Physics with SPD experiment at NICA Collider

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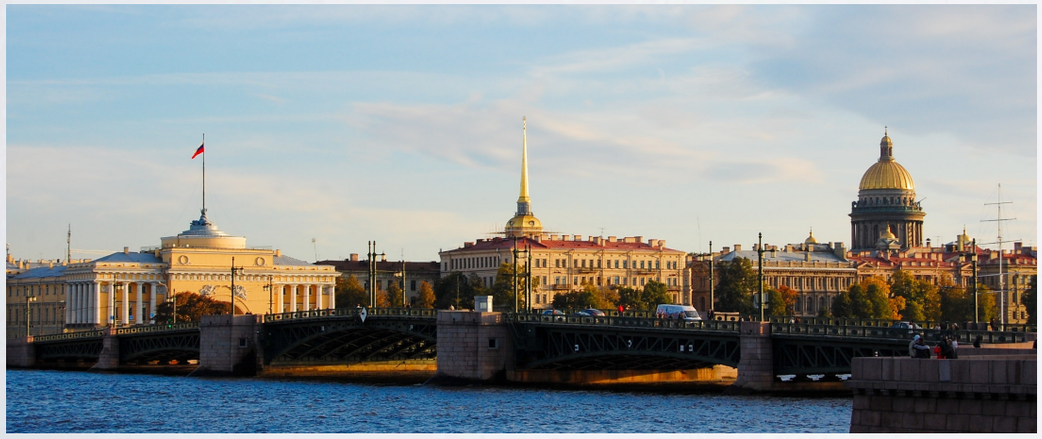
on behalf of the SPD Collaboration



The LXXI International conference "NUCLEUS – 2021. Nuclear physics and elementary particle physics. Nuclear physics technologies"

Main SPD physics goal

Spin Physics Detector (SPD) (http://spd.jinr.ru):
a universal particle physics facility at NICA collider.

➥ **Main SPD goal:**
understanding of the strong interactions using both polarized and unpolarized pp- and dd- collisions at √s up to 27 GeV with high-luminosity.

To this end, it will be studied 3D quark-gluon structure of proton and deuteron with emphasis of gluon PDF and TMDs at high x.

➥ **In addition, it will be carried out a comprehensive program, at the initial period of SPD data taking, for a broad range of particle and nuclear physics**

Parton distribution function (PDF)
Transverse momentum distribution (TMD)

SPD at NICA (JINR, Dubna)

NICA:
Nuclotron-based Ion Collider fAcility

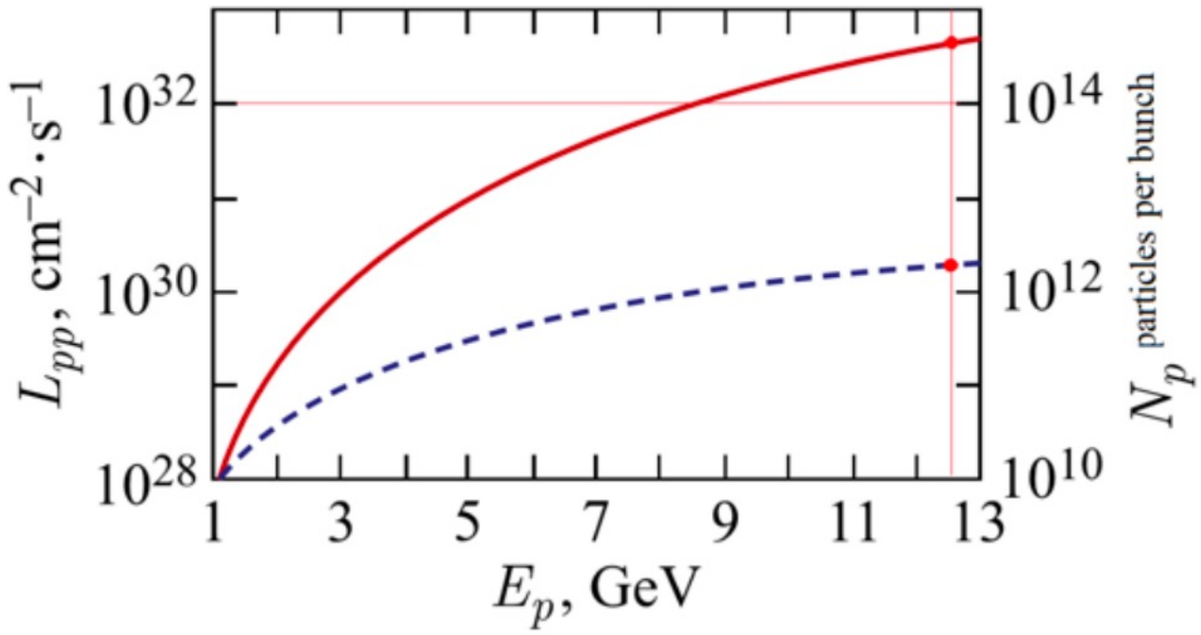
$$p^{\uparrow}p^{\uparrow} : \sqrt{s} \leq 27\ GeV$$

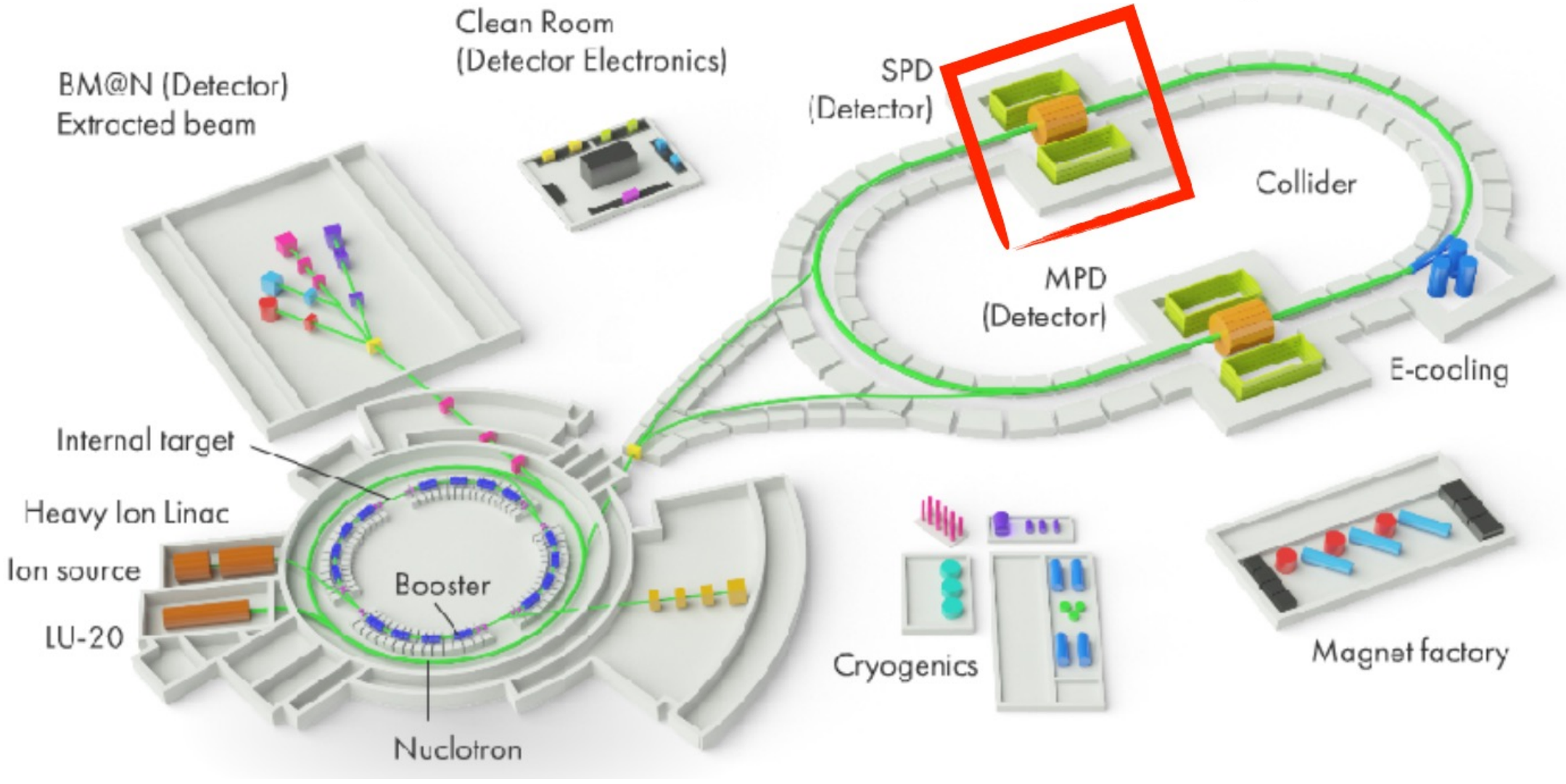
$$d^{\uparrow}d^{\uparrow} : \sqrt{s} \leq 13.5\ GeV$$

$$d^{\uparrow}p^{\uparrow} : \sqrt{s} \leq 19\ GeV$$

U, L, T

|P|>70%

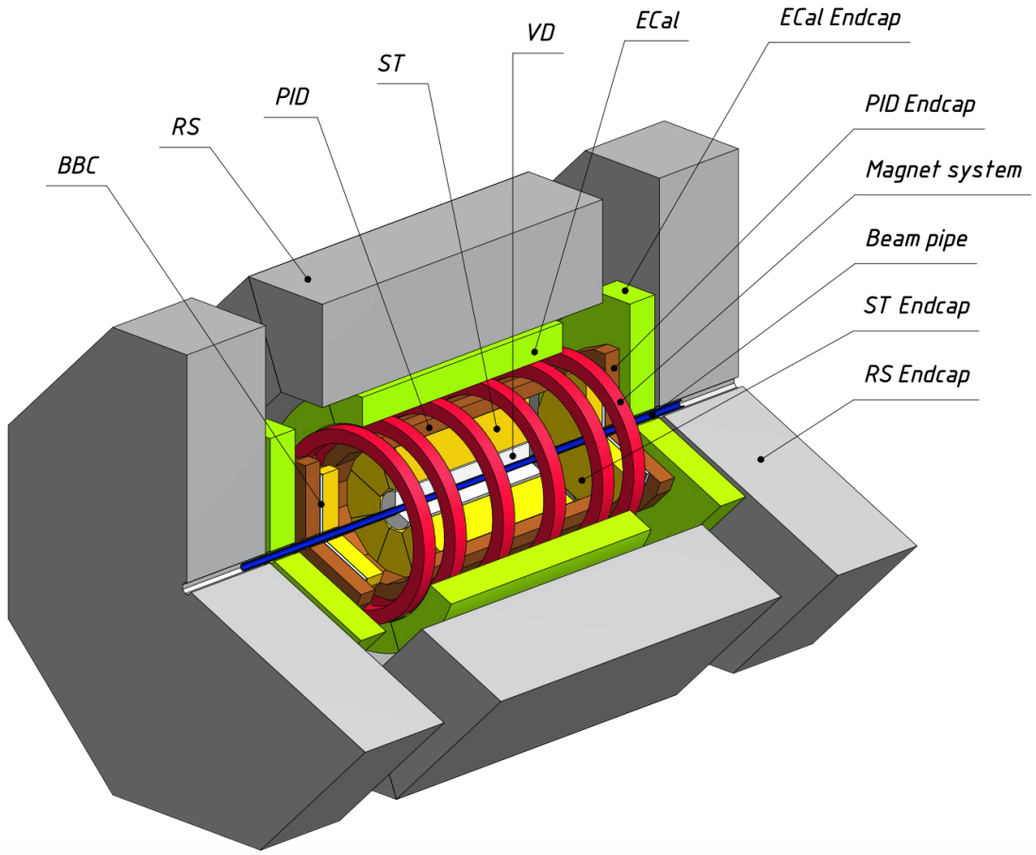


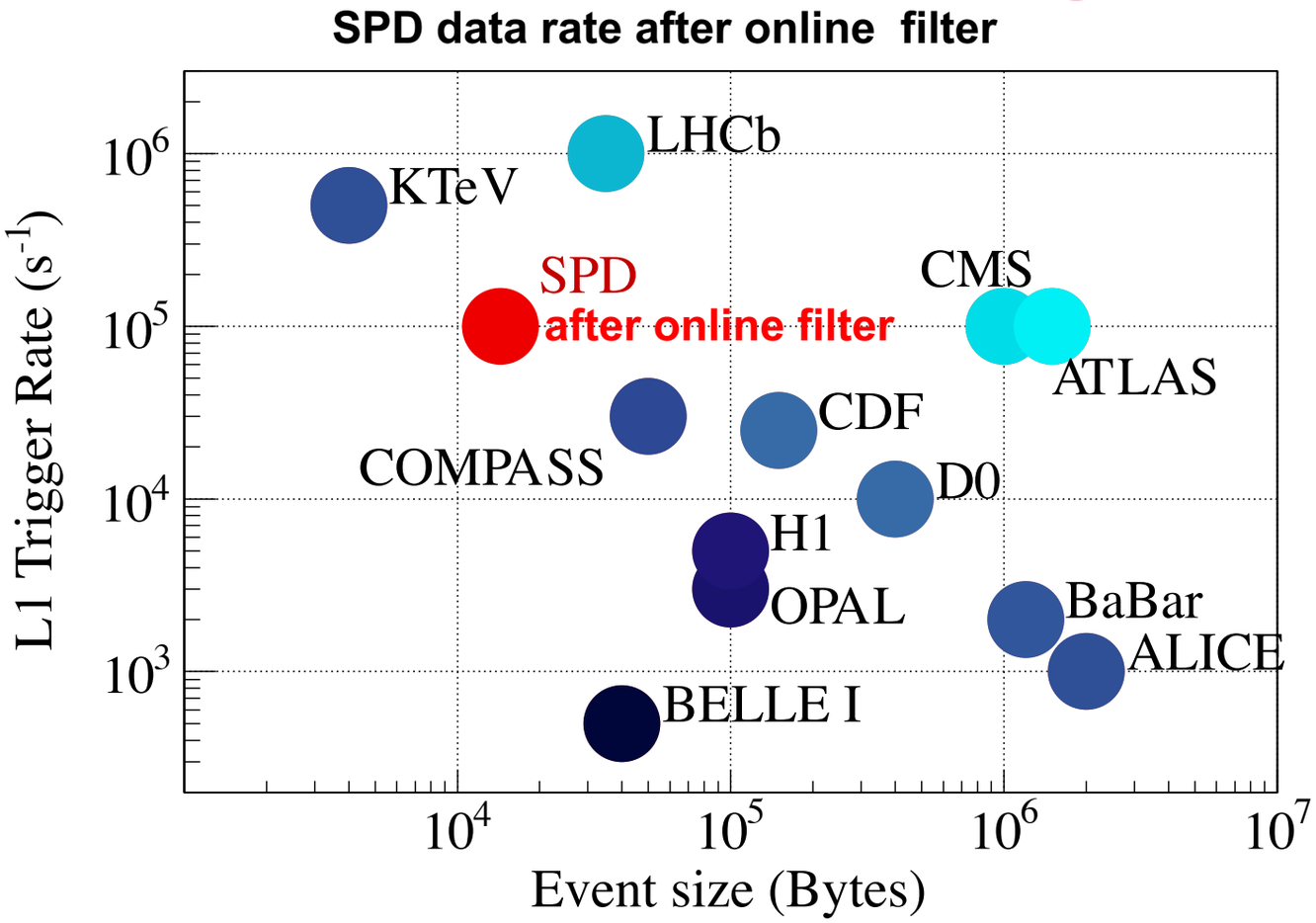


NICA site at JINR, Dubna: May 2021

SPD detector data flow

No hardware trigger at the SPD detector to avoid a possible bias:
3 MHz event/s at 10^{32} cm^2/s design luminosity
20 GB/s ➡ 3 10^3 events/year ➡ 200 PB/year



