SPD experiment at JINR

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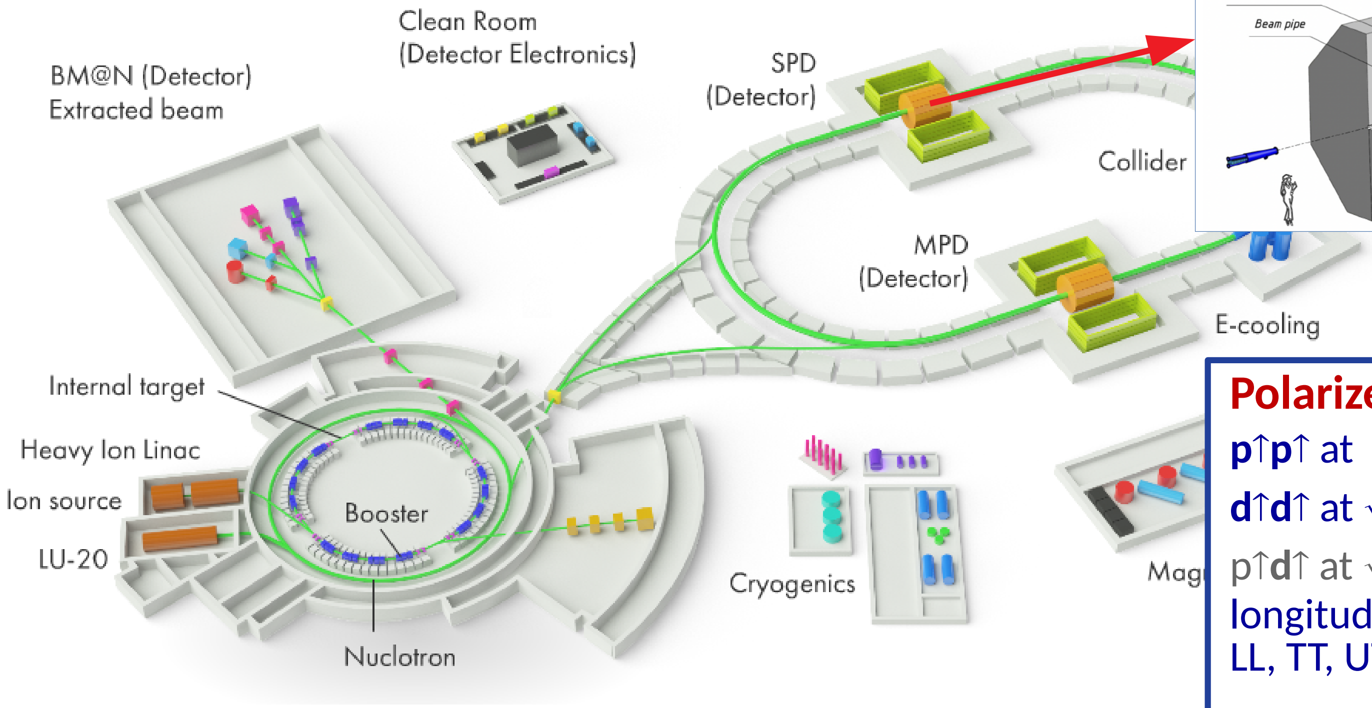
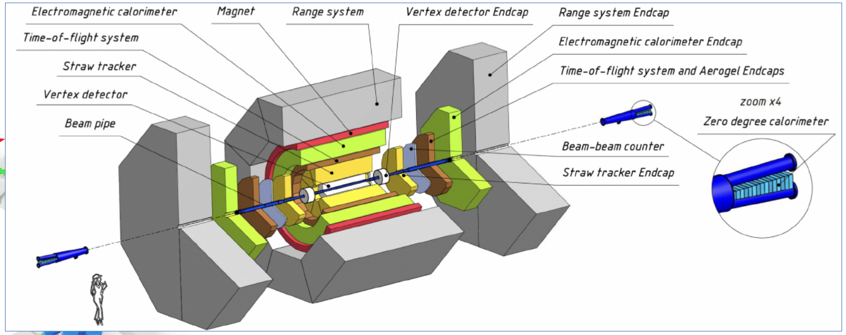
XXI Lomonosov Conference on Elementary Particle Physics
24-30 August 2023

Nuclotron-based Ion Collider fAcility (NICA)

Joint Institute for Nuclear Research (Dubna)



Spin Physics Detector (SPD)



Polarized beams

p↑p↑ at $\sqrt{s_{pp}}$ ≤ **27 GeV, L_{av} ≈ 10^{32} cm^{-2}s^{-1}**

d↑d↑ at $\sqrt{s_{NN}}$ ≤ **13.5 GeV**

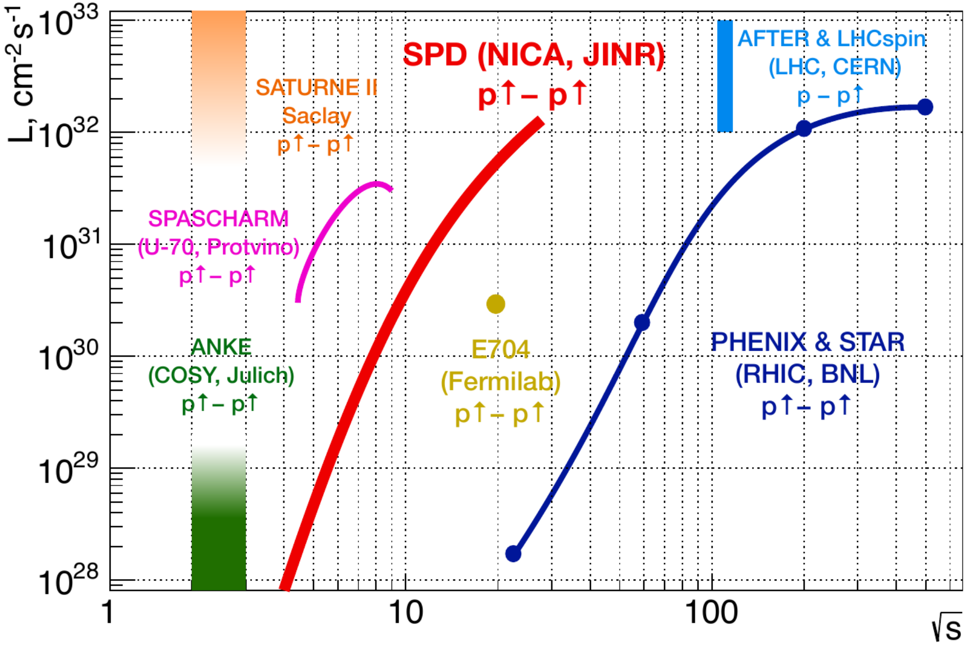
p↑**d**↑ at $\sqrt{s_{NN}}$ ≤ **19 GeV**

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

Operation: after **2028**

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.

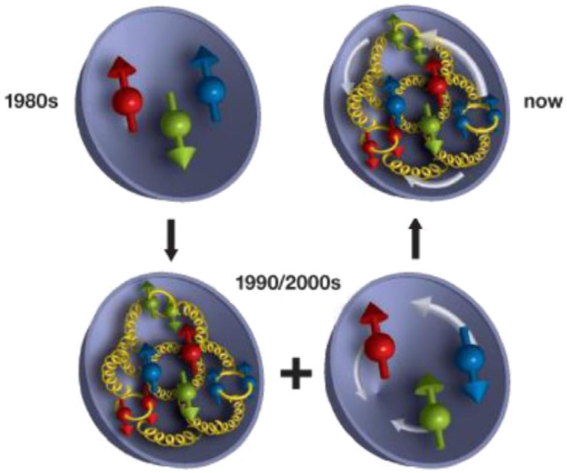
Nucleon structure

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

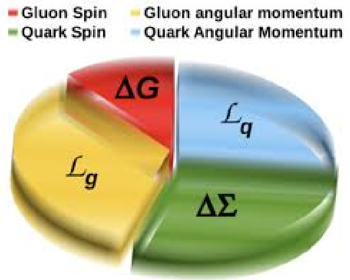
Nucleon tomography aims to understand how hadrons are build in terms of elementary degrees of freedom in QCD.

- 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 see quarks and gluons?



Our understanding of nucleon structure



Spin decomposition of proton

Figure credit: Physics Reports 911, 2021, 1

Nucleon tomography

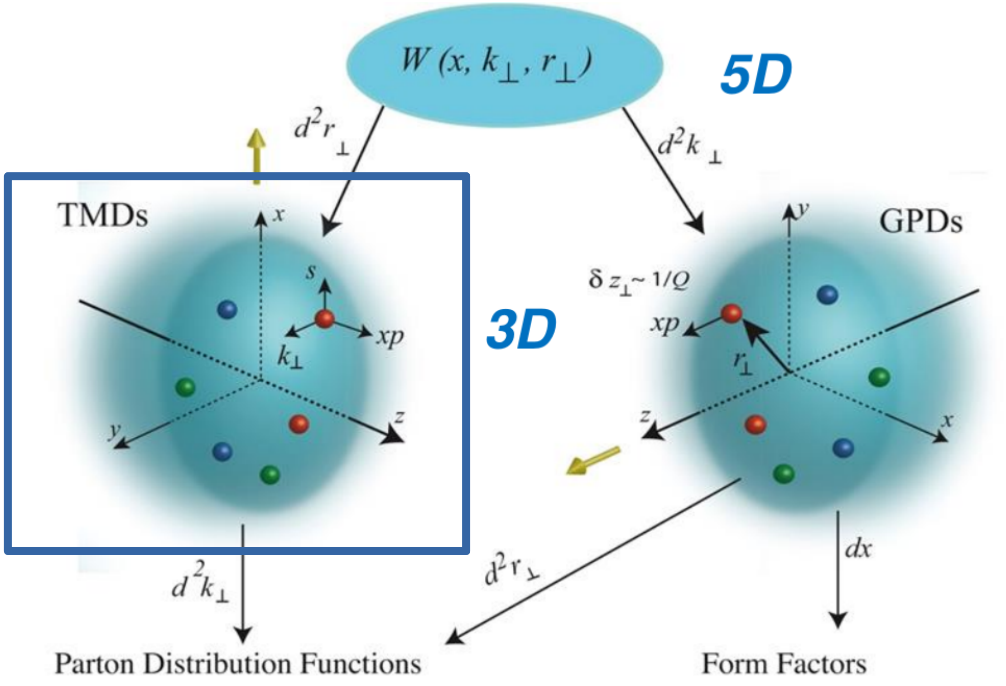


Figure credit: J.-P. Cheng

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

gluon pol. / nucleon pol.

