

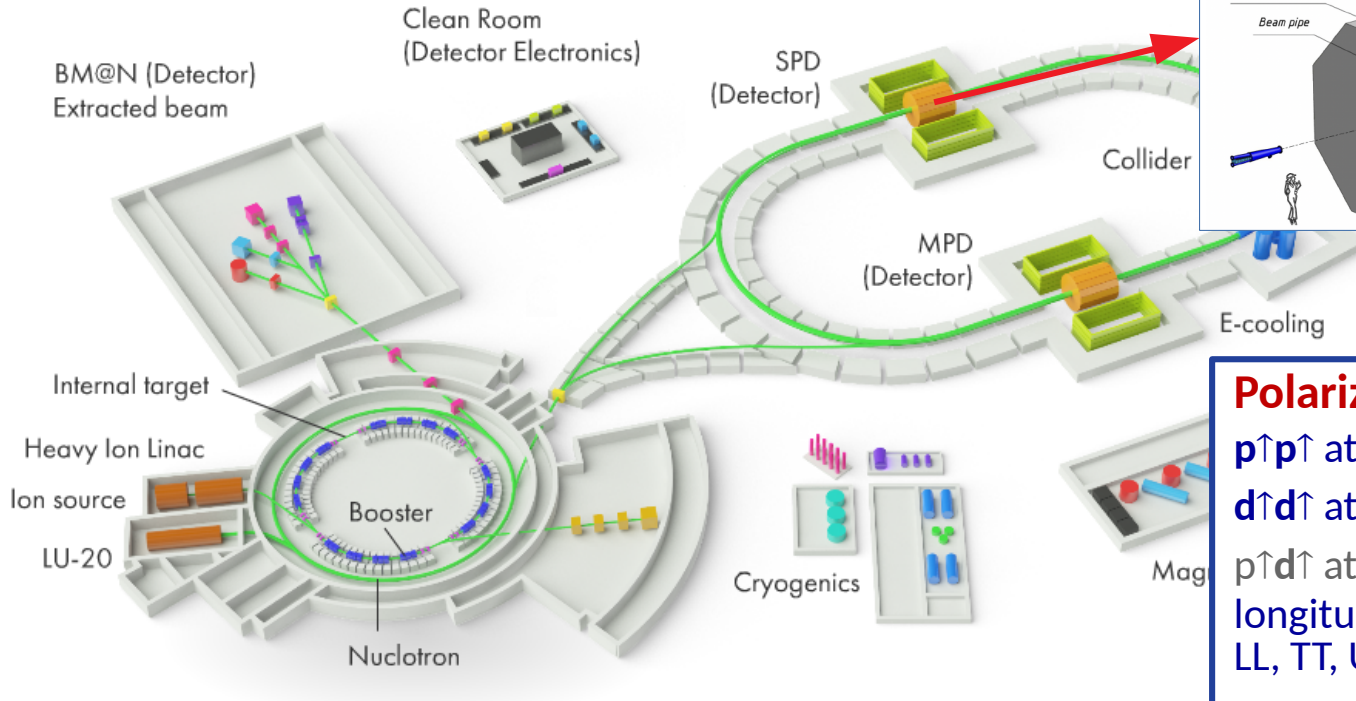
# SPD experiment at JINR

Igor Denisenko  
(on behalf of the SPD Collaboration)  
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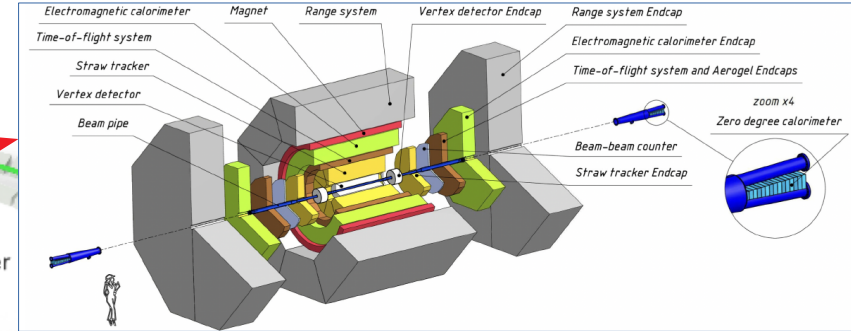
XXI Lomonosov Conference on Elementary Particle Physics  
24-30 August 2023

# Nuclotron-based Ion Collider Facility (NICA)

**Joint Institute for Nuclear Research (Dubna)**



## Spin Physics Detector (SPD)



### Polarized beams

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

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

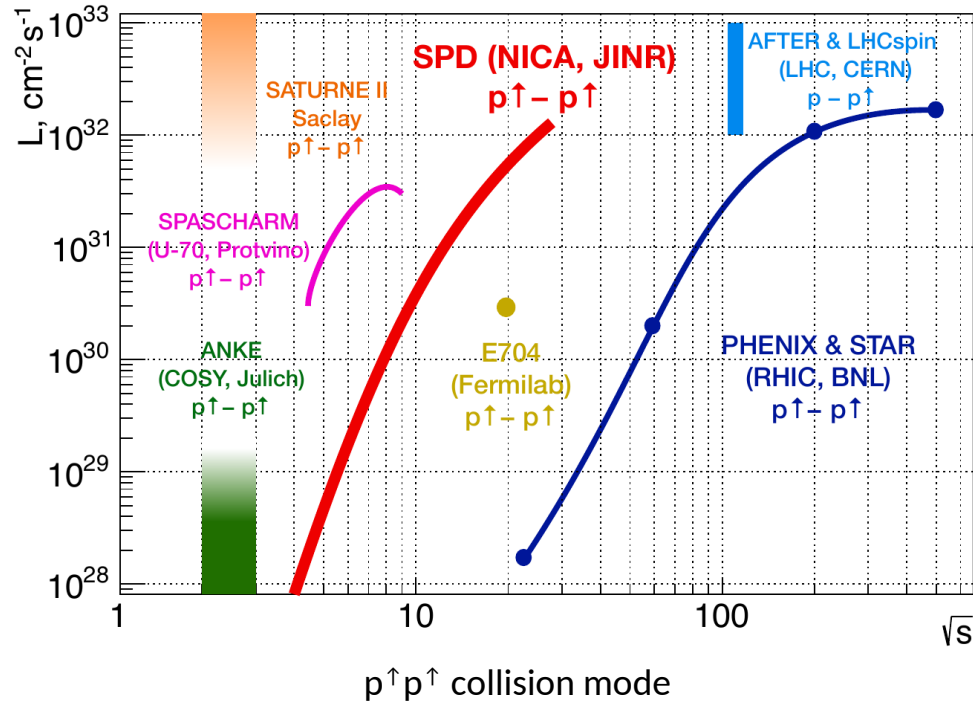
$p\uparrow d\uparrow$  at  $\sqrt{s_{NN}} \leq 19 \text{ GeV}$

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

Operation: after 2028

# NICA and other facilities

SPD CDR (arXiv:2102.00442)



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	$p^\uparrow - p^\uparrow$ $d^\uparrow - d^\uparrow$ $p^\uparrow - d$ , $p - d^\uparrow$	$p^\uparrow - p^\uparrow$	$e^\uparrow - p^\uparrow$ , $d^\uparrow$ , ${}^3\text{He}^\uparrow$	$p - p^\uparrow$ , $d^\uparrow$	$p - p^\uparrow$
Center-of-mass energy $\sqrt{s_{NN}}$ , GeV	$\leq 27$ ( $p-p$ ) $\leq 13.5$ ( $d-d$ ) $\leq 19$ ( $p-d$ )	63, 200, 500	20-140 ( $ep$ )	115	115
Max. luminosity, $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$	$\sim 1$ ( $p-p$ ) $\sim 0.1$ ( $d-d$ )	2	1000	up to $\sim 10$ ( $p-p$ )	4.7
Physics run	>2025	running	>2030	>2025	>2025

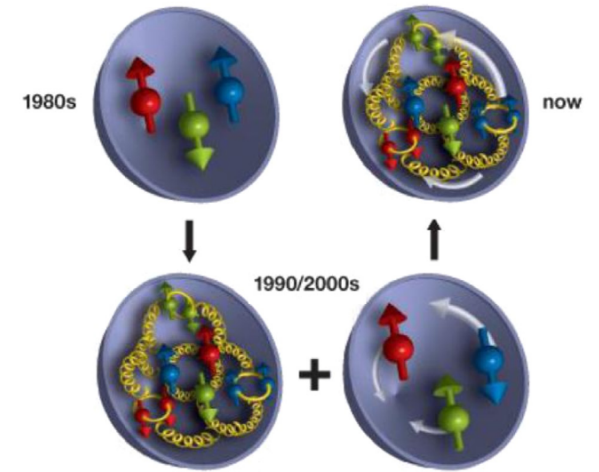
NICA is unique for double polarized  $d^\uparrow d^\uparrow$  collisions at these energies.

# Nucleon structure

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

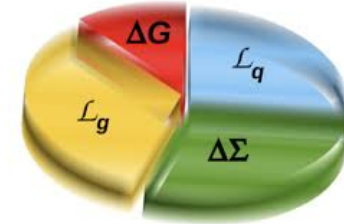
Nucleon tomography aims to understand how hadrons are built in terms of elementary degrees of freedom in QCD.

