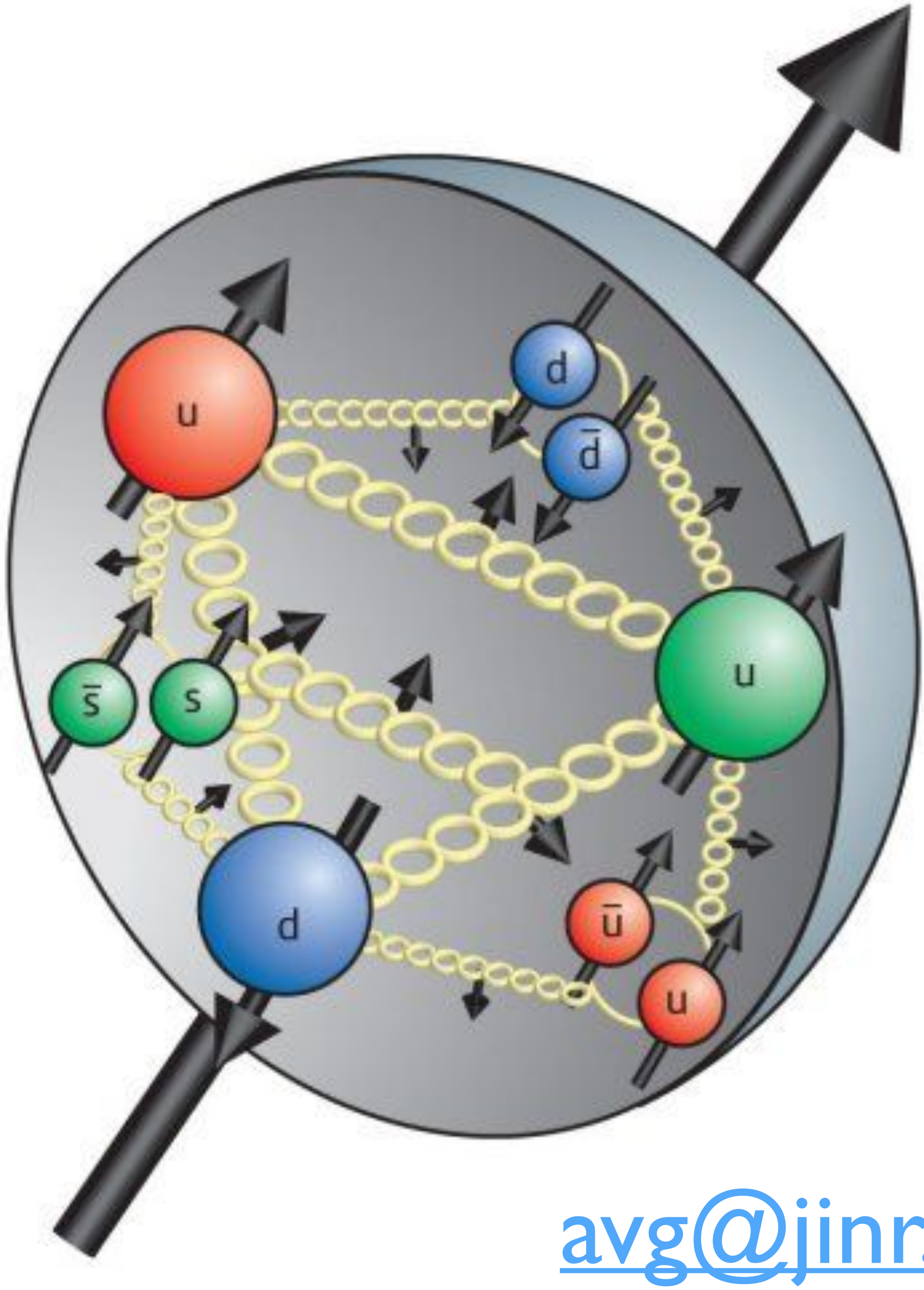
Modern concept of the nucleon structure

A. Guskov
DLNP, JINR



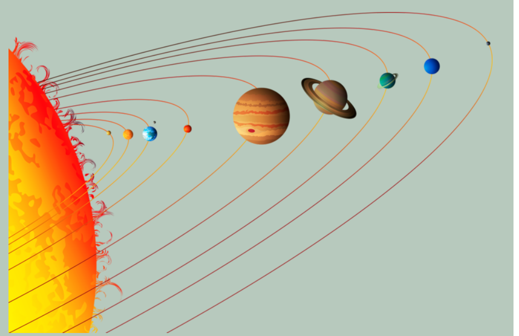
28th International Scientific
Conference of Young Scientists
and Specialists

avg@jinr.int

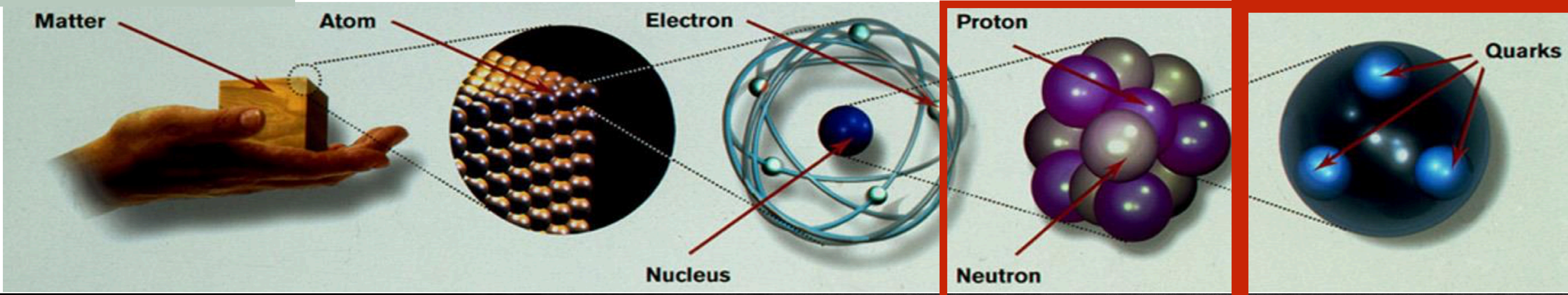
Fundamental interactions

Star systems

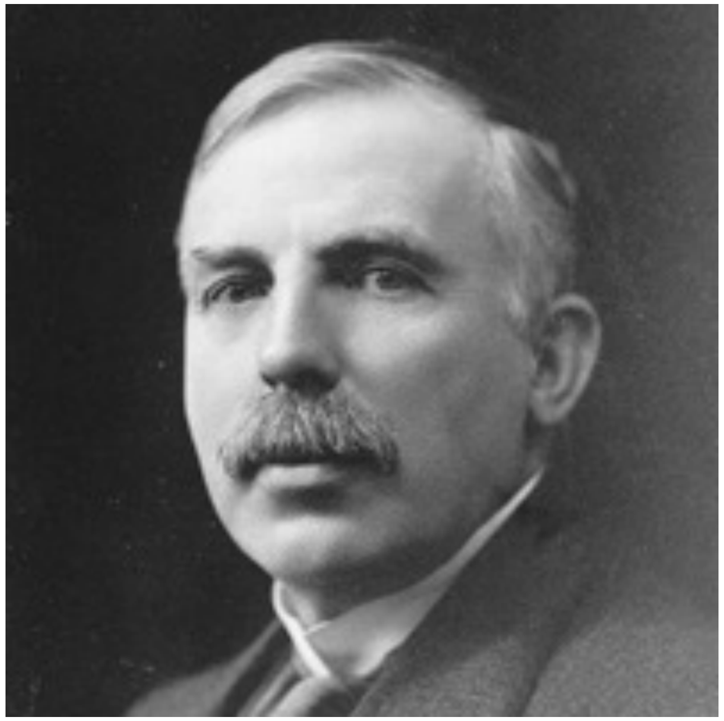
Planet systems



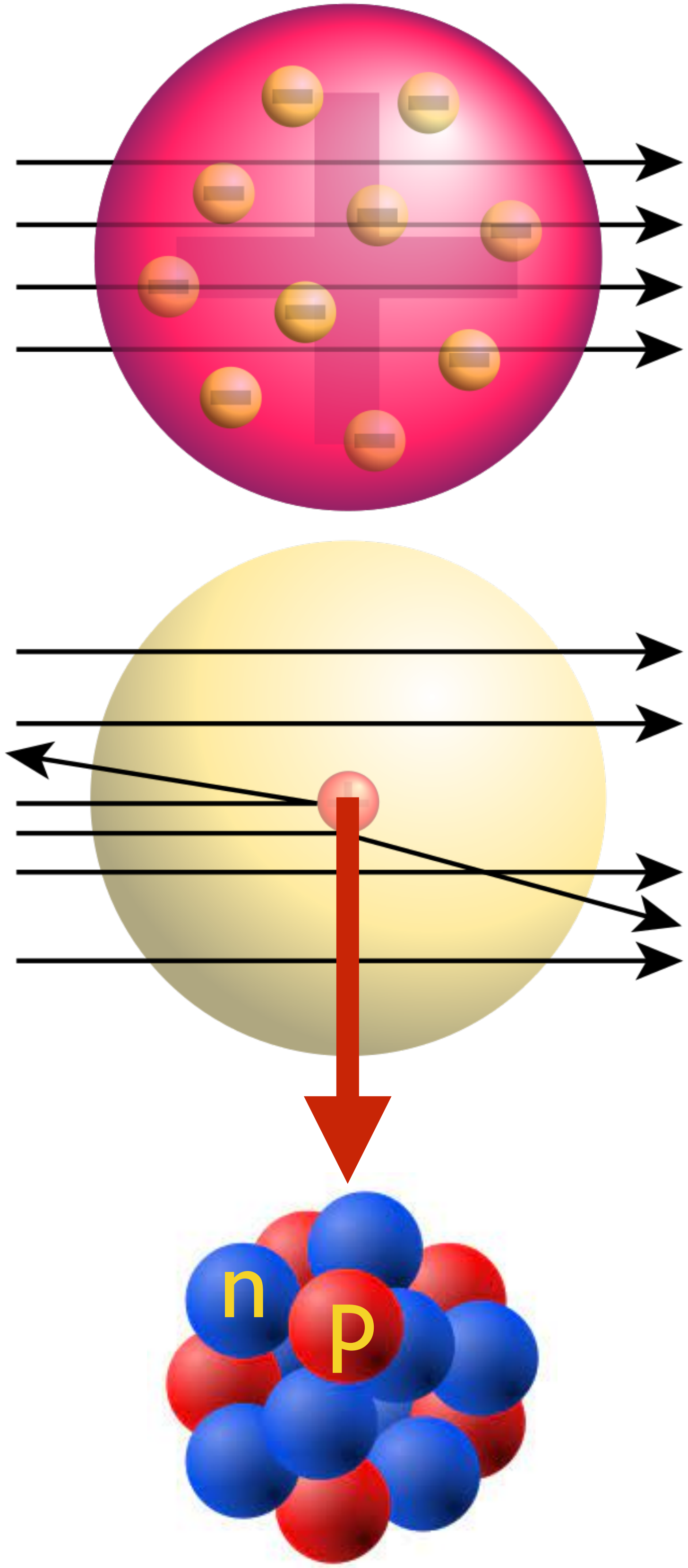
Interaction Property	Gravitational	Weak	Electromagnetic	Strong	
		Electroweak		Fundamental	Residual
Acts on:	Mass - Energy	Flavor	Electric charge	Color charge	Atomic nuclei
Particles experiencing:	All particles	quarks, leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (Not yet observed)	W^+, W^- and Z^0	γ (photon)	Gluons	Mesons
Strength at the scale of quarks:	10^{-41}(predicted)	10^{-4}	1	60	Not applicable to quarks
Strength at the scale of protons/neutrons:	10^{-36}(predicted)	10^{-7}	1	Not applicable to hadrons	20

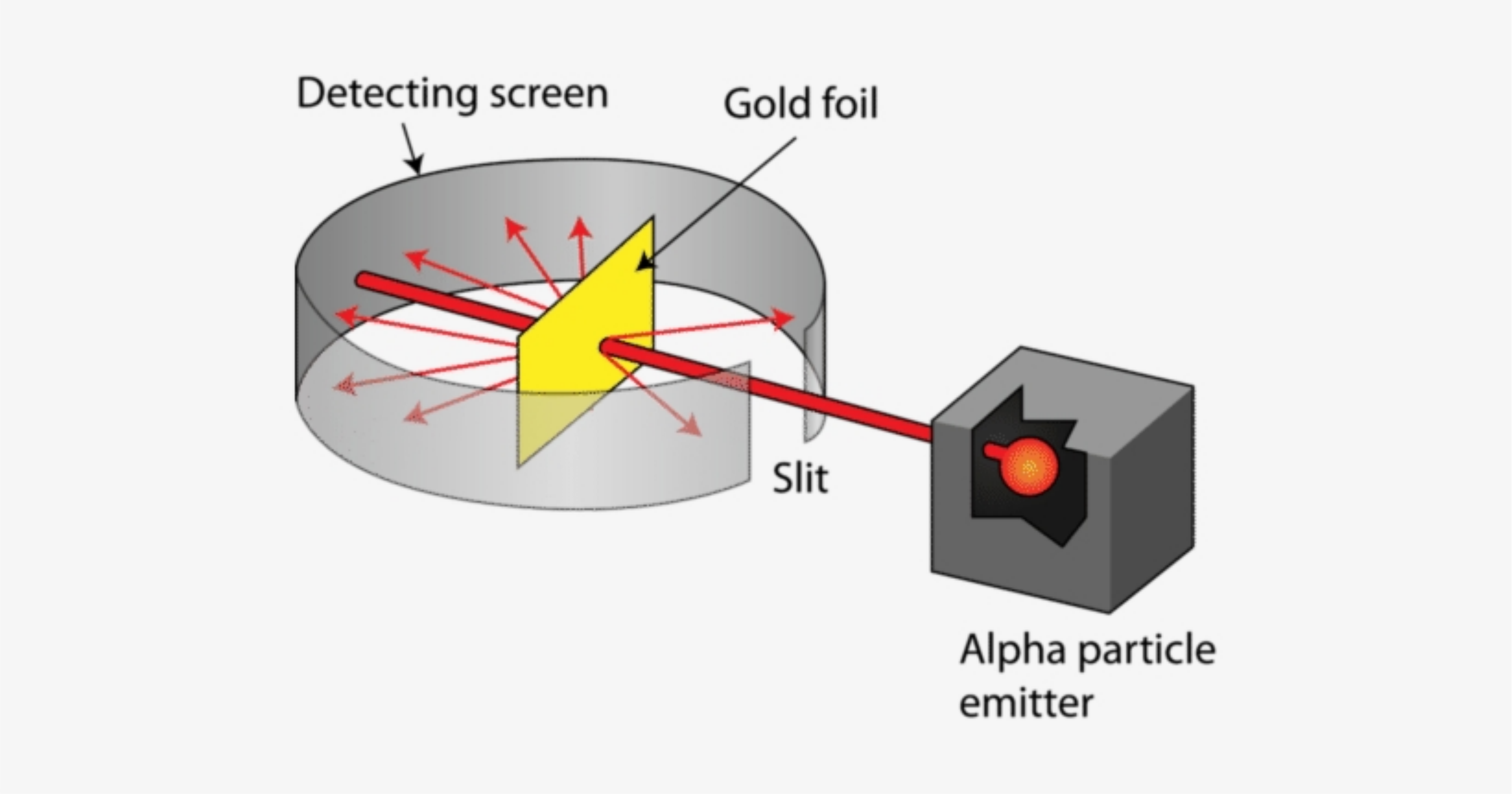


Rutherford experiment



E. Rutherford
1909-1913

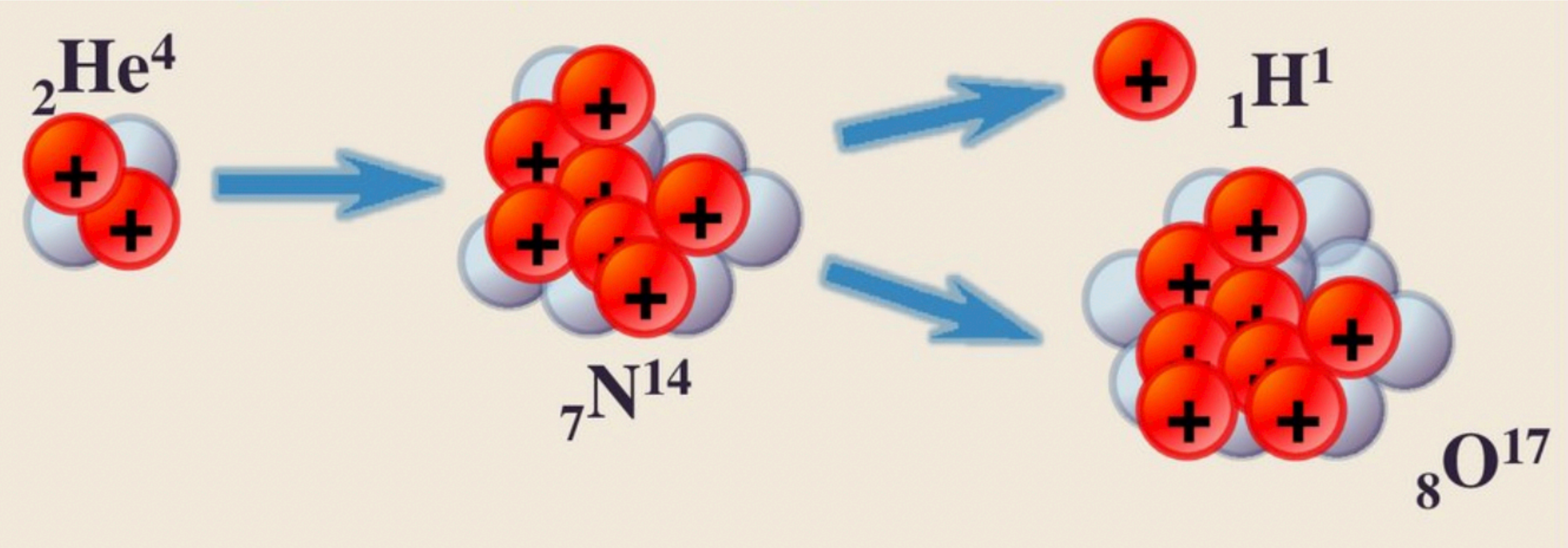




Discovery of the proton

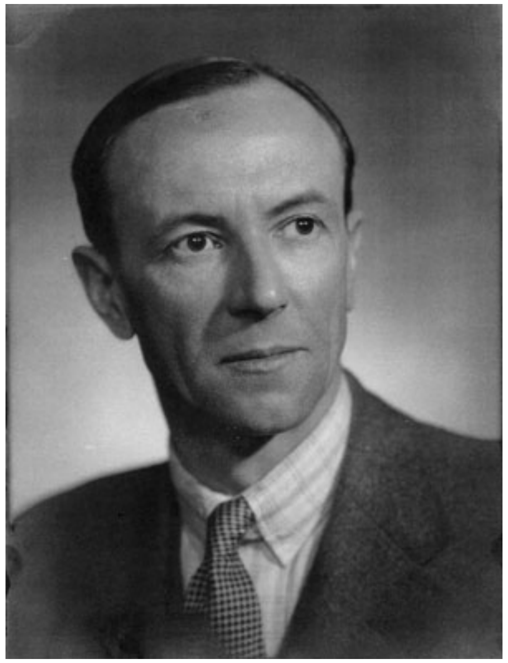
E. Rutherford, 1919

$$ {}^{14}_{7}N + {}^{4}_{2}He \rightarrow {}^{17}_{8}O + {}^{1}_{1}H $$



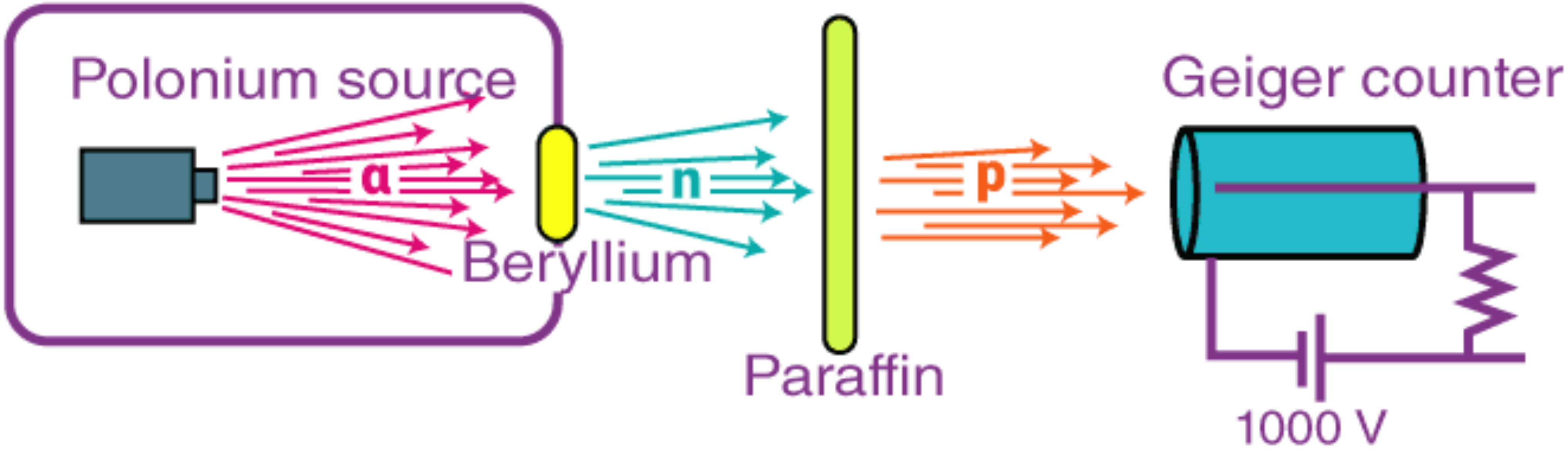
What is keeping the proton in the nucleus?!

Discovery of the neutron



J. Chadwick, 1932, the Nobel Prize in 1961

$$^{9}_{4}Be + ^{4}_{2}He \rightarrow ^{12}_{6}C + n$$



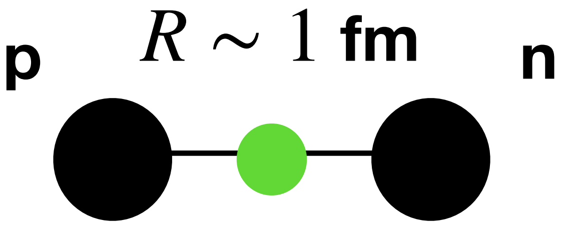
Yukawa potential

H. Yukawa, 1934

Exchange nature of nuclear forces

$$\Delta E \Delta t \geq \hbar$$

$$\Delta t = R/c$$



carrier particle

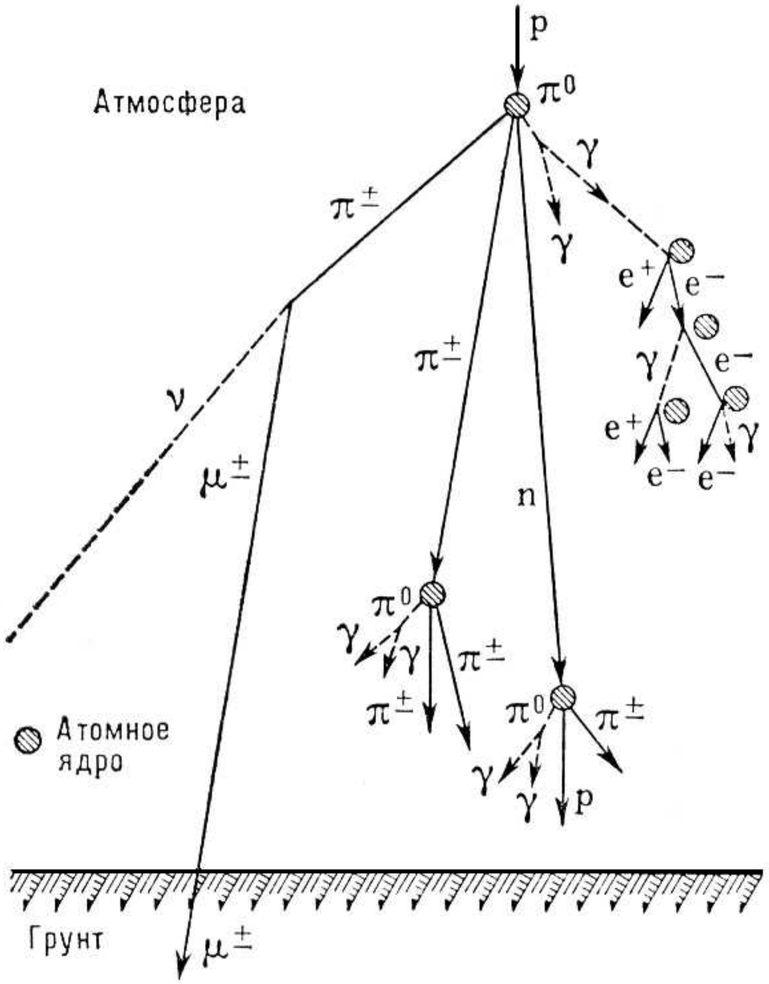
meson

$$m = \frac{\Delta E}{c^2} \sim \frac{\hbar}{Rc} = 200\, MeV$$

Potential of nucleon-nucleon interaction

$$V(r) = -g^2 \frac{e^{-mcr/\hbar}}{r}$$

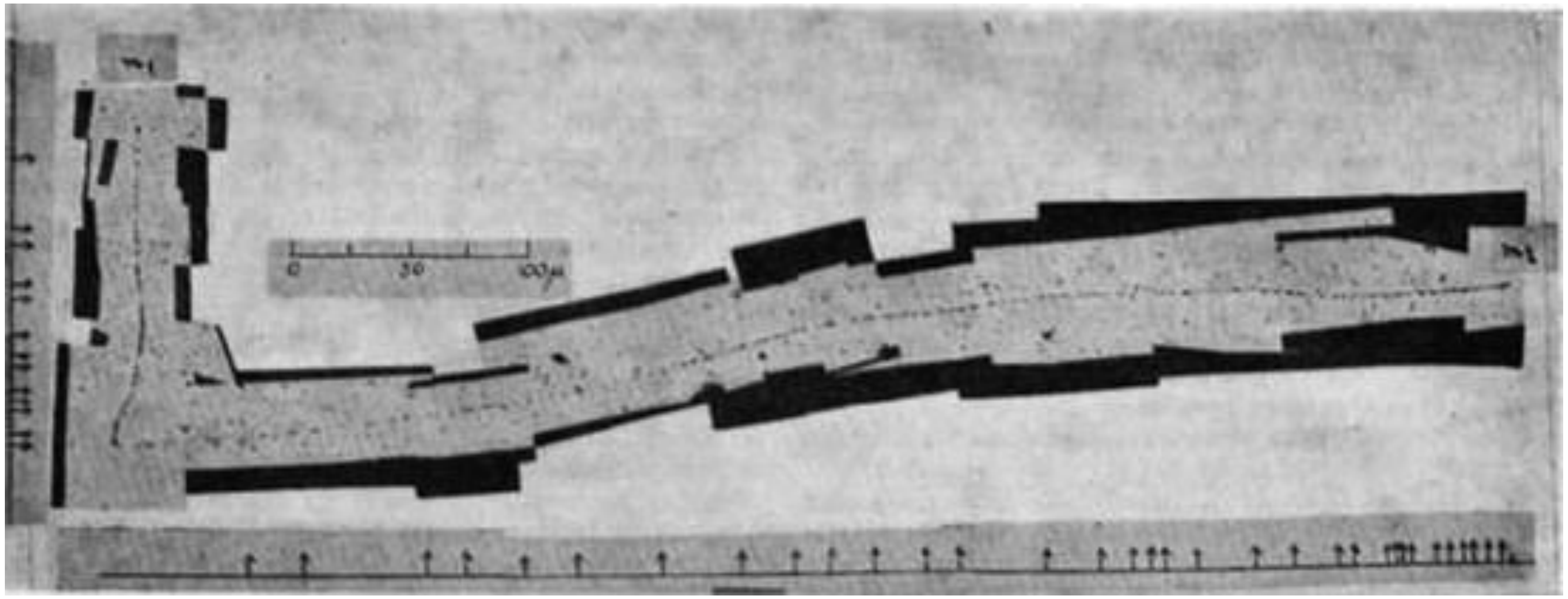
Discovery of $\pi^{\pm}$-mesons



1947

The nuclear emulsion was irradiated in the mountains by secondary cosmic rays. Short tracks of particles stopped in the emulsion were found, which then decayed.

