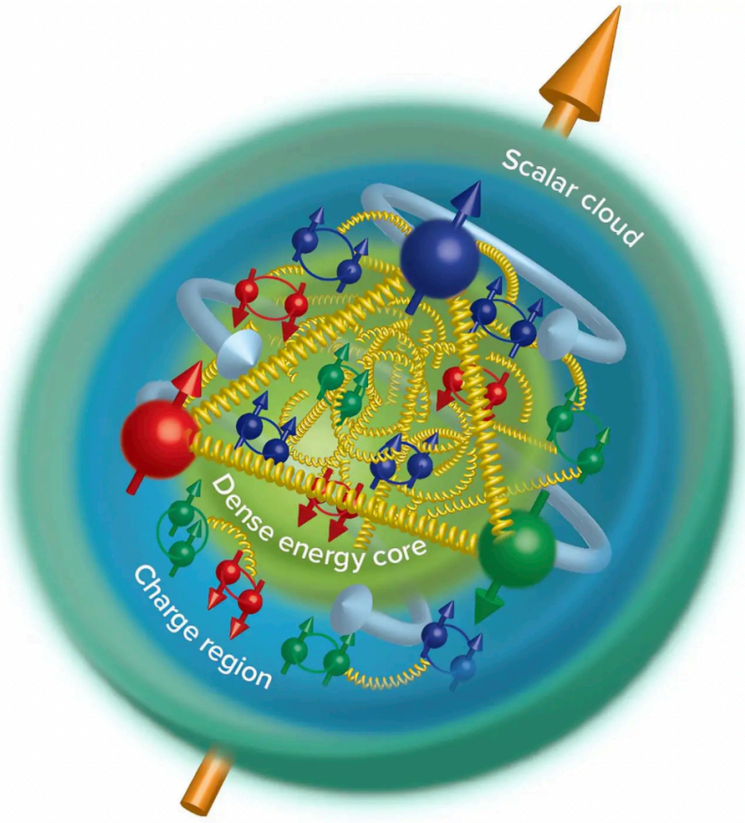
Spin Physics Detector project @ NICA

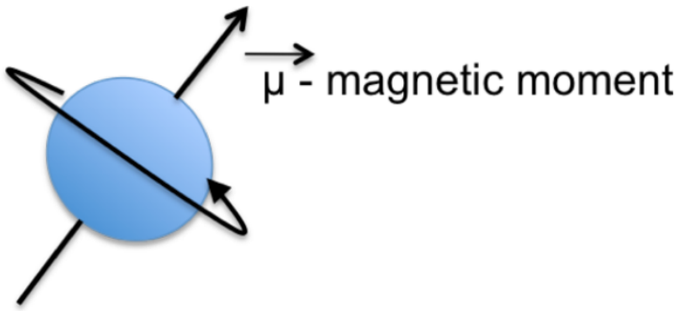
A. Guskov, JINR



MEPhI
18.12.23

avg@jinr.int

Proton as a complex object



$$\vec{\mu}_S = g_S \times \frac{e}{2m} \times \vec{S}$$

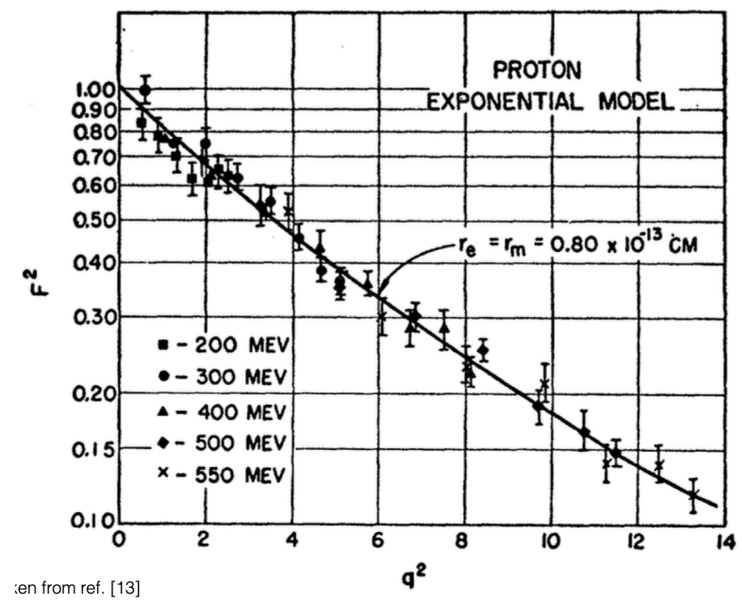
	g_S (expected)	g_S (measured)
e	-2	-2.0023
p	2	**5.58**
n	0	**-3.83**

1930-s

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

Proton size and structure

R. Hofstadter - Nobel Prize in 1961



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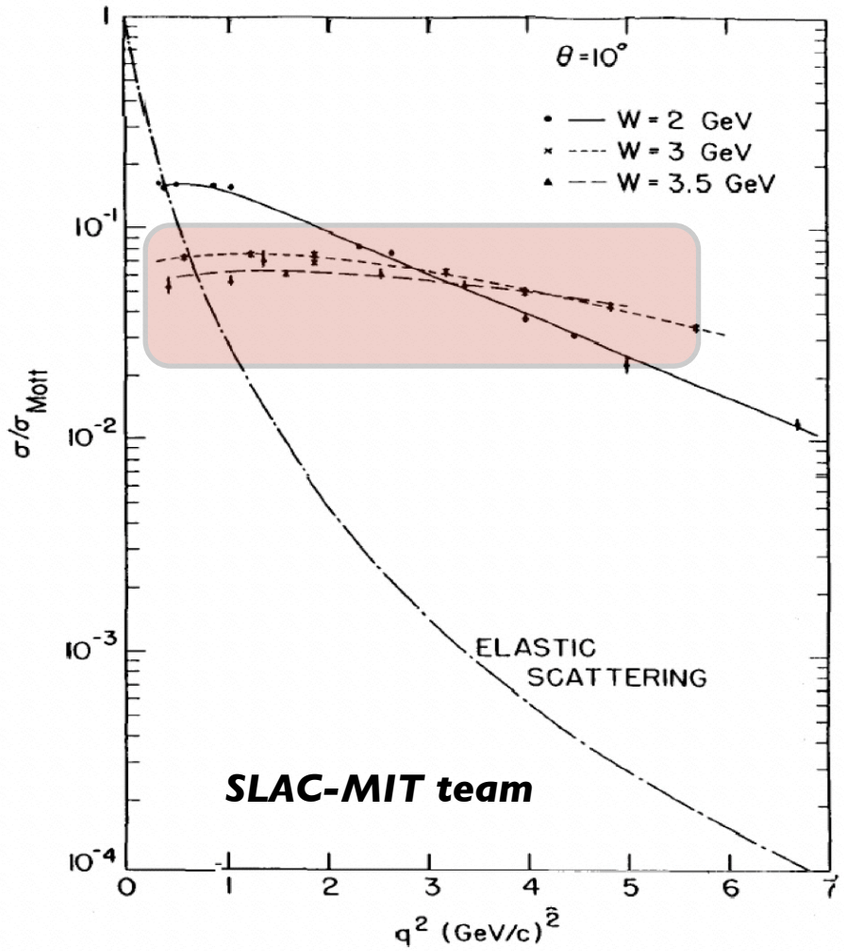


J. Friedman, H. Kendall, R. Taylor - Nobel Prize in 1990

Partons - point-like objects inside the proton

Form-factor

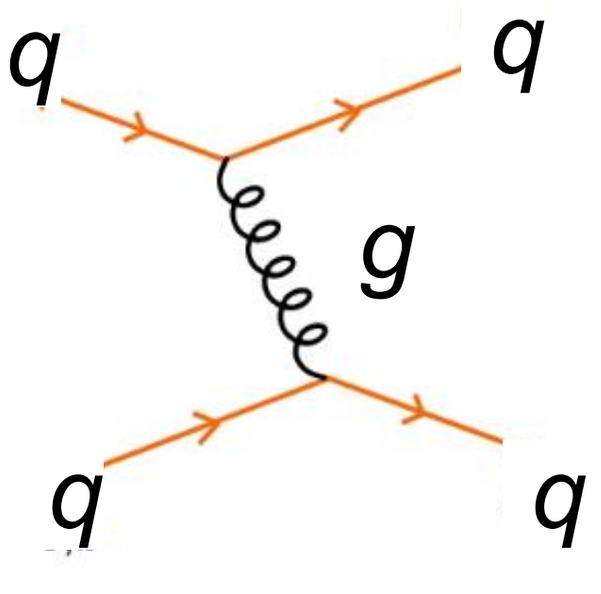
$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\text{point-like}} \times F^2(q^2)$$

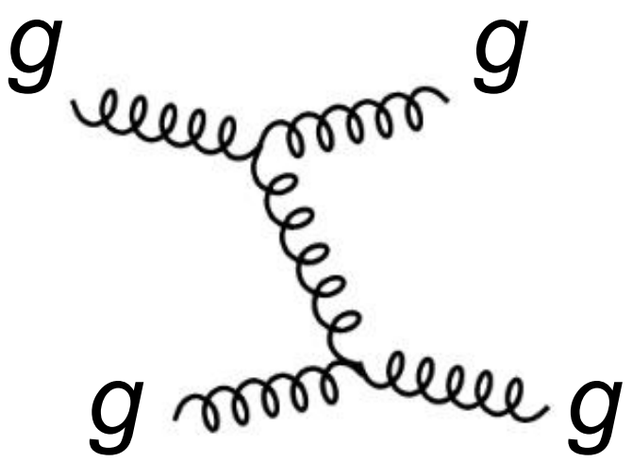
$$F(q^2) \approx 1 - \frac{q^2 < r^2 >}{6\hbar^2}$$

Partonic model - 1969

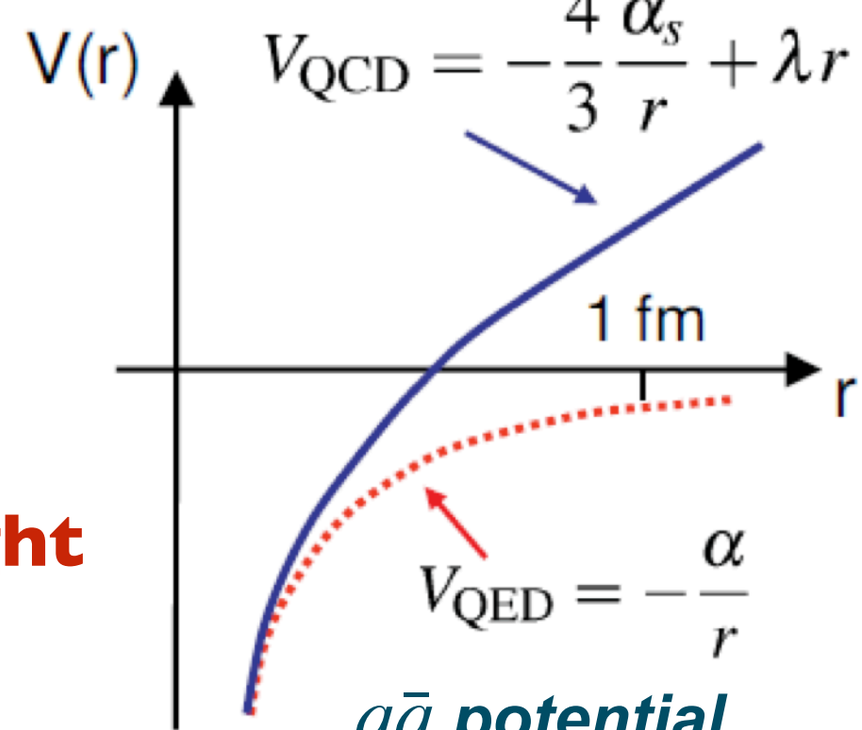
R. Feynman

Quantum ChromoDynamics - QCD

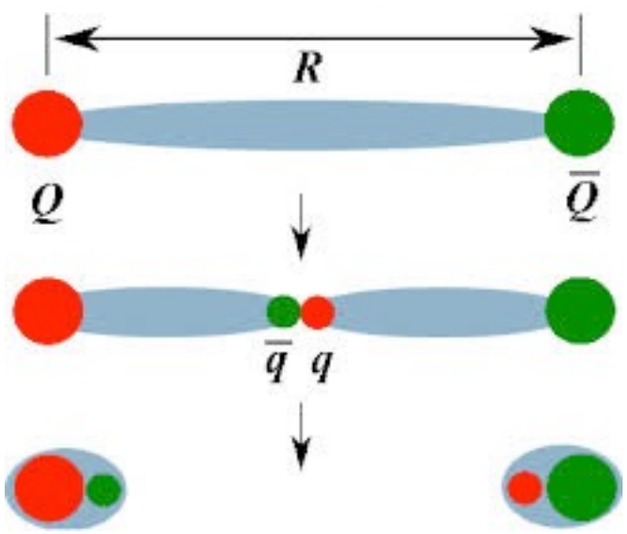




Analog in electrodynamics: **light emitting light !**



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

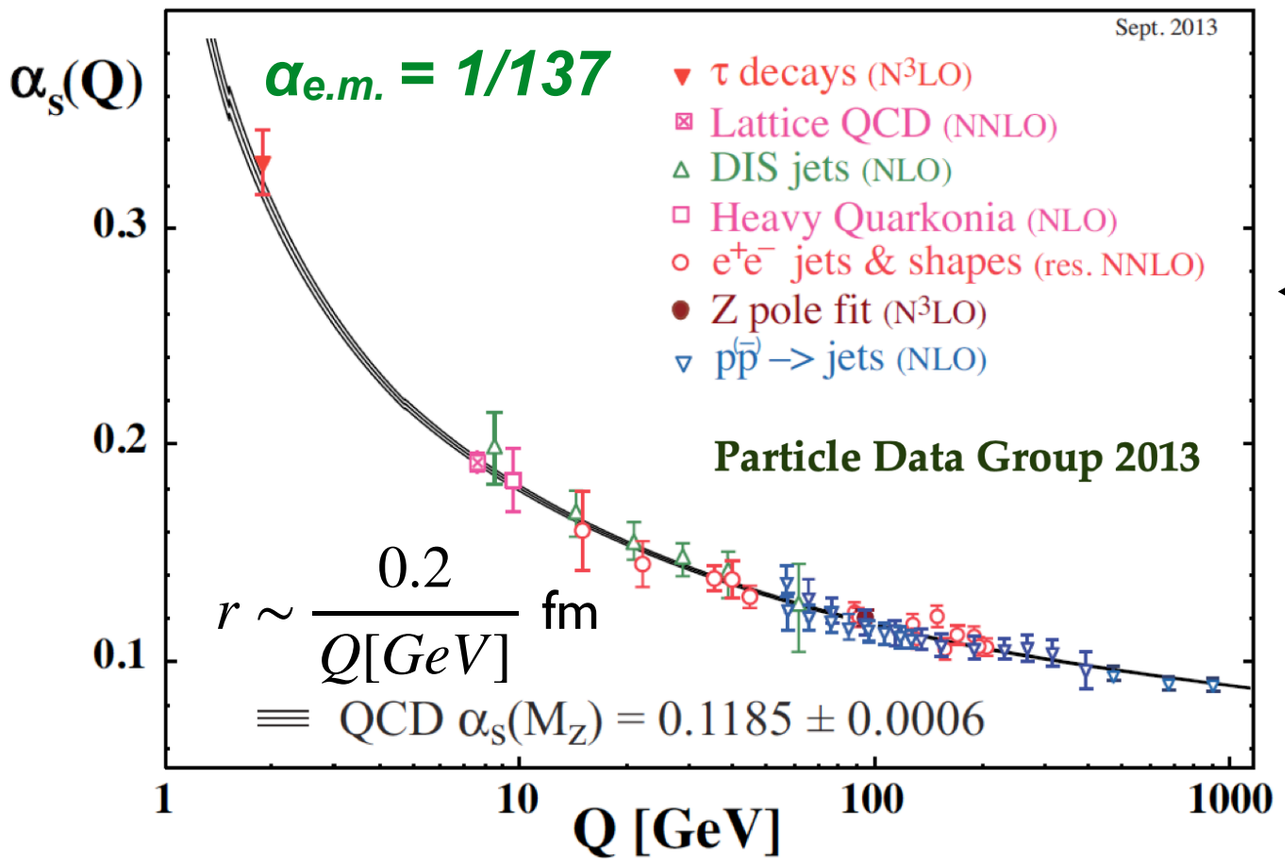


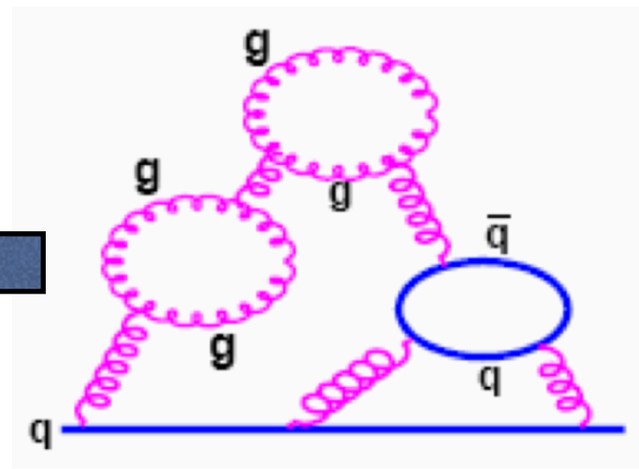
Quark confinement at large scale
but asymptotic freedom at below 1 fm

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

Problem to describe hadrons ab initio

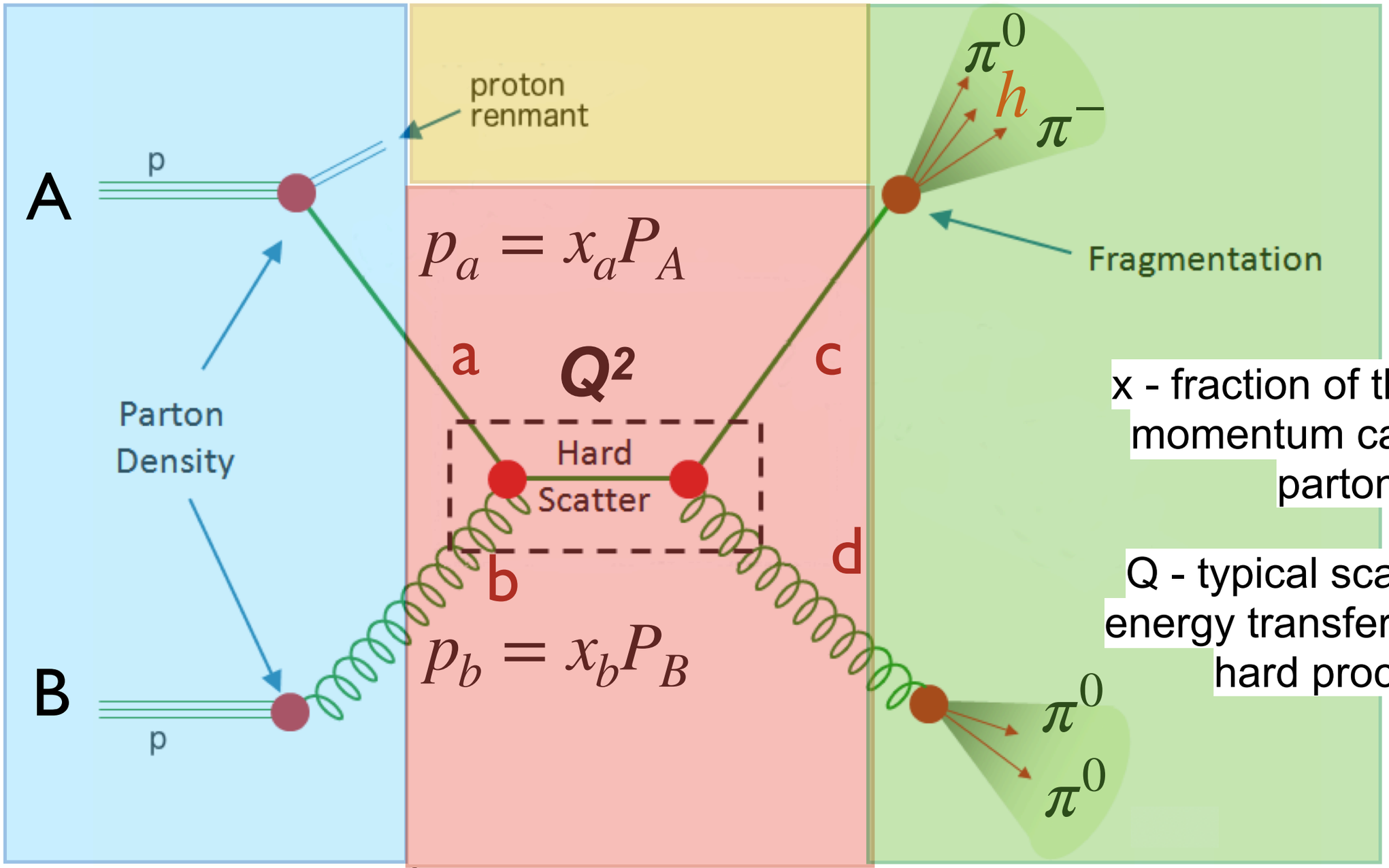
QCD is the true theory of the interaction between quarks and gluons. However, the possibilities to obtain quantitative predictions on its basis are **limited**.





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

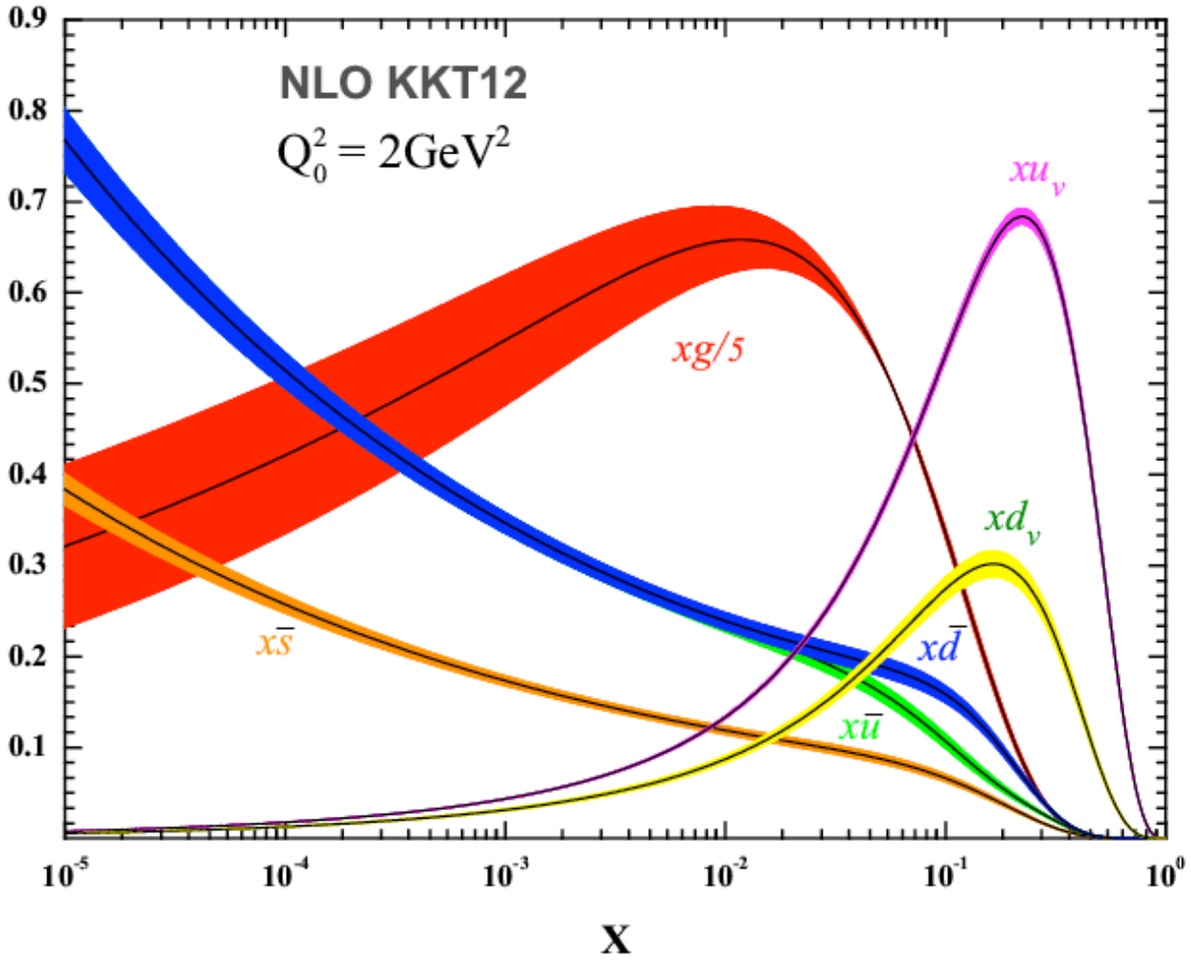
Q - typical scale of the energy transferred in the hard process

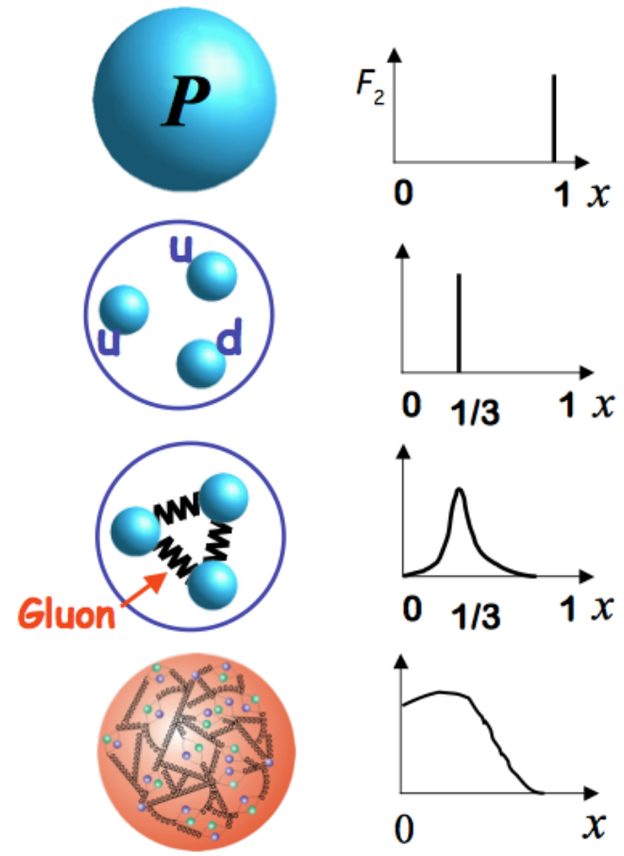
$$\sigma_{AB\to hX} = \sum_{a,b=q,\bar{q},g} \int dx_a dx_b f(x_a, Q^2) f(x_b, Q^2) \times \hat{\sigma}_{ab\to cd}(x_a, x_b, Q^2) \times D_{cd\to h}$$

$Q^2 >> 1\ GeV^2/c^2$

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

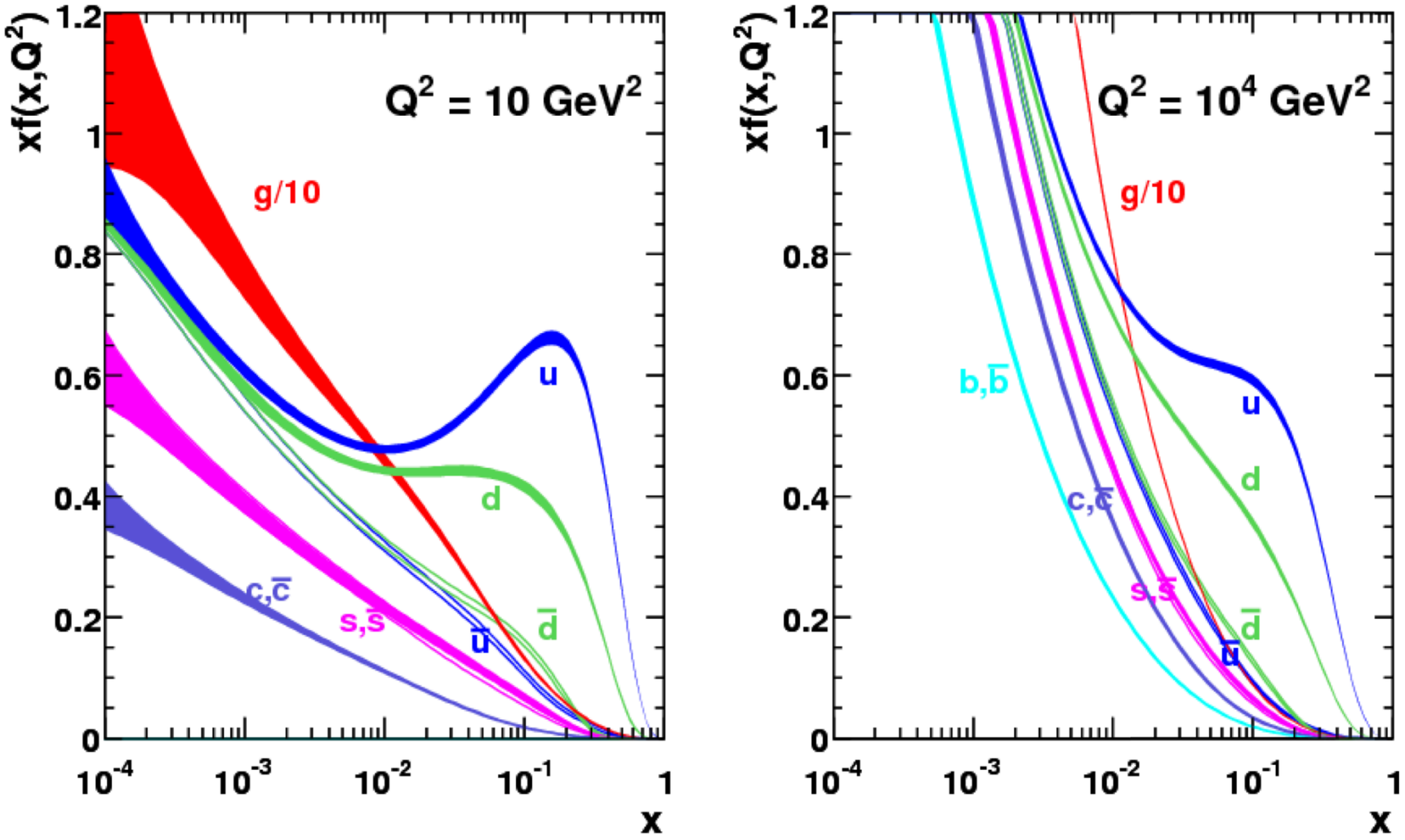




PDFs are universal, they are independent on the hard process

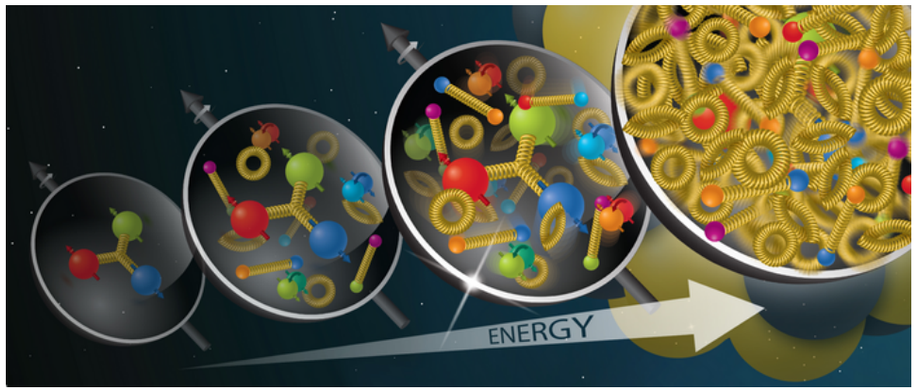
PDFs cannot be calculated in QCD from the first principles!

