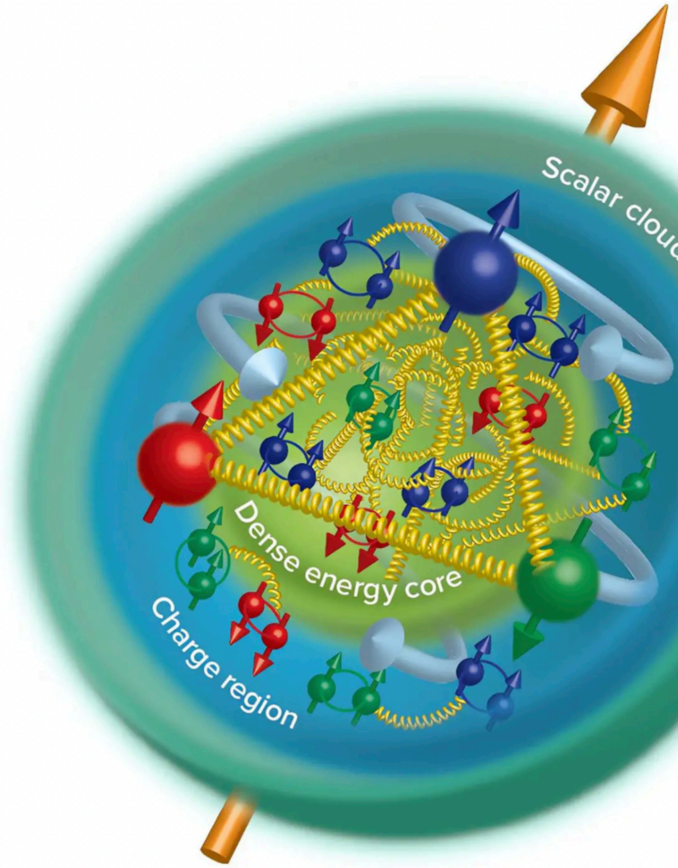
Spin physics in hadronic interactions SPD @ NICA



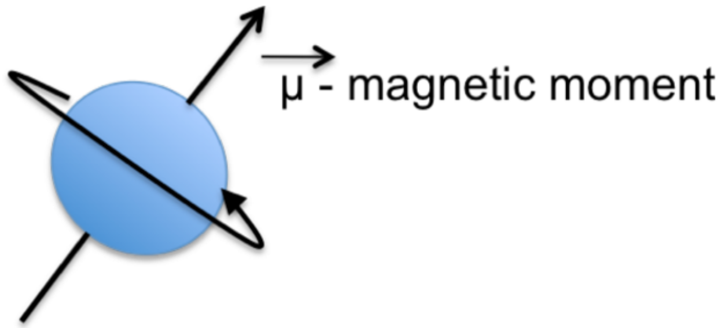
NICA Days 2023

Belgrade, Serbia
02-03
10.23

A. Guskov, JINR

avg@jinr.int

Proton as a complex object



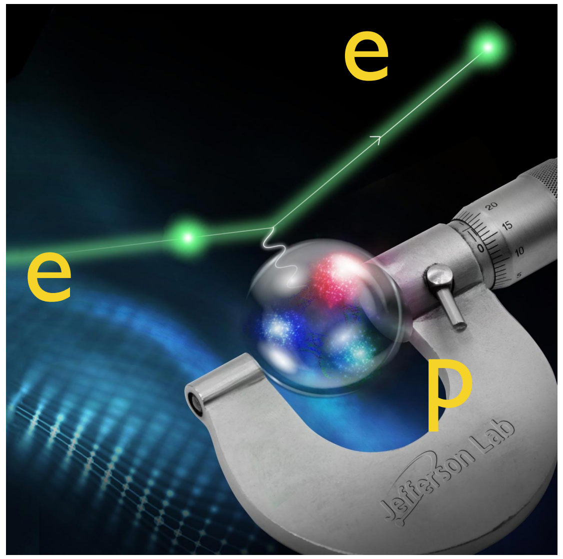
$$\overrightarrow{\mu_S} = g_S \times \frac{e}{2m} \times \vec{S}$$

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

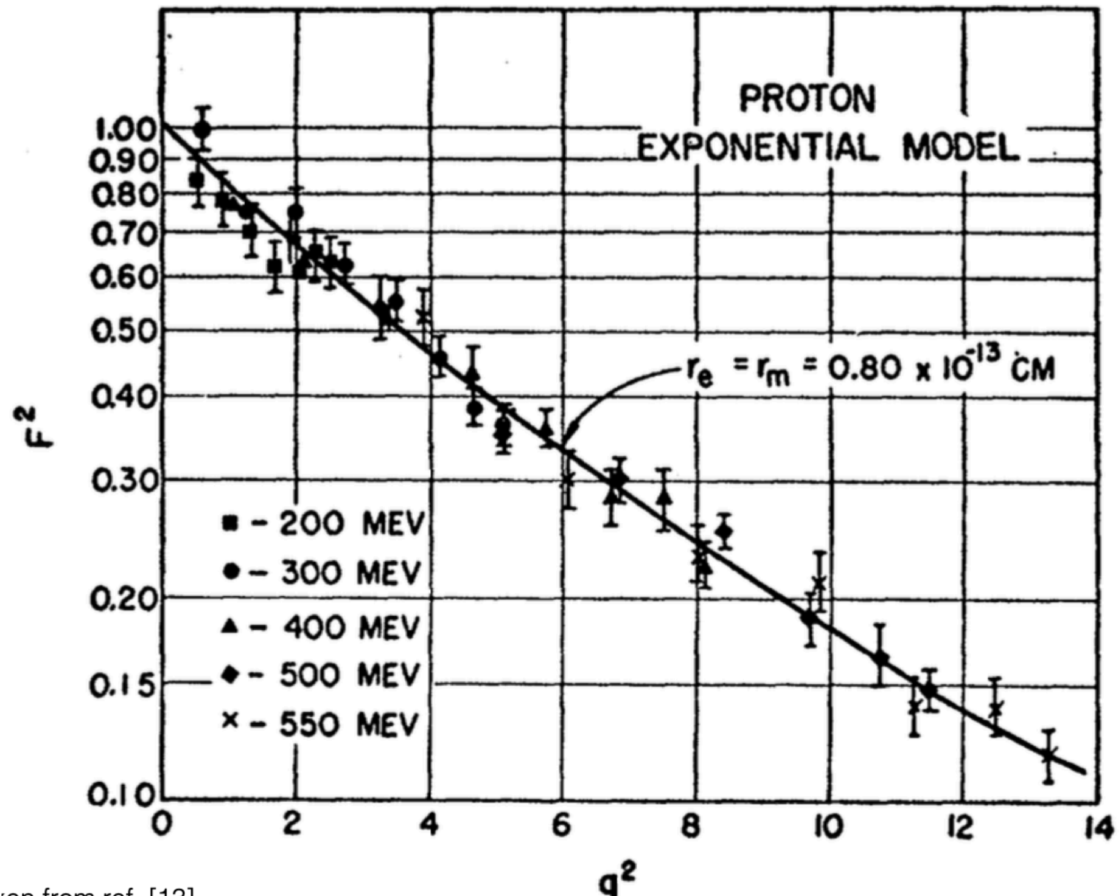
1930-s

It seems that nucleons are not point-like structureless objects!

Proton size



R. Hofstadter - Nobel Prize in 1961



ken from ref. [13]

Form-factor

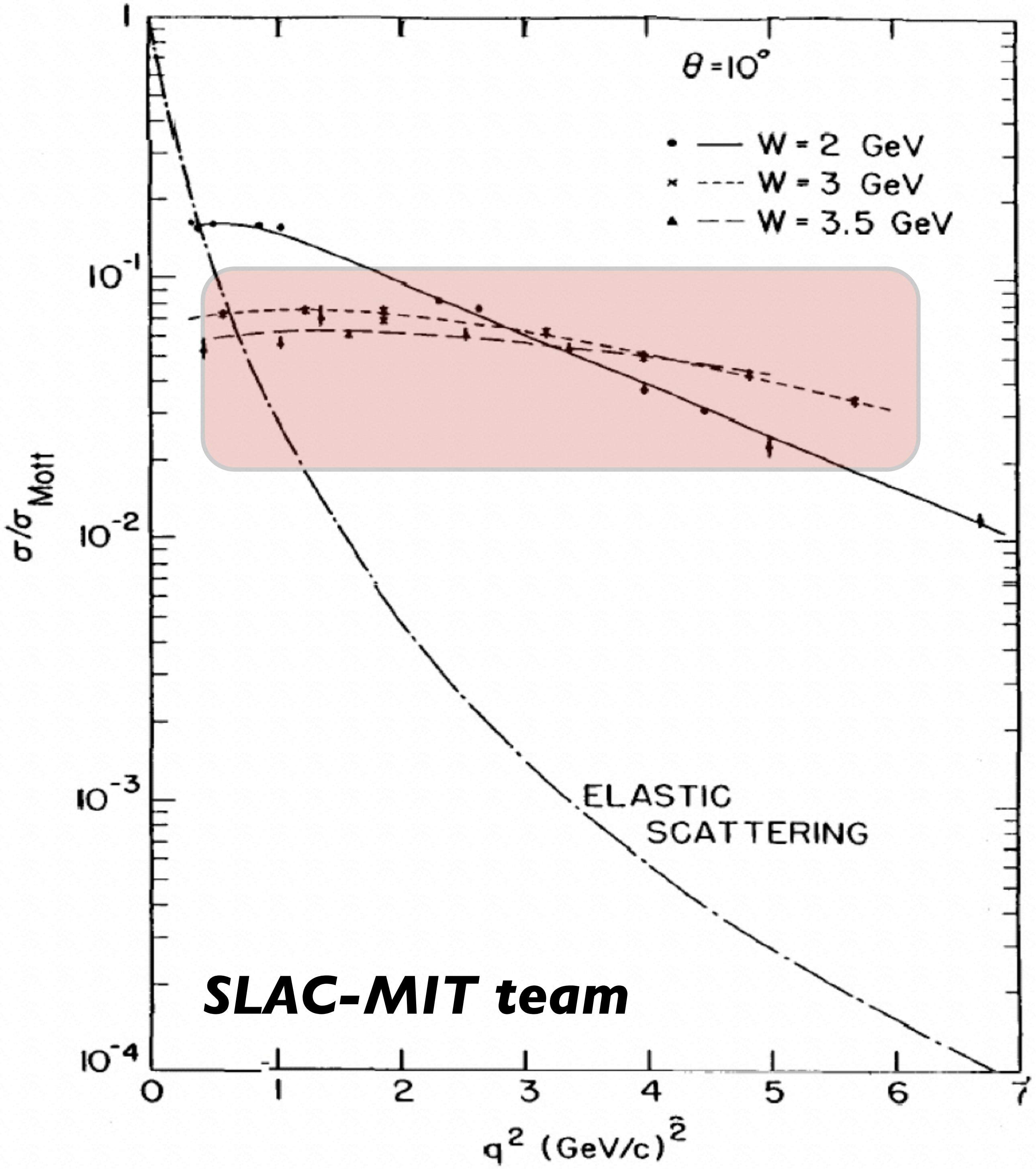
$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\text{point-like}} \times F^2(q^2)$$

transferred (four)-momentum

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

charge radius

Partons



J. Friedman, H. Kendall, R. Taylor - Nobel Prize in 1990

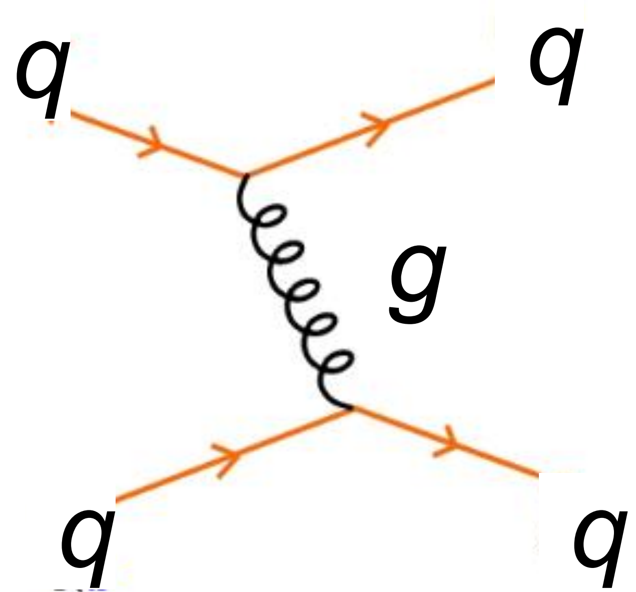
Partons - point-like objects inside the proton

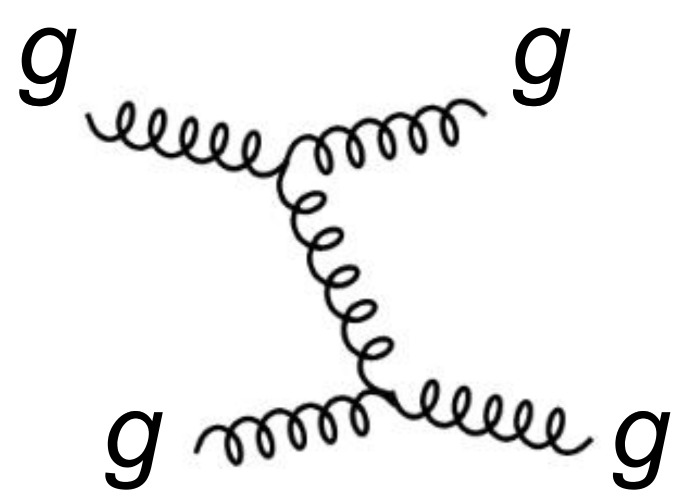
Partonic model -1969

R. Feynman

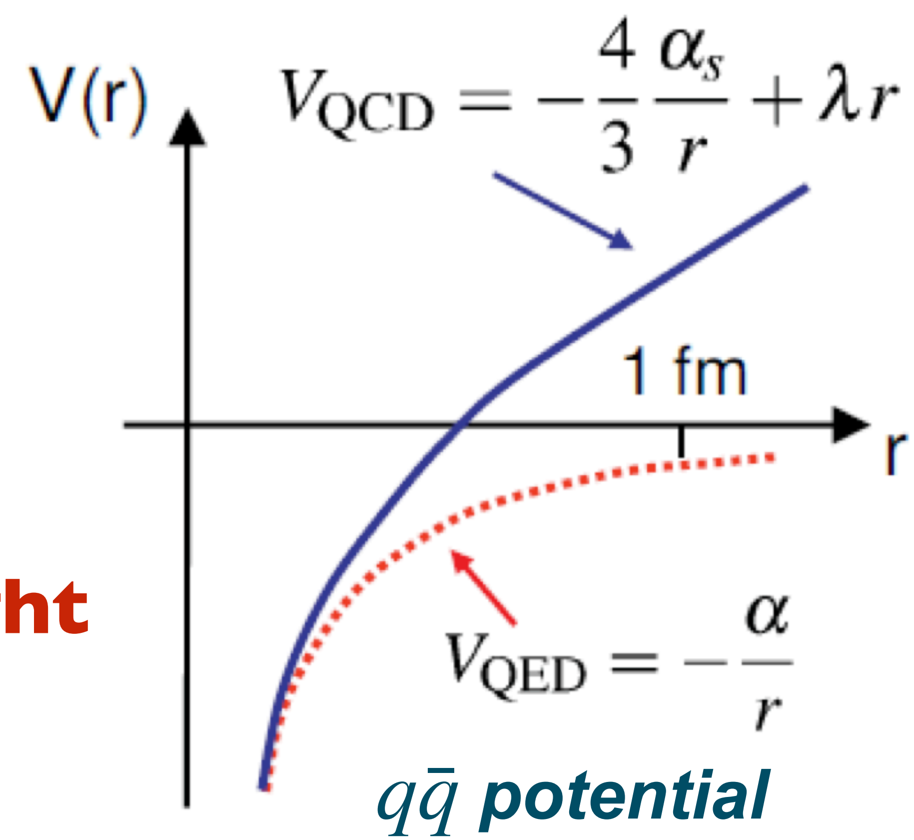
In the beginning of 70th charged partons were associated with quarks