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$



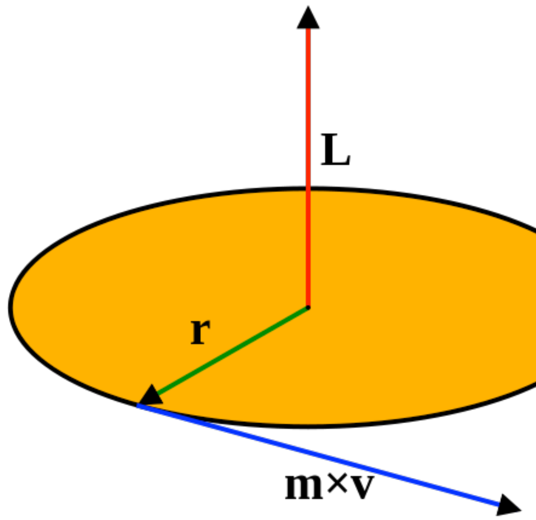
1950

Discovery of neutral π-meson

$$\pi^0 \rightarrow 2\gamma$$

Spin

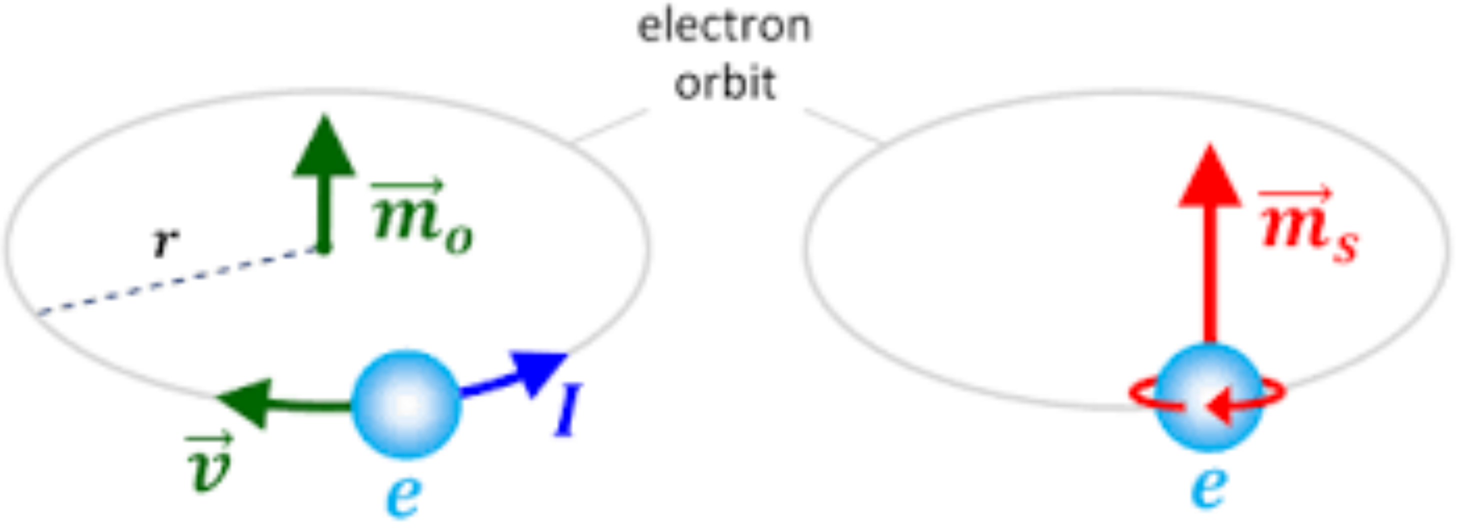
Angular momentum is a measure of the amount of rotation



$$\vec{L} = \vec{r} \times \vec{p}$$ ***- in classics***

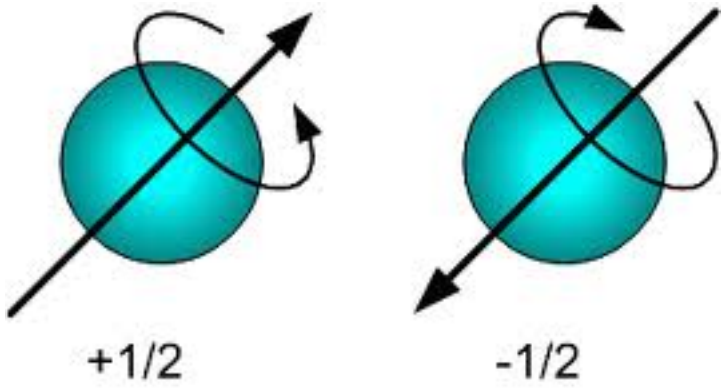
Spin of fundamental particle is its intrinsic angular momentum not related with rotation

Every particle can have an orbital momentum and a spin at the same time



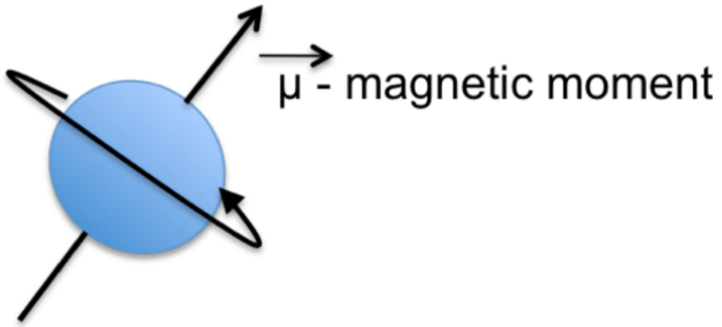
Spin is a solely quantum-mechanical phenomenon

Proton spin: 1/2
Units: ħ



Total momentum (spin) of a composite particle is determined the particle's spin is determined by the spin and the angular momenta of its components

Complexity of nucleons



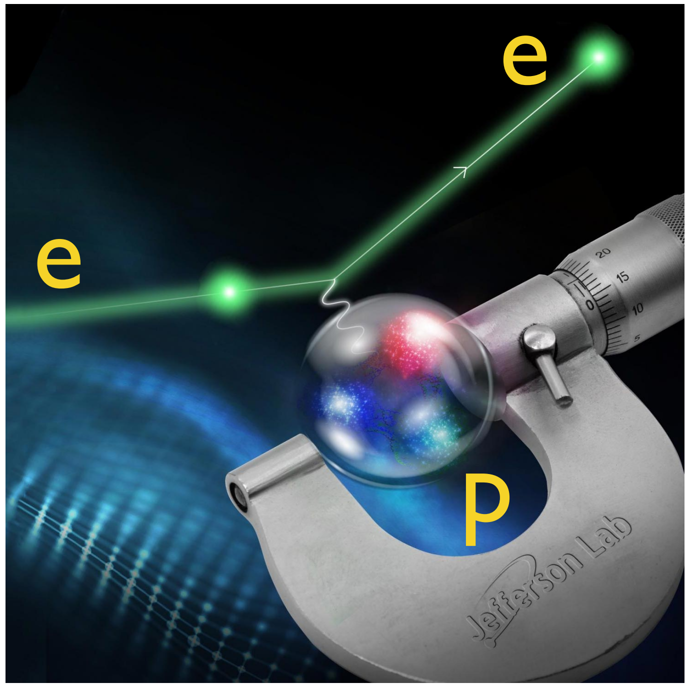
$$\overrightarrow{\mu_S} = g_S \times \frac{e}{2m} \times \vec{S}$$

	gs (expected)	gs (measured)
e	-2	-2.0023
p	2	**5.58**
n	0	**-3.83**

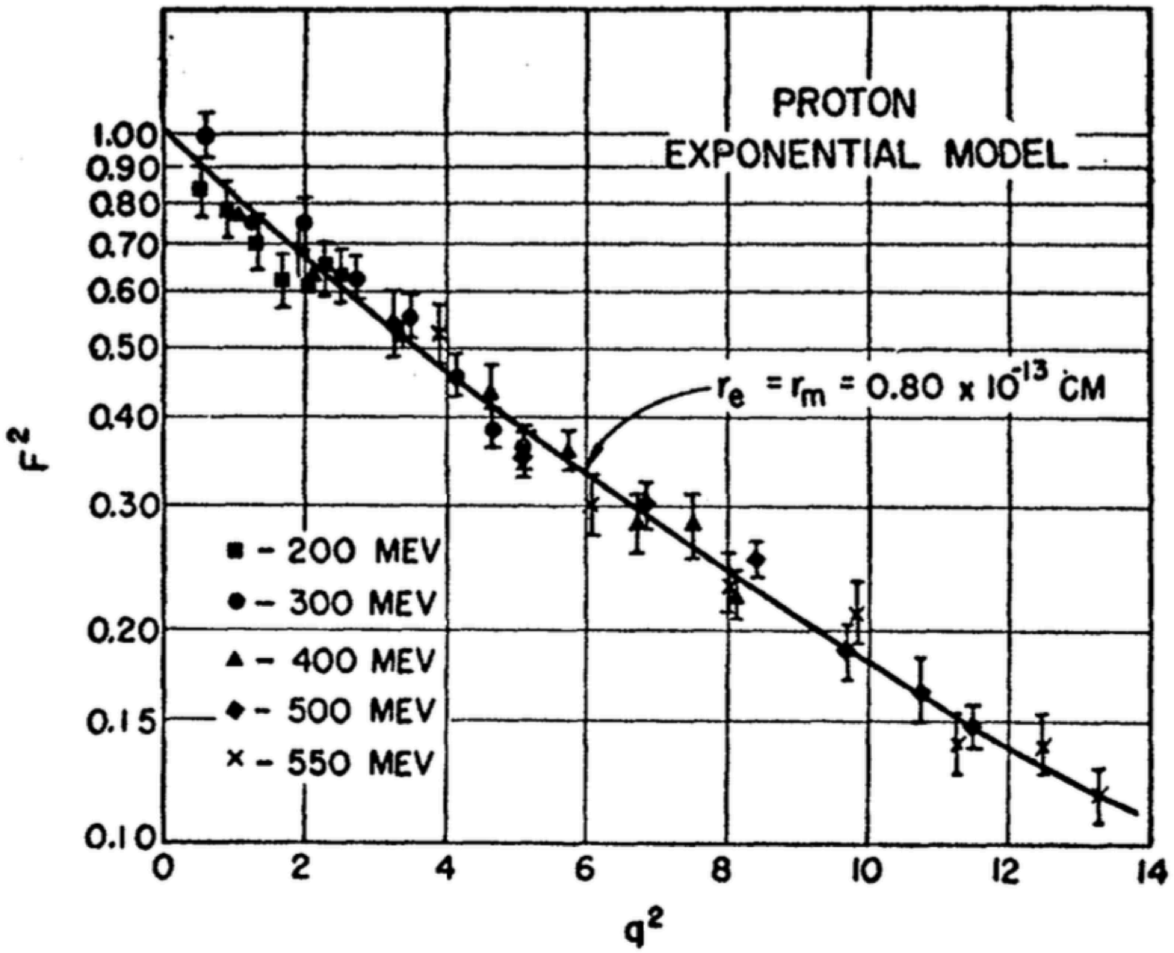
1930s

This was the first indication that nucleons could be composite objects.

Proton size



R. Hofstadter - the Nobel Prize in 1961



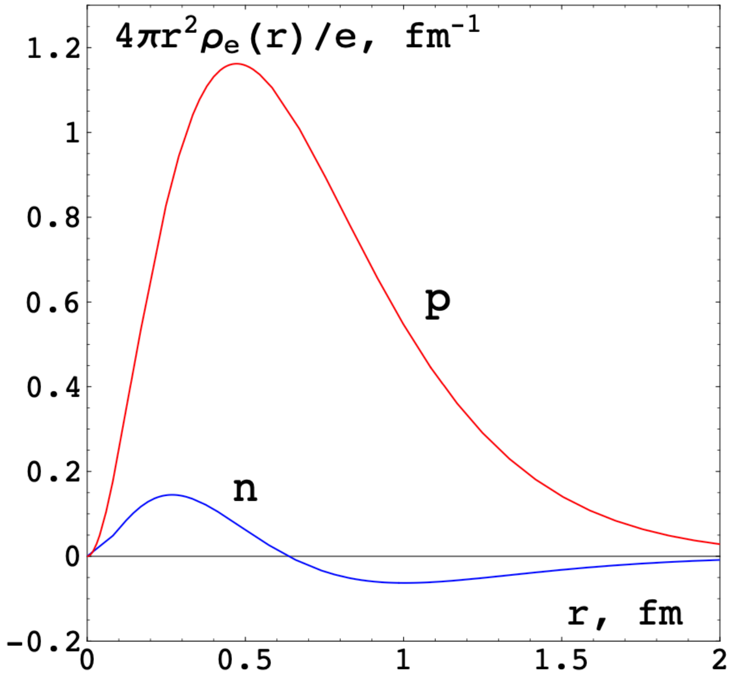
$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\text{point-like}} \times F^2(q^2)$$

Form-factor

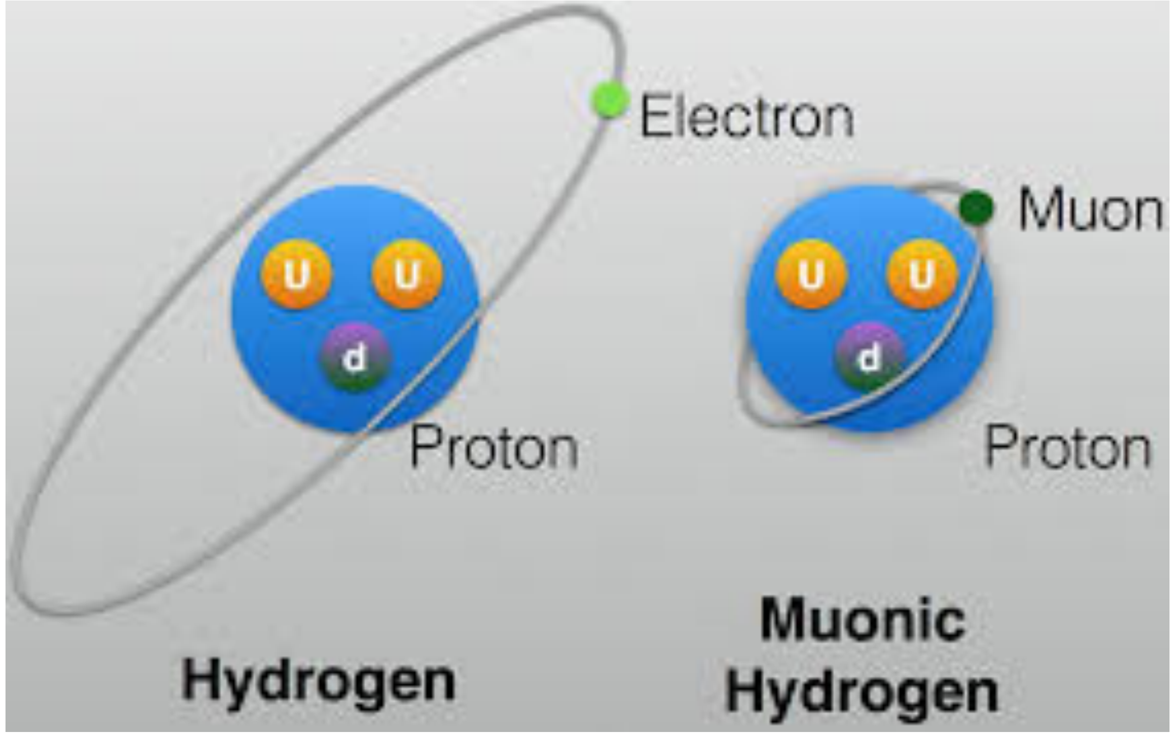
transferred (four)-momentum

$$F(q^2) \approx 1 - \frac{q^2 < r^2 >}{6\hbar^2}$$

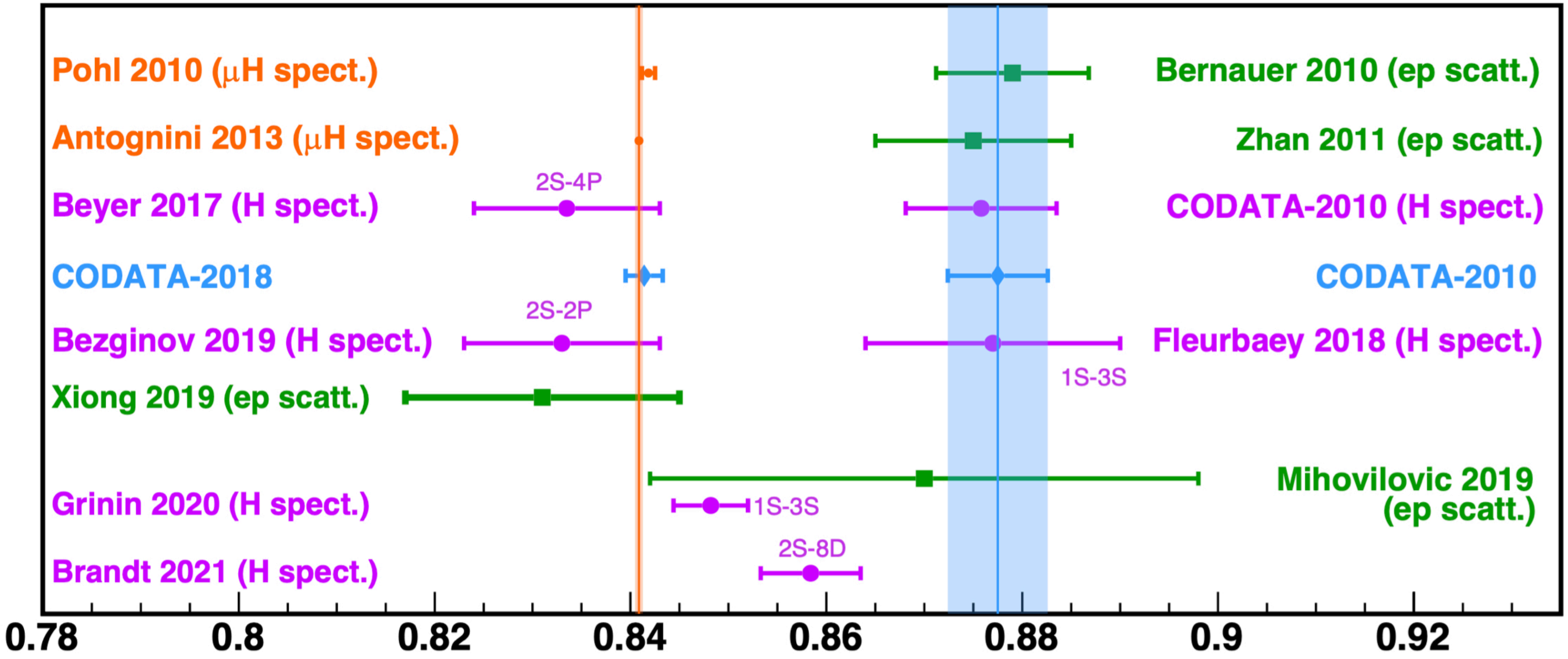
charge radius



Proton radius puzzle

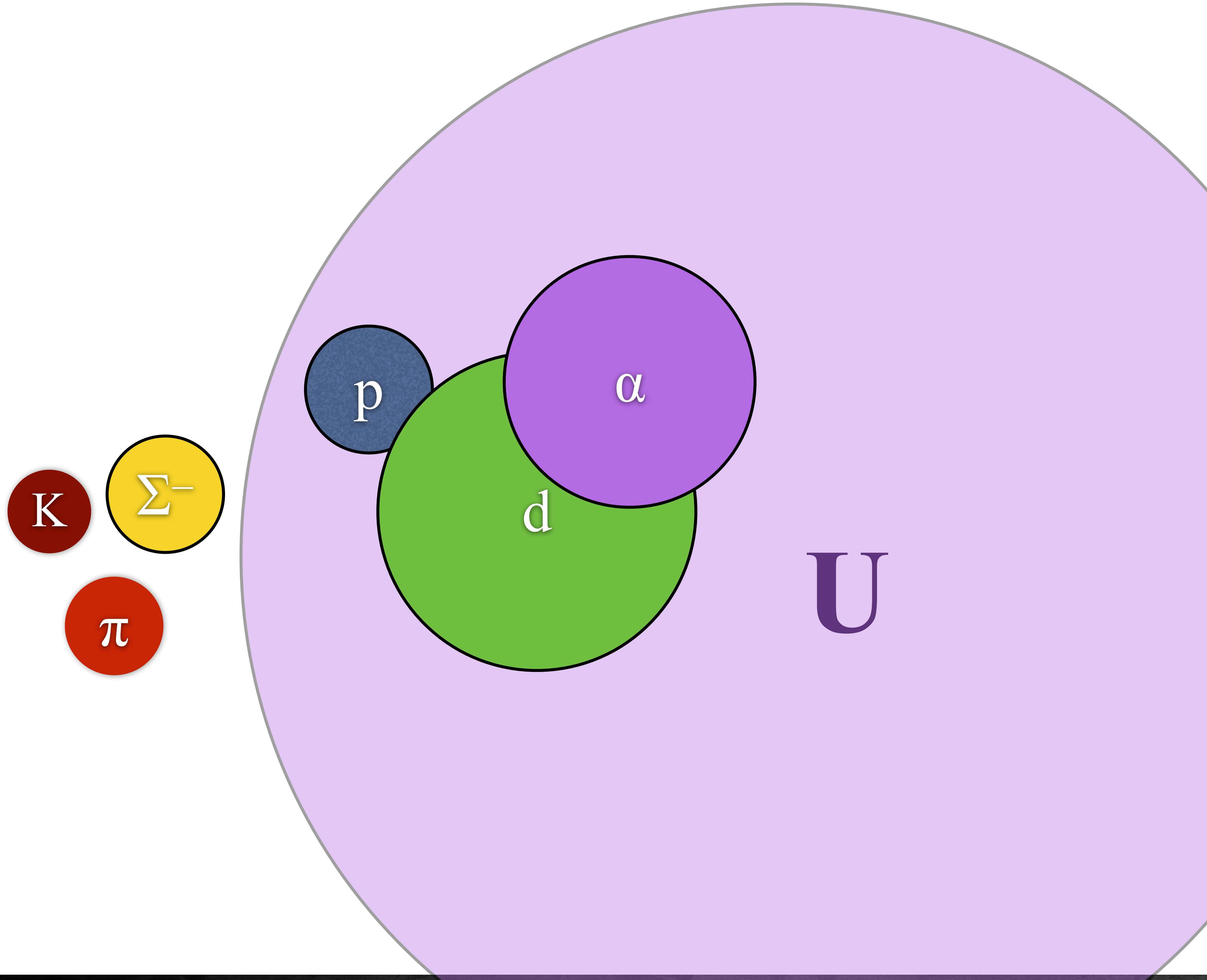


Different approaches gives different results

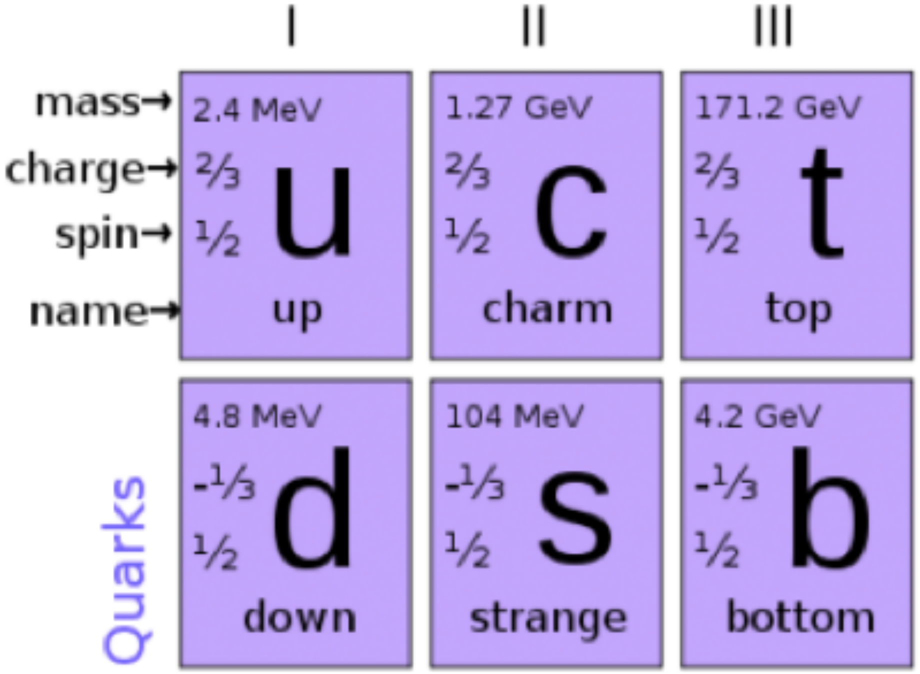


Solved or not?