- 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

■ Gluon Spin    ■ Gluon angular momentum  
■ Quark Spin    ■ Quark Angular Momentum



Spin decomposition of proton



# Nucleon tomography

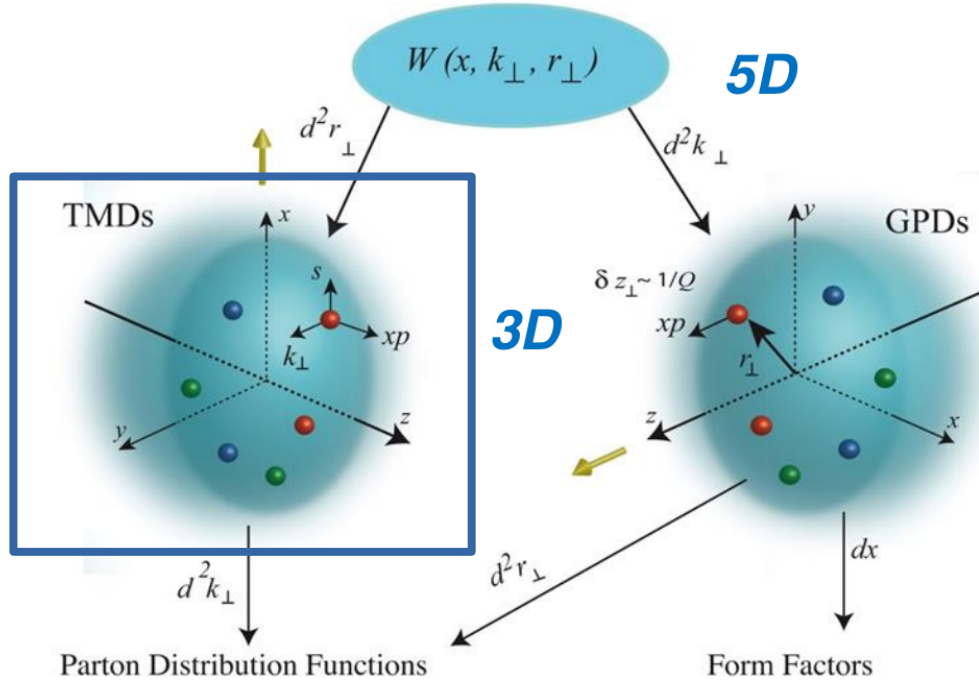


Figure credit: J.-P. Cheng

- **Significant progress on quark TMDs** over the last decades (for details see e.g. TMD Handbook, arxiv:2304.03302).
- **Our knowledge on gluon TMD remains rather scarce.**

		gluon pol.	
		$U$	linear
nucleon pol.	$U$	$f_1^g$	$h_1^{+g}$
	$L$		$g_1^g$
	$T$	$f_{1T}^{+g}$	$g_{1T}^g$

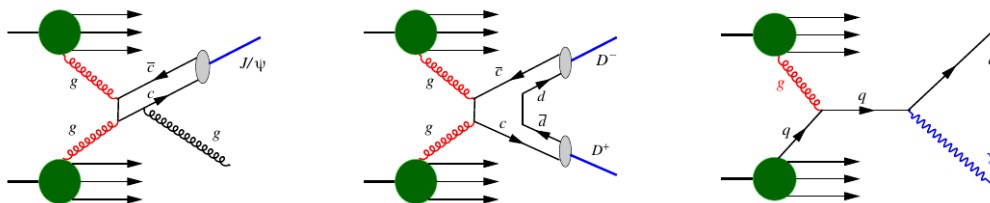
Leading twist gluon TMD PDFs  
(two times more due to gauge links)

# SPD experiment



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 and mass crises.
- Many other aspects of QCD to be studied in such collisions.

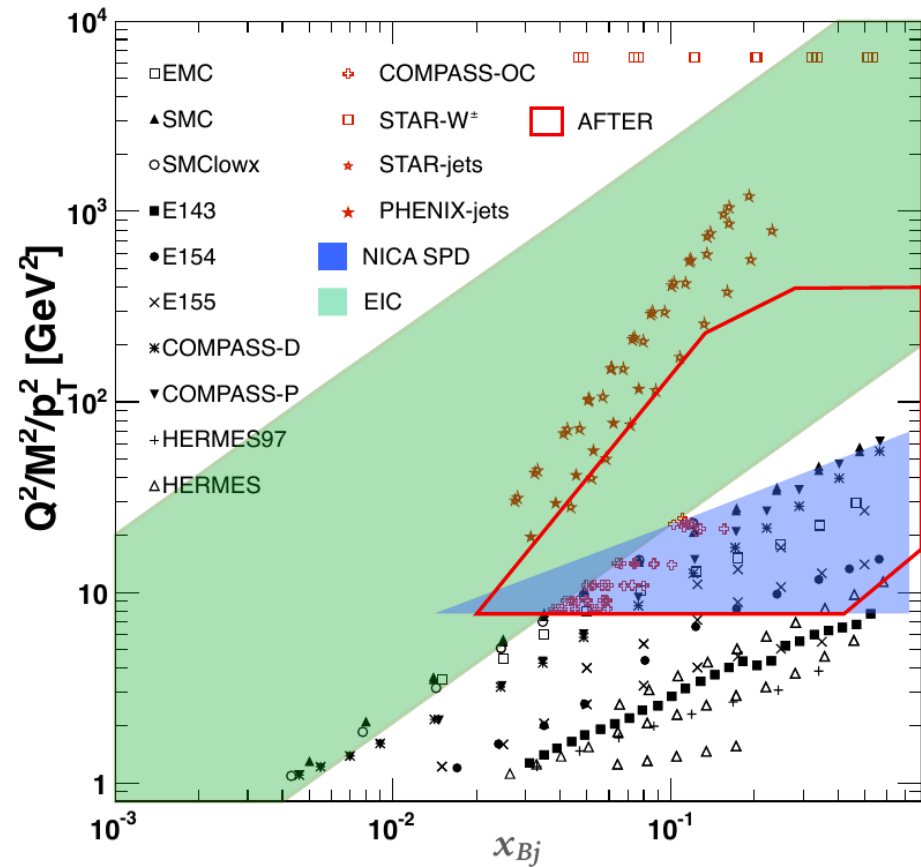
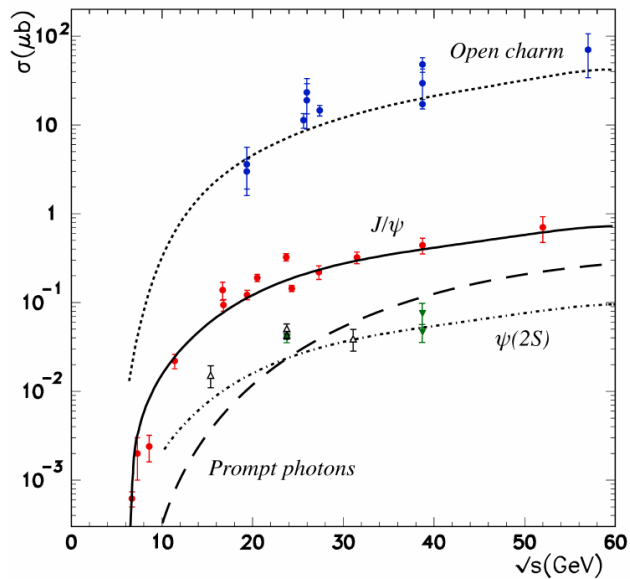
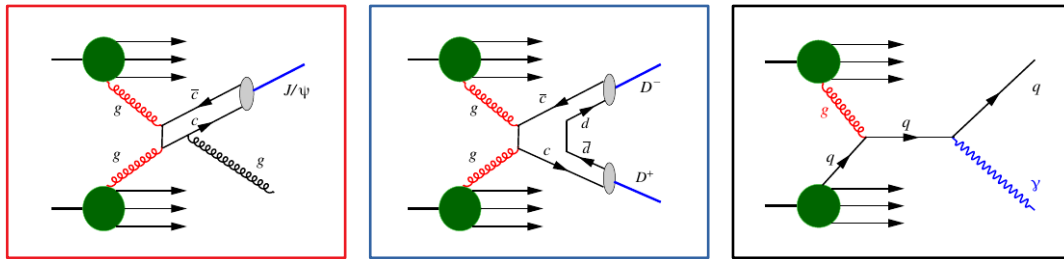
gluon pol.

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 gauge links)

# SPD kinematic coverage

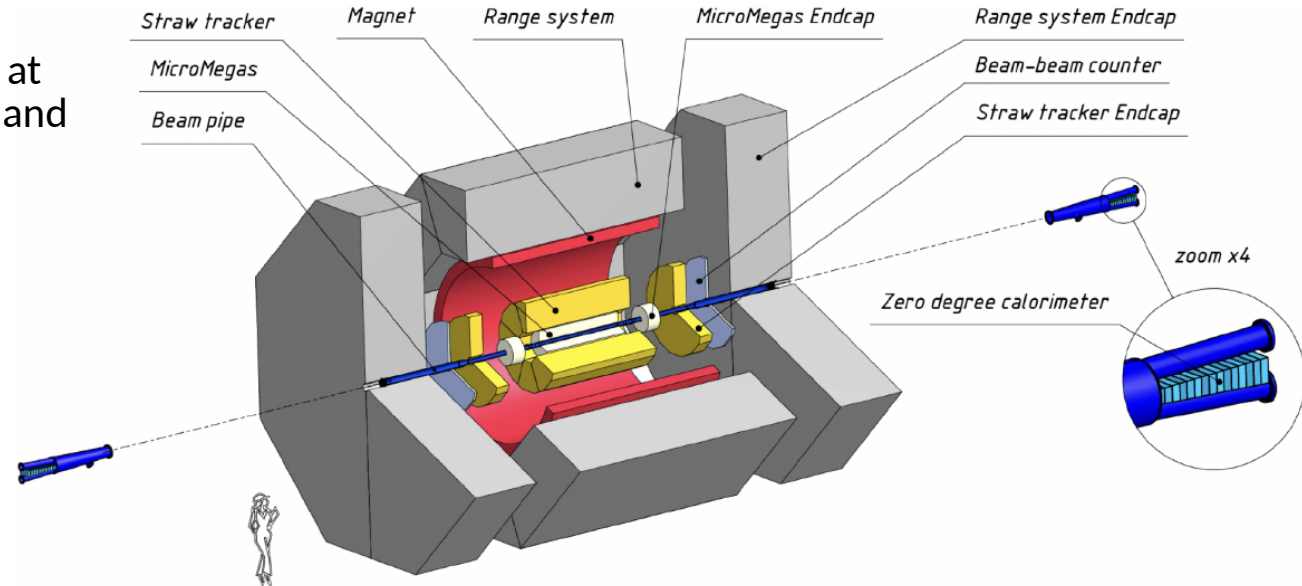


# SPD initial stage

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

- Polarized and unpolarized phenomena at **low energies** ( $3.4 \text{ GeV} < \sqrt{s_{NN}} < 10 \text{ GeV}$ ) 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

## Straw tracker:

- $\sigma \sim 150 \mu\text{m}$
- $\sigma(dE/dx) = 8.5 \%$

## Micromegas central tracker:

$\sigma \sim 150 \mu\text{m}$

**BBC** and **ZDC** for online polarimetry

## Physical program:

- spin effects in p-p, p-d, and d-d elastic scattering
- spin effects in hyperon production
- multiquark correlations (SRC)
- dibaryon resonances
- physics of light and intermediate nuclei collisions
- hypernuclei
- open charm and charmonia production near threshold
- large pT hadron production to study diquark structure of proton
- antiproton production measurements for astrophysics and BSM search
- ...