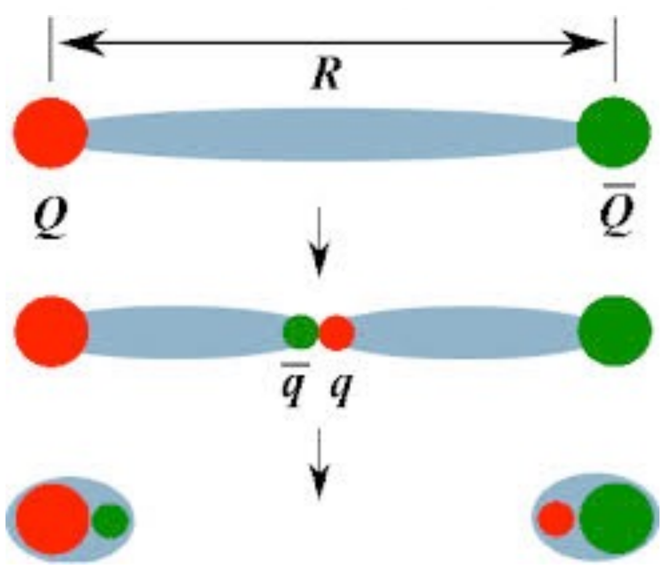
Quantum ChromoDynamics - QCD





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



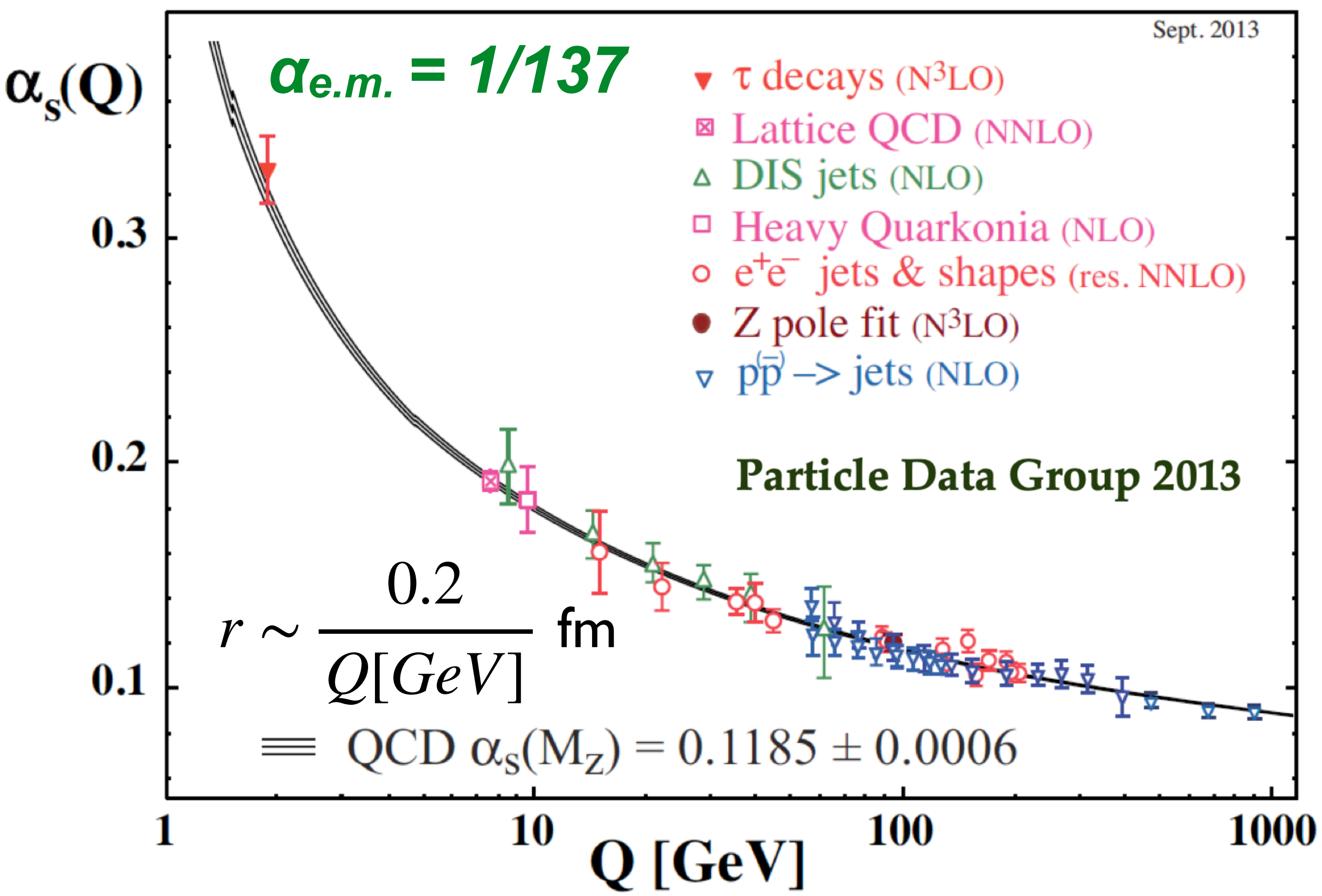


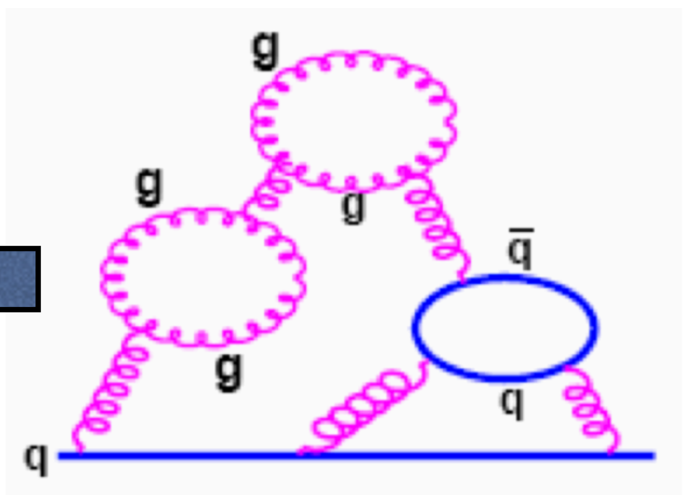
Quark confinement at large scale

but asymptotic freedom at below 1 fm

D.Gross, D. Politzer, F. Wilczek - Nobel Prize in 2004

Problem to describe hadrons ab initio

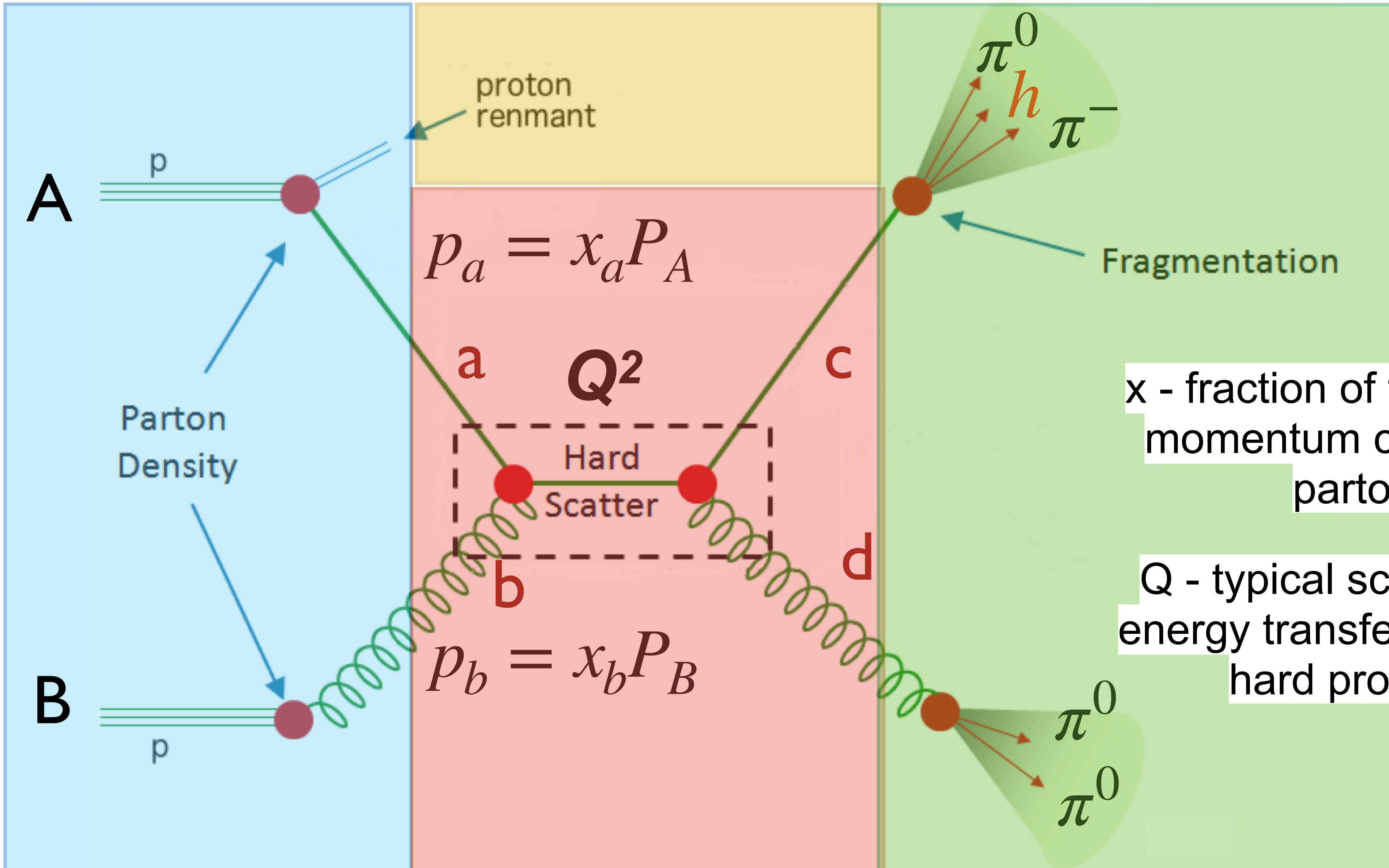




Confinement is not strictly proven!

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

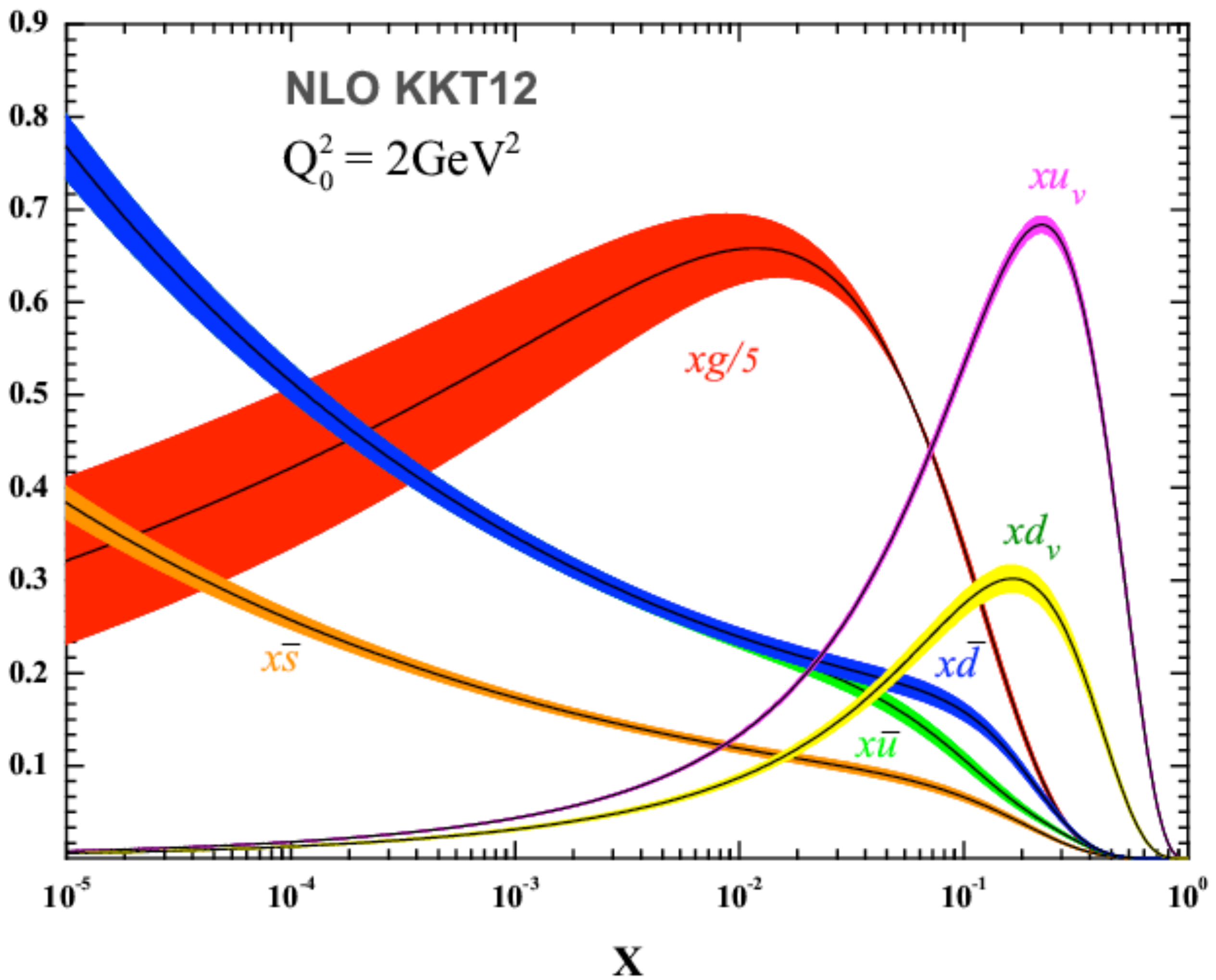
Q - typical scale of the energy transferred in the hard process

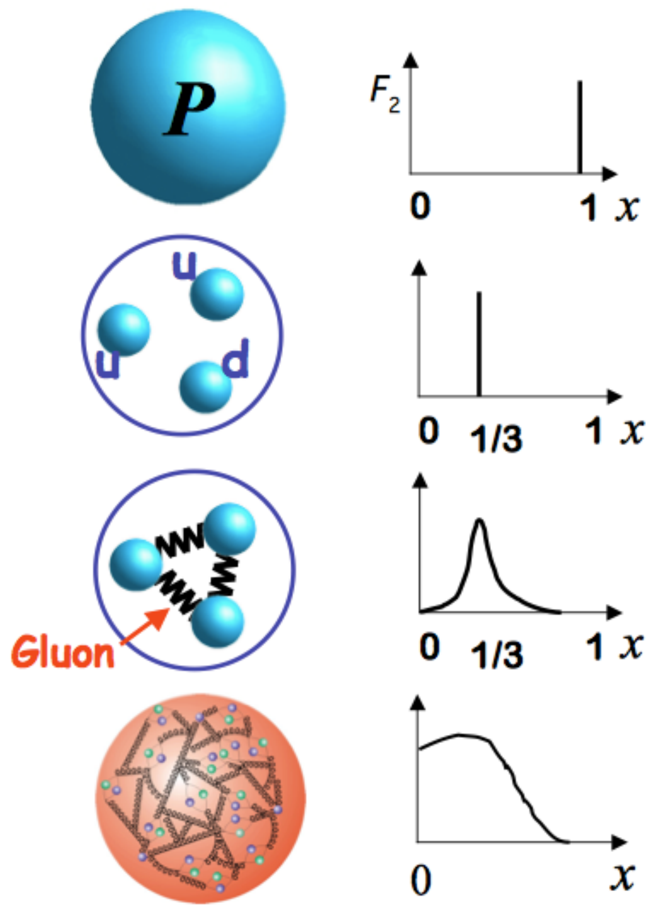
$$\sigma_{AB\to hX} = \sum_{a,b=q,\bar{q},g} \int dx_a dx_b f(x_a, Q^2) f(x_b, Q^2) \times \hat{\sigma}_{ab\to cd}(x_a, x_b, Q^2) \times D_{cd\to h}$$

$Q^2 >> 1$ 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

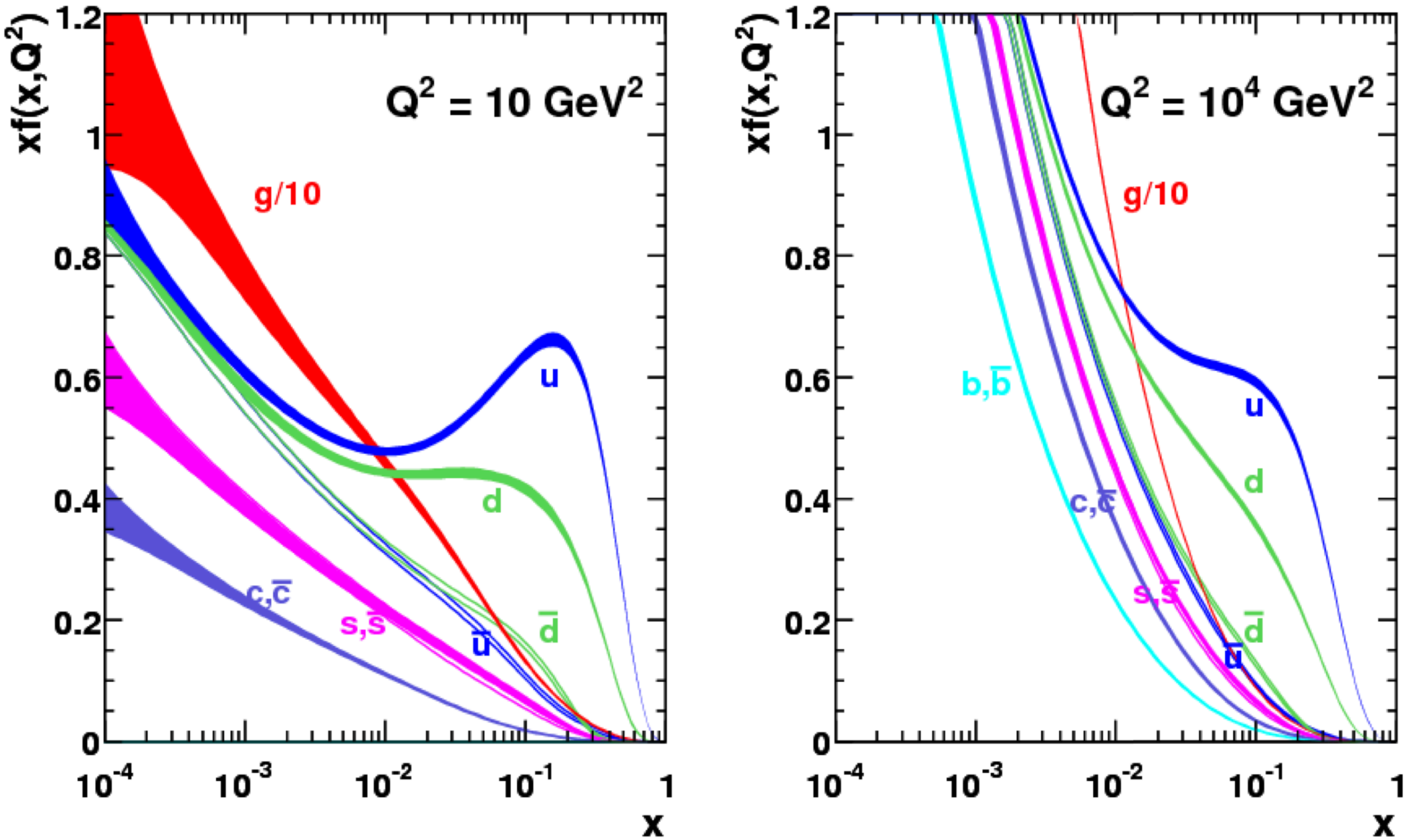




PDFs are universal, they are independent on the hard process

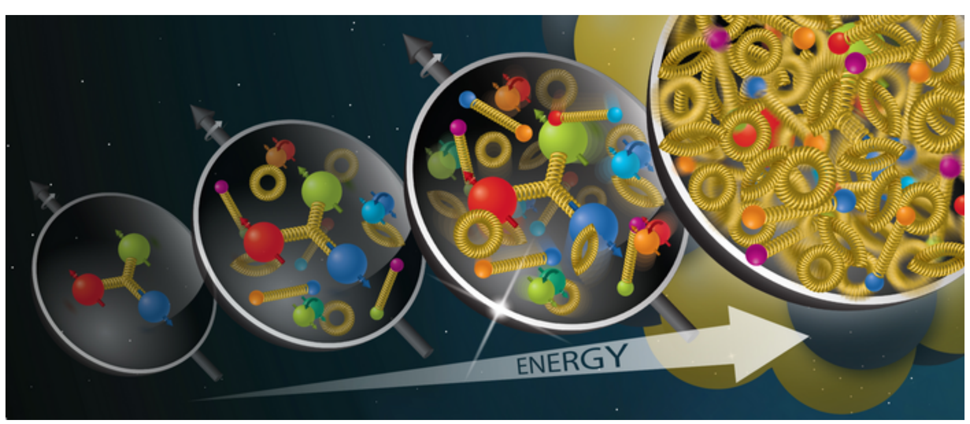
PDFs cannot be calculated in QCD from the first principles!

Parton Distribution Functions



$$\sum_i \int dx\, x q_i(x) = 1$$

q_i	momentum
d_V	0.111
u_V	0.267
d_S	0.066
u_S	0.053
s_S	0.033
c_S	0.016
total	0.546



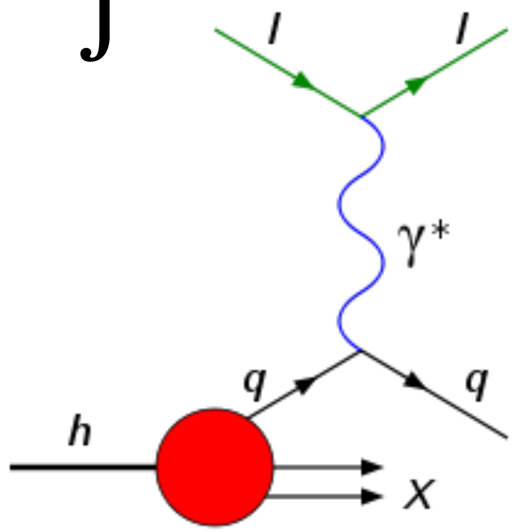
g = 1−0.546 = 0.454

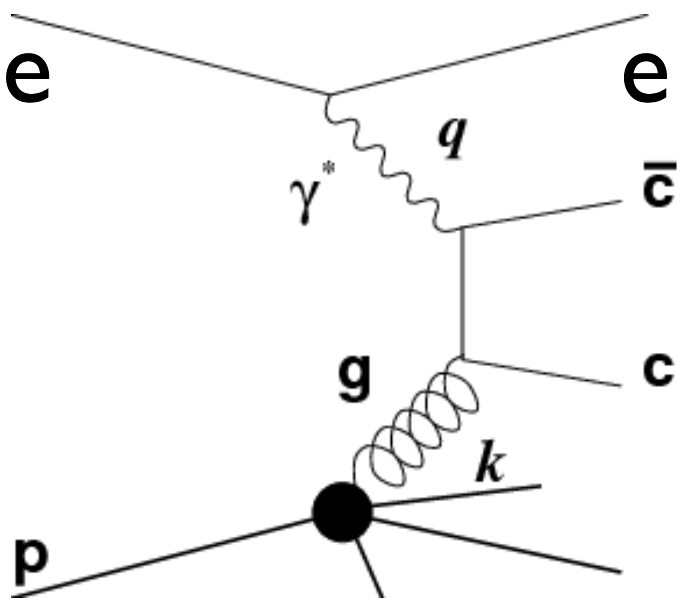
Sea partons becomes more important at high Q^2

How to access PDFs ?