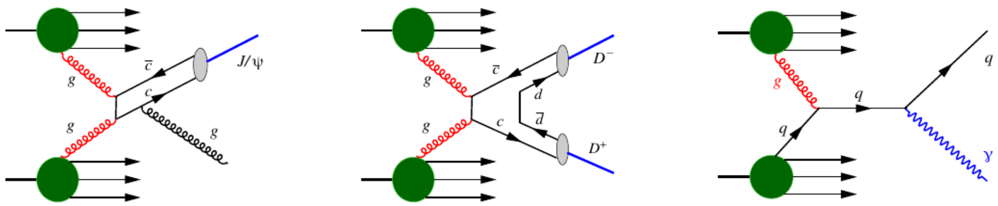
nucleon pol.	U	circular	linear
U	f_1^g		$h_1^{\perp g}$
L		g_1^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_1^g, $h_{1T}^{\perp g}$

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

SPD experiment

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

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

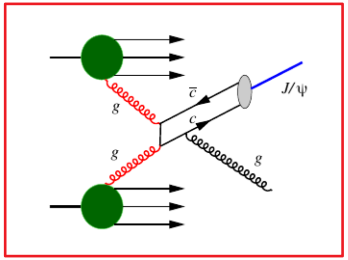


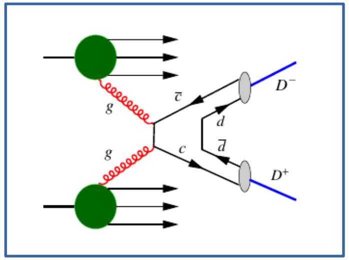
- Measurements at SPD should help to improve our understanding of QCD and resolve spin and mass crises.
- Many other aspects of QCD to be studied in such collisions.

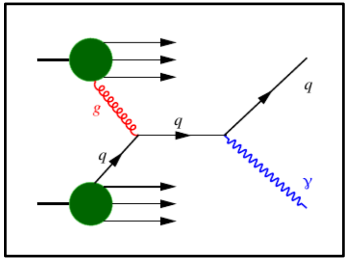
nucleon pol. \ gluon pol.	U	circular	linear
U	f_1^g		$h_1^{\perp g}$
L		g_1^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_1^g, h_{1T}^{\perp g}$

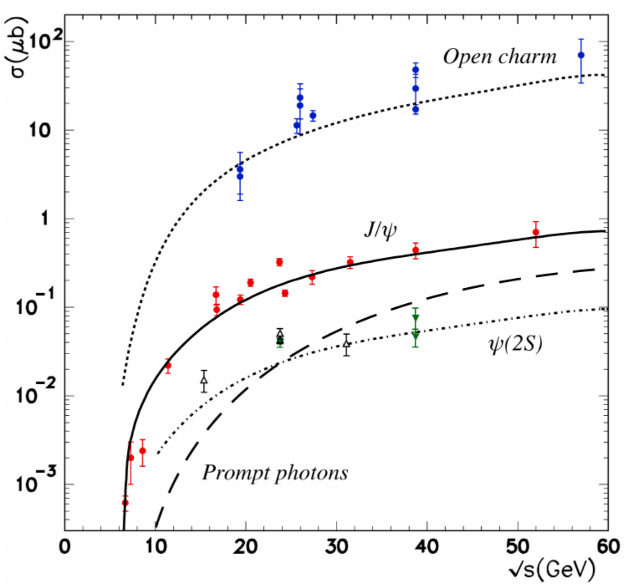
Leading twist gluon TMD PDFs (two times more due to gauge links)

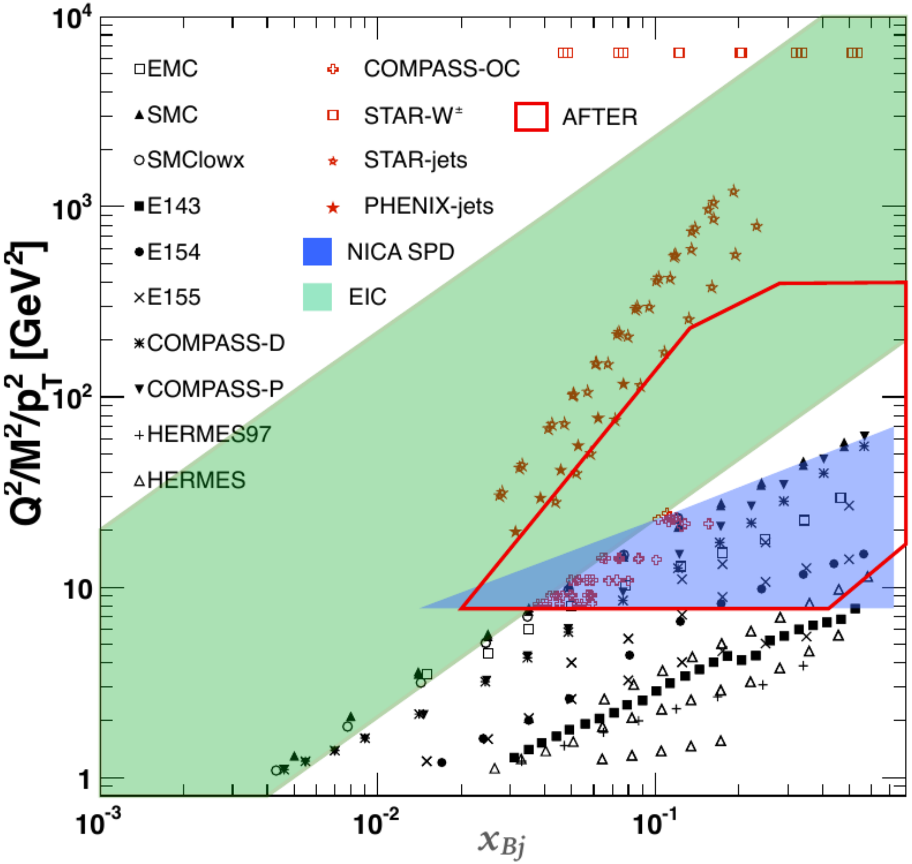
SPD kinematic coverage











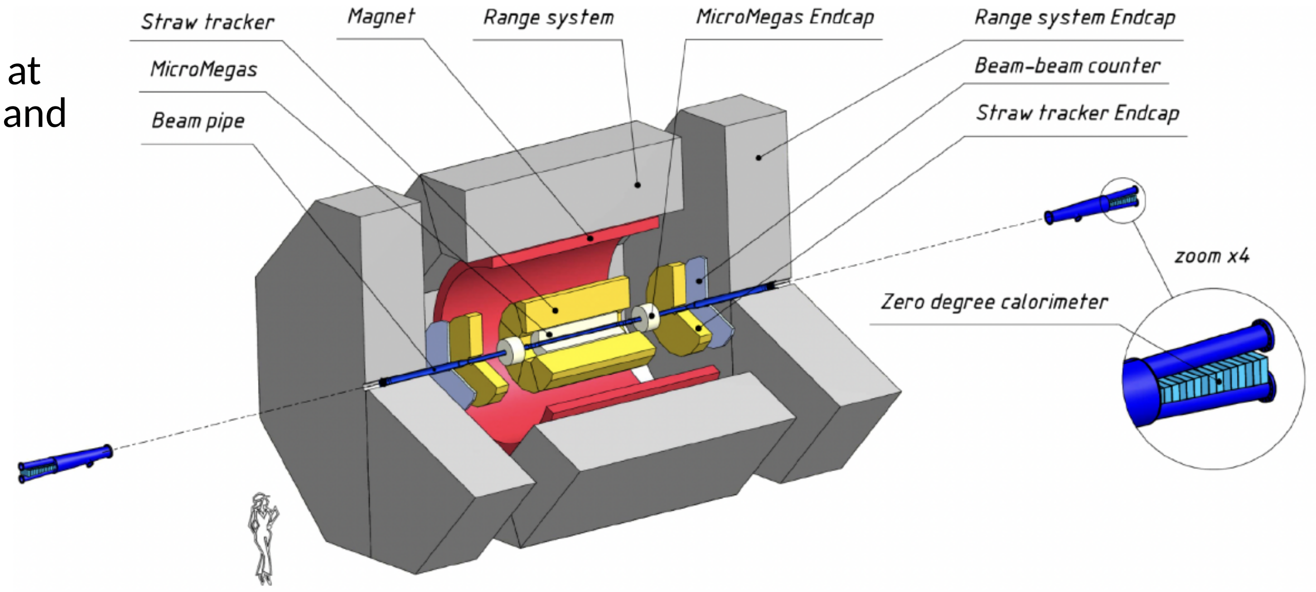
arXiv:2011.15005

SPD initial stage

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

Magnetic field up to **1.2 T**

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



Range System
muon identification and coarse hadron calorimetry

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

Micromegas central tracker:
σ ~ 150 μm

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)
- large pT hadron production to study diquark structure of proton
- dibaryon resonances
- hypernuclei
- physics of light and intermediate nuclei collisions
- open charm and charmonia production near threshold
- antiproton production measurements for astrophysics and BSM search
- …

