# Статус экперимента SPD

**В.Т. Ким**

# SPD at NICA (JINR, Dubna)

## NICA:
## Nuclotron-based Ion Collider fAcility

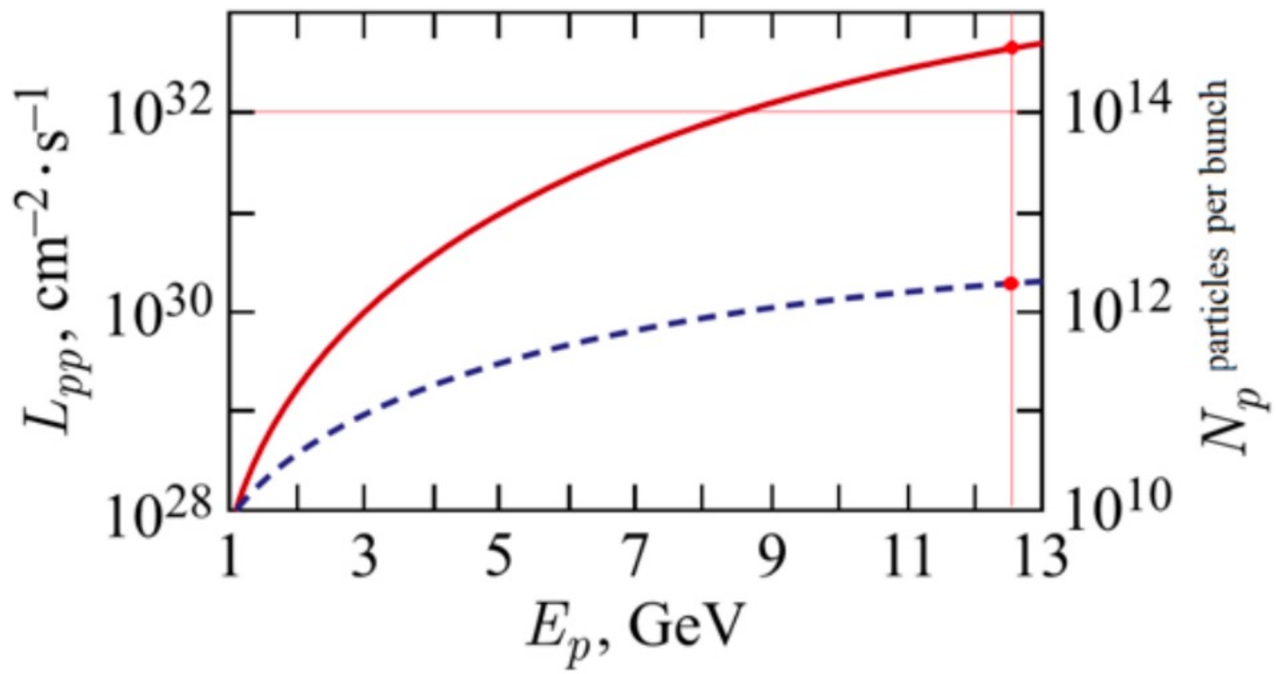
$$p^{\uparrow}p^{\uparrow} : \sqrt{s} \leq 27\ GeV$$

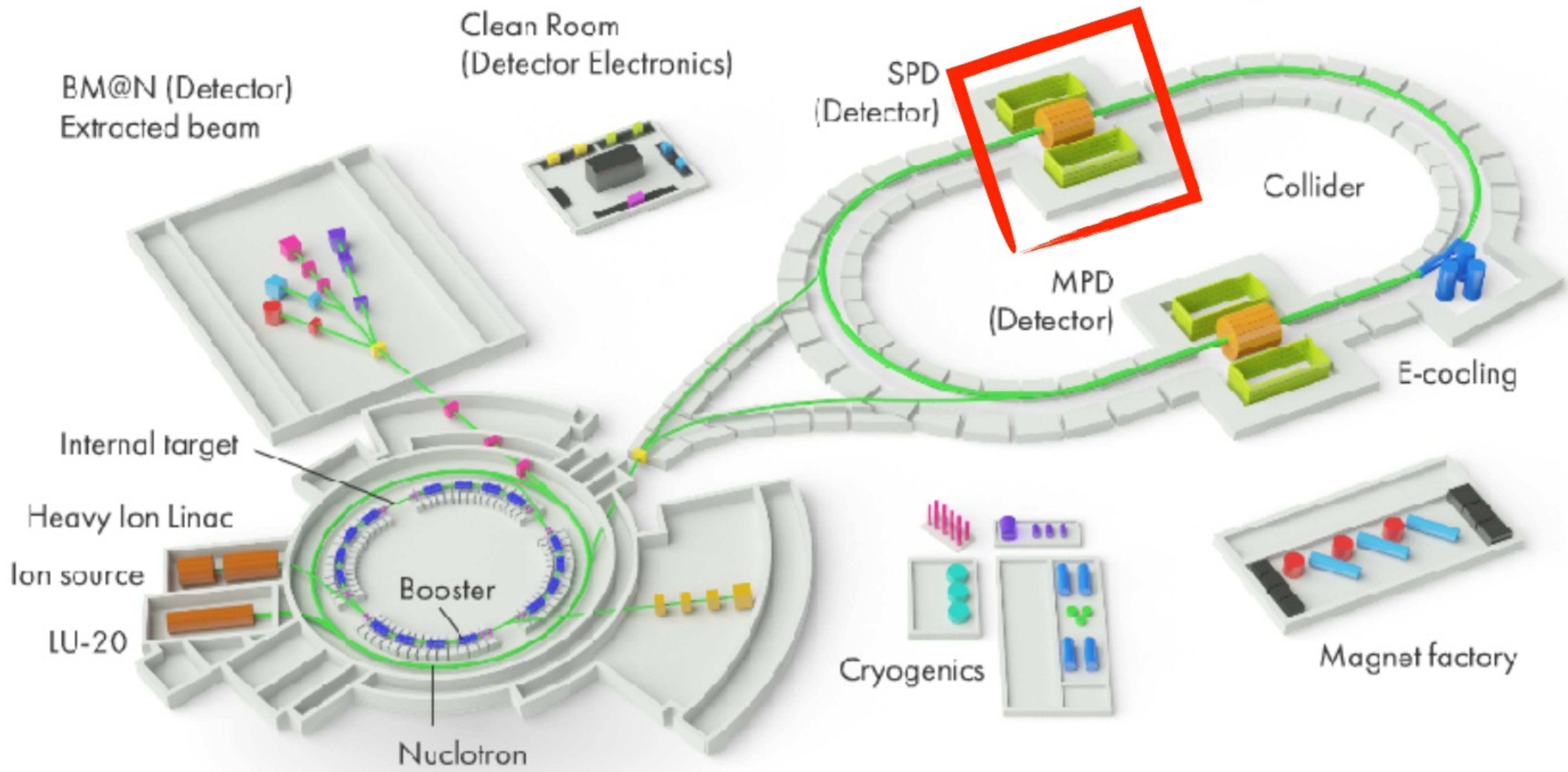
$$d^{\uparrow}d^{\uparrow} : \sqrt{s} \leq 13.5\ GeV$$