Deep Inelastic Scattering

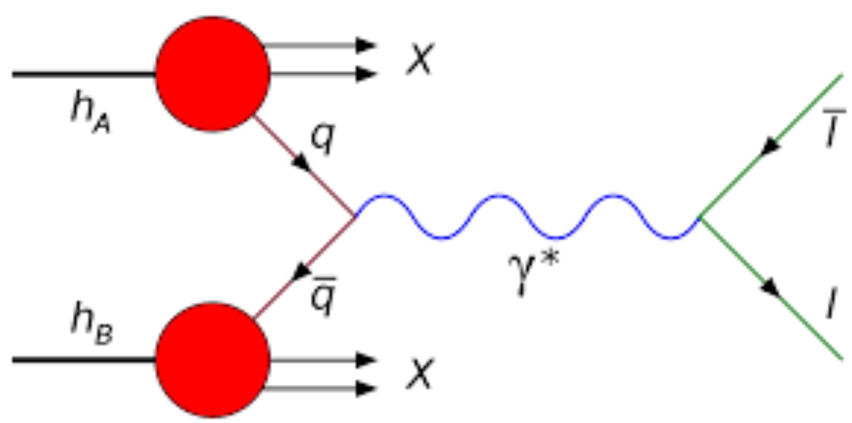
$$\sigma = \int \hat{\sigma} q(x) dx$$

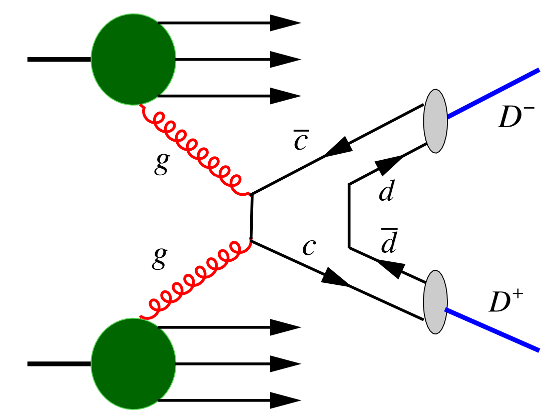




Hadronic interactions

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

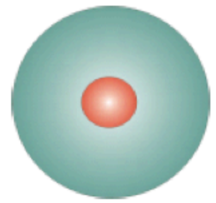




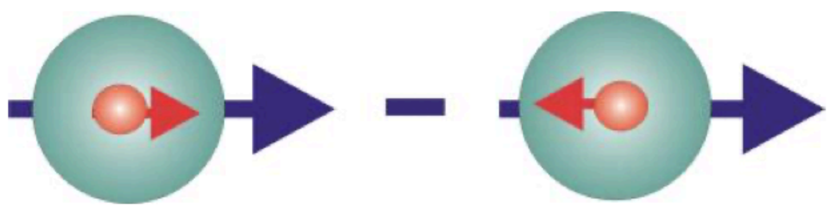
CTEQ Collaboration
JAM Collaboration
DSSV Collaboration
NNPDF Collaboration
…

Polarized proton

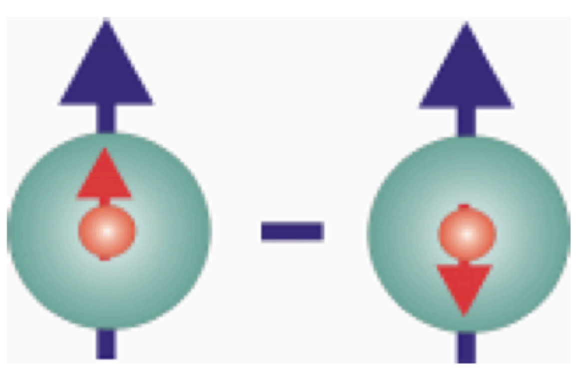
f(x)



Δf(x)



Δ_Tf(x)



P

Unpolarized PDF

unpolarized DIS

Helicity

polarized DIS

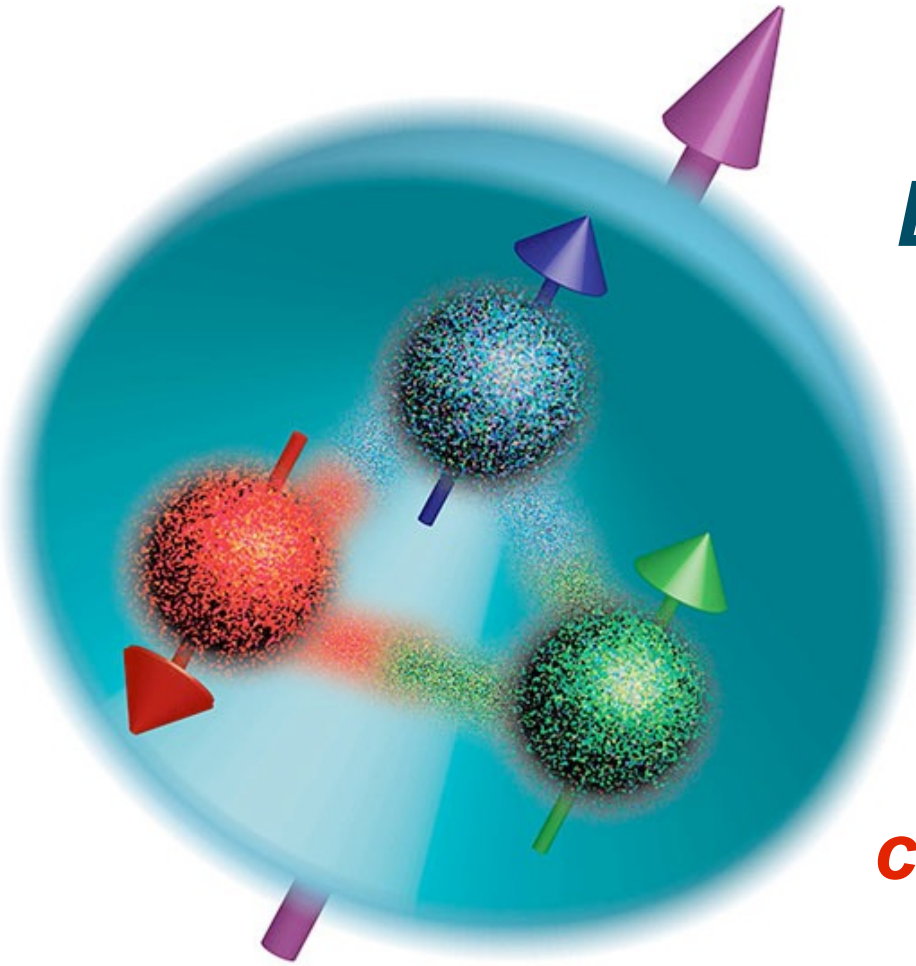
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \sim \Delta q$$

Transversity

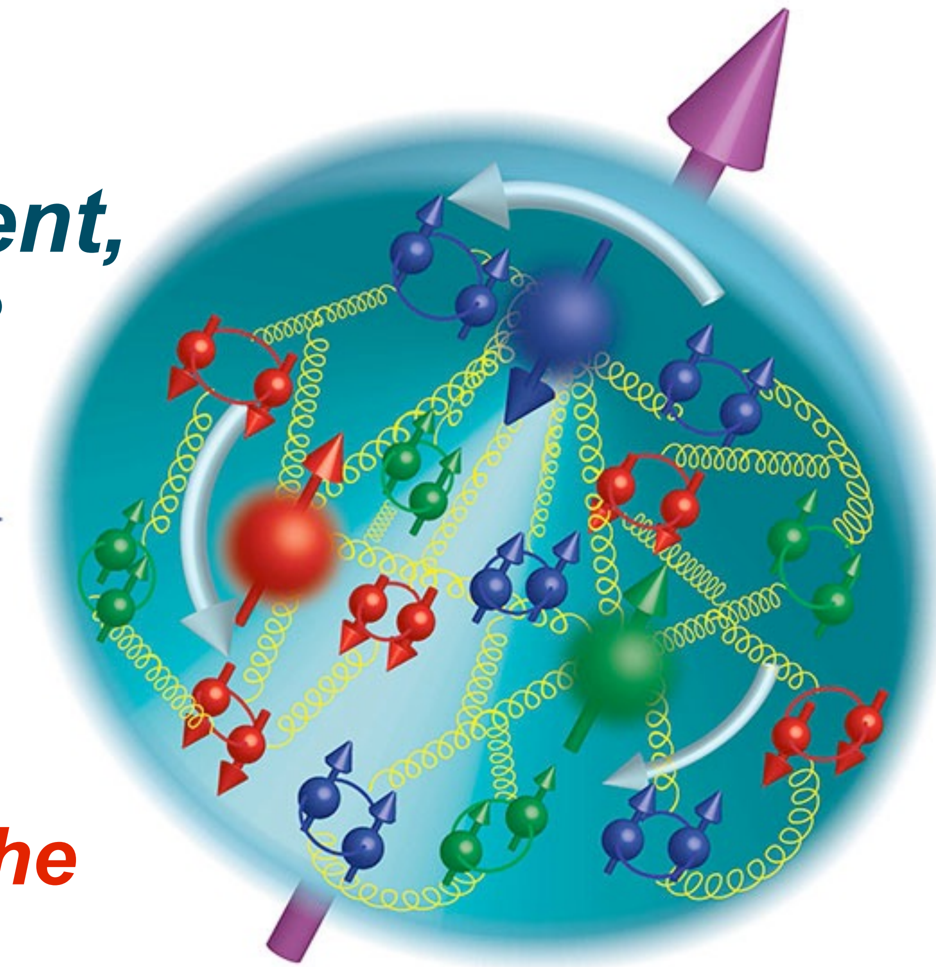
polarized SIDIS

Azimuthal asymmetryes A_N

Spin crisis



EMC experiment, CERN 1988



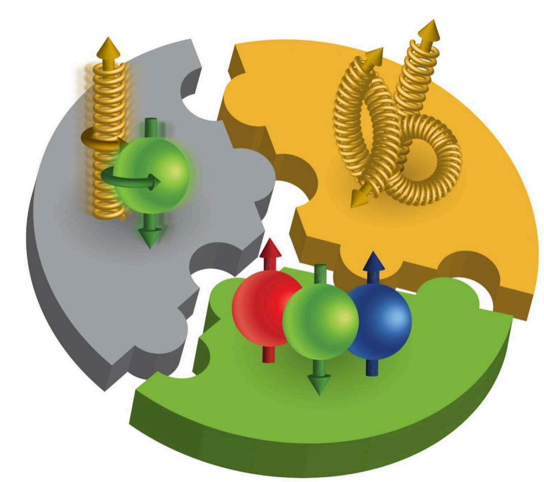
Quark contribution to the proton spin is below 30%!

Naive quark model

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

Real situation

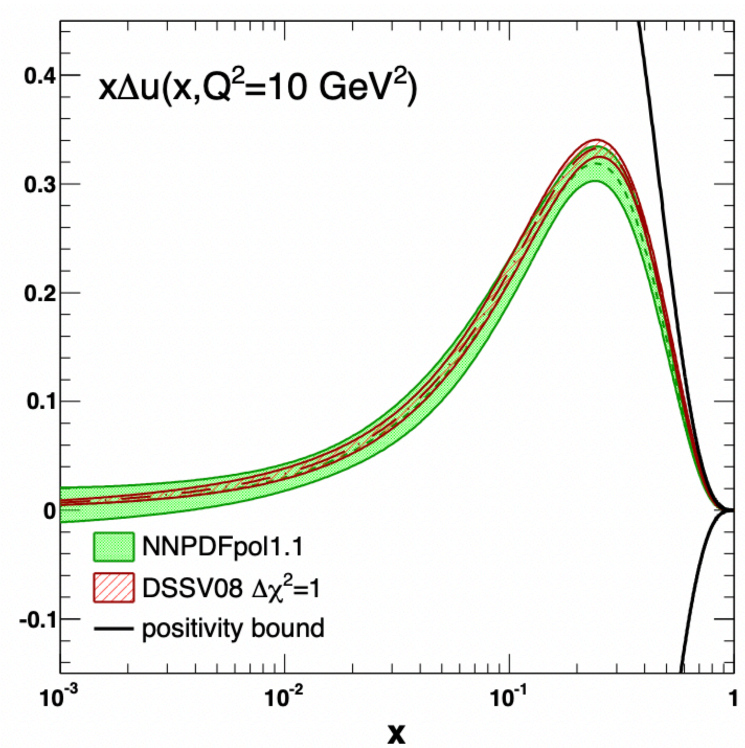
L - orbital moments of quarks and gluons

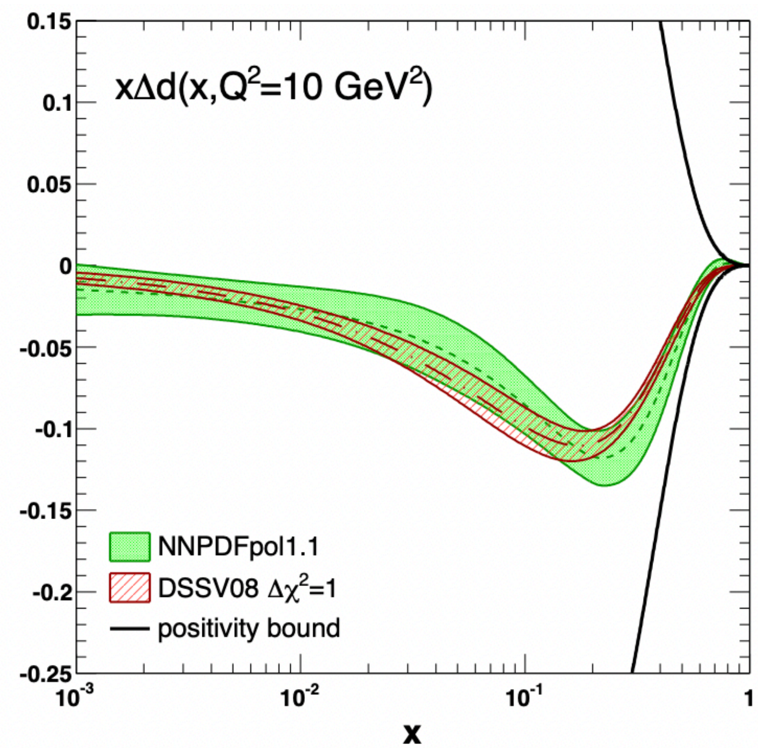


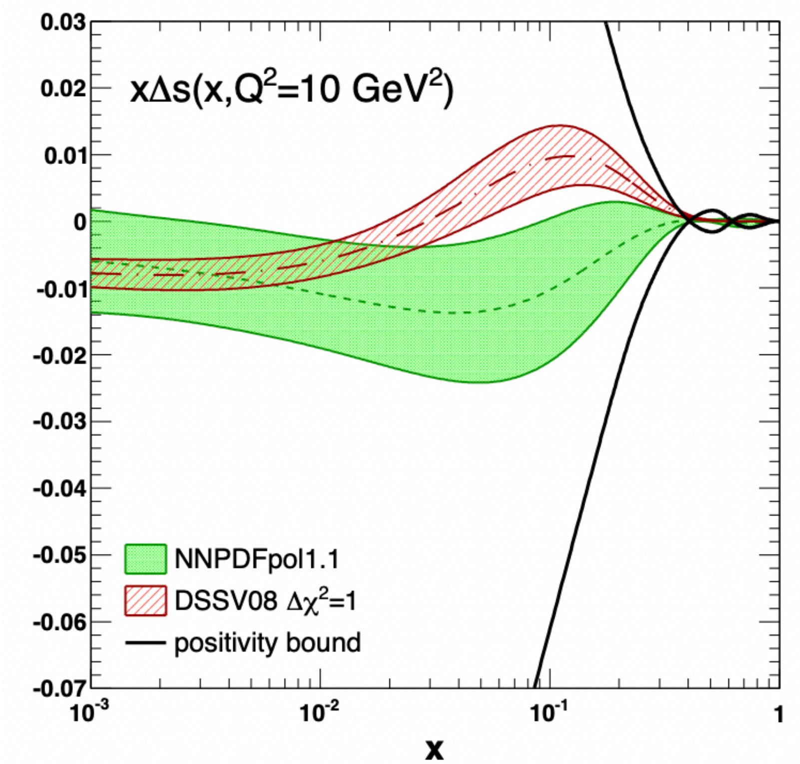
$$S_N = ½ = ½\,\Delta\Sigma + \Delta G + L$$

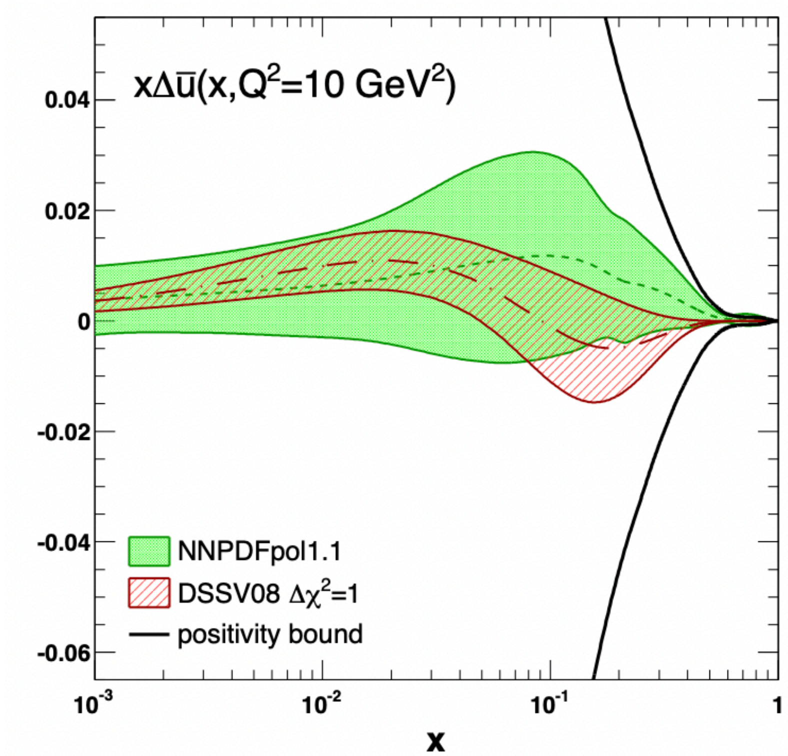
Spin crisis: quarks

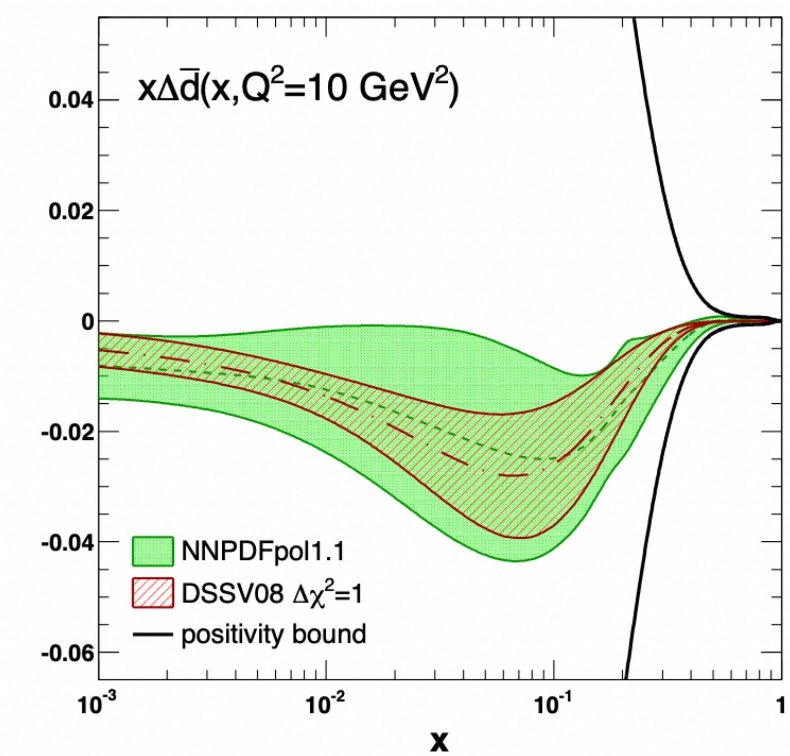
Longitudinal polarization of quarks:











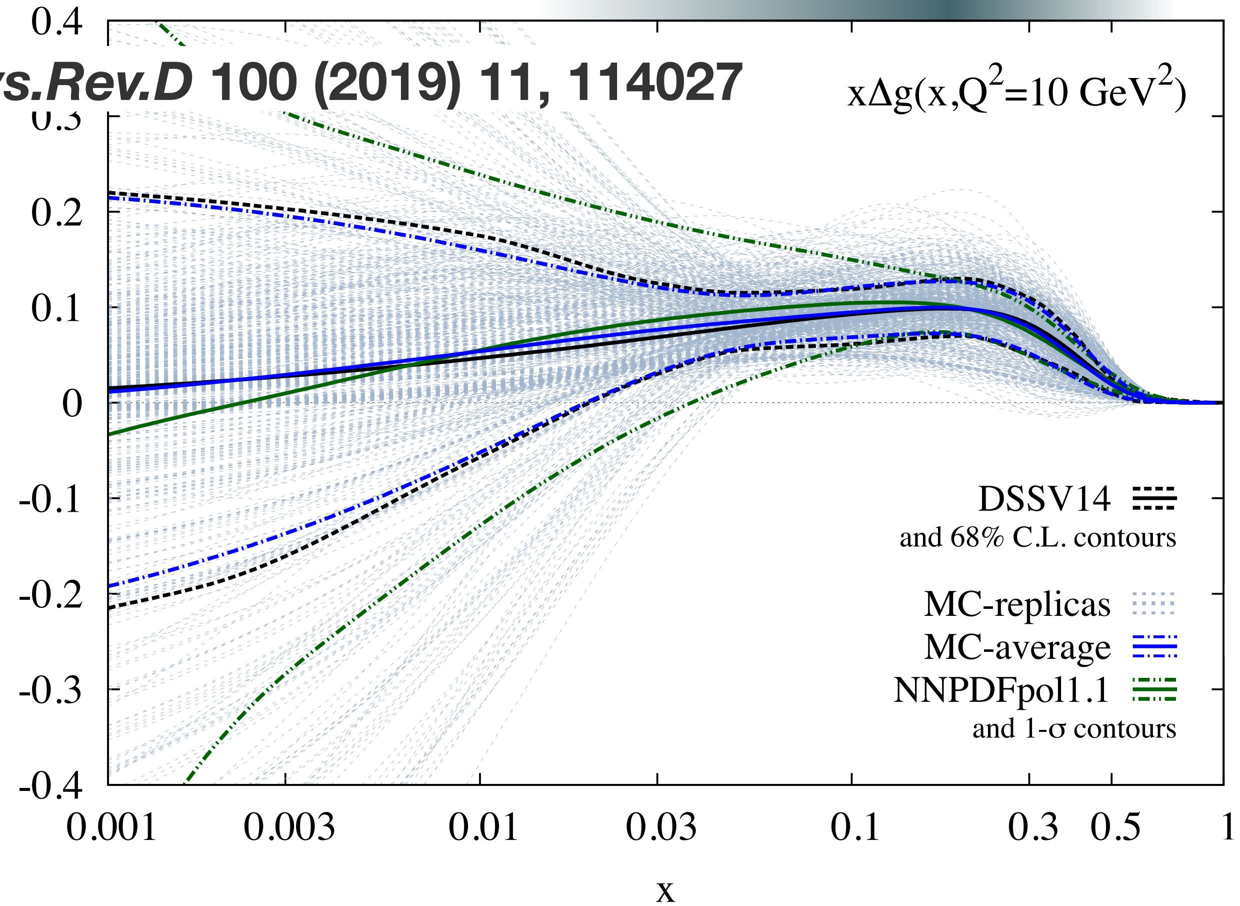
$S_N = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$

