Spin Physics at NICA SPD

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(on behalf of the SPD Collaboration)
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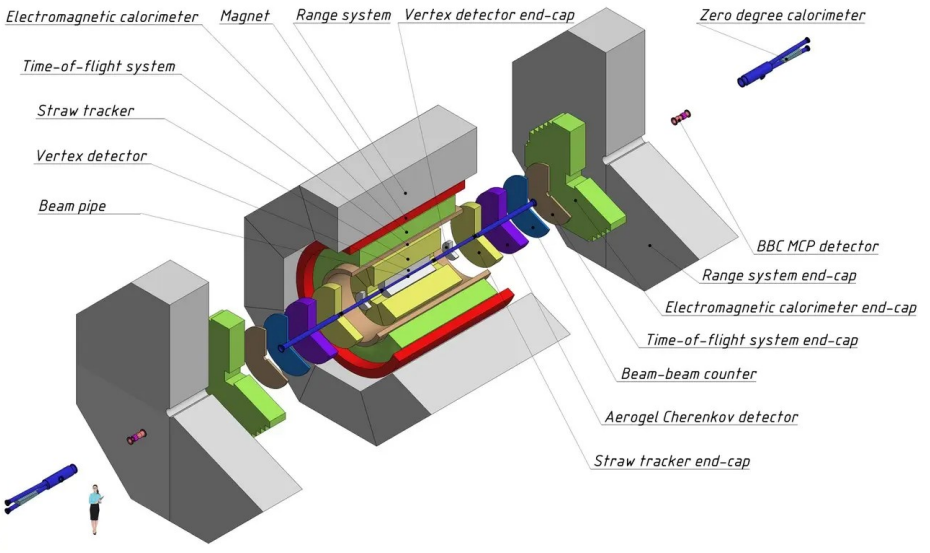
Particle Physics at Intermediate and High Energies

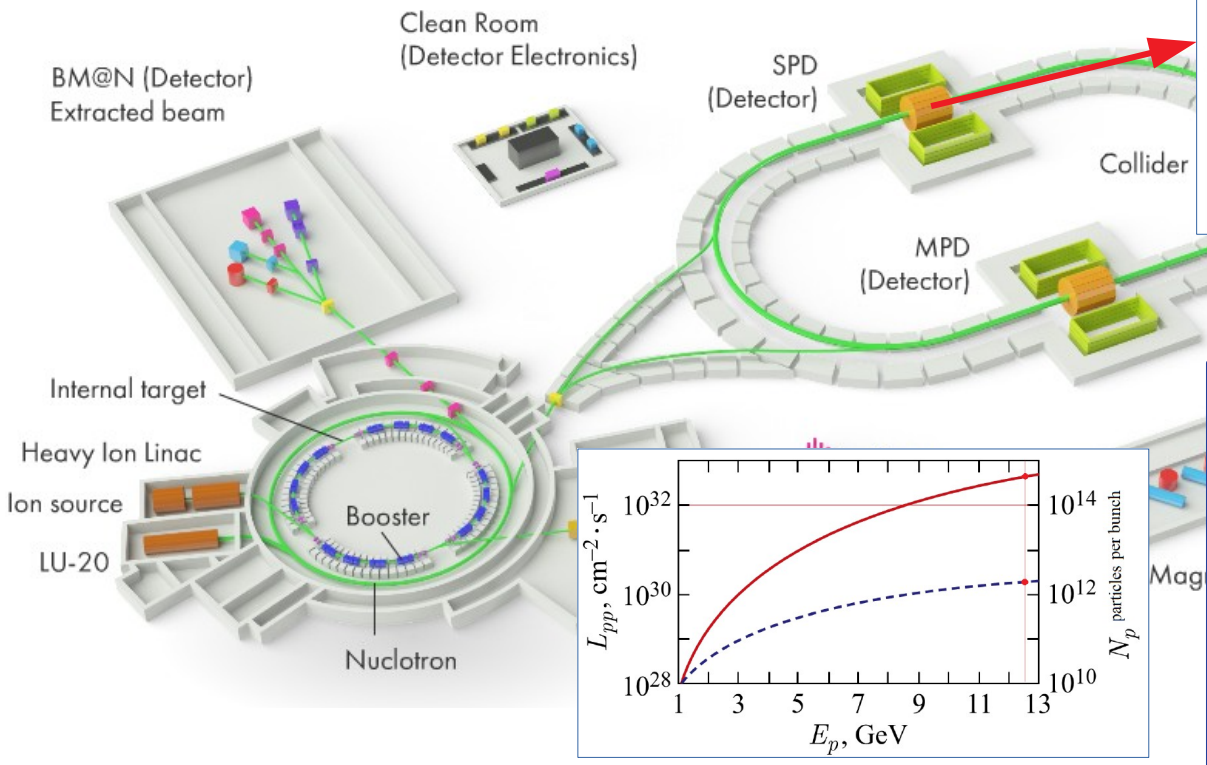
NRC "Kurchatov Institute" - IHEP, Protvino

02.06.26 – 05.06.26

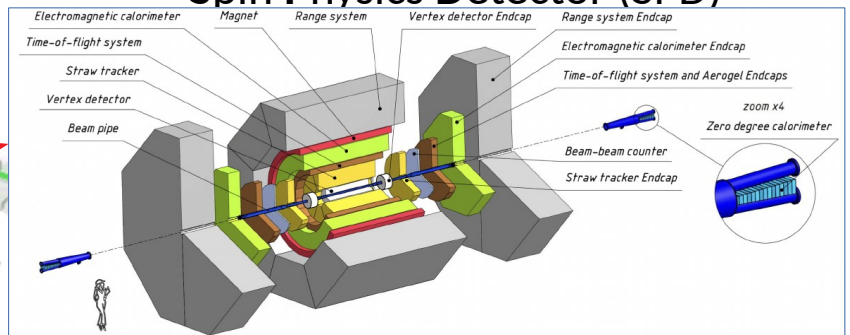


Nuclotron-based Ion Collider fAcility (NICA)

Joint Institute for Nuclear Research (Dubna)



Spin Physics Detector (SPD)



Polarized beams

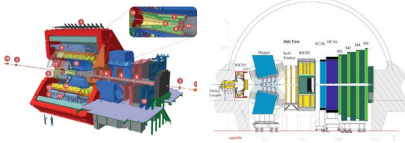
$p^{\uparrow}p^{\uparrow}$ at $\sqrt{s_{pp}} \leq 27$ GeV, $L_{av} \approx 10^{32}$ cm^{-2}s^{-1}

$d^{\uparrow}d^{\uparrow}$ at $\sqrt{s_{NN}} \leq 13.5$ GeV

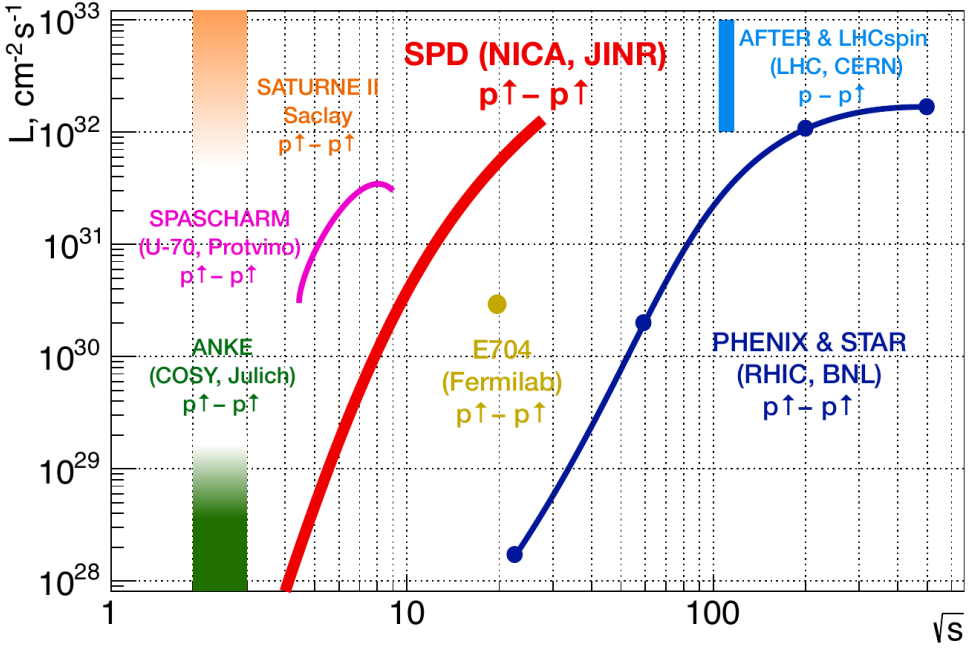
$p^{\uparrow}d^{\uparrow}$ at $\sqrt{s_{NN}} \leq 19$ GeV

longitudinal and transverse polarization (UU, LL, TT, UT, LT) > 70%

NICA and other facilities



SPD CDR (arXiv:2102.00442)



$p^{\uparrow}p^{\uparrow}$ collision mode

Experimental facility	SPD @NICA [30]	RHIC [29]	EIC [26]	AFTER @LHC [24]	SpinLHC [25]
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

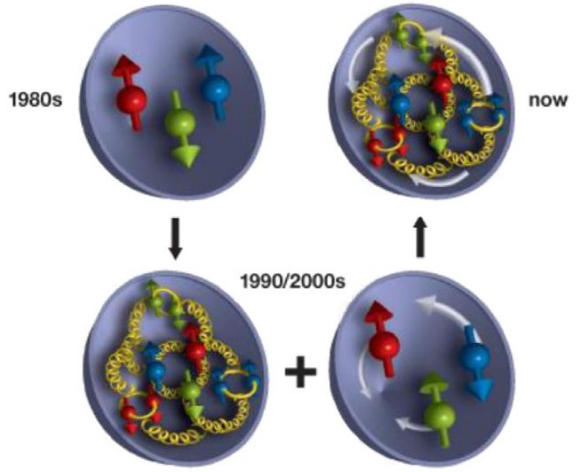
NICA is unique for double polarized $d^{\uparrow}d^{\uparrow}$ collisions at these energies.

Nucleon structure

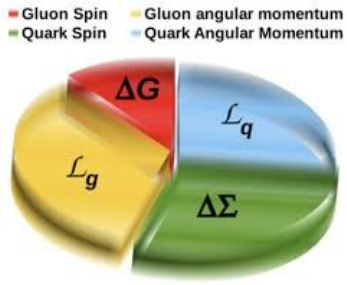
Hadron structure is one of the keys to understand bound states in QCD.

Nucleon tomography aims to understand how hadrons are build in terms of elementary degrees of freedom in QCD.

- How quarks and gluons, and their spins are distributed in a nucleon in transverse positional space and transverse momentum space?
- How nucleon spin emerges from spin and internal motion of valence and sea quarks and gluons?