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

*U, L, T*

$|P| > 70\%$



# ОИЯИ, Дубна: NICA, сентябрь 2022

# Основные цели эксперимента SPD

Spin Physics Detector (SPD) (http://spd.jinr.ru):
Универсальный детектор на коллайдере NICA

➥ Основные цели SPD:
понимание сильных взаимодействий используя поляризованные и неполяризованные pp- и dd- соударения $\sqrt{s} < 27$ ГэВ

- 3D структура протона и дейтрона, в особенности, PDF и TMD при больших x

➥ В добавок, запланирована программа в начальный период работы SPD для широкой области исследований ядерной физики и физики частиц

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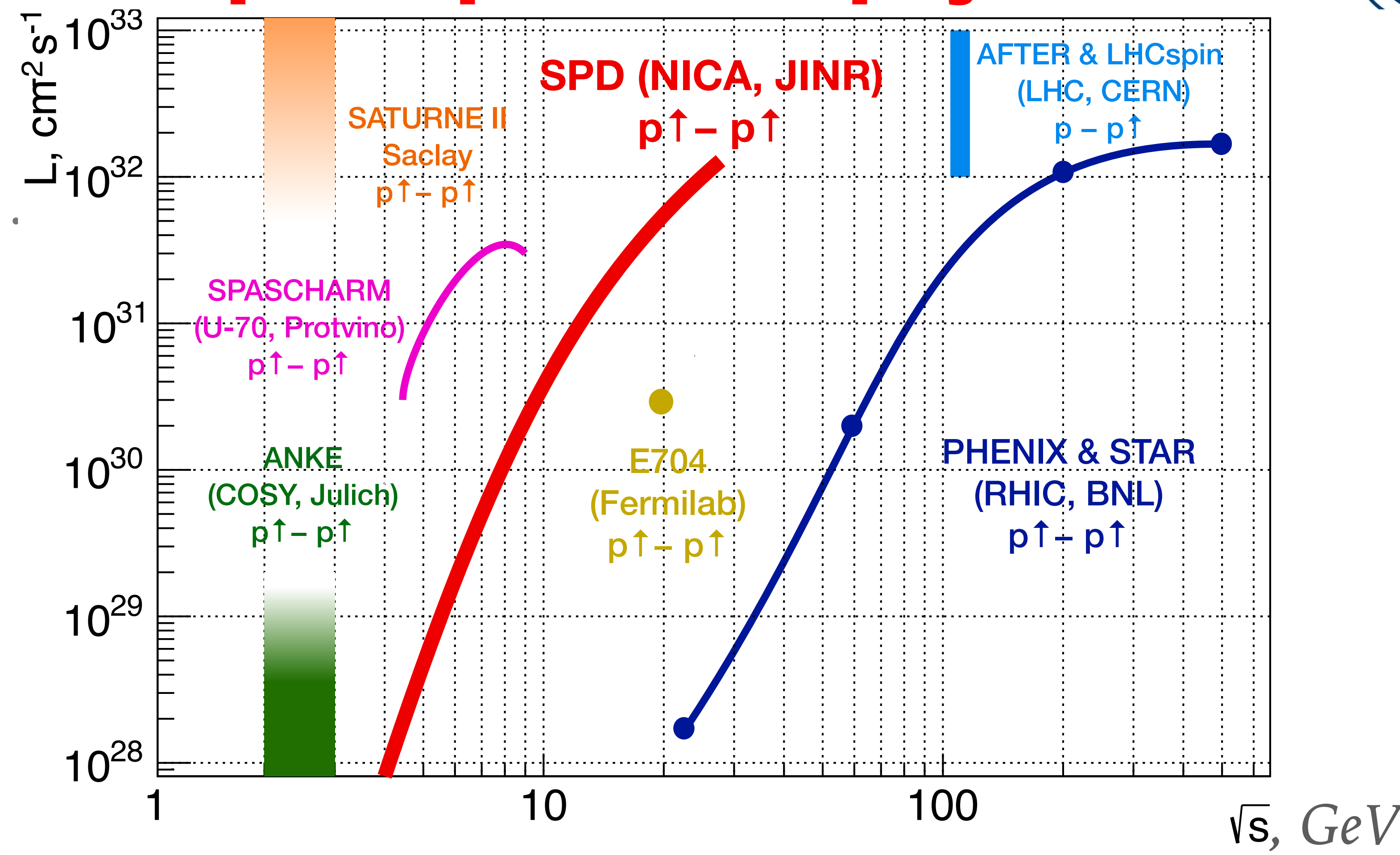
Parton distribution function (PDF) – функции распределения партонов
Transverse momentum distribution (TMD) – партонные распределения с учетом поперечного импульса

