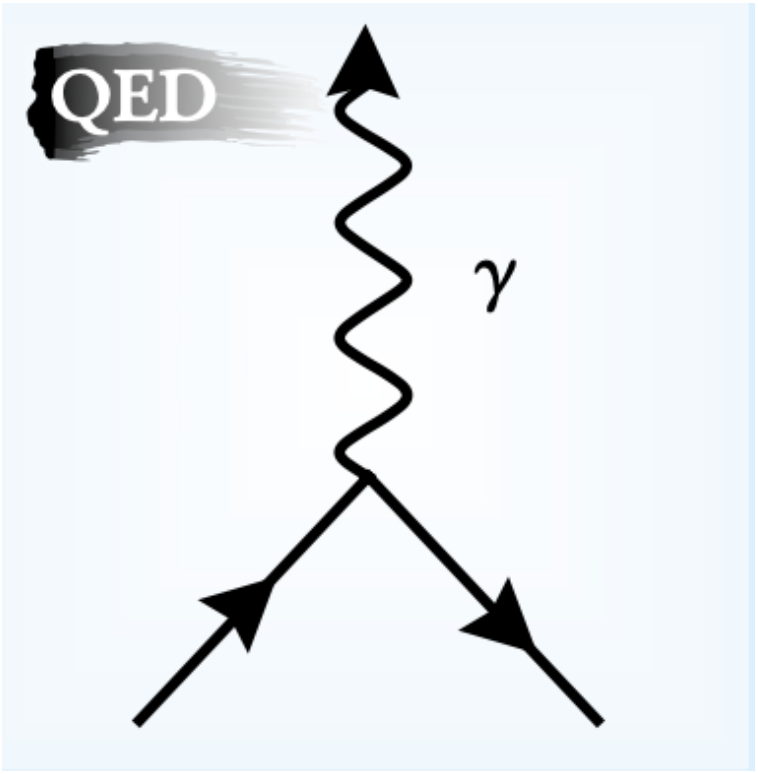
Some interesting results:

- Gluons carry colour.
- The coupling "runs".
- Weak at high energies $\Rightarrow$ asymptotic freedom
- Strong at low energies $\Rightarrow$ confinement

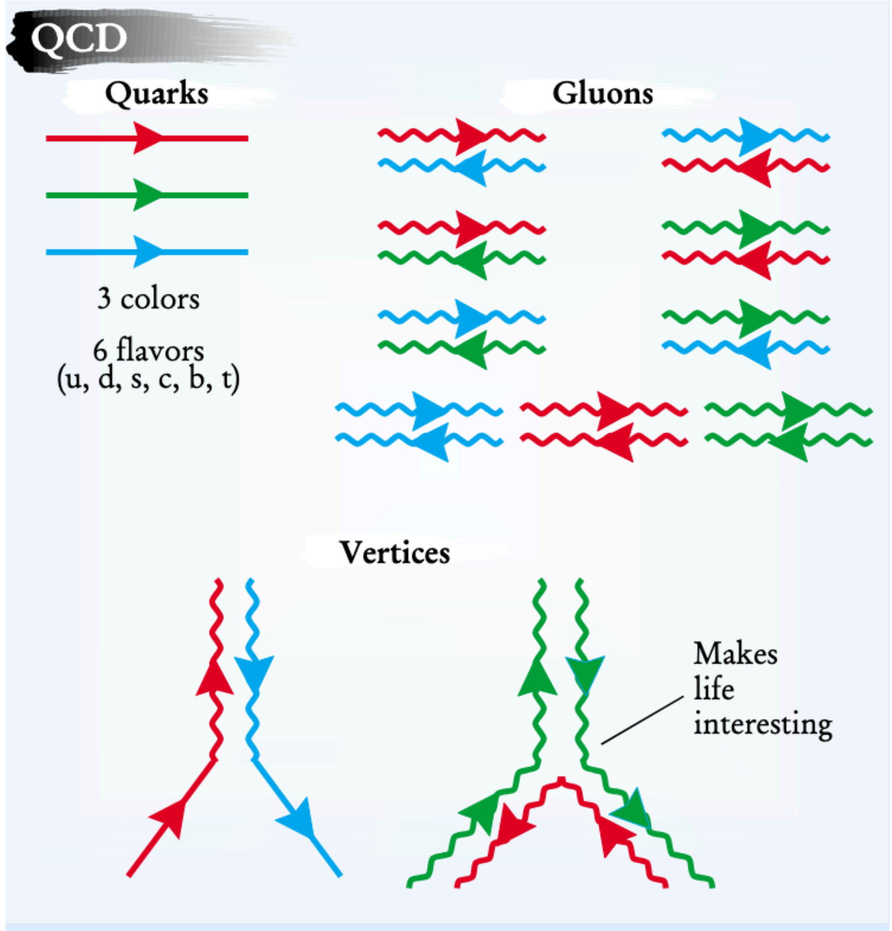
QED vs. QCD

Two key features that distinguish QCD from QED:

1. Quarks interact more strongly the further they are apart, and more weakly as they are close by → Asymptotic Freedom!
   - No other force does this.
   - Gluons *interact with themselves* because they also carry colour charge.
   - Photons are not electrically charged and do not interact with each other.
2. QED has two types of charge — positive and negative — whereas QCD has three — red, green, and blue.

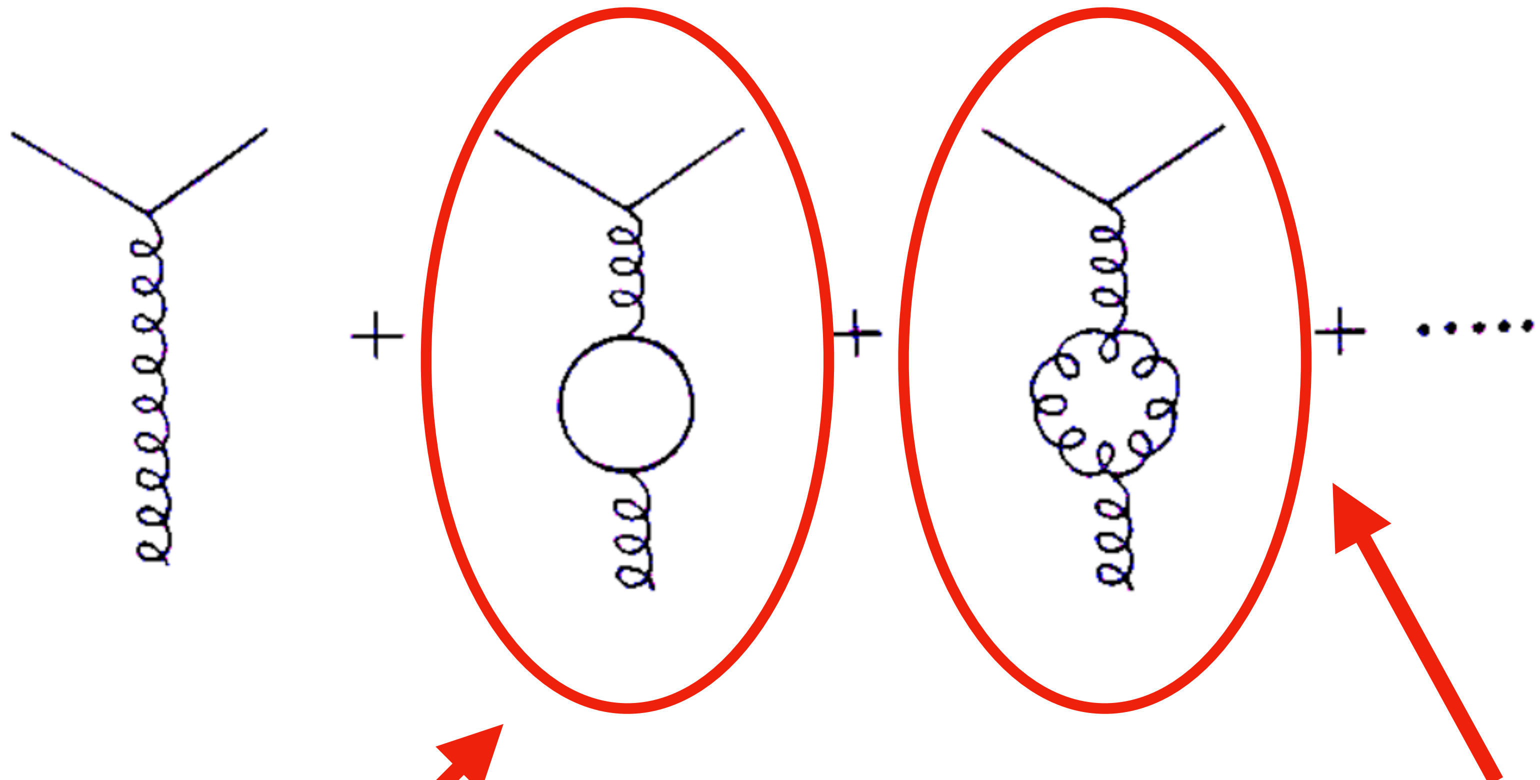


Primitive vertex



Strong Coupling

Loop Contributions



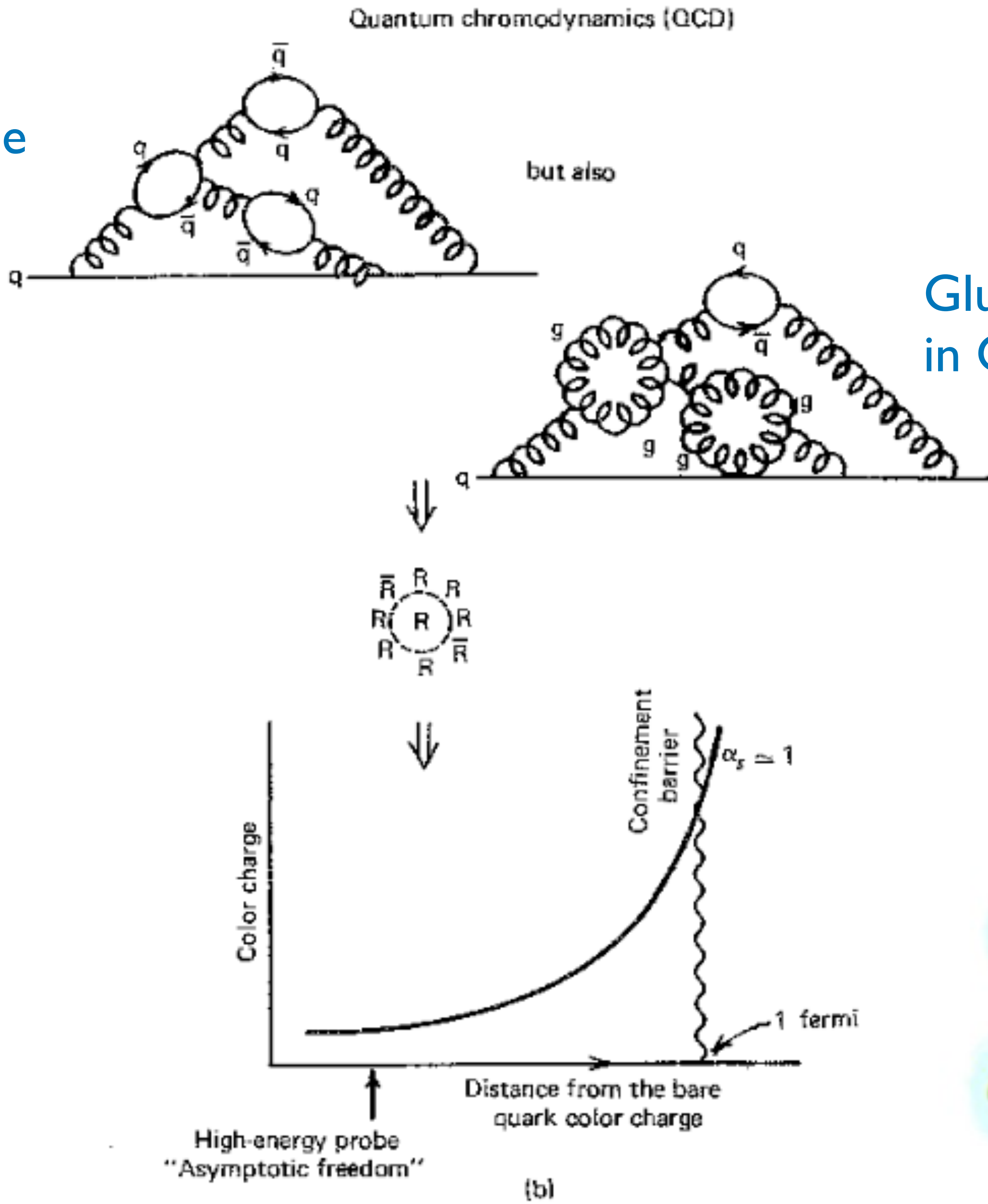
Similar to QED
Quark loops like lepton loops in QED.
For each flavour, large mass suppressed

Only in QCD

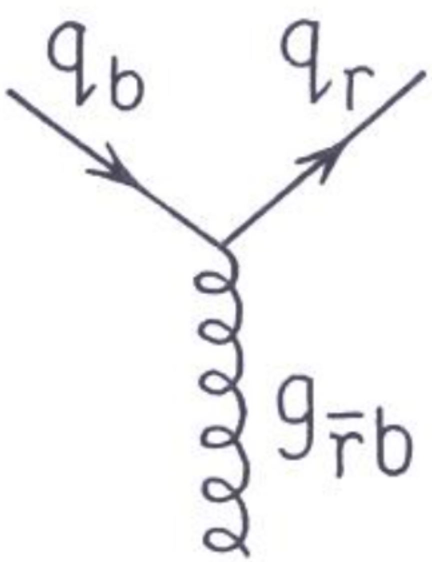
- 8 gluons
- Larger contribution
- Opposite Sign
- Asymptotic Freedom

