Spin Physics Detector

SPD NICA

Physics with SPD experiment at NICA Collider

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for the SPD Collaboration

14th APCTP-BLTP JINR JOINT WORKSHOP
9-14 July 2023, Pohang, Korea

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 and TMD 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 ~ few MeV

➥ **quark-gluon dynamics of nucleon structure provides most of the mass of the visible Universe!**

Why Spin?

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

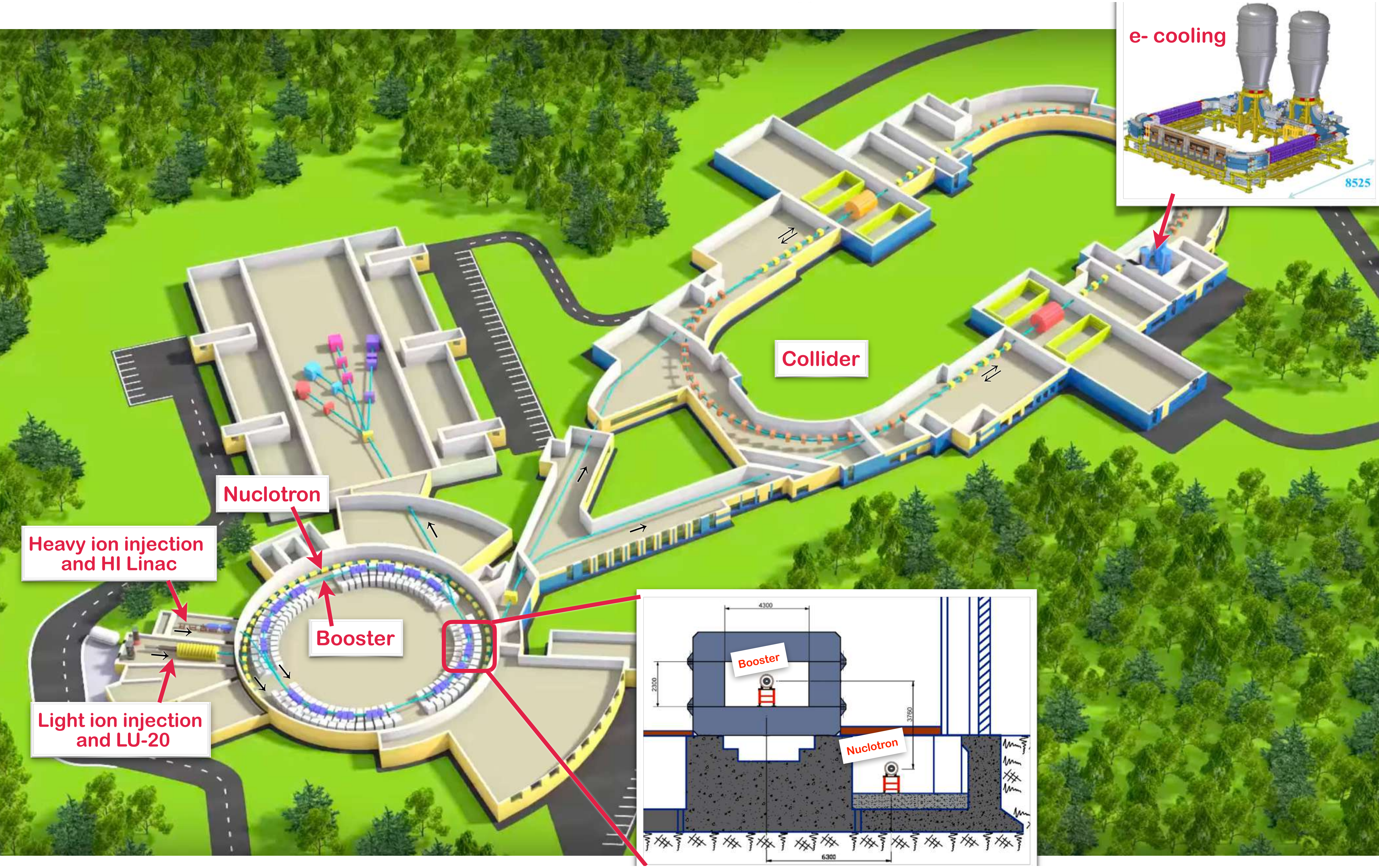
Elliot Leader, Spin in Particle Physics, Cambridge U. Press (2001)

"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."

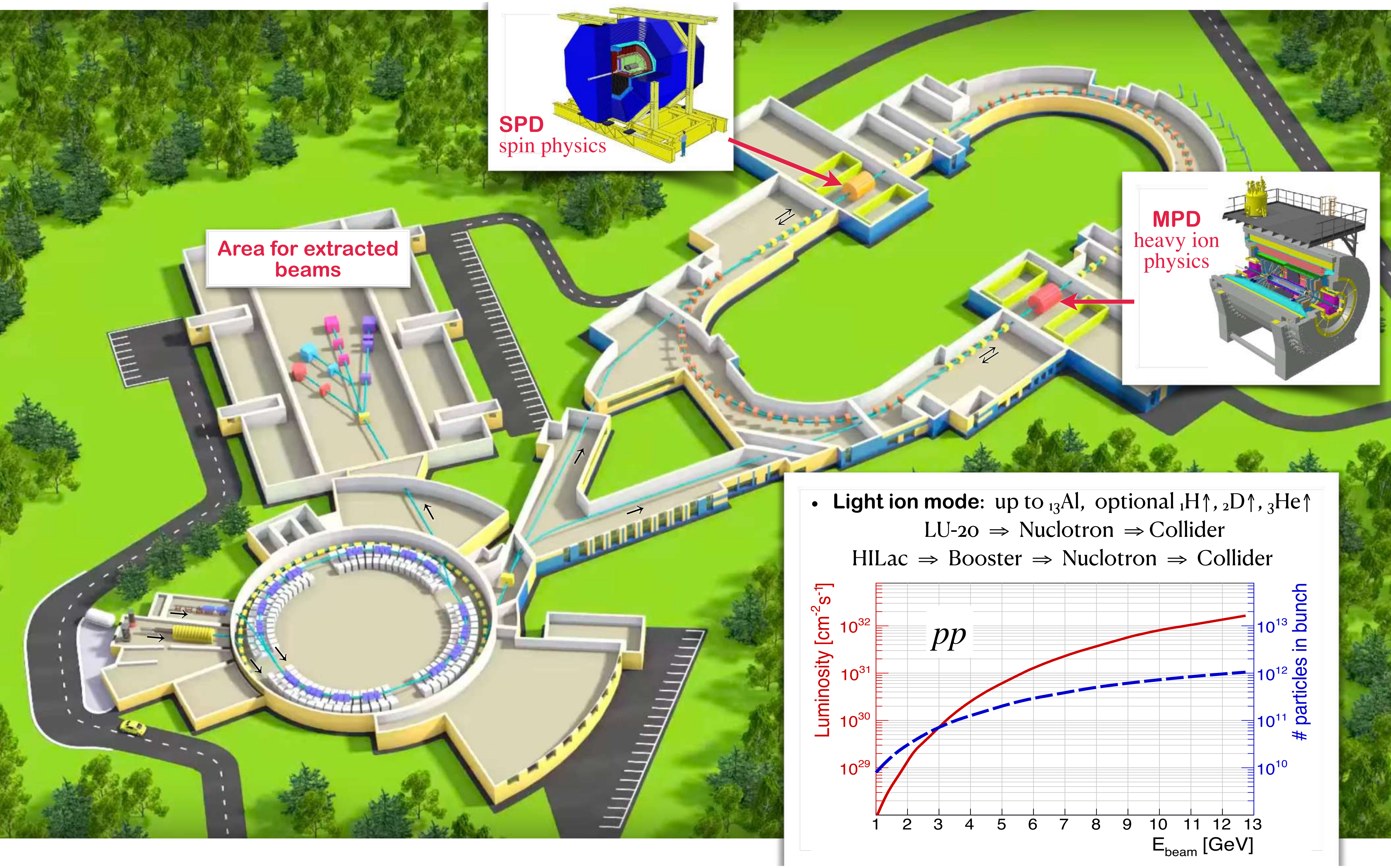
J. D. Bjorken, Proc. Adv. Research Workshop on QCD Hadronic Processes, St. Croix, Virgin Islands (1987).

V. Mochalov (NRC - IHEP)

NICA Accelerator Complex at JINR, Dubna



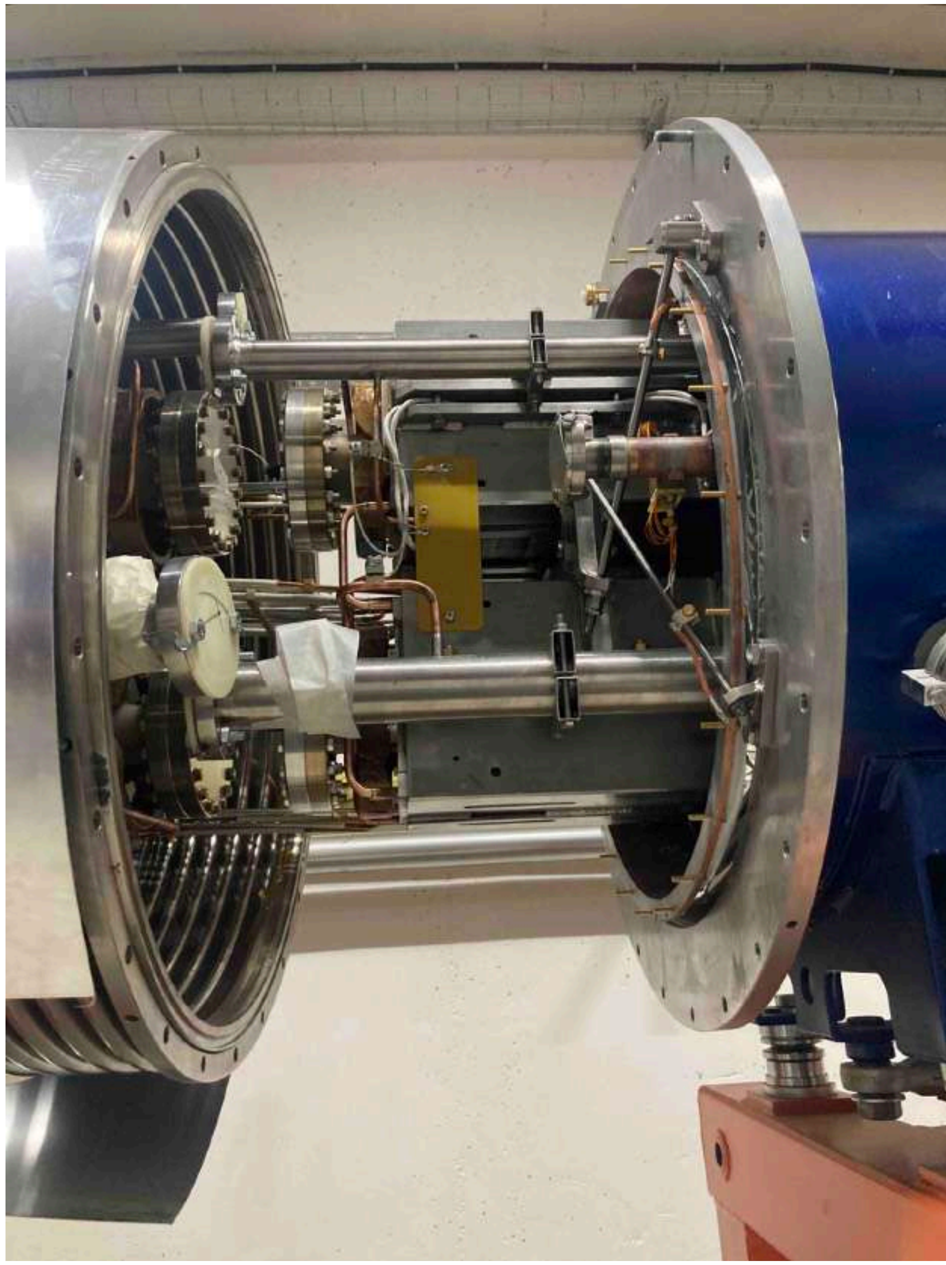
Experiments NICA collider



- **Light ion mode**: up to $_{13}$Al, optional $_{1}H\uparrow$, $_{2}D\uparrow$, $_{3}He\uparrow$
  LU-20 ⇒ Nuclotron ⇒ Collider
  HILac ⇒ Booster ⇒ Nuclotron ⇒ Collider

NICA Complex at JINR (Sep 2022)

NICA Collider at JINR



SPD at NICA (JINR, Dubna)

NICA:
Nuclotron-based Ion Collider fAcility

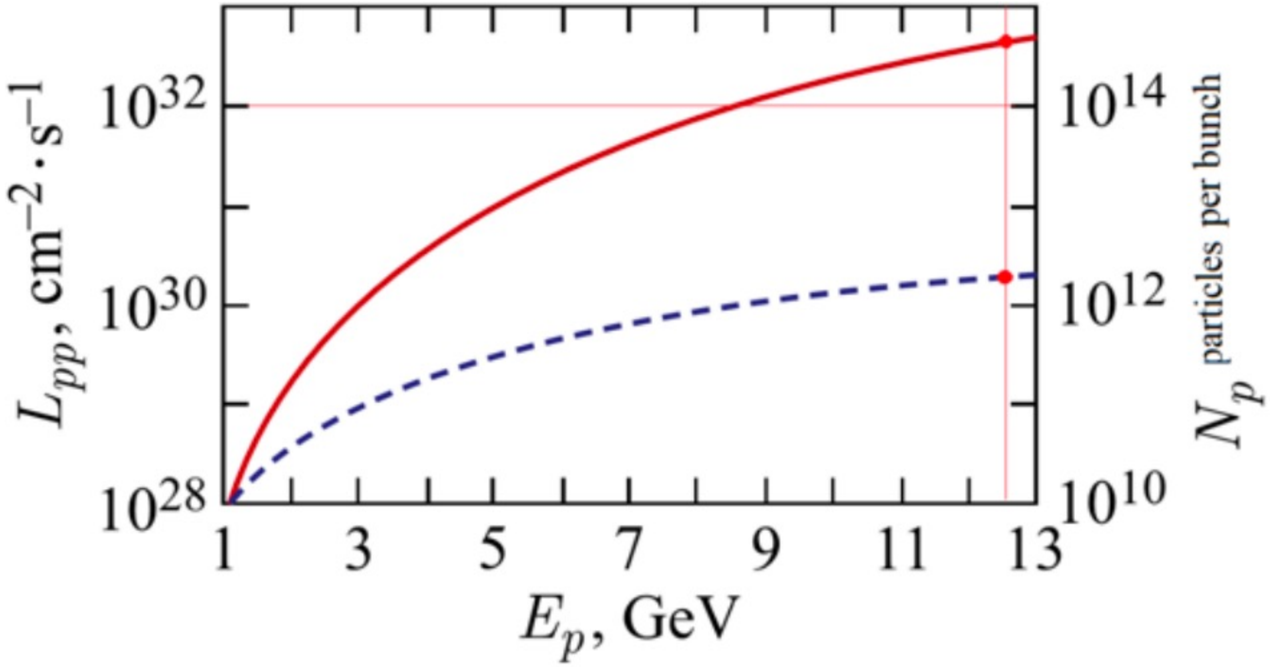
$$p^{\uparrow}p^{\uparrow} : \sqrt{s} \leq 27\ GeV$$

