Physics with SPD experiment at NICA

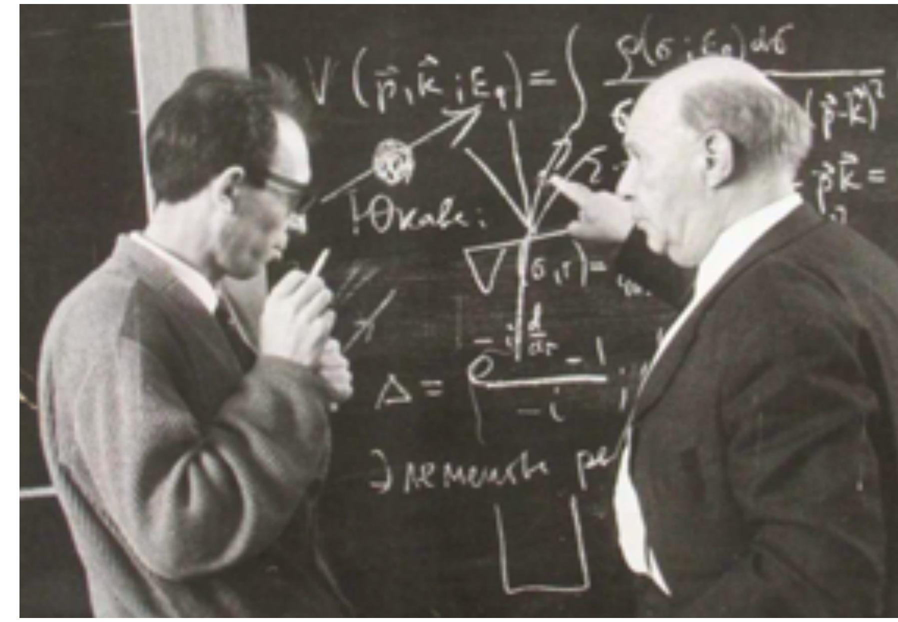
Victor T. Kim

Petersburg Nuclear Physics Institute NRC KI, Gatchina

for the SPD Collaboration

19th High Energy Spin Physics Workshop
Dubna, 4–8 September 2023
dedicated to 90th-Anniversary of A.V. Efremov

Anatoly V. Efremov: Scientist and Teacher



Anatoly Vasilievich Efremov
26 Dec. 1933 – 1 Jan. 2021

➥ 1958 Moscow Physics Engineering Institute 1958
1958 BLTP JINR, Dubna
1962 PhD - dispersion relations for pion scattering
1971 Dr. Sci. - asymptotics of Feynman diagrams

➥ process factorization of quantum field theory — I.F. Ginzburg
QCD factorization of inclusive hard processes — A.V. Radyushkin
QCD factorization of exclusive hard processes — A.V. Radyushkin

cumulative processes, fluctons, nuclear structure functions V.K., G.I. Lykasov
A.B. Kaidalov, N.V. Slavin

➥ spin physics – handedness
QCD transverse polarization O.V. Teryaev
spin proton crisis: gluon anomaly O.V. Teryaev
spin distribution functions O.V. Teryaev, K. Goeke, P. Schweizer,
COMPASS Coll.

Main SPD physics goal

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

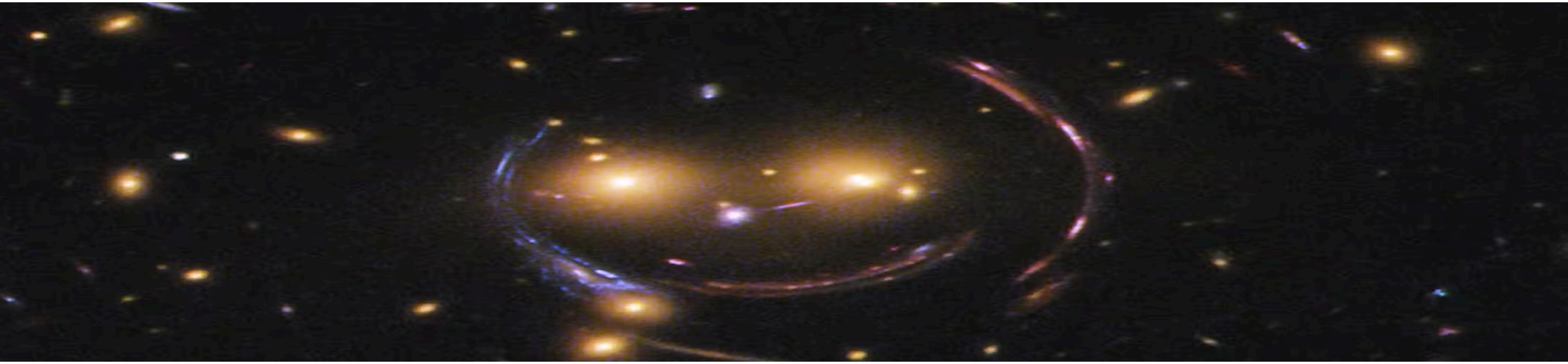
➥ **Main SPD goal:**
understanding of the strong interactions using both polarized and unpolarized pp- and dd- collisions at $\sqrt{s}$ up to 27 GeV with high-luminosity

To this end, it will be studied (un)polarized 3D quark-gluon structure of proton and deuteron with emphasis of gluon PDF(x) and TMD(x,kT) 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)

Why nucleon structure?



proton mass -> the visible Universe mass

Electroweak Higgs boson provides:

quark mass ~ ten MeV ≃ 1% of the visible Universe mass

➥ **quark-gluon dynamics of nucleon structure provides:**

~ 99% of the mass of the visible Universe!

Why Spin?

"Experiments with spin have killed more theories than any other single physical parameter"

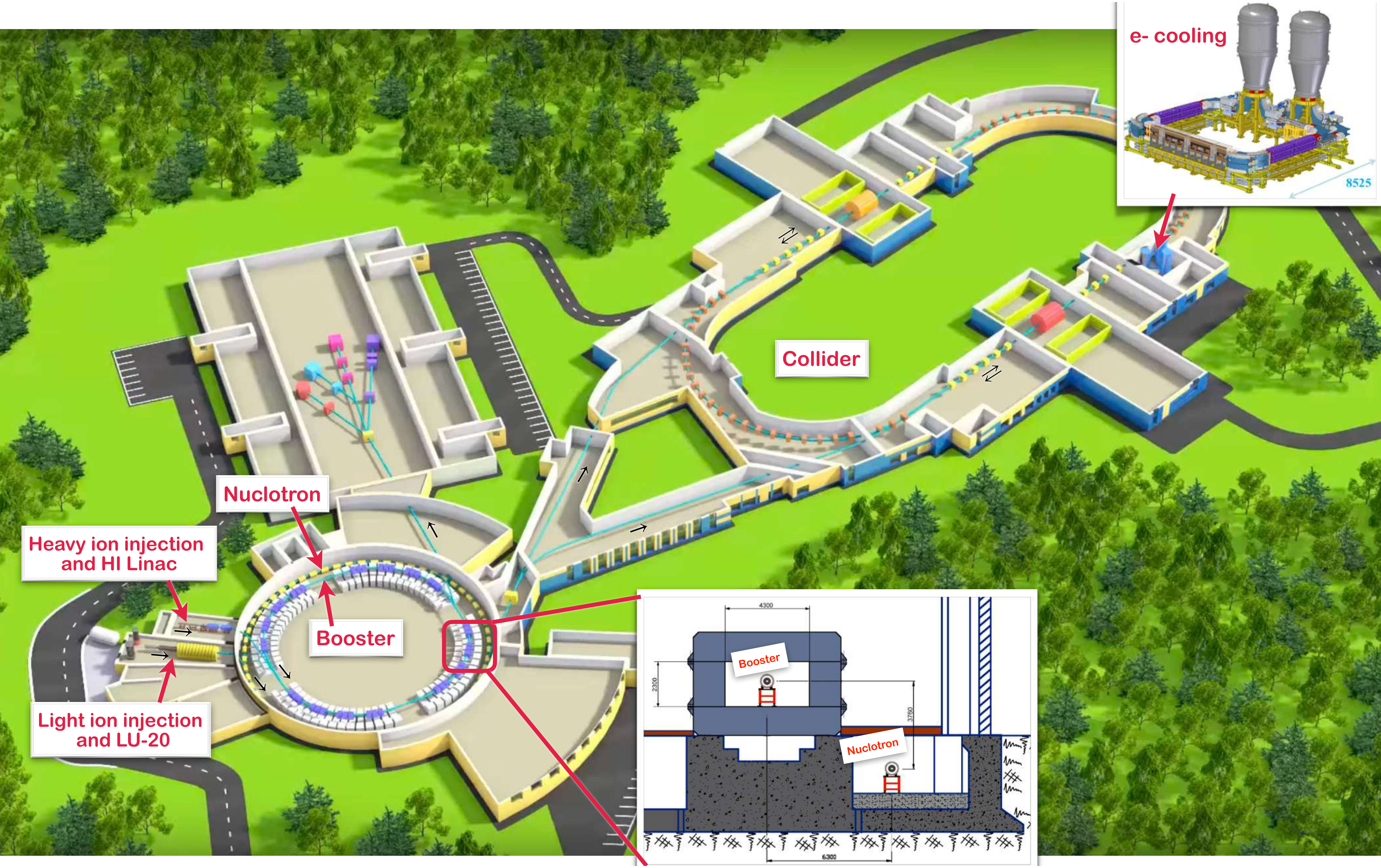
Elliot Leader, Spin in Particle Physics, Cambridge U. Press (2001)

"Polarisation data has often been the graveyard of fashionable theories. If theorists had their way they might well ban such measurements altogether out of self-protection."

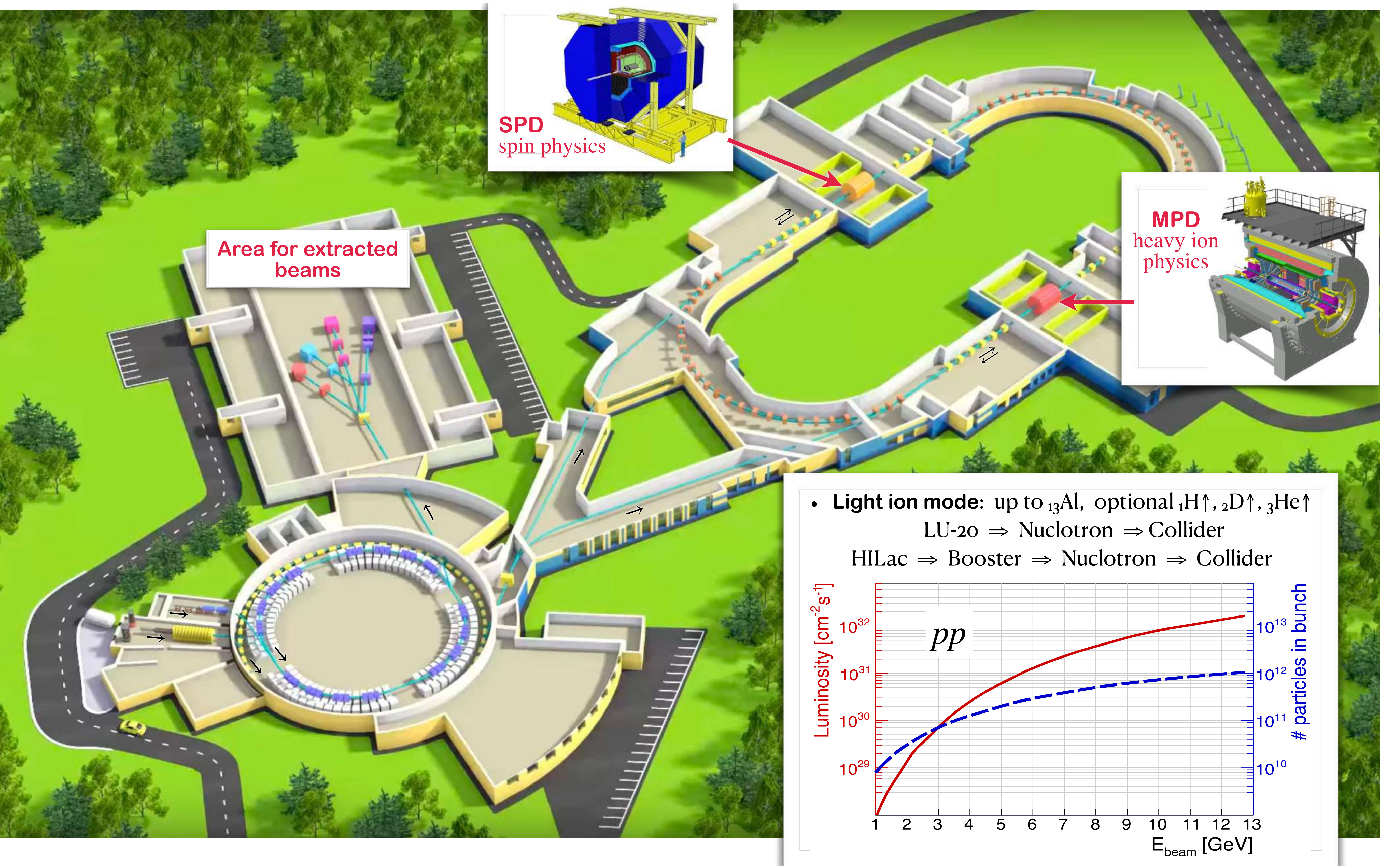
J. D. Bjorken, Proc. Adv. Research Workshop on QCD Hadronic Processes, St. Croix, Virgin Islands (1987).

V. Mochalov (NRC KI - IHEP)

NICA Accelerator Complex at JINR, Dubna

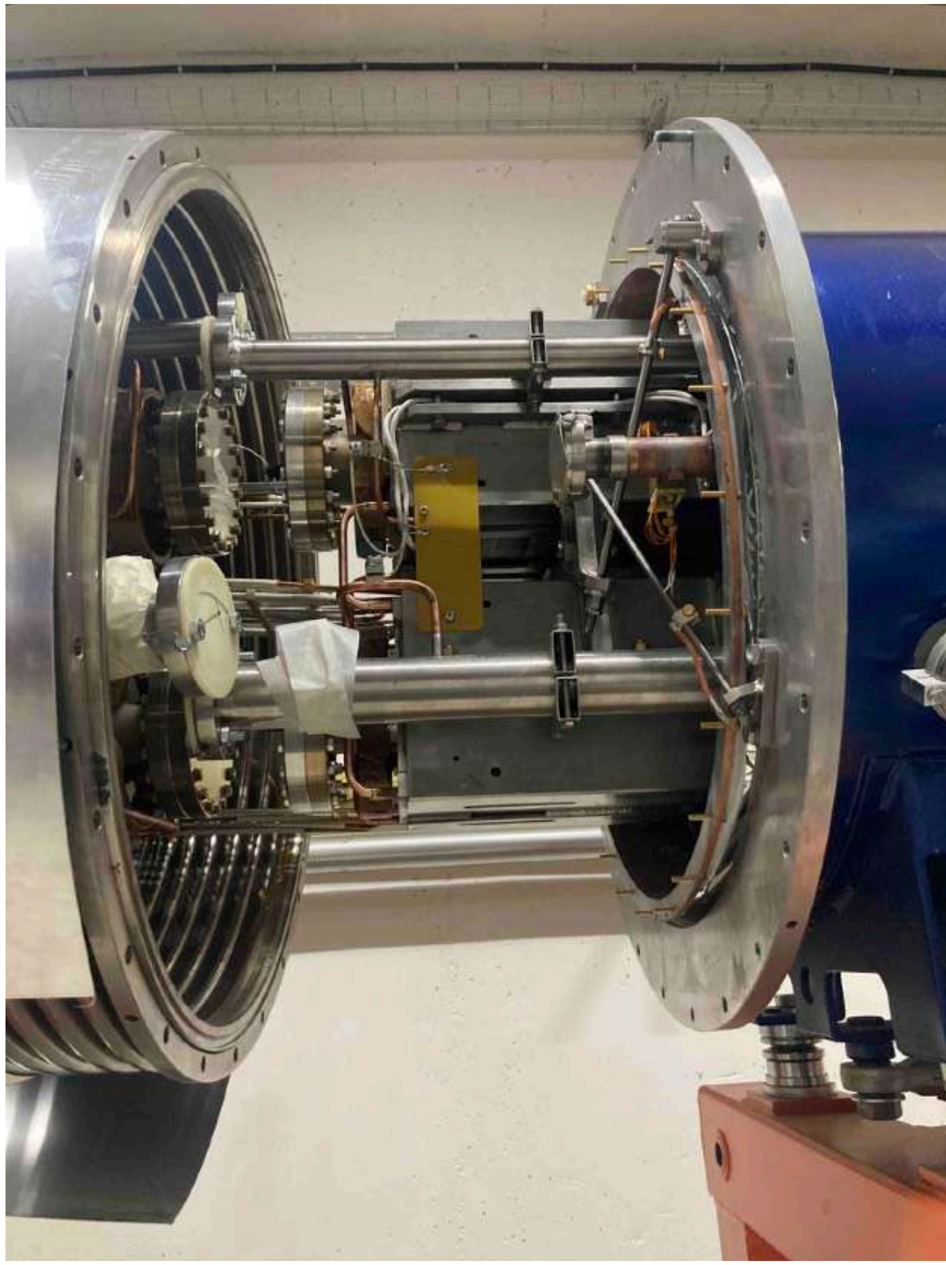


Experiments NICA collider



NICA Complex at JINR

NICA Collider at JINR



NICA:
Nuclotron-based Ion Collider fAcility

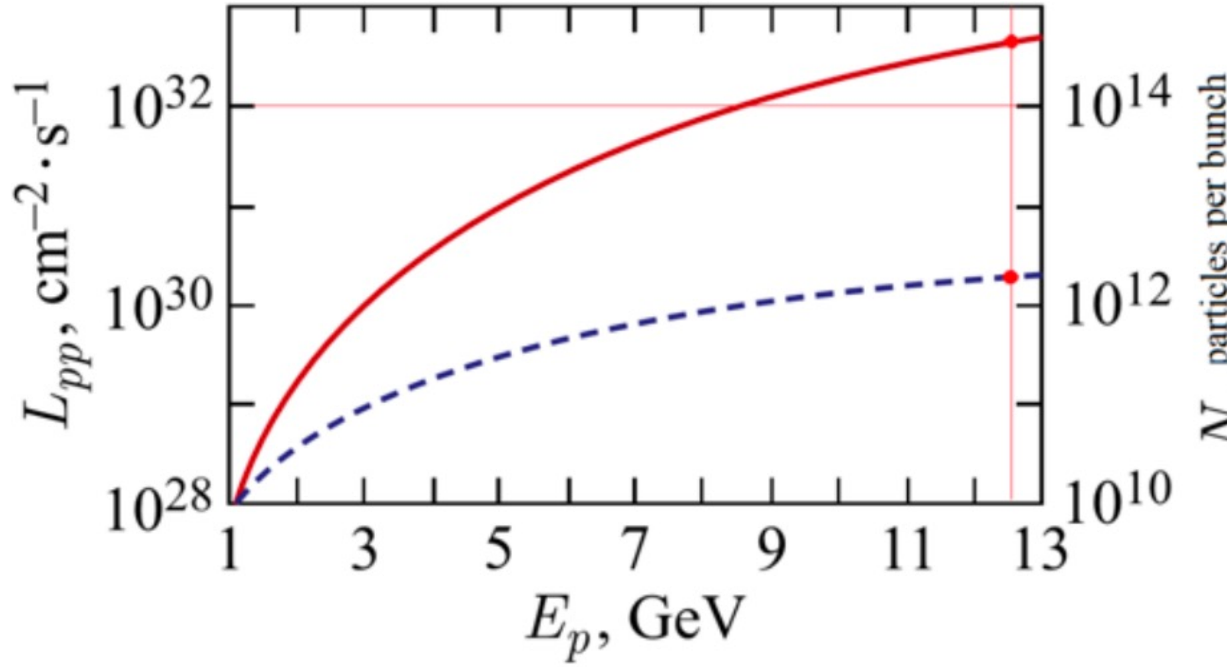
$p^{\uparrow}p^{\uparrow} : \sqrt{s} \leq 27\ GeV$

