Nucleon spin structure with NICA SPD

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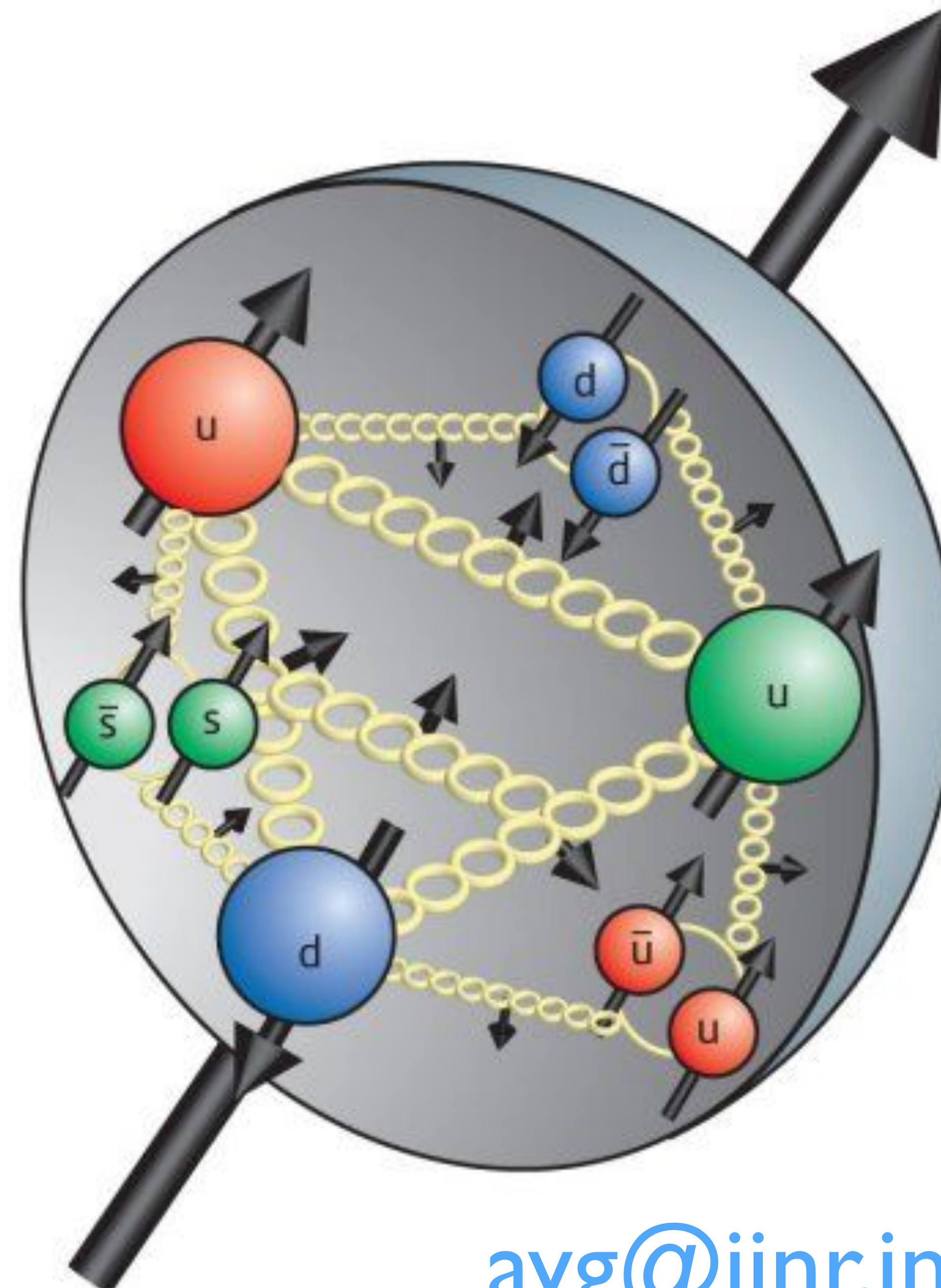
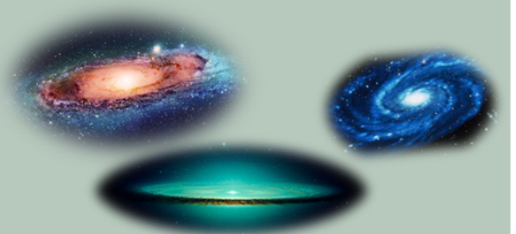
SPD
NICA



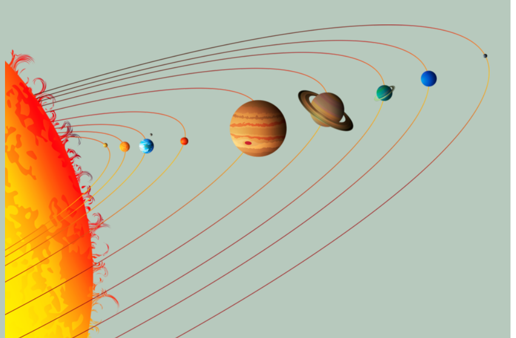
avg@jinr.int

Fundamental interactions

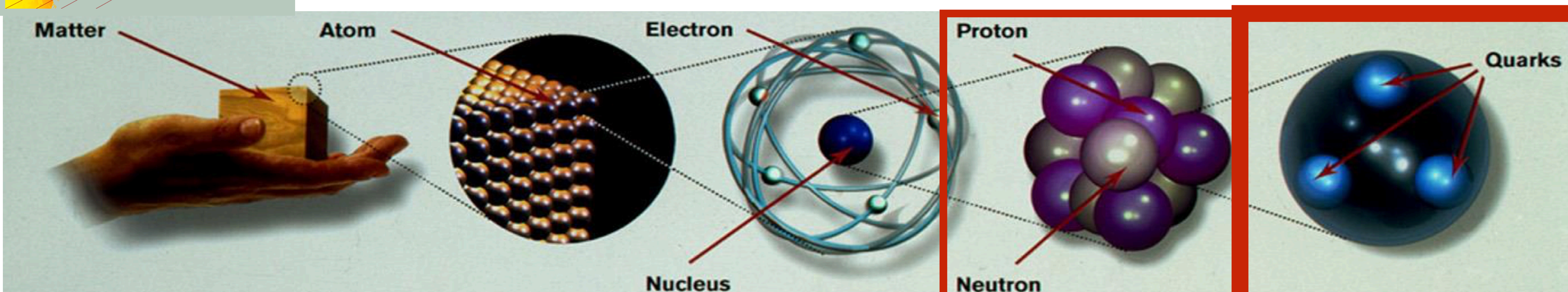
Star systems



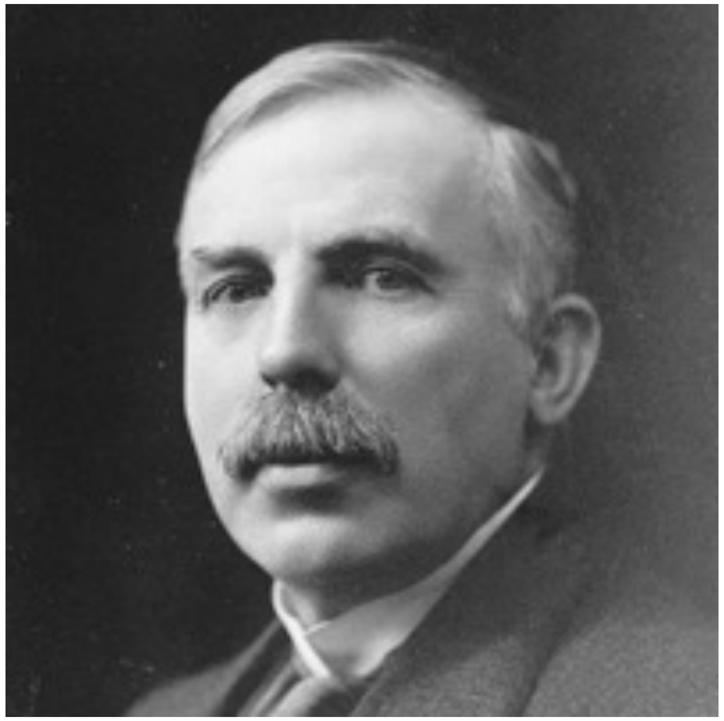
Planet systems



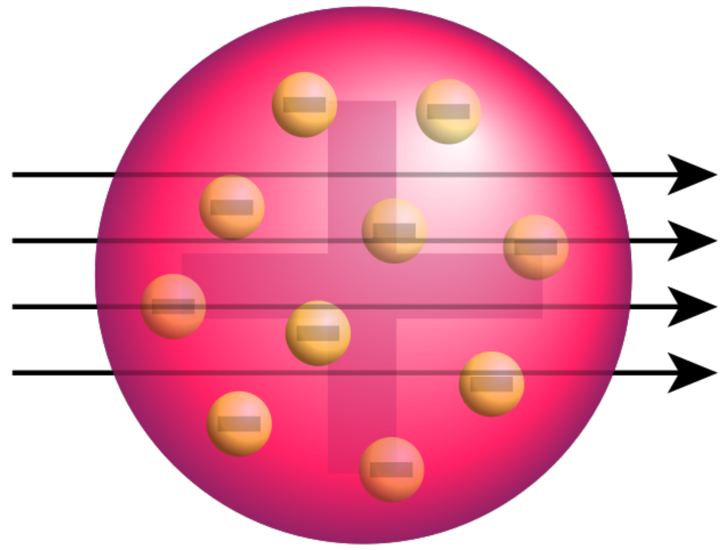
Interaction / Property	Gravitational	Weak	Electromagnetic	Strong	
		Electroweak		Fundamental	Residual
Acts on:	Mass - Energy	Flavor	Electric charge	Color charge	Atomic nuclei
Particles experiencing:	All particles	quarks, leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (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

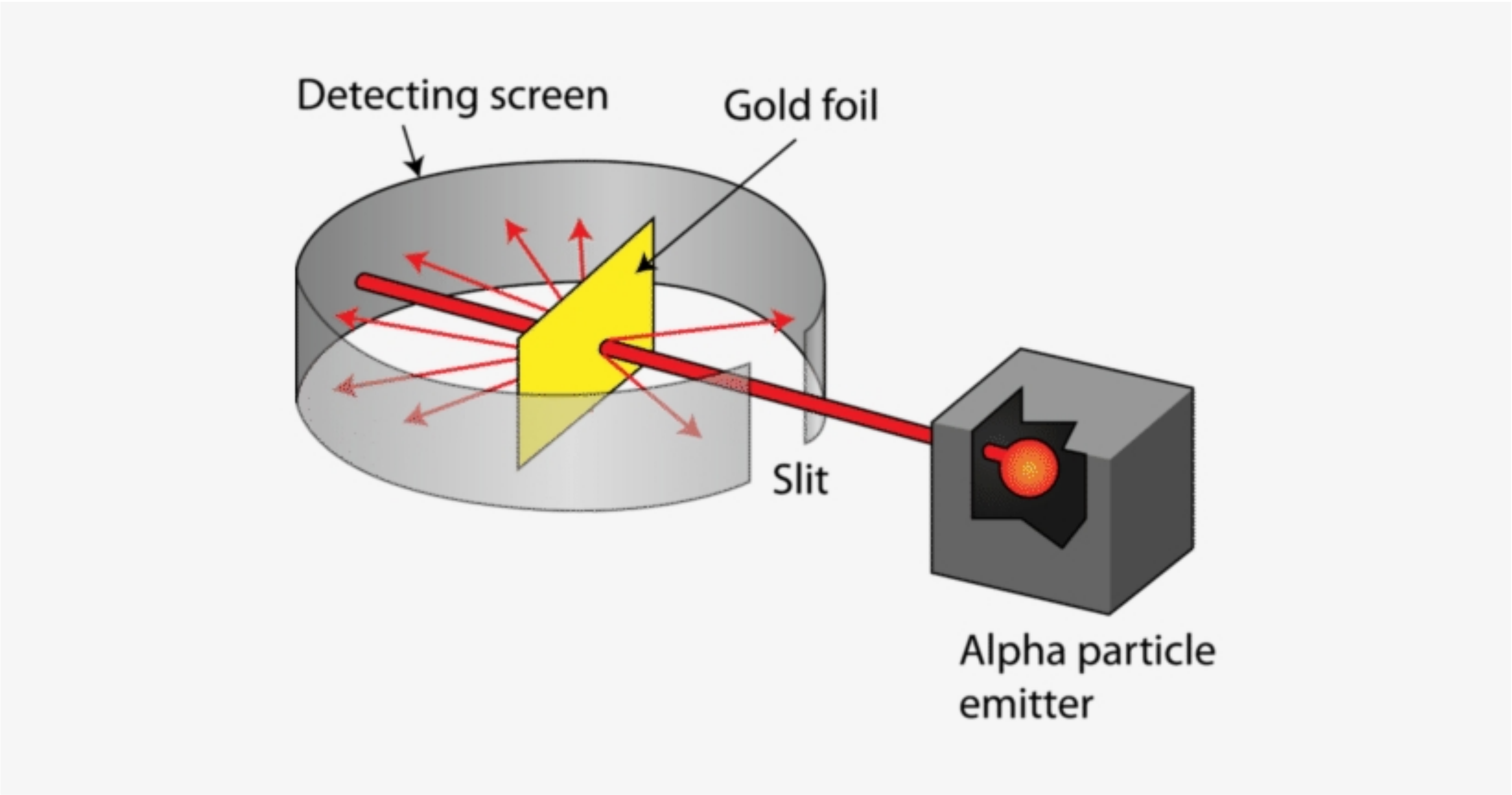


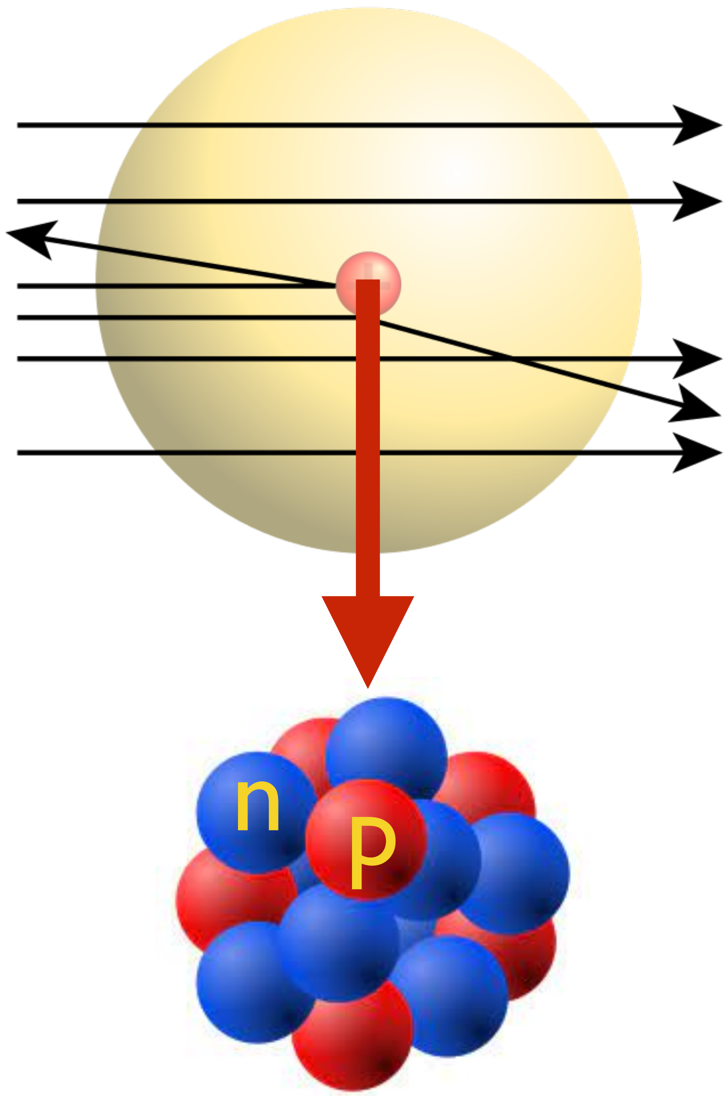
Rutherford experiment



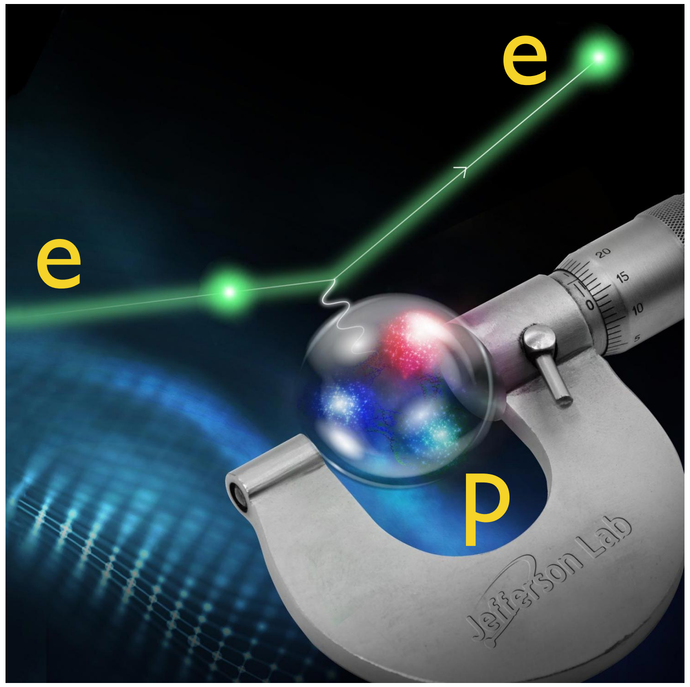
E. Rutherford
1909-1913



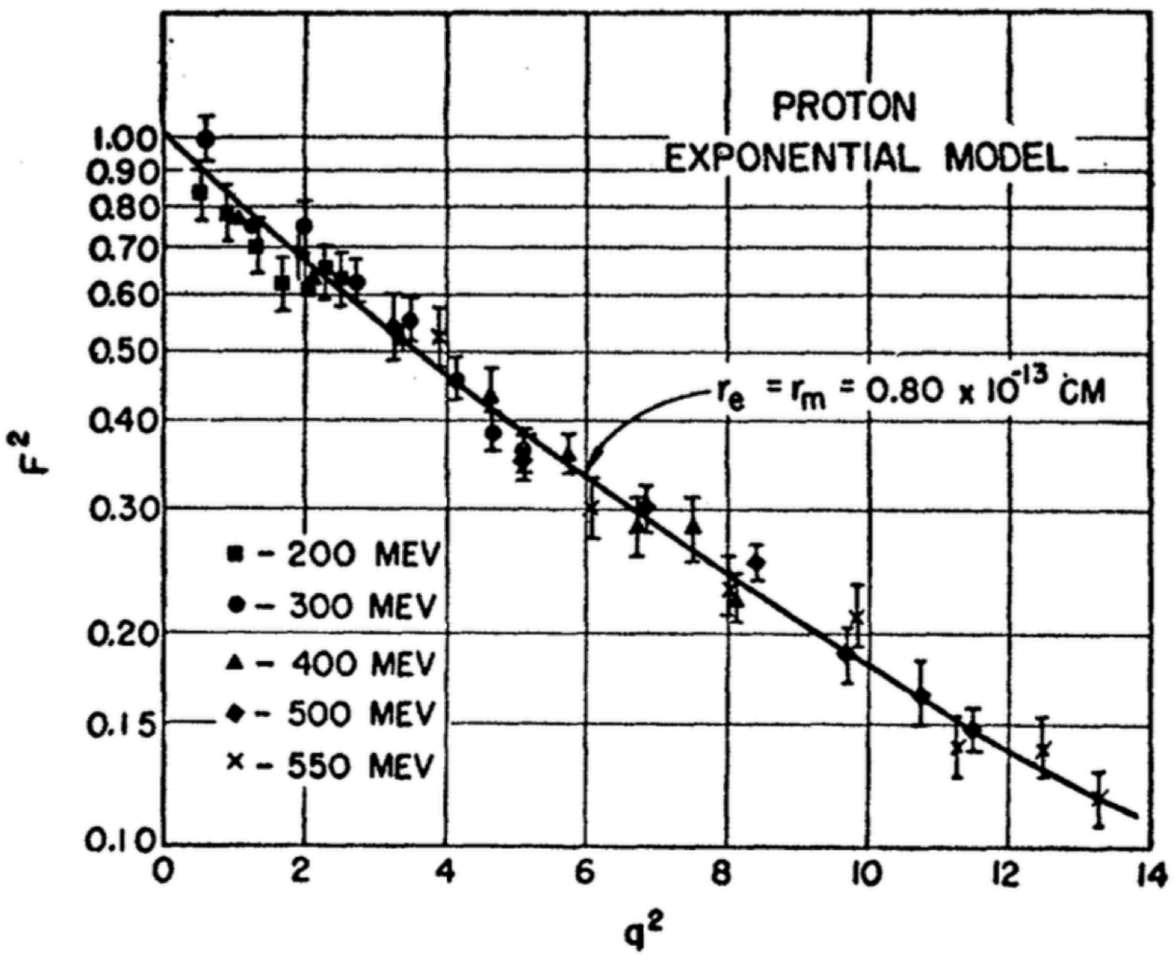




Proton size



R. Hofstadter - the Nobel Prize in 1961



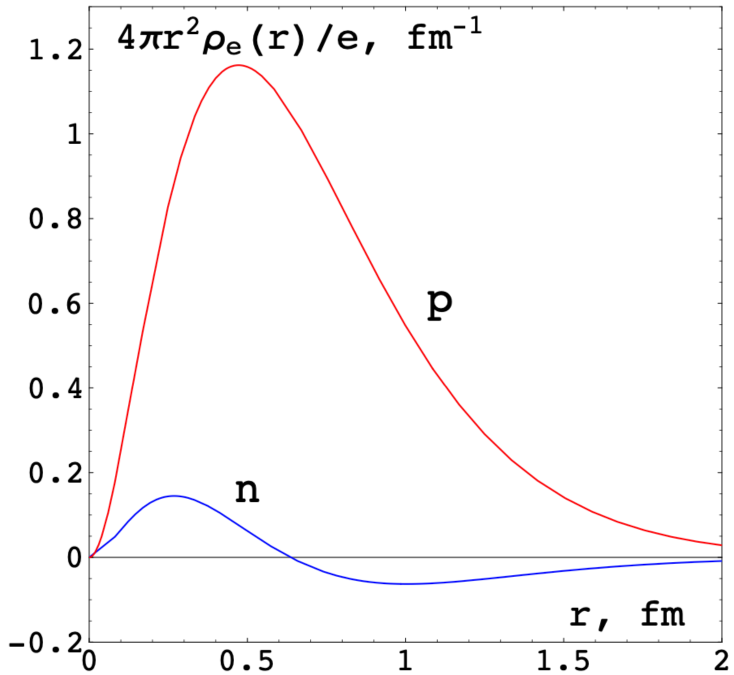
$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\text{point-like}} \times F^2(q^2)$$