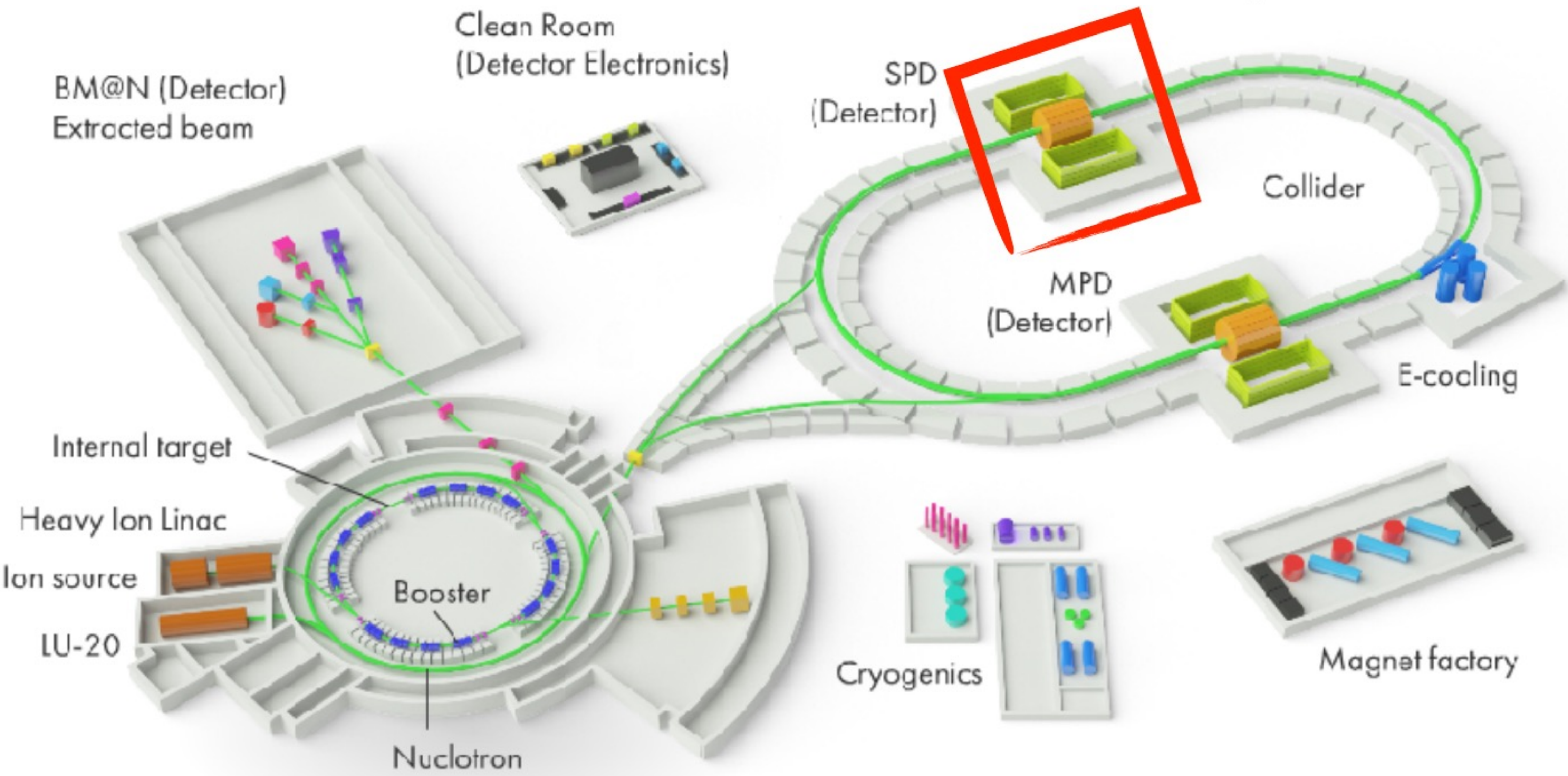
$$d^{\uparrow}d^{\uparrow} : \sqrt{s} \leq 13.5\ GeV$$