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



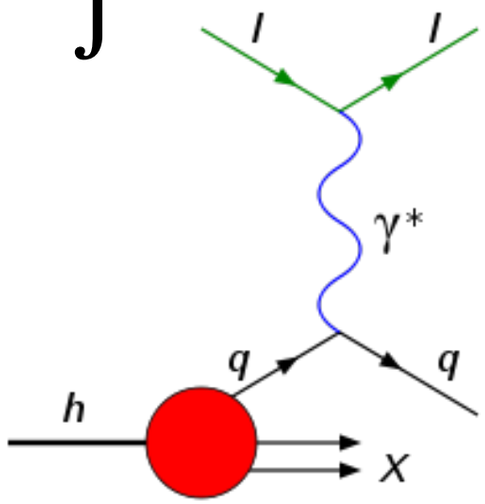
$$g = 1 - 0.546 = 0.454$$

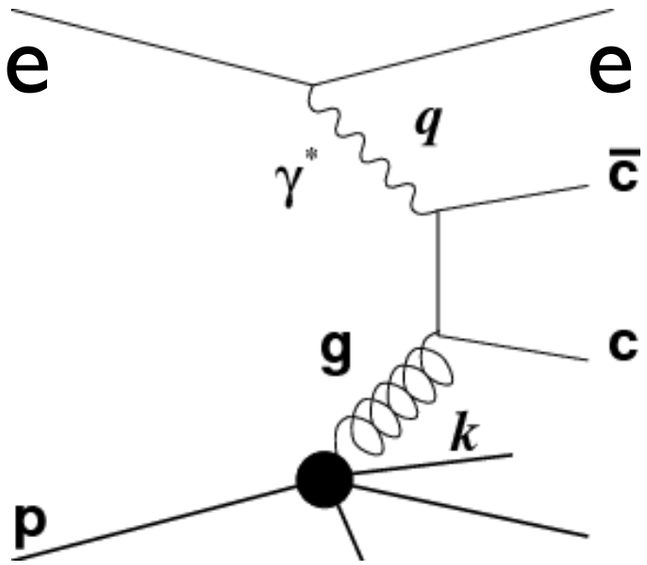
Sea partons becomes more important at high Q^2

How to access PDFs ?

Deep Inelastic Scattering

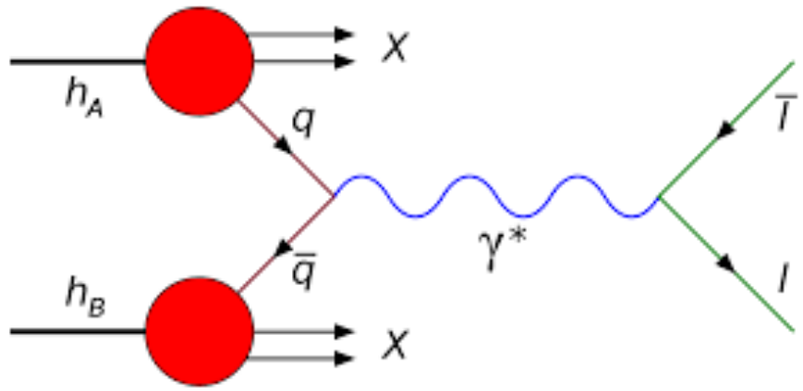
$$\sigma = \int \hat{\sigma} q(x) dx$$

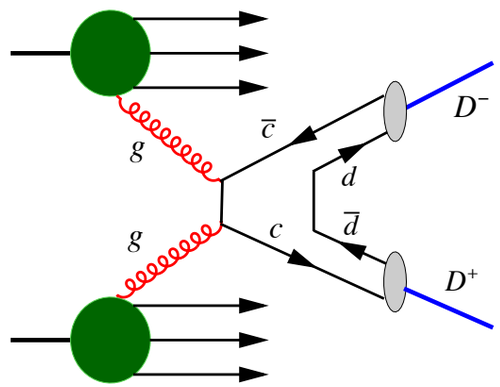




Hadronic interactions

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



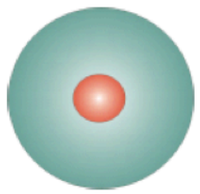


CTEQ Collaboration
JAM Collaboration
DSSV Collaboration
NNPDF Collaboration

…

Polarized proton

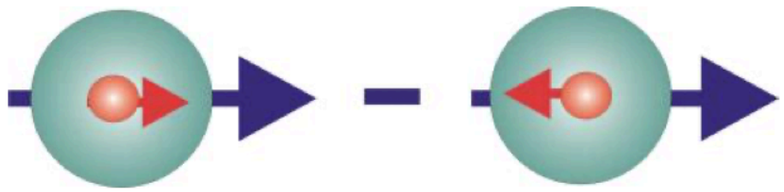
$f(x)$



Unpolarized PDF

unpolarized DIS

$\Delta f(x)$

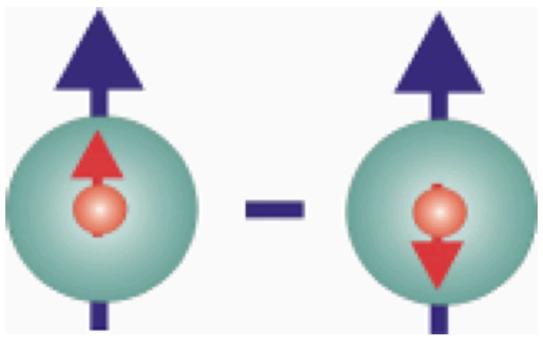


Helicity

polarized DIS

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

$\Delta_T f(x)$



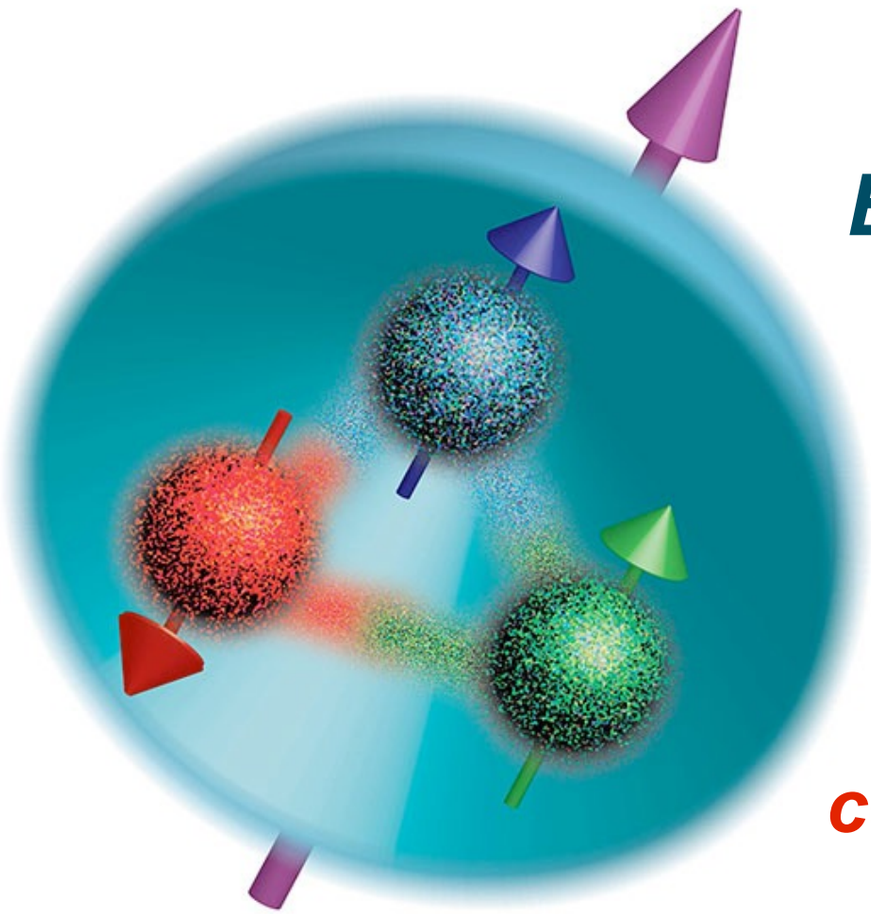
Transversity

polarized SIDIS

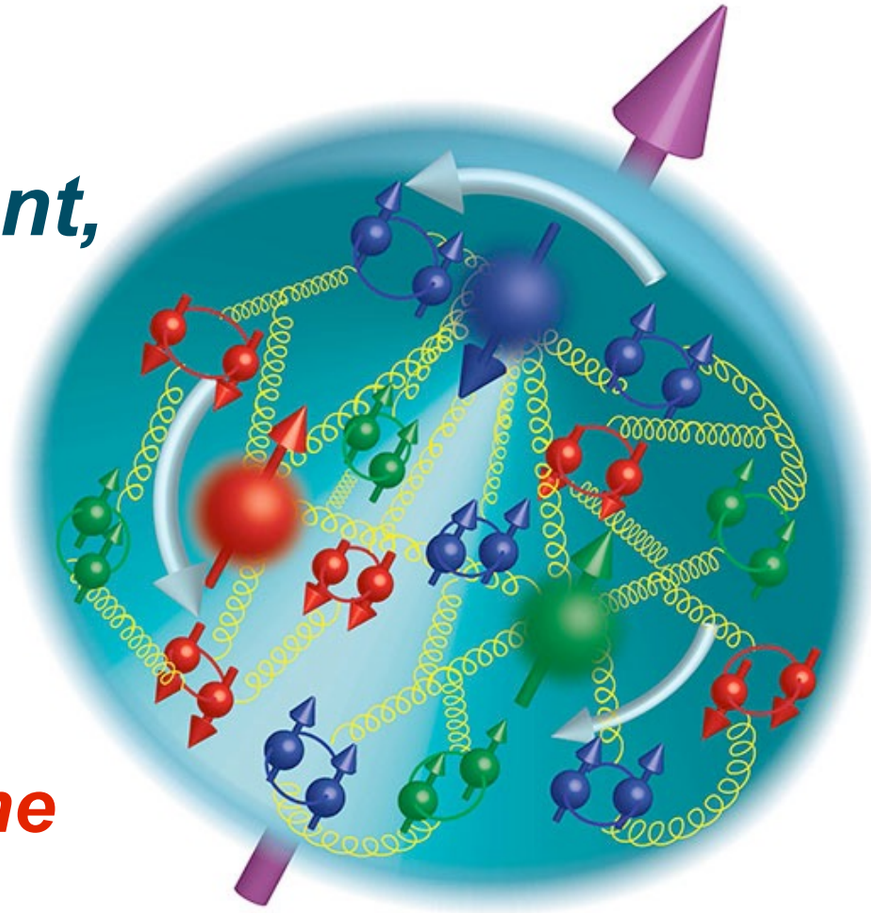
Azimuthal asymmetryes A_N

P

Spin crisis



EMC experiment, CERN 1988



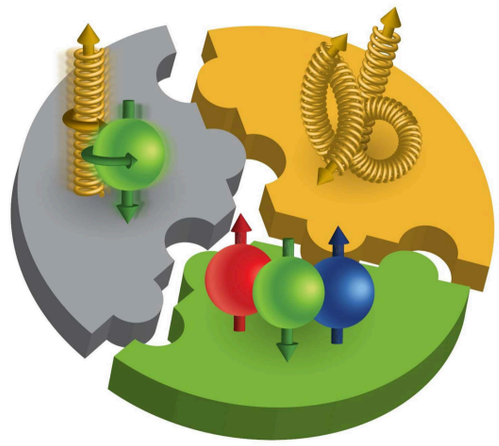
Quark contribution to the proton spin is below 30%!

Naive quark model

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

Real situation

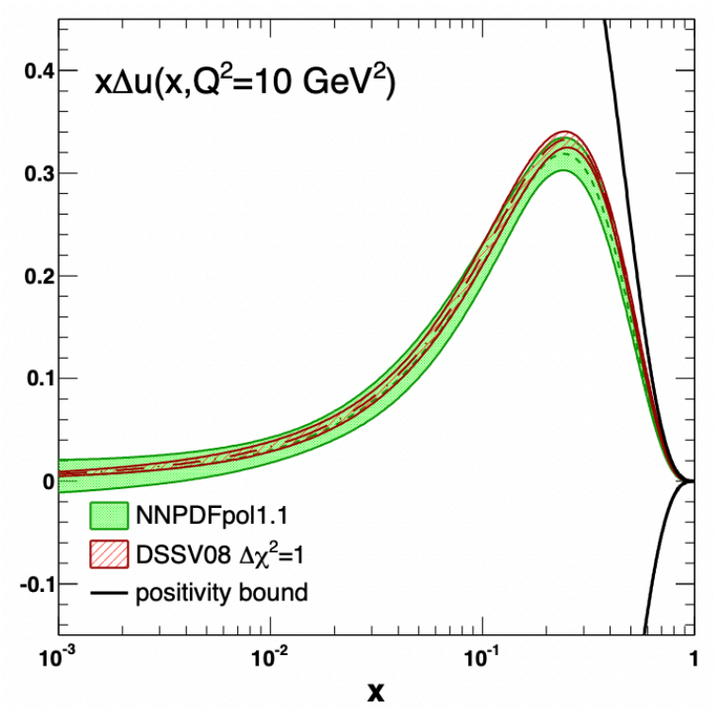
L - orbital moments of quarks and gluons

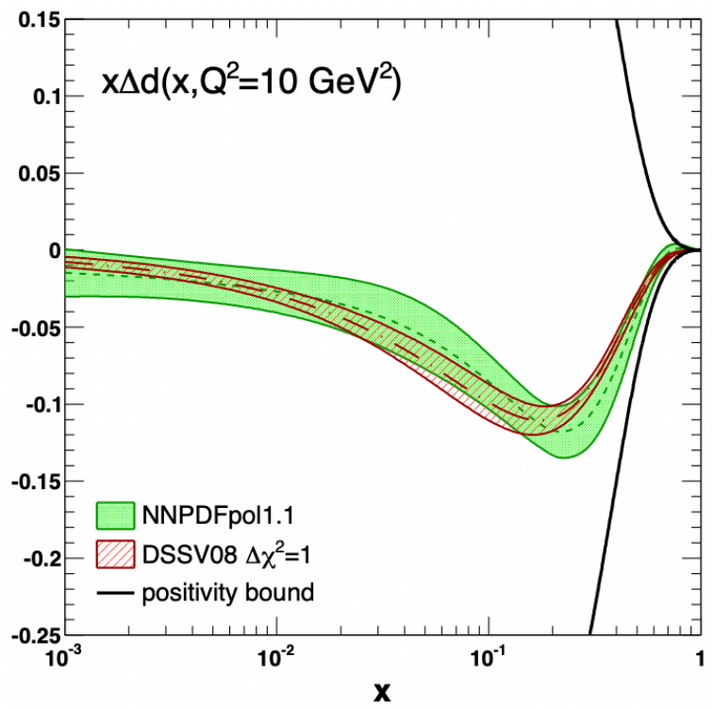


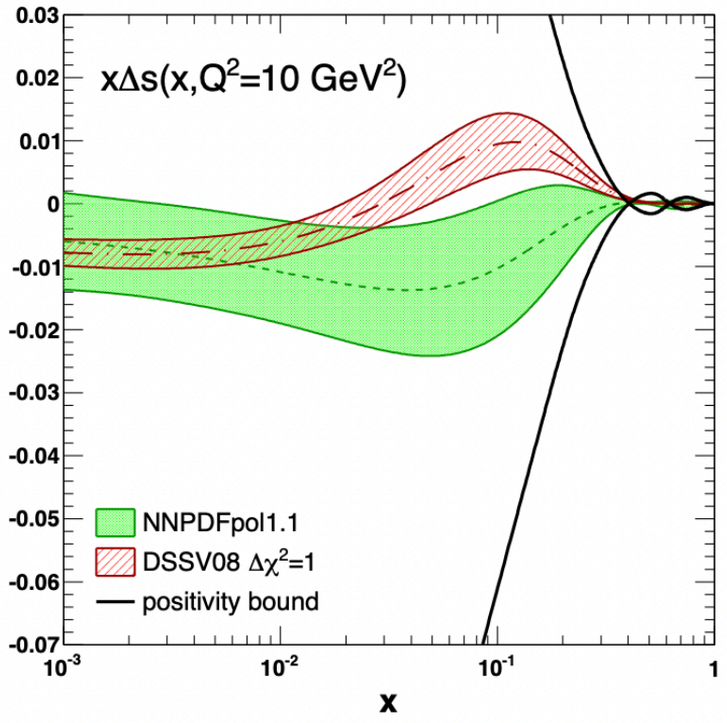
$$S_N = ½ = ½\,\Delta\Sigma + \Delta G + L$$

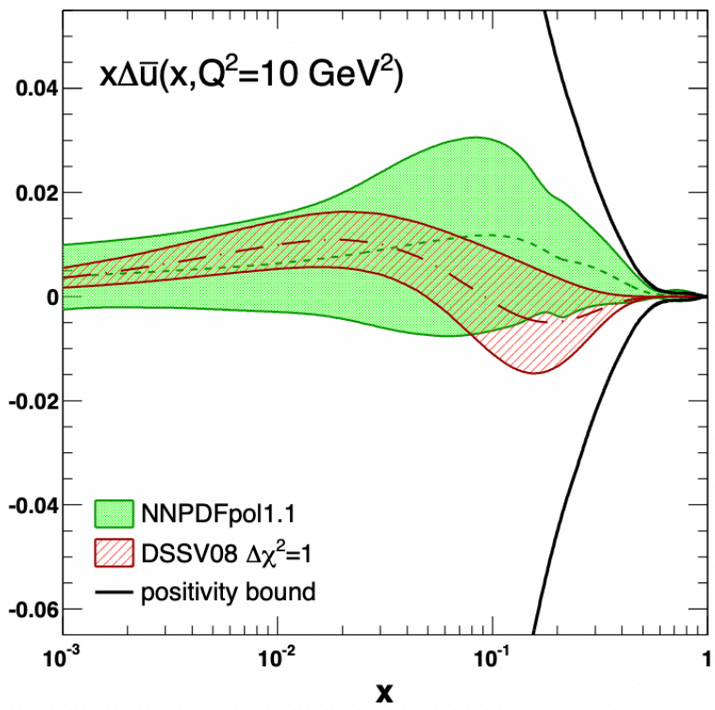
Spin crisis: quarks

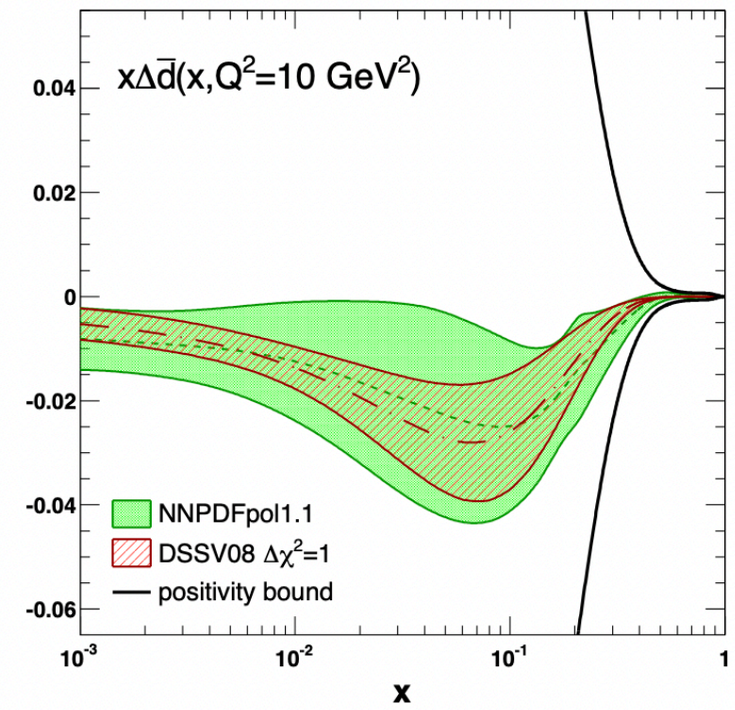
Longitudinal polarization of quarks:









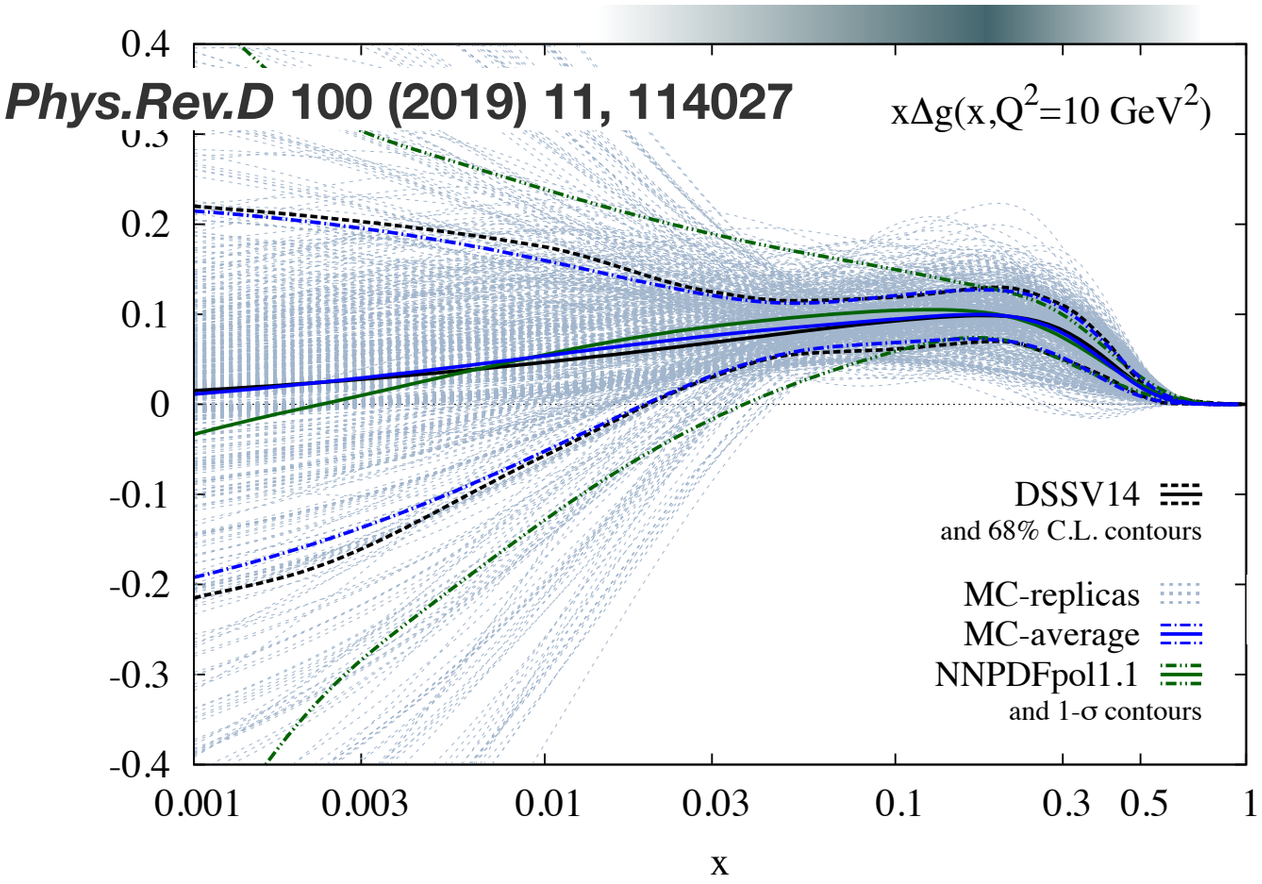


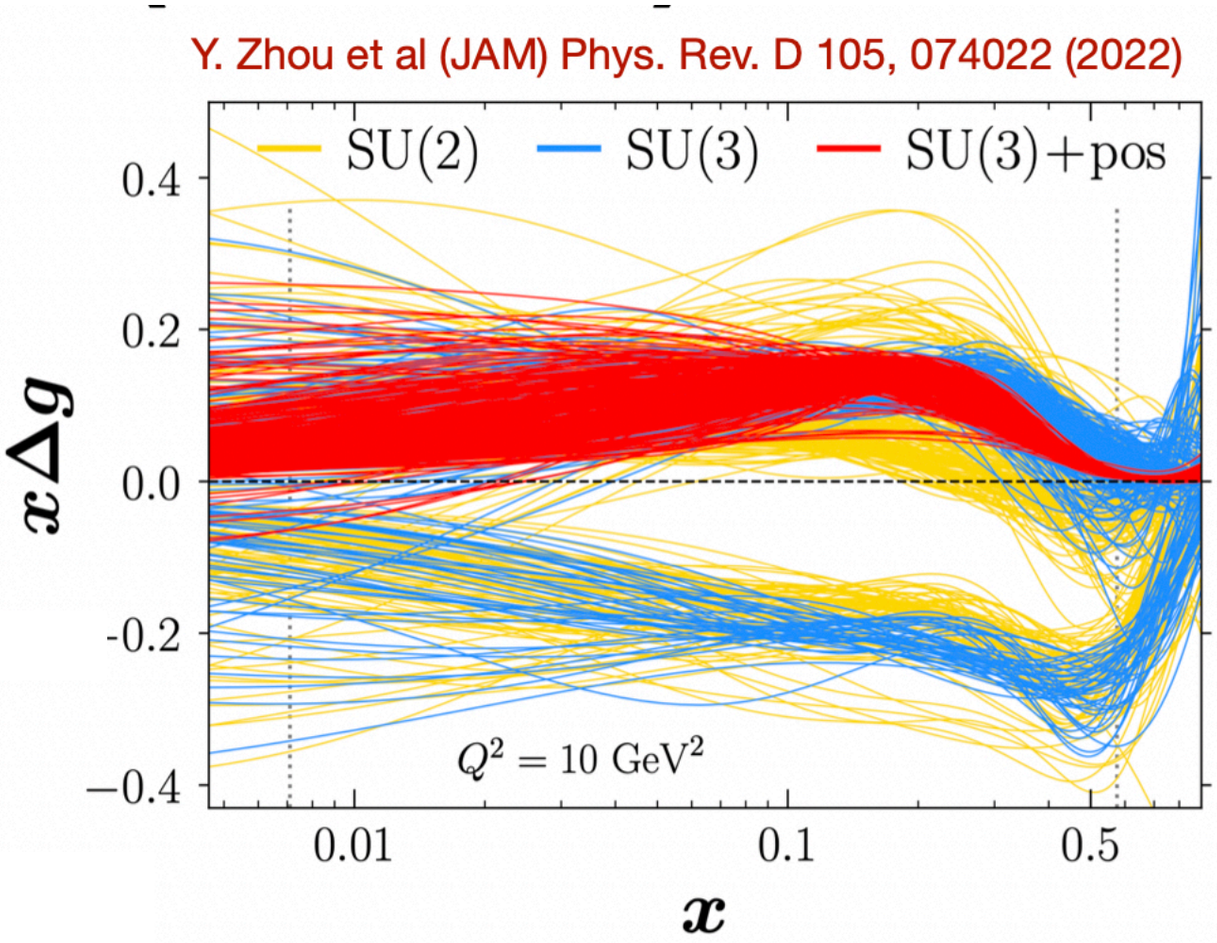
$S_N = ½ = ½\,\Delta\Sigma + \Delta G + L$