Our understanding of nucleon structure



Spin decomposition of proton

Figure credit: Physics Reports 911, 2021, 1

Nucleon tomography

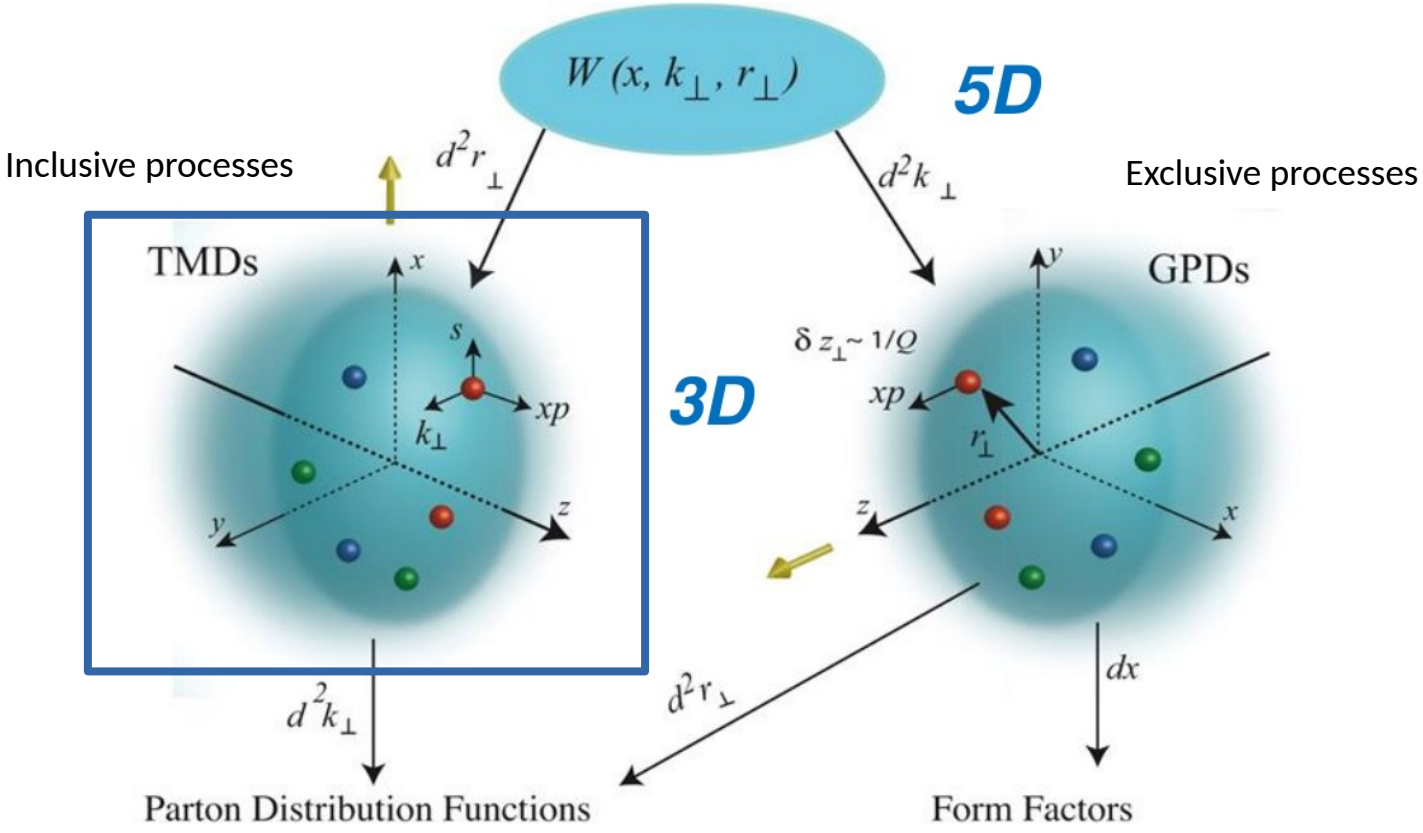


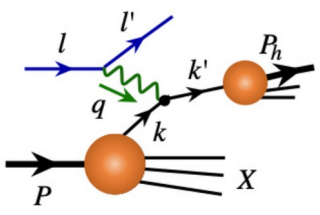
Figure credit: J.-P. Cheng

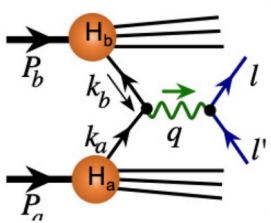
Quark TMDs

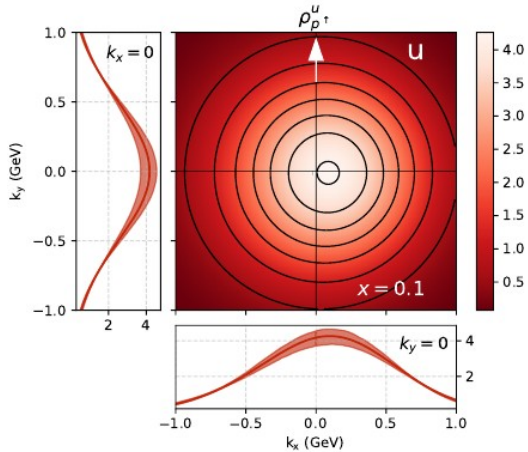
Leading Quark TMDPDFs — Nucleon Spin — Quark Spin

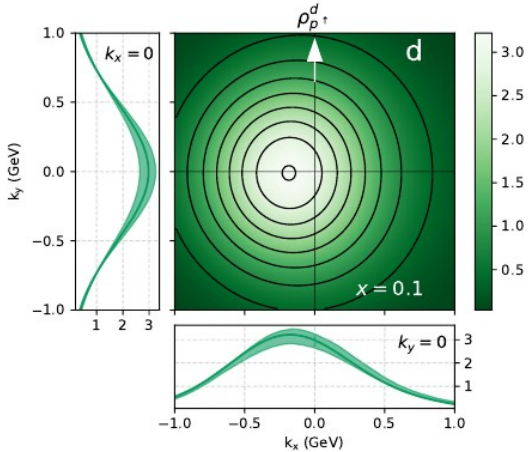
Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	f_1 = Unpolarized		$h_1^\perp$ = Boer-Mulders
L		g_1 = Helicity	$h_{1L}^\perp$ = Worm-gear
T	$f_{1T}^\perp$ = Sivers	$g_{1T}^\perp$ = Worm-gear	h_1 = Transversity; $h_{1T}^\perp$ = Pretzelosity

Significant progress on **quark TMDs** over the last decades (for details see e.g. TMD Handbook, PLB 827, 136961 (2022)).









The density distribution of an unpolarized quark with flavor a in a proton polarized along the +y direction and moving towards the reader as a function of (k_x , k_y) at Q^2 = 4 GeV^2 (PLB 827, 136961 (2022))

Gluon TMDs and the SPD experiment

Our knowledge on gluon TMD remains rather scarce.

gluon pol.

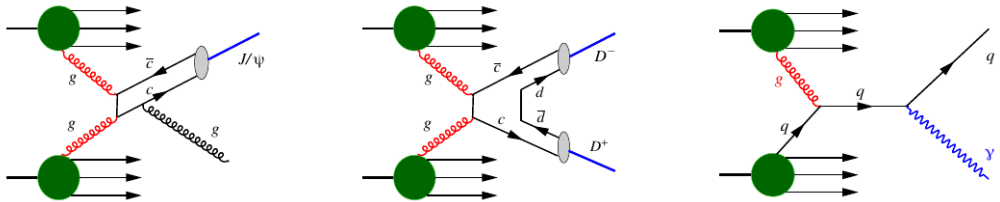
nucleon pol.	U	circular	linear
U	f_1^g		$h_1^{\perp g}$
L		g_1^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_1^g, $h_{1T}^{\perp g}$

Leading twist gluon TMD PDFs
(**two times more** due to proper gauge link choice)

h_1^g is can be nonzero only for deuteron.

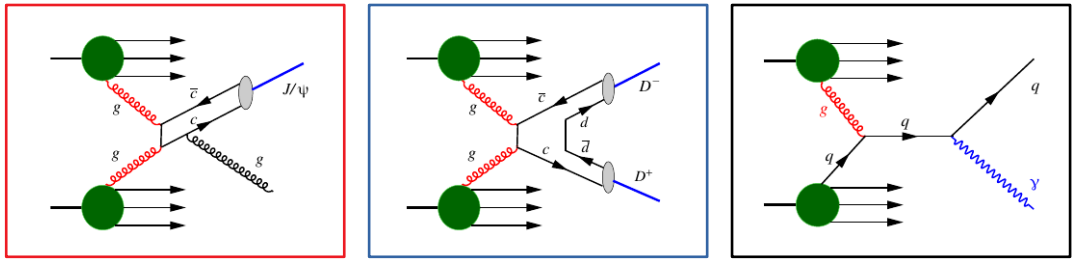
Main goal of the experiment – spin-dependent gluon structure of proton and deuteron.

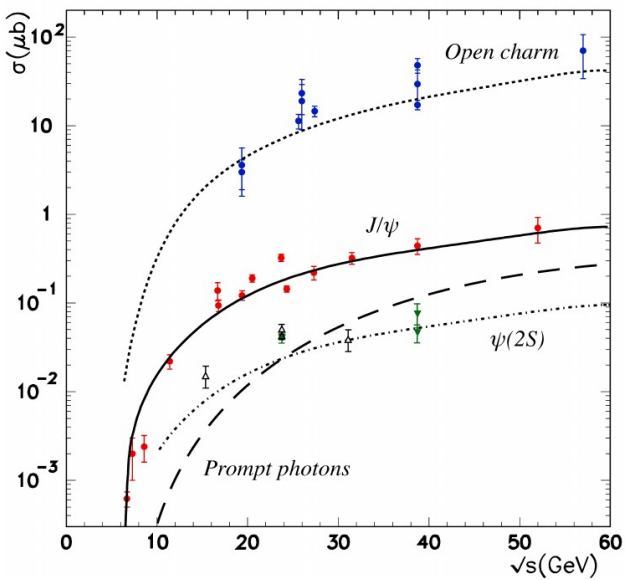
- Three probes of gluon structure chosen in this energy range:

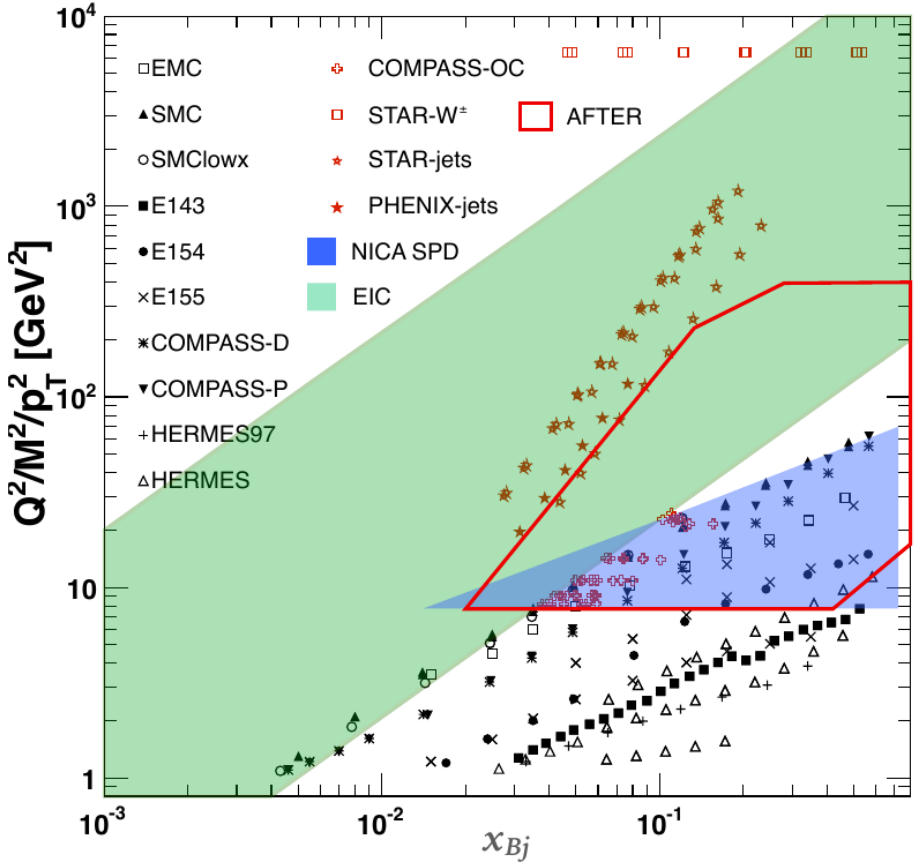


- Measurements at SPD should help to improve our understanding of QCD and resolve spin crises.
- Many other aspects of QCD to be studied in such collisions.