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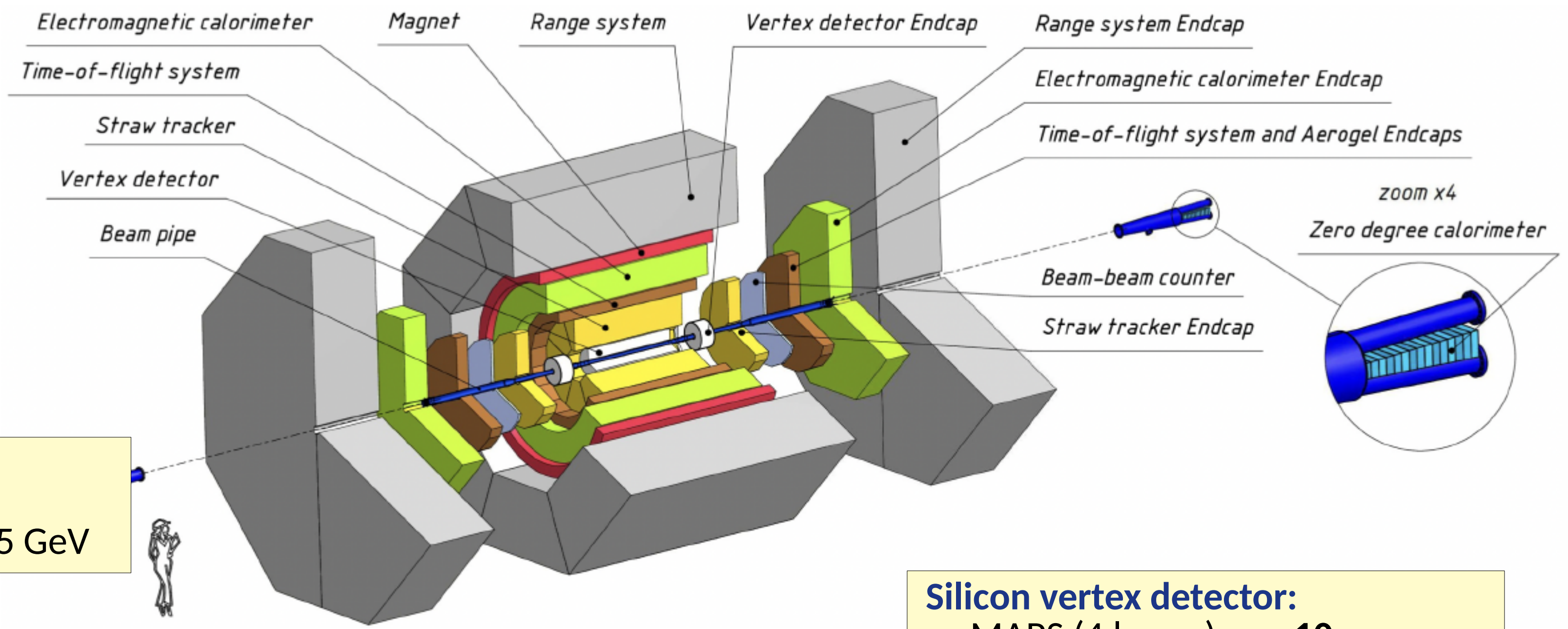
[i] *Sukhoi State Technical University of Gomel, Gomel, 246746 Belarus*
[j] *Budker Institute of Nuclear Physics of SB RAS, Novosibirsk, 630090 Russia*

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

SPD final layout

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

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



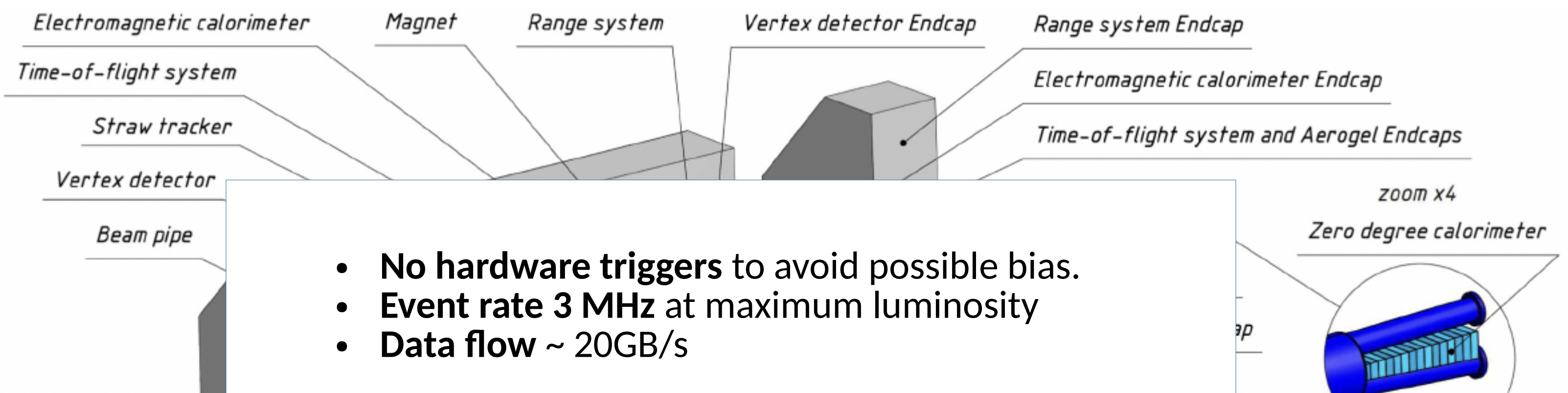
Time of flight system:
σ = 50 ps
3σ π/K separation for p < 1.5 GeV

Threshold aerogel counters in endcaps for pion kaon separation in the range
1.0 GeV < p < 2.5 GeV

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/



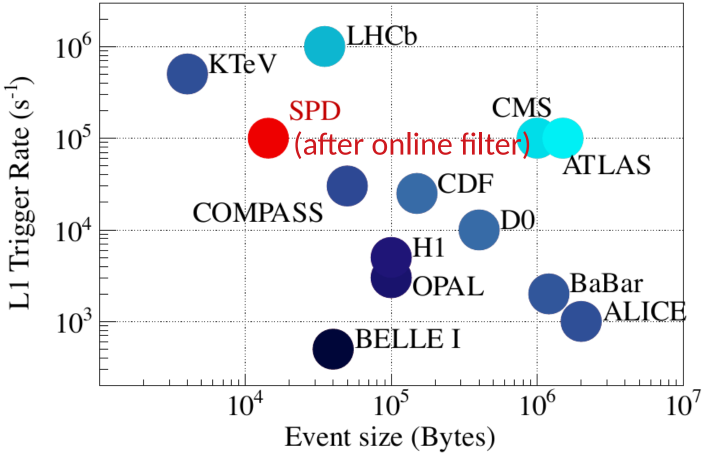
Electromagnetic calorimeter:
σE/E = 5%/√E ⊕ 1%

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

Threshol
for pion k
range **1.0**

tor:
μm,
μm

- **No hardware triggers** to avoid possible bias.
- **Event rate 3 MHz** at maximum luminosity
- **Data flow** ~ 20GB/s



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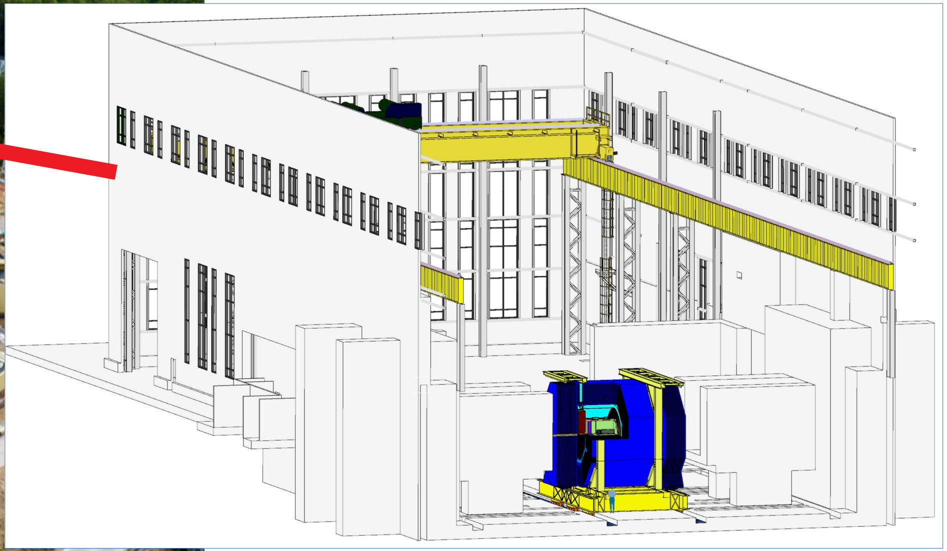
Progress in Particle and Nuclear Physics
Volume 119, July 2021, 103858