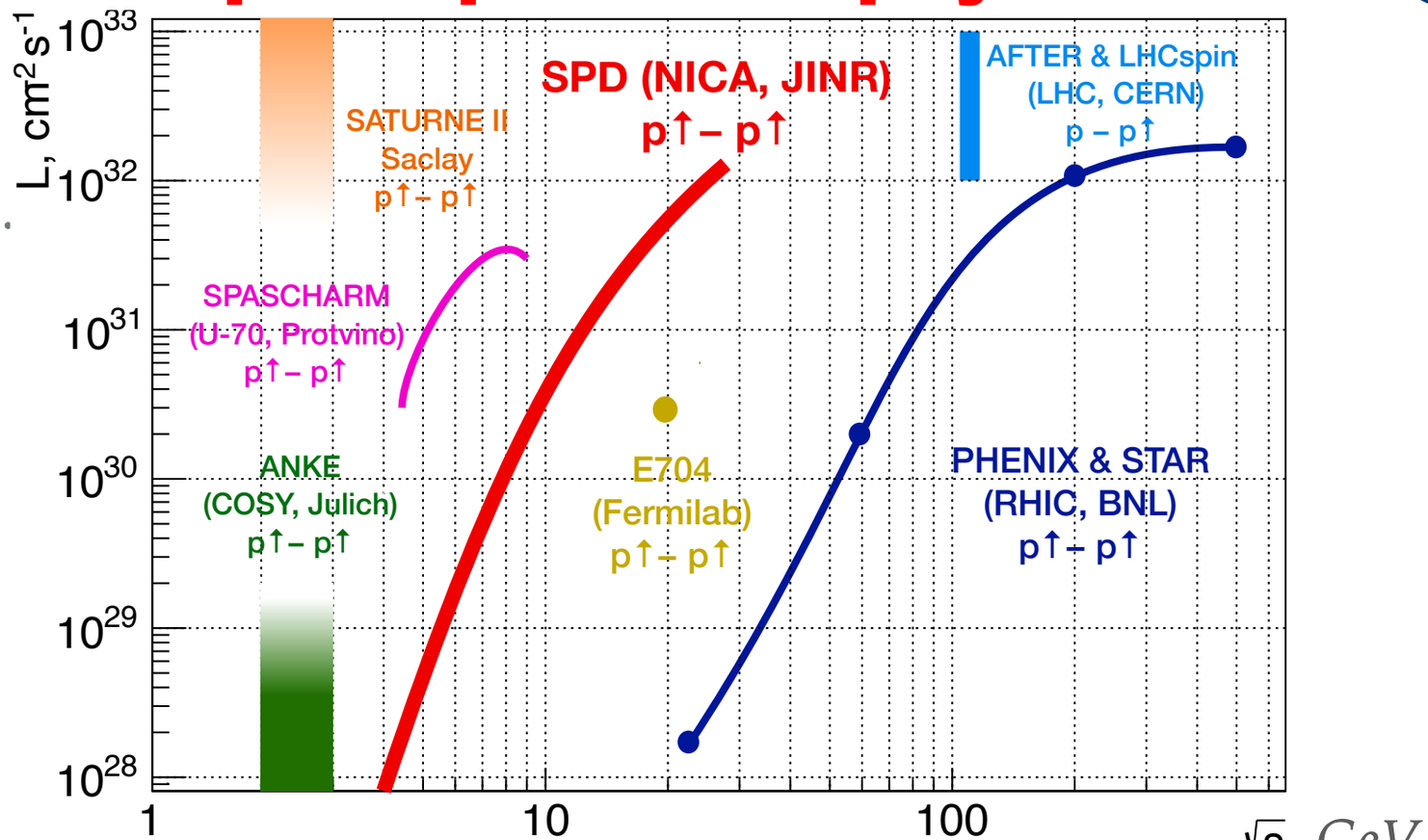


The SPD setup is a medium scale detector in size, but a large scale one in data rate!

Comparable in data rate with ATLAS and CMS at LHC

SPD in World landscape of polarized physics

p↑ p↑-mode ➡



Experimental facility	SPD @NICA	RHIC	EIC	AFTER @LHC	LHCspin
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-$d^{\uparrow}$	$p^{\uparrow}$-$p^{\uparrow}$	$e^{\uparrow}$-$p^{\uparrow}$, $d^{\uparrow}$, $^3He^{\uparrow}$	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

⬅ SPD is unique in d↑ d↑-mode!

SPD project timeline

2007 Idea of SPD project is included to NICA activities at JINR

2014 SPD Letter of Intent is approved by JINR PAC

2016, 2018 SPD-oriented workshops in Prague

2019 SPD project is approved by JINR PAC (up to 2022)
The 1st SPD proto-Collaboration meeting

2020 Completion of SPD Conceptual Design Report
http://arxiv.org/abs/2102.00442
Two SPD-physics papers were submitted for publication

2021 SPD Collaboration is established
Preparation of SPD Technical Design Report is started

2025+ Start of SPD operation

SPD Collaboration: established in July 2021

Spin Physics Detector

The NICA-SPD Collaboration, July 2021

Armenia
Belarus
Chile
China
Cuba
Czechia
Egypt
France
Italy
Poland
Russia
Serbia
South Africa
Ukraine

33 laboratories and individual contributors from 14 countries

~ 300 participants

SPD Physics highlights

► **Spin Physics Detector (SPD) at NICA (http://spd.jinr.ru):**
a universal setup for comprehensive study of
polarized and unpolarized gluon content of proton and deuteron
in polarized and unpolarized high-luminosity pp- and dd- collisions at $\sqrt{s} \leq 27$ GeV

► **Complementing main probes: charmonia (J/Psi, higher states),**
open charm and direct photons in inclusive and semi-inclusive modes

► **SPD can reveal significant insights on:**
- **gluon helicity structure**
- **unpolarized gluon PDF at high x in proton and deuteron**
- **gluon transversity in deuteron**

► **Comprehensive physics program for the initial period of data taking**
(can be performed even at reduced energy and luminosity)

SPD Physics:

Progress in Particle and Nuclear Physics
Volume 119, July 2021, 103858

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], M. Radici [c], A. Rymbekova [a], V. Saleev [l, a], A. Shipilova [l, a], Qin-Tao Song [s], O. Teryaev [a]

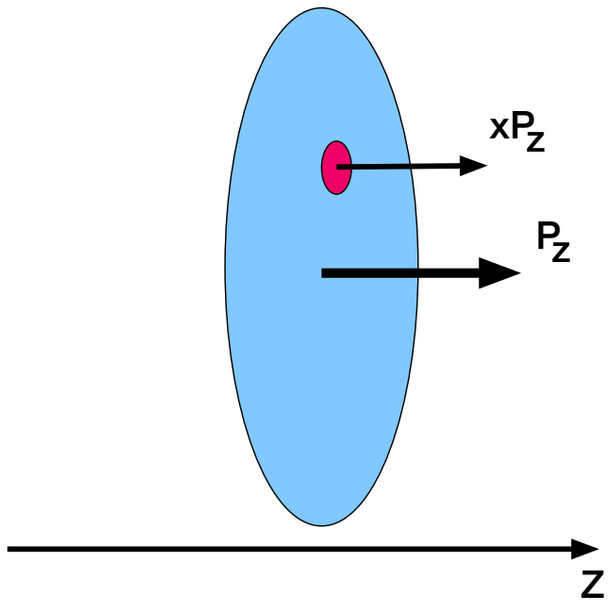
ArXiv e-Print: 2011.15005 [hep-ex]

Possible studies at the first stage of the NICA collider operation with polarized and unpolarized proton and deuteron beams

V. V. Abramov [1], A. Aleshko [2], V. A. Baskov [3], E. Boos [2], V. Bunichev [2], O. D. Dalkarov [3], R. El-Kholy [4], A. Galoyan [5], A. V. Guskov [6], V. T. Kim [7, 8], E. Kokoulina [5, 9], I. A. Koop [10, 11, 12], B. F. Kostenko [13], A. D. Kovalenko [5], V. P. Ladygin [5], A. B. Larionov [14, 15], A. I. L'vov [3], A. I. Milstein [10, 11], V. A. Nikitin [5], N. N. Nikolaev [16, 26], A. S. Popov [10], V.V. Polyanskiy [3], J.-M. Richard [17], S. G. Salnikov [10], A. A. Shavrin [7, 18], P. Yu. Shatunov [10, 11], Yu. M. Shatunov [10, 11], O. V. Selyugin [14], M. Strikman [19], E. Tomasi-Gustafsson [20], V. V. Uzhinsky [13], Yu. N. Uzikov [6, 21, 22, *], Qian Wang [23], Qiang Zhao [24, 25], A. V. Zelenov [7]

to appear in Phys. Elem. Part. At. Nucl. 2021
JINR E2-2021-12
ArXiv e-Print: 2102.08477 [hep-ph]

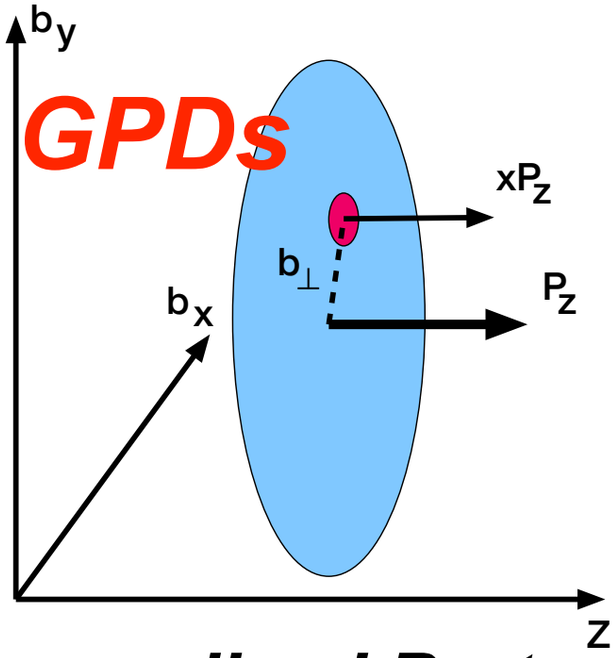
SPD: towards 3D-structure of nucleon



Collinear approximation

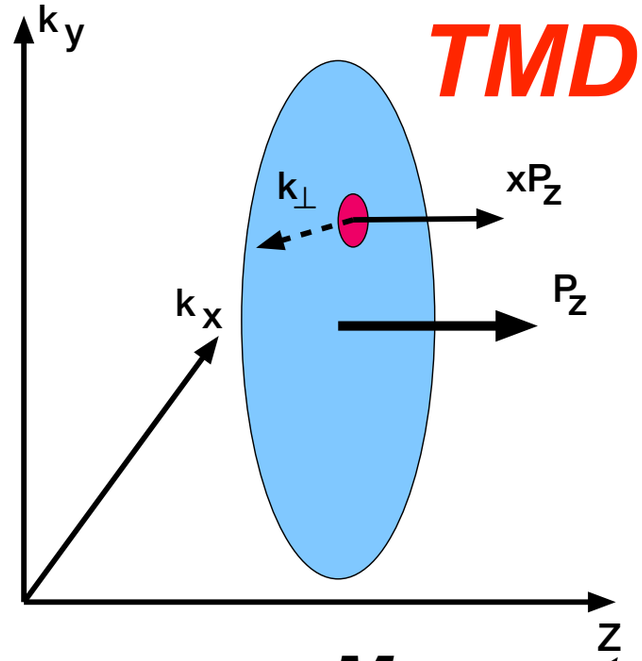
(common PDF)