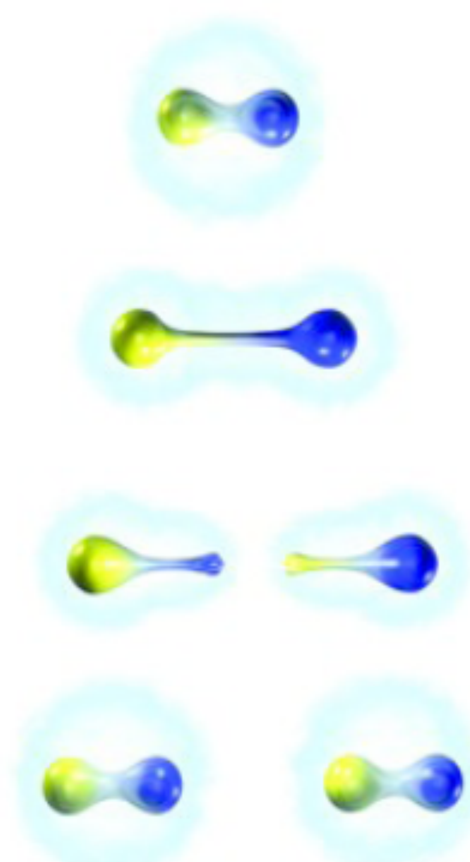
Strong Coupling

QED Analogue



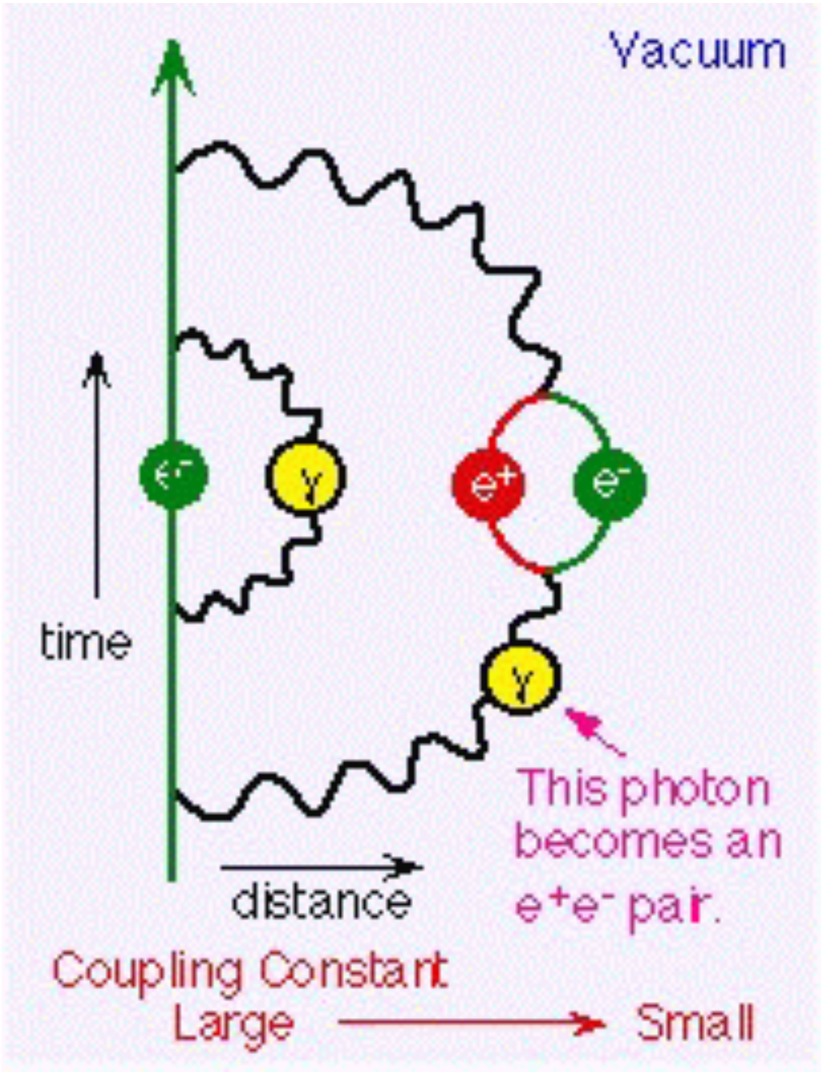
Gluon self-coupling in QCD



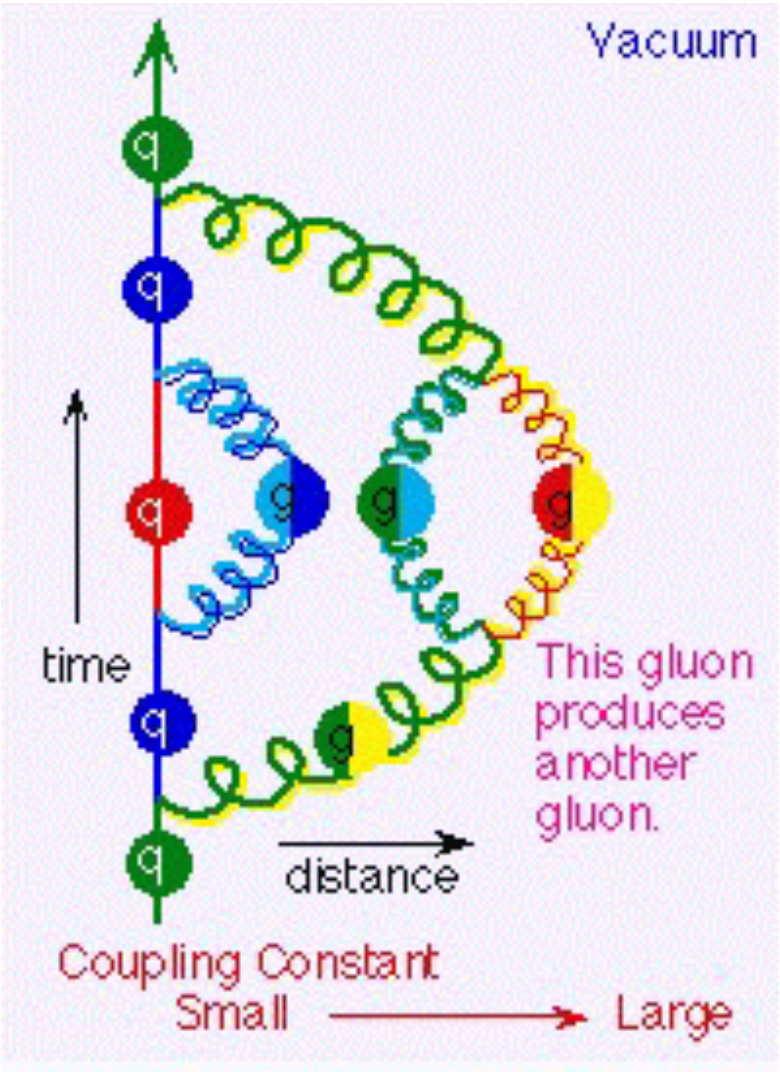


Strong Coupling

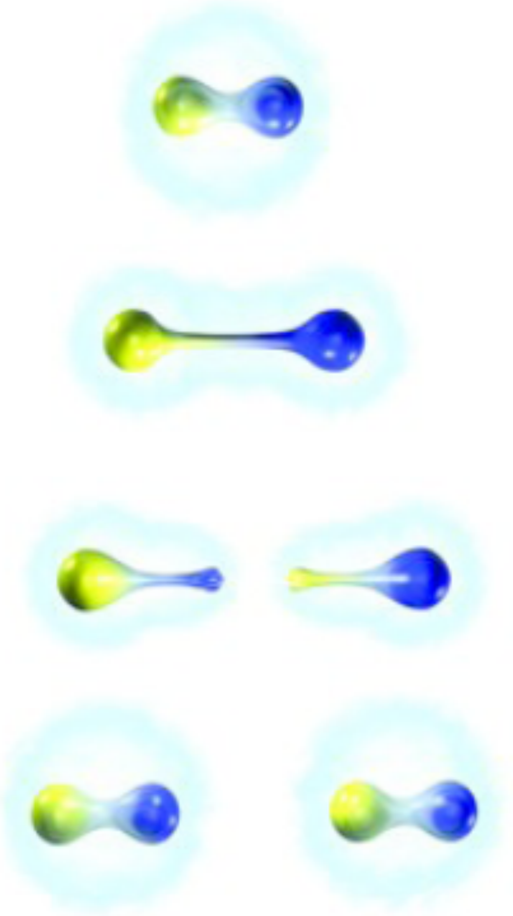
Charge Screening



electron

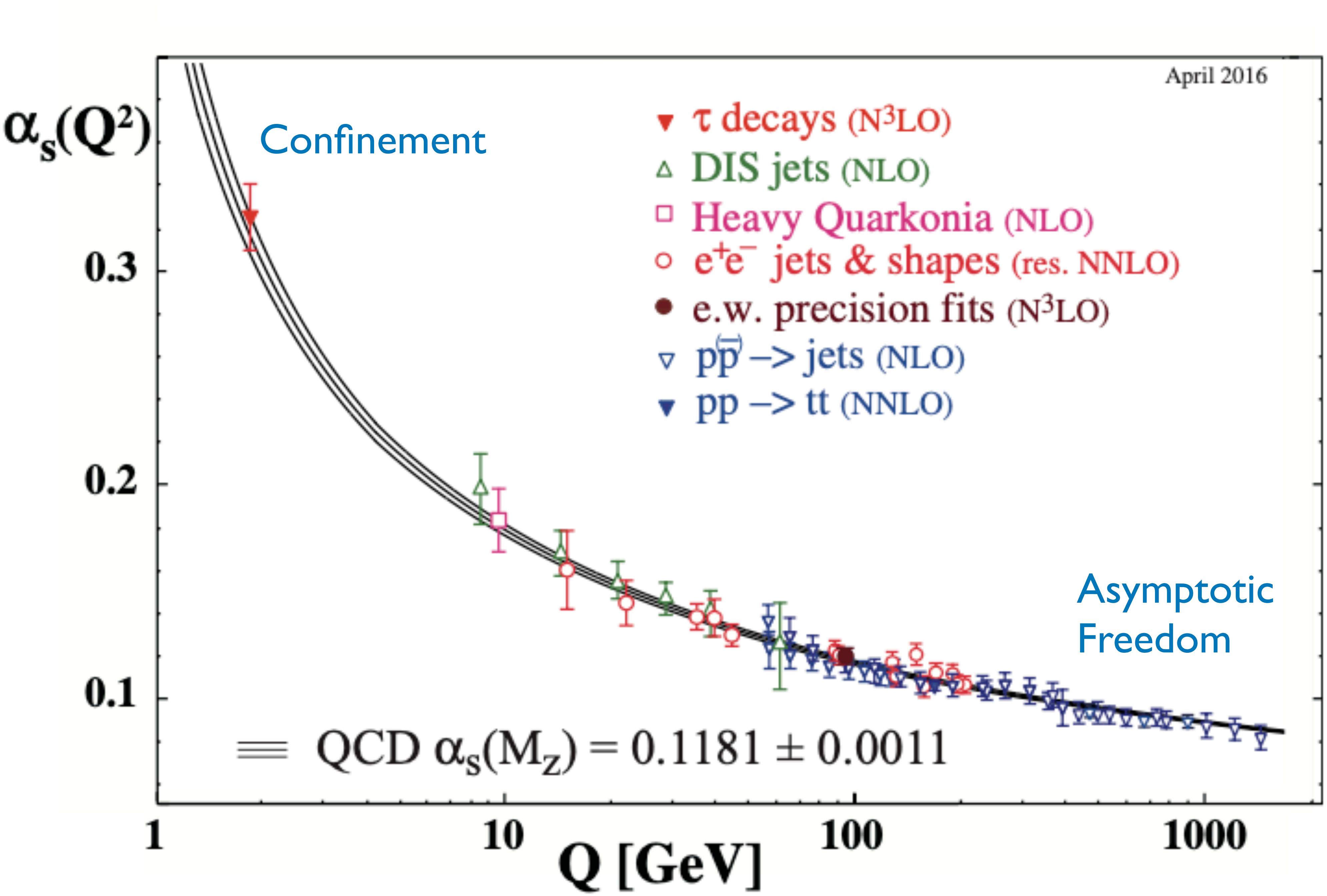


quark



You get "anti-screening" from the gluon-gluon interaction.

QCD Lagrangian



Nobel Prize 2004

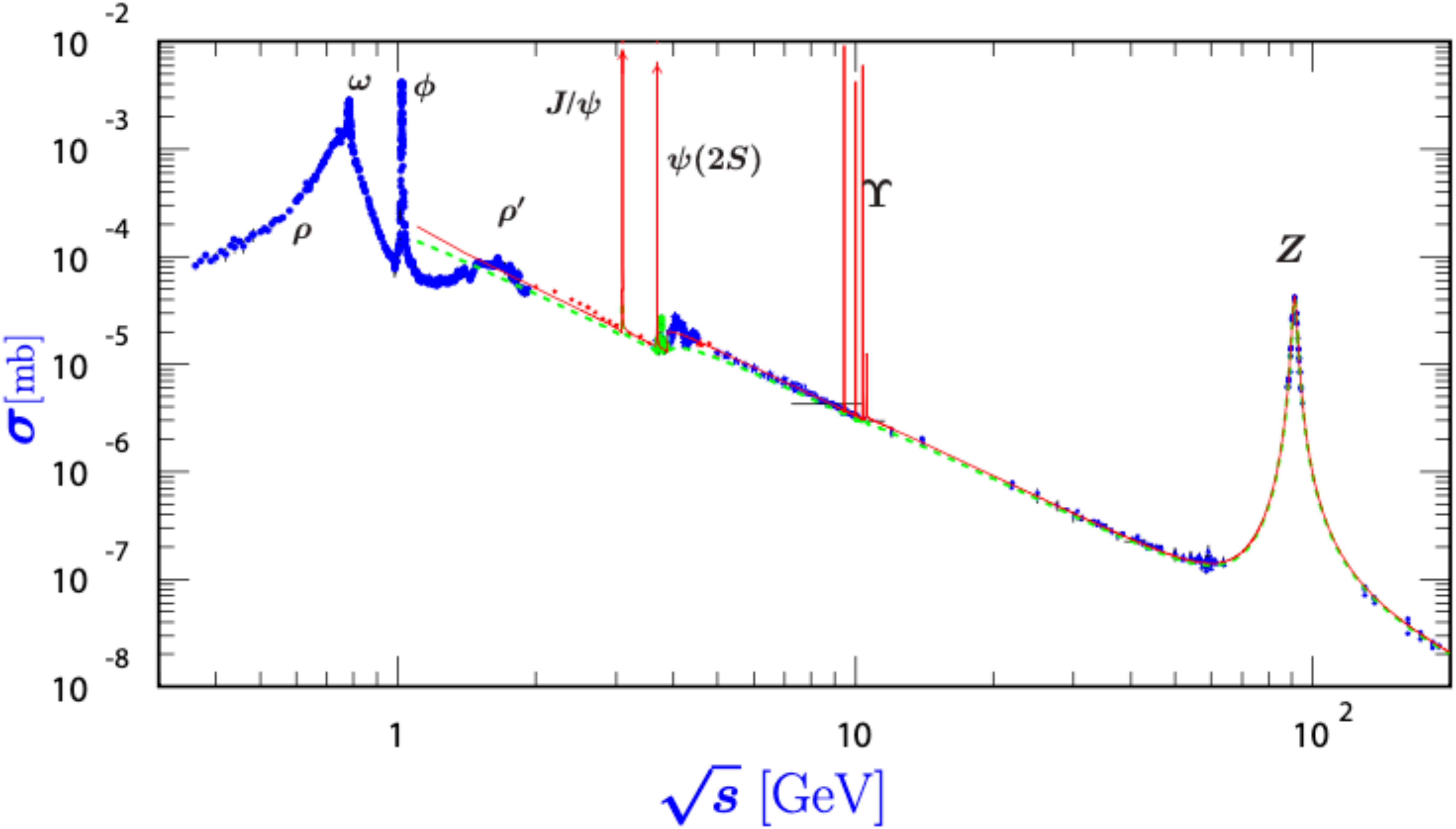
Wilczek, Gross, Politzer

Close-range behaviour

$\alpha_s \to 0$ as $Q \to \infty$

Electron-Positron Annihilation

e^+e^- Collider Data

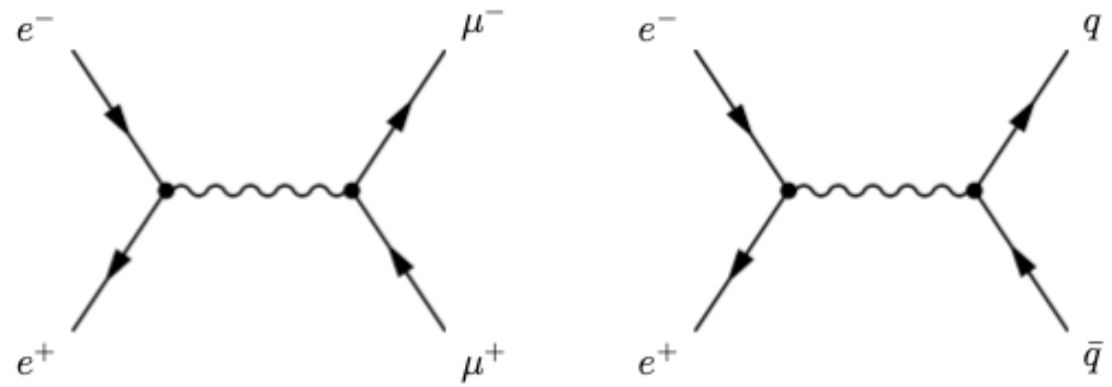


$e^+e^- \rightarrow$ Hadrons, with overall $J^{PC} = 1^{--}$

Electron-Positron Annihilation

General Features

Idea: Relate $q\bar{q}$ cross section to known (QED) cross section



$\mu^+\mu^-$ cross section from QED: $\sigma(e^+e^- \to \mu^+\mu^-) = \dfrac{4\pi\alpha^2}{3s}$

$q\bar{q}$ cross section (also only from QED!): $\sigma(e^+e^- \to q\bar{q}) = N_c\, e_q^2\, \sigma(e^+e^- \to \mu^+\mu^-)$

with $e_q = \begin{cases} -1/3 & \text{for } q = d, s, b \\ +2/3 & \phantom{\text{for } q =} u, c, t \end{cases}$

and $N_c = 3$ is the number of colours

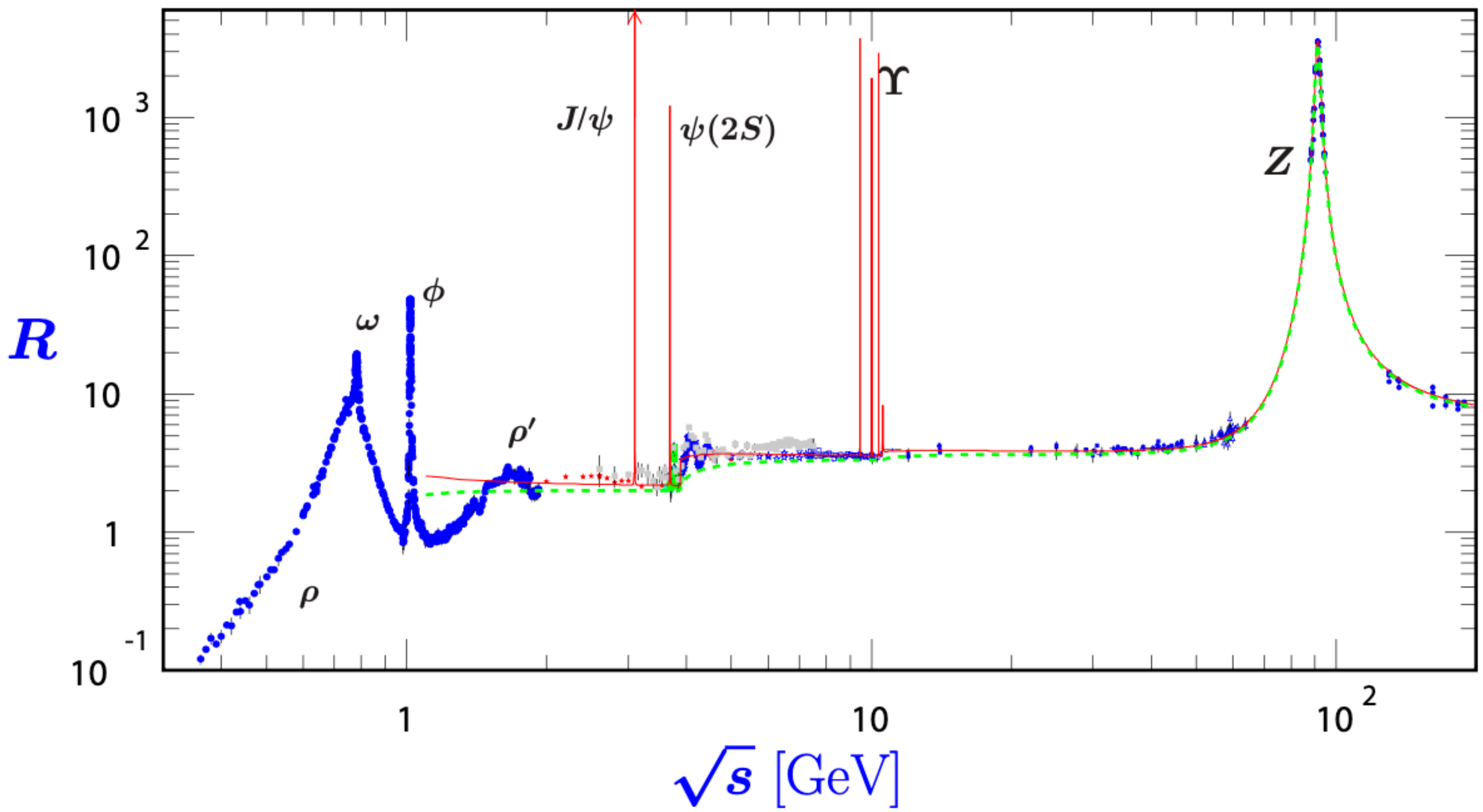
Then we define the ratio

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

Electron-Positron Collider

$$e^+e^- \rightarrow \text{Hadrons}$$

With QCD corrections: $R = \sum_q 3e_q^2 \left(1 + \frac{\alpha_s(Q^2)}{\pi}\right)$



Confirmed quark charge

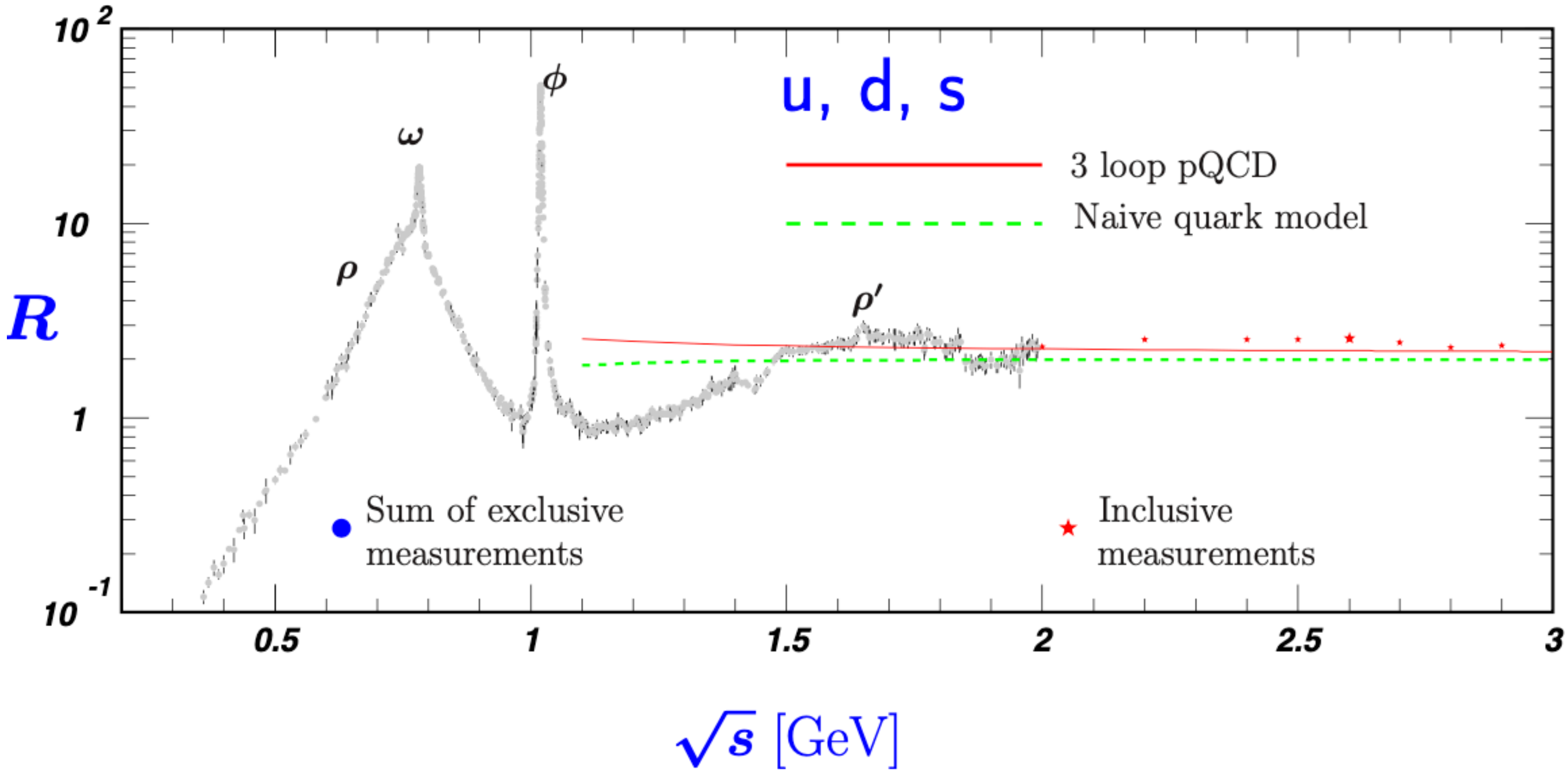
Confirmed colour hypothesis

Shows production thresholds for quark flavour production

Electron-Positron Collider

$$e^+e^- \to \text{Hadrons}$$

3 Light quarks

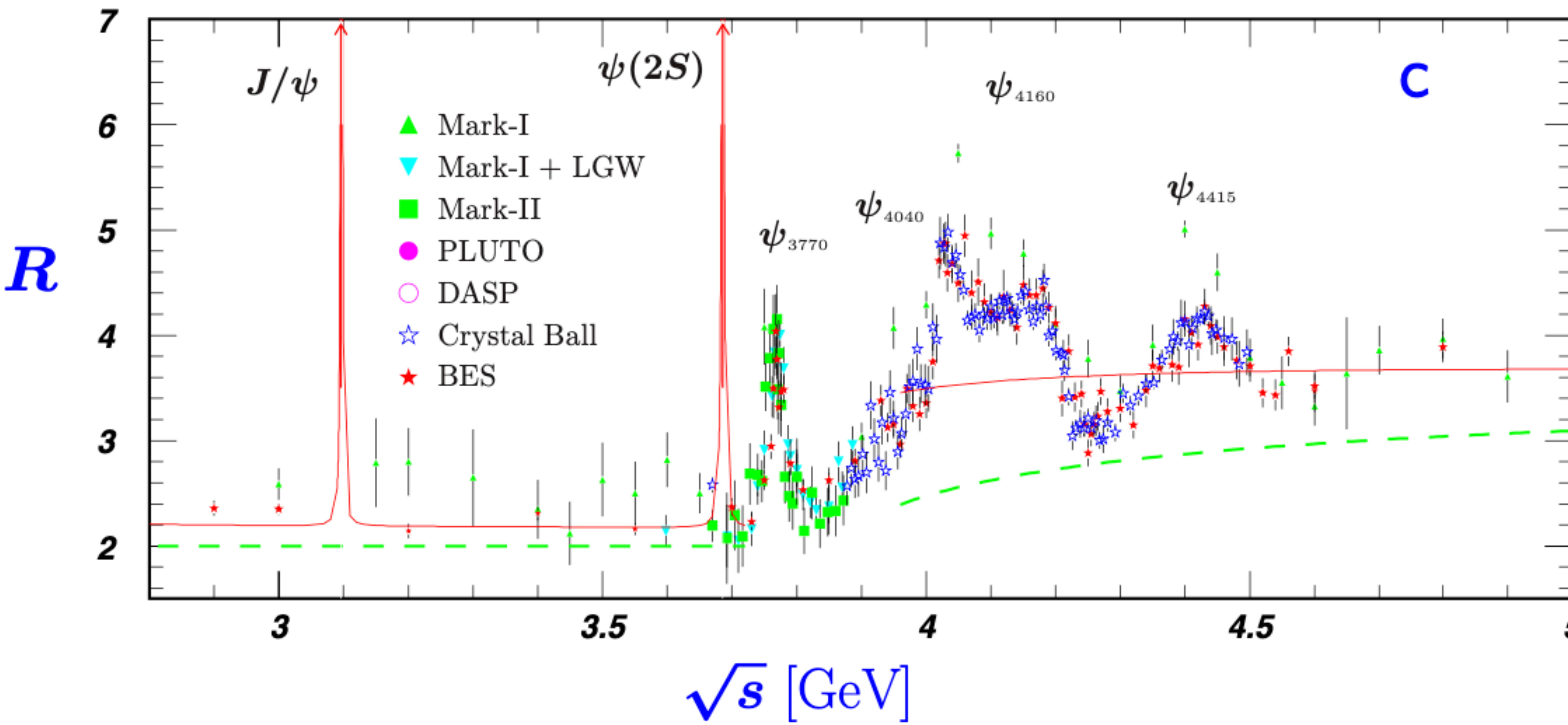


$$R = \sum_q 3e_q^2 = 3\left[\left(\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(-\frac{1}{3}\right)^2\right] = 2$$