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

U, L, T

$|P| > 70\%$

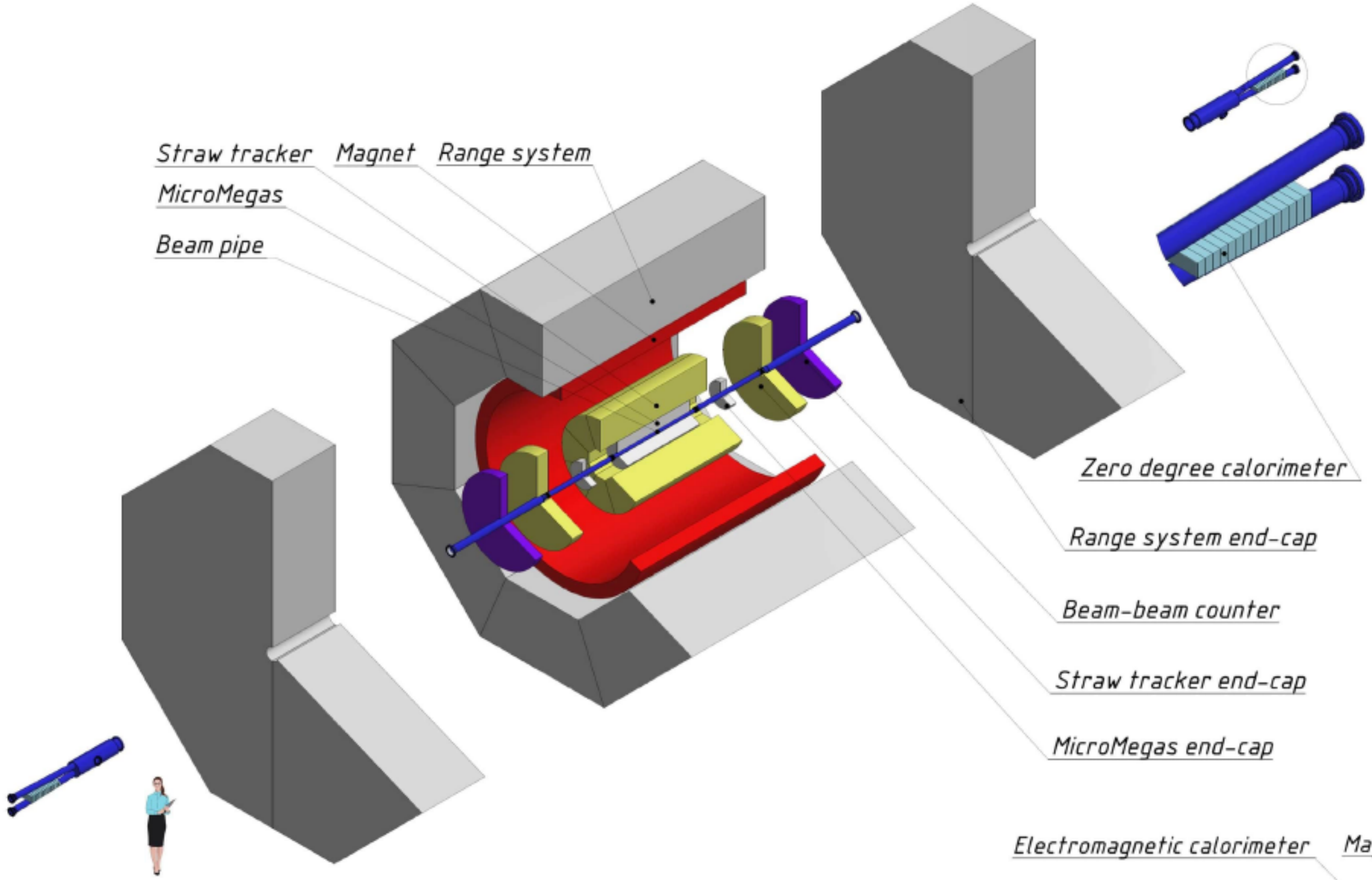




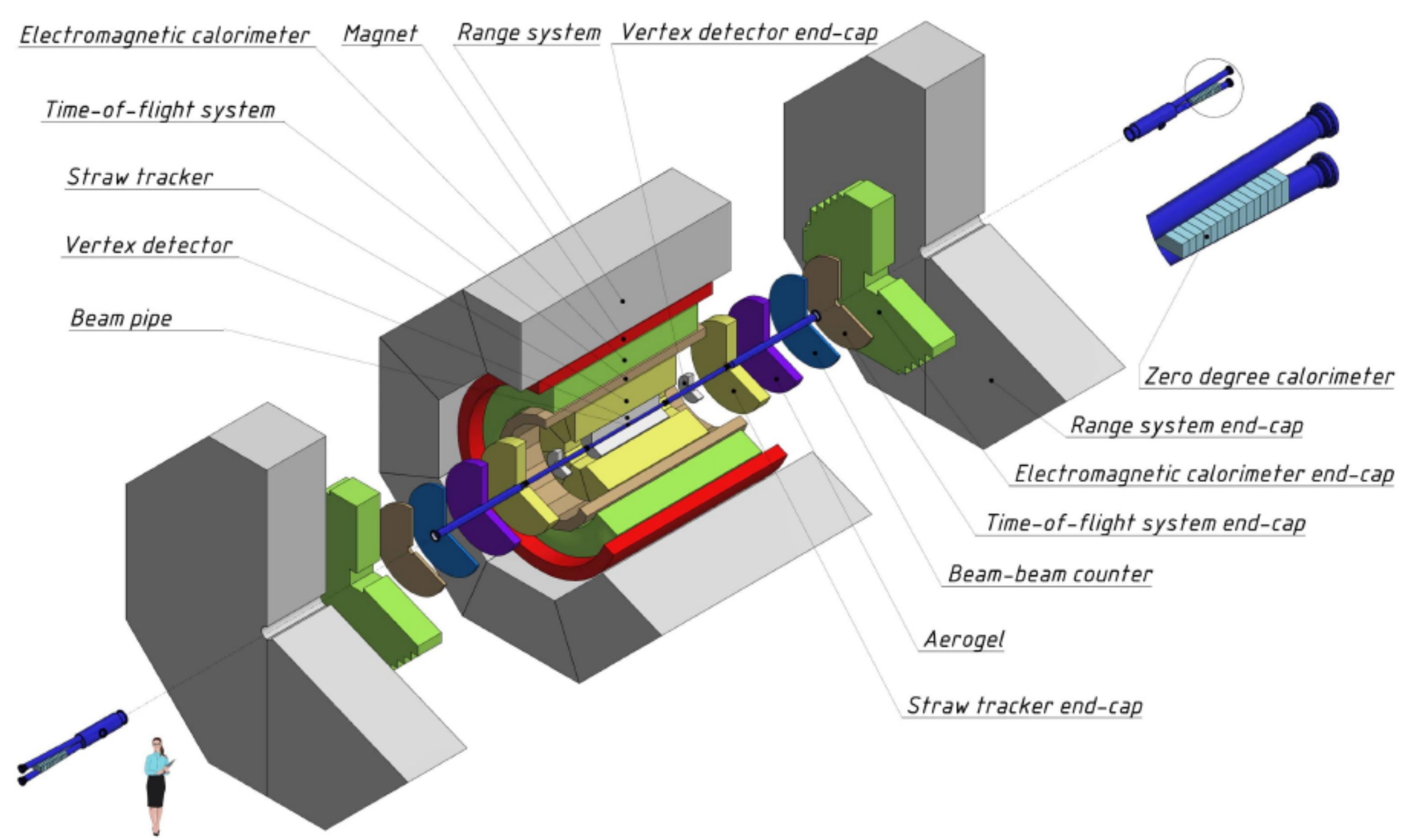
SPD Technical Design Report

SPD TDR version 1: January 2023

<- SPD: the Stage I Layout



SPD: the Final Layout of the Stage II ->



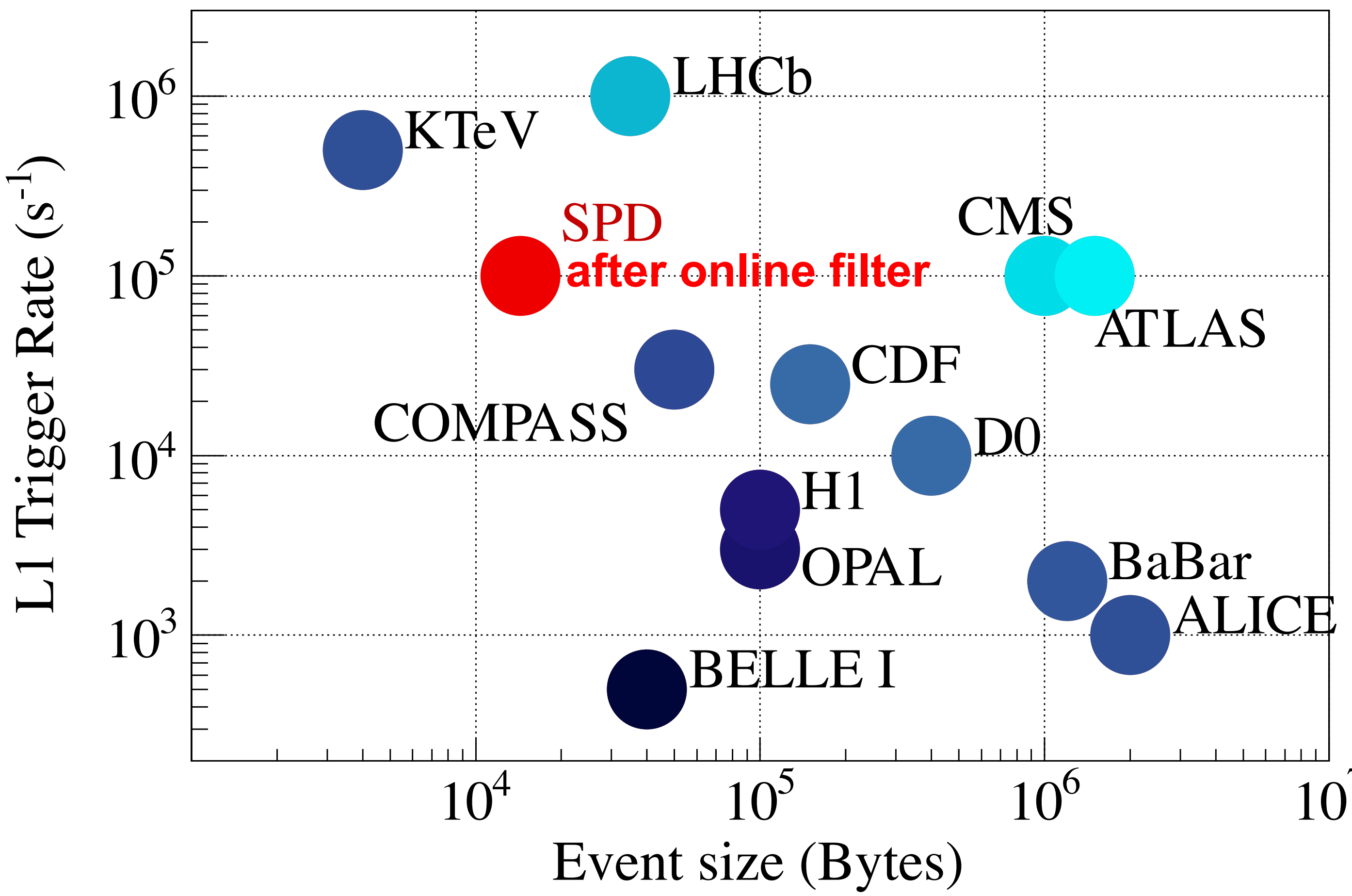
SPD detector data flow

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

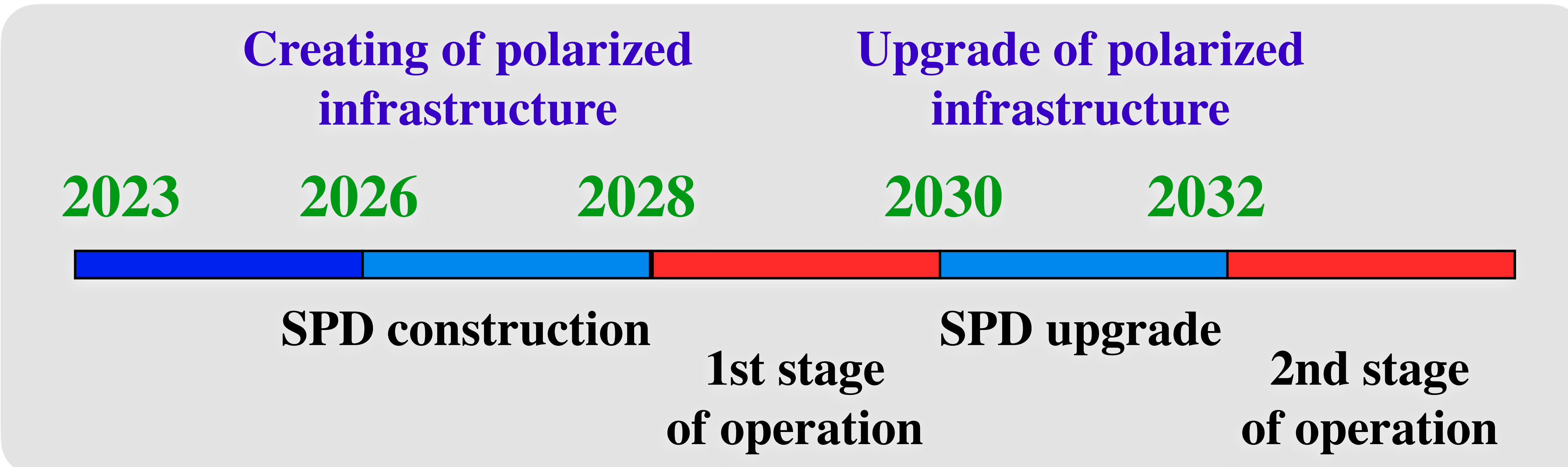
SPD data rate after online filter



SPD Collaboration: established in July 2021

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

SPD project timeline



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

ArXiv e-Print: 2011.15005 [hep-ex]

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

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]

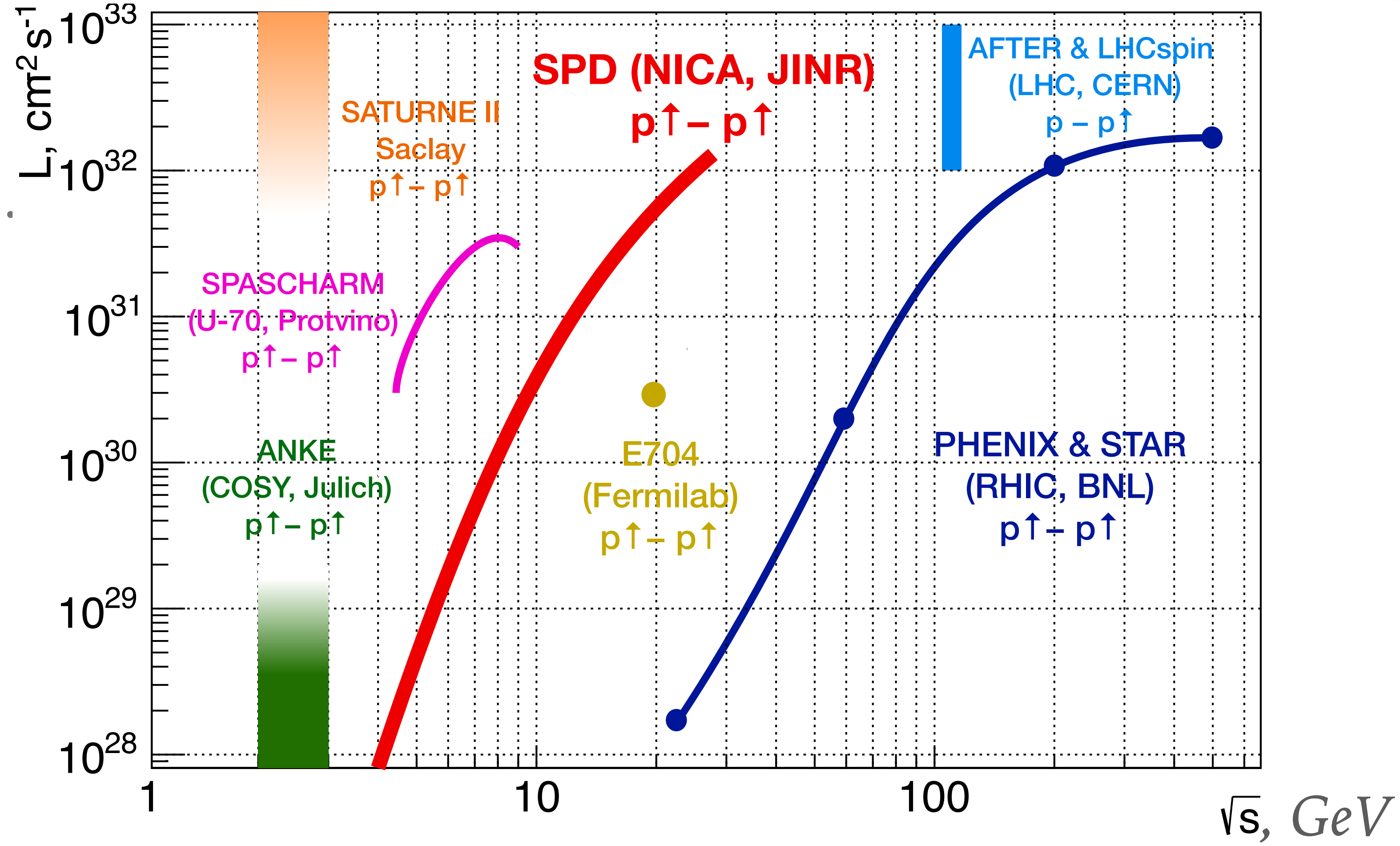
to appear in Phys. Elem. Part. At. Nucl. 2021

JINR E2-2021-12

ArXiv e-Print: 2102.08477 [hep-ph]

SPD in World landscape of polarized physics

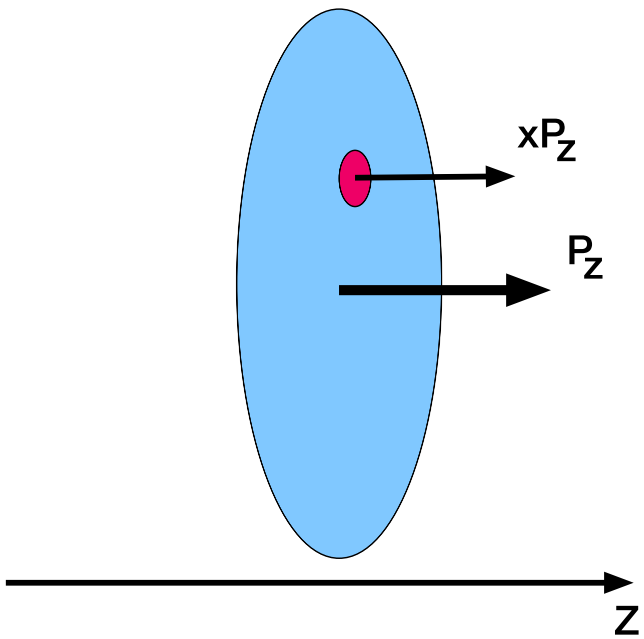
p↑ p↑-mode ➡



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-$d^{\uparrow}$	$p^{\uparrow}$-$p^{\uparrow}$	$e^{\uparrow}$-$p^{\uparrow}$, $d^{\uparrow}$, $^{3}\mathrm{He}^{\uparrow}$	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!

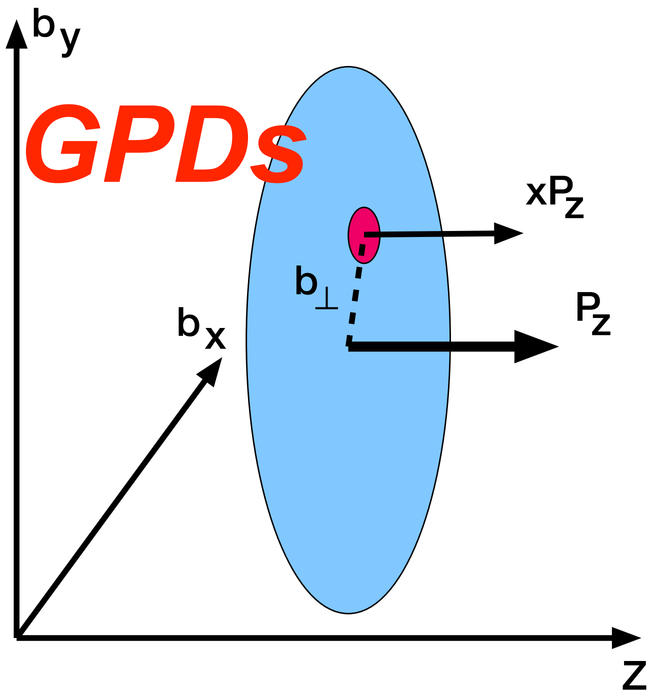
SPD: towards 3D-structure of nucleon



Collinear approximation

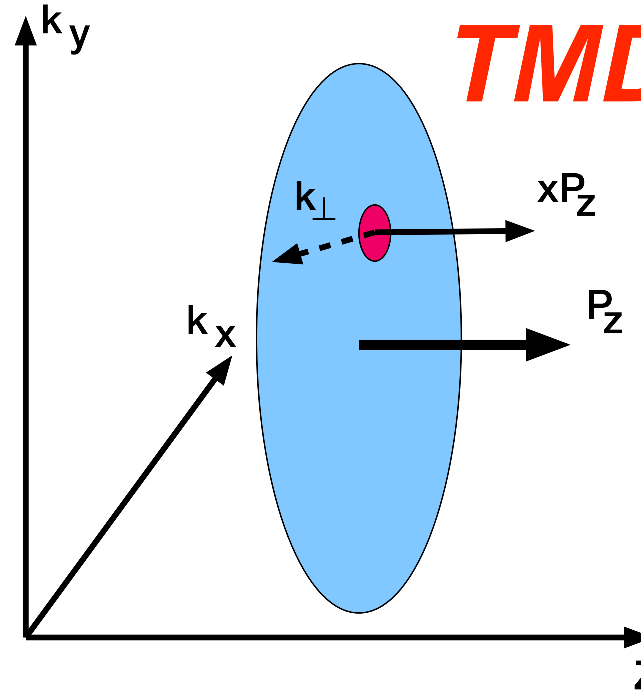
(common PDF)

GPDs



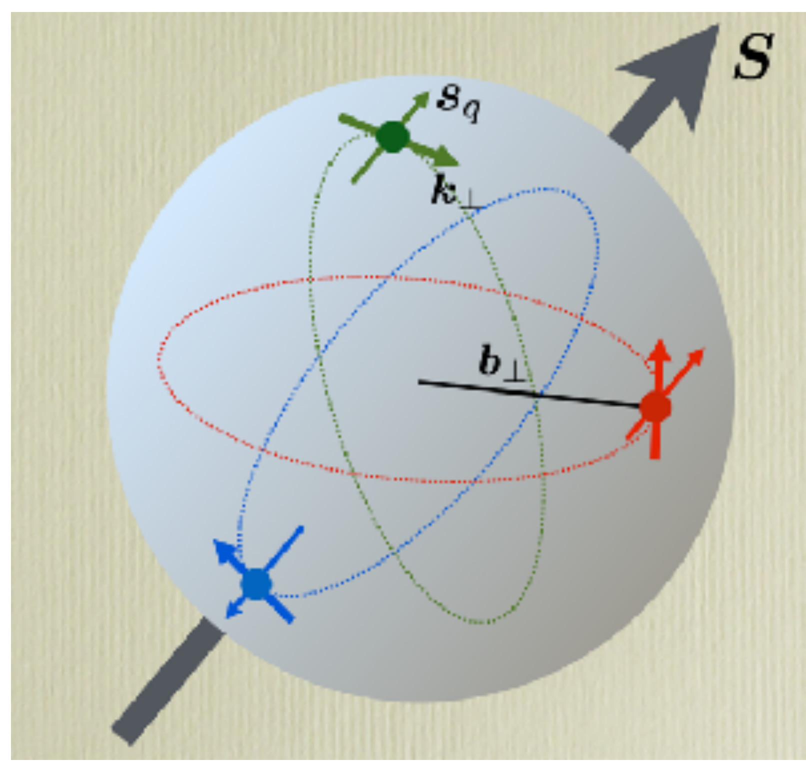
Generalized Parton Distributions

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; logQ^2) ⬅ modulo logQ^2 - DGLAP evolution

Extension to parton 3D-distribitions:

- ► Generalized parton distributions (GPDs): G(x, b, n; logQ^2)
  b - impact parameter, n – unit vector
- ► Unintegrated over kT PDF: Φ(x, kT, n; logQ^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
$g^q_L(x, kT)$ ⬅ L-polarized (chiral) quarks in L-polarized N ⬅ helicity
$g^q_T(x, kT)$ ⬅ L-polarized (chiral) quarks in T-polarized N ⬅ worm-gear
$h^q_T(x, kT)$ ⬅ T-polarized quarks in T-polarized N ⬅ pretzelocity