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

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

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<sup>g</sup> Petersburg Nuclear Physics Institute, NRC KI, Gatchina, Russia

<sup>h</sup> St. Petersburg Polytechnic University, St. Peterburg, Russia

<sup>i</sup> Sukhoi State Technical University of Gomel, Gomel, 246746 Belarus

<sup>j</sup> Budker Institute of Nuclear Physics of SB RAS, Novosibirsk, 630000 Russia

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

# SPD final layout

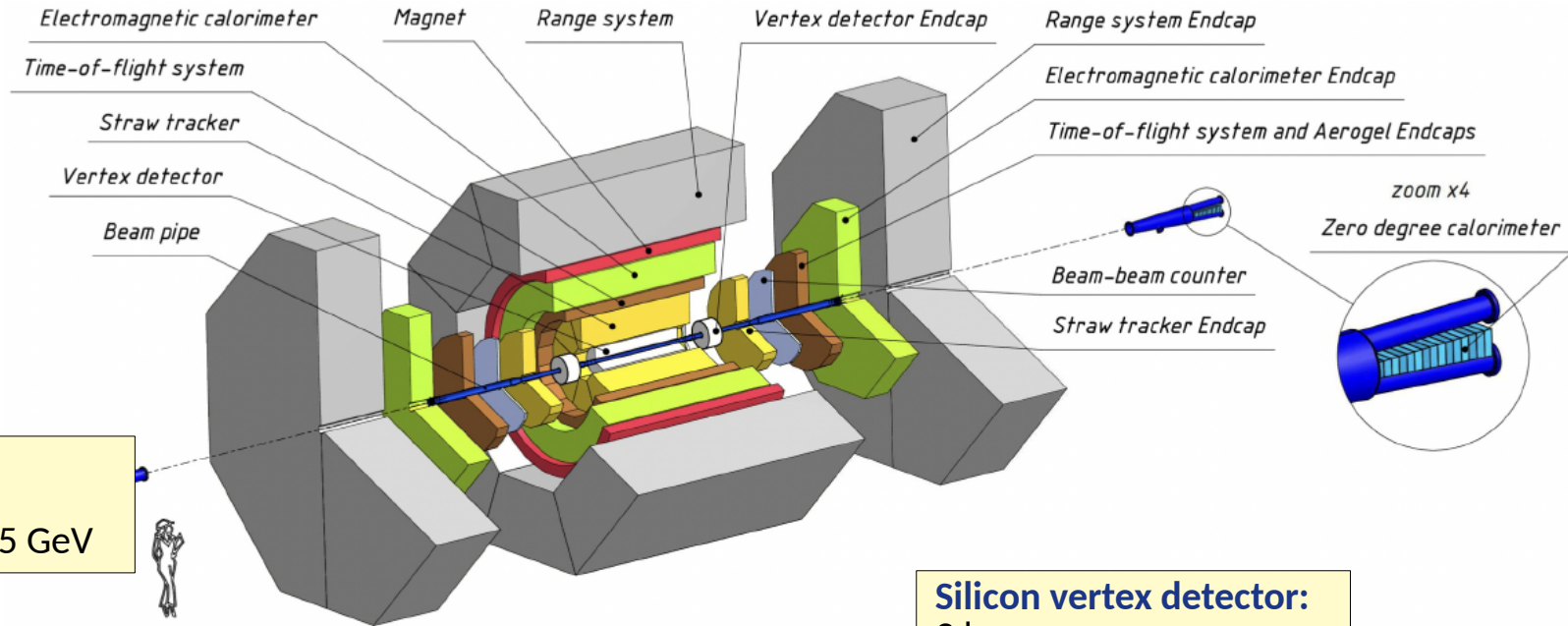
SPD TDR can be found at <http://spd.jinr.ru/spd-cdr/>

**Electromagnetic calorimeter:**  
 $\sigma E/E = 5\%/\sqrt{E} \oplus 1\%$

**Time of flight system:**  
 $\sigma = 50$  ps  
 $3\sigma$   $\pi/K$  separation for  $p < 1.5$  GeV

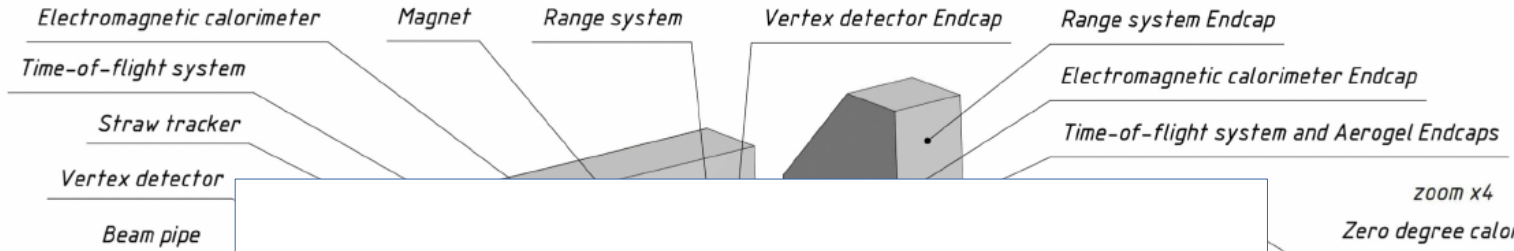
**Threshold aerogel counters in endcaps for pion kaon separation in the range**  
 $1.0 \text{ GeV} < p < 2.5 \text{ GeV}$

**Silicon vertex detector:**  
3 layers  
• MAPS:  $\sigma = 25 \mu\text{m}$   
• DSSD:  $\sigma_\phi = 27.4 \mu\text{m}$ ,  
 $\sigma_z = 81.3 \mu\text{m}$



# SPD final layout

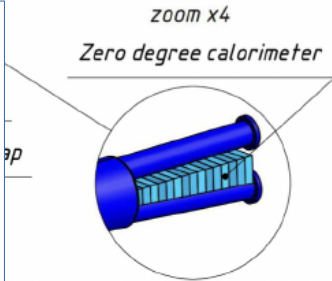
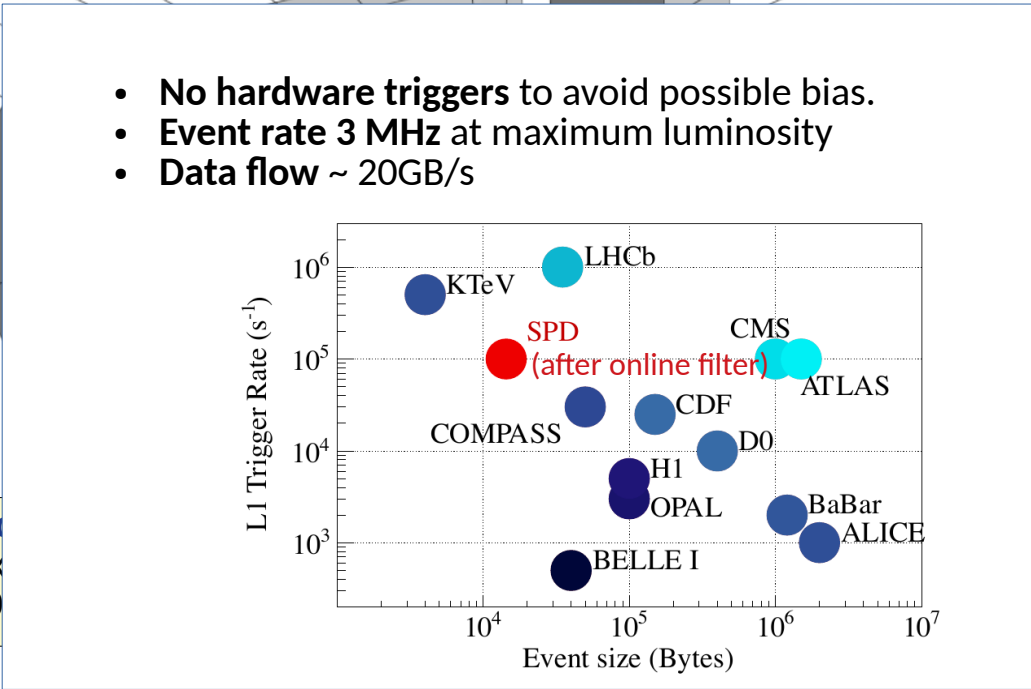
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**Electromagnetic calorimeter:**  
 $\sigma E/E = 5\%/\sqrt{E} \oplus 1\%$

**Time of flight system:**  
 $\sigma = 50 \text{ ps}$   
 $3\sigma \pi/K$  separation for  $p < 1.5 \text{ GeV}$

**Threshold**  
 for pion k  
 range 1.0



tor:  
 $\mu\text{m},$   
 $\mu\text{m}$



## Physical program:

- unpolarized and polarized proton and deuteron structure:
  - gluon helicity
  - 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
- ...