Form-factor

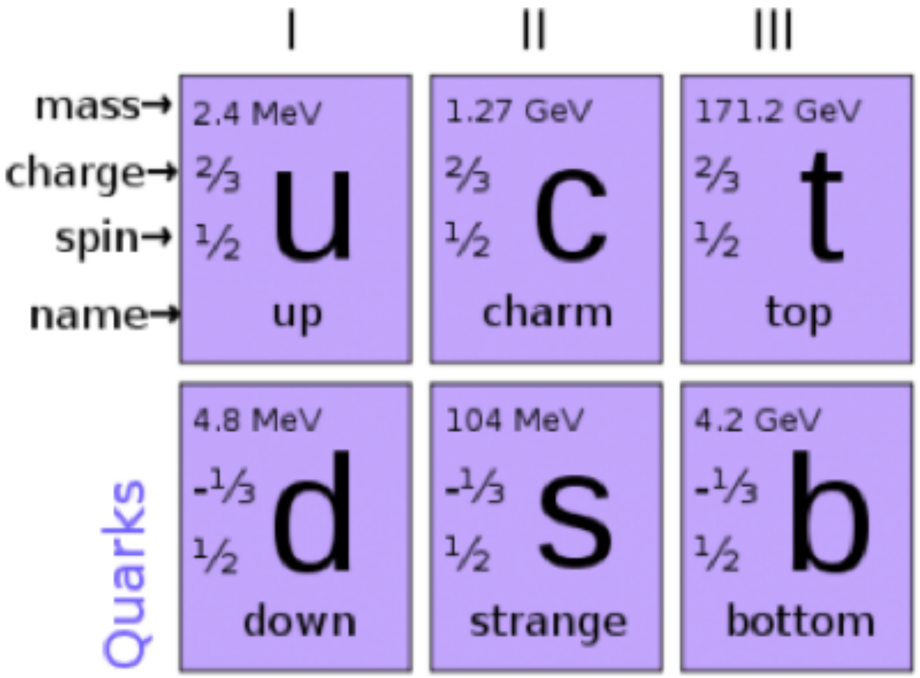
transferred (four)-momentum

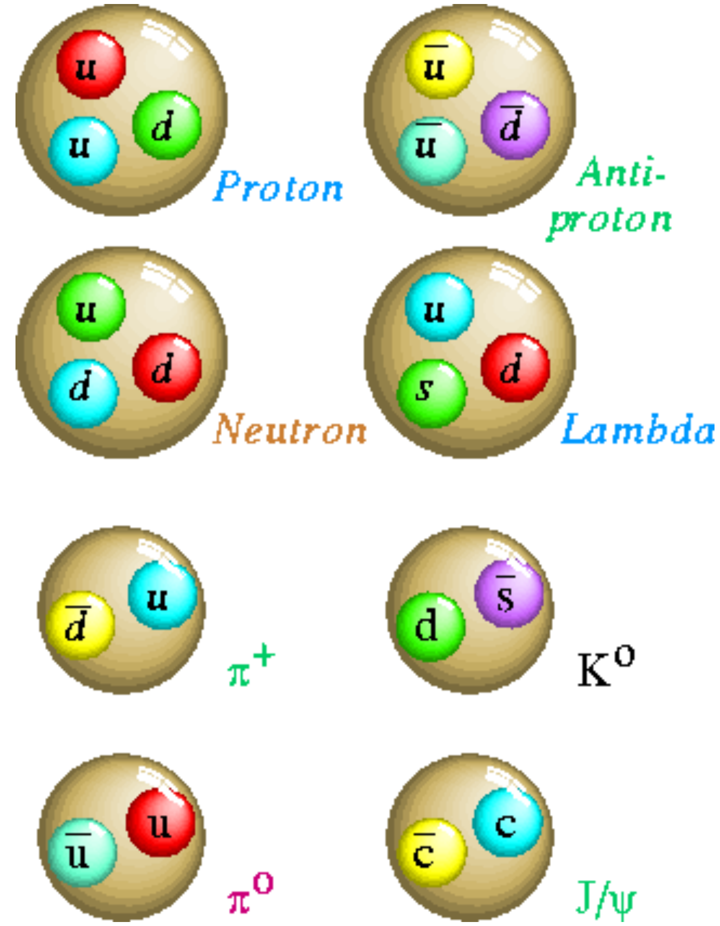
$$F(q^2) \approx 1 - \frac{q^2 < r^2 >}{6\hbar^2}$$

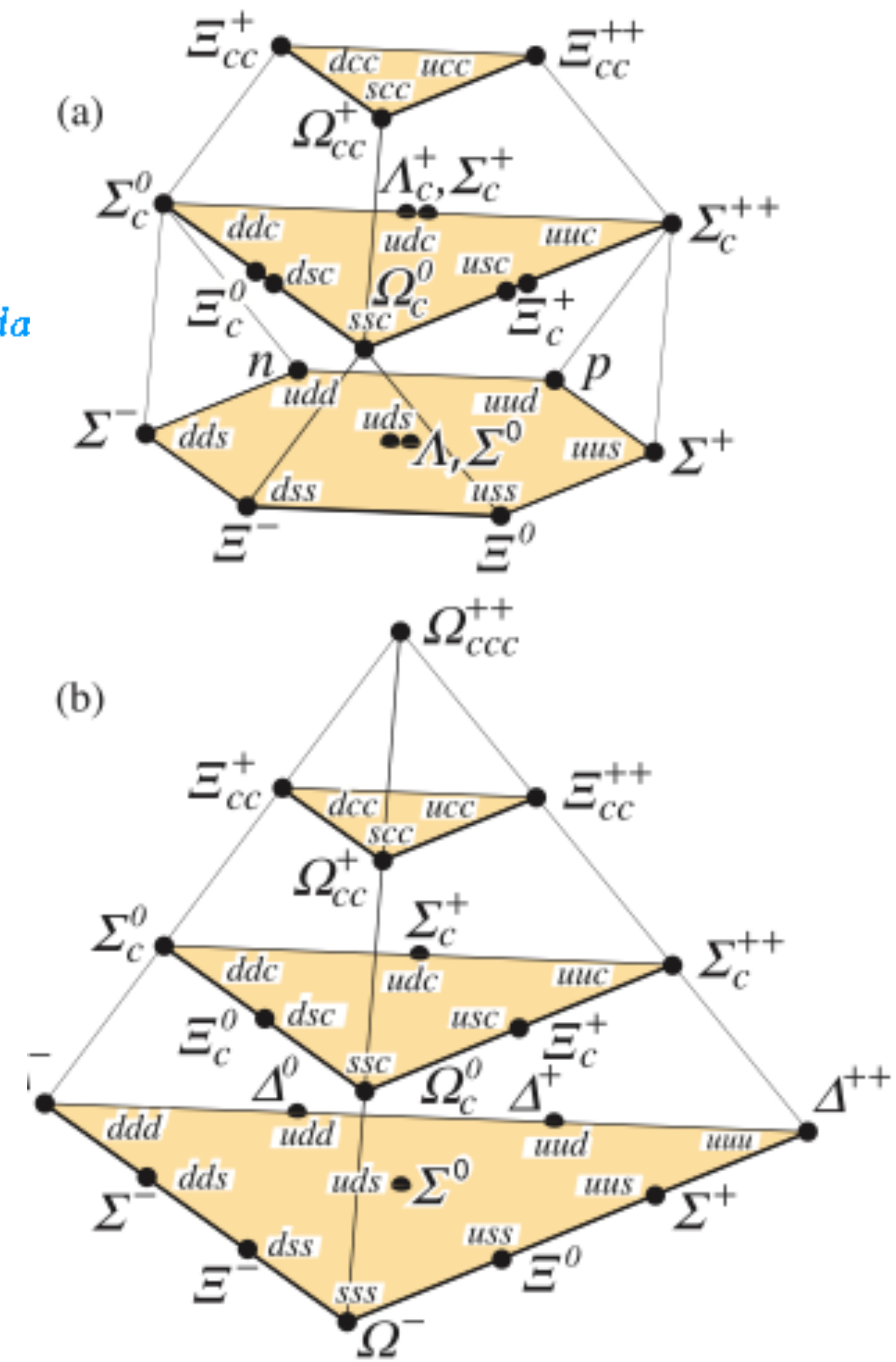
charge radius



Quarks



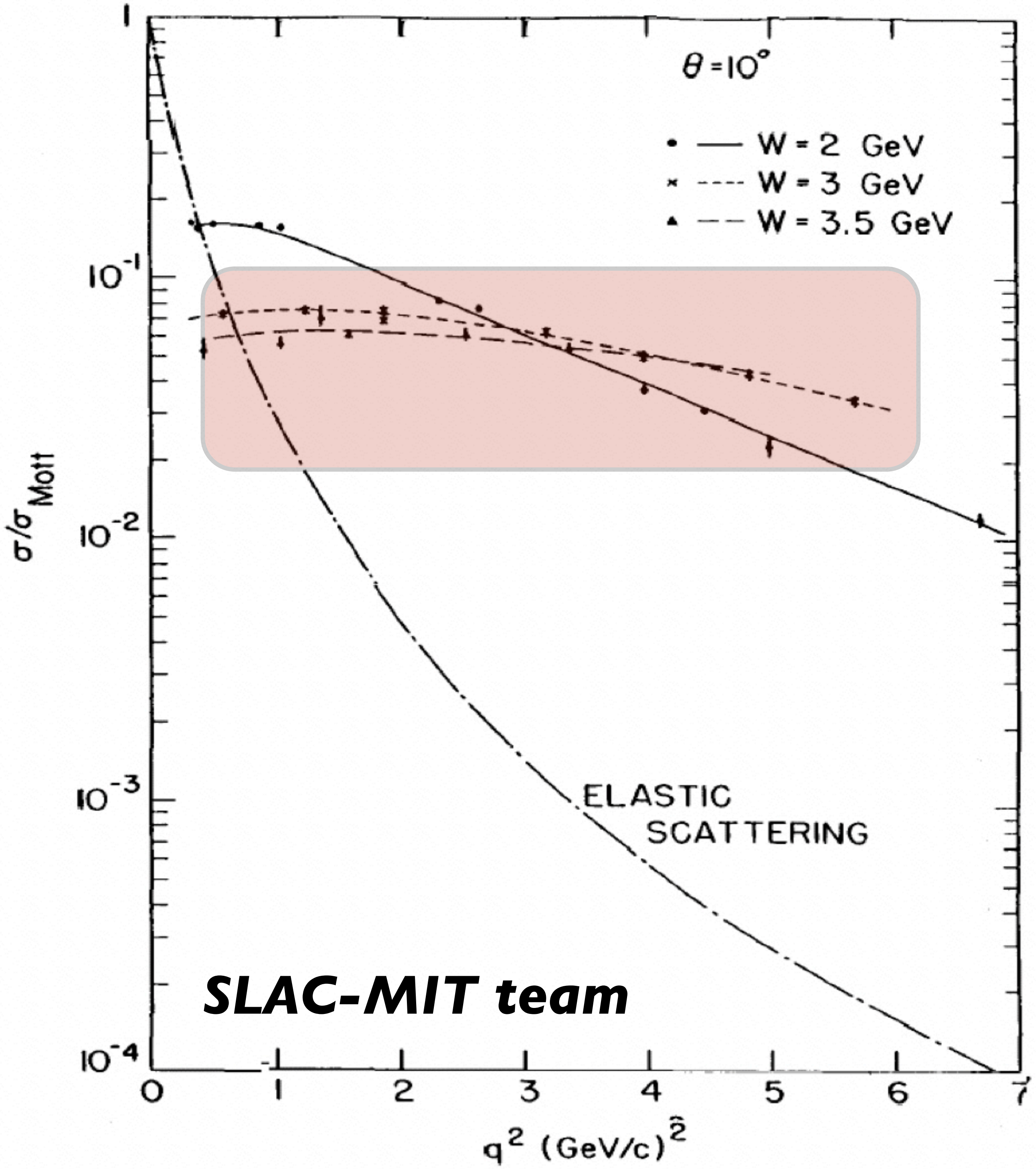




1964

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

Partons



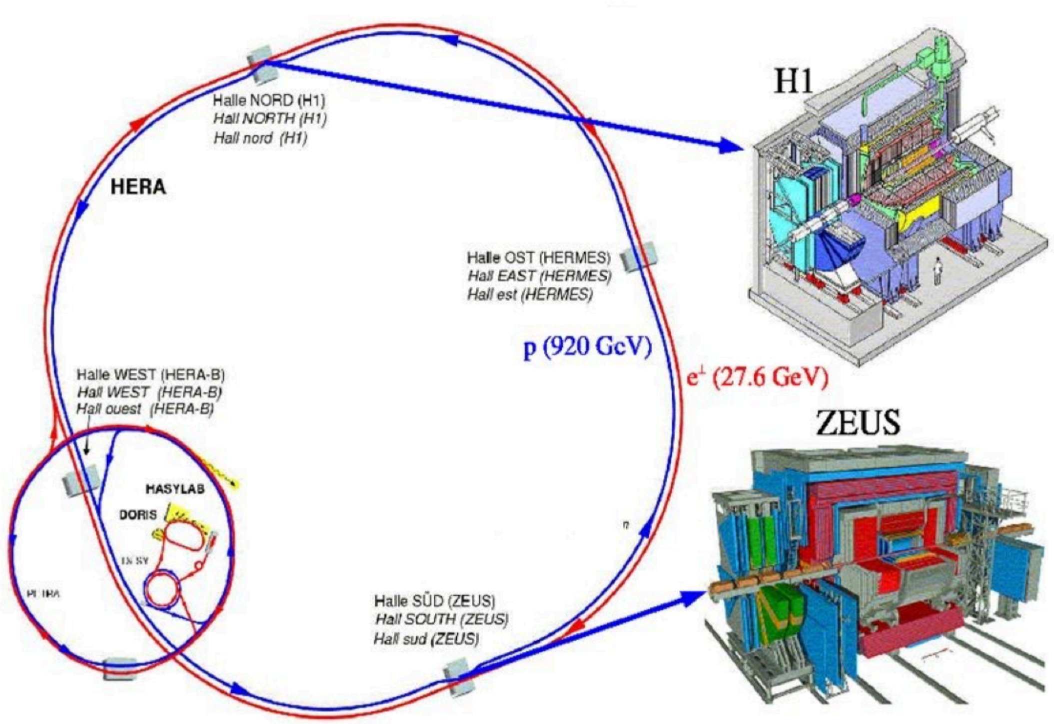
Partons - point-like objects inside the proton

Partonic model - 1969

R. Feynman

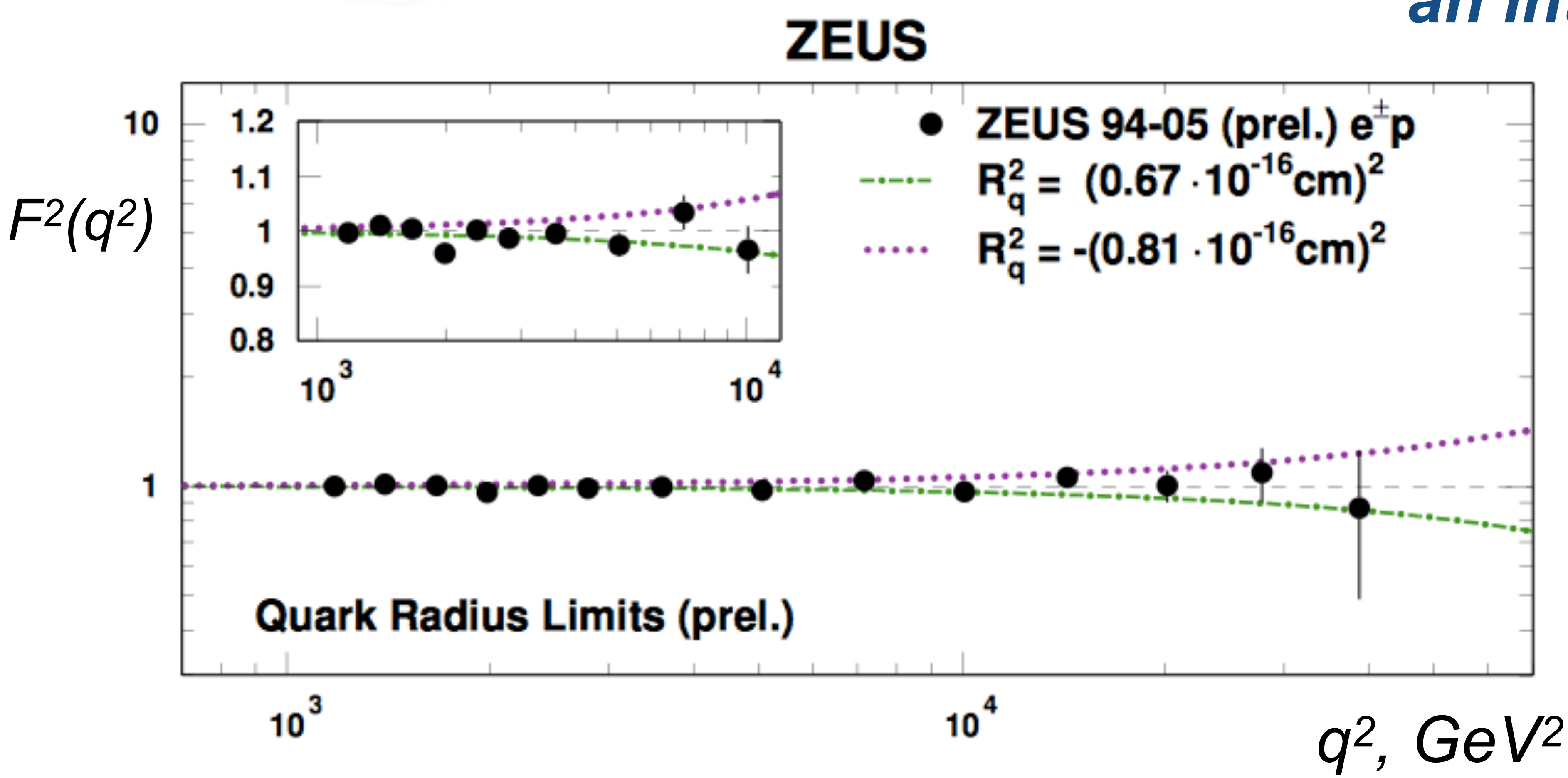
In the beginning of 70th charged partons were associated with quarks

Quark size?



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

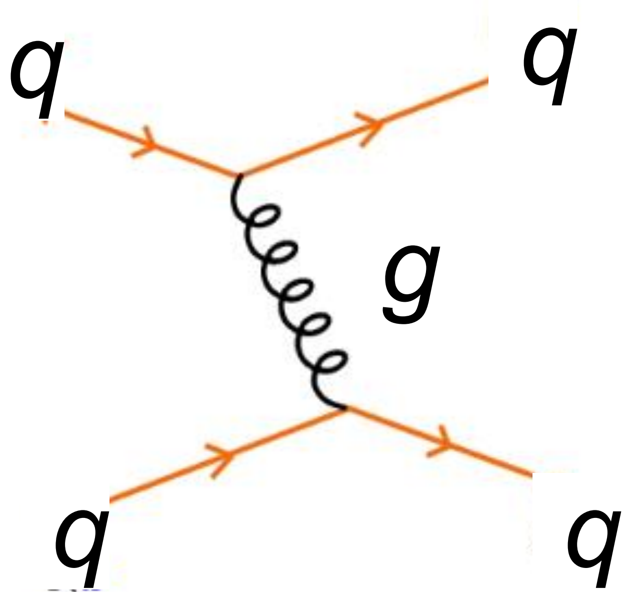
At the moment there is no indication that quarks have an internal structure

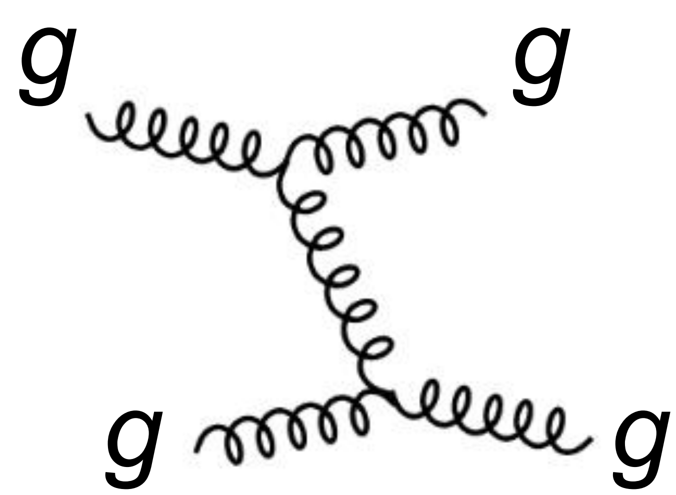


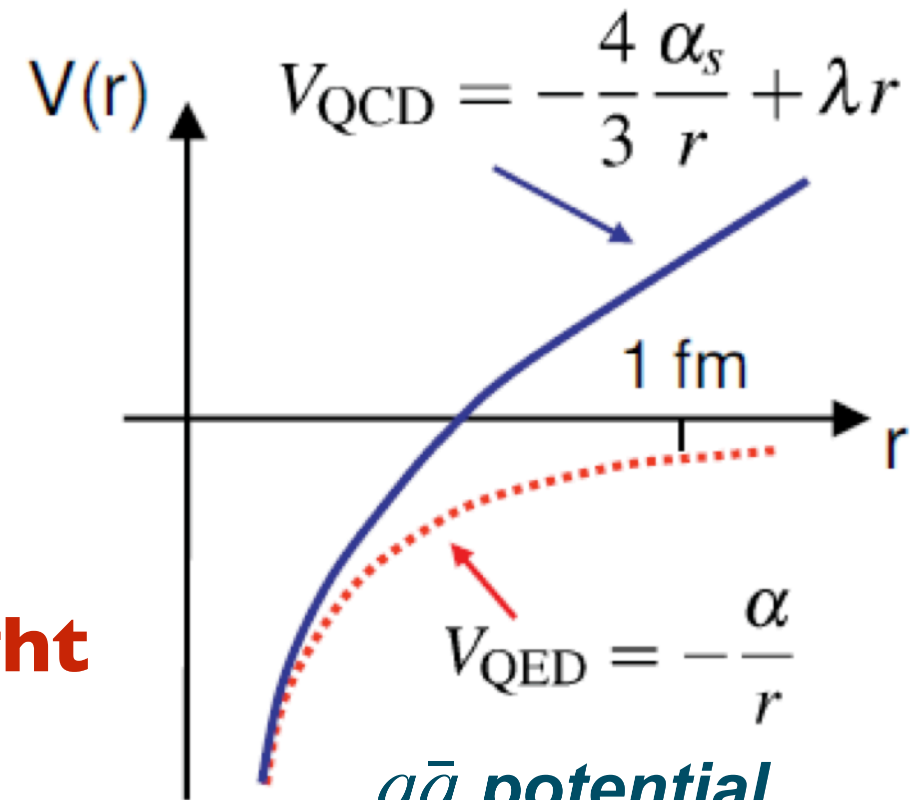
$$F(q^2) \approx 1 - \frac{q^2 < r_q^2 >}{6\hbar^2}$$