Electron-Positron Collider

$$e^+e^- \rightarrow \text{ Hadrons}$$

Include charm

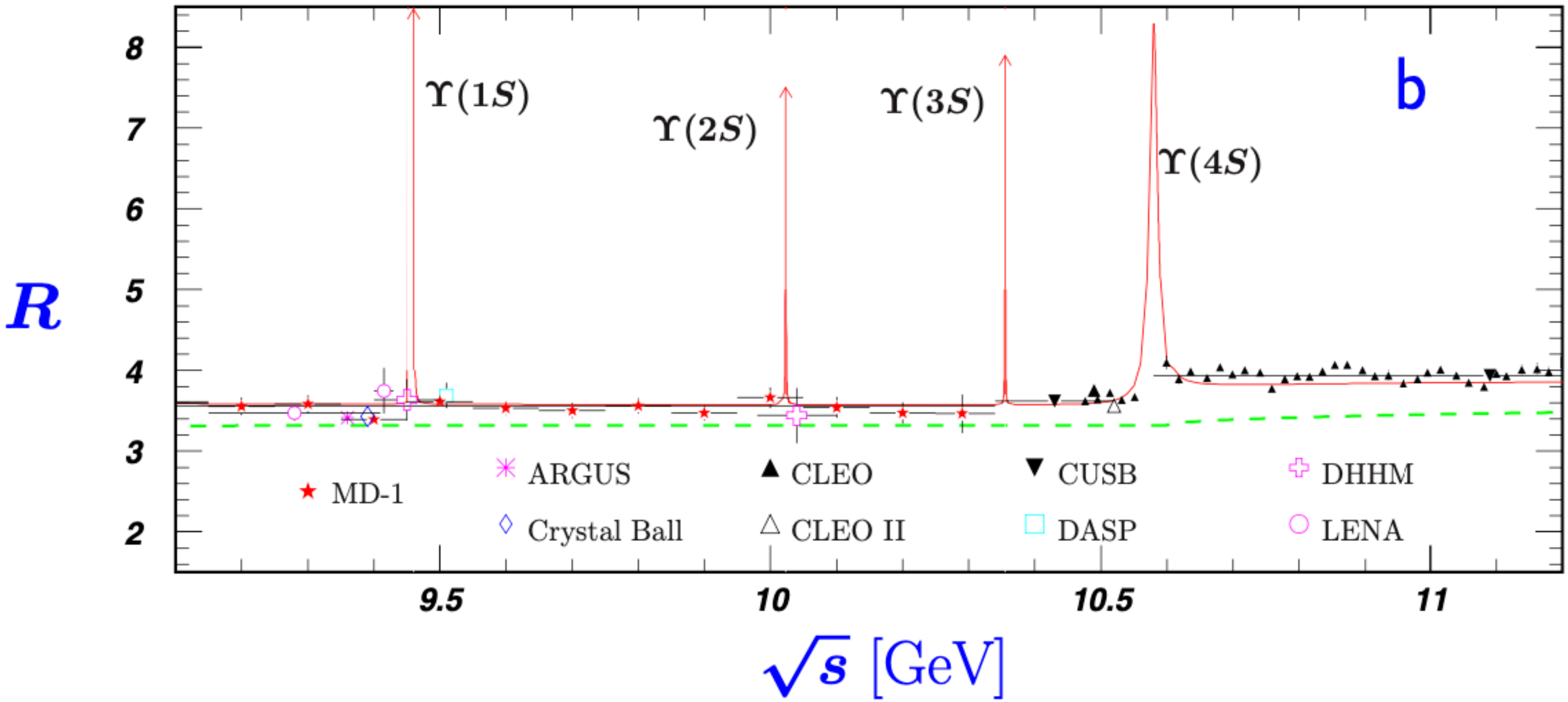


$$R = \sum_q 3e_q^2 = 3\left[\left(\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2\right] = \frac{10}{3}$$

Electron-Positron Collider

$$e^+e^- \rightarrow \text{Hadrons}$$

and bottom



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

Consequences of QCD

Symmetries of the Lagrangian: Parity

$\mathscr{L}_{\mathrm{QCD}}$ is invariant under parity transformation, i.e. $\vec{r} \rightarrow -\vec{r}$

$$\hat{P} \text{ acting on } (t, \vec{r}) \rightarrow (t - \vec{r})$$

Eigenvalues:

$$\hat{P}\phi(t, \vec{r}) = P\phi(t, \vec{r}) \text{ with Eigenvalues } P = \pm 1$$

Consequences for Hadrons:

- All states can be decomposed into states with $P = 1$ or $P = -1$.
- For systems of hadrons, we just multiply the parity of the individual hadrons together to get the system parity $\rightarrow$ multiplicative quantum number.
- Hadrons produced via QED/QCD from a state with definite parity also have the same total parity.
- Additional $U(1)$ symmetries for baryon number, charge, lepton number $\rightarrow$ combined parity operators.
- Define intrinsic parity $P_{\text{proton}} = P_{\text{neutron}} = P_{\text{electron}} = 1$

Consequences of QCD

Symmetries of the Lagrangian: Parity

Example: Parity of the pion using ${}^2\mathrm{H} + \pi^- \rightarrow n + n$

Measure angular momentum (i.e. angular distribution)

Intrinsic parity $P_{proton} = P_{neutron} = 1$

$$\left.\begin{array}{lll} \text{Deuteron has spin} & S_d & = 1 \\ \text{Pion has spin} & S_\pi & = 0 \\ \text{S-wave} & L & = 0 \end{array}\right\} \Rightarrow \begin{array}{l} \text{Total orbital angular momentum of the final state} \\ L = 1 \Rightarrow P = (-1)^L \end{array}$$

n is a Fermion $\rightarrow$ antisymmetric

$$\text{Sum} \quad \underset{p}{(1)} \quad \underset{n}{(1)} \quad \underset{\text{Pion}}{(P_\pi)} = \underset{L=1}{(-1)} \quad \underset{n}{(1)} \quad \underset{n}{(1)}$$

$\Rightarrow$ Pion has intrinsic parity $P_\pi = -1$, i.e. it is a *pseudoscalar* particle!

General Approach:

- Calculate parity of initial state.
- Examine strong and EM (not weak!) decays, determine angular momenta.
- Find intrinsic parity

Consequences of QCD

Symmetries of the Lagrangian: Charge Conjugation

$\mathscr{L}_{\mathrm{QCD}}$ is invariant under parity transformation, i.e. exchange particle $\leftrightarrow$ antiparticle

$$\hat{C}\,|\phi\rangle \to |\bar{\phi}\rangle$$

Same properties as the parity operator:

- Eigenvalues $C = \pm 1$
- Multiplicative quantum number for a system
- **NEW:** only neutral particles can be eigenstates, otherwise the eigenvalue equation $\hat{Q}\,|f\rangle = q\,|f\rangle$ does not hold

Experimental determination: e.g. C-Parity of the pion from decay $\pi^0 \to \gamma + \gamma$
C-Parity of the photon from $C(\gamma) = -1$ from QED
Multiplicative $\Rightarrow C(\pi^0) = (-1)(-1) = 1$

Quantum numbers of the pion: $J^{PC} = 0^{-+}$

Natural Quantum Numbers

"Natural" quantum numbers for mesons: J^{PC} with $|L-S| \leq J \leq |L+S|$

$$\hat{P}\left[R(r)Y_{lm}(\theta,\phi)\right] = Y_{lm}(\pi-\theta,\phi+\pi) = (-1)^l Y_{lm}(\theta,\phi) \quad \Rightarrow \quad \boxed{\hat{P}\,|\,q\bar{q}\rangle = (-1)^{L+1}\,|\,q\bar{q}\rangle}$$

Charge Parity of a Meson as Quark-Antiquark pair: $\hat{C}\,|\,q\bar{q}\rangle = C\,|\,q\bar{q}\rangle$

Charge conjugation corresponds to the exchange of a quark/antiquark

$L = 0,2,4,\ldots$ symmetric, $L = 1,3,5\ldots$ antisymmetric $\Rightarrow C \sim (-1)^L$

Spin $\Rightarrow C \sim (-1)^{S+1}$

Exchange particle $\rightarrow$ antiparticle $\Rightarrow C \sim (-1)$

$$\hat{C}\,|\,q\bar{q}\rangle = (-1)^L(-1)^{S+1}(-1)\,|\,q\bar{q}\rangle = \boxed{(-1)^{L+S}\,|\,q\bar{q}\rangle}$$

$^{2S+1}L_J$	S	L	J	P	C	J^{PC}	Mesons	Name
$^1S_0$	0	0	0	$-$	$+$	0^{-+}	π η η' K	pseudo-scalar
$^3S_1$	1	0	0	$-$	$-$	1^{--}	ρ ω ϕ K^*	vector
$^1P_1$	0	1	1	$+$	$-$	1^{+-}	b_1 h_1 h_1' K_1	pseudo-vector
$^3P_0$	1	1	0	$+$	$+$	0^{++}	a_0 f_0 f_0' K_0^*	scalar
$^3P_1$	1	1	1	$+$	$+$	1^{++}	a_1 f_1 f_1' K_1	axial vector
$^3P_2$	1	1	2	$+$	$+$	2^{++}	a_2 f_2 f_2' K_2^*	tensor

Allowed: $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 1^{++}, 2^{--}, 2^{-+}, 2^{++}, 3^{--}, 3^{+-}, 3^{++}, \ldots$

Not allowed: $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$ $\Rightarrow$ Exotic Mesons

Theory Approaches

QCD is complicated!

1. **High** Q (small distances)
   Expansion in powers of α_s
   Perturbation theory
   Pretty successful!
2. **Low** Q (large distances)
   Non-perturbative regime
   Approximations difficult

Methods for Low-Energy QCD

Phenomenological models ⇒ Potential models, Quark models
Discretize space-time ⇒ Lattice QCD
Effective degrees of freedom ⇒ Chiral Perturbation Theory

Non-Relativistic Potential

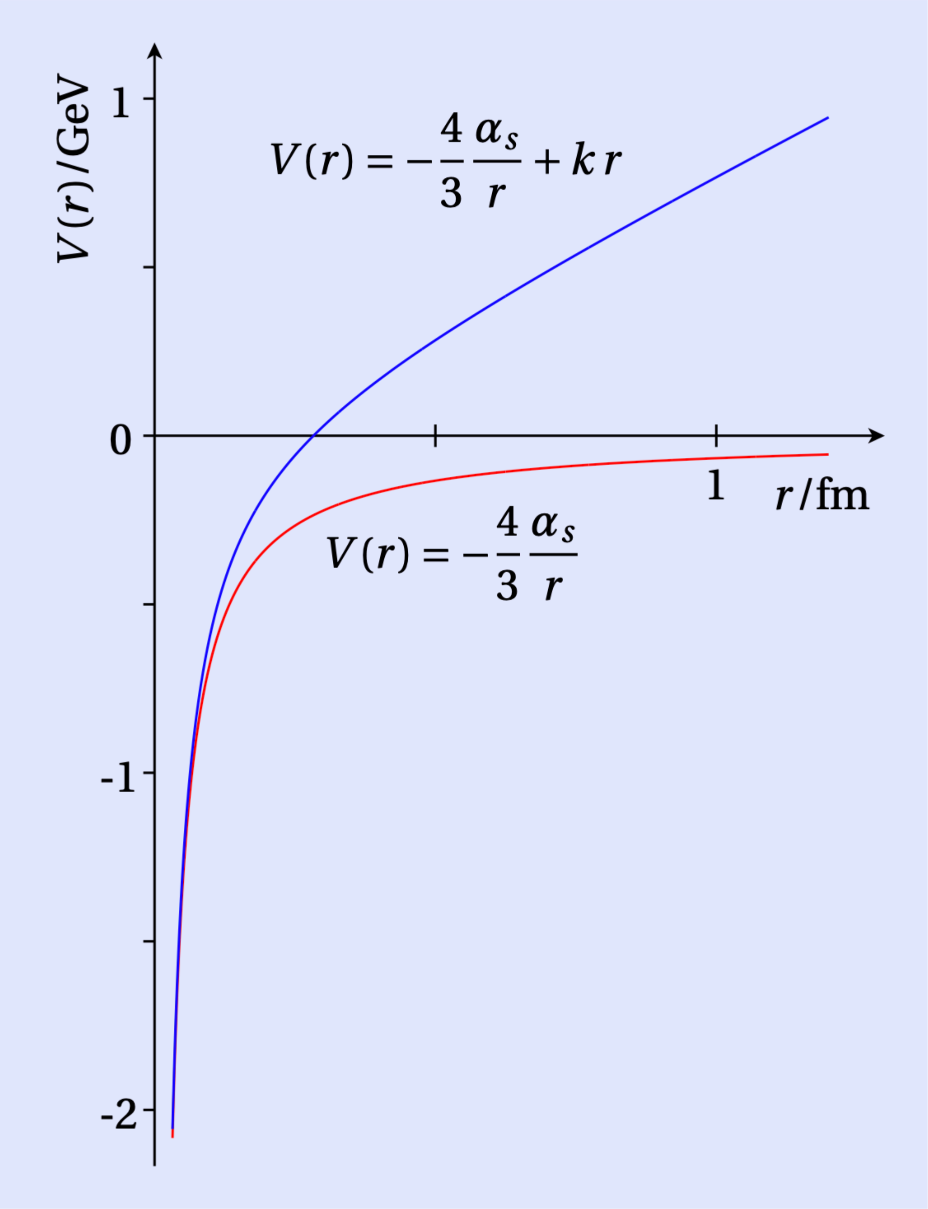
The functional form of the potential is chosen to reproduce the asymptotic behaviour of the strong interaction.
Useful for heavy quarks, such as $c\bar{c}$

At small distances we have asymptotic freedom and the potential is Coulomb like:

$$V(r) \underset{r\to 0}{\longrightarrow} -\frac{4}{3}\frac{\alpha_s(r)}{r}$$

At large distances we have confinement that works like a spring:

$$V(r) \underset{r\to\infty}{\longrightarrow} kr$$



$$\alpha_s(\mu) = \frac{4\pi}{\left(11 - \frac{2}{3}n_f\right)\ln\left(\frac{\mu^2}{\Lambda^2}\right)}$$

n_f is the number of flavours

$\Lambda \approx 0.2$ GeV the QCD scale parameter

k is the spring constant ≈ 1 GeV/fm

Lattice QCD

The Brute Force Method

"Lattice field theory is the non-perturbative approach to QFT through regularised Euclidean functional integrals.
The regularisation is based on discretisation of the action which preserves gauge invariance at all stages"

Preserves gauge invariance
Defines observables without reference to perturbation theory
Allows for stochastic evaluation of observables

Divide continuous spacetime into a discrete lattice.
Do calculations.
Extrapolate to the continuum.

Requires LOTS of computing power.

Lattice QCD

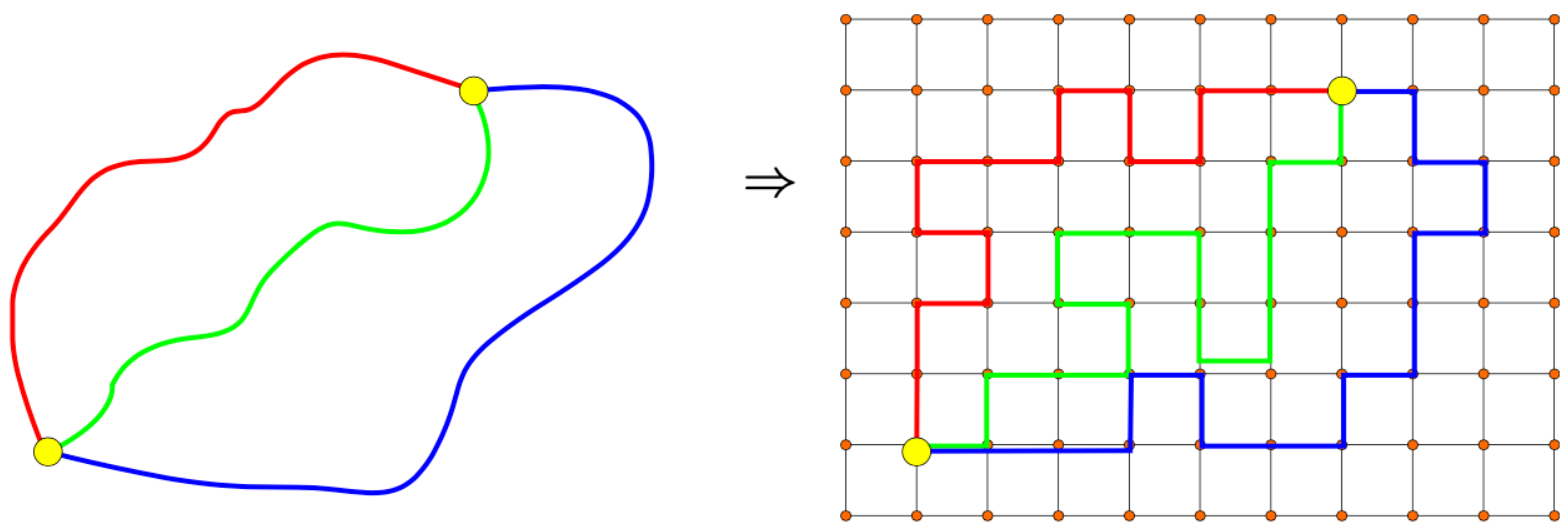
Start with Feynman's Path Integral Formulation of QM

$$\Psi(x_2, t_2) = \frac{1}{Z}\int e^{iS}\,\Psi(x_1, t_1)\,\mathscr{D}x$$

where $\int \mathscr{D}x$ is the integration over ALL paths $x(t)$ with $x(0) = x_1$