~30%

Spin crisis: gluons

accessible with SPD





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

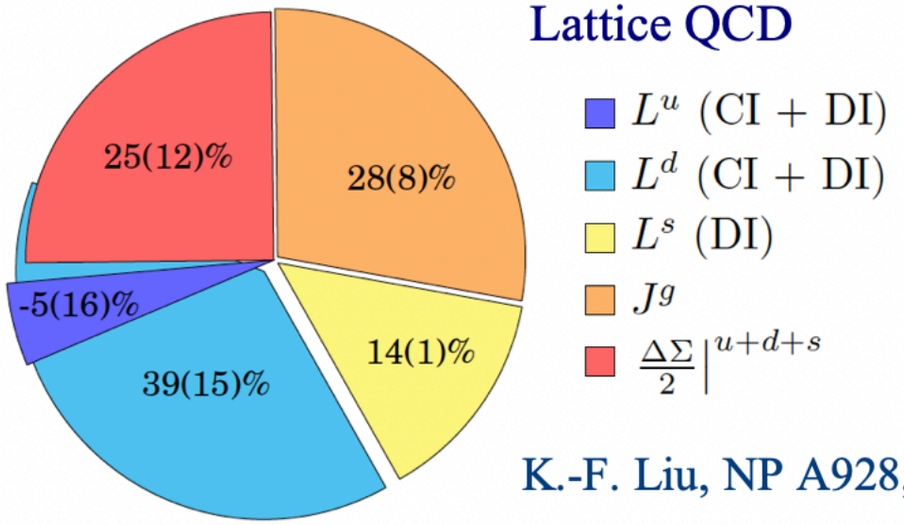
Positivity removed from JAM helicity gluon PDF

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

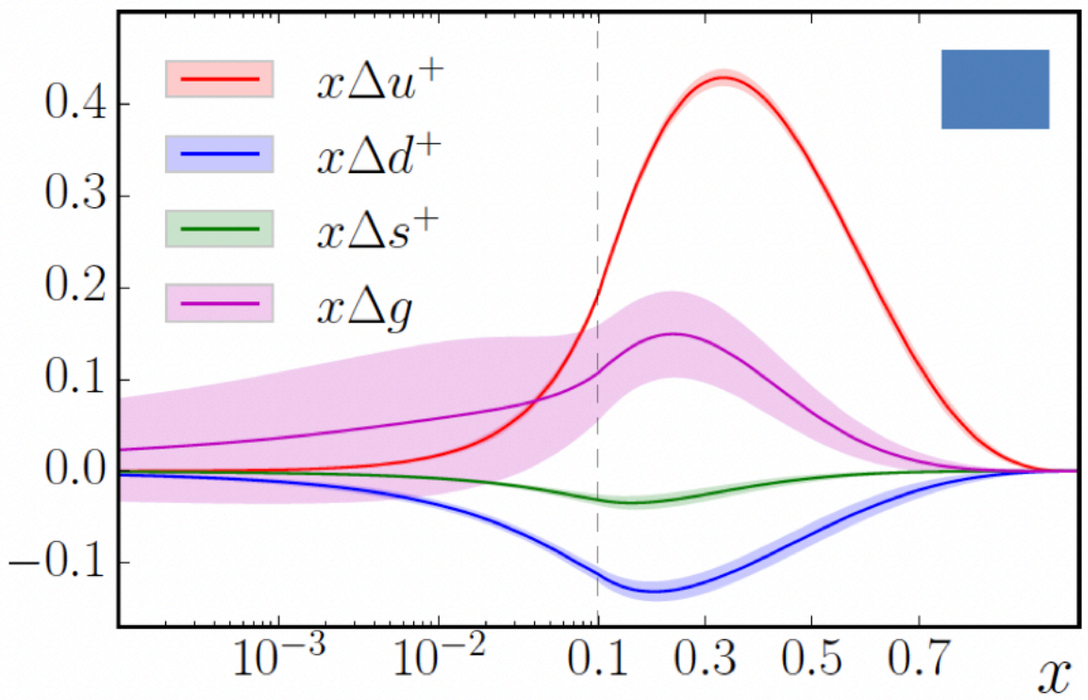
Spin balance

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

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



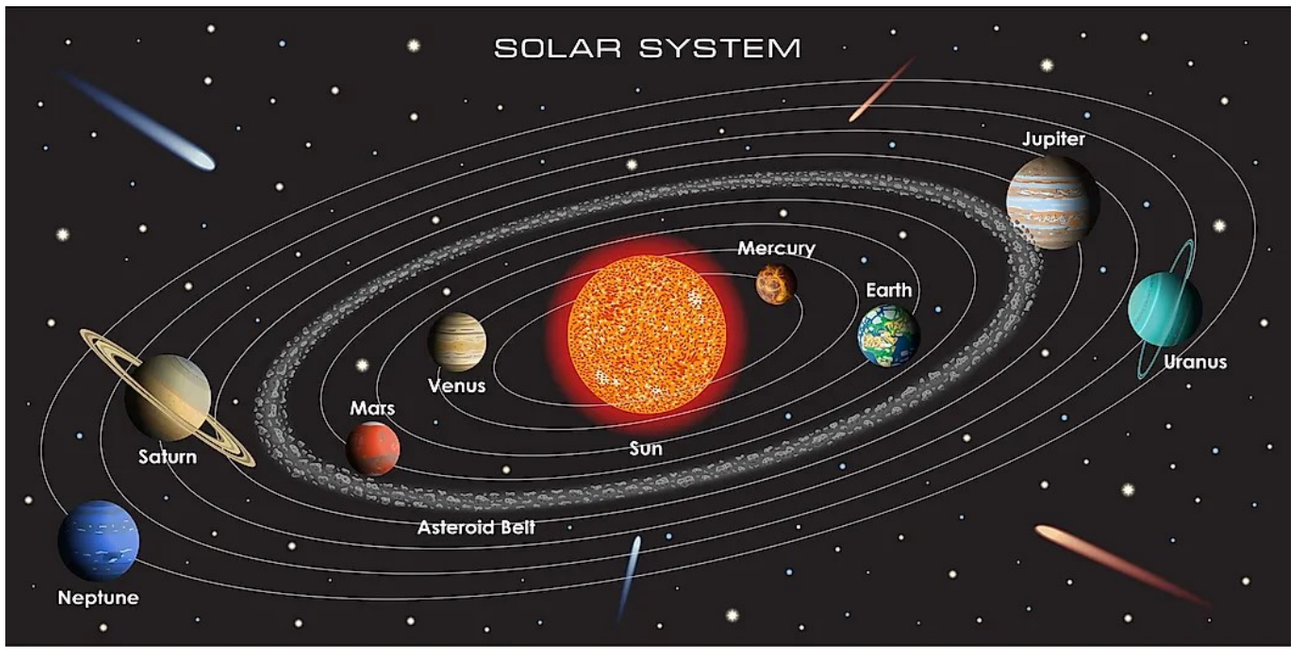
K.-F. Liu, NP A928, 99 (2014).



JAM Collaboration, PRD (2016).

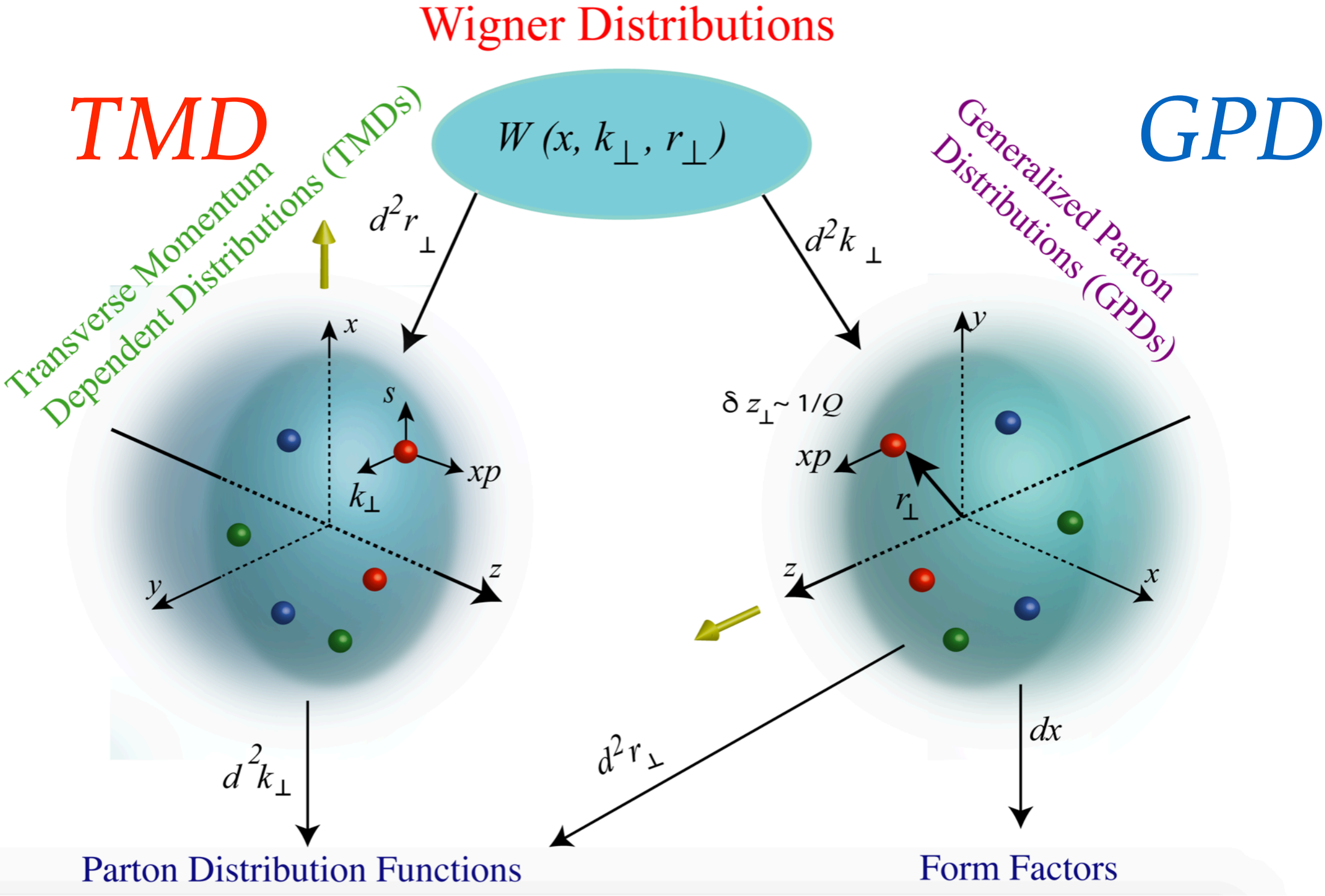
To access angular momenta info about 3D structure is needed!

For Solar System

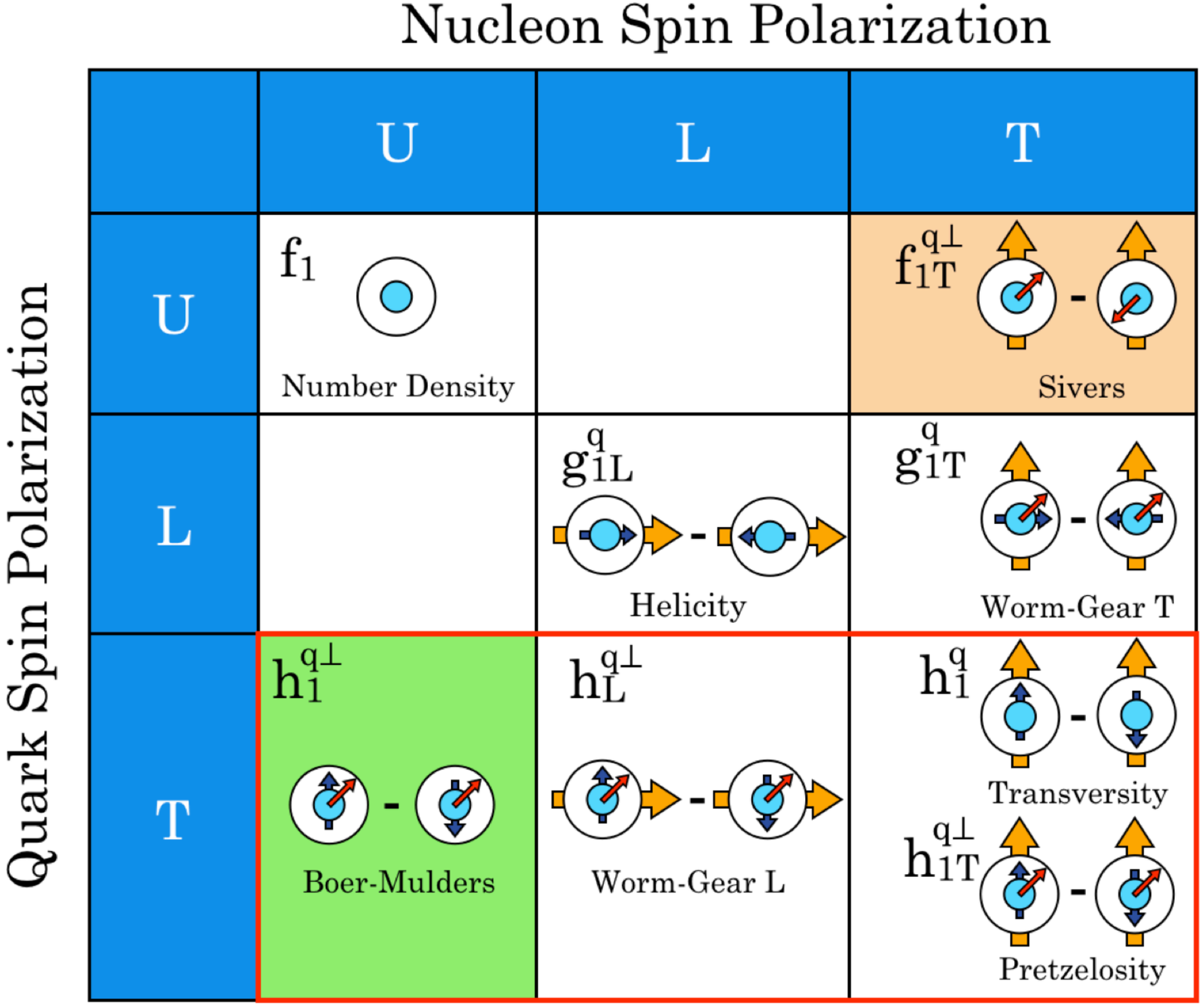


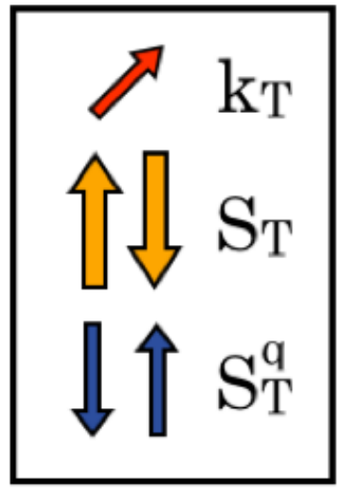
98% is angular moment!

3D-tomography of proton



TMD PDFs

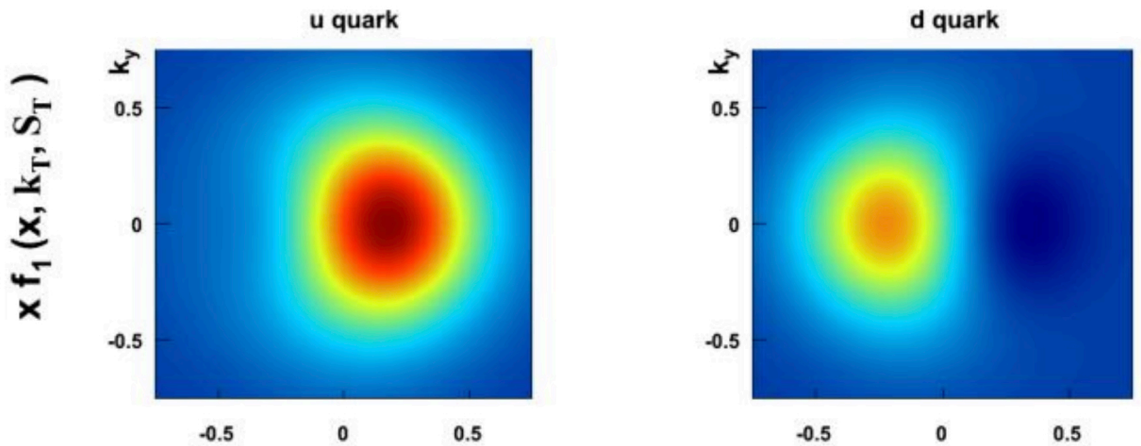




5 additional (TMD) functions describing the correlation between the nucleon spin, parton spin, and parton transverse momentum.

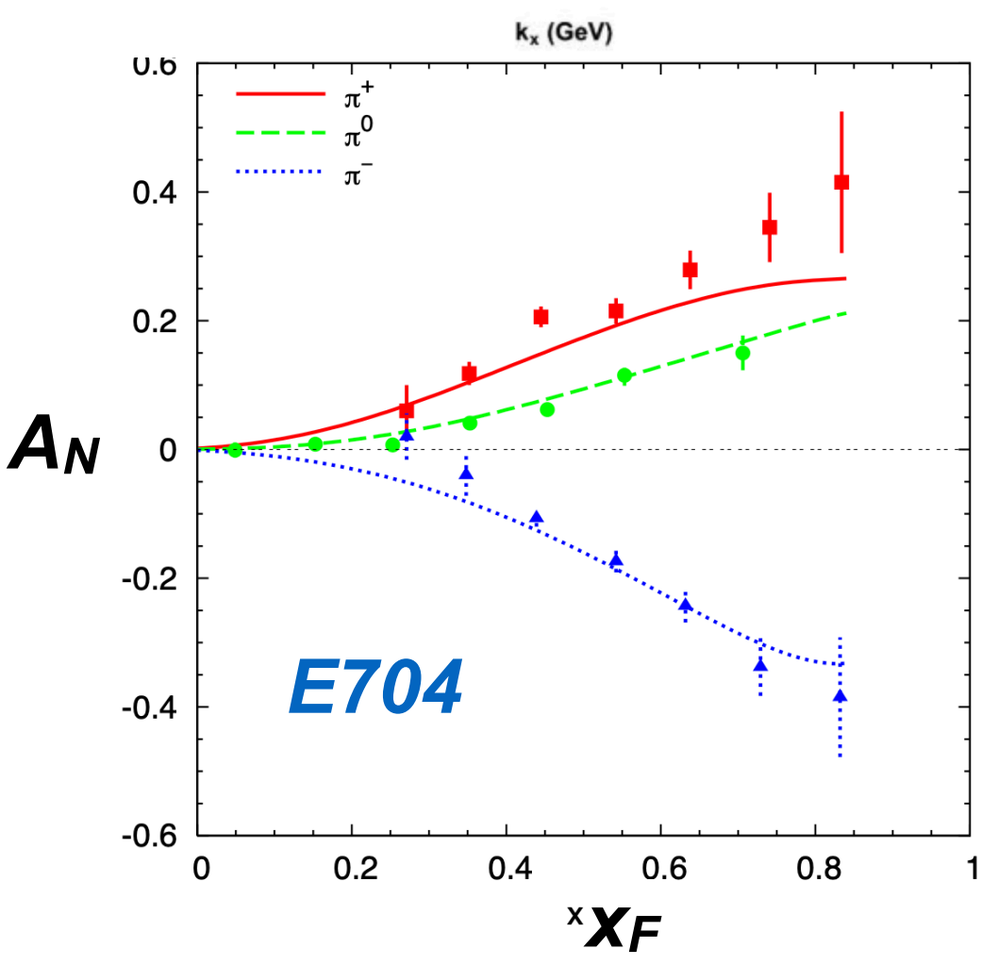
TMD effects: Sivers effect

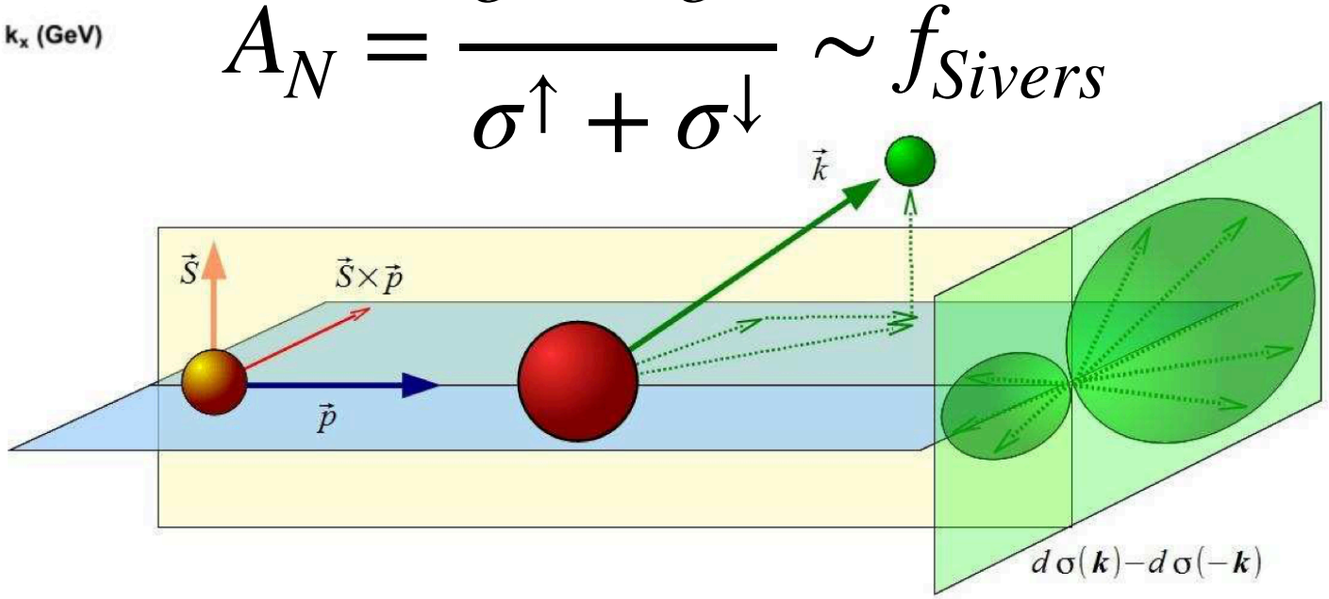
Probabilities to meet in a transversely polarized proton a parton moving to the left and to the right with respect to the $(\vec{S}, \vec{p})$ plane are different!



x=0.1

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

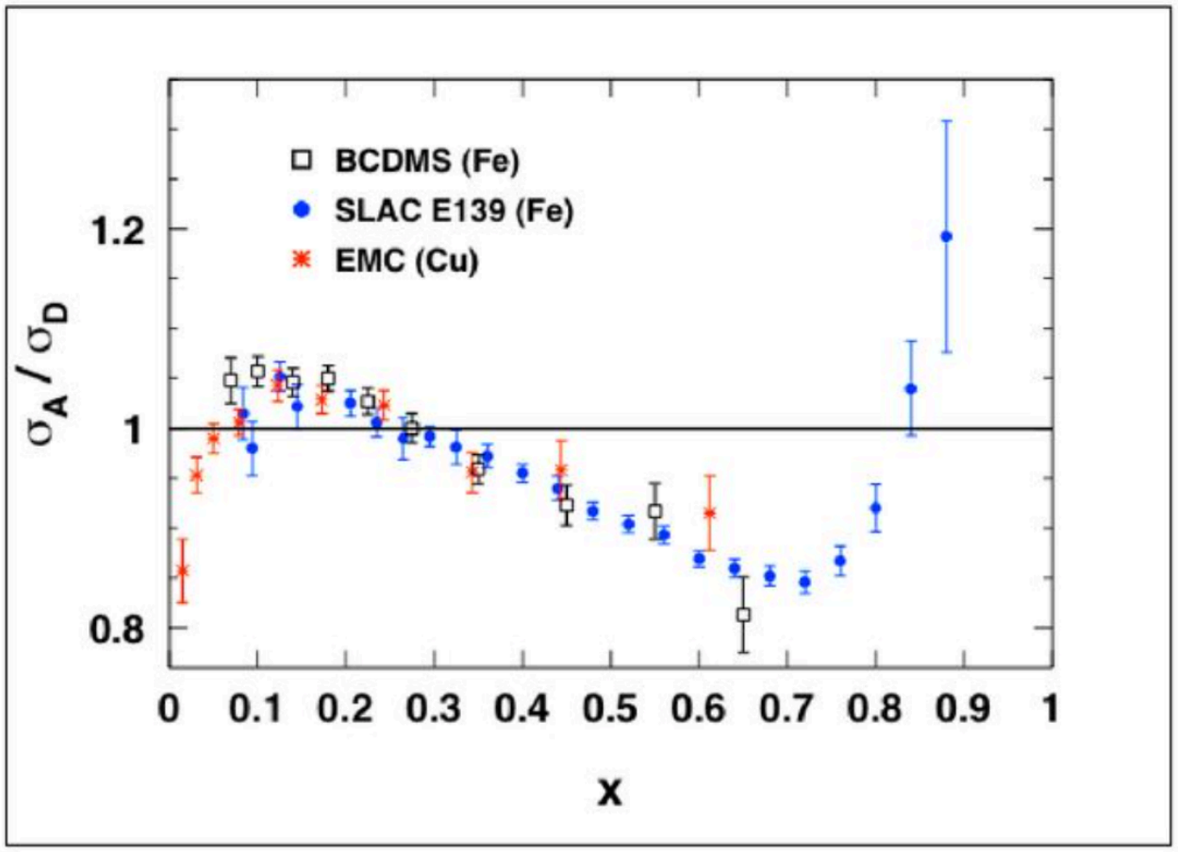




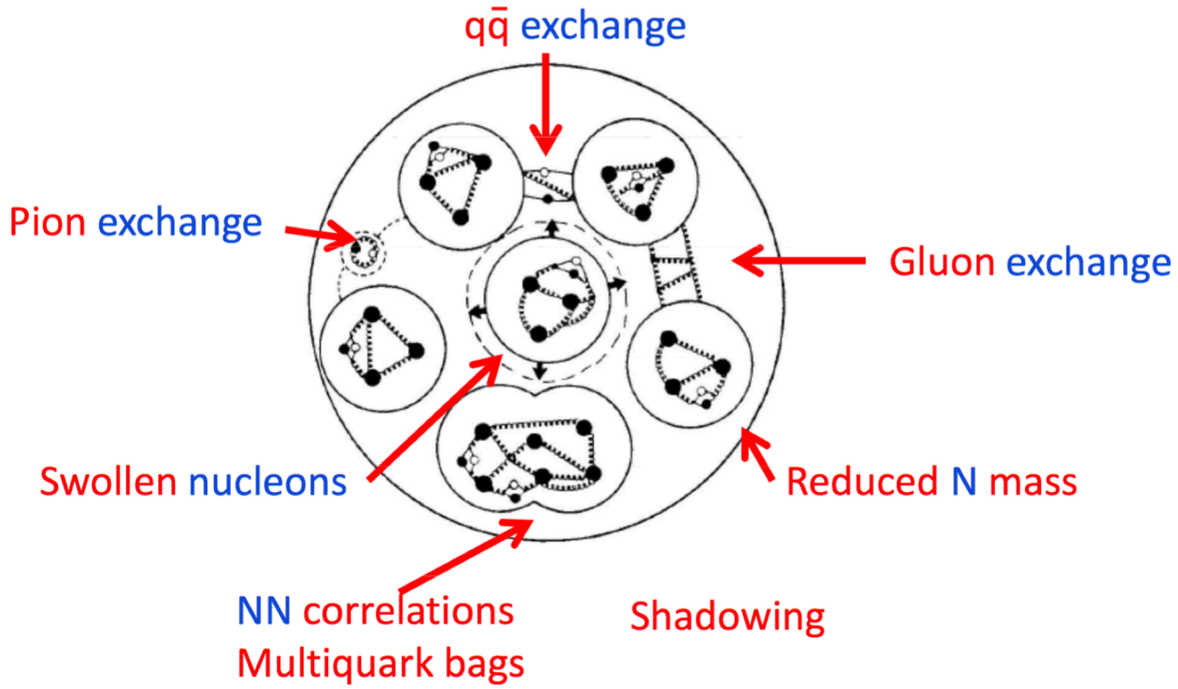
The Sievers effect is usually observed together with the Collins effect, an asymmetry arising from the fragmentation of the final state.

EMC-effect

EMC collaboration, 1982



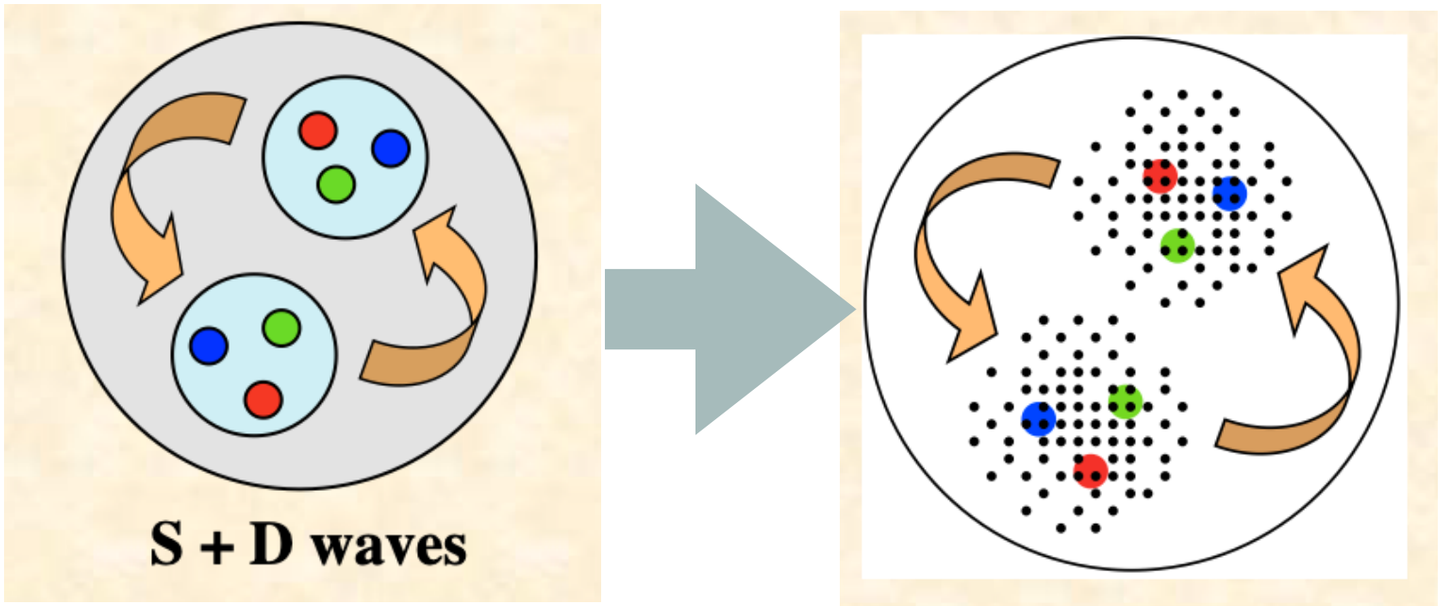
The nucleon "knows" which nucleus it is in!