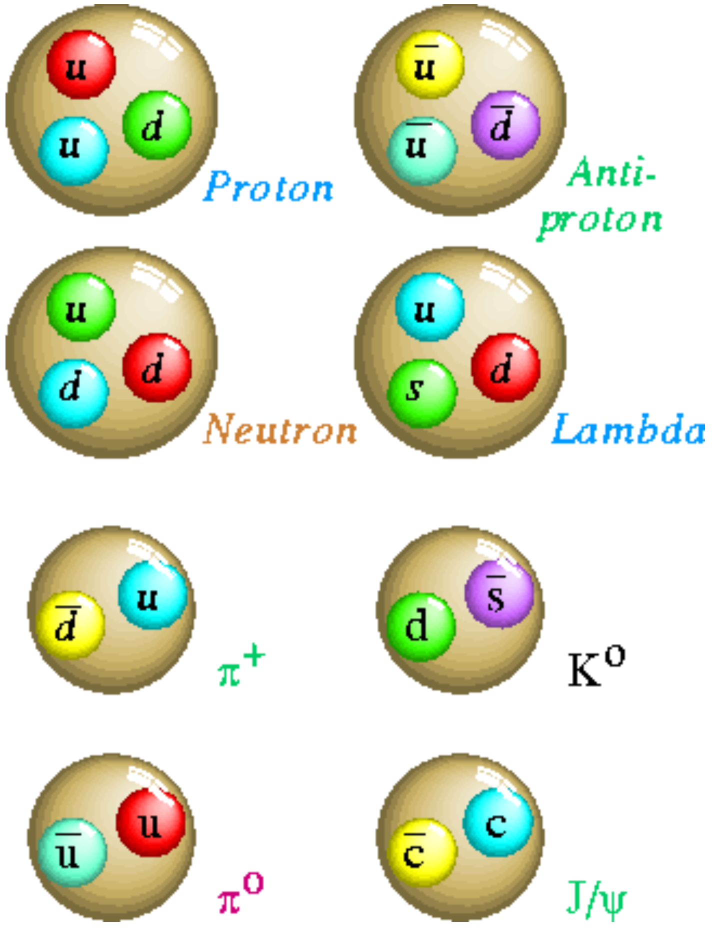
Hadrons in scale

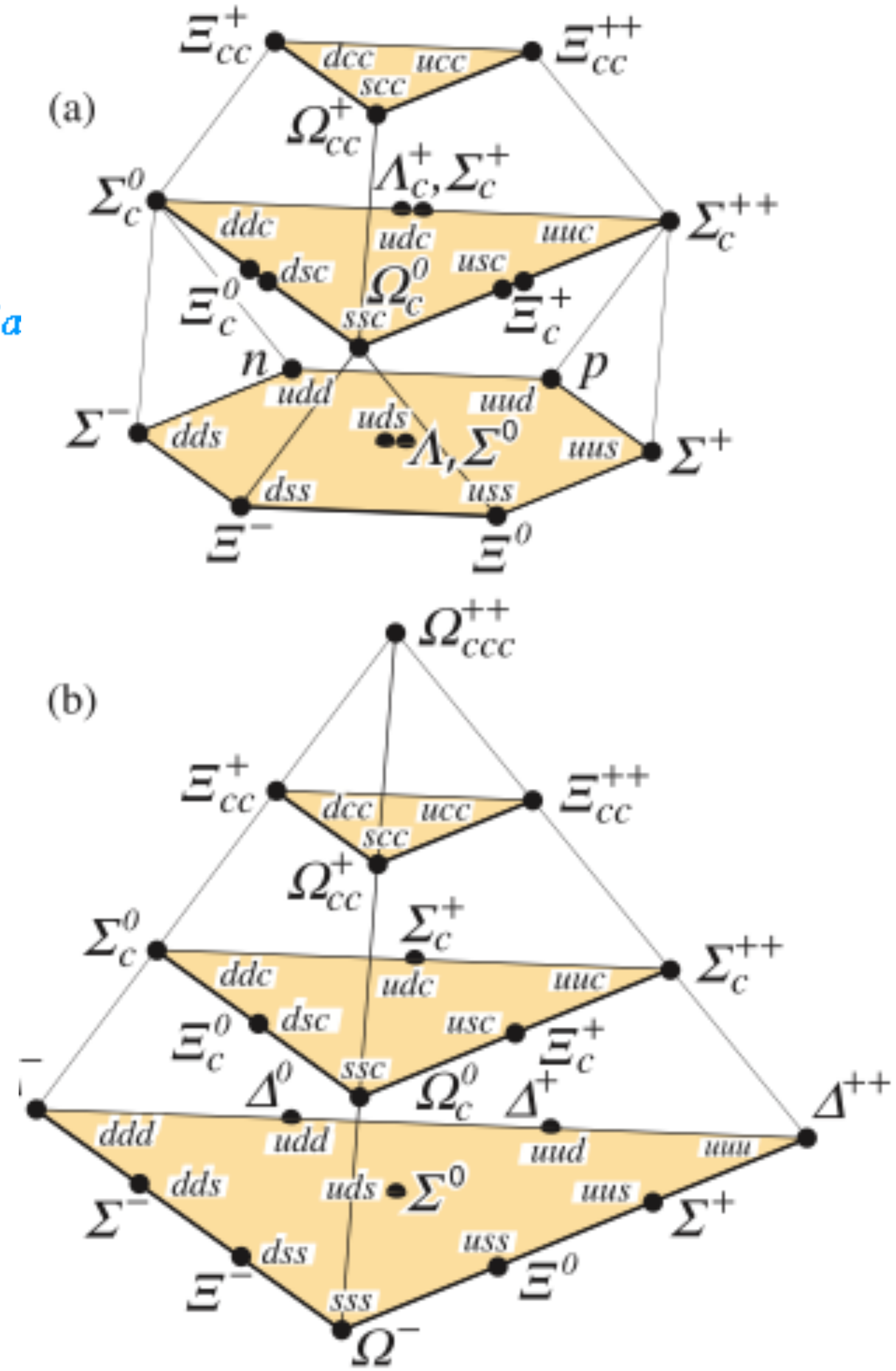


Quarks



	I	II	III
mass→	2.4 MeV	1.27 GeV	171.2 GeV
charge→	⅔	⅔	⅔
spin→	½	½	½
	u	c	t
name→	up	charm	top
	4.8 MeV	104 MeV	4.2 GeV
	-⅓	-⅓	-⅓
	½	½	½
	d	s	b
	down	strange	bottom

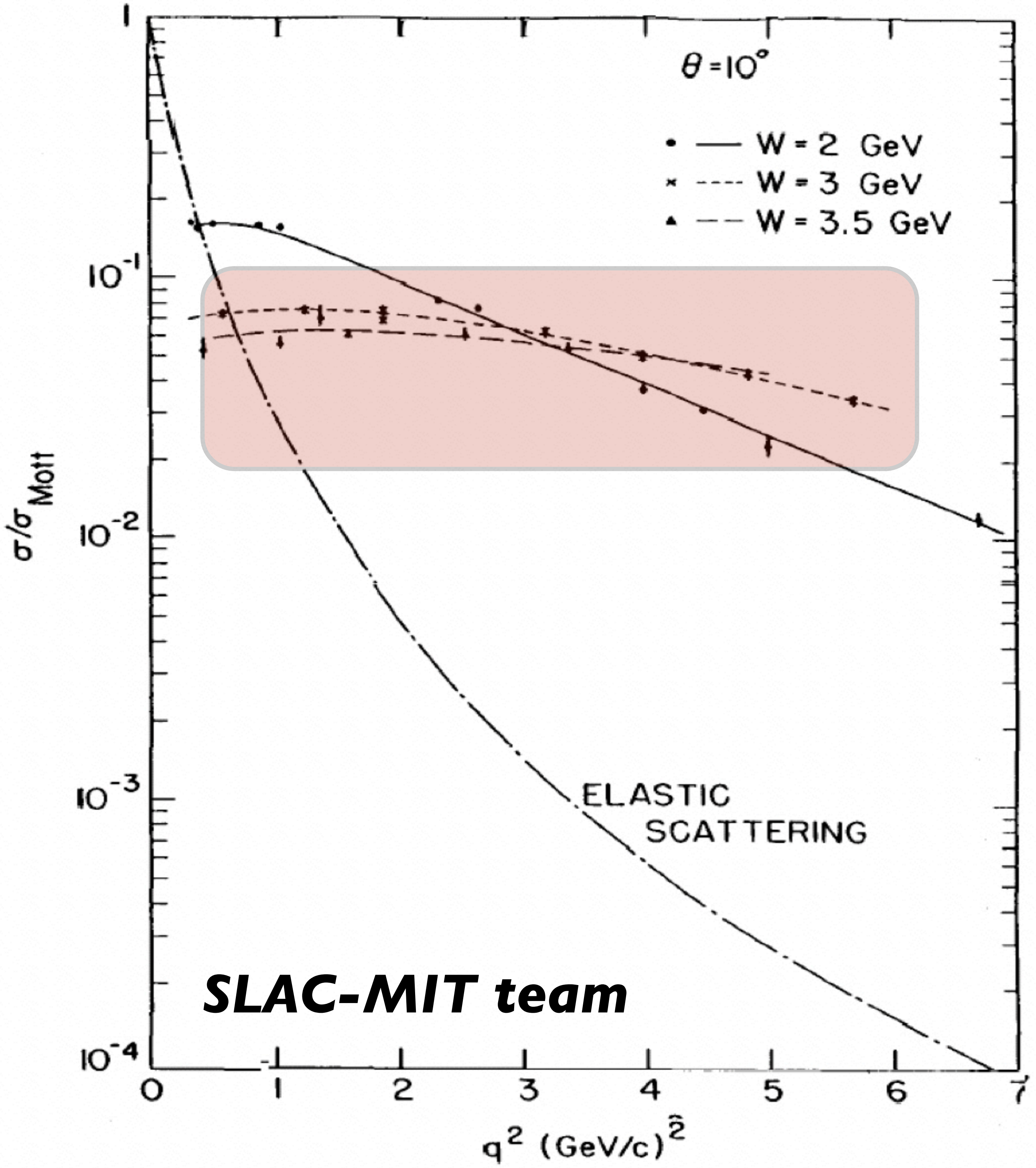




1964

M. Gell-Mann and G. Zweig -
Nobel Prize in 1969

Partons



SLAC-MIT team

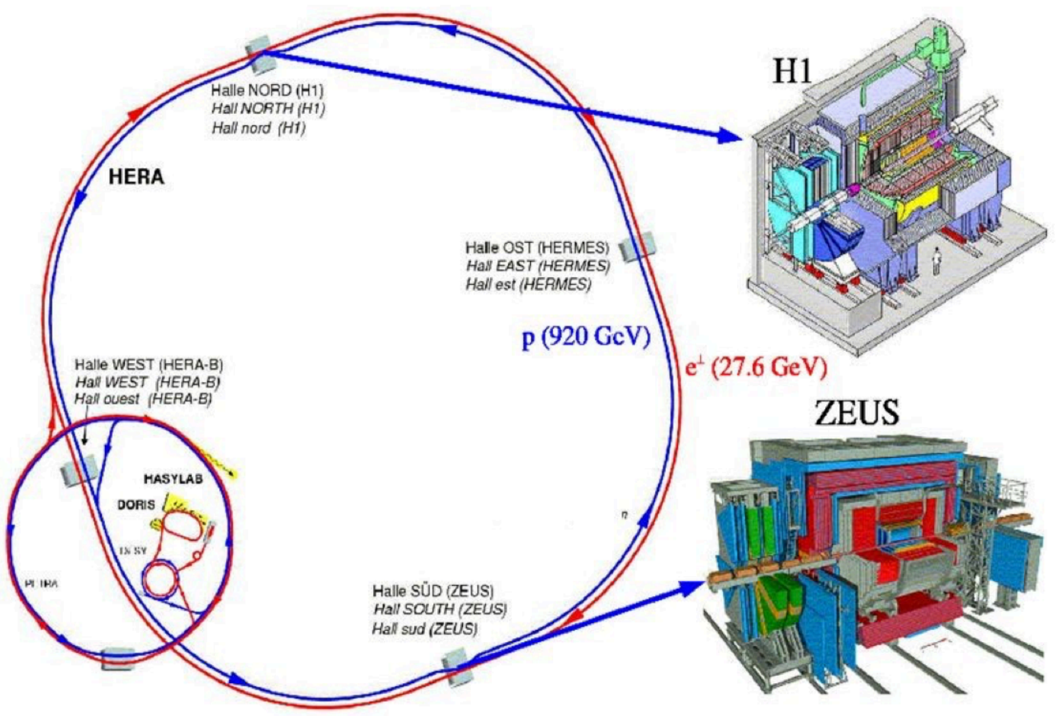
Partons - point-like objects inside the proton

Partonic model - 1969

R. Feynman

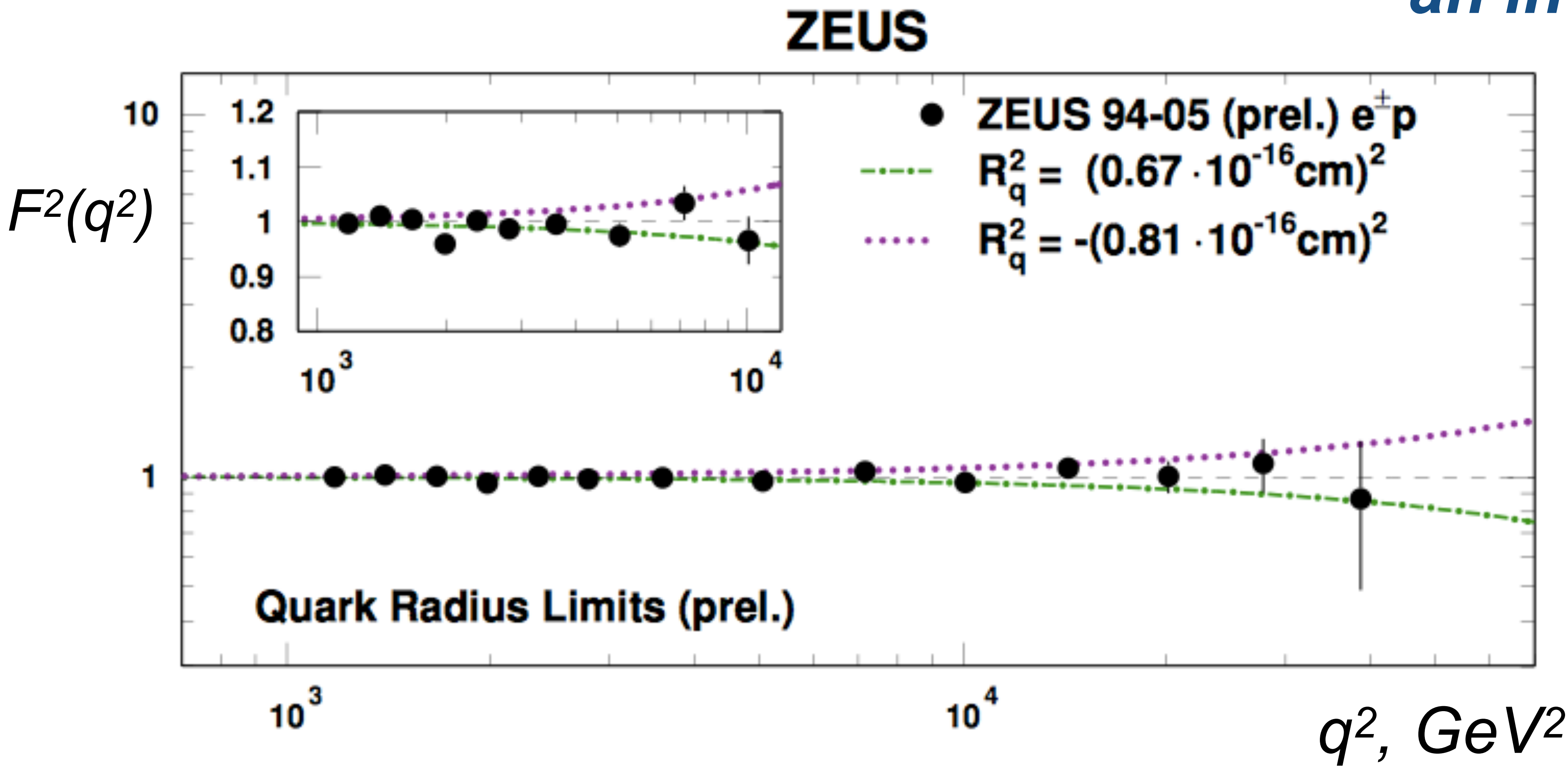
In the beginning of 70th charged partons were associated with quarks

Quark size?



HERA - high-energy electron-proton collider at DESY (1992-2007)

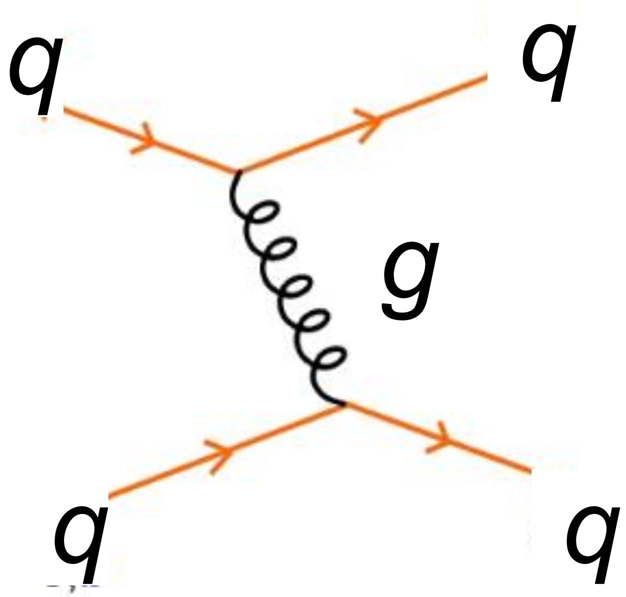
At the moment there is no indication that quarks have an internal structure

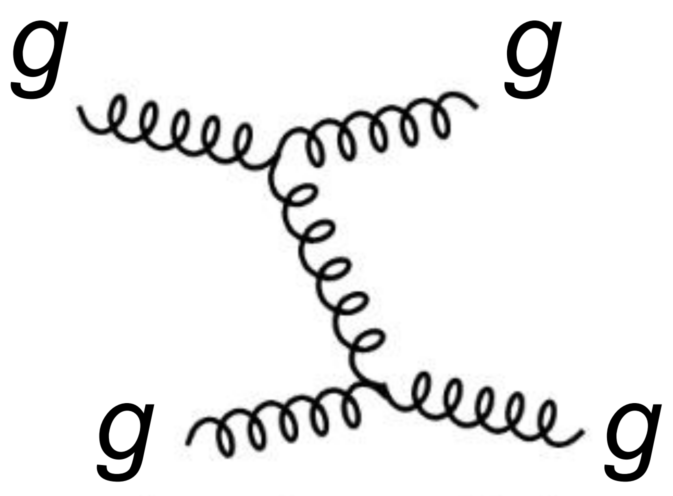


$$F(q^2) \approx 1 - \frac{q^2 < r_q^2 >}{6\hbar^2}$$

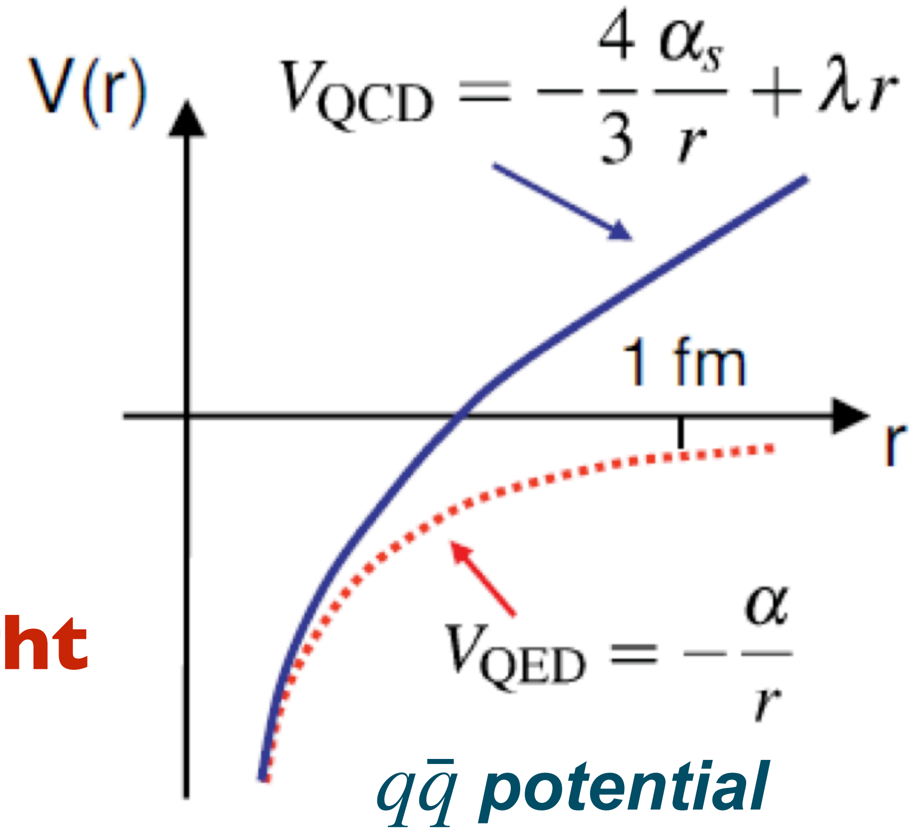
$r_q < 0.7 \times 10^{-3}$ fm

Quantum ChromoDynamics - QCD





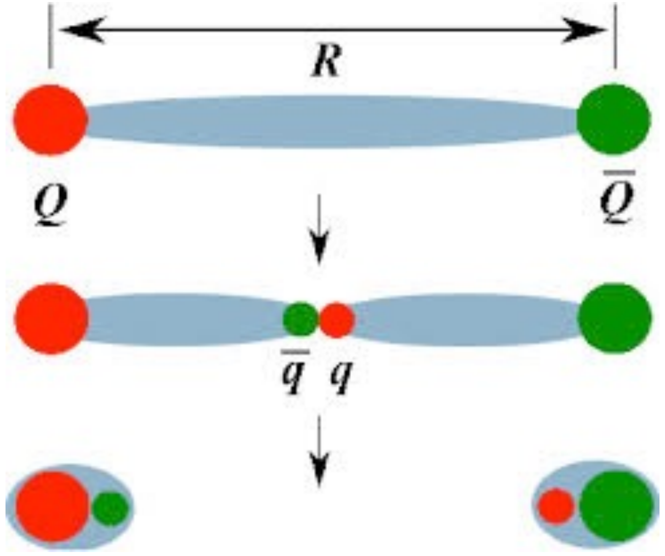
Analog in electrodynamics: **light emitting light !**

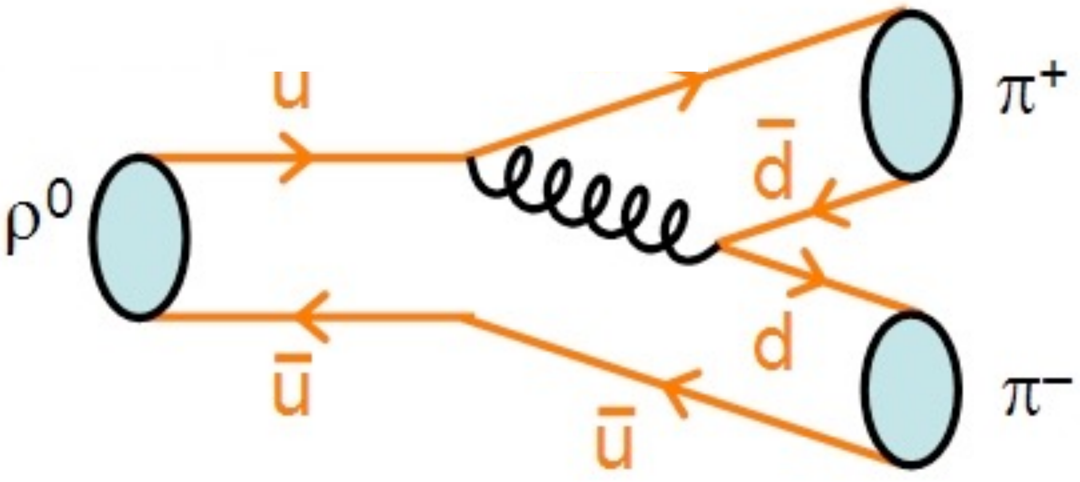


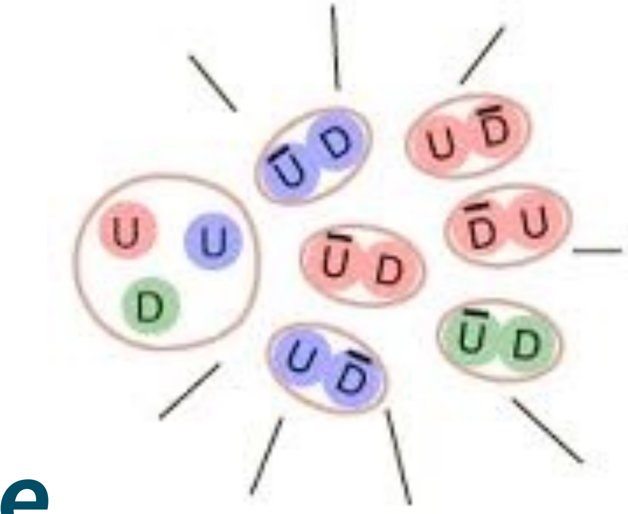
$$V_{\mathrm{QCD}} = -\frac{4}{3}\frac{\alpha_s}{r} + \lambda r$$

$$V_{\mathrm{QED}} = -\frac{\alpha}{r}$$

$q\bar{q}$ **potential**







Quark confinement at large scale

but asymptotic freedom at below 1 fm

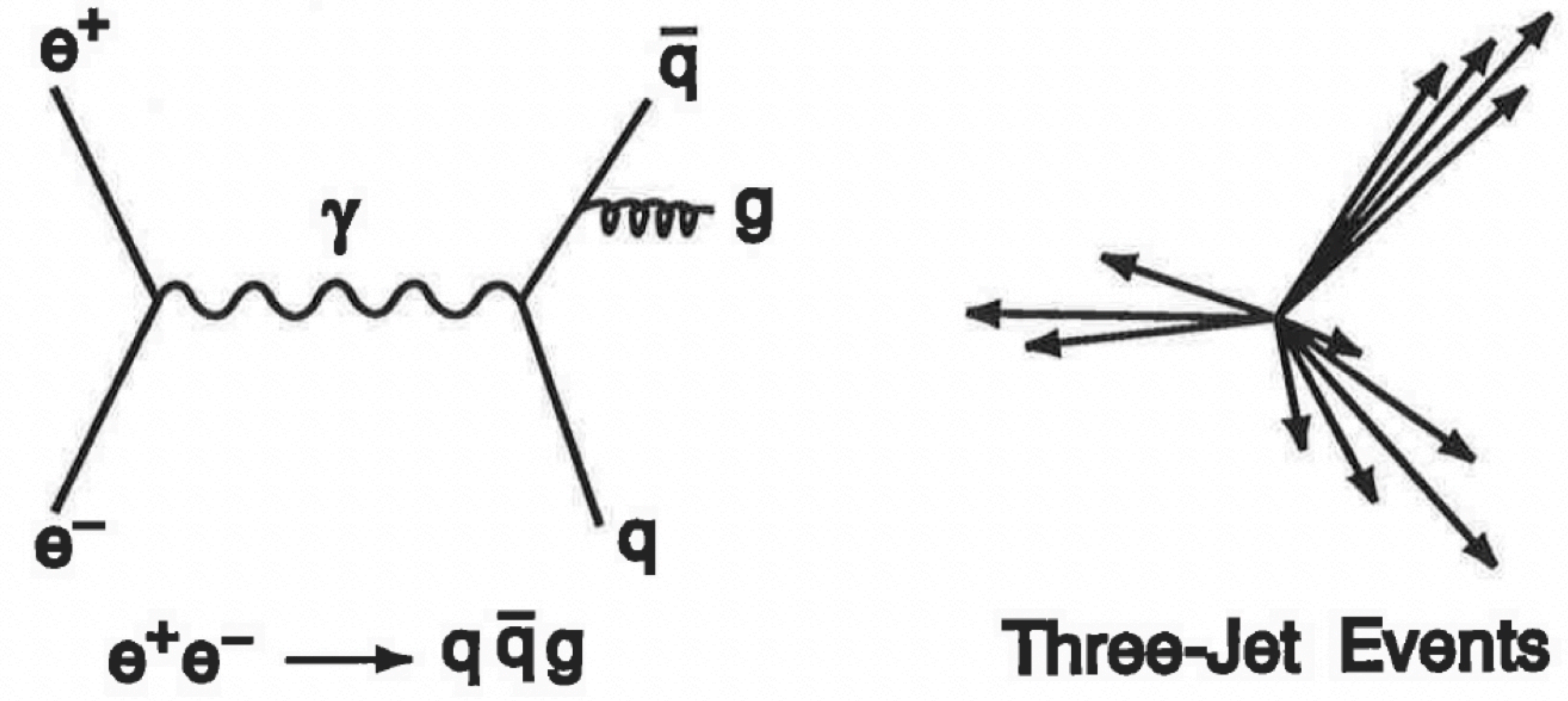
Gluon

- Self-interacting particle
- 8 gluons
- m=0 (theoretical value)
- m < 1.3 MeV (experimental limit)
- Spin = 1