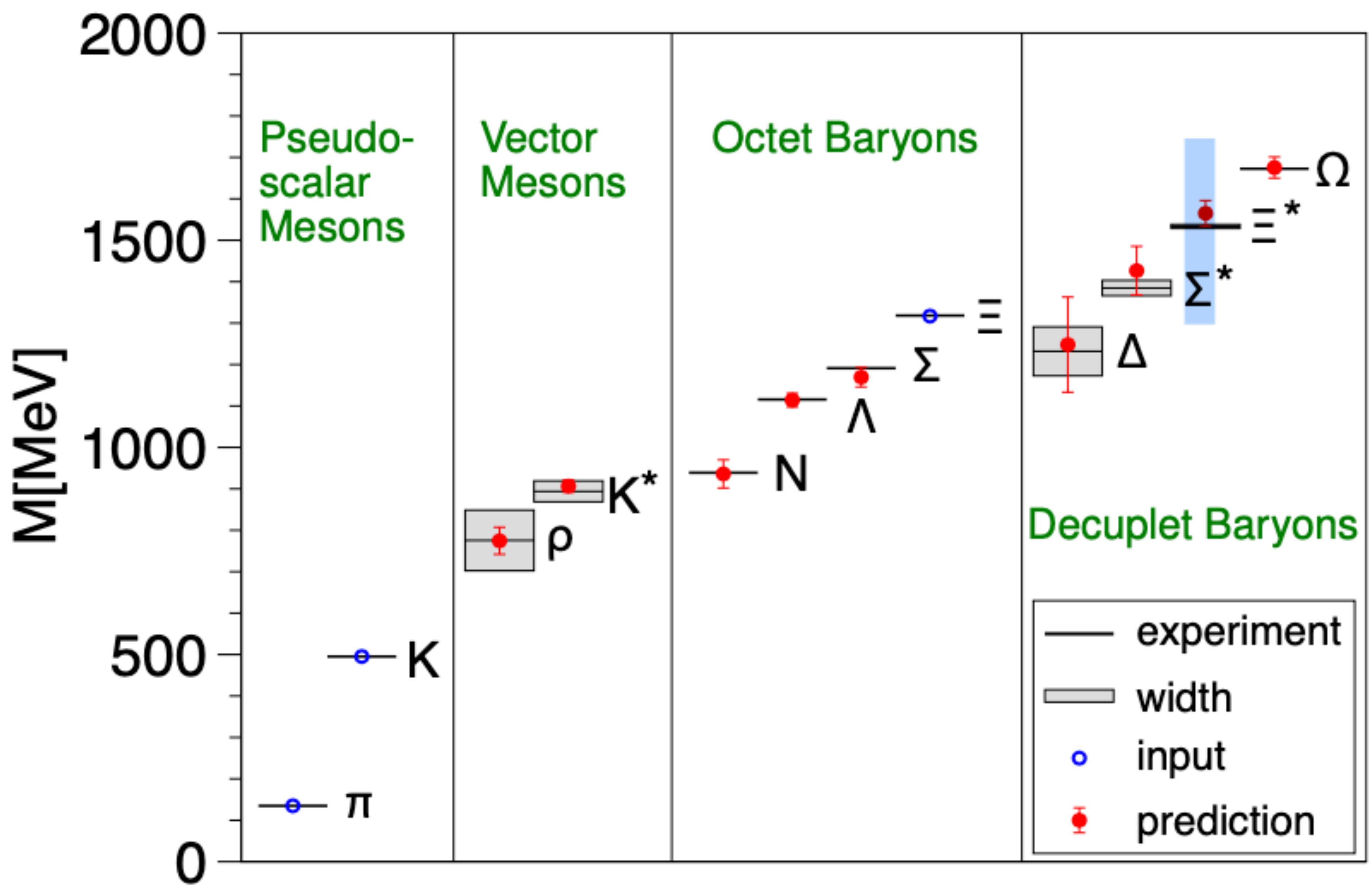
and the action $S = \int_{t_1}^{t_2} L(x, \dot{x}, t)\,dt$

(a.k.a. Fermat's principle, Hamilton's principle, principle of least action)



Lattice QCD — Summary

- Gauge invariant
- Works in the non-perturbative regime
- Finite volume, finite momentum
- Requires lots of computing power



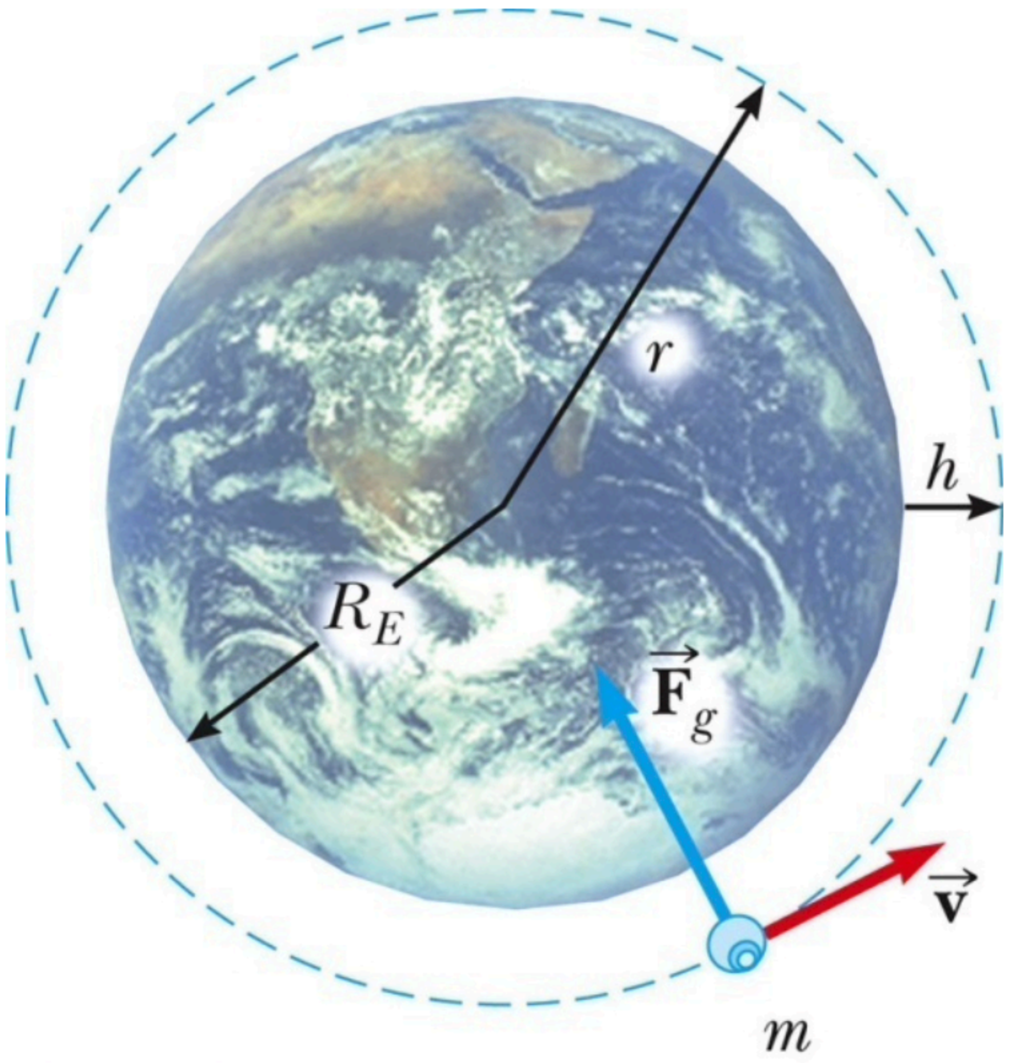
S. Durr, et al., Science 322 (2008).

Effective Field Theory

Replace the quarks and gluons with effective degrees of freedom that are relevant at this scale.

A Classical Example

$$V(h) = mgR_E \sum_{i=1}^{\infty} (-1)^{i-1} \left(\frac{h}{R_E}\right)^i$$



Degree of freedom: m
Symmetries: translations parallel to the Earth's surface and rotations about an axis normal to it.

$$V(r) = -\frac{GMm}{r} \quad \rightarrow \quad V(h) = mgh$$

Effective Field Theory

Approximate Symmetries of QCD

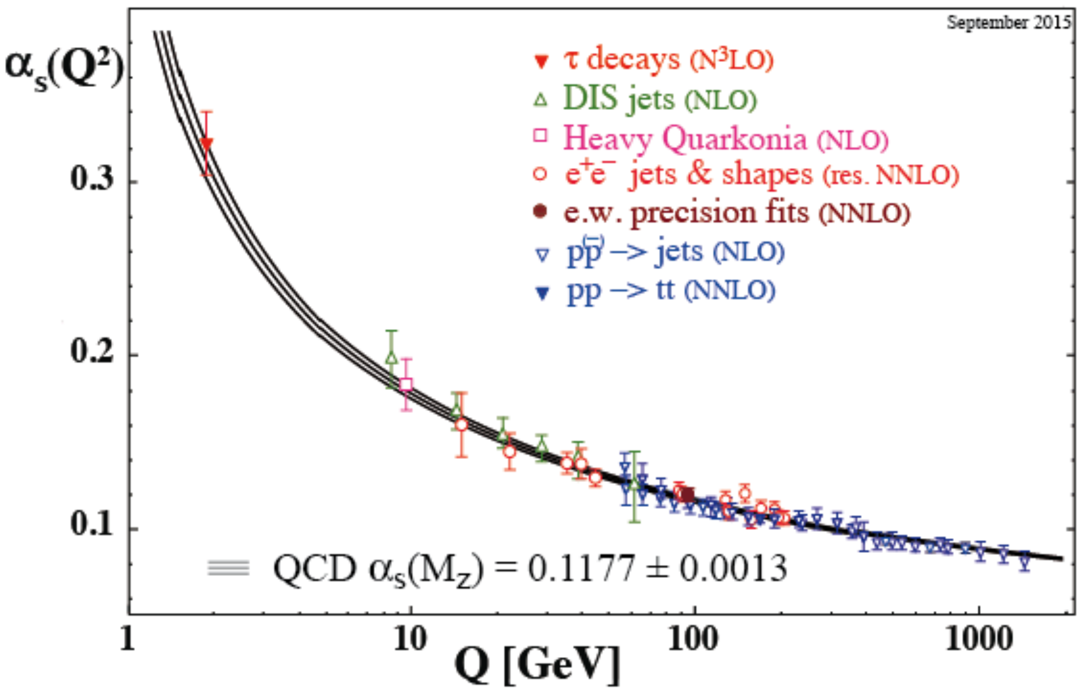
Replace the quarks and gluons with effective degrees of freedom that are relevant at this scale.

Effective Theories involve a systematic expansion of QCD.

At High Energies $Q \to \infty$, Quarks and Gluons are relevant
  Perturbative QCD, Expansion in $1/Q$

Very slow hadrons $Q \to 0$
  Pions and Kaons are relevant
  Approximate Symmetries $\to$ Expansion in Q

Heavy quarks $m_Q \to \infty$
  Light quarks and gluons relevant
  Use approximate symmetries
    $\to$Expansion in $1/m_Q$



Effective Field Theory

Approximate Symmetries of QCD

Low-energy approximation to a more fundamental theory (QCD).

Most general Lagrangian consistent with all symmetries. Relevant degrees of freedom are the pions, nucleons, etc.

Breakdown scale $\Lambda \approx 1$ GeV. The mass of the lightest omitted degree of freedom.

Challenges: infinite number of terms in the Lagrangian, non-normalizable in the traditional sense.

Solution:

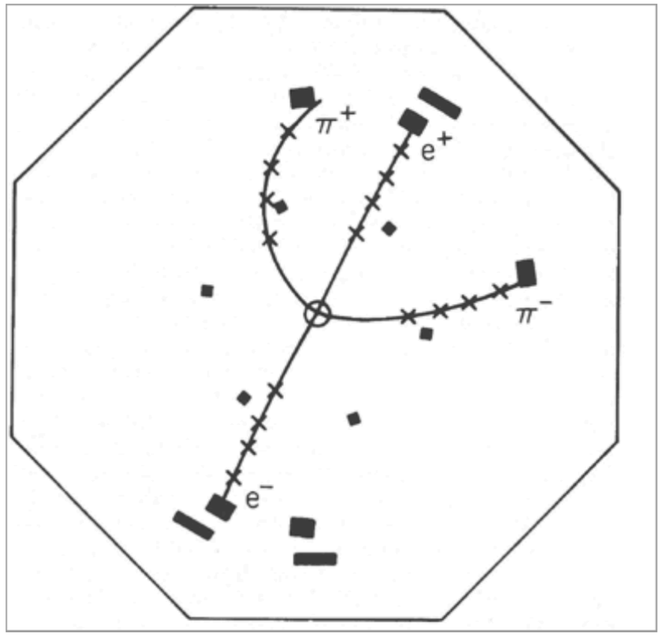
Expansion in q/Λ and power counting (q is typical momentum and masses).
Finite number of terms in the Lagrangian.

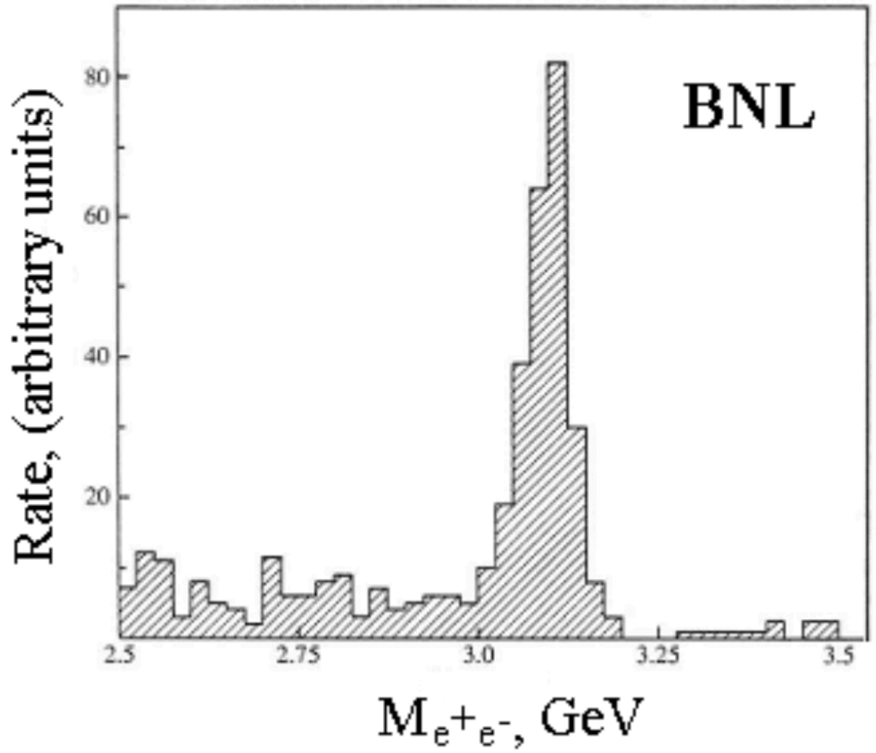
Renormalizable to given order $\Rightarrow$ finite number of Low-Energy Constants (LECs).

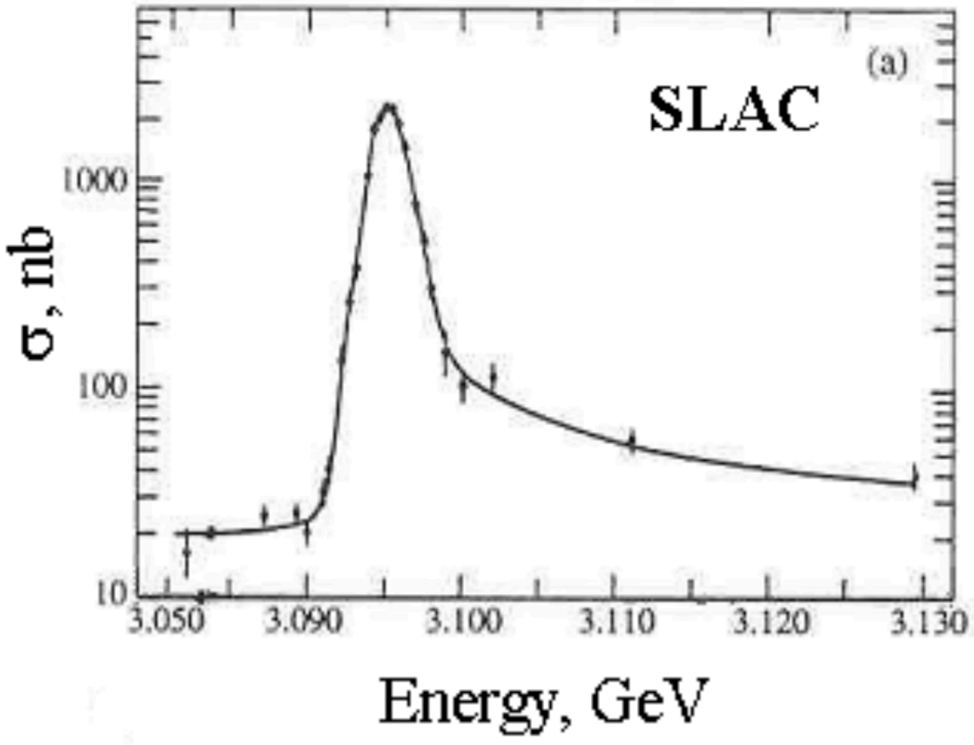
More LECs come in as you go up in order...

Charmonium

November Revolution 1974
Simultaneous discovery of the (heavy) J/ψ at SLAC and BNL
Bound state of $|c\bar{c}\rangle$ $\rightarrow$ "Charmonium"
First evidence of the charm quark.
Strong confirmation of the quark model
Discovery of $\psi(2S) \rightarrow J/\psi(e^+e^-)\pi^+\pi^-$ soon followed

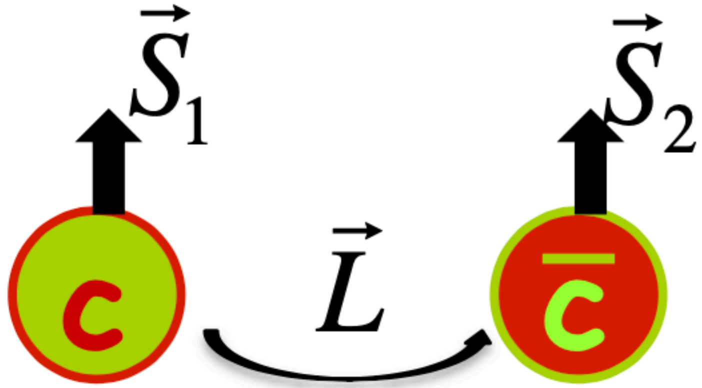






Charm quarks are very heavy, and therefore not relativistic
Unlike the lighter quarks u, d, s

Charmonium Properties



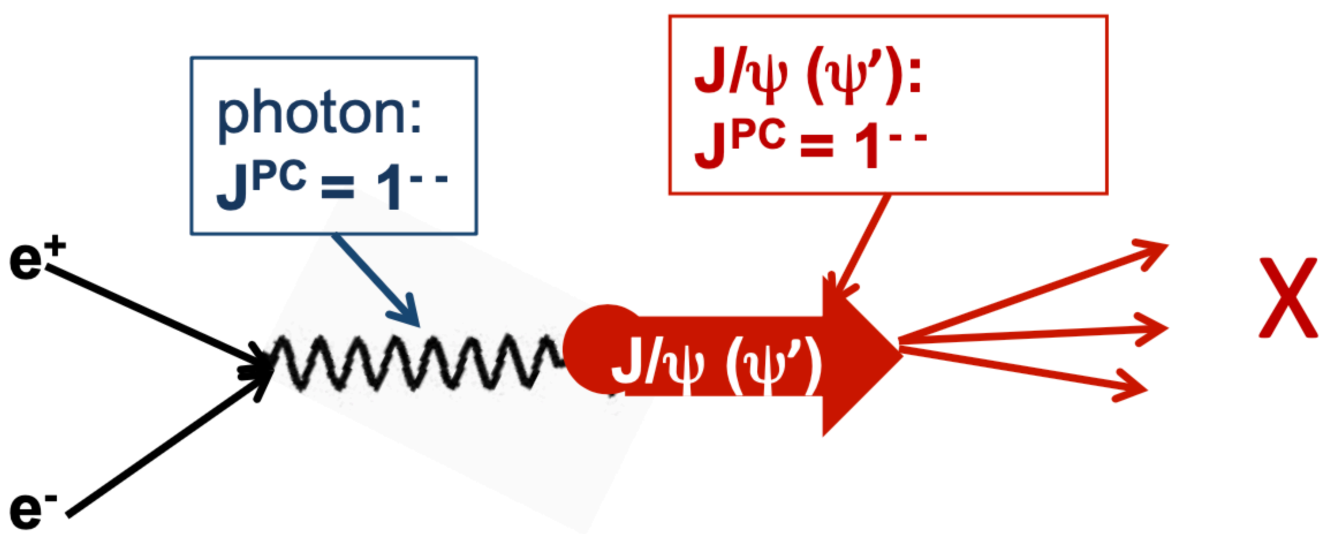
J/ψ has the same J^{PC} as the photon, 1^{--}