Open questions:

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

Deuteron

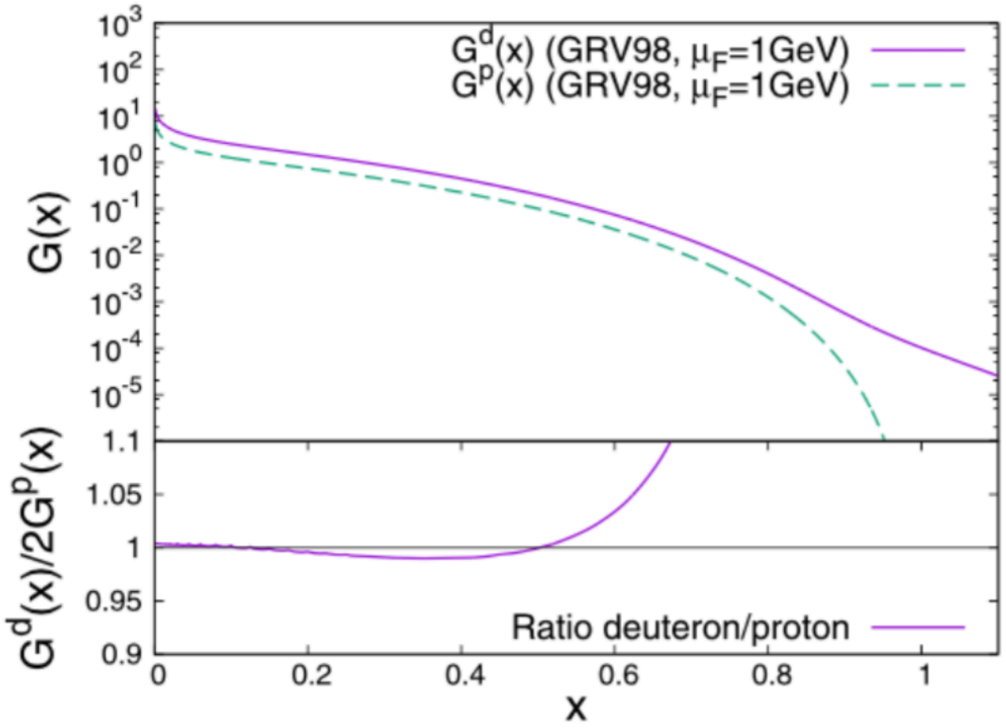


Deuteron is not just proton + neutron!

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

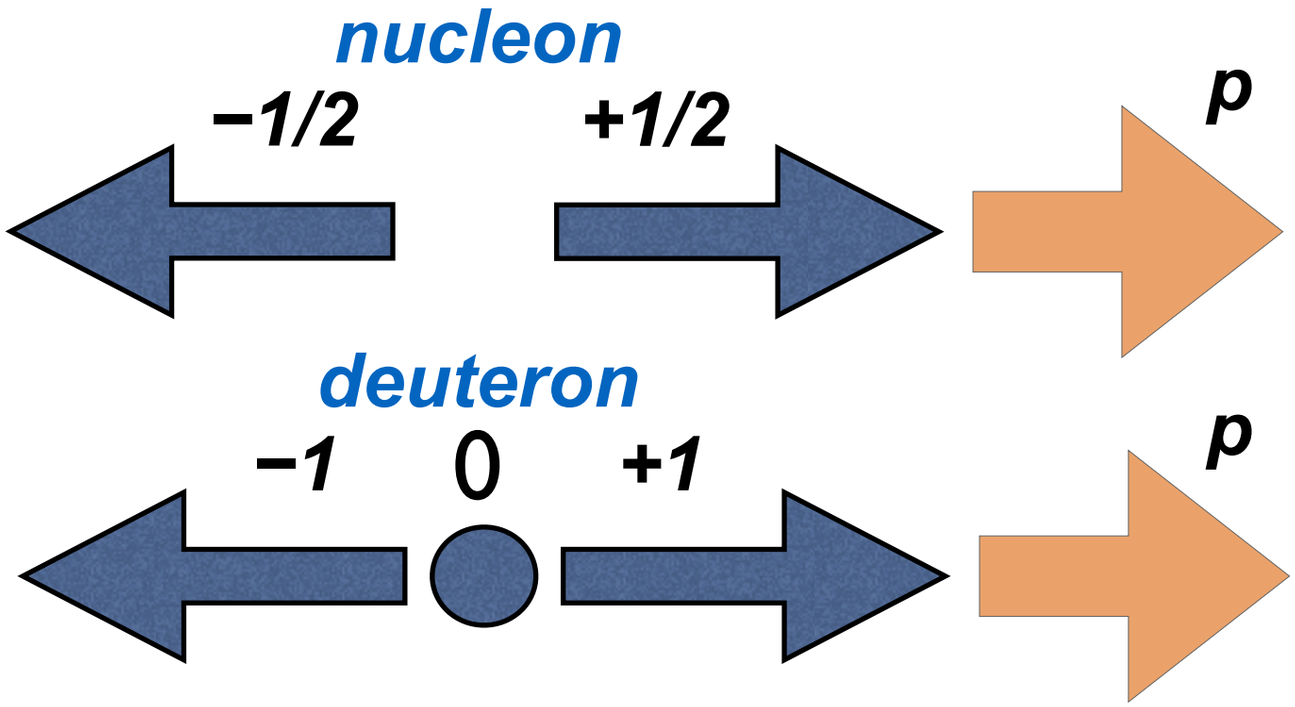
hidden color

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



More gluons at large x with respect to nucleon?

Deuteron as spin-1 particle



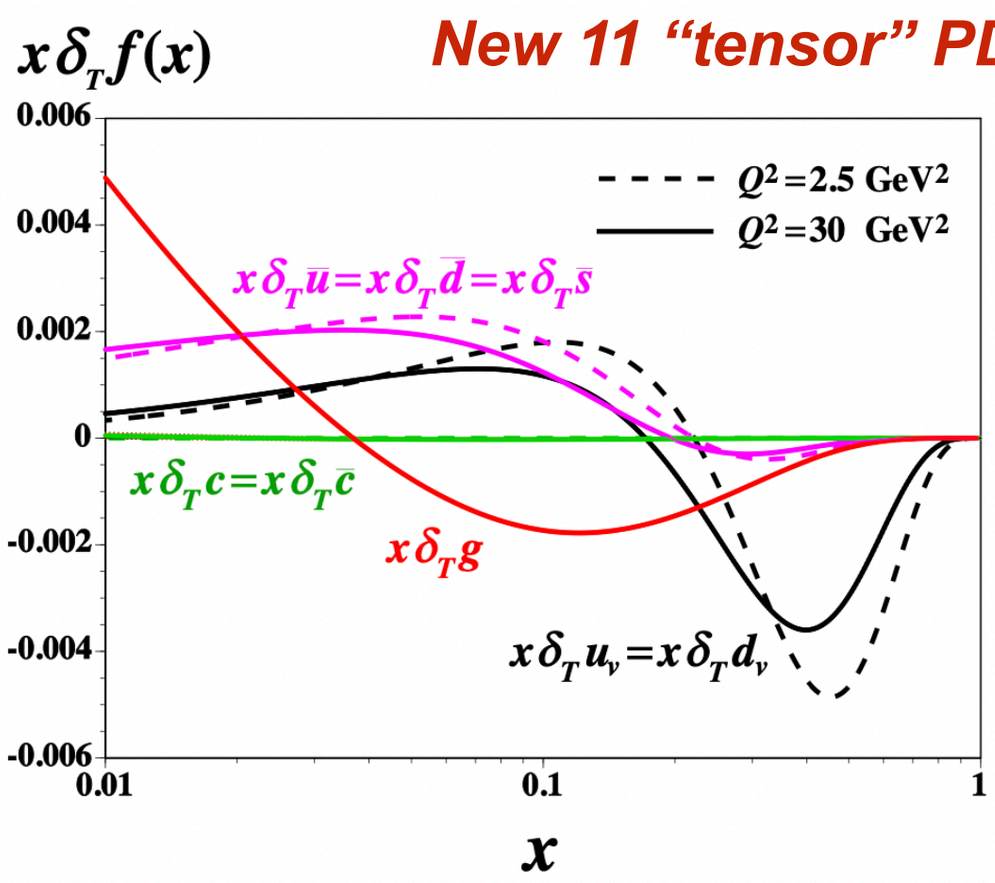
Vector polarization

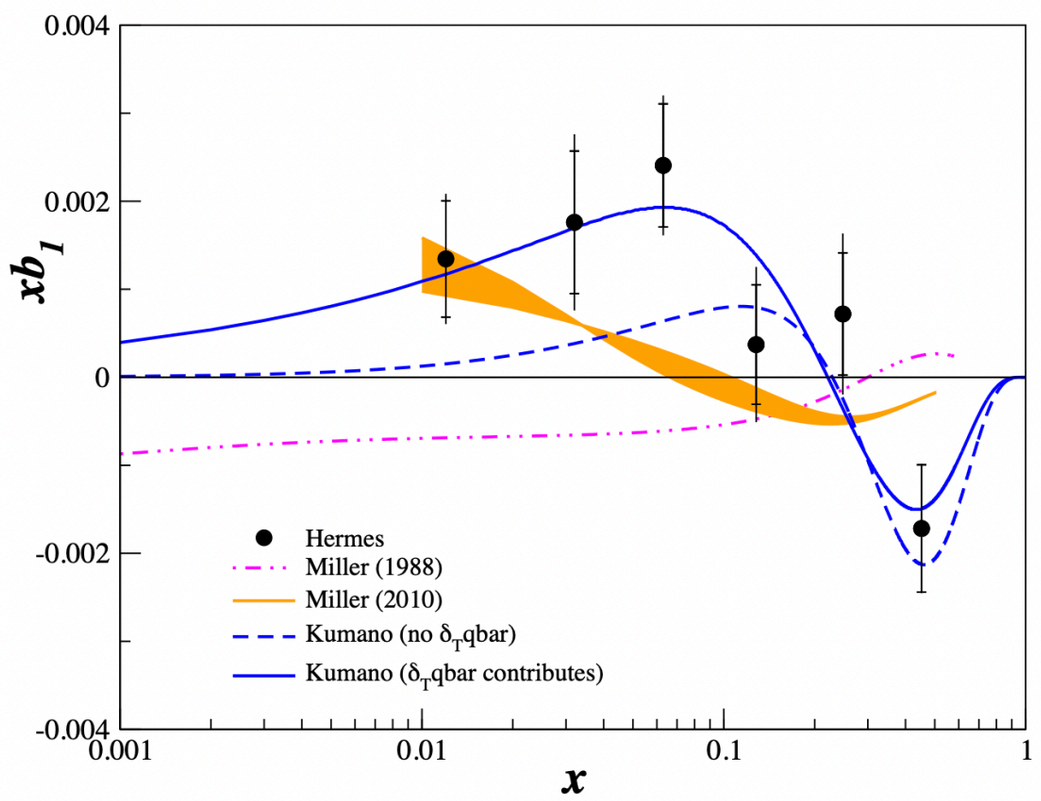
$$\frac{N_{1/2} - N_{-1/2}}{N_{1/2} + N_{-1/2}}$$

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

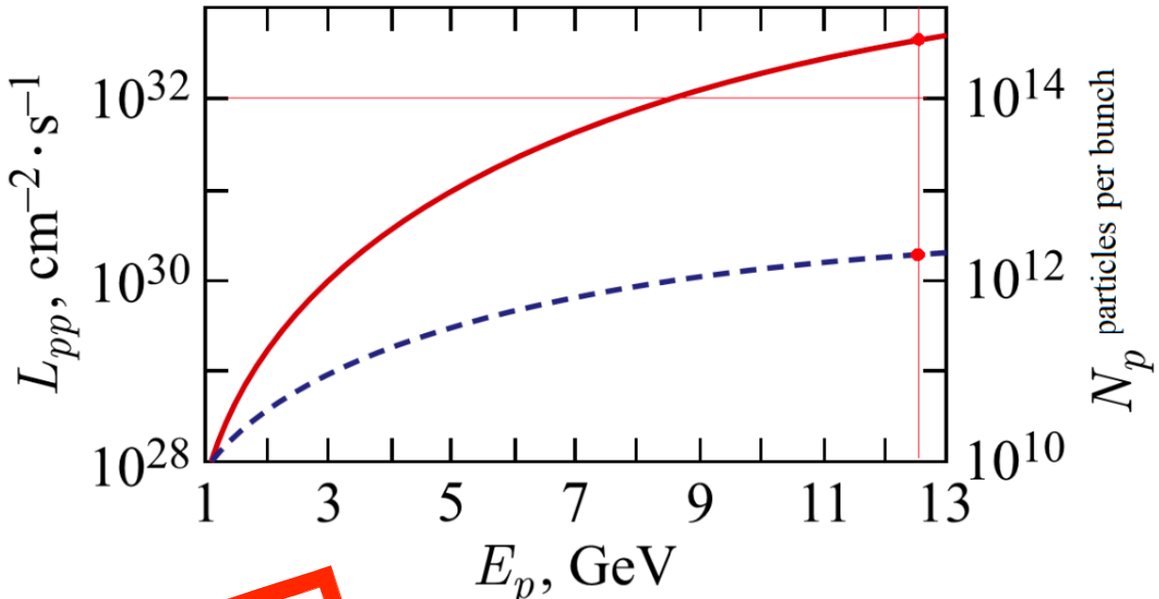
NICA - Nuclotron-based Ion Collider fAcility

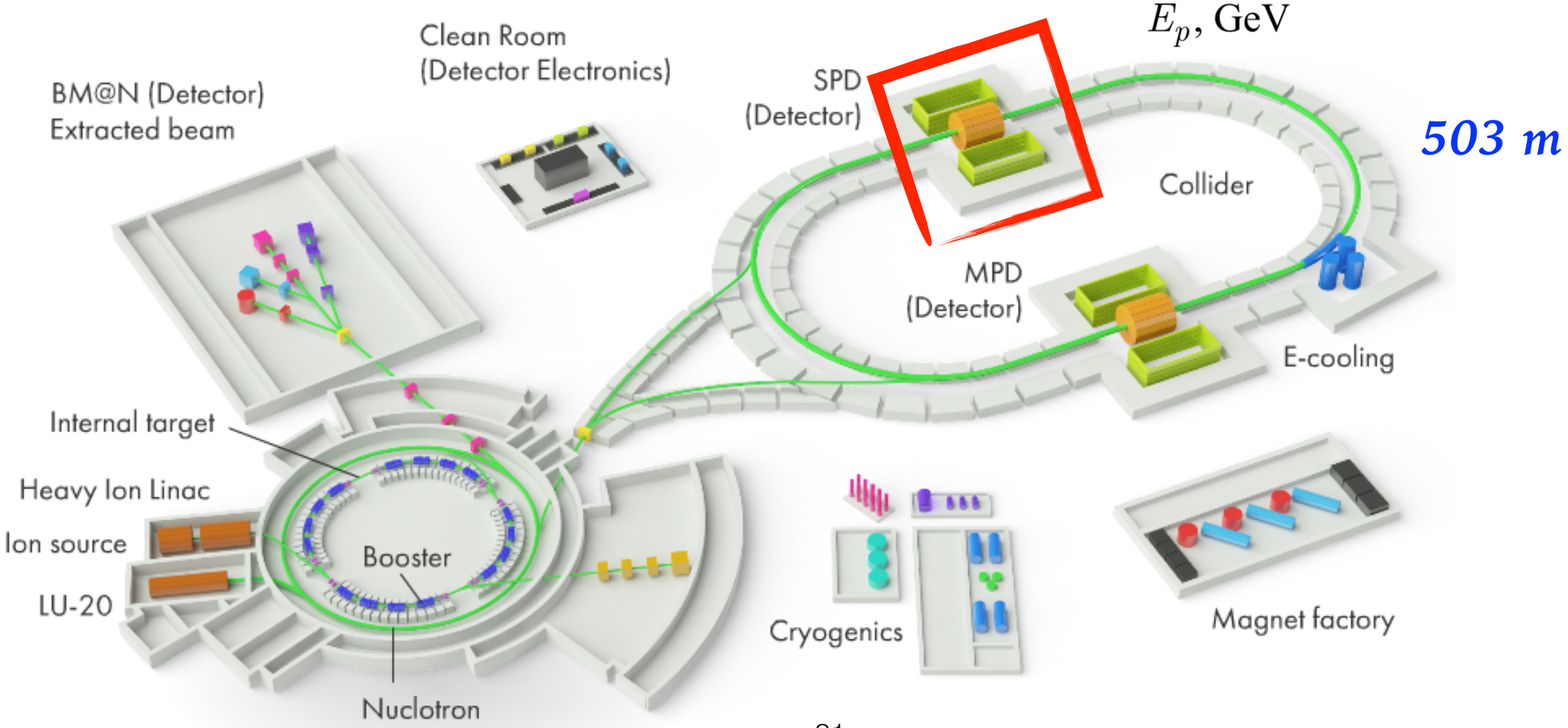
$p^{\uparrow}p^{\uparrow} : \sqrt{s} \leq 27\ GeV$

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

U, L, T

$|P| > 70\%$

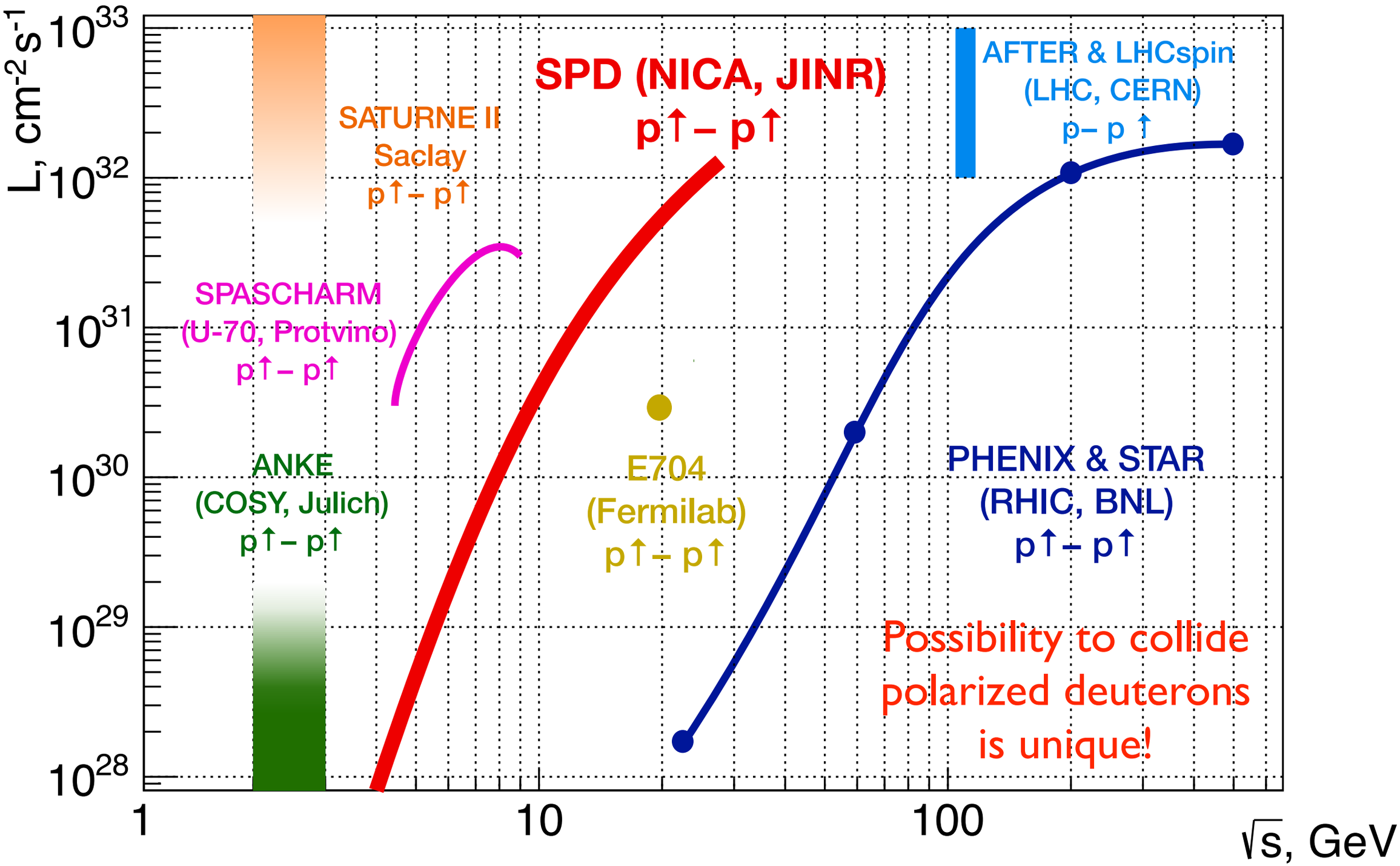




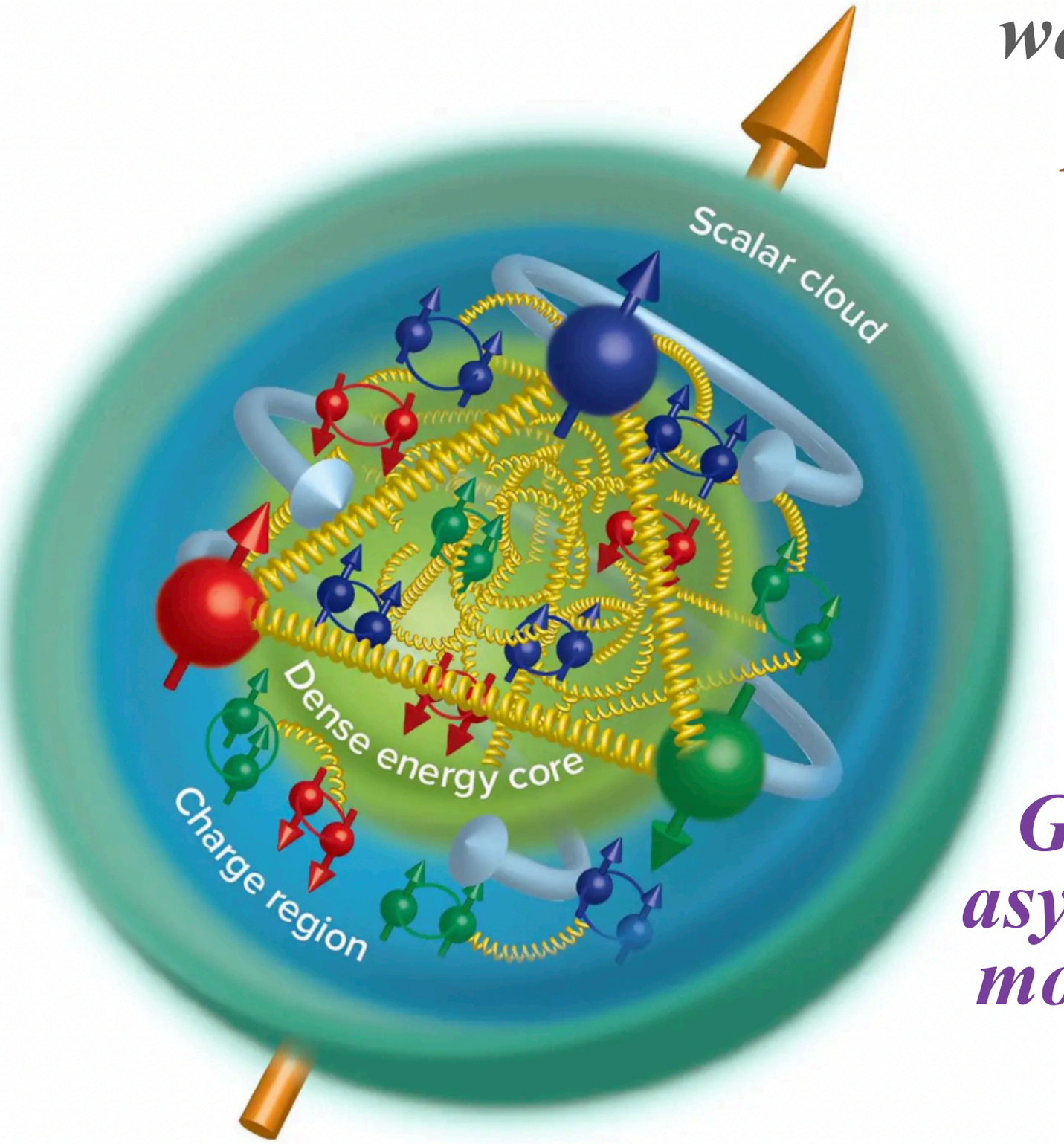
503 m

NICA complex

SPD and others



Spin Physics @ NICA



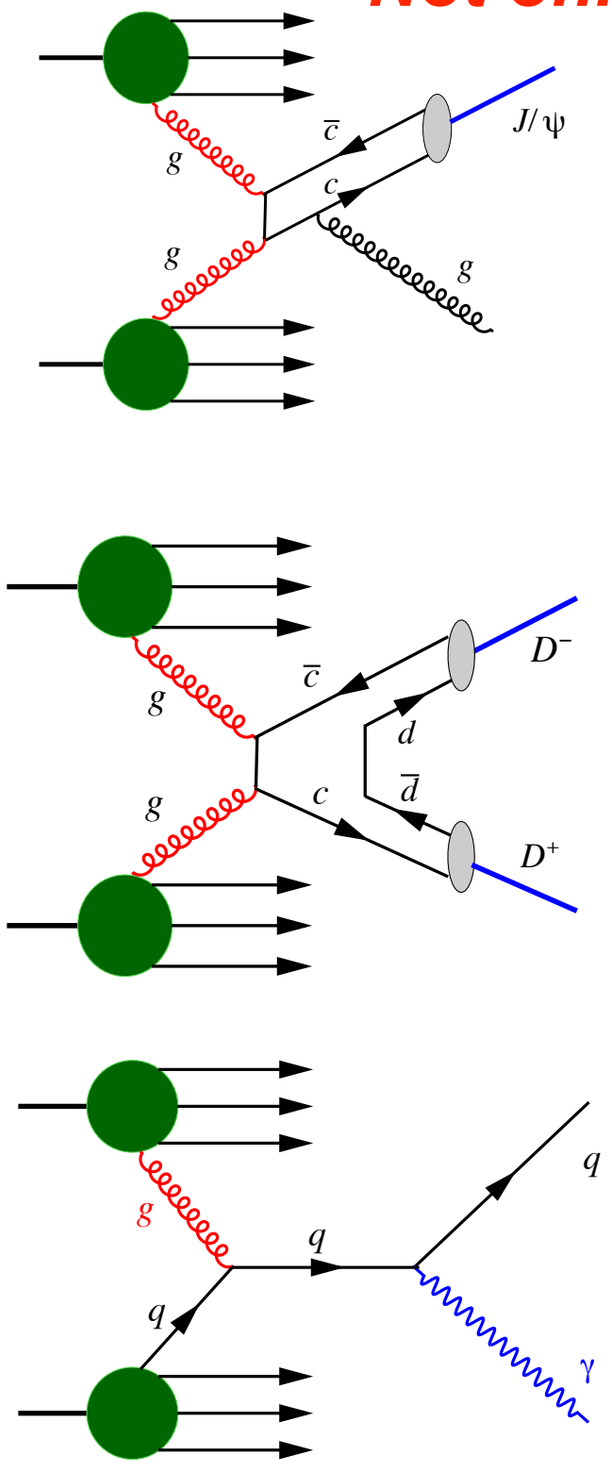
we plan to study how the proton and deuteron spin!