PETRA collider

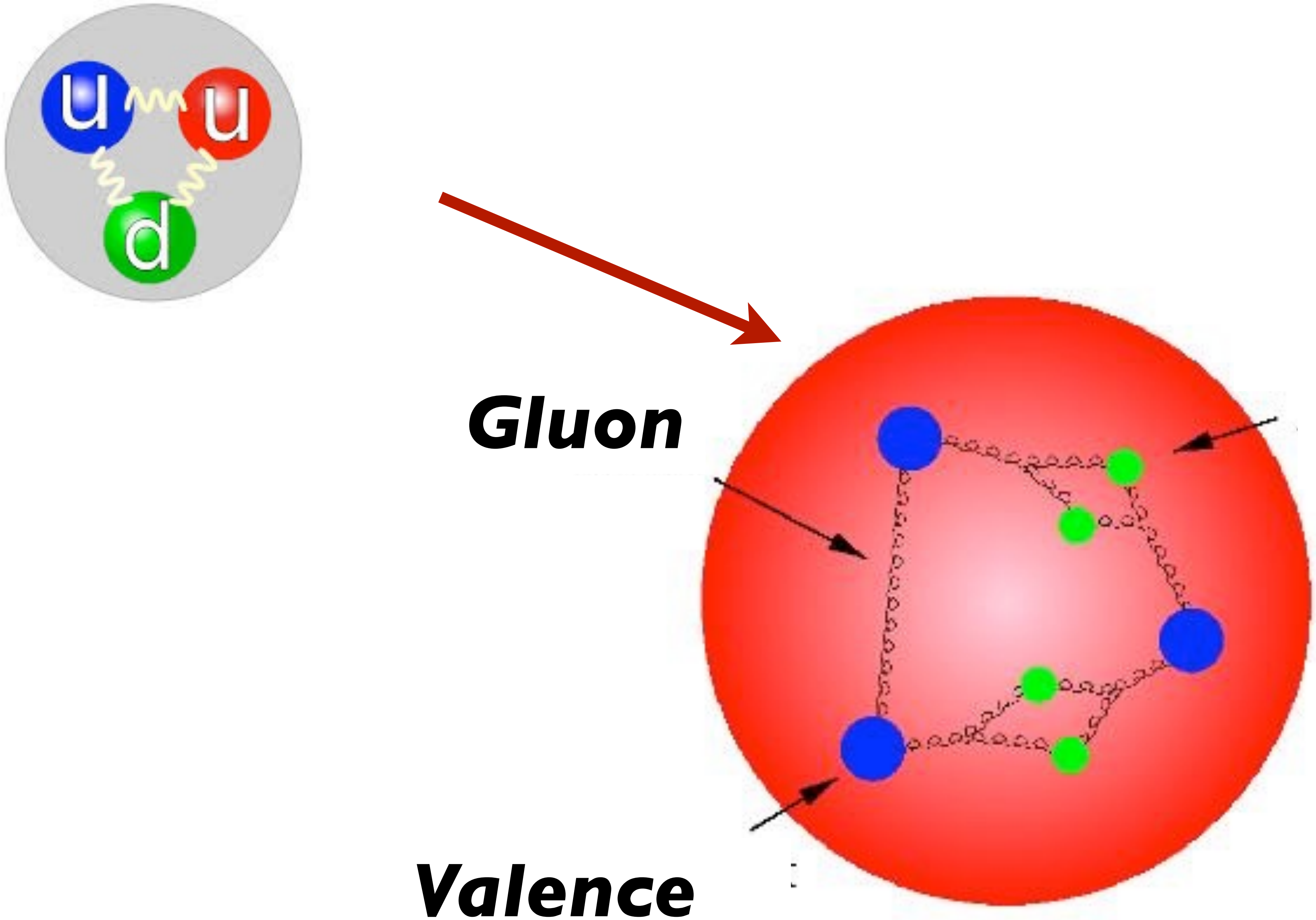
$$\sqrt{s} = 27\ GeV$$

1979



Valence and sea quarks

Proton



Gluon

Sea quarks and antiquarks

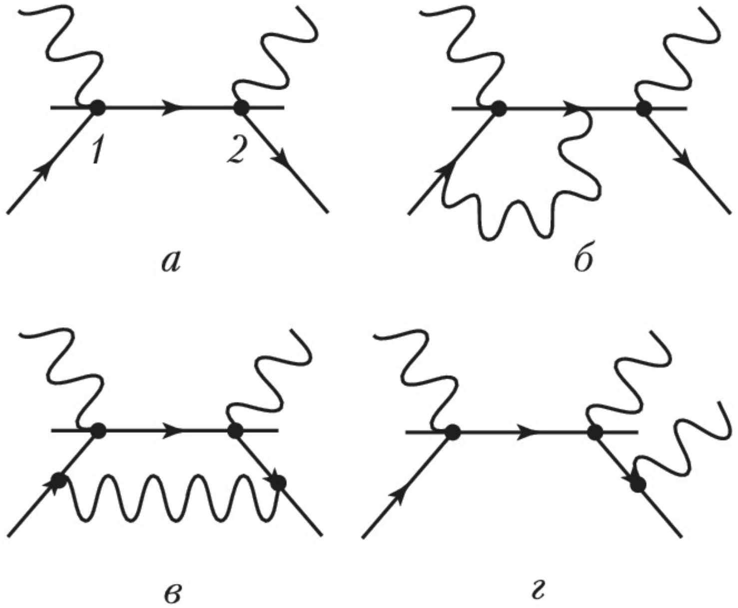
Valence quark

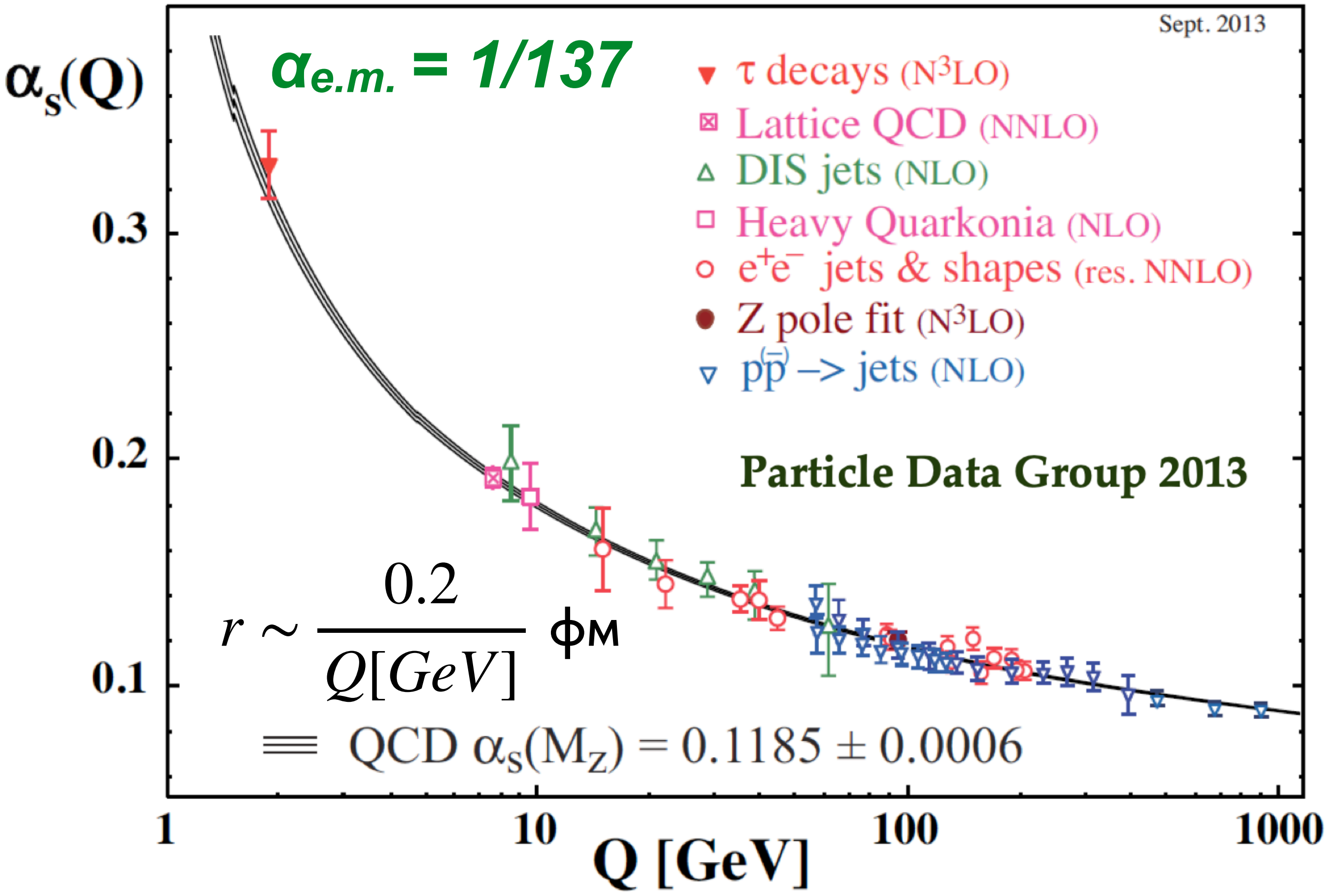
Problem to describe hadrons ab initio

Feynman diagrams - perturbative approach

$$\sigma \sim \sum_{n}^{\infty} c_n \alpha^n$$ ***α - interaction constant***

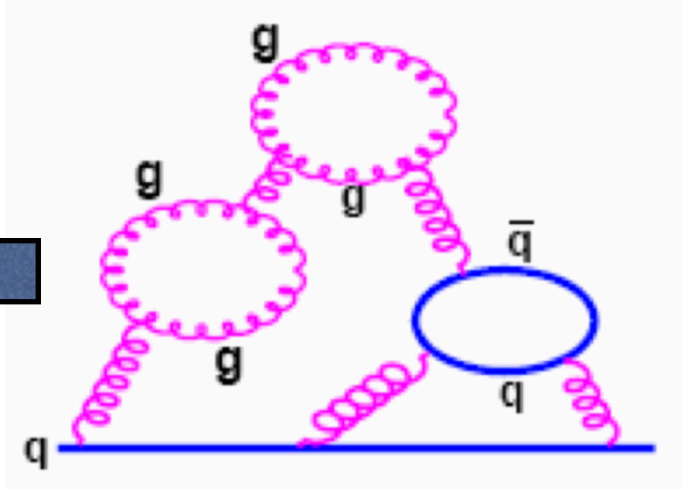
Fast convergence for α<<1





$\alpha_{e.m.} = 1/137$

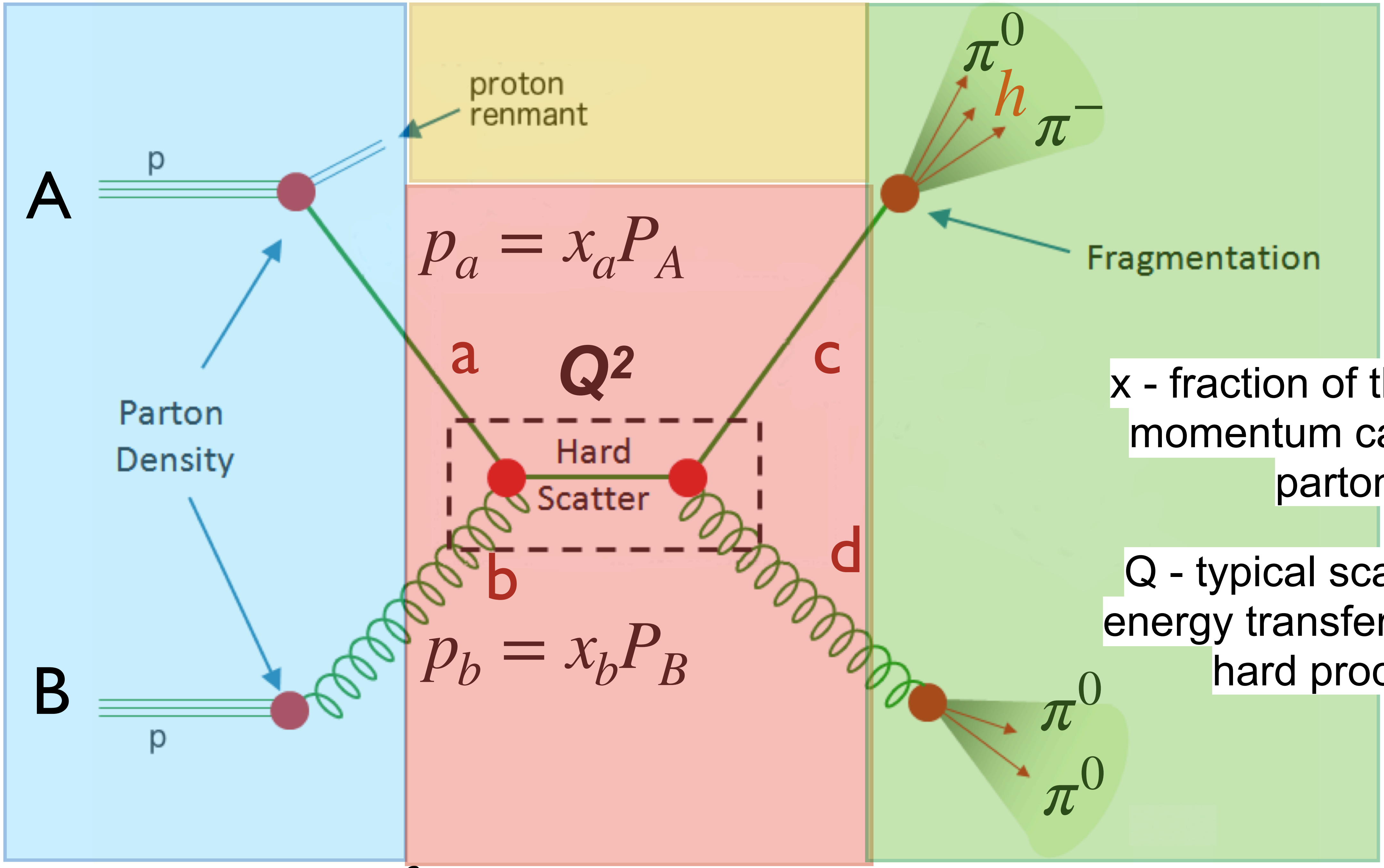
$$r \sim \frac{0.2}{Q[GeV]} \text{ фм}$$



Confinement is not strictly proven!

Unlike the hydrogen atom, we cannot (yet?) describe from first principles the structure of hadrons and their interactions at low energies

Factorization theorem



x - fraction of the proton momentum carried by parton

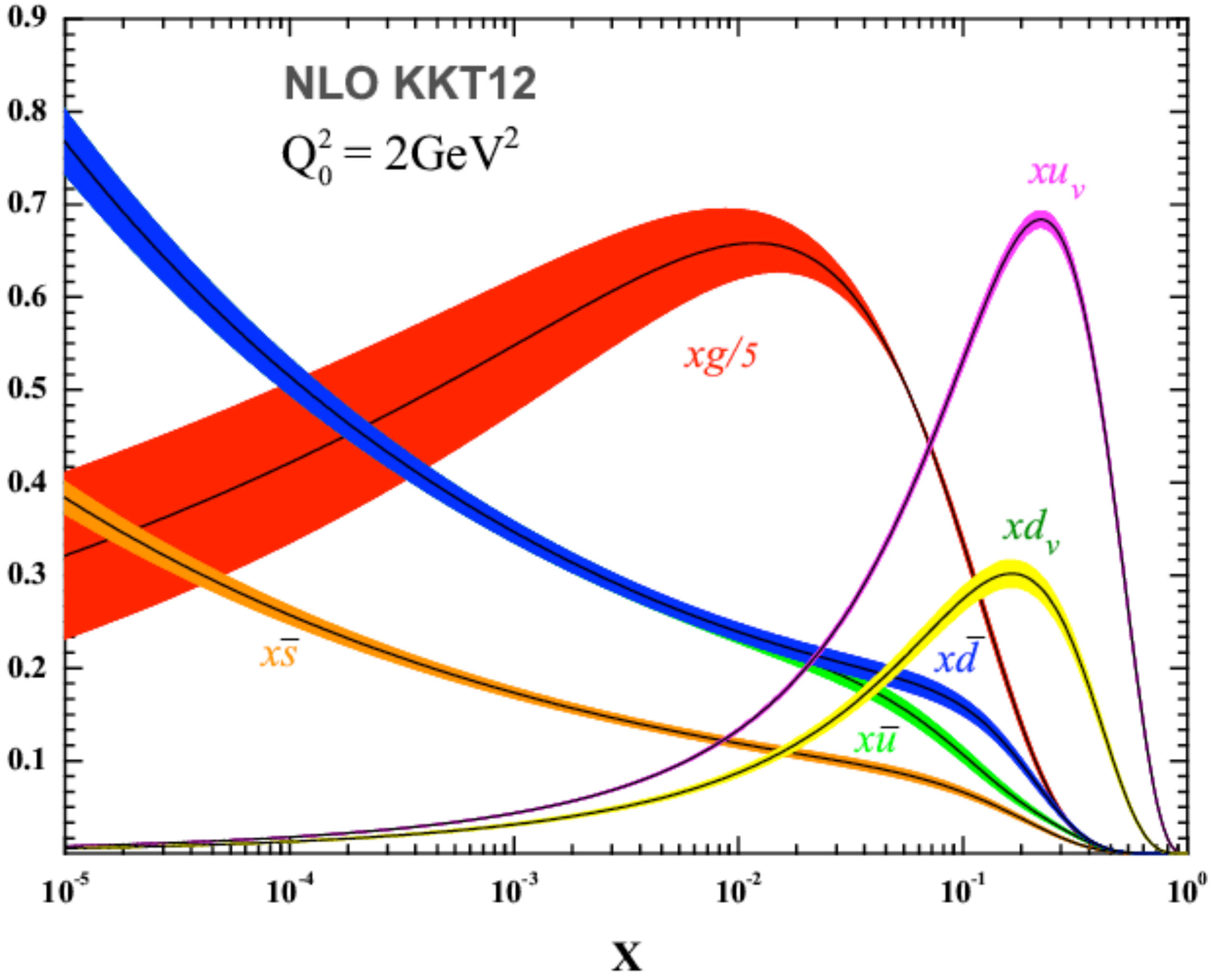
Q - typical scale of the energy transferred in the hard process

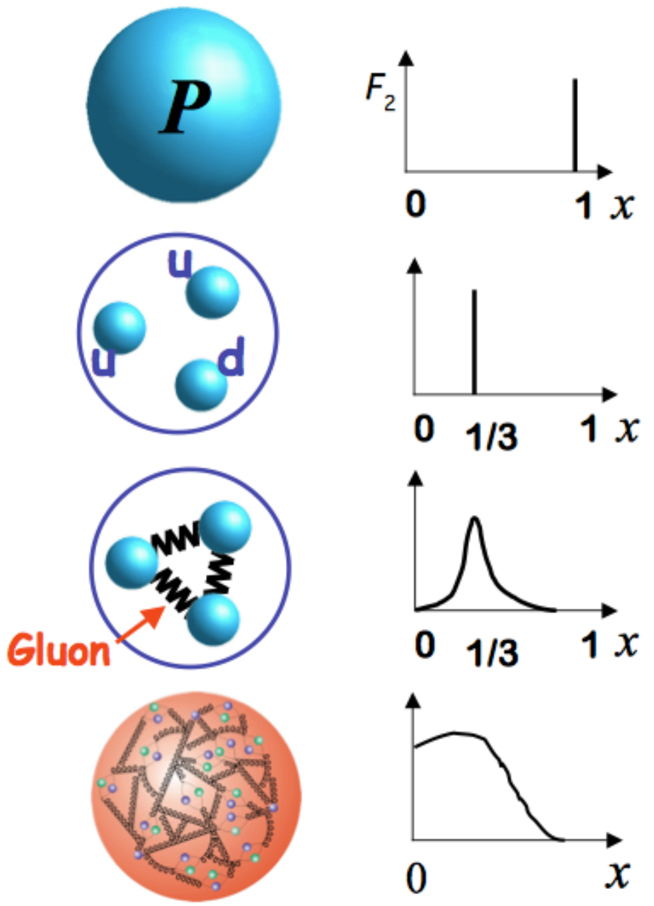
$$\sigma_{AB\to hX} = \sum_{a,b=q,\bar{q},g} \int dx_a dx_b \boxed{f(x_a, Q^2) f(x_b, Q^2)} \times \boxed{\hat{\sigma}_{ab\to cd}(x_a, x_b, Q^2)} \times \boxed{D_{cd\to h}}$$

$$\boxed{Q^2 >> 1\ \mathrm{GeV}^2/c^2}$$

Parton Distribution Functions

Parton Distribution Functions PDFs $f(x,Q^2)$ describes probability for given Q^2 to find inside the proton a parton carrying momentum fraction x

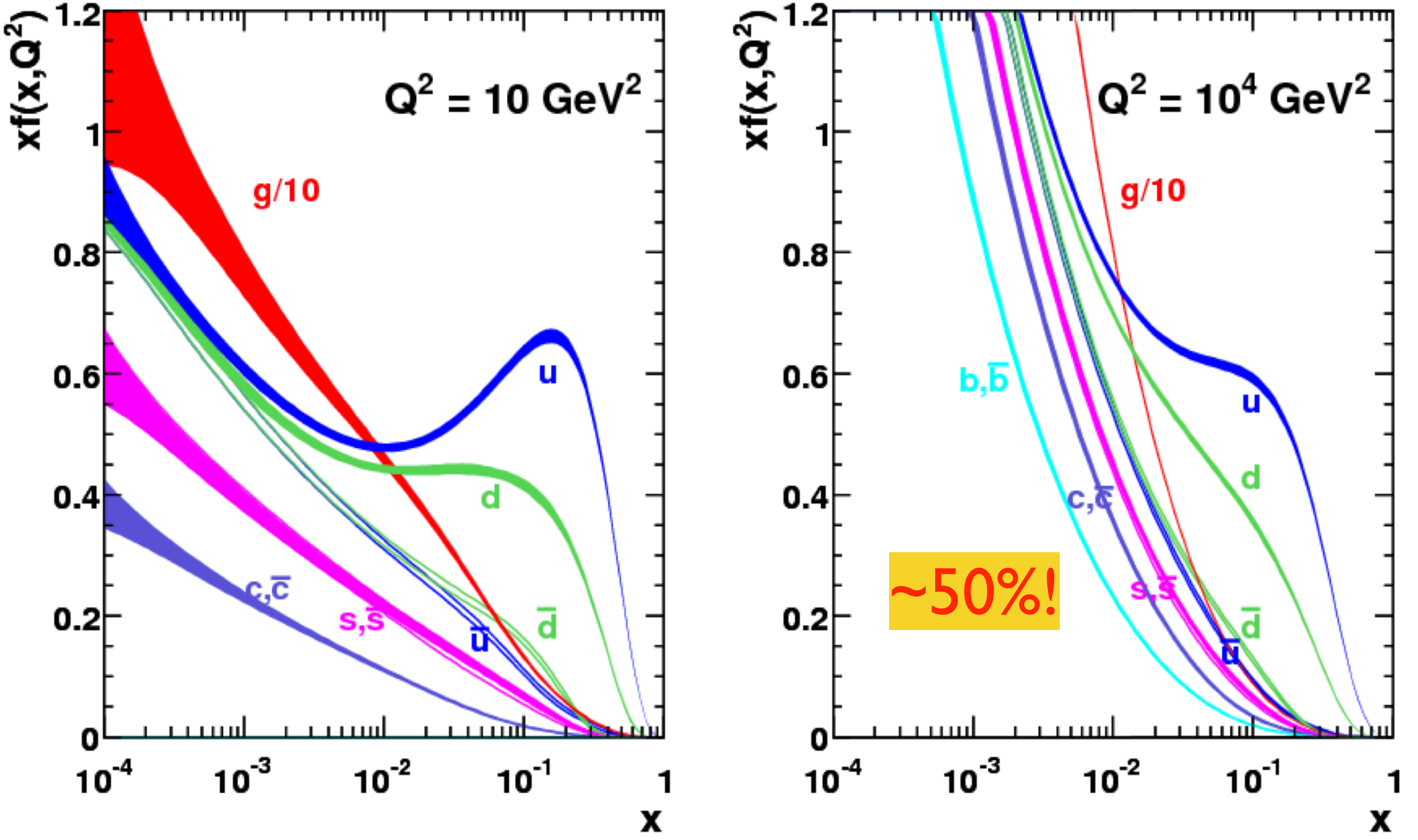




PDFs are universal, they are independent on the hard process

PDFs cannot be calculated in QCD from the first principles!

Parton Distribution Functions



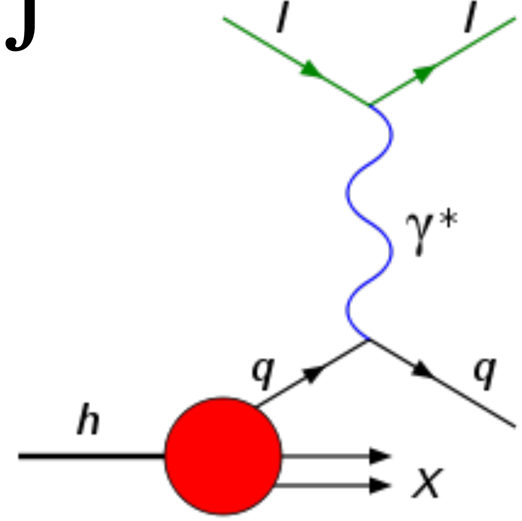
Sea partons becomes more important at high Q²

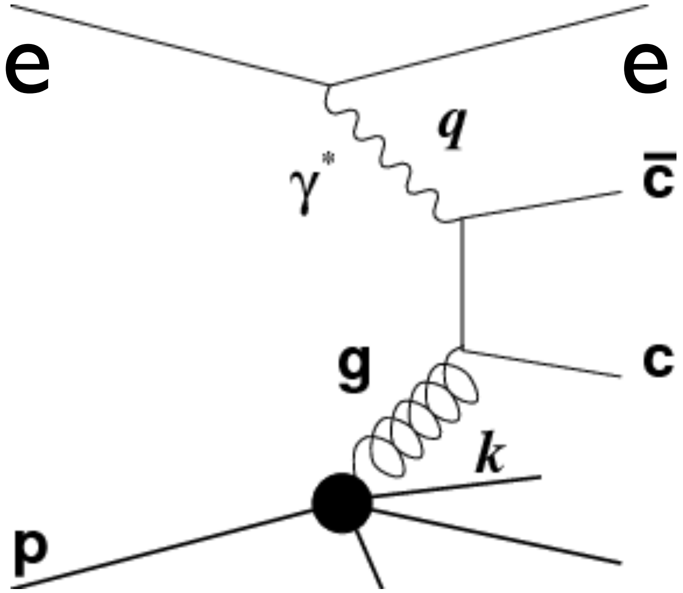
QCD evolution equations: $f(x, Q_1^2) \rightarrow f(x, Q_2^2)$

How to measure PDFs ?