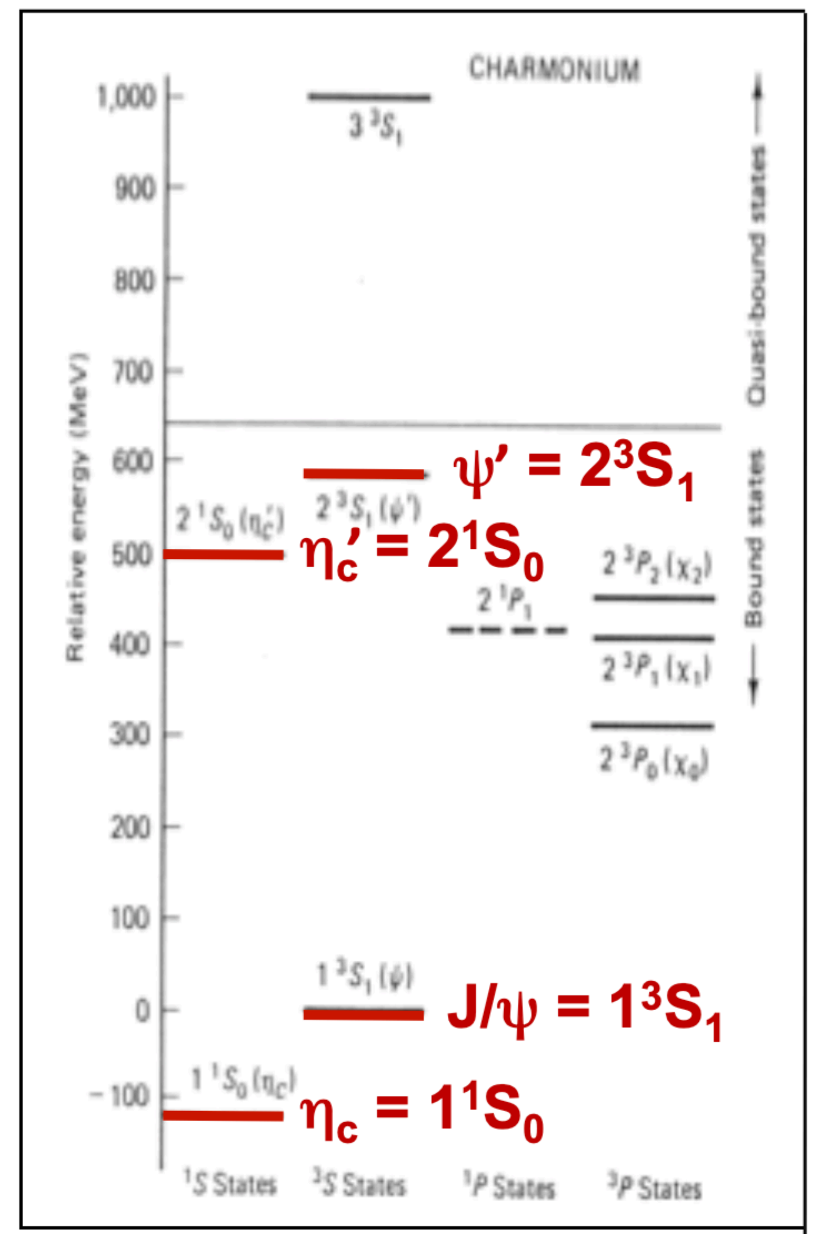
$$n^{2S+1}L_J$$

Very similar to the spectroscopic notation for electron orbitals

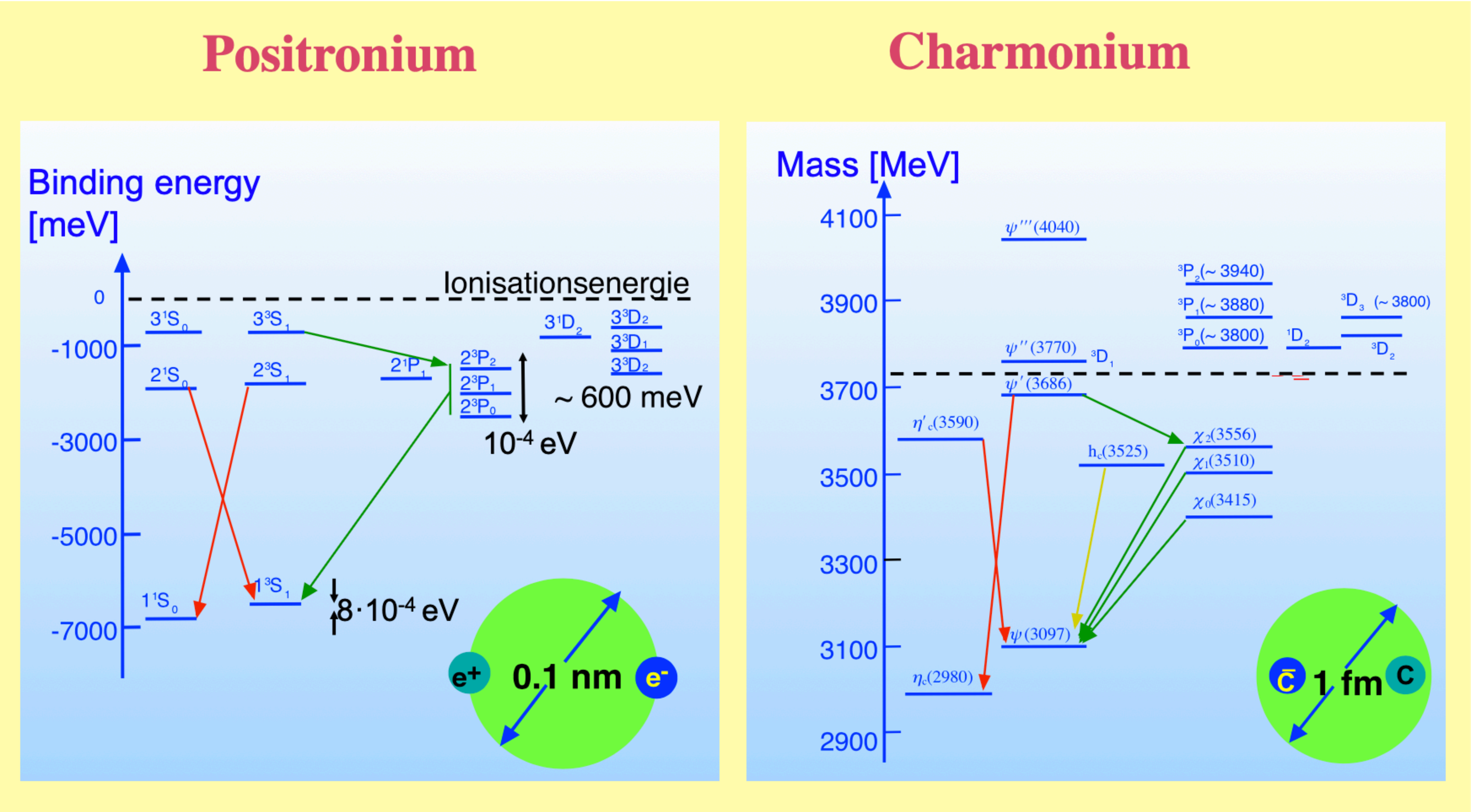
$$\vec{S} = \vec{S}_1 + \vec{S}_2$$
$$\vec{J} = \vec{L} + \vec{S}$$
$$P = (-1)^{L+1}$$
$$C = (-1)^{L+S}$$

$S_1 = S_2 = 1/2$ so either $S = 0$ (singlet) or $S = 1$ (triplet)





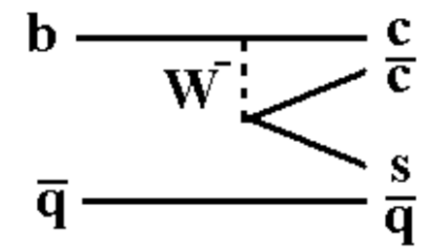
The positronium of QCD



Production of Charmonium

Colour suppressed $b \to c$ decay

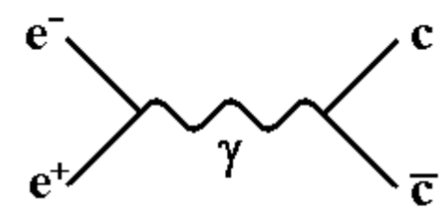
- Predominantly from B-meson decays

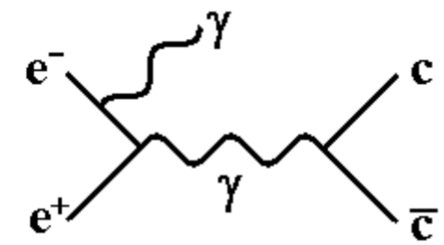


BELLE

e^+e^- annihilation / Initial-State Radiation (ISR)

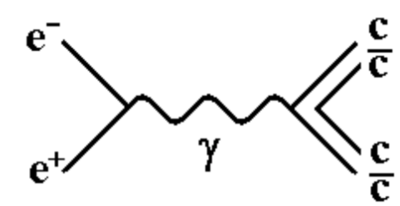
- e^+e^- collision below nominal c.m. energy
- $J^{PC} = 1^{--}$





Double charmonium production

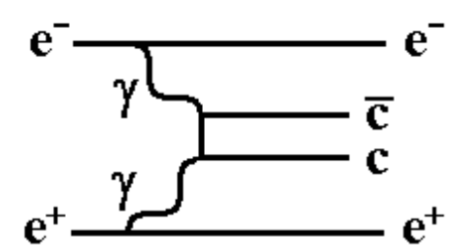
- Typically one J/ψ or ψ plus 2nd $c\bar{c}$ state



BESIII

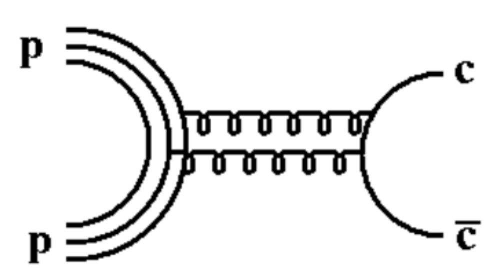
Two photon production

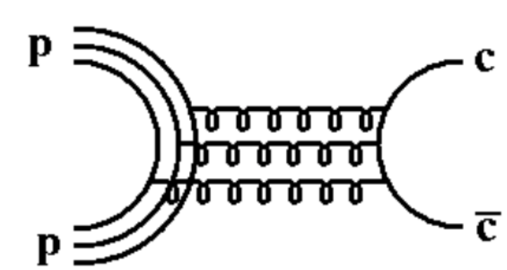
- Access to $C = +1$ state



$p\bar{p}$ annihilation

- All quantum numbers available



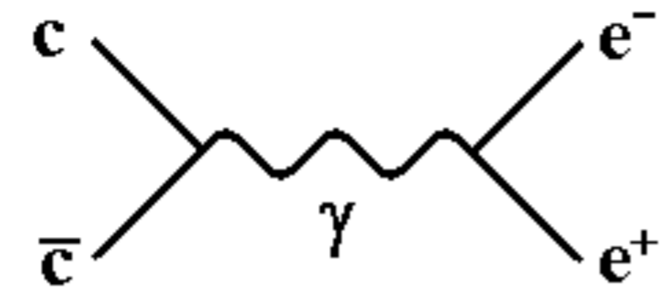


PANDA

Decay of Charmonium

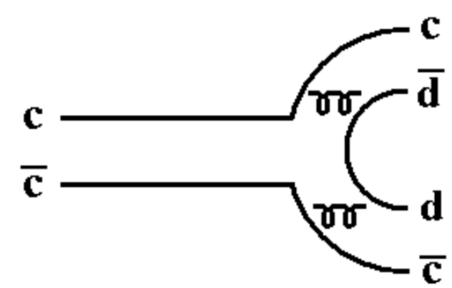
Annihilation:

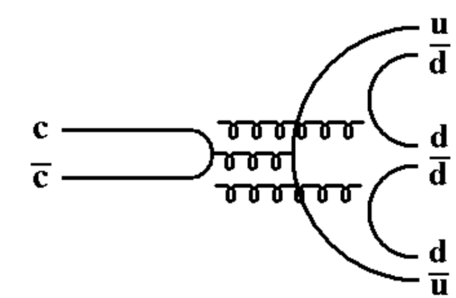
- Generally suppressed for bound state
- Decay to leptons is a clean experimental signal



Strong interaction:

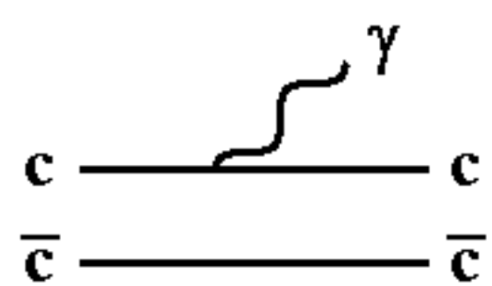
- Dominant above ~3.72 GeV (D mesons)
- Suppressed below this mass threshold

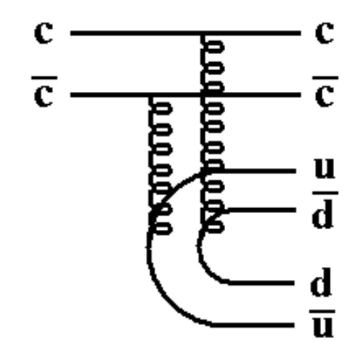




Radiative:

- EM radiative transition emitting photon
- Emit gluons producing light quarks





Features:

- Suppression of strong decays leads to (relatively) long lifetimes, narrow widths
- Radiative decays are competitive; often most accessible transitions

Charmonium

One set of hadrons that are particularly simple are the charmonium mesons

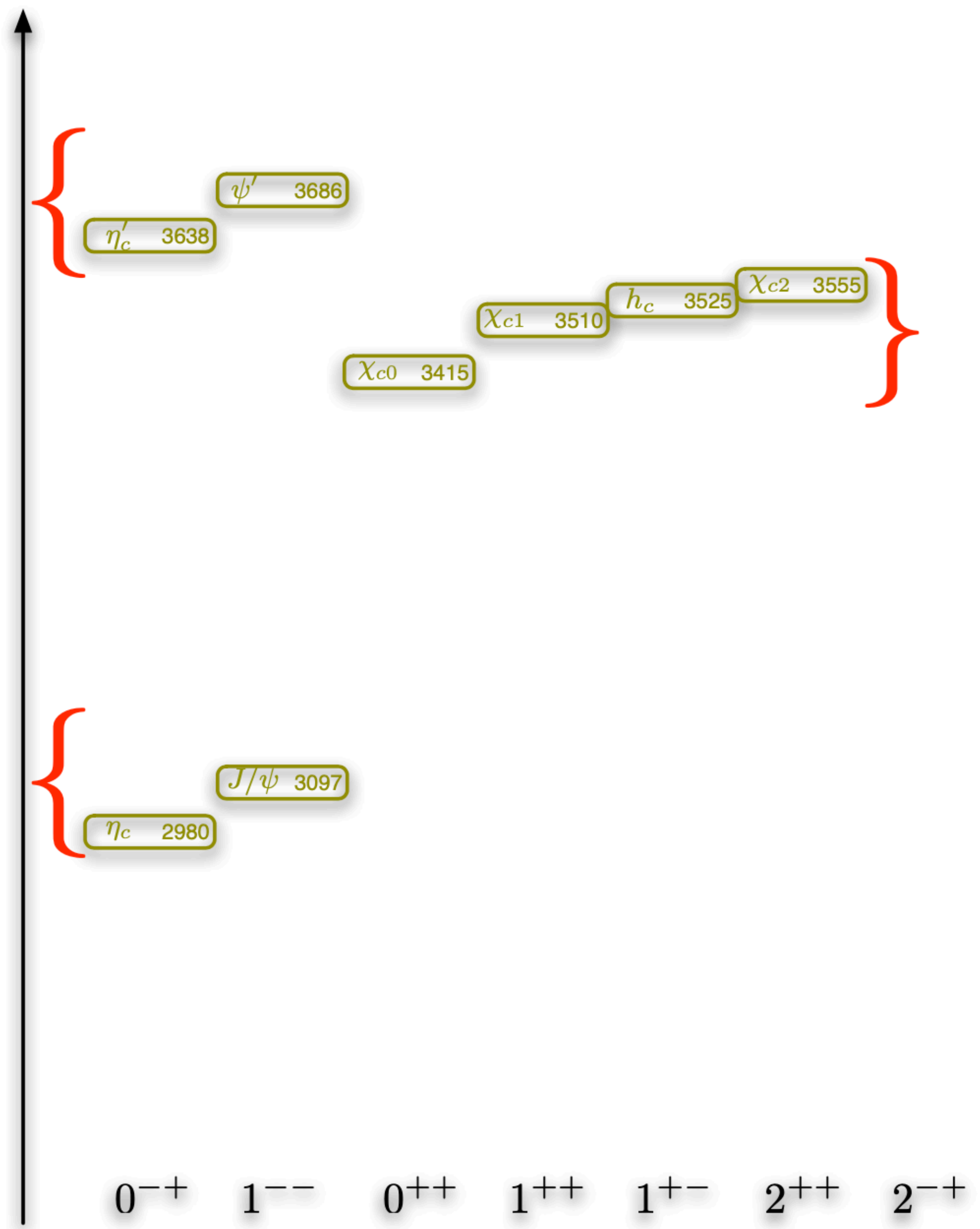
Each box represents an observed particle

Particles fall in groups - ‘gross structure’ splitting within a group - ‘fine structure’ reminds us of quantum mechanics of atoms

A reasonable description of the spectrum of charmonium comes from solving the Schrödinger equation assuming a potential between a charm quark and an anti-charm quark

$$m_n = 2m_c + E_n$$

$$\frac{1}{m_n}\nabla^2\psi + V(r)\psi = E_n\psi$$



XYZ States

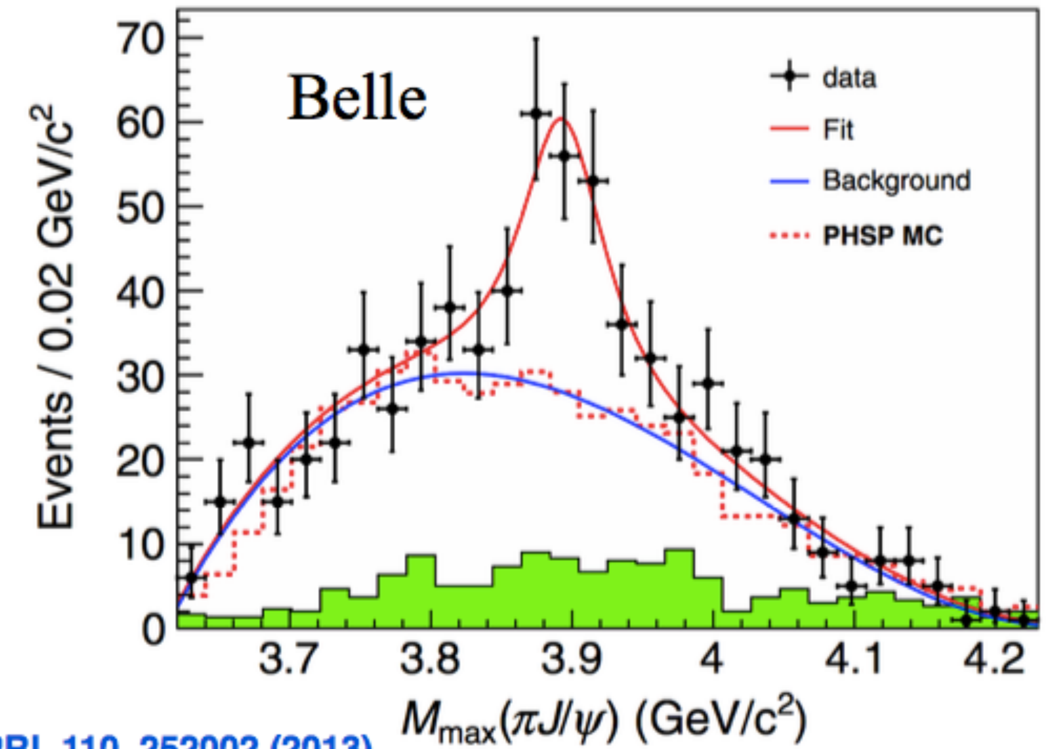
Recent evidence for *non-standard* exotic heavy mesons.

The so called ***XYZ* states**.

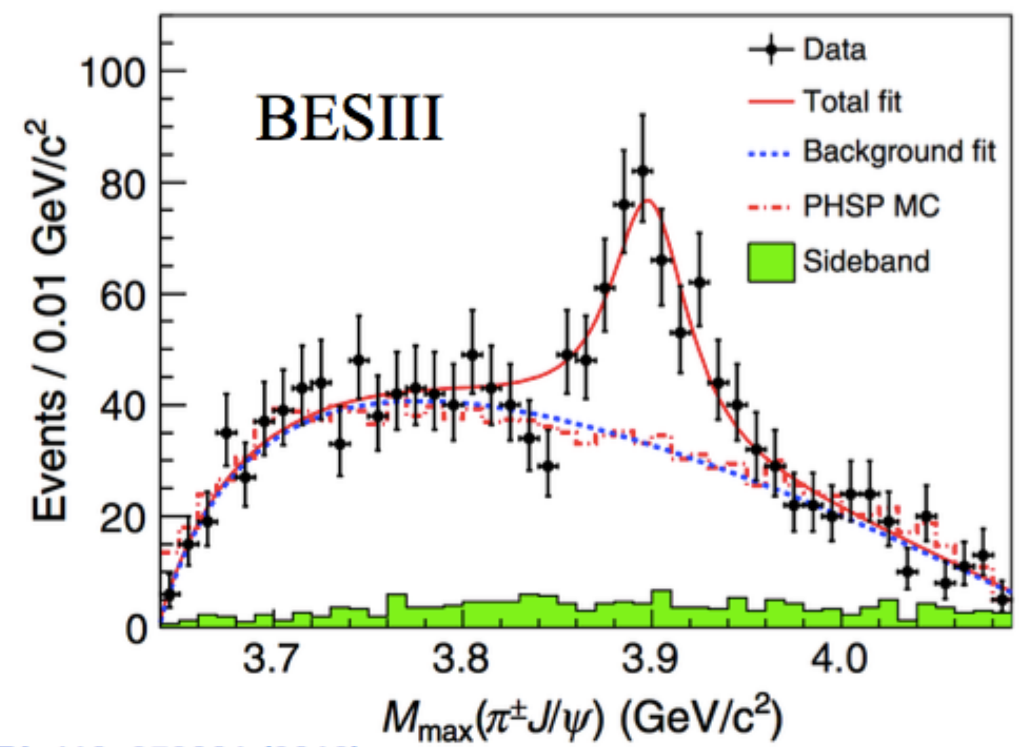
- ***Y* states:** same quantum numbers as the photon. $J_{PC} = 1^{--}$
- ***Z* states:** all exotic charge states. Decay into quarkonium state and a light charged meson.
- ***X* states:** all other neutral states with quantum numbers NOT $J_{PC} = 1^{--}$

Charmonium structure discovered at Belle and observed at both BESIII and LHCb in the decay of the $\Upsilon(4260)$, given the name $X(3872)$.