SPD kinematic coverage

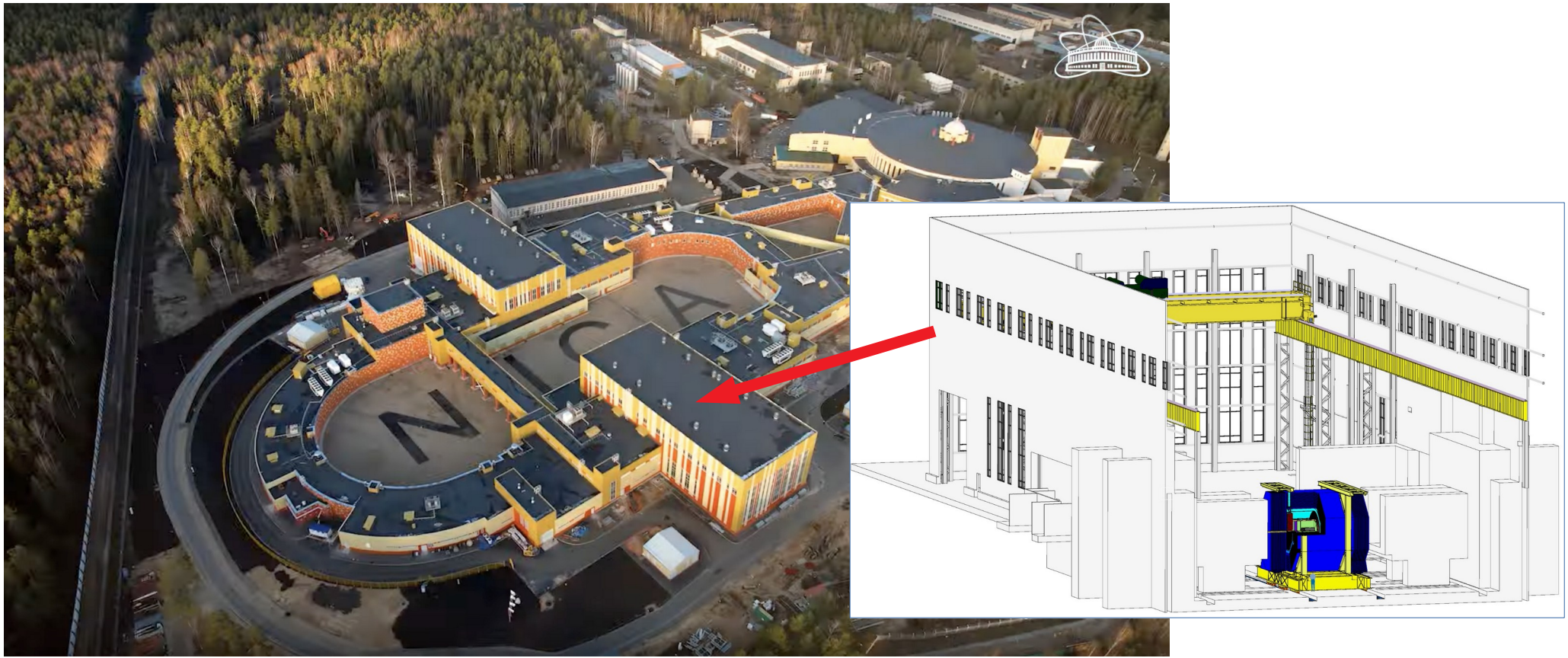






arXiv:2011.15005

Detector construction site

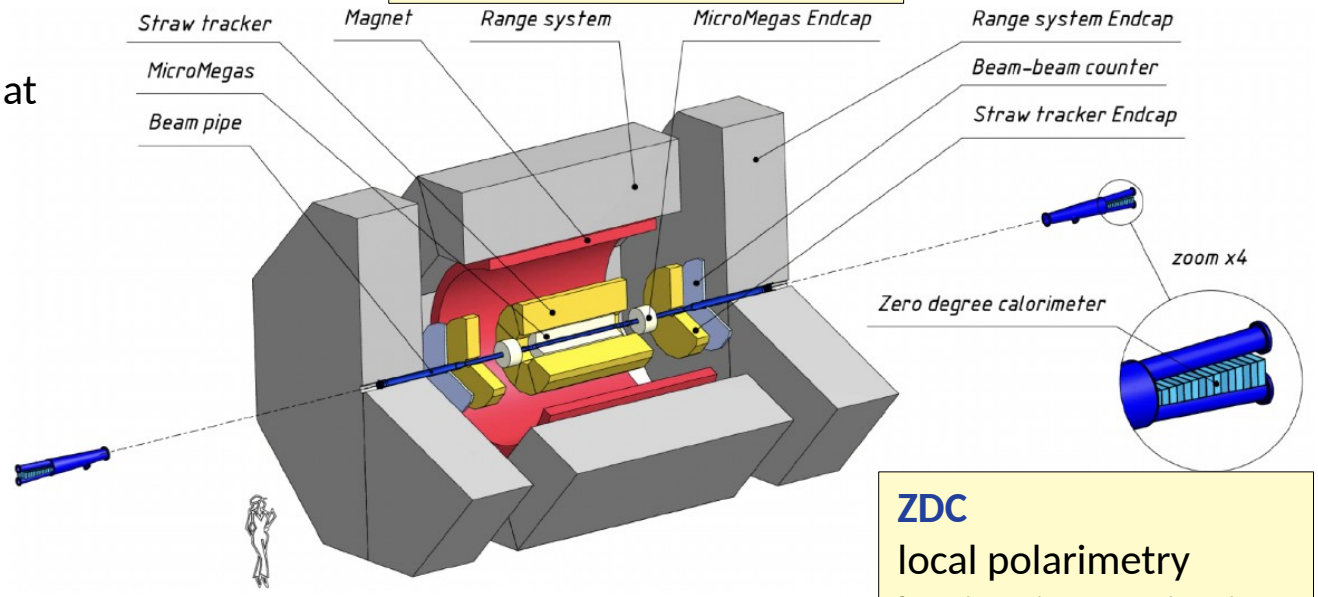


SPD initial stage

SPD TDR: Natural Sci. Rev. 1 1, 2024 (arXiv:2404.08317)

- Polarized and unpolarized phenomena at **low energies** (3.4 GeV < $\sqrt{s_{pp}}$ < 9.4 GeV) and **reduced luminosity**
- p-p, d-d, and ion collisions (up to Ca)
- Simplified detector set-up
- Up to 2 years of data taking

Magnetic field up to **1.2 T**



Range System
muon identification and coarse hadron calorimetry

ZDC
local polarimetry
luminosity monitoring

BBC
local polarimetry
luminosity monitoring

Straw tracker:
- **σ ~ 150 μm**
- **σ(dE/dx) = 8.5%**

Micromegas central tracker:
σ ~ 150 μm

SPD initial stage

Physical program:

- spin effects in p-p and d-d scattering
- spin effects in hyperon production
- multiquark fluctons
- large p_T hadron production to study diquark structure of proton
- quark-instanton scattering
- color transparency in quasi-free pd interactions
- probing of non-baryonic content of deuteron
- dibaryon resonances
- hypernuclei
- physics of light and intermediate nuclei collisions
- …

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Possible Studies at the First Stage of the NICA Collider Operation with Polarized and Unpolarized Proton and Deuteron Beams

V. V. Abramov[a], A. Aleshko[b], V. A. Baskov[c], E. Boos[b], V. Bunichev[b], O. D. Dalkarov[c], R. El-Kholy[d], A. Galoyan[e], A. V. Guskov[f], V. T. Kim[g, h], E. Kokoulina[e, i], I. A. Koop[k, l, m], B. F. Kostenko[m], A. D. Kovalenko[e, †], V. P. Ladygin[e], A. B. Larionov[o, n], A. I. L'vov[c], A. I. Milstein[j, k], V. A. Nikitin[e], N. N. Nikolaev[p, z], A. S. Popov[j], V. V. Polyanskiy[c], J.-M. Richard[q], S. G. Salnikov[j], A. A. Shavrin[r], P. Yu. Shatunov[j, k], Yu. M. Shatunov[j, k], O. V. Selyugin[n], M. Strikman[s], E. Tomasi-Gustafsson[t], V. V. Uzhinsky[m], Yu. N. Uzikov[f, u, v, *], Qian Wang[w], Qiang Zhao[x, y], and A. V. Zelenov[g]

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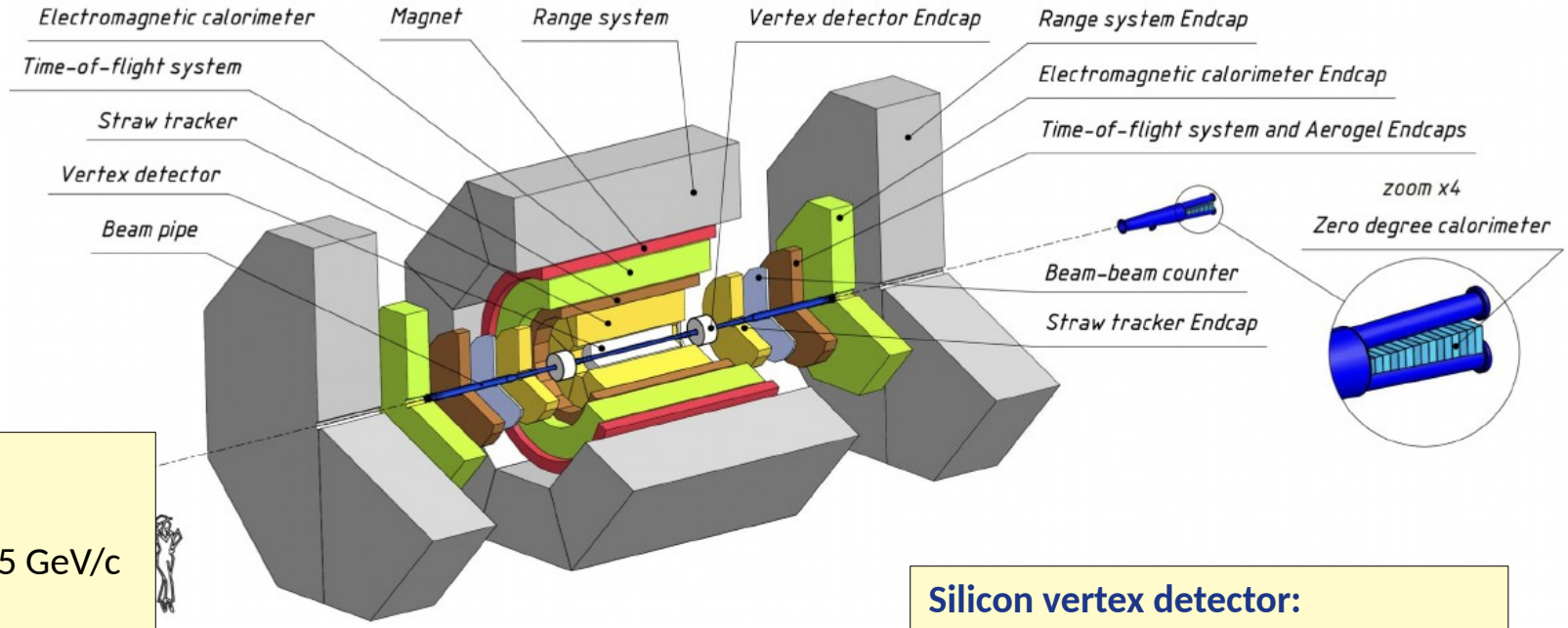
[i] *Sukhoi State Technical University of Gomel, Gomel, 246746 Belarus*
[j] *Budker Institute of Nuclear Physics of SB RAS, Novosibirsk, 630090 Russia*

Physics of Particles and Nuclei 52, 1044 (2021)
arXiv:2102.08477

SPD final layout

SPD TDR: Natural Sci. Rev. 1 1, 2024 (arXiv:2404.08317)

Electromagnetic calorimeter:
σE/E = 5%/√E ⊕ 1%



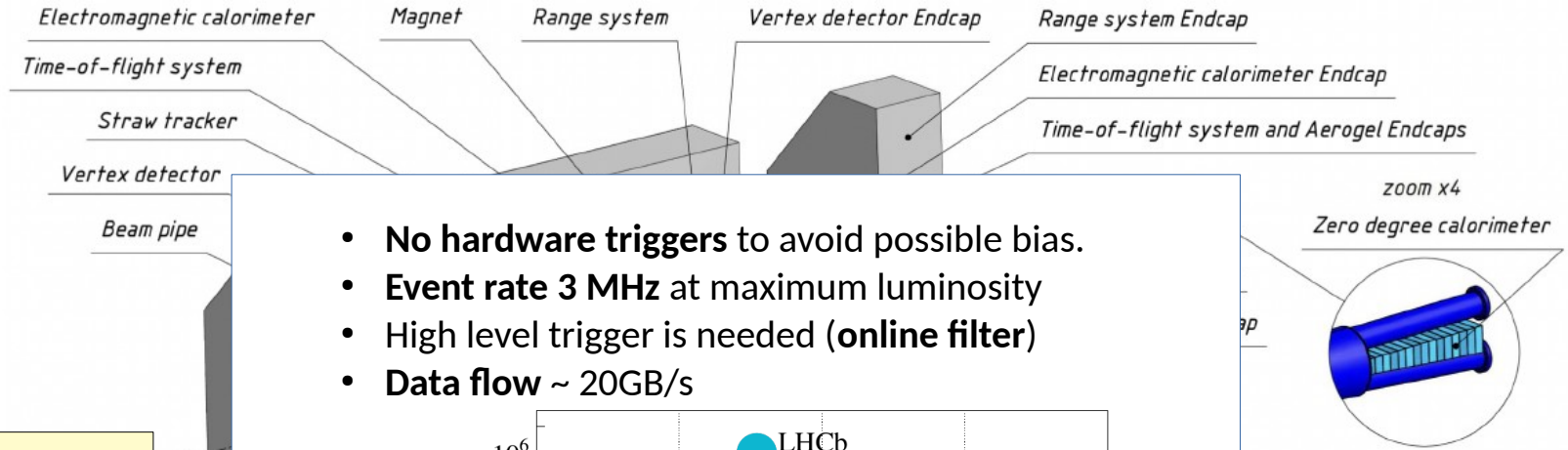
Time of flight system:
σ = 50 ps
3σ π/K separation for p < 1.5 GeV/c