GPDs

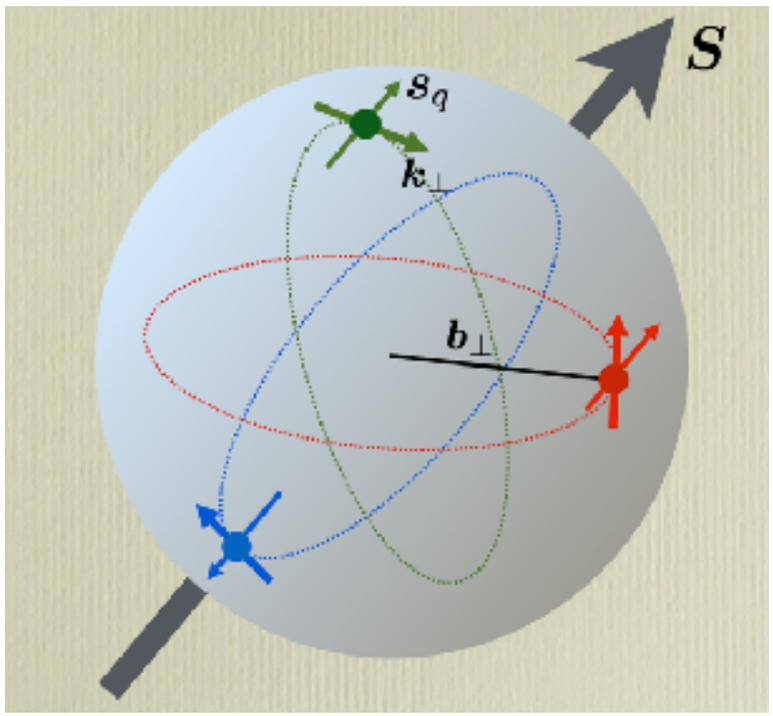


Generalized Parton Distributions

TMD PDFs



Transverse Momentum Dependent PDFs



3D structure of nucleon

connection to orbital moment

Parton Distribution Functions (PDFs): 1D ➡ 3D

Parton 1D-distribitions:

Integrated over kT PDF: $f(x; \log Q^2)$ ⬅ **modulo $\log Q^2$ - DGLAP evolution**

Extension to parton 3D-distribitions:

- **Generalized parton distributions (GPDs): $G(x, b, n; \log Q^2)$**
  b - impact parameter, n – unit vector
- **Unintegrated over kT PDF: $\Phi(x, kT, n; \log Q^2)$ (two theory approaches):**
  - **Unintegrated collinear PDF (uPDF)**
  - **Transverse momentum distribution (TMD)**

TMD: quarks in polarized nucleon

Nucleon (N) with momentum P and spin polarization S=(U,L,T)

New information in quark TMD of nucleon: $\Phi^q(x, P, S)$

$\Phi^q(x, P, S)$ contains time-even functions:

$f^q(x, kT)$ ⬅ unpolarized quarks in unpolarized N ⬅ density

$g^g_L(x, kT)$ ⬅ L-polarized (chiral) quarks in L-polarized N ⬅ helicity

$g^g_T(x, kT)$ ⬅ L-polarized (chiral) quarks in T-polarized N ⬅ worm-gear

$h^q_T(x, kT)$ ⬅ T-polarized quarks in T-polarized N ⬅ pretzelocity

and time-odd functions (spin-orbital correlations):

$f^{\perp g}_L(x, kT)$ ⬅ unpolarized quarks in T-polarized N ⬅ Sivers f.

$h^{\perp q}_T(x, kT)$ ⬅ T-polarized quarks in unpolarized N ⬅ Boer-Mulders f.

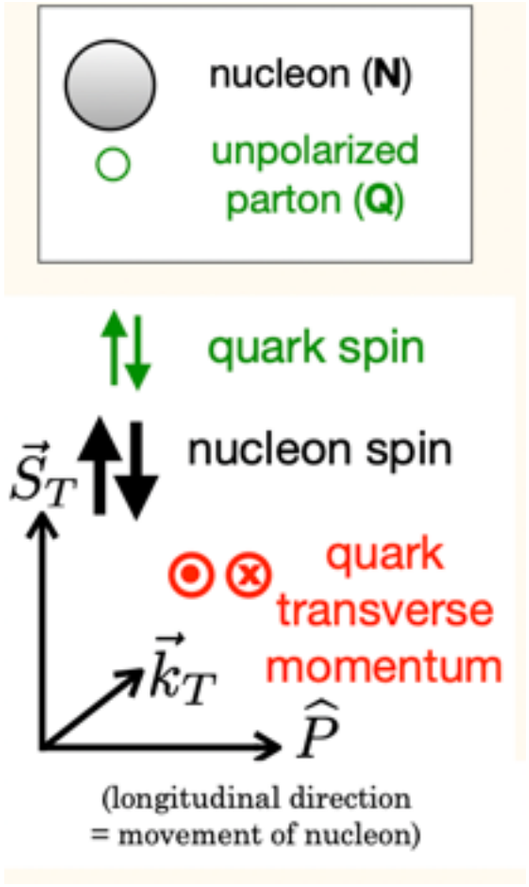
Integrated over kT quark TMDs:

$f^q(x) = q(x) = q_{L=+}(x) + q_{L=-}(x)$

$g^q_L(x) = \Delta q(x) = q_{L=+}(x) - q_{L=-}(x)$ ⬅ helicity (chirality)

$h^q_T(x) = \delta q(x) = q_{T=+}(x) - q_{T=-}(x)$ ⬅ transversity

TMDs: quarks in nucleon



N \ Q	U	L	T
U	f_1 number density		$h_1^\perp$ Boer-Mulders
L		g_1 helicity	$h_{1L}^\perp$ worm-gear
T	$f_{1T}^\perp$ Sivers	$g_{1T}^\perp$ worm-gear	h_1 transversity; $h_{1T}^\perp$ pretzelosity

Gluon TMD with SPD

Unpolarized gluons at high x in proton and deuteron

Gluon helicity

Gluon Boer-Mulders function

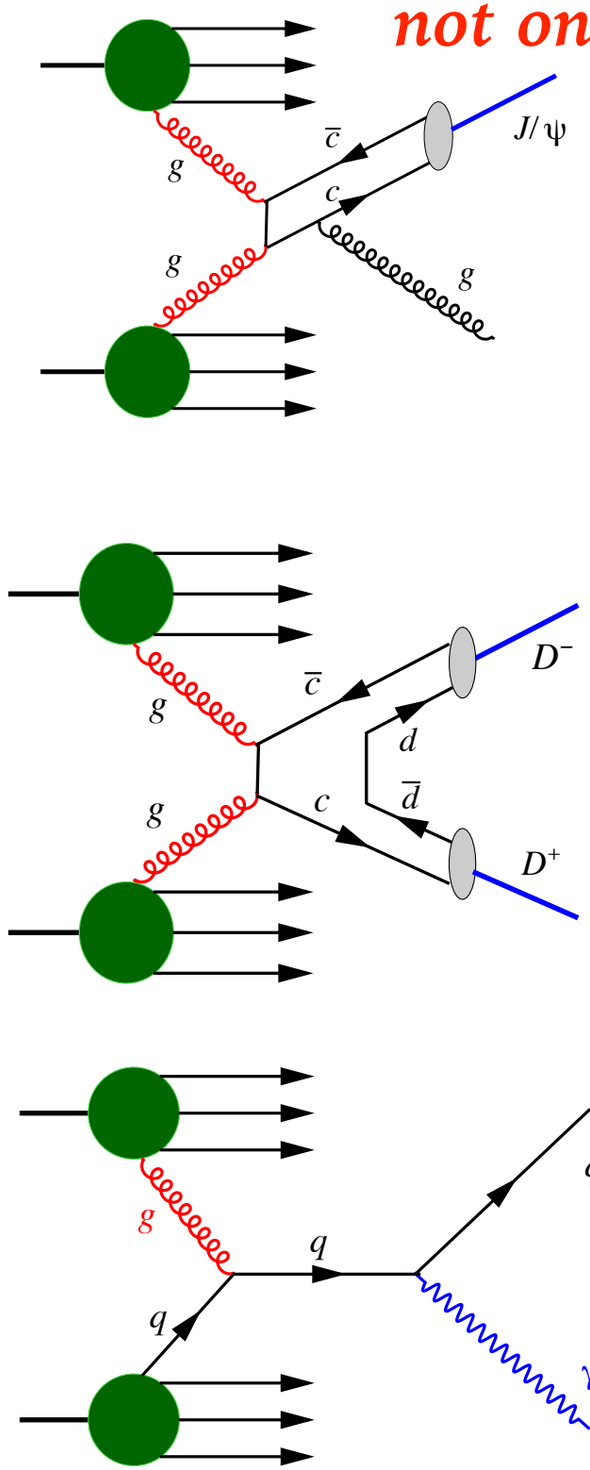
GLUONS	*unpolarized*	*circular*	*linear*
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_{1T}^g, h_{1T}^{\perp g}$