Superposition of exotic and conventional $c\bar{c}$ states??

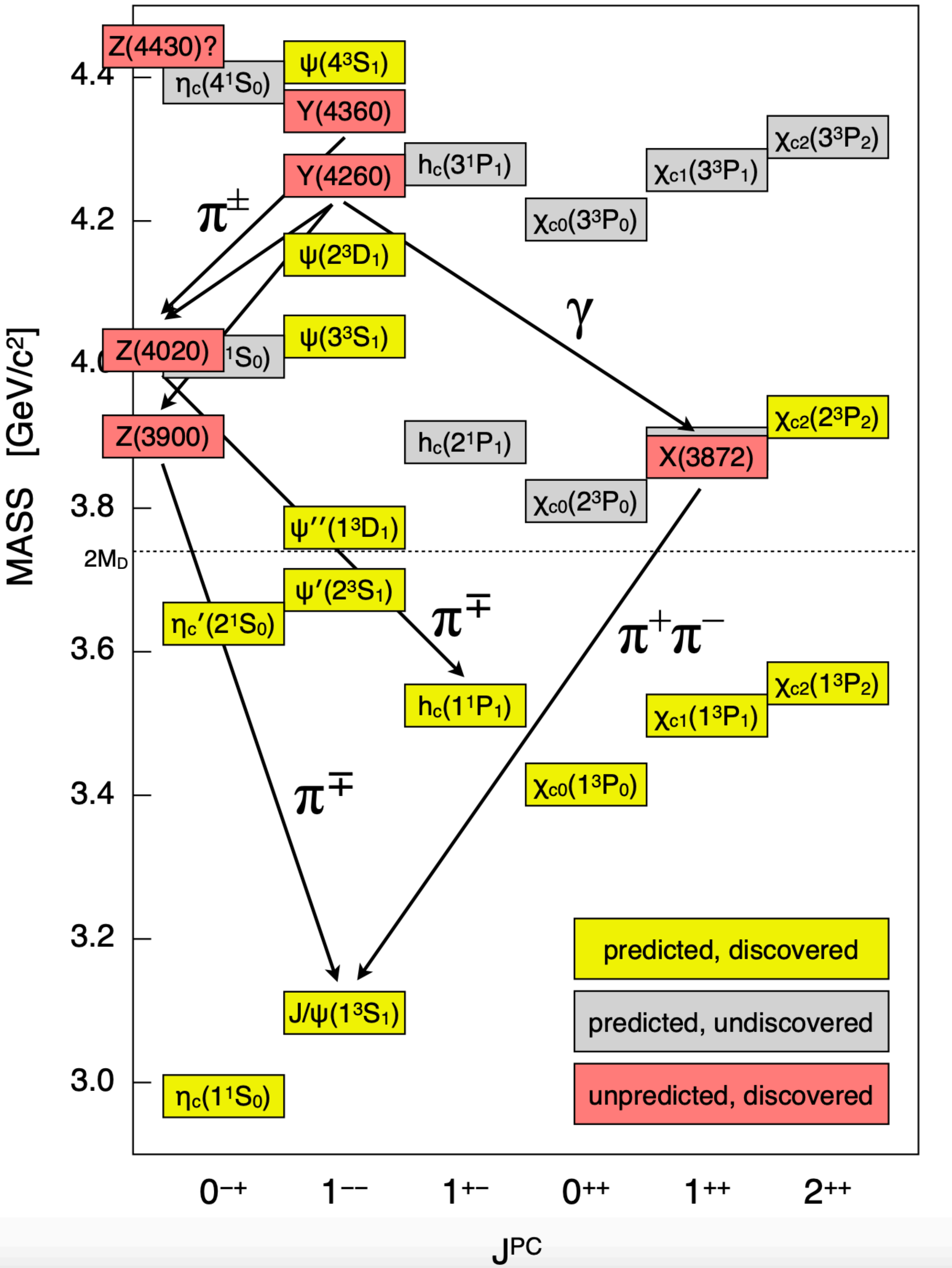


PRL 110, 252002 (2013)



PRL 110, 252001 (2013)

Charmonium States



The quark model describes most of charmonium remarkably well.

But the XYZ states point beyond the quark model.

BESIII can directly produce the Y(4260) and Y(4360) in e+e− annihilation.

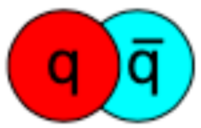
BESIII has observed “charged charmoniumlike structures” — the Zc(3900) and the Zc!(4020).

BESIII has also observed a transition to the X(3872).

Possible Hadrons

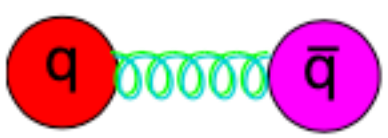
QCD does not explicitly require only 2- and 3-quark states. Anything that is colourless is fair game.

Totalitarian Principle: Anything that isn't forbidden is compulsory.



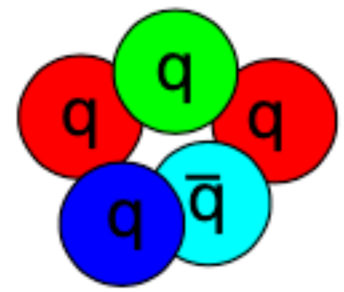
$q\bar{q}$ Meson

qqq Baryon

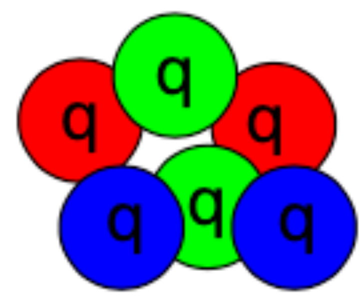


$q\bar{q}g$ Hybrid

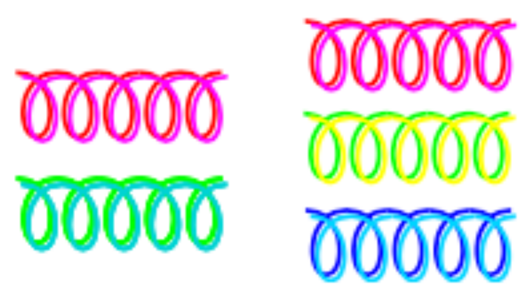
$q\bar{q}q\bar{q}$ Tetraquark



$qqqq\bar{q}$ Pentaquark



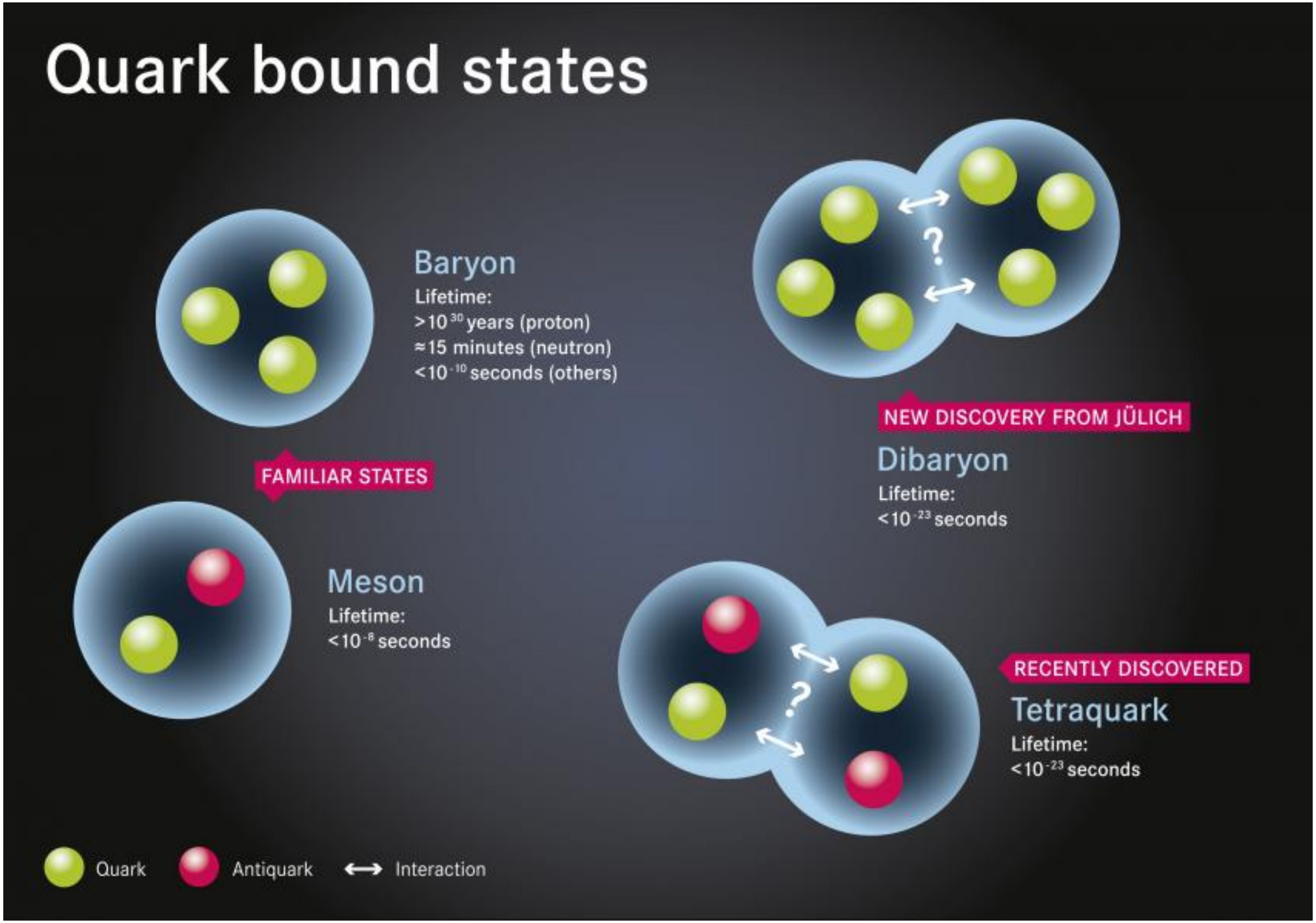
$qqqqqq$ Dibaryon
$qqq\overline{qqq}$



$g\bar{g}$, ggg Glueballs

A new "zoo" of exotic mesons is possible!

Exotic Hadrons

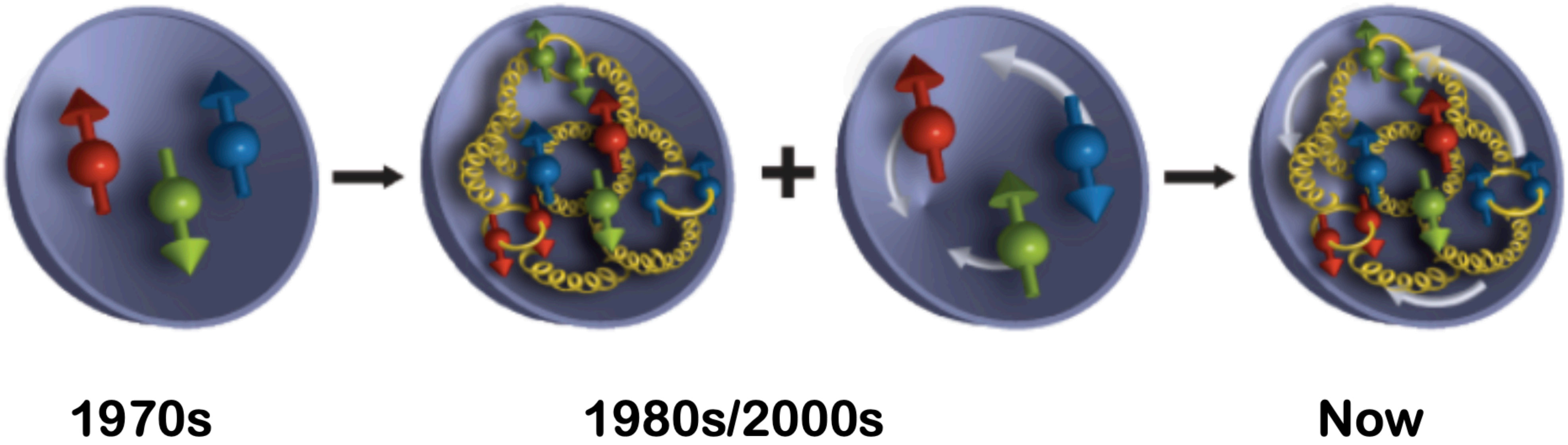


Many interesting questions about exotic mesons and other higher-energy phenomena!

…but we still don’t fully our old friends the **nucleon** and the **pion**.

Hadron Structure

Evolving understanding of the proton.



Hadrons are strongly interacting, relativistic bound states of quarks and gluons.
Still lots of open questions, including mass, spin, etc.
Lots of work still to be done.

Gluons are very intriguing particles!

Massless, yet, responsible for nearly all visible mass.

Carry colour charge, responsible for colour confinement and strong force.

But, also for asymptotic freedom.

Motivation for the proposed Electron-Ion Collider (EIC).

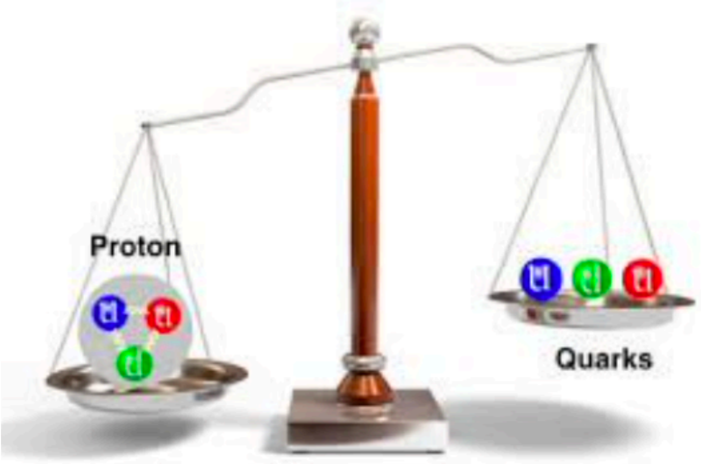
New facility with enormous Hadron Physics potential!

Scientific Motivation for the EIC

The EIC hopes to shed some light on **three important questions:**

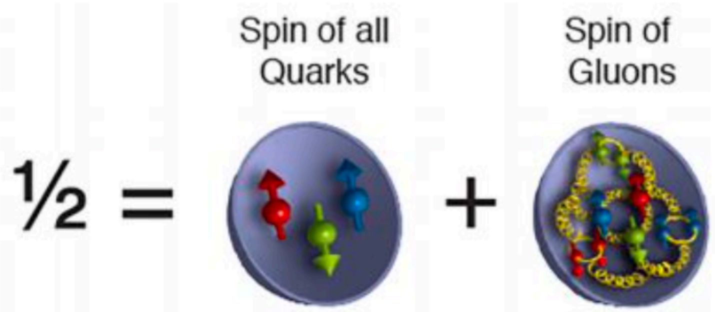
1. How does the **mass of the nucleon** arise?

   While the Higgs mechanism can explain all of the mass of the electron, it accounts for only a small part of the mass of the proton and neutron.



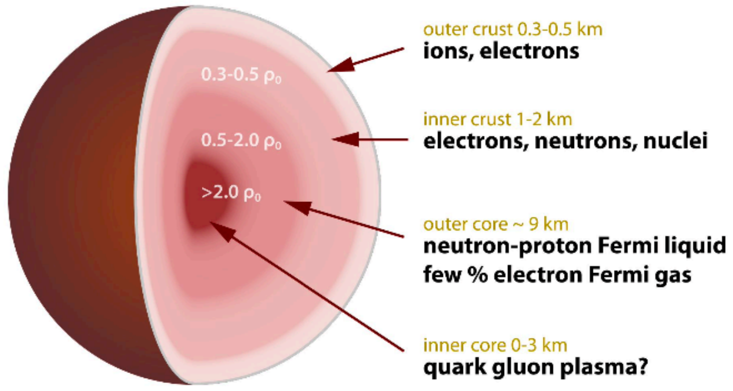
2. How does the **spin of the nucleon** arise?

   Three spin-1/2 quarks, bound by gluons, each with angular momentum, form a spin-1/2 proton.



3. What are the **emergent properties of dense systems of gluons**?

   How does nuclear matter behave at extremely high densities found in astrophysical systems?



Emergent Dynamics in QCD

Quarks and gluons are kind of a big deal…

Massless gluons, and almost massless quarks, through their interactions generate most of the mass of the nucleons.

Gluons carry 50% of the proton's momentum, a significant fraction of the nucleon's spin, and are essential for the dynamics of confined partons.

Properties of hadrons are emergent phenomena, resulting not only from the equation of motion but are also inextricably tied to the properties of the QCD vacuum. Striking examples besides confinement are spontaneous symmetry breaking and anomalies.

The nucleon-nucleon forces emerge from quark-gluon interactions — *how this occurs remains a mystery…*

Experimental insight and guidance are crucial for complete understanding of how hadrons and nuclei emerge from quarks and gluons.

Proton Mass $m_p \approx 938$ MeV/c^2

Proton constituents: $2\ u$ quarks $\rightarrow$ 2×3 MeV/c^2 ≈ 6 MeV/c^2

$1\ d$ quark $\rightarrow$ 1×6 MeV/c^2 ≈ 6 MeV/c^2

Total quark mass in proton: 12 MeV/c^2 !

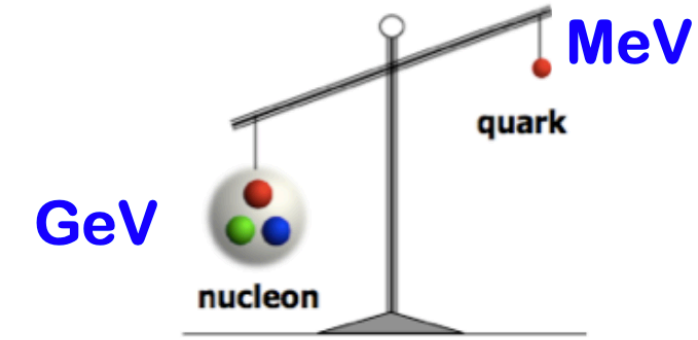
Where does the proton's mass come from?!

It's incorporated in the binding energy associated with the gluons!

99% of our mass comes from the quark-gluon interactions in the nucleon.

VERY COMPLEX SYSTEM!

Understanding Nucleon Mass



Relativistic motion

χ symmetry breaking

Quantum fluctuation

$$M = \overbrace{E_q + E_g} + \chi m_q + T_g$$

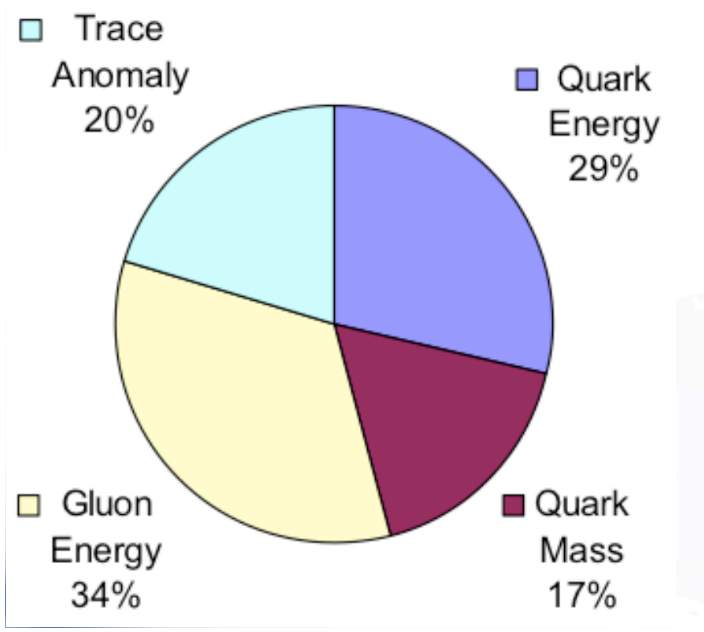
Trace anomaly

Quark energy

Gluon energy

Quark mass

Preliminary Lattice Results



"... The vast majority of the nucleon's mass is due to quantum fluctuations of quark- antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. ..."