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

Quantum ChromoDynamics - QCD

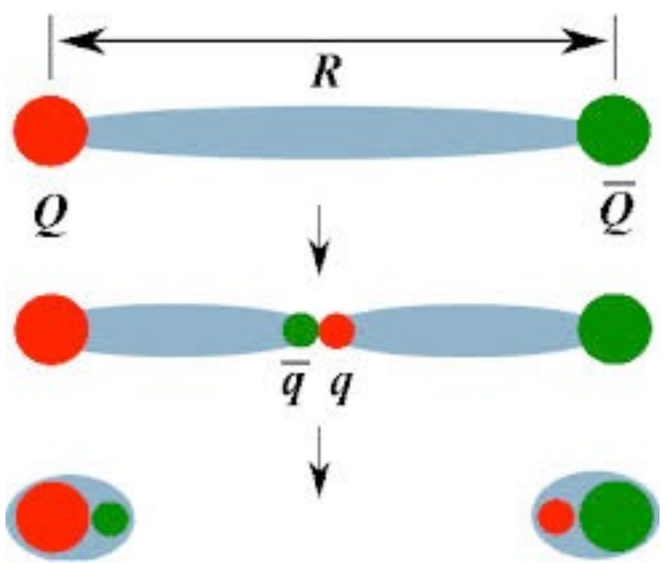


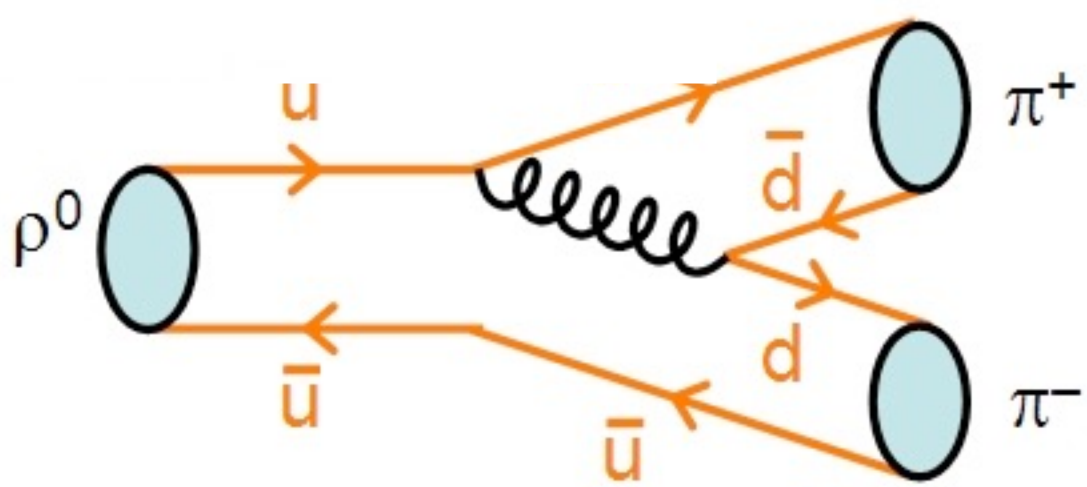


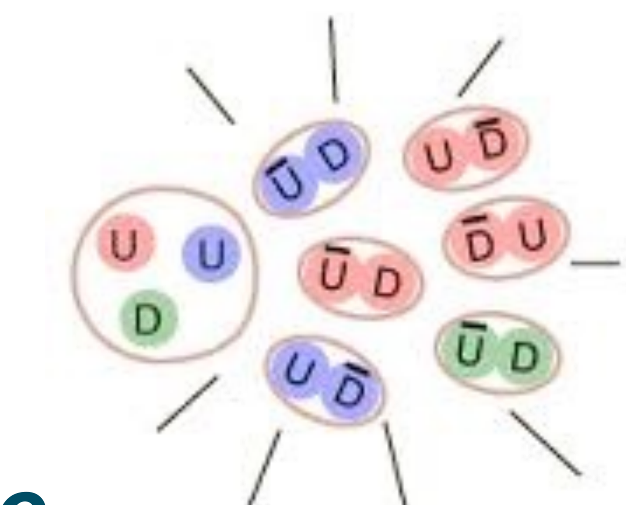


$q\bar{q}$ **potential**

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



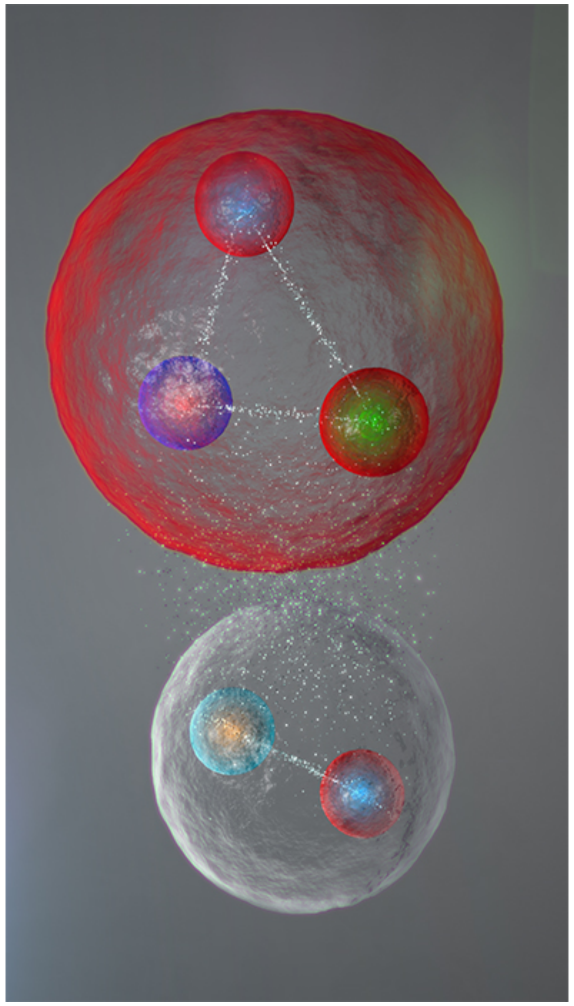




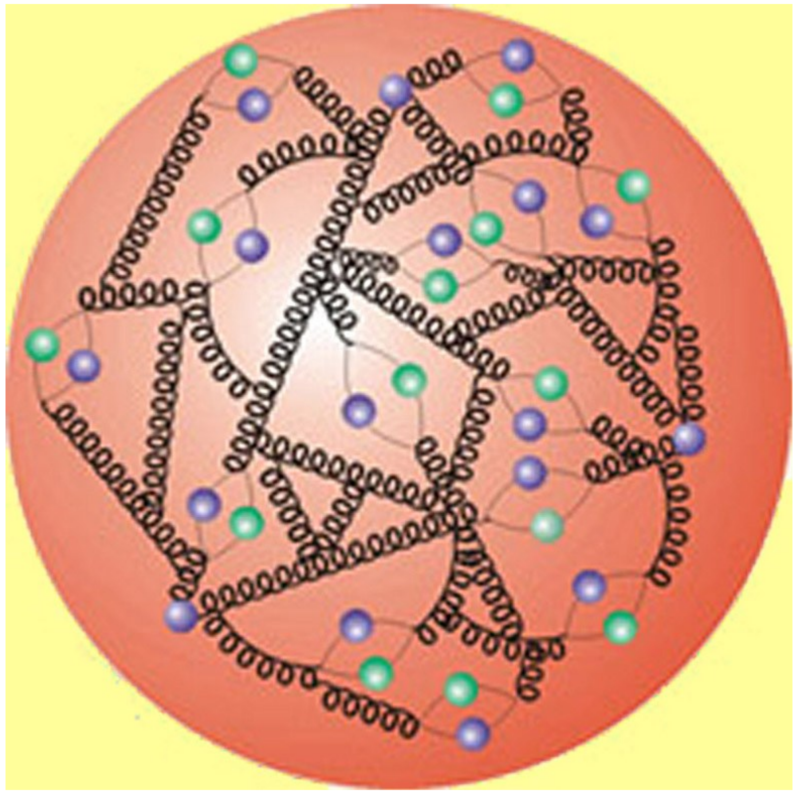
Quark confinement at large scale
but asymptotic freedom at below 1 fm

QCD - main directions

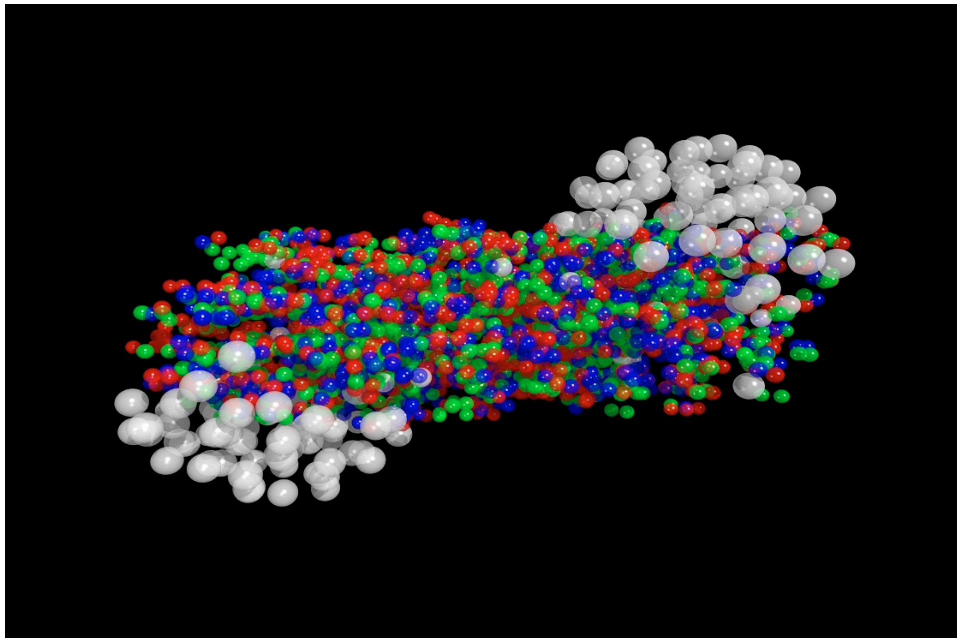
Hadron spectroscopy



Hadron structure



Hadronic matter under extremal conditions

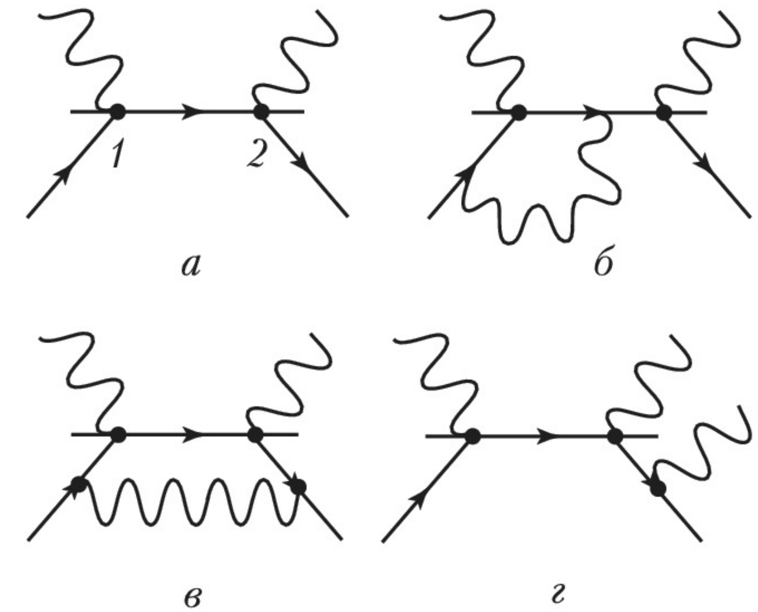


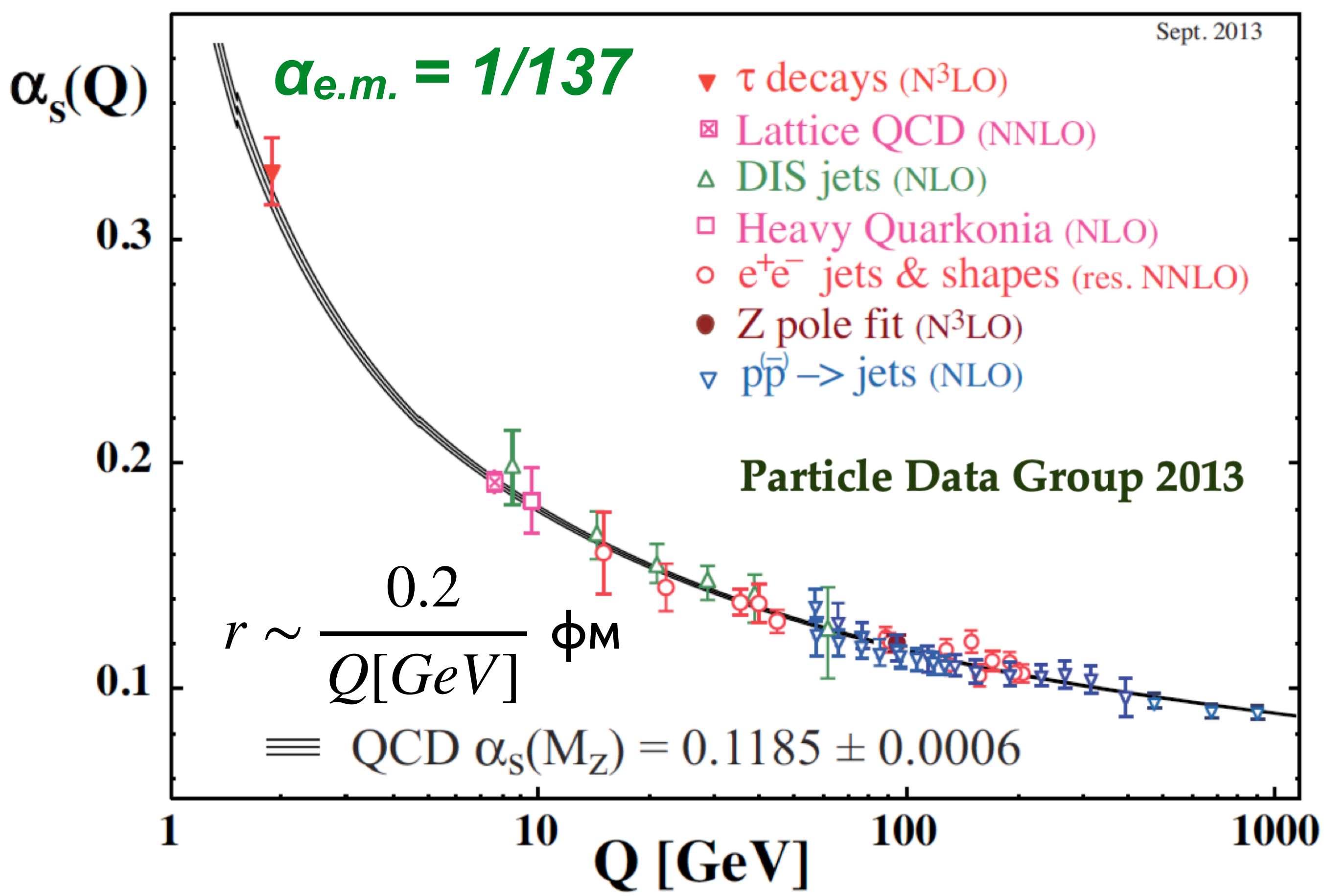
Problem to describe hadrons ab initio

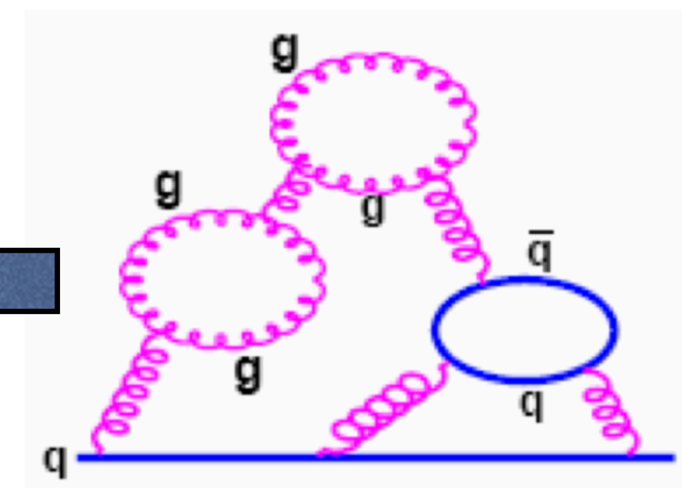
Feynman diagrams - perturbative approach

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

Fast convergence for α<<1



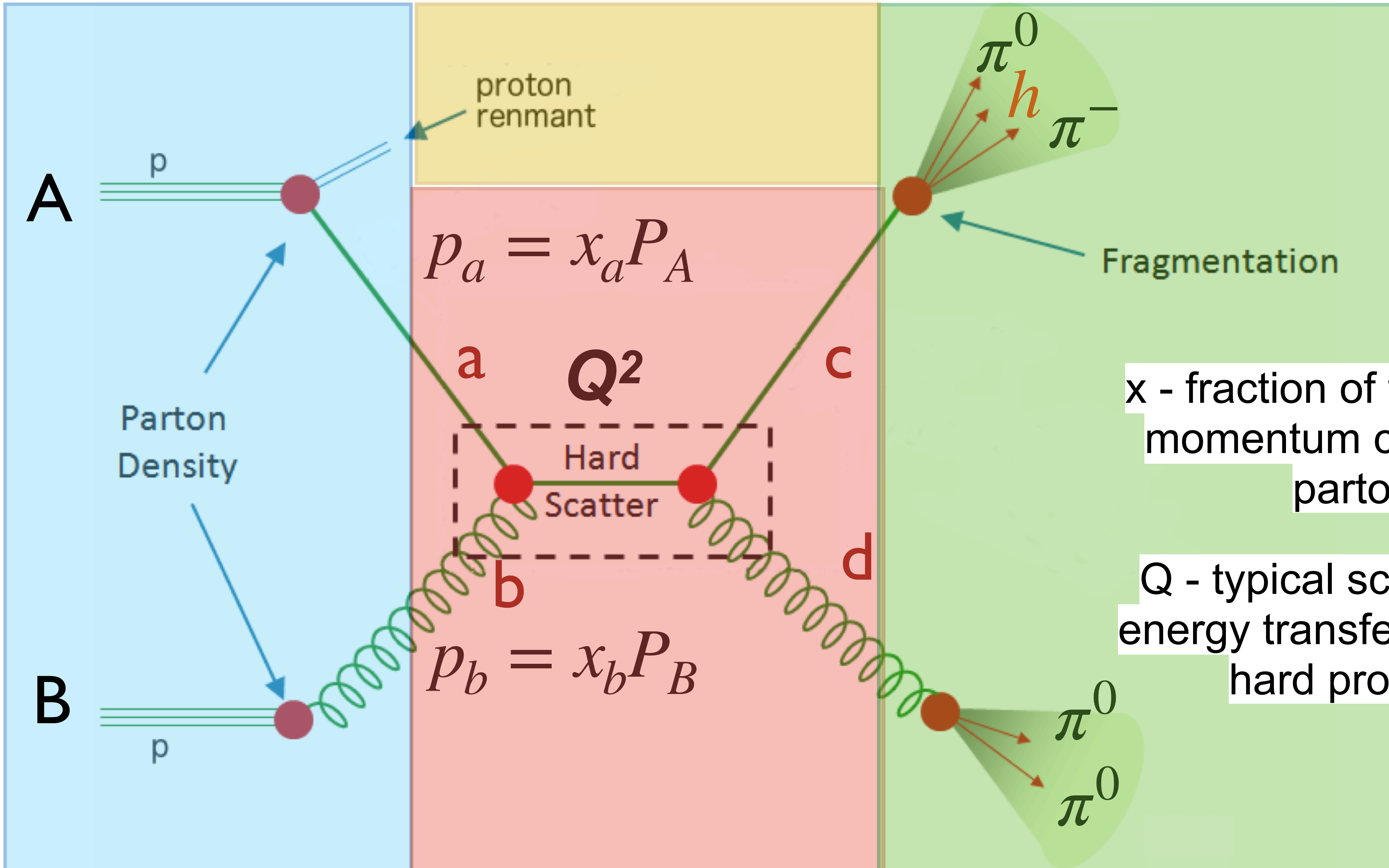




Unlike the hydrogen atom, we cannot (yet?) describe from first principles the structure of hadrons and their interactions at low energies

Confinement is not strictly proven!