Deep Inelastic Scattering (DIS)

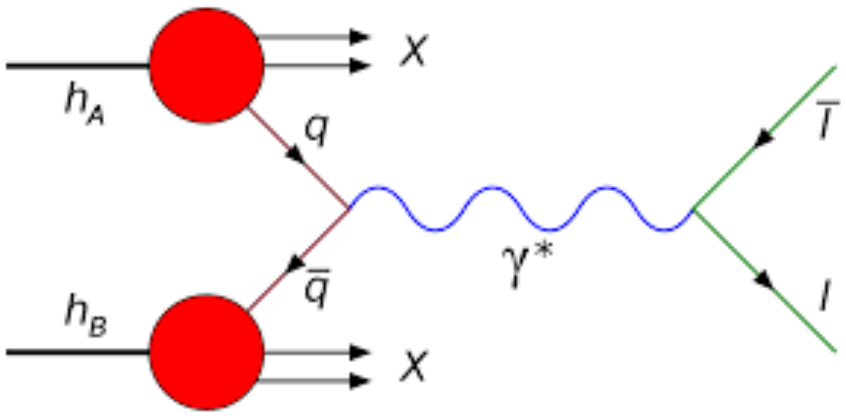
$$\sigma = \int \hat{\sigma} q(x) dx$$

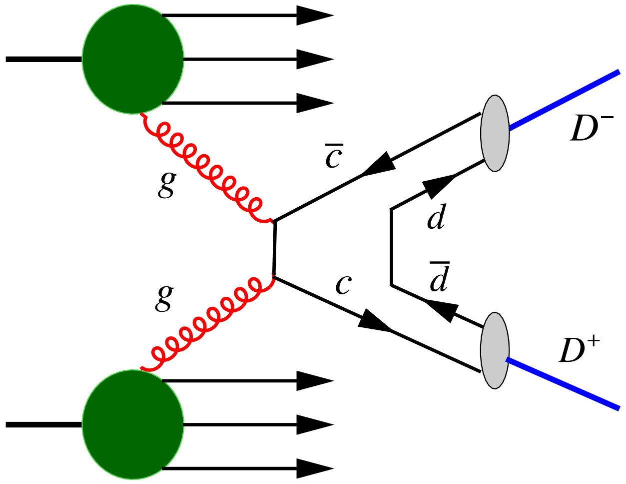




Hadronic interactions

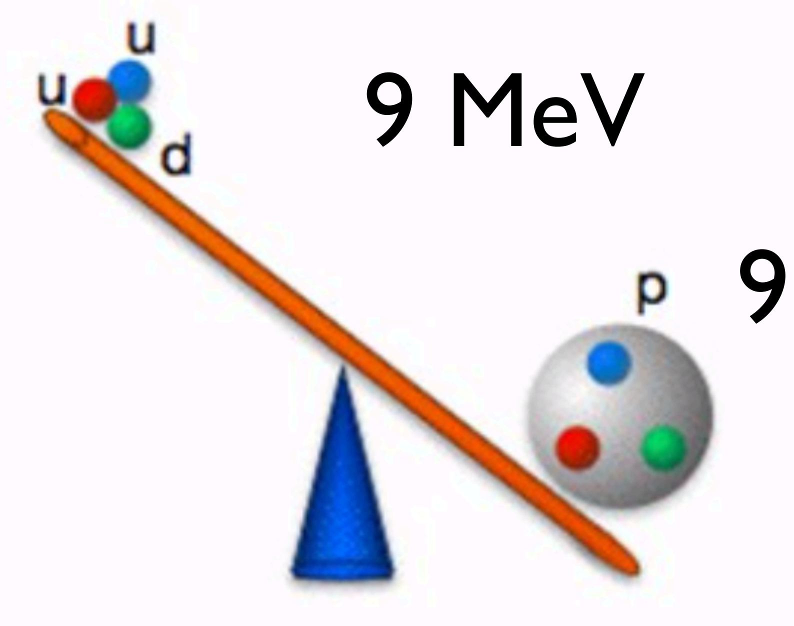
$$\sigma = \int\int \hat{\sigma} q_A(x_A) q_B(x_B) dx_A dx_B$$





CTEQ Collaboration
JAM Collaboration
DSSV Collaboration
NNPDF Collaboration
…

Proton mass

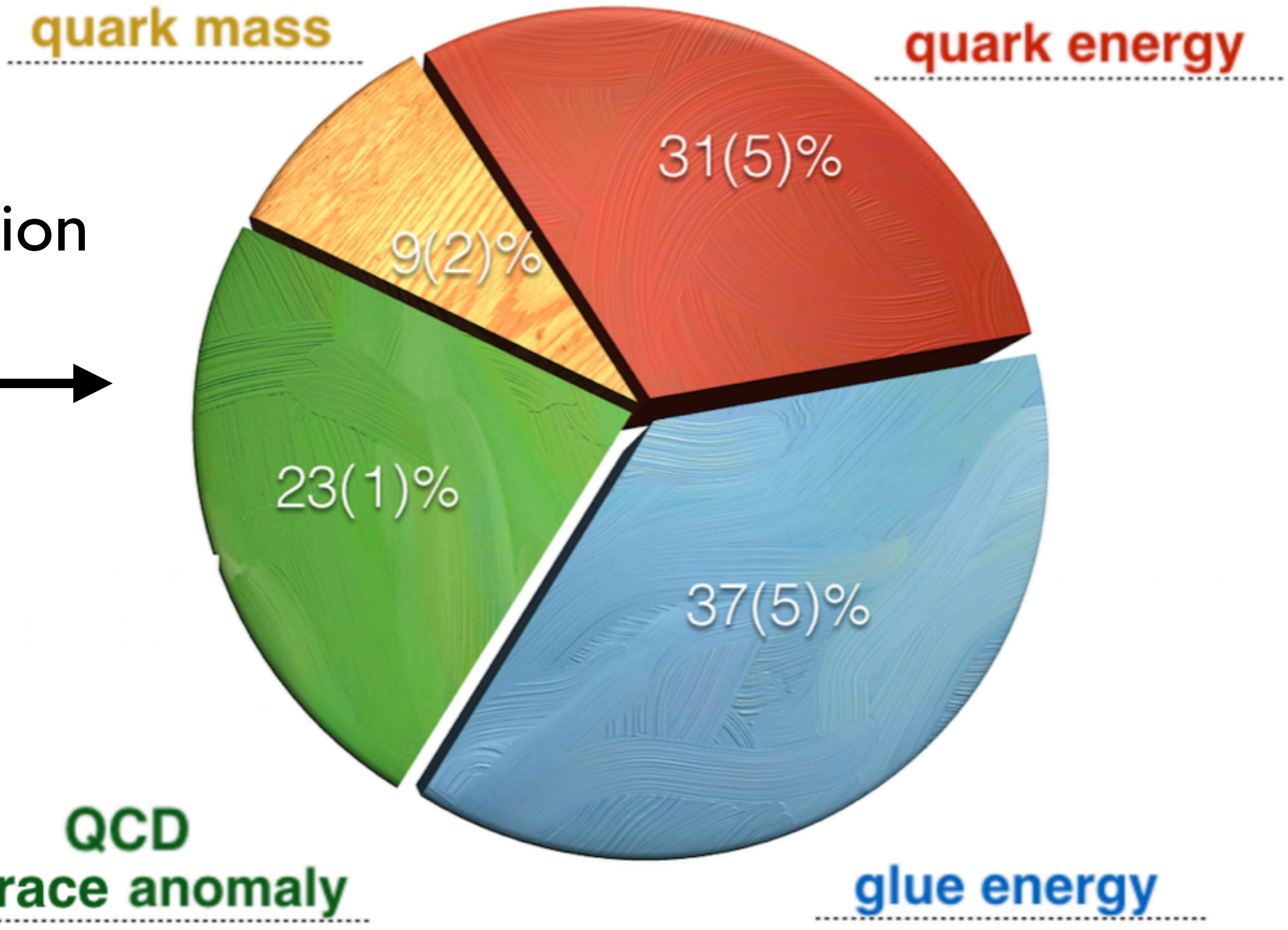


9 MeV

938 MeV

The Higgs mechanism has almost nothing to do with the formation of proton mass!

Model-dependent decomposition of the proton mass



Proton mass

9 MeV

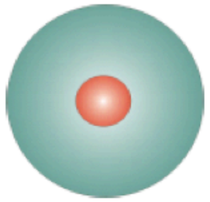
938 MeV

The Higgs mechanism has almost nothing to do with the ... *ss!*

It seems, gluons are even more important than quarks!

Polarized proton

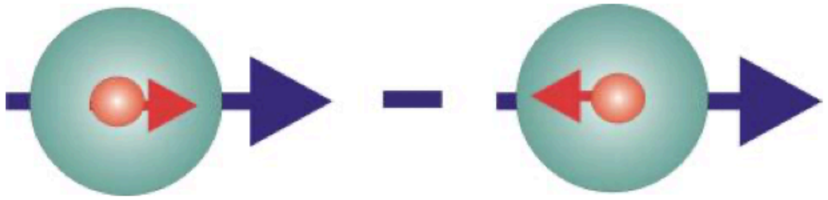
$f(x)$



Unpolarized PDF

Cross section

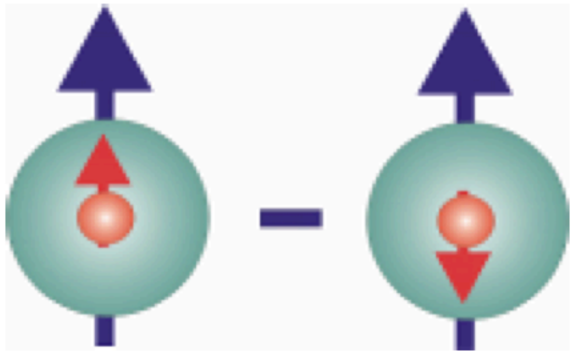
$\Delta f(x)$



Helicity

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \sim \Delta q$$

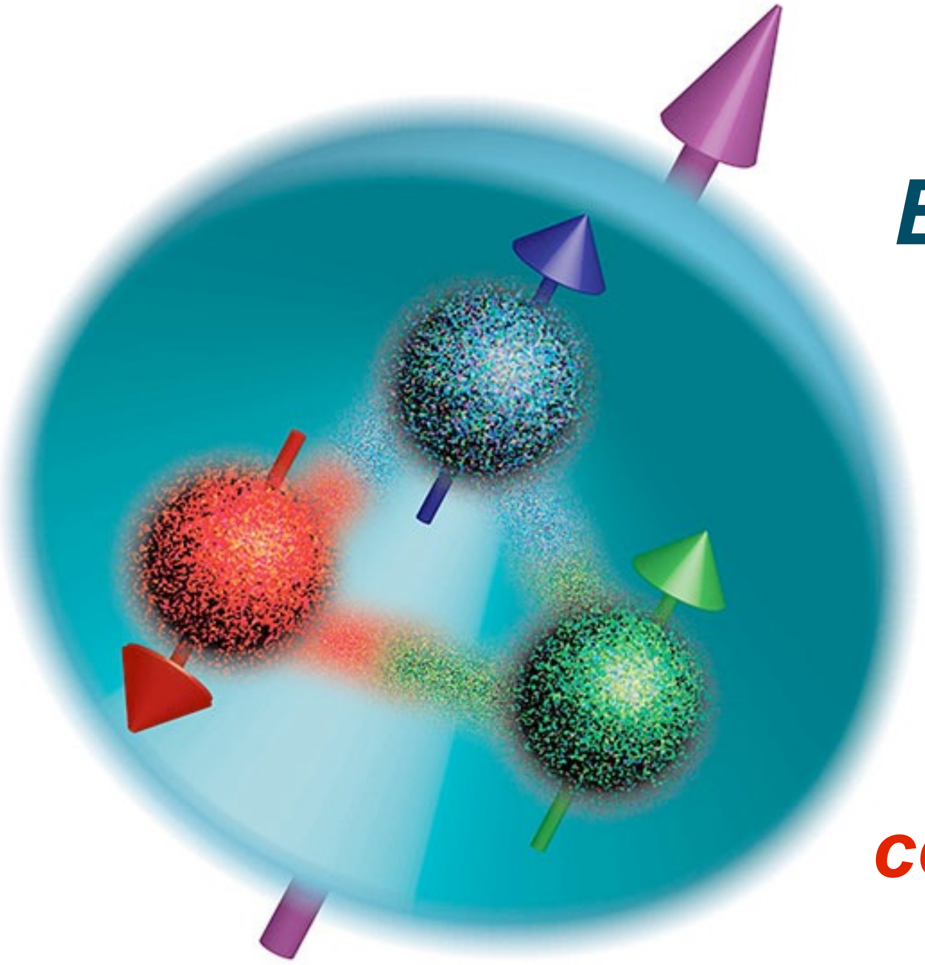
$\Delta_T f(x)$



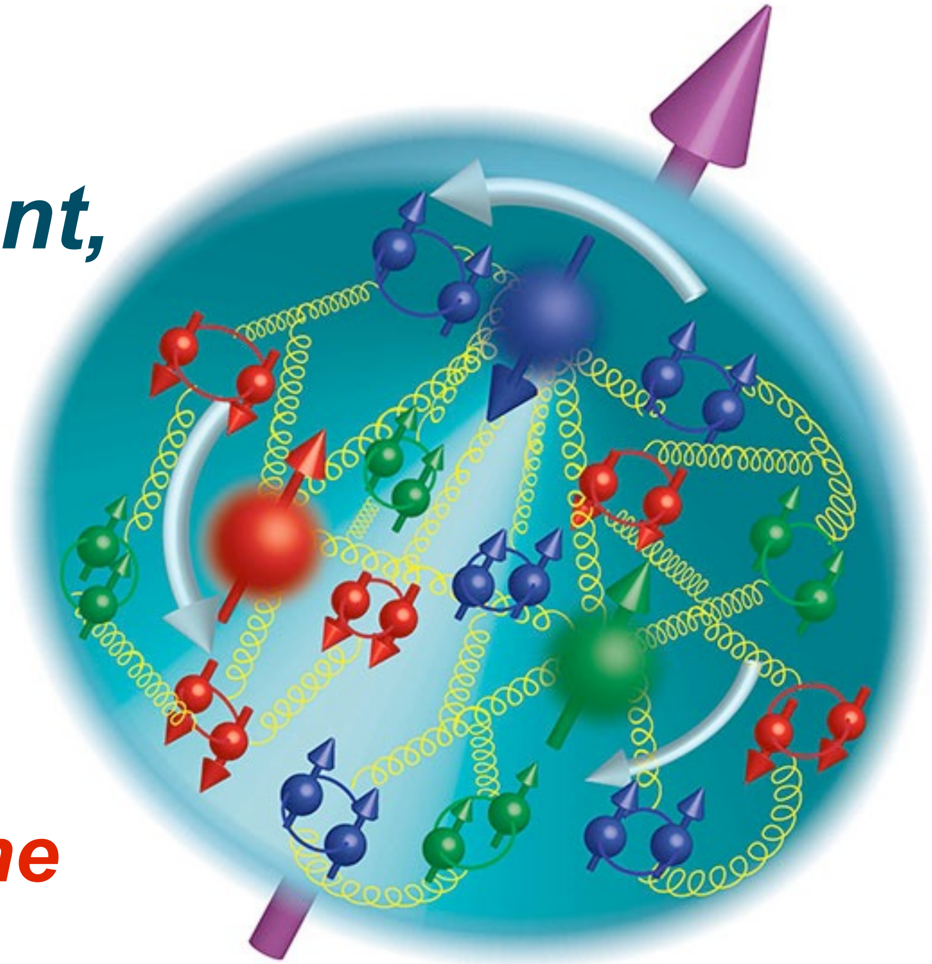
Transversity

Angular asymmetries

Spin crisis



EMC experiment, CERN 1988



Quark contribution to the proton spin is below 30%!

Naive quark model

Real situation

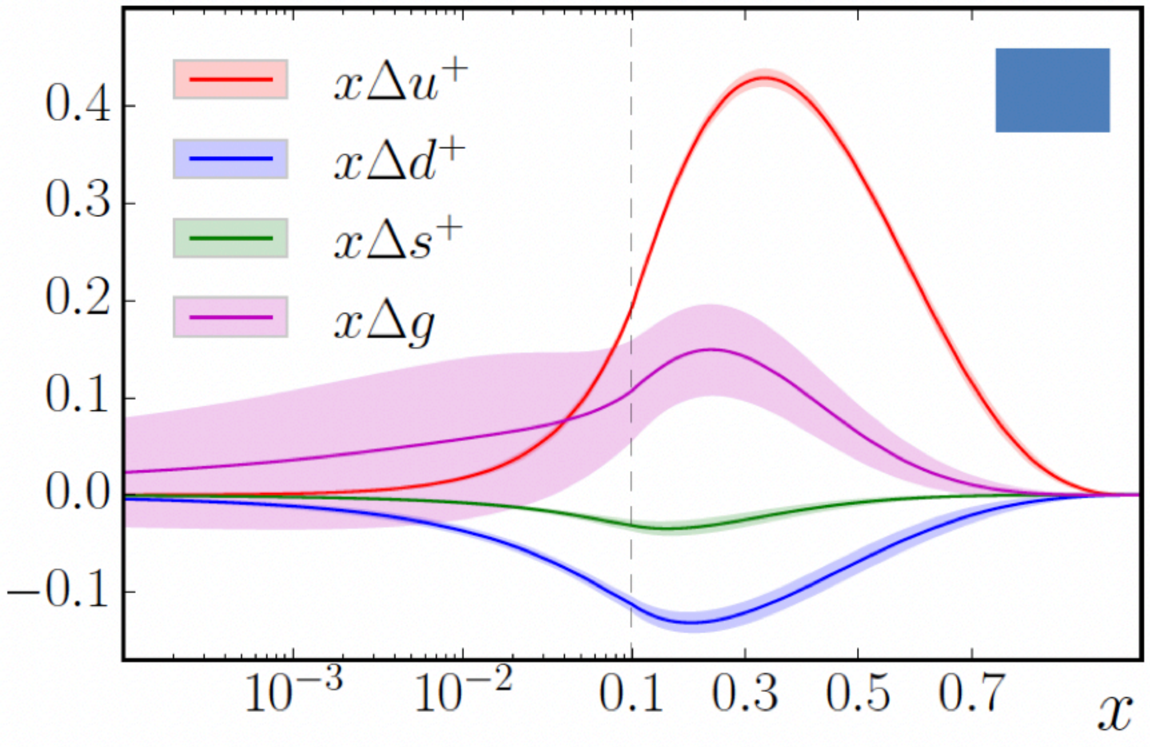
$$\frac{1}{2} = \sum_{q=u,u,d} (\frac{\vec{1}}{2})$$

***L* - orbital moments of quarks and gluons**

$$S_N = ½ = ½\,\Delta\Sigma + \Delta G + L$$

Spin crisis

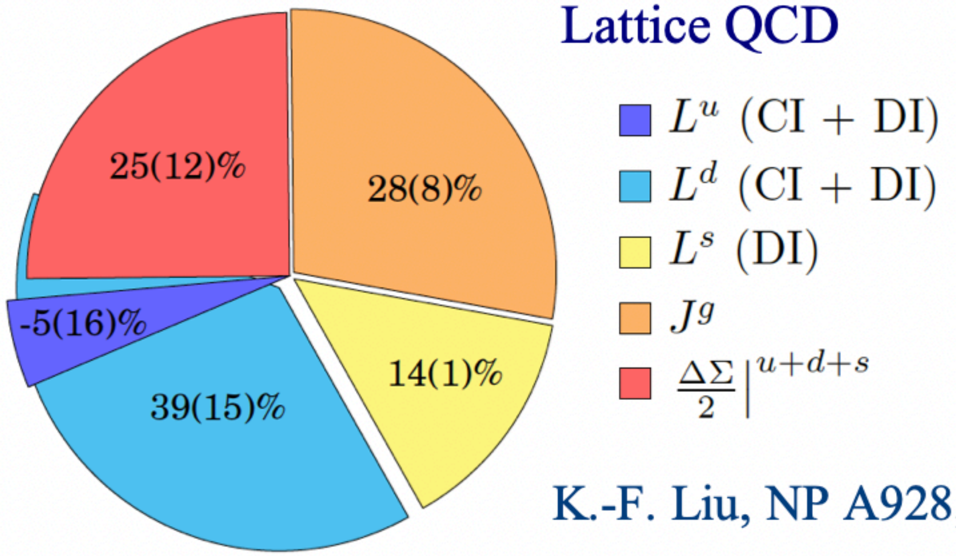
$$J = \overset{\sim 30\%}{\frac{1}{2}\Delta\Sigma} + \underset{\sim 10\text{-}20\%}{\Delta G} + \overset{?}{L_q} + \overset{?}{L_g}$$



JAM Collaboration, PRD (2016).

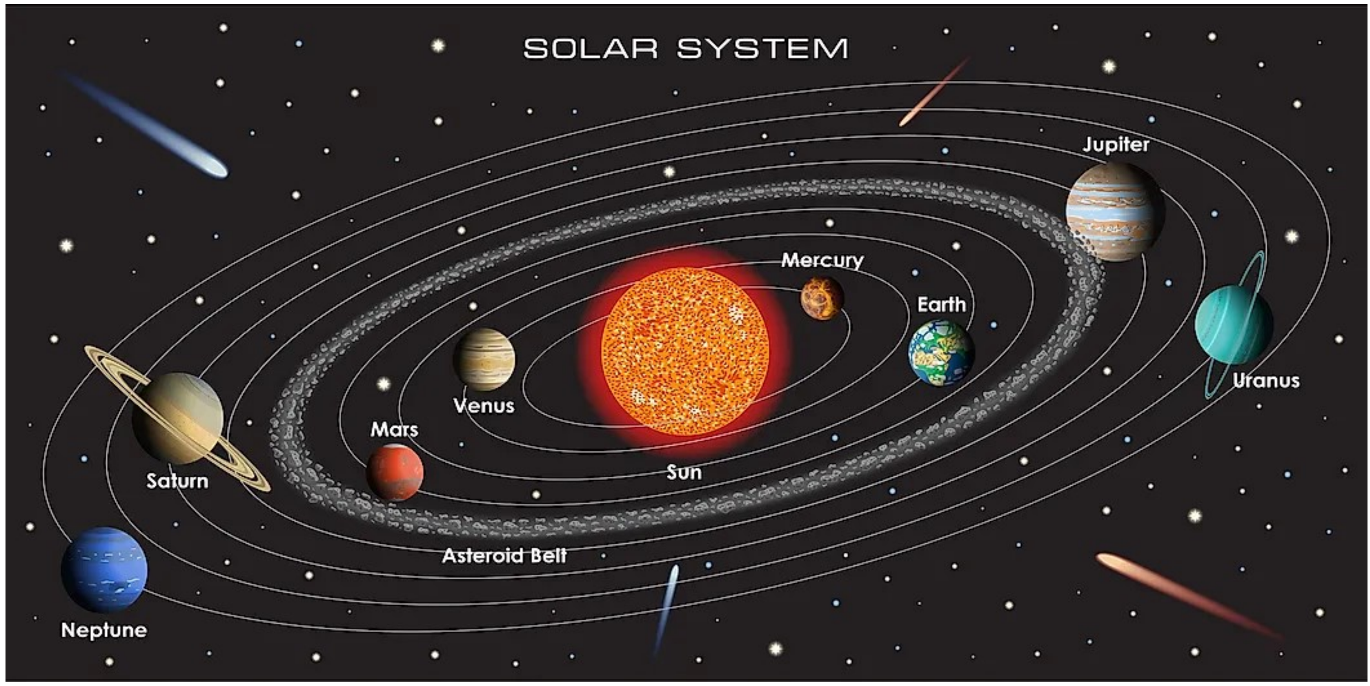
To access the angular momenta we must study the 3D structure of the nucleon!

Lattice QCD



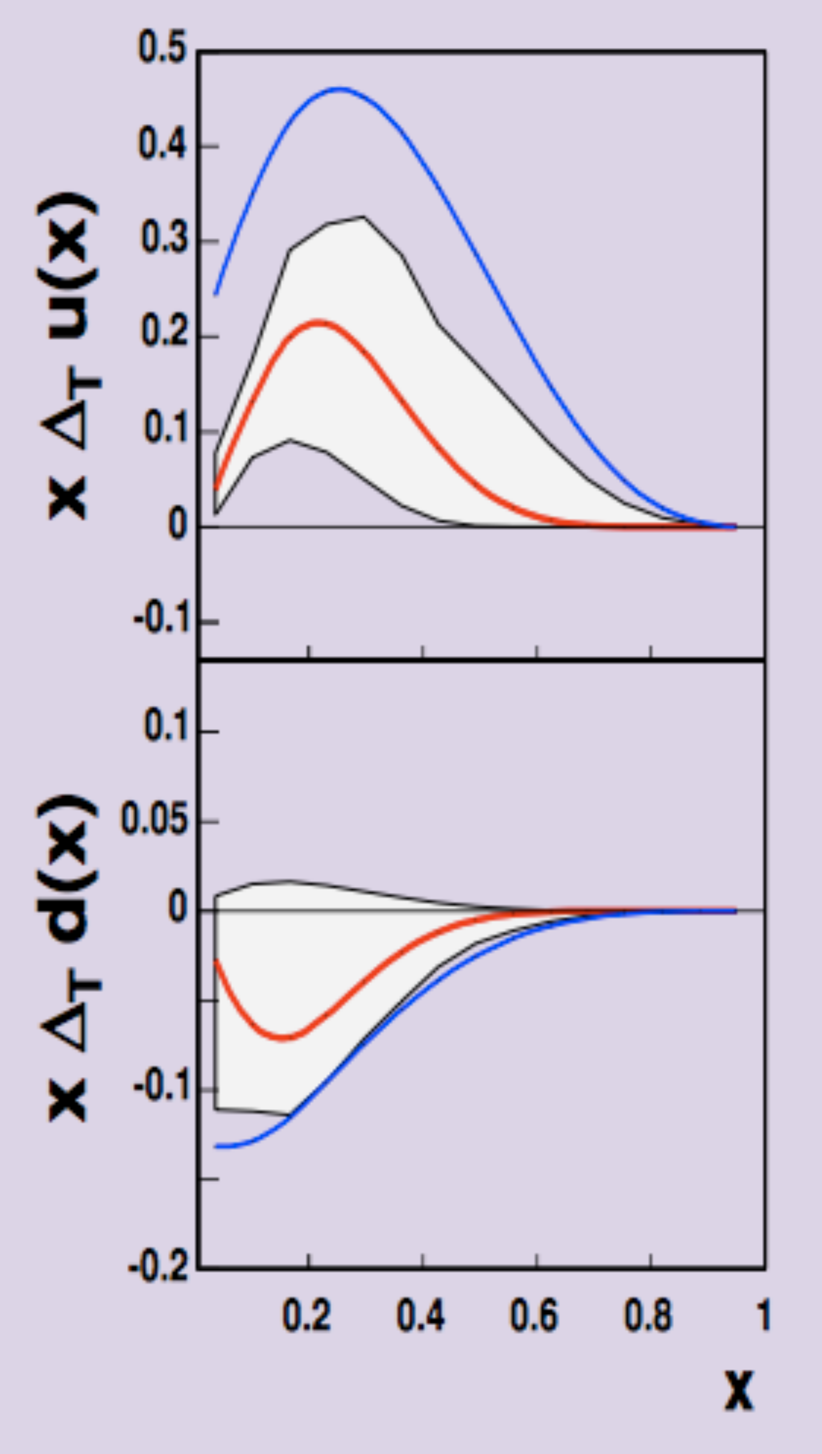
K.-F. Liu, NP A928, 99 (2014).

For Solar System



98% is angular moment!