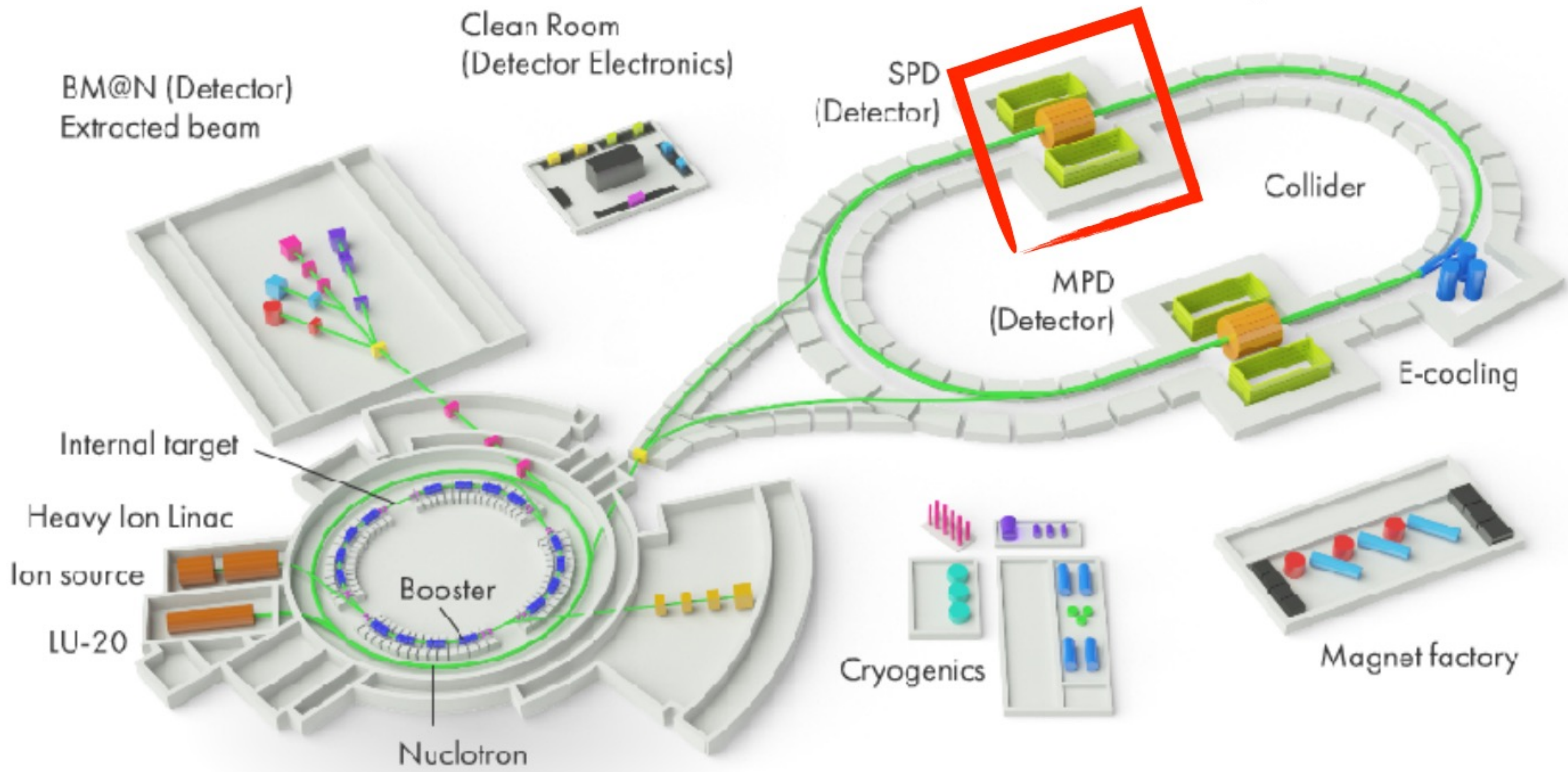
$d^{\uparrow}d^{\uparrow} : \sqrt{s} \leq 13.5\ GeV$

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

U, L, T

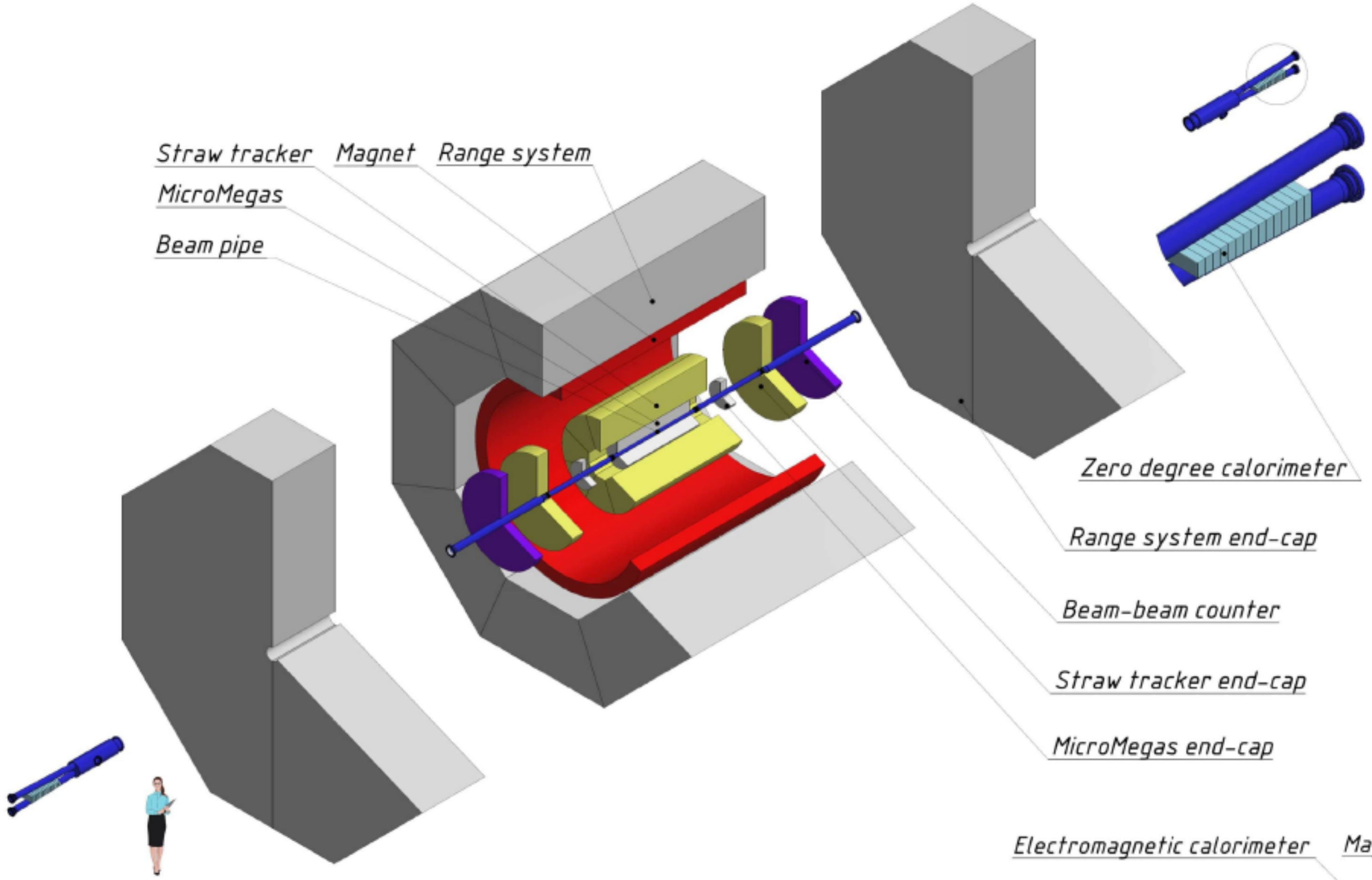
$|P| > 70\%$





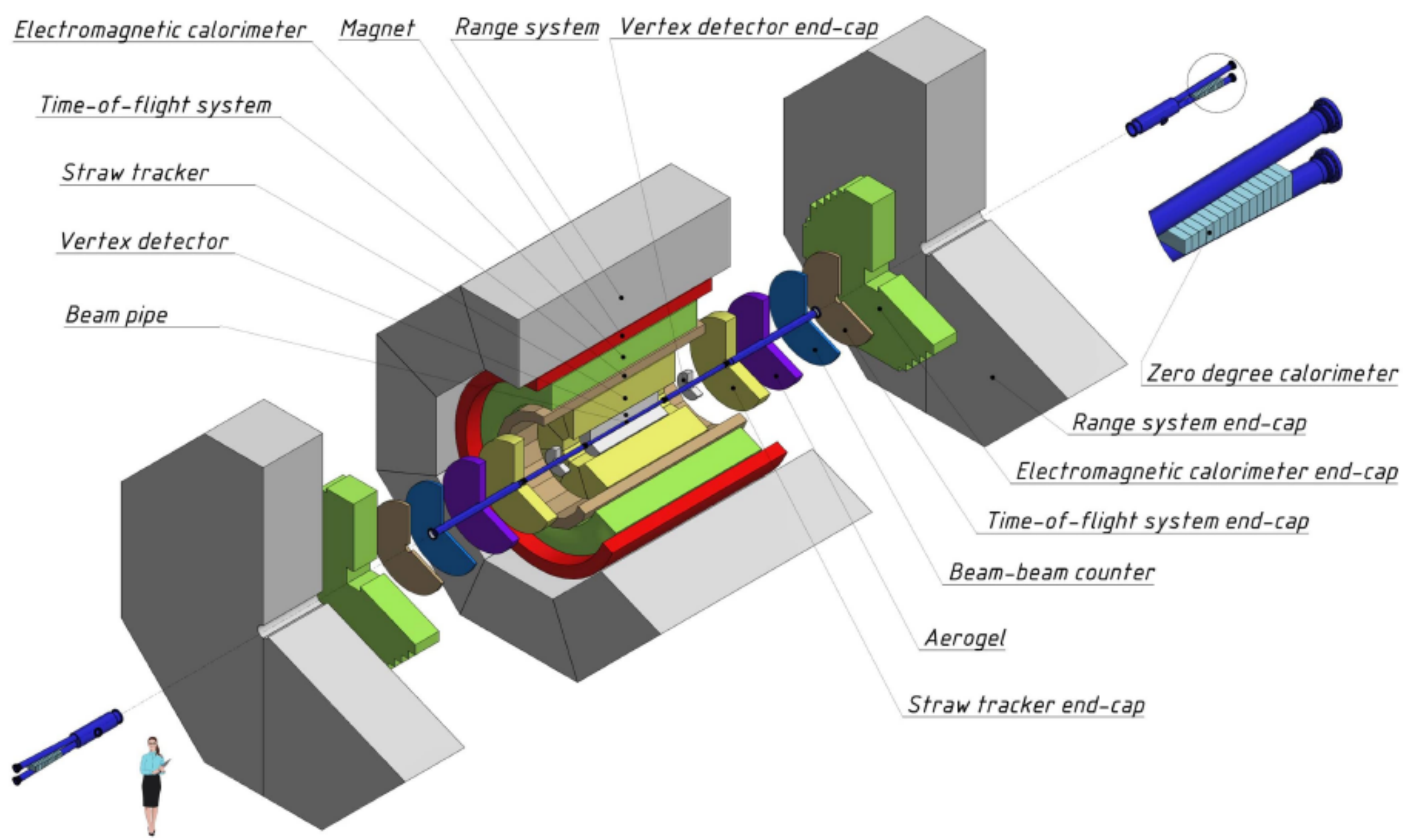
SPD Technical Design Report

SPD TDR version 1: January 2023



<- SPD: the Stage I

SPD: the Stage II ->



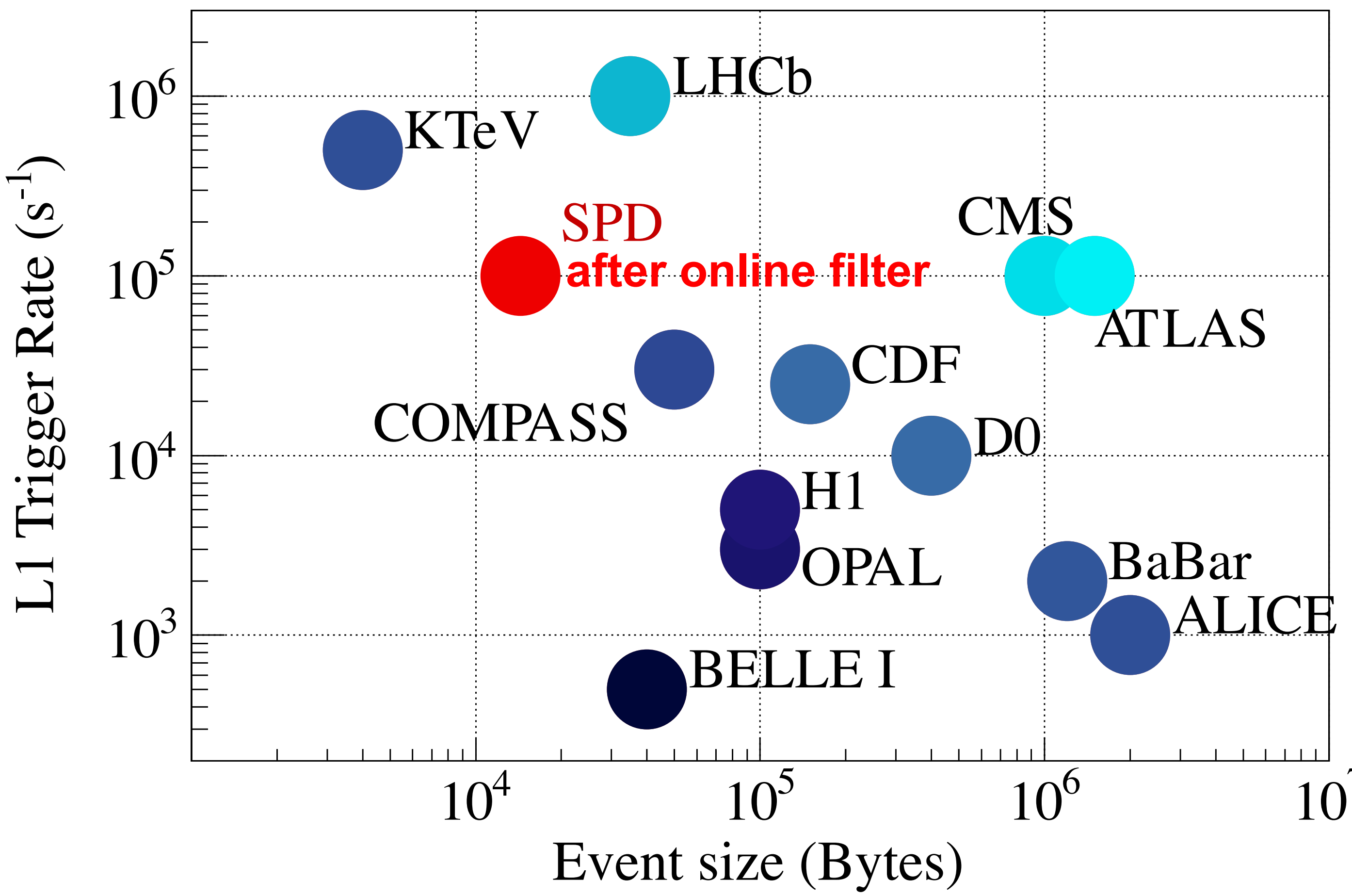
SPD detector data flow

No hardware trigger at the SPD detector to avoid a possible bias:
3 MHz event/s at 10^{32} cm²/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 the LHC Run 1

SPD data rate after online filter

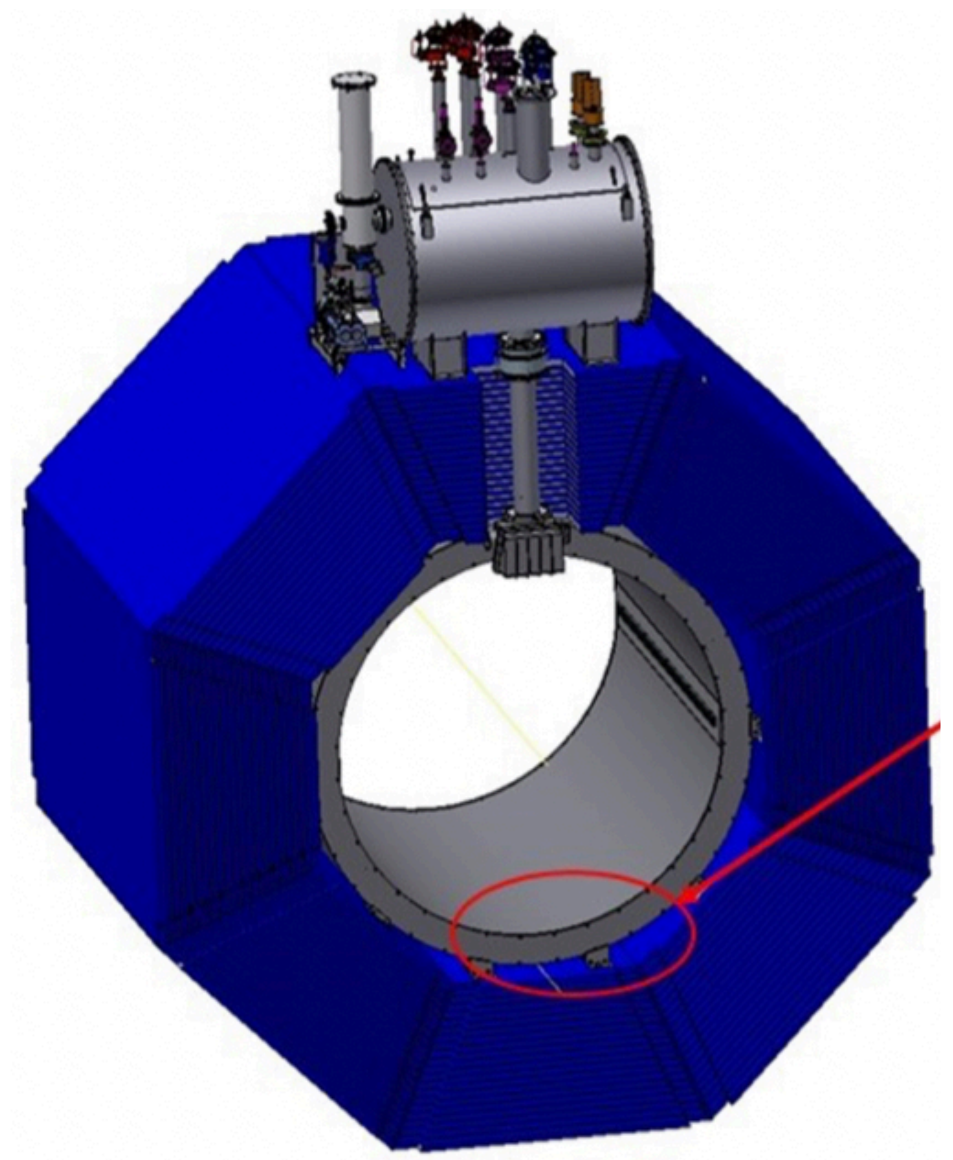


SPD Technical Design Report: Magnet

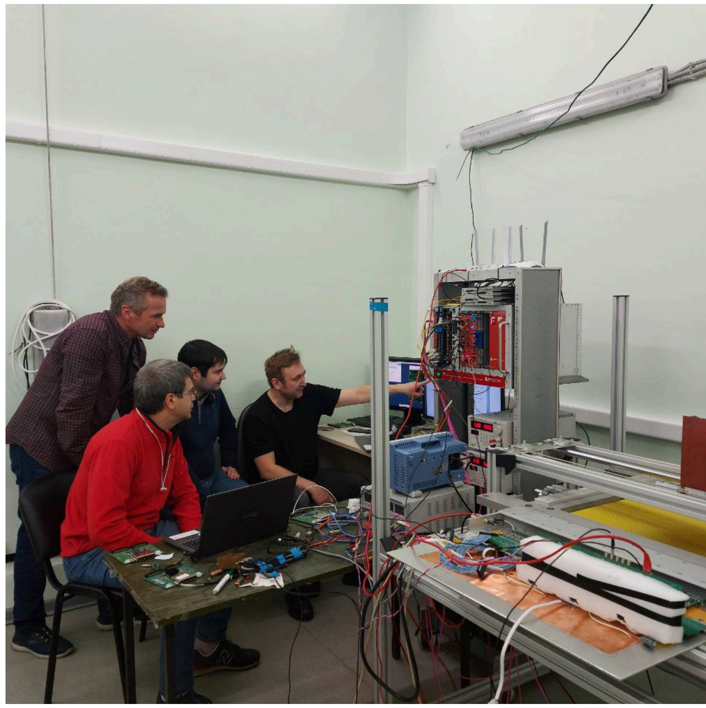
An Important Decision of SPD Technical Board (6 December 2022)