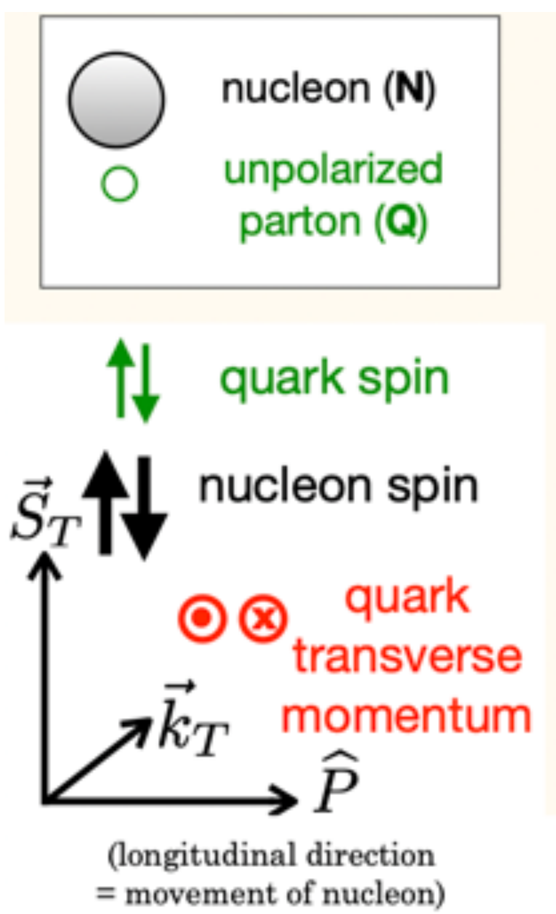
and time-odd functions (spin-orbital correlations):

$f^{\perp q}_L(x, kT)$ ⬅ 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, $h_{1T}^{\perp g}$

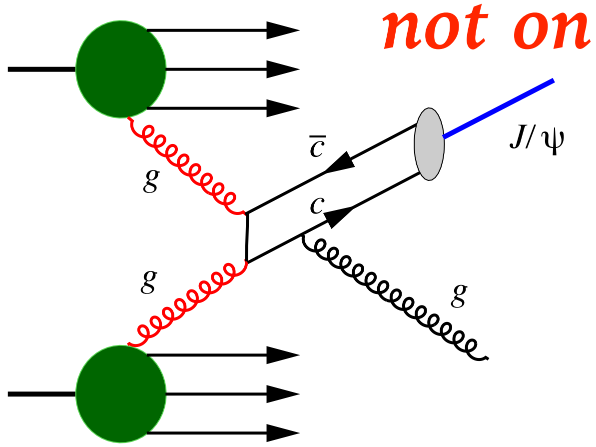
Gluon Sivers function

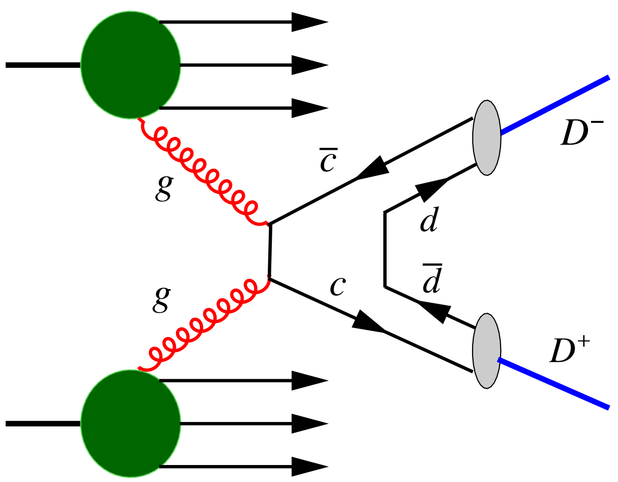
Gluon transversity in deuteron

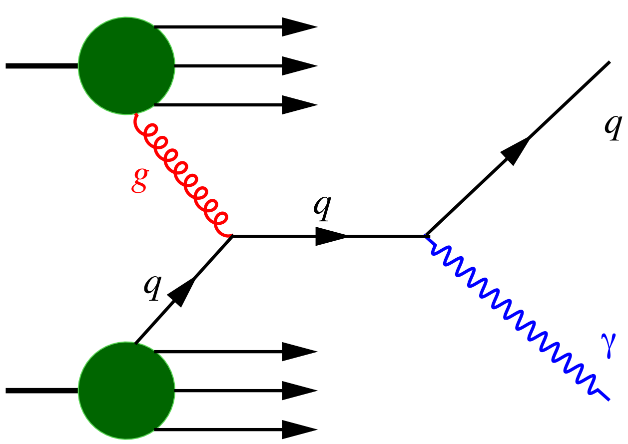
Gluon probes at SPD: charmonia, open charm, direct photons

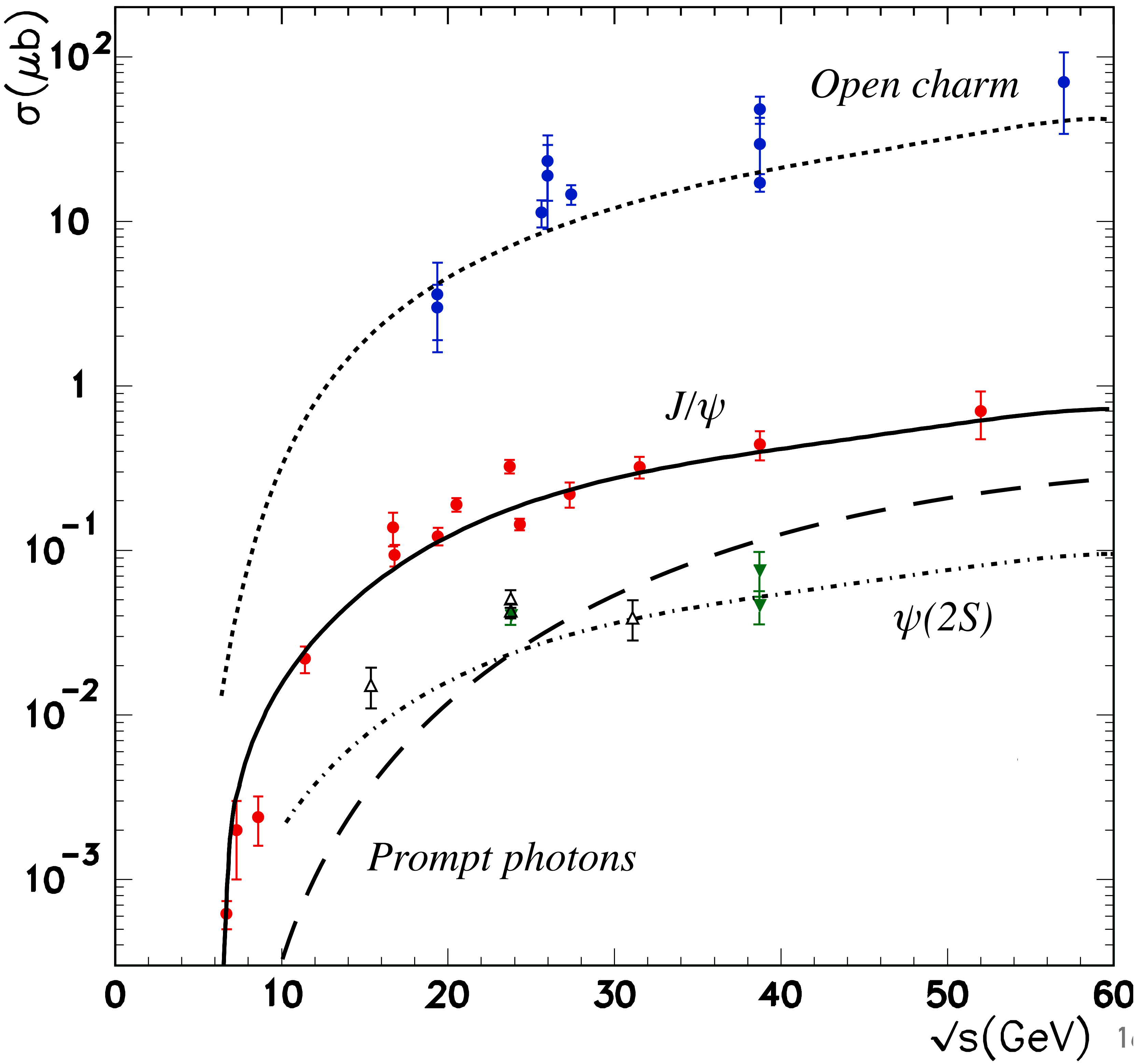
not only J/ψ!