Progress in Particle and Nuclear Physics

Volume 119, July 2021, 103858



Review

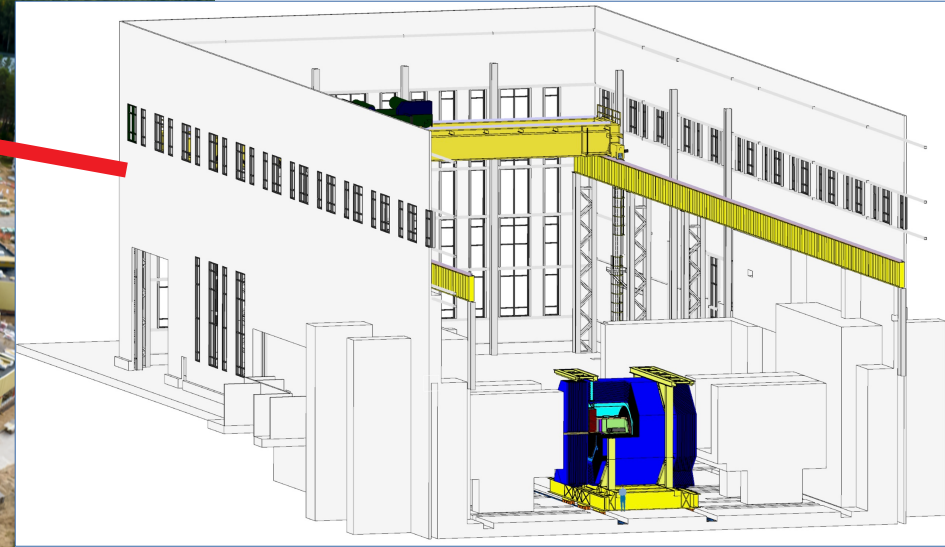
## On the physics potential to study the gluon content of proton and deuteron at NICA SPD

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

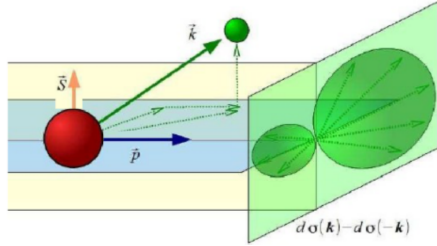


# Construction site

2021

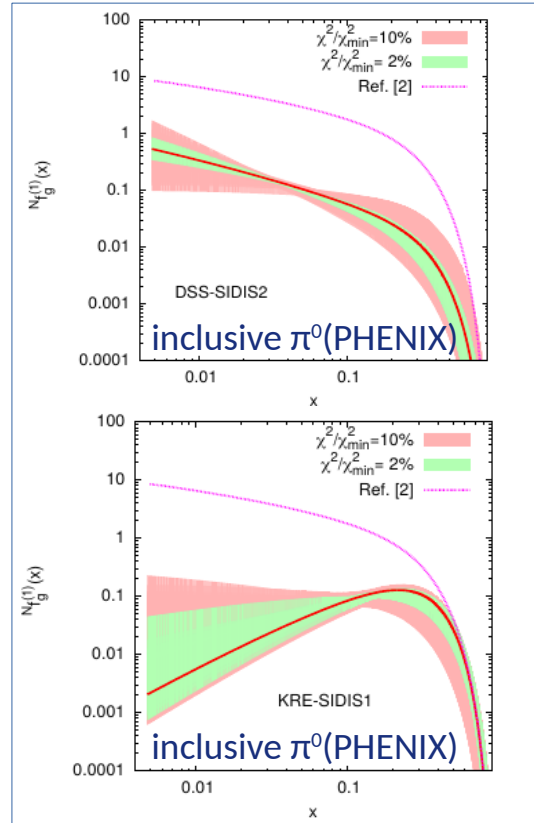


# Gluon Sivers function

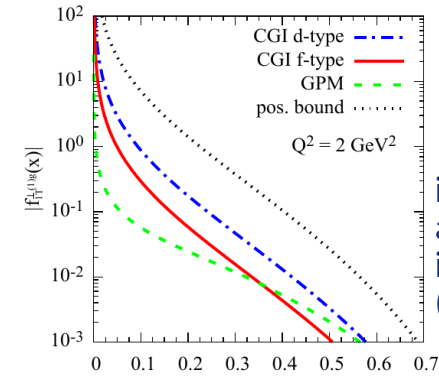


- GSF – correlation between transverse spin and gluon  $k_T$
- Poorly known, extracted in GPM, CGI-GPM and very recently TMD approaches (spectator model)
- Probed by TSSA

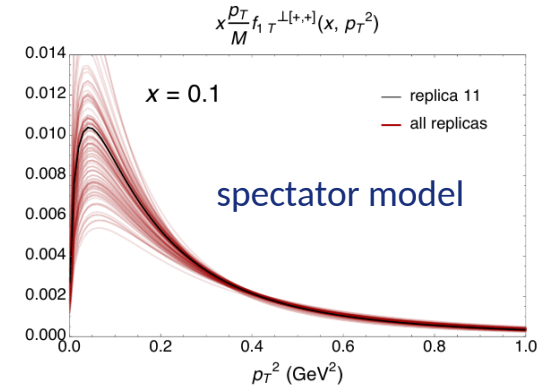
$$\sigma(\phi) \propto 1 + P \cdot A_N \sin(\phi_{\text{pol}} - \phi)$$



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

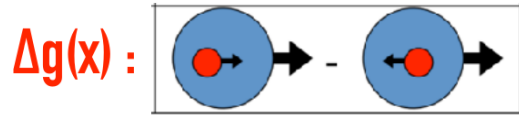


Maximized first kT moments for GSF, CGI-GPM (PRD99, 036013 (2019))

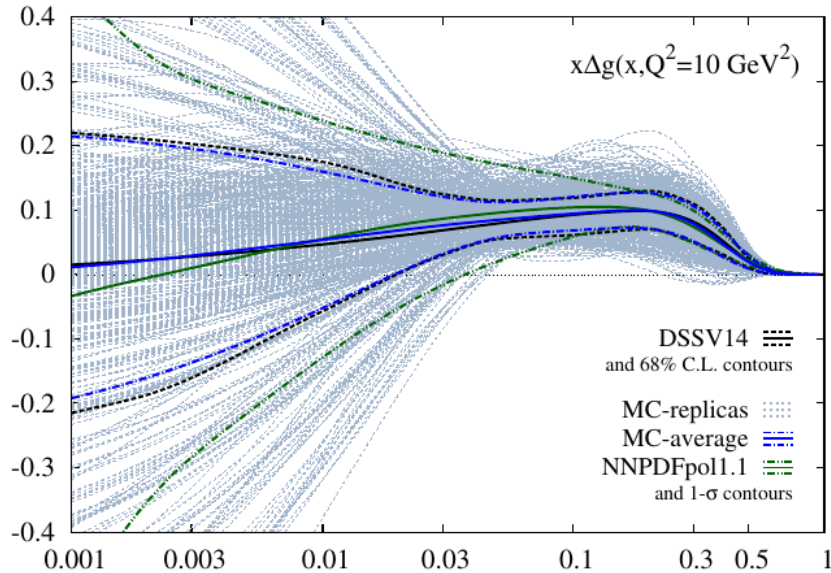


$p_T$ -dependence for f-type Sivers TMD in the **spectator model**, Bacchetta, Celiberto, Radici, 2022

# Gluon helicity distribution

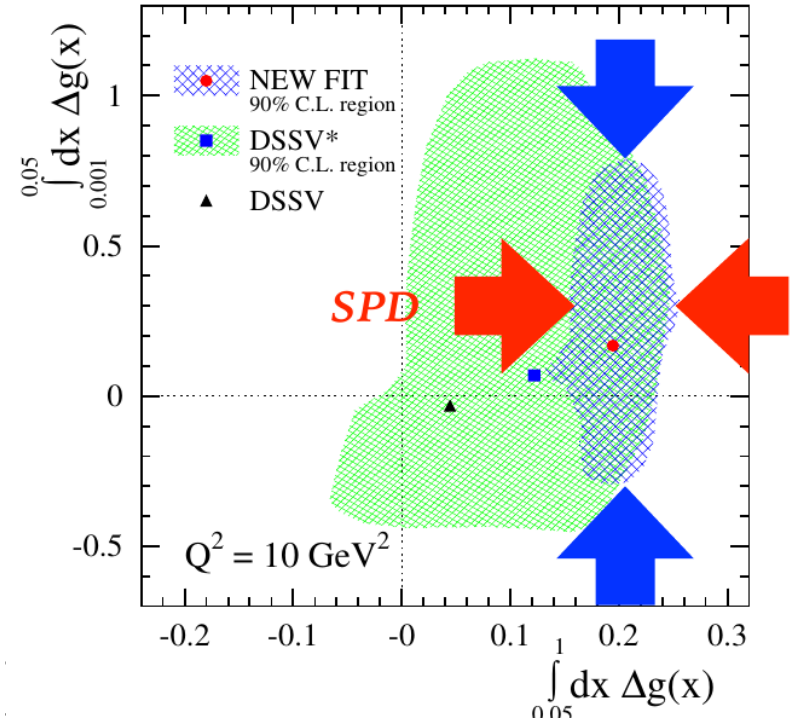


$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$



Phys. Rev. D 100, 114027 (2019)

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



Other extractions: LSS15, JAM17

# Charmonia production as a probe of gluon TMD PDFs

## Charmonia production

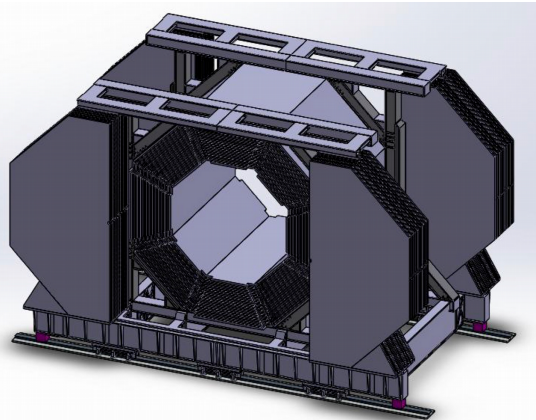
- dominated by gluon-gluon fusion
- high cross-section
- $J/\psi$  can be easily reconstructed from the  $\mu^+\mu^-$  decay,  $\psi(2S)$  and  $\chi_{cJ}$  can be reconstructed based on this decay
- hadronization of  $c\bar{c}$  pair is not well understood theoretically:
  - (Improved) Color Evaporation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