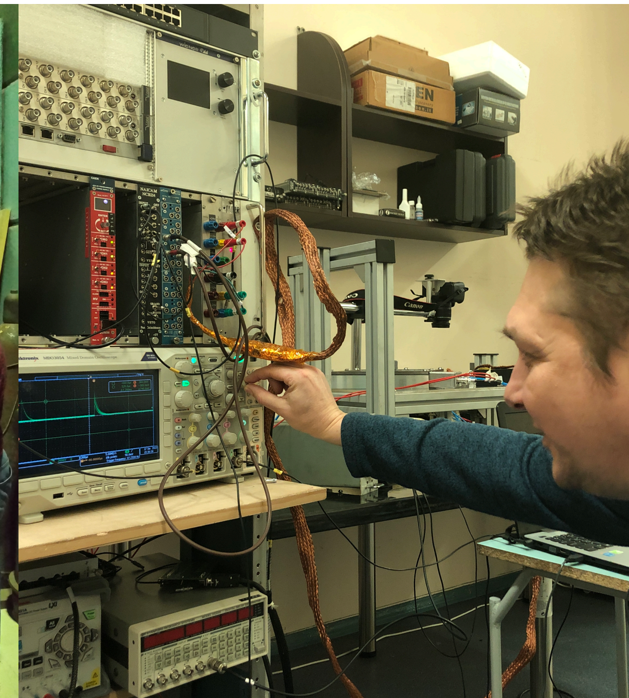
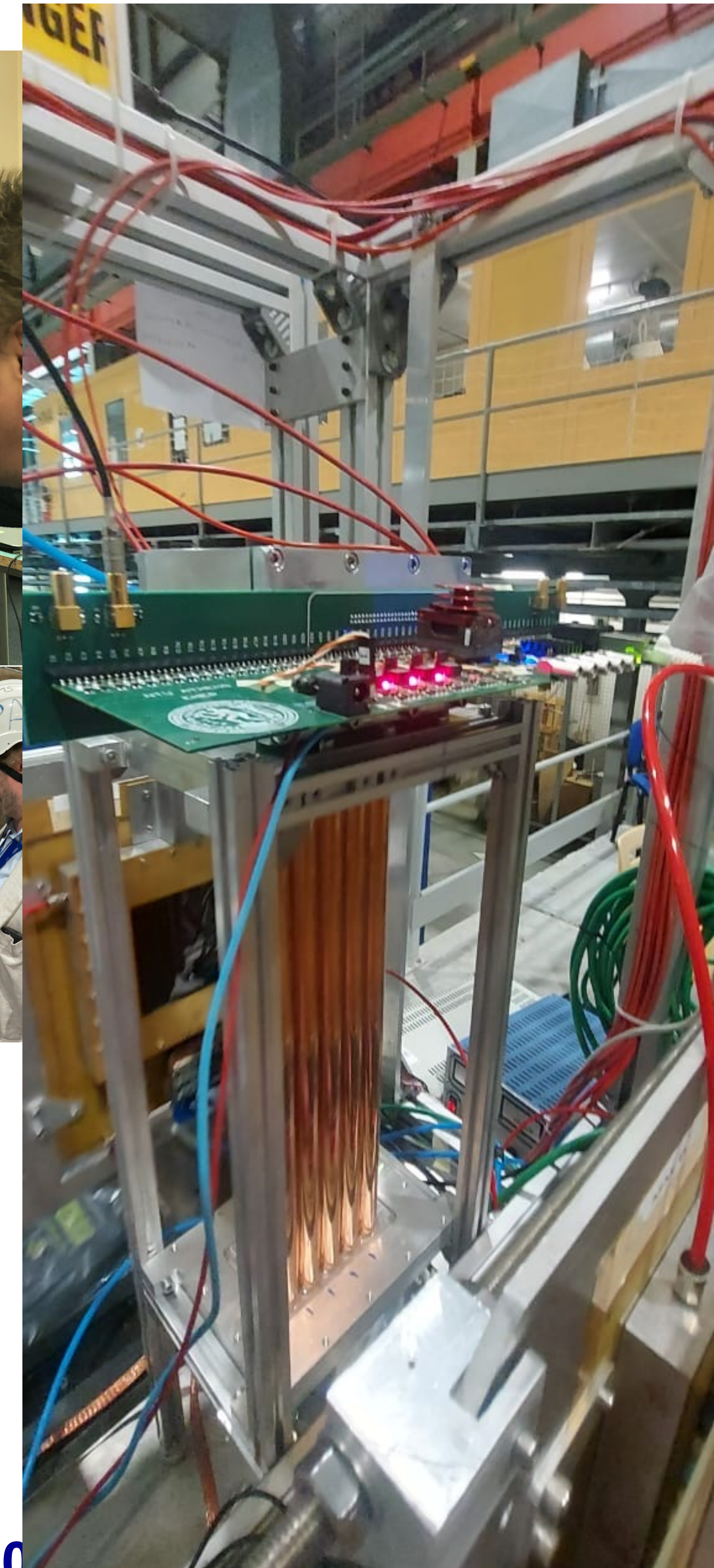
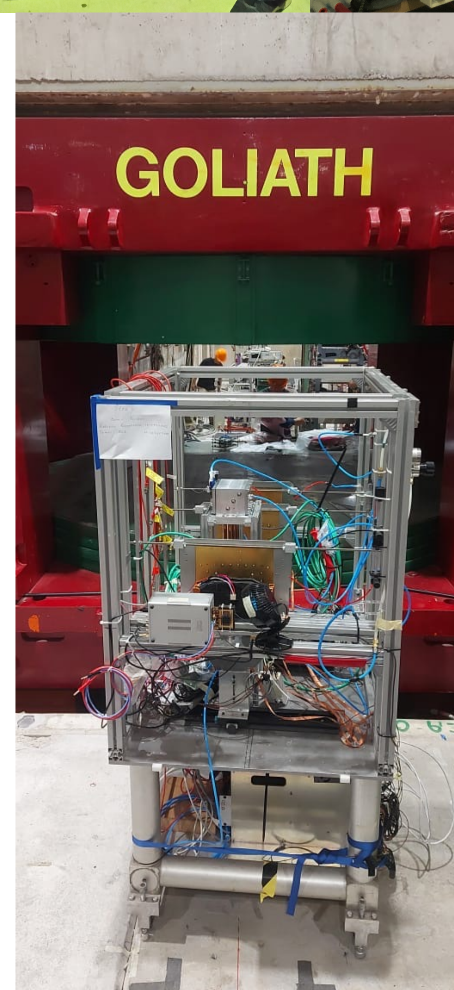
SPD Magnet Committee reviewed two concepts of SPD Magnetic System:
- LHEP JINR, Dubna (Nuclotron-cable based)
- BINP RAS, Novosibirsk (Rutherford-cable based – a la Panda) <- accepted

Superconducting Solenoid
1 Tesla



SPD R&Ds



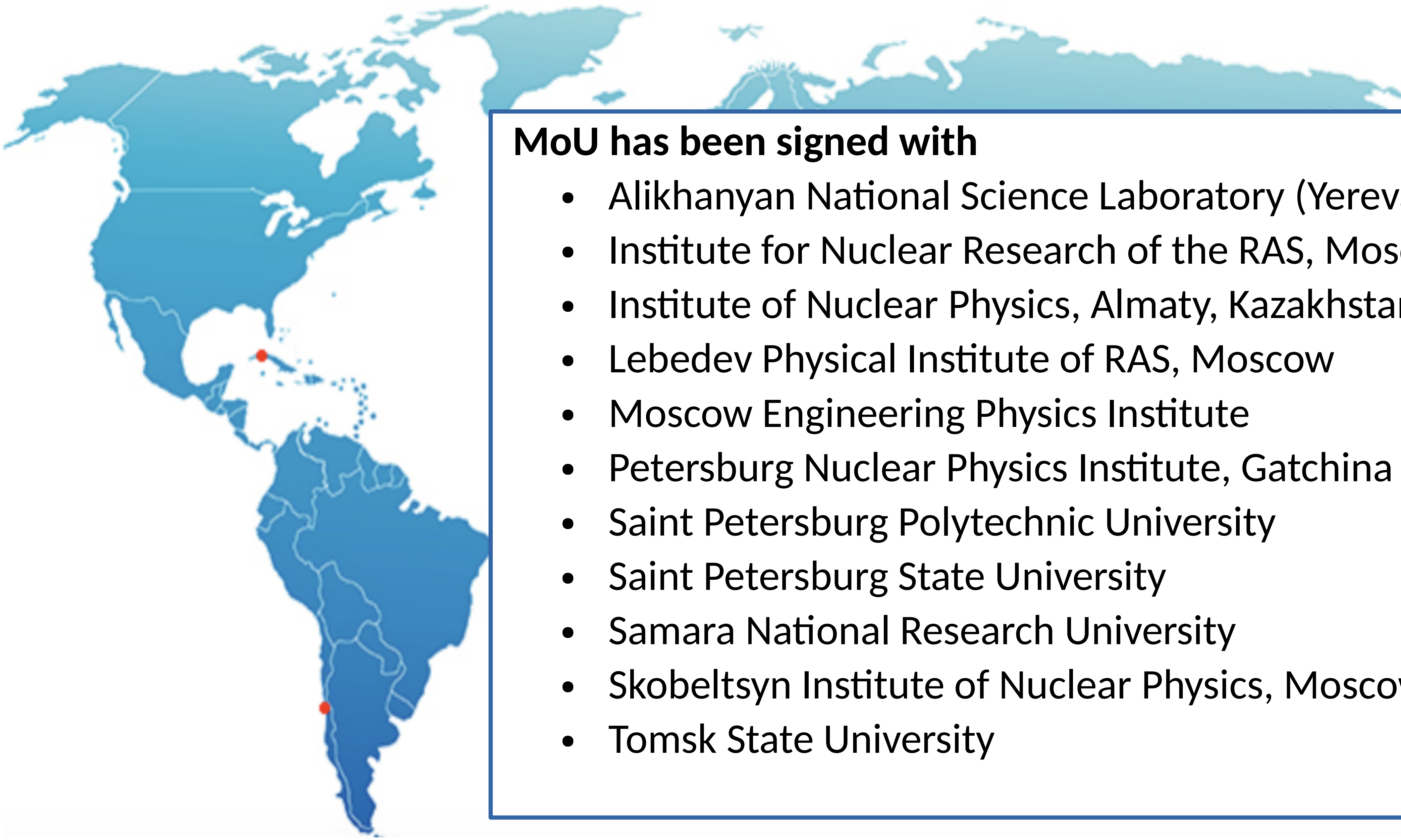




SPD Straw Tracker test beams: CERN SPS, PNPI SC-1000

SPD Collaboration: established in July 2021

13 countries
32 teams > 300 participants
SPD co-spokespersons: Alexey Guskov (JINR) & Victor Kim (NRC KI - PNPI)

SPD Collaboration: signing MoU since May 2022



MoU has been signed with

- Alikhanyan National Science Laboratory (Yerevan Physics Institute)
- Institute for Nuclear Research of the RAS, Moscow
- Institute of Nuclear Physics, Almaty, Kazakhstan
- Lebedev Physical Institute of RAS, Moscow
- Moscow Engineering Physics Institute
- Petersburg Nuclear Physics Institute, Gatchina
- Saint Petersburg Polytechnic University
- Saint Petersburg State University
- Samara National Research University
- Skobeltsyn Institute of Nuclear Physics, Moscow State University
- Tomsk State University

The 3rd SPD Collaboration Meeting, October 2022

SPD project timeline

Igor A. Savin
1930-2023

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

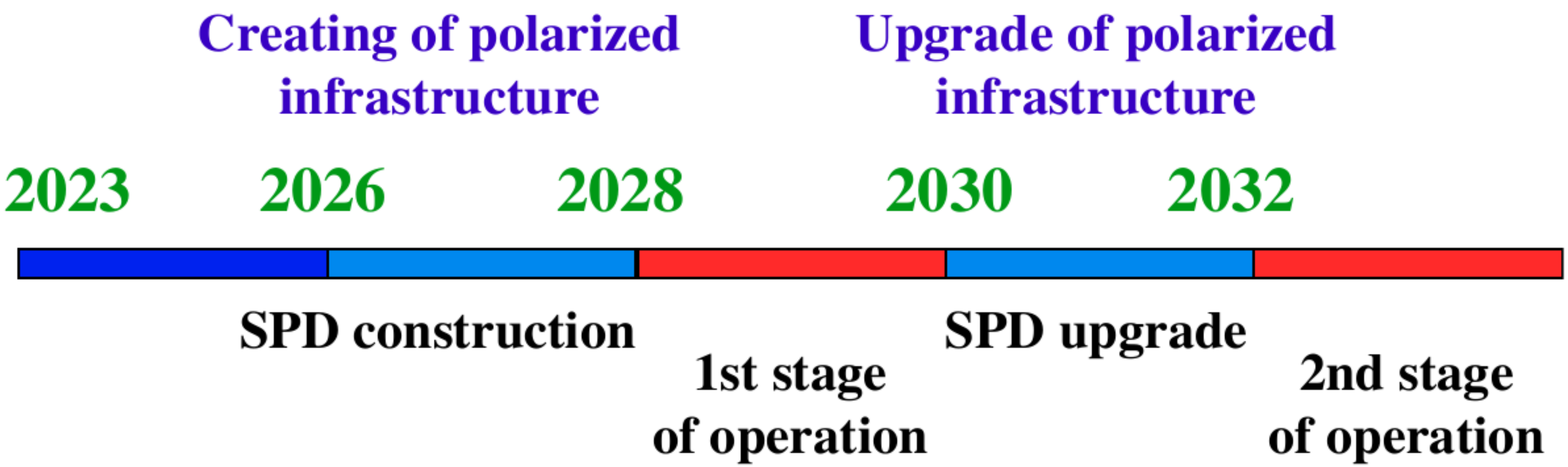
2014: SPD LoI approved by JINR PAC

2020: Completion of SPD CDR (arXiv:2102.00442v3)

2021: SPD Collaboration is established, preparation of **TDR** is started

Jan 2023: 1-st version of SPD TDR presented JINR PAC (http://spd.jinr.ru/spd-cdr/)

TDR to be finalized by the end of 2023.



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
- testing factorization properties

A. Datta, A. Terekhin, …

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

SPD Physics:

ELSEVIER

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

Review

ArXiv e-Print: 2011.15005 [hep-ex]

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]

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

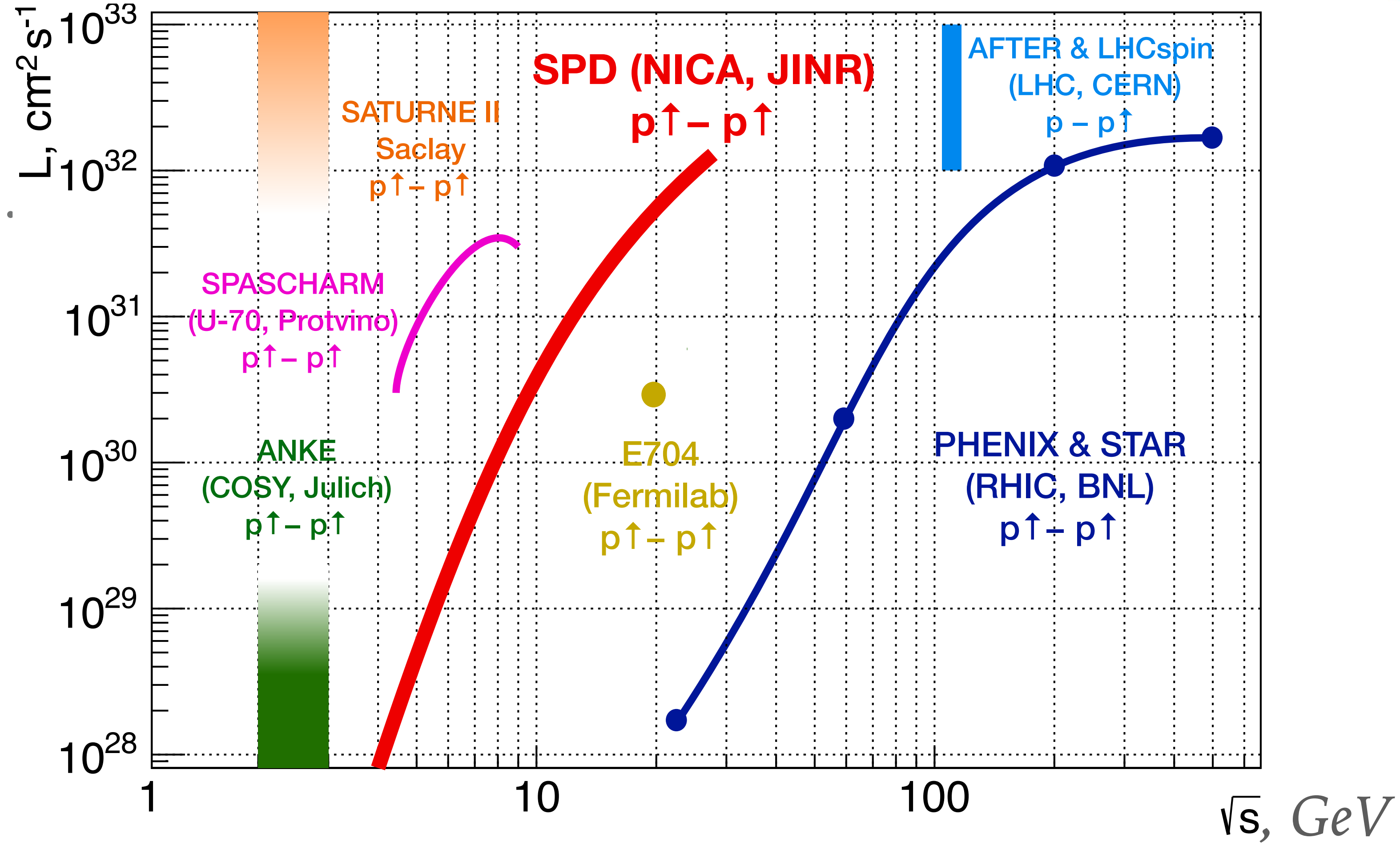
to appear in Phys. Elem. Part. At. Nucl. 2021

JINR E2-2021-12
ArXiv e-Print: 2102.08477 [hep-ph]

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]

SPD in World landscape of polarized physics

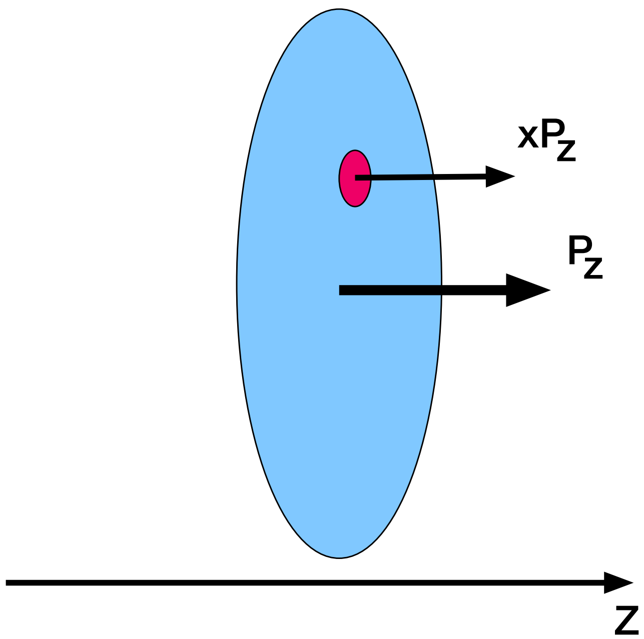
p↑ p↑-mode ➡



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-$d^{\uparrow}$	$p^{\uparrow}$-$p^{\uparrow}$	$e^{\uparrow}$-$p^{\uparrow}$, $d^{\uparrow}$, ^{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

⬅ SPD is unique in d↑ d↑-mode!