Gluon Sivers function

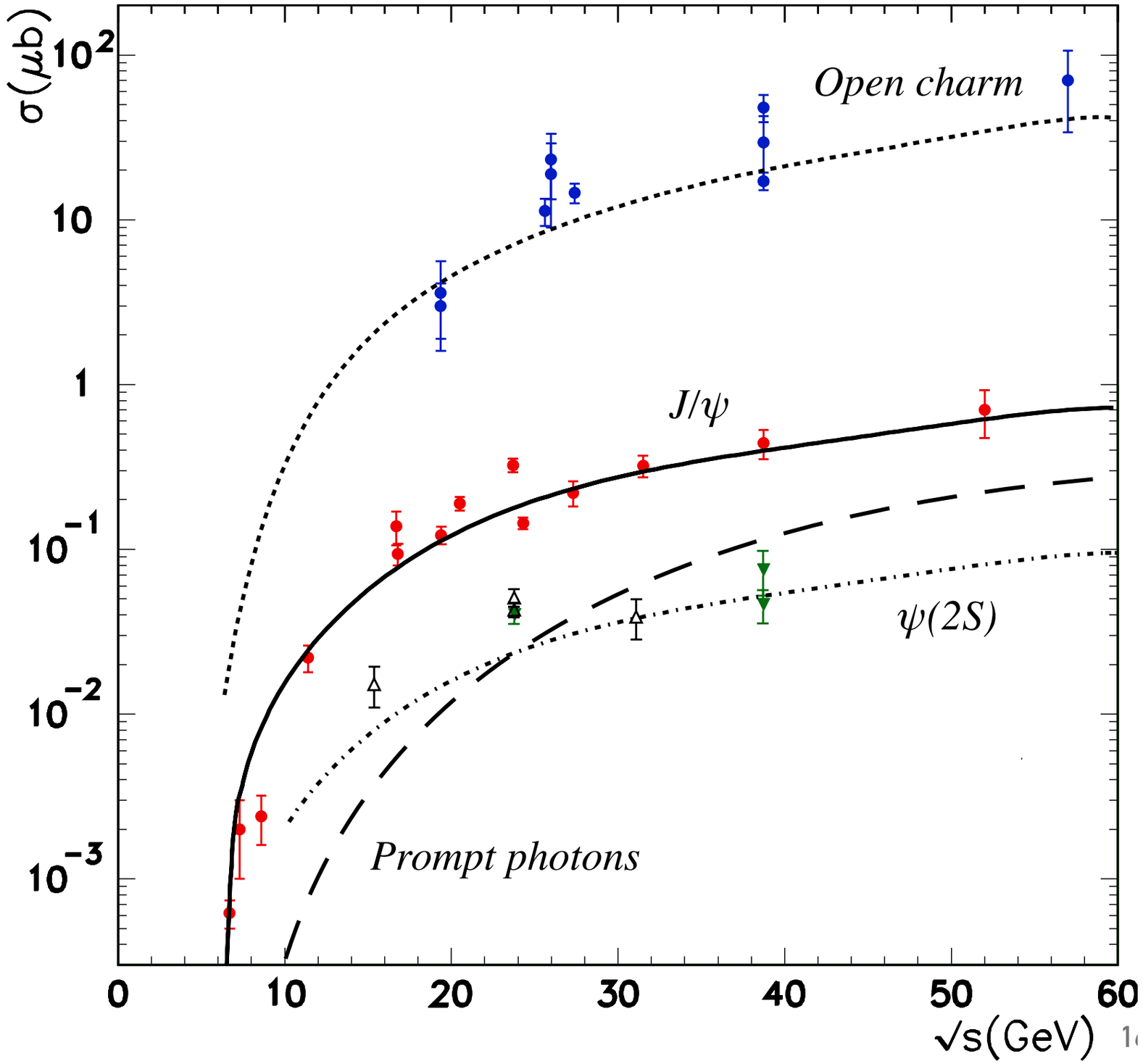
Gluon transversity in deuteron

Gluon probes at SPD: charmonia, open charm, direct photons

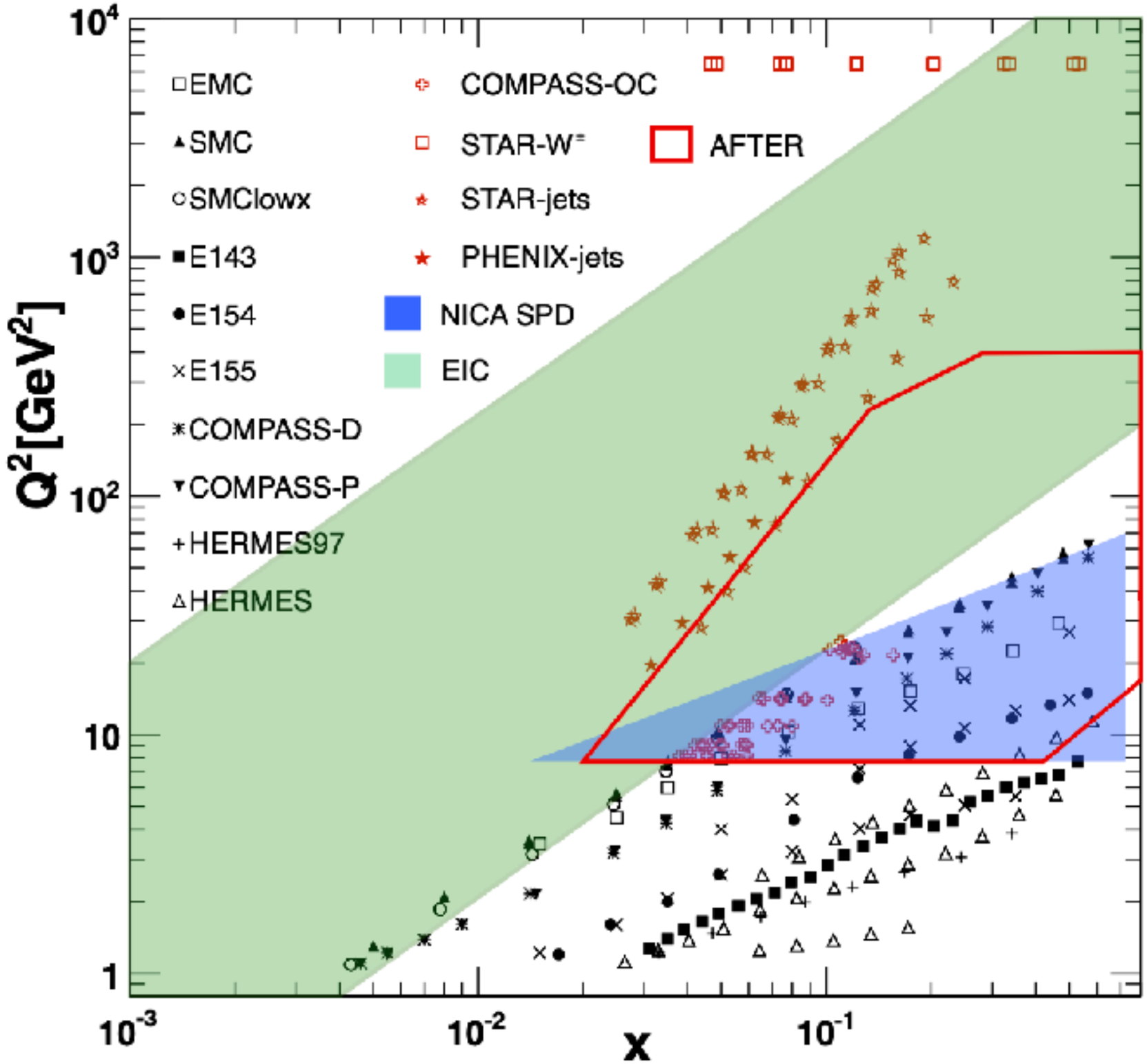
not only J/ψ!



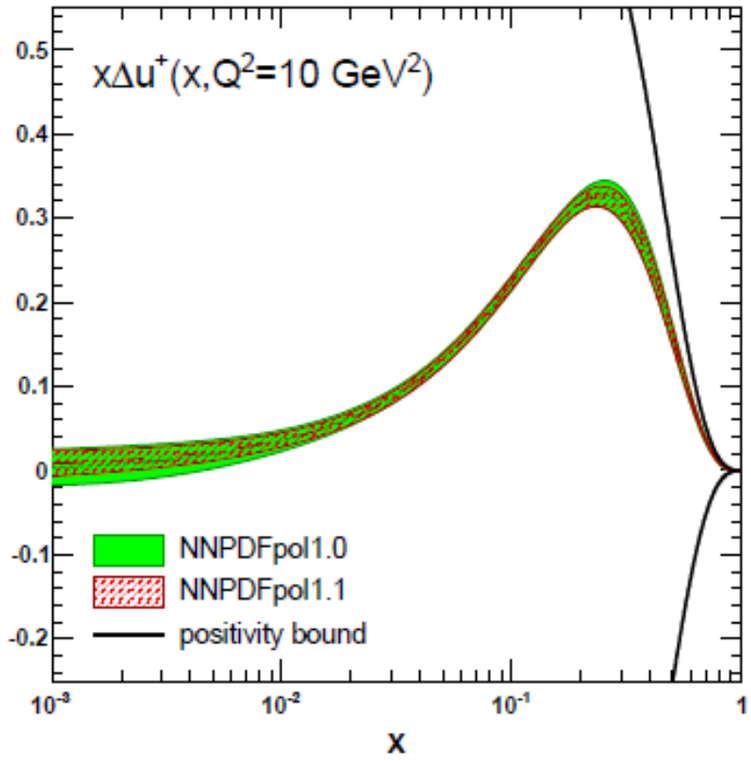
$\sigma = PDF_1 \otimes PDF_2 \otimes \hat{\sigma}_{12}$

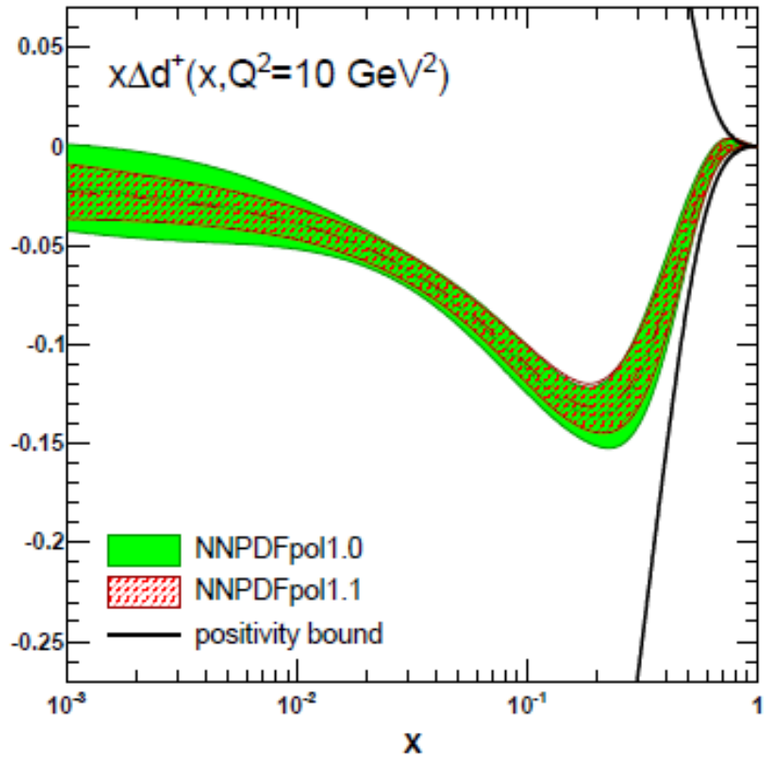


PDF kinematic range



NNPDF Coll.: quark and gluon helicity PDFs of proton

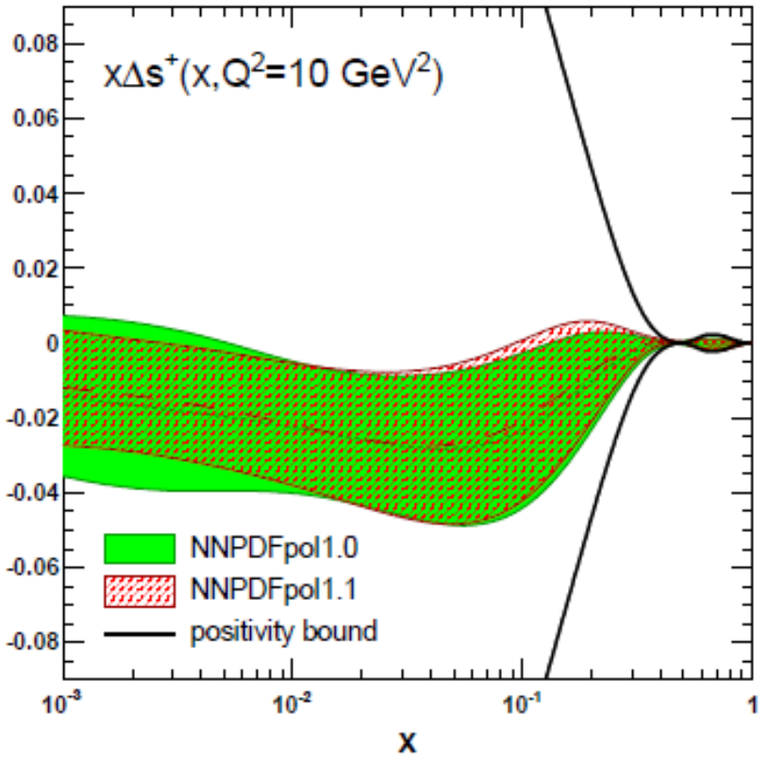


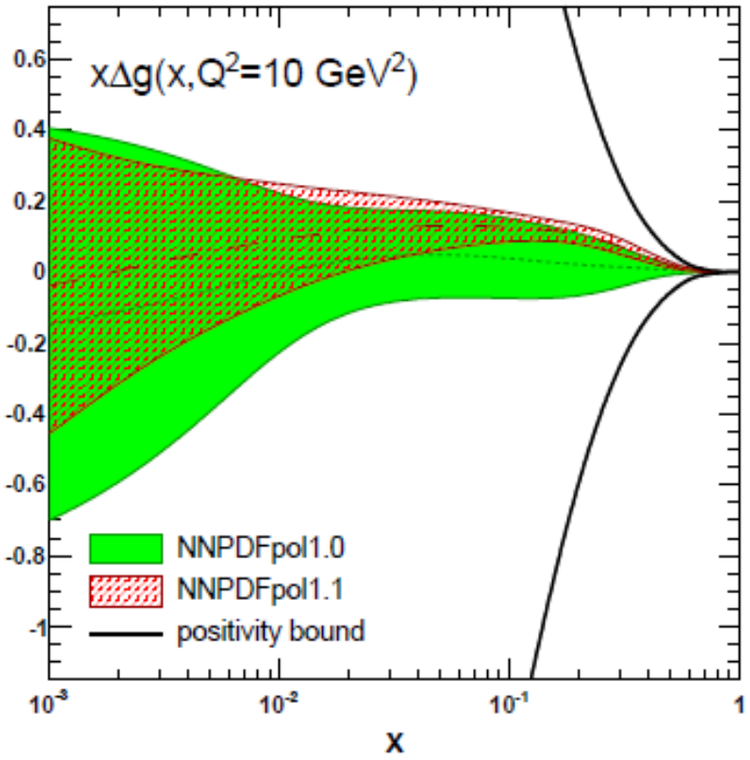


NNPDF Coll.:
E. Nocera et al. (2014)

Quark helicity PDF:
few percent level uncertainties

It is measured with
high precision in DIS



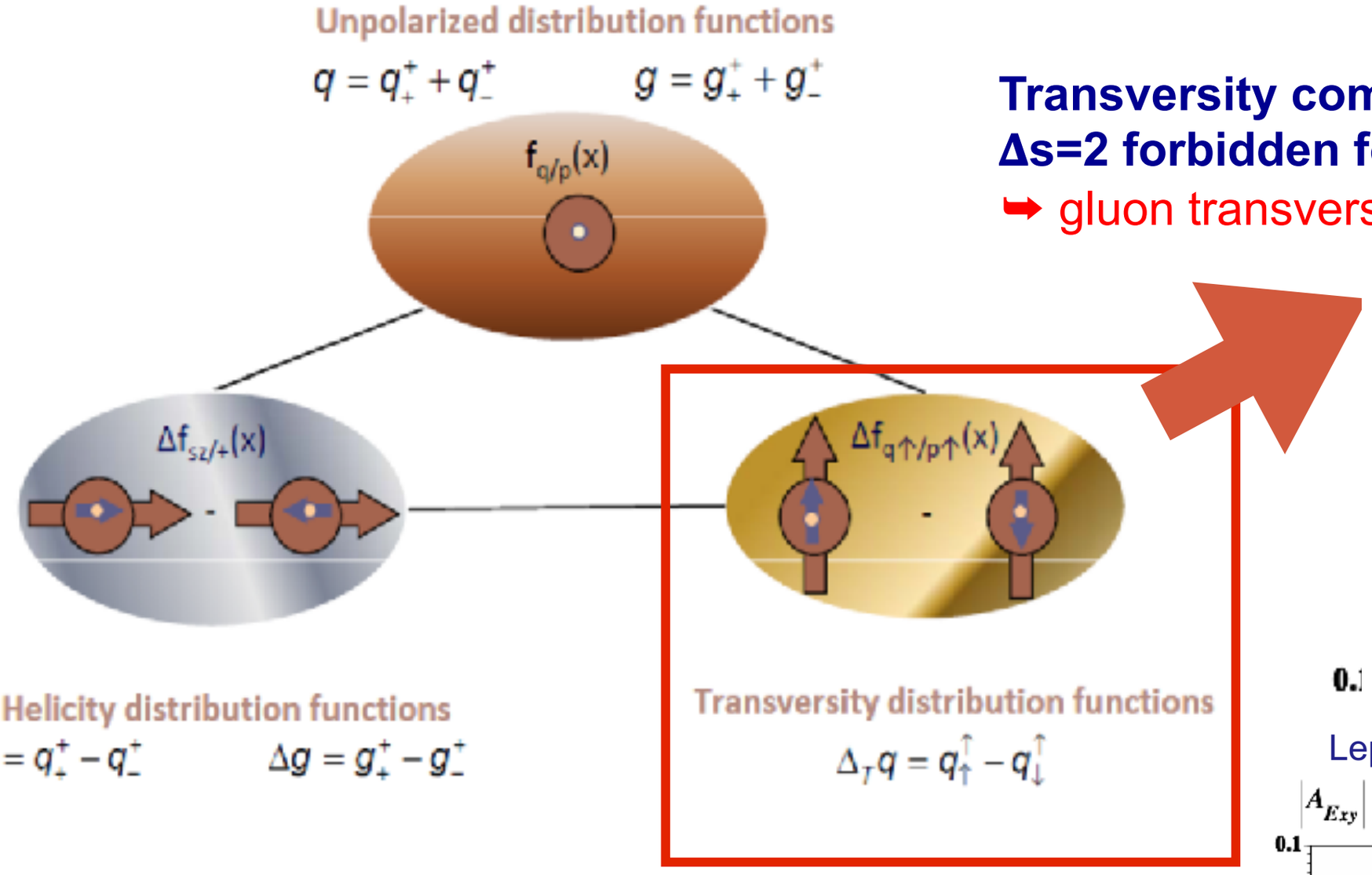


Gluon helicity PDF:
still rather high uncertainties!