~30%

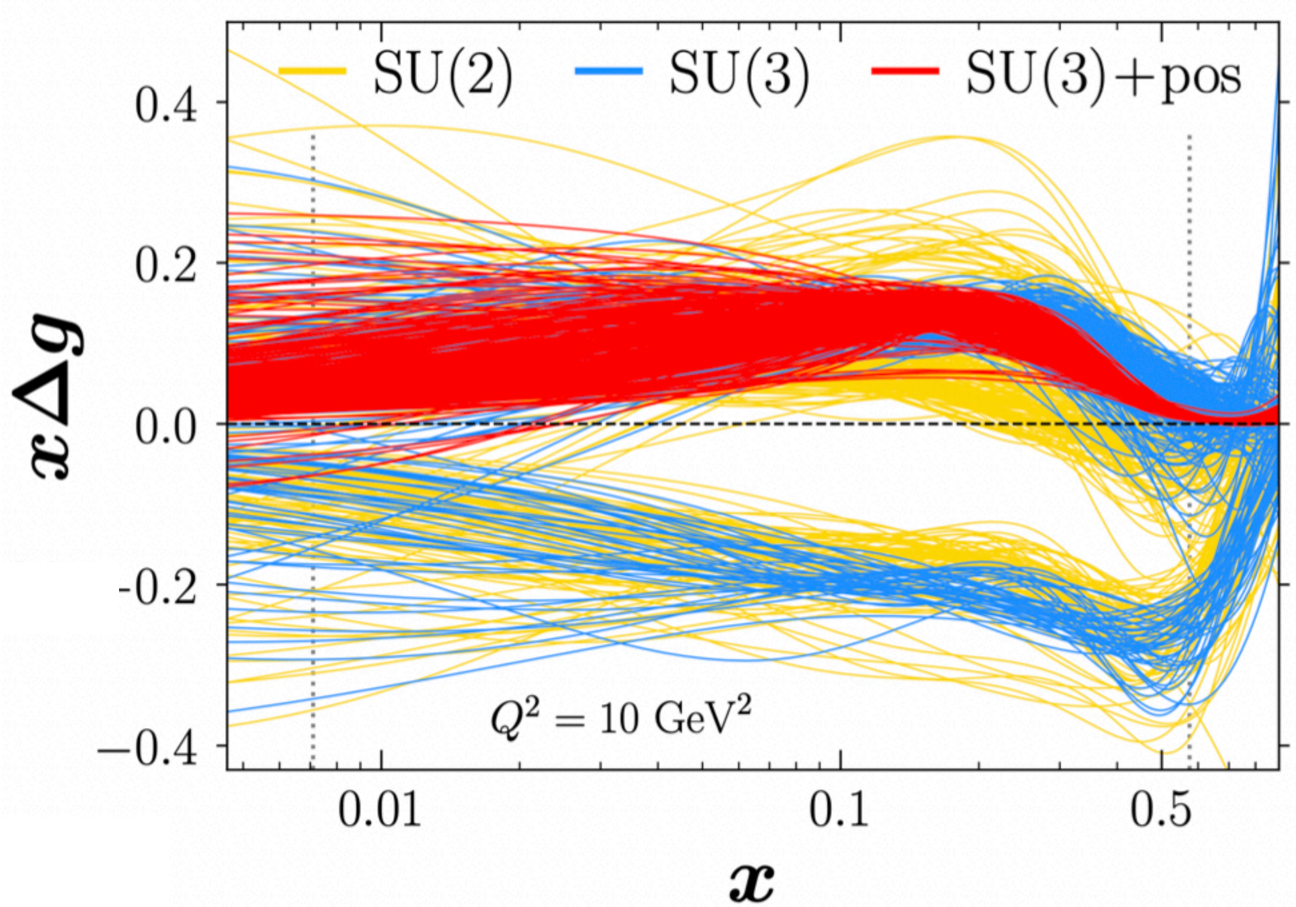
Spin crisis: gluons

accessible with SPD

Phys.Rev.D 100 (2019) 11, 114027



Y. Zhou et al (JAM) Phys. Rev. D 105, 074022 (2022)



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

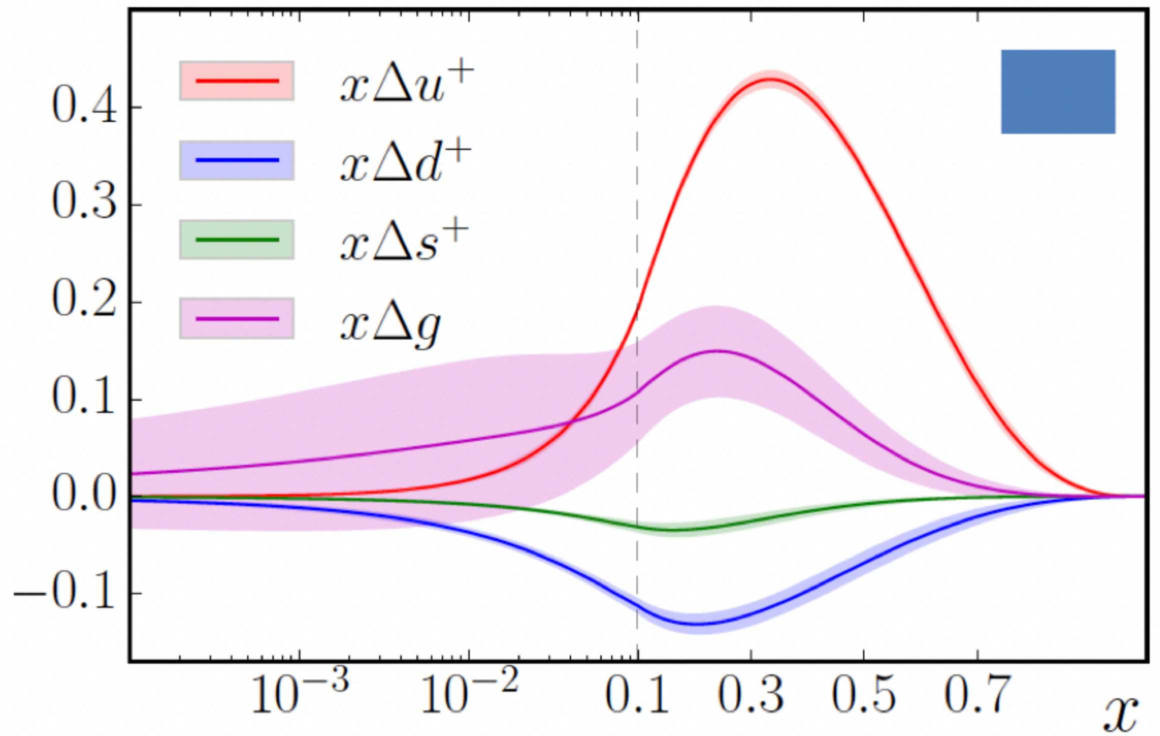
Positivity removed from JAM helicity gluon PDF

$$A_{LL}^{c\bar{c}} \approx \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\Delta g(x_2)}{g(x_2)} \otimes \hat{a}_{LL}^{gg\to c\bar{c}X} \qquad A_{LL}^{\gamma} \approx \frac{\Delta g(x_1)}{g(x_1)} \otimes A_{1p}(x_2) \otimes \hat{a}_{LL}^{gq(\bar{q})\to\gamma q(\bar{q})} + (1 \leftrightarrow 2)\,.$$

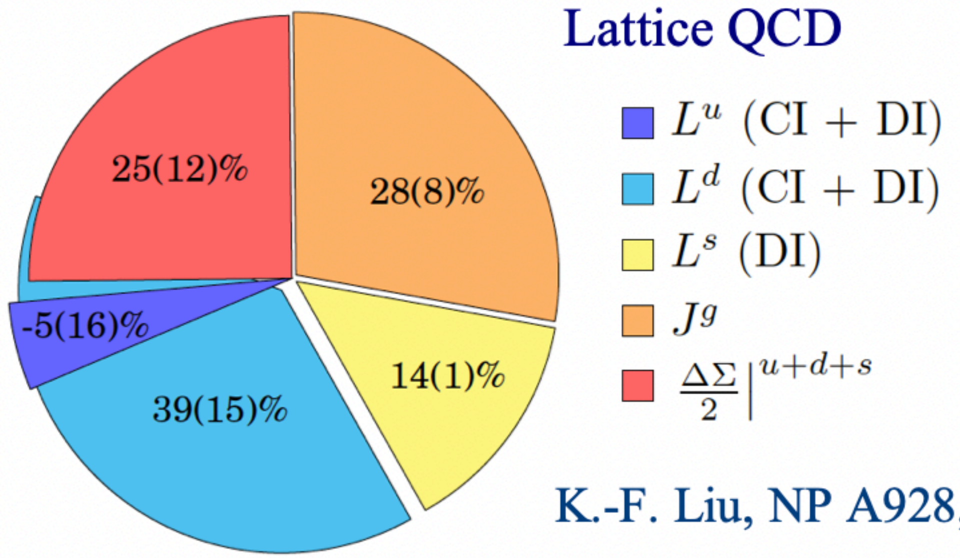
Spin balance

$$J = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

~30% (for $\frac{1}{2}\Delta\Sigma$), ~10-20% (for ΔG), ? (for L_q), ? (for L_g)



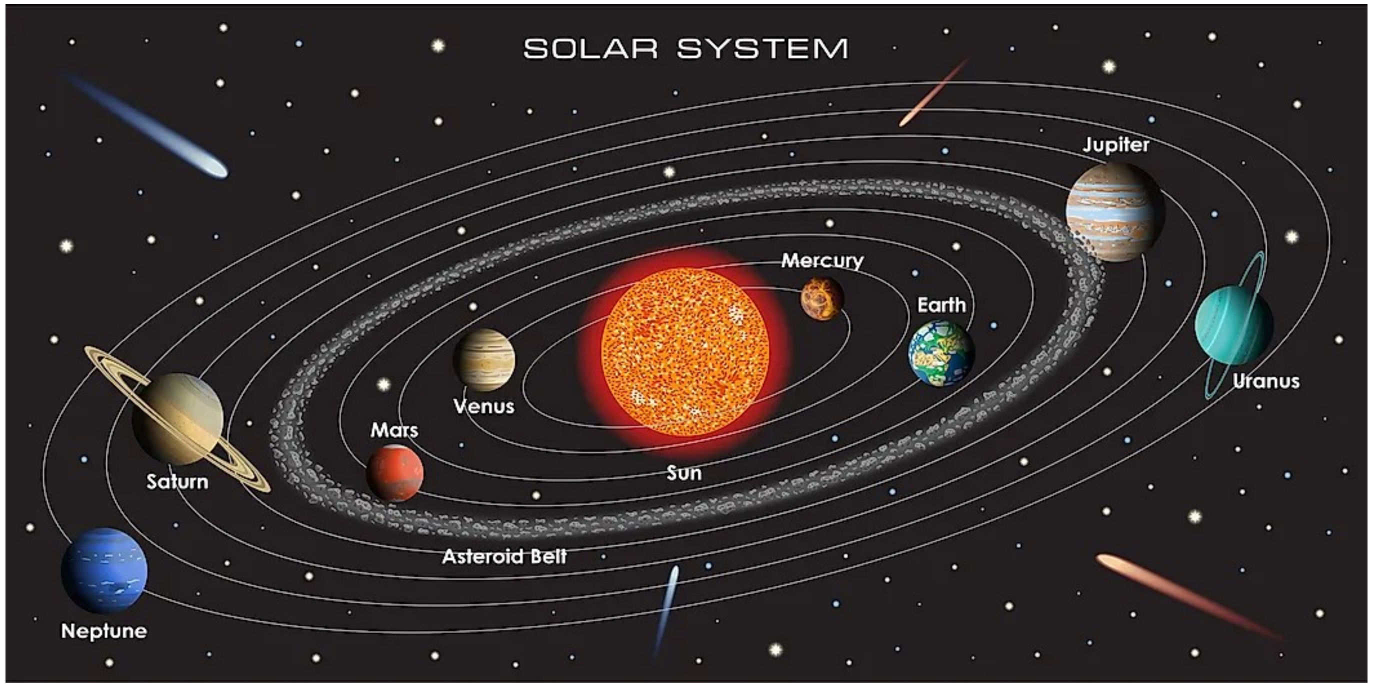
JAM Collaboration, PRD (2016).



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

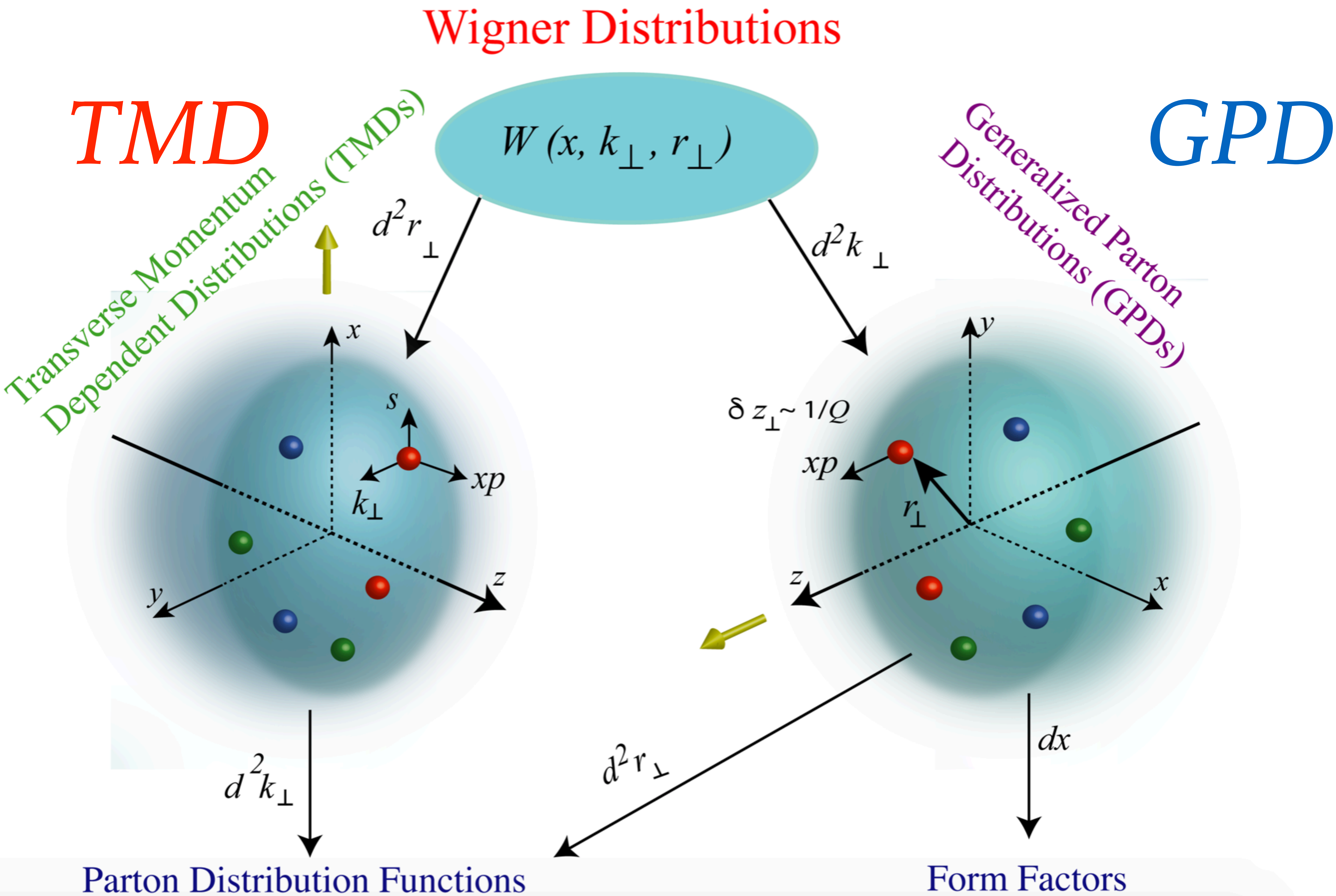
To access angular momenta info about 3D structure is needed!

For Solar System

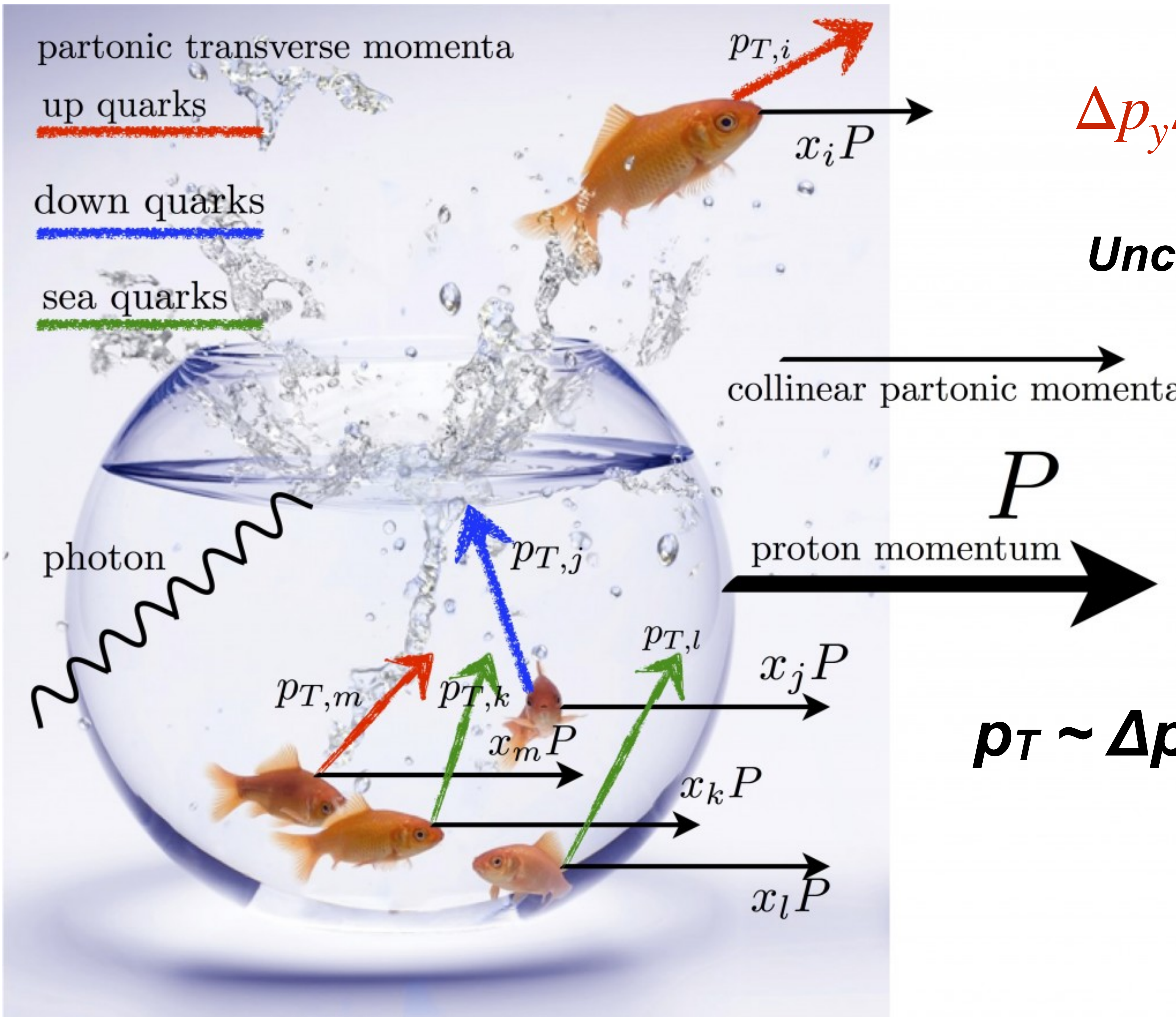


98% is angular moment!

3D-tomography of proton



Where transverse momentum come from?