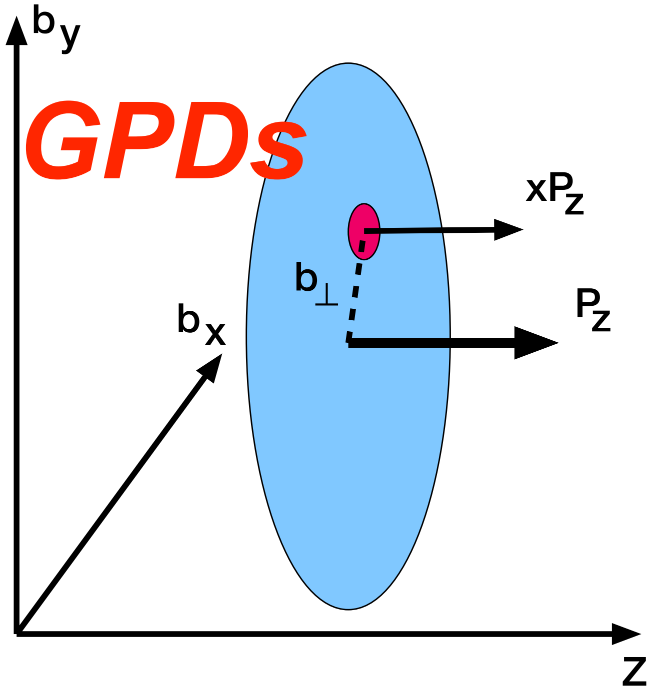
SPD: towards 3D-structure of nucleon



Collinear approximation

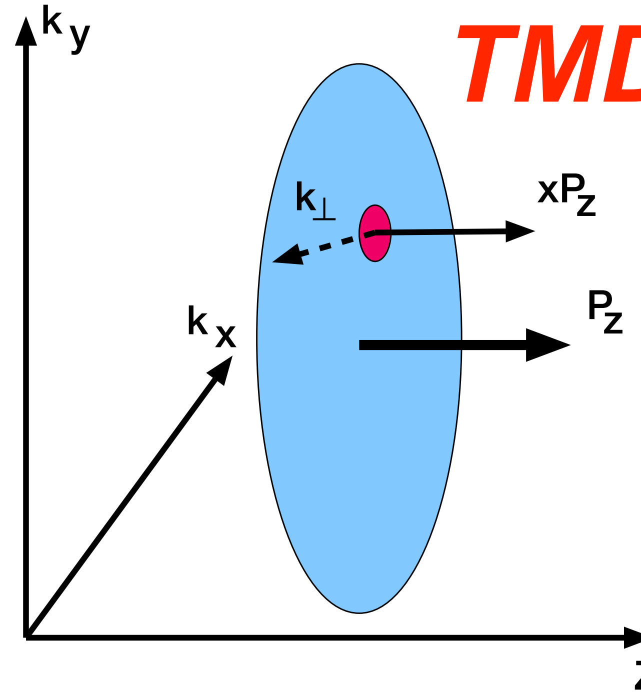
(common PDF)

GPDs

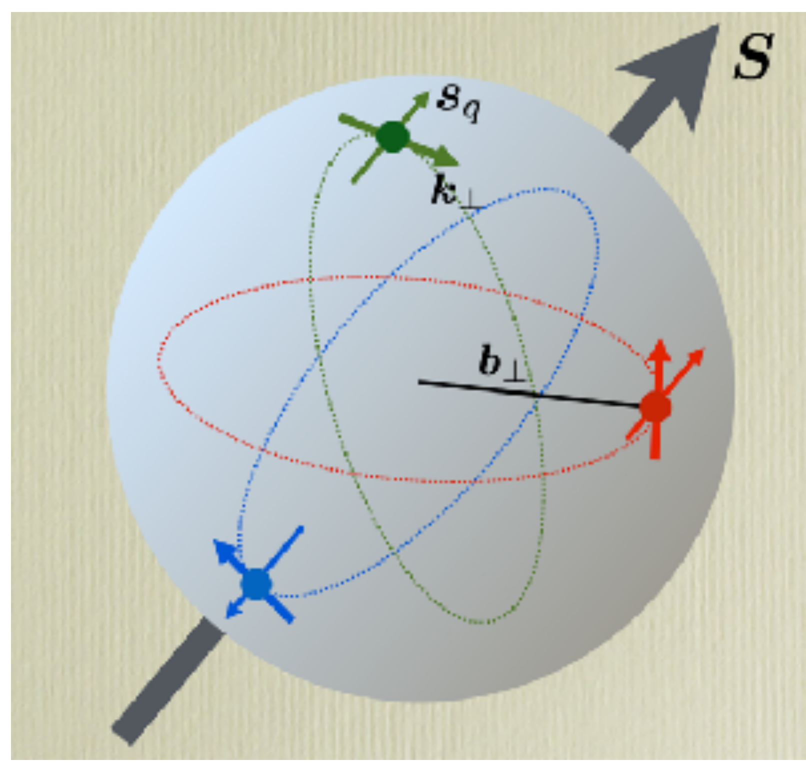


Generalized Parton Distributions

TMD PDFs



Transverse Momentum Dependent PDFs



3D structure of nucleon

connection to orbital moment

13

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

Parton 1D-distribitions:

Integrated over kT PDF: f(x; logQ²) ⬅ **modulo logQ² - DGLAP evolution**

Extension to parton 3D-distribitions:

- **Generalized parton distributions (GPDs): G(x, b, n; logQ²)**
  b - impact parameter, n – unit vector

- **Unintegrated over kT PDF: Φ(x, kT, n; logQ²) (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.

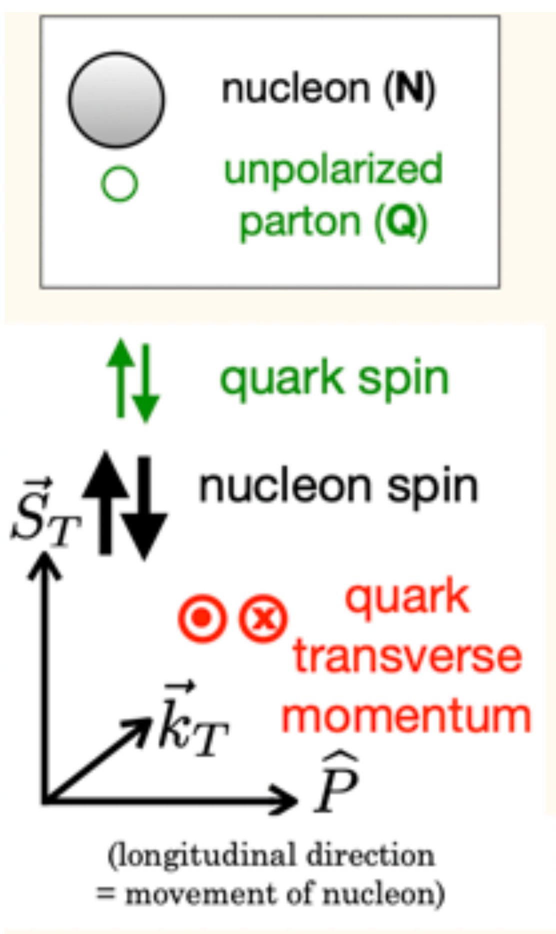
Integrated over kT quark TMDs:

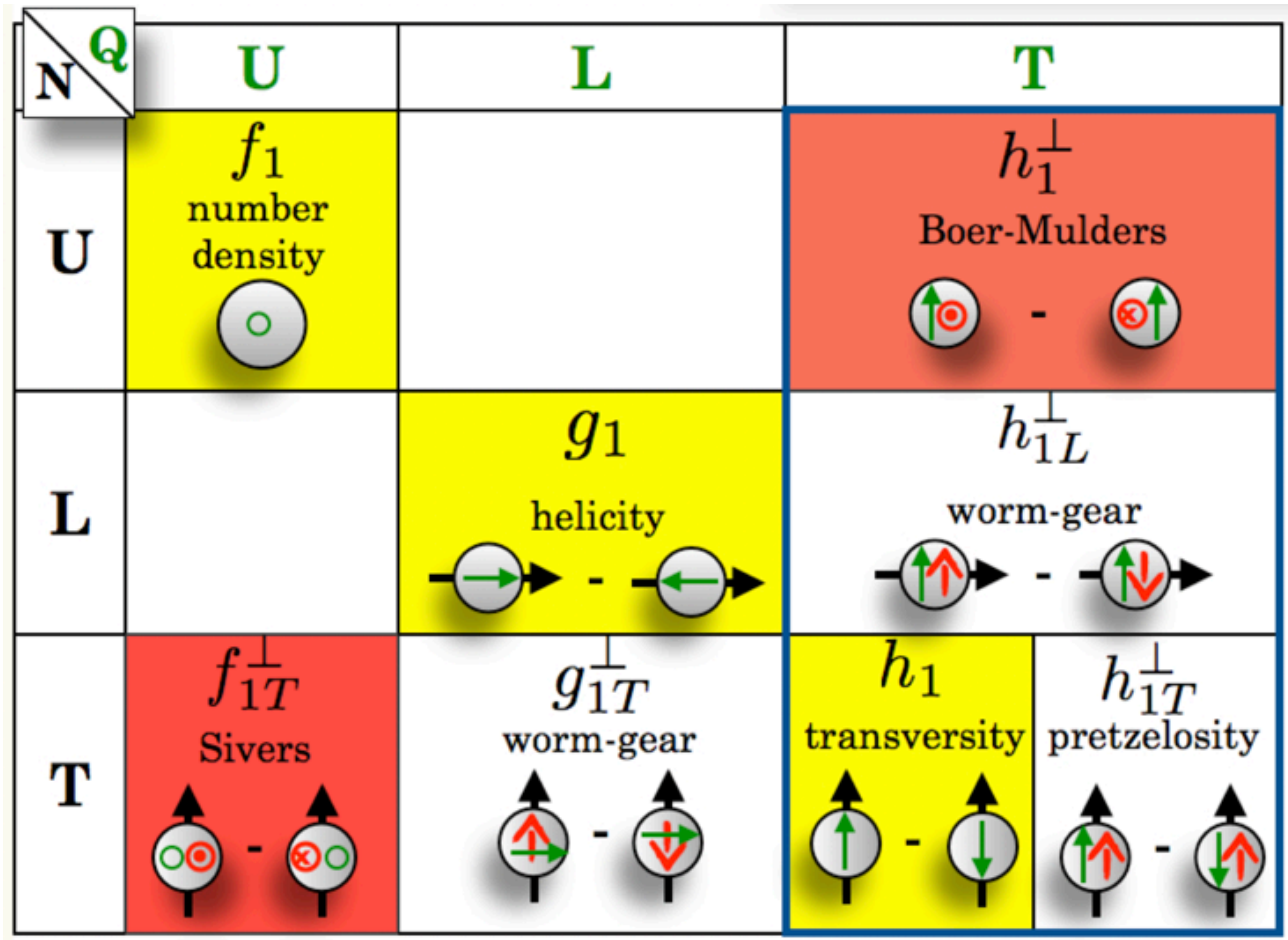
$f^q(x) = q(x) = q_{L=+}(x) + q_{L=-}(x)$

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

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

TMDs: quarks in nucleon





Gluon TMD with SPD

Unpolarized gluons at high x in proton and deuteron

Gluon helicity

Gluon Boer-Mulders function

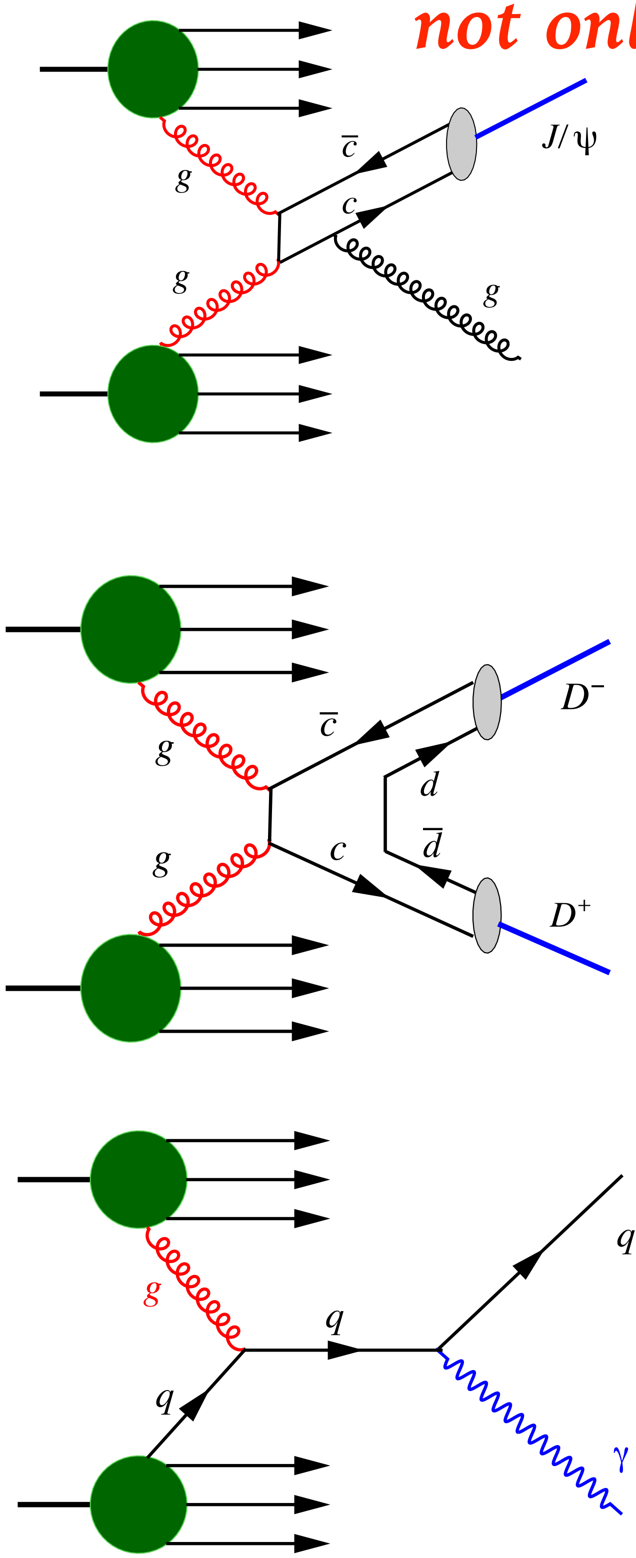
GLUONS	*unpolarized*	*circular*	*linear*
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_{1T}^g, $h_{1T}^{\perp g}$

Gluon Sivers function

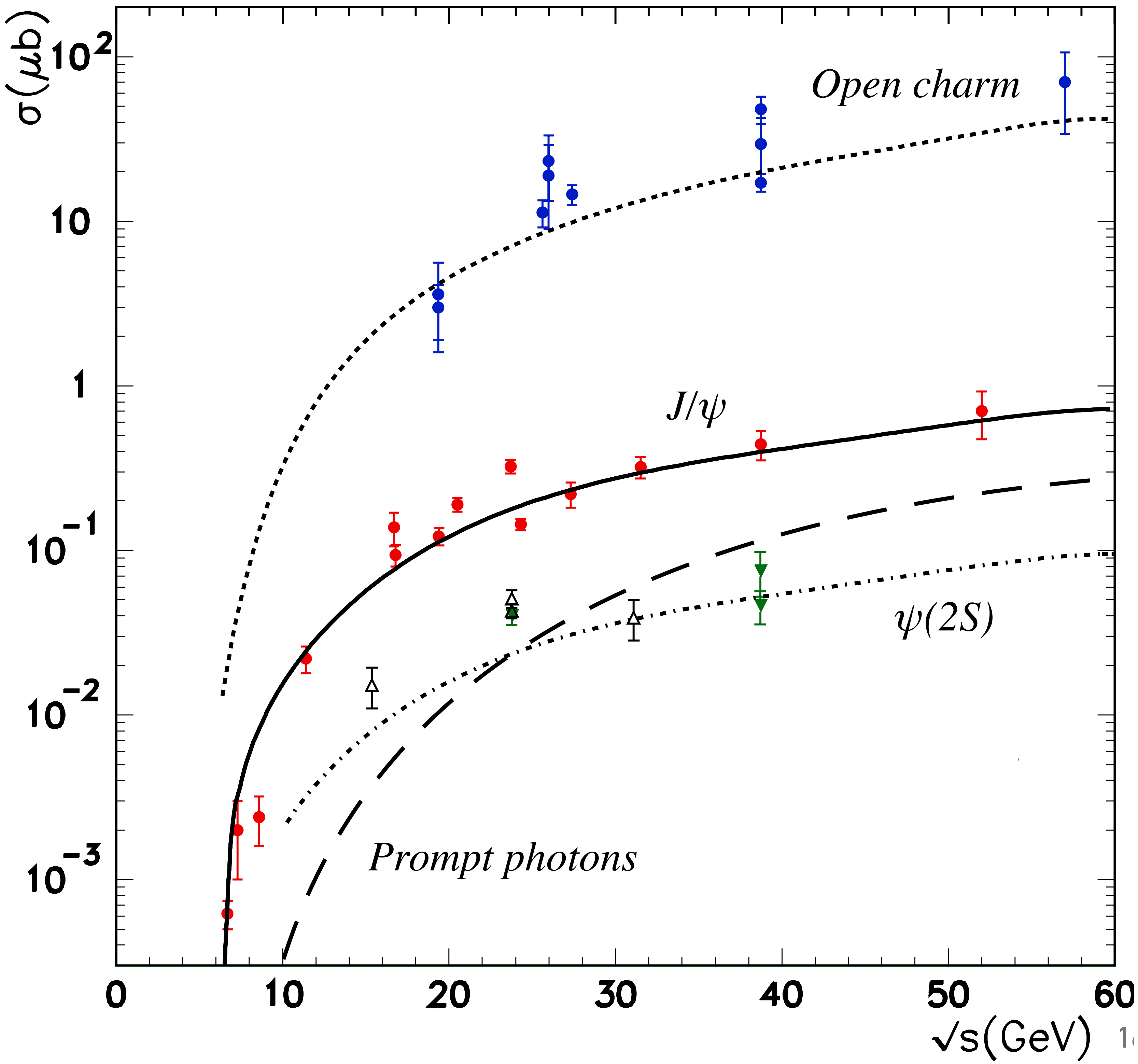
Gluon transversity in deuteron

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

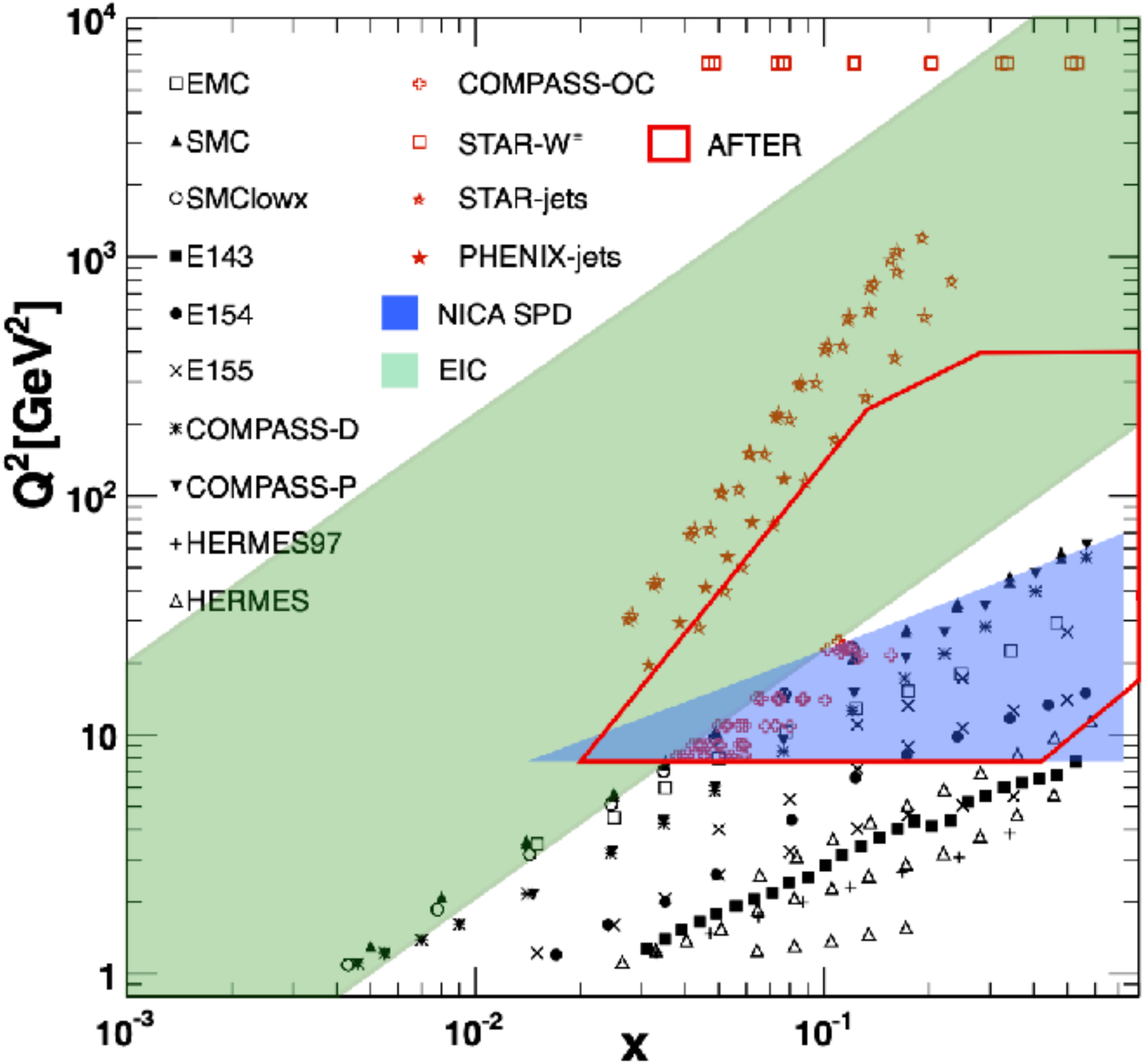
not only J/ψ!