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

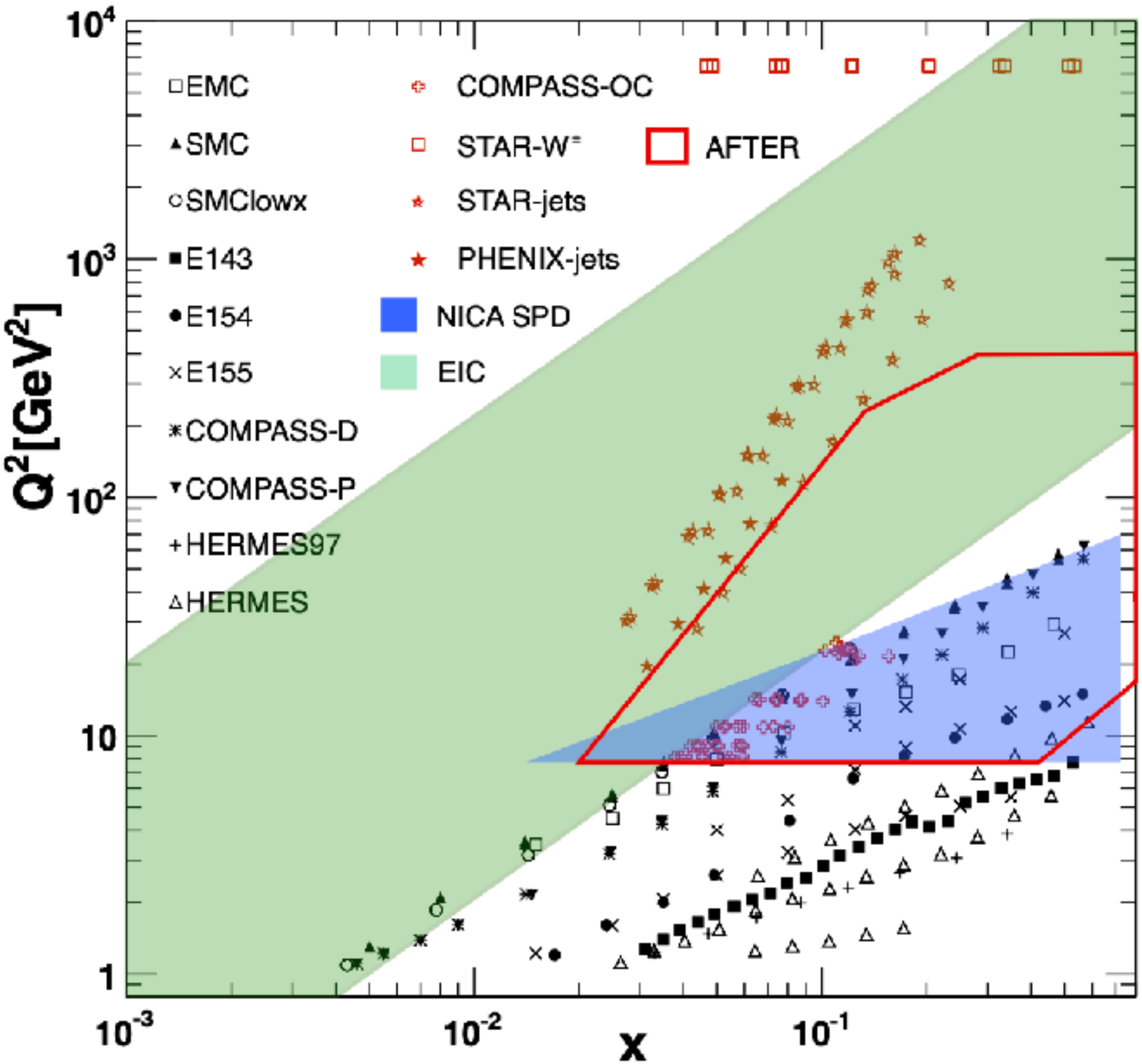




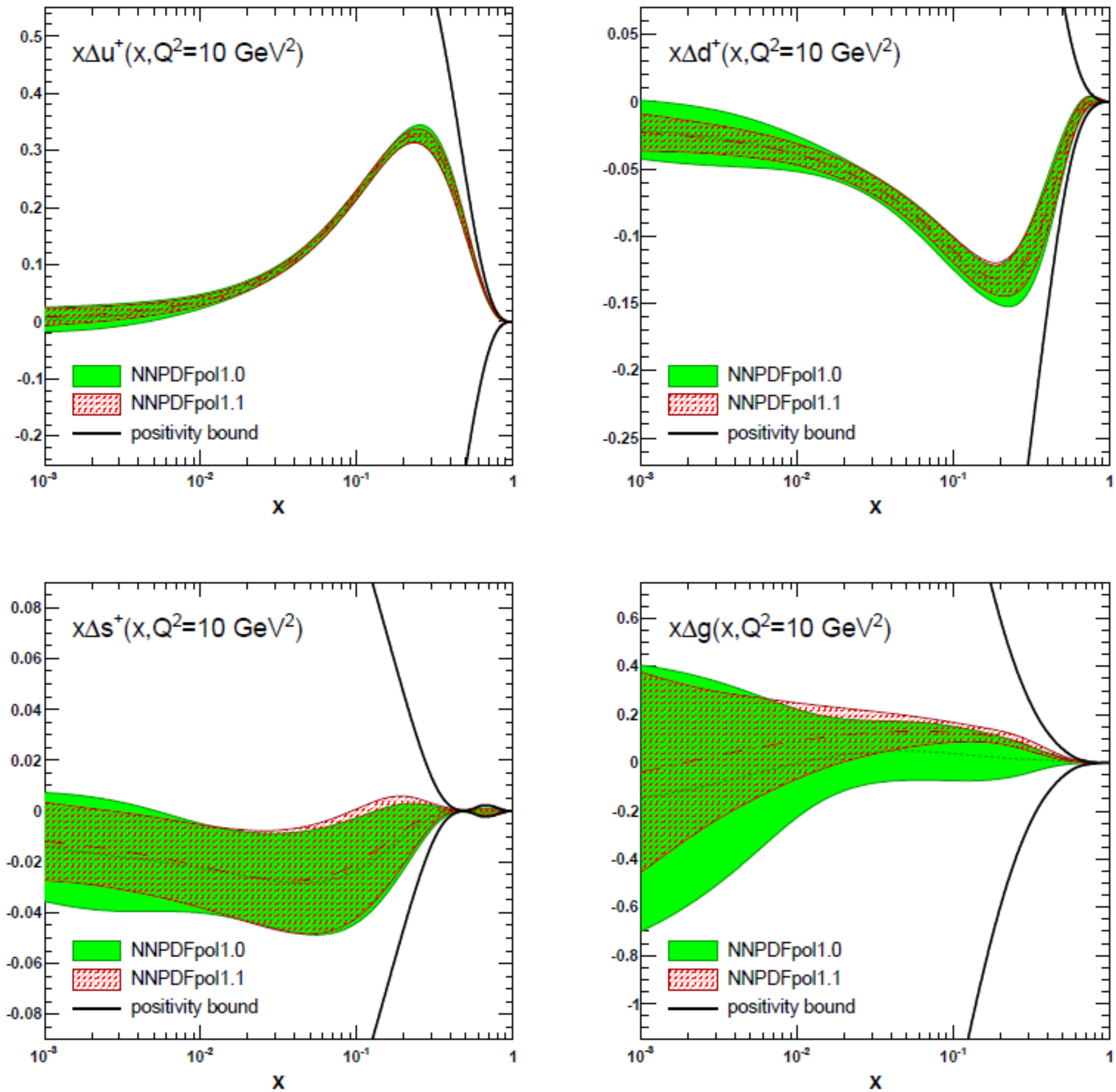




PDF kinematic range



NNPDF Coll.: quark and gluon helicity PDFs of proton



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

Quark helicity PDF:
few percent level uncertainties

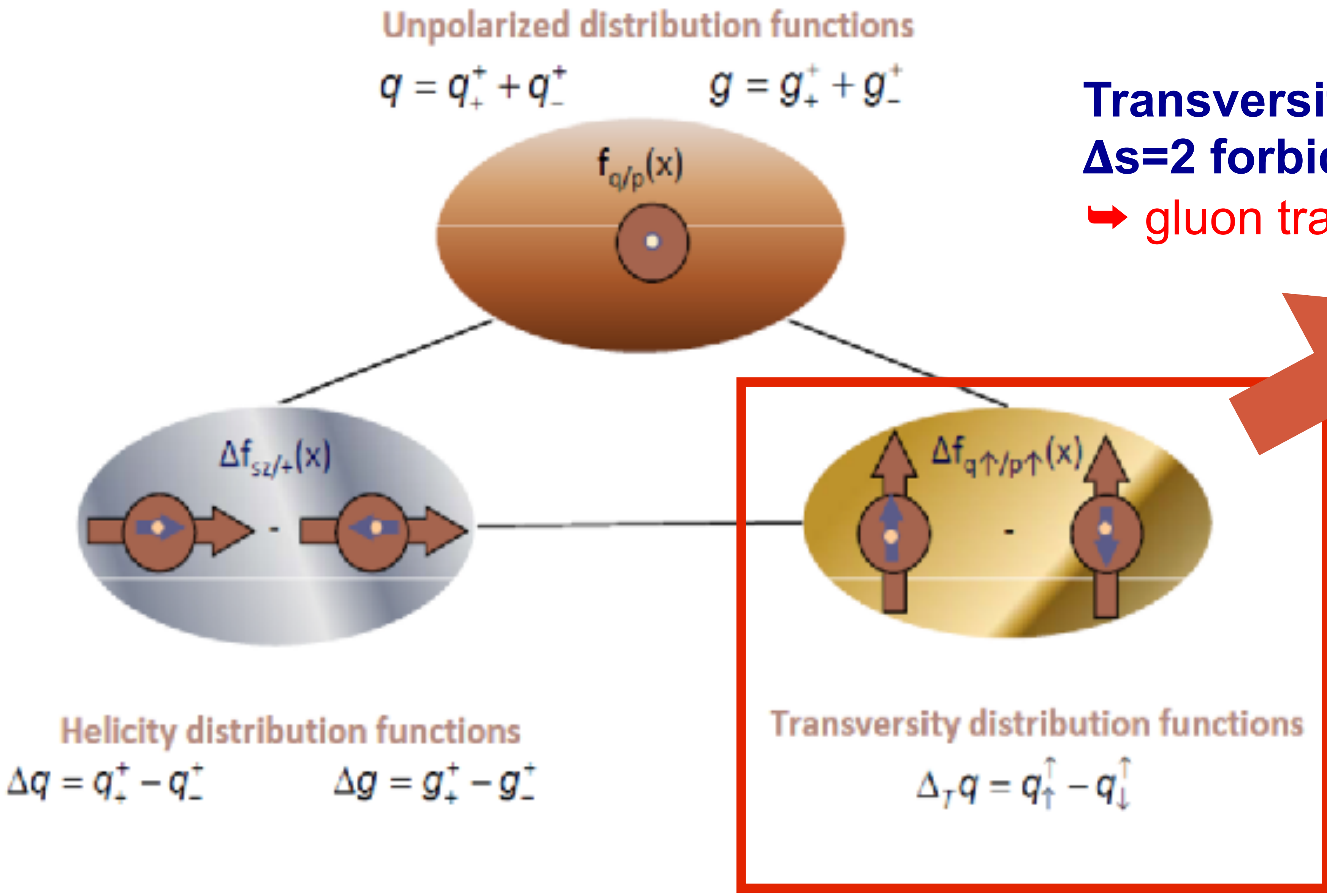
It is measured with
high precision in DIS

Gluon helicity PDF:
still rather high uncertainties!

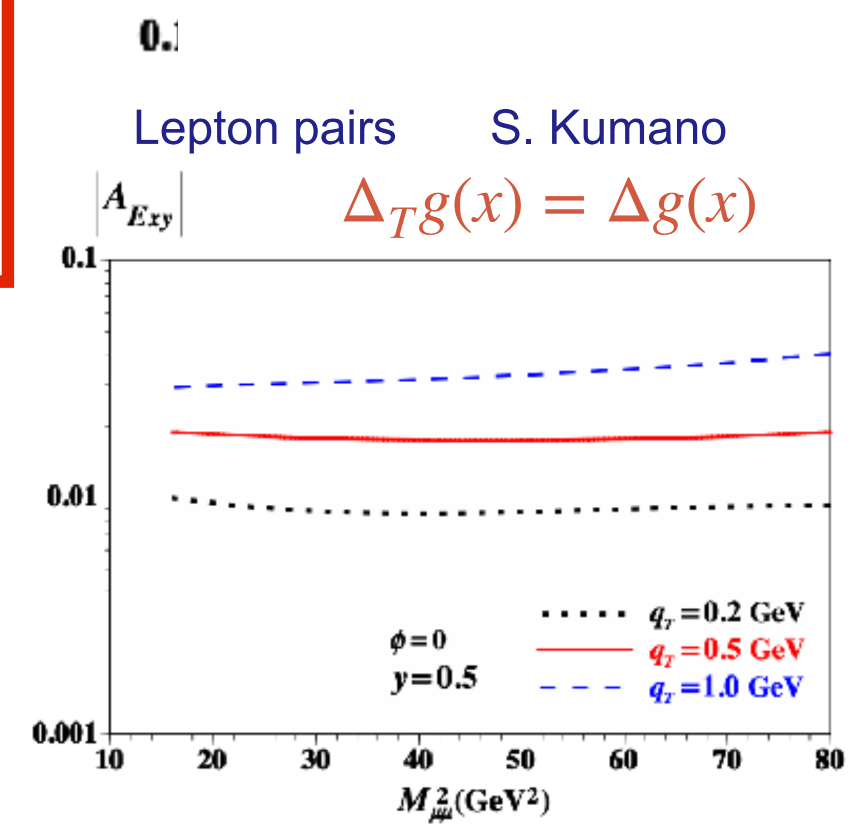
Hadron collisions have a better
sensitivity to measure it.

⬅ 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

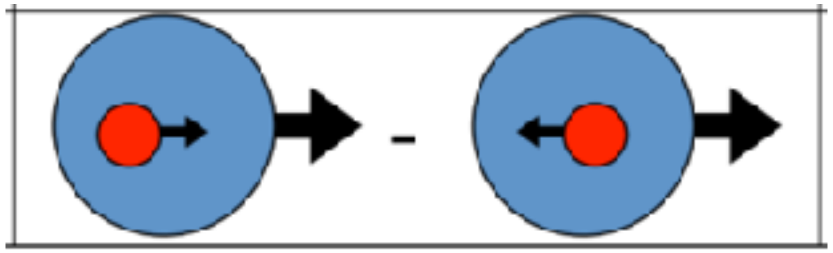


SPD has a unique opportunity to measure
gluon transversity in deuteron for the first time!

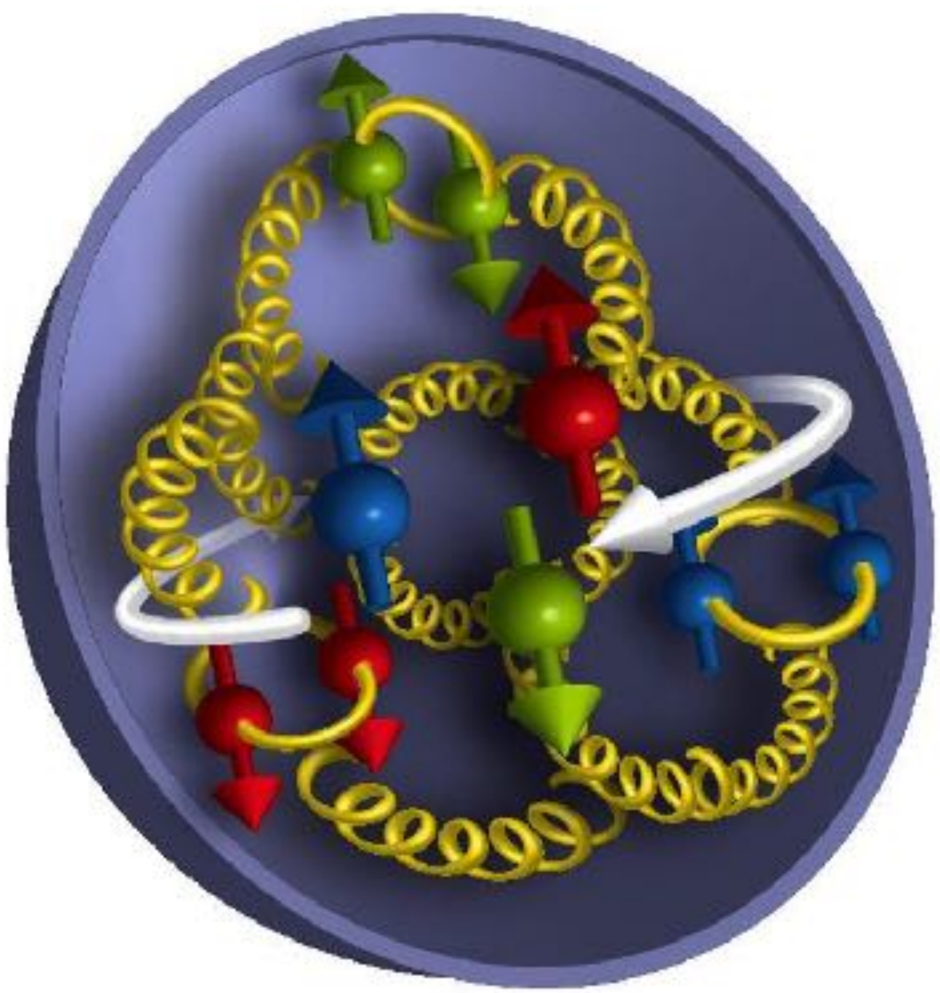
To probe new non-nucleonic degrees of freedom in deuteron!

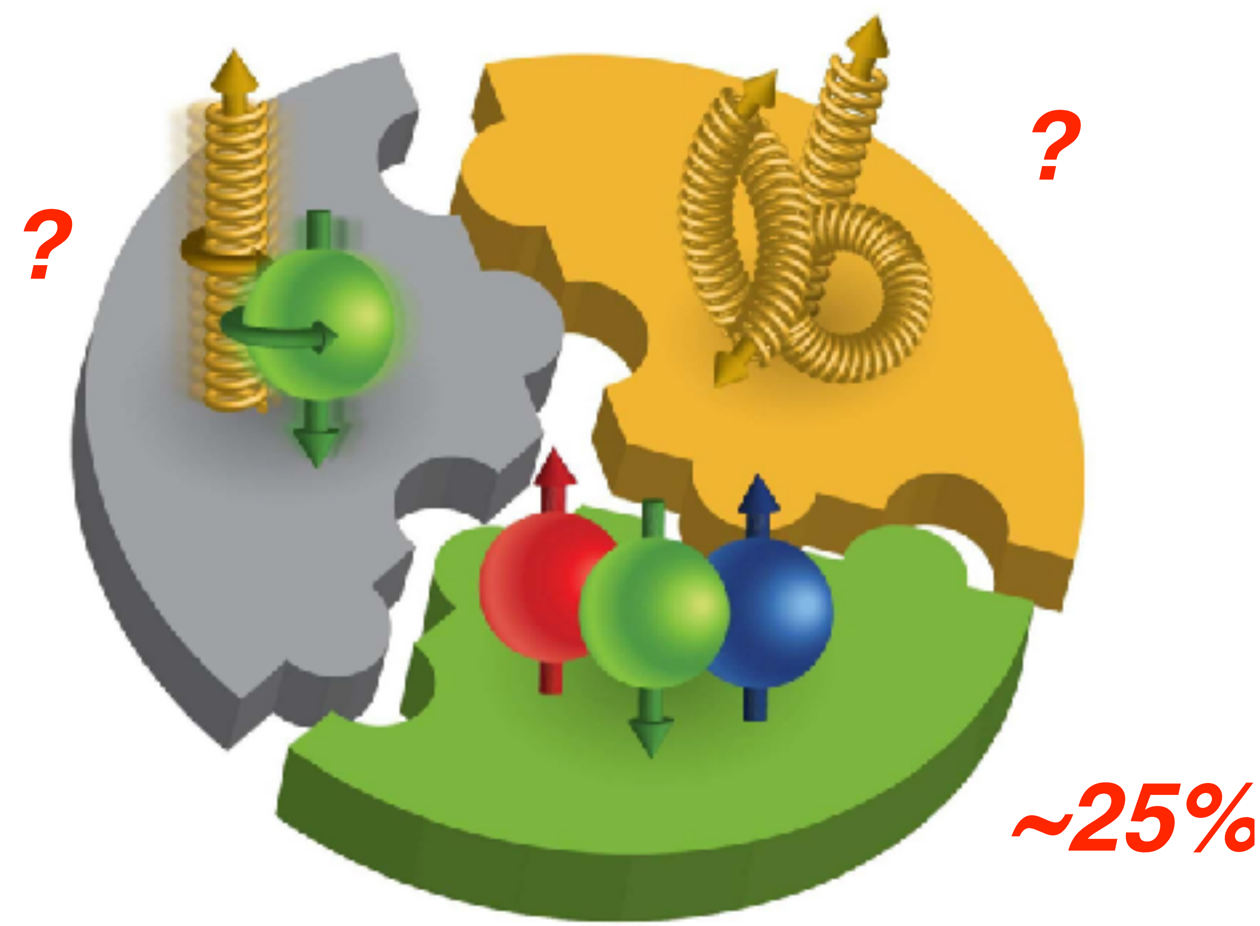
Helicity gluon PDF Δg(x): Spin Crisis

Δg(x) :