FARICH in *endcaps* for pion/kaon separation for particle momentum up to **5.5 GeV/c**

Silicon vertex detector:
- MAPS (4 layers): **σ = 10 μm**
- DSSD (3 layers): **σ_φ = 27.4 μm,**
  σ_z = 81.3 μm

SPD final layout

SPD TDR can be found at http://spd.jinr.ru/spd-cdr/

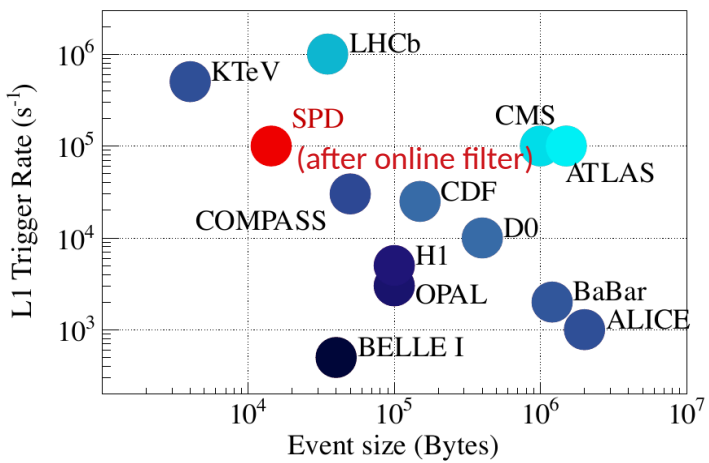


Electromagnetic calorimeter:
σE/E = 5%/√E ⊕ 1%

Time of flight system:
σ = 50 ps
3σ π/K separation for p < 1.5 GeV/c

FARICH ir
separatio
momentu

- **No hardware triggers** to avoid possible bias.
- **Event rate 3 MHz** at maximum luminosity
- High level trigger is needed (**online filter**)
- **Data flow** ~ 20GB/s



tor:

μm,

μm

SPD 2-nd stage

Physical program:

- unpolarized and polarized proton and deuteron structure:
  - gluon helicty
  - gluon TMDs (Sivers and Boer-Mulders)
  - gluon transversity and tensor polarized gluon distribution in deuteron
  - unpolarized proton and deuteron gluon PDF at high x
  - non-nucleonic degrees of freedom in deuteron…
- tests of QCD factorization
- charmonia production mechanisms
- …

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Progress in Particle and Nuclear Physics

Volume 119, July 2021, 103858

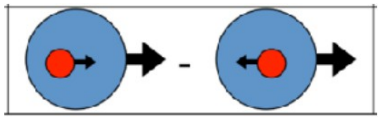
Review

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

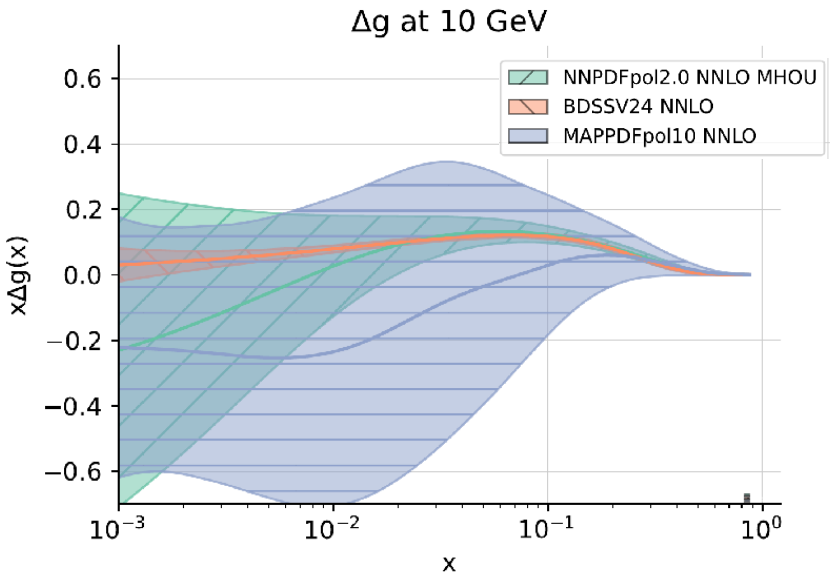
A. Arbuzov [a], A. Bacchetta [b, c], M. Butenschoen [d], F.G. Celiberto [b, c, e, f], U. D'Alesio [g, h], M. Deka [a], I. Denisenko [a], M.G. Echevarria [i], A. Efremov [a], N.Ya. Ivanov [a, j], A. Guskov [a, k], A. Karpishkov [l], [a], Ya. Klopot [a, m], B.A. Kniehl [d], A. Kotzinian [j, o], S. Kumano [p], J.P. Lansberg [q], Keh-Fei Liu [r] … O. Teryaev [a]

Gluon helicity distribution

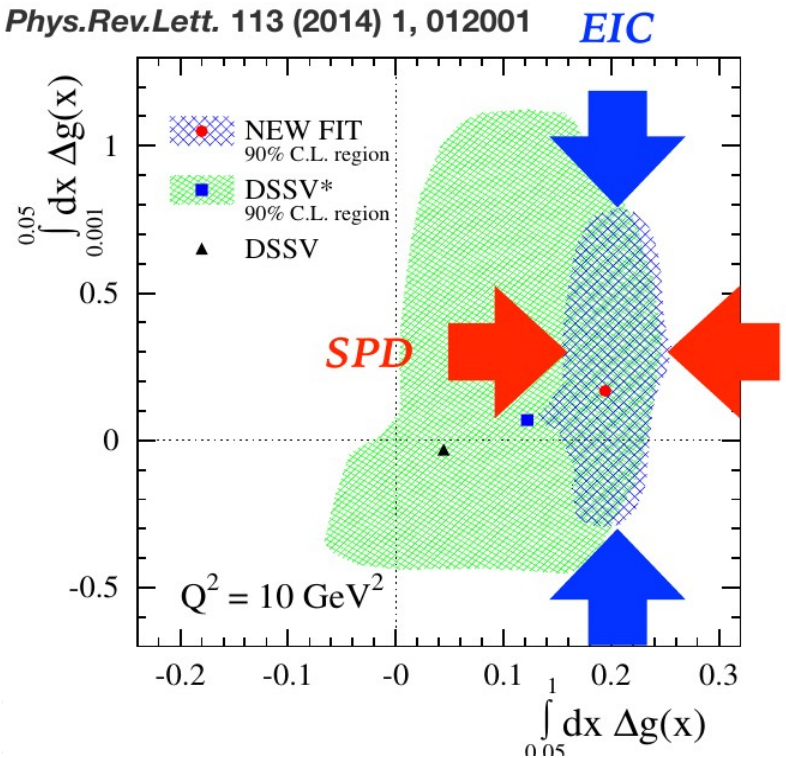
$\Delta g(x)$:



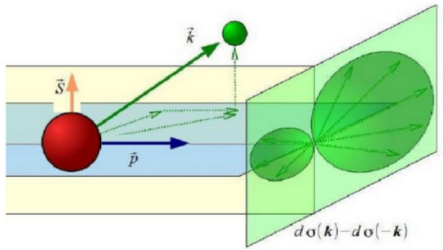
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$



arXiv:2503.11814



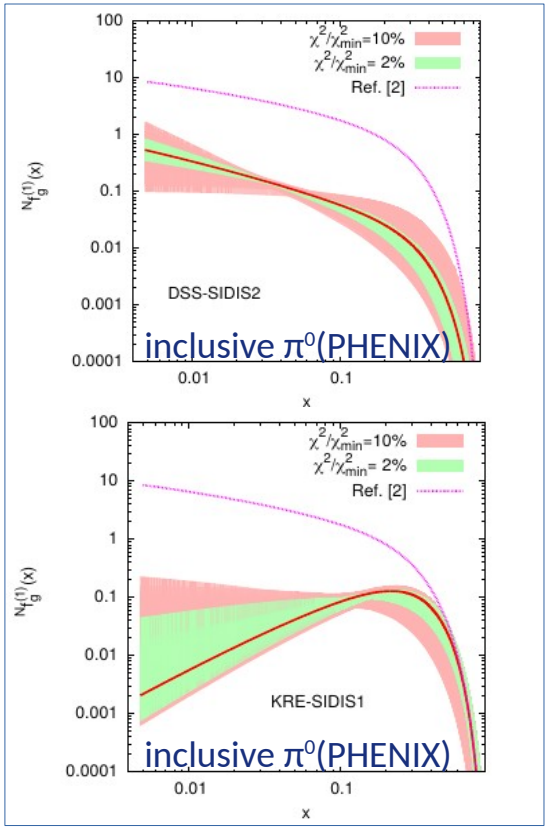
Gluon Sivers function



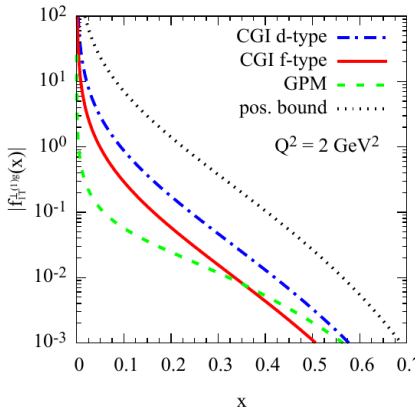
- GSF – correlation between transverse spin and gluon k_T
- Can be indirectly related to gluon OAM
- Probed by TSSA

$$\sigma(\phi) \propto 1 + P \cdot A_N \sin(\phi_{\mathrm{pol}} - \phi)$$

- Poorly known, extracted in GPM, CGI-GPM, and very recently TMD approaches (spectator model)



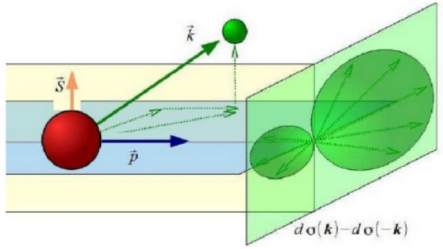
First kT moments for GSF, GPM (JHEP09(2015)119))

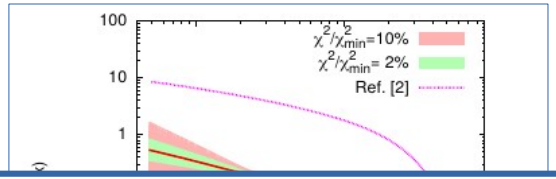


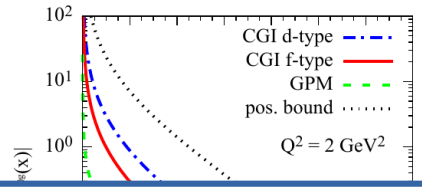
inclusive π^0 and inclusive D ($p^\uparrow p \to \mu^\pm X$)

Maximized first kT moments for GSF, CGI-GPM (PRD99, 036013 (2019))