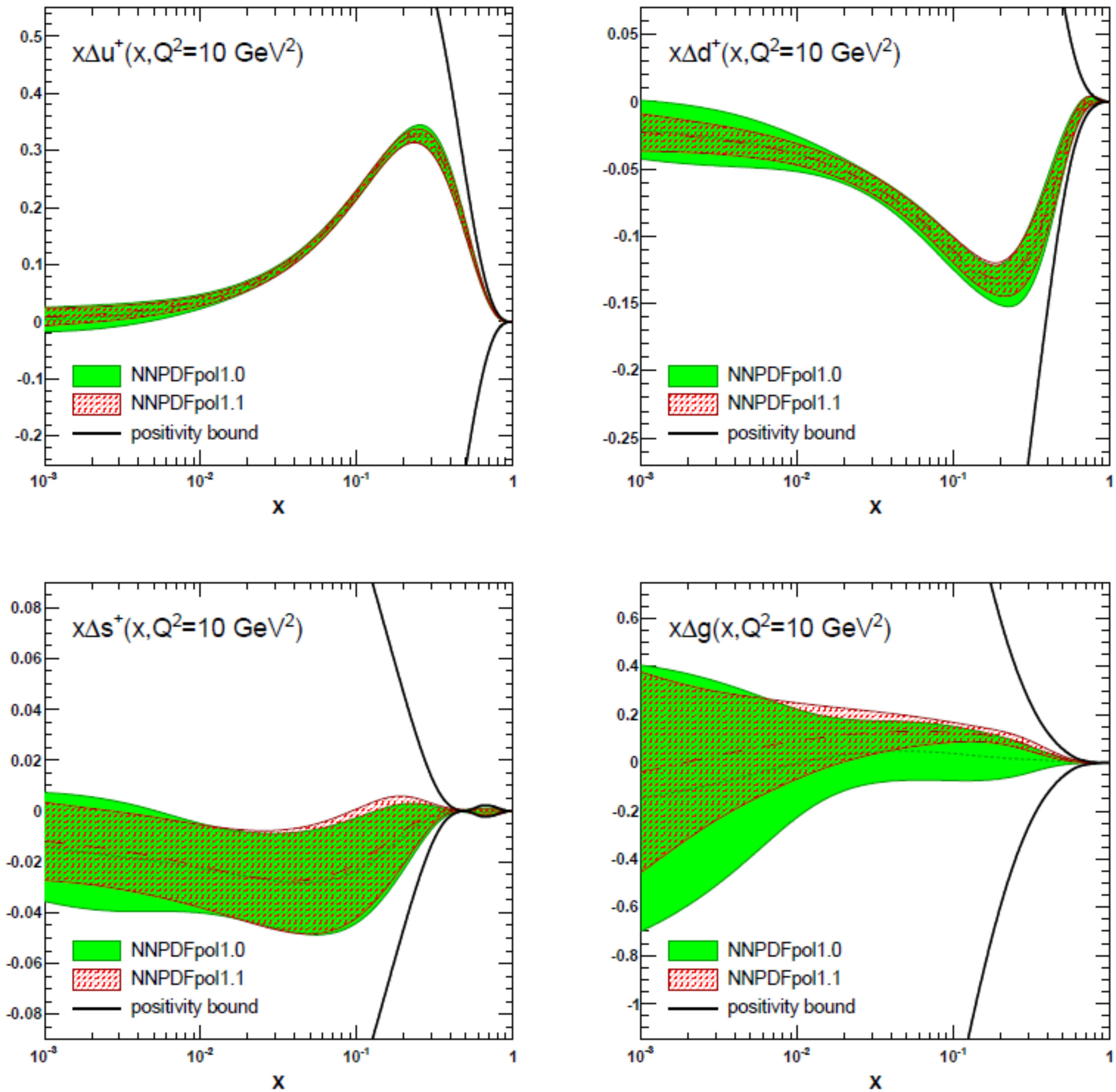
$$\sigma = PDF_1 \otimes PDF_2 \otimes \hat{\sigma}_{12}$$



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

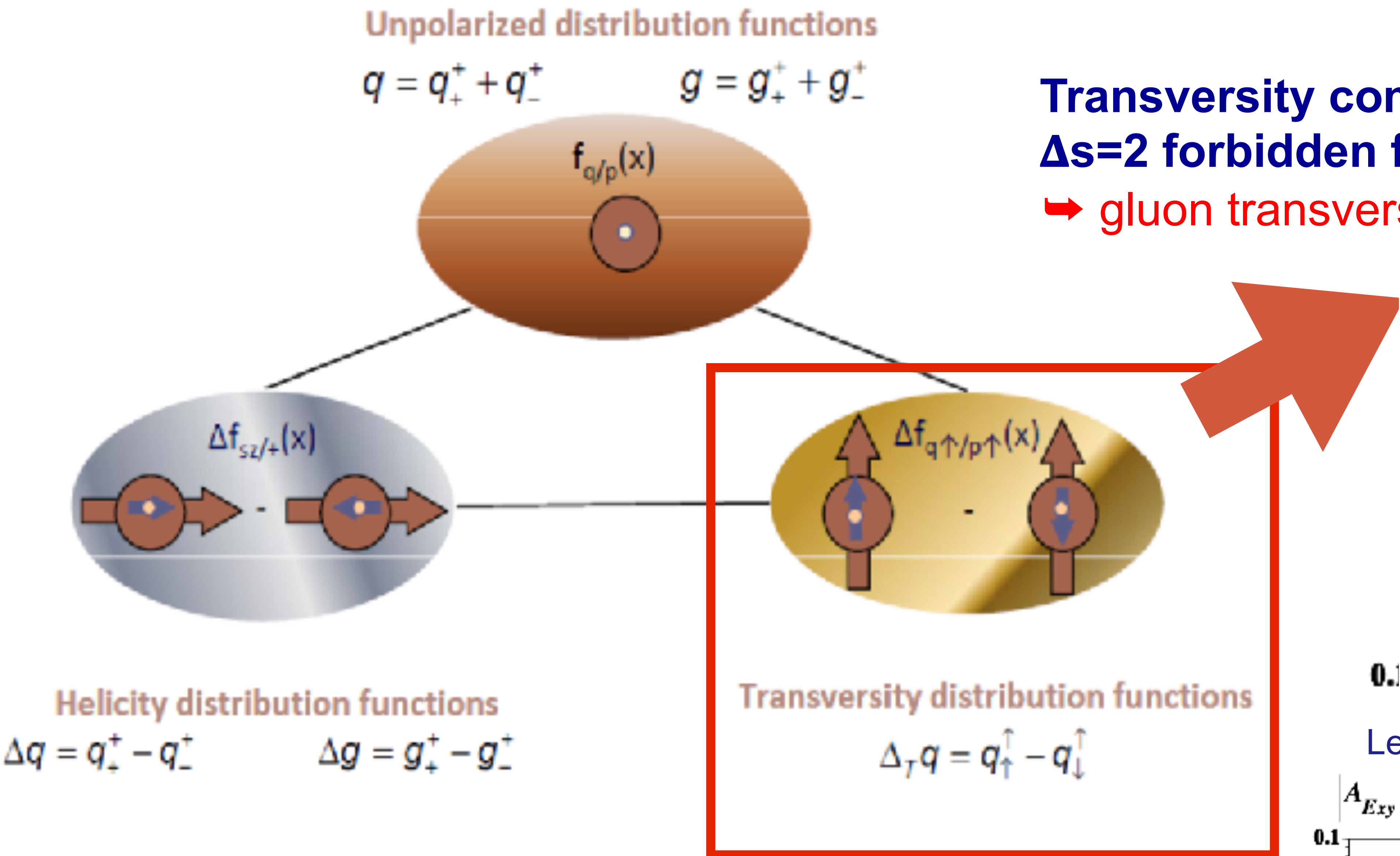
It is measured with
high precision in DIS

Gluon helicity PDF:
still rather high uncertainties!

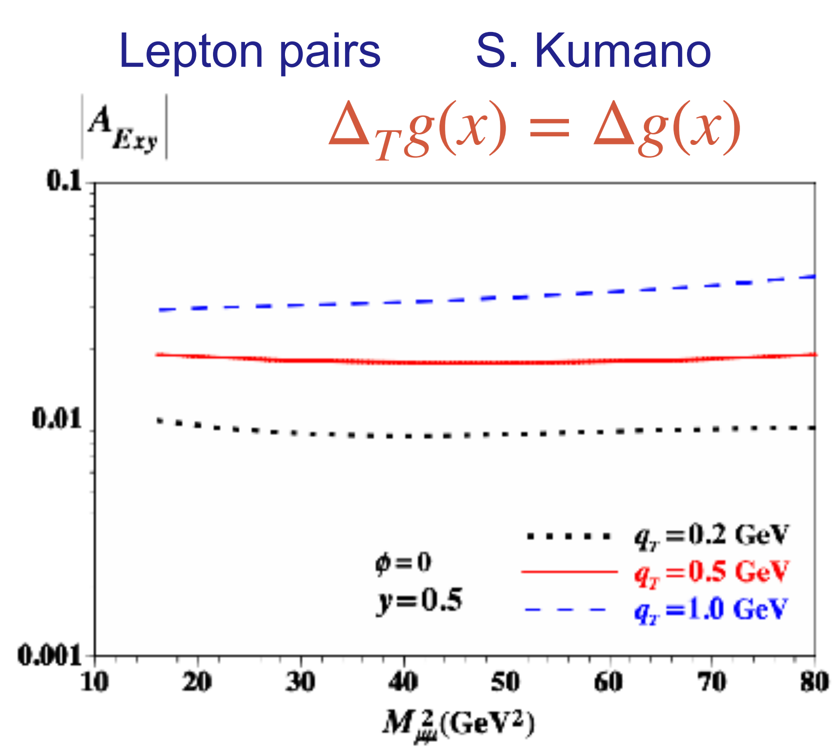
Hadron collisions have a better
sensitivity to measure it.

⬅ 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

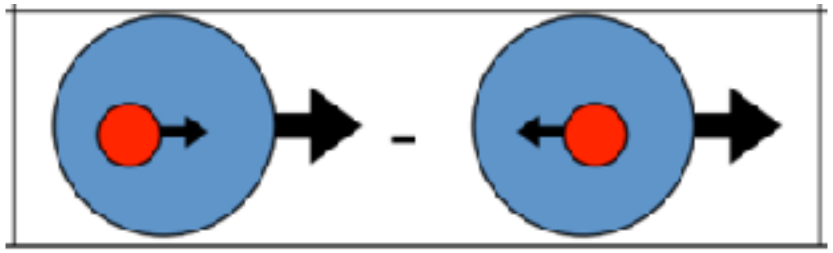


SPD has a unique opportunity to measure
gluon transversity in deuteron for the first time!

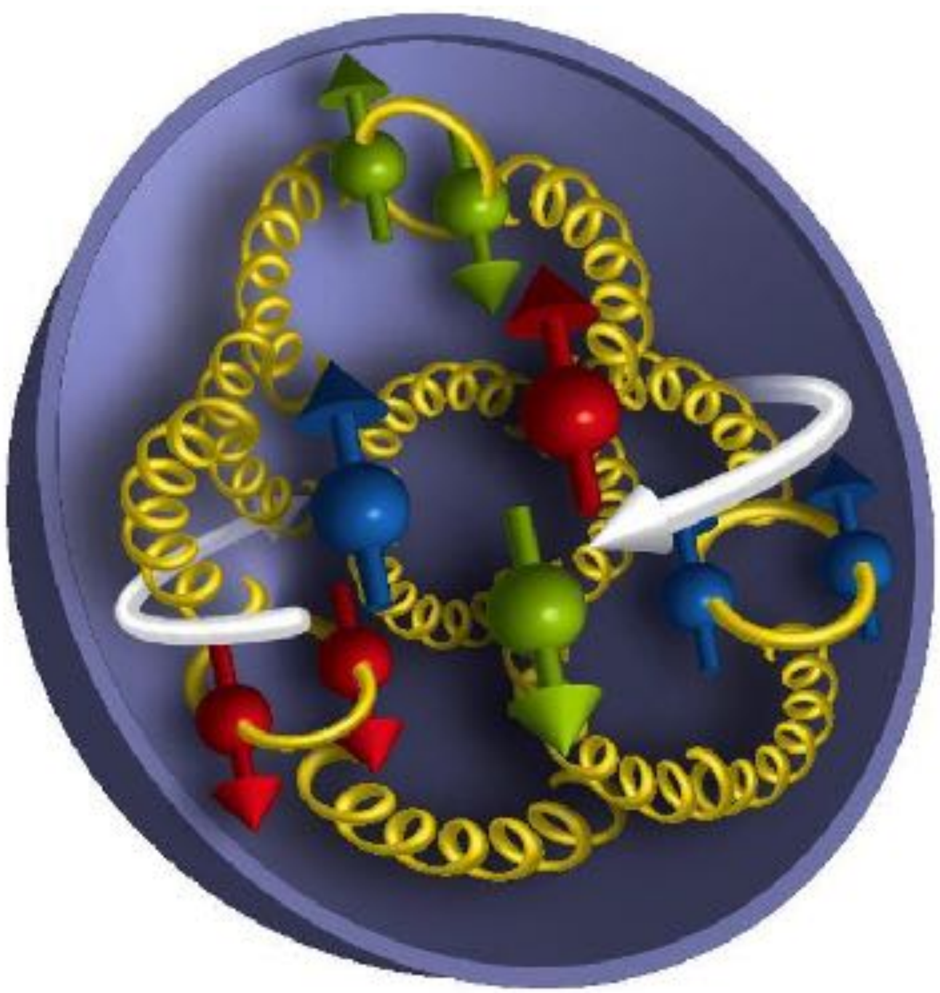
To probe new non-nucleonic degrees of freedom in deuteron!

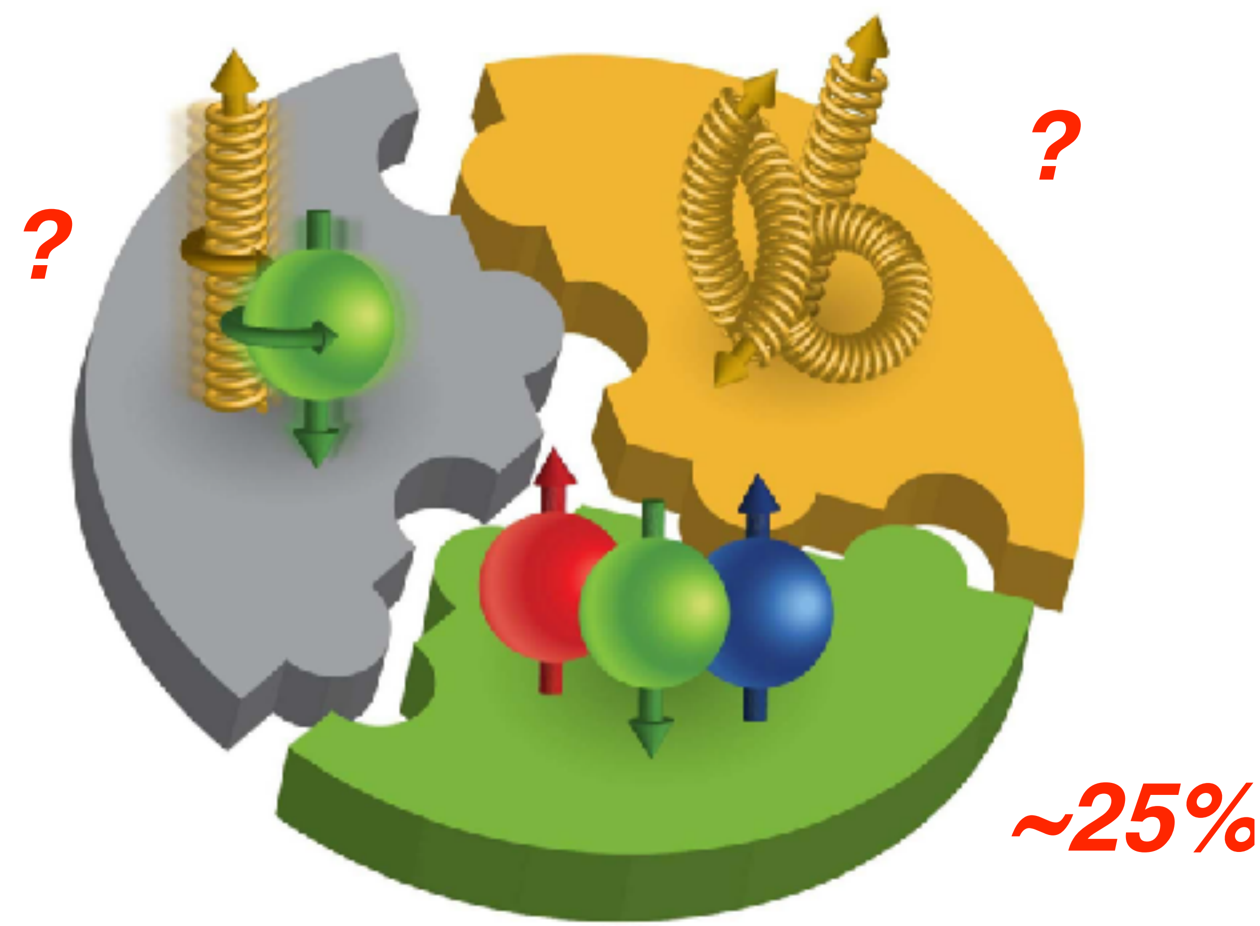
Helicity gluon PDF Δg(x): Spin Crisis

Δg(x) :