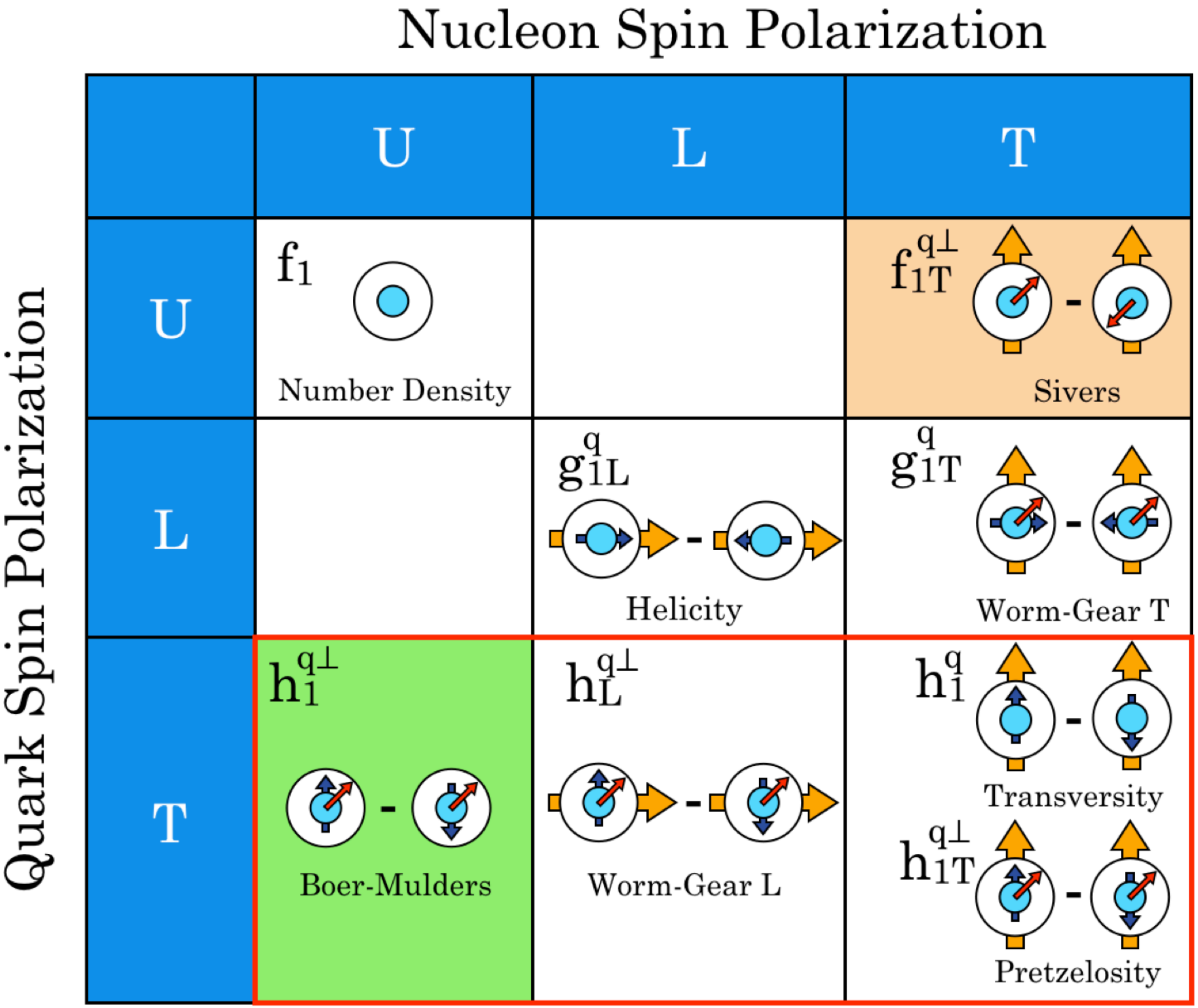
$$\Delta p_y \Delta y \geq \frac{h}{2\pi}$$

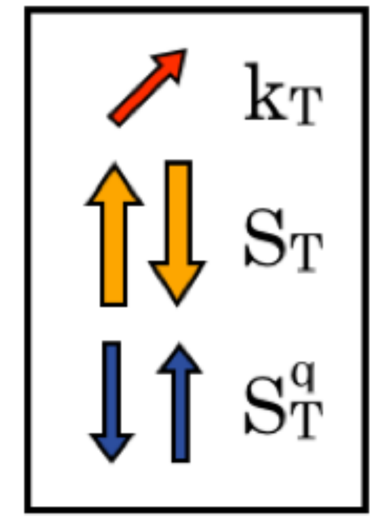
Uncertainty relation:

$$\boldsymbol{\Delta y \sim \langle r_p \rangle}$$

$\langle r_p \rangle = 0.88$ fm

$$\boldsymbol{p_T \sim \Delta p_y \geq 0.2\ \mathrm{GeV}/c}$$

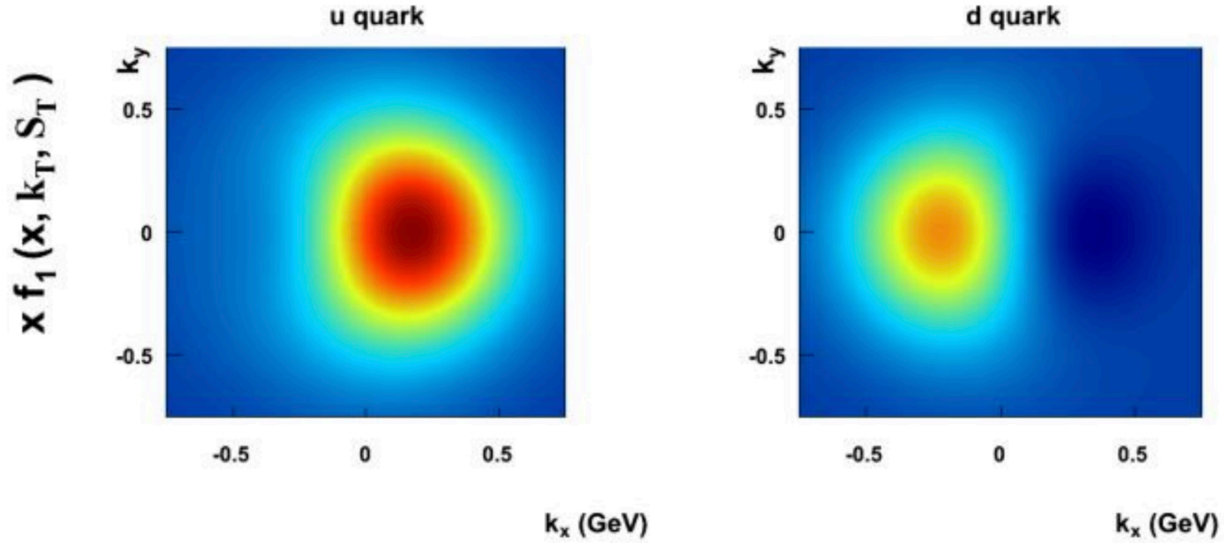




5 additional (TMD) functions describing the correlation between the nucleon spin, parton spin, and parton transverse momentum.

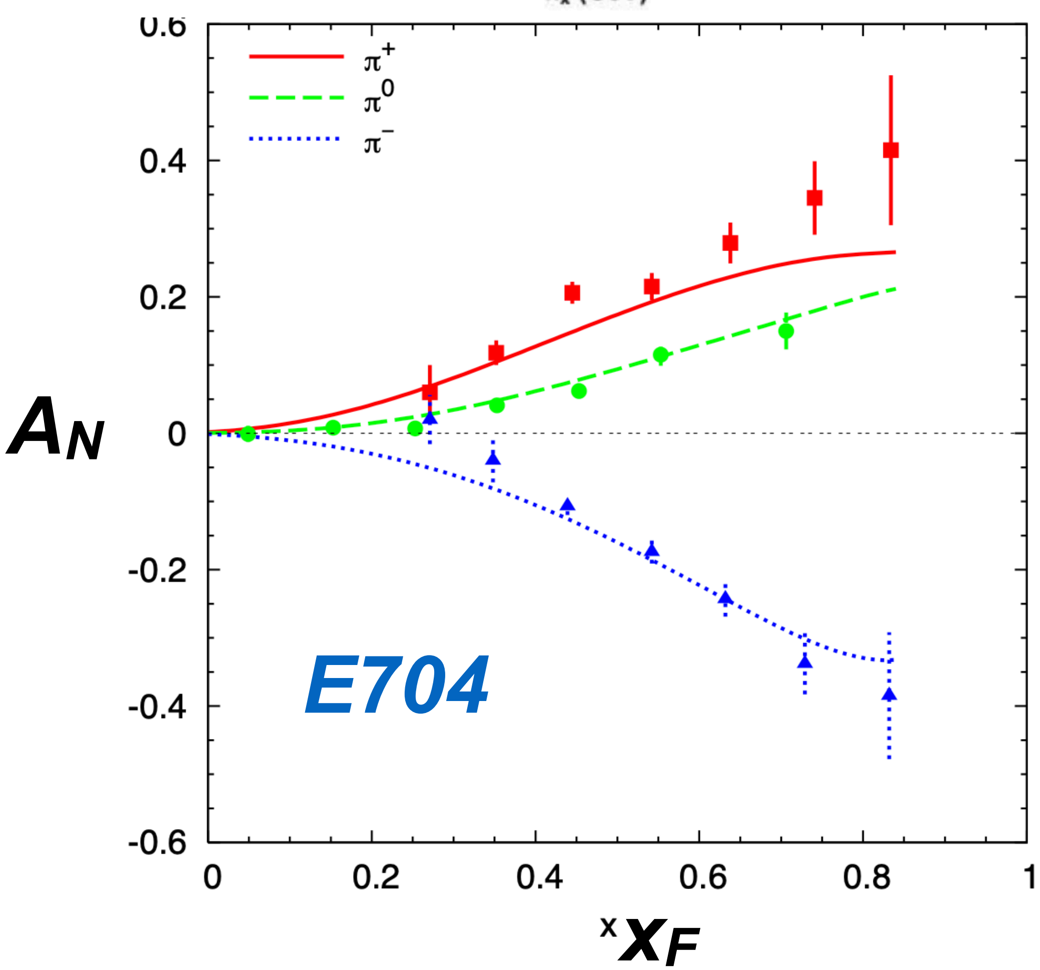
TMD effects: Sivers effect

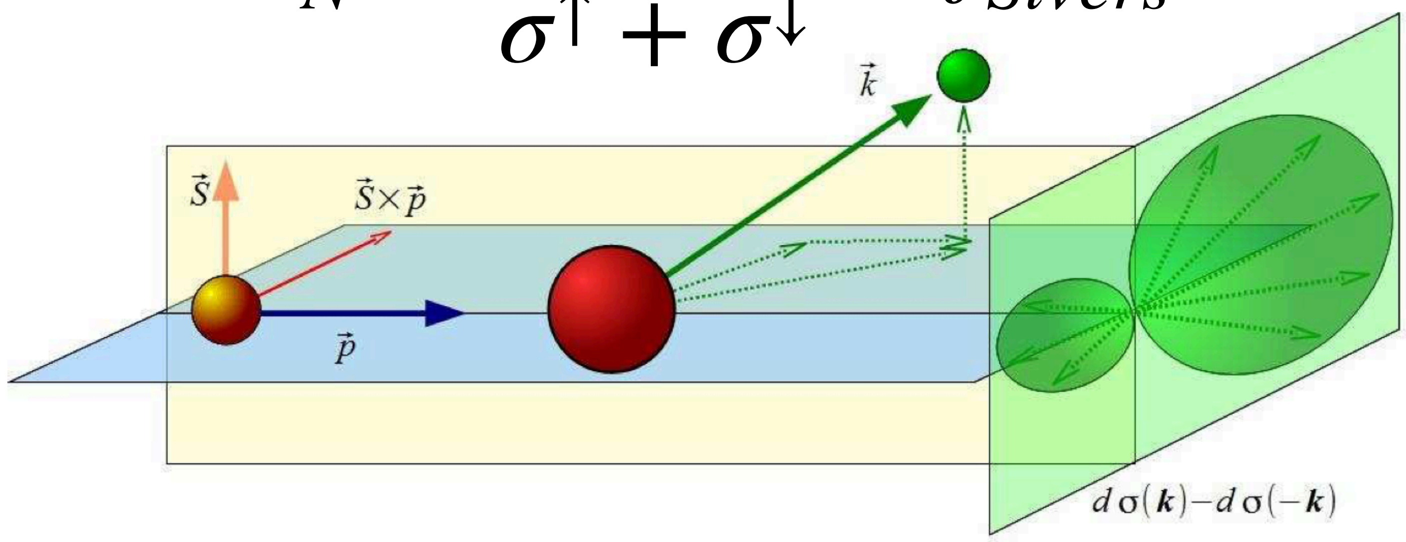
Probabilities to meet in a transversely polarized proton a parton moving to the left and to the right with respect to the $(\vec{S}, \vec{p})$ plane are different!



x=0.1

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

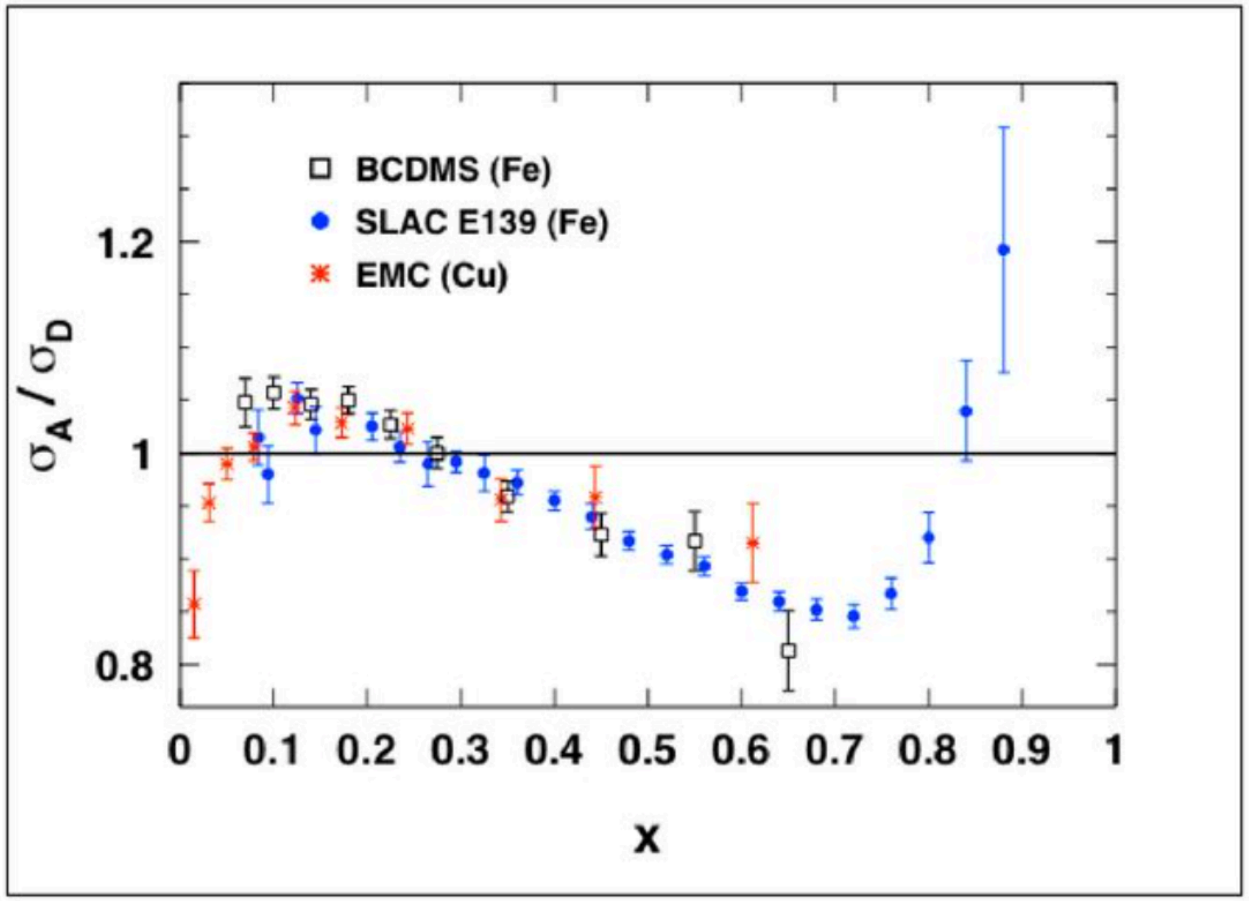




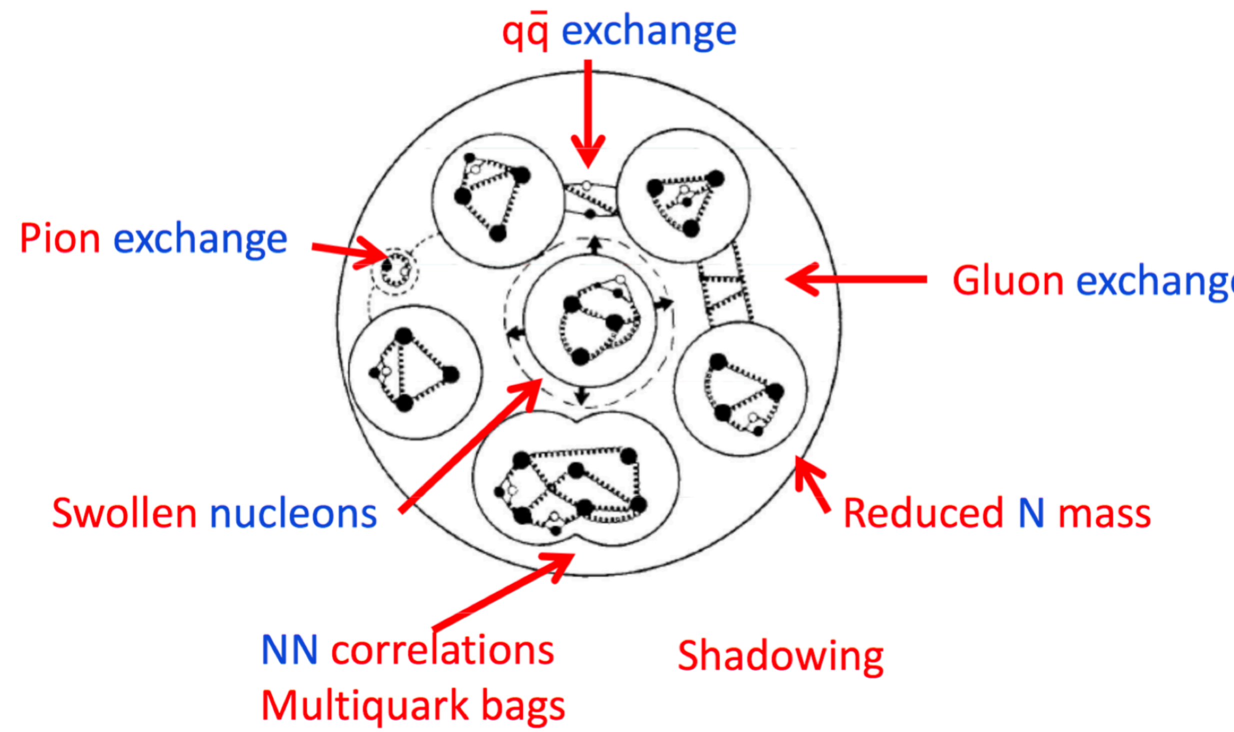
The Sievers effect is usually observed together with the Collins effect, an asymmetry arising from the fragmentation of the final state.

EMC-effect

EMC collaboration, 1982



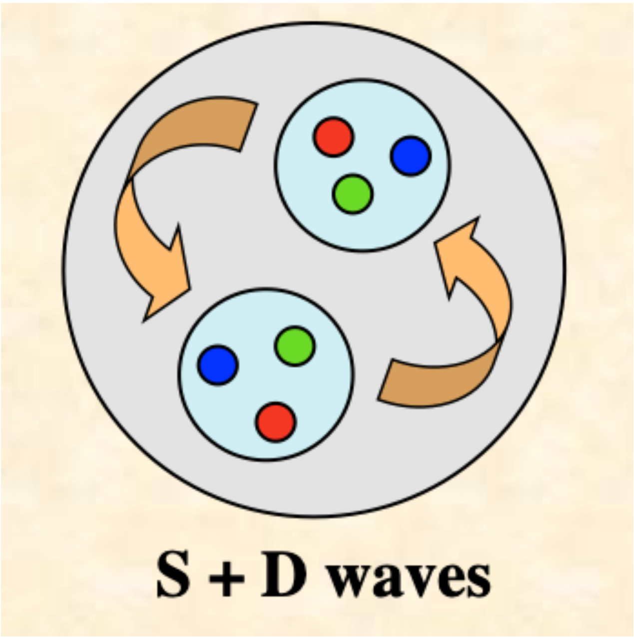
The nucleon "knows" which nucleus it is in!