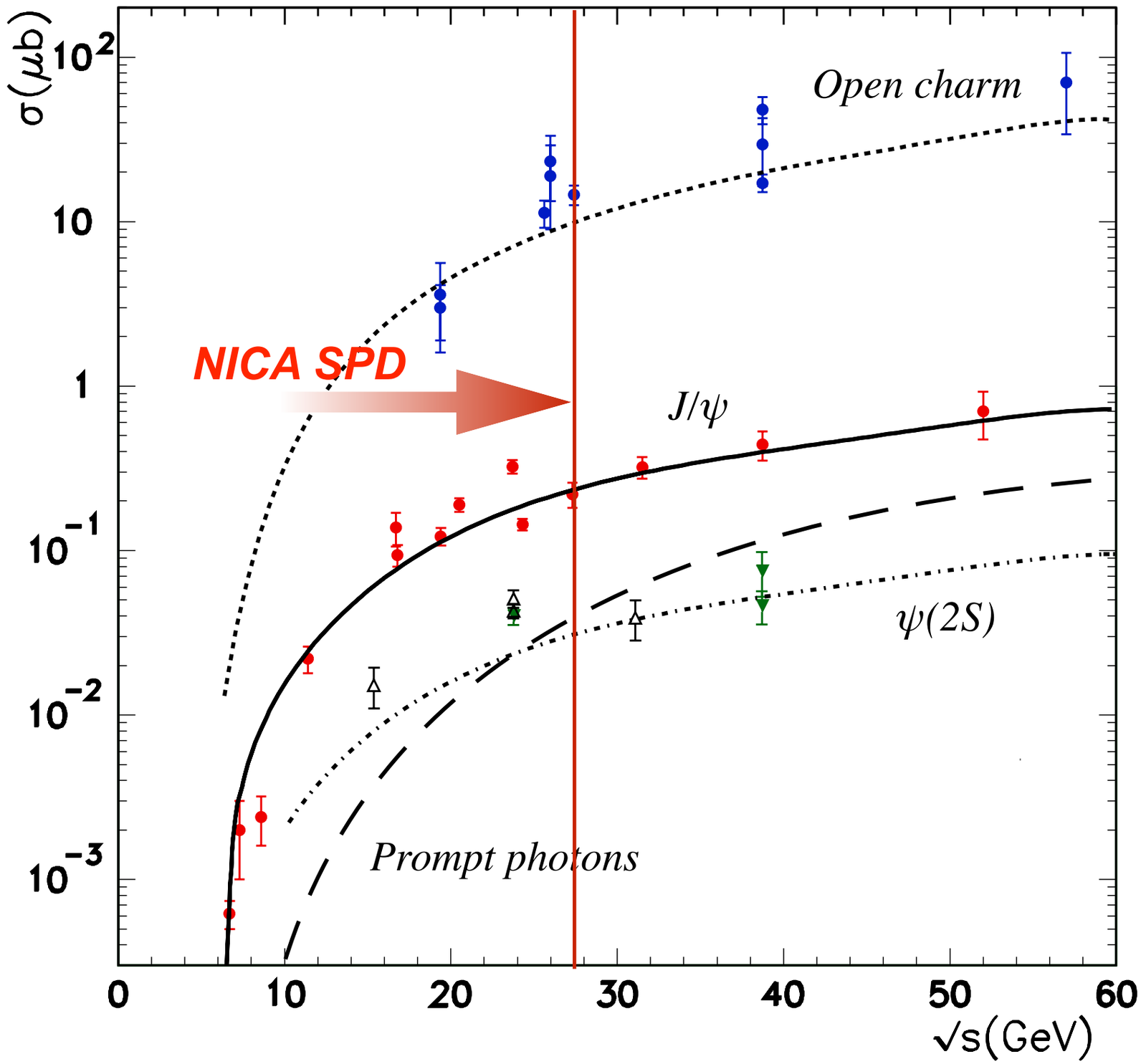
especially their gluon component!

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)

ARTICLE IN PRESS

Progress in Particle and Nuclear Physics xxx (xxxx) xxx

arXiv:2011.15005

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Review

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

A. Arbuzov [a], A. Bacchetta [b,c], M. Butenschoen [d], F.G. Celiberto [b,c,e,f], U. D'Alesio [g,h], M. Deka [a], I. Denisenko [a], M.G. Echevarria [i], A. Efremov [a], N.Ya. Ivanov [a,j], A. Guskov [a,k,*], A. Karpishkov [l,a], Ya. Klopot [a,m], B.A. Kniehl [d], A. Kotzinian [j,o], S. Kumano [p], J.P. Lansberg [q], Keh-Fei Liu [r], F. Murgia [h], M. Nefedov [l], B. Parsamyan [a,n,o], C. Pisano [g,h], M. Radici [c], A. Rymbekova [a], V. Saleev [l,a], A. Shipilova [l,a], Qin-Tao Song [s], O. Teryaev [a]

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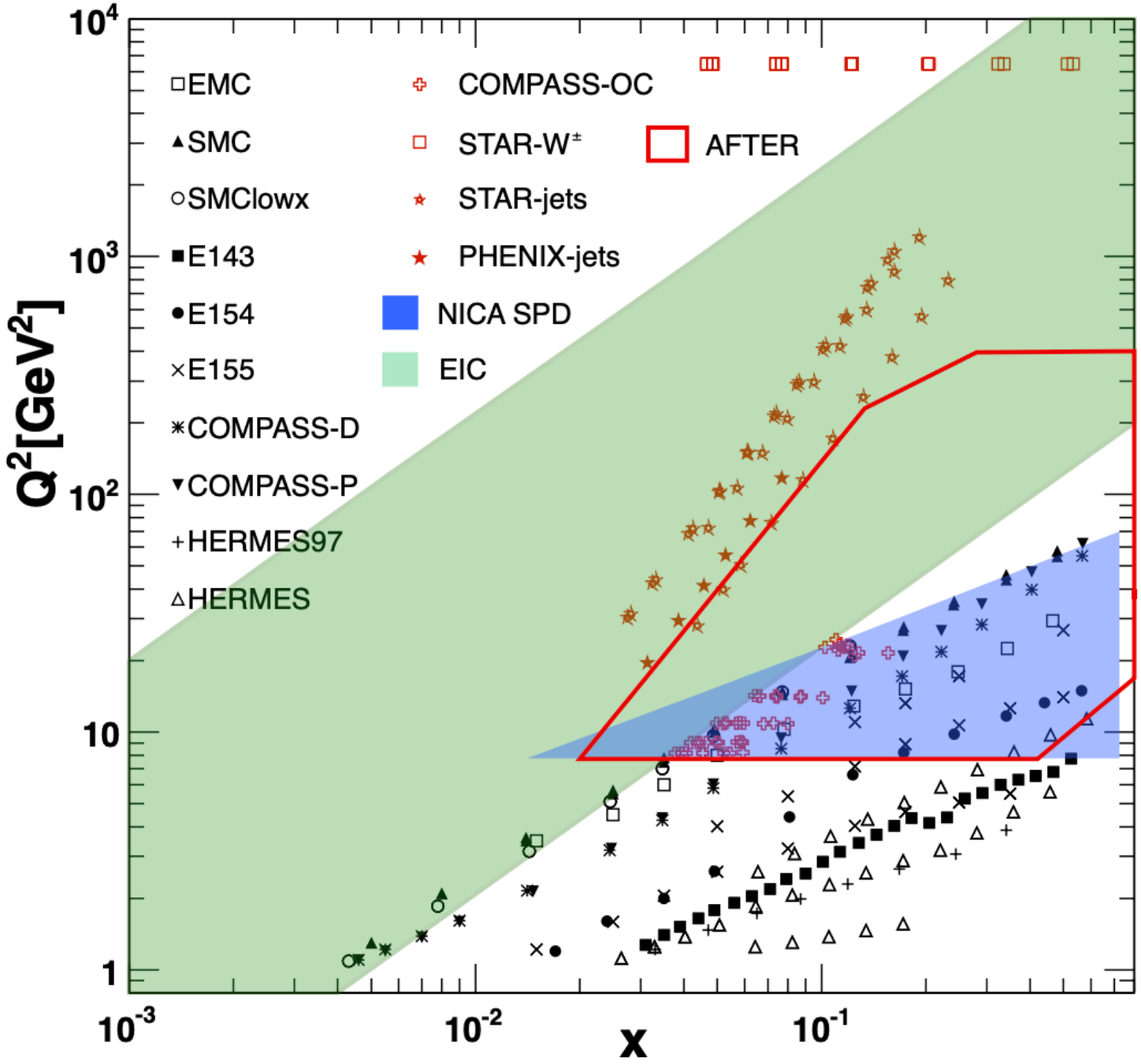
On the physics potential to study the gluon content of proton and deuteron at NICA SPD #1

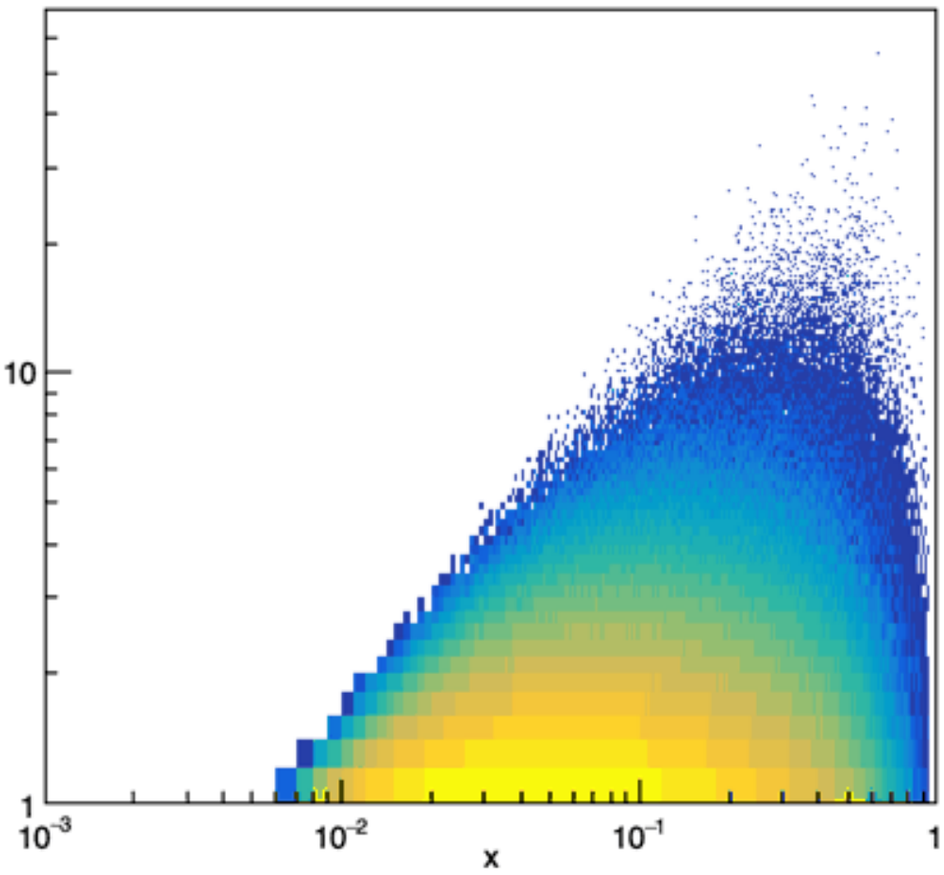
A. Arbuzov (Dubna, JINR), A. Bacchetta (Pavia U. and INFN, Pavia), M. Butenschoen (Hamburg U., Inst. Theor. Phys. II), F.G. Celiberto (Pavia U. and INFN, Pavia and ECT, Trento and Fond. Bruno Kessler, Povo), U. D'Alesio (Cagliari U. and INFN, Cagliari) et al. (Nov 30, 2020)

Published in: *Prog.Part.Nucl.Phys.* 119 (2021) 103858 • e-Print: 2011.15005 [hep-ex]