# SPD in World landscape of polarized physics

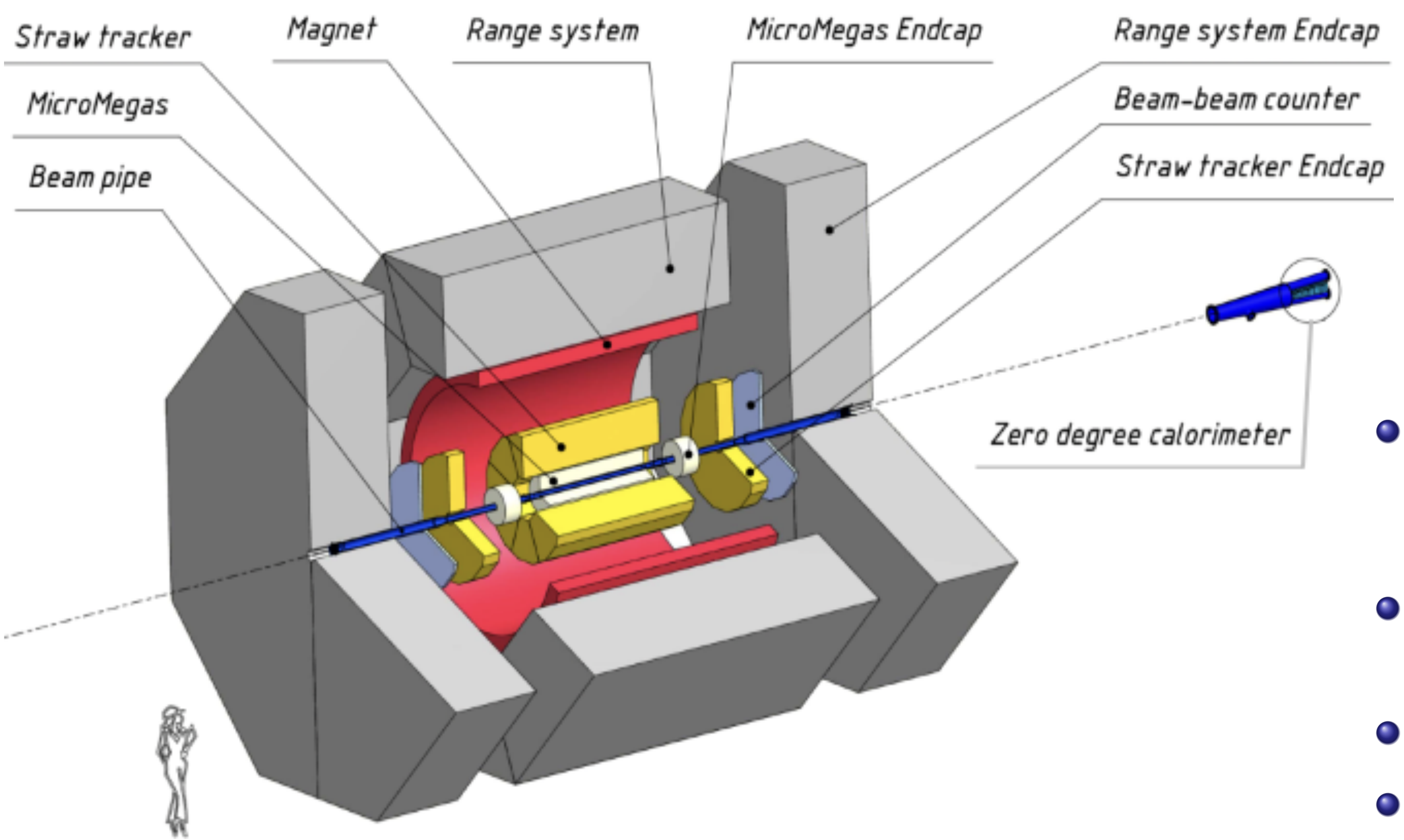
p↑ p↑-mode ➡




| 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!

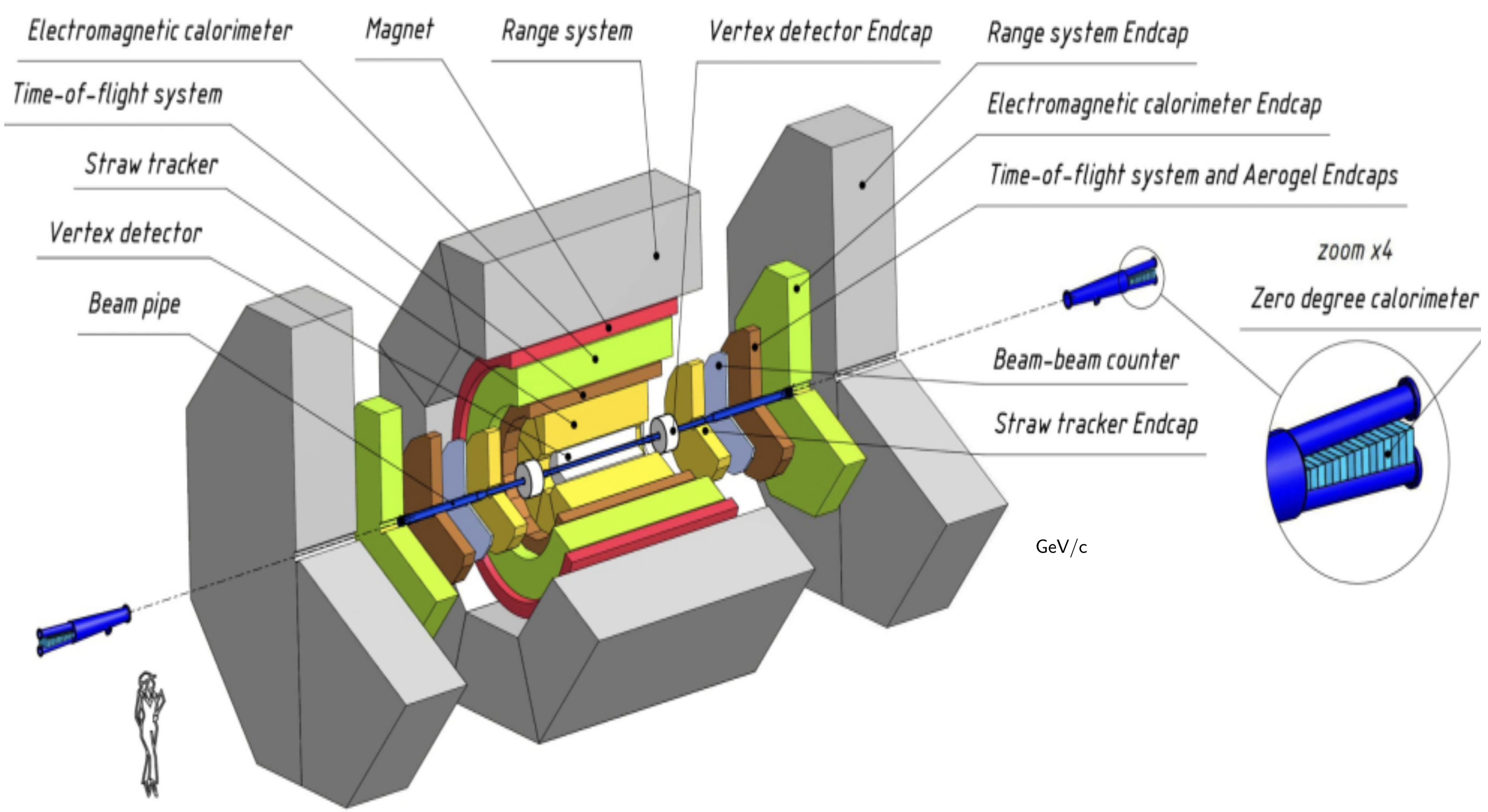
# SPD detector at the Stage I




- Trackers:charged track and momentum, limited PID
- Range System:rough hadronic calorimeter, muon/hadron separation

- Possible light ion collisions alongside *pp*, *dd*
- Up to $\sqrt{s} = 10$ GeV and reduced luminosity
- Solenoidal field $B \sim 1$ T
- BBC and ZDC for online polarimetry
- Micromegas central tracker
- Straw Tracker $\delta \sim 150\ \mu$m, $\delta(\frac{dE}{dx}) = 8.5\%$

# SPD detector at the Stage II




- Event rate at peak luminosity and energy $\sim 3$ MHz
- Silicon vertex detector : MAPS/DSSD
- Time of flight (TOF) for PID ($\delta_t \sim 50$ ps), $\pi/K$ separation upto 1.5 GeV/c
- Electromagnetic calorimeter (ECAL) ($\frac{\delta_E}{E} = \frac{5\%}{\sqrt{E}} + 1\%$)
- Aerogel counter in endcaps, extends $\pi/K$ separation upto 2.5 GeV/c

- Improved vertex detector for short lived particle decays
- TOF+AGel for better PID
- ECAL for $\gamma, e^{\pm}$ identification