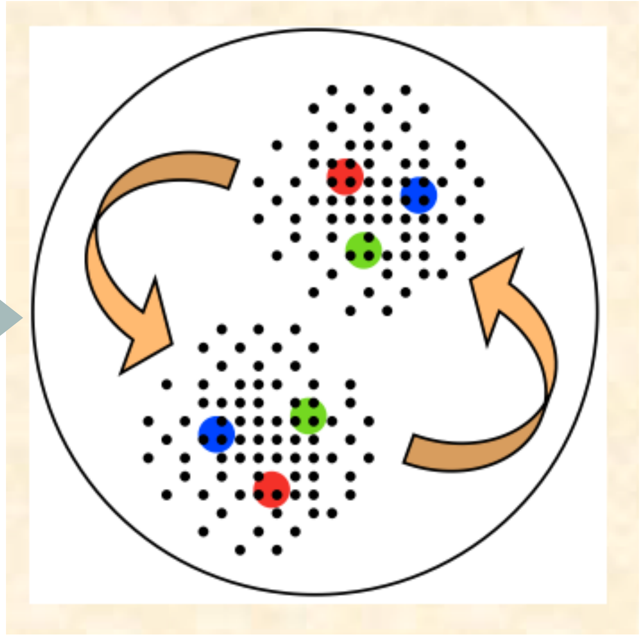


Open questions:

- flavour-separated EMC-effect
- gluon EMC-effect
- polarized EMC effect

Deuteron



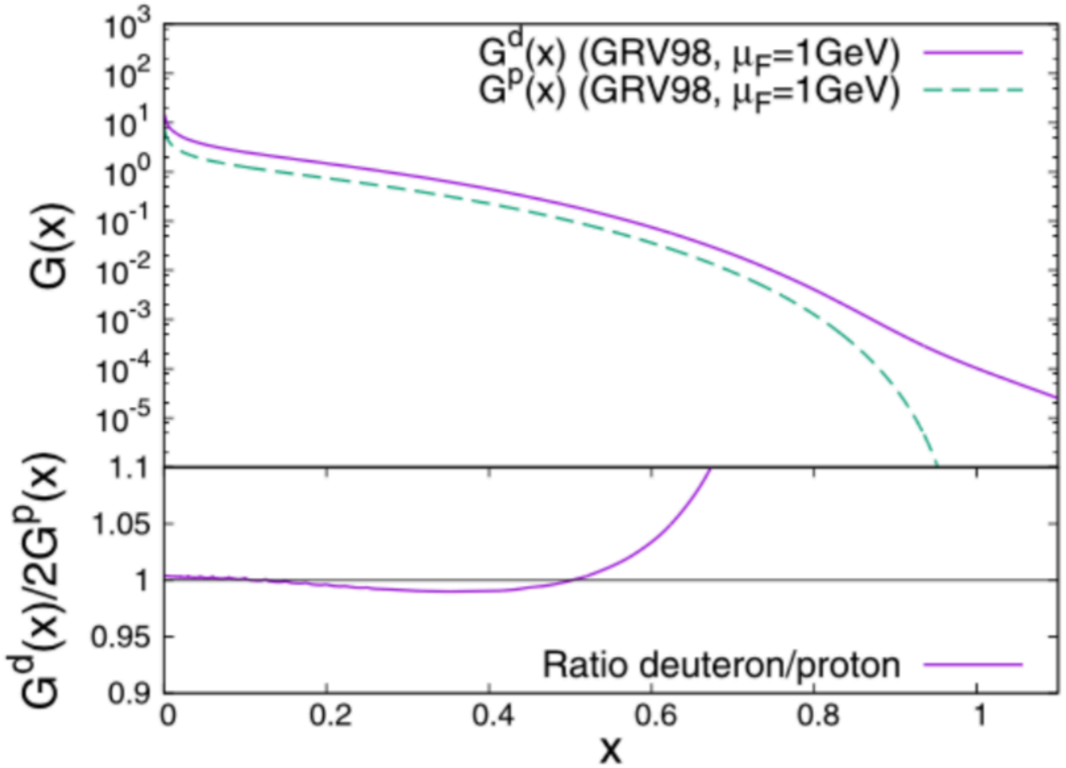


Deuteron is not just proton + neutron!

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

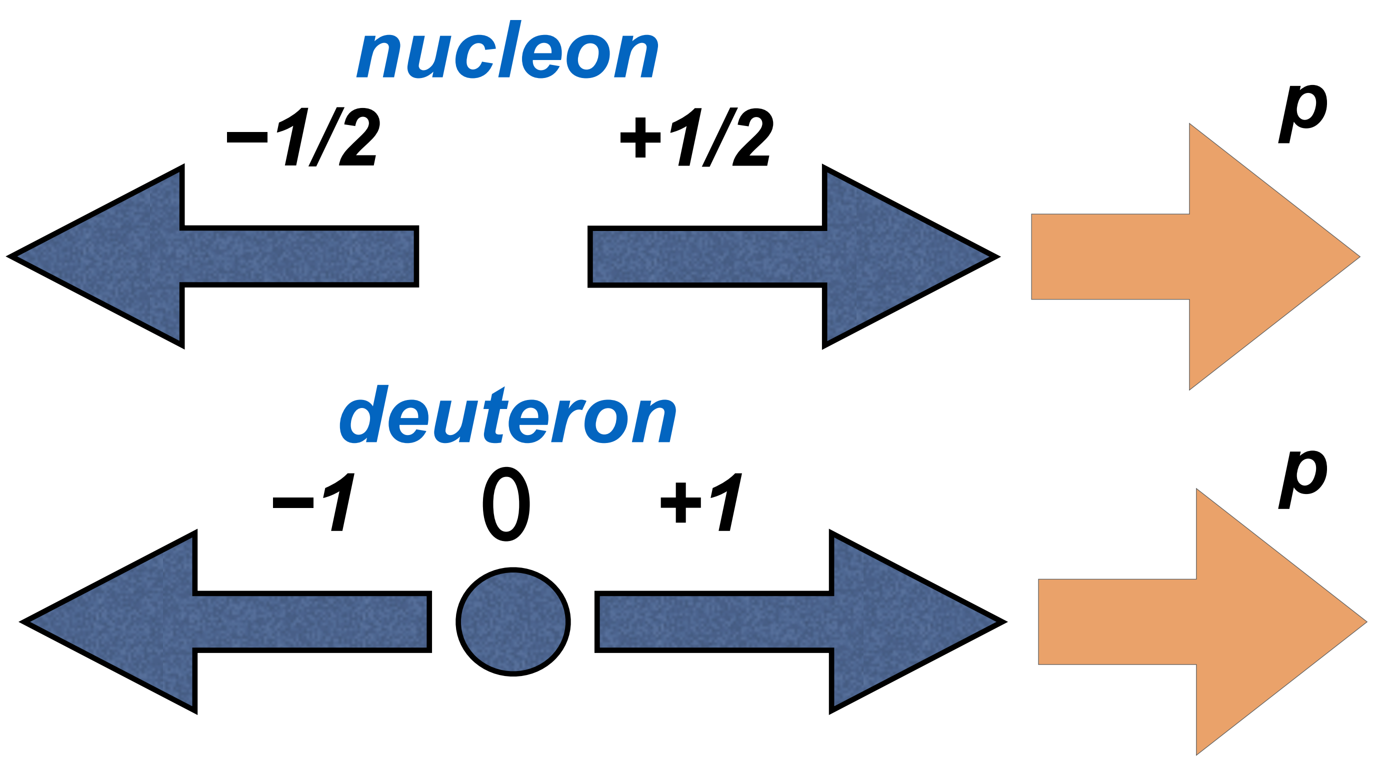
hidden color

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



More gluons at large x with respect to nucleon?

Deuteron as spin-1 particle



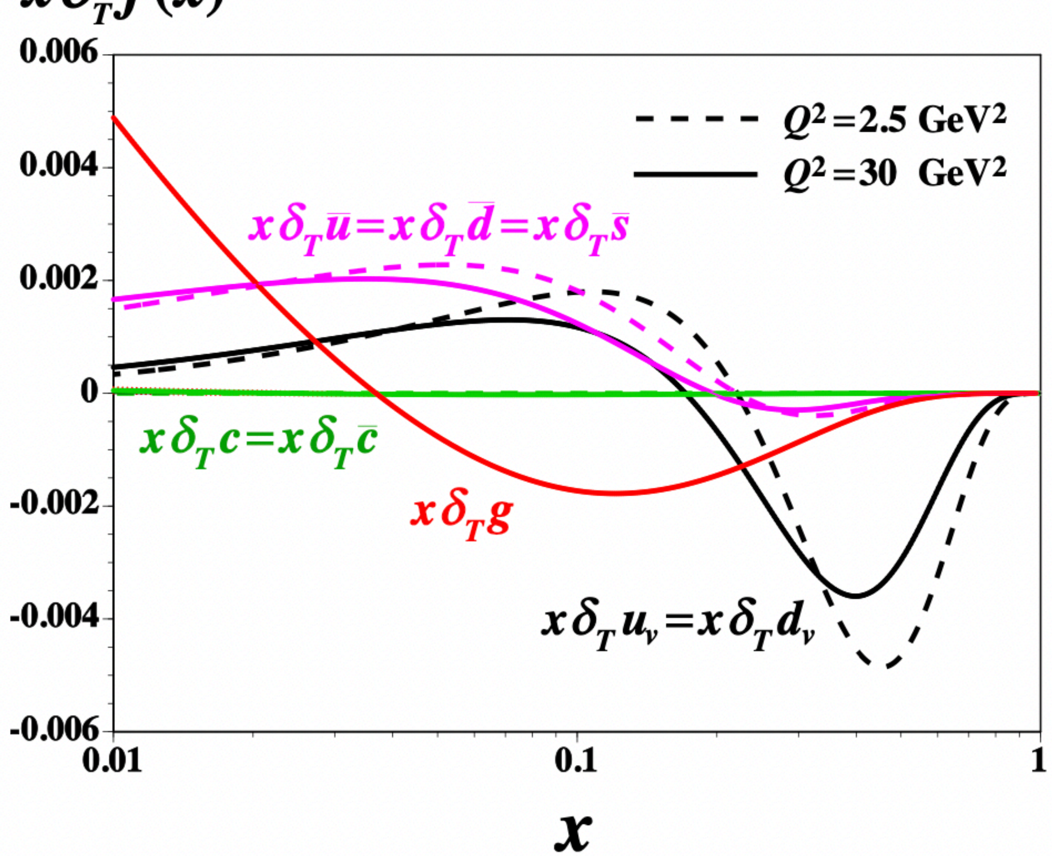
Vector polarization

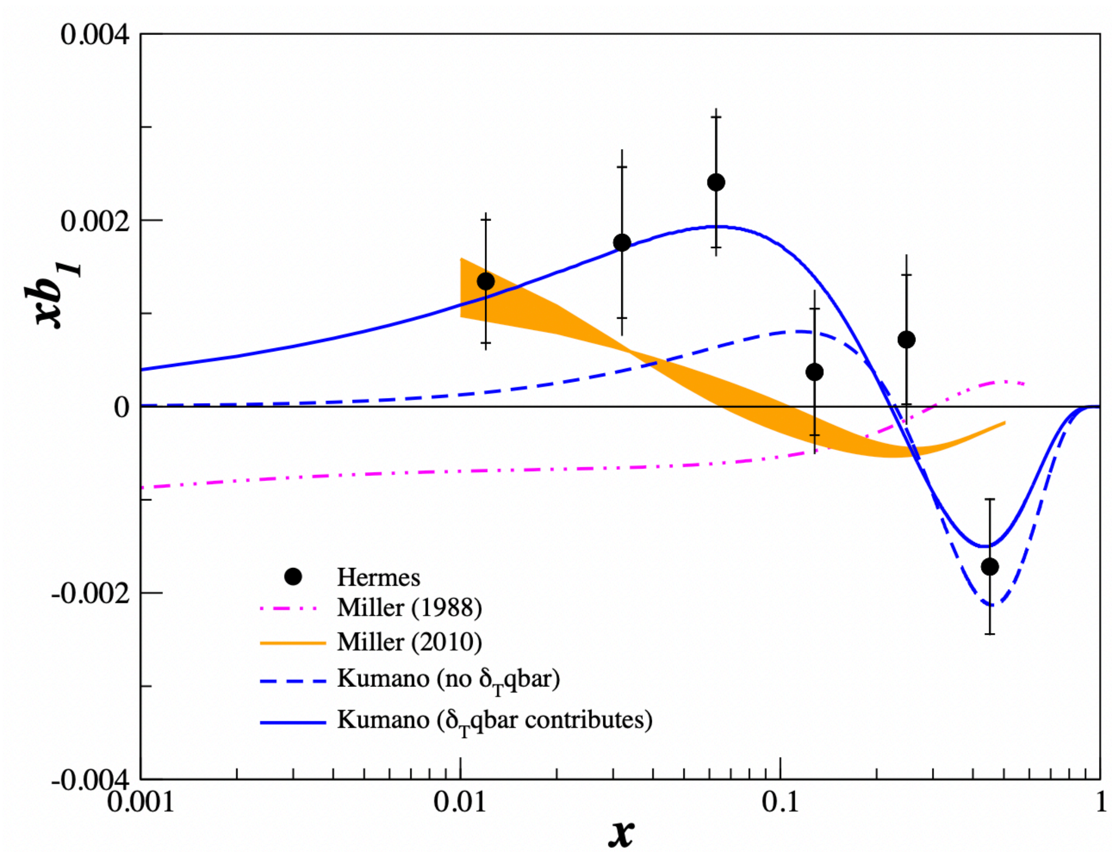
$$\frac{N_{1/2} - N_{-1/2}}{N_{1/2} + N_{-1/2}}$$

Tensor polarization

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

New 11 "tensor" PDFs, mostly unknown





Spin Physic Detector @ NICA

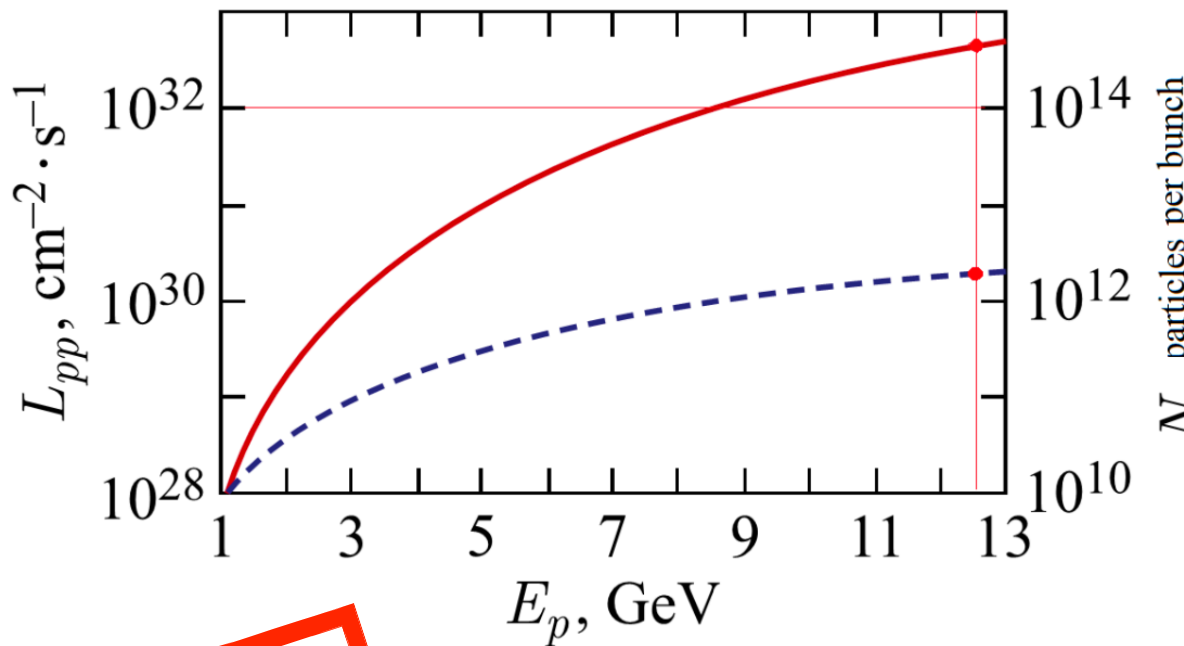
NICA - Nuclotron-based Ion Collider fAcility

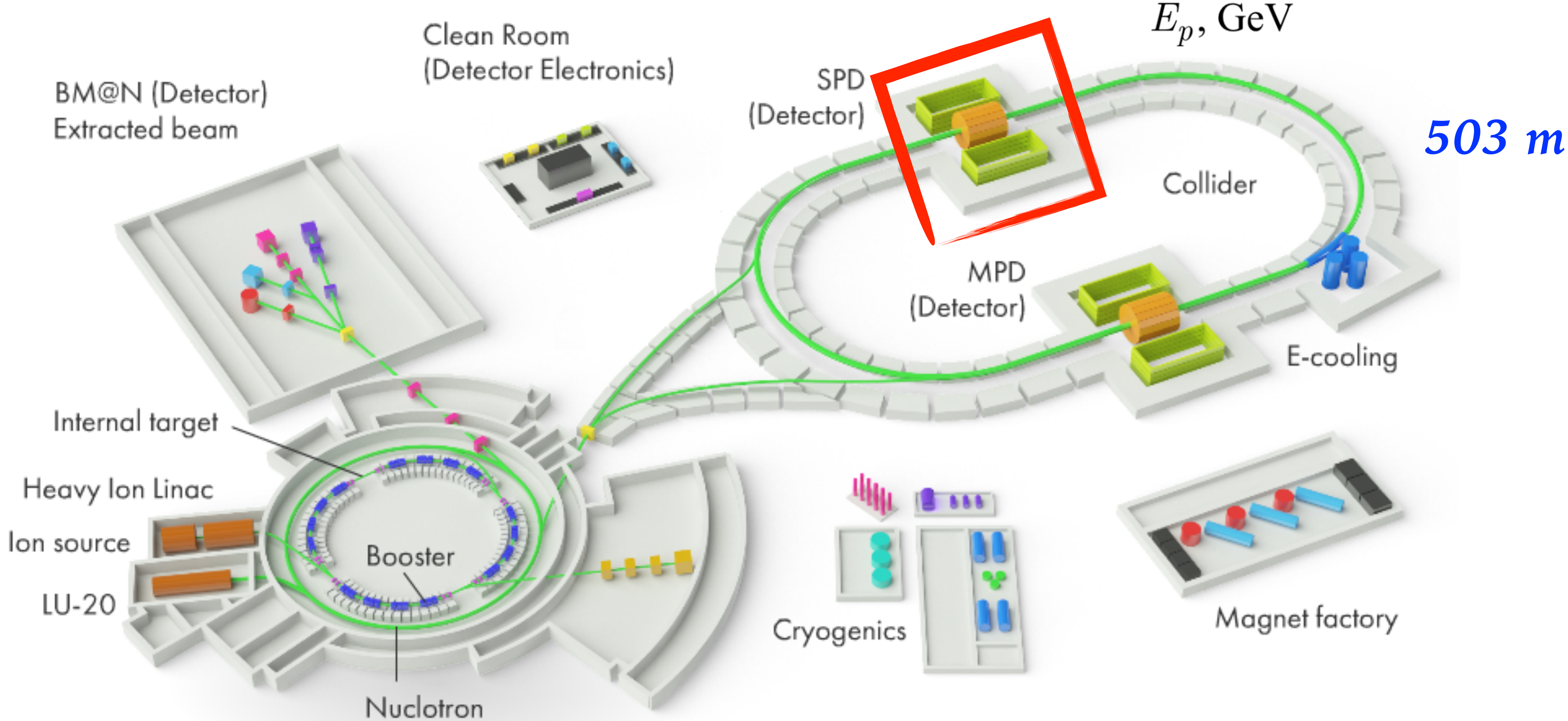
$p^{\uparrow}p^{\uparrow}: \sqrt{s} \leq 27\ GeV$