## Charmonia production at SPD

- High statistics: 12 million inclusive  $J/\psi(\rightarrow\mu^+\mu^-)$  events per year
- Wide kinematic coverage
- Ability to measure also production properties of  $\psi(2S)$ ,  $\chi_{c1}$  and  $\chi_{c2}$
- 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  $\rightarrow$  shape functions (Echevarria, 2019)



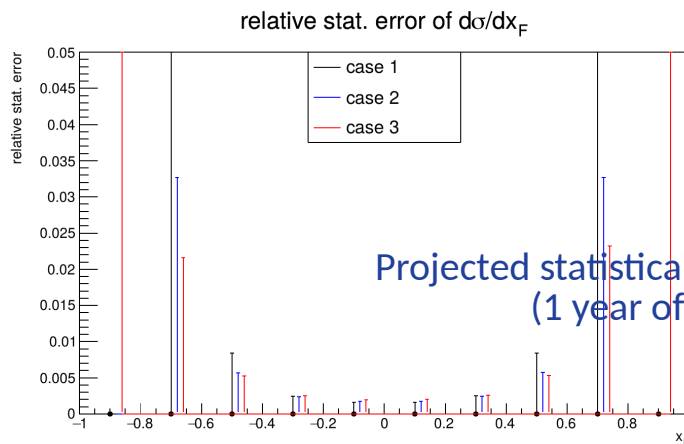
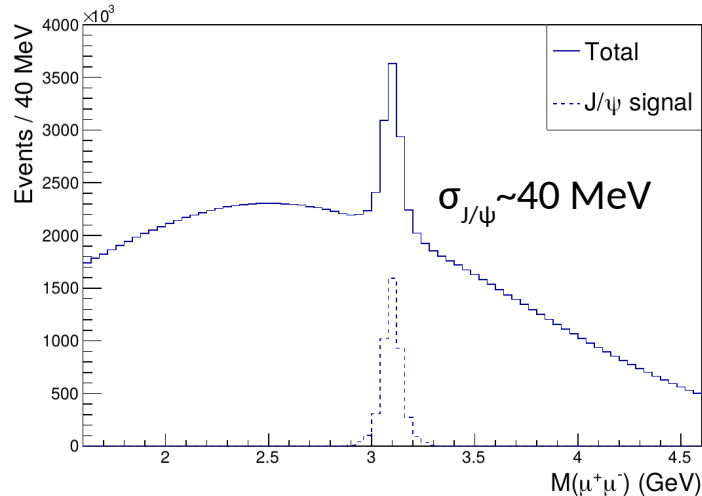
# Inclusive $J/\psi$ measurements



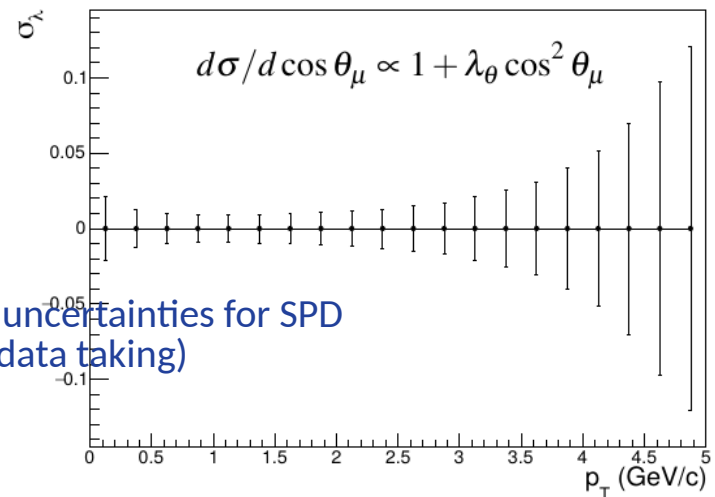
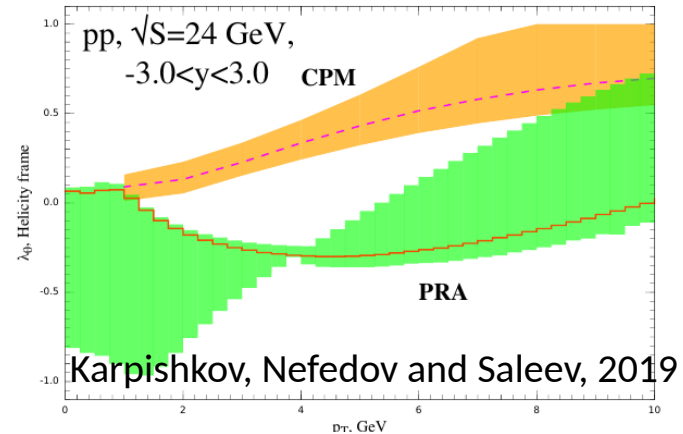
- Reconstruction efficiency:  $\sim 40\%$
- Statistics:  $\sim 4.5\text{--}5.0$  M (selected events) per year
- Large background due to pion decays and muon misidentification in RS

## Observables:

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

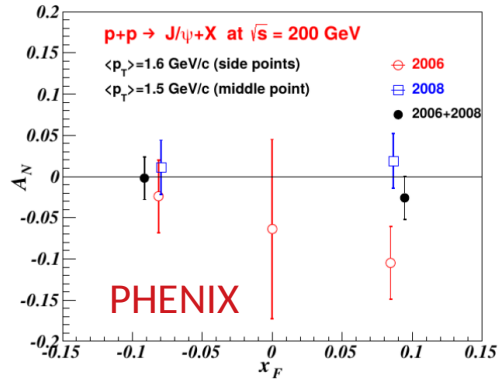


Projected statistical uncertainties for SPD  
(1 year of data taking)



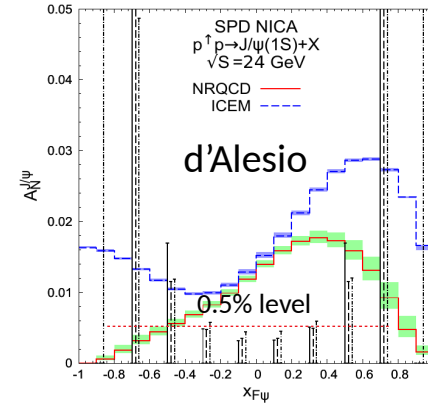
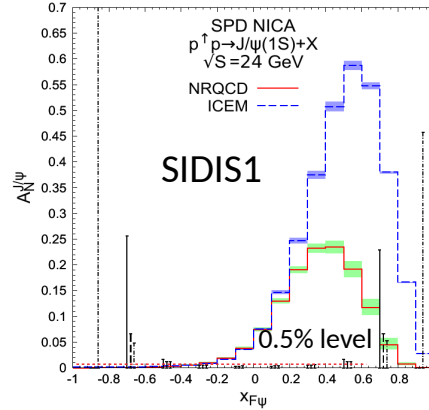
# $A_N$ for inclusive $J/\psi$ production

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

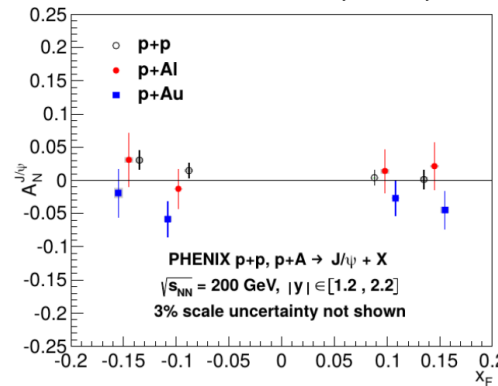


GPM

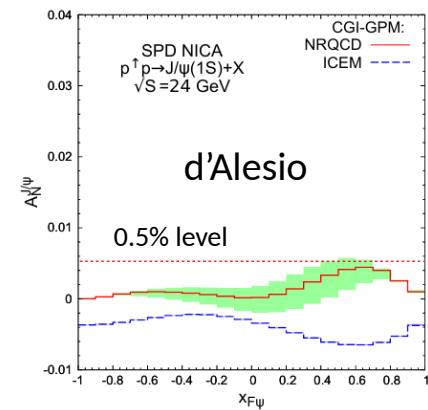
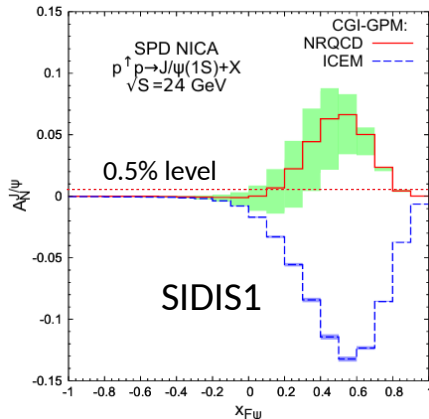
Projected stat. uncertainties and predictions from PRD104, 016008 (2021)



PRD82, 112008 (2010)



CGI-GPM



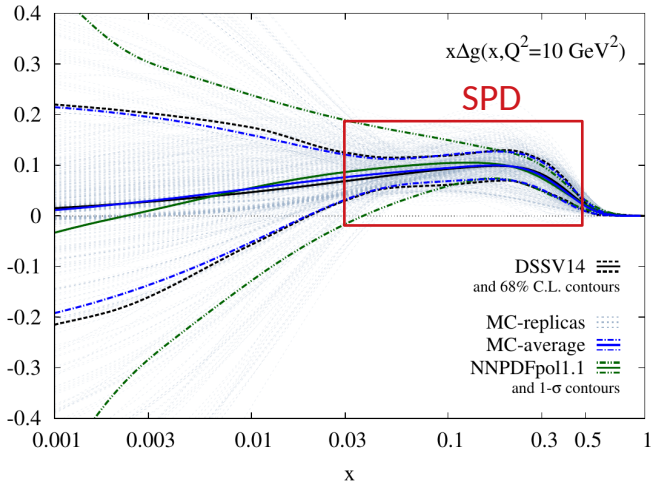
PRD98, 012006 (2018)