Gluon Sivers function







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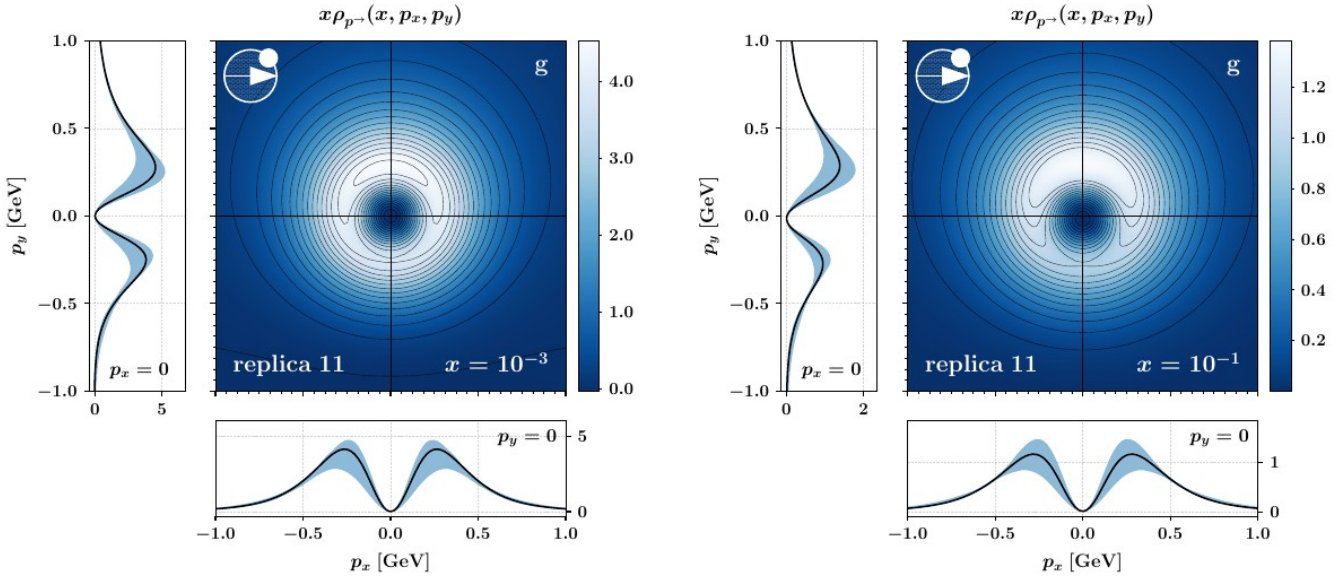
- Poorly known, extracted in GPM, CGI-GPM, and very recently TMD approaches (spectator model)

Spectator model calculations



Unpolarized gluon density for a transvsersely polarized nucleon along X-axis, (Q=1.64 GeV) in the **spectator model -** Bacchetta, Celiberto, Radici (EPJC 84 (2024) 6, 576)

Charmonia production as a probe of gluon TMD PDFs

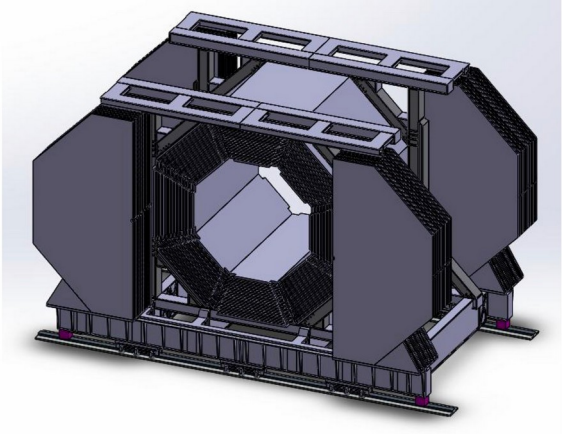
Charmonia production

- dominated by gluon-gluon fusion
- high cross-section
- J/ψ can be easily reconstructed from the $\mu^+\mu^-$ decay, ψ(2S) and χ_{cJ} can be reconstructed based on this decay
- hadronization of $c\bar{c}$ pair is not well understood theoretically:
  - (Improved) Color Evaporation Model
  - CSM
  - NRQCD
- TMD factorization does not always hold
- η_c might be the best probe, but its observation is challenging experimentally
- the J/ψ signal is “contaminated” by feed-down contributions

Charmonia production at SPD

- High statistics, wide kinematic coverage
- Ability to measure also production properties of ψ(2S), χ_{c1} and χ_{c2}
- Strategy is to obtain all possible measurements in the wide kinematic range
- Constrain both theoretical approaches and PDFs
- Our p_T are mostly below $M_{J/\psi}$
- NRQCD LDME → shape functions (Echevarria, 2019)

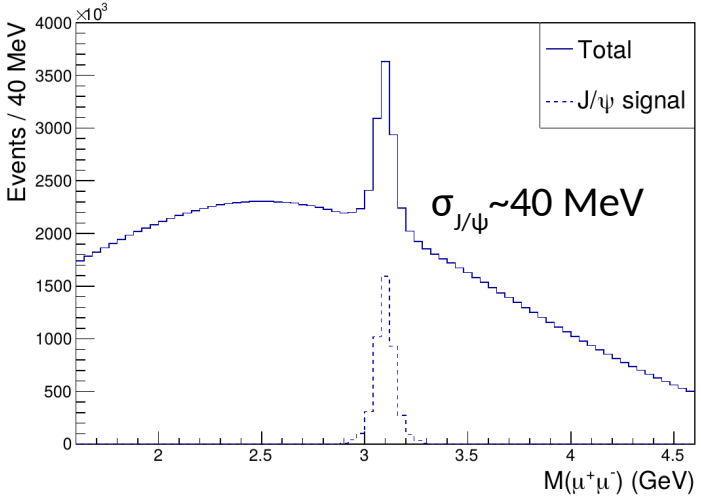
Inclusive J/ψ measurements

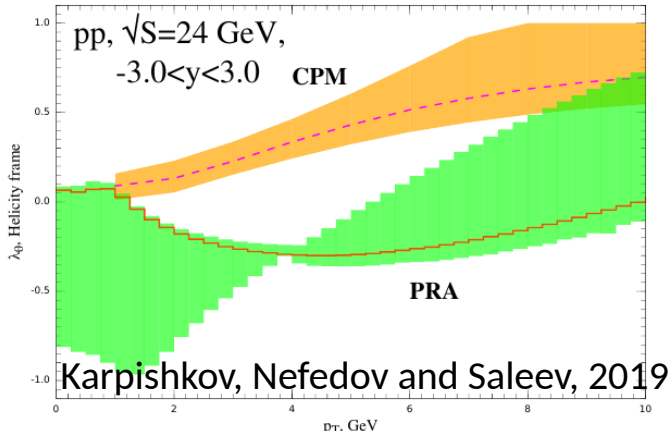


- Reconstruction efficiency: ~40%
- Statistics: ~ 4.5 – 5.0 M (selected events) per year
- Large background due to pion decays and muon misidentification in RS

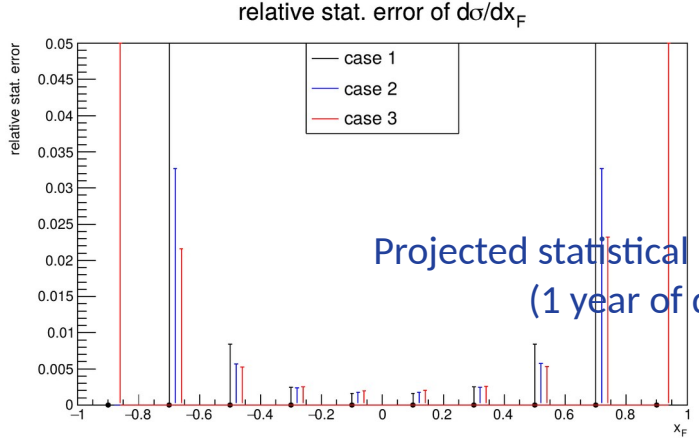
Observables:

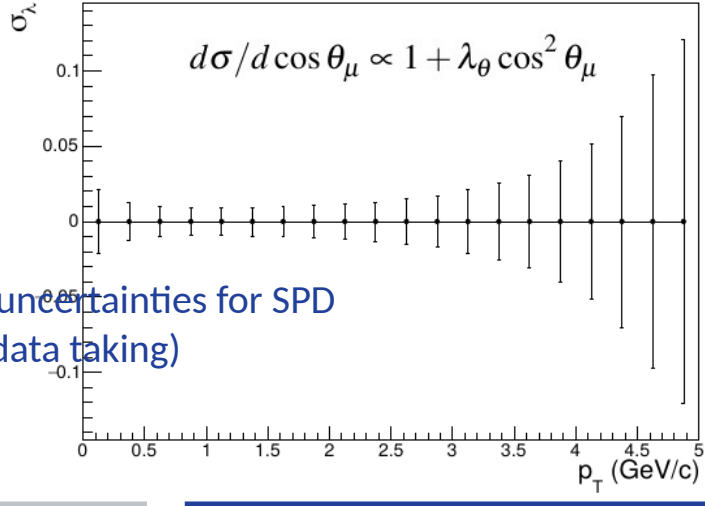
- cross-section, p_T-, x_F-dependencies
- polarization
- asymmetries





Karpishkov, Nefedov and Saleev, 2019

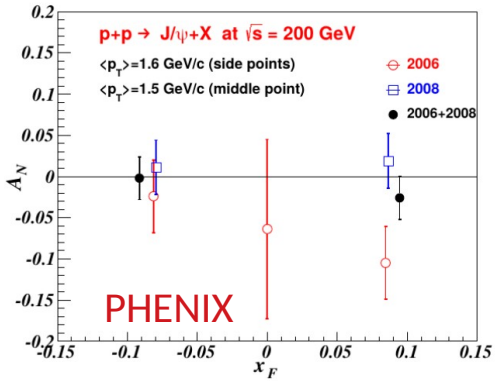




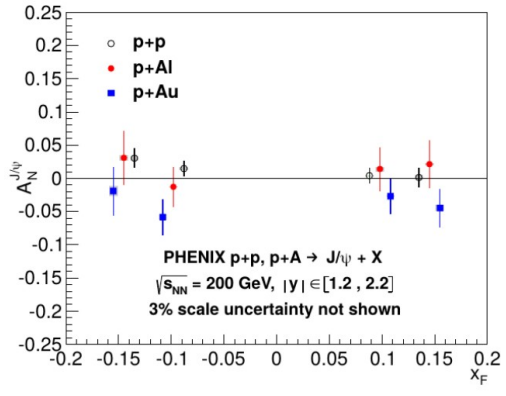
Projected statistical uncertainties for SPD
(1 year of data taking)

A_N for inclusive J/ψ production

$$\sigma(\phi) \propto 1 + P \cdot A_N \sin(\phi_{\text{pol}} - \phi)$$



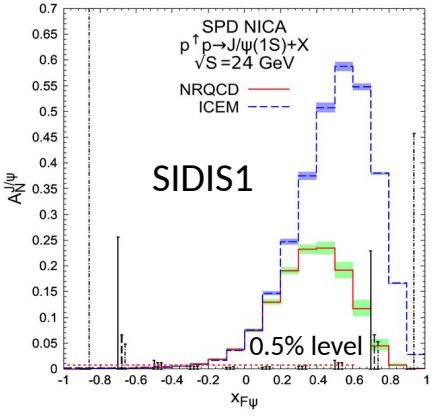
PRD82, 112008 (2010)

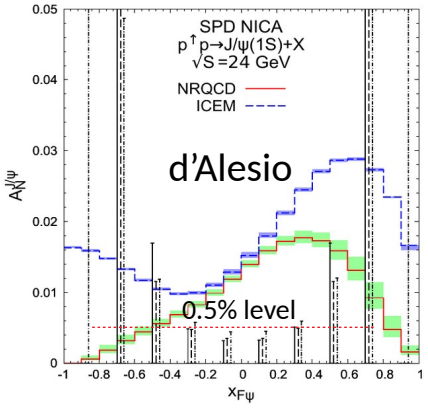


PRD98, 012006 (2018)

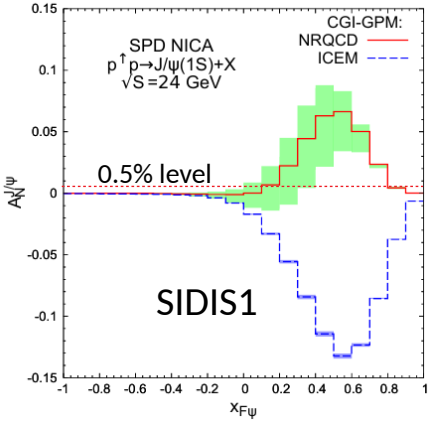
Projected stat. uncertainties and predictions from PRD104, 016008 (2021)