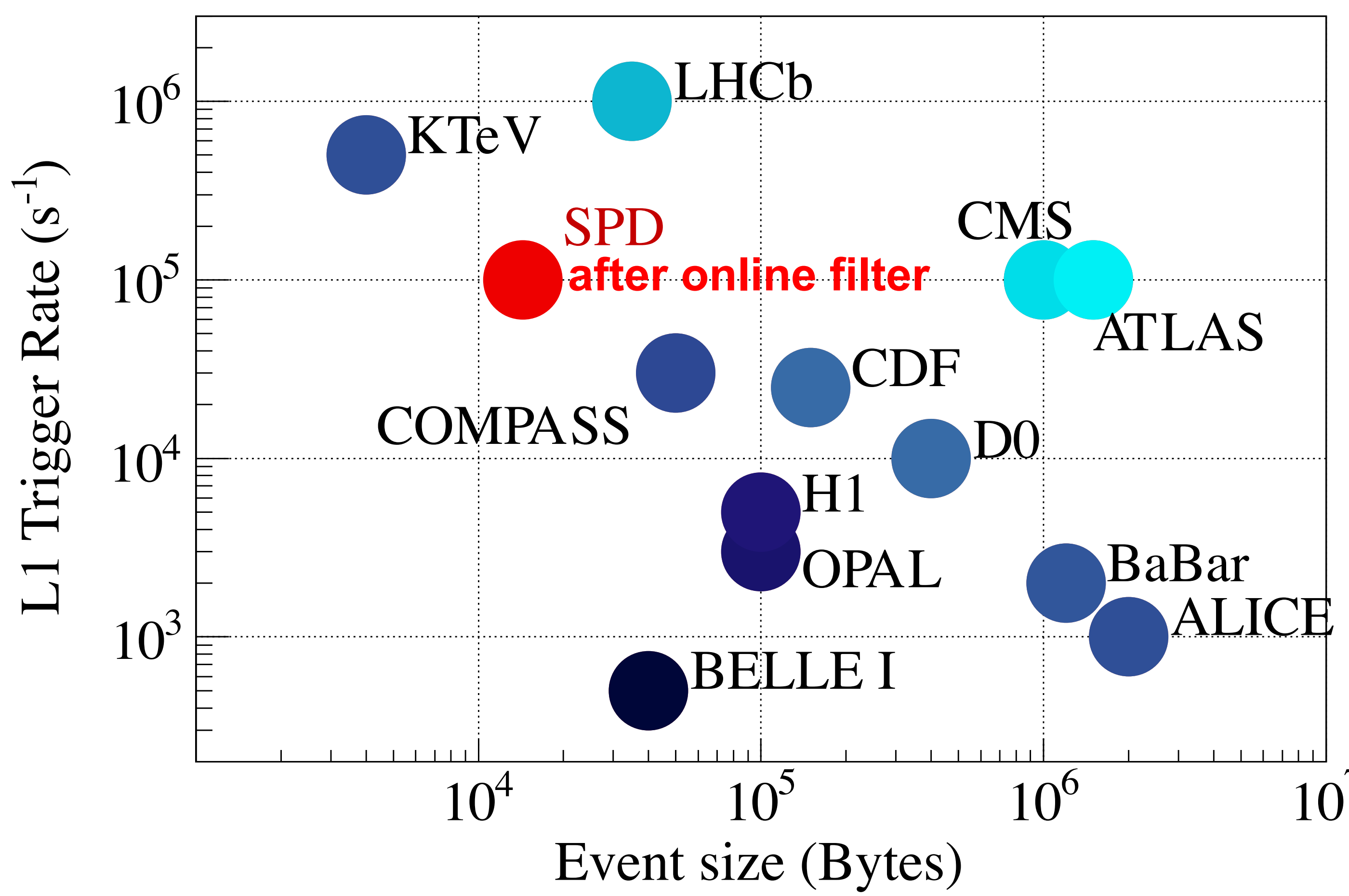
# SPD detector data flow

**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**

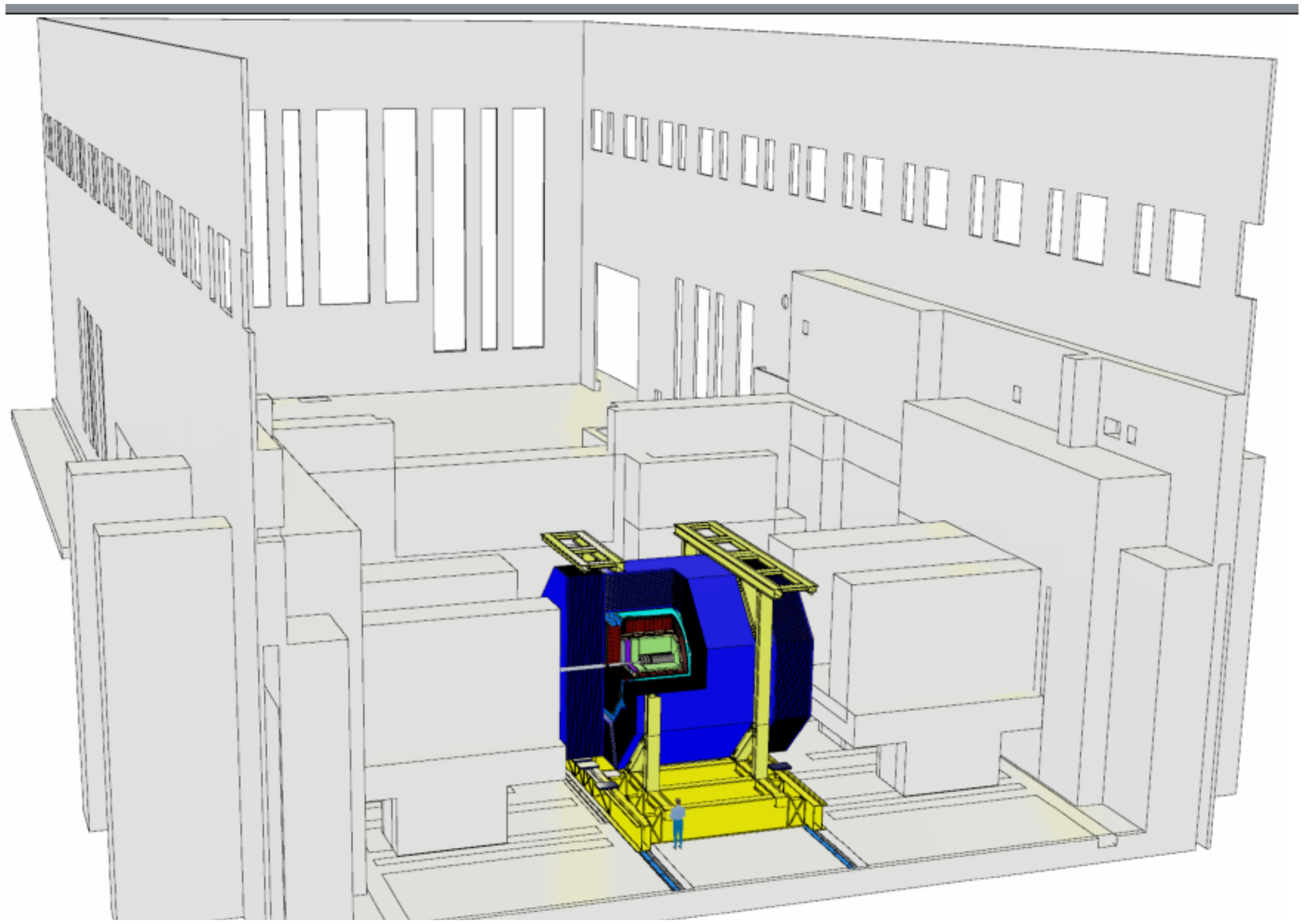
**The SPD setup is a medium scale detector in size,**
**but a large scale one in data rate!**
**Comparable in data rate with ATLAS and CMS at LHC**