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

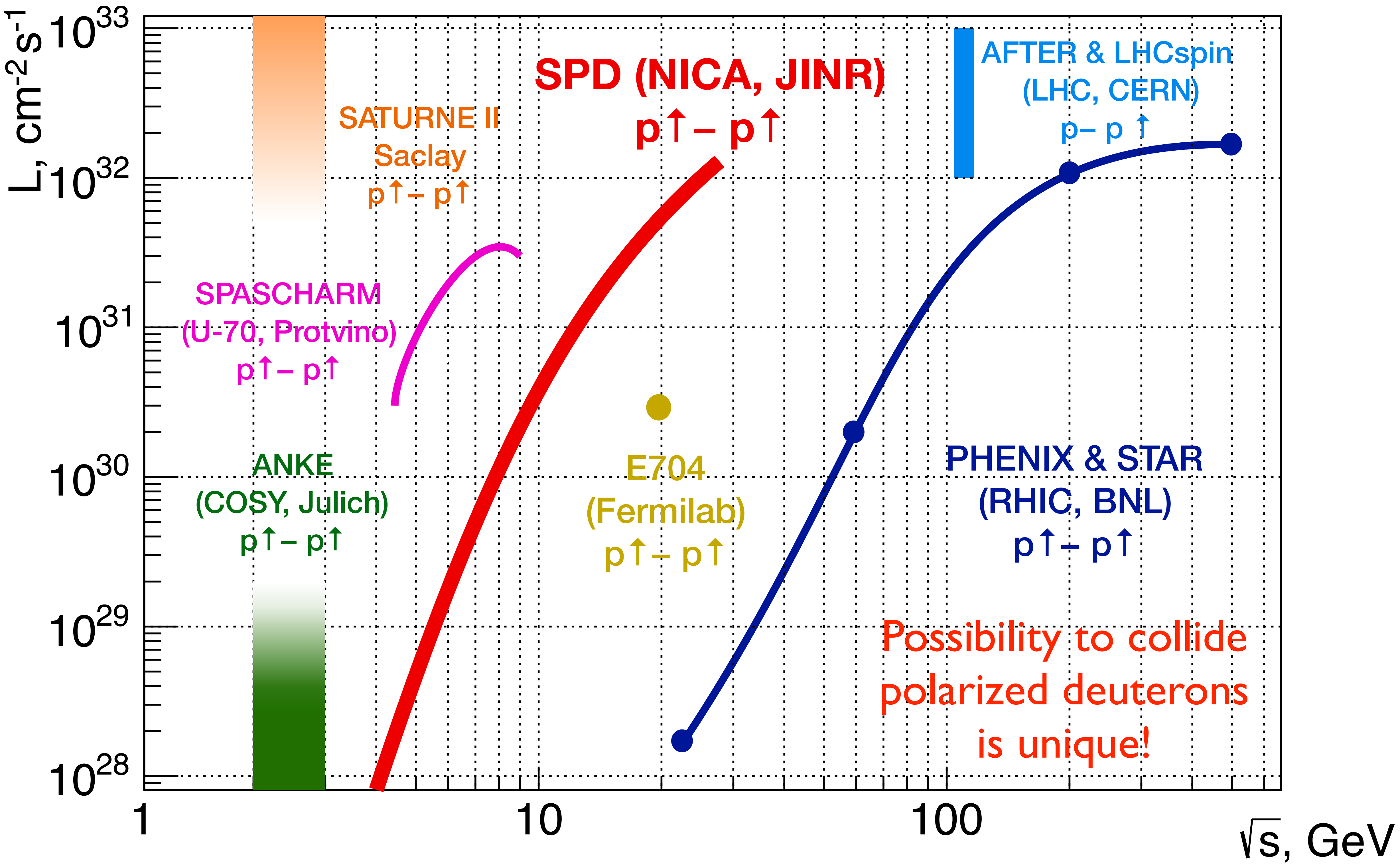
U, L, T

$|P| > 70\%$

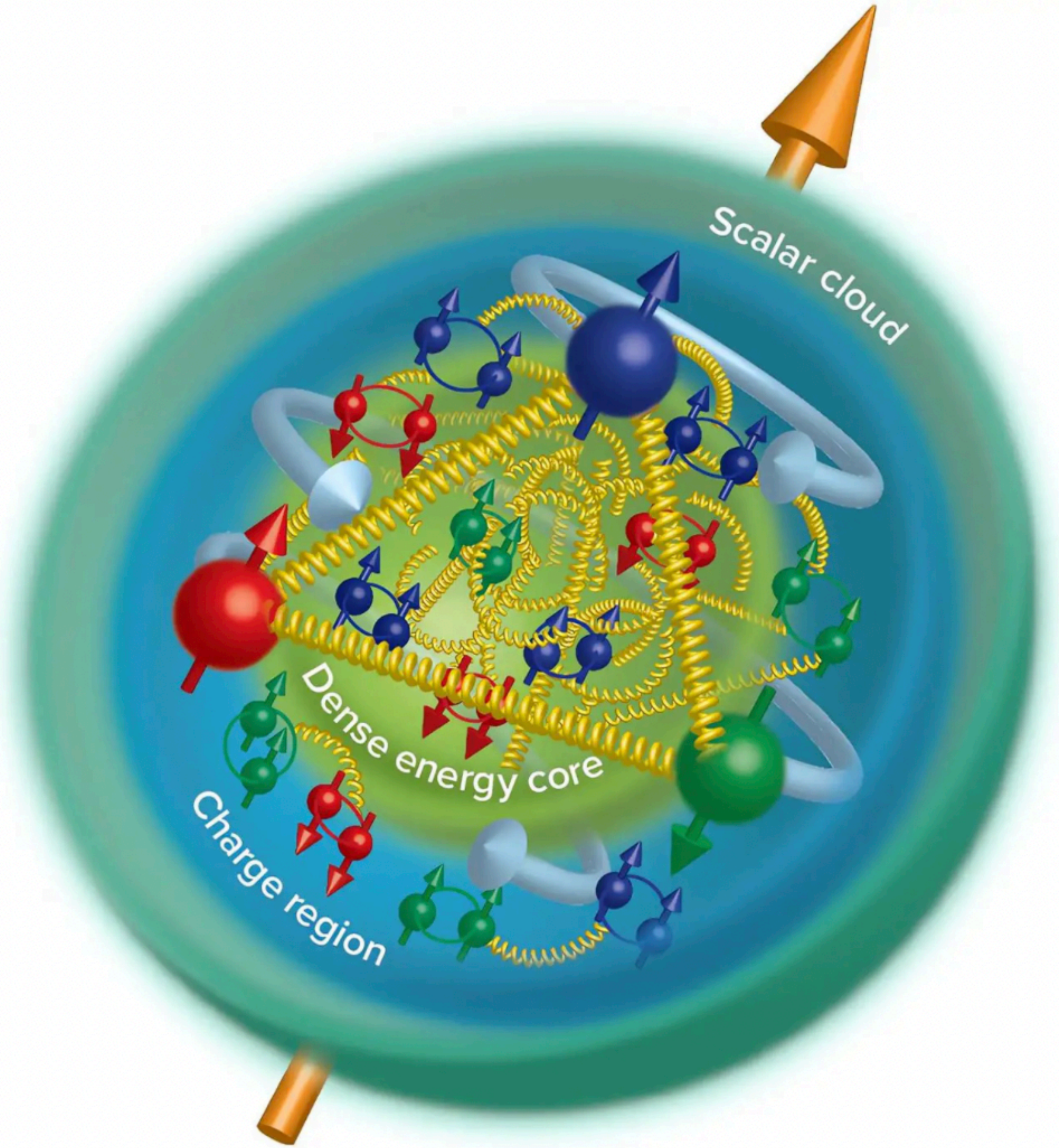




SPD and others

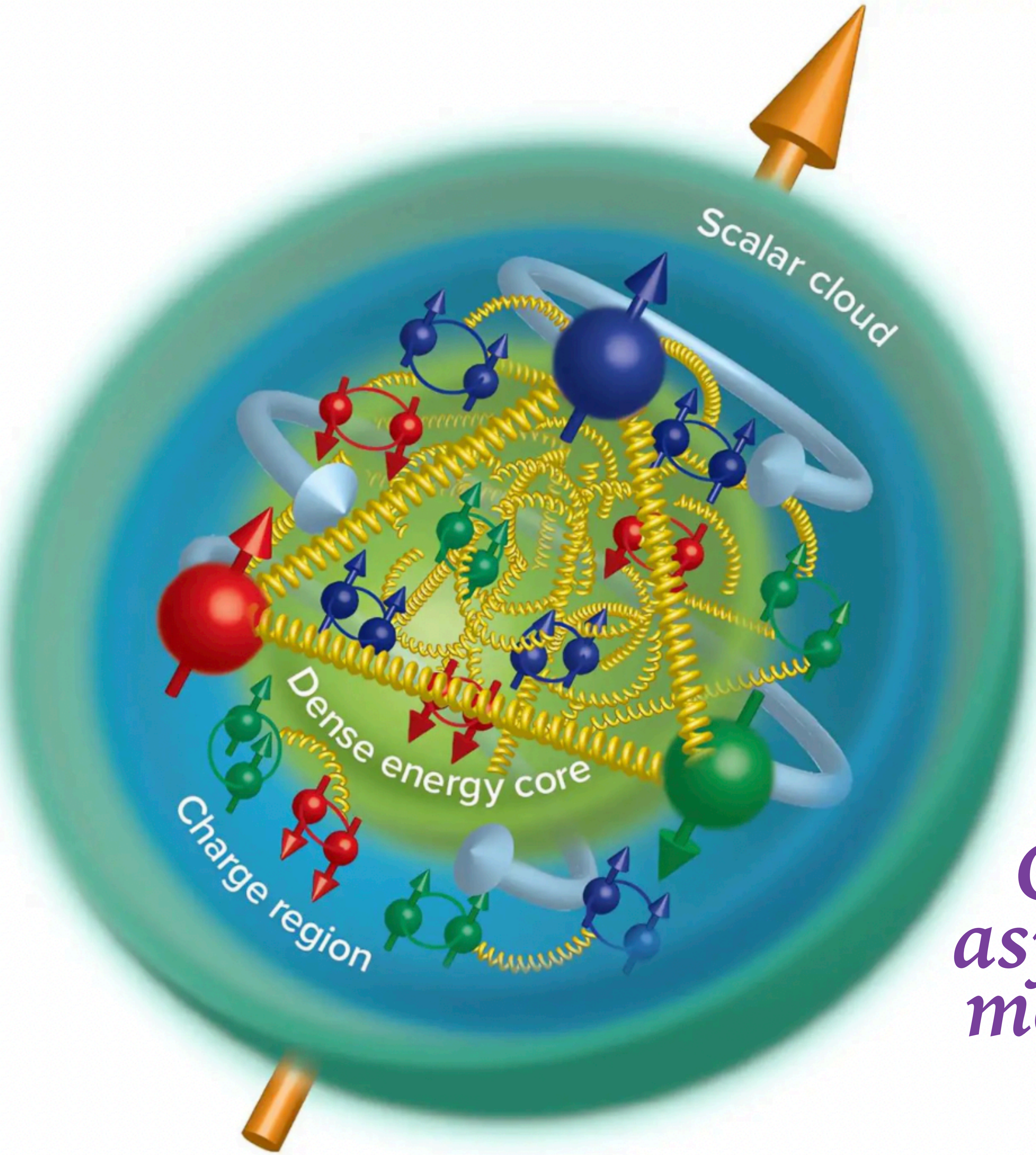


Spin Physics @ NICA



we plan to study *how the proton and deuteron spin*

Spin Physics @ NICA



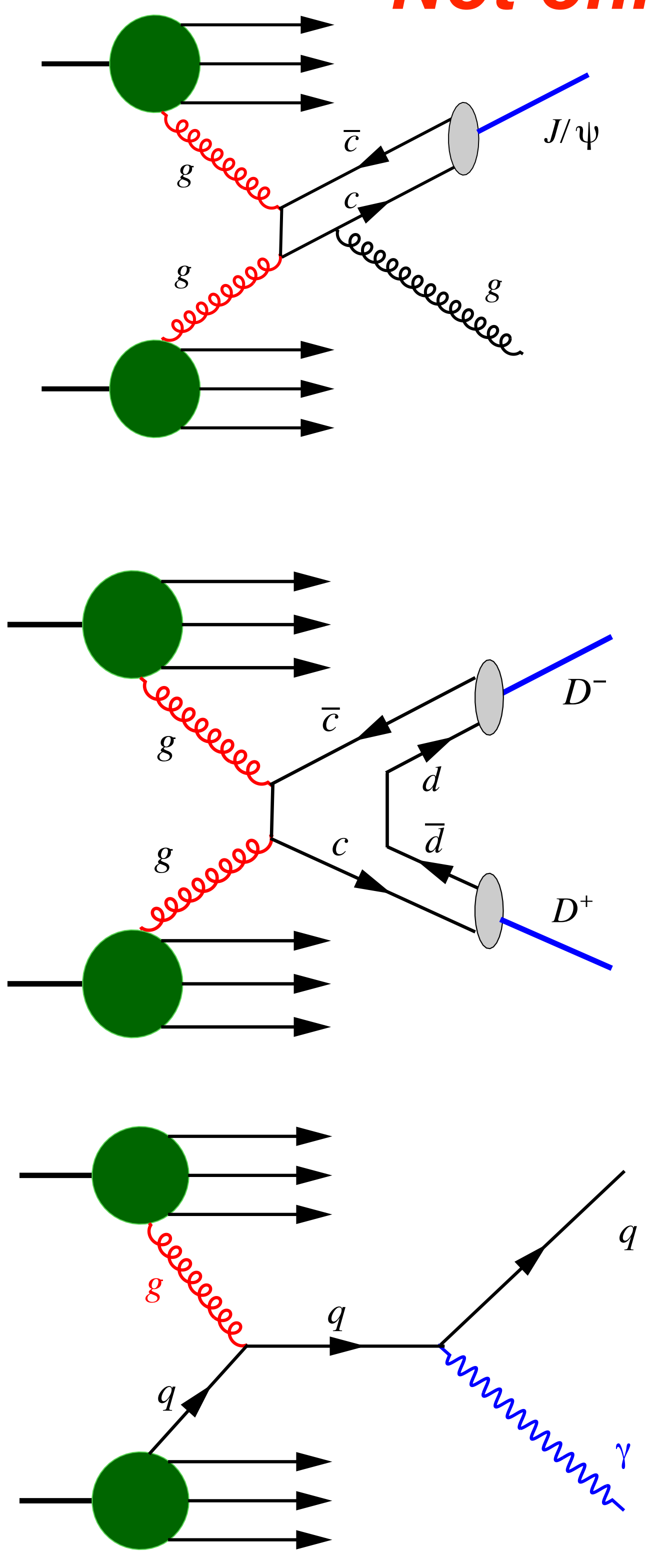
we plan to study how the proton and deuteron spin!

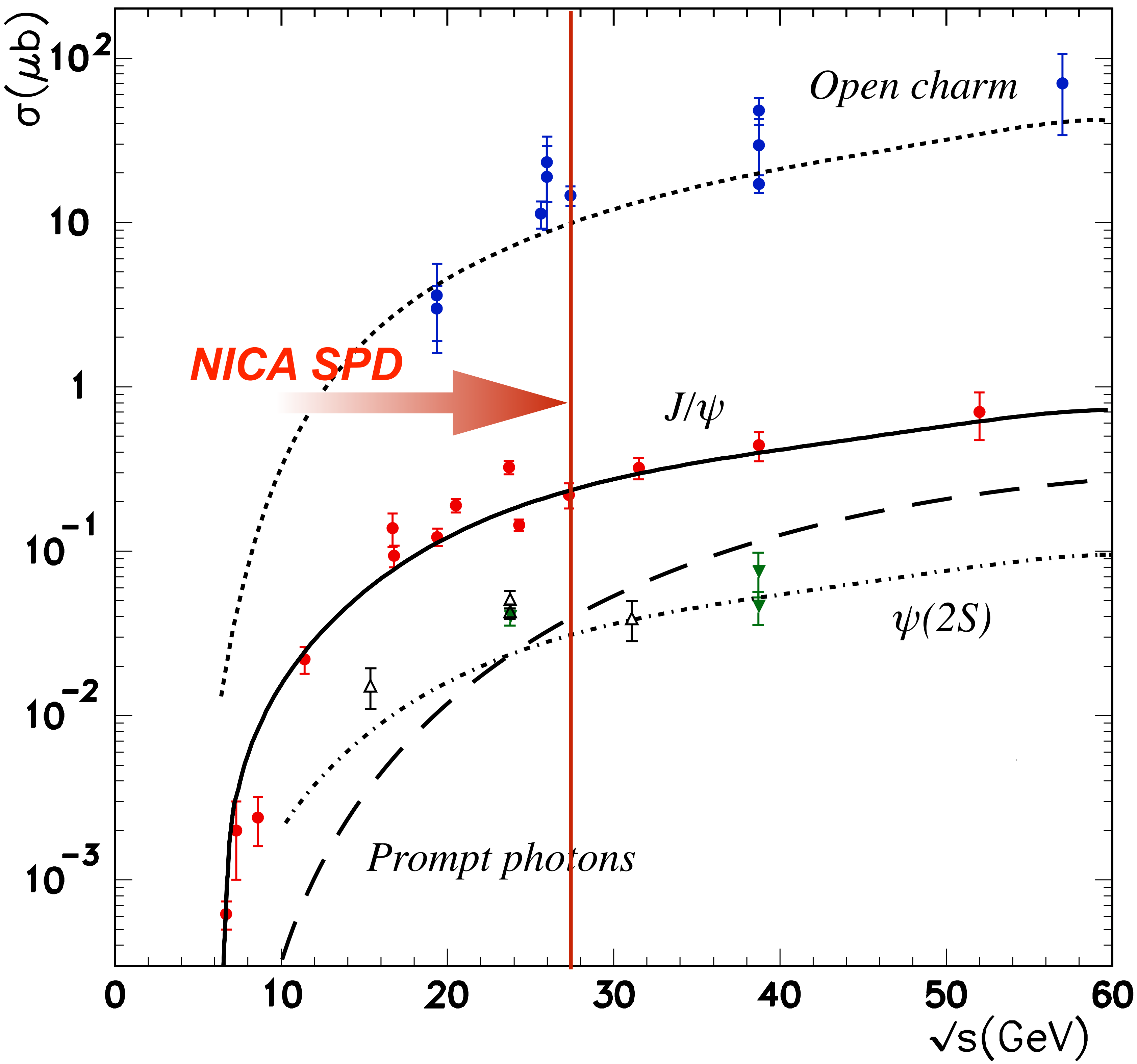
especially their gluon component!

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

SPD and gluon structure of nucleon

Not only J/ψ!





SPD gluon program

JPPNP: 103858 Model 3G pp. 1–43 (col. fig: NIL)

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Review

On the physics potential to study the gluon content of proton and deuteron at NICA SPD

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On the physics potential to study the gluon content of proton and deuteron at NICA SPD #1

A. Arbuzov (Dubna, JINR), A. Bacchetta (Pavia U. and INFN, Pavia), M. Butenschoen (Hamburg U., Inst. Theor. Phys. II), F.G. Celiberto (Pavia U. and INFN, Pavia and ECT, Trento and Fond. Bruno Kessler, Povo), U. D'Alesio (Cagliari U. and INFN, Cagliari) et al. (Nov 30, 2020)