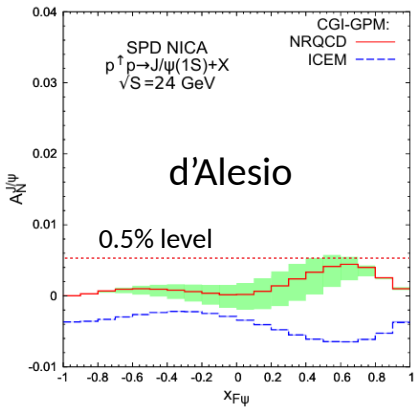
GPM





CGI-GPM



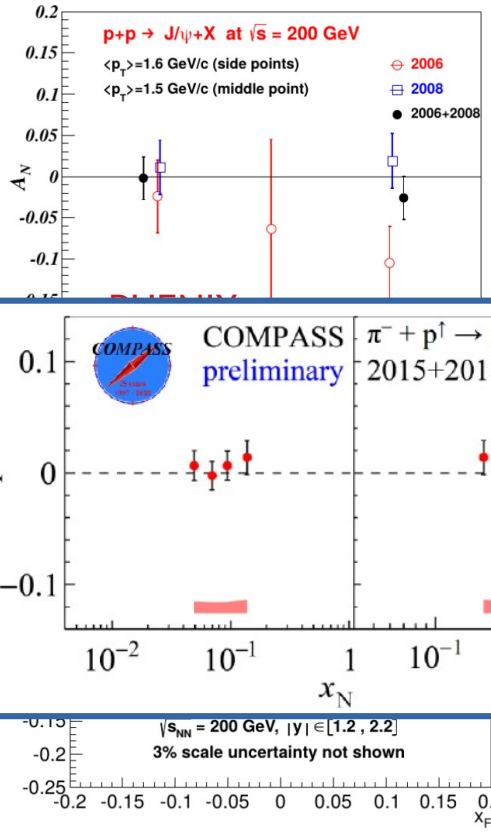


Here and in the following P = 0.7 and is assumed constant during the run.

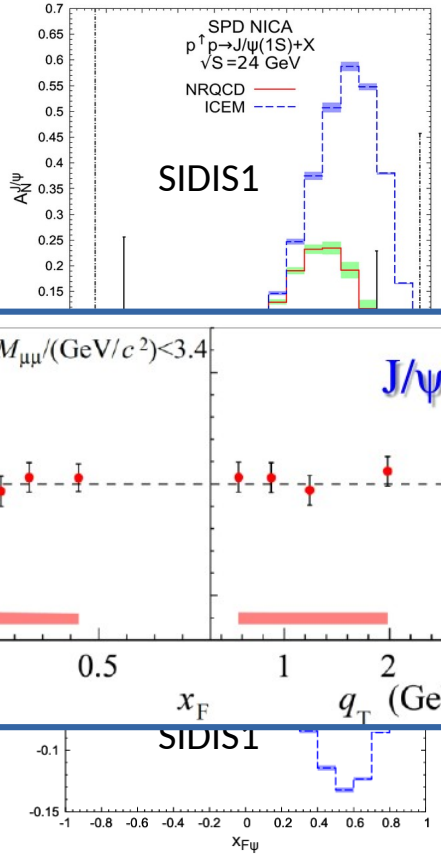
A_N for inclusive J/ψ production

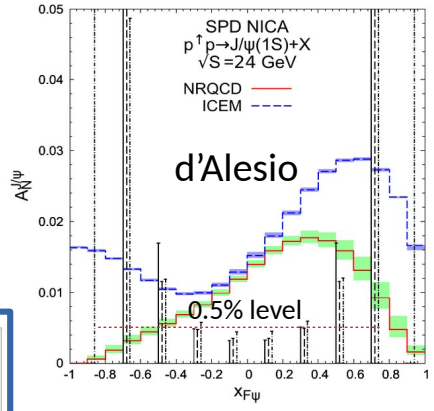
$$\sigma(\phi) \propto 1 + P \cdot A_N \sin(\phi_{\mathrm{pol}} - \phi)$$

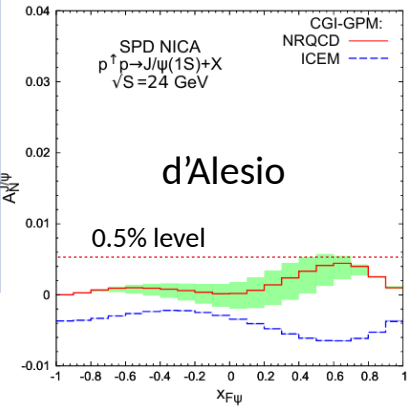
Projected stat. uncertainties and predictions from PRD104, 016008 (2021)



GPM







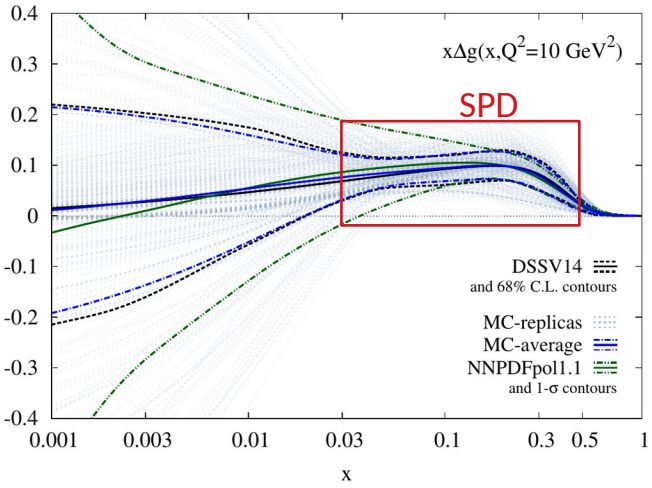
PRD98, 012006 (2018)

Here and in the following P = 0.7 and is assumed constant during the run.

A_{LL} for inclusive J/ψ production

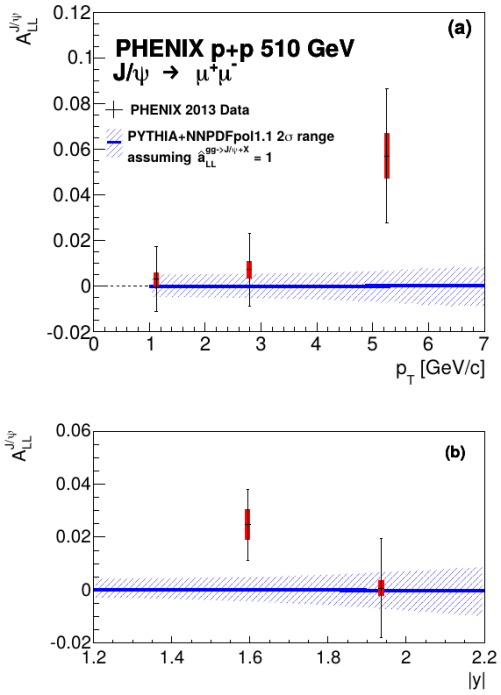
$$A_{LL}^{J/\psi} = \frac{\Delta\sigma}{\sigma} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

$$A_{LL}^{J/\psi} \approx \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\Delta g(x_2)}{g(x_2)} \otimes \hat{a}_{LL}^{gg \to J/\psi + X}$$



PRD100 114027 (2019)

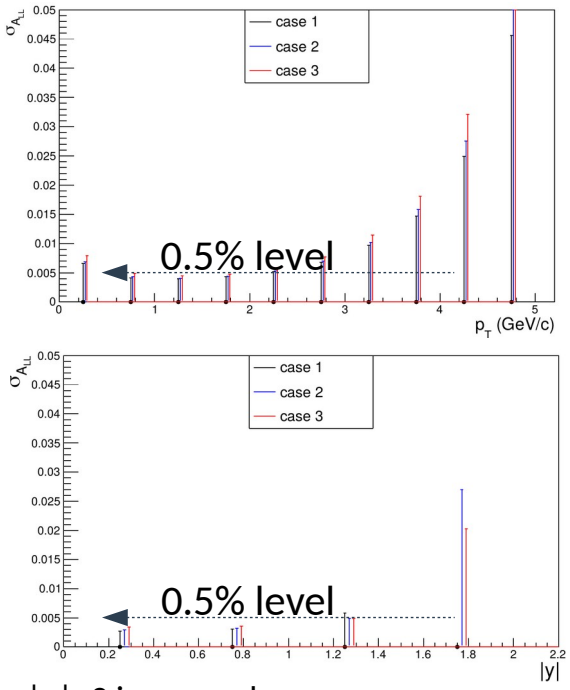
PRD94 112008 (2016)



$x_1 \sim 5 \times 10^{-2}$

$x_2 \sim 2 \times 10^{-3}$

Projected statistical uncertainties for SPD

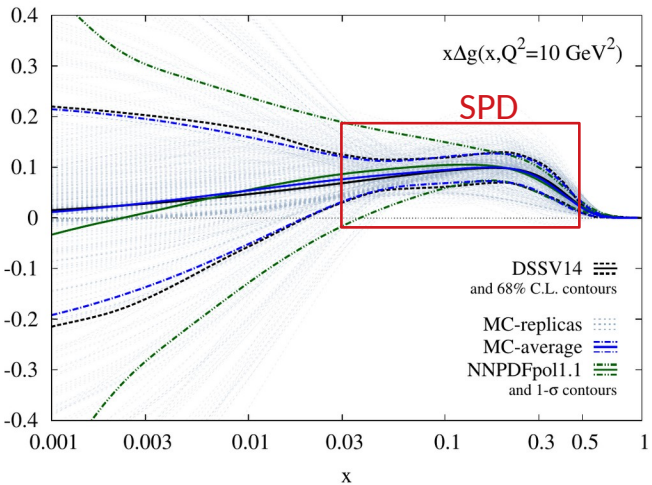


- |y|<2 is covered
- At SPD both $\Delta g(x_1)$ and $\Delta g(x_2)$ are expected to be close to the maximum
- A measurable A_{LL} of the order of 1-10% can be expected

A_{LL} for inclusive J/ψ production (impact of SPD measurements)

$$A_{LL}^{J/\psi} = \frac{\Delta\sigma}{\sigma} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

$$A_{LL}^{J/\psi} \approx \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\Delta g(x_2)}{g(x_2)} \otimes \hat{a}_{LL}^{gg \to J/\psi + X}$$

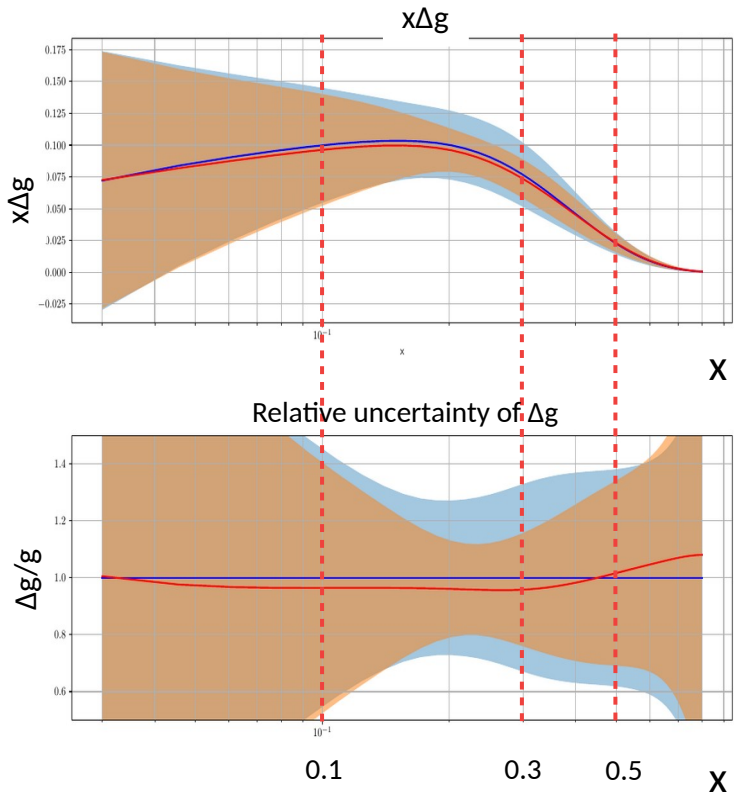


PRD100 114027 (2019)