Hadron collisions have a better sensitivity to measure it.

⬅ SPD has a good opportunity!

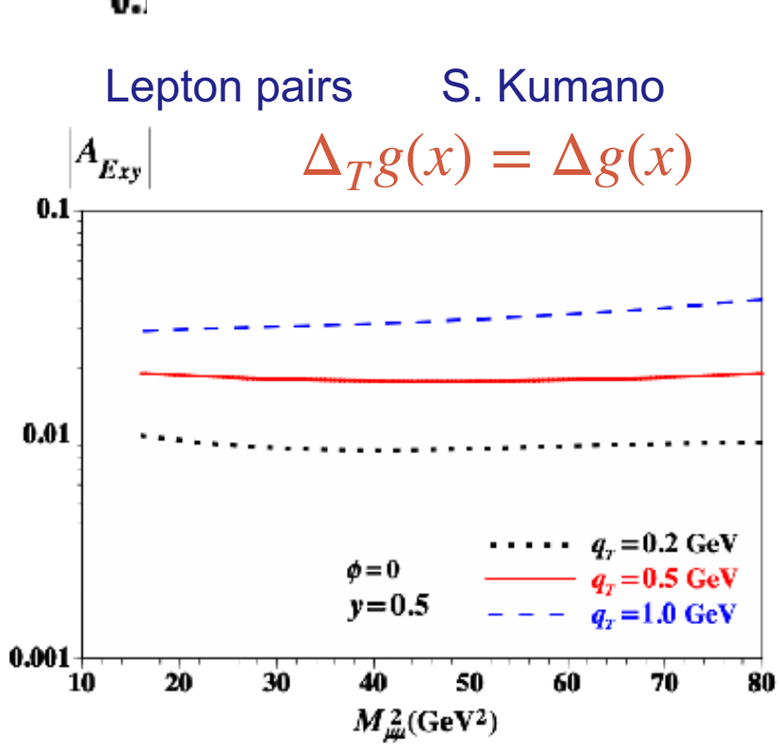
Gluon transversity of deuteron:



Transversity comes from spin-flip:
Δs=2 forbidden for spin-½ nucleon in LO
➥ gluon transversity in nucleon ≈ 0

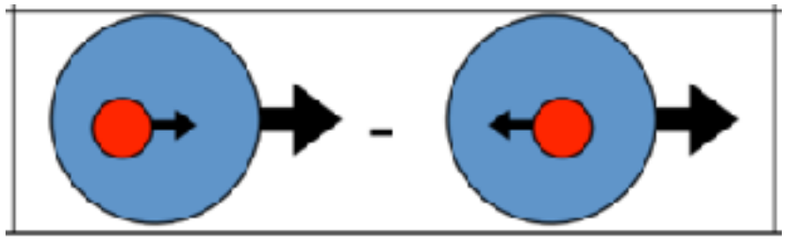
SPD has a unique opportunity to measure
gluon transversity in deuteron for the first time!

To probe new non-nucleonic degrees of freedom in deuteron!

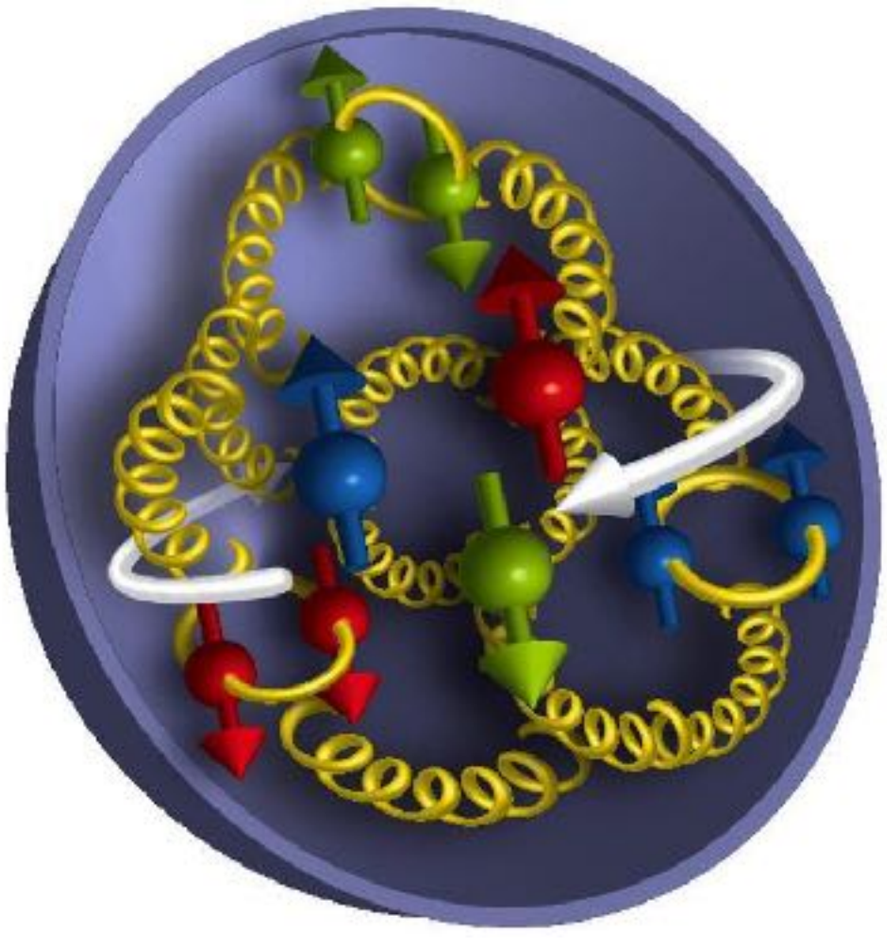


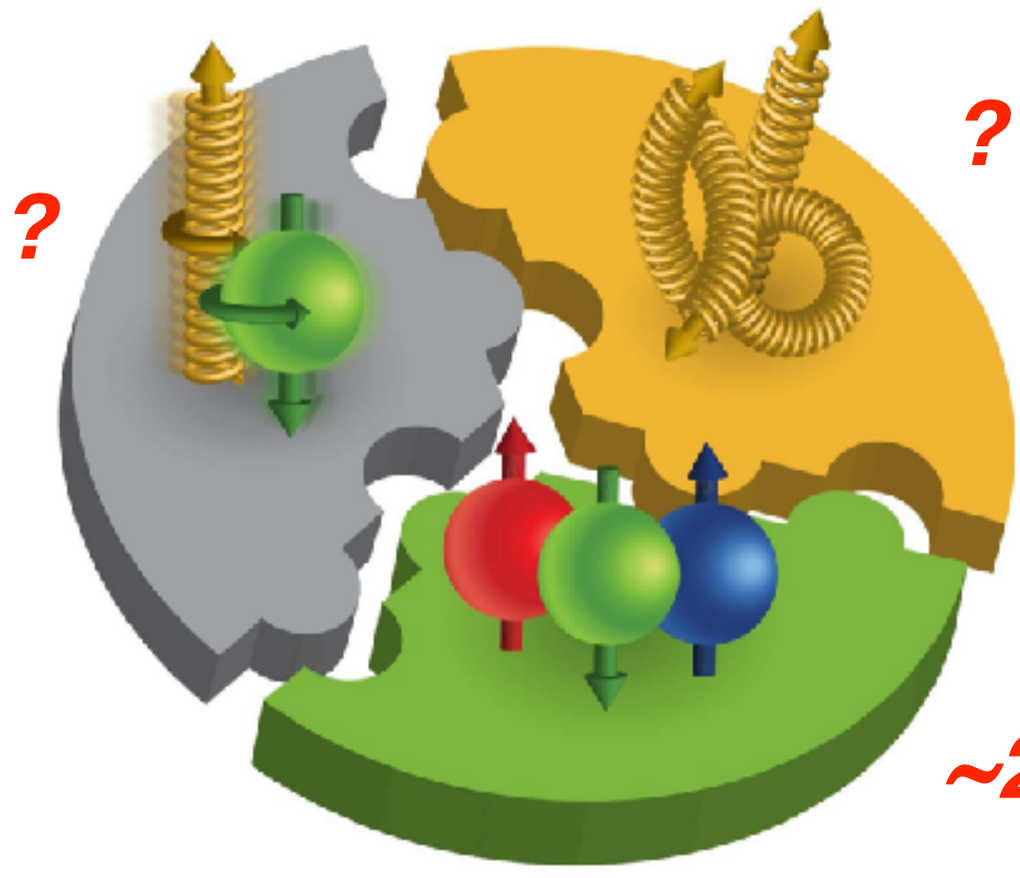
Helicity gluon PDF Δg(x): Spin Crisis

Δg(x) :



$$\Delta G = \int_0^1 \Delta g(x) dx$$



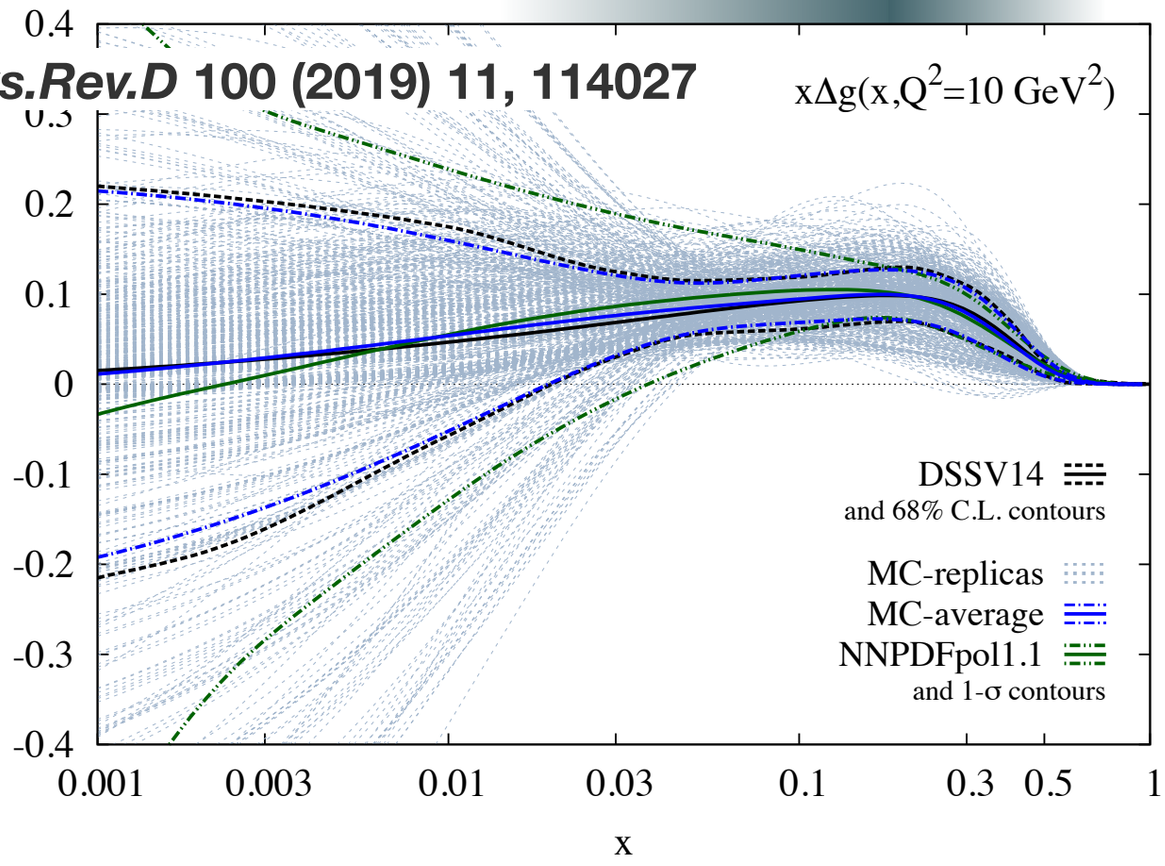


$$S_N = ½ = ½\,\Delta\Sigma + \Delta G + L$$

Helicity gluon PDF Δg(x):