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

# $A_{LL}^{J/\psi}$ for inclusive $J/\psi$ production

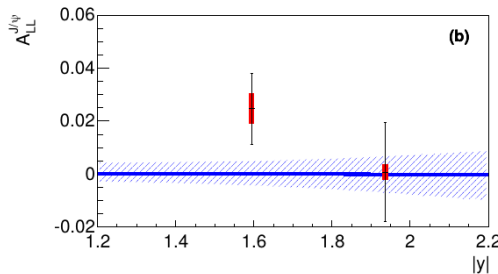
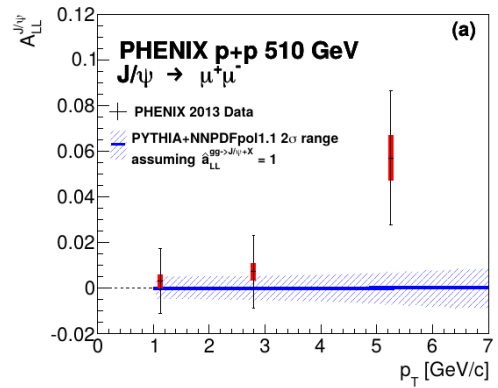
$$A_{LL}^{J/\psi} = \frac{\Delta\sigma}{\sigma} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

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



PRD100 114027 (2019)

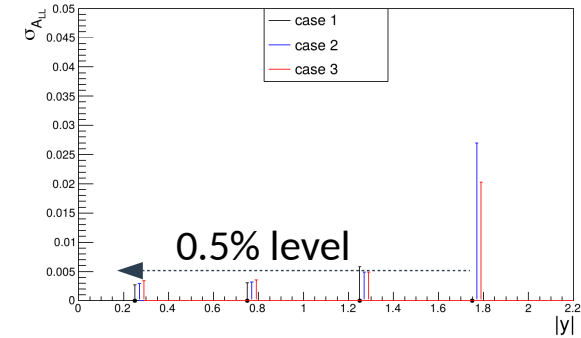
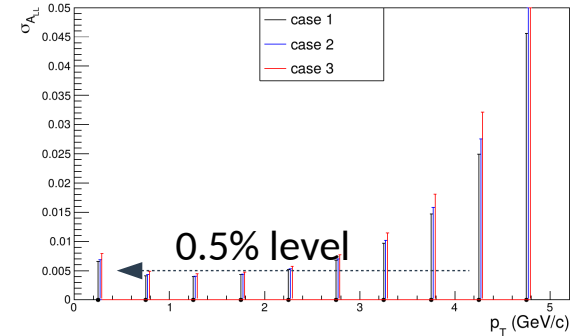
PRD94 112008 (2016)



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

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

Projected statistical uncertainties for SPD

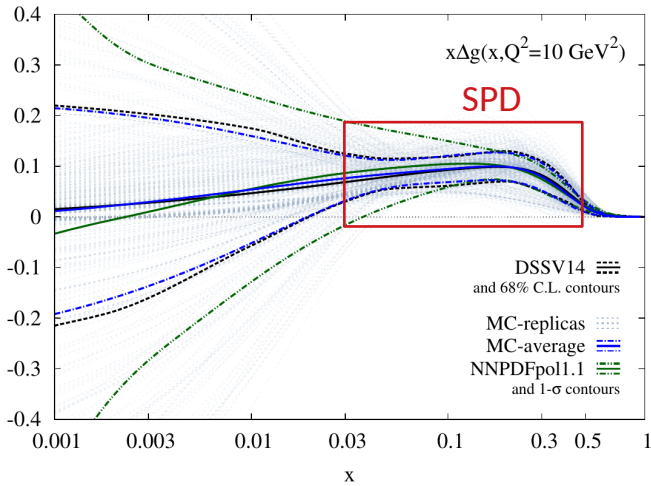


- $|y| < 2$  is covered
- At SPD both  $\Delta g(x_1)$  and  $\Delta g(x_2)$  are expected to be close to the maximum
- A measurable  $A_{LL}$  of the order of 1-10% can be expected

# $A_{LL}$ for inclusive $J/\psi$ production (impact of SPD measurements)

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

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

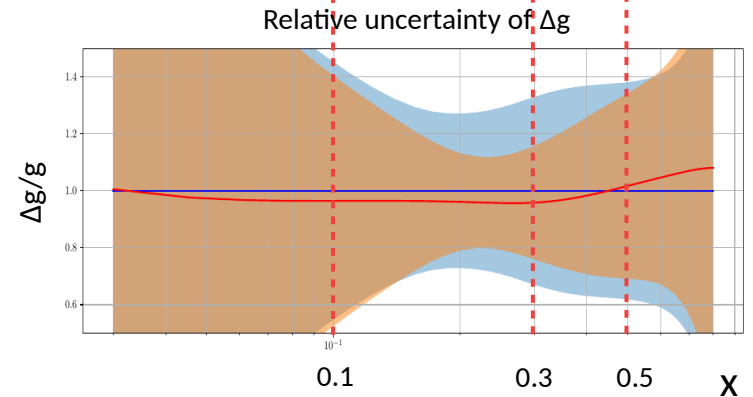
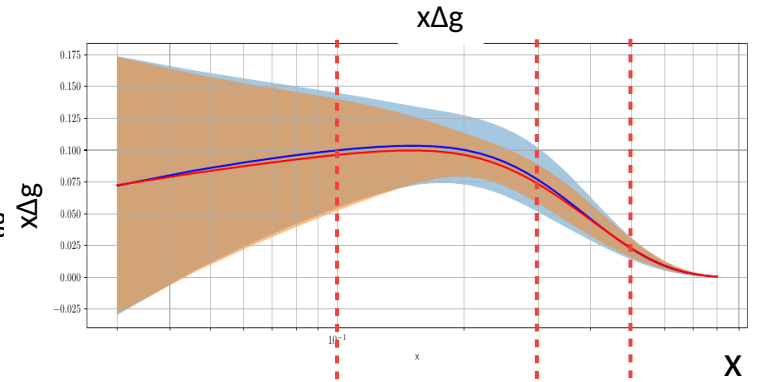


PRD100 114027 (2019)

Impact of SPD data is estimated by

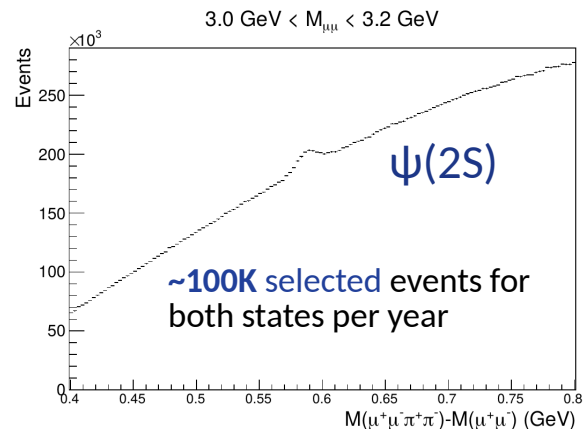
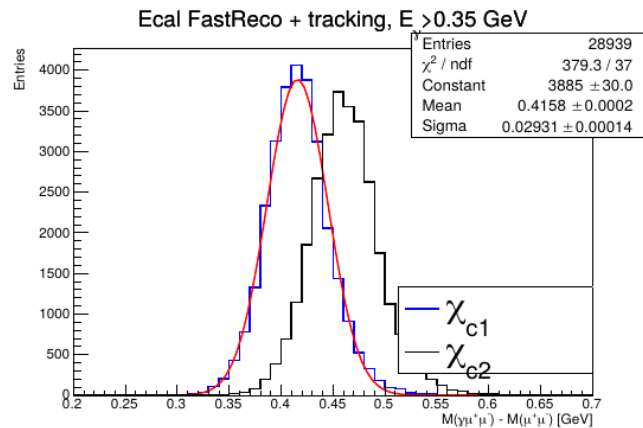
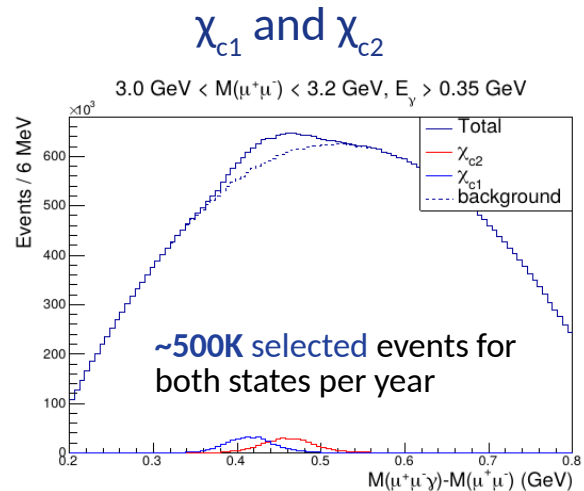
- generating “SPD data” according to [NNPDFPol1.1](#)
- prescribing **stat. errors** estimated for 1 year data taking at SPD with  $\sqrt{s} = 27$  GeV
- Bayesian reweighing of MC replicas