Factorization theorem



x - fraction of the proton momentum carried by parton

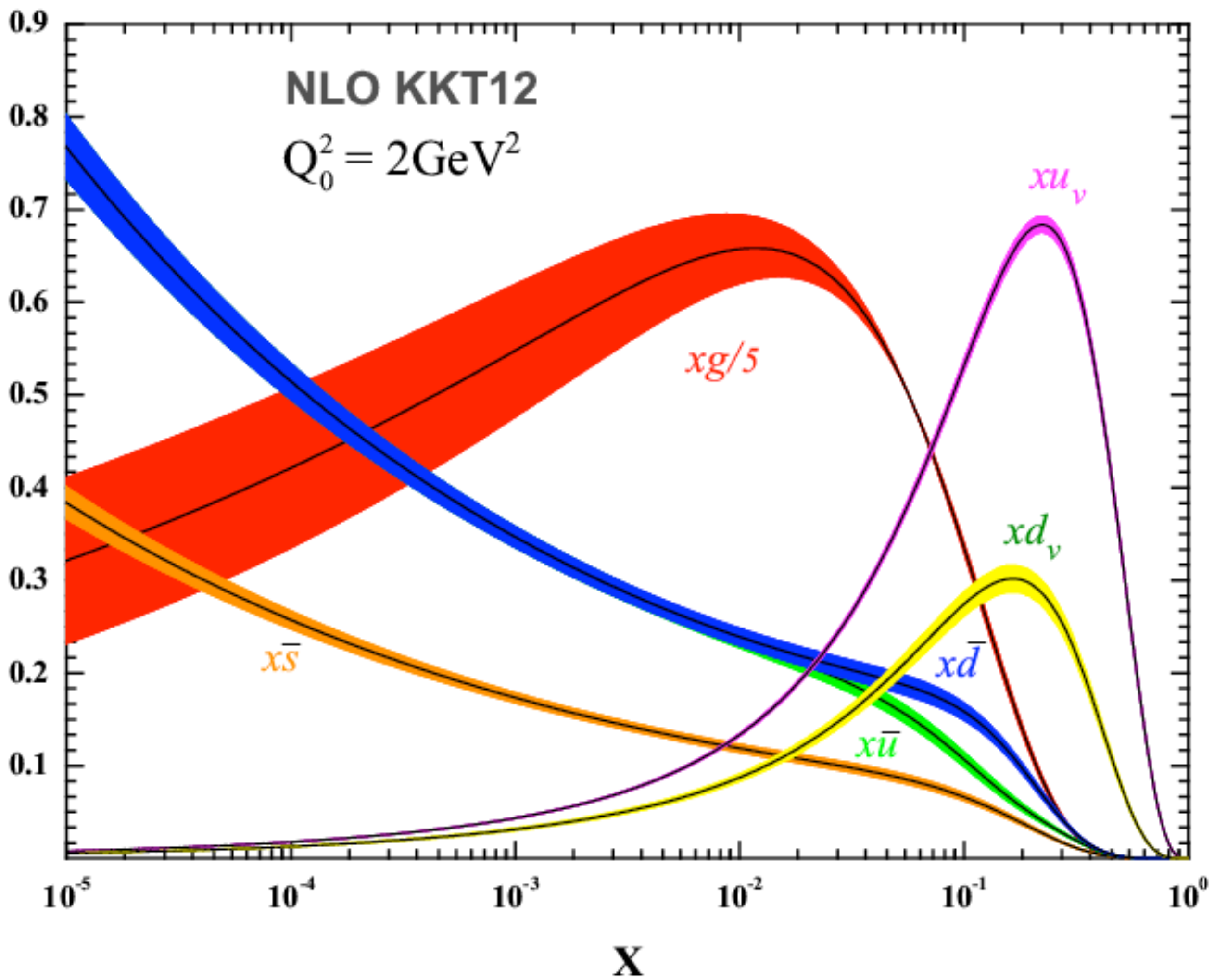
Q - typical scale of the energy transferred in the hard process

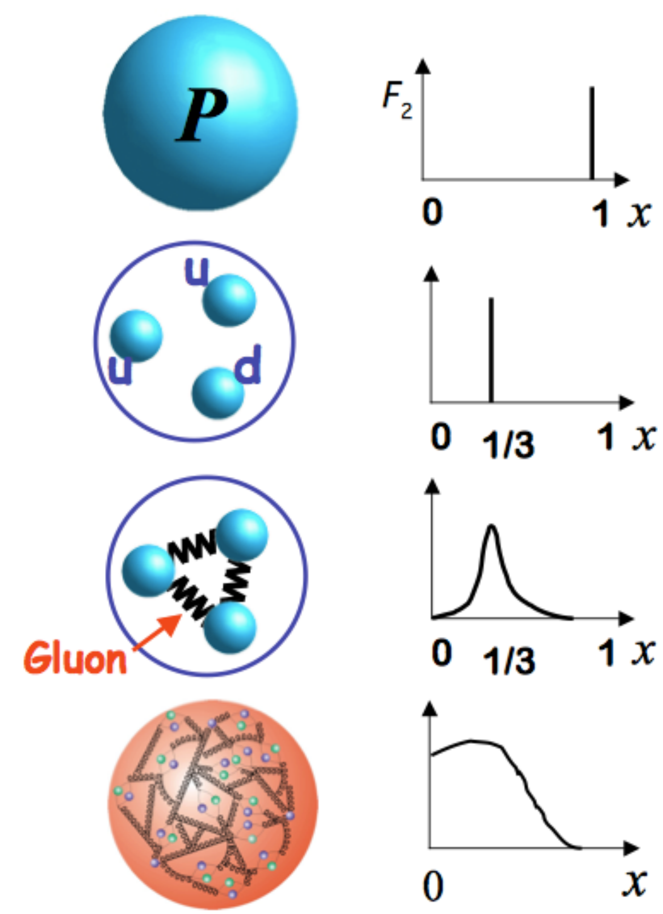
$$\sigma_{AB\to hX} = \sum_{a,b=q,\bar{q},g} \int dx_a dx_b \boxed{f(x_a, Q^2) f(x_b, Q^2)} \times \boxed{\hat{\sigma}_{ab\to cd}(x_a, x_b, Q^2)} \times \boxed{D_{cd\to h}}$$

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

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

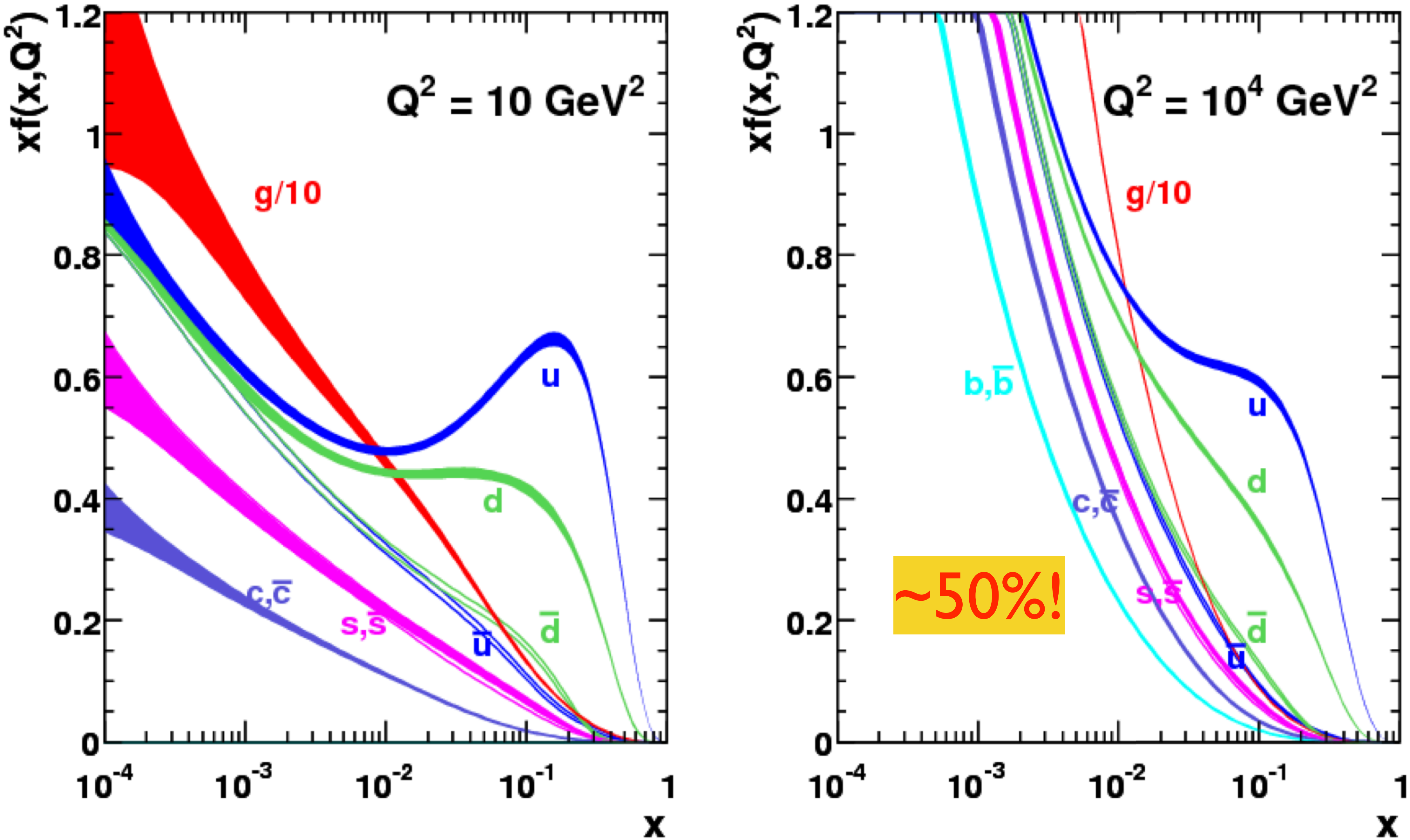




PDFs are universal, they are independent on the hard process

PDFs cannot be calculated in QCD from the first principles!

Parton Distribution Functions



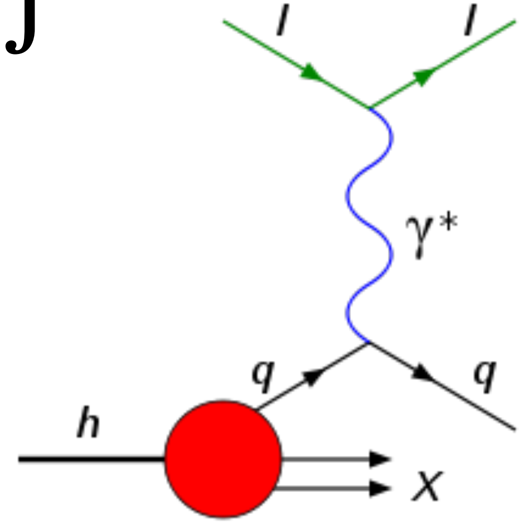
Sea partons becomes more important at high Q^2

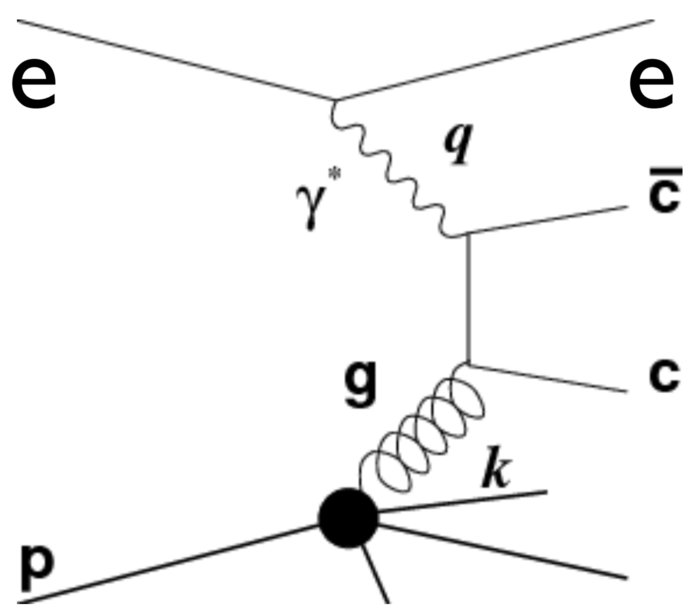
QCD evolution equations: $f(x, Q_1^2) \rightarrow f(x, Q_2^2)$

How to measure PDFs ?

Deep Inelastic Scattering (DIS)

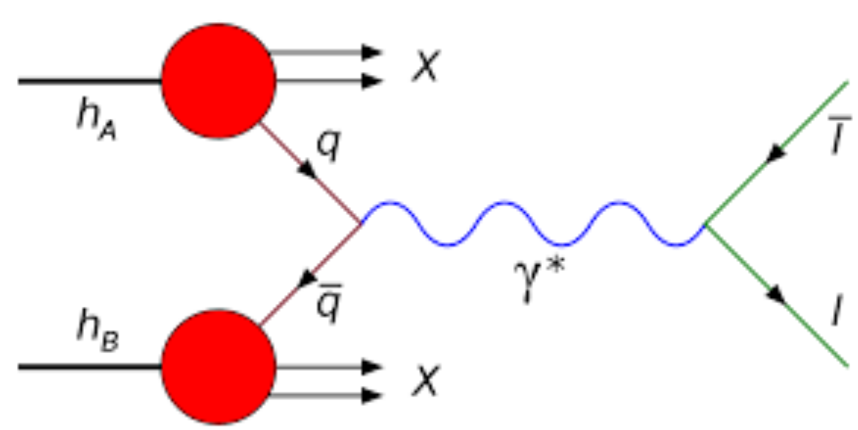
$$\sigma = \int \hat{\sigma} q(x) dx$$

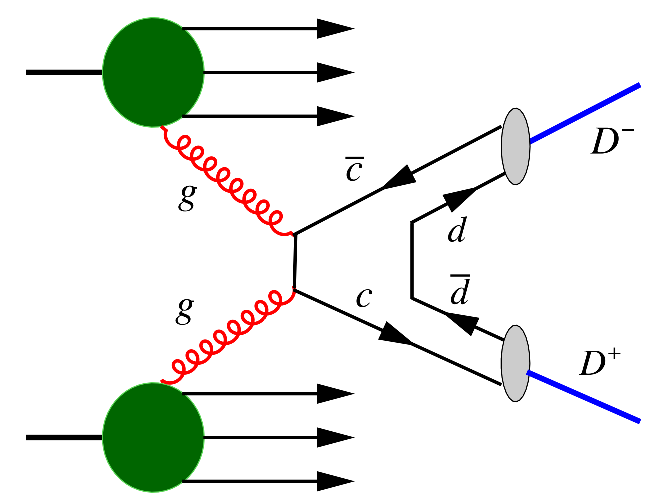




Hadronic interactions

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





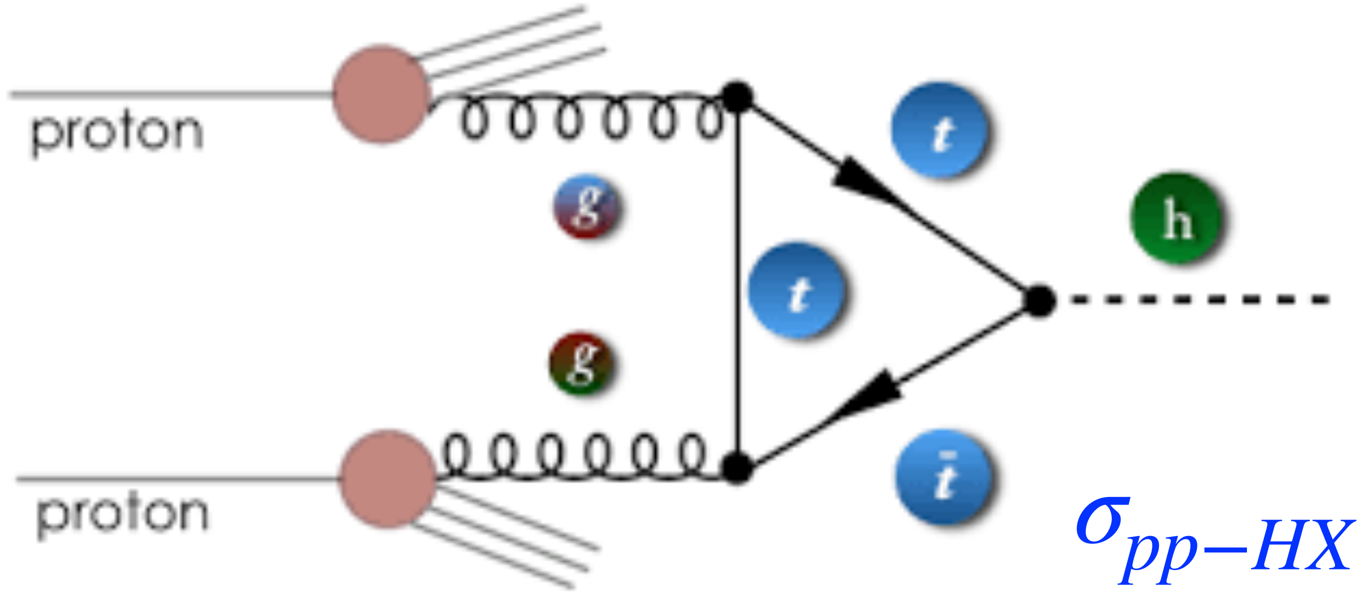
DIS is ideal to access quarks

For gluons hadronic interactions are preferable

Why we should measure PDFs?

Parton Distribution Functions of hadron are as *fundamental quantities* as its mass, magnetic moment, electromagnetic radius, etc.

Parton Distribution Functions, due to their universality, are a *necessary ingredient* for the search and exploration of a *new physics*.

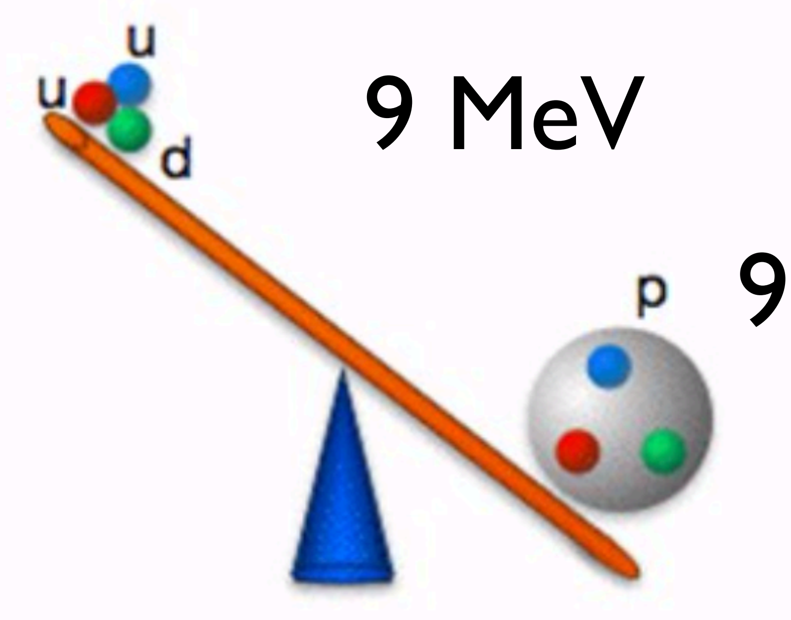


Theory

$$\sigma_{pp-HX} = f(x_1) \otimes f(x_2) \otimes \hat{\sigma}_{gg \to H}$$

Experiment

Proton mass

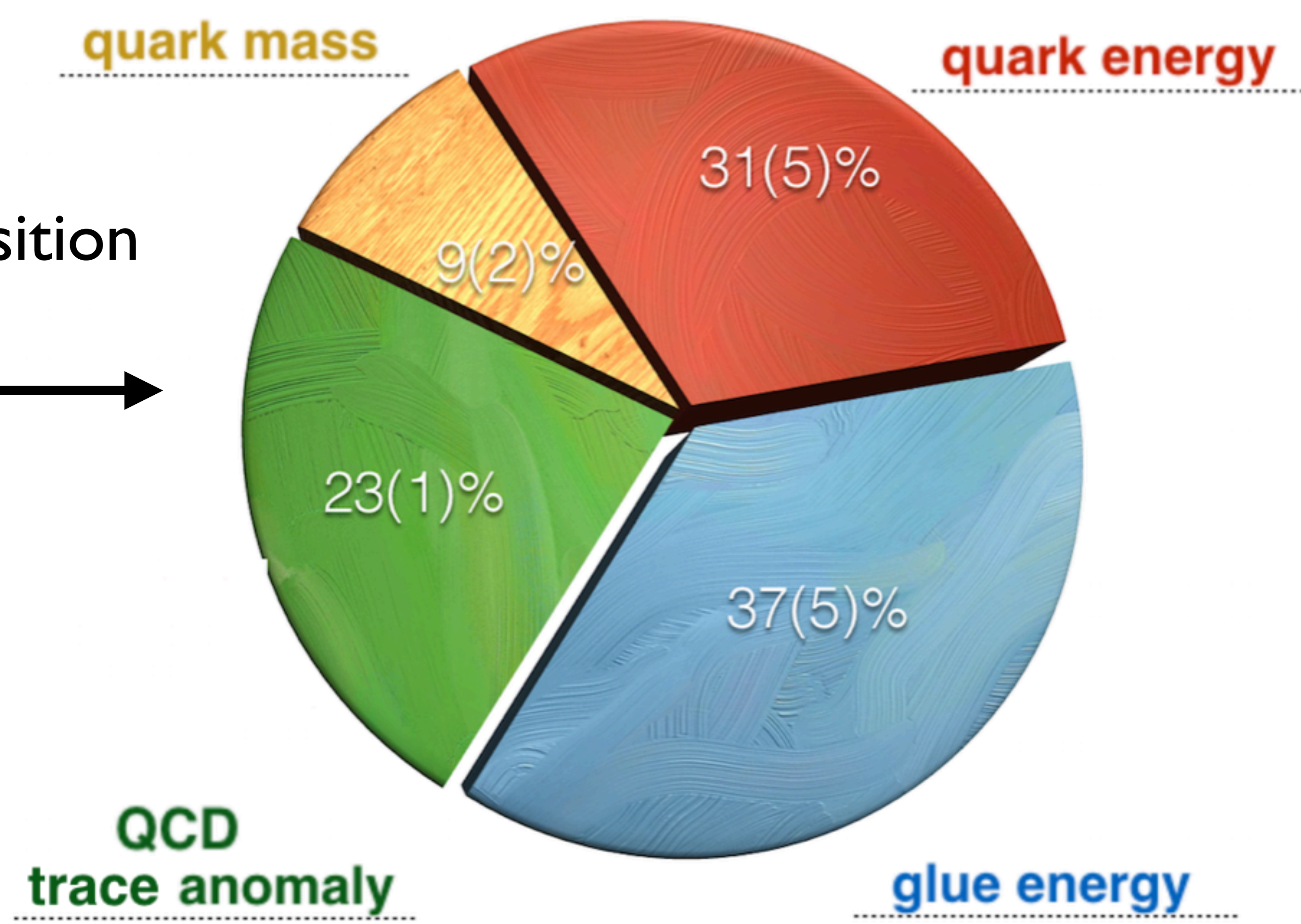


9 MeV

938 MeV

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

Model-dependent decomposition of the proton mass

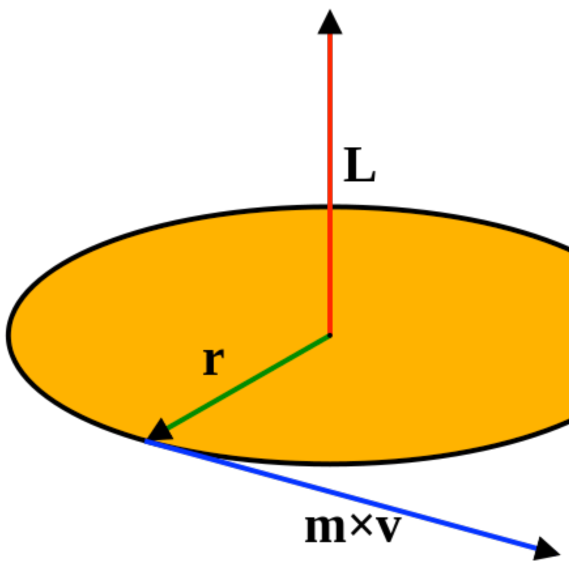


Proton mass

The Higgs mechanism has almost nothing to do with the

It seems, gluons are even more important than quarks!