Review

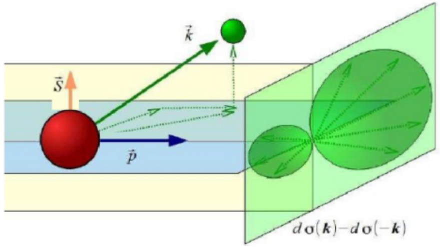
On the physics potential to study the gluon content of proton and deuteron at NICA SPD

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]

Construction site



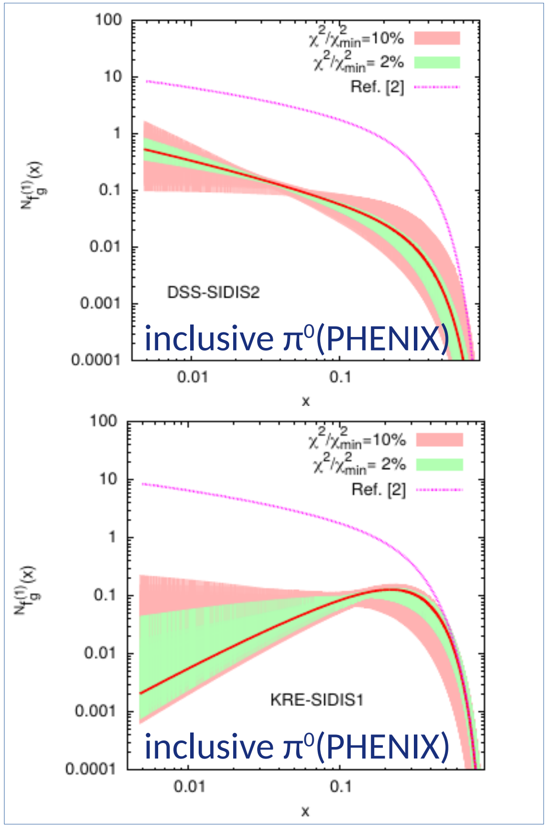
Gluon Sivers function



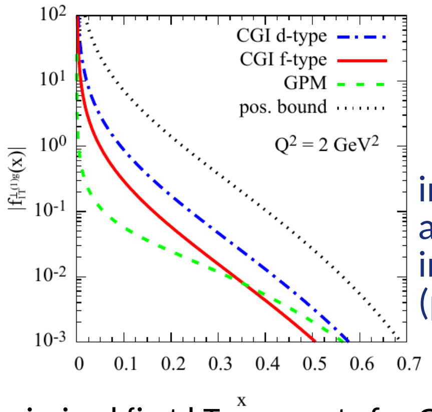
- GSF – correlation between transverse spin and gluon k_T
- Probed by TSSA

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

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

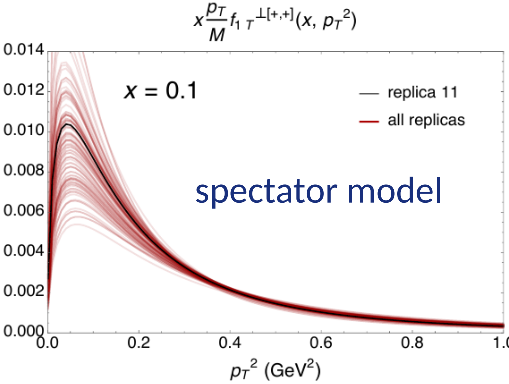


First kT moments for GSF, GPM (JHEP09(2015)119))



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

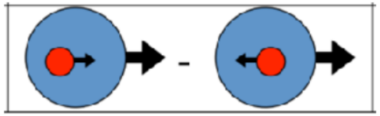
Maximized first kT moments for GSF, CGI-GPM (PRD99, 036013 (2019))



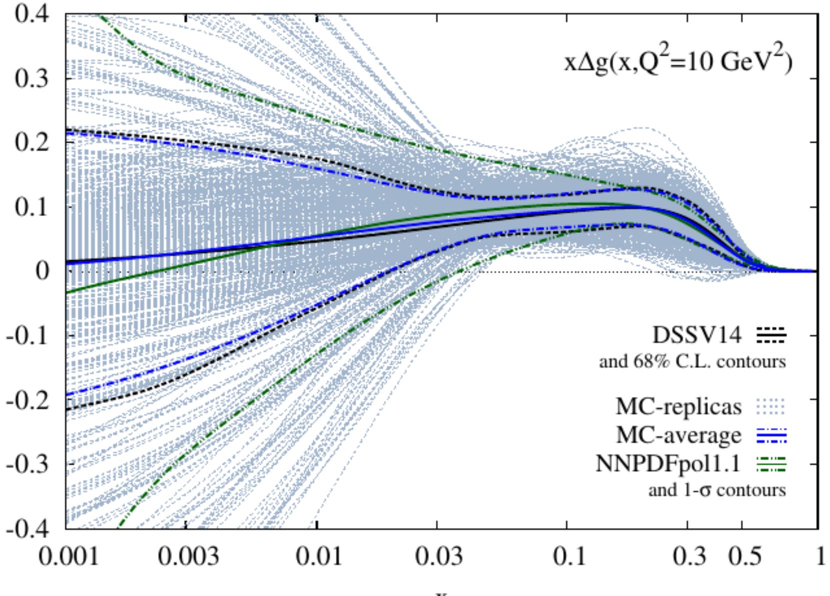
p_T-dependence for f-type Sivers TMD in the **spectator model**, Bacchetta, Celiberto, Radici, 2022

Gluon helicity distribution

$\Delta g(x)$:

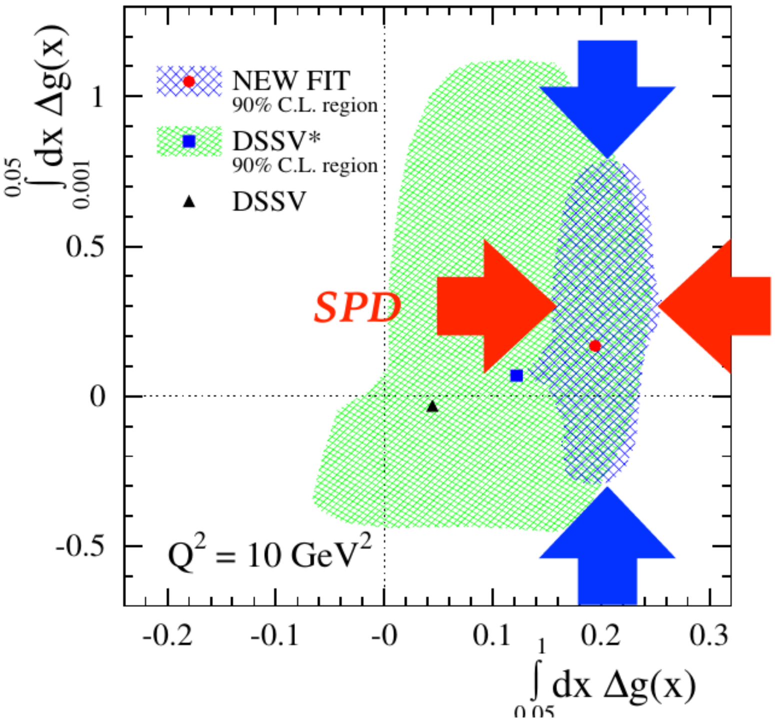


$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$



Phys. Rev. D 100, 114027 (2019)

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



Other extractions: LSS15, JAM17

Charmonia production as a probe of gluon TMD PDFs

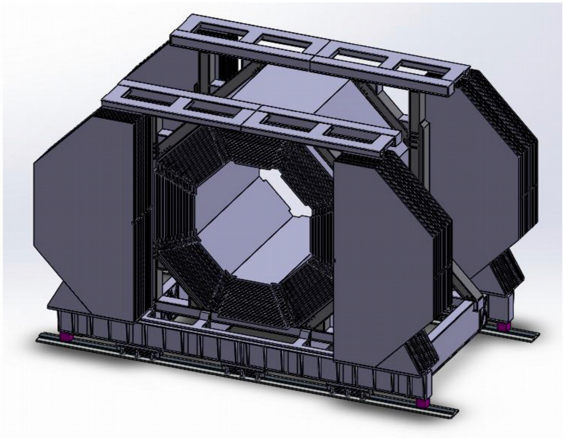
Charmonia production

- dominated by gluon-gluon fusion
- high cross-section
- J/ψ can be easily reconstructed from the $\mu^+\mu^-$ decay, $\psi(2S)$ 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 is not always possible
- 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: 12 million inclusive $J/\psi(\rightarrow\mu^+\mu^-)$ events per year
- Wide kinematic coverage
- Ability to measure also production properties of $\psi(2S)$, 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 $\rightarrow$ shape functions (Echevarria, 2019)