## Considerations of SPD Tier-1 at PNPI

**SPD data rate after online filter**



# SPD detector site



# SPD project timeline

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

**2014** SPD Letter of Intent is approved by JINR PAC

**2016, 2018** SPD-oriented workshops in Prague

**2019** SPD project is approved by JINR PAC (up to 2022)
The 1st SPD proto-Collaboration meeting

**2020** Completion of SPD Conceptual Design Report (CDR)
*http://arxiv.org/abs/2102.00442*

**2021** (July) SPD Collaboration is established
Two SPD-physics papers were published

**2023** (January) SPD Technical Design Report (TDR): 1st public version

**2028+** Start of SPD operation

# SPD Collaboration: established in July 2021

Spin Physics Detector

*The NICA-SPD Collaboration, July 2021*

*Armenia*
*Belarus*
*Chile*
*China*
*Cuba*
*Czechia*
*Egypt*
*France*
*Italy*
*Poland*
*Russia*
*Serbia*
*South Africa*
*Ukraine*

*33 laboratories and individual contributors from 14 countries*

*~ 300 participants*

# 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:

ELSEVIER

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

ArXiv e-Print: 2011.15005 [hep-ex]

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], 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]

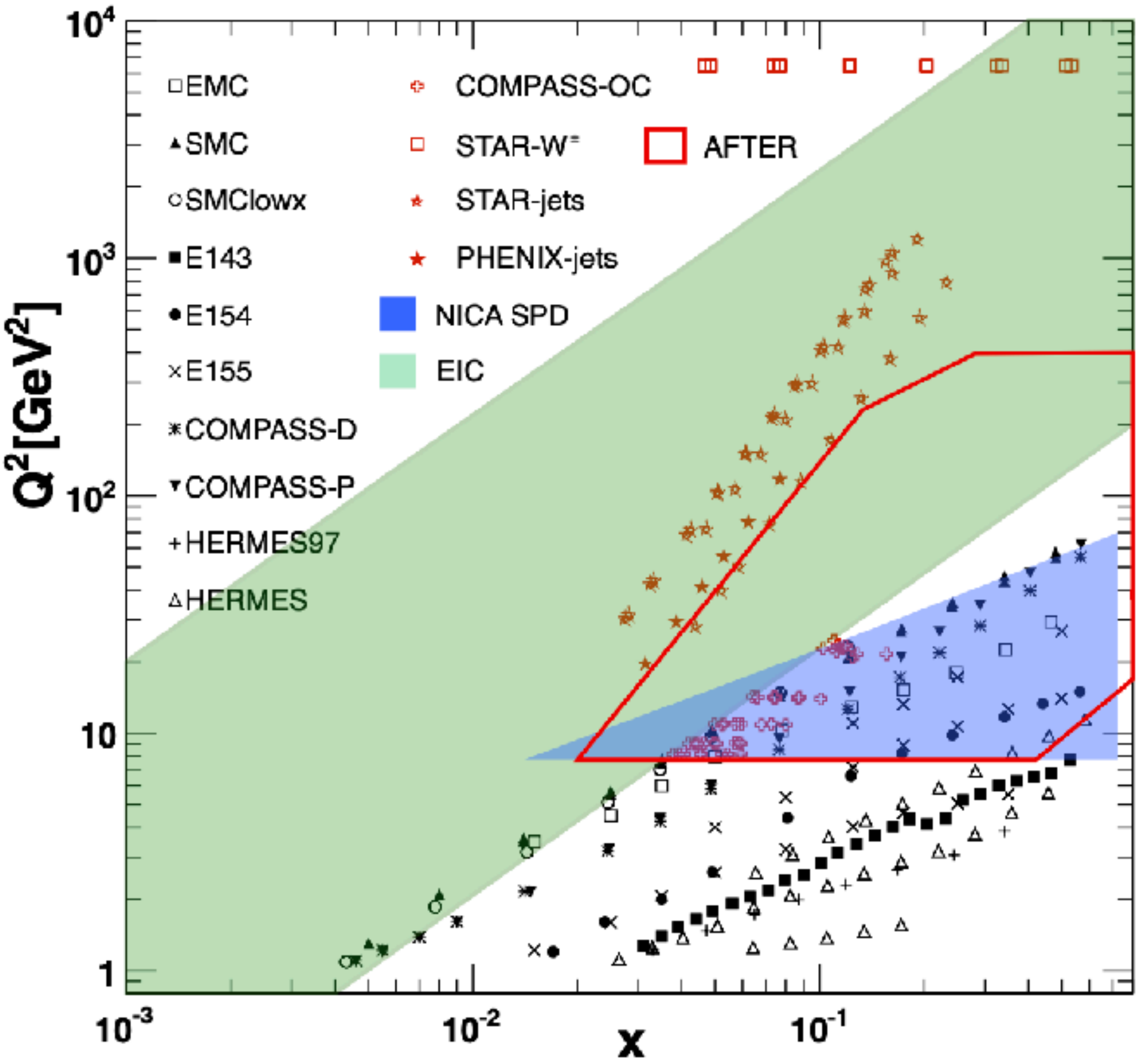
## Possible studies at the first stage of the NICA collider operation with polarized and unpolarized proton and deuteron beams

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]