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



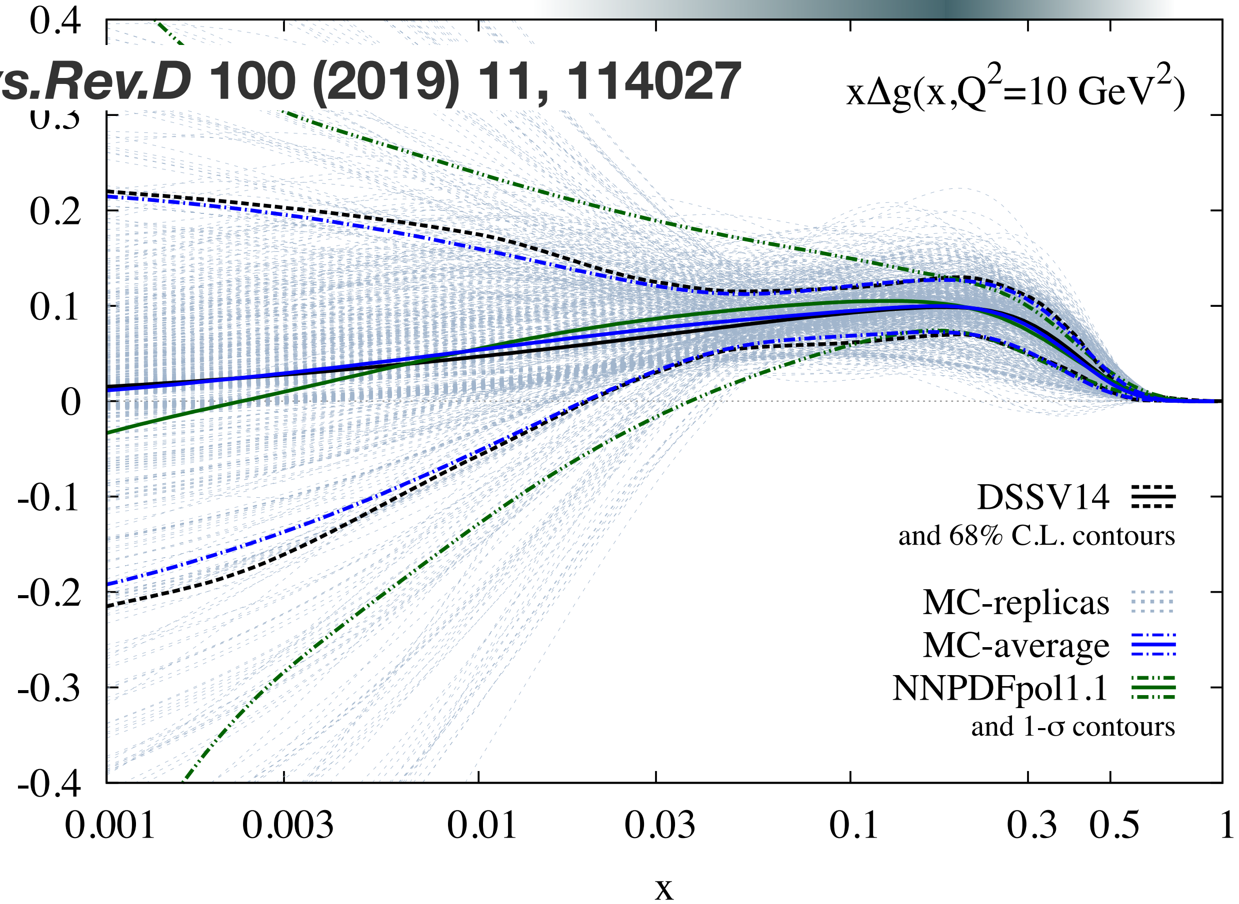


$$S_N = ½ = ½\ \Delta\Sigma + \Delta G + L$$

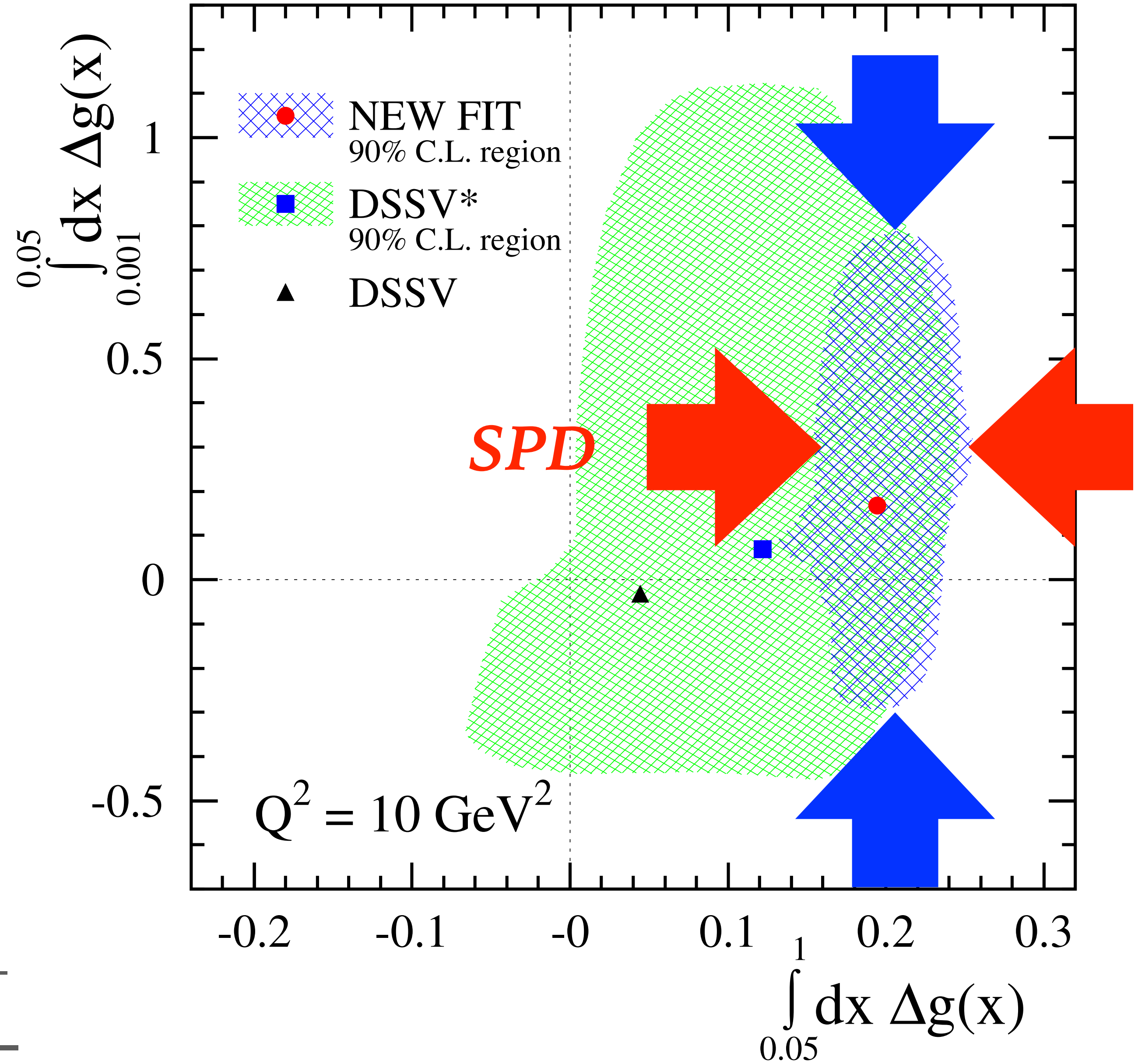
Helicity gluon PDF Δg(x):

accessible with SPD

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



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

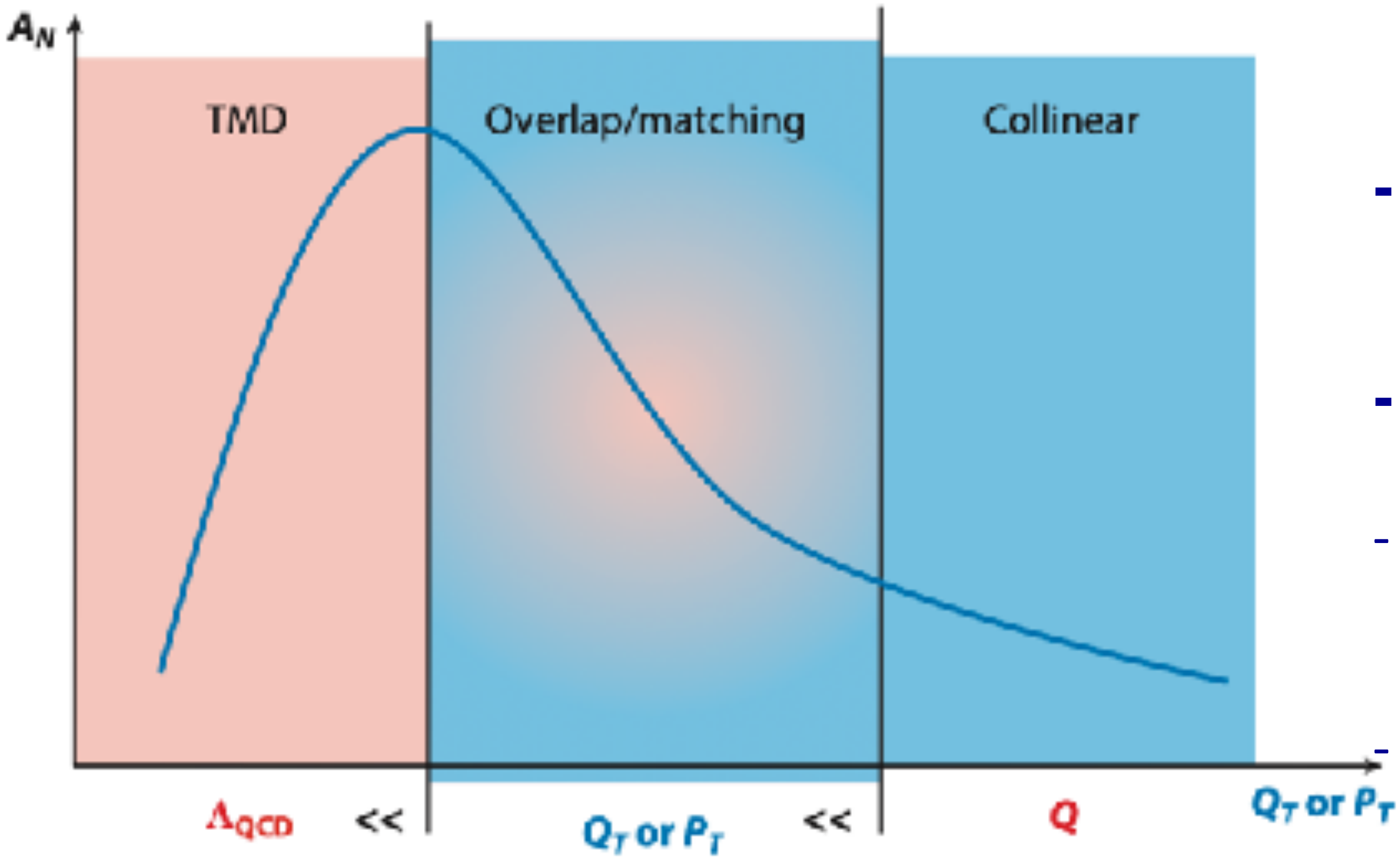


SPD could help to reduce uncertainty of ΔG at large x

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

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

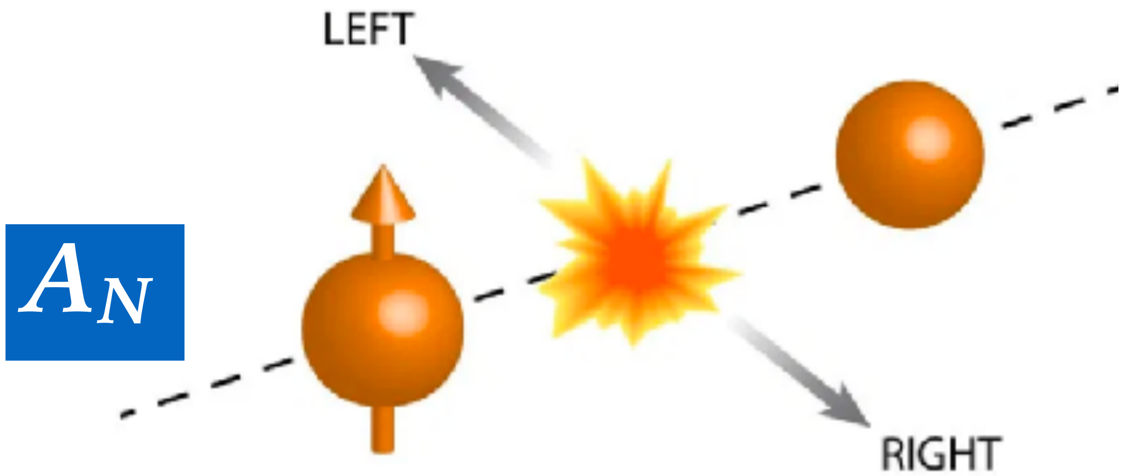
Gluon TMD effects: gluon Sivers function



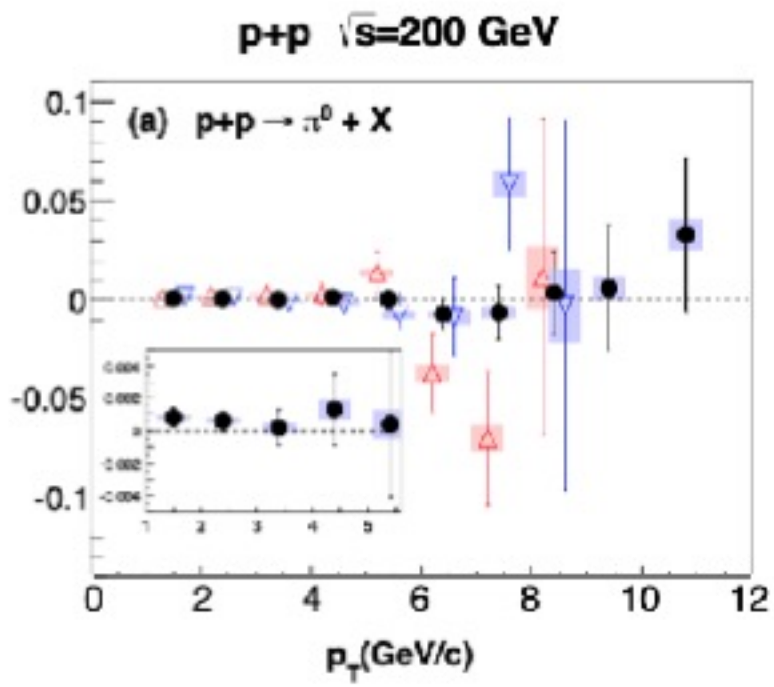
- Collinear factorization: twist-2 and twist-3
- TMD-factorization
- Overlap/matching region
- Nontrivial x and kT correlation?