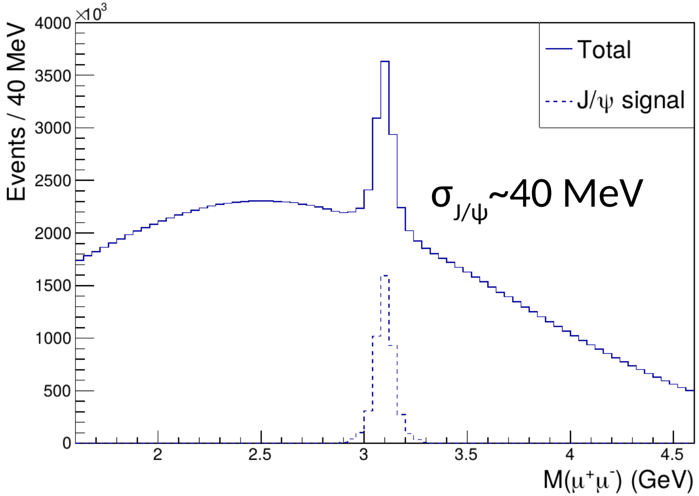
Inclusive J/ψ measurements

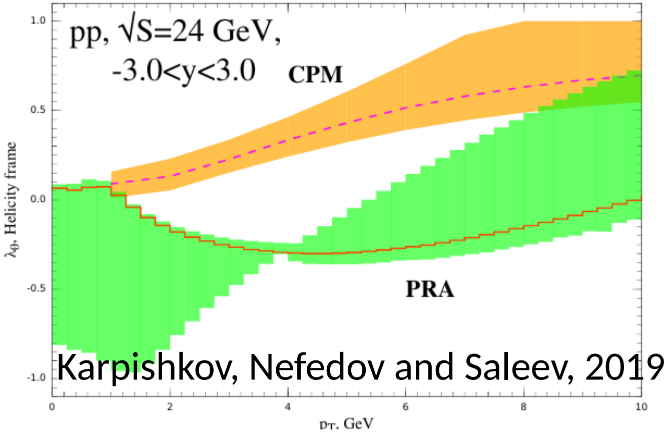


- Reconstruction efficiency: ~40%
- Statistics: ~ 4.5–5.0 M (selected events) per year
- Large background due to pion decays and muon misidentification in RS

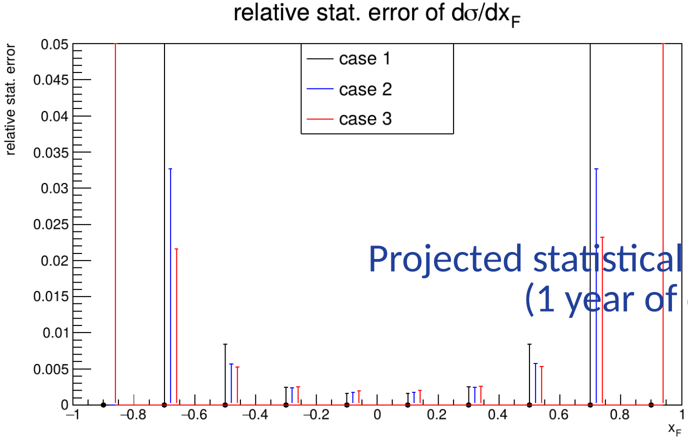
Observables:

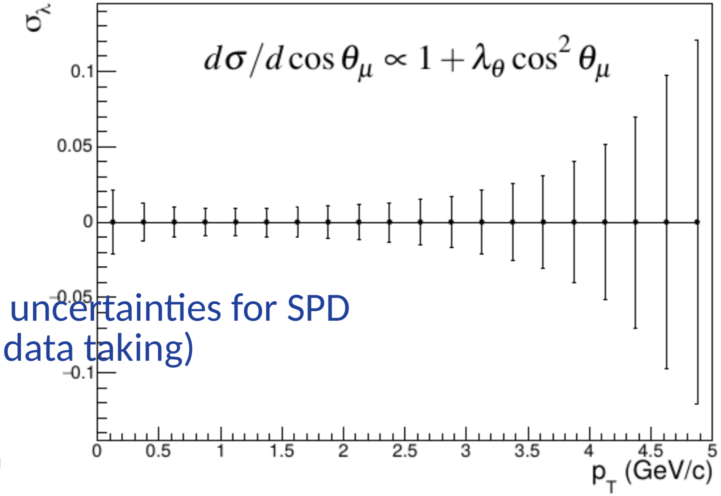
- cross-section, p_T-, x_F-dependencies
- polarization
- asymmetries





Karpishkov, Nefedov and Saleev, 2019

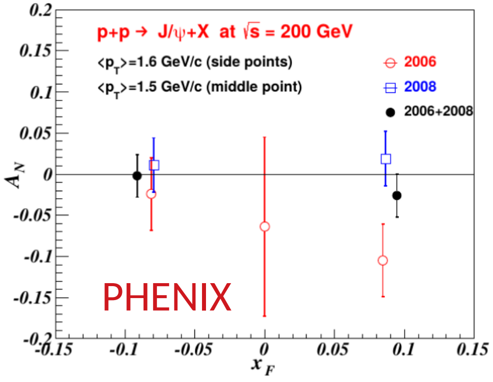




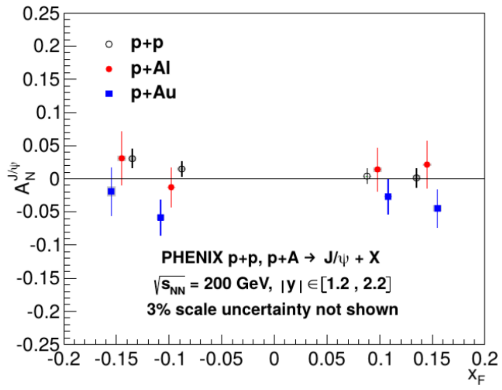
Projected statistical uncertainties for SPD
(1 year of data taking)

A_N for inclusive J/ψ production

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



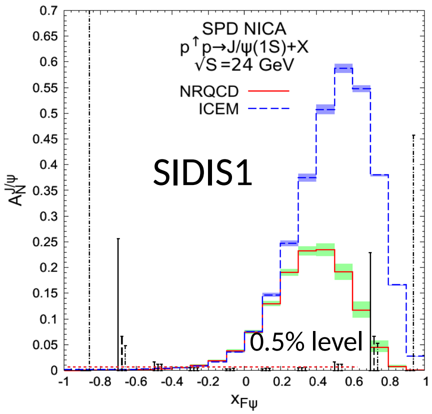
PRD82, 112008 (2010)

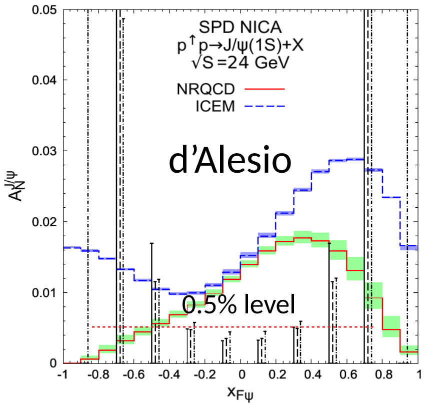


PRD98, 012006 (2018)

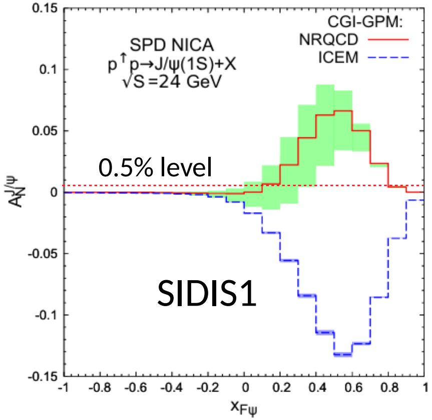
Projected stat. uncertainties and predictions from PRD104, 016008 (2021)

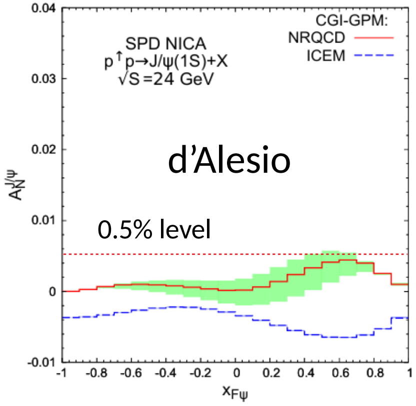
GPM





CGI-GPM



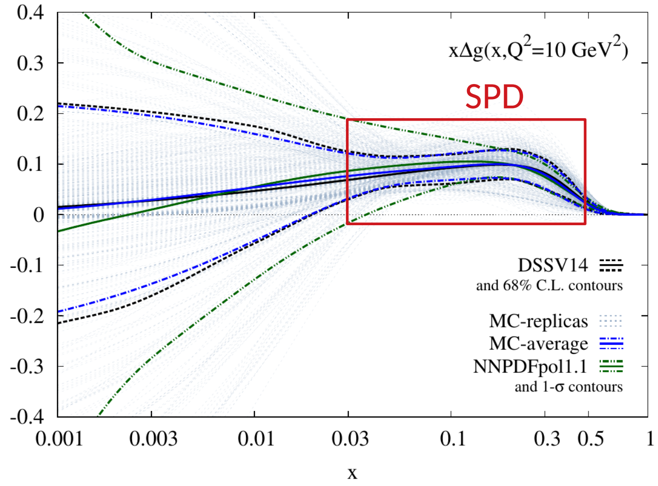


Here and in the following P = 0.7 and is assumed constant during the run.