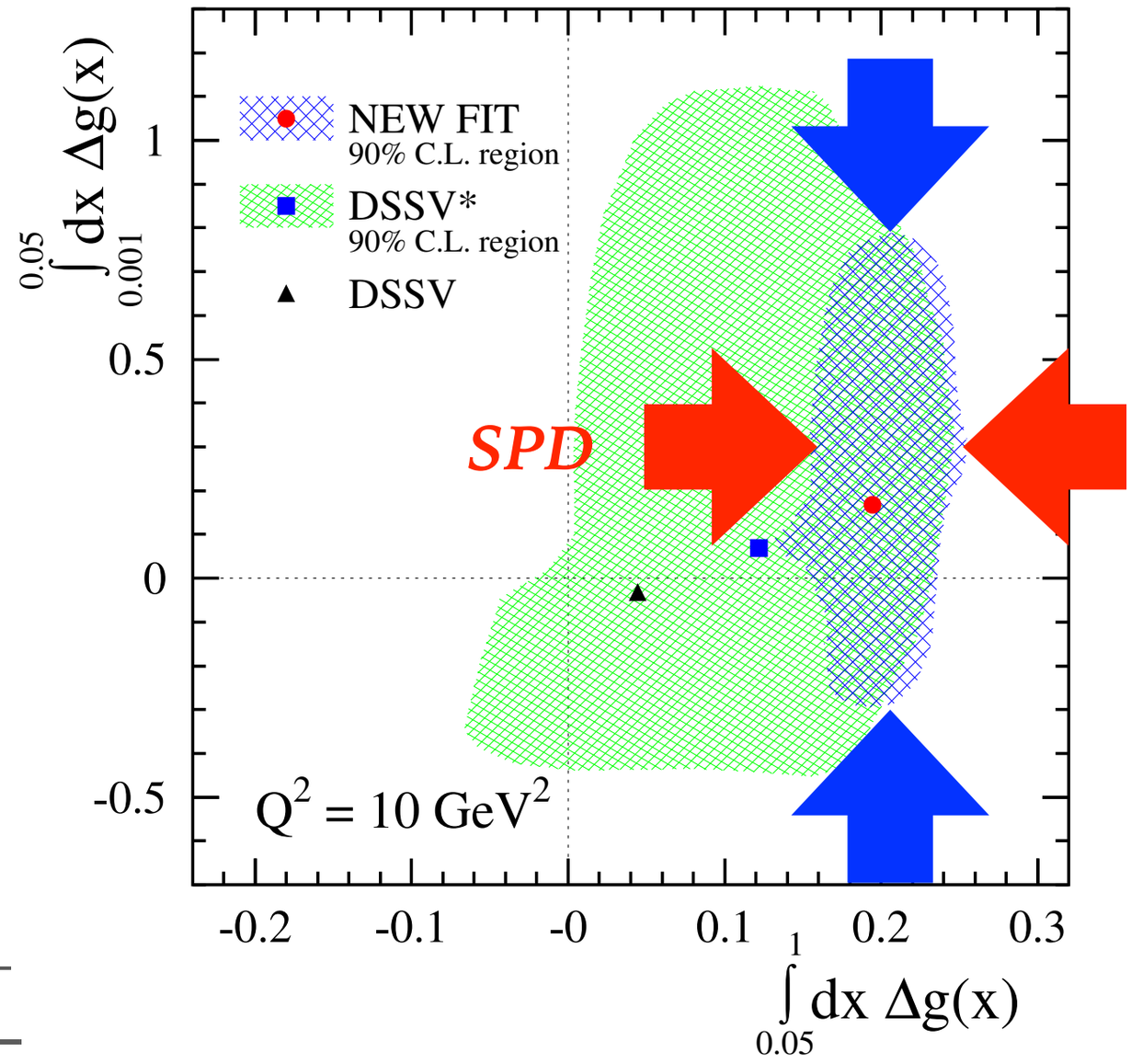
accessible with SPD

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



Phys.Rev.Lett. 113 (2014) 1, 012001

EIC

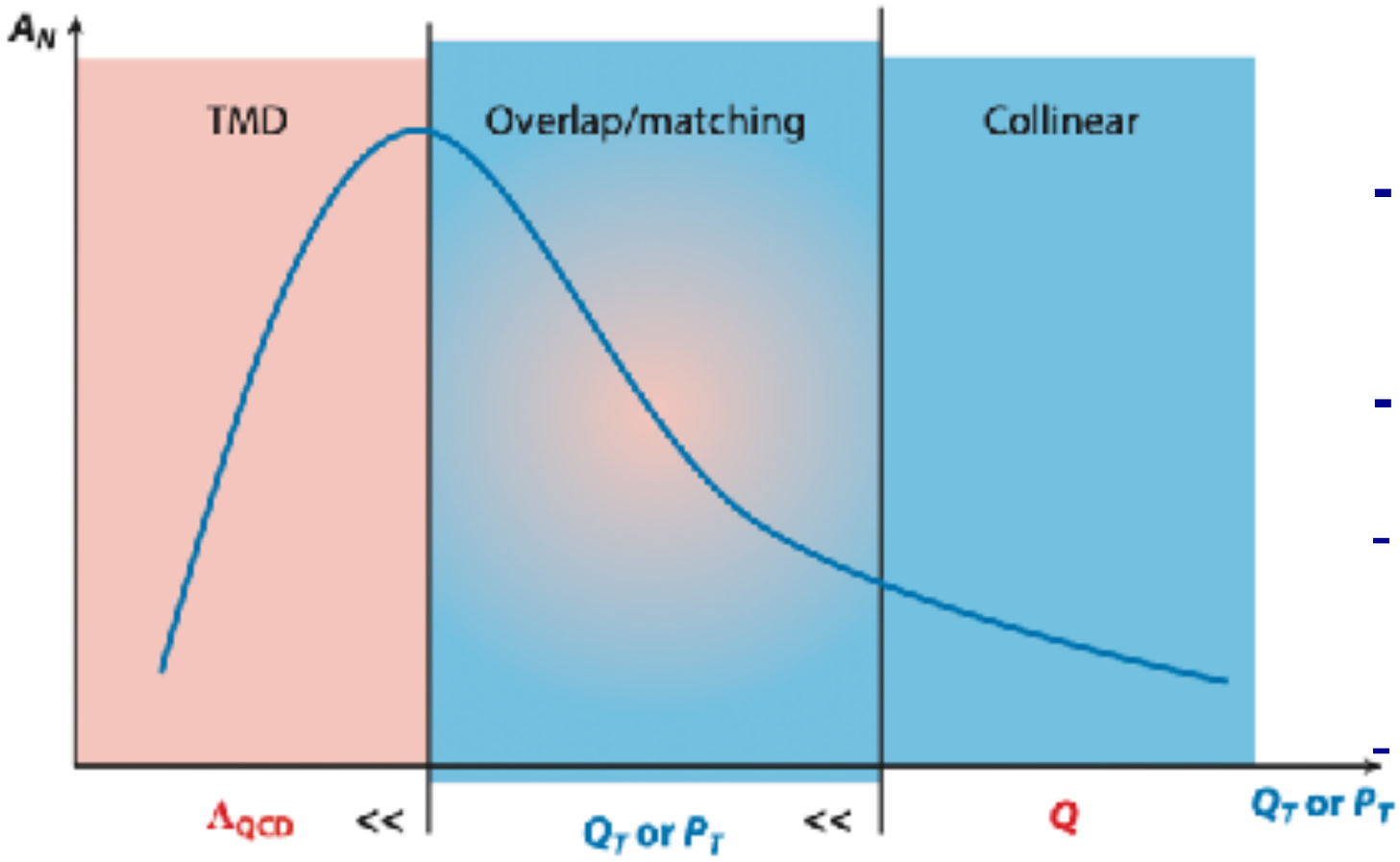


SPD could help to reduce uncertainty of ΔG at large x

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

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

Gluon TMD effects: gluon Sivers function



- Collinear factorization:
  twist-2 and twist-3

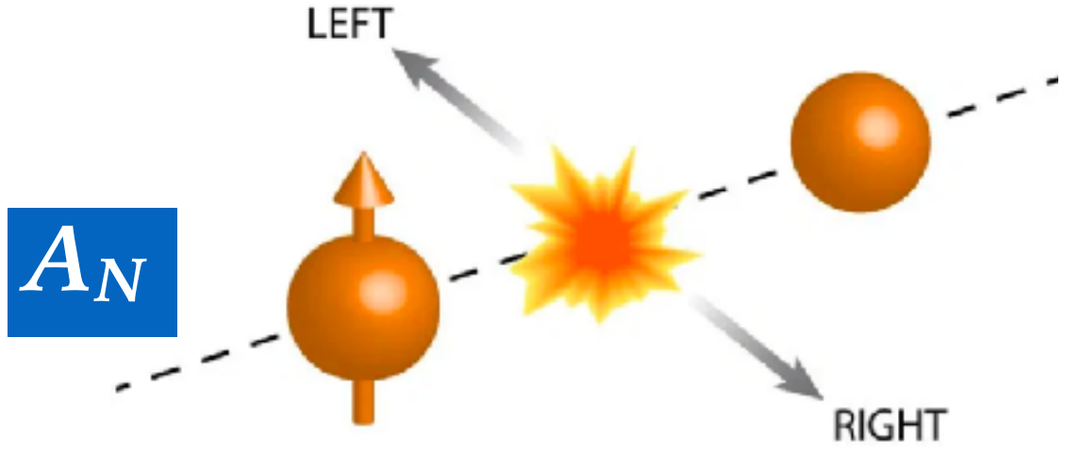
- TMD-factorization

- Overlap/matching region

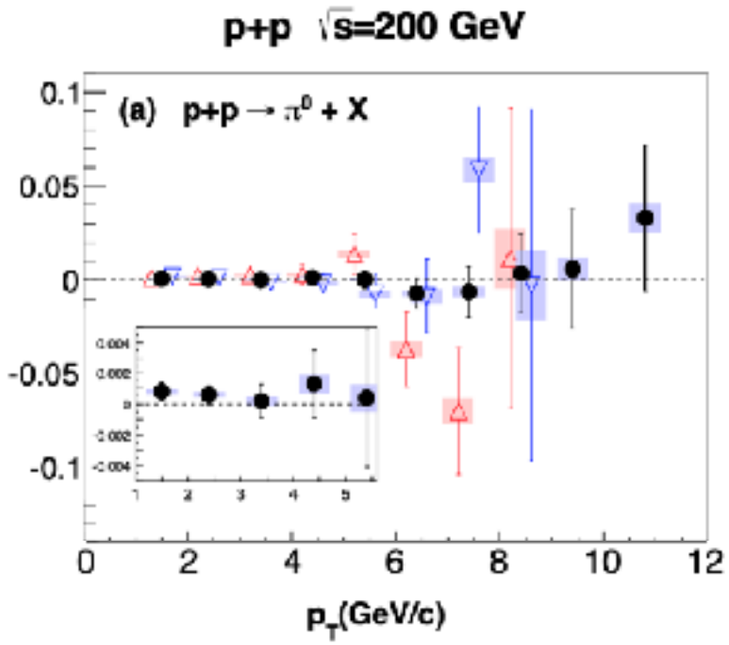
- Nontrivial x and kT correlation?

Sivers effect: L-R asymmetry
of unpolarized kT-distribution
in T-polarized nucleon