Impact of SPD data is estimated by

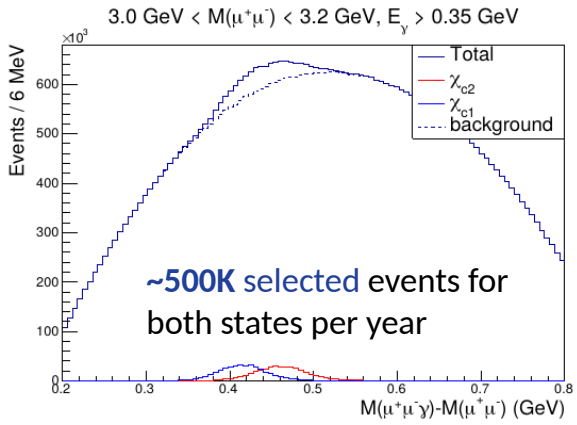
- generating "SPD data" according to NNPDFPol1.1
- prescribing **stat. errors** estimated for 1 year data taking at SPD with √s = 27 GeV
- Bayesian reweighing of MC replicas

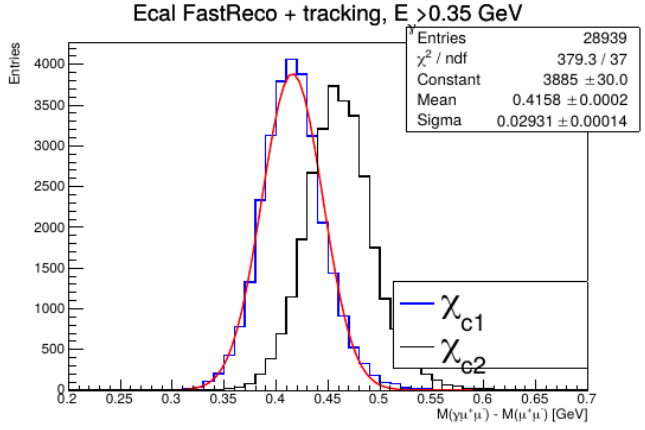
The relative uncertainty decreases by a factor of ~2 for x ~ 0.2-0.3.

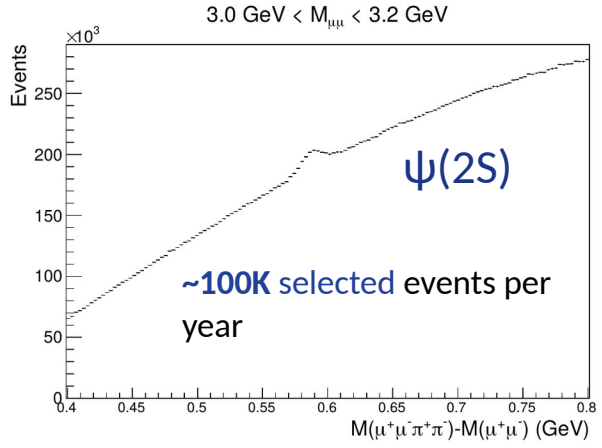


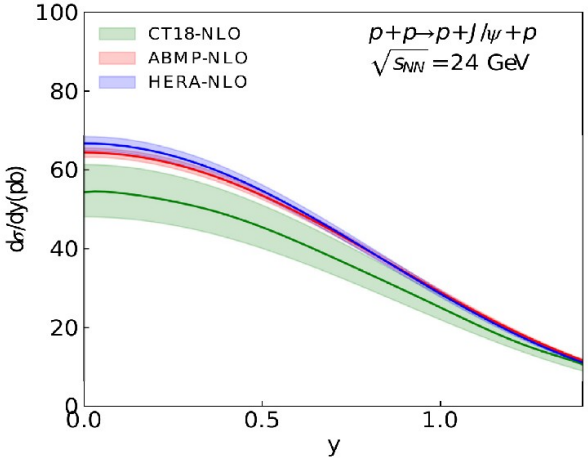
On other measurements with charmonia

χ_{c1} and χ_{c2}





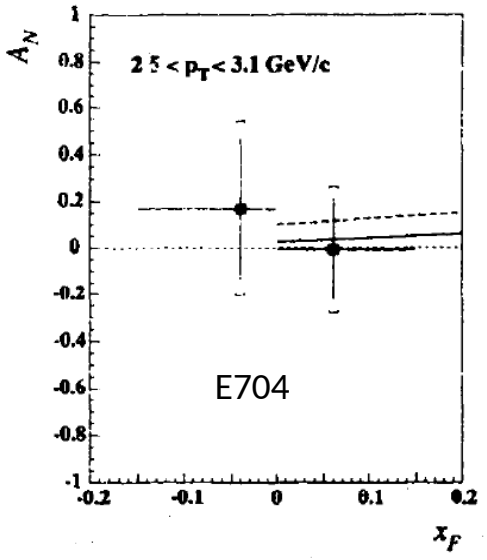




Xie, Goloskokov, EPJC85, 680 (2025)

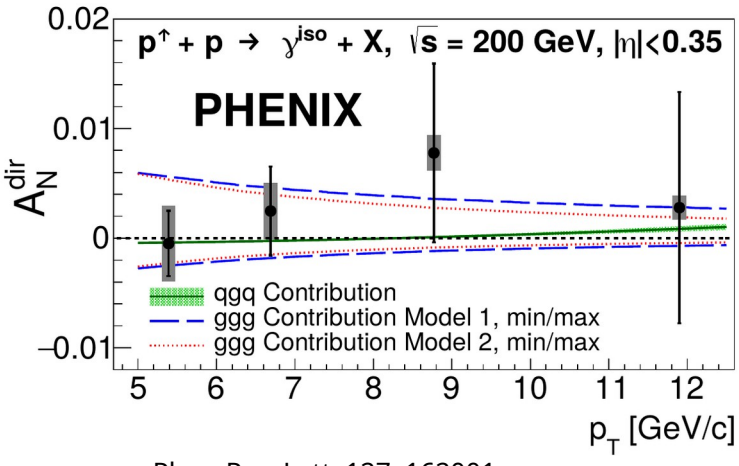
- Double J/ψ production
  - 50-100 events/year for both J/ψ dilepton decay modes
  - p_T dependence complimentary to high energy experiments
- J/ψγ: limited statistics and large background
- Exclusive J/ψ production for GPD?

Prompt photons: A_N

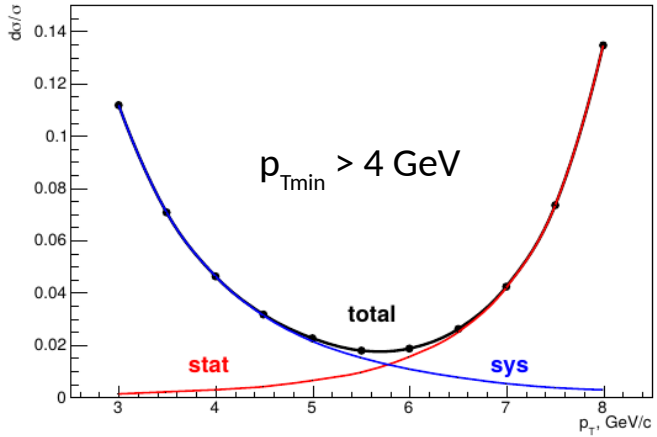


PLB345, 569 (1995)

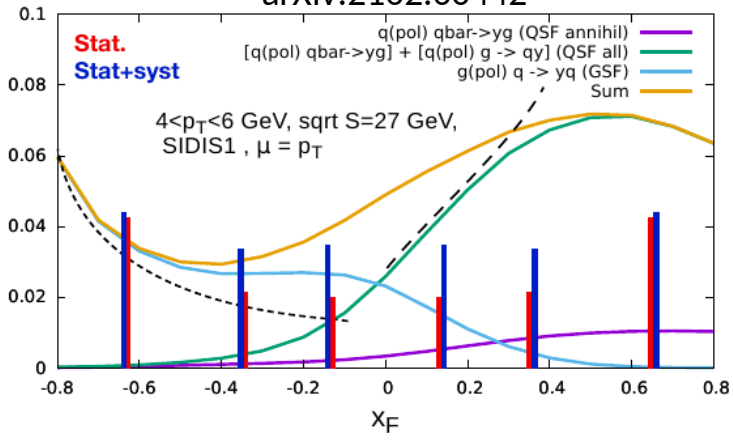
- Straightforward theoretical interpretation
- very challenging experimentally



Phys. Rev. Lett. 127, 162001



arXiv:2102.00442



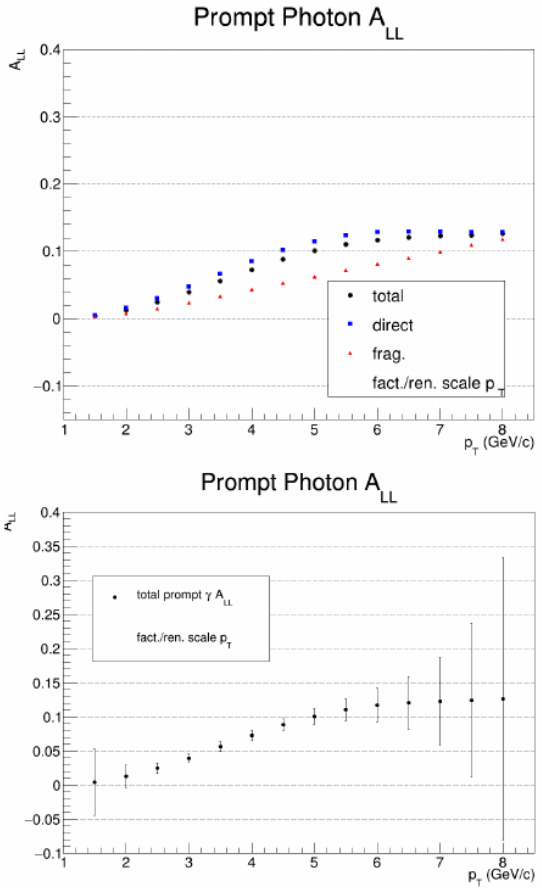
Predictions: Saleev, Shipilova, 2020

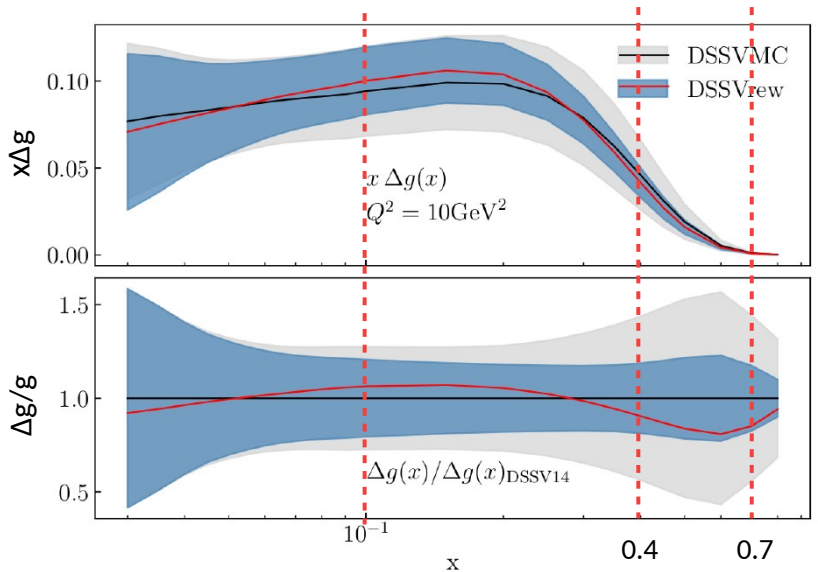
Prompt photons: A_{LL}

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

Impact of SPD data is estimated by

- generating “SPD data” according to current PDFs (NLO, NNPDF3.0, DSSV2014) – W. Vogelsong, 2021
- prescribing errors estimated for 1 year data taking at SPD with √s = 27 GeV
- Bayesian reweighing of MC replicas