A_{LL} for inclusive J/ψ production

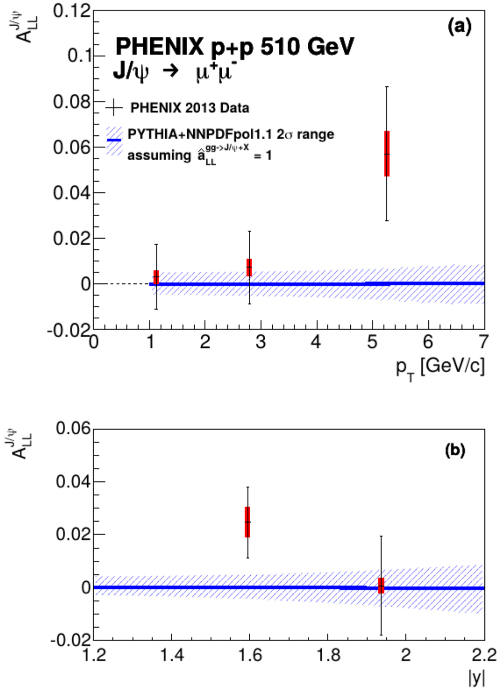
$$A_{LL}^{J/\psi} = \frac{\Delta\sigma}{\sigma} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

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



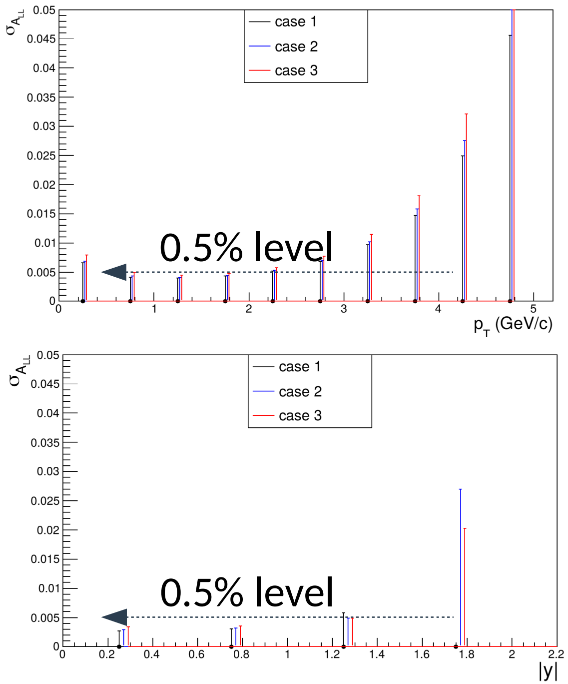
PRD100 114027 (2019)

PRD94 112008 (2016)



$x_1 \sim 5\times10^{-2}$
$x_2 \sim 2\times10^{-3}$

Projected statistical uncertainties for SPD

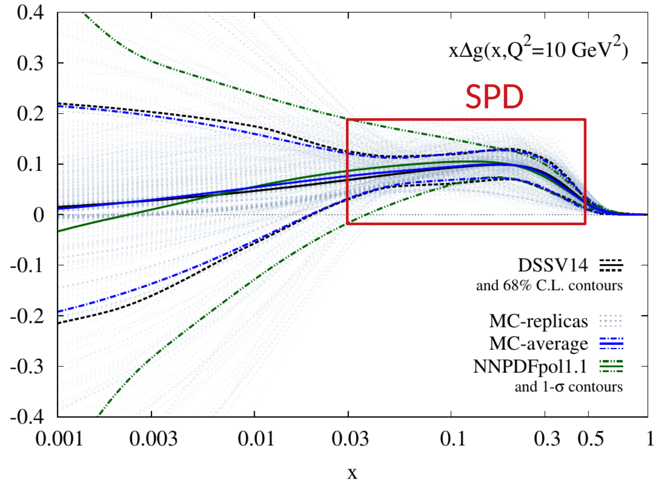


- |y|<2 is covered
- At SPD both $\Delta g(x_1)$ and $\Delta g(x_2)$ are expected to be close to the maximum
- A measurable A_{LL} of the order of 1-10% can be expected

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

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

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

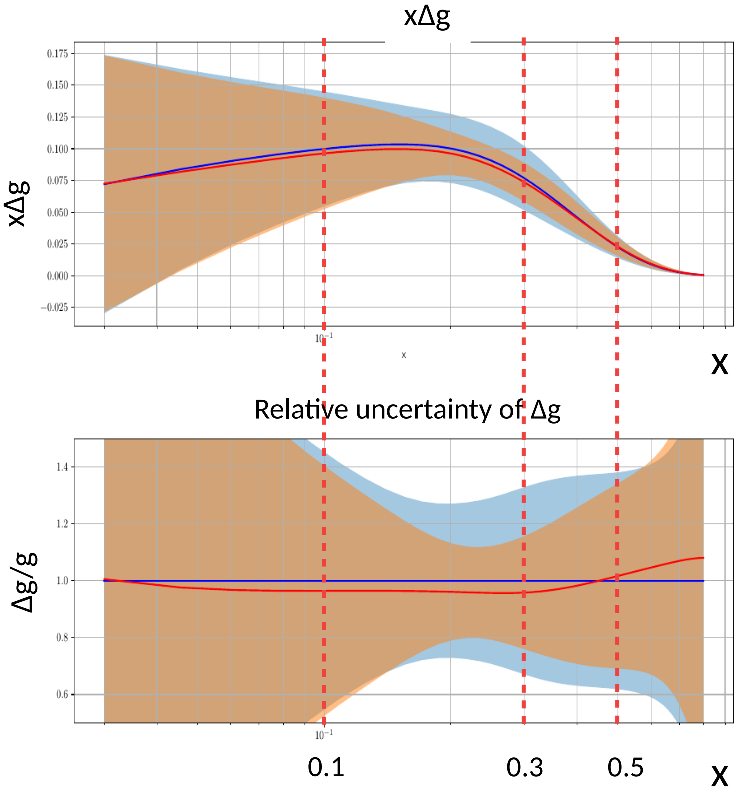


PRD100 114027 (2019)

Impact of SPD data is estimated by

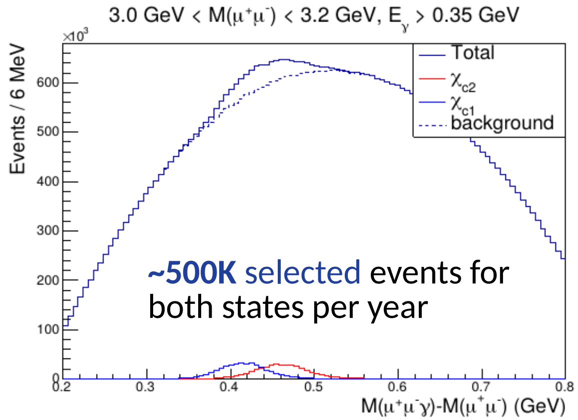
- generating "SPD data" according to NNPDFPol1.1
- prescribing **stat. errors** estimated for 1 year data taking at SPD with √s = 27 GeV
- Bayesian reweighing of MC replicas

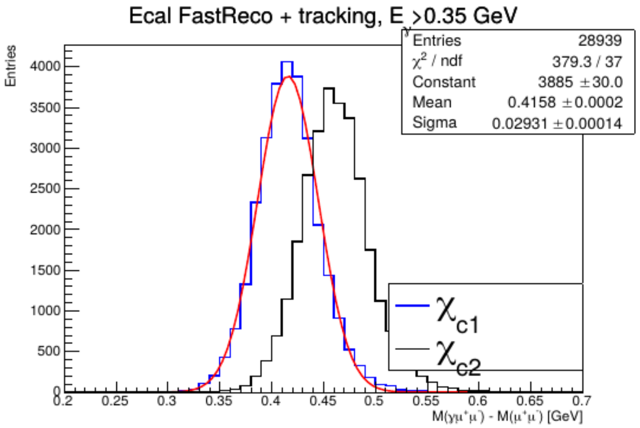
The relative uncertainty decreases by a factor of ~2 for x ~ 0.2-0.3.

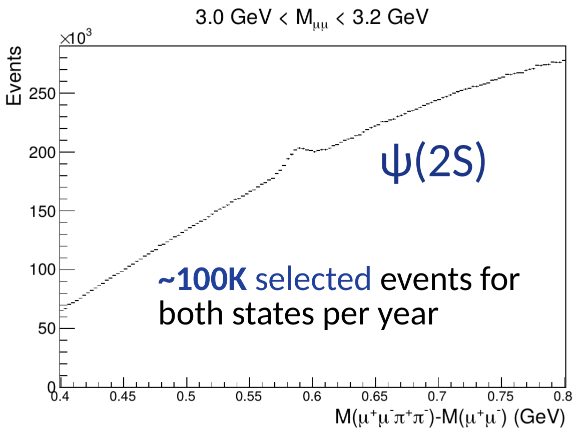


On other measurements with charmonia

χ_{c1} and χ_{c2}

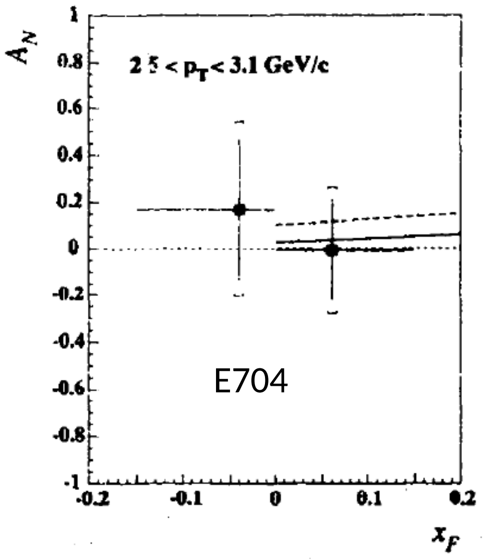






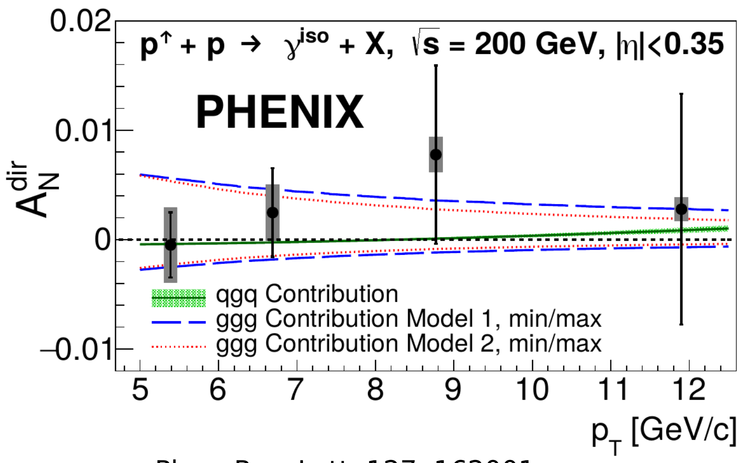
- $\eta_c \to p\bar{p}, \Lambda\bar{\Lambda}, \phi\phi$?
  - 500K selected events for $\eta_c \to p\bar{p}$
  - huge background
- Double J/ψ production
  - 50-100 events/year for both J/ψ dilepton decay modes
  - pT dependence complimentary to high energy experiments
- $J/\psi\gamma$: limited statistics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