Collins effect: due to fragmentation
of polarized parton



Gluon Sivers function

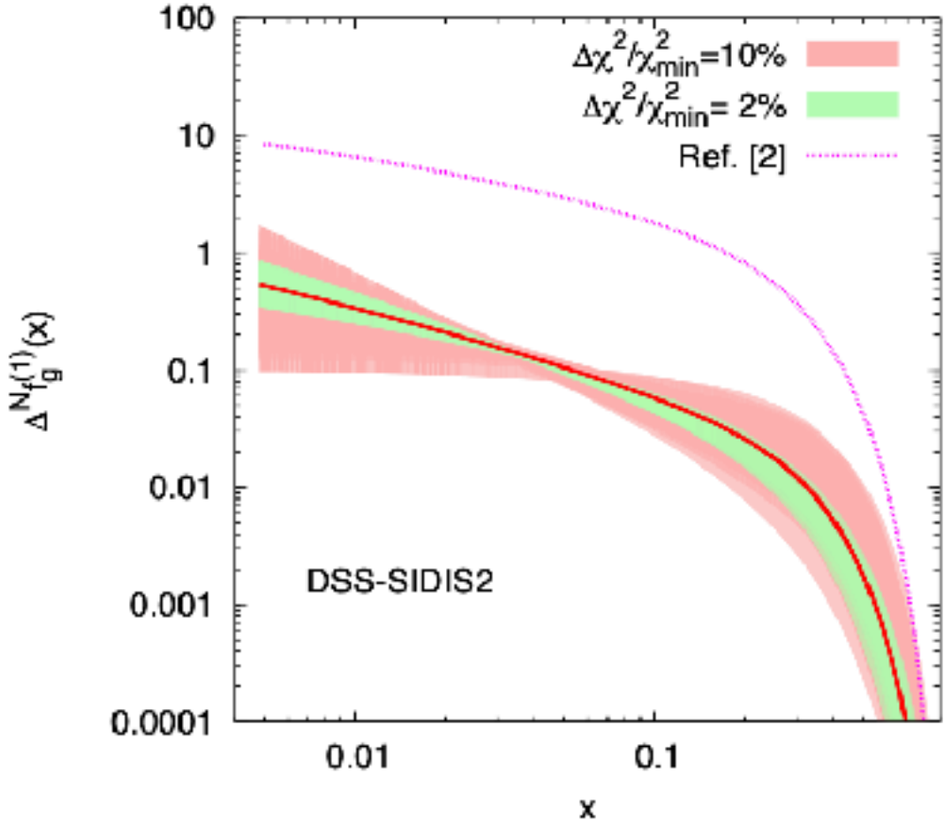


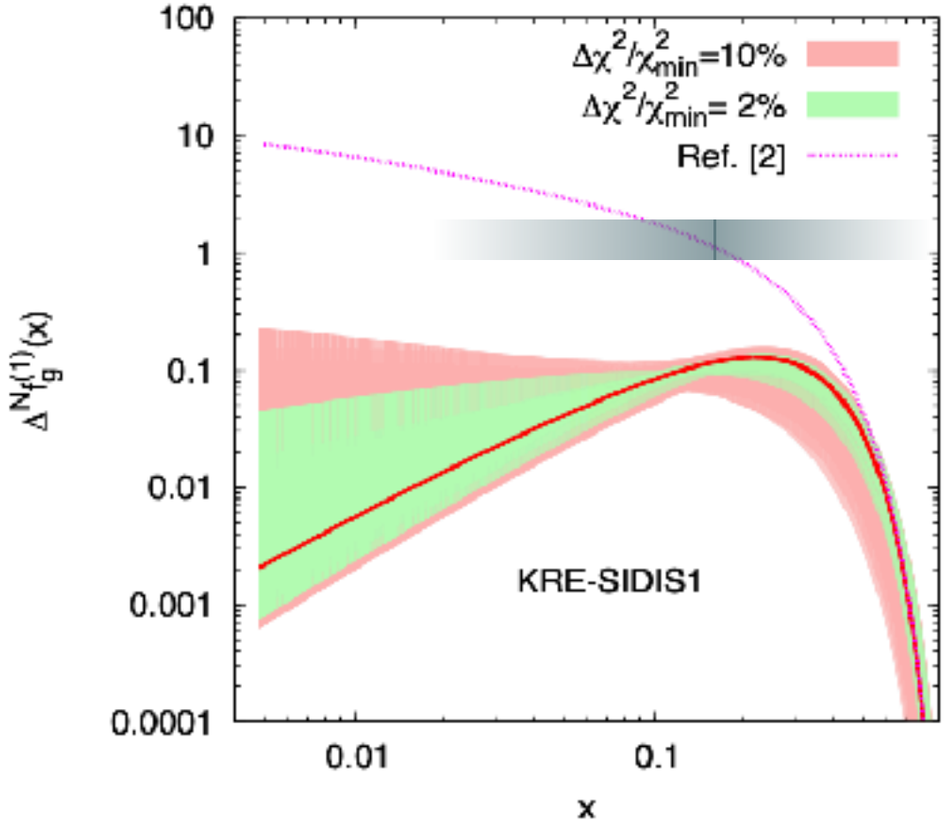
Phys.Rev.D **90 (2014) 1, 012006**

PHENIX

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

***JHEP* 09 (2015) 119**



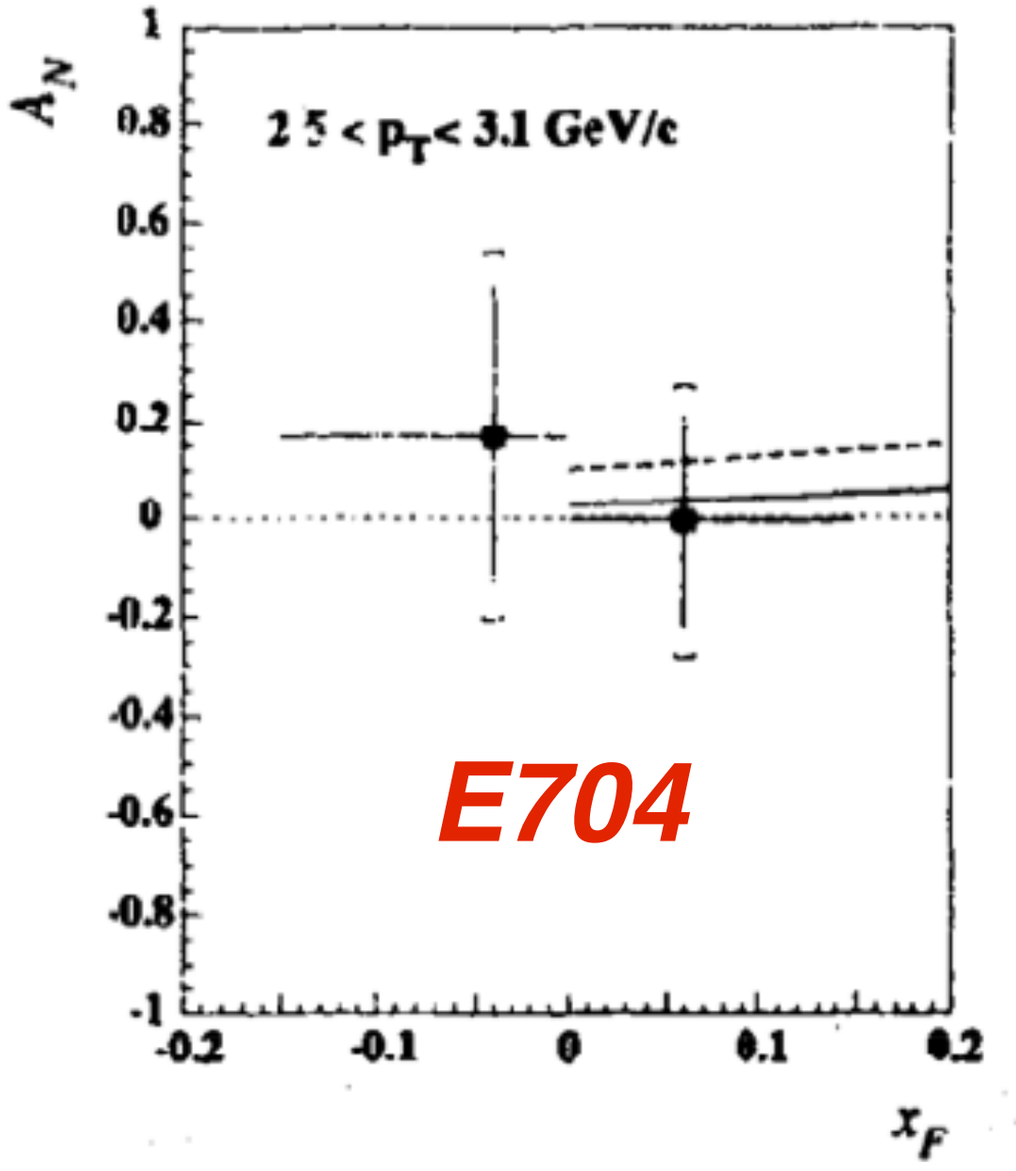


SPD

… and at NICA energies (fixed target at FNAL)

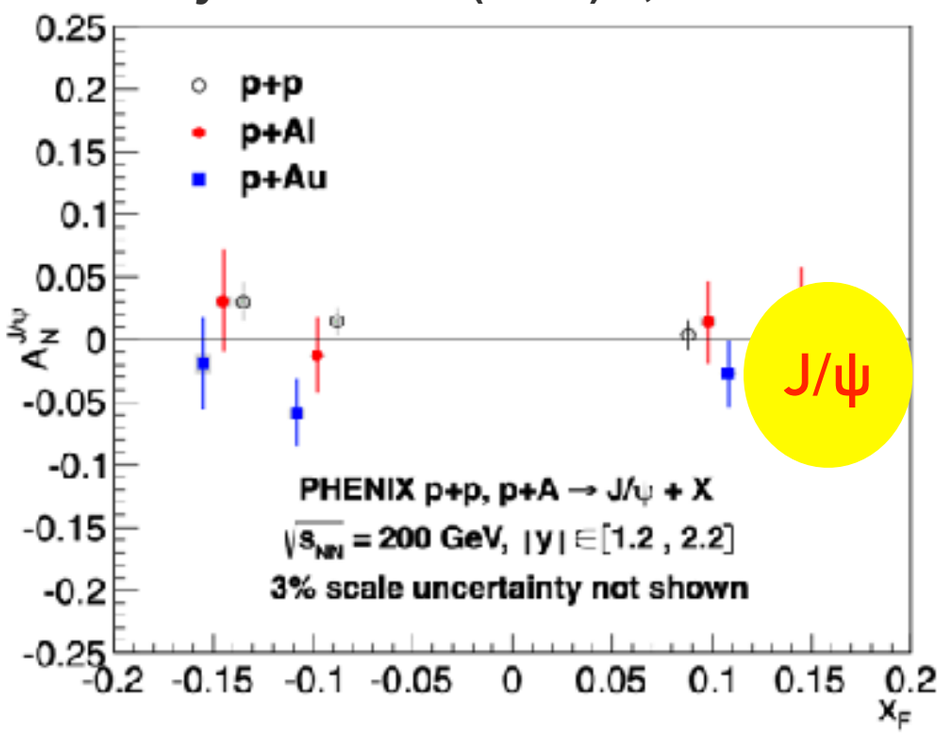
E704 at FNAL: fixed target 200 GeV

Phys. Lett. B 345 (1995)