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



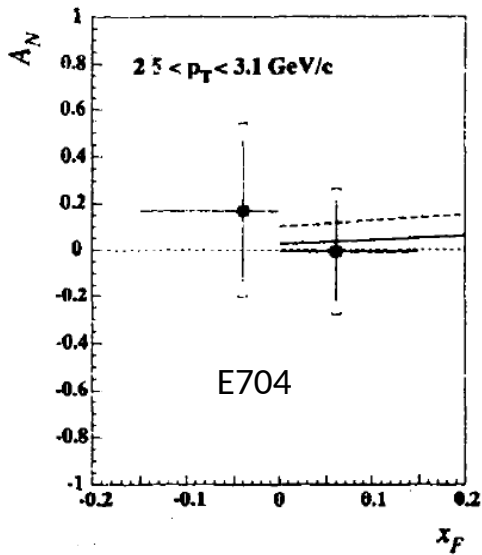


# On other measurements with charmonia



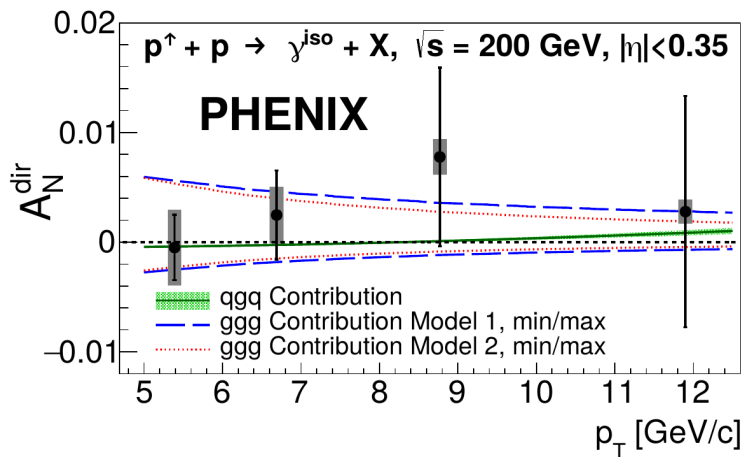
- $\eta_c \rightarrow p\bar{p}, \Lambda\bar{\Lambda}, \phi\phi?$ 
  - 500K selected events for  $\eta_c \rightarrow p\bar{p}$
  - huge background
- Double  $J/\psi$  production
  - 50-100 events/year for both  $J/\psi$  dilepton decay modes
  - $p_T$  dependence complimentary to high energy experiments
- $J/\psi\gamma$ : limited statistics and large background

# Prompt photons: $A_N$

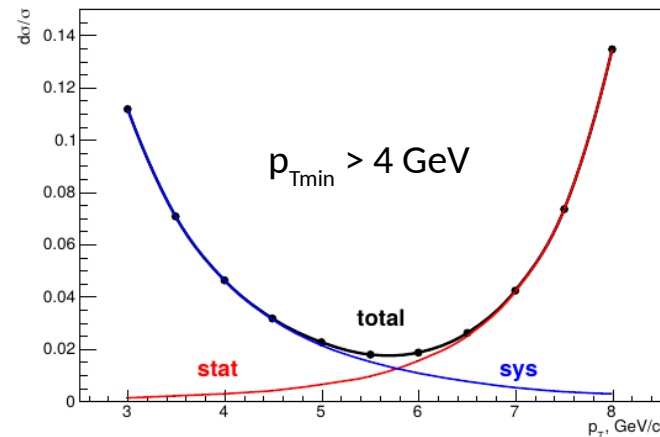


PLB345, 569 (1995)

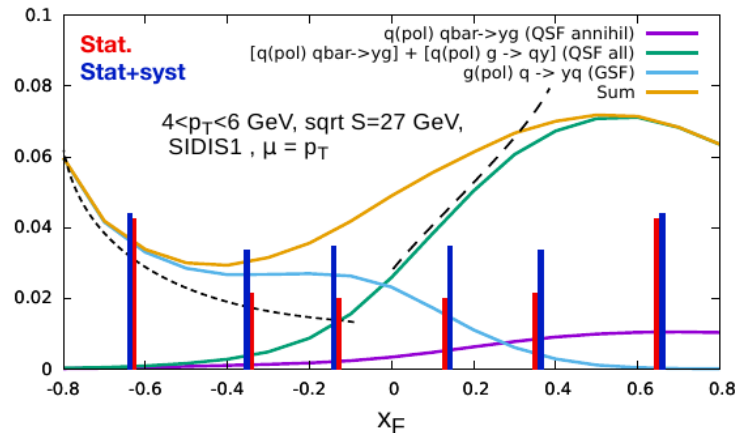
- Straightforward theoretical interpretation
- **very challenging experimentally**



Phys. Rev. Lett. 127, 162001



arXiv:2102.00442



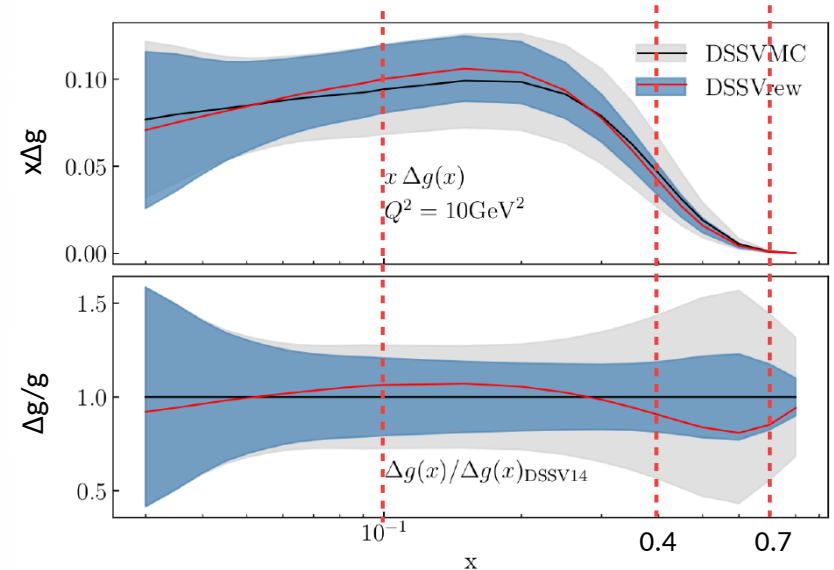
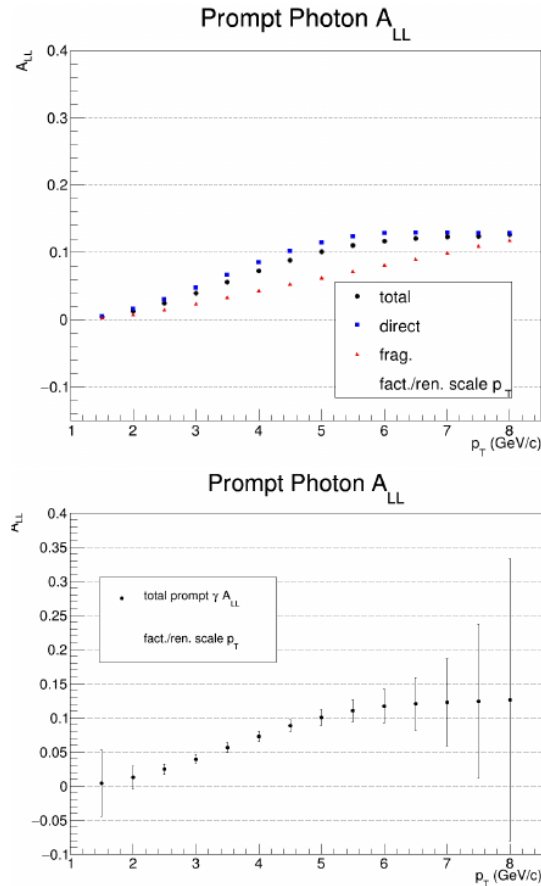
Predictions: Saleev, Shipilova, 2020

# Prompt photons: $A_{LL}^\gamma$

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

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  $\sqrt{s} = 27$  GeV
- Bayesian reweighing of MC replicas

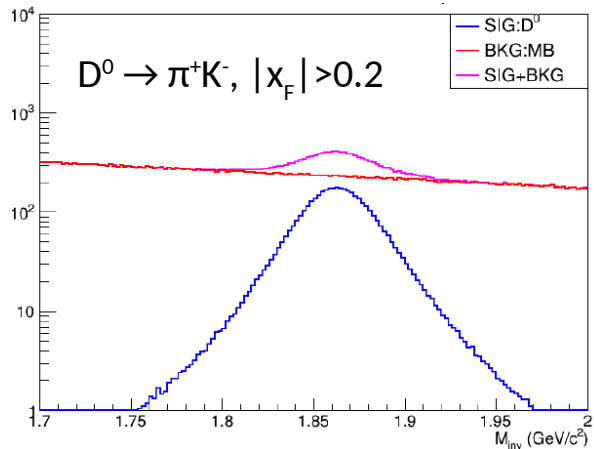
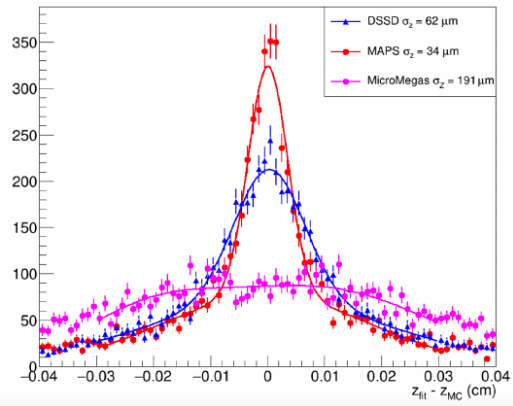


Predictions with new “data” added (top) and ratio of the uncertainties (bottom).  
Courtesy R. Sassot, I. Borsa, 2021.