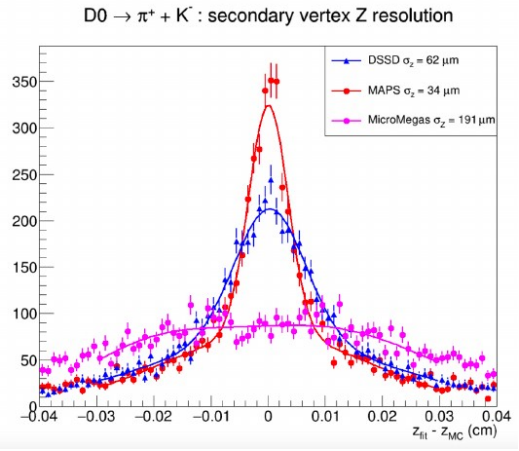


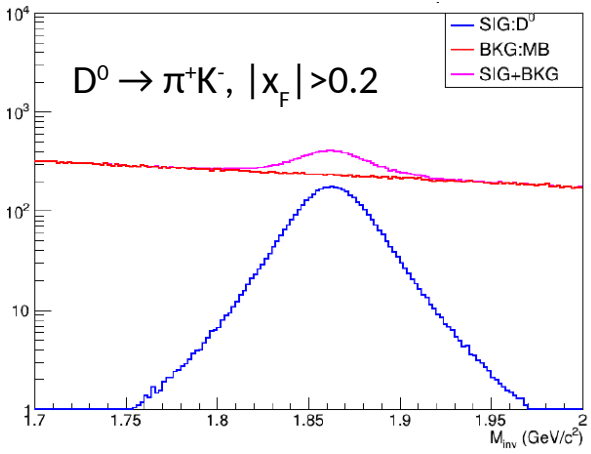


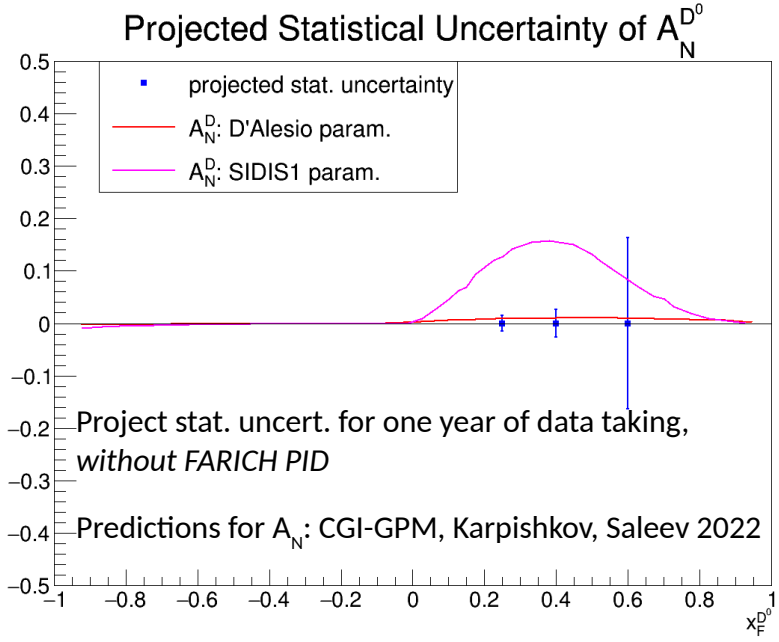
Predictions with new “data” added (top) and ration of the uncertainties (bottom). Courtesy R. Sassot, I. Borsa, 2021.

Uncertainties are reduced by factor of 2 for 0.4 < x < 0.7

Measurements with D mesons







- The largest production cross-section (almost two orders of magnitude larger than for J/ψ)
- Small D-meson boost at our energies
- Interpretation requires c-quark FF
- Projected uncertainties shown for D^0 only
- D meson pair production – probe for Boer-Mulders function

Deuteron gluon structure

$\sigma(x_F, p_T)$, vector and tensor angular asymmetries

Nonbaryonic content of deuteron:

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

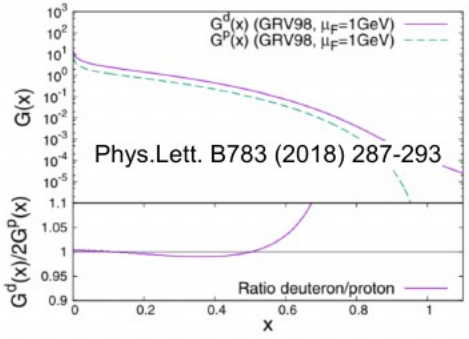
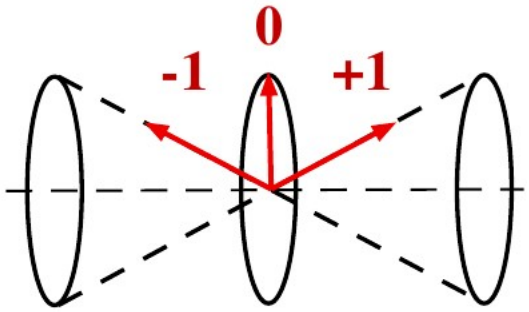
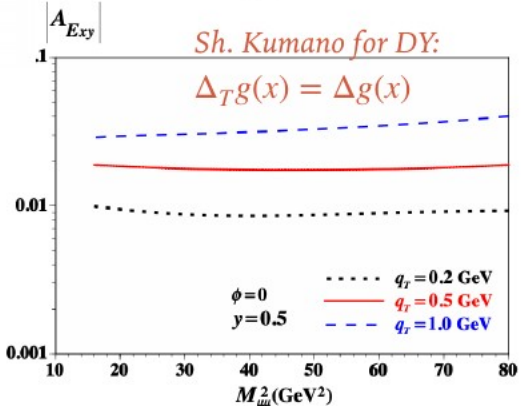


Fig. 6. Gluon PDF in the deuteron and in the nucleon.

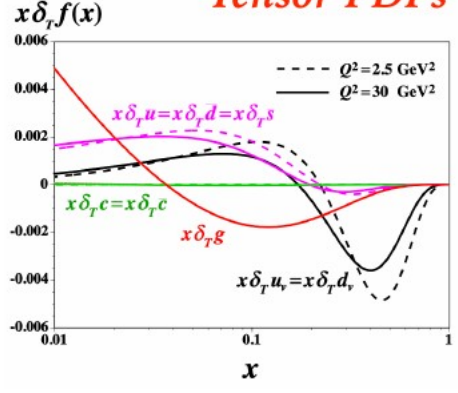


Gluon transversity

Unpolarized gluons at high x:

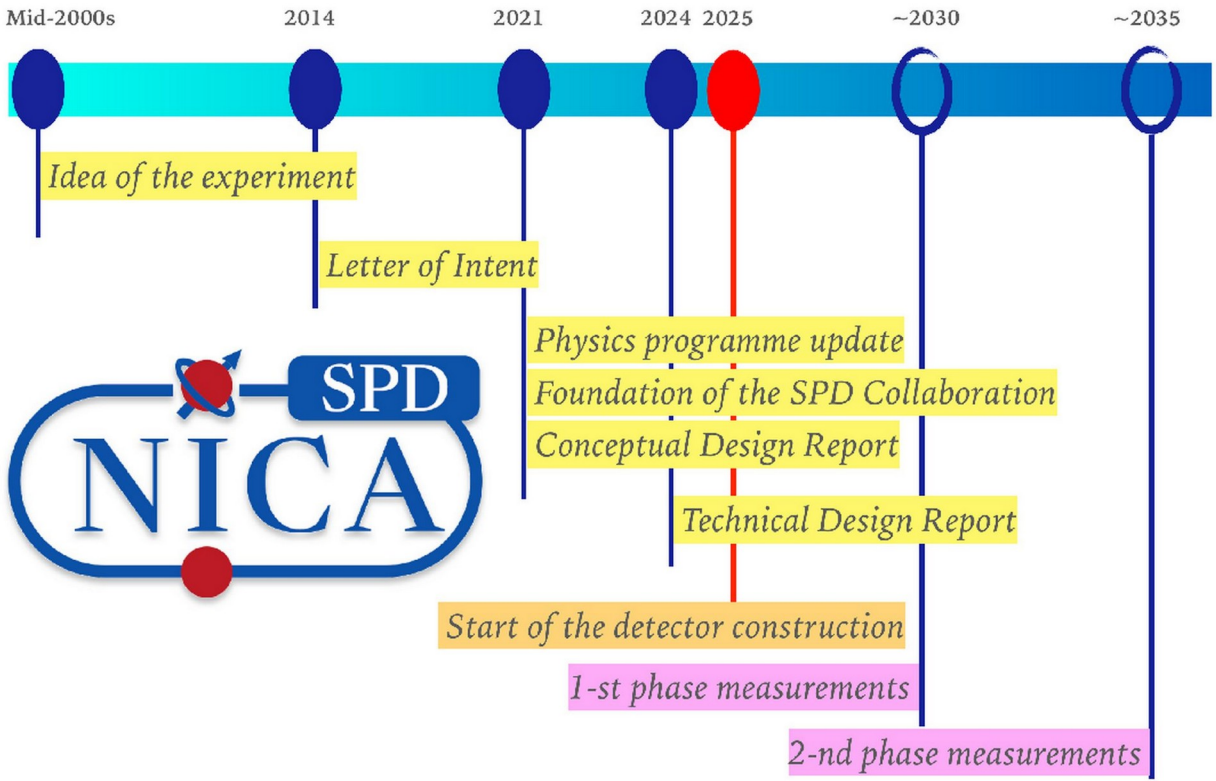


Tensor PDFs



SPD project

- SPD Technical Design Report passed international expertise and published: Natural Sci. Rev. 1 1 (2024) arxiv link
- The first phase of the SPD project is included into the JINR's 7-year plan (2024-2030)



SPD Collaboration

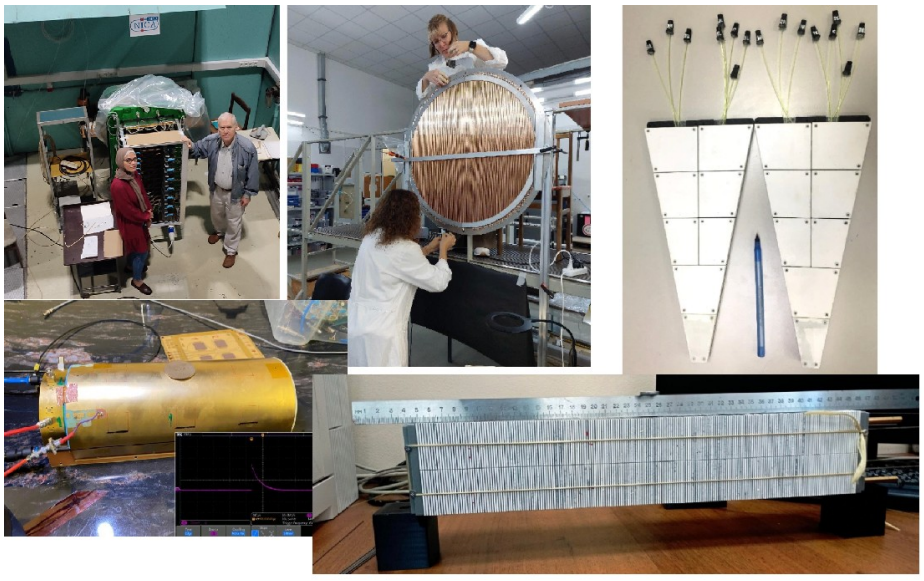
XI SPD Collaboration meeting, Tomsk State University, May 18-22, 2026

The SPD Collaboration consists of 36 institutes from 14 countries and has more than 400 participants.

Summary

- The SPD experiment is a comprehensive facility to study **polarized** and **unpolarized gluon content** of **proton** and **deuteron** at **high x** in p-p and d-d collisions with **√s up to 27 GeV**. The detector is optimized for three complementary probes: charmonia production, prompt photons, and D-meson production.
- SPD can contribute to:
  - gluon TMD (Sivers and Boer-Mulders)
  - gluon helicity PDF
  - gluon transversity in deuteron
  - unpolarized gluon PDFs of proton and deuteron
  - …
- The SPD physics program also covers large variety of different aspects of QCD during the initial and final stages of the experiment.
- The SPD Collaboration is active and growing.
- The physical program of SPD experiment with respect to nucleon gluon content is complementary to those of experiments at RHIC, EIC, and proposed fixed target program at LHC (AFTER, LHC-Spin) and EicC.

spd.jinr.ru



Thank you!