Spin



Angular momentum is a measure of the amount of rotation

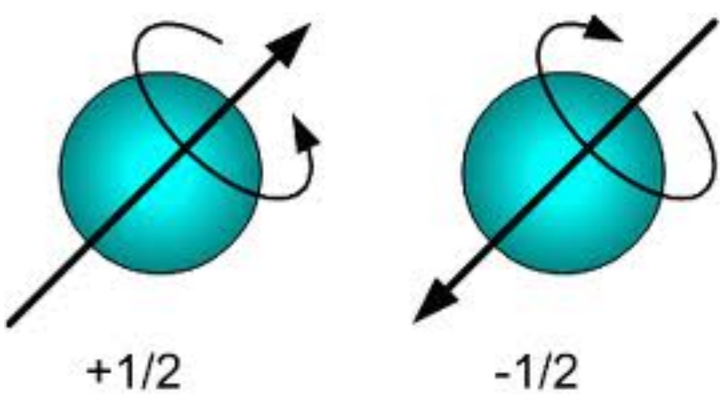
$$\vec{L} = \vec{r} \times \vec{p}$$

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

Spin is a solely quantum-mechanical phenomenon

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

Proton spin: 1/2

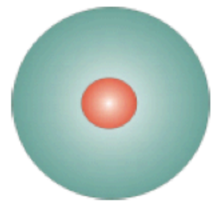


Total momentum (spin) of a composite particle is determined the particle's spin is determined by the spin and the angular momenta of its components

Units: $\hbar$

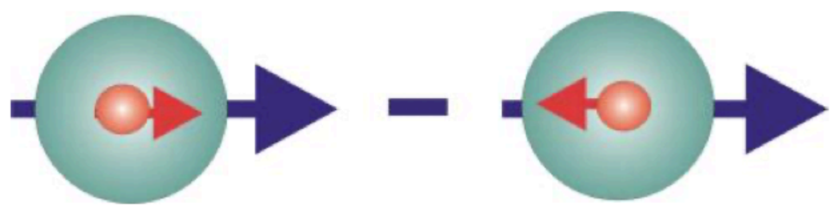
Polarized proton

f(x)



Unpolarized PDF

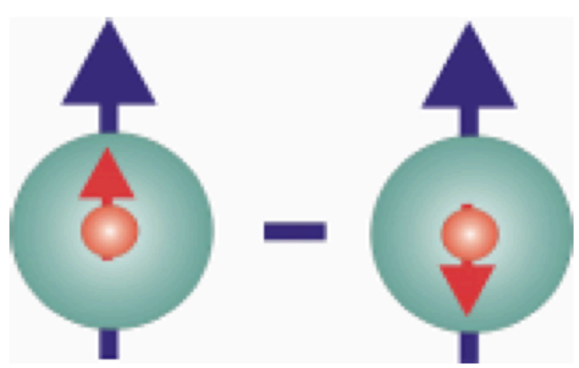
Δf(x)



Helicity

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

Δ_Tf(x)

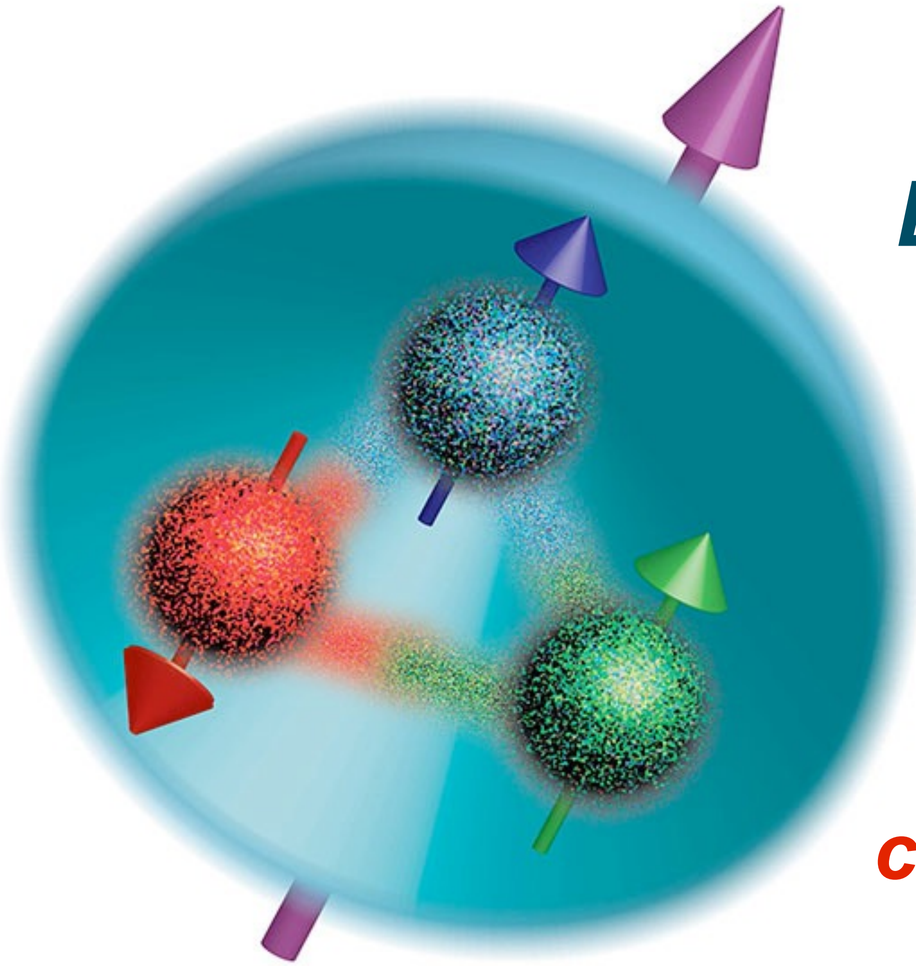


Transversity

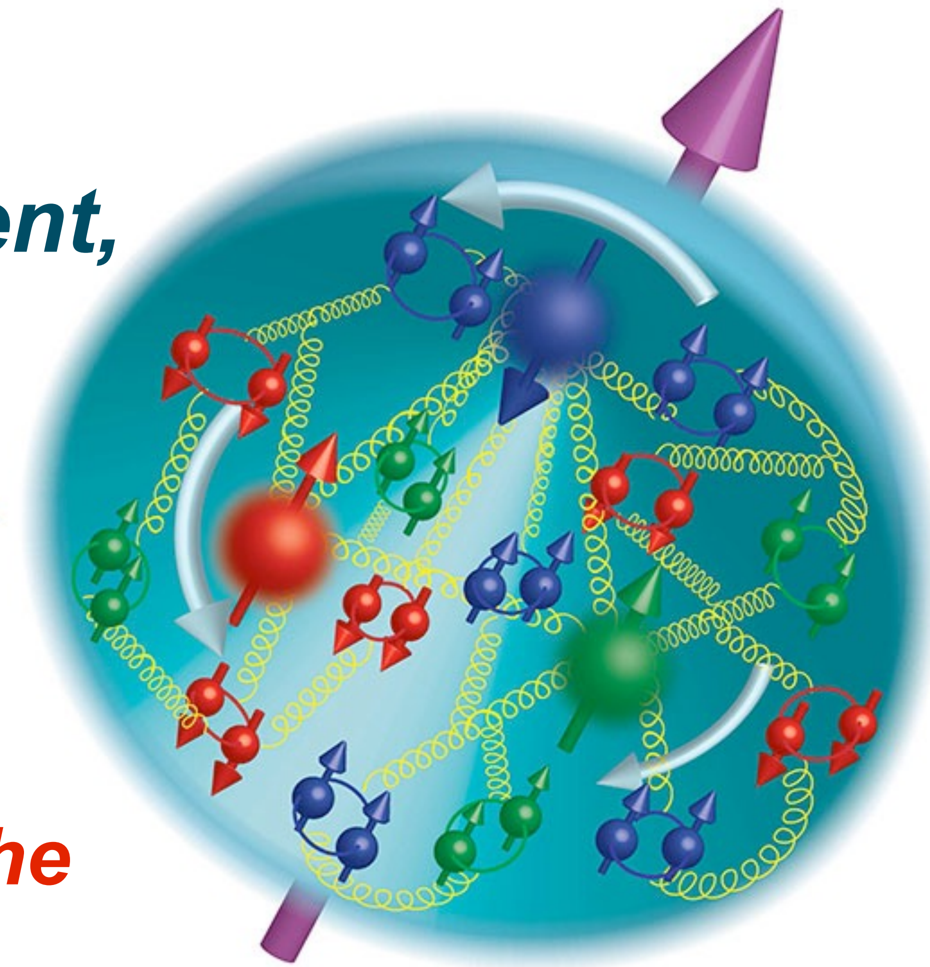
A_{TT}

P

Spin crisis



EMC experiment,
CERN 1988



Quark contribution to the proton spin is below 30%!

Naive quark model

Real situation

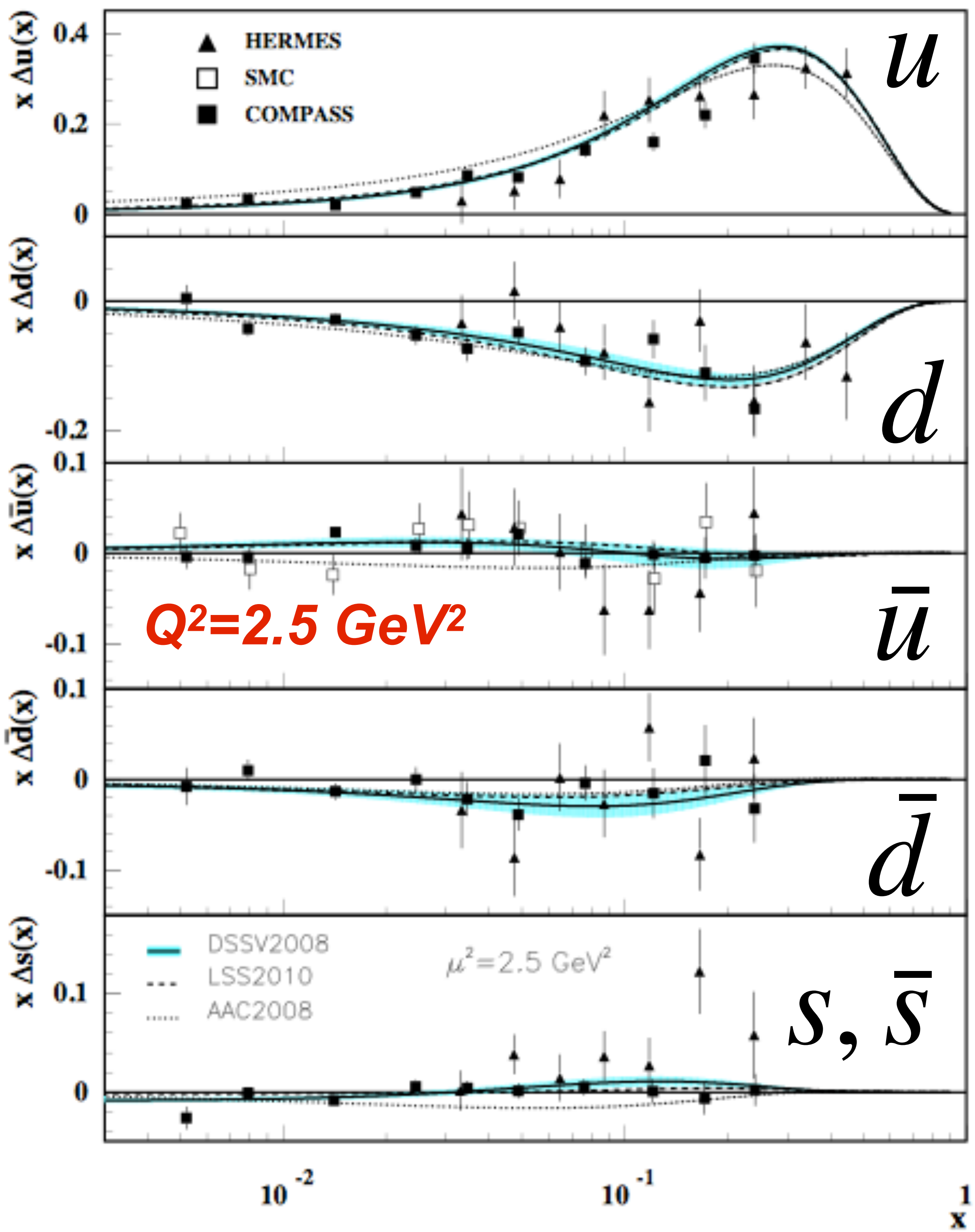
$$\frac{1}{2} = \sum_{q=u,u,d} (\frac{\vec{1}}{2})$$

L - orbital moments of quarks and gluons

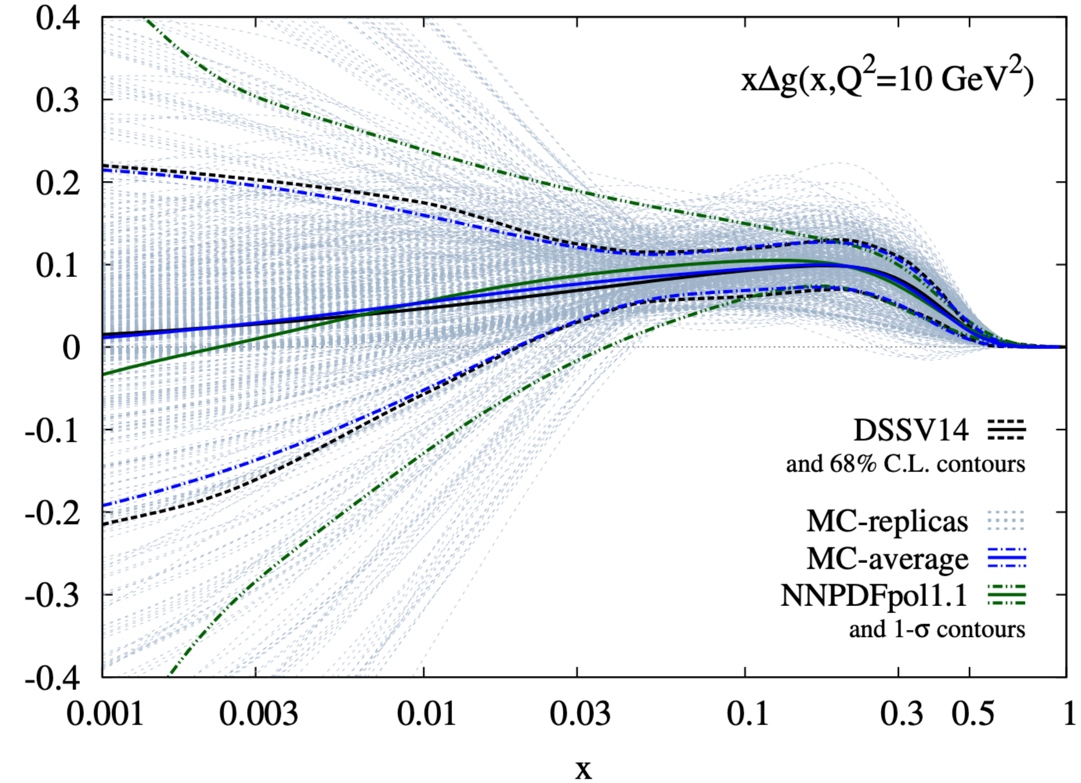
$$\boxed{S_N = \tfrac{1}{2} = \tfrac{1}{2}\,\Delta\Sigma + \Delta G + L}$$

Spin crisis

ПрLongitudinal polarization of quarks:



… and gluons:

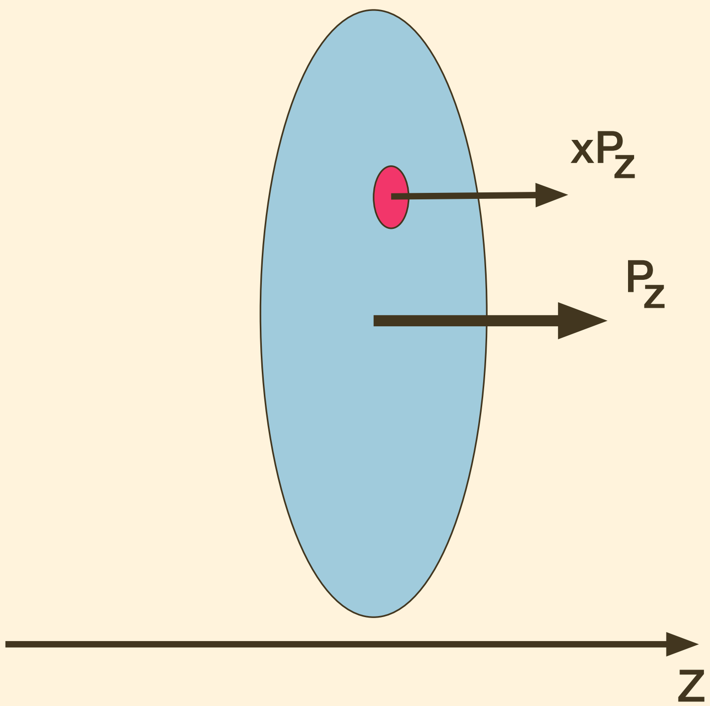


$$S_N = ½ = ½\,\Delta\Sigma + \Delta G + L$$

~30%

~ ?

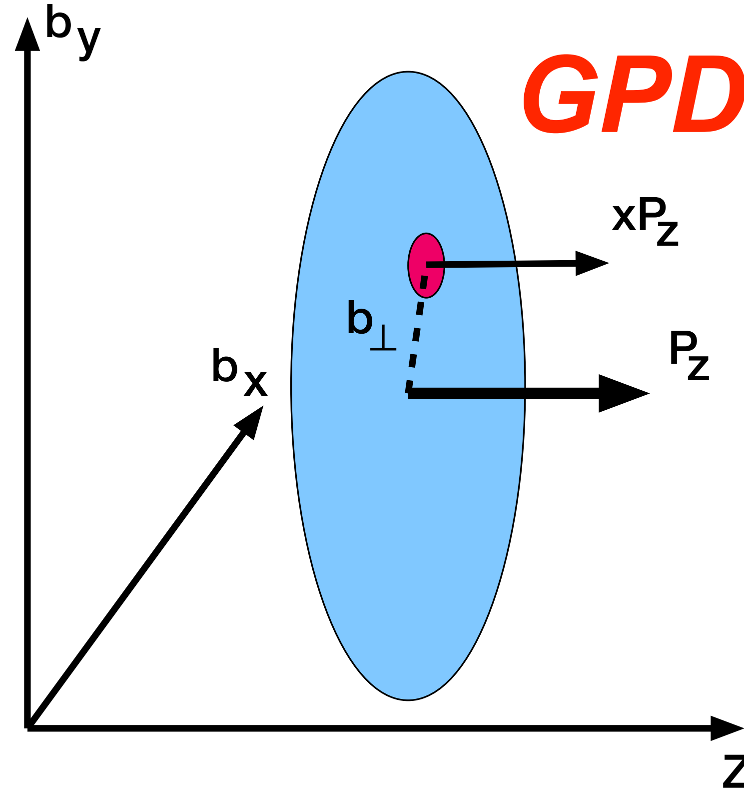
3D-tomography of proton



Colliniar approximation

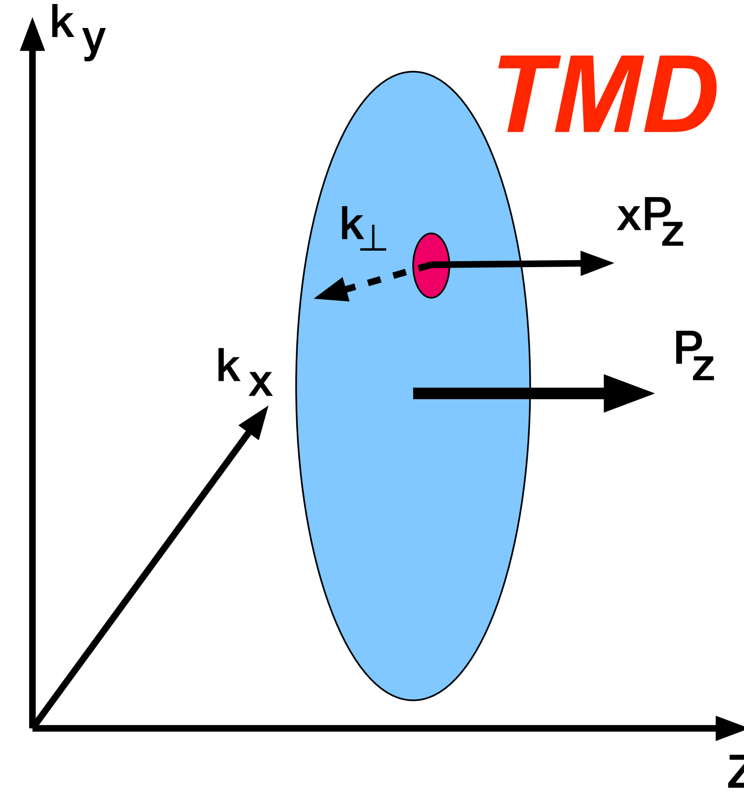
(usual PDFs)

GPDs

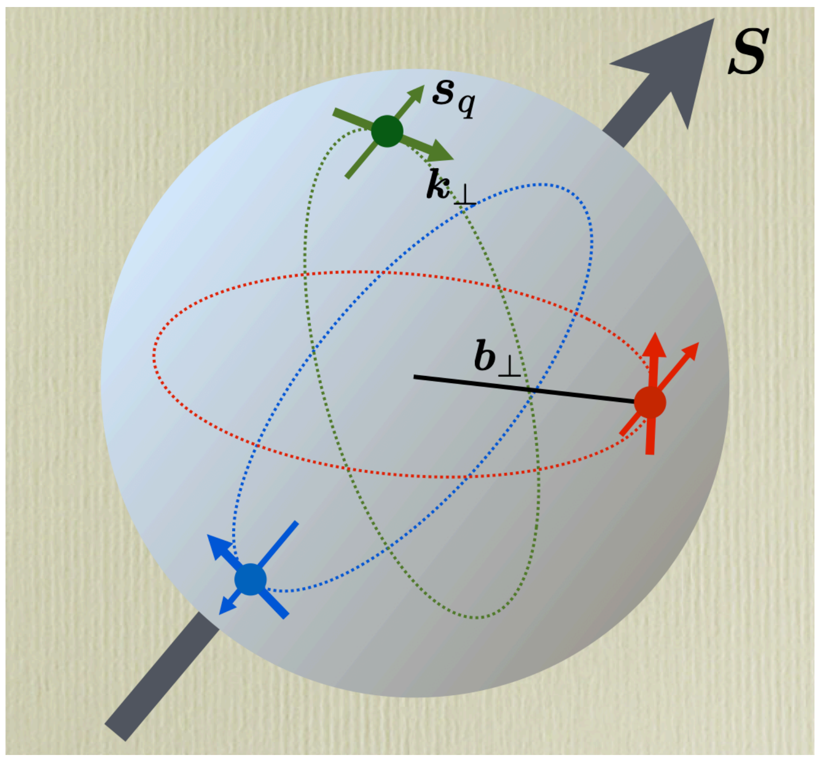


Generalized Parton Distributions

TMD PDFs



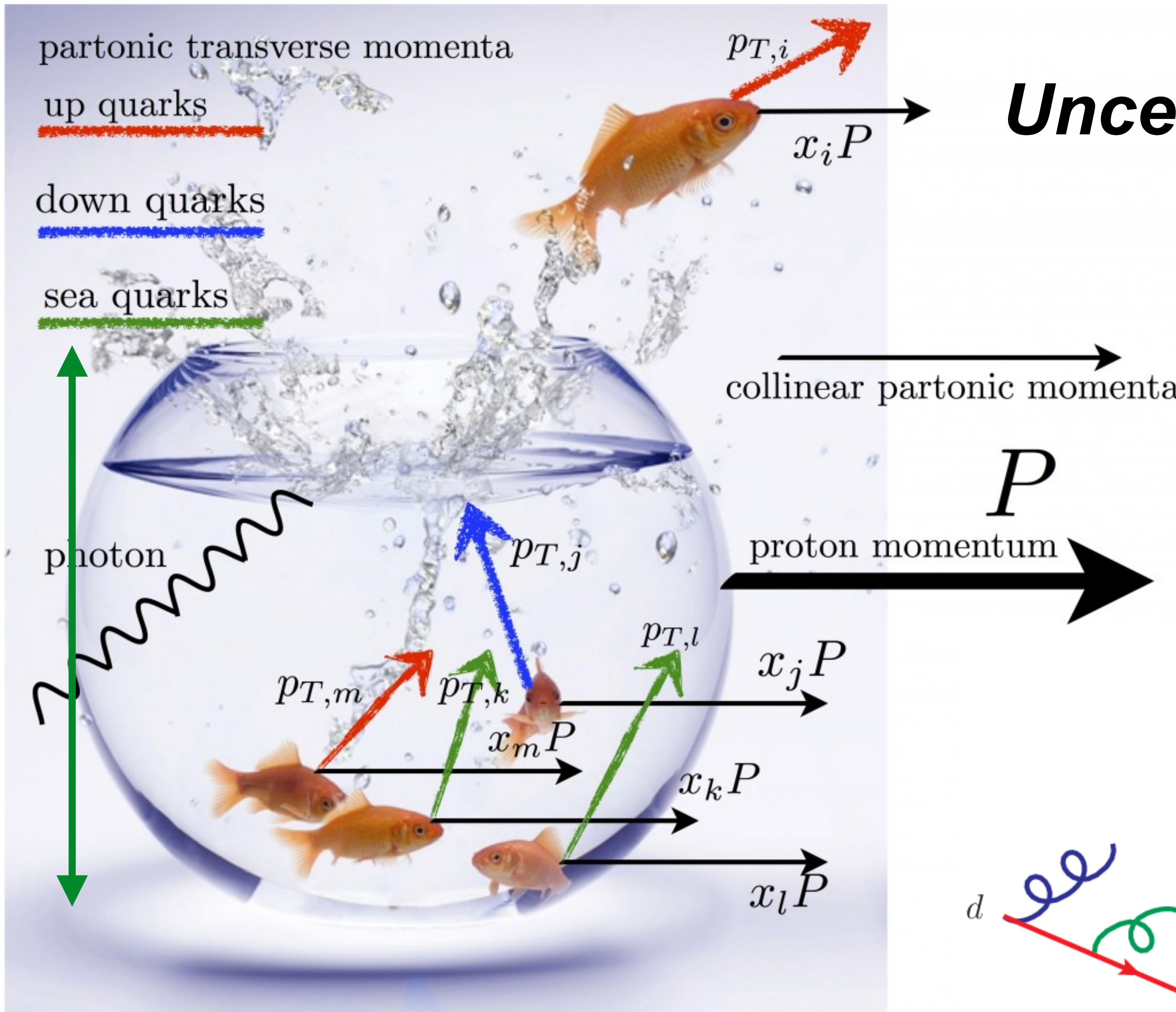
Transverse Momentum Dependent PDFs



“3D” structure of proton

Relation to orbital moment

Where transverse momentum come from?