Gluon induced TMD effects: existing results for A_N

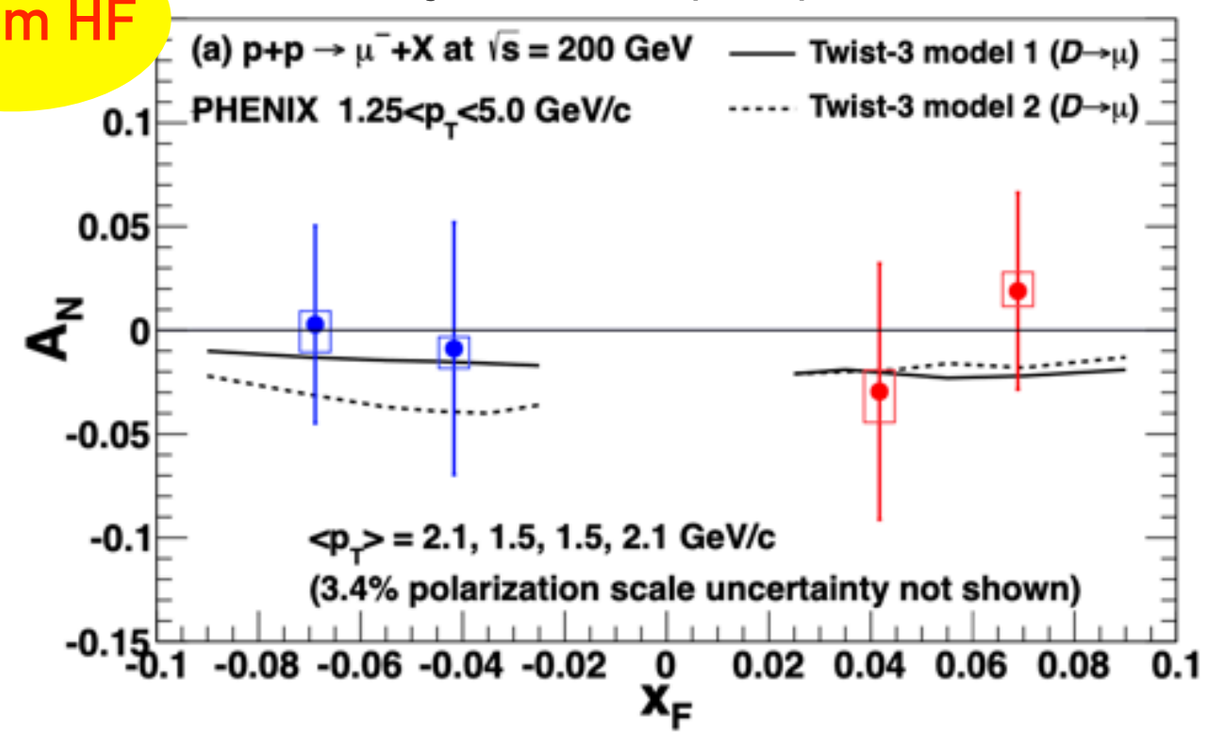
Phys.Rev.D 98 (2018) 1, 012006

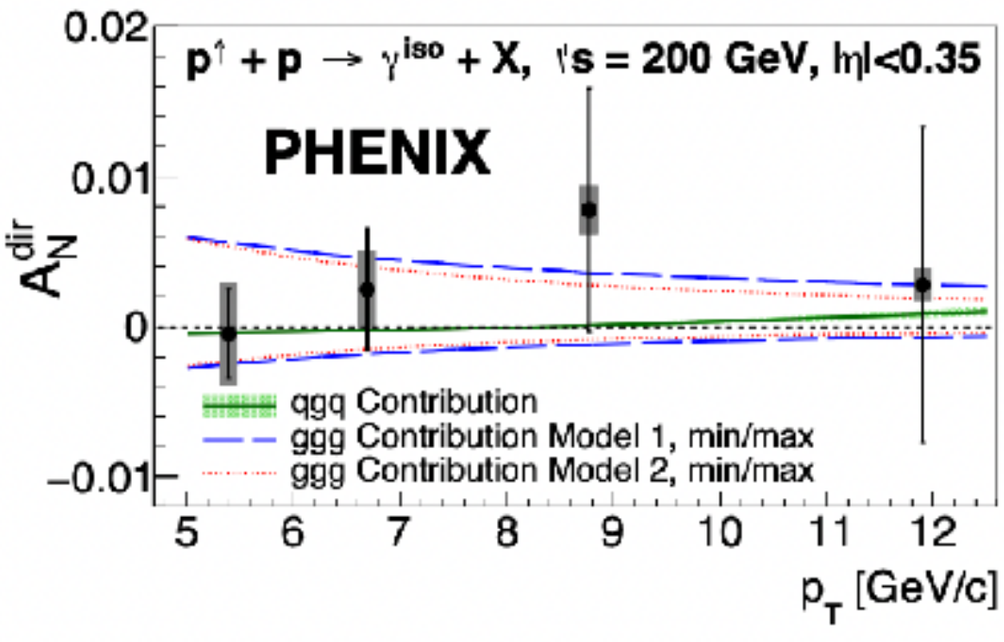


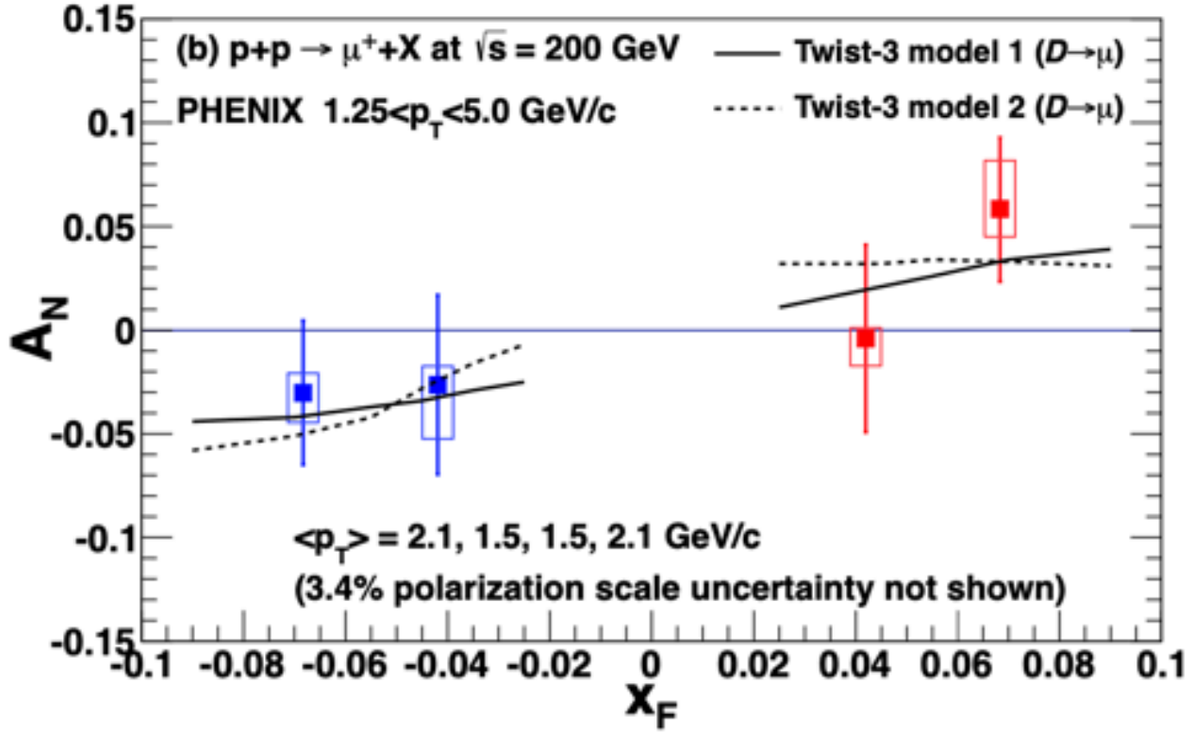
J/ψ

μ from HF

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

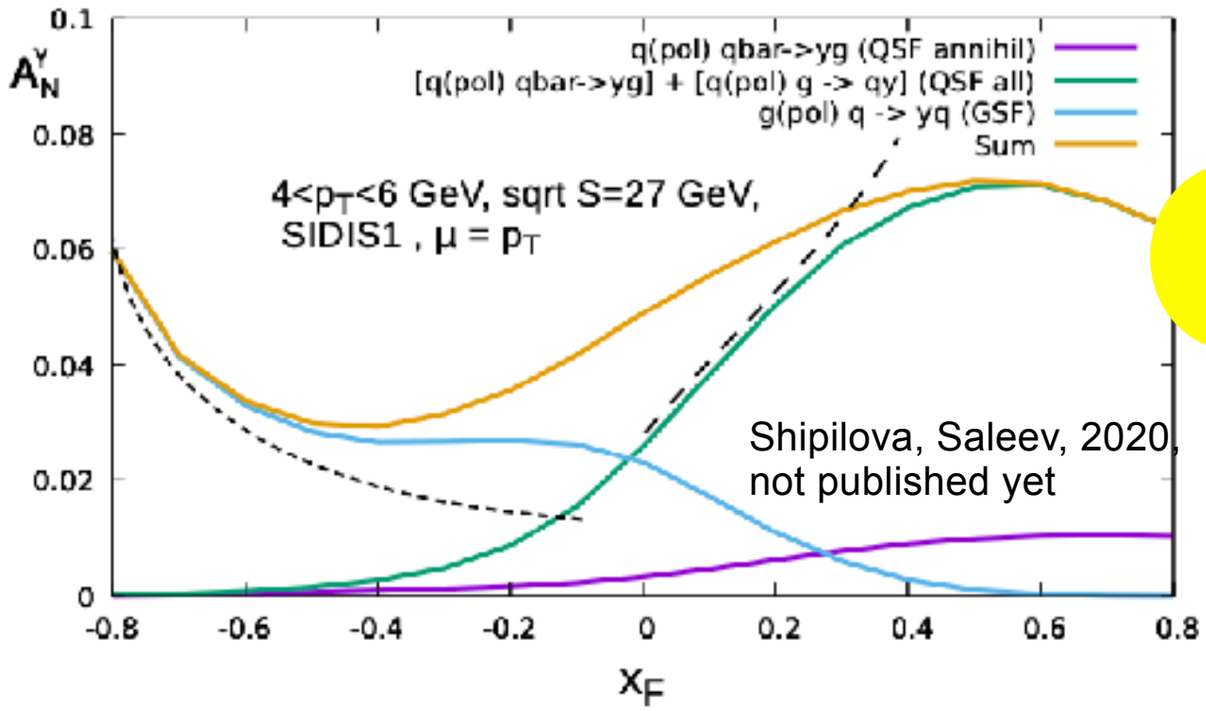




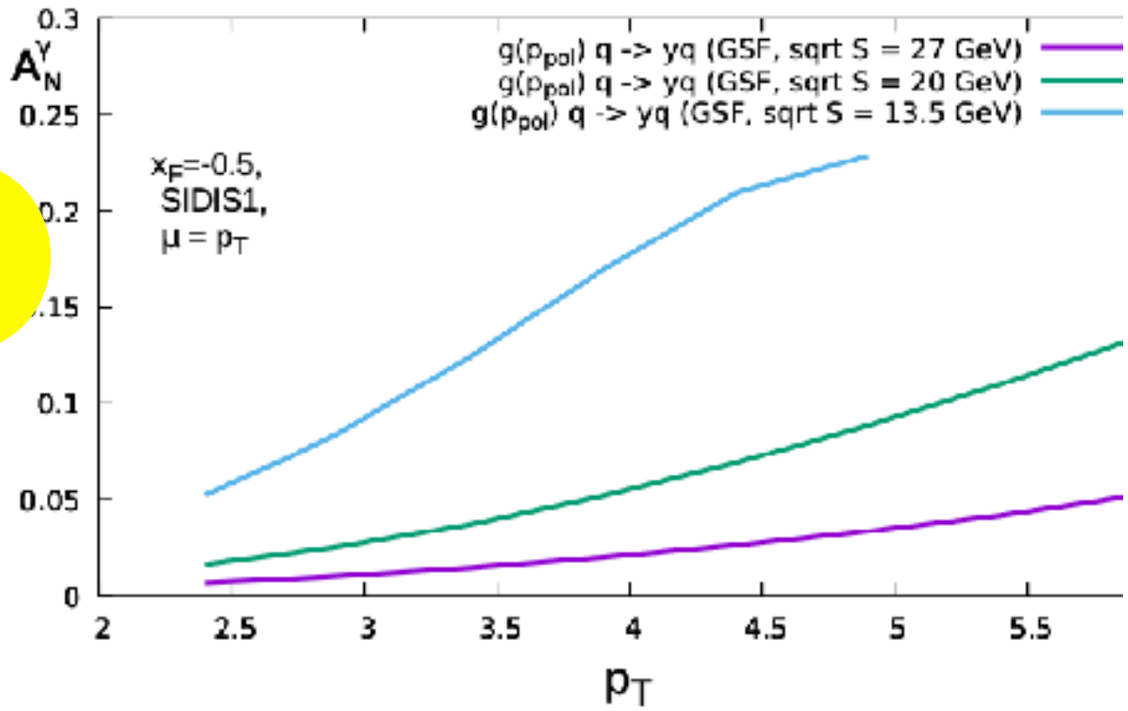


Gluon induced TMD effects: expected results for A_N

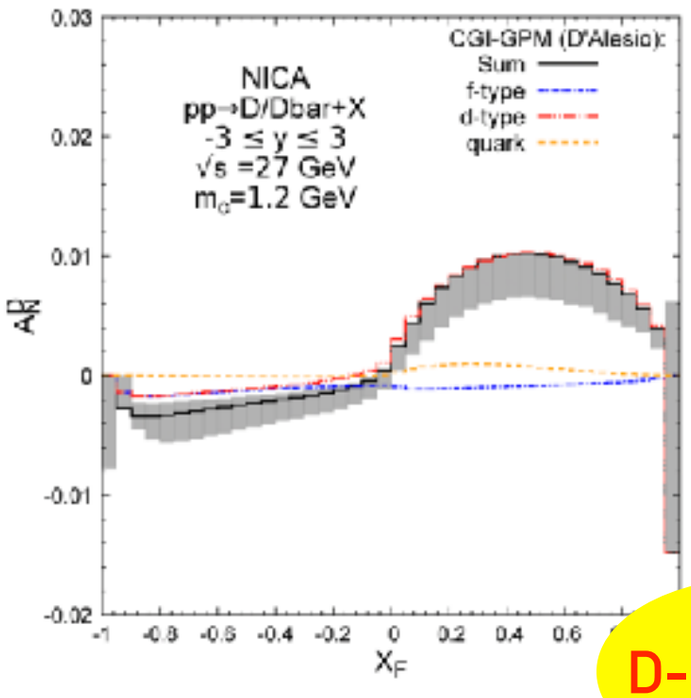
Sivers effect impact

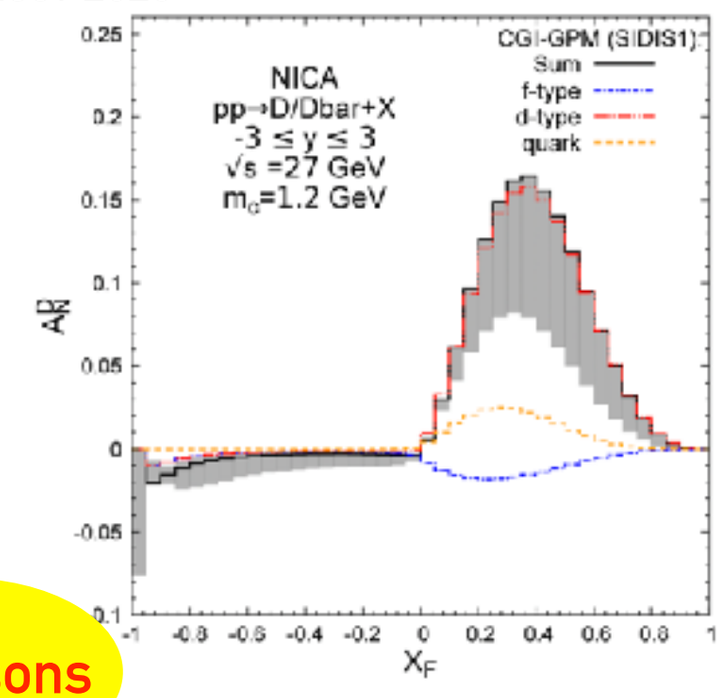


γ

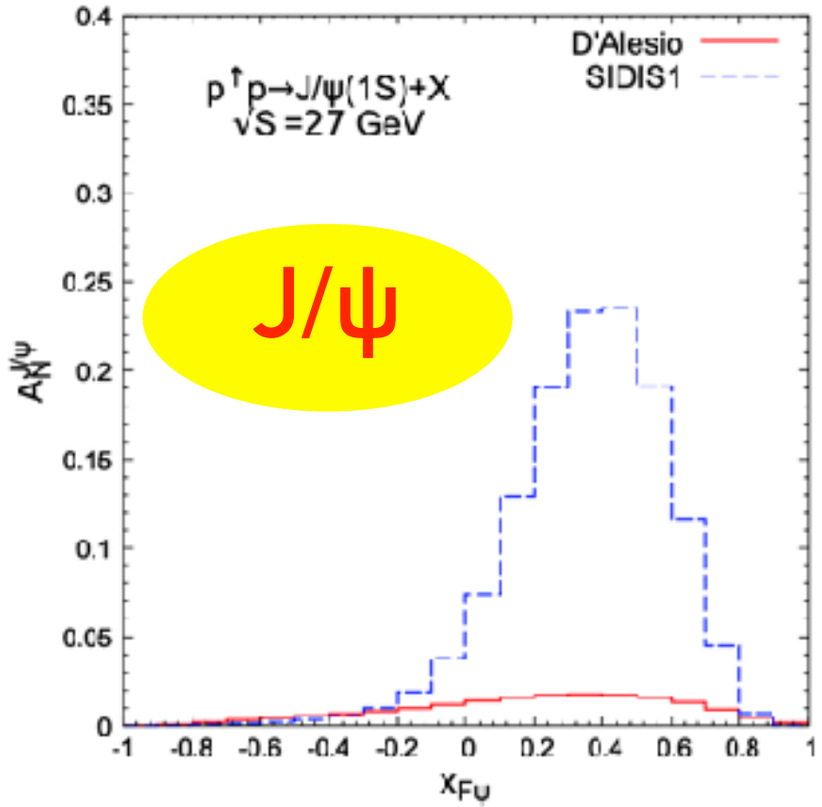


Saleev 2020





D-mesons



J/ψ

SPD Physics at the initial stage

V.V. Abramov et al., to appear in PEPAN, JINR E2-2021-12, e-Print: 2102.08477 [hep-ph]

Comprehensive and rich physics program at the initial stage of SPD data taking:

- **Spin effects in pp-, pd- and dd- (quasi)elastic scattering**
- **Spin effects in hyperon production**
- **Multiquark correlations (SRC) in deuteron and light nuclei**
- **Dibaryon resonances**
- **Hypernucleus production**
- **Open charm and charmonia production near threshold**
- **Large-pT hadron production to study diquark structure of proton**
- **Semi-inclusive large-pT hadron production to study multiparton scattering**
- **Antiproton production measurement for astrophysics and BSM search**
- **…**

Summary

► **Spin Physics Detector (SPD), a universal setup at NICA (http://spd.jinr.ru): for comprehensive study of polarized and unpolarized gluon content of proton and deuteron in polarized and unpolarized high-luminosity pp- and dd- collisions at √s up to 27 GeV**

► **Complementing main probes: charmonia (J/Psi, higher states), open charm and direct photons**

► **SPD can reveal significant insights towards 3D gluon structure:**

- gluon helicity structure

- unpolarized gluon PDF at high x in proton and deuteron

- gluon transversity in deuteron

- Comprehensive and rich physics program for the fist period of data taking

- SPD physics program is complementary to the other intentions to study gluon content of nuclei (RHIC, AFTER@LHC, LHC-spin, EIC) and mesons (COMPASS++/AMBER, EIC)

- **SPD CDR: arXiv:2102.00442**
- **SPD physics:**

A. Arbuzov et al. ,Prog. Part. Nucl.Phys. 119 (2021) 103858 e-Print: 2011.15005 [hep-ex]
V.V. Abramov et al., to appear in PEPAN, JINR E2-2021-12, e-Print: 2102.08477 [hep-ph]