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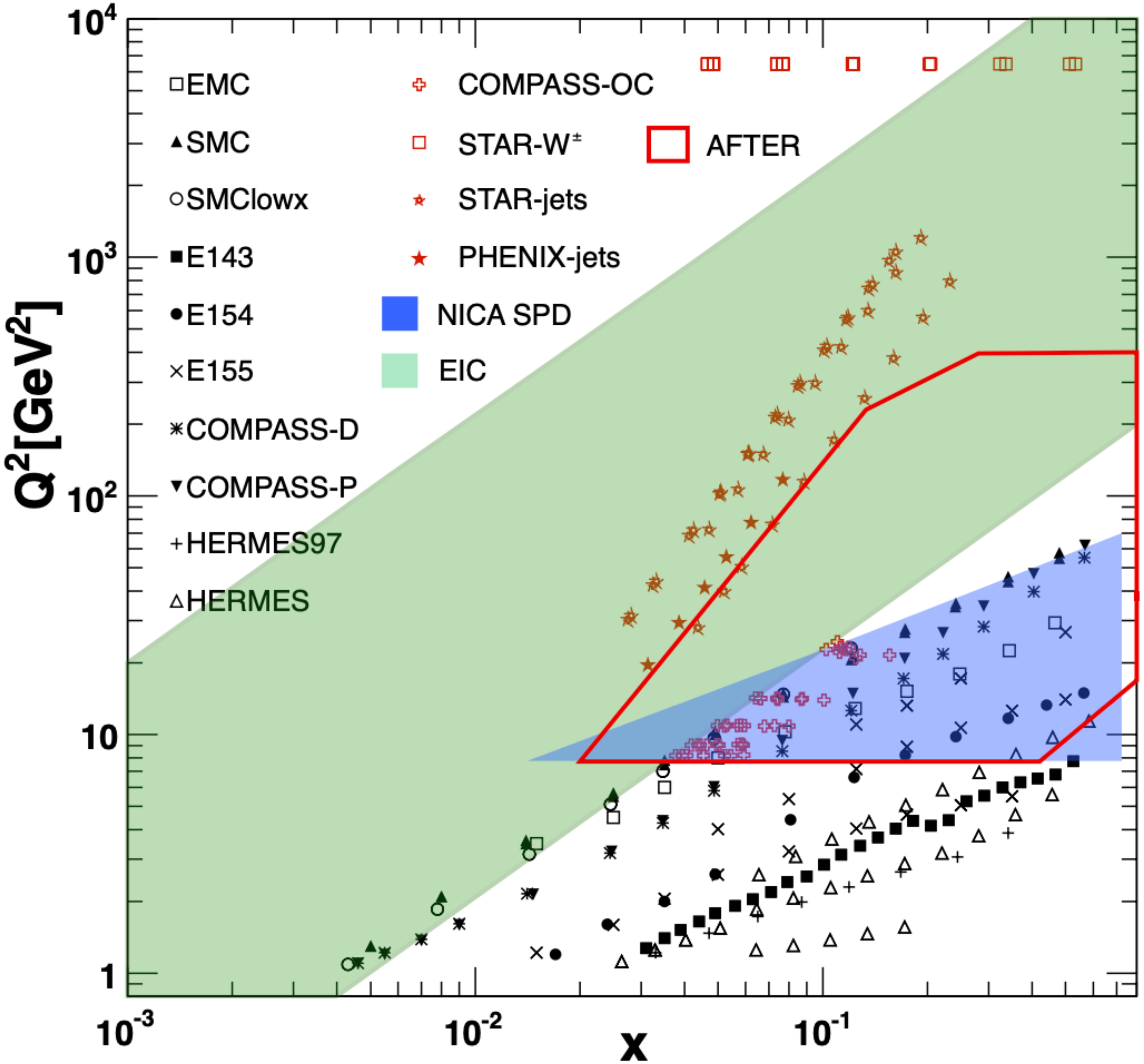
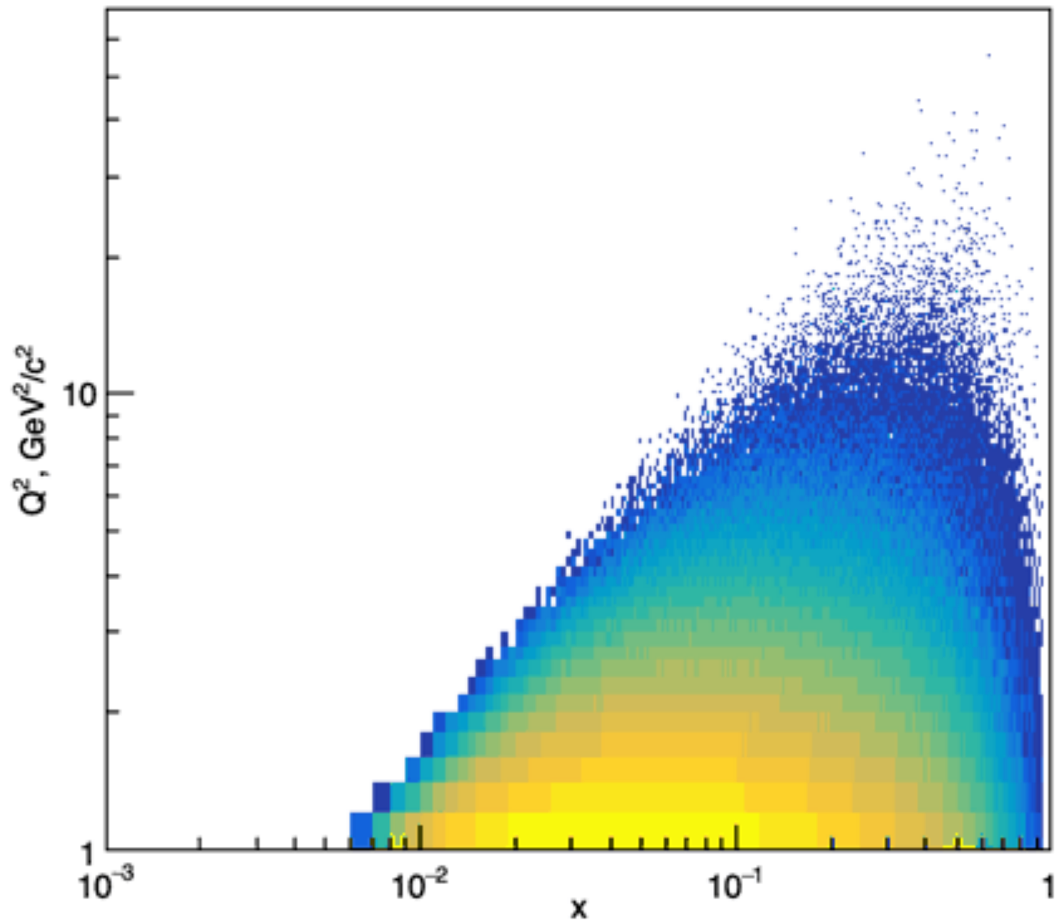
pdf DOI cite claim reference search 51 citations

SPD and others

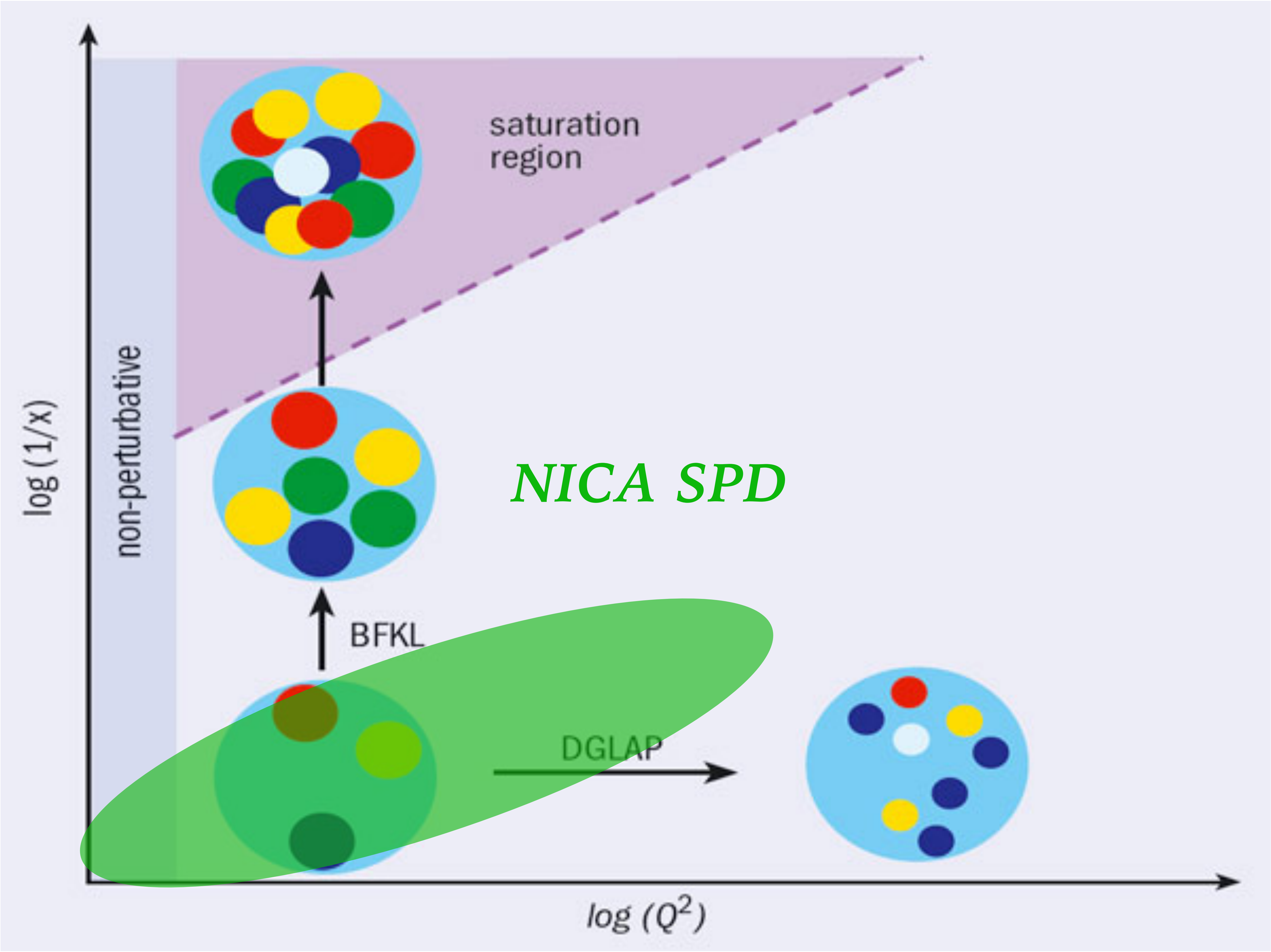




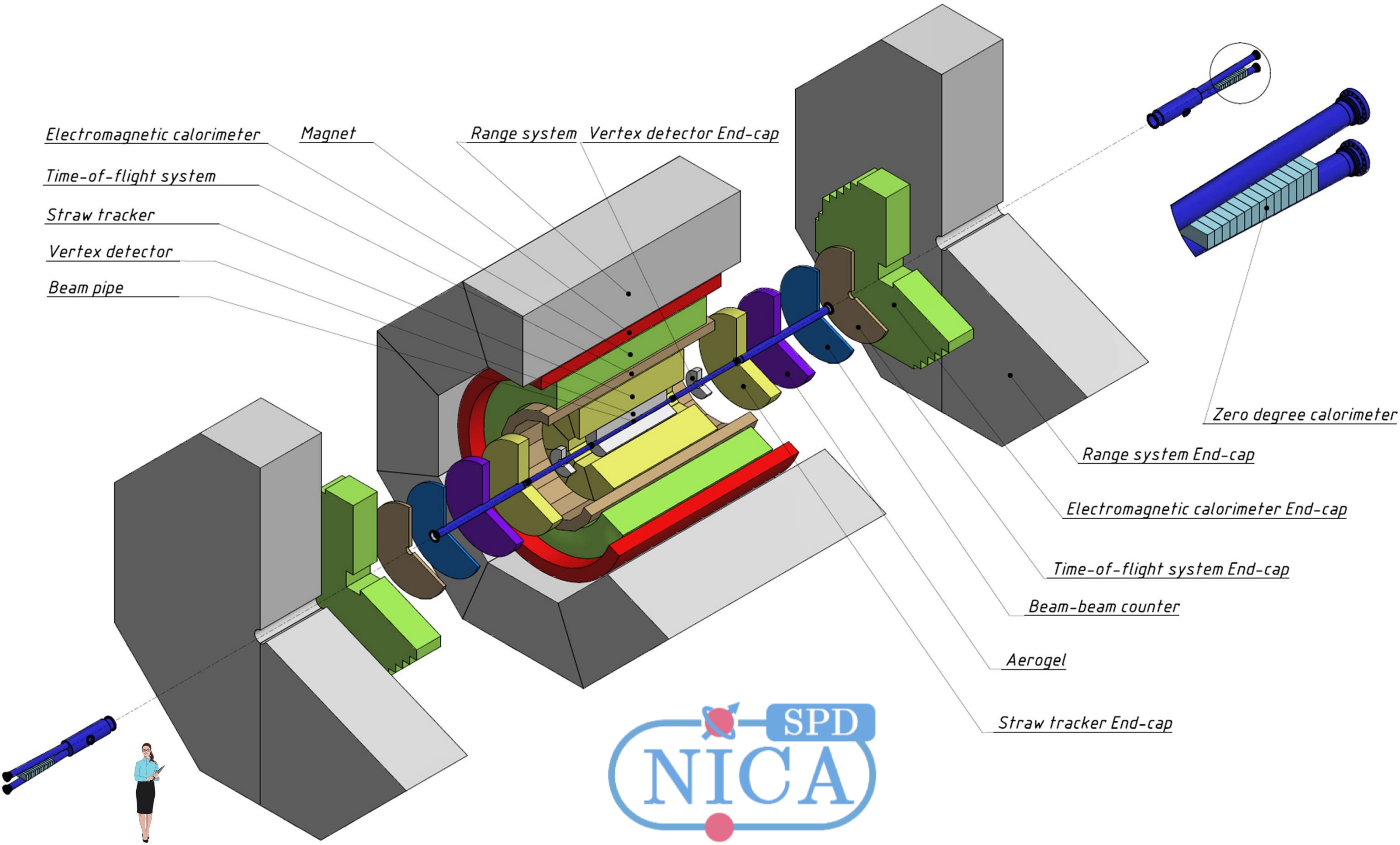
$Q^2 = 1\ GeV^2/c^2, <x> = 0.16$

$Q^2 = 10\ GeV^2/c^2, <x> = 0.3$

QCD landscape & SPD



SPD setup



SPD
NICA

SPD: two stages

Creating of polarized infrastructure

Upgrade of polarized infrastructure

Start of NICA operation

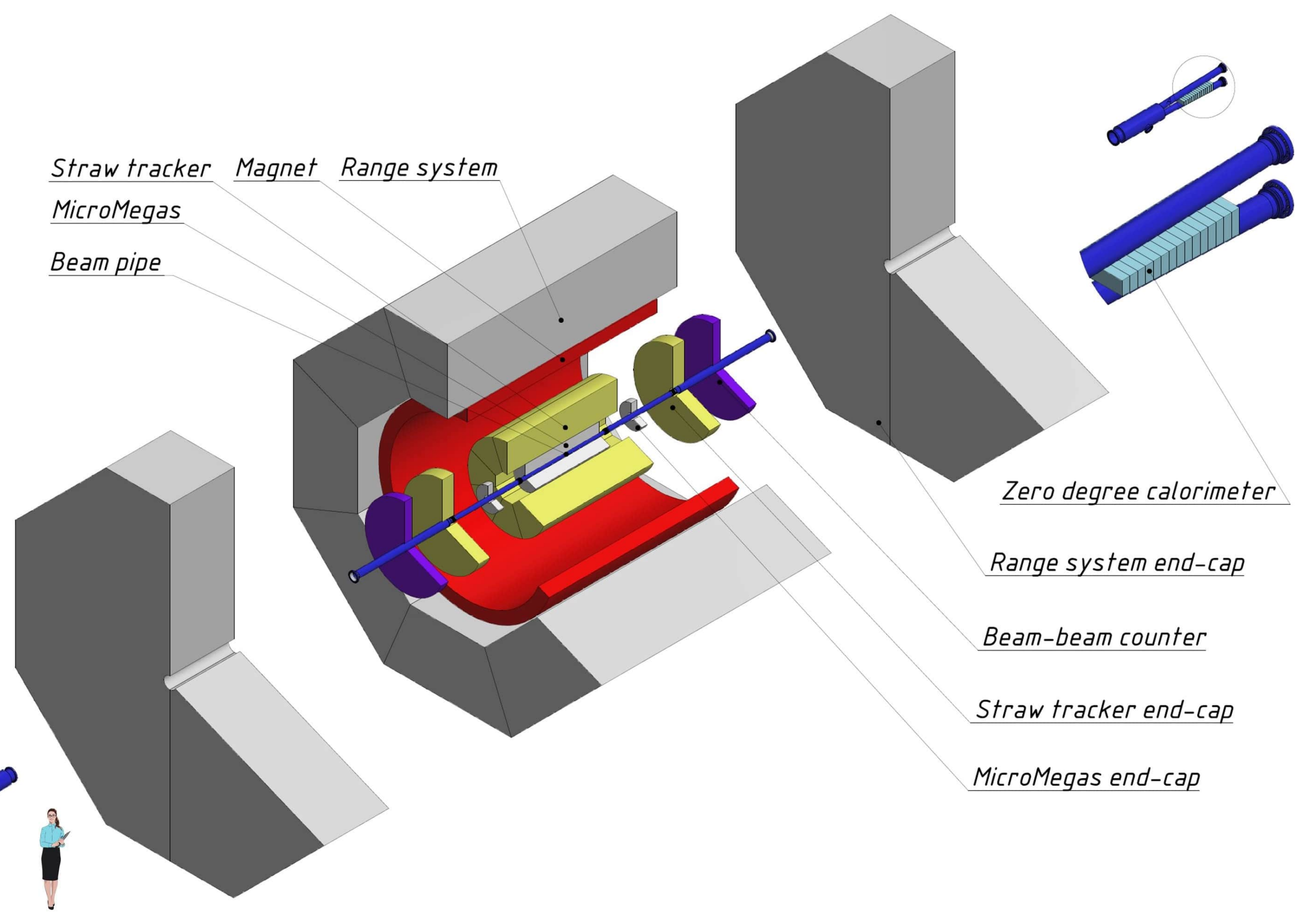
+4 years *+6 years* *+8 years*

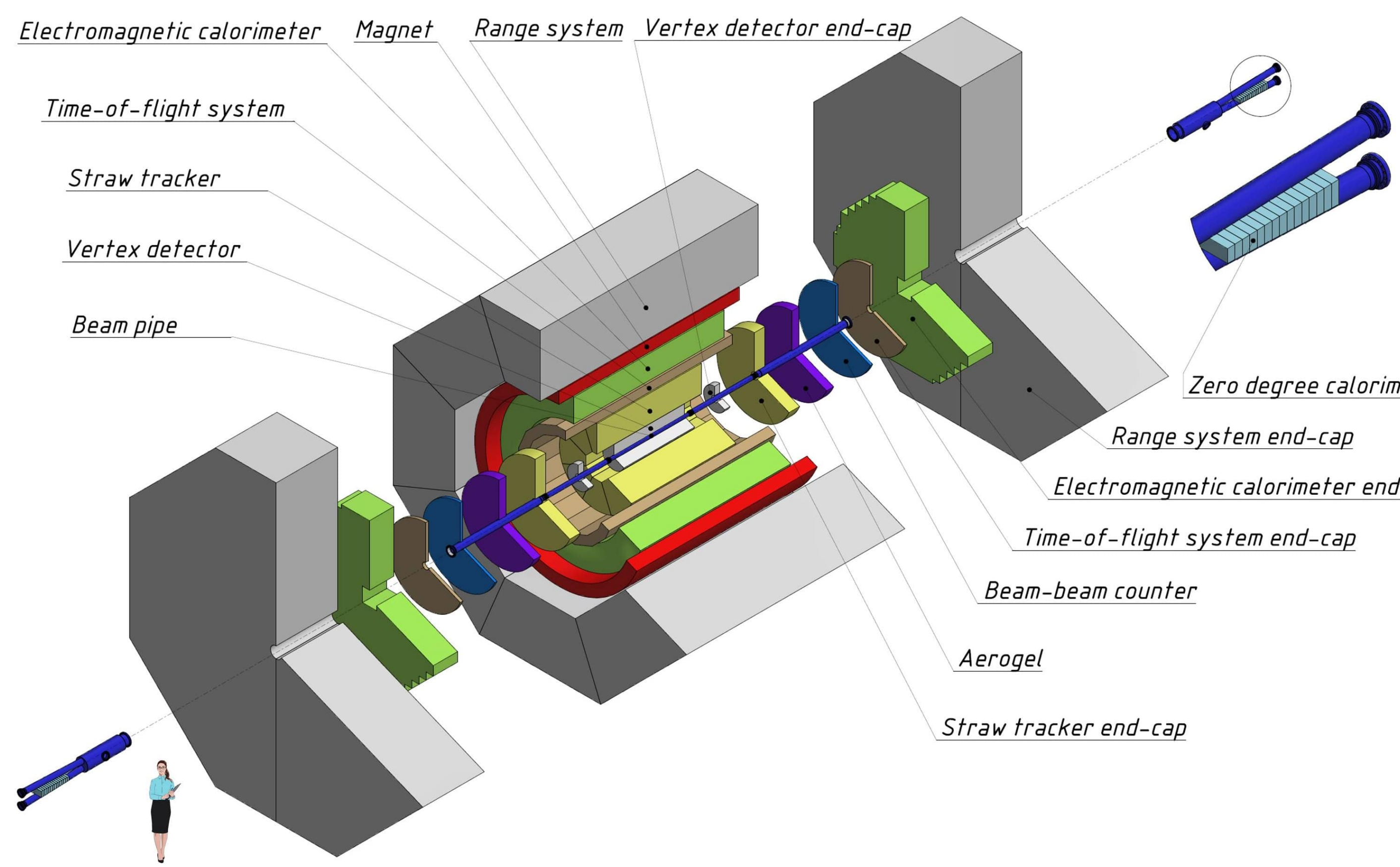
SPD construction

1st stage of operation

SPD upgrade

2nd stage of operation





SPD collaboration

33 institutes from 15 states, ~300 members

Proton structure: Hall of Fame

Summary

- The **Spin Physics Detector** at the NICA collider is a universal facility for comprehensive study of polarized and unpolarized **gluon content of proton and deuteron**; in polarized high-luminosity **p-p** and **d-d** collisions at $\sqrt{s} \leq 27\ GeV$;
- Complementing main probes such as **charmonia** (J/ψ and higher states), **open charm** and **prompt photons** will be used for that;
- SPD can contribute significantly to investigation of
  - gluon helicity;
  - gluon-induced TMD effects (Sivers and Boer-Mulders);
  - unpolarized gluon PDFs at high-x in proton and deuteron;
  - gluon transversity in deuteron;
  - …
- Comprehensive physics program for the first period of data taking: spin effects in p-p, p-d and d-d elastic scattering, spin effects in hyperon production, multiquark correlations, dibaryon resonances, physics of light and intermediate nuclei collisions, exclusive reactions, hypernuclei, open charm and charmonia near threshold, etc.;
- **The SPD gluon physics program is complementary to the other intentions to study the gluon content of nuclei (RHIC, AFTER, LHC-Spin, EIC, JLab experiments) and mesons (AMBER, EIC);**
- More information including **SPD CDR** and **TDR** could be found at http://spd.jinr.ru .

Frontiers of particle physics