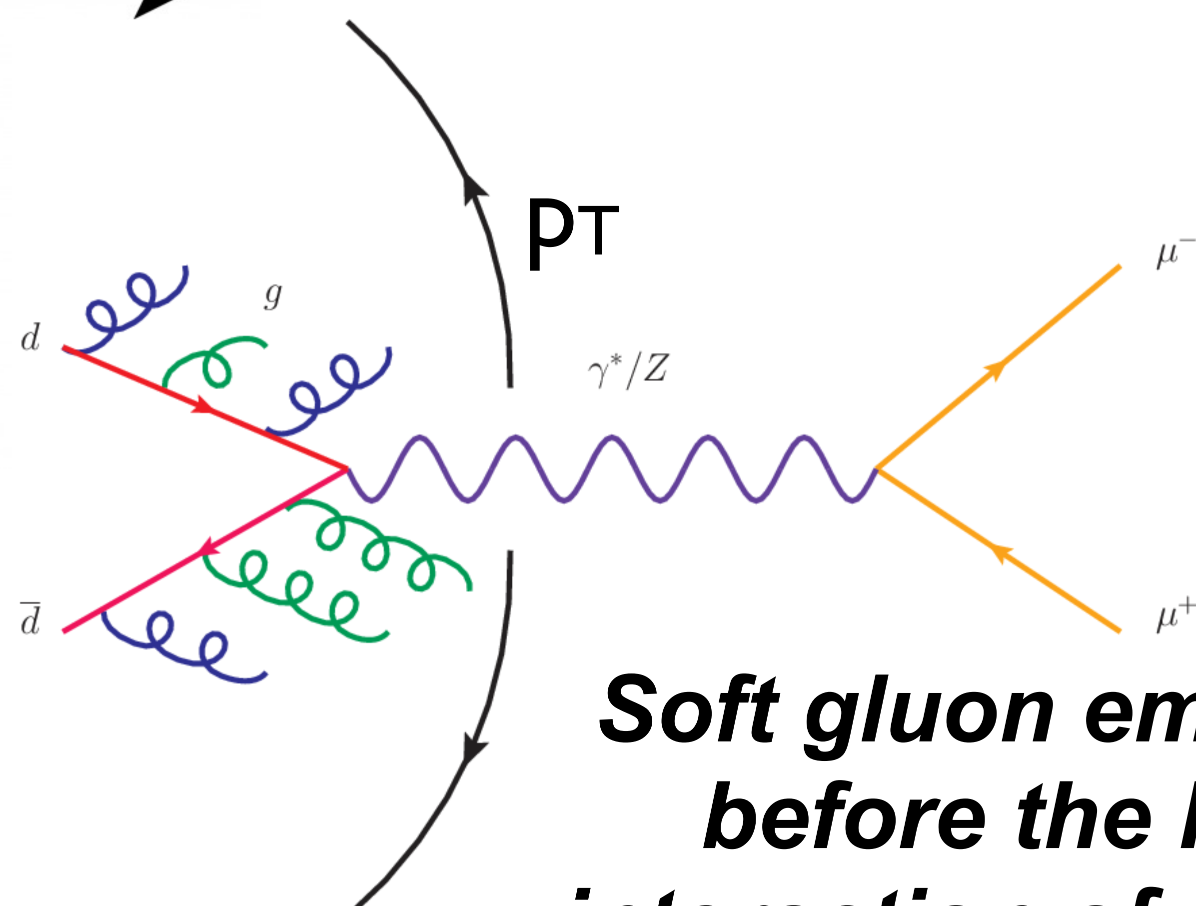


$\langle r_p \rangle = 0.88$ фм

Uncertainty relation: $\Delta p_y \Delta y \geq \dfrac{h}{2\pi}$

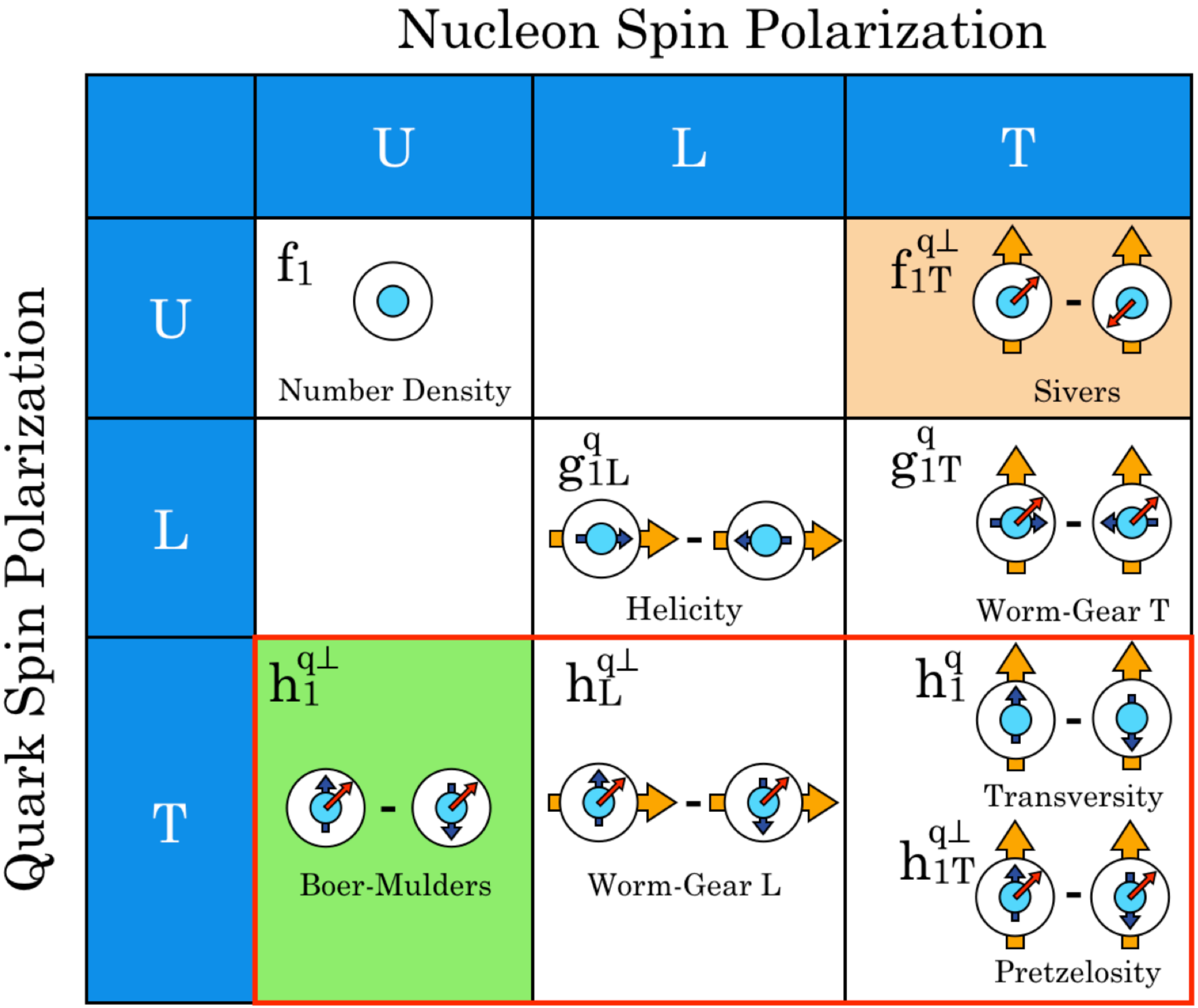
$\Delta y \sim \langle r_p \rangle$

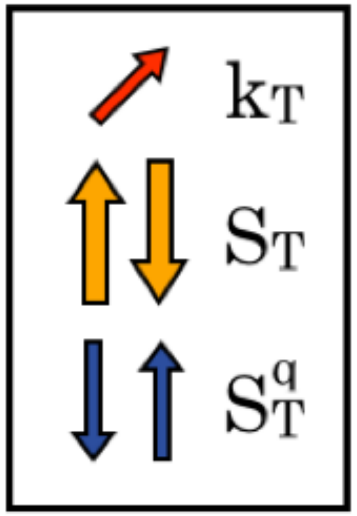
$p_T \sim \Delta p_y \geq 0.2$ GeV/c



Soft gluon emission before the hard interaction of partons

TMD PDF



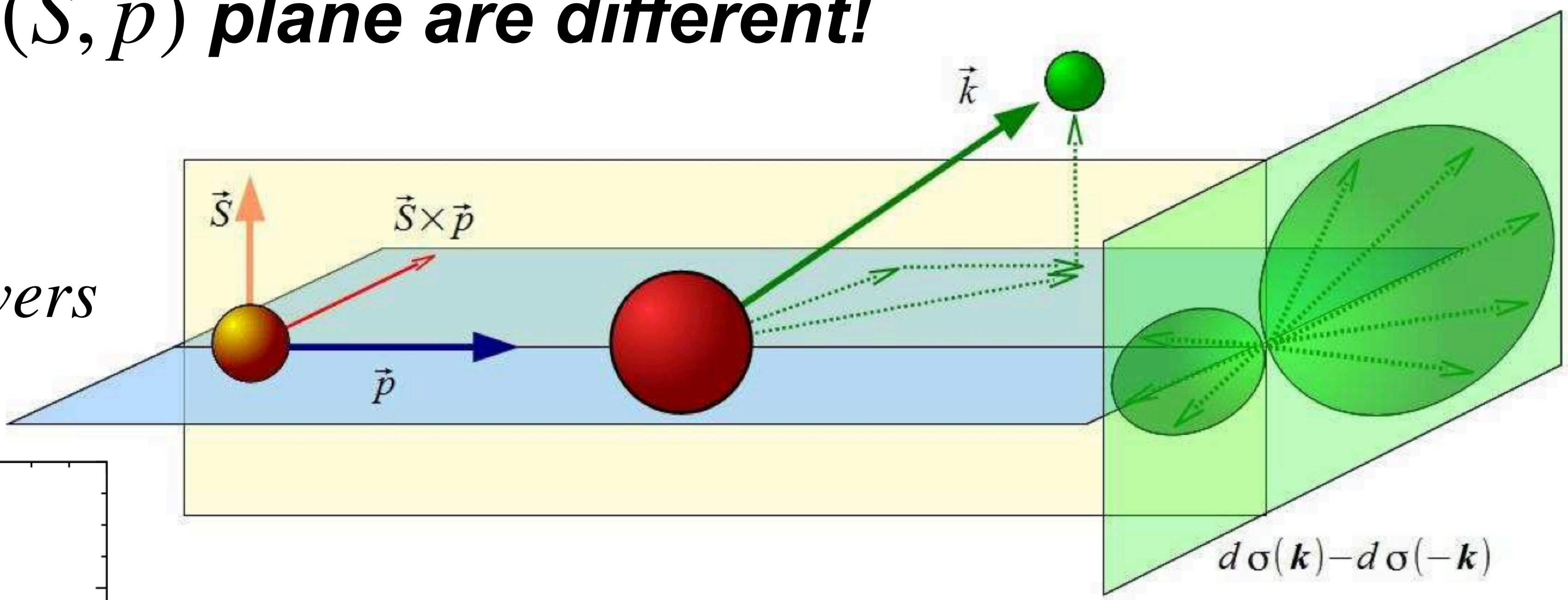


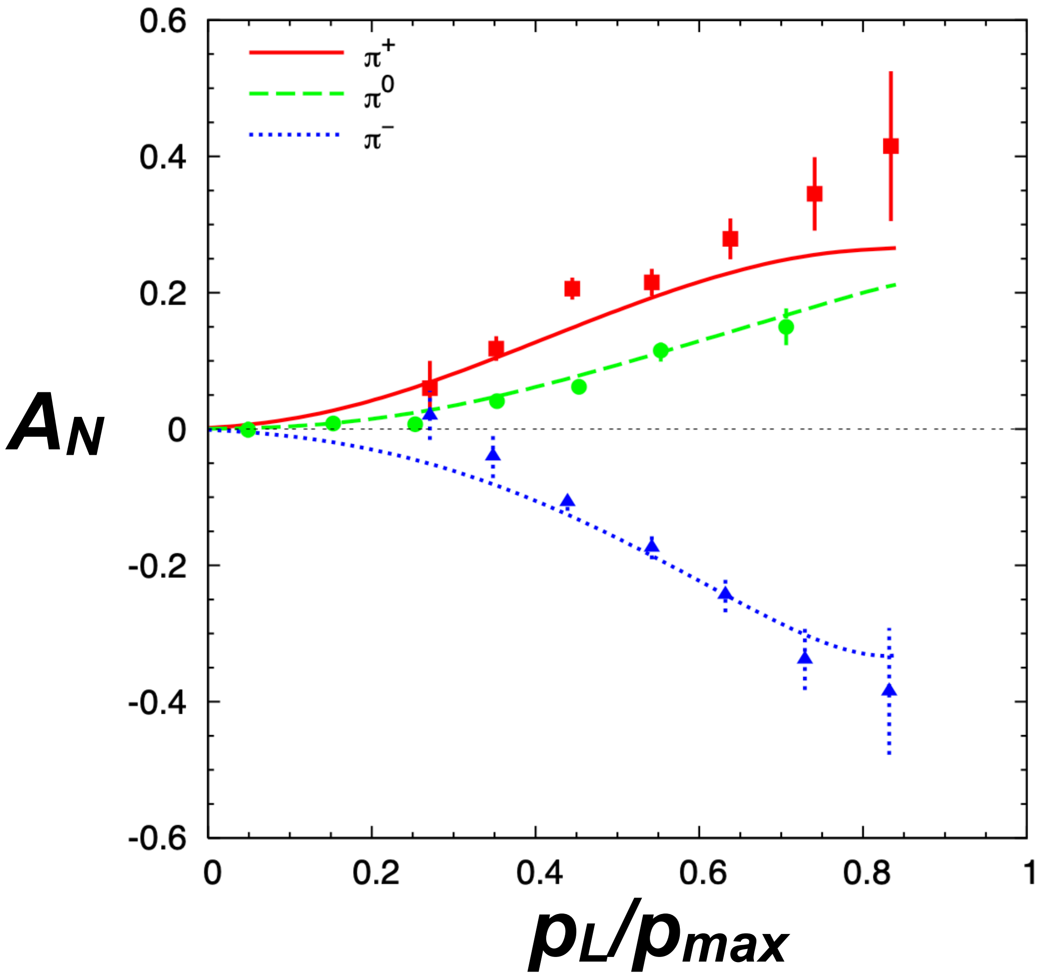
***5 additional (TMD) functions* describing the correlation between the nucleon spin, parton spin, and parton transverse momentum.**

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!

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

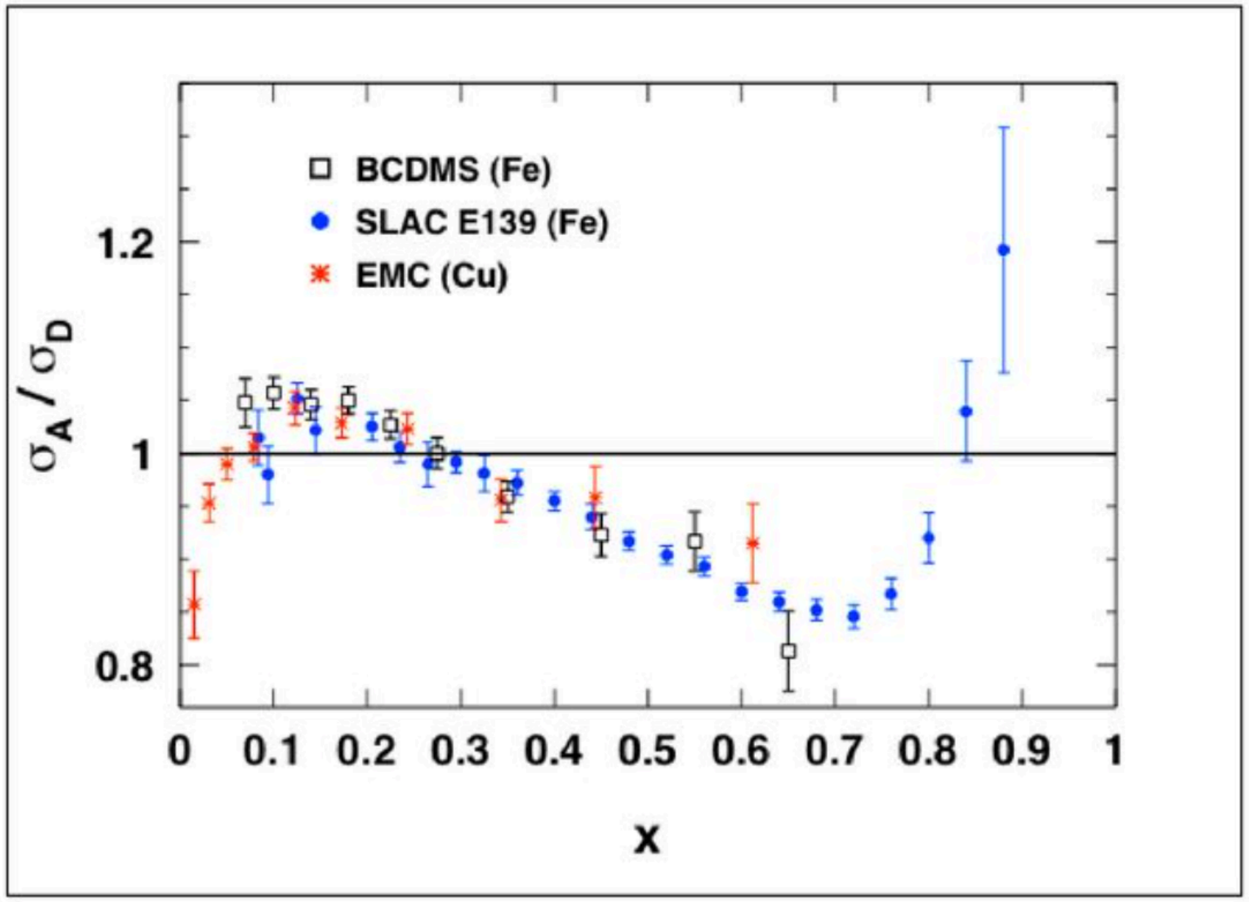




E704

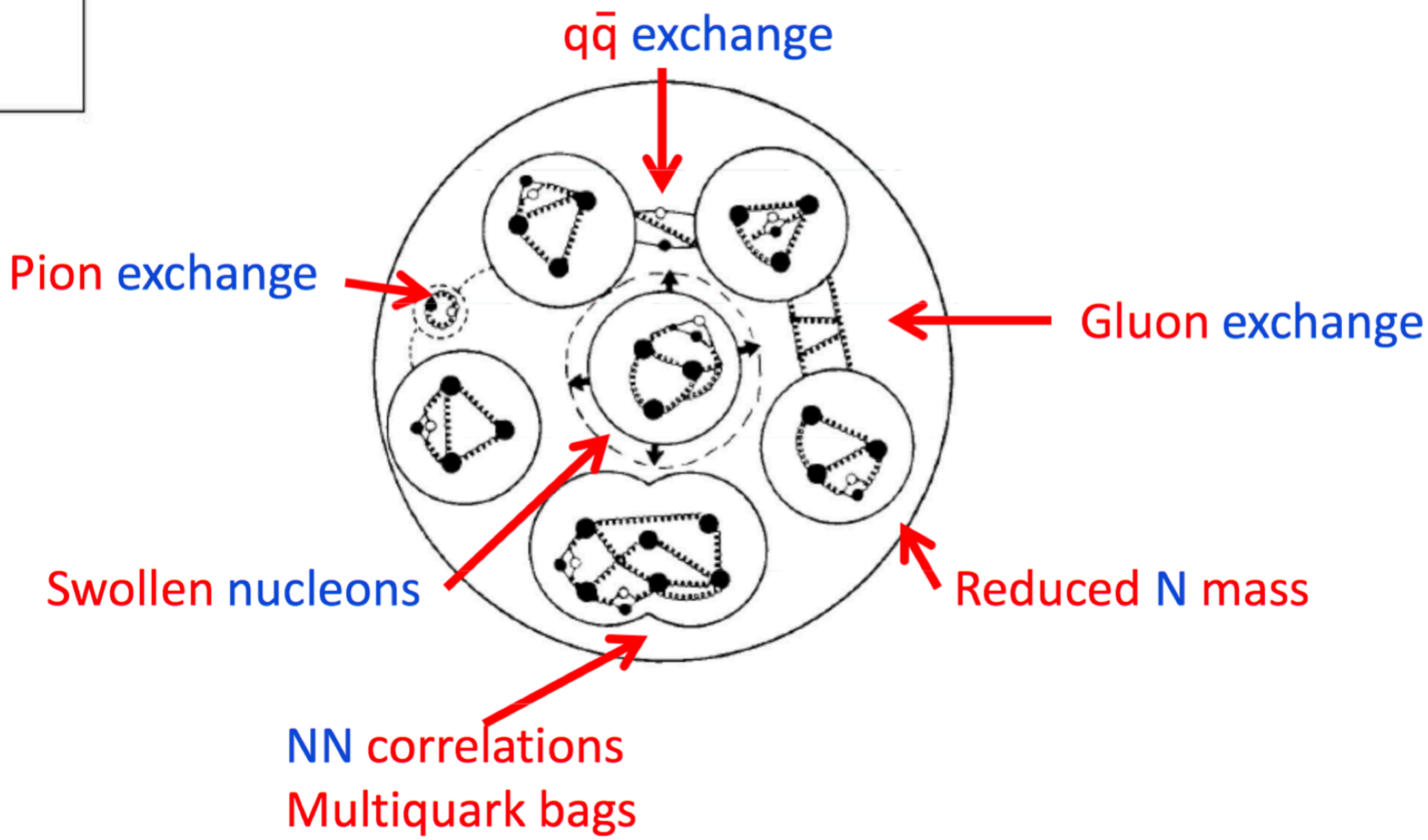
The Sievers effect is usually observed together with the Collins effect, an asymmetry arising from the fragmentation of the final state.