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

Collins effect: due to fragmentation of polarized parton



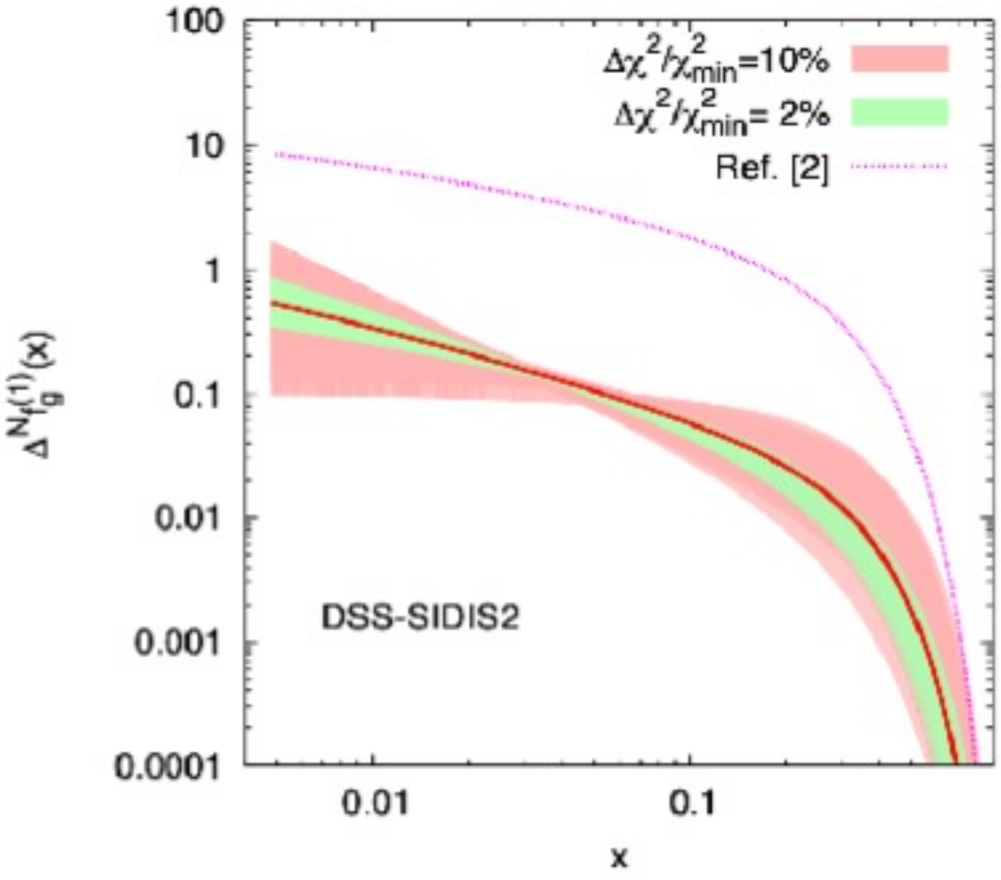
Gluon Sivers function



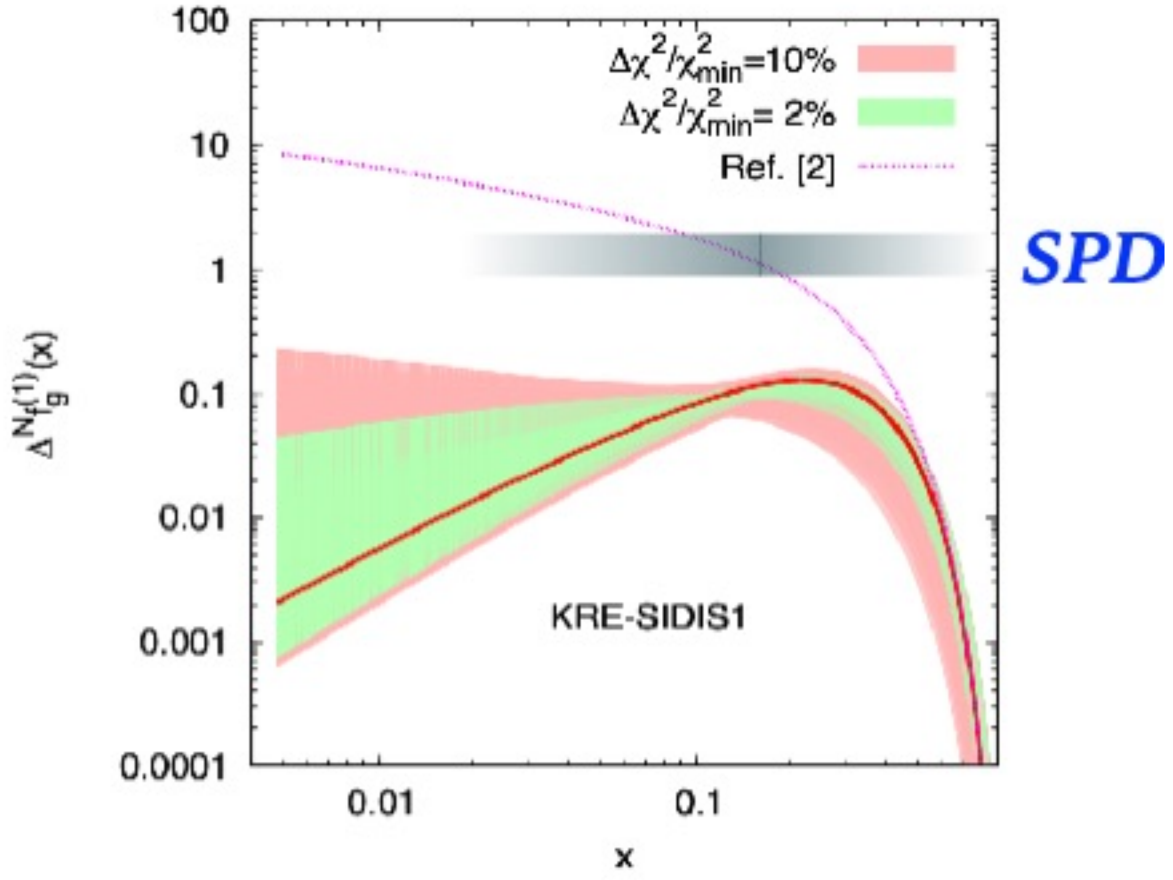
Phys.Rev.D 90 (2014) 1, 012006

PHENIX

First k⊥-moment of the gluon Sivers function



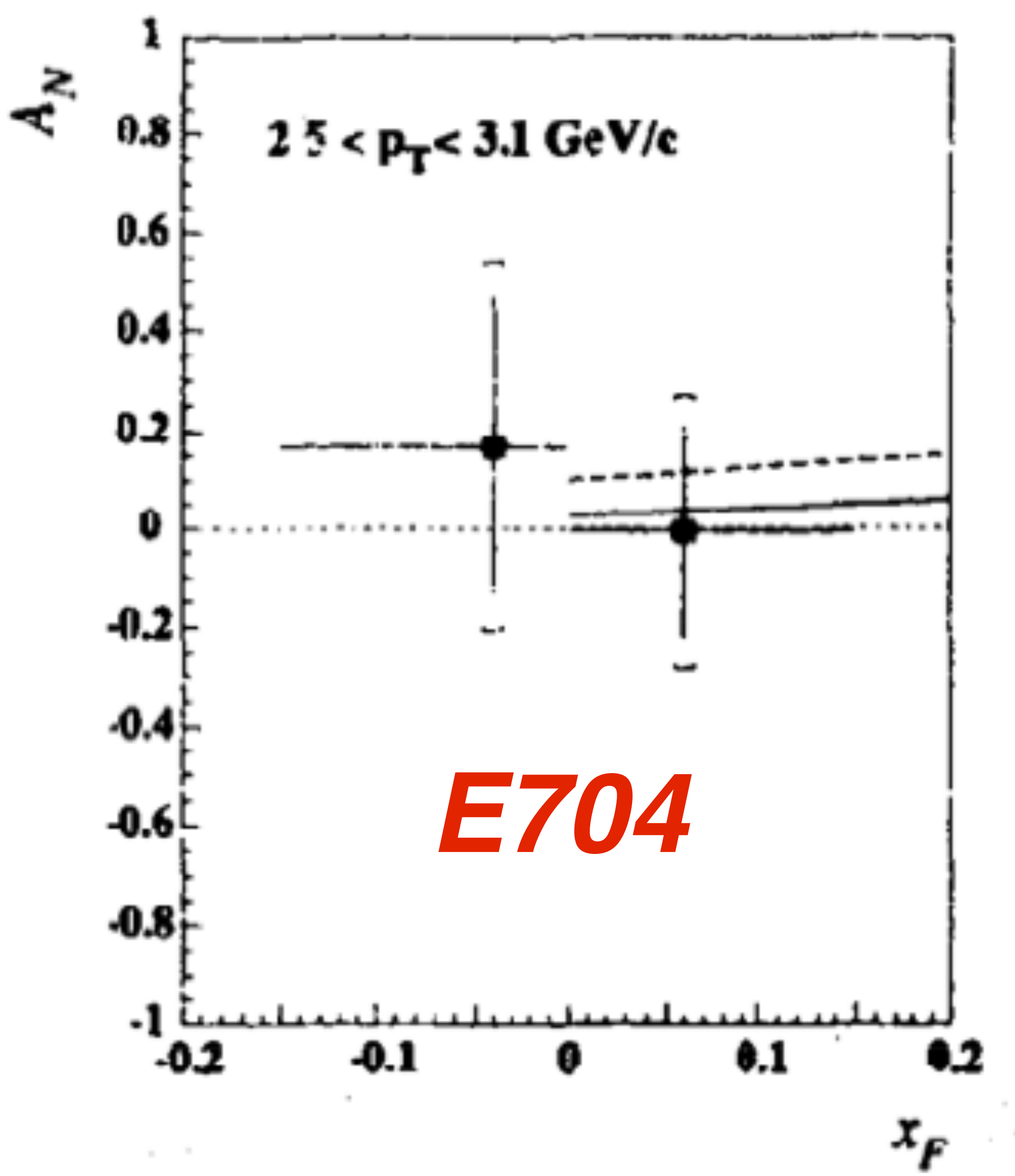
JHEP 09 (2015) 119



... and at NICA energies (fixed target at FNAL)

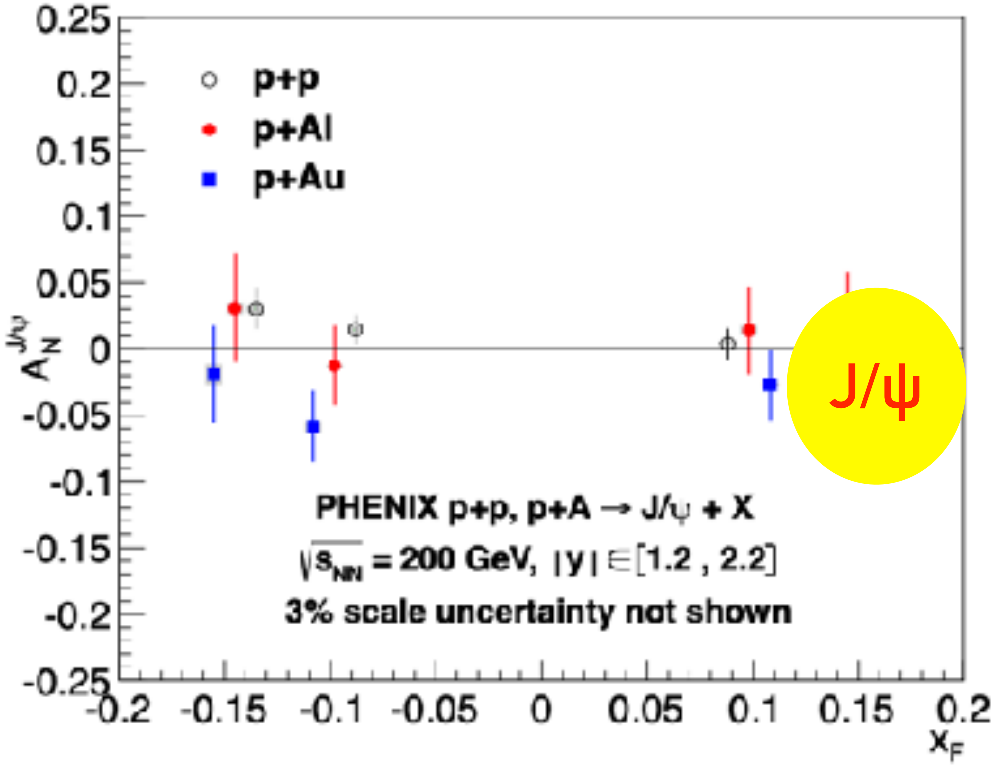
E704 at FNAL: fixed target 200 GeV

Phys. Lett. B 345 (1995)



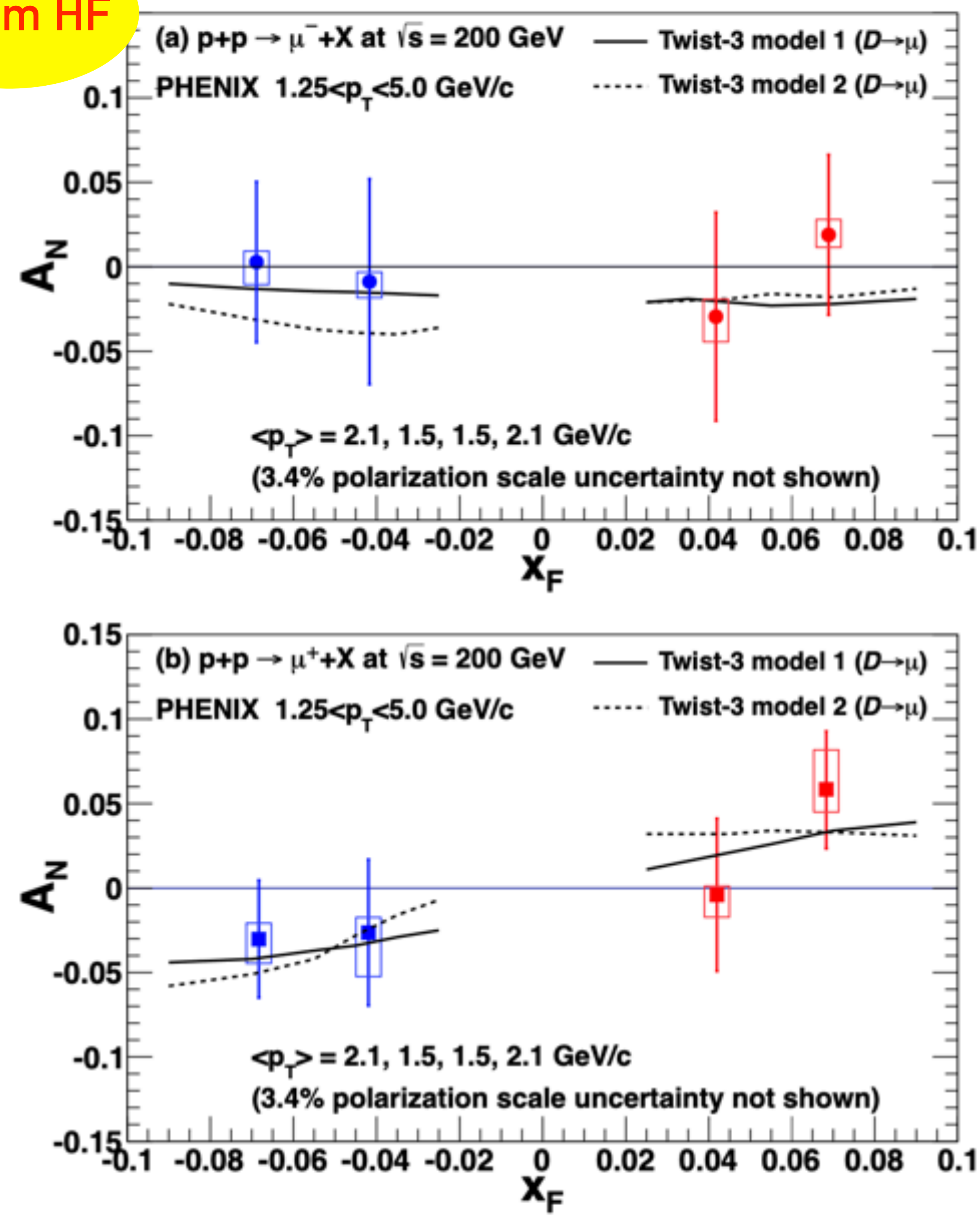
Gluon induced TMD effects: existing results for A_N