Prompt photons: A_N

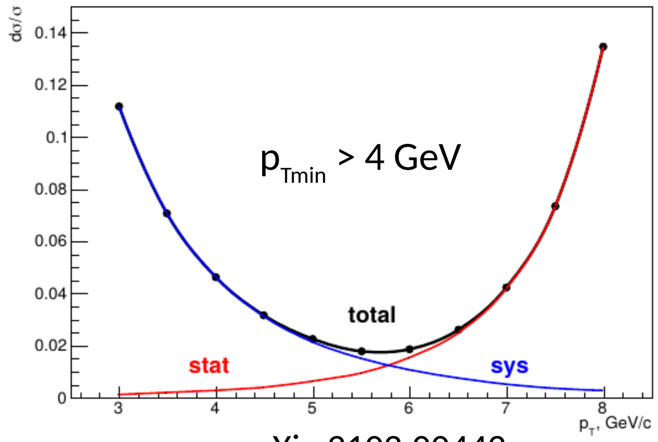


PLB345, 569 (1995)

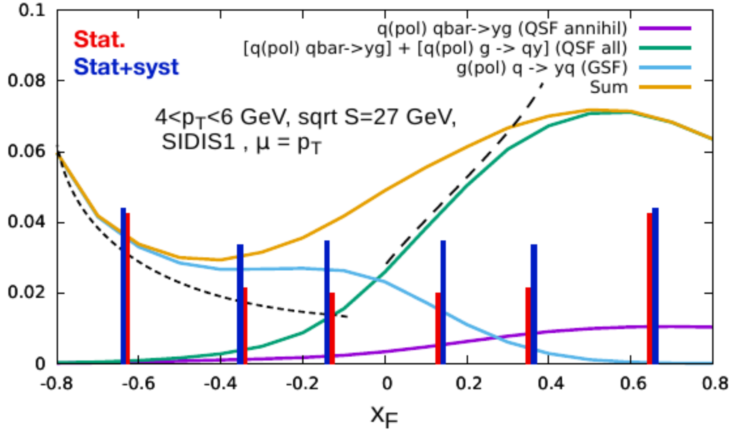
- Straightforward theoretical interpretation
- very challenging experimentally



Phys. Rev. Lett. 127, 162001



arXiv:2102.00442



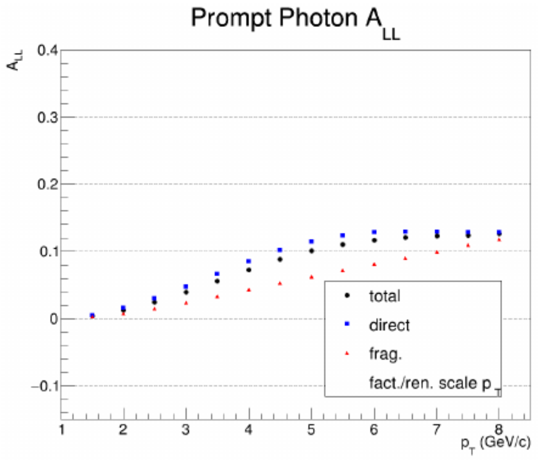
Predictions: Saleev, Shipilova, 2020

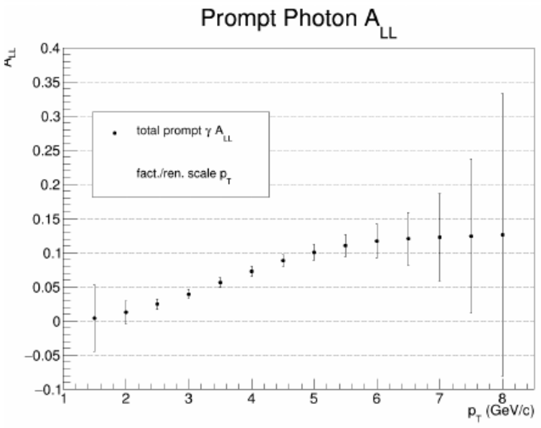
Prompt photons: A_{LL}

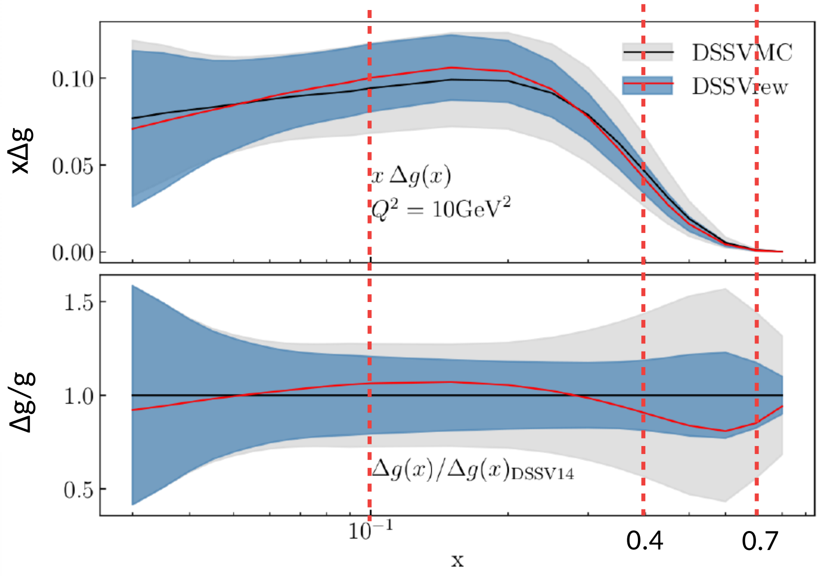
$$A_{LL}^{\gamma} \approx \frac{\Delta g(x_1)}{g(x_1)} \otimes A_{1p}(x_2) \otimes \hat{a}_{LL}^{gq(\bar{q})\to\gamma q(\bar{q})} + (1 \leftrightarrow 2)$$

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



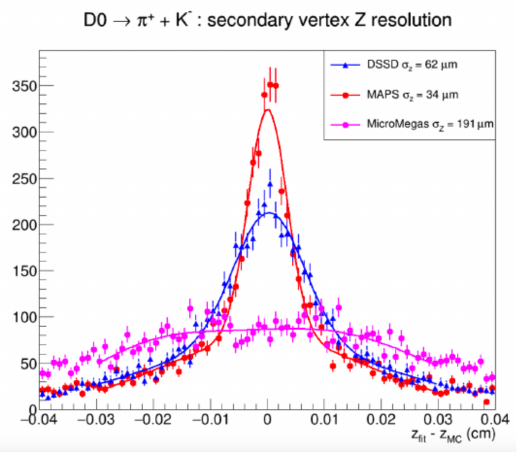


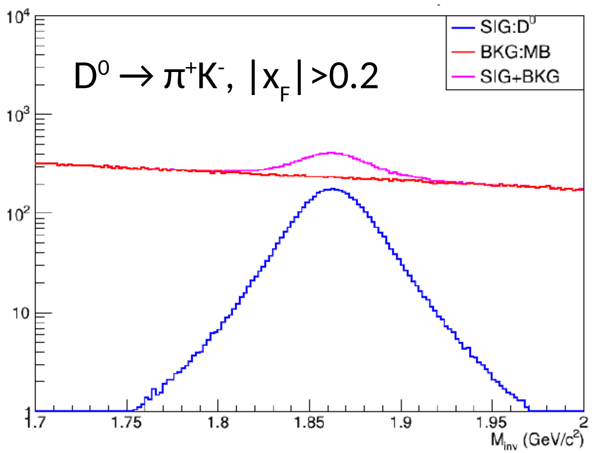


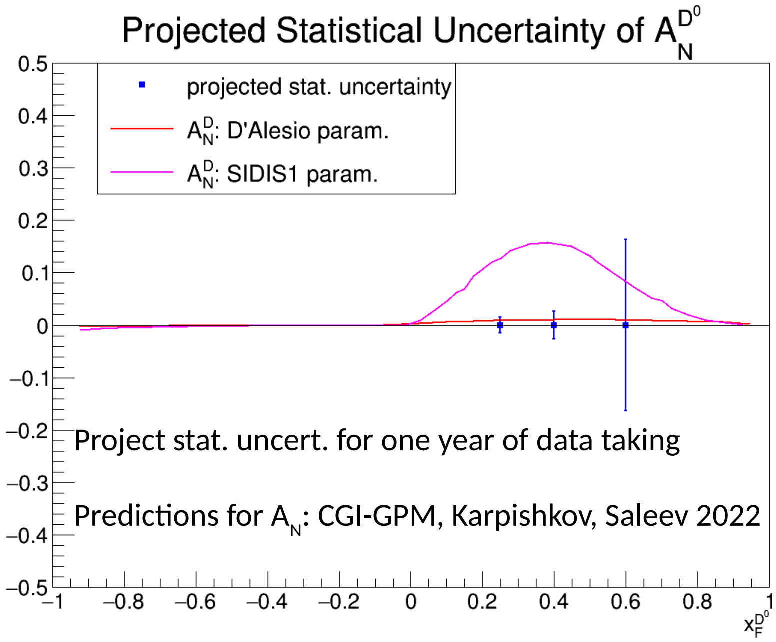
Predictions with new "data" added (top) and ration of the uncertainties (bottom). Courtesy R. Sassot, I. Borsa, 2021.