Transversity Δ_T or h_1

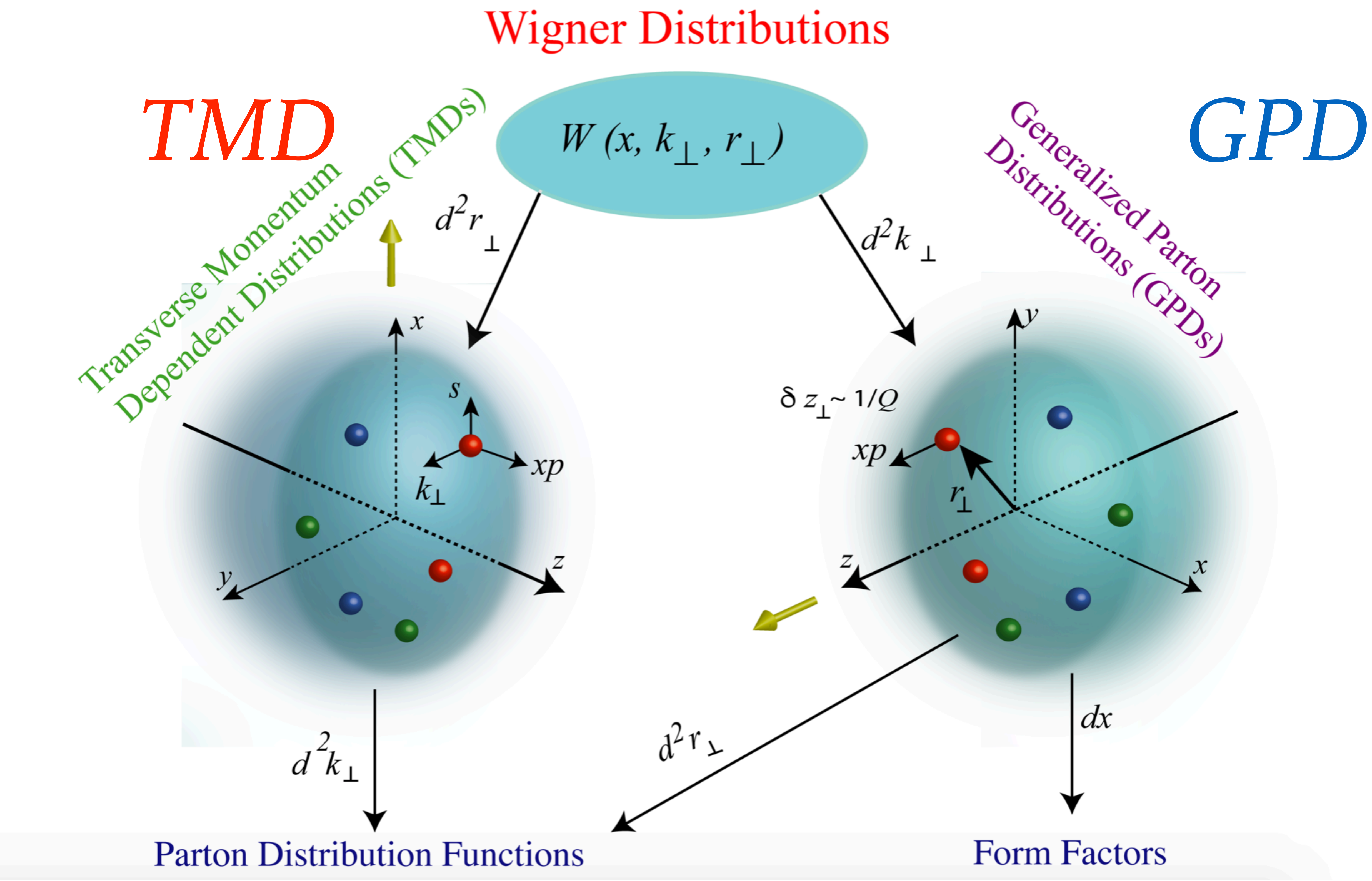


- *u and d quarks are polarized in opposite directions*

- *uncertainty is too high*

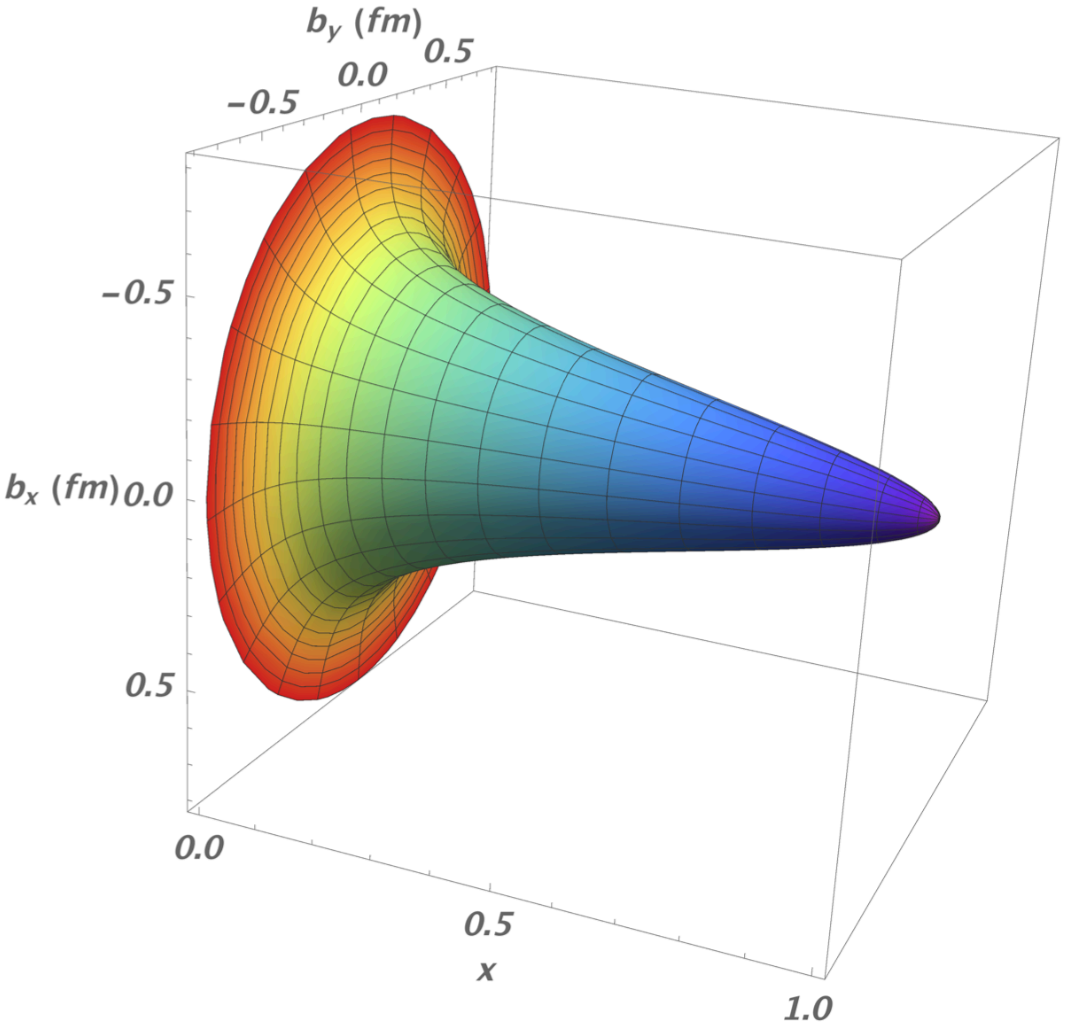
- *no sense for gluons in nucleon*

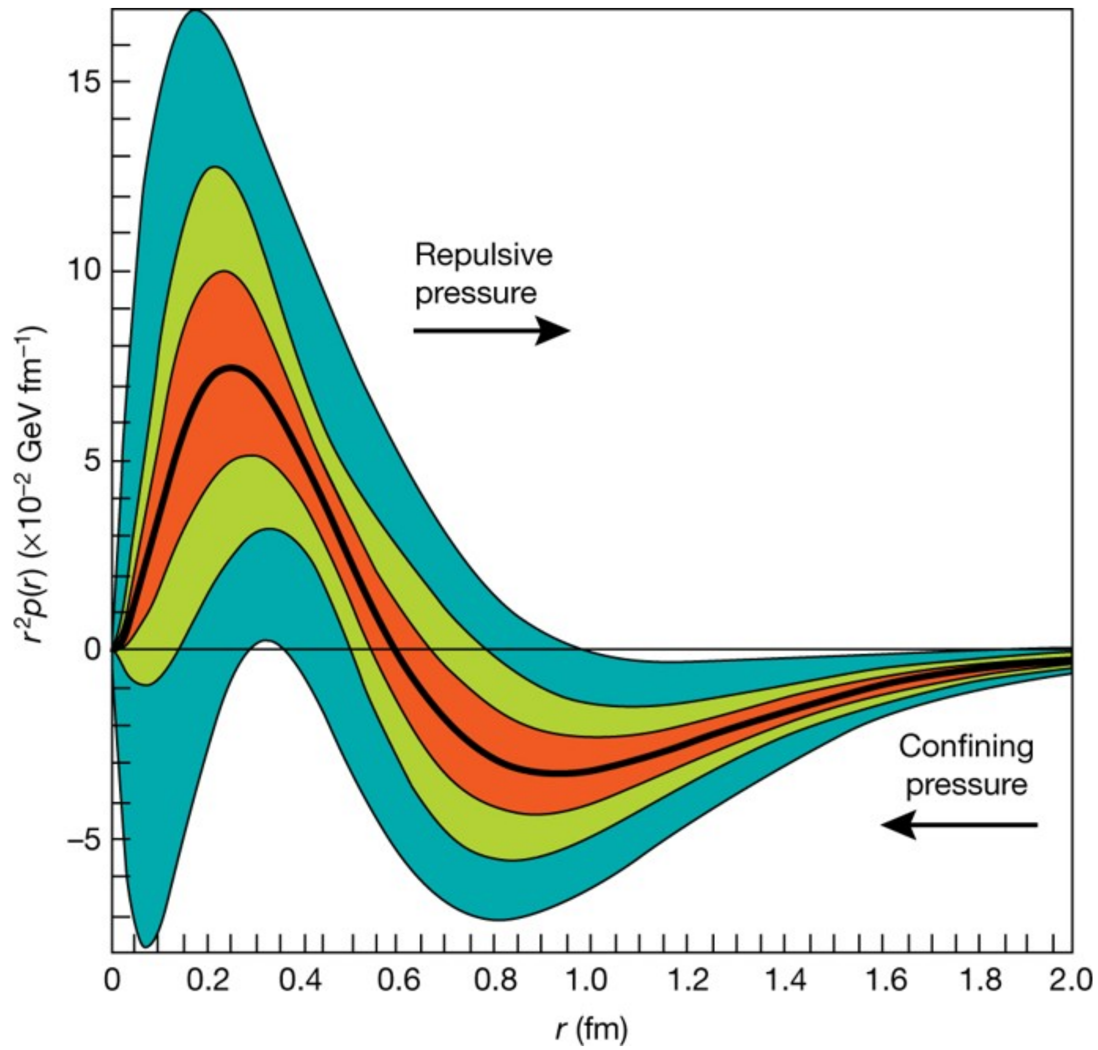
3D-tomography of proton



3D-proton & GPD

The size of the proton depends on which scale x we touch it !

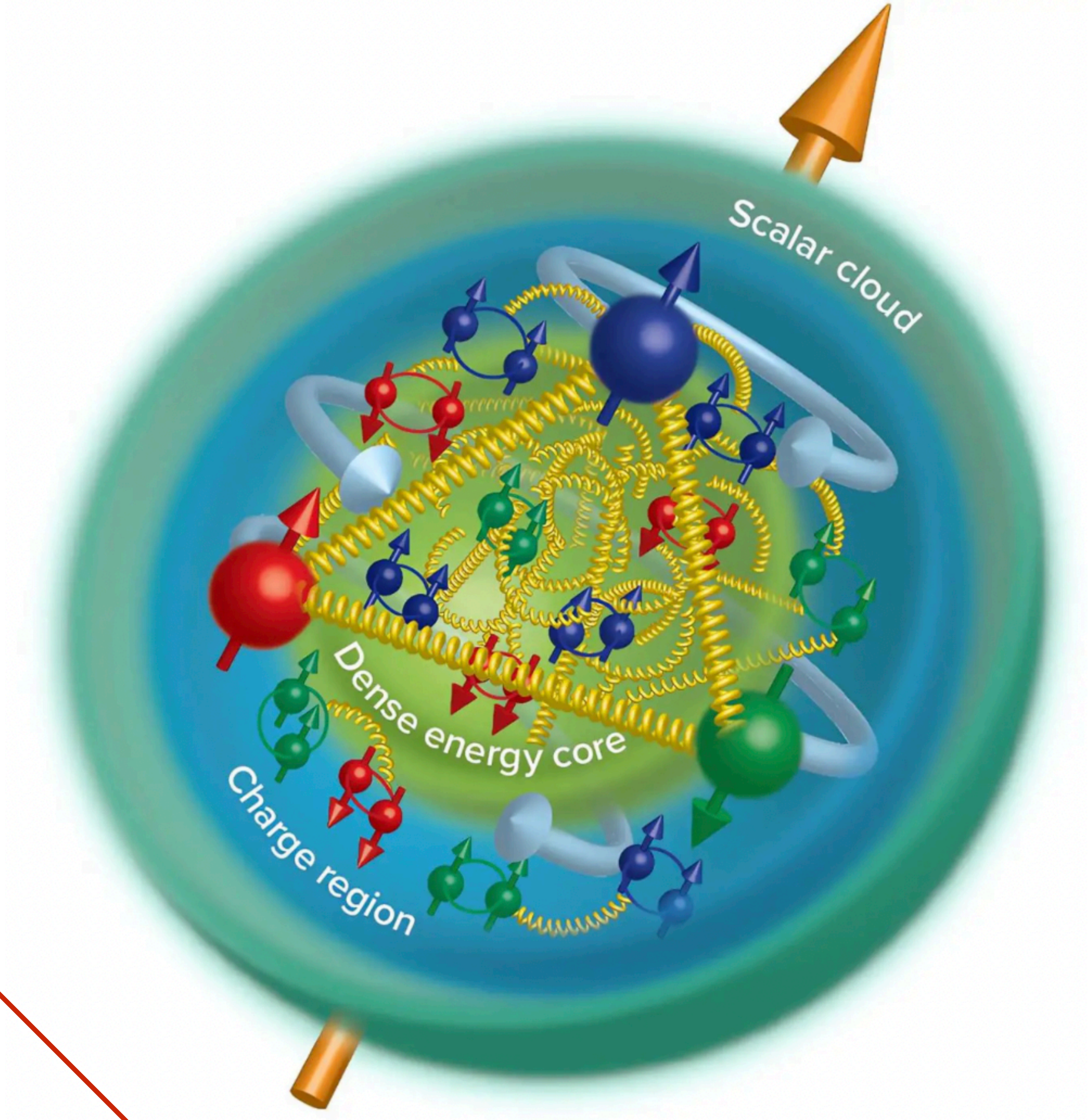




Pressure of the hadronic matter in the proton is about 10^{34} Pa!

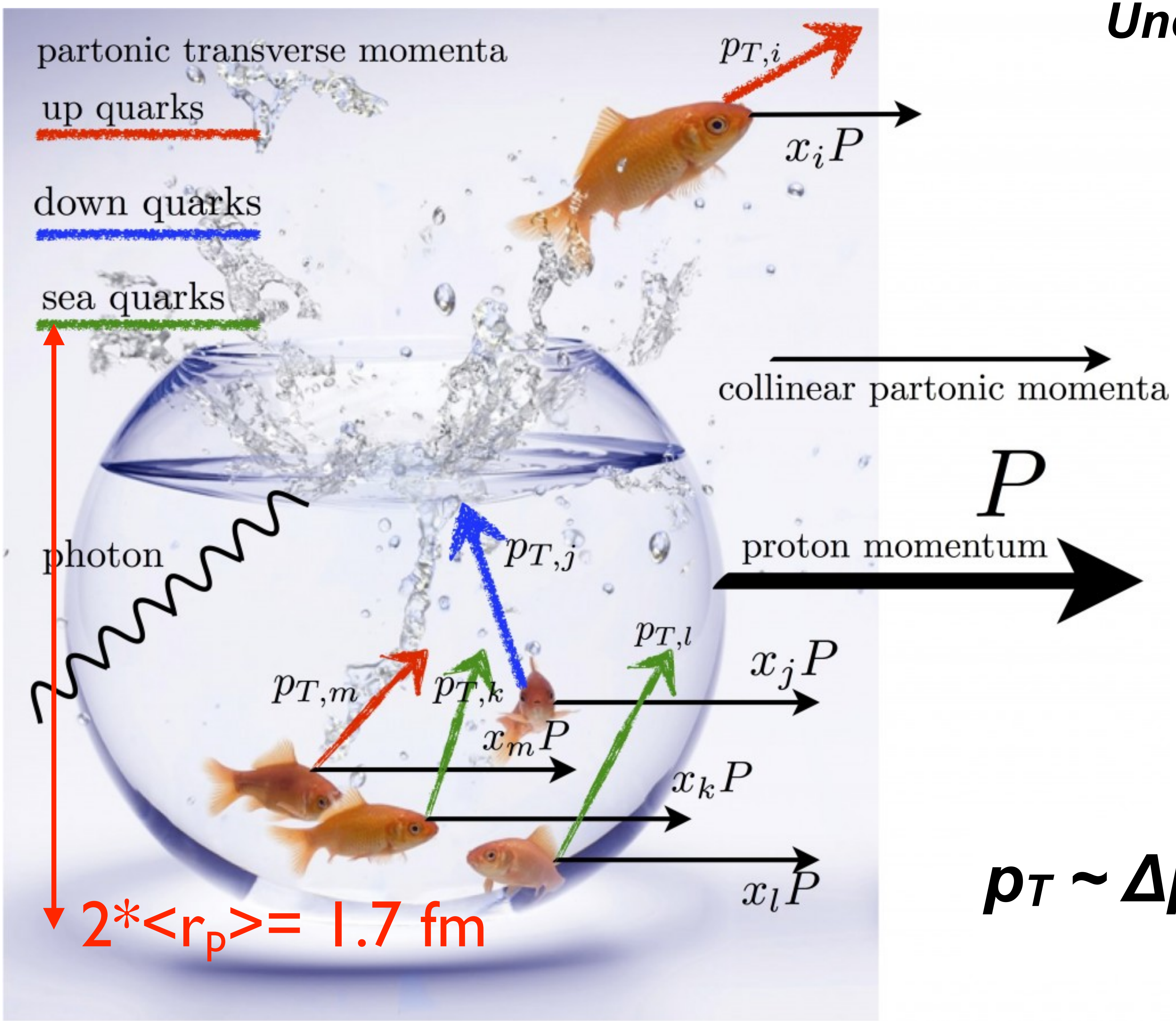
Three proton radii

	Distribution	R, fm
charge	Electric charge	0.84
mass	Mass (gluons)	0.5 - 0.75
weak	Weak charge	1.55



GPD-based calculations

Where transverse momentum come from?



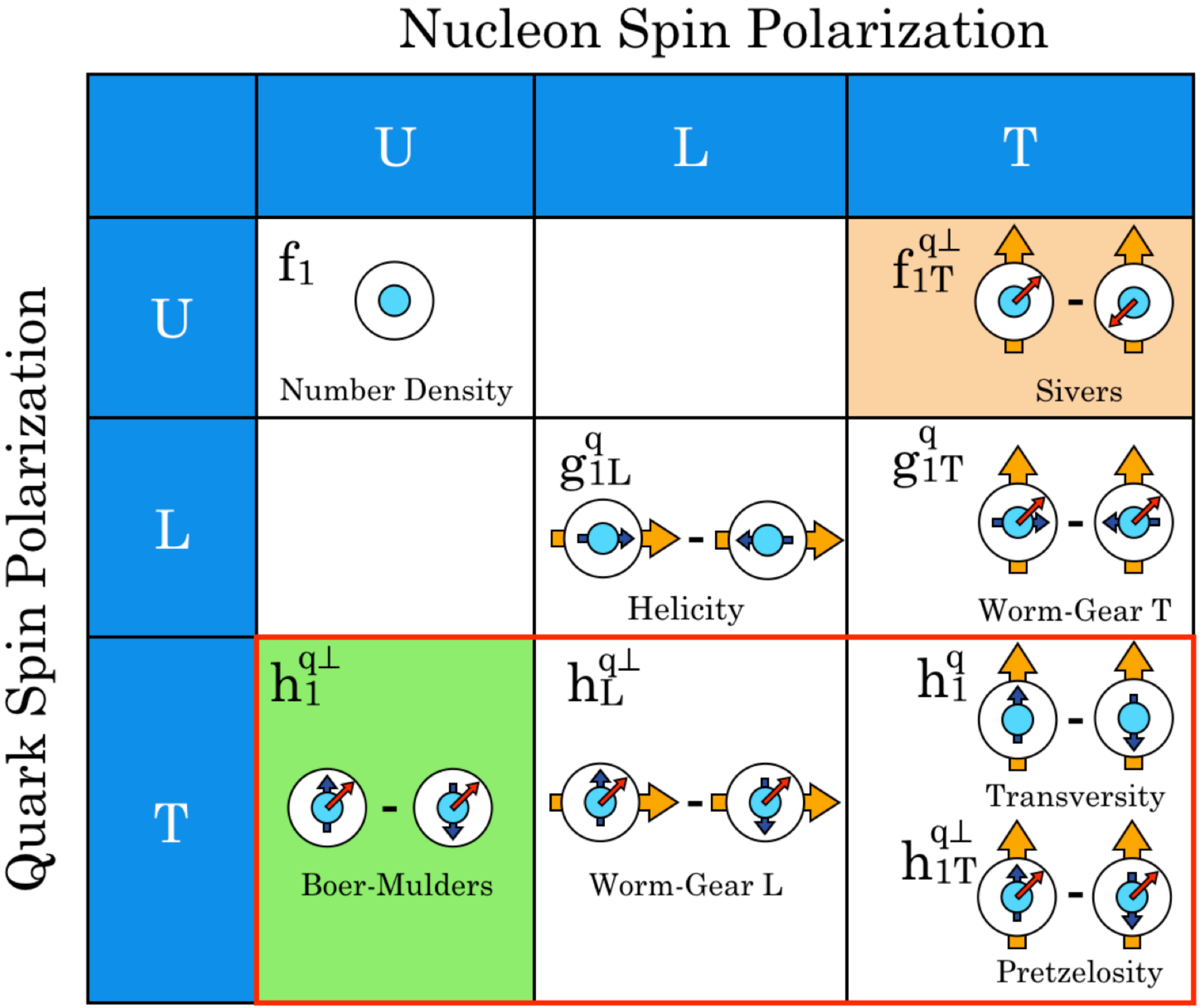
Uncertainty relation:

$$\Delta p_y \Delta y \geq \frac{h}{2\pi}$$

$$\Delta y \sim 2\langle r_p\rangle$$

$$p_T \sim \Delta p_y \geq 0.1\ \mathrm{GeV}/c$$

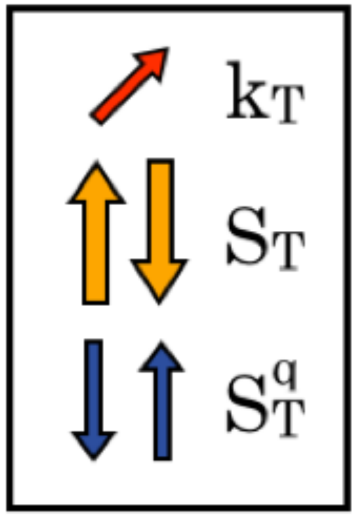
TMD PDF



Nucleon Spin Polarization

Quark Spin Polarization

	U	L	T
U	f_1 Number Density		$f_{1T}^{q\perp}$ Sivers
L		g_{1L}^{q} Helicity	g_{1T}^{q} Worm-Gear T
T	$h_1^{q\perp}$ Boer-Mulders	$h_L^{q\perp}$ Worm-Gear L	h_1^{q} Transversity $h_{1T}^{q\perp}$ Pretzelosity

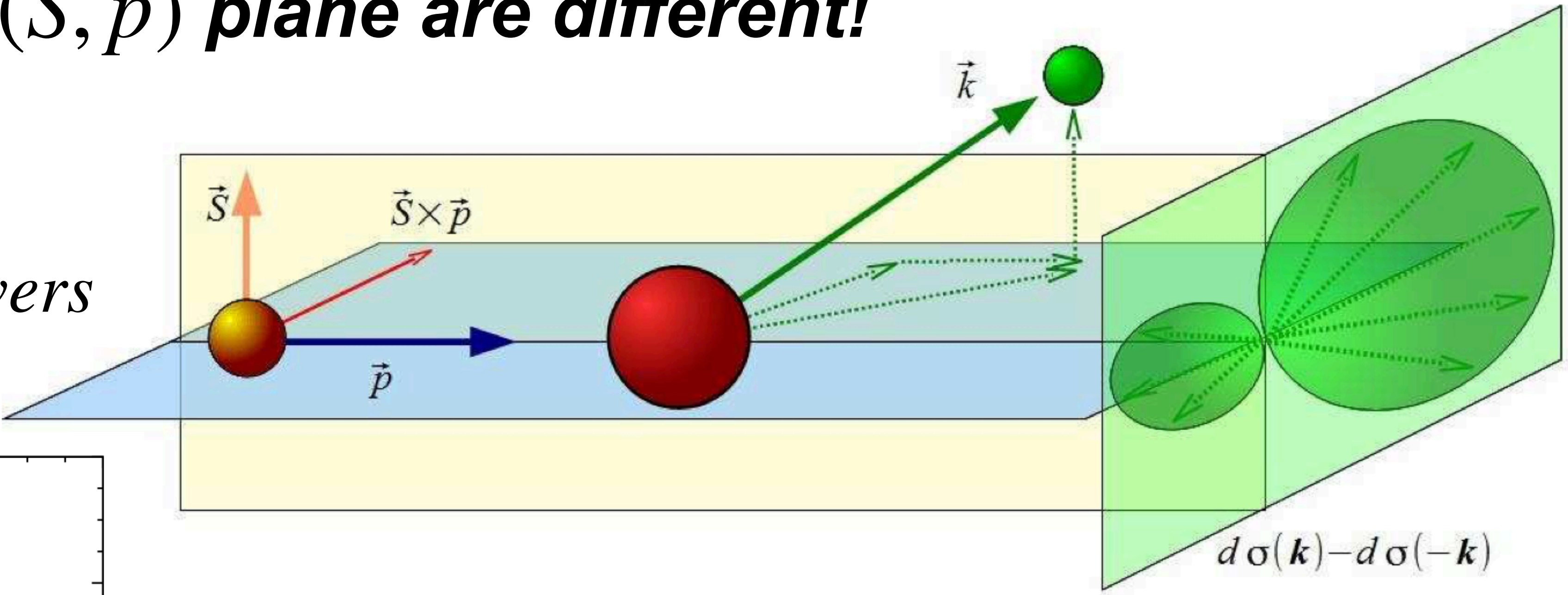


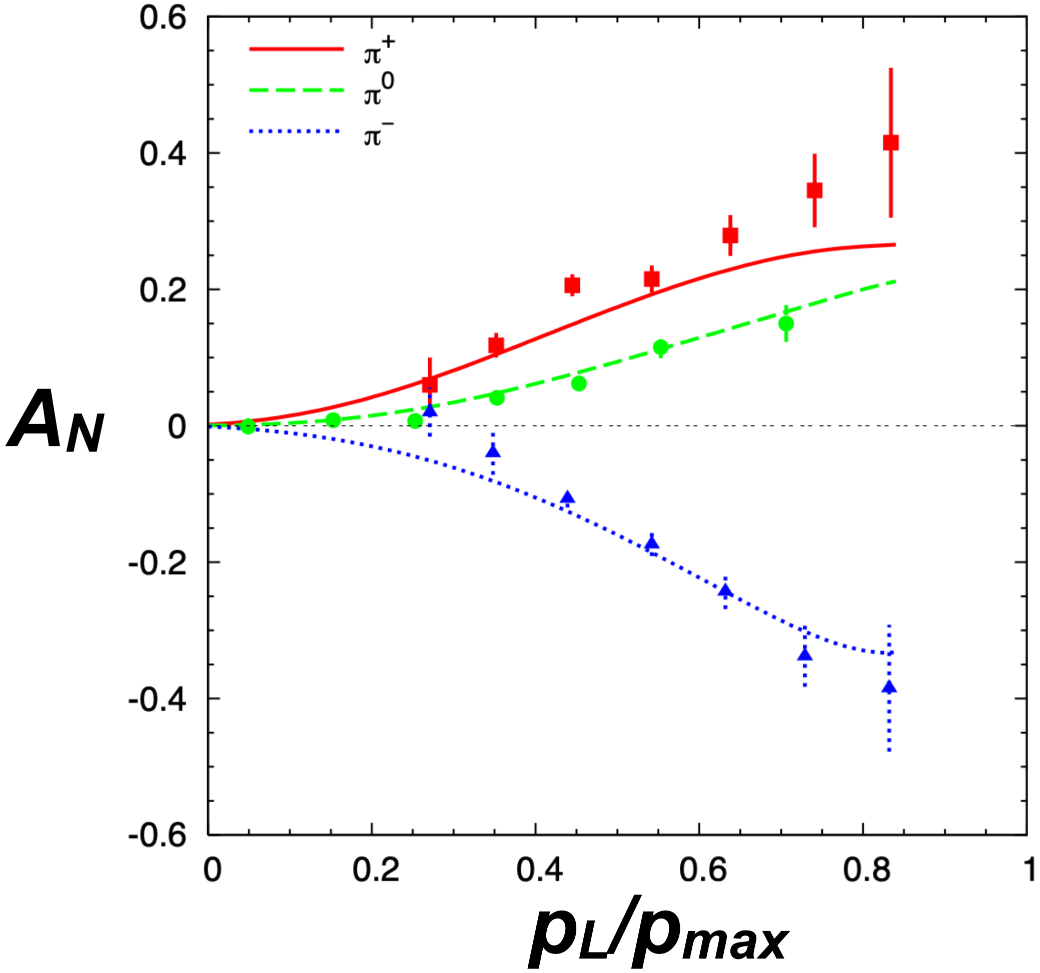
5 additional (TMD) functions describing the correlation between the nucleon spin, parton spin, and parton transverse momentum.