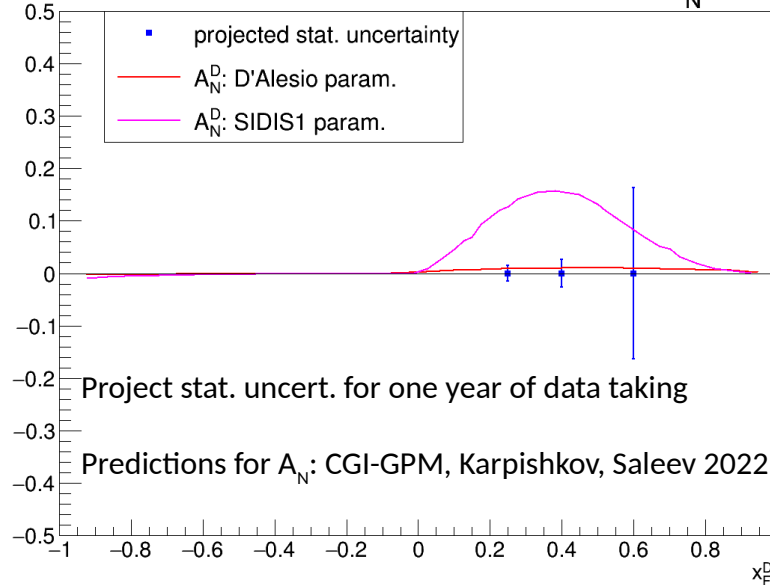
Uncertainties are reduced by factor of 2 for  $0.4 < x < 0.7$

# Measurements with D mesons

$D^0 \rightarrow \pi^+ + K^-$ : secondary vertex Z resolution



Projected Statistical Uncertainty of  $A_N^{D^0}$



- The largest production cross-section (almost two orders of magnitude larger than for  $J/\psi$ )
- 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:

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

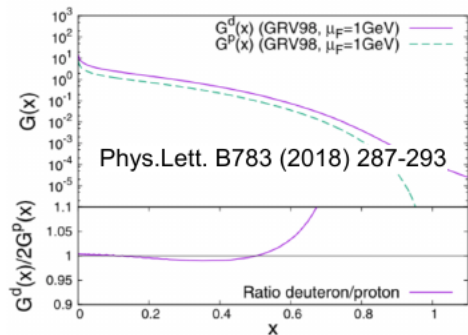
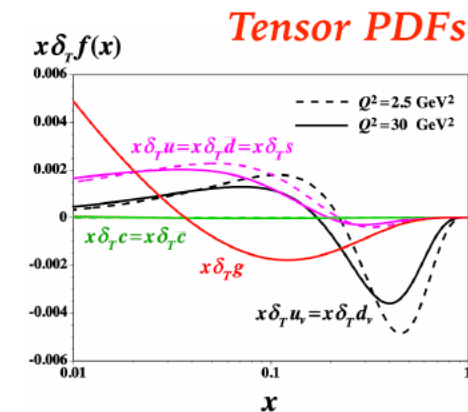
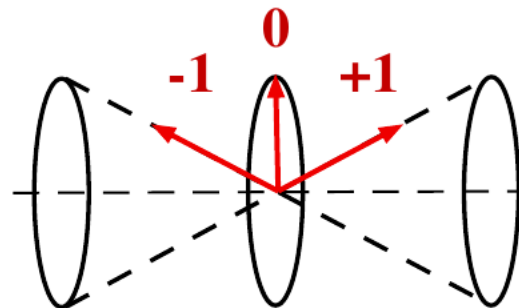
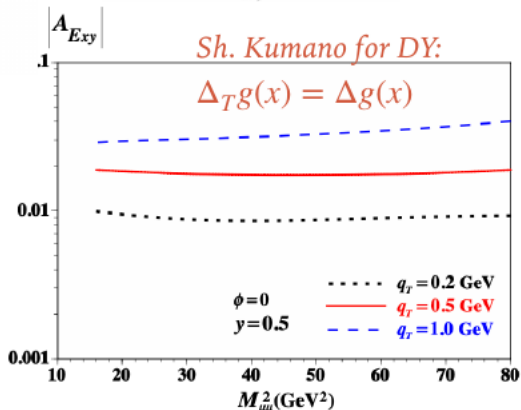
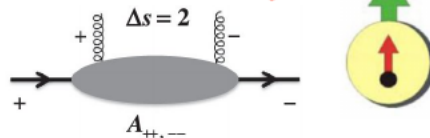


Fig. 6. Gluon PDF in the deuteron and in the nucleon.

Unpolarized  
gluons at high  $x$ :

Gluon transversity



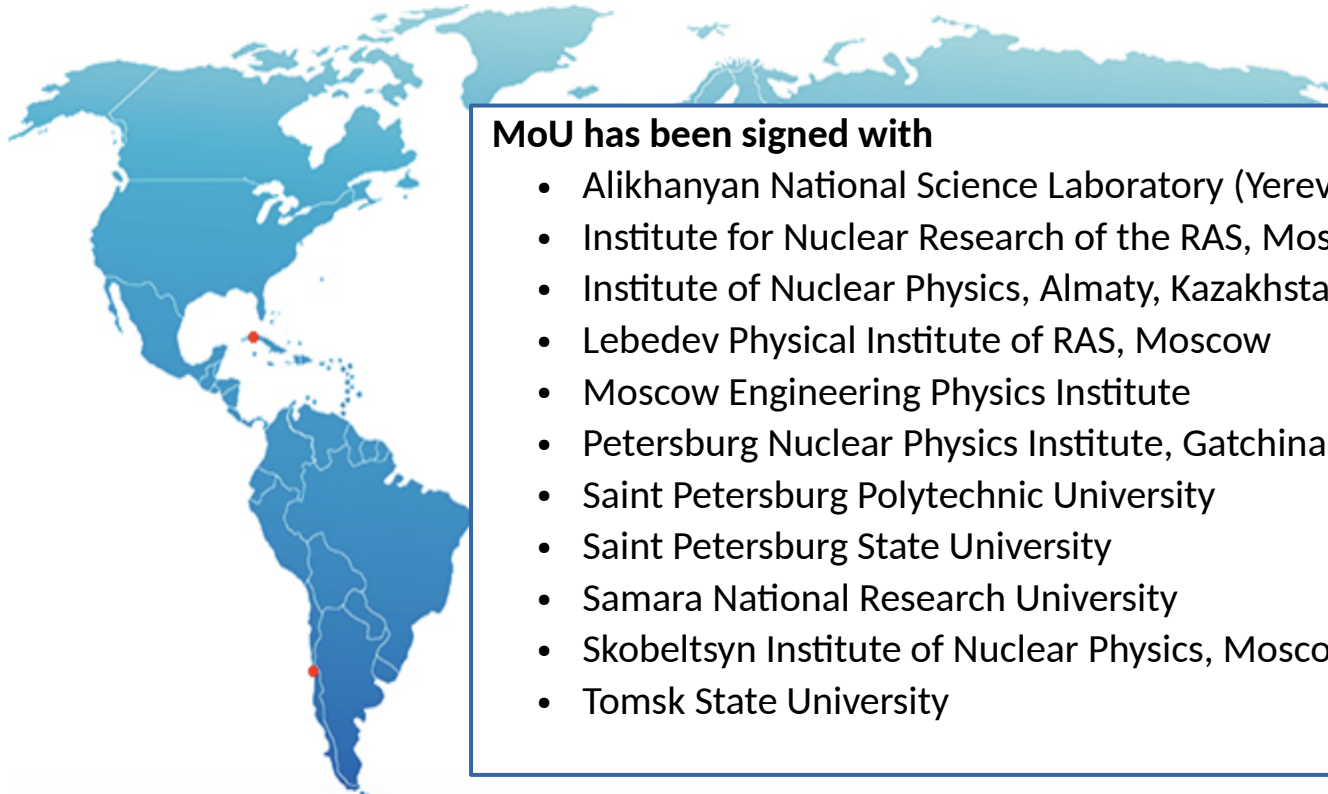
# Running strategy

Physics goal	Required time	Experimental conditions
First stage		
Spin effects in $p$ - $p$ scattering dibaryon resonances	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 deconfinement, $\bar{p}$ 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 polarized" PDFs	1 year	$d_{tensor}$ - $d_{tensor}$ , $\sqrt{s_{NN}} = 13.5$ GeV or/and $d_{tensor}$ - $p_T$ , $\sqrt{s_{NN}} = 19$ GeV

# SPD Collaboration



SPD Collaboration now consists of more than 300 scientists from many countries.



## 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

SPD Collaboration now consists of more than 300 scientists from many countries.



# SPD project timeline and tentative operating plan

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

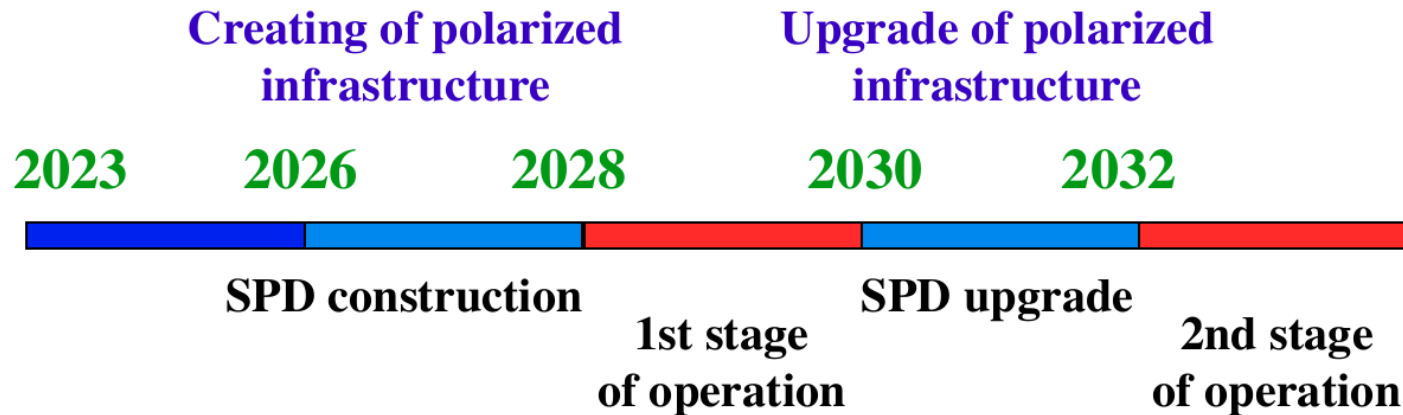
**2014:** SPD Lol approved by JINR PAC

**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.**



# 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  **$\sqrt{s}$  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
  - unpolarized gluon PDFs of proton and deuteron
  - gluon transversity in deuteron
  - ...
- Apart from that, the SPD physics program covers large variety of different aspects of QCD during the initial and final stages of the experiment.
- 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).