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



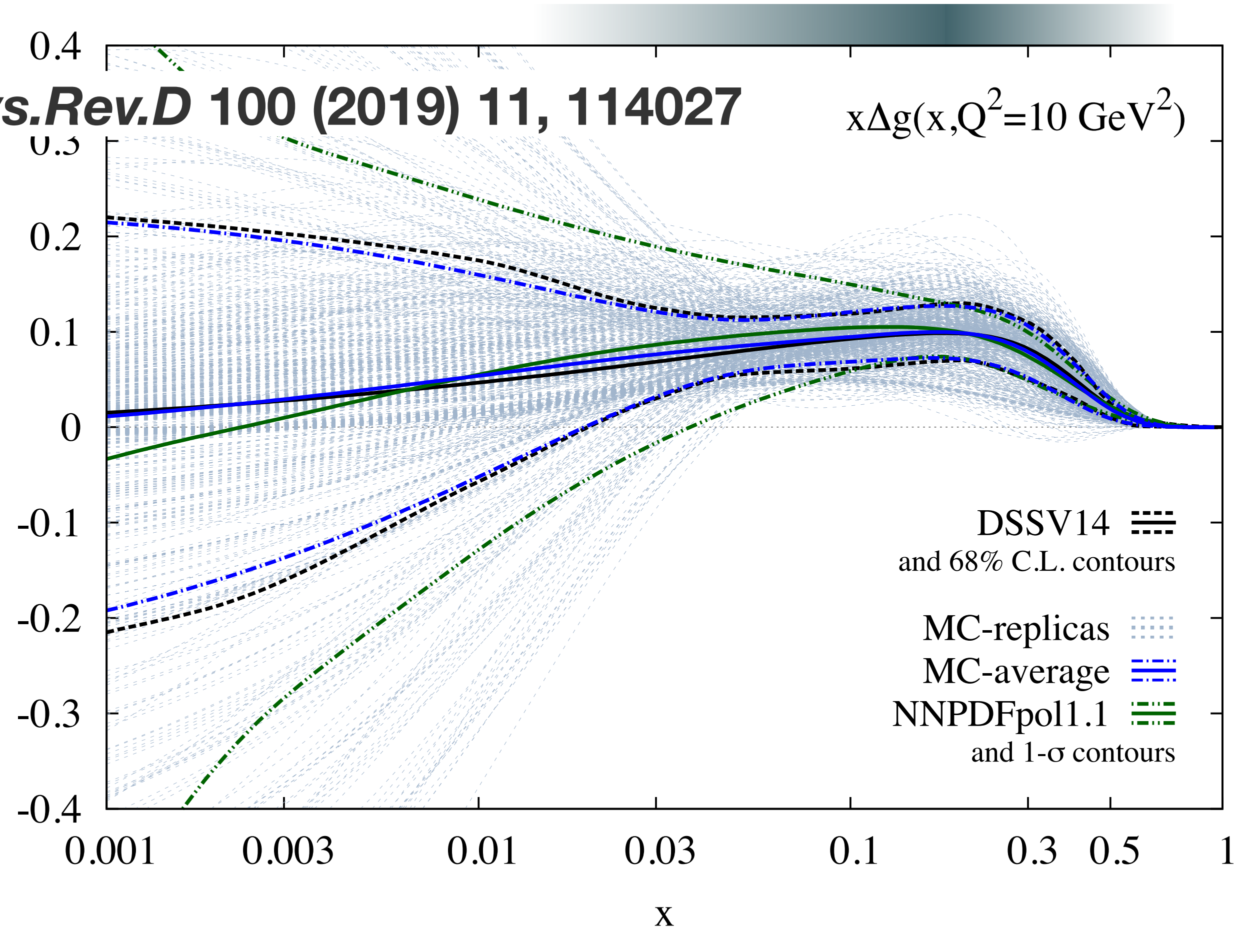


$S_N = ½ = ½\ \Delta\Sigma + \Delta G + L$

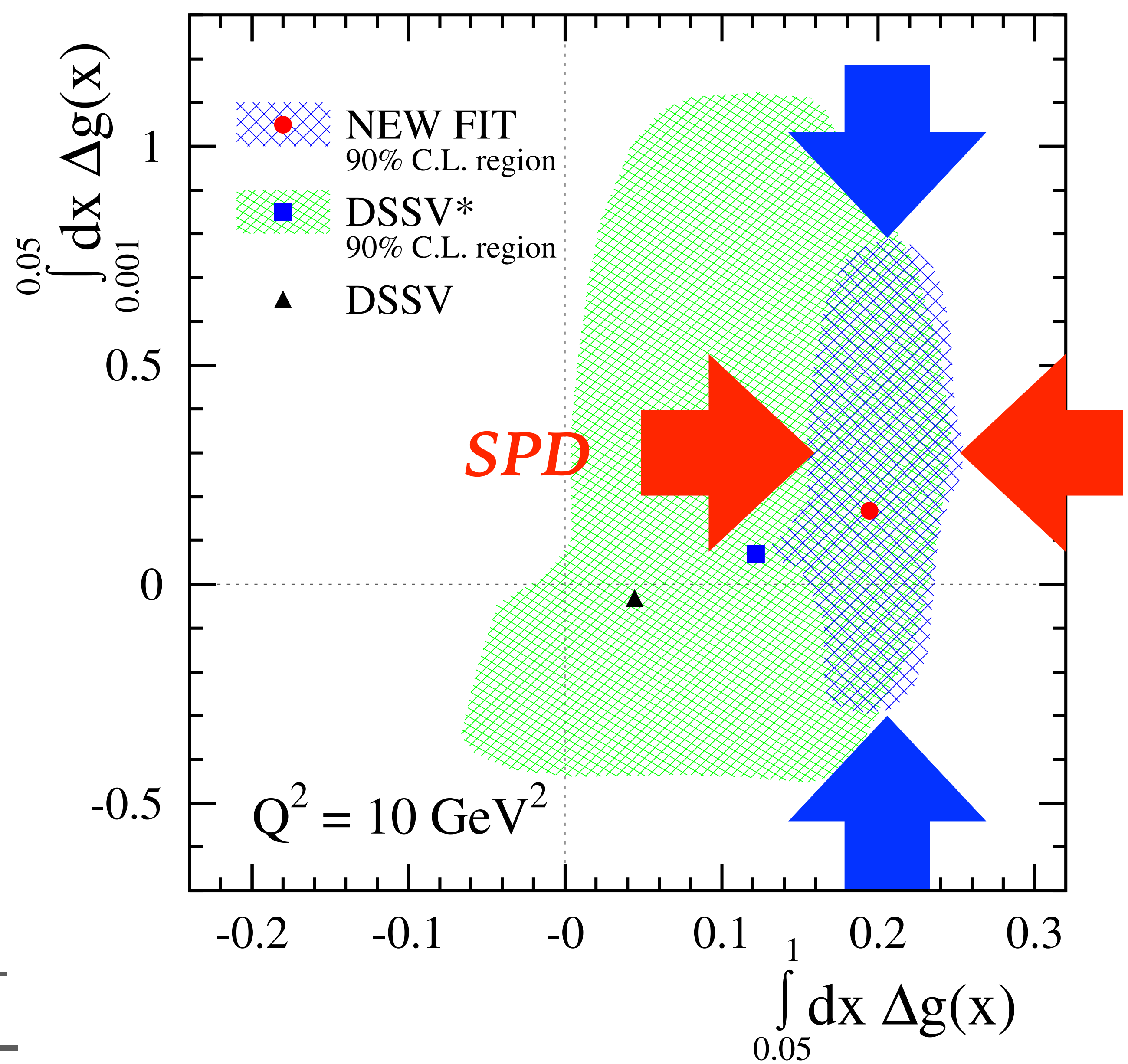
Helicity gluon PDF Δg(x):

accessible with SPD

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



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

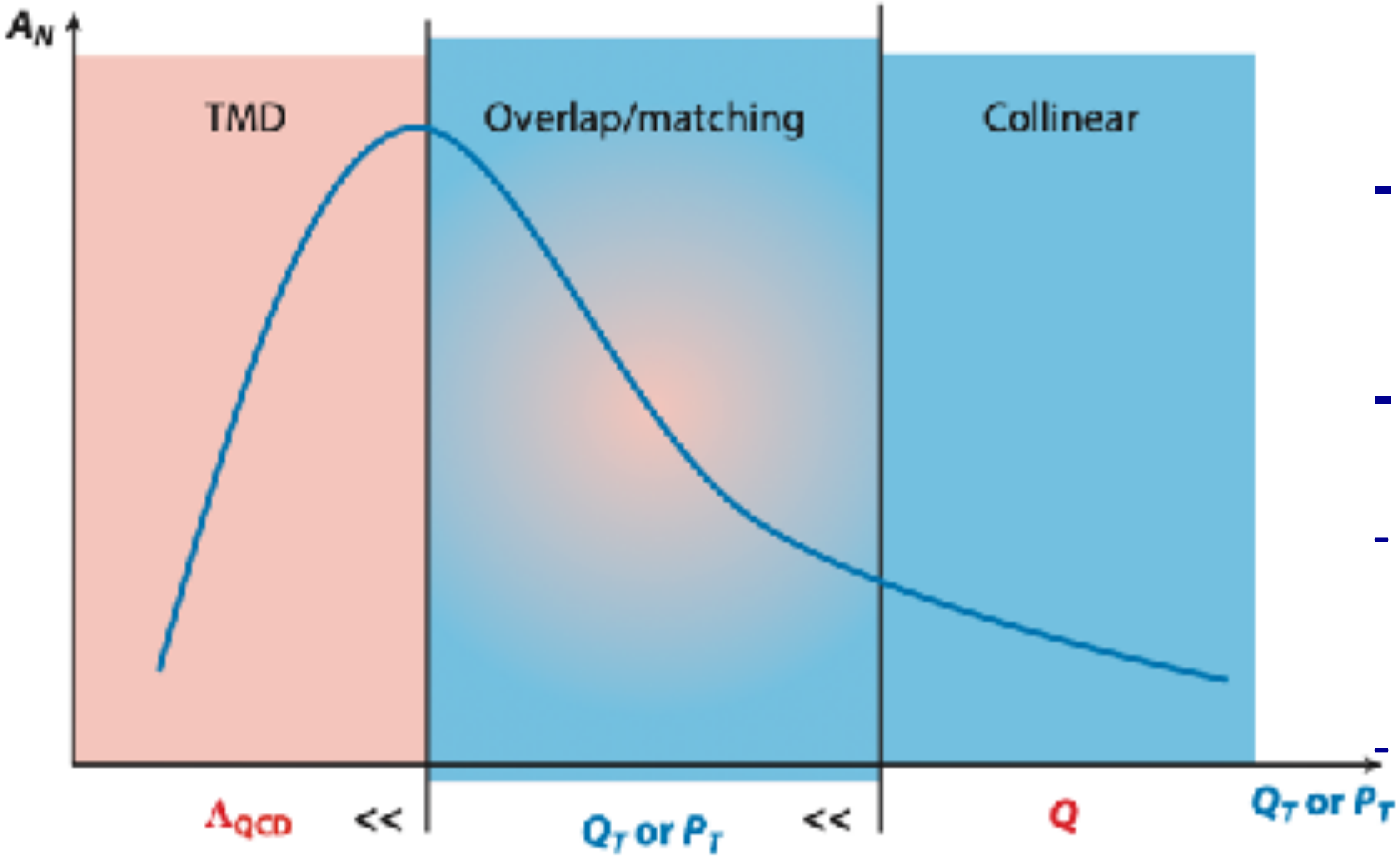


SPD could help to reduce uncertainty of ΔG at large x

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

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

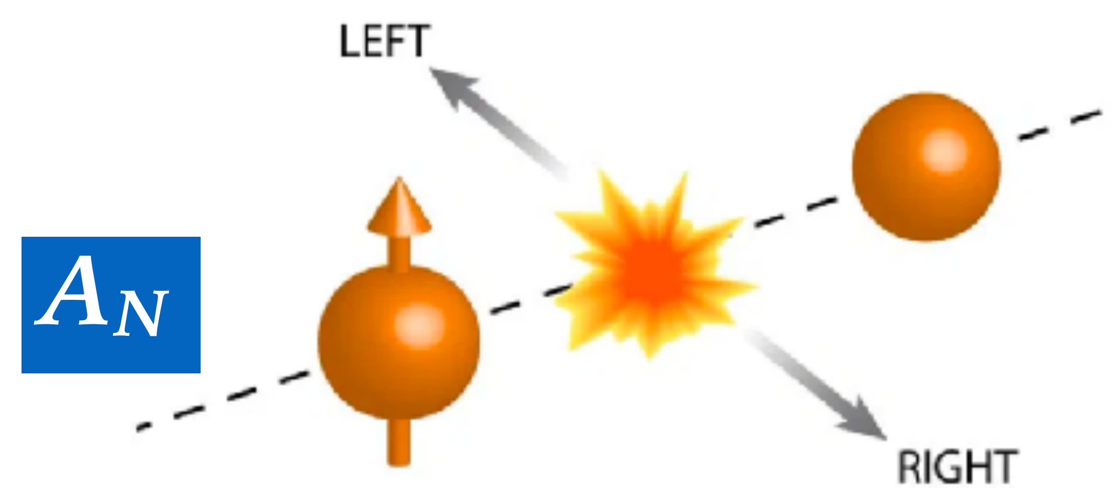
Gluon TMD effects: gluon Sivers function



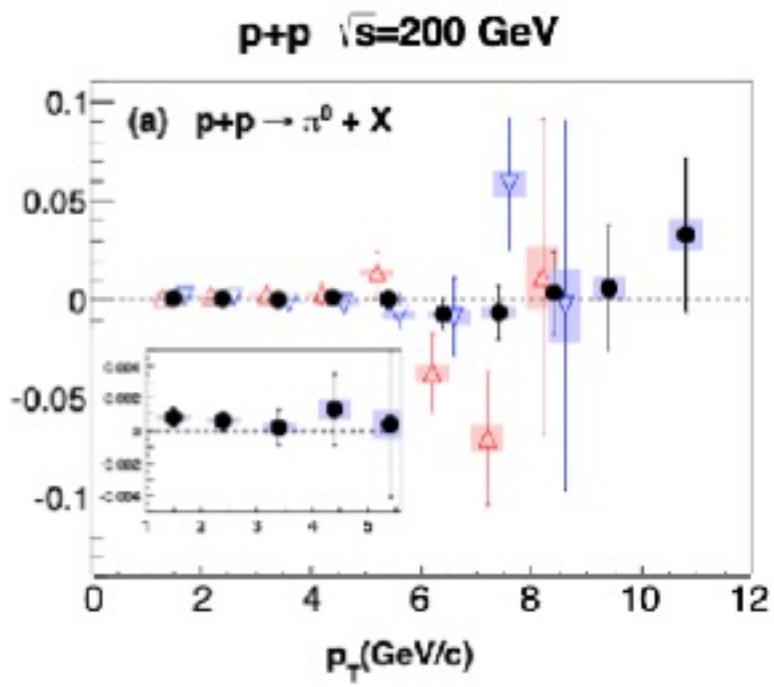
- Collinear factorization: twist-2 and twist-3
- TMD-factorization
- Overlap/matching region
- Nontrivial x and kT correlation?

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

Collins effect: due to fragmentation of polarized parton



Gluon Sivers function

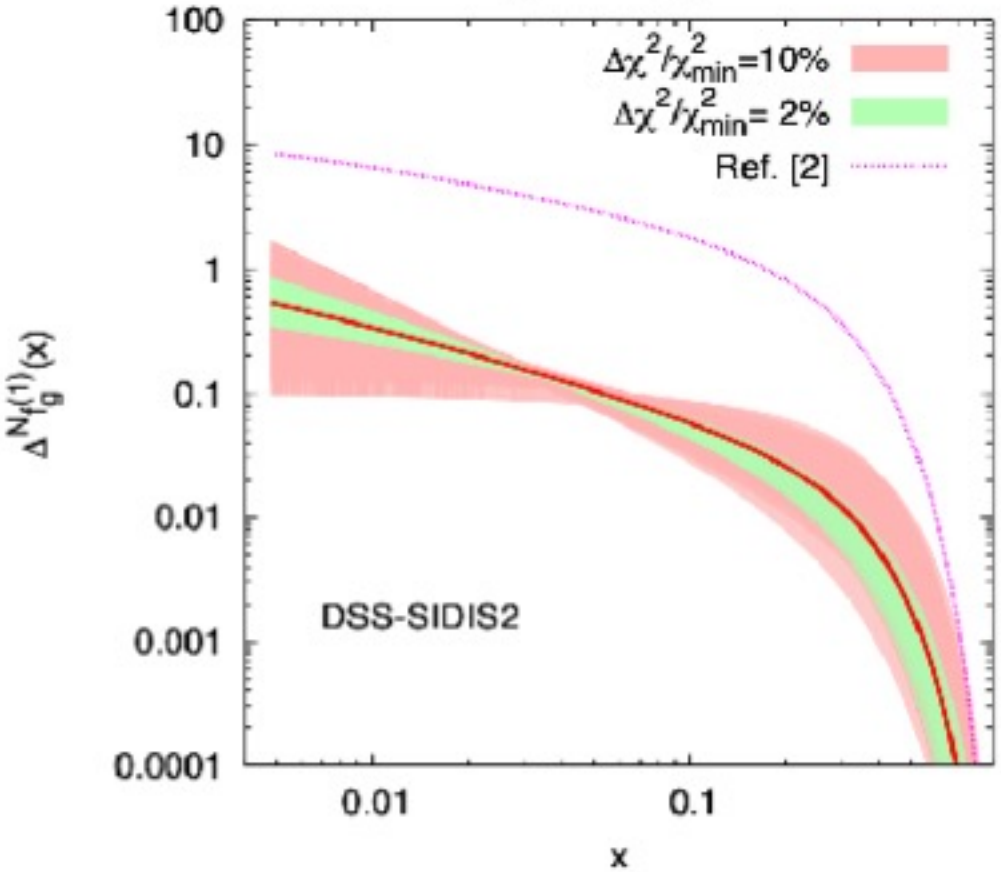


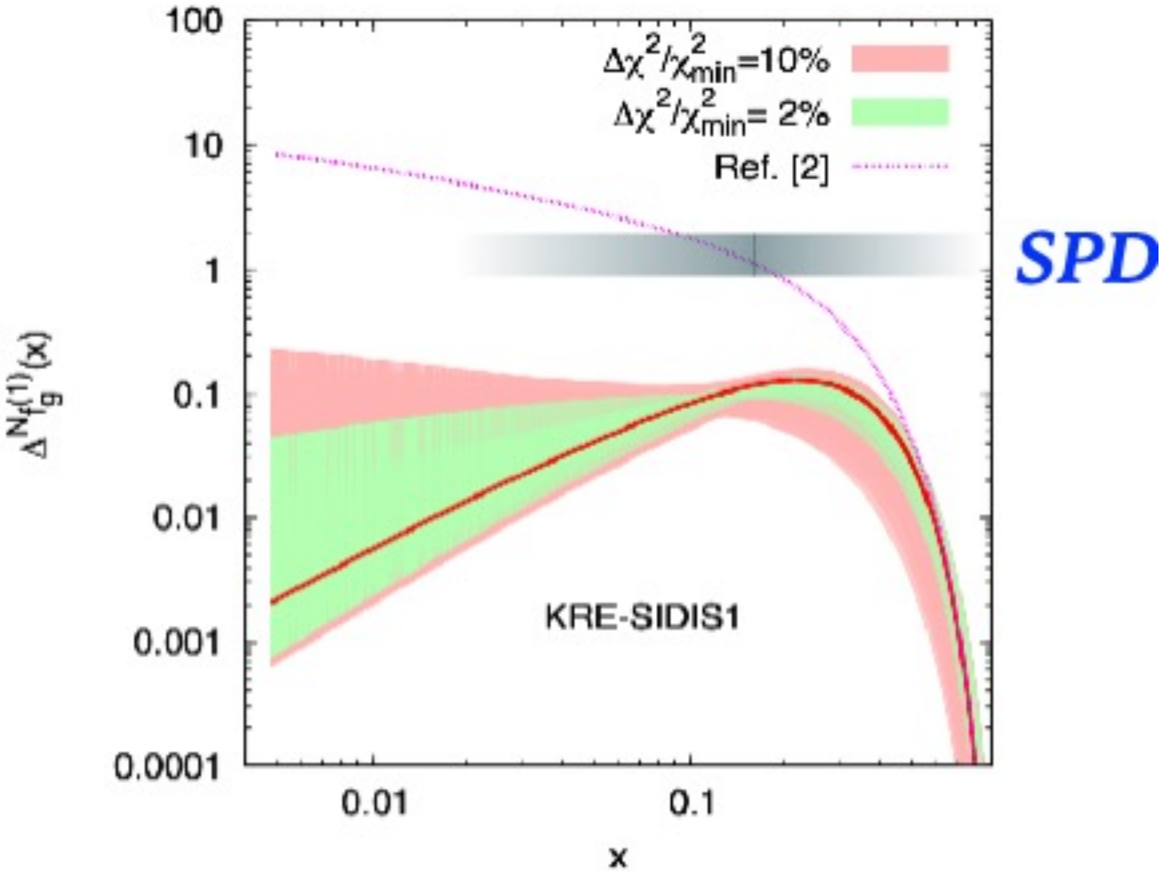
***Phys.Rev.D* 90 (2014) 1, 012006**

PHENIX

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

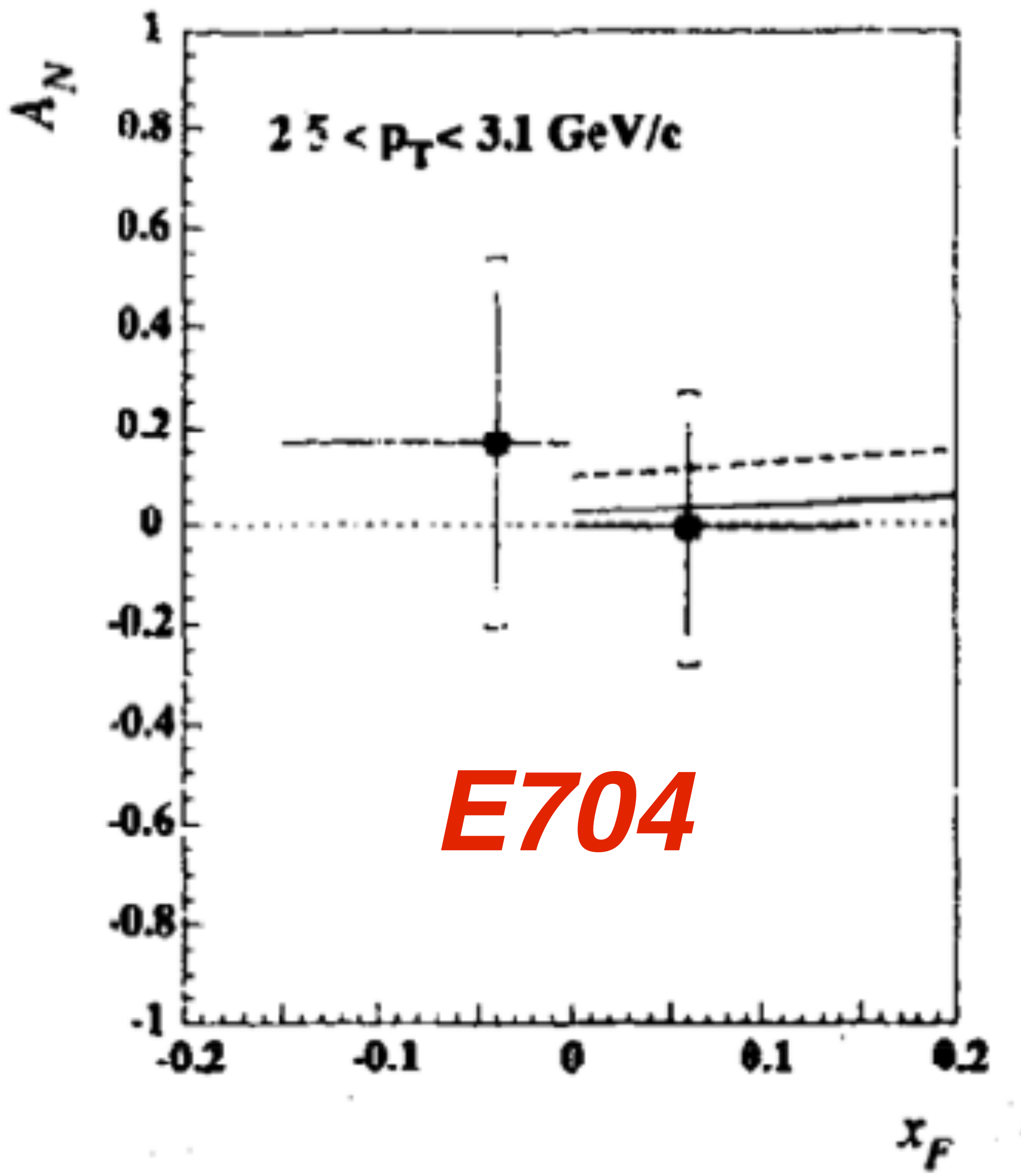
***JHEP* 09 (2015) 119**





E704 at FNAL: fixed target 200 GeV

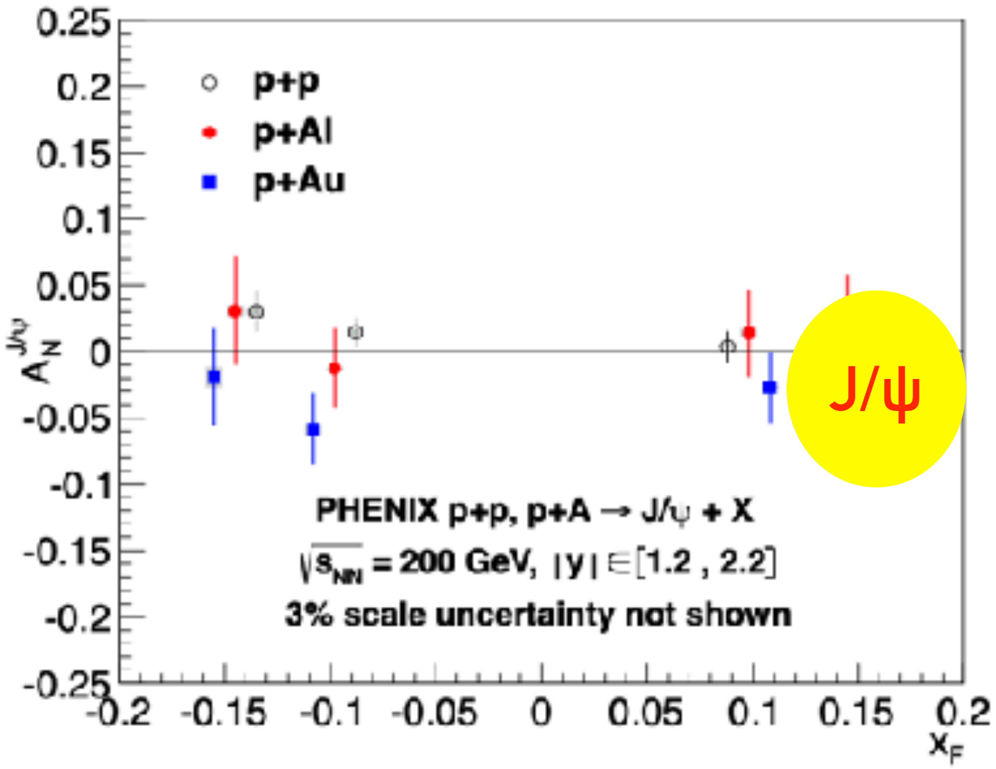
Phys. Lett. B 345 (1995)