Phys. Part. Nucl. Vol.52, 2021, 1044

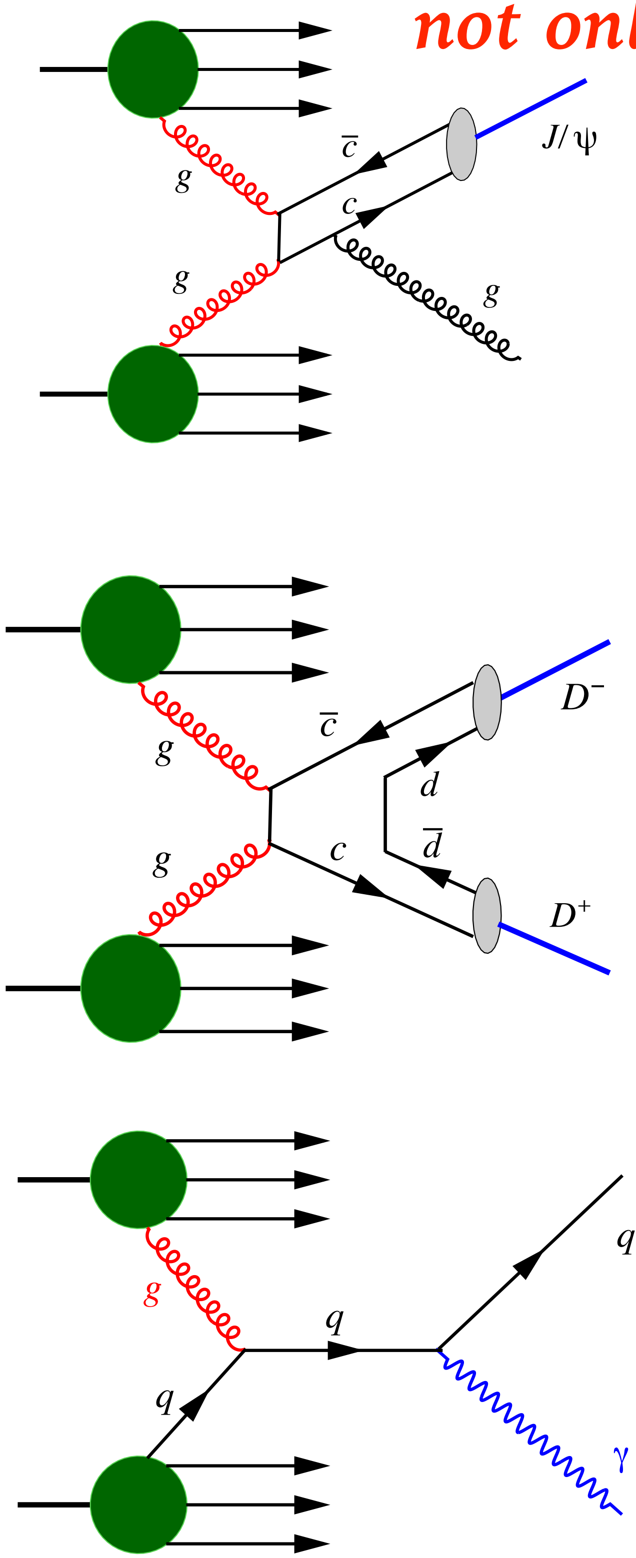
ArXiv e-Print: 2102.08477 [hep-ph]