TMD effects: Sivers effect

Probabilities to meet in a transversely polarized proton a parton moving to the left and to the right with respect to the $(\vec{S},\vec{p})$ plane are different!

$$A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \sim f_{Sivers}$$

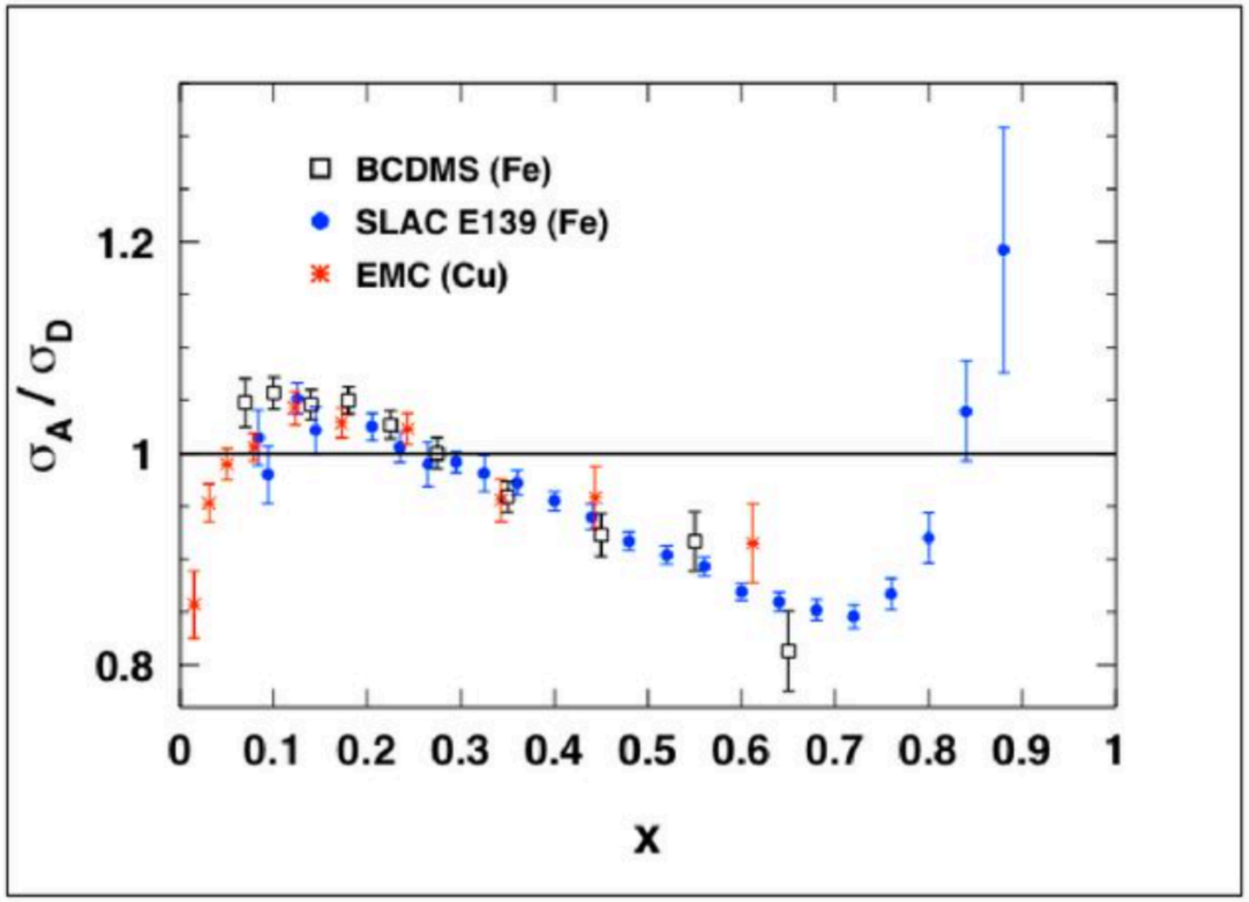




E704

The Sievers effect is usually observed together with the Collins effect, an asymmetry arising from the fragmentation of the final state.

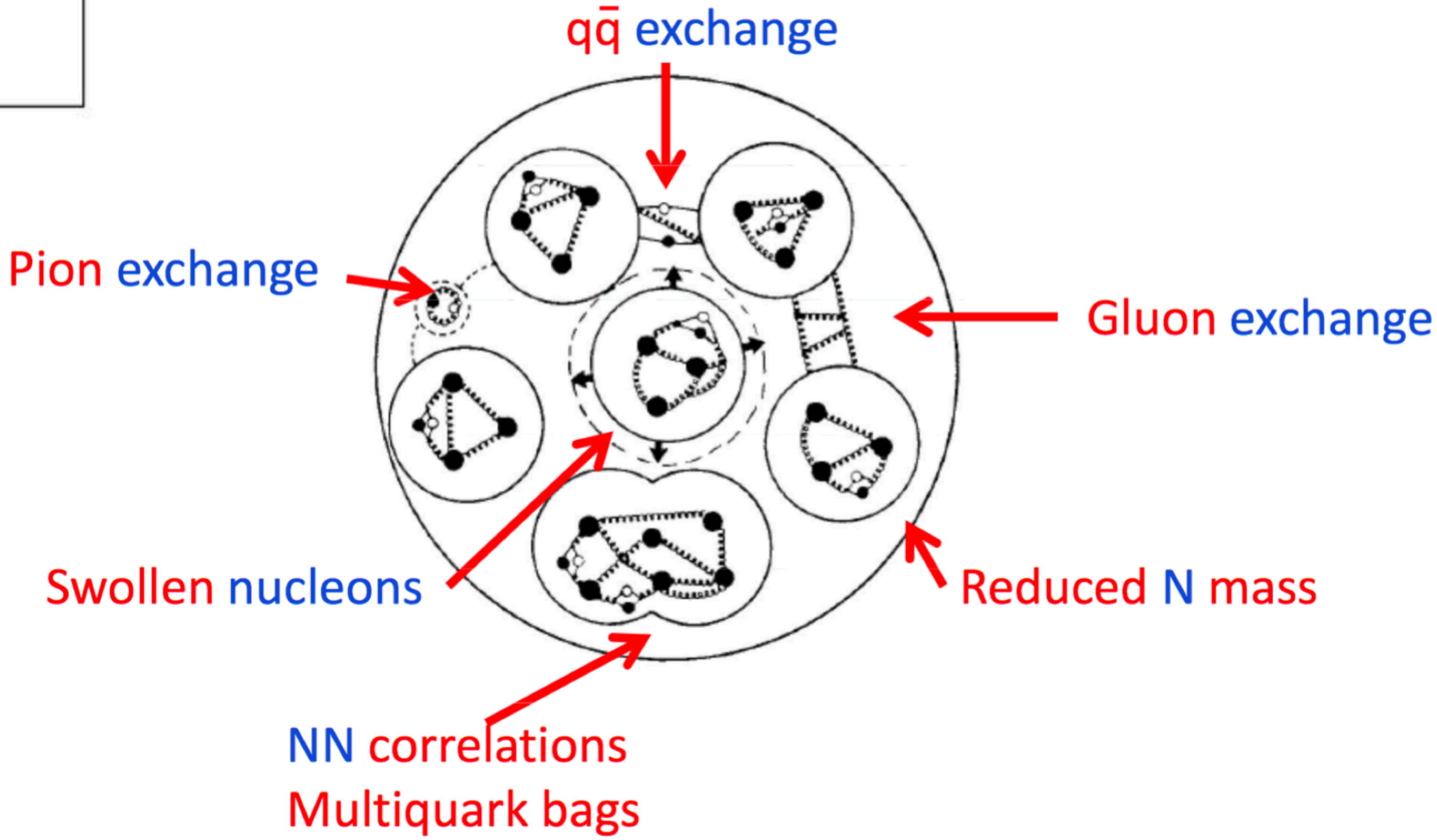
EMC-effect



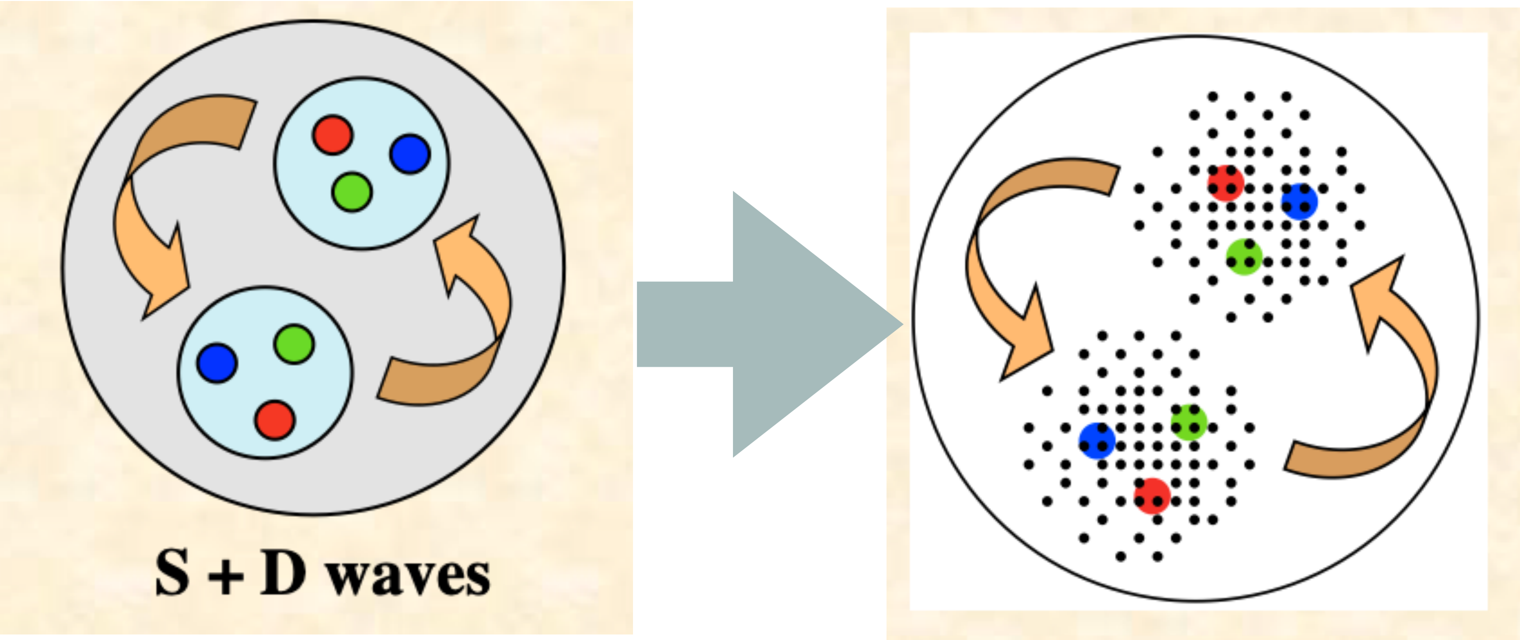
EMC collaboration, 1982

The nucleon "knows" which nucleus it is in!

x>1 is possible!



Deuteron

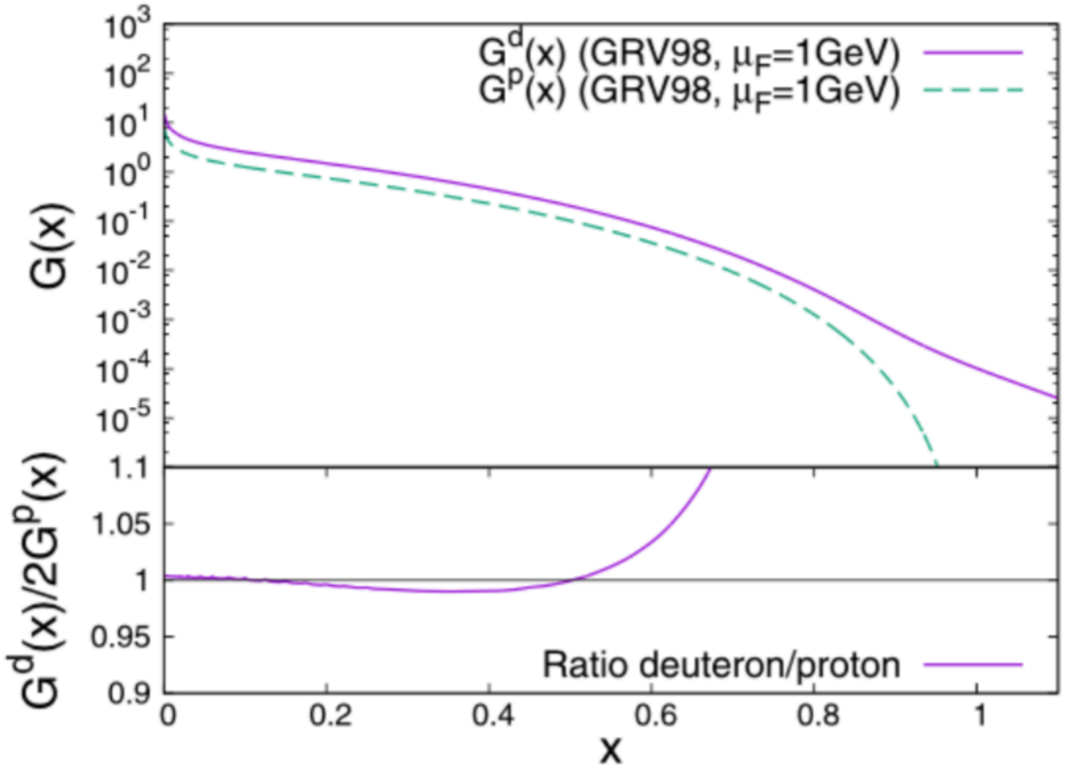


Deuteron is not just proton + neutron!

$$|6q\rangle = c_1|NN\rangle + c_2|\Delta\Delta\rangle + \boxed{c_3|CC\rangle}$$

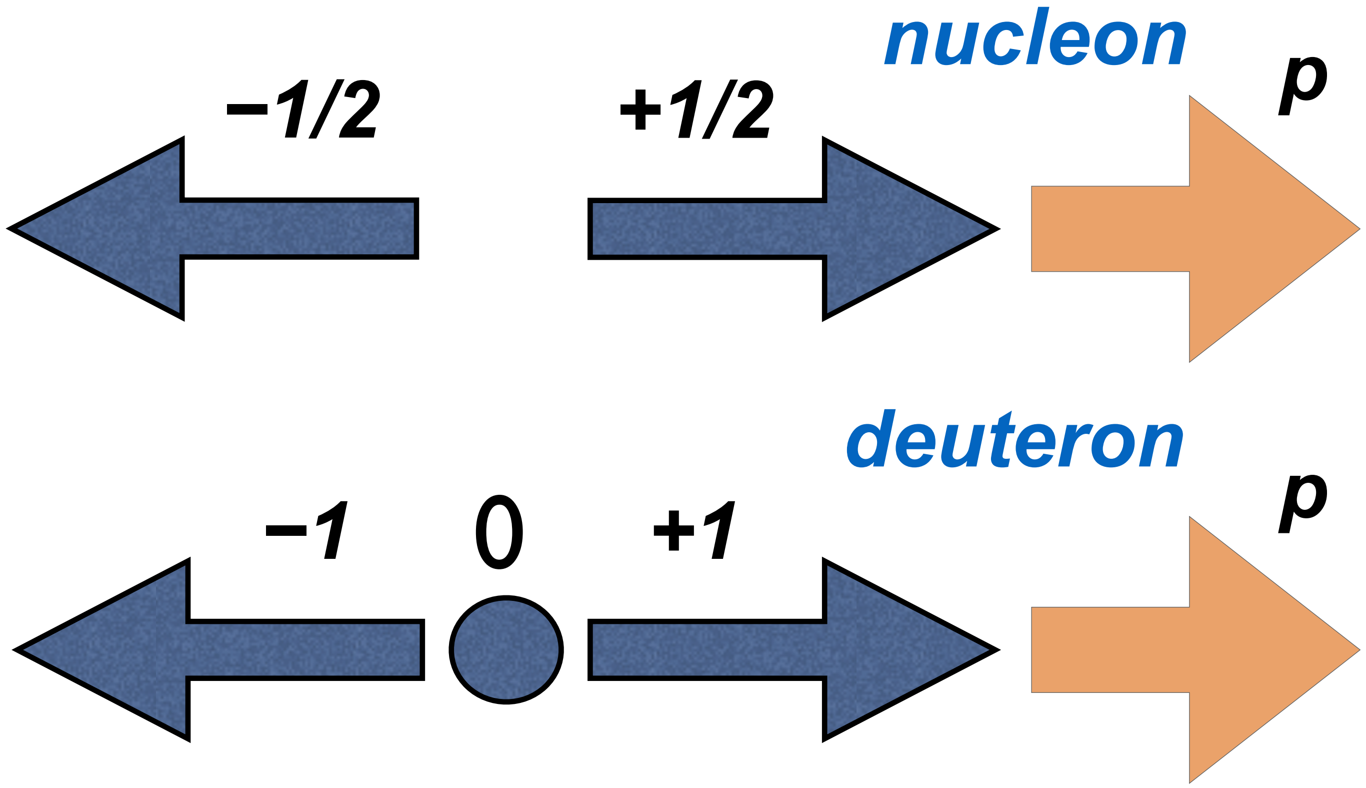
hidden color

In some models the HC fraction is up to 90%!



More gluons at large x with respect to nucleon?

Deuteron as spin-1 particle



Vector polarization

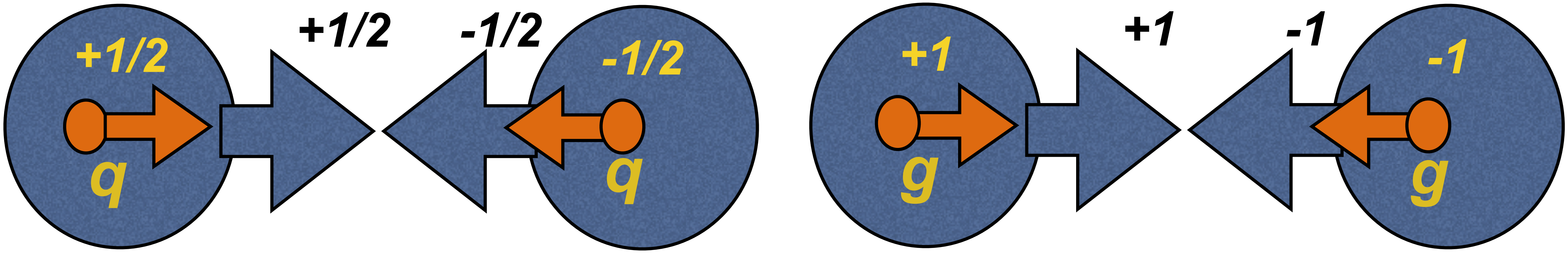
$$\frac{N_{1/2} - N_{-1/2}}{N_{1/2} + N_{-1/2}}$$

Tensor polarization

$$\frac{2N_0 - (N_{-1} + N_1)}{2N_0 + N_{1/2} + N_{-1/2}}$$

New "tensor" PDFs, mostly unknown

New possibilities for gluons:



hard processes with gluon spin flip are impossible in spin-1/2 nucleon

but possible in deuteron!

Open questions

- Nucleon PDFs at low x
- Unpolarized and polarized 3-D structure of nucleon
- Partonic structure of other hadrons
- Flavor-dependent and gluon EMC-effect
- Polarized EMC-effect
- Polarized structure of nuclei with spin ≥1
- Factorization tests
- Proton radius puzzle
- …

Hadron structure: main actors

DESY

hermes

BNL

PHENIX

STAR

sPHENIX

EICC

EIC

ECCE

JLAB

CLAS12

SoLID

GlueX

Fermilab

SeaQuest

E906

SPIN QUEST

JINR

SPD

NICA

CERN

COMPASS

AMBER

LHC spin

AFTER

Spin Physic Detector @ NICA

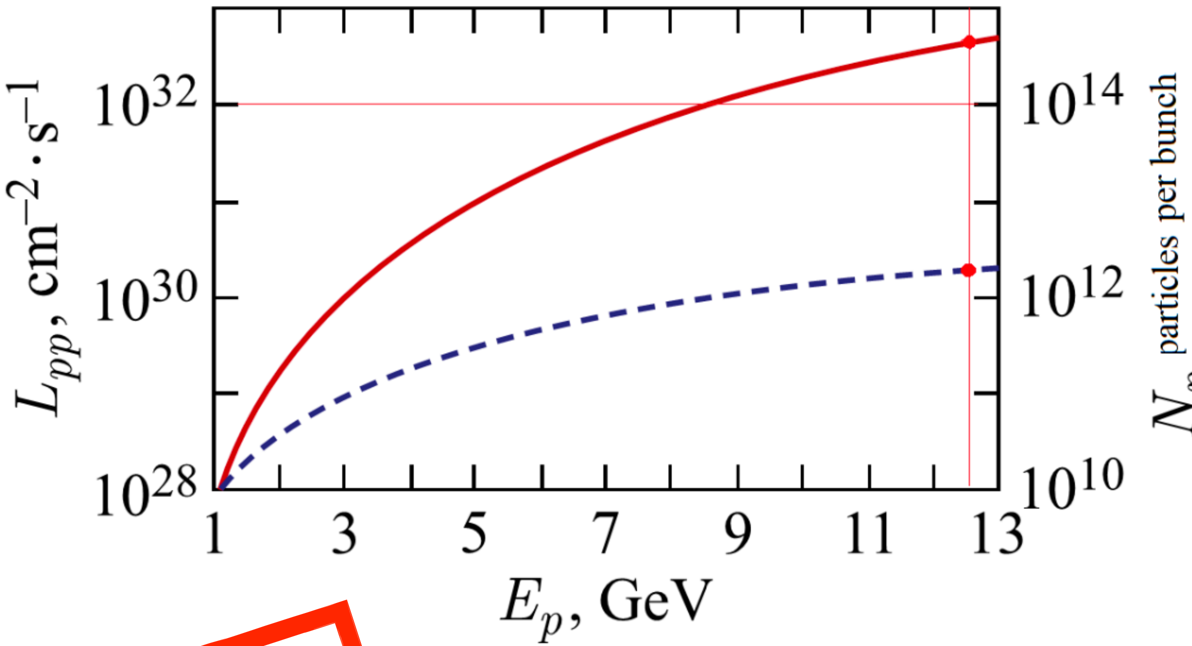
NICA - Nuclotron-based Ion Collider fAcility

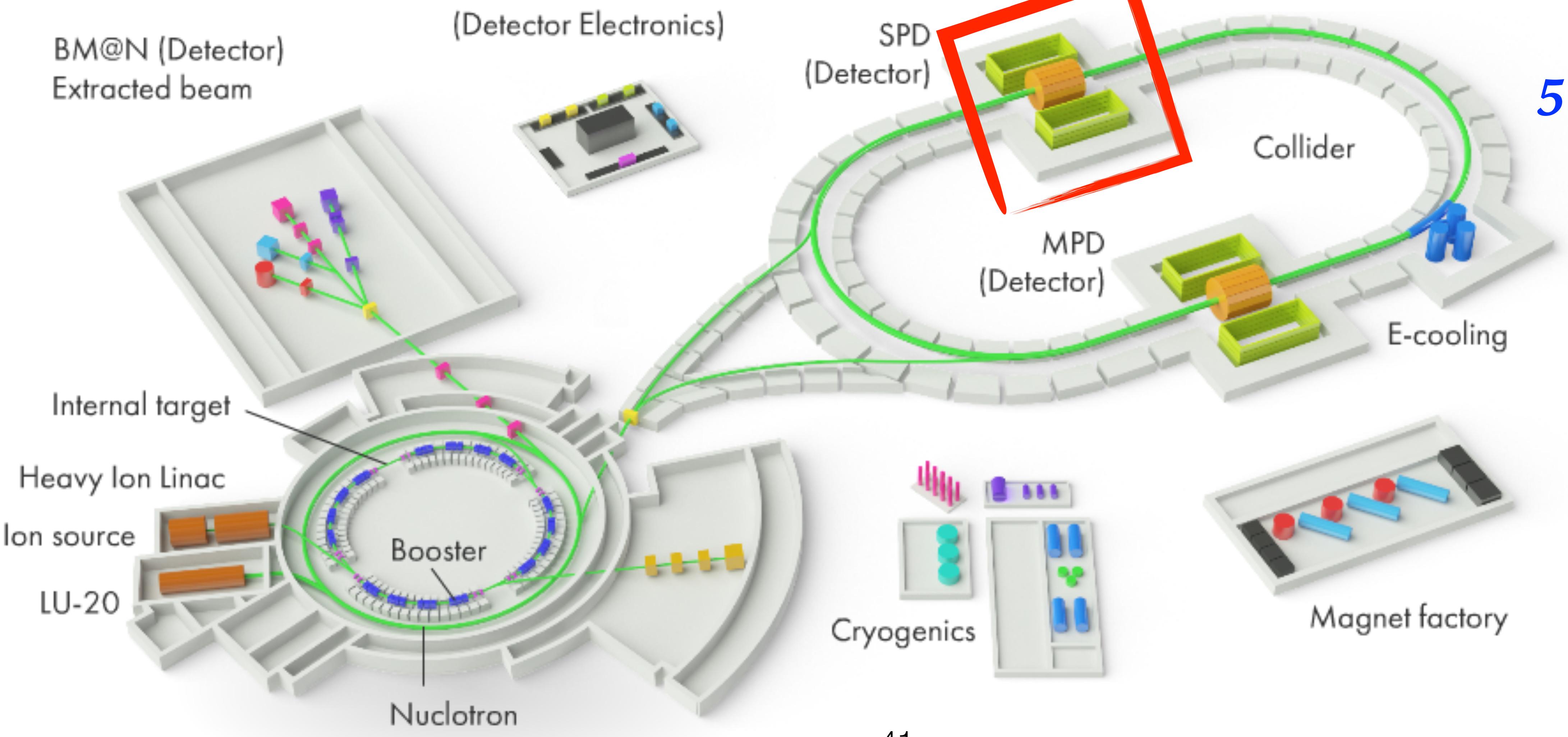
$p^{\uparrow}p^{\uparrow} : \sqrt{s} \leq 27\ GeV$