pdf | DOI | cite | claim | reference search | 51 citations

SPD and others

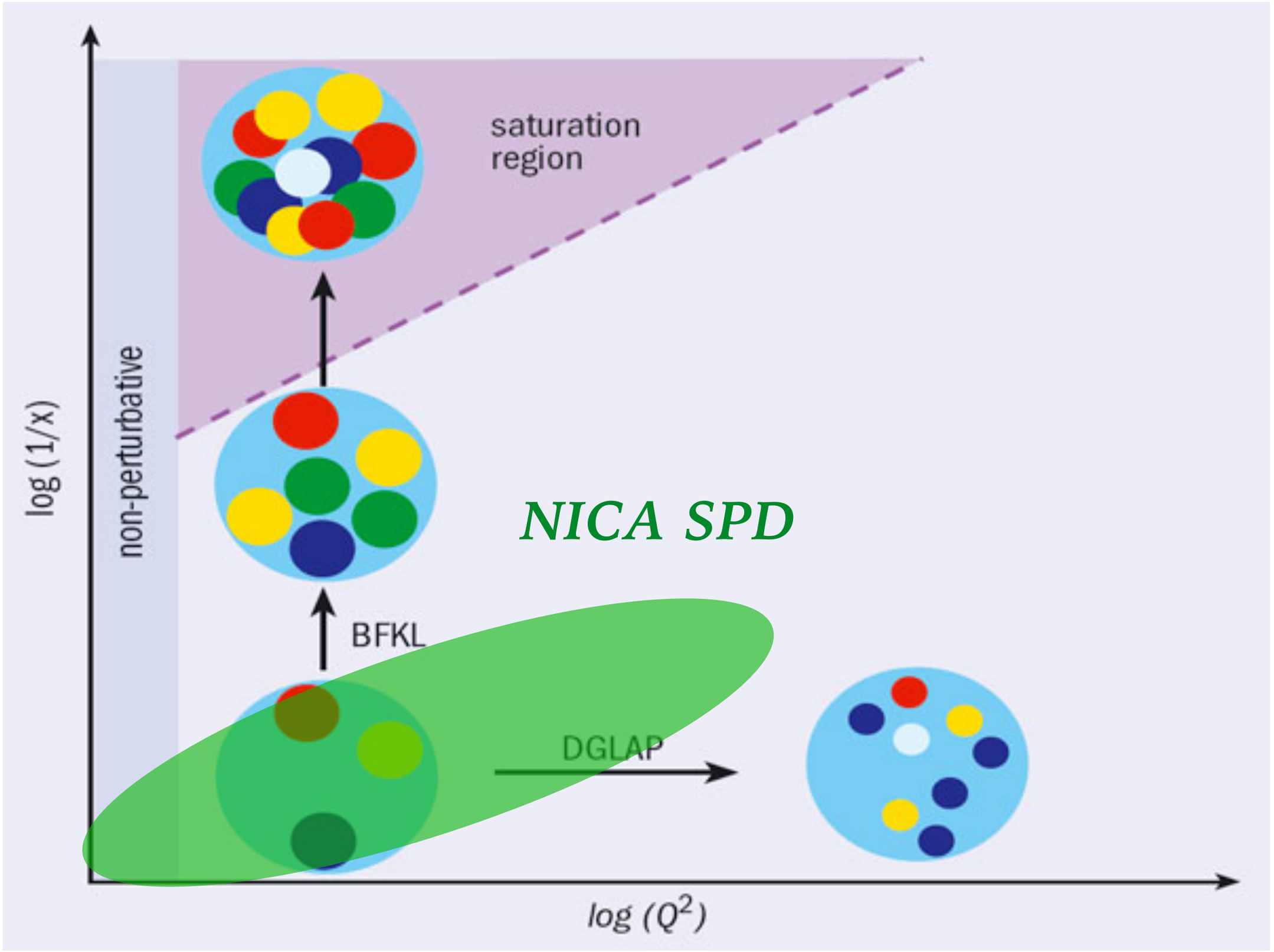




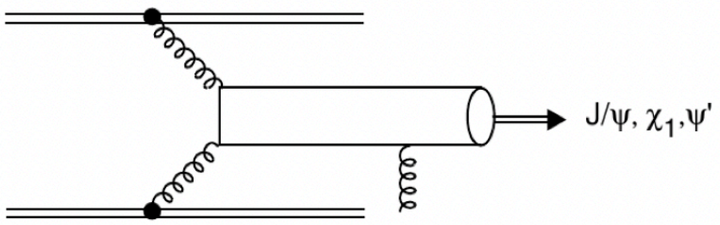
$$Q^2 = 1\ GeV^2/c^2, < x > = 0.16$$

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

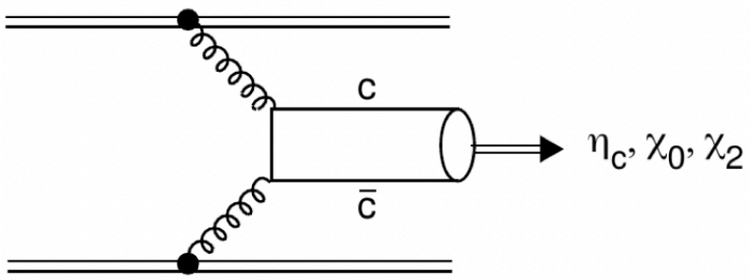
QCD landscape & SPD

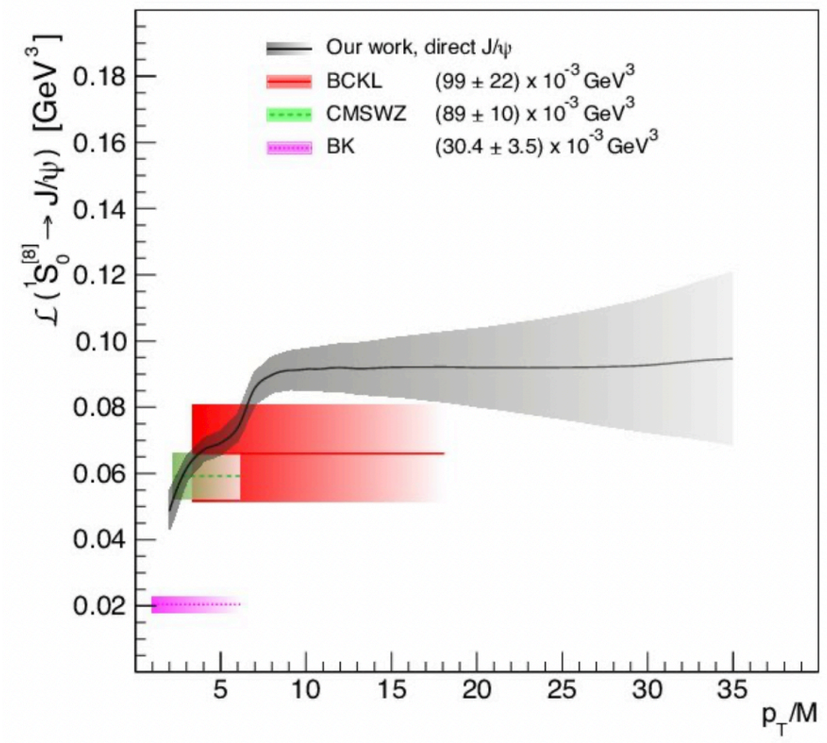


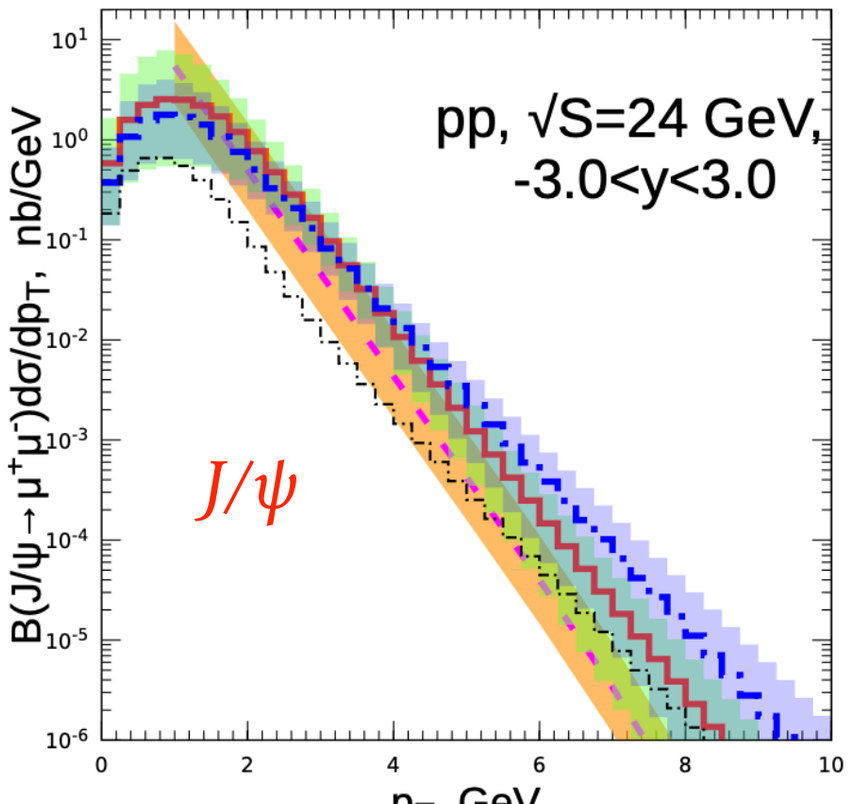
Charmonia production

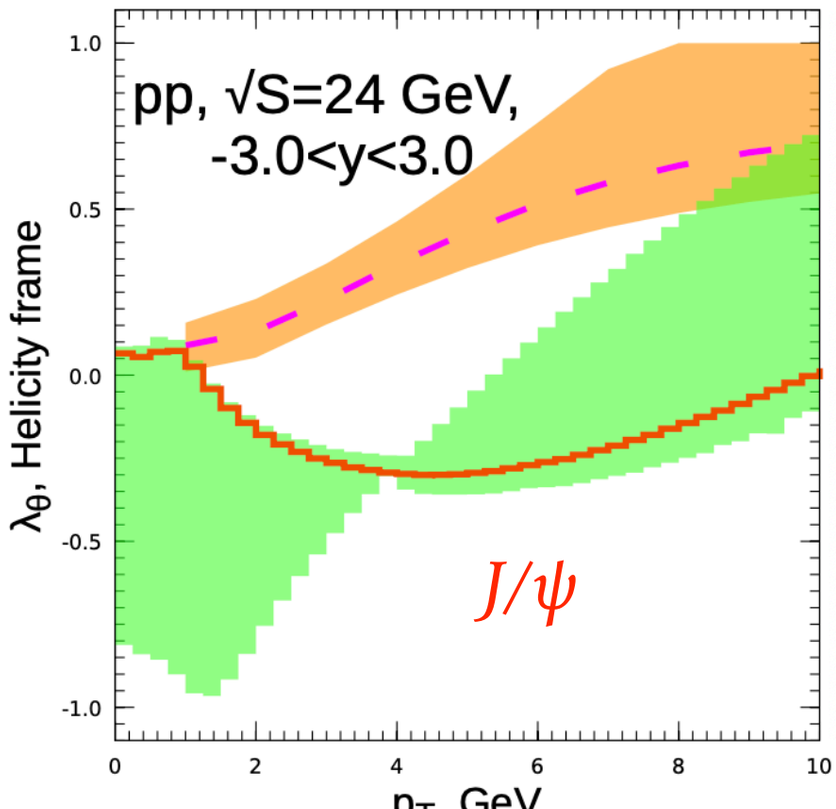


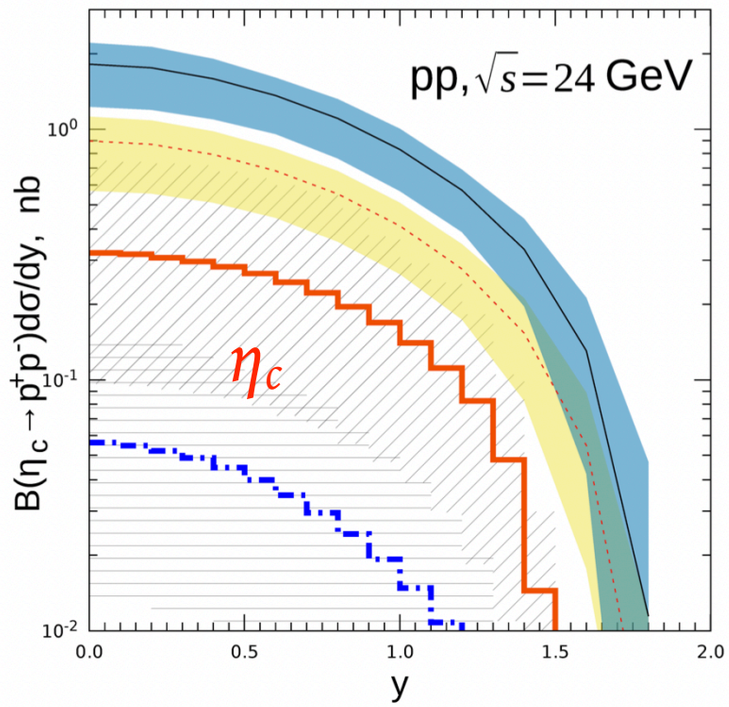
NRQCD — LDMEs



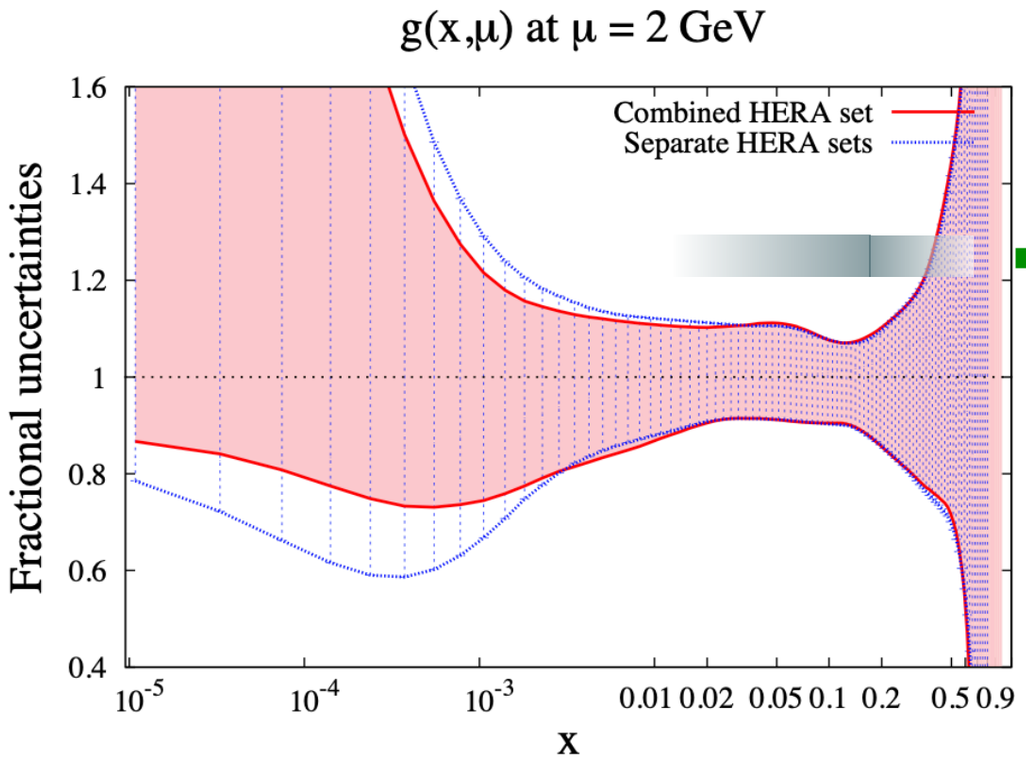


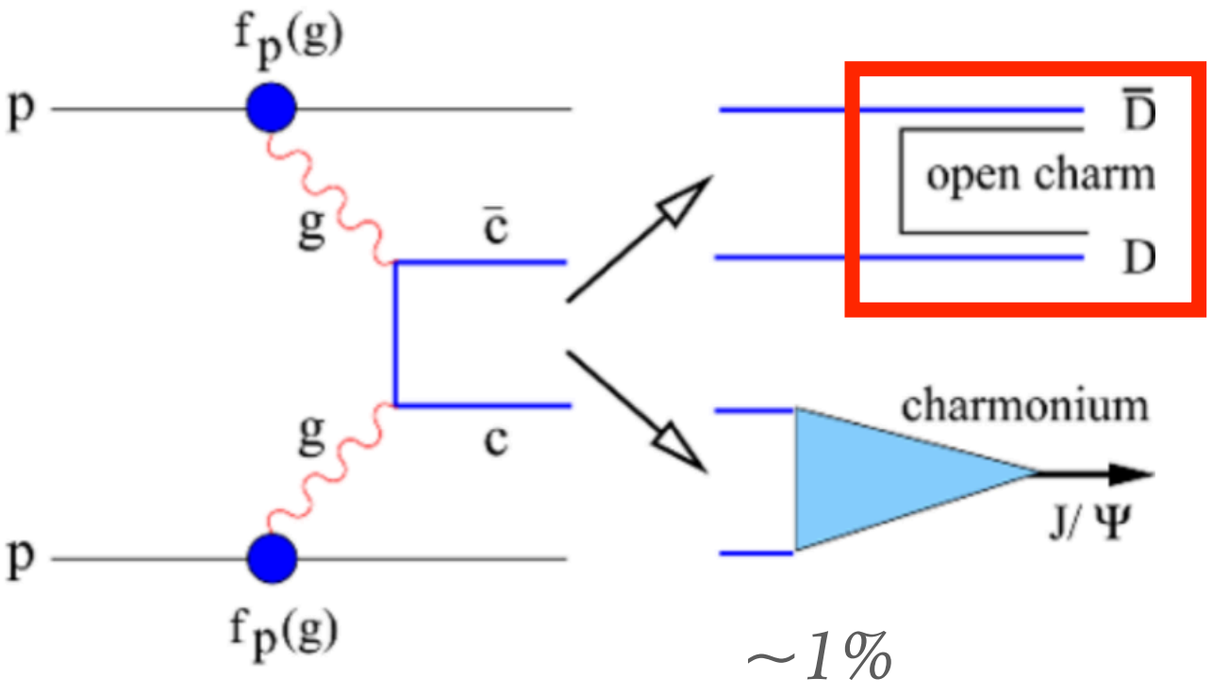






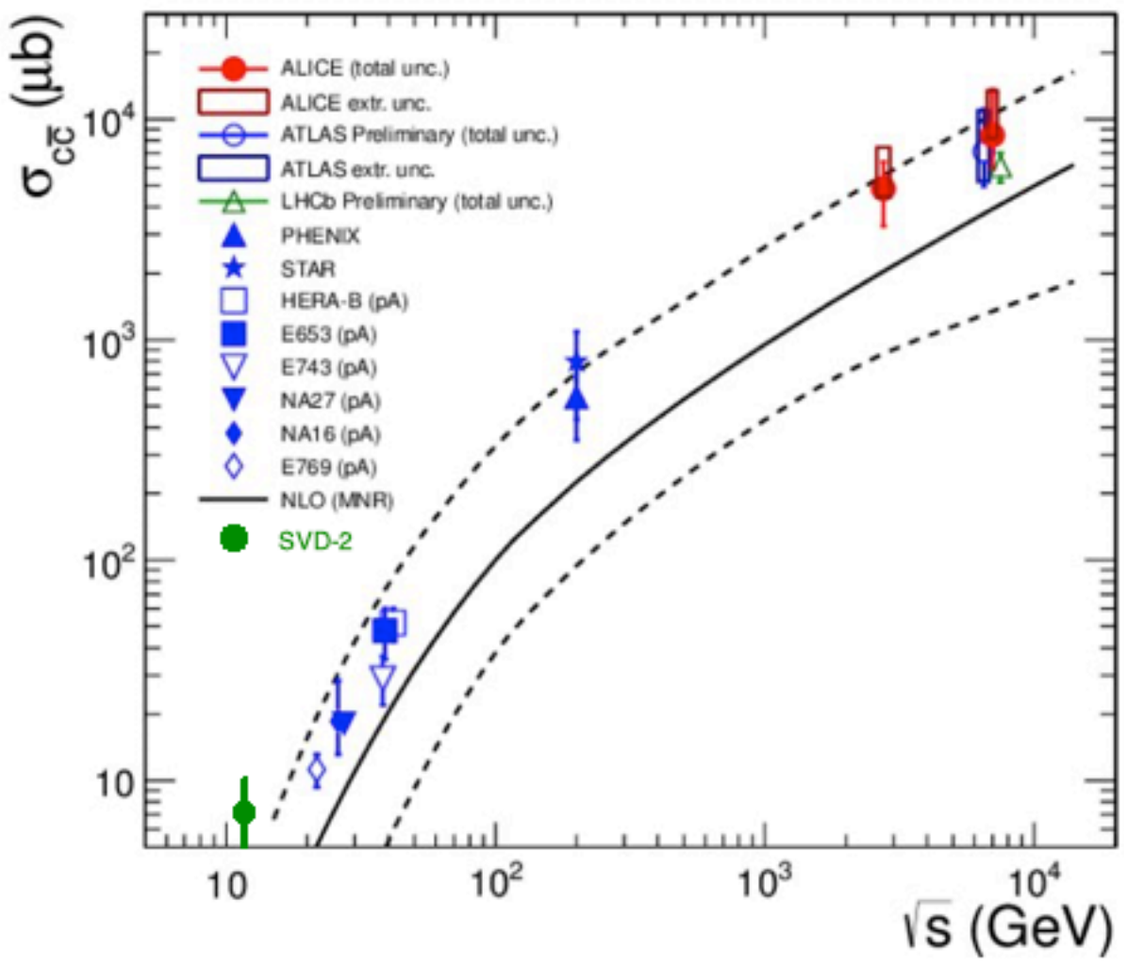
unpolarized gluons in proton at high x



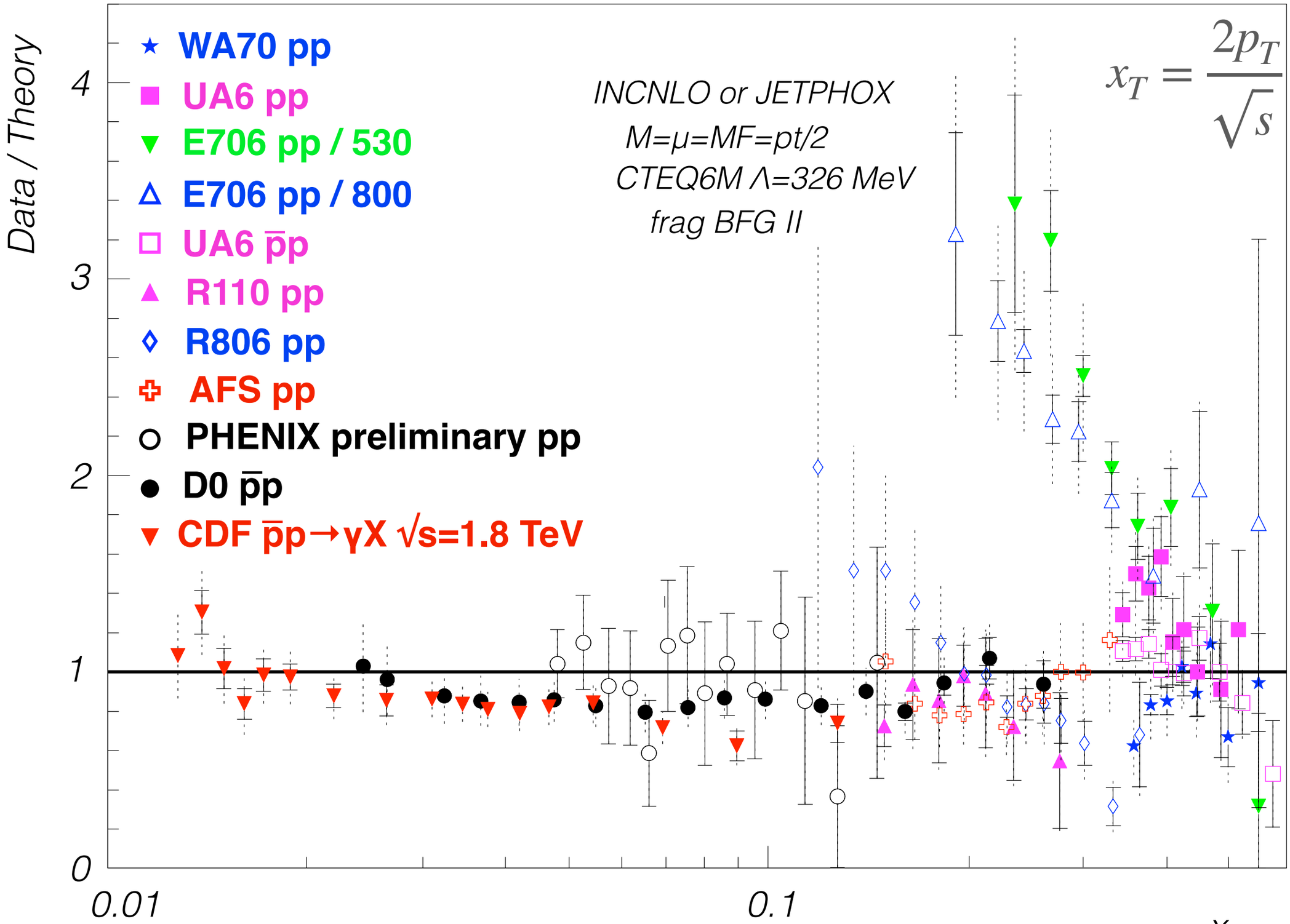


~1%

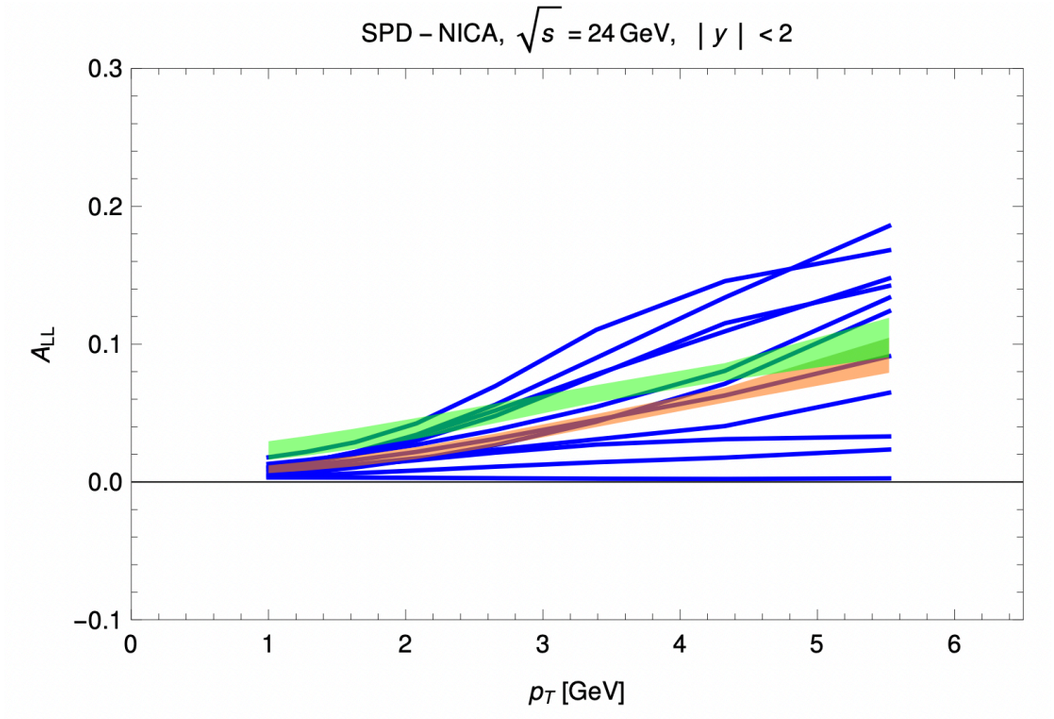
→ *Good opportunity for SPD*



Prompt photon puzzle



Gluon helicity function $\Delta g(x)$: expectations for A_{LL} at NICA energies



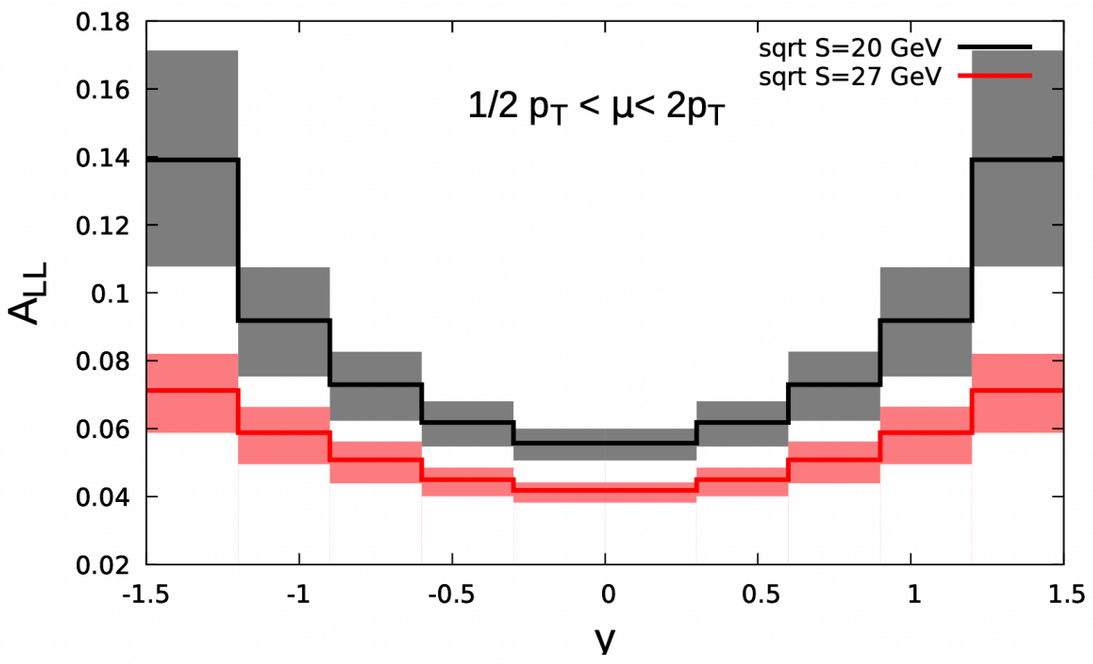
$gg \to J/\psi g$

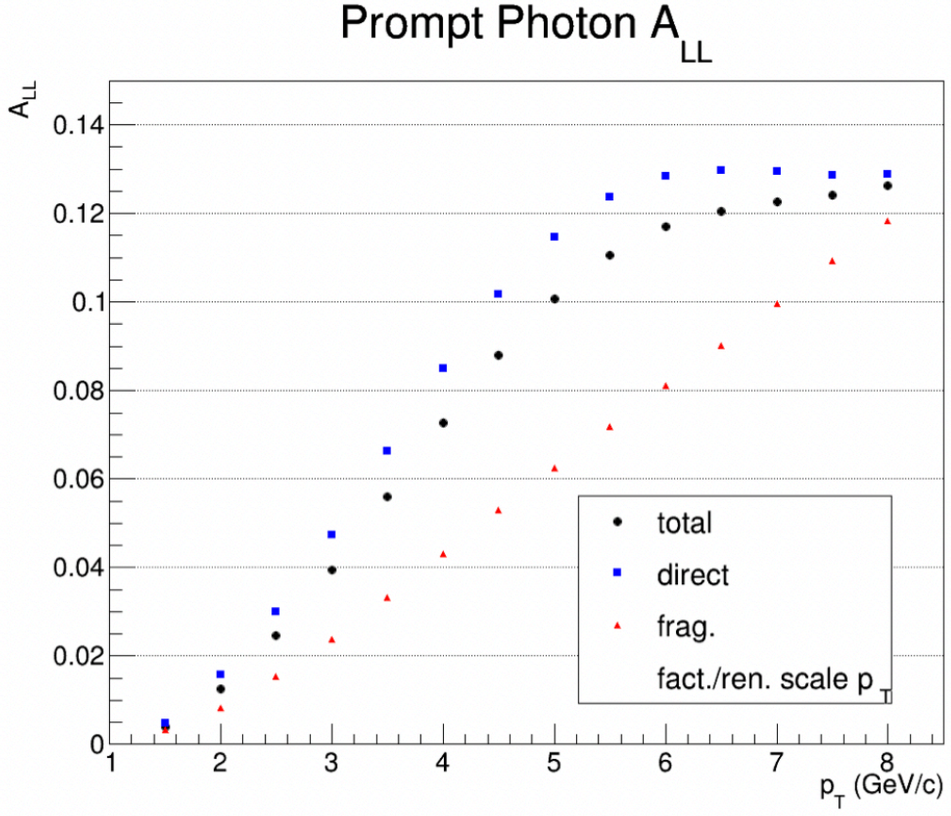
M. Nefedov

W. Vogelsang

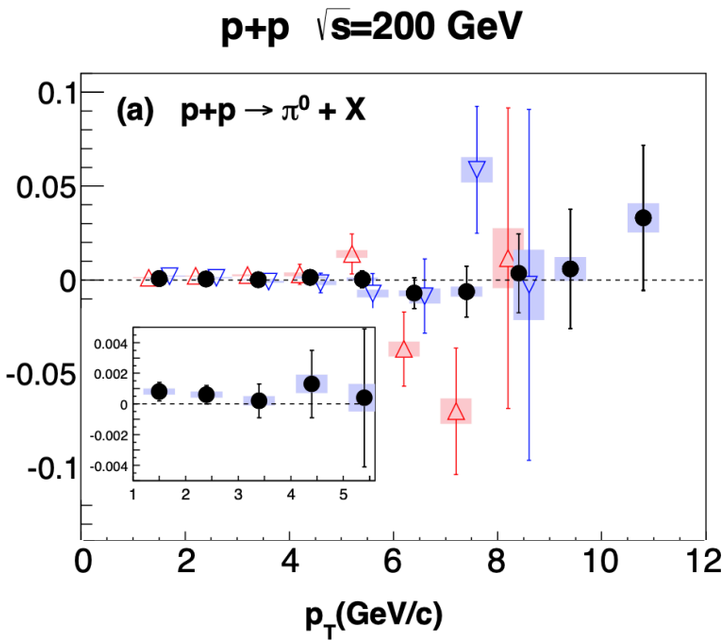
A. Shipilova

$qg \to q\gamma$





Gluon Sivers function $\Delta^{g}_{N}(x,k_T)$

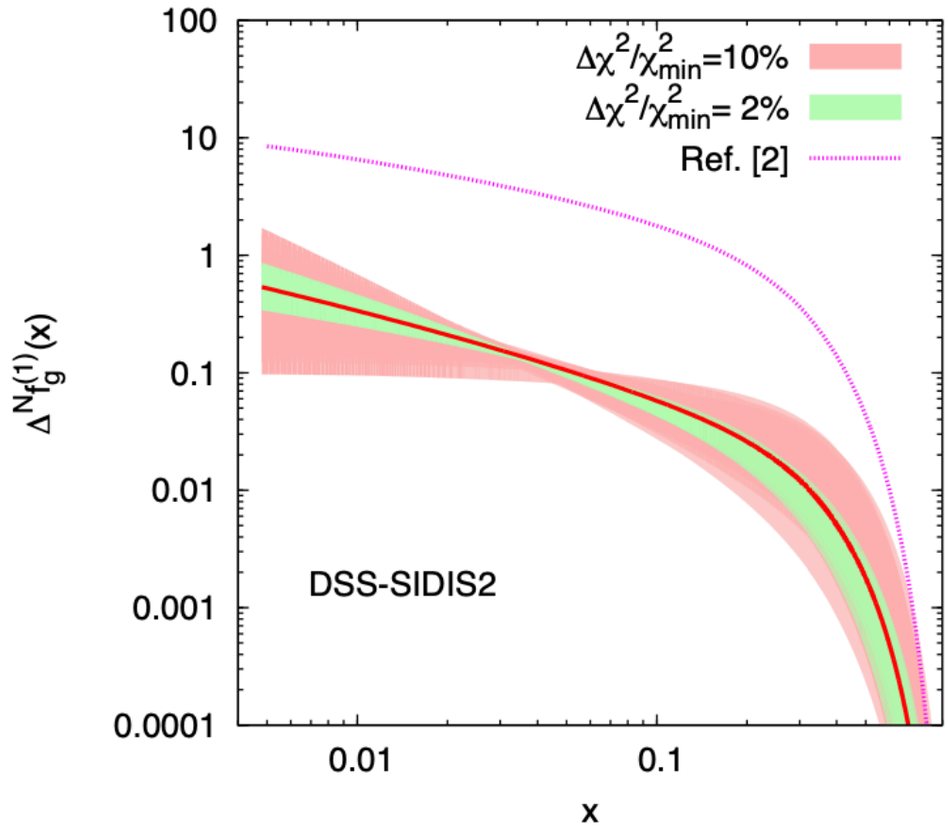


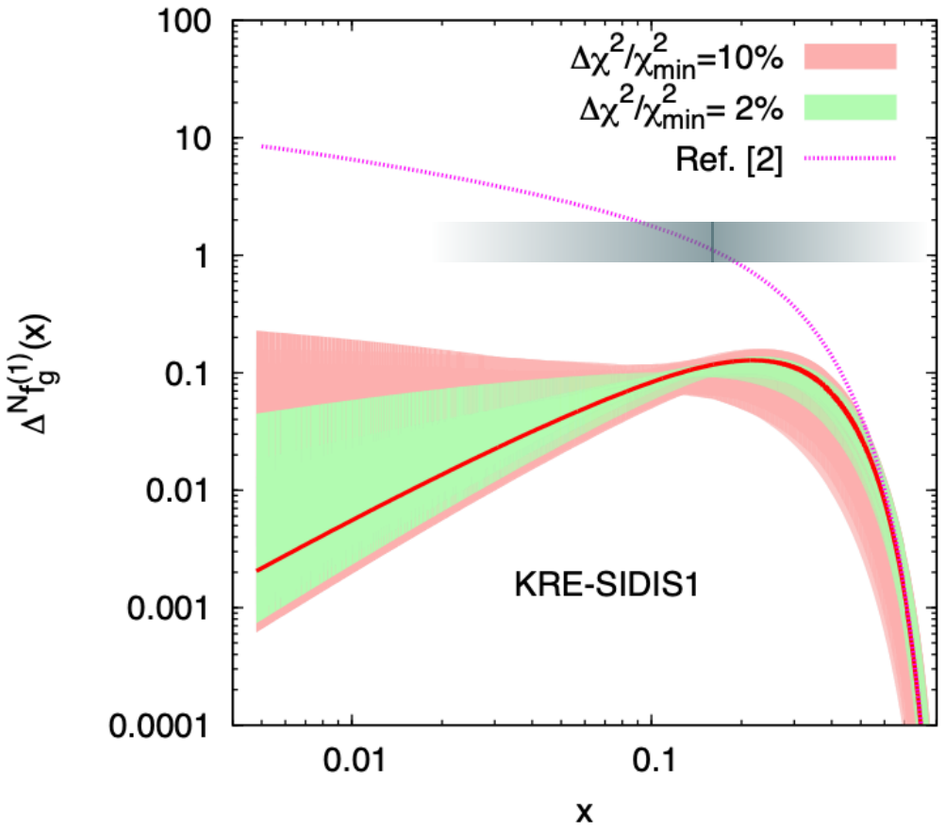
Phys.Rev.D **90 (2014) 1, 012006**

PHENIX

First $k_\perp$-moment of the gluon Sivers function

JHEP 09 (2015) 119

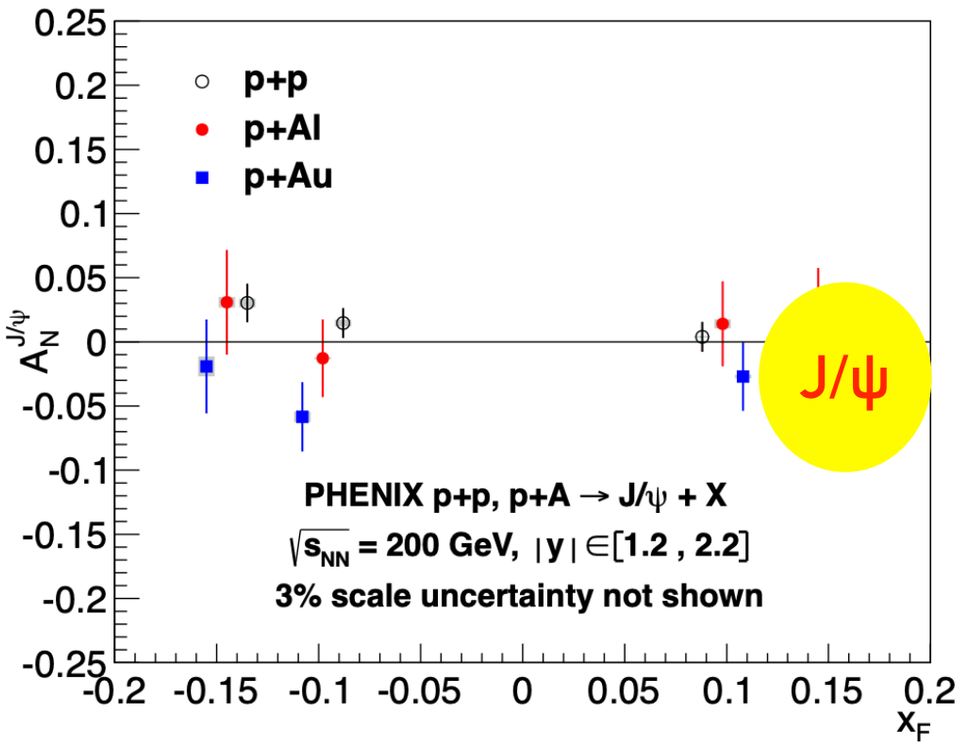


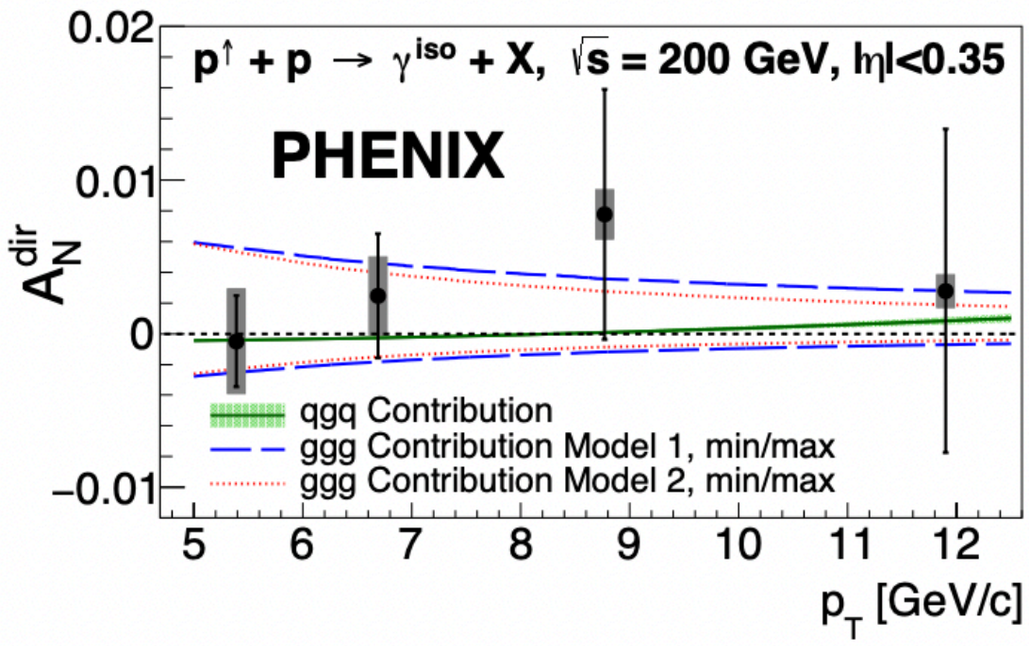


SPD

Gluon-induced TMD effects : existing results for A_N

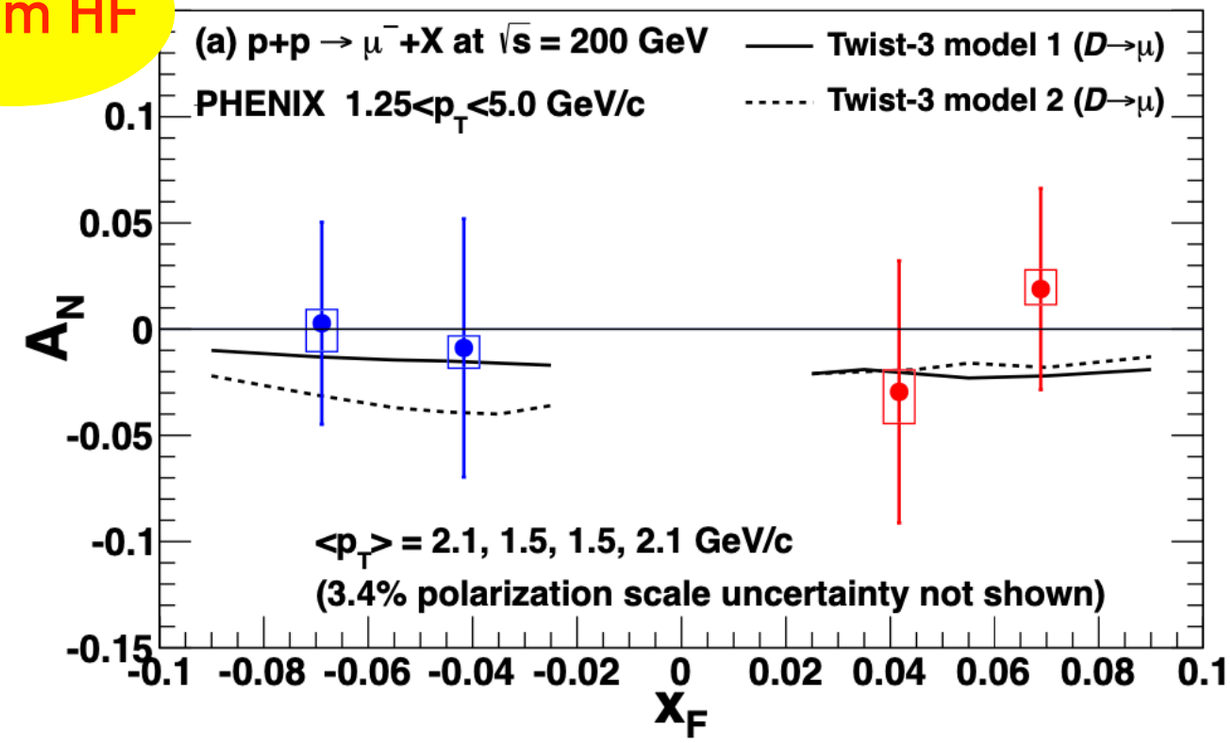
Phys.Rev.D 98 (2018) 1, 012006