EMC-effect

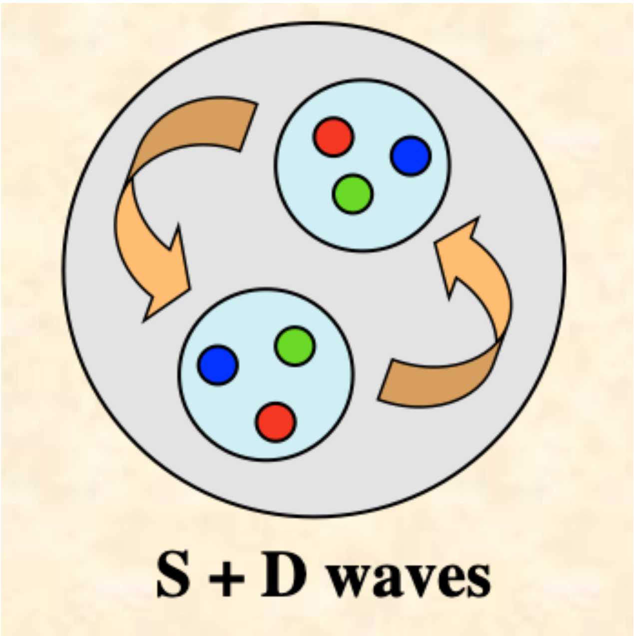


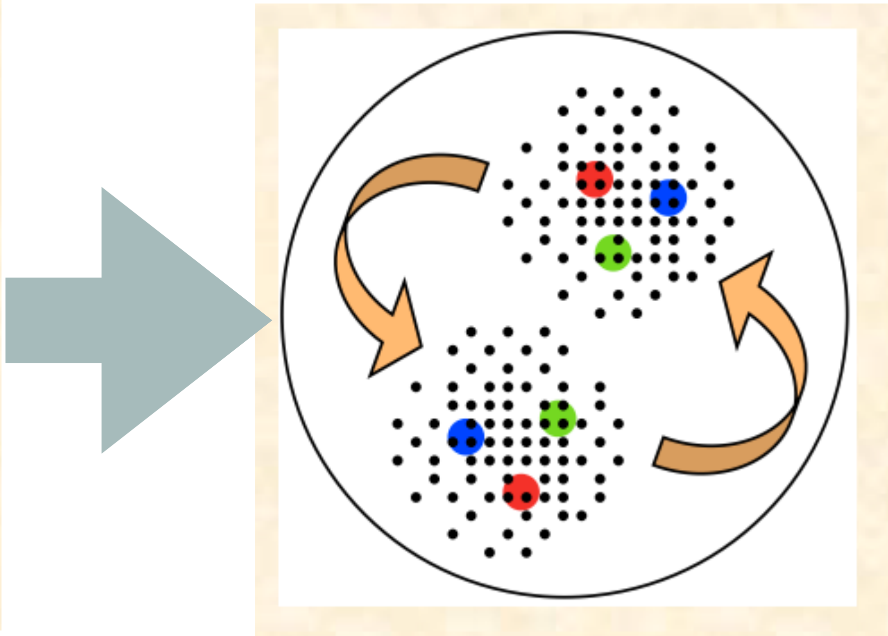
EMC collaboration, 1982

The nucleon "knows" which nucleus it is in!



Deuteron



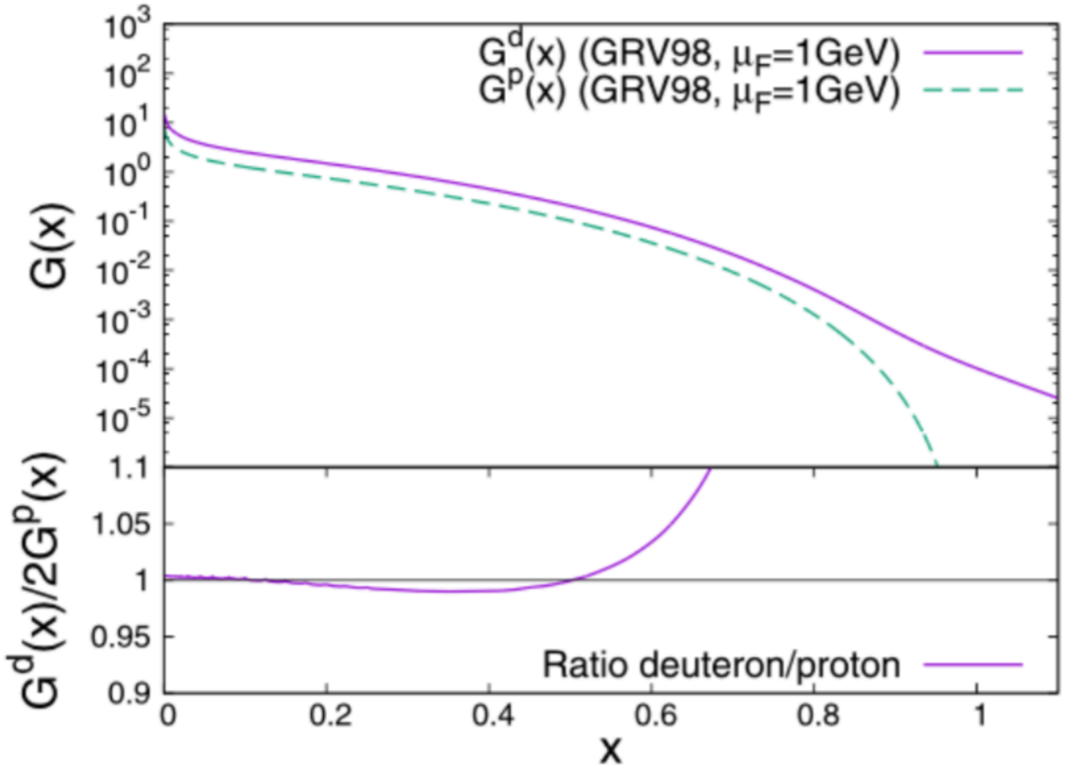


Deuteron is not just proton + neutron!

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

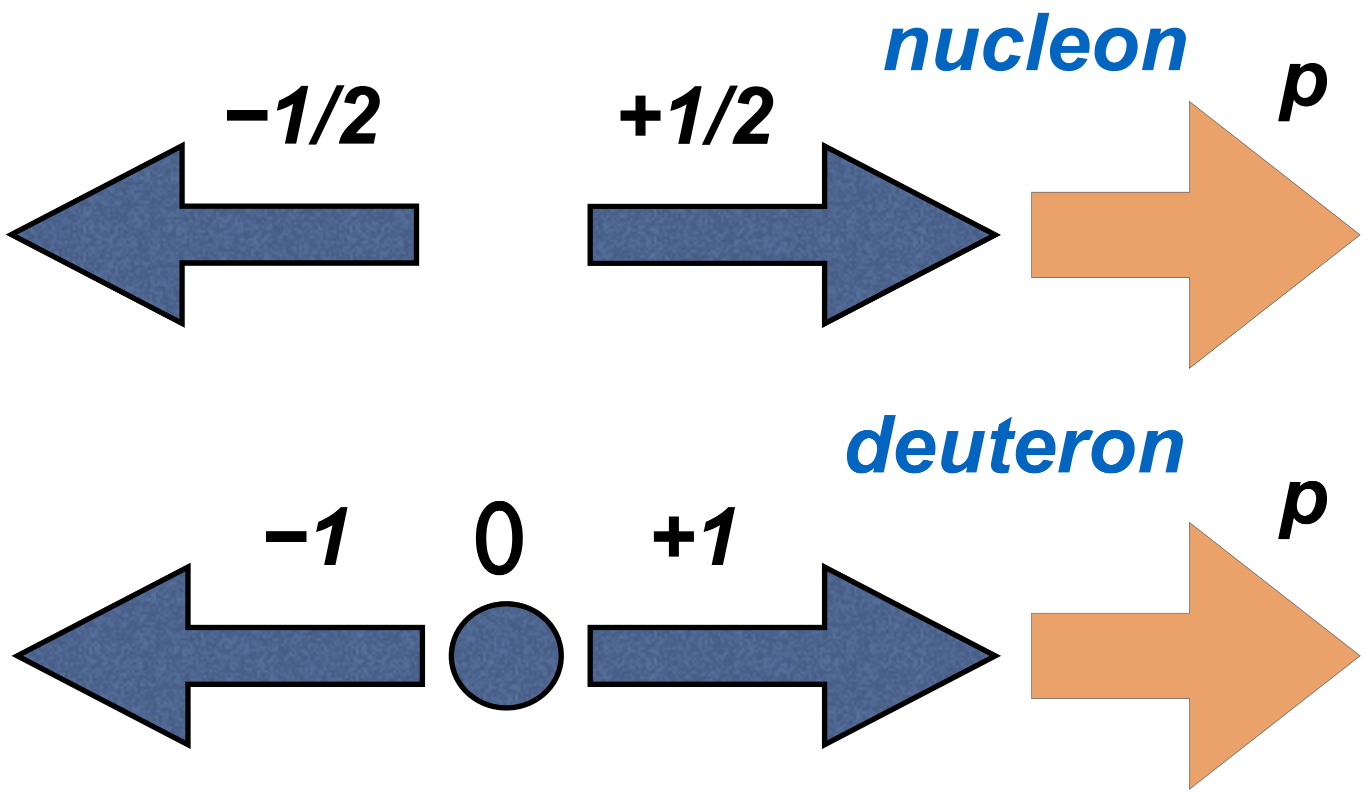
hidden color

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

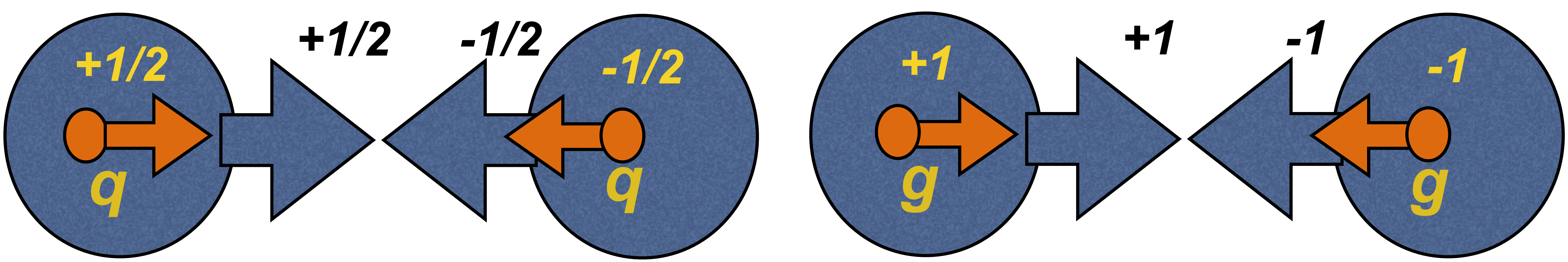
$$\frac{N_{1/2} - N_{-1/2}}{N_{1/2} + N_{-1/2}}$$

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

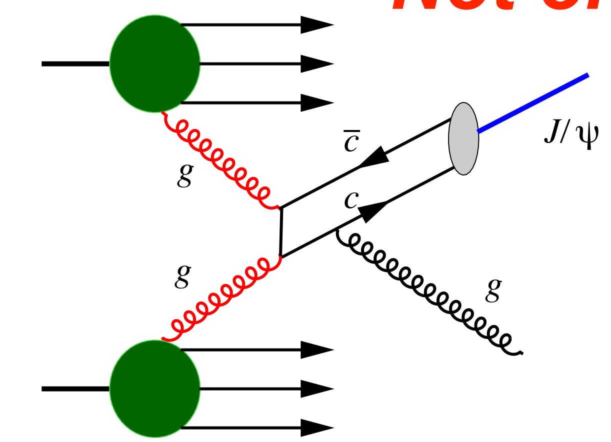
but possible in deuteron!

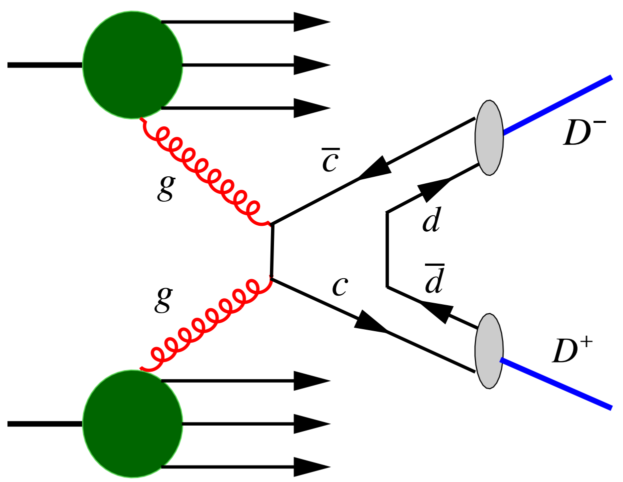
SPD at NICA

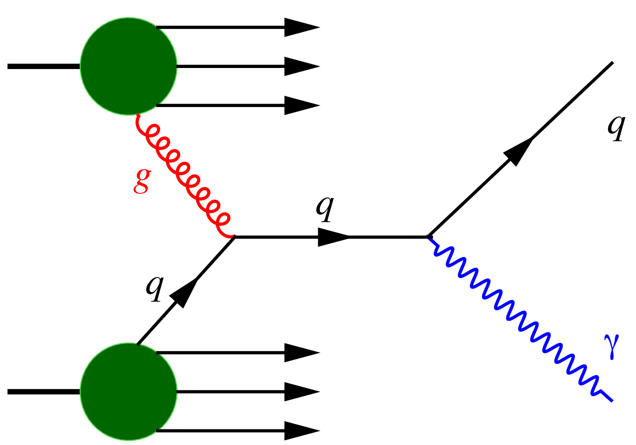
SPD
BM@N (Detector)
Extracted beam
Heavy Ion
Linac
Collider
MPD
E-cooling
Nuclotron
LU-20
Booster
NICA

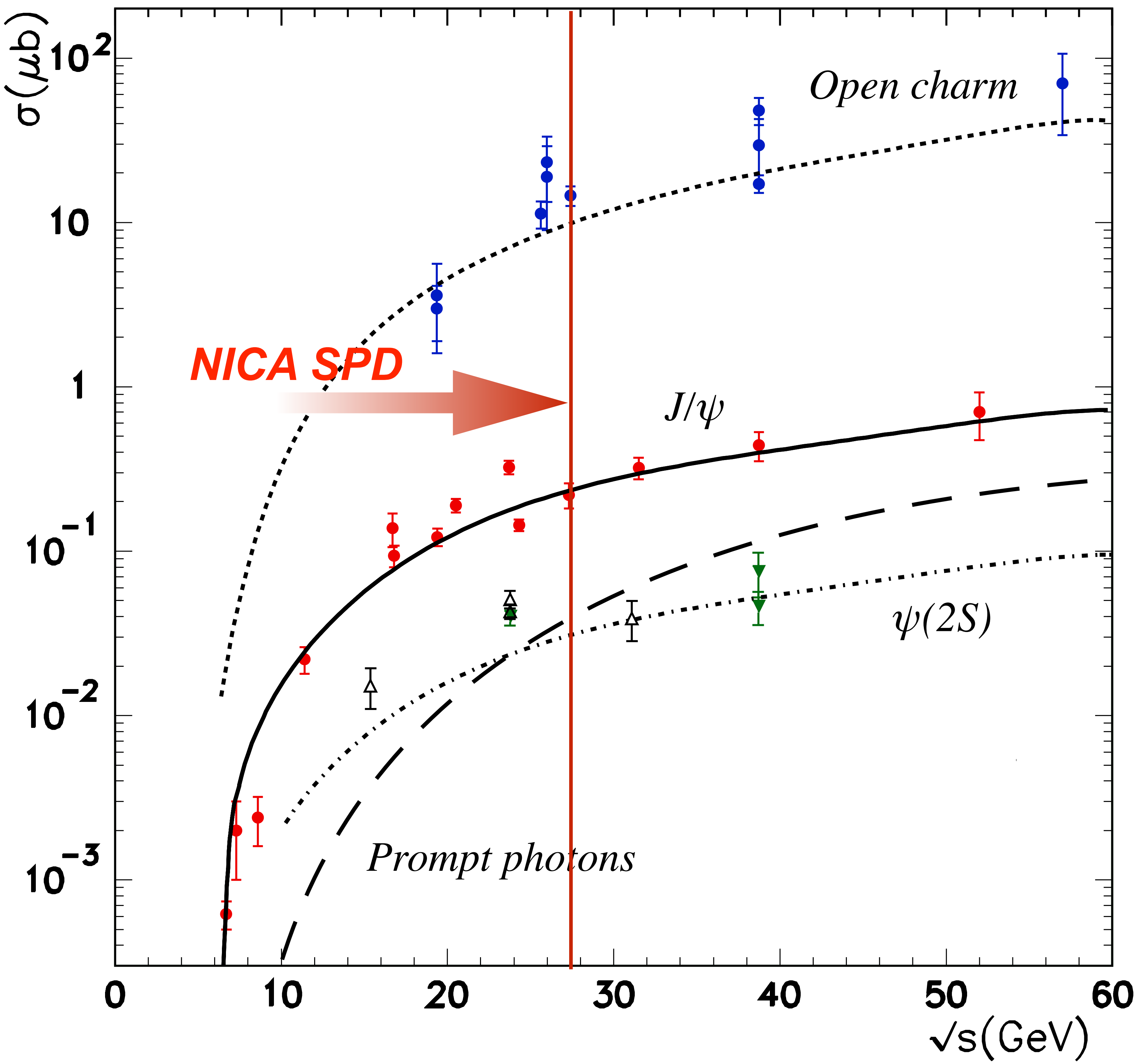
SPD and gluon structure of nucleon

Not only J/ψ!