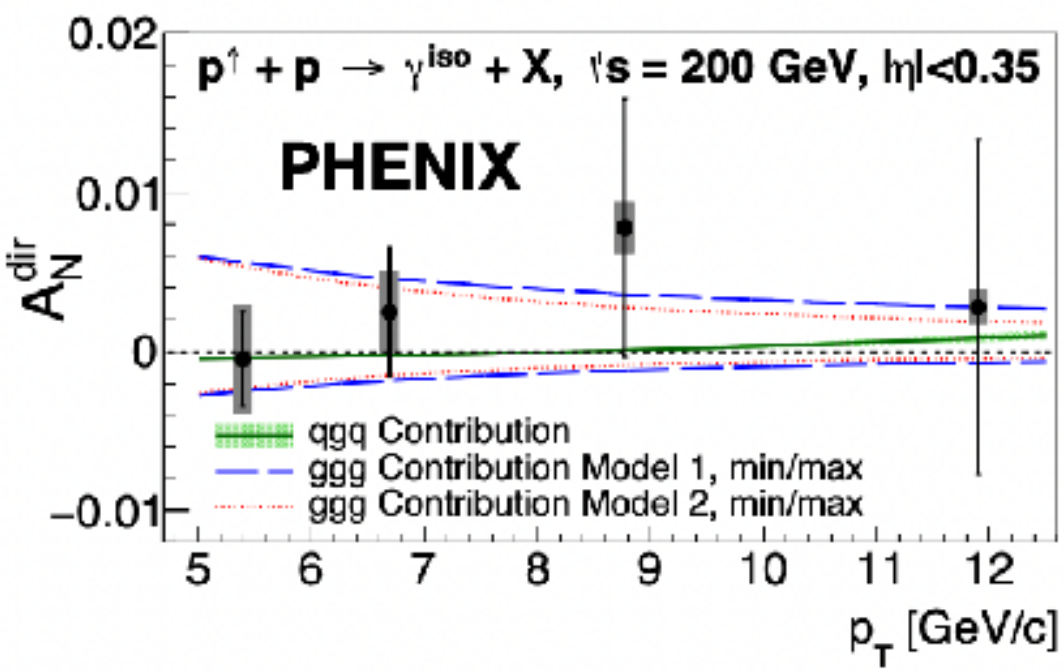
Gluon induced TMD effects: existing results for A_N