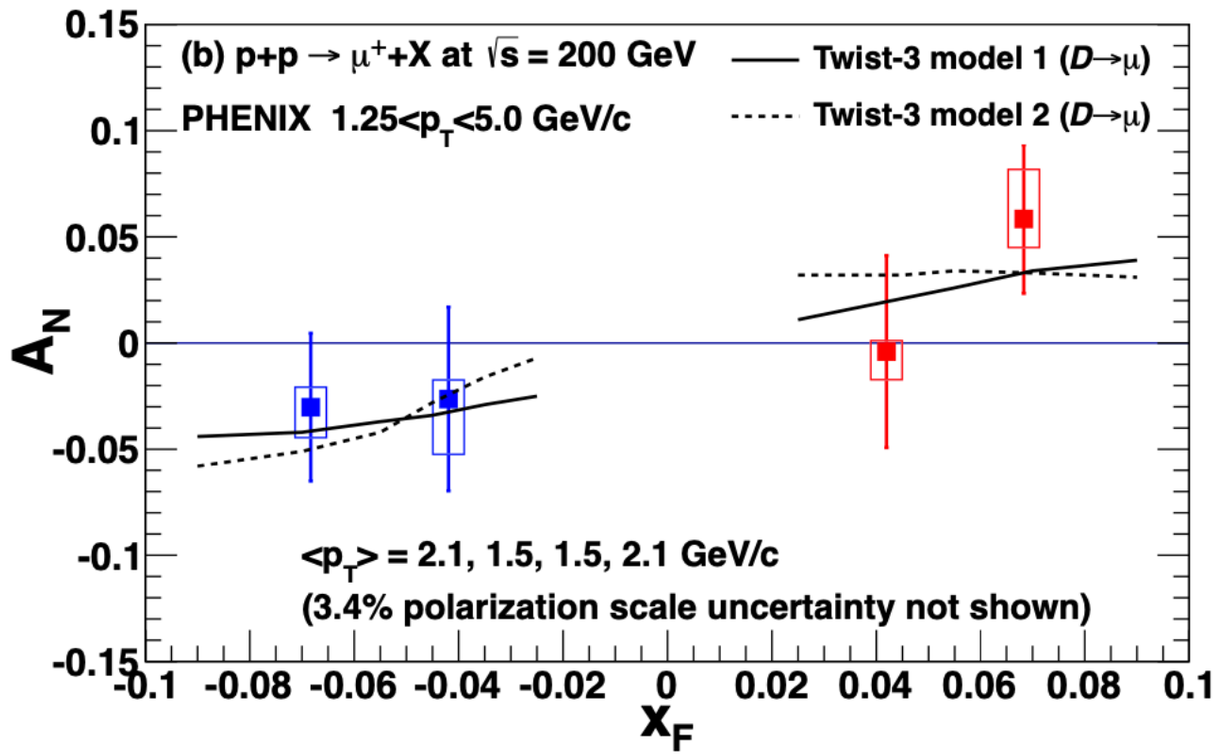




μ from HF

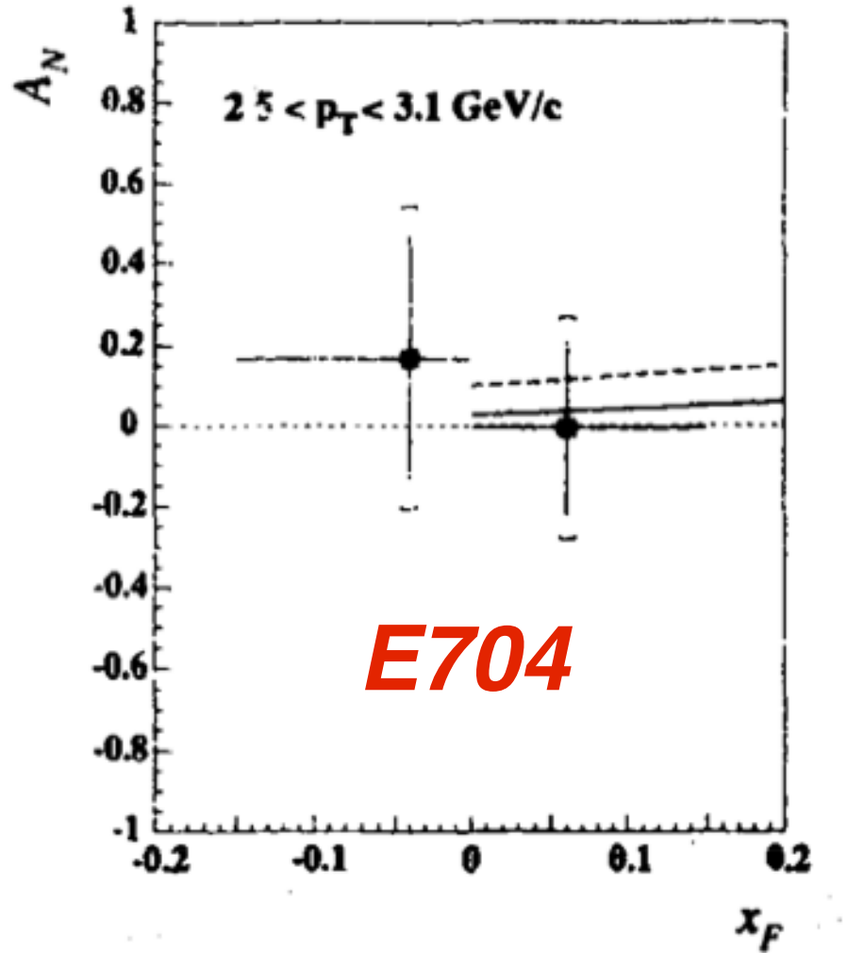
Phys.Rev.D 95 (2017) 11, 112001





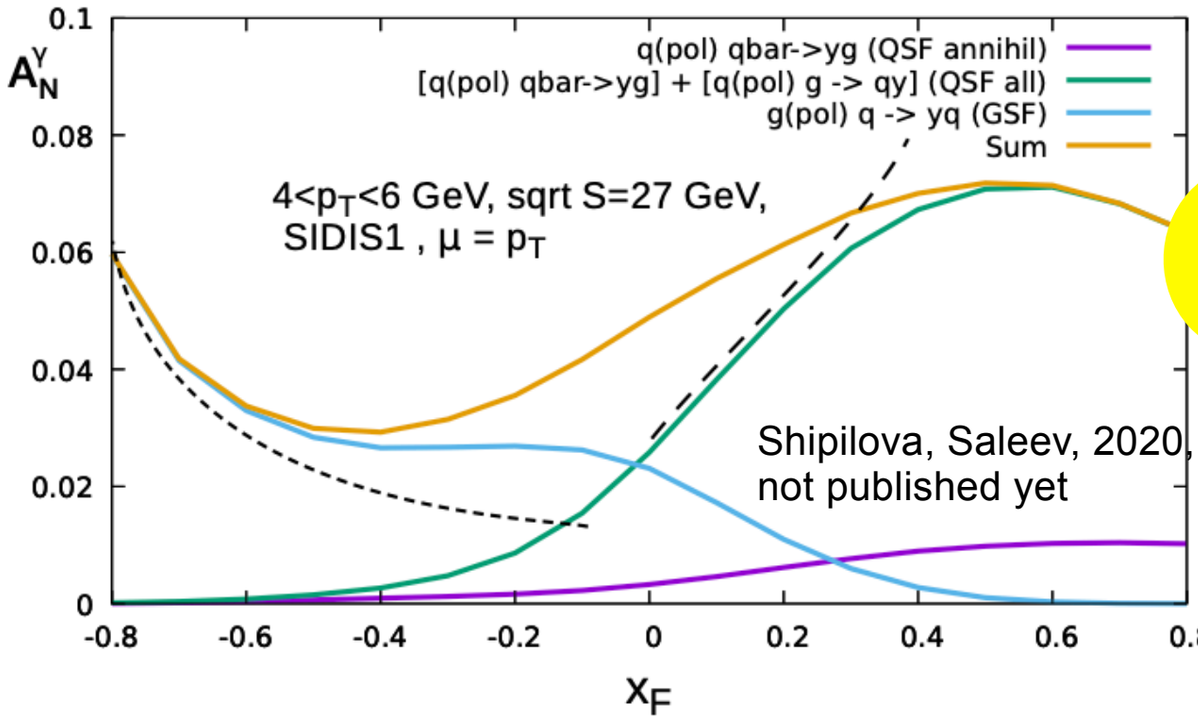
… and At NICA energies

Phys. Lett. B 345 (1995)

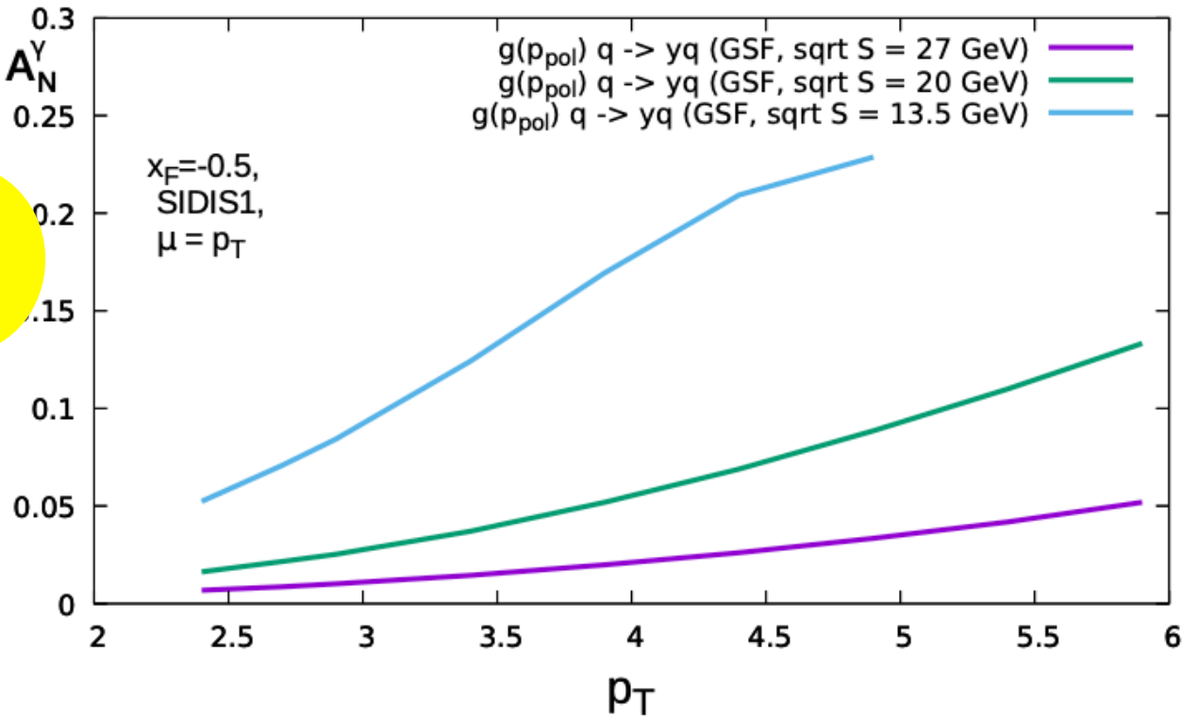


Gluon-induced TMD effects: expectations for A_N

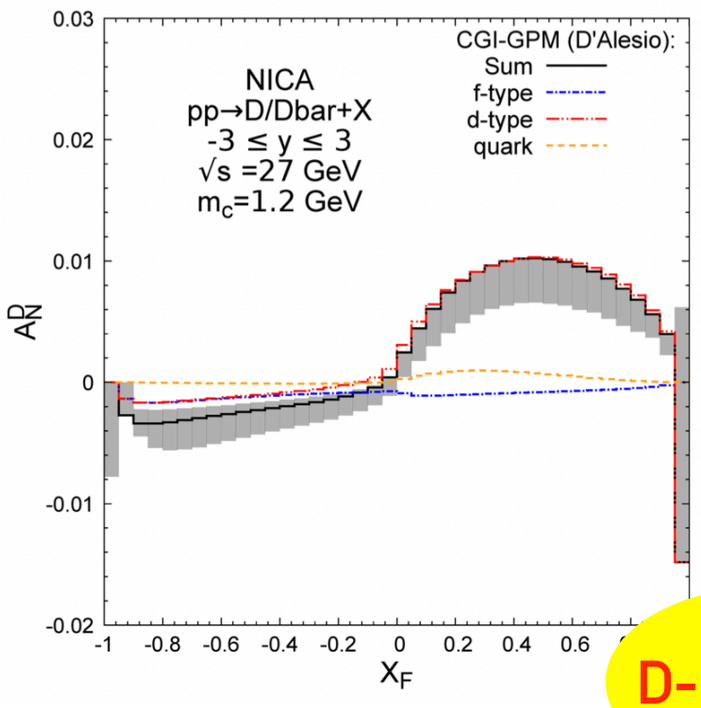
Sivers effect contribution

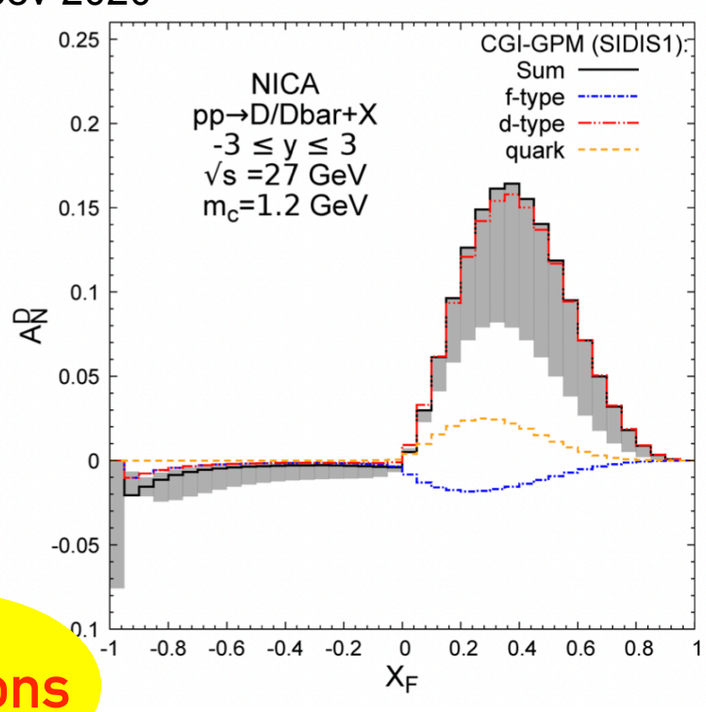


Y

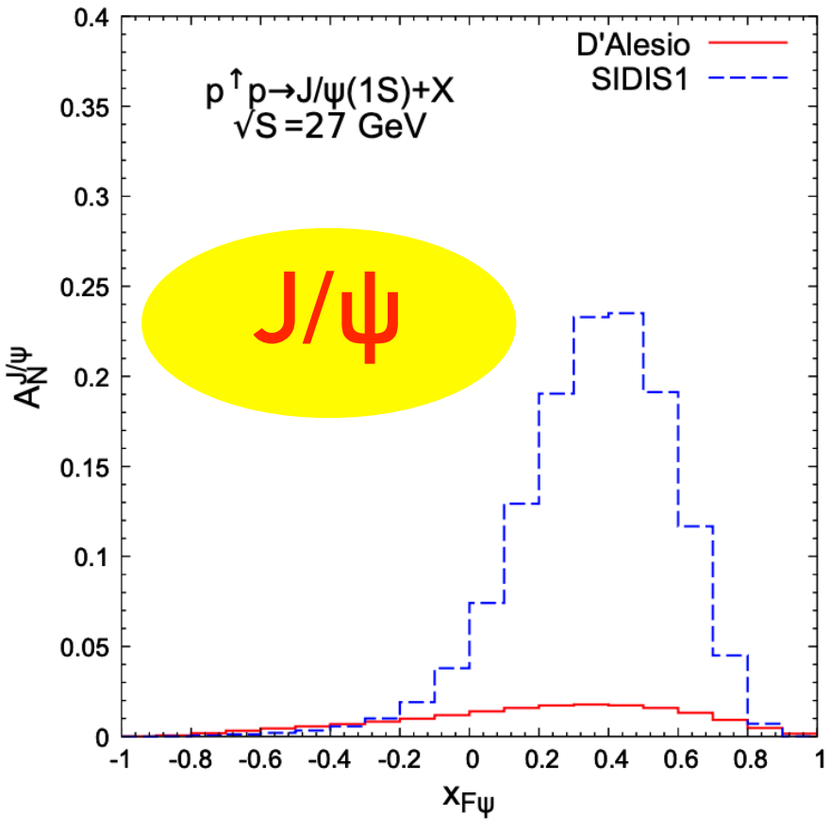


Saleev 2020

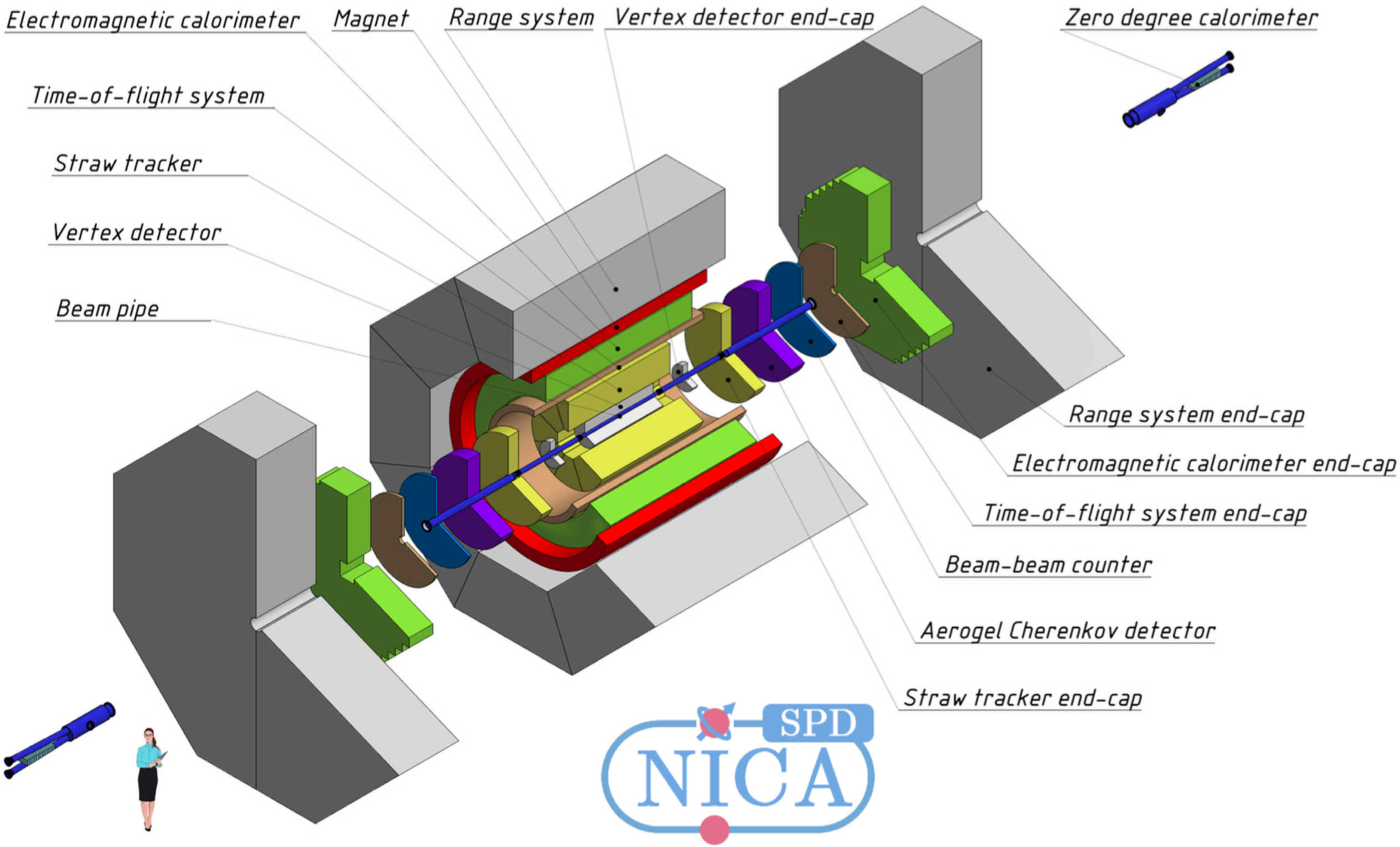




D-mesons



SPD setup


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

SPD: two stages

Creating of polarized infrastructure

Upgrade of polarized infrastructure

Start of NICA operation

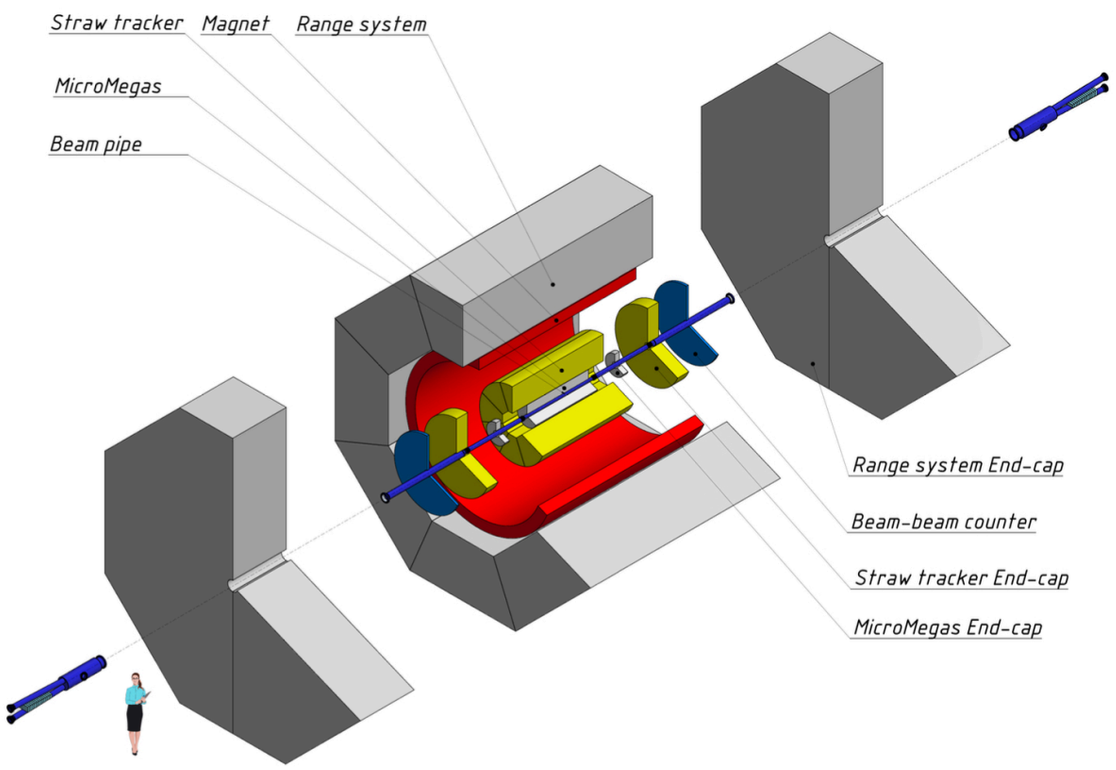
+4 years *+6 years* *+8 years*

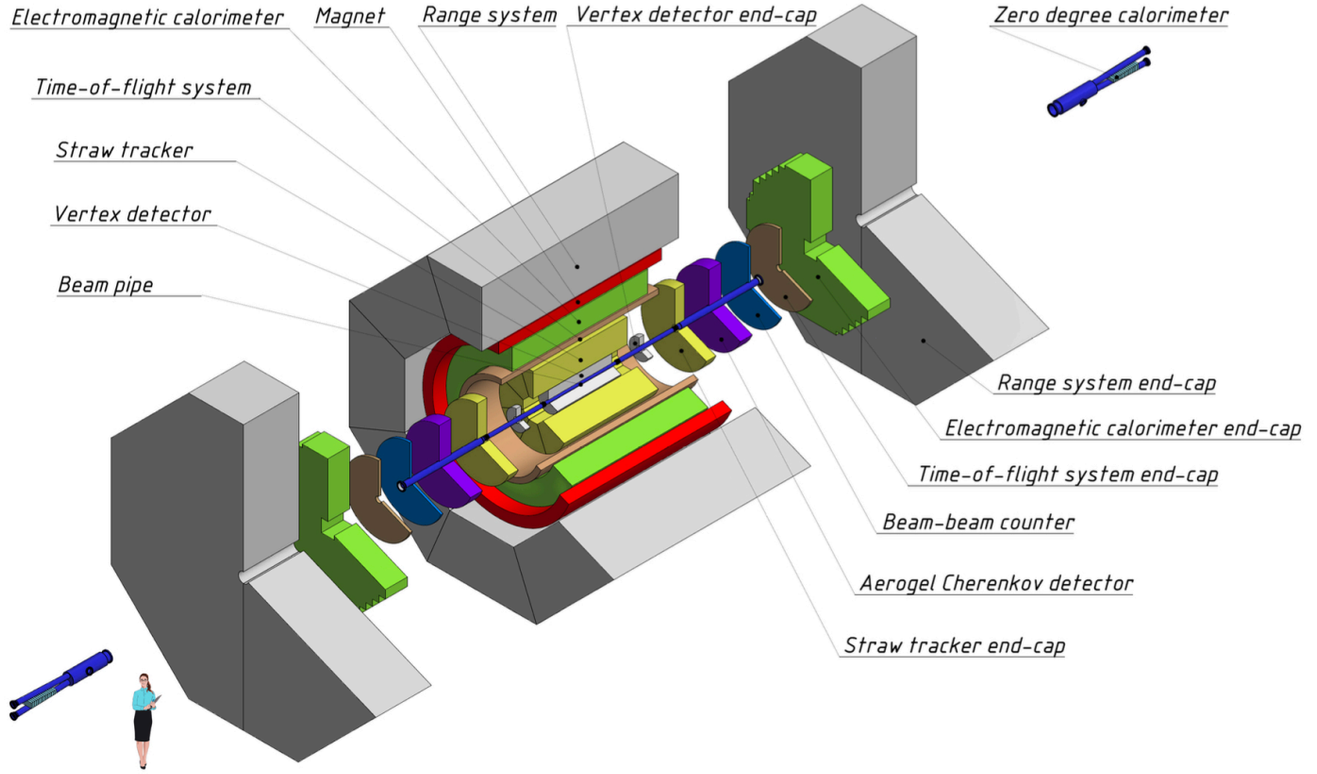
SPD construction

1st stage of operation

SPD upgrade

2nd stage of operation





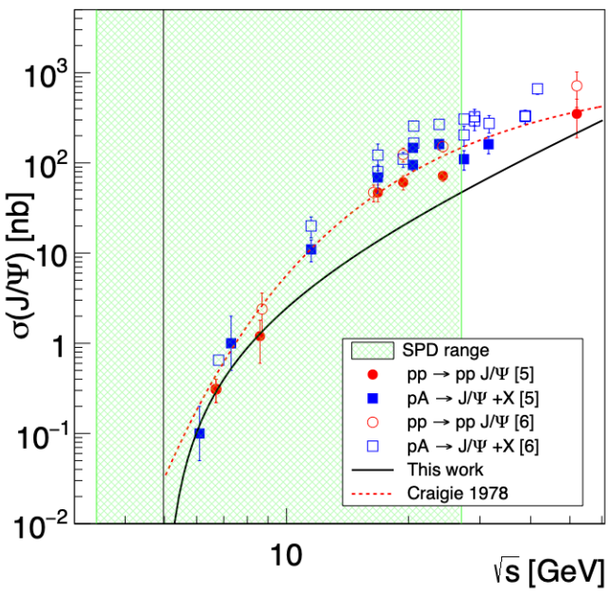
Physic of the first stage

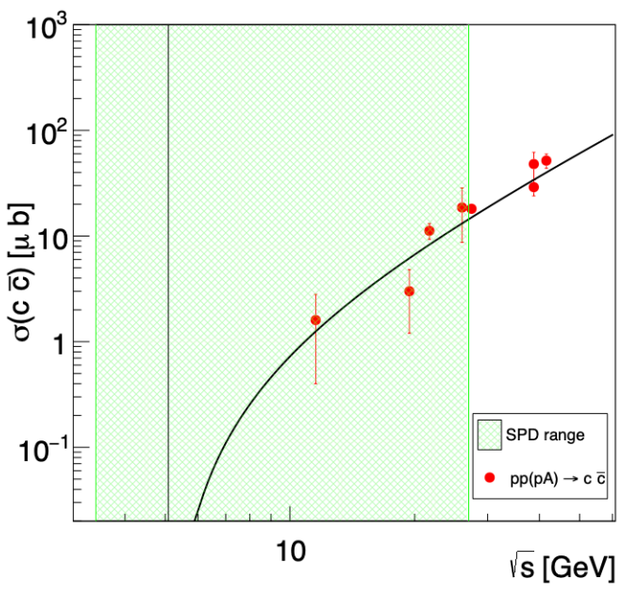
Non-perturbative QCD — *Perturbative QCD*

$\sqrt{s}$

- Spin effects in p-p, p-d and d-d elastic scattering
- Spin effects in hyperons production
- Multiquark correlations $pp \to (6q)^* \to N\,N\,Mesons,$
- Dibaryon resonances
- Physics of light and intermediate nuclei collision
- Exclusive reactions
- Hypernucei $dd \to K^+\,K^+\,{}^{4}_{\Lambda\Lambda}\mathrm{n},$
- Open charm and charmonia near threshold

arXiv:2102.08477

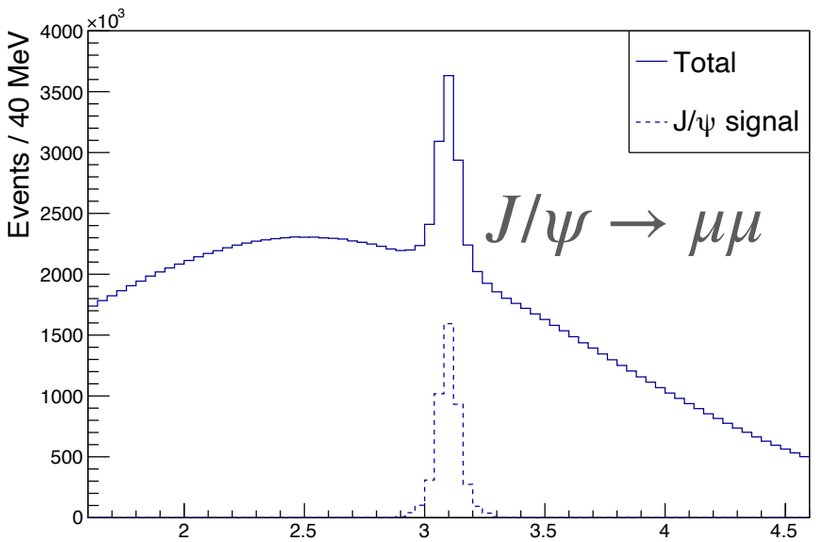


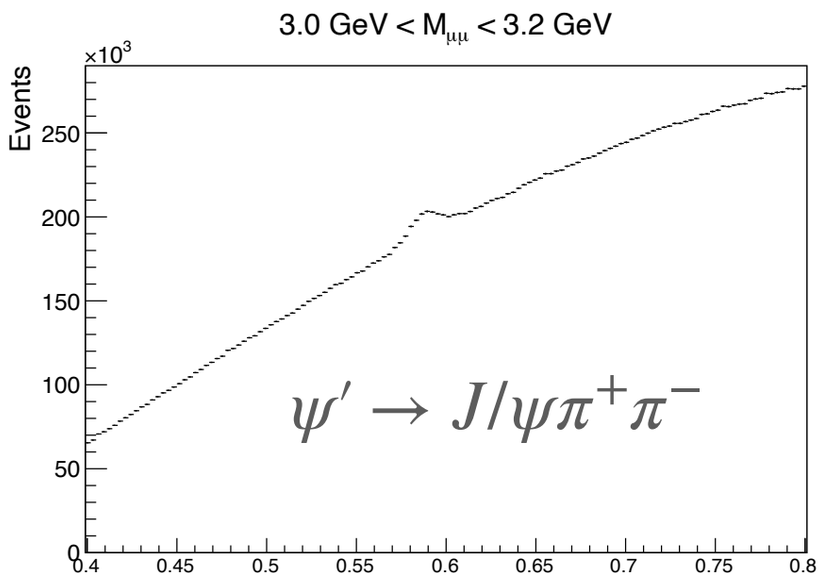


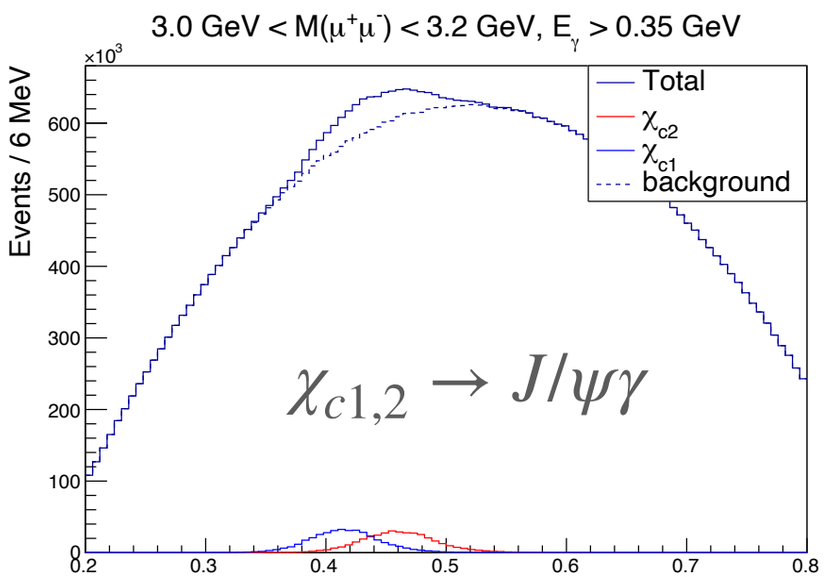
- Auxiliary measurements for astrophysics