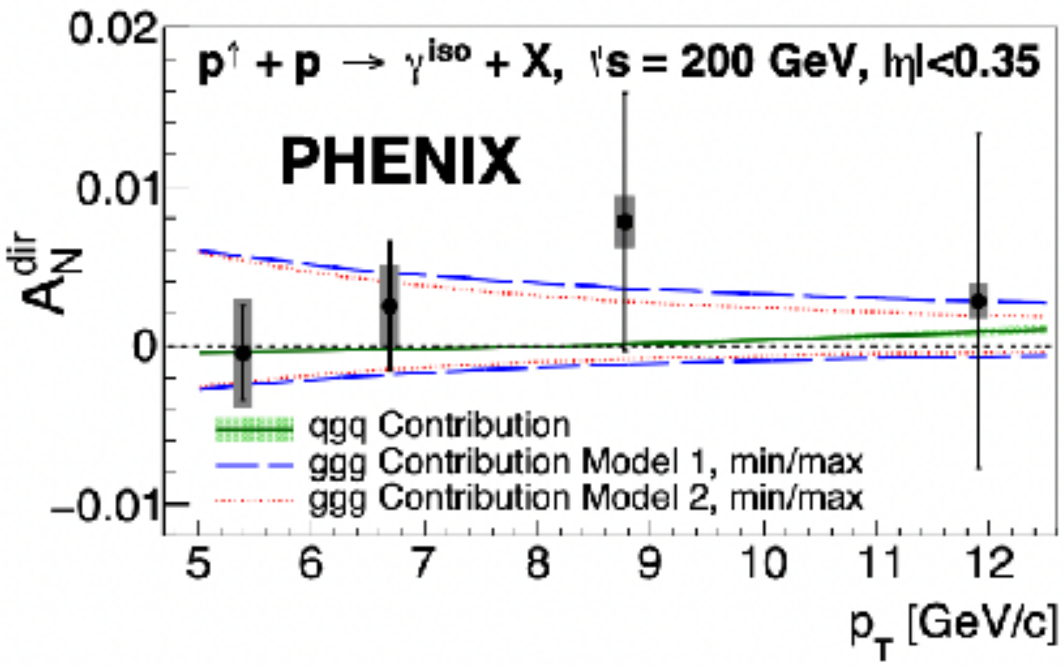
Phys.Rev.D 98 (2018) 1, 012006



μ from HF

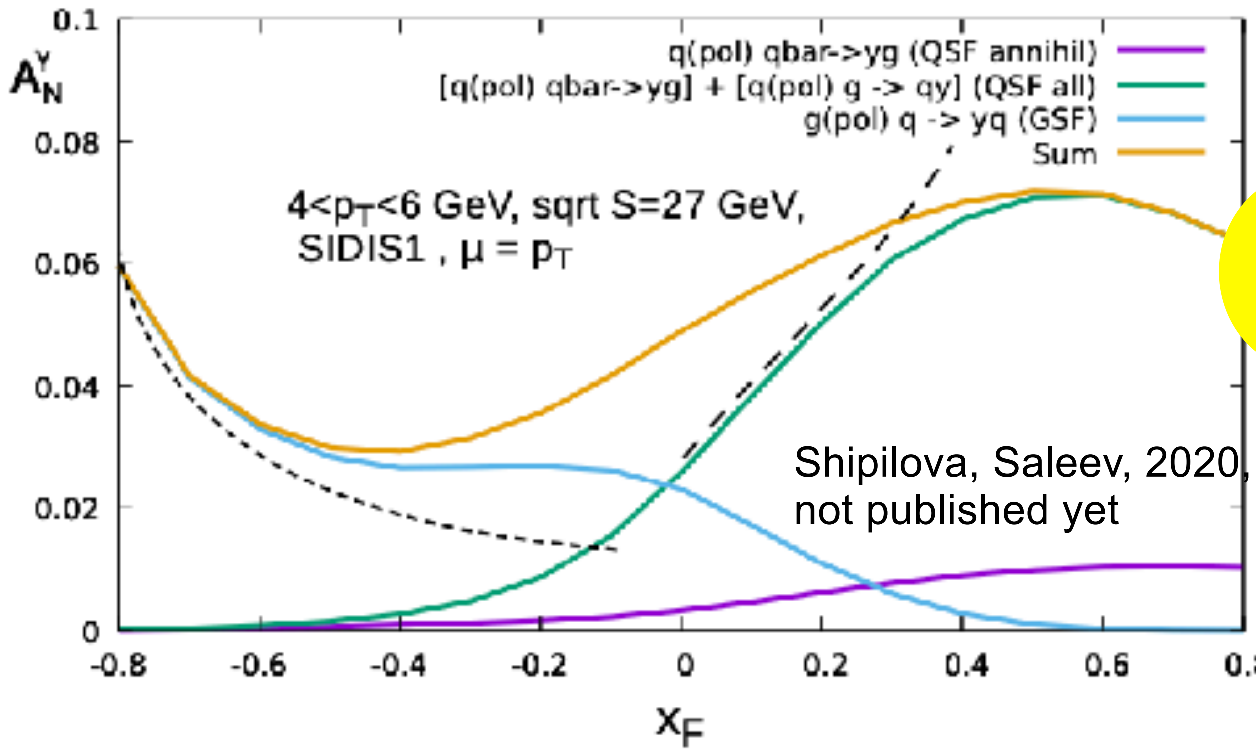
Phys.Rev.D 95 (2017) 11, 112001



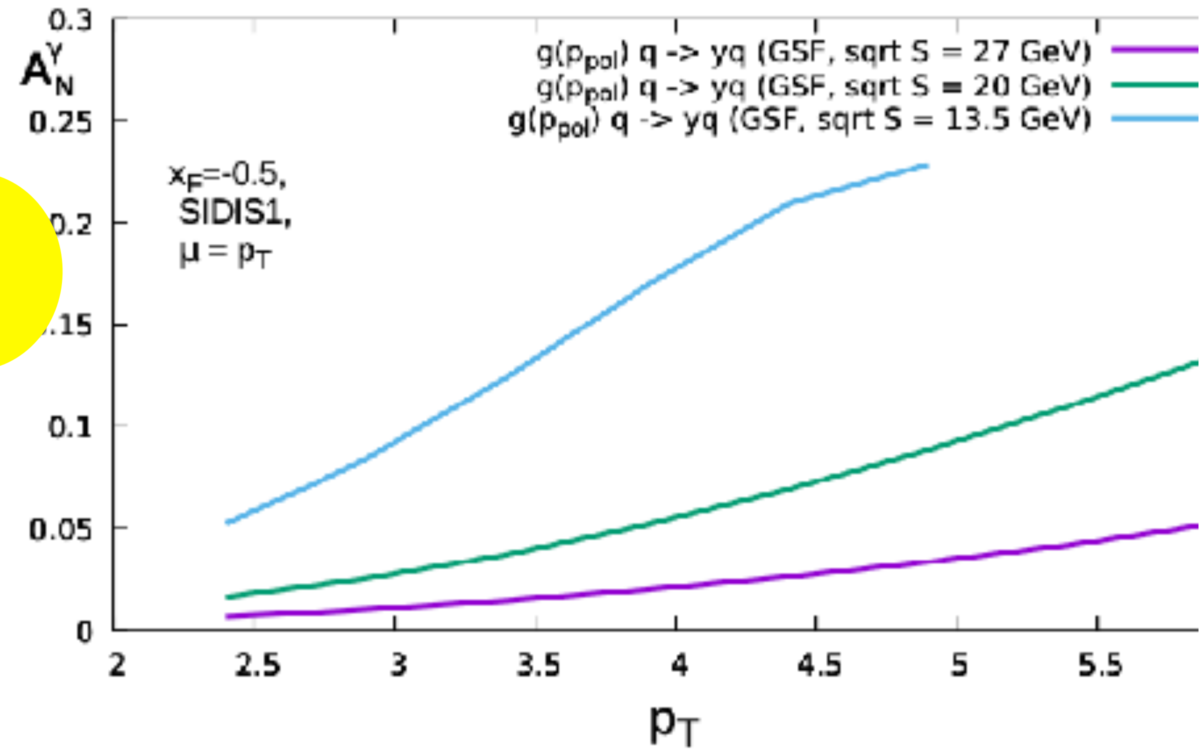


Gluon induced TMD effects: expected results for A_N

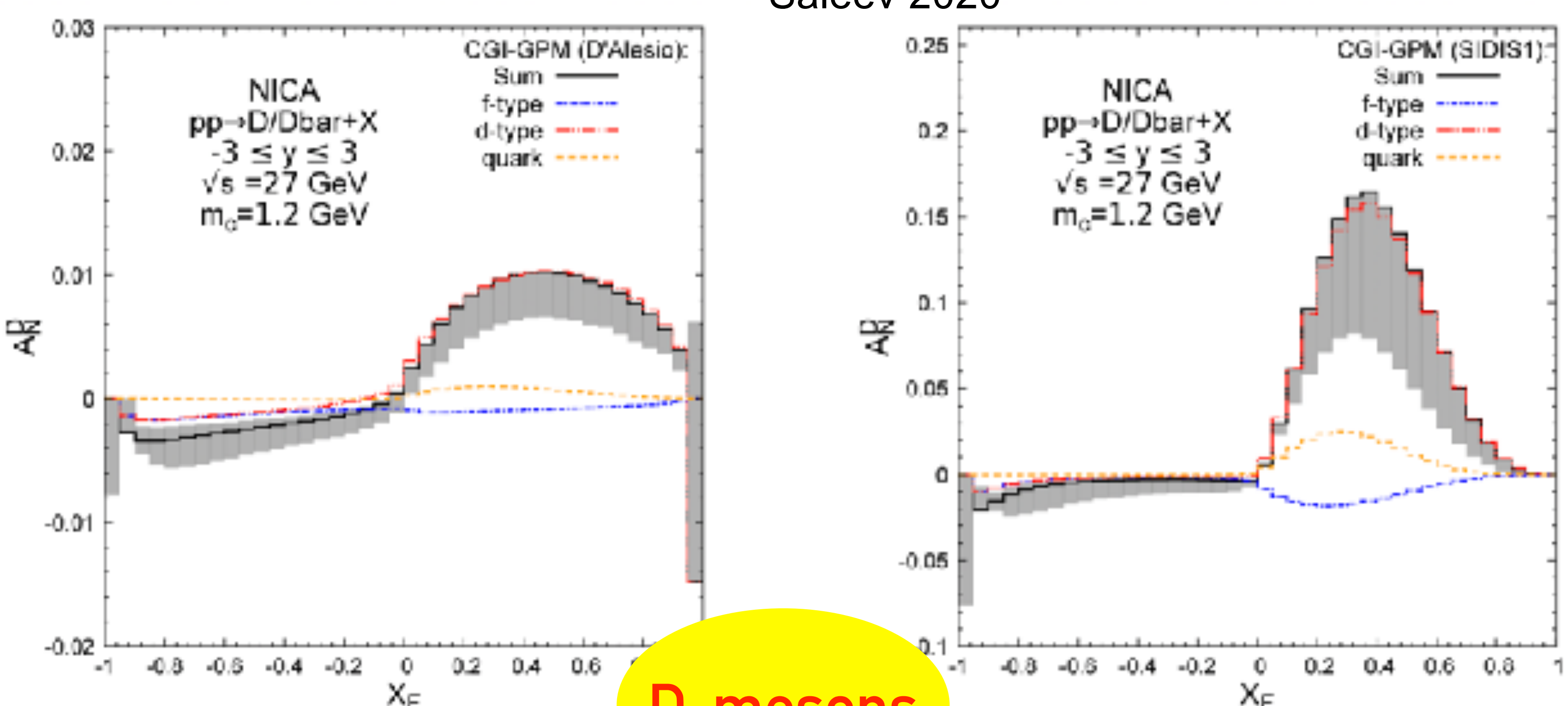
Sivers effect impact



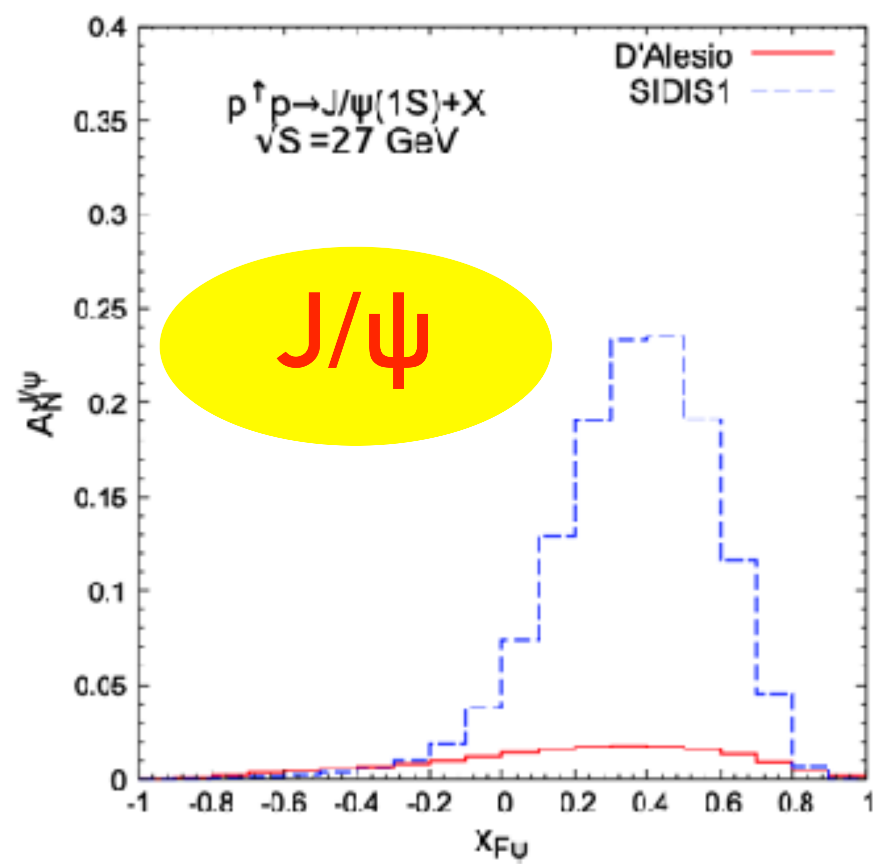
γ



Saleev 2020



D-mesons



J/ψ

SPD Physics at the initial stage

V.V. Abramov et al., 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**
- ► …

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