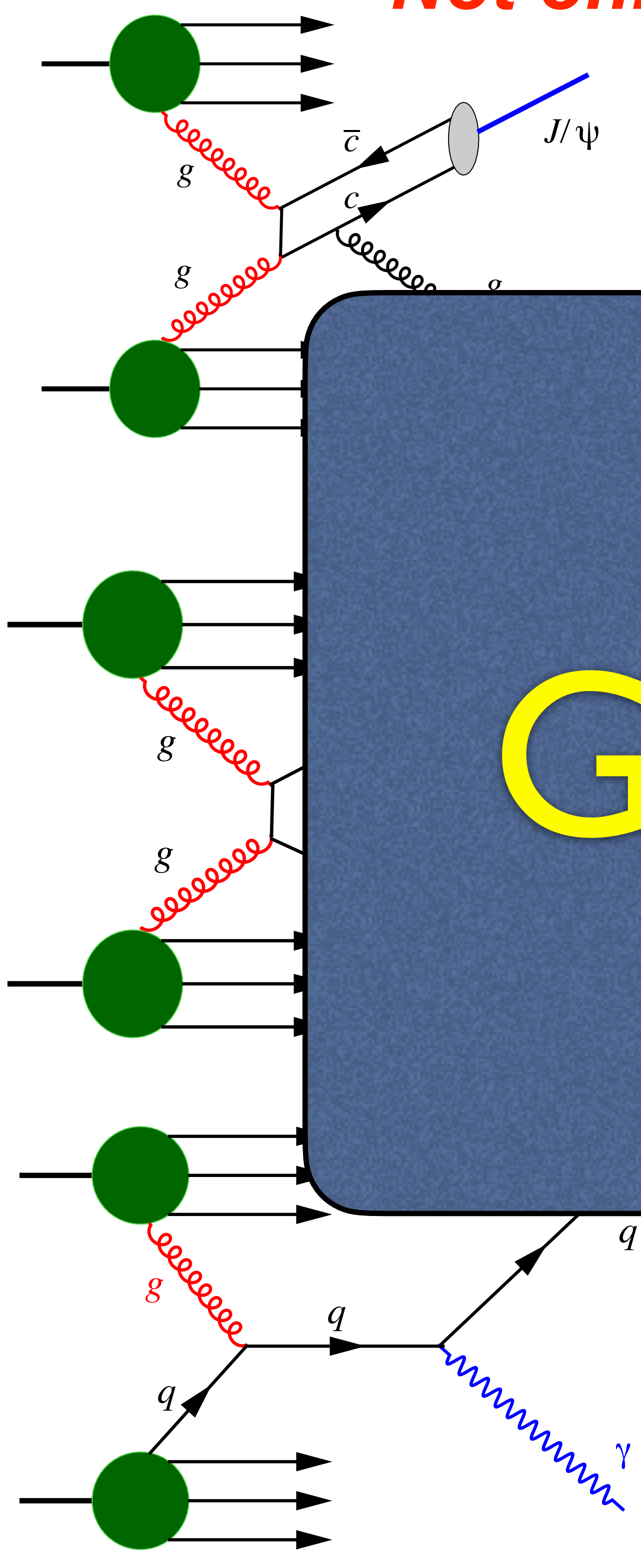


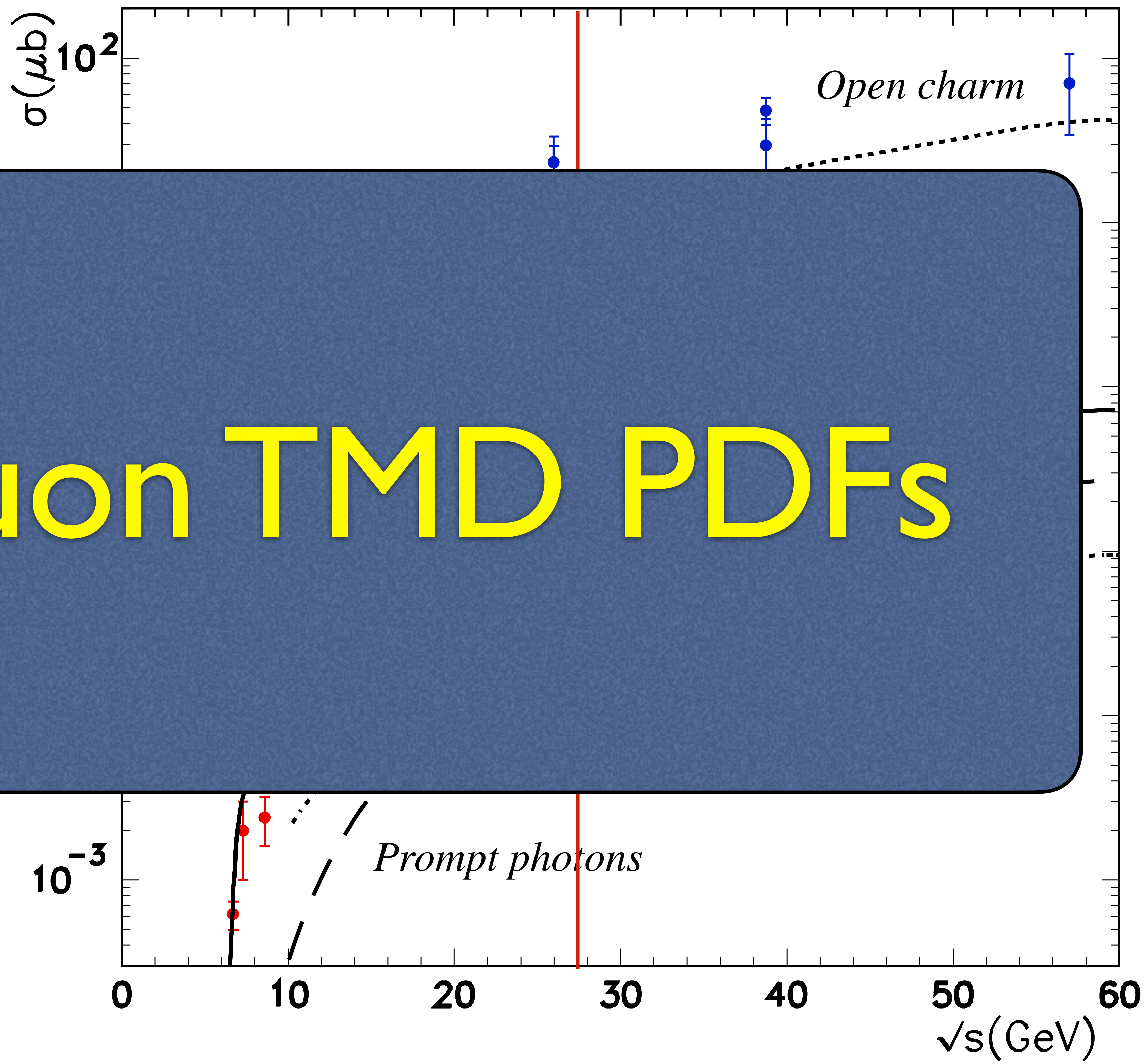




SPD and gluon structure of nucleon

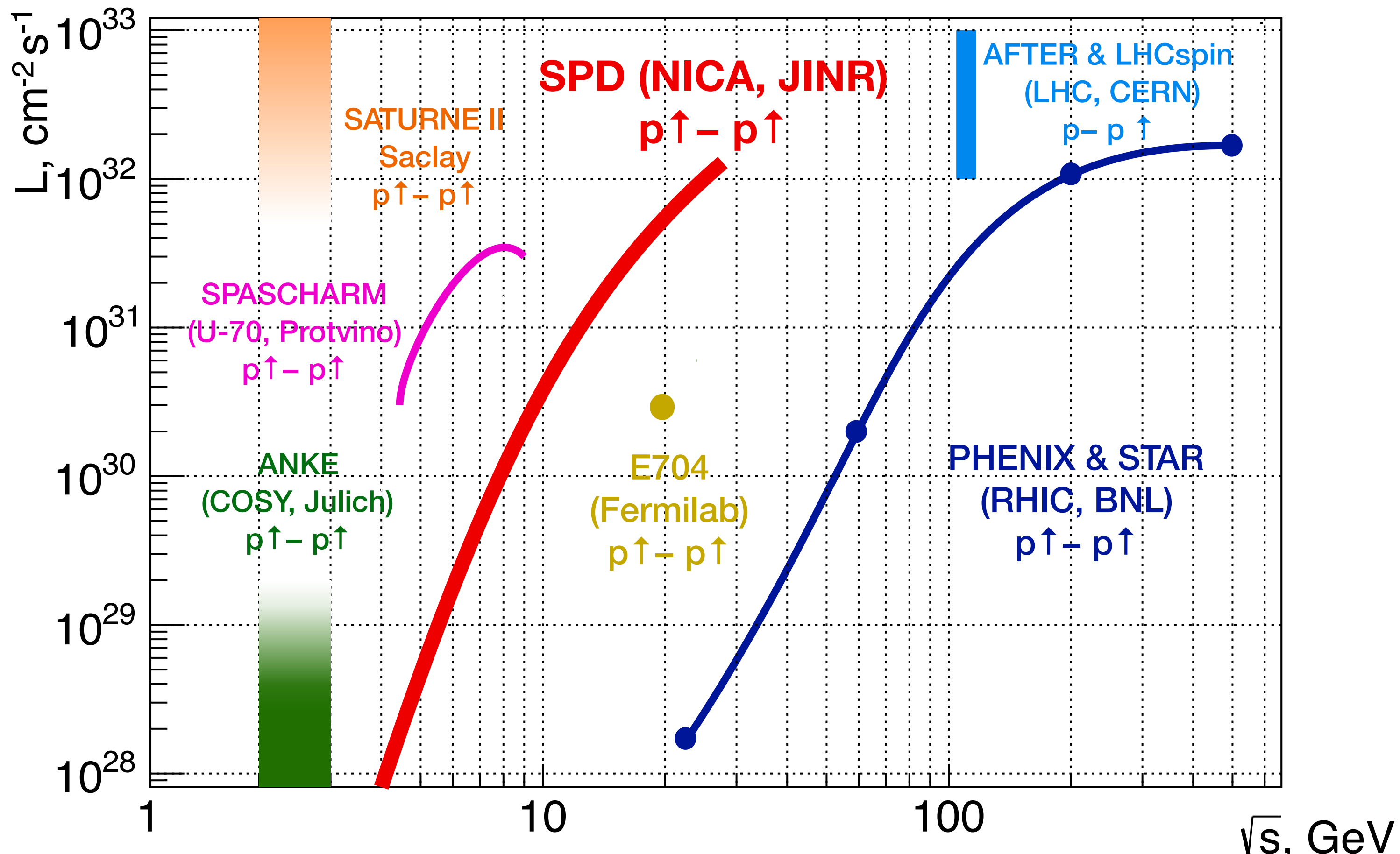
Not only J/ψ!

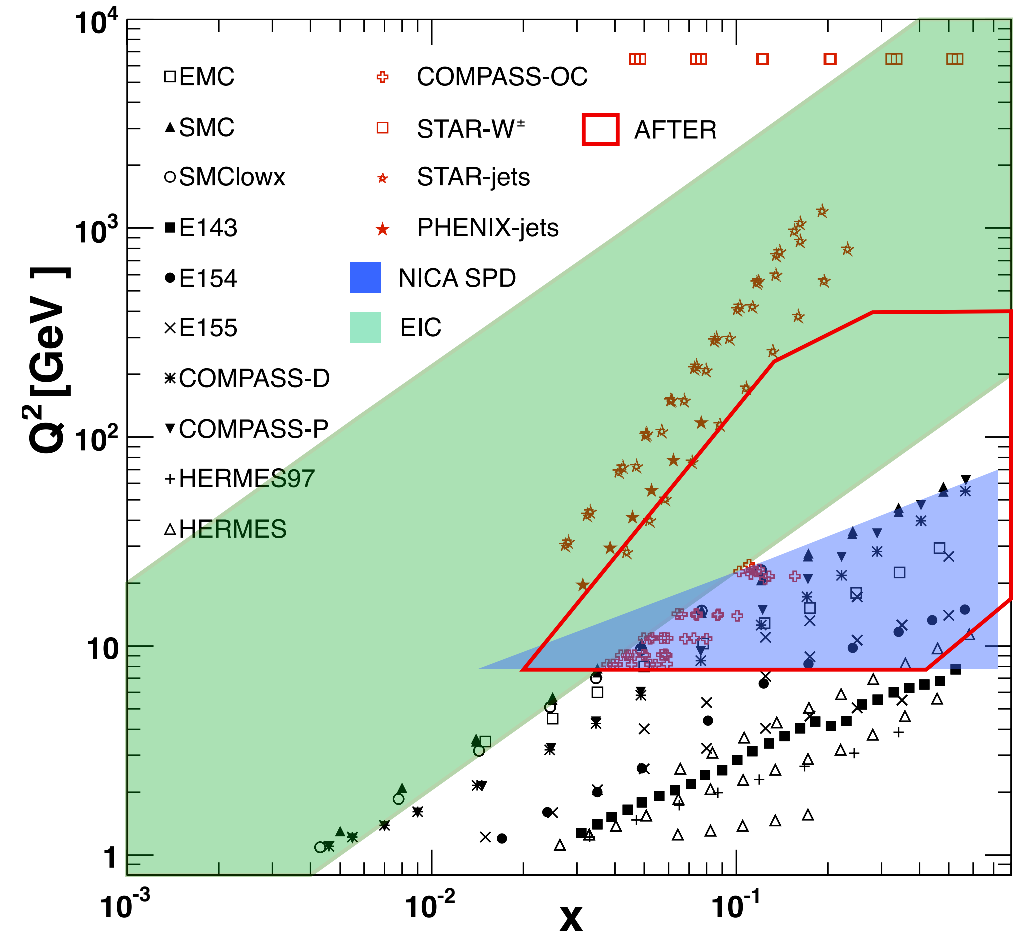




Gluon TMD PDFs

SPD and others



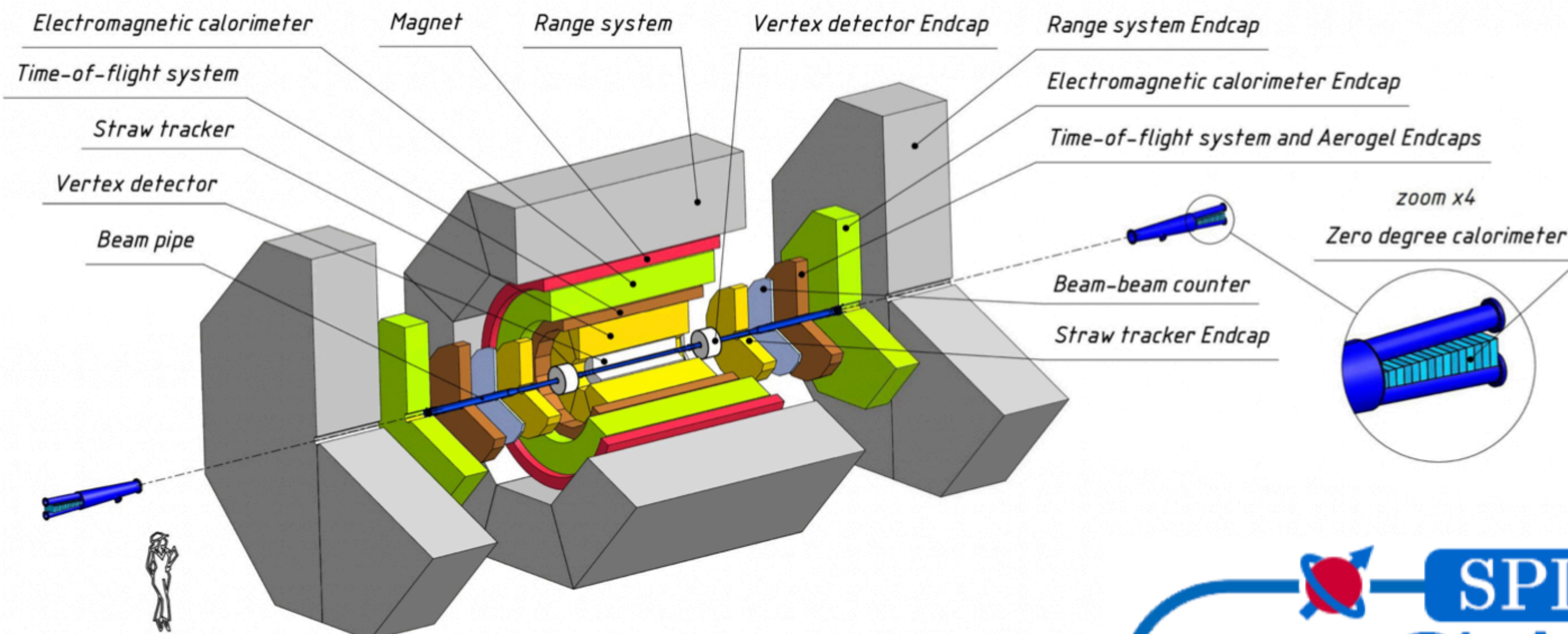


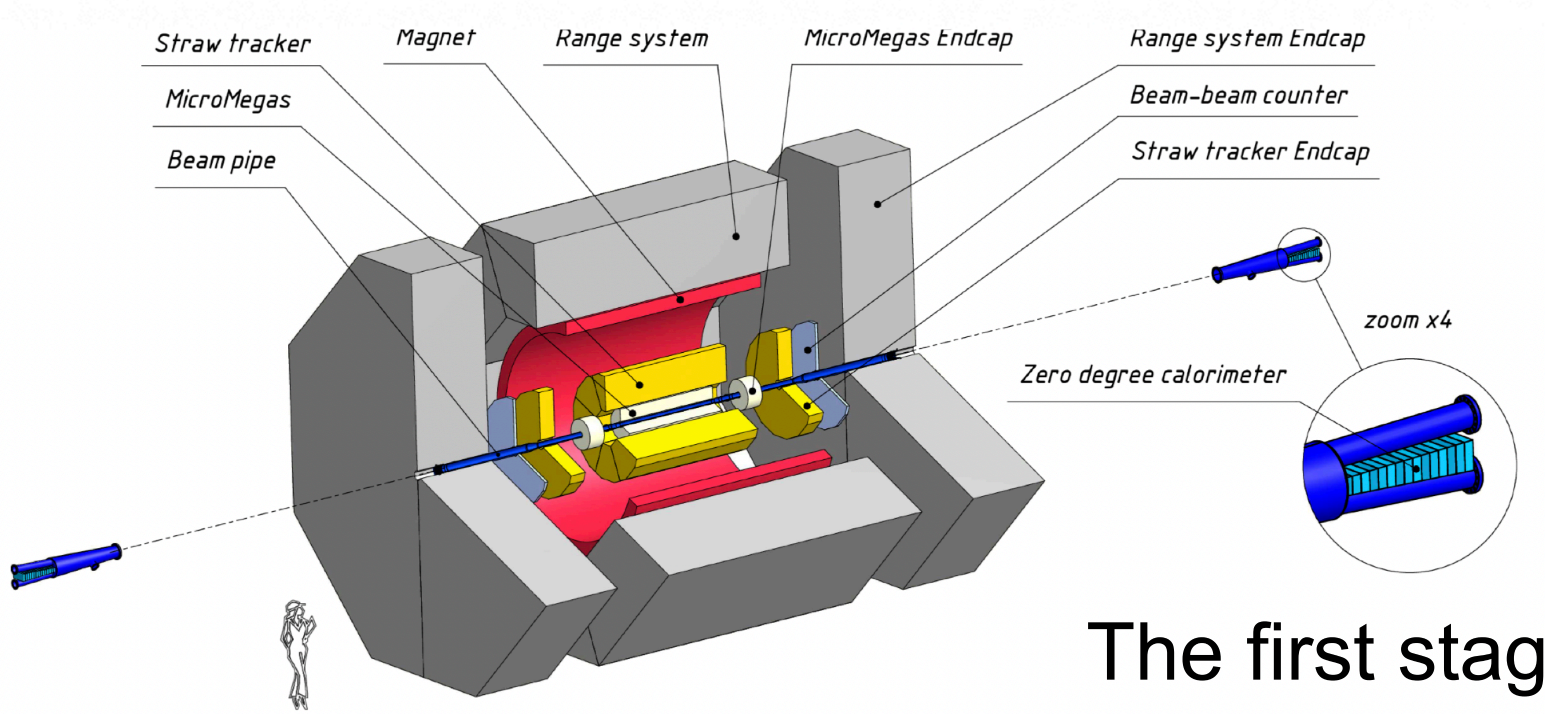
Experimental facility	SPD @NICA	RHIC	EIC	AFTER @LHC	SpinLHC
Scientific center	JINR	BNL	BNL	CERN	CERN
Operation mode	collider	collider	collider	fixed target	fixed target
Colliding particles & polarization	$p^{\uparrow}$-$p^{\uparrow}$ $d^{\uparrow}$-$d^{\uparrow}$ $p^{\uparrow}$-d, p-$d^{\uparrow}$	$p^{\uparrow}$-$p^{\uparrow}$	$e^{\uparrow}$-$p^{\uparrow}$, $d^{\uparrow}$,^{3}He$^{\uparrow}$	p-$p^{\uparrow}$,$d^{\uparrow}$	p-$p^{\uparrow}$
Center-of-mass energy $\sqrt{s_{NN}}$, GeV	≤27 (p-p) ≤13.5 (d-d) ≤19 (p-d)	63, 200, 500	20-140 (ep)	115	115
Max. luminosity, 10^{32} cm^{-2} s^{-1}	∼1 (p-p) ∼0.1 (d-d)	2	1000	up to ∼10 (p-p)	4.7
Physics run	>2025	running	>2030	>2025	>2025

This region was never systematically studied in polarized hadron collisions

Possibility to collide polarized deuterons is unique!

SPD experimental setup





The first stage

SPD international collaboration

31 institutes from 14 countries, ~300 members

SPD Conceptual Design Report was issued in the beginning of 2021

*It was approved by the international **Detector Advisory Committee** and **the JINR Program Advisory Committee for Particle Physics***

Growth of Knowledge

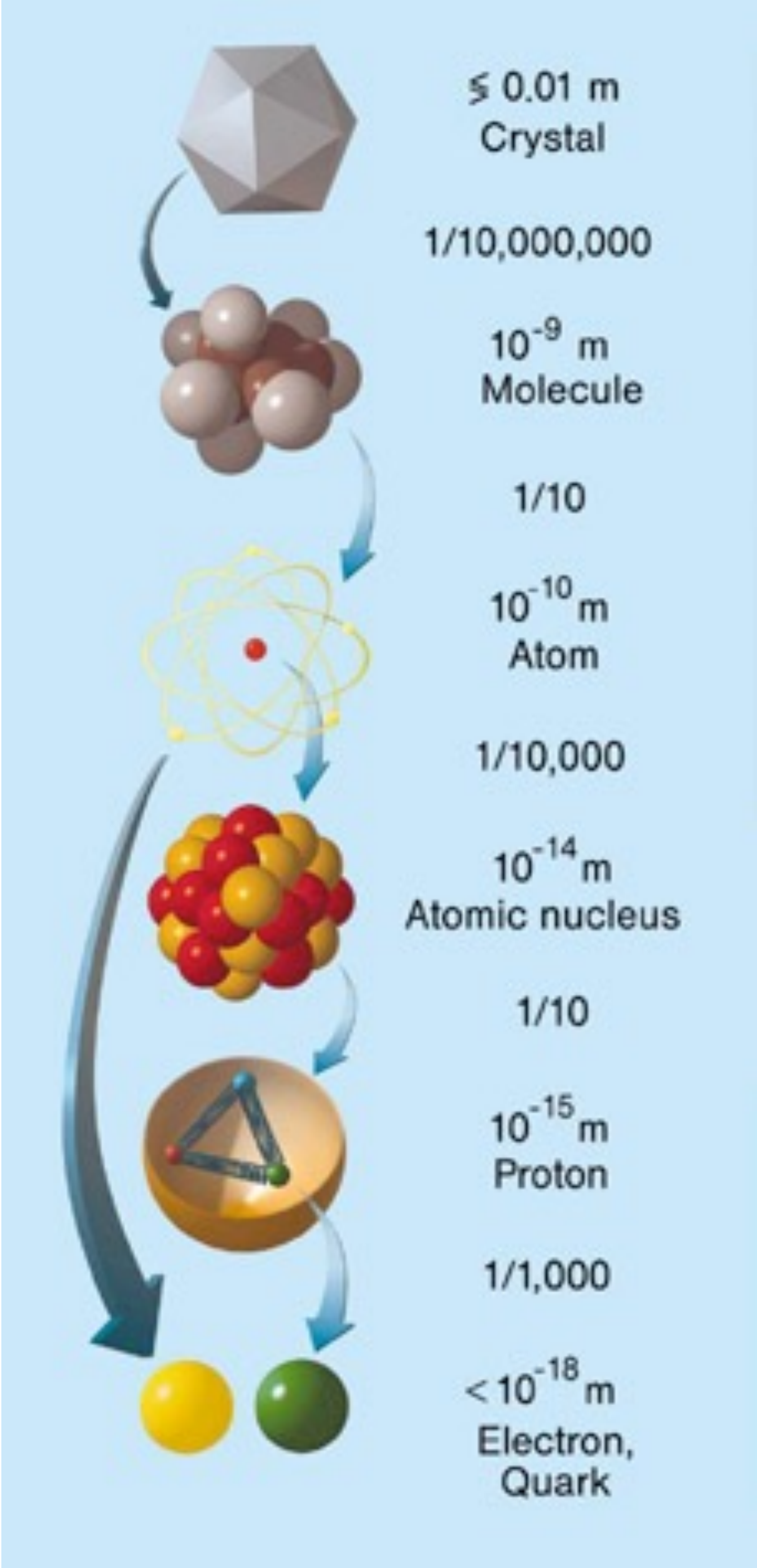
Naive concepts

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

Continental drift, 1912

Age of Discovery, XV-XIX centuries

Summary



The point in the study of the internal structure of nucleons has not been set. This part of particle physics awaits new researchers, both theorists and experimentalists. A future SPD experiment at the NICA collider gives a chance to do the next step.