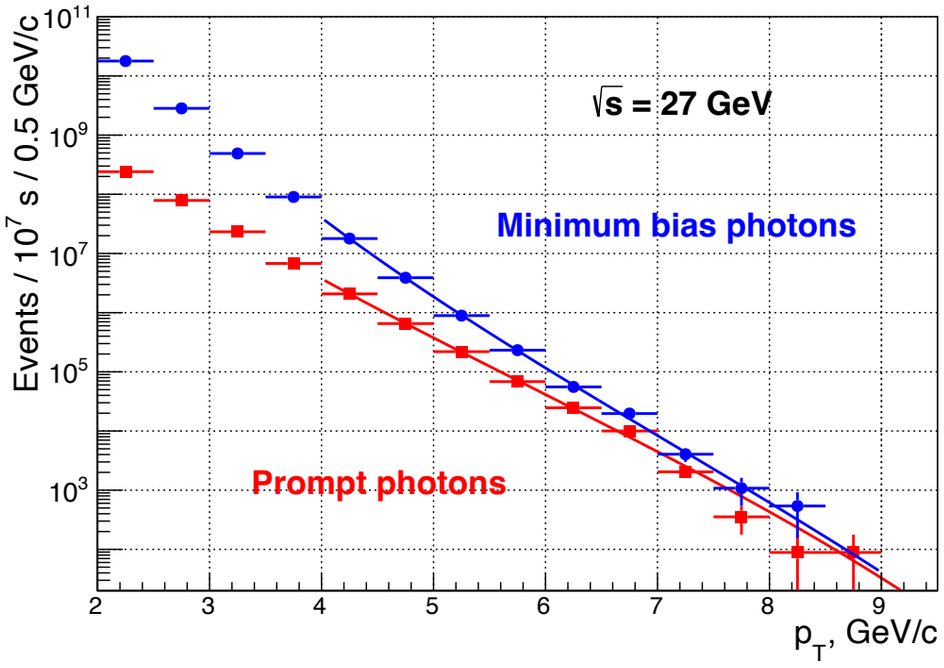
Physics performance for gluon probes

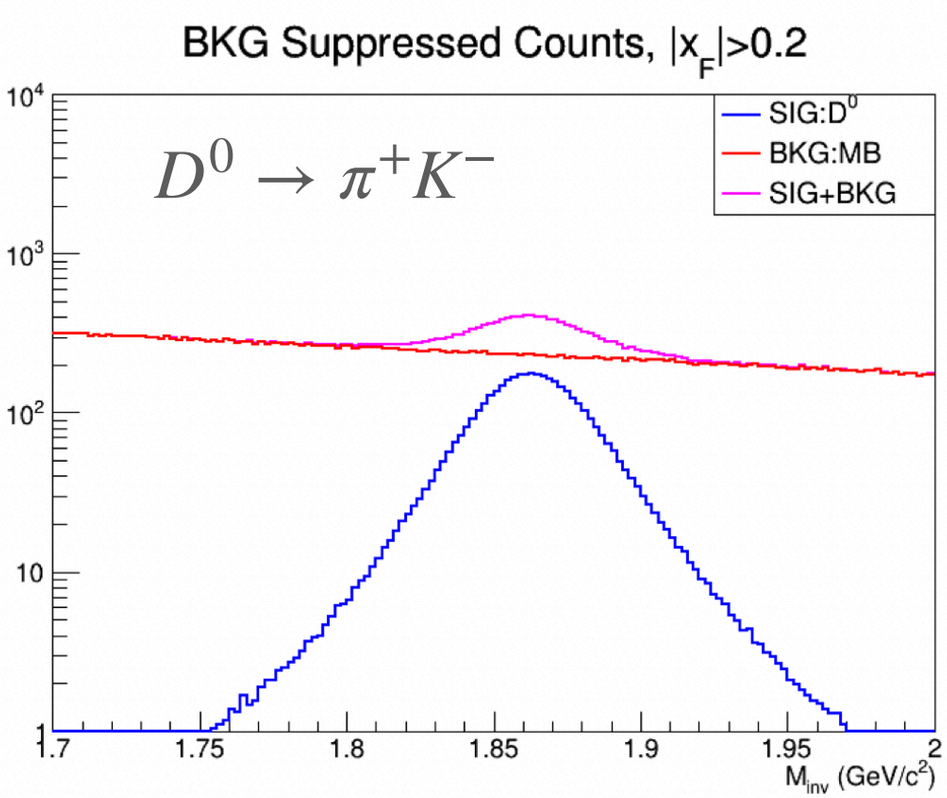
(1 year=10^7 s)



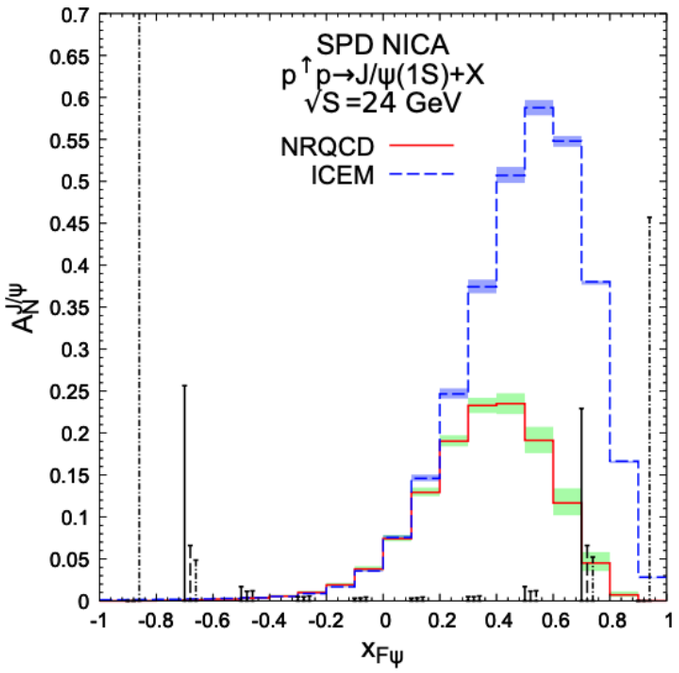




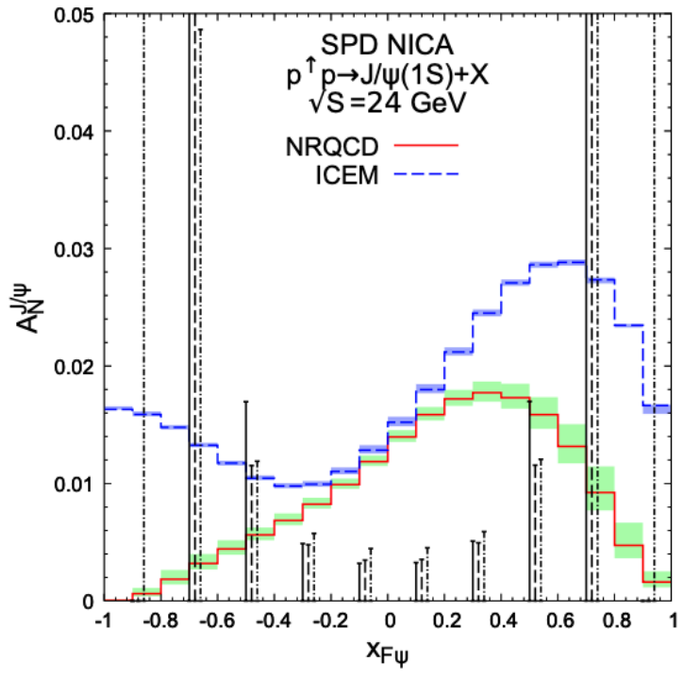


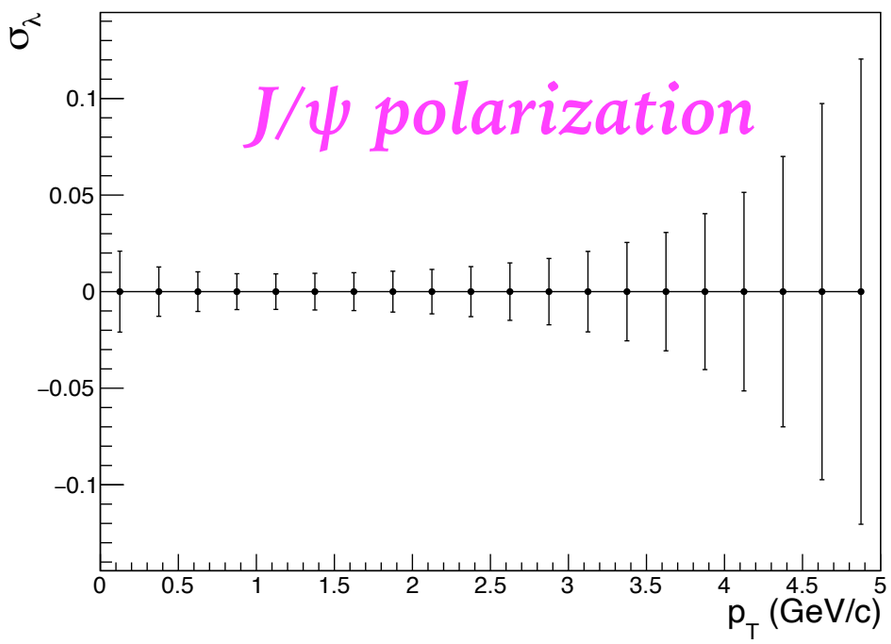


Physics performance: accuracies



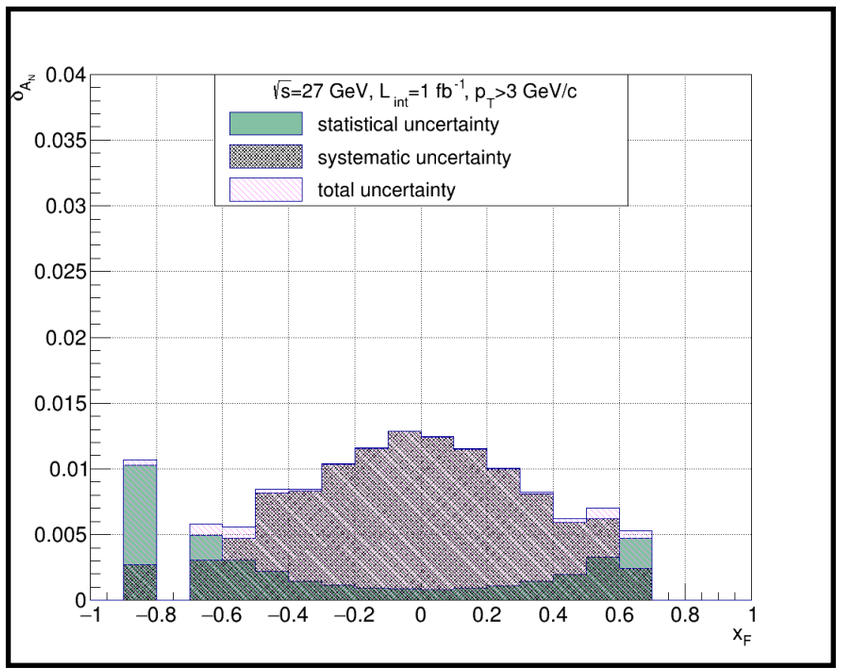
J/ψ



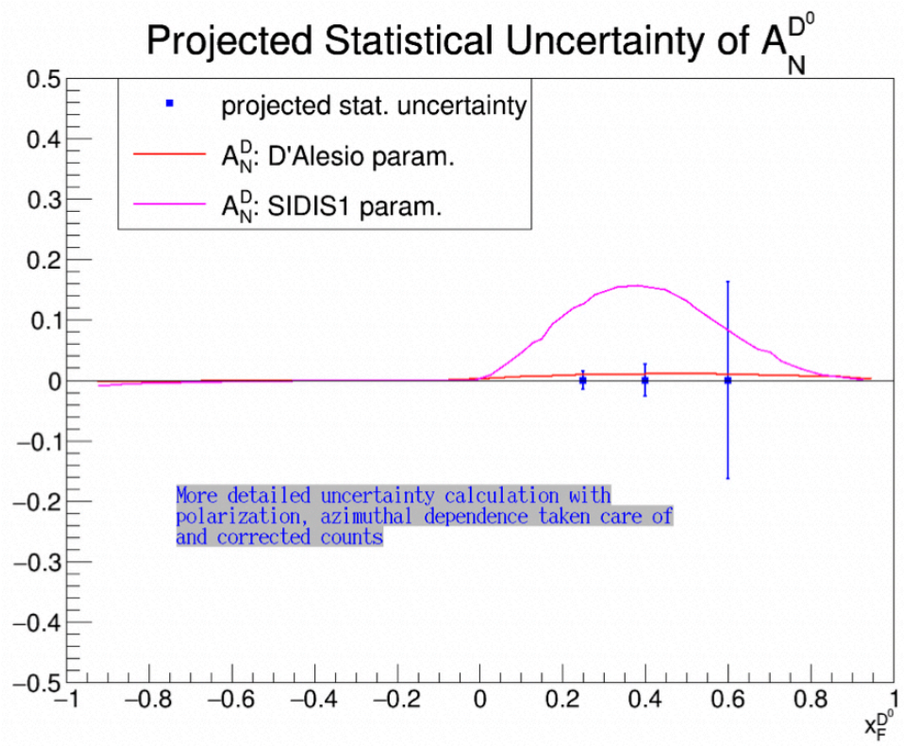


J/ψ polarization

Different inputs for gluon Sivers function

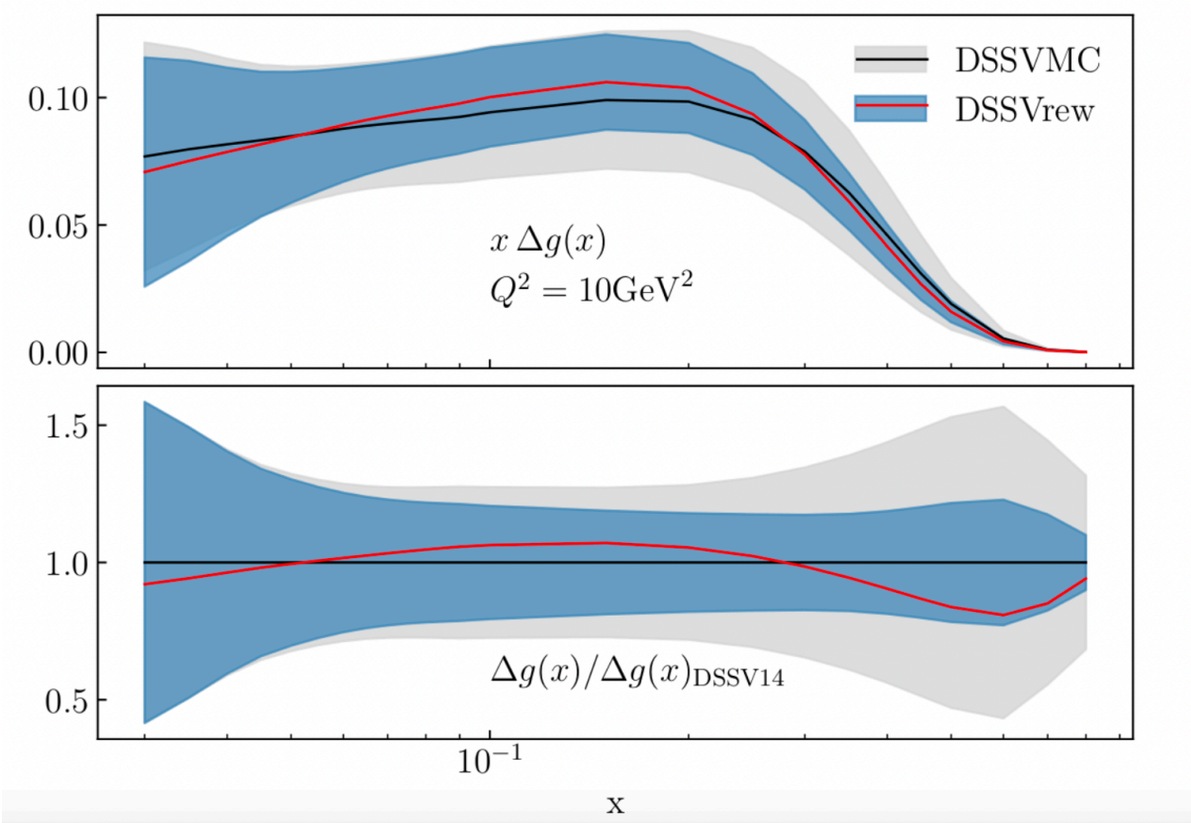


prompt-γ

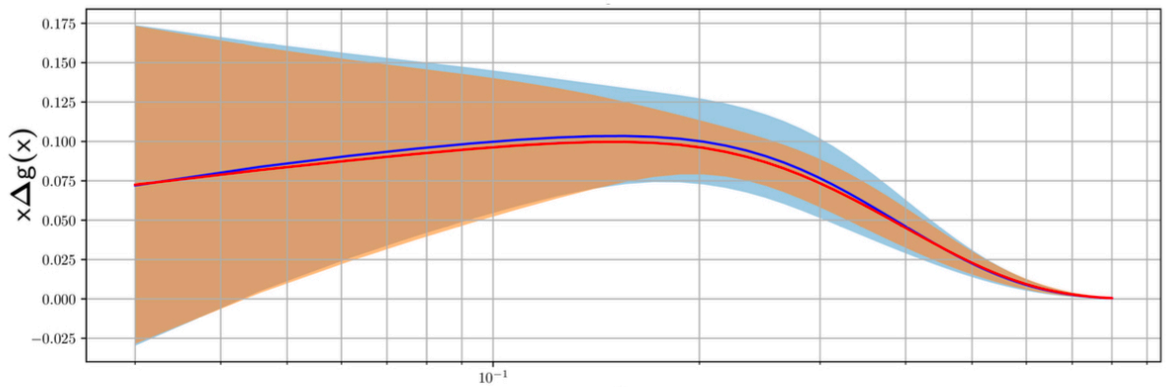


D⁰

Impact of SPD measurements to the world data for $\Delta g(x)$



A_{LL} *for prompt photons*



A_{LL} *for* J/ψ

SPD collaboration

Signed MoU (12+3):

A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute), Yerevan
NRC “Kurchatov Institute” - PNPI, Gatchina
Samara National Research University (Samara University), Samara
Saint Petersburg Polytechnic University St. Petersburg
Saint Petersburg State University, St. Petersburg
Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow
Tomsk State University, Tomsk
Belgorod State University, Belgorod
Lebedev Physical Institute of RAS, Moscow
Institute for Nuclear Research of the RAS, Moscow
National Research Nuclear University MEPhI, Moscow
Institute of Nuclear Physics (INP RK), Almaty
NRC “Kurchatov Institute”, Moscow (NRC KI)
Higher Institute of Technologies and Applied Sciences, Havana
Institute for Nuclear Problems of BSU, Minsk

35 institutes from 15 states, ~300 members

http://spd.jinr.ru/

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

https://arxiv.org/abs/2102.00442

SPD **Technical Design Report** was presented firstly in Jan 2023, is updating now and should pass via the international expertise in 2024

http://spd.jinr.ru/wp-content/uploads/2023/03/TechnicalDesignReport_SPD2023.pdf

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

Proton structure: Hall of Fame

hermes

PHENIX

STAR

GLUEX

COMPASS

CLAS12

SeaQuest
E906

SPIN
QUEST

SoLID

sPHENIX

AFTER

LHC spin

AMBER

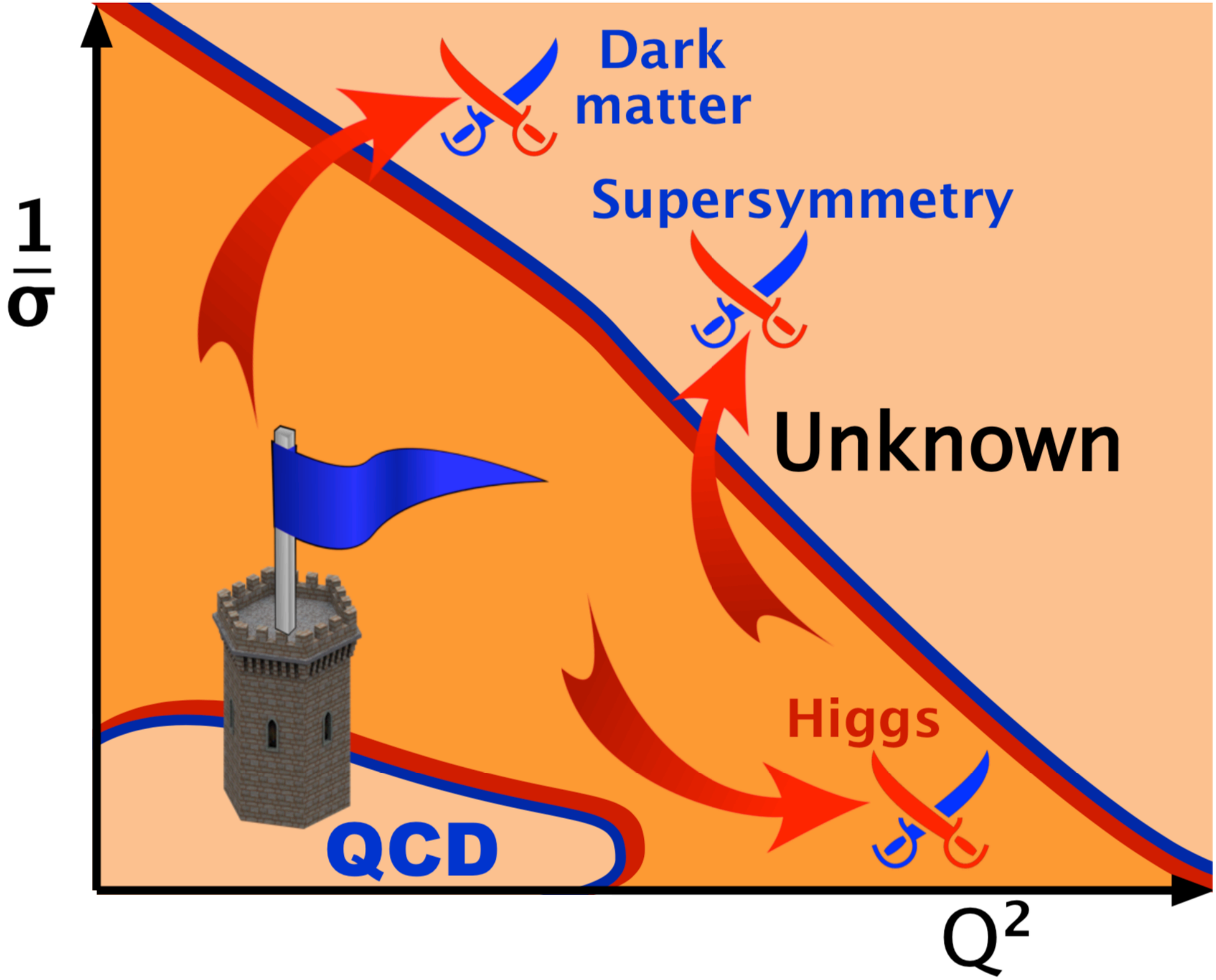
SPD
NICA

ECCE

Summary

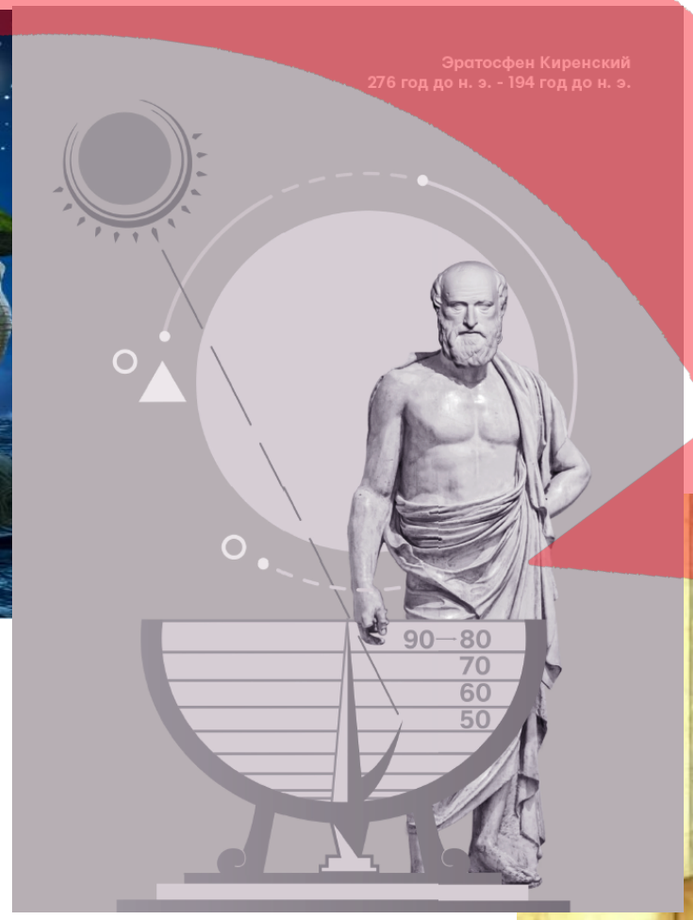
- The **Spin Physics Detector** at the NICA collider is a universal facility for comprehensive study of polarized and unpolarized **gluon content of proton and deuteron**; in polarized high-luminosity **p-p** and **d-d** collisions at $\sqrt{s} \leq 27\ GeV$;
- Complementing main probes such as **charmonia** (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

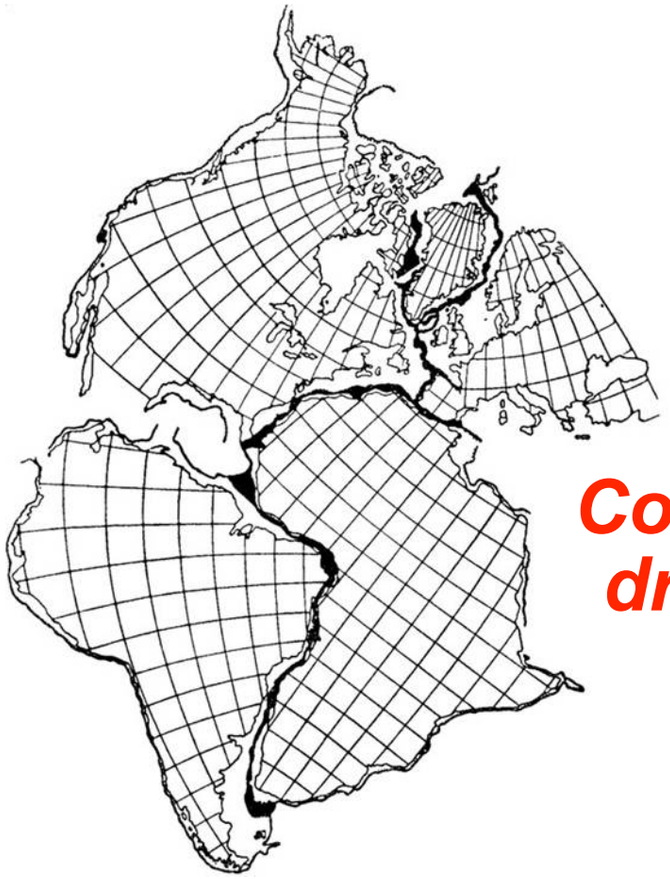


Growth of Knowledge

Naive concepts



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



Continental drift, 1912

Age of Discoveries, XV-XIX centuries