The DOE 2015 Long Range Plan for Nuclear Science

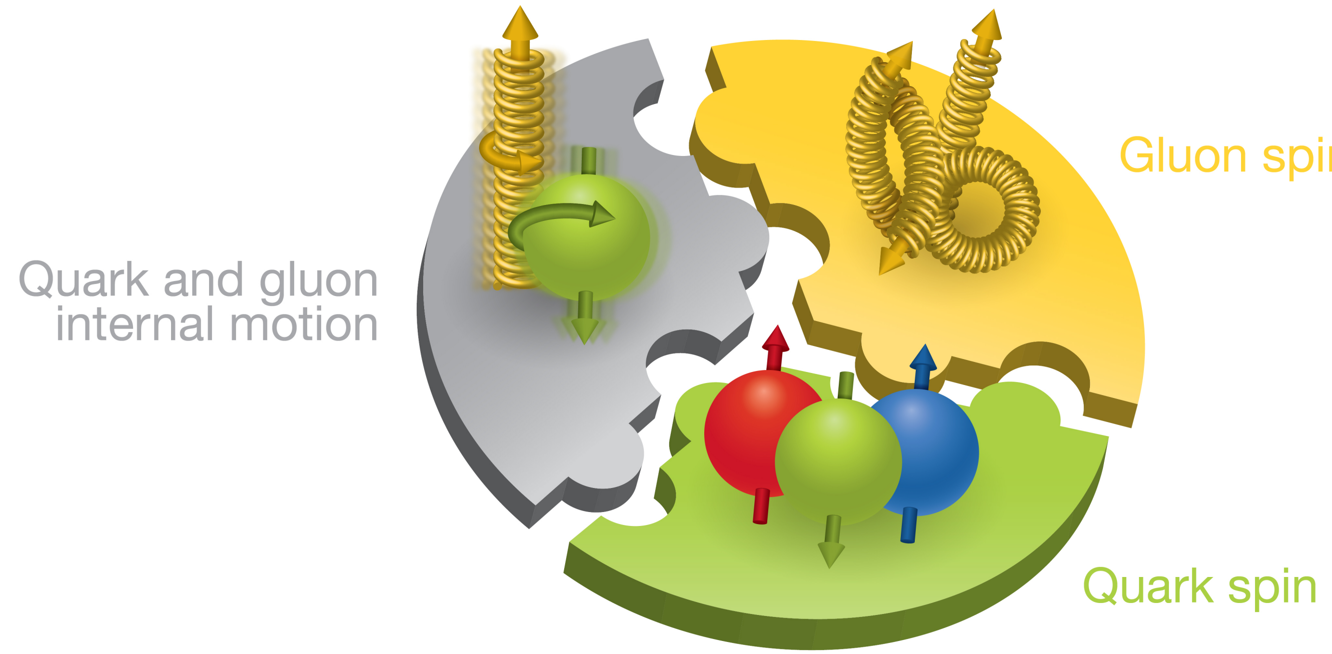
EIC:

- Trace anomaly via Υ production near threshold
- Quark-Gluon energy from q-g momentum fractions

Proton Spin

"Helicity sum rule"

$$\frac{1}{2} = \frac{1}{2}\underbrace{\Delta\Sigma}_{\text{quark spin}} + \underbrace{\Delta G}_{\text{gluon spin}} + \underbrace{\sum_q L_q^z + L_g^z}_{\text{orbital angular momentum}}$$



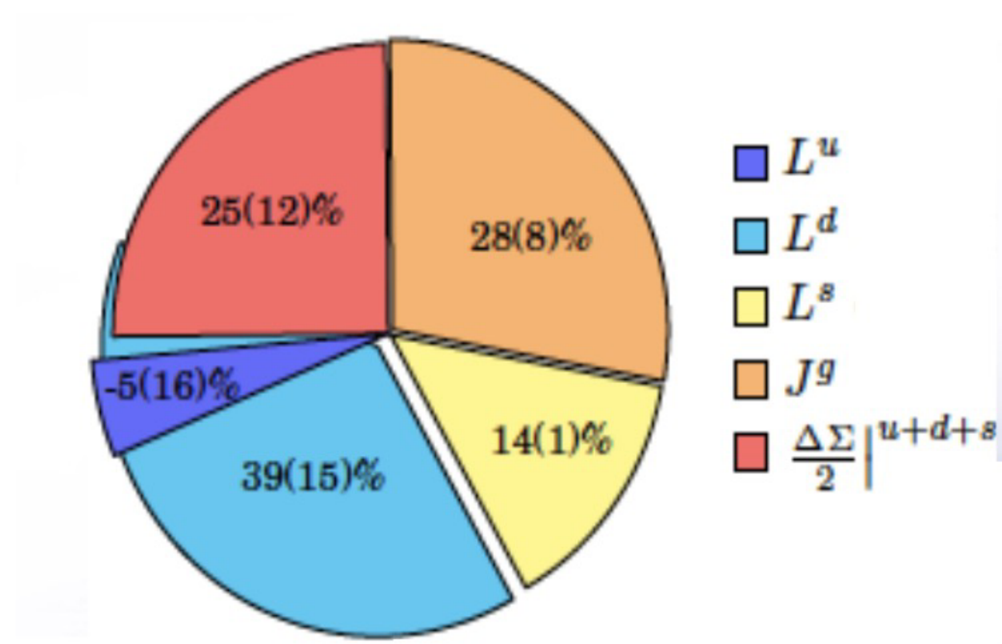
Spin and Lattice: Recent Activities

Gluon's spin contribution on Lattice: $S_G = 0.5(0.1)$

Yi-Bo Yang et al. PRL **118**, 102001 (2017) .

J_q calculated on Lattice QCD:

QCD Collaboration, PRD **91**, 014505 (2015).



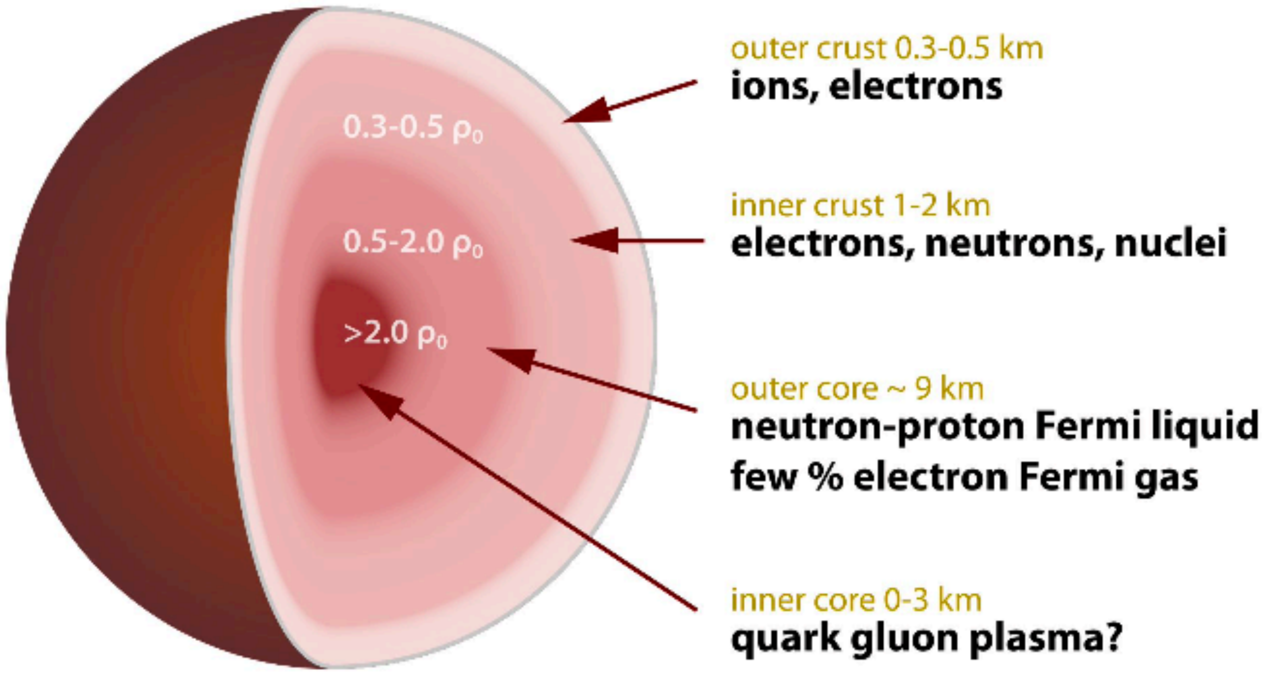
EIC:	Precise determination of polarized PDFs of quark sea and gluons. →	Precision $\Delta\Sigma$ and ΔG Magnitude of $\sum_q L_q^z + L_g^z$

Emergent Properties of Dense Systems of Gluons

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

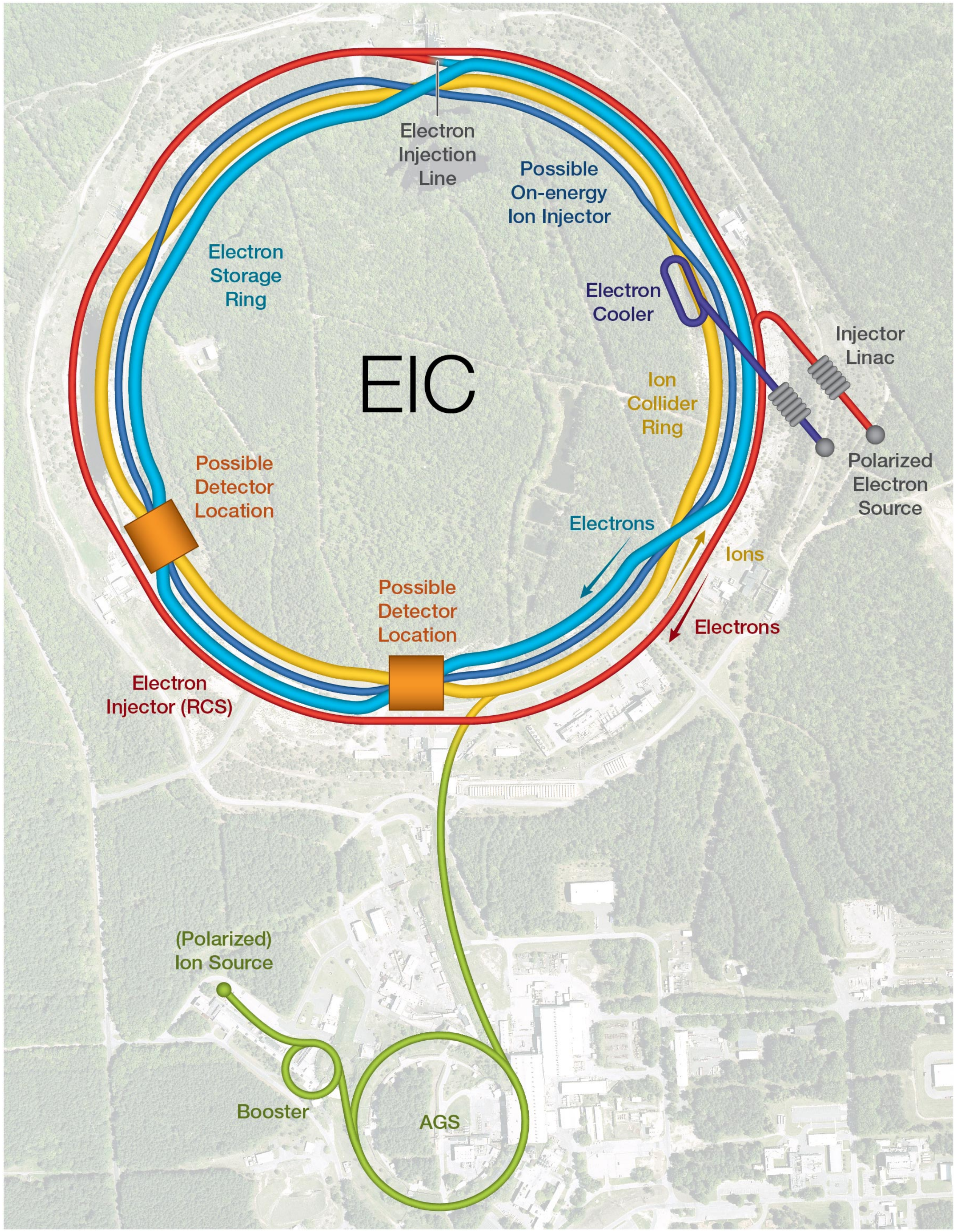
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

EIC:
C.M. energy
High luminosity



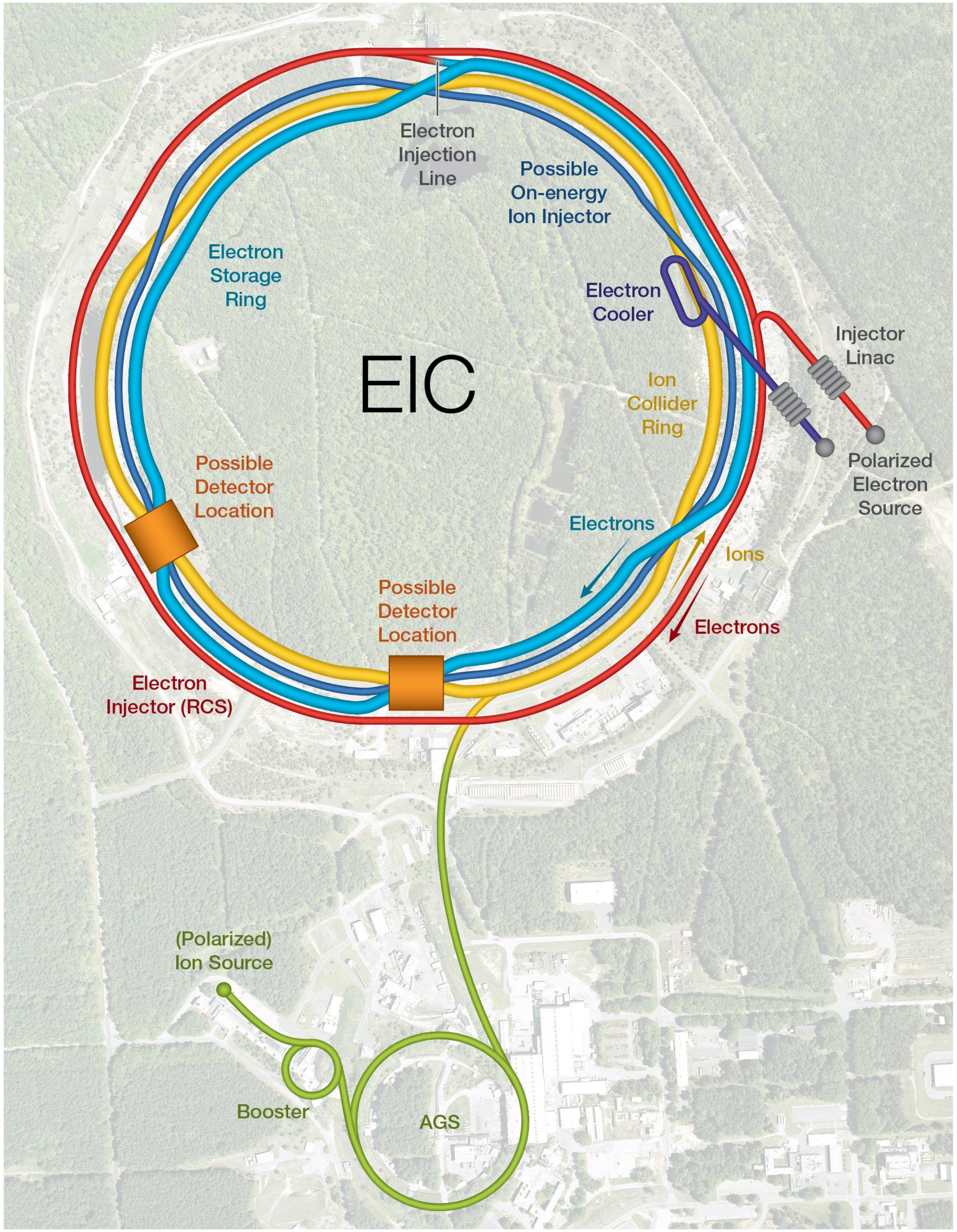
What is the Electron-Ion Collider?

- **First major collider** to be built in North America in the 21st century.
  - **Polarized electrons:** 10–20 GeV
  - **Polarized light ions:** (p, d, ^{3}He) and unpolarized nuclei → U, 50–250 GeV
  - C.M. energy of $\sqrt{s} = 28 - 140$ GeV
  - **High luminosity** $10^{33} - 10^{34}$ cm^{-2}s^{-1}
  - 2nd interaction region possible
- International facility with estimated cost of about US$2B
- Large community of 1000+ users at 220+ institutions in 30+ countries
- Site: BNL on Long Island, NY.

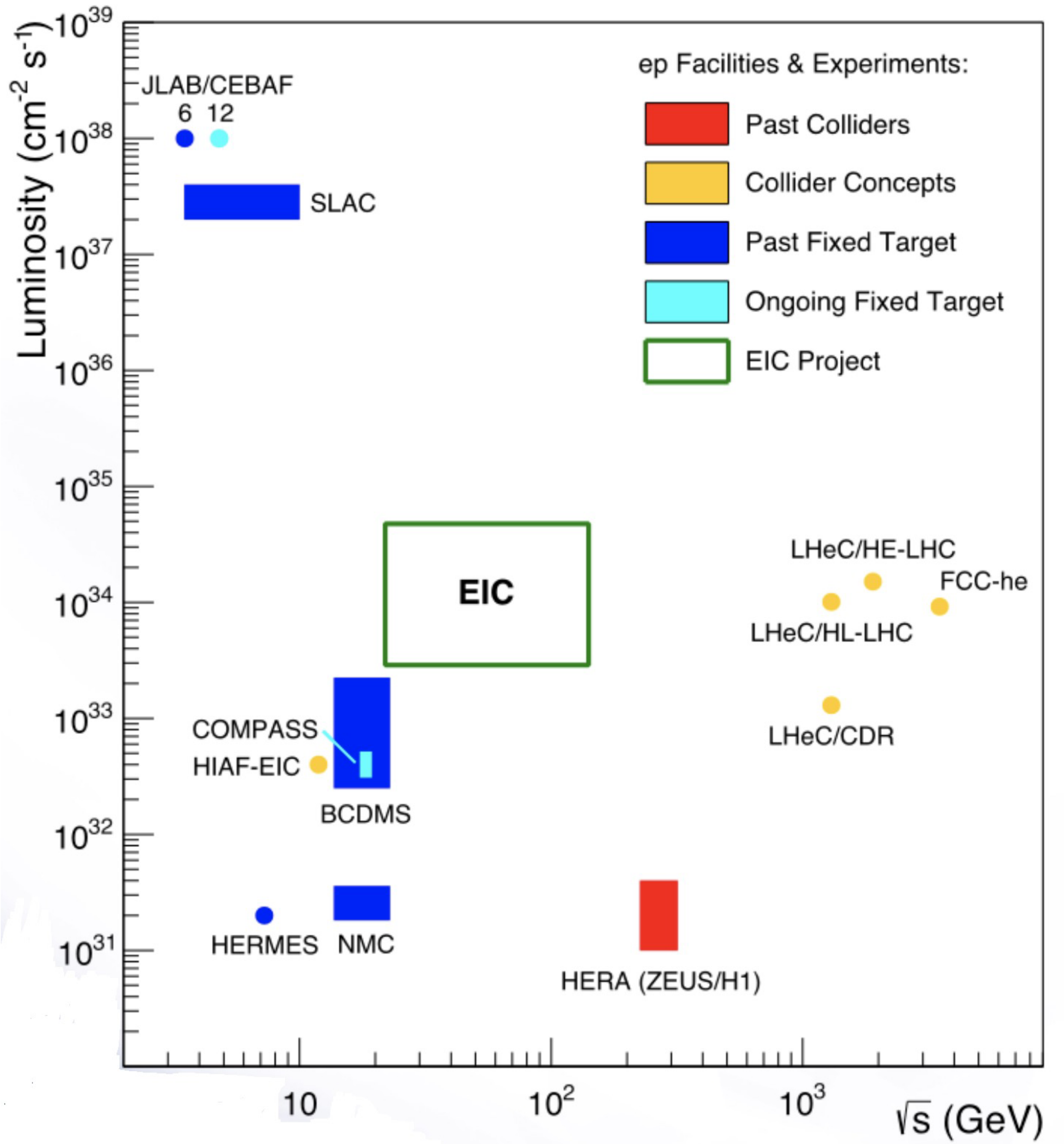


What is the Electron-Ion Collider?

- Make use of existing Relativistic Heavy Ion Collider (RHIC).
- Existing tunnel, detector halls, hadron injector complex (AGS).
- Build new 20-GeV electron linac and add high-intensity storage ring in same tunnel.
- Achieve high-luminosity, high-energy *e-p/A* collisions with full-acceptance detectors.
- High luminosity achieved by extensions of state-of-the-art beam cooling techniques.