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

Measurements with D mesons





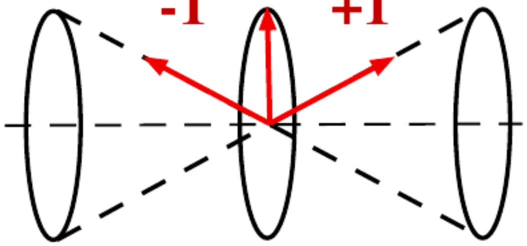


- The largest production cross-section (almost two orders of magnitude larger than for J/ψ)
- Small D-meson boost at our energies
- Interpretation requires c-quark FF
- Projected uncertainties shown for D^0 only
- D meson pair production – probe for Boer-Mulders function

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

Nonbaryonic content of deuteron:

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



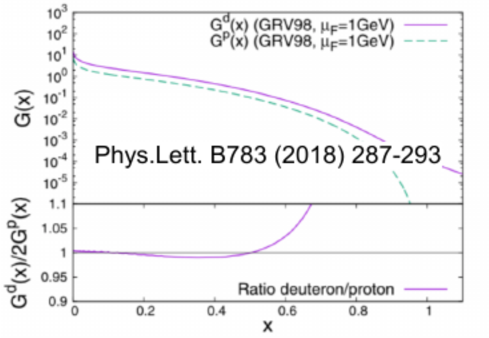
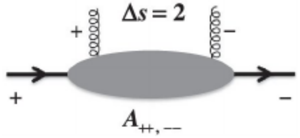
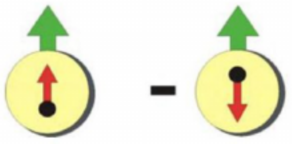


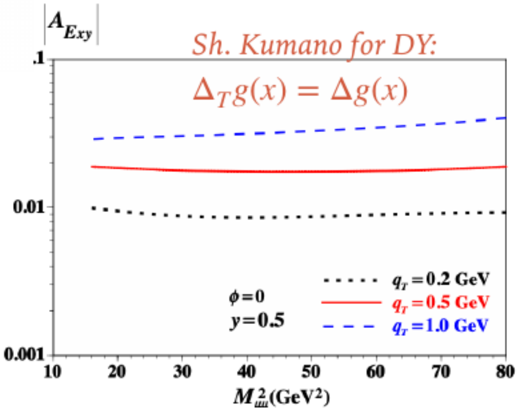
Fig. 6. Gluon PDF in the deuteron and in the nucleon.

Unpolarized gluons at high x:

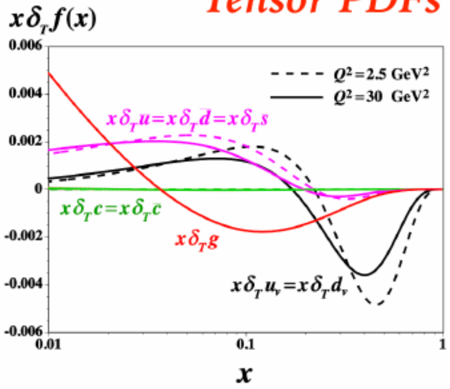
Gluon transversity







Tensor PDFs



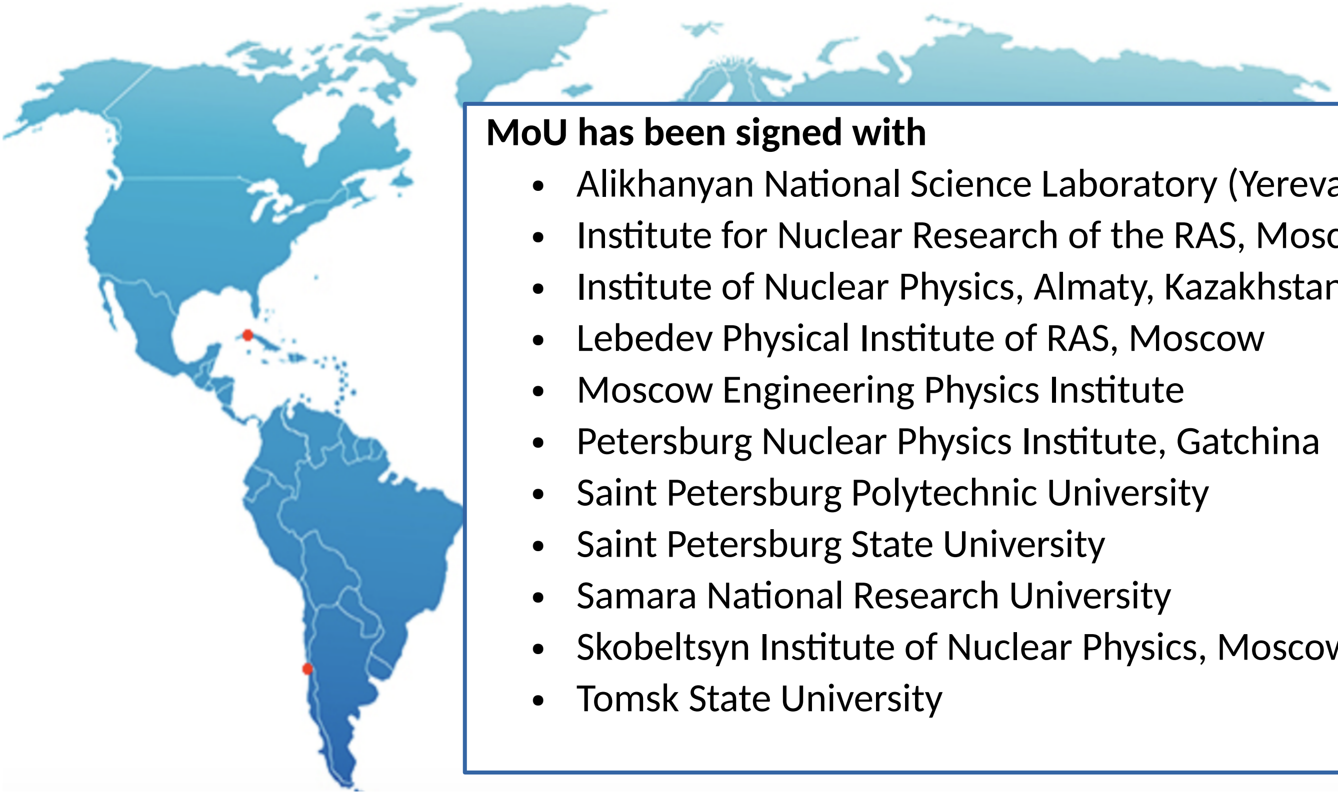
Running strategy

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

SPD Collaboration

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

SPD Collaboration



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

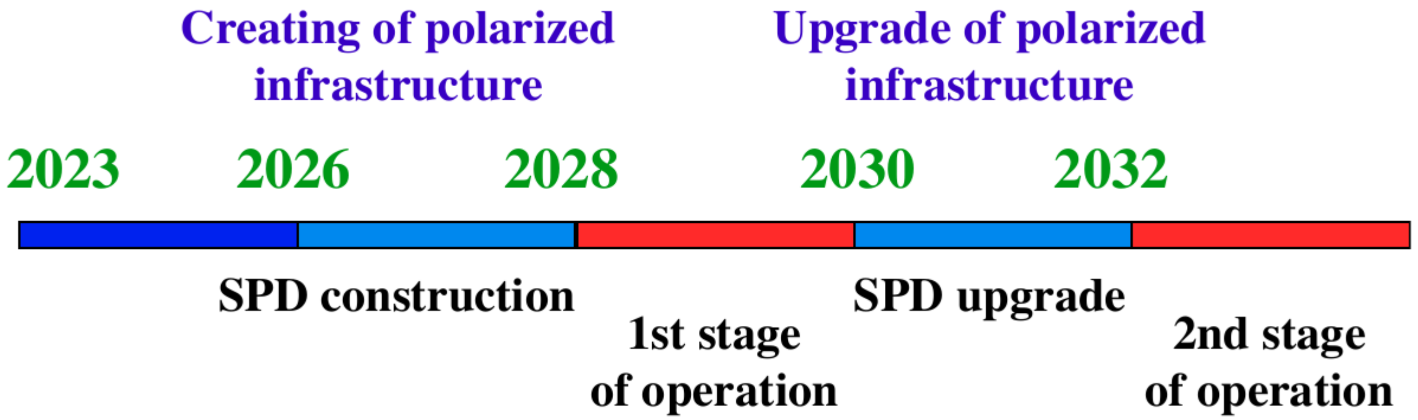
2014: SPD LoI approved by JINR PAC

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.



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
  - gluon transversity in deuteron
  - unpolarized gluon PDFs of proton and 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).

spd.jinr.ru