# PDF kinematic range

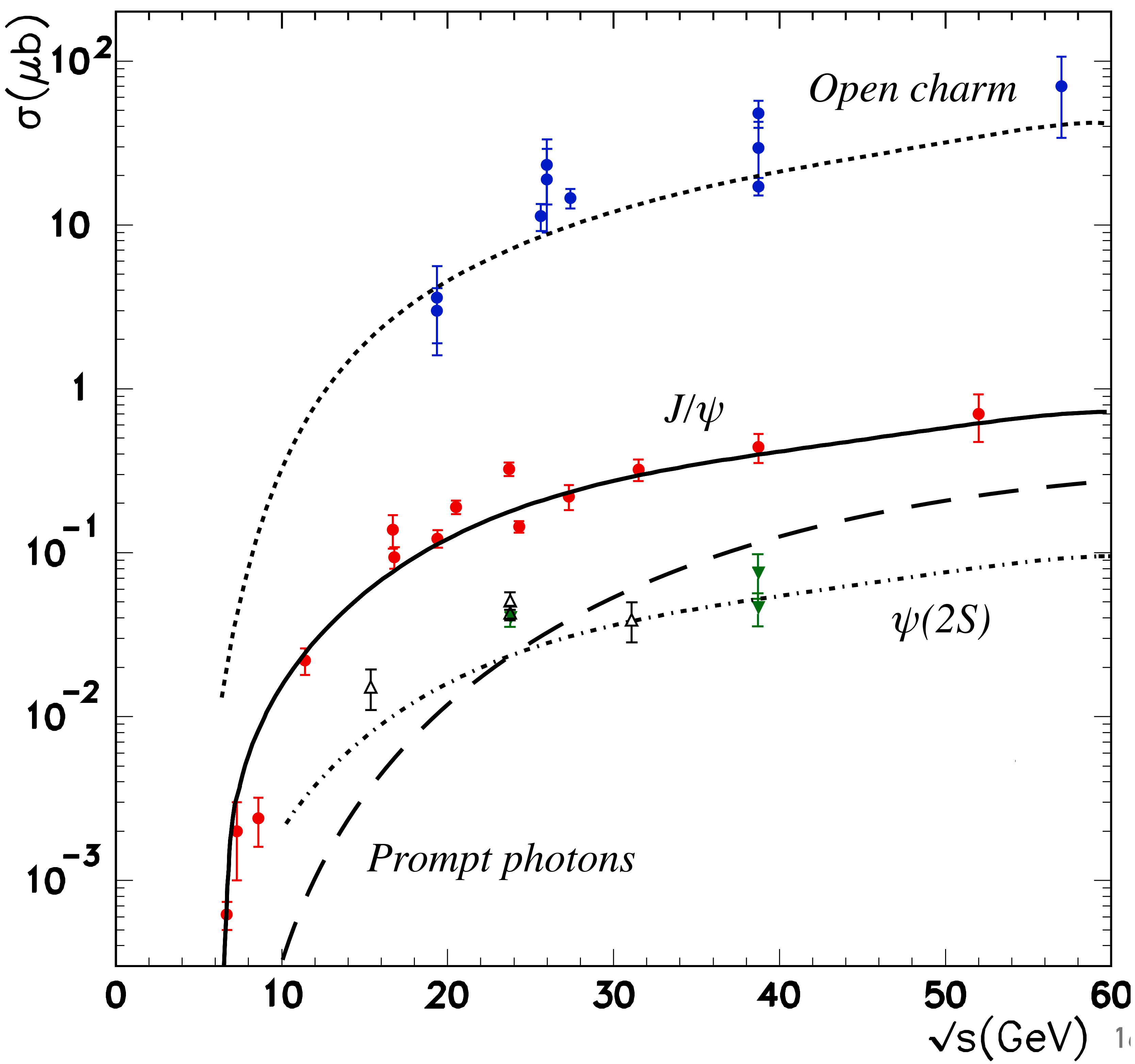


# Gluon probes at SPD: charmonia, open charm, direct photons

*not only J/ψ!*

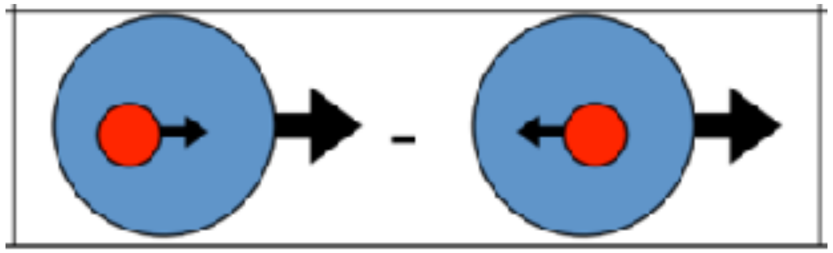



$$\sigma = PDF_1 \otimes PDF_2 \otimes \hat{\sigma}_{12}$$

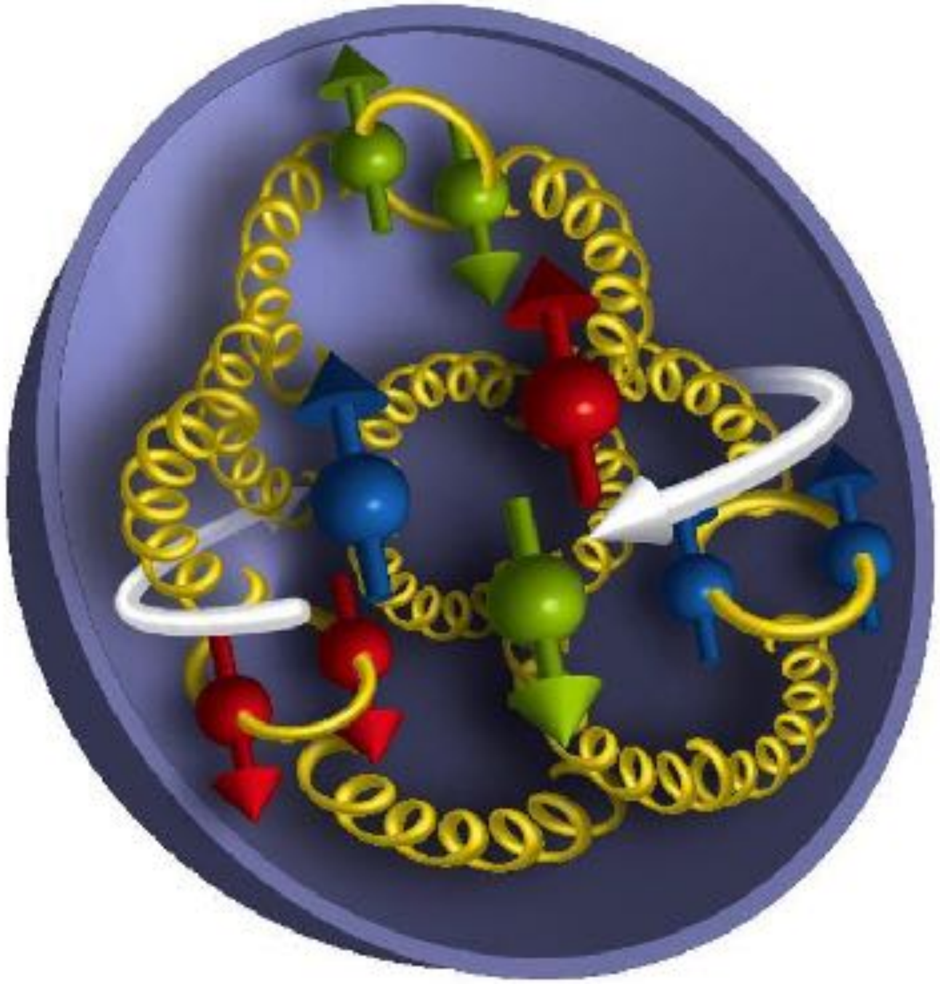


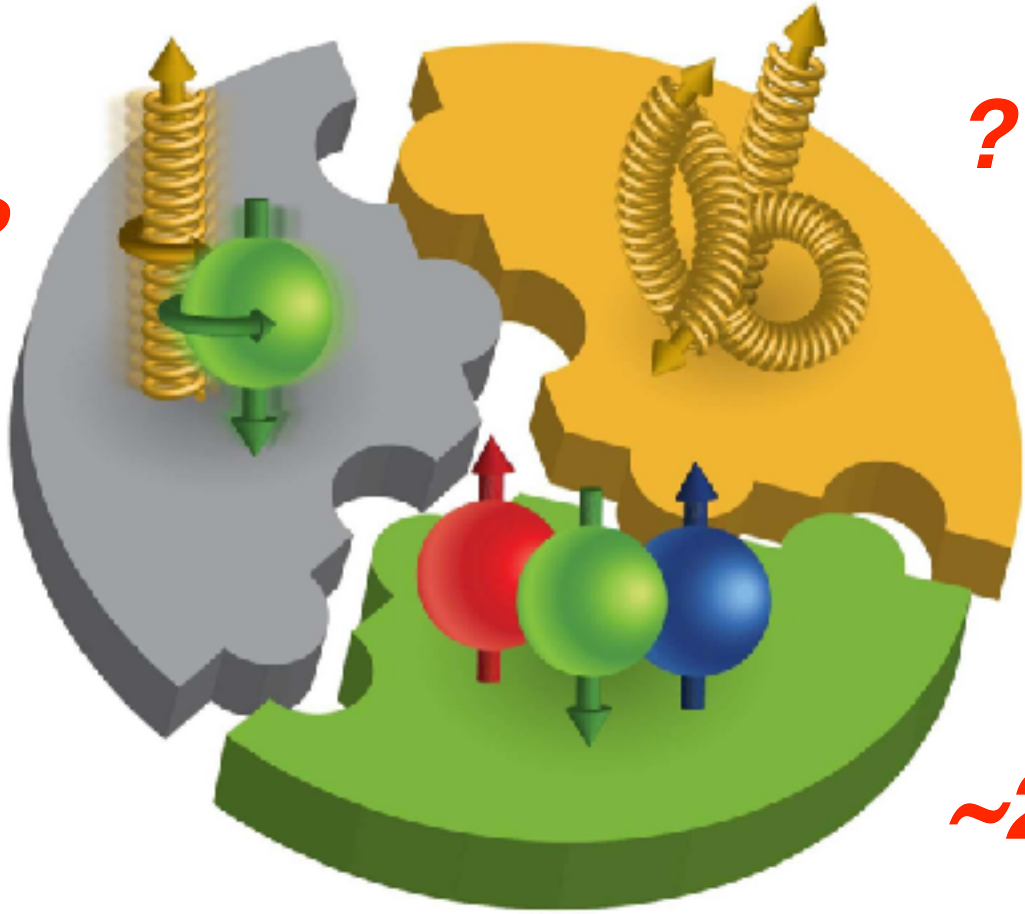
# Helicity gluon PDF Δg(x): Spin Crisis

Δg(x) :