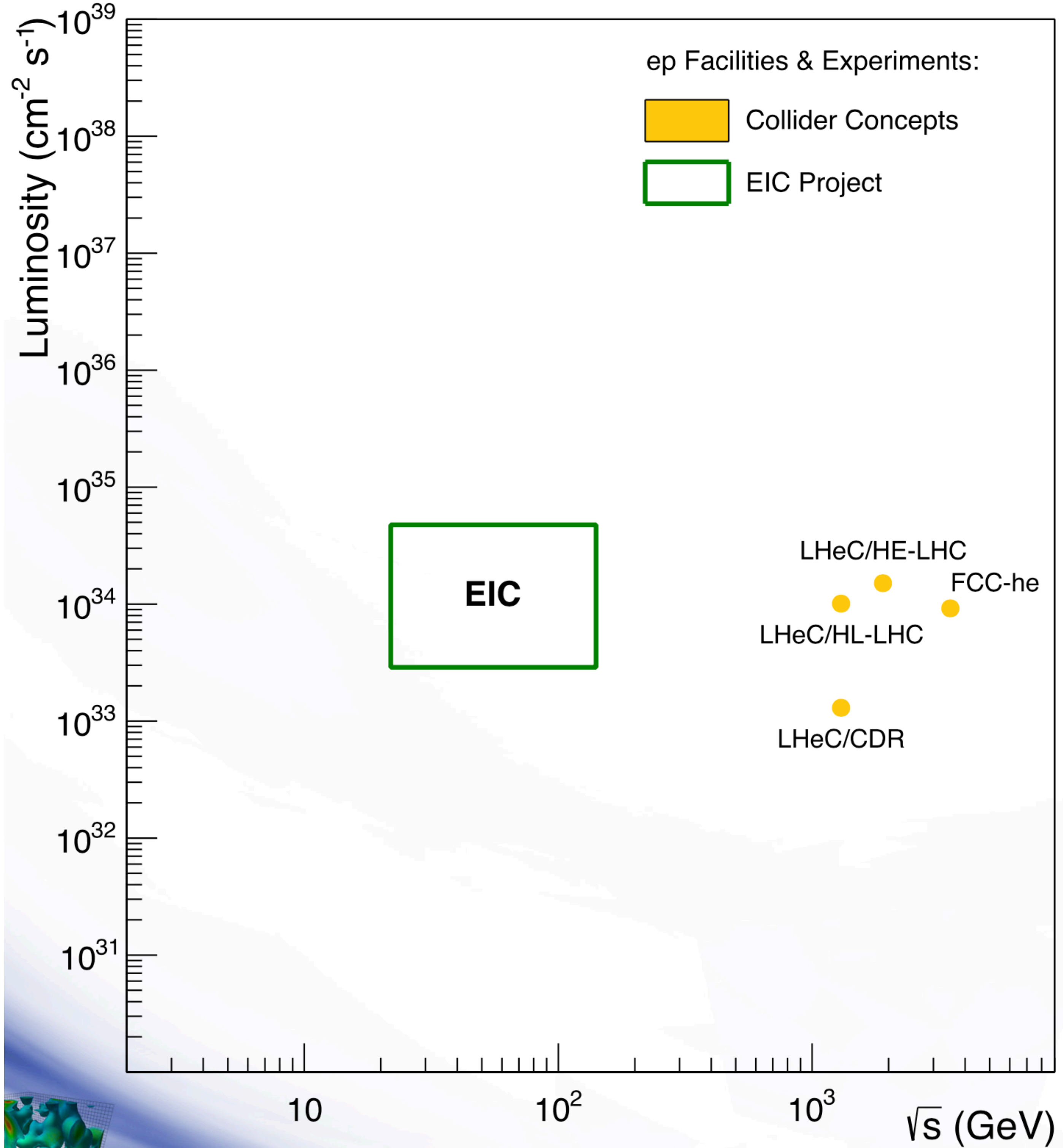
EIC Compared to other DIS Facilities



All DIS Facilities in the world.

DIS — Deep Inelastic Scattering

EIC Compared to other DIS Facilities



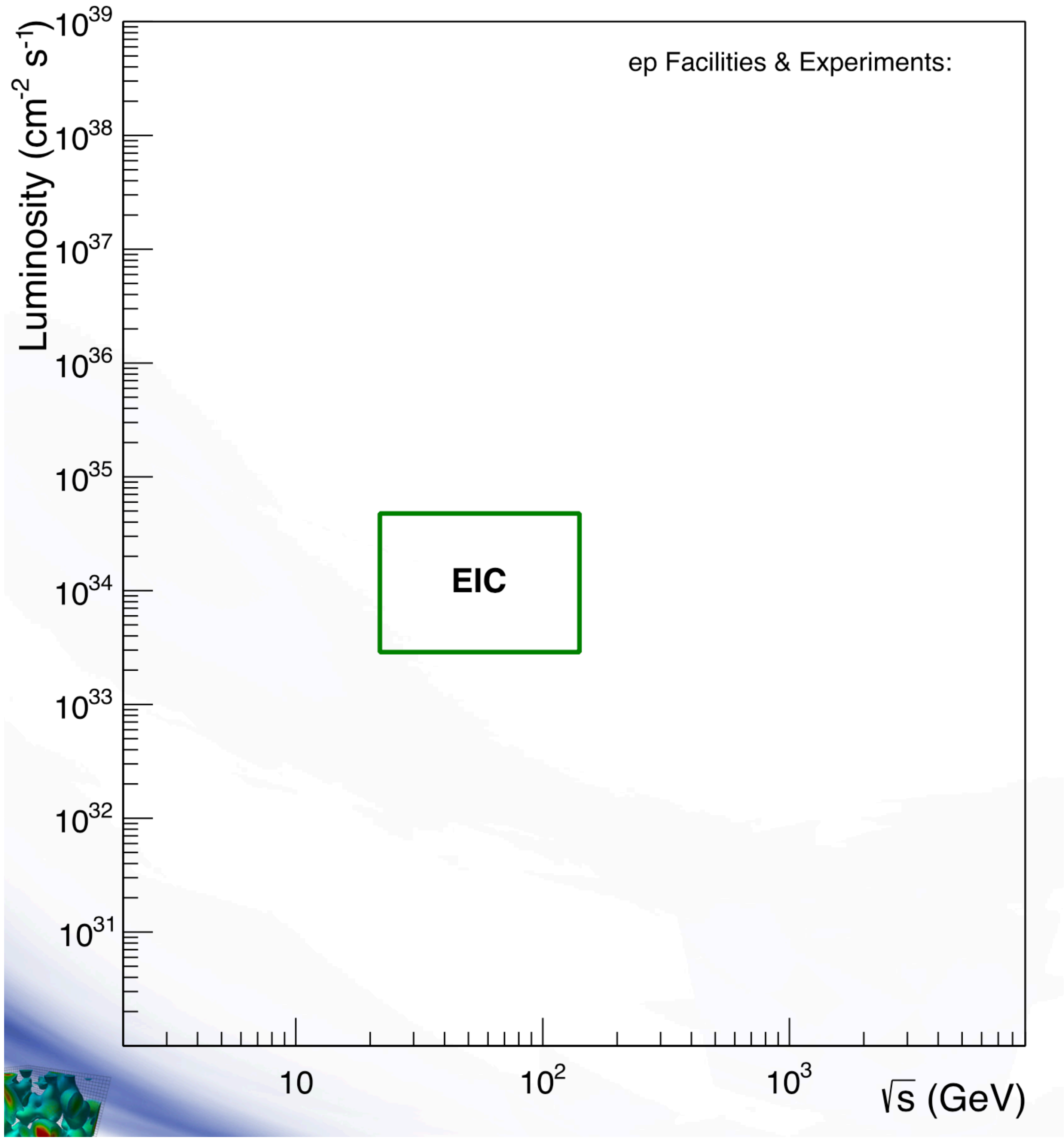
All DIS Facilities in the world.

However, if we ask for:

1. high luminosity and wide range of $\sqrt{s}$

DIS — Deep Inelastic Scattering

EIC Compared to other DIS Facilities



All DIS Facilities in the world.

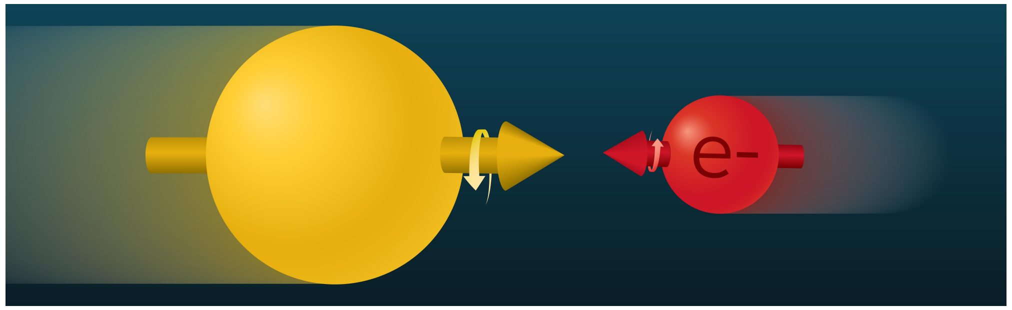
However, if we ask for:

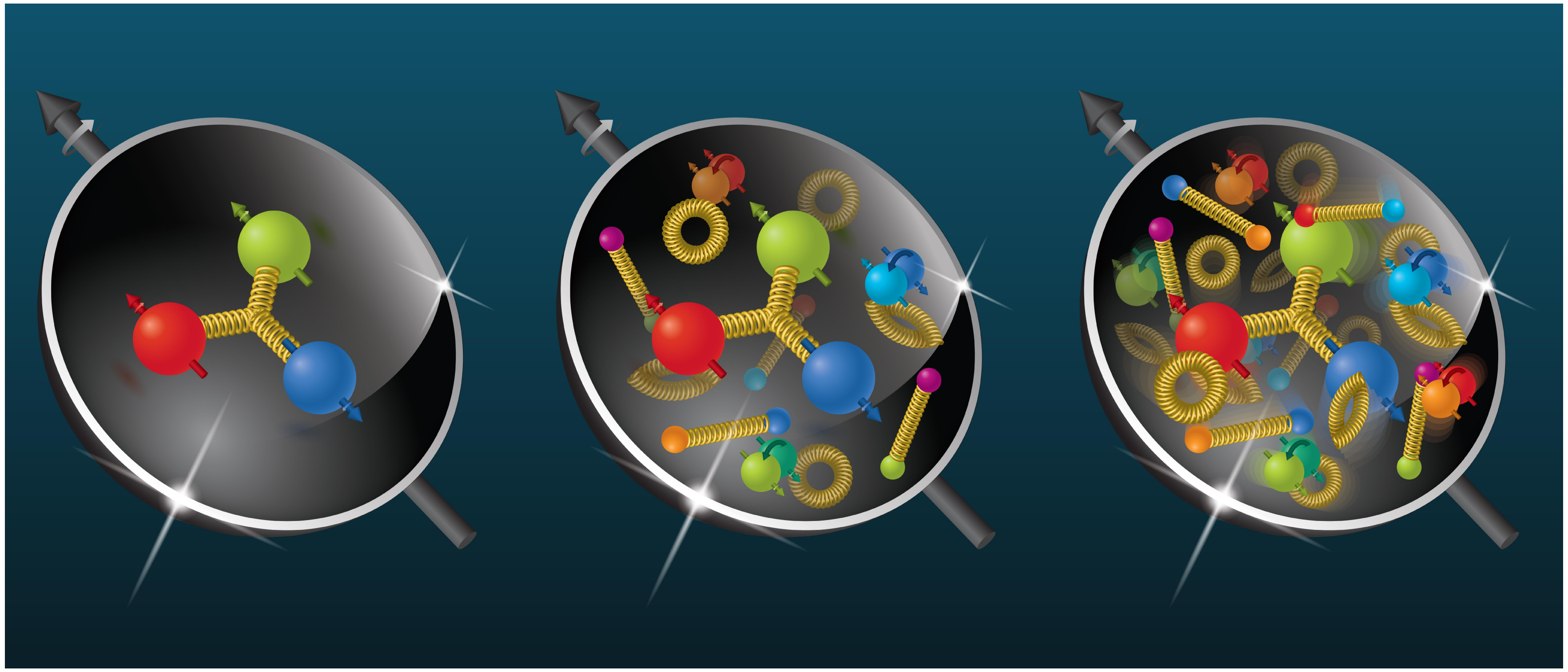
1. high luminosity and wide range of $\sqrt{s}$
2. polarized lepton and hadron beams
3. nuclear beams

EIC is unique!

DIS — Deep Inelastic Scattering

The World's First Polarized Electron-Proton Collider





Polarized proton as a laboratory for QCD

How are the sea quarks and gluons — and their spins — ***distributed in space and momentum*** inside the nucleon?

How do the ***nucleon properties emerge*** from them and their interactions?

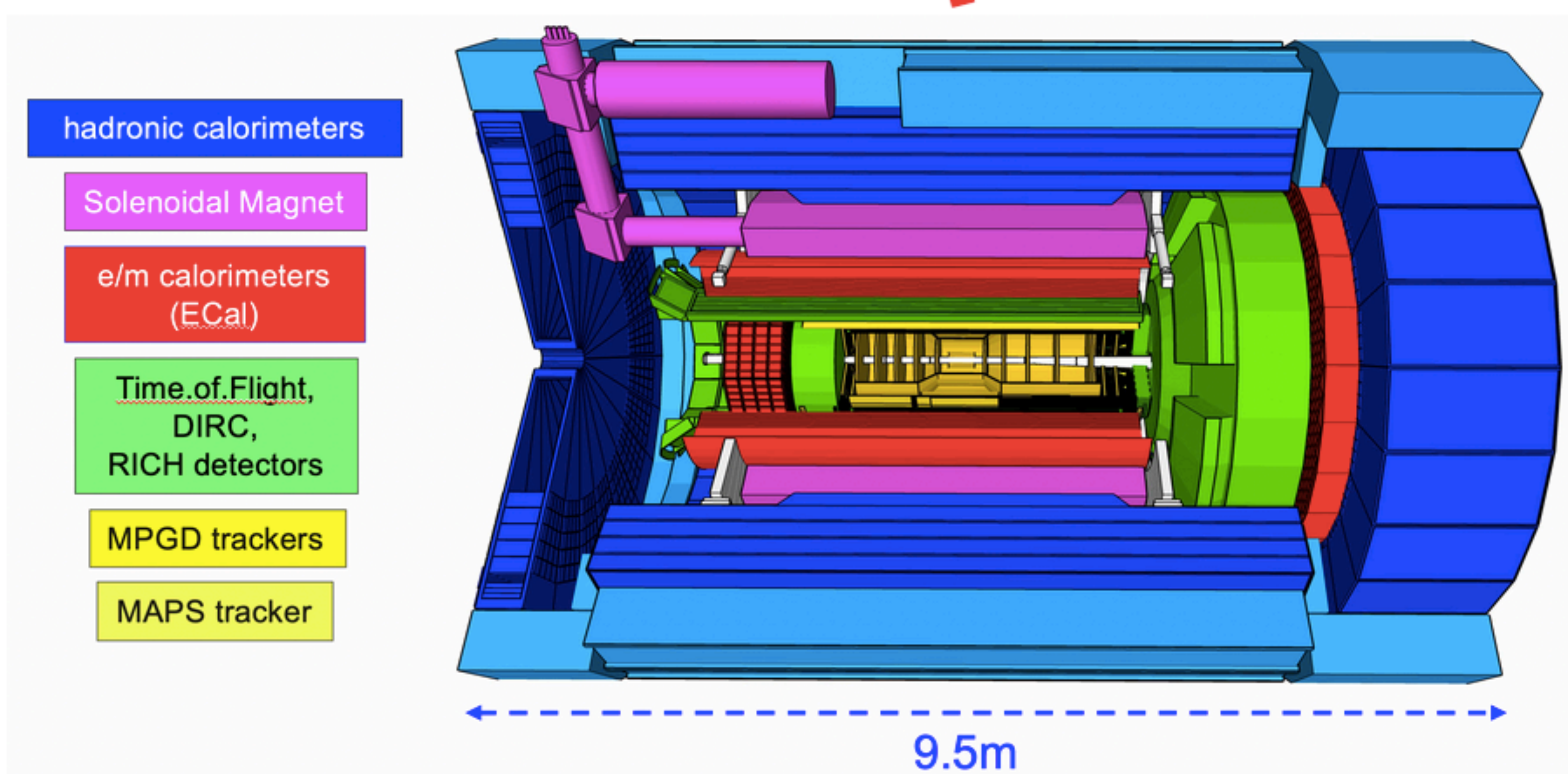
ePIC Detector for the EIC

ECCE + ATHENA = ePIC

Lepton Endcap

ePIC

Hadron Endcap



p/A Beam

e^- Beam

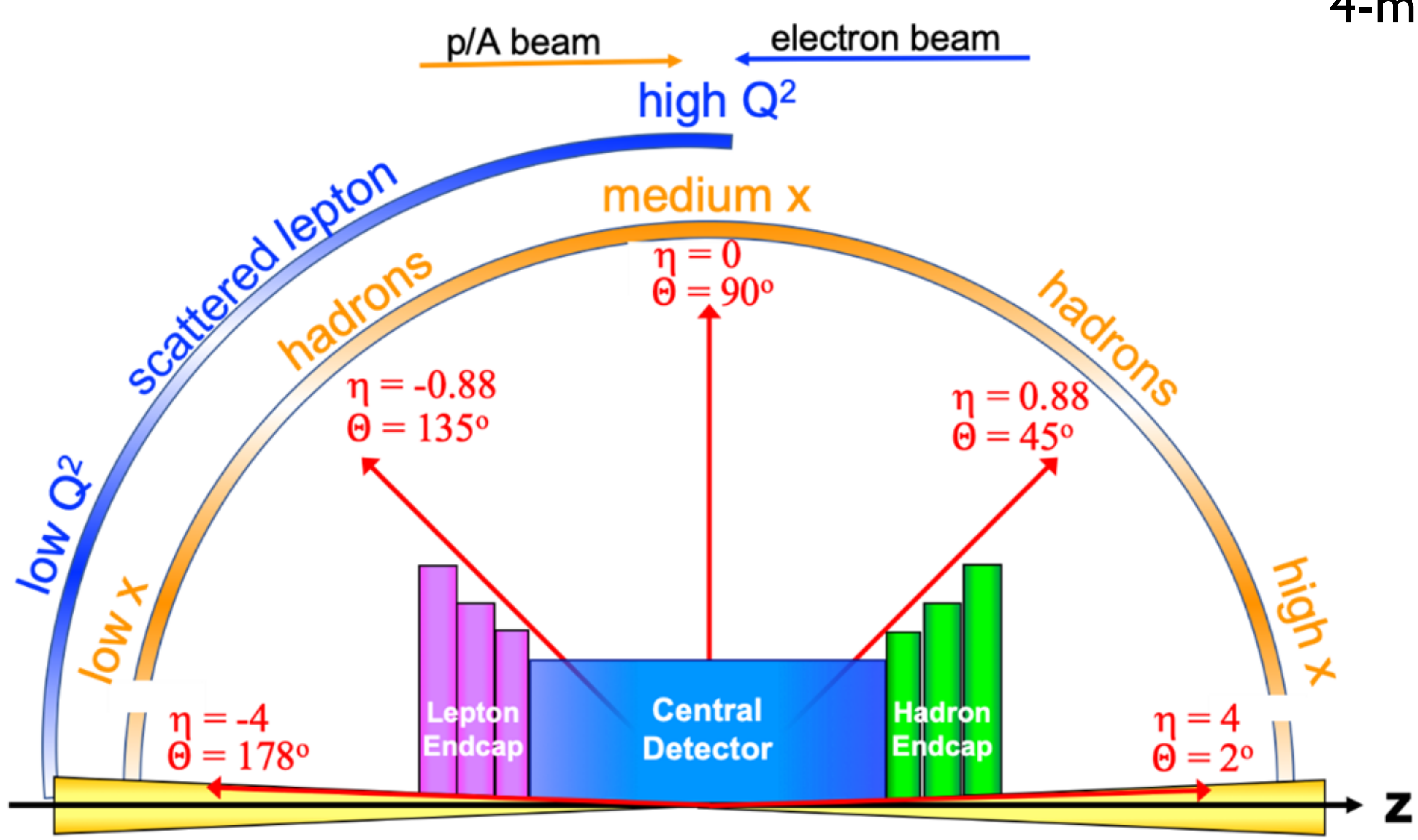
Calorimetry for the ePIC Detector

Electromagnetic calorimeter:

- Measure E, θ for photons and identify electrons.
- Backward: $PbWO_4$ Crystals
- Forward: W/SciFi
- Barrel: Pb/SciFi + Imaging

Hadronic calorimeter:

- Measure energy and position of charged hadrons, neutrons, and K_L^0
- Main challenge is resolution for low-E hadrons
- Fe/Scintillator sandwich with longitudinal segmentation



4-mom transfer of virtual photon

$$Q^2 = -q^2 = -(k-k')^2$$

Momentum fraction

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

Pseudo rapidity

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

Note: The Barrel has a very wide kinematic coverage!