$d^{\uparrow}d^{\uparrow} : \sqrt{s} \leq 13.5\ GeV$

U, L, T

$|P| > 70\%$



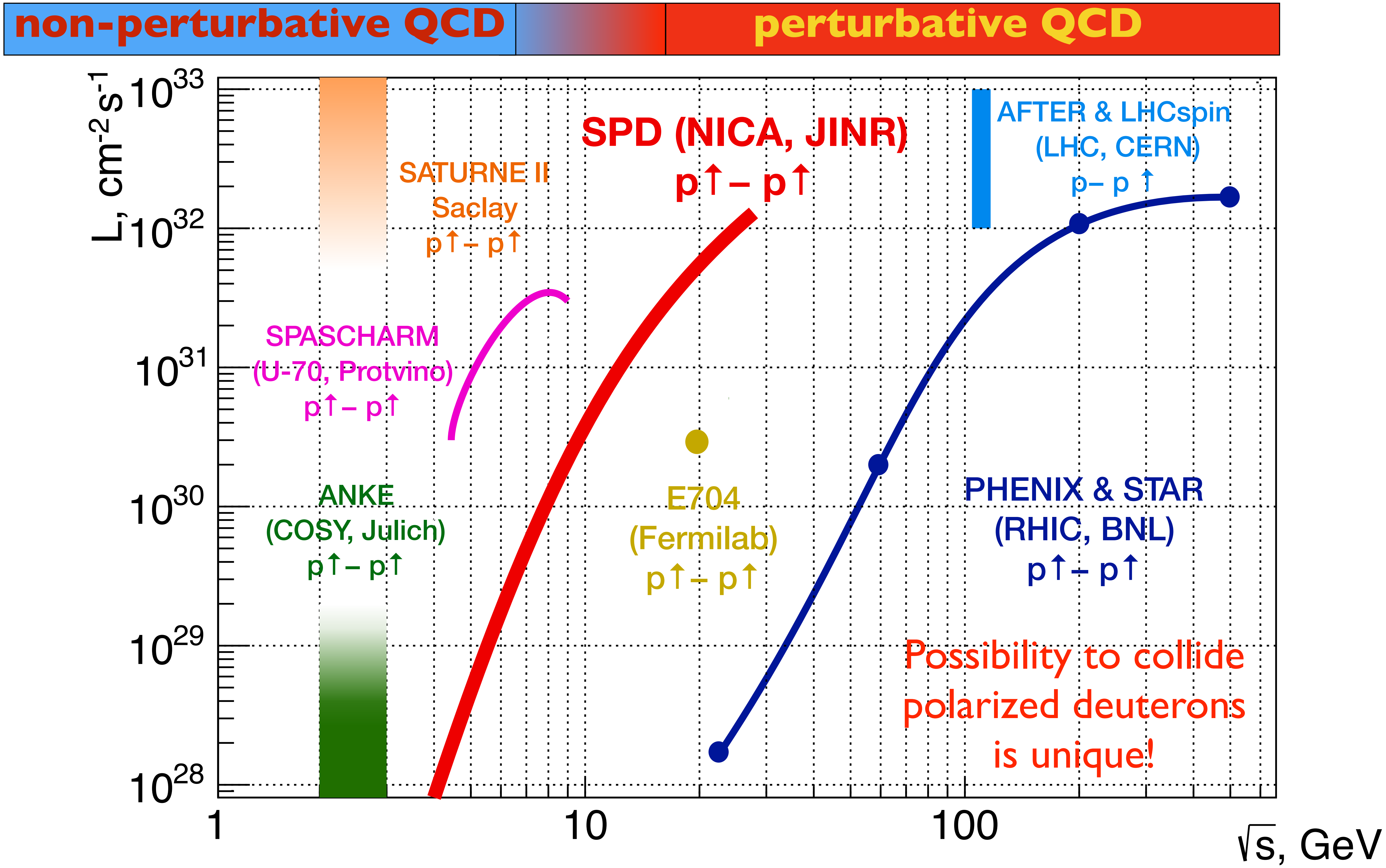


503 m

NICA collider

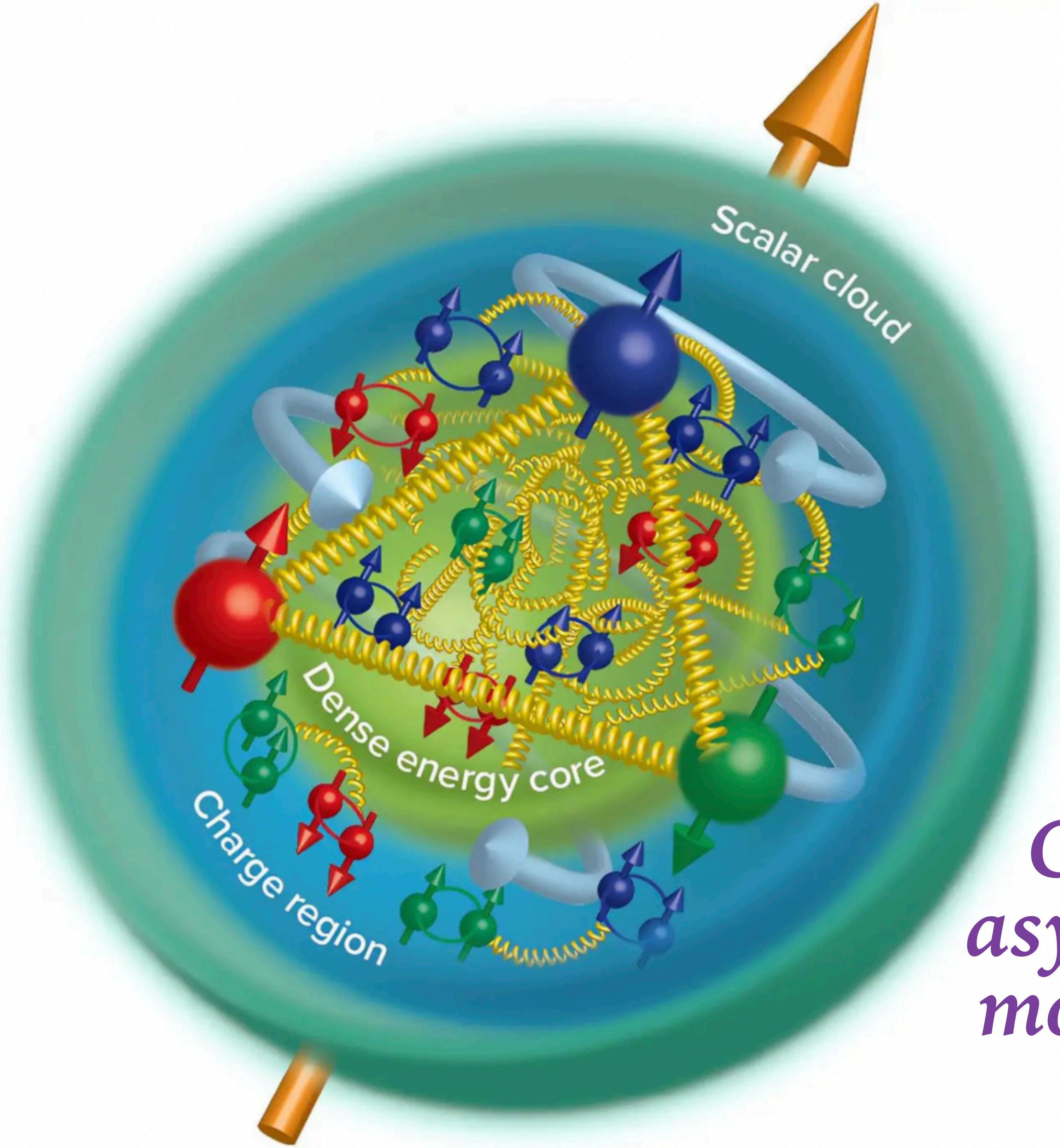
NICA collider

SPD and others



Possibility to collide polarized deuterons is unique!

Spin Physics @ NICA



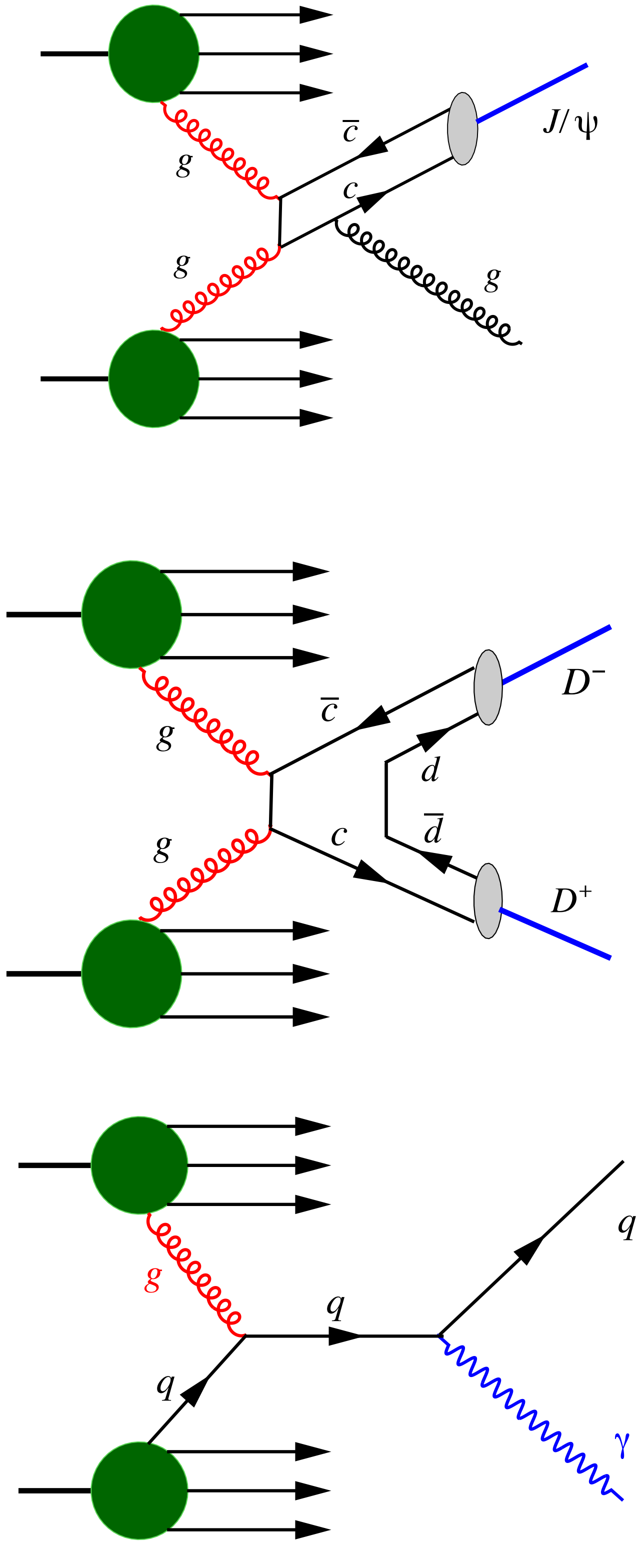
we plan to study how the proton and deuteron spin!

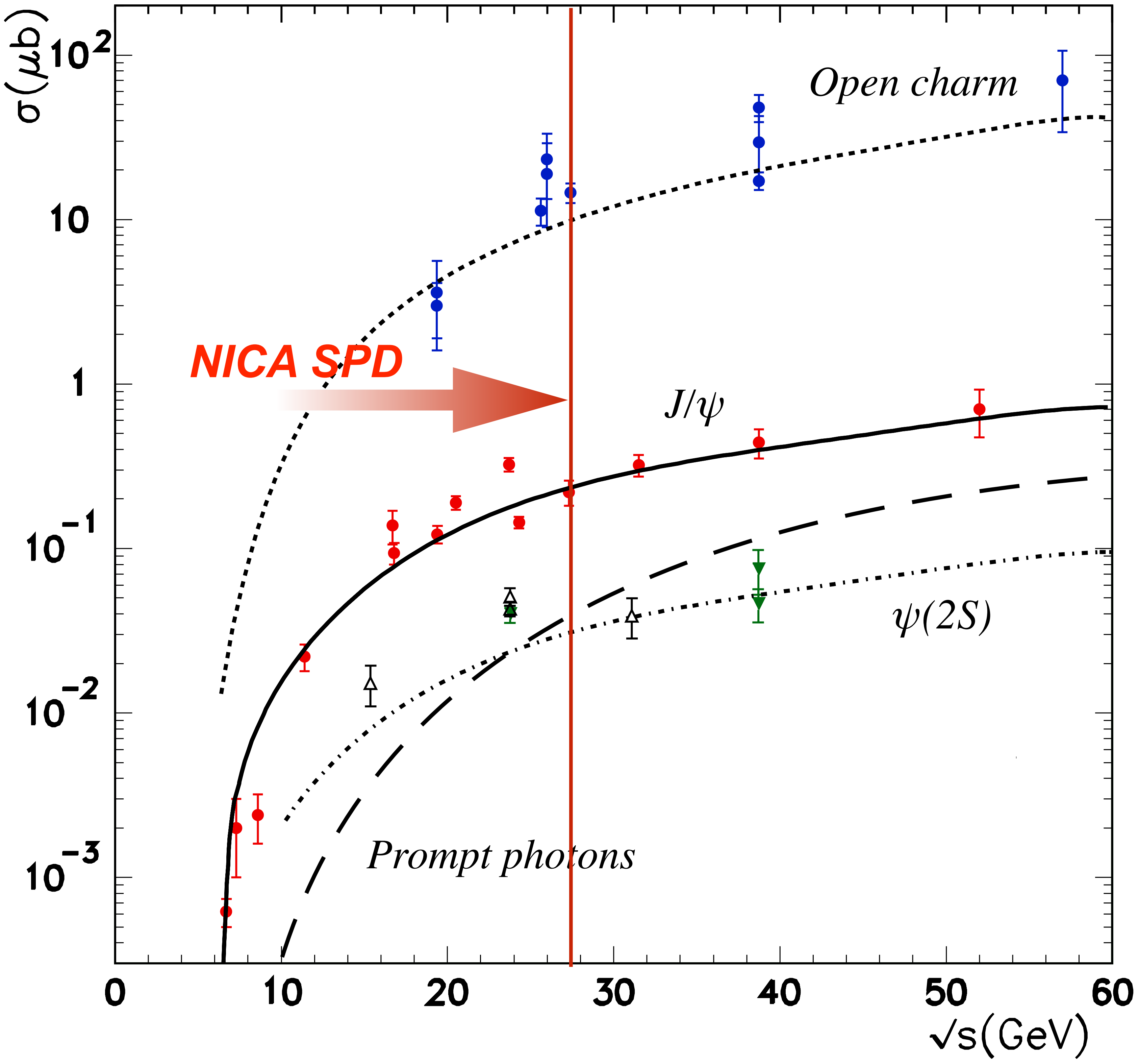
especially their gluon component!

Gluon TMD PDFs via asymmetries and angular modulations in the cross sections

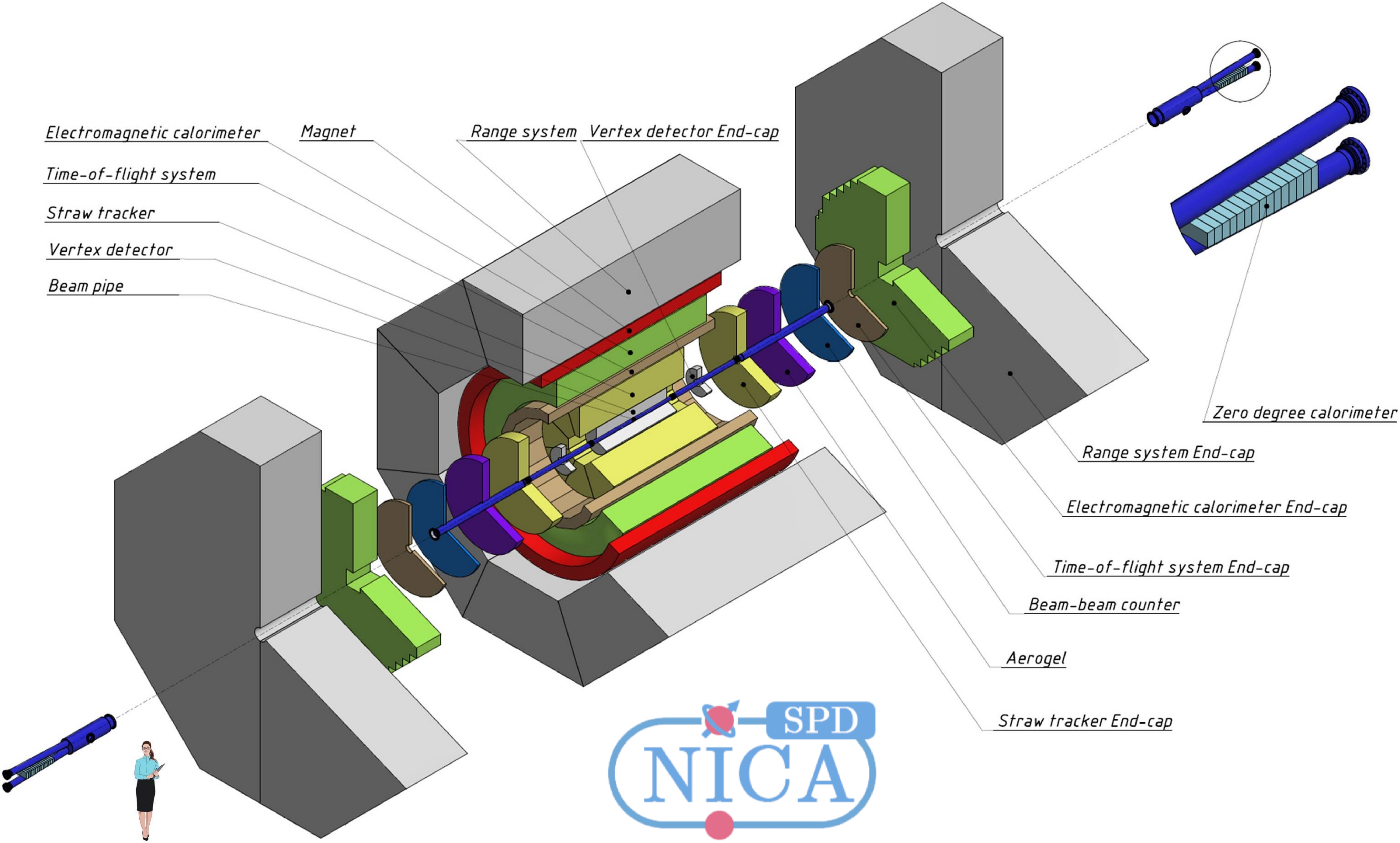
SPD and gluon structure of nucleon

Not only J/ψ!





SPD setup


Electromagnetic calorimeter
Magnet
Range system
Vertex detector End-cap
Time-of-flight system
Straw tracker
Vertex detector
Beam pipe
Zero degree calorimeter
Range system End-cap
Electromagnetic calorimeter End-cap
Time-of-flight system End-cap
Beam-beam counter
Aerogel
Straw tracker End-cap
SPD
NICA

SPD: two stages

Creating of polarized infrastructure

Upgrade of polarized infrastructure

Start of NICA operation

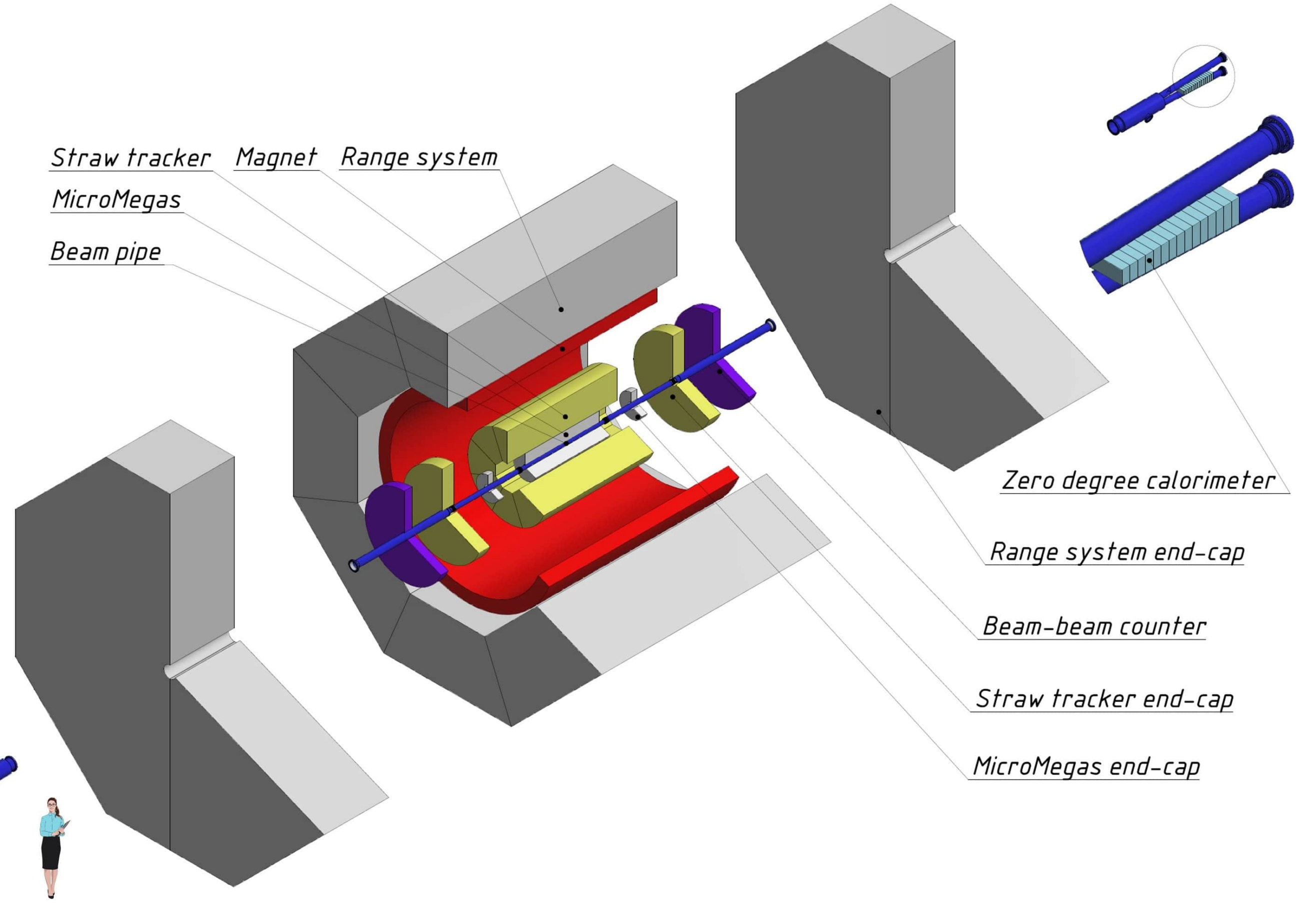
+4 years *+6 years* *+8 years*

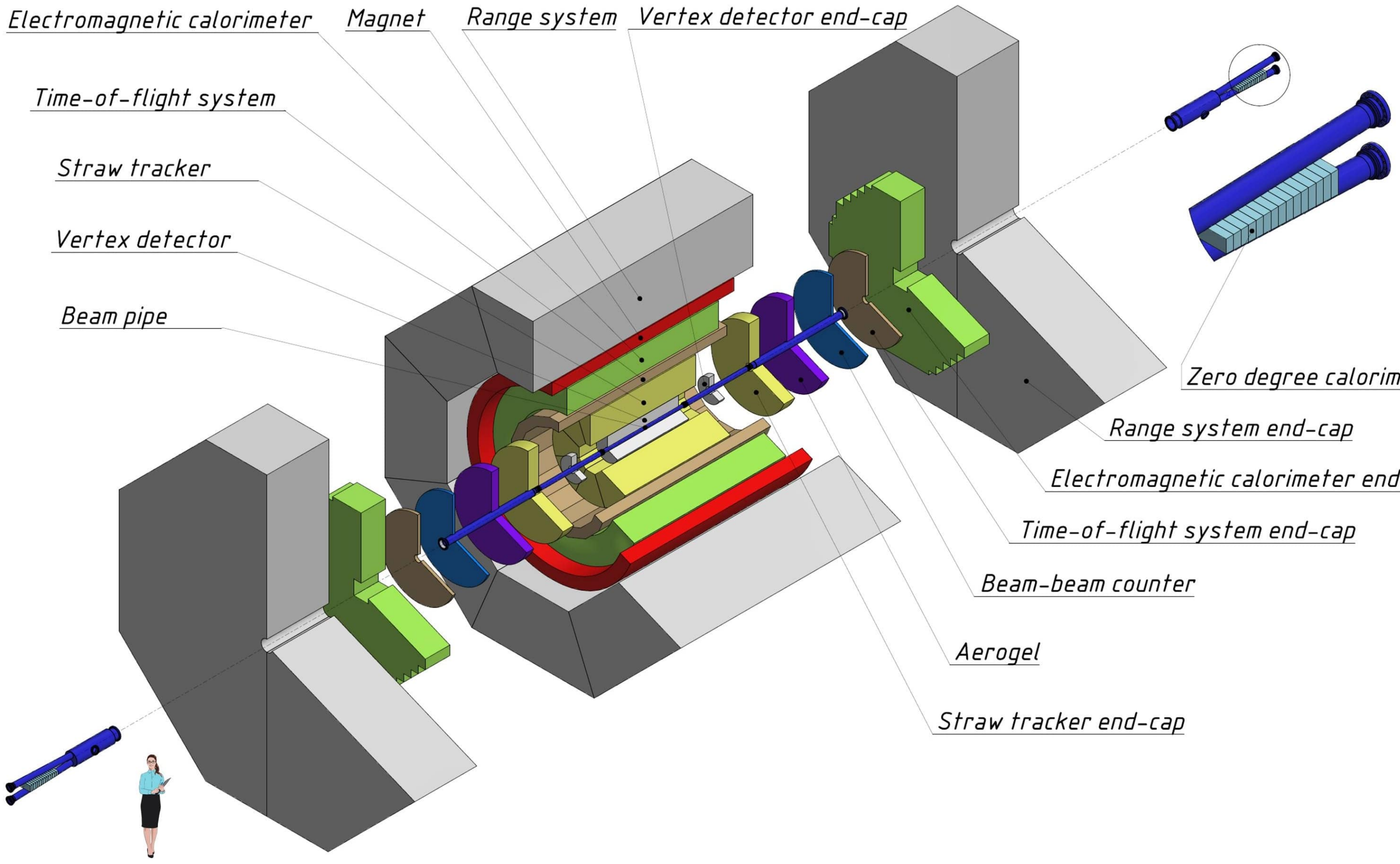
SPD construction

1st stage of operation

SPD upgrade

2nd stage of operation





SPD collaboration

38 institutes from 15 states, >300 members

Present status of the project

SPD **Conceptual Design Report** was presented firstly in Jan 2021 and approved by the JINR PAC for Particle physics after an international expertise in Jan 2022

SPD **Technical Design Report** was presented firstly in Jan 2023, than it was updated and passed via the international expertise in 2024

The SPD team moving from the R&D phase to the construction of the detector

SPD: 14 countries, 32 institutes, ~300 participants

- SPD CDR was approved in Jan'2022;
- detectors prototyping/tests are ongoing;
- new version of TDR – Jan'2024;
- start of operation (Stage-I) – 2028;
- 50 papers and 70 conference reports.

BM@N: 5 countries, 13 institutes, >200 participants

BM@N setup for heavy ions (2022)

4th NICA run (2022-2023):

- 550M events Xe+CsI at 3.0A, 3.8A G
- analysis is ongoing;
- so far: 80 publications and 80 repor including "Quark Matter", "Strangeness in Quark Matter", etc

BM@N setup for SRC

First observation of the Short-Range Correlations in inverse kinematics:

The **first phase** of the SPD project is included into the JINR's 7-year plan (2024-2030)

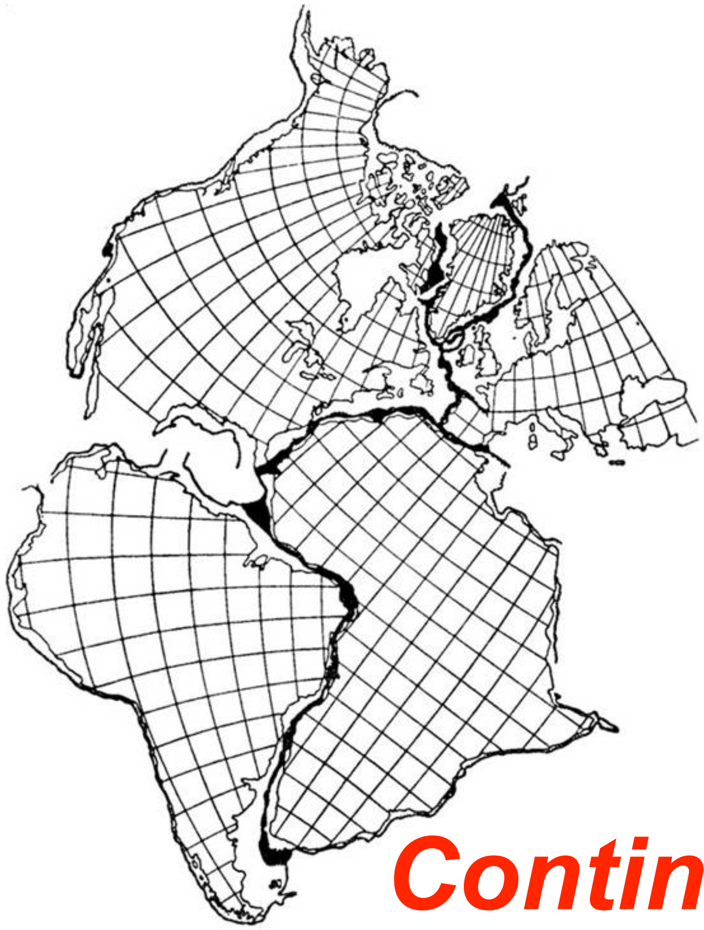
https://spd.jinr.ru/

Growth of Knowledge

Naive concepts

The Earth is a sphere!
II century B.C.

Age of Discovery, XV-XIX centuries



Continental drift, 1912