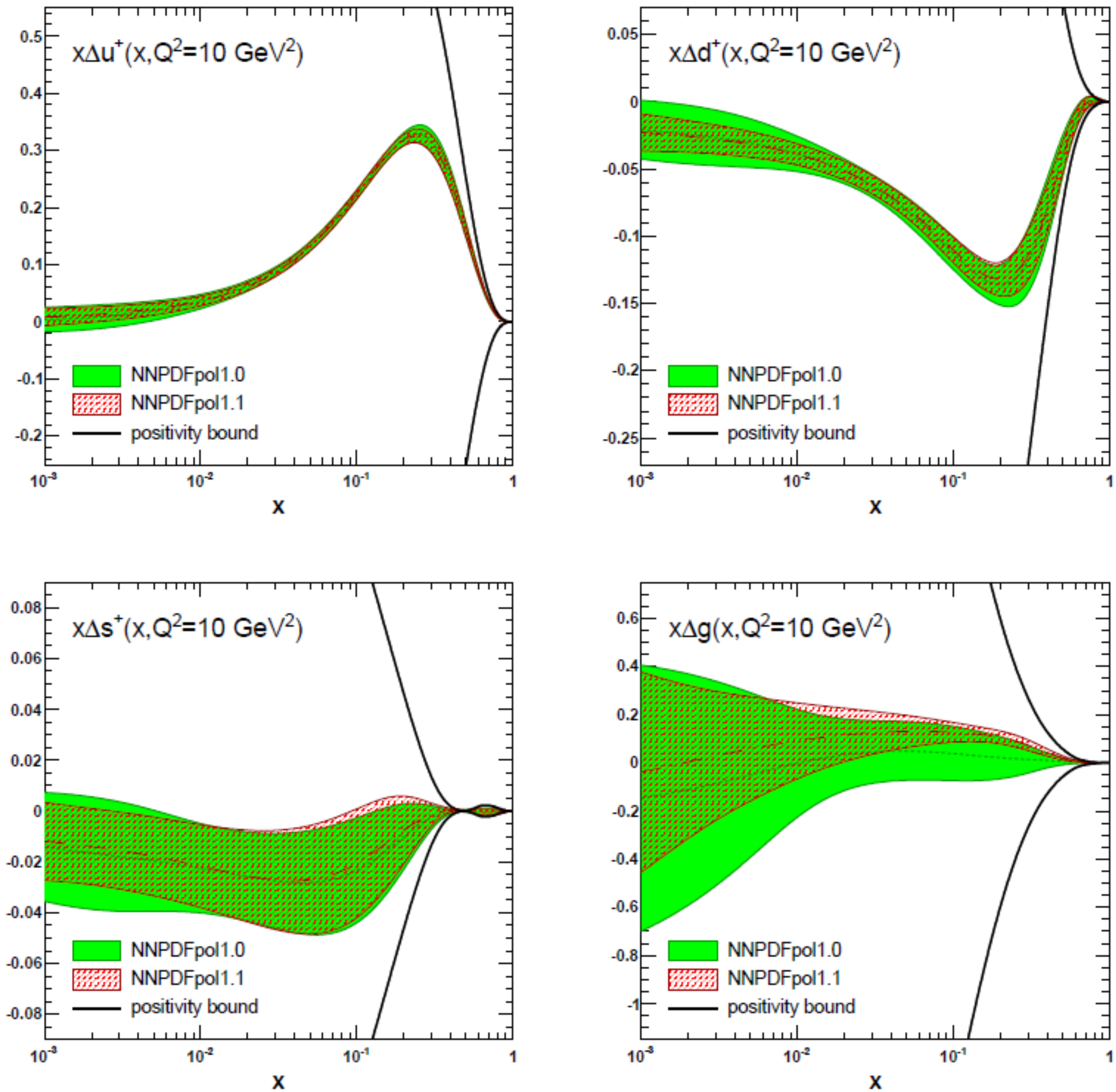

$$\Delta G = \int_0^1 \Delta g(x) dx$$






$$S_N = \tfrac{1}{2} = \tfrac{1}{2}\,\Delta\Sigma + \Delta G + L$$

# 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**

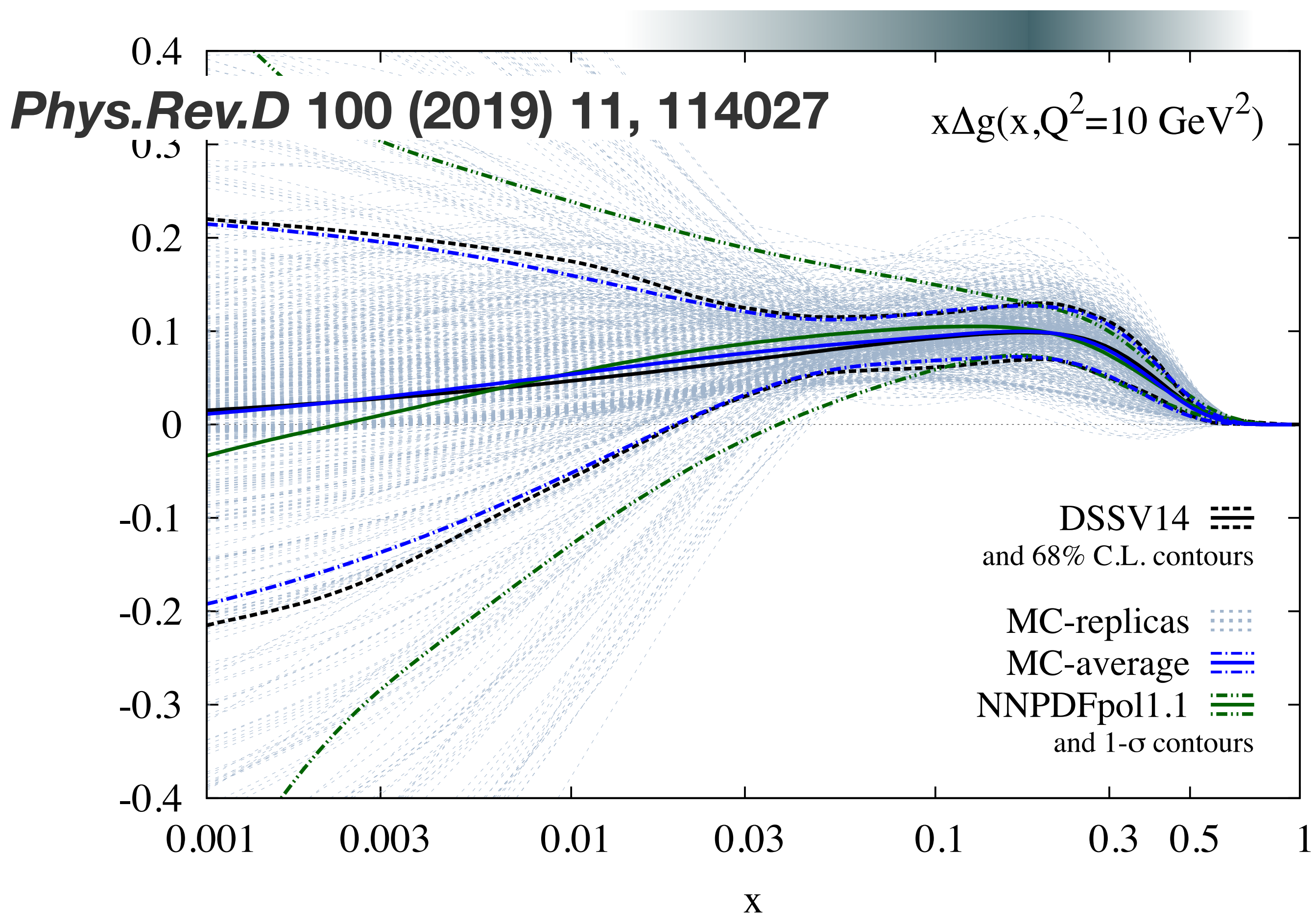
**Gluon helicity PDF:**
**still rather high uncertainties!**

**Hadron collisions have a better**
**sensitivity to measure it.**