μ from HF

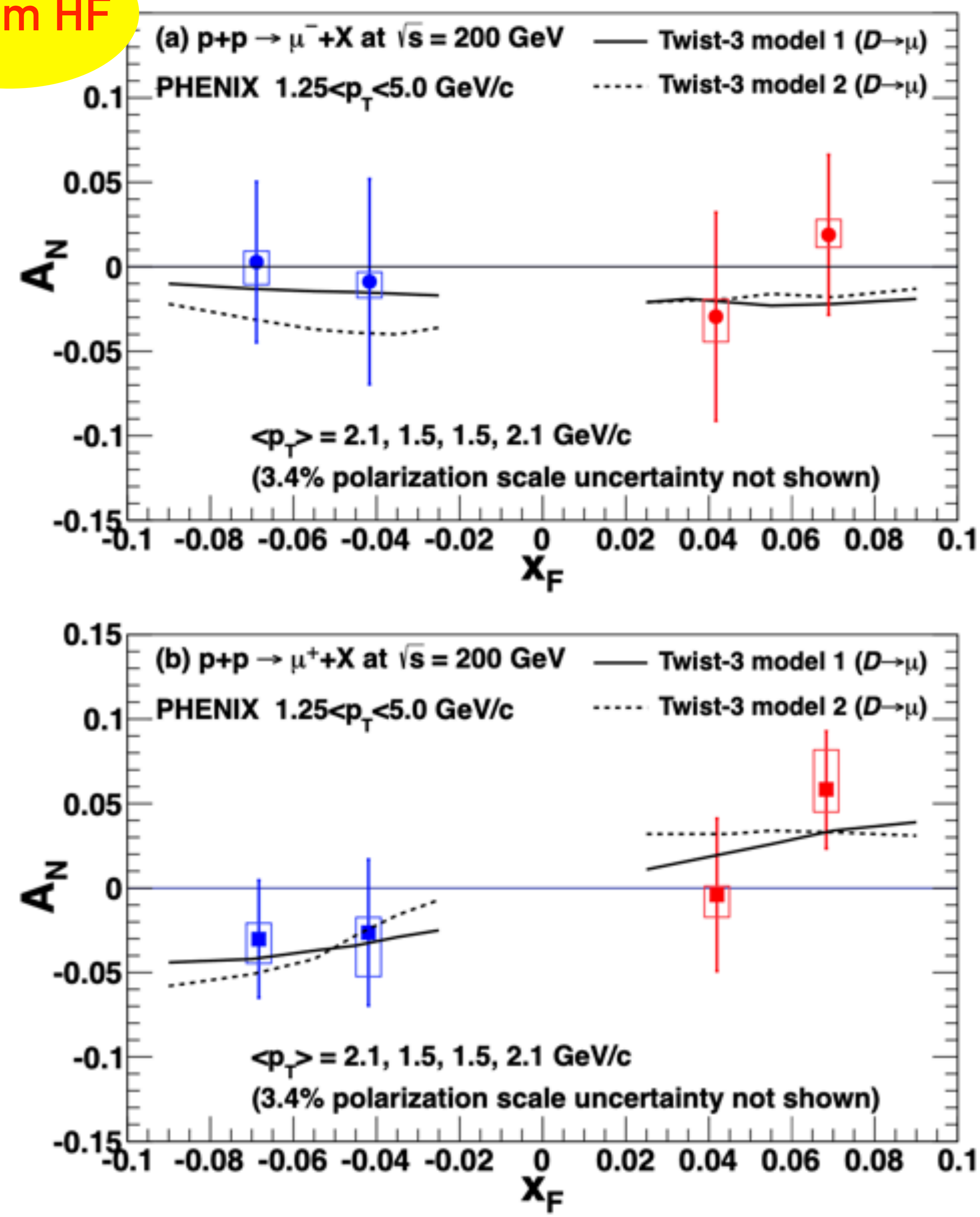
Phys.Rev.D 98 (2018) 1, 012006



J/ψ

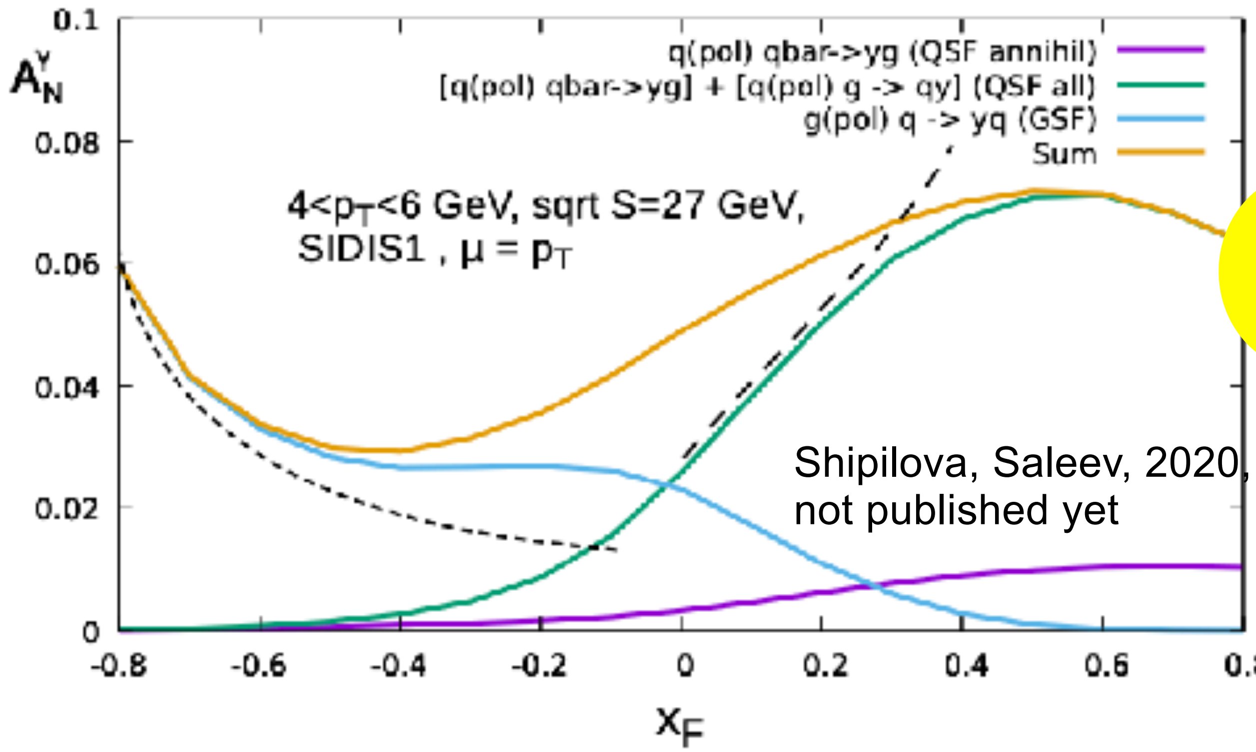


Phys.Rev.D 95 (2017) 11, 112001

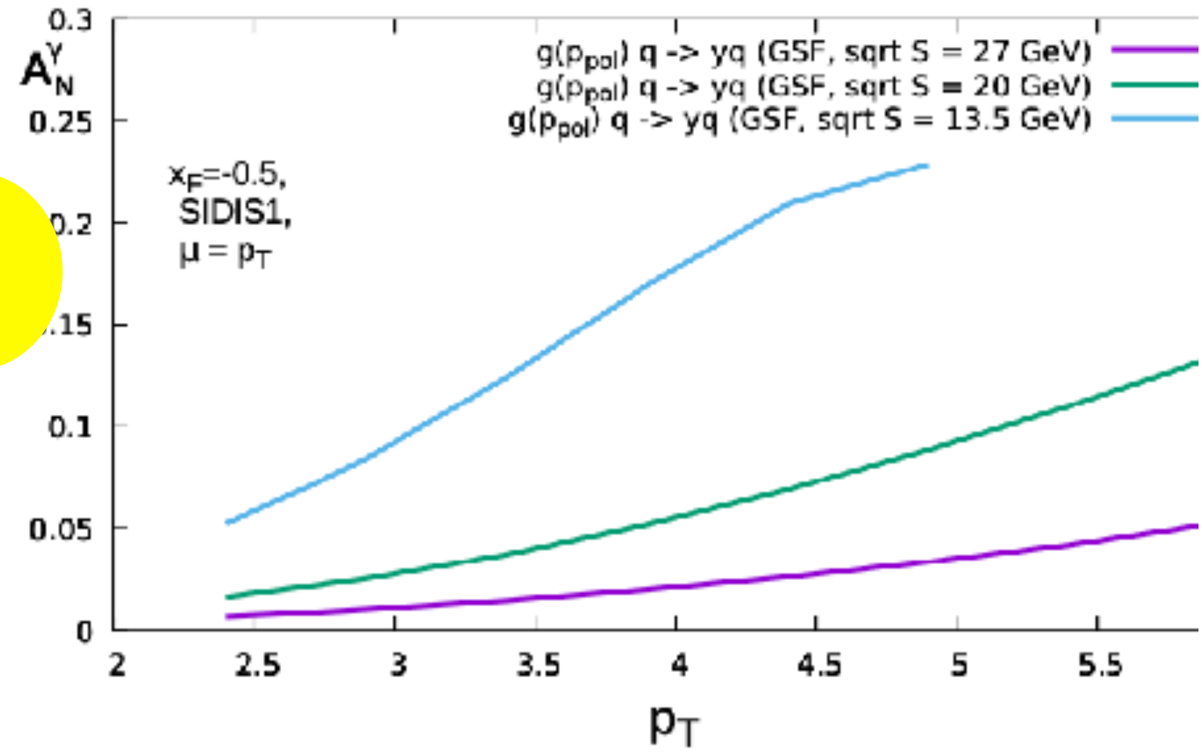


Gluon induced TMD effects: expected results for A_N

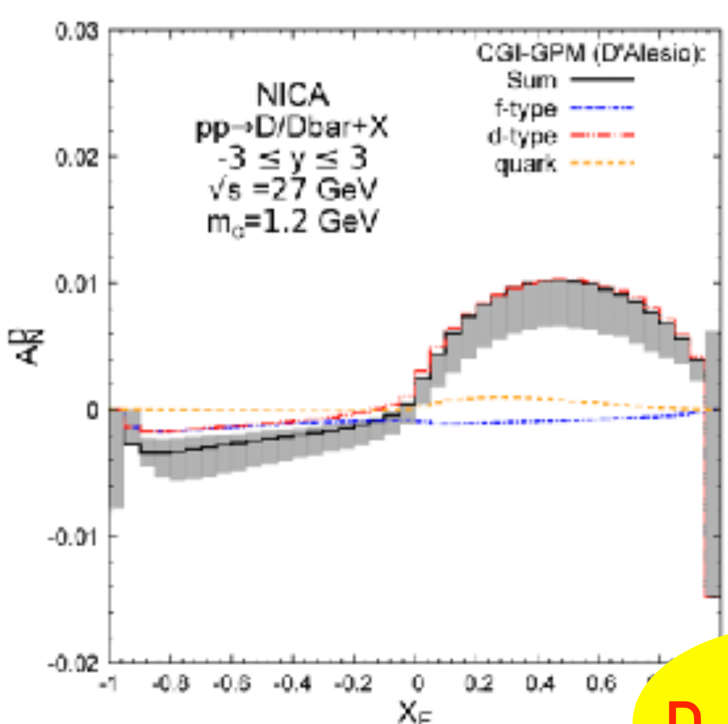
Sivers effect impact

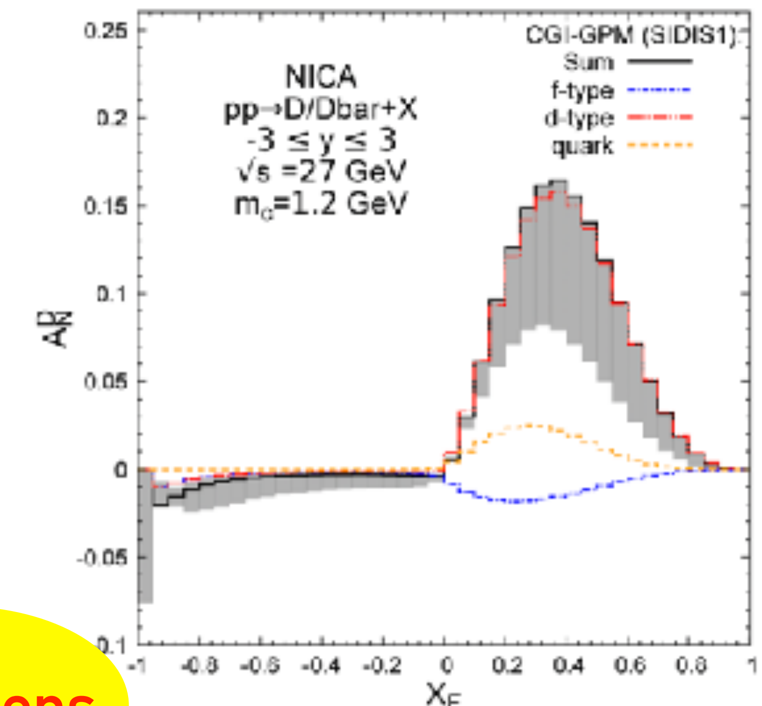


γ

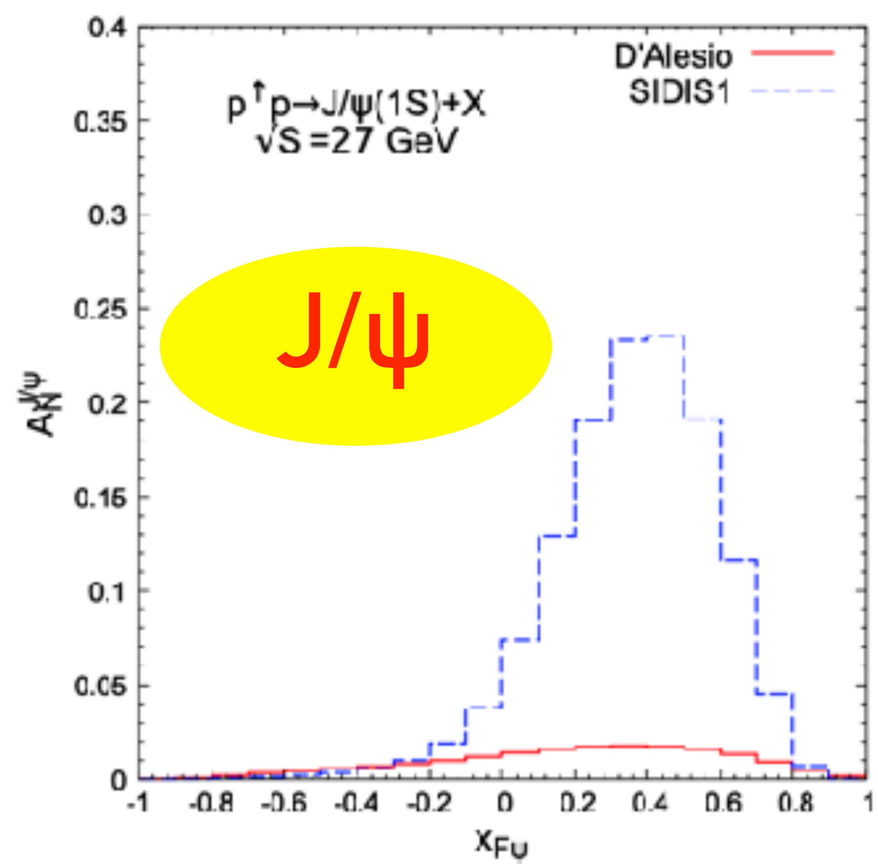


Saleev 2020





D-mesons



J/ψ

SPD Physics at the initial stage

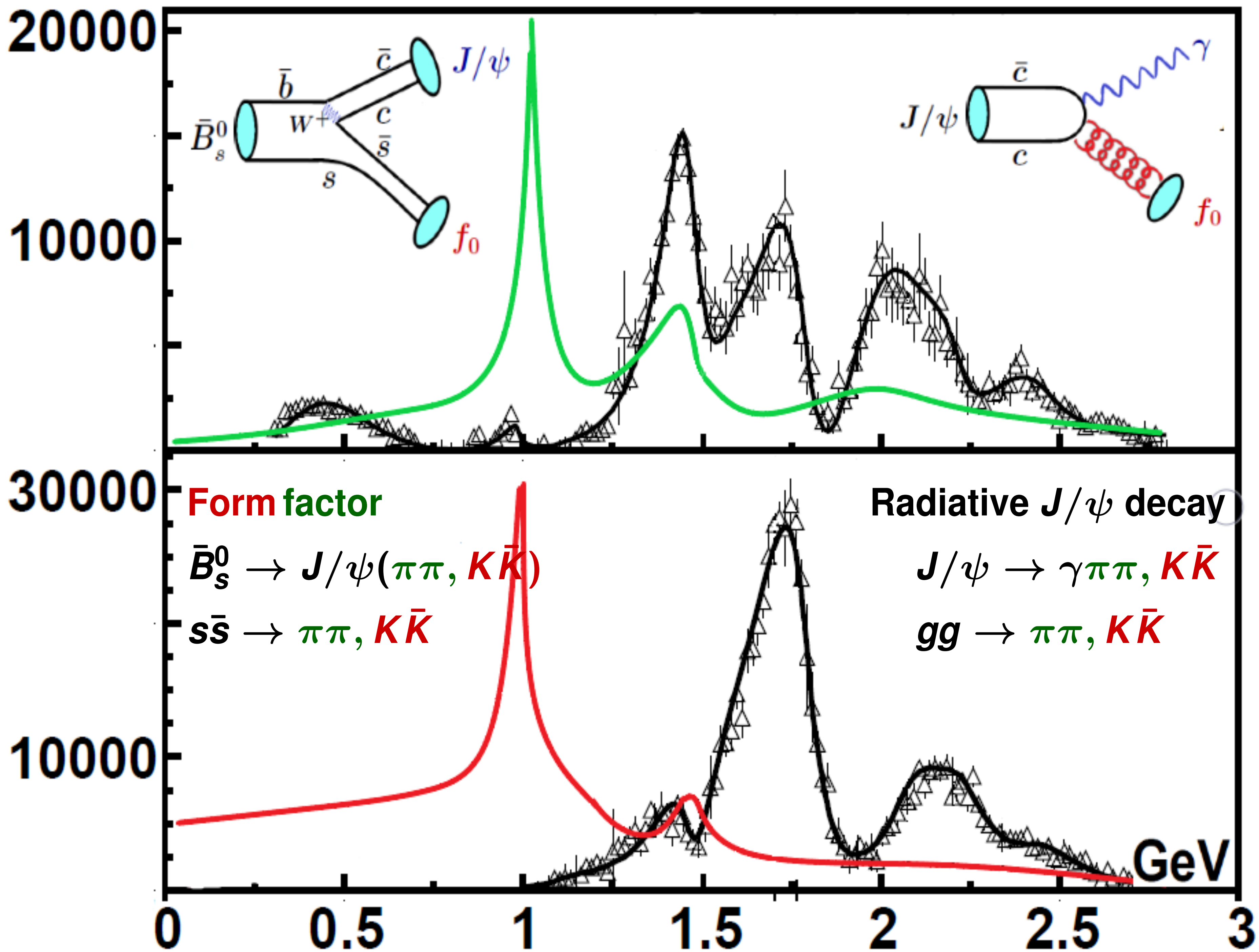
V.V. Abramov et al., Phys. Part. Nucl. 52 (2021) 1044, e-Print: 2102.08477 [hep-ph]

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
- ► …

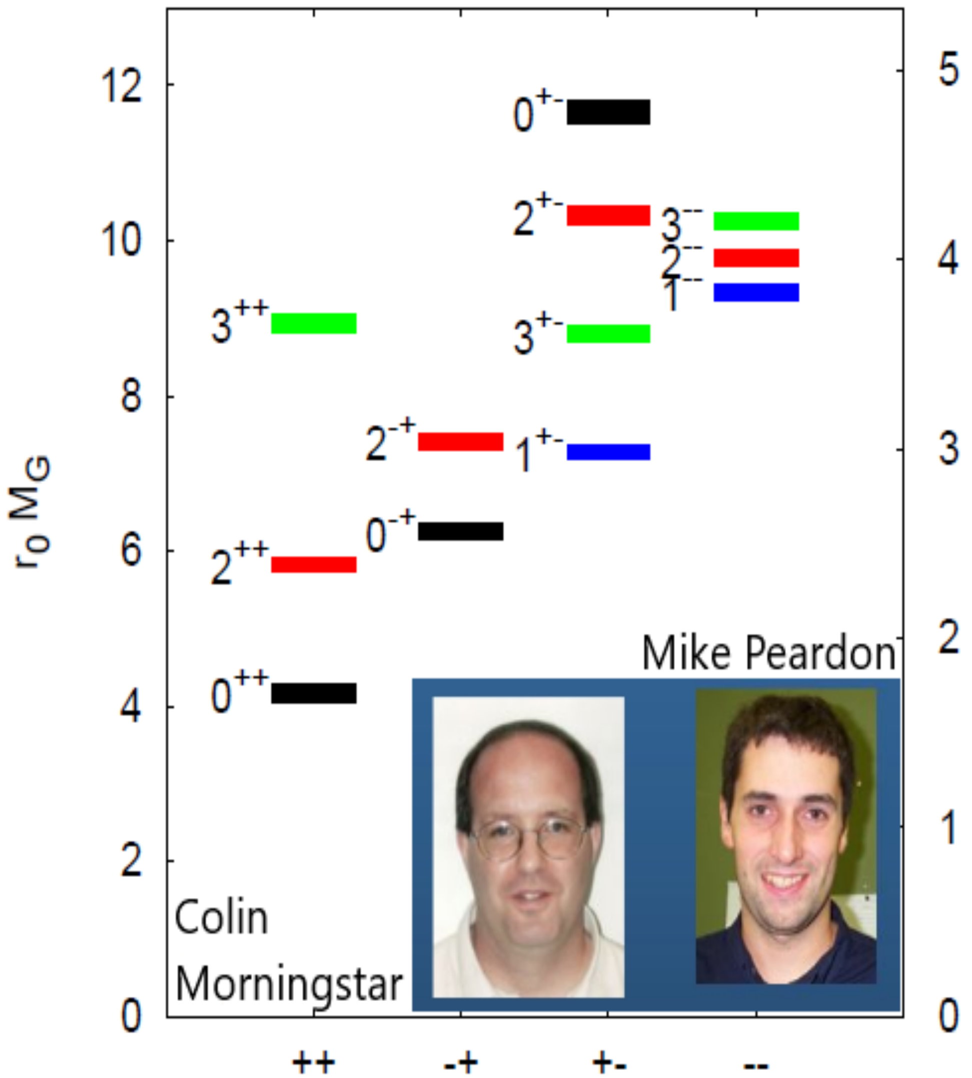
SPD Physics at the initial Stage: exotic states

Evidence for strong gluon-gluon interaction



S. Ropertz, C. Hanhart and B. Kubis, Eur. Phys. J. C 78, no.12, 1000 (2018).
R. Aaij *et al.* [LHCb], Phys. Rev. D 89, R. Aaij *et al.* [LHCb], JHEP 08, 037 (2017).

SPD Physics at the initial Stage: glueball in central diffraction



The scalar glueball is expected in the mass range from 1700 to 2000 MeV

0^{++}	$1710 \pm 50 \pm 80$ MeV
2^{++}	$2390 \pm 30 \pm 120$ MeV
0^{-+}	$2560 \pm 35 \pm 120$ MeV

Y. Chen *et al.* "Glueball spectrum and matrix elements on anisotropic lattices," Phys. Rev. D 73, 014516 (2006).

0^{++}	1980 MeV	1920 MeV
2^{++}	2420 MeV	2371 MeV
0^{-+}	2220 MeV	

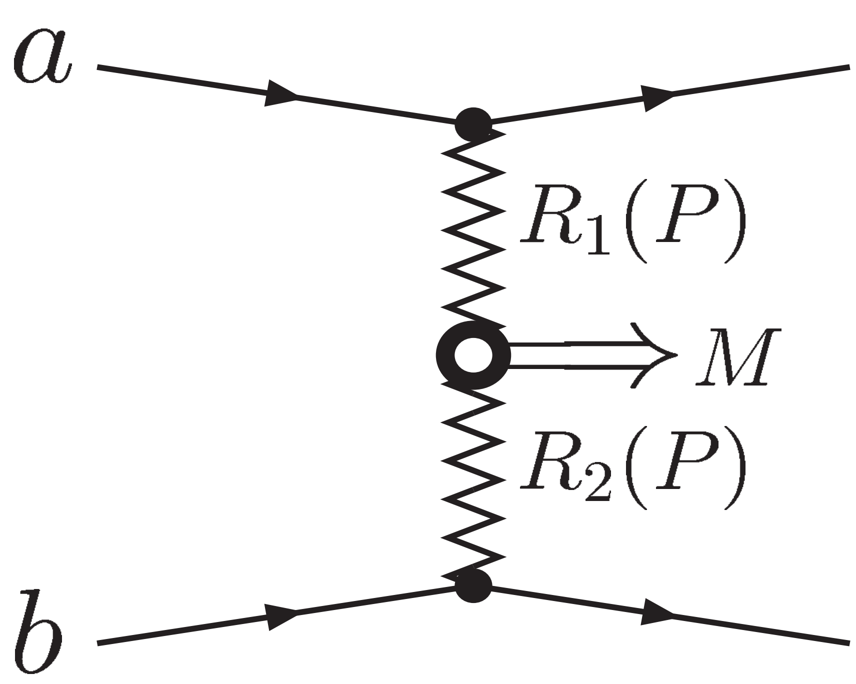
A. P. Szczepaniak and E. S. Swanson, "The Low lying glueball spectrum," Phys. Lett. B 577, 61-66 (2003).
M. Rinaldi and V. Vento, "Meson and glueball spectroscopy within the graviton soft wall model," Phys. Rev. D 104, no.3, 034016 (2021).

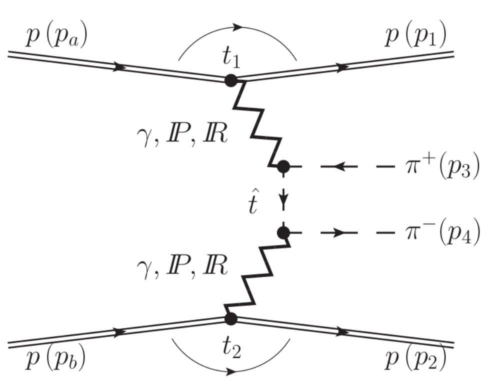
0^{++}	1850 ± 130 MeV
0^{-+}	2580 ± 180 MeV

M. Q. Huber, C. S. Fischer and H. Sanchis-Alepuz, "Spectrum of scalar and pseudoscalar glueballs from functional methods," Eur. Phys. J. C 80, no.11, 1077 (2020).

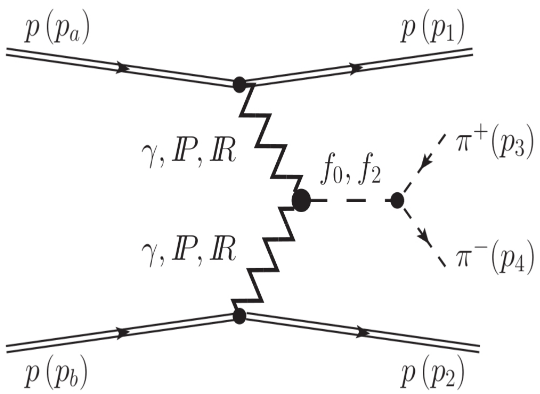
A. Sarantsev 2023

SPD Physics at the initial Stage: exotic states in central diffraction

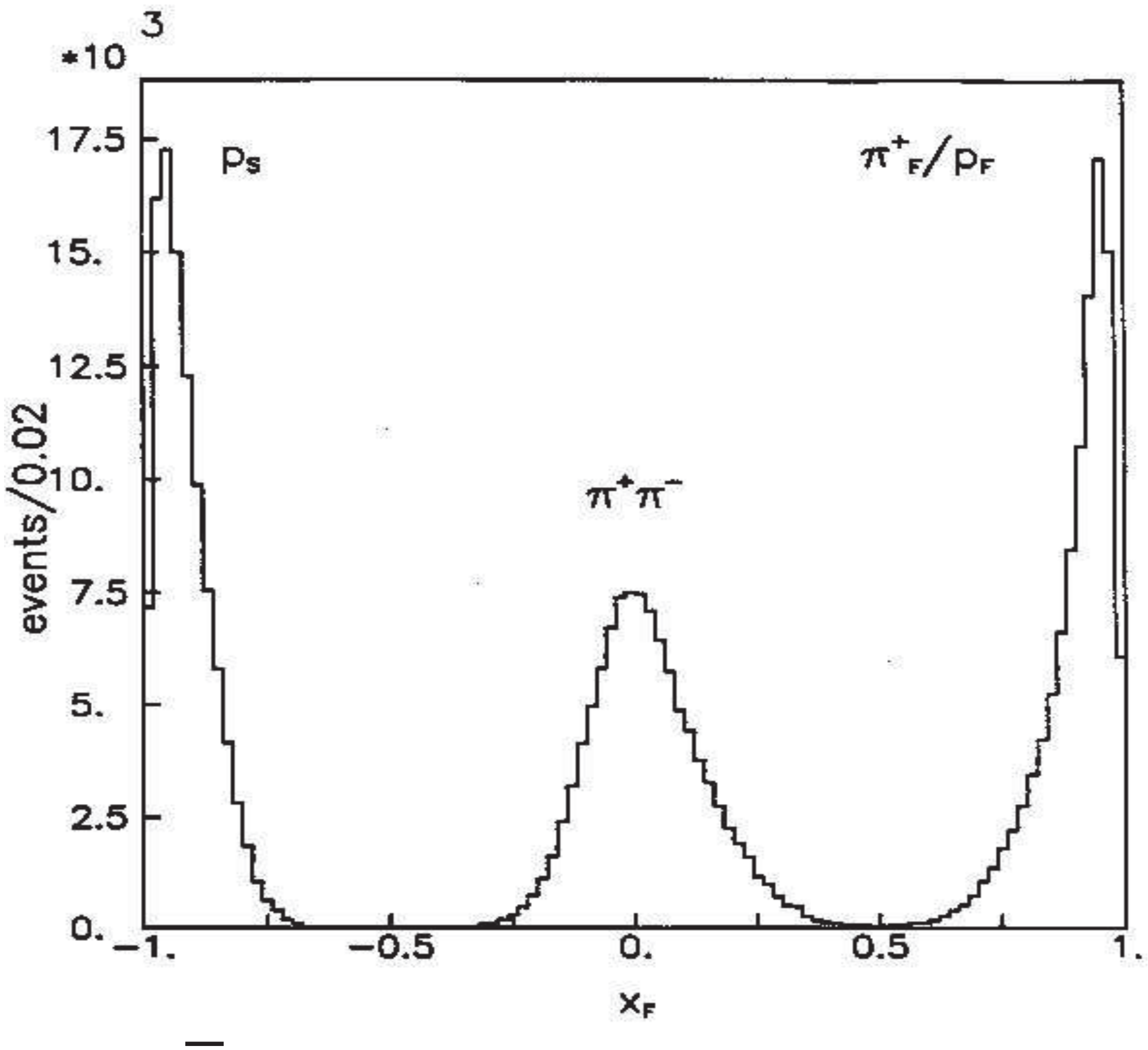




Non resonant production of 2 pions

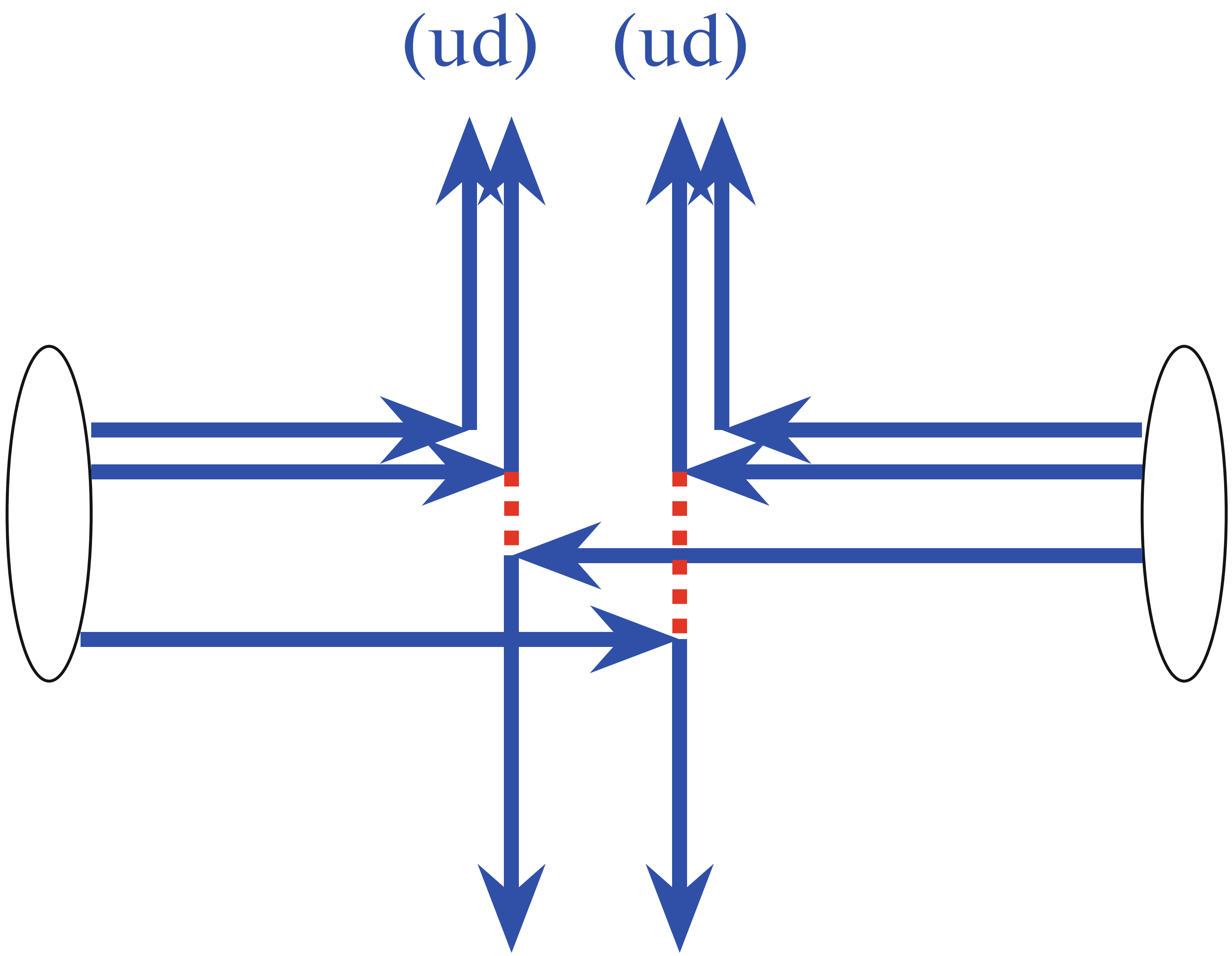


Resonance production of 2 pions



A. Sarantsev 2023

SPD Physics at the initial Stage: exotic states pentaquark, dihyperon, etc. production



A. Efremov, V. Kim 1987
V. Abramov et al 2021

SPD Experiment: Running Strategy

Physics goal	Required time	Experimental conditions
First stage		
Spin effects in p-p scattering dibaryon resonanses	0.3 year	$p_{L,T}$-$p_{L,T}$, $\sqrt{s}$ <7.5 GeV
Spin effects in p-d scattering, non-nucleonic structure of deuteron, $\bar{p}$ yield	0.3 year	d_{tensor}-p, $\sqrt{s}$ <7.5 GeV
Spin effects in d-d scattering hypernuclei	0.3 year	d_{tensor}-d_{tensor}, $\sqrt{s}$ <7.5 GeV
Hyperon polarization, SRC, ... multiquarks	together with MPD	ions up to Ca
Second stage		
Gluon TMDs, SSA for light hadrons	1 year	p_T-p_T, $\sqrt{s}$ =27 GeV
TMD-factorization test, SSA, charm production near threshold, onset of deconfinment, $\bar{p}$ yield	1 year	p_T-p_T, 7 GeV< $\sqrt{s}$ <27 GeV (scan)
Gluon helicity, ...	1 year	p_L-p_L, $\sqrt{s}$ =27 GeV
Gluon transversity, non-nucleonic structure of deuteron, "Tensor porlarized" PDFs	1 year	d_{tensor}-d_{tensor}, $\sqrt{s_{NN}} = 13.5$ GeV or/and d_{tensor}-p_T, $\sqrt{s_{NN}} = 19$ GeV

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 $\sqrt{s}$ 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 and TDR: http://spd.jinr.ru
- SPD physics:

A. Arbuzov et al. ,Prog. Part. Nucl. Phys. 119 (2021) 103858 e-Print: 2011.15005 [hep-ex]
V.V. Abramov et al., Phys. Part. Nucl. 52 (2021) 1044, e-Print: 2102.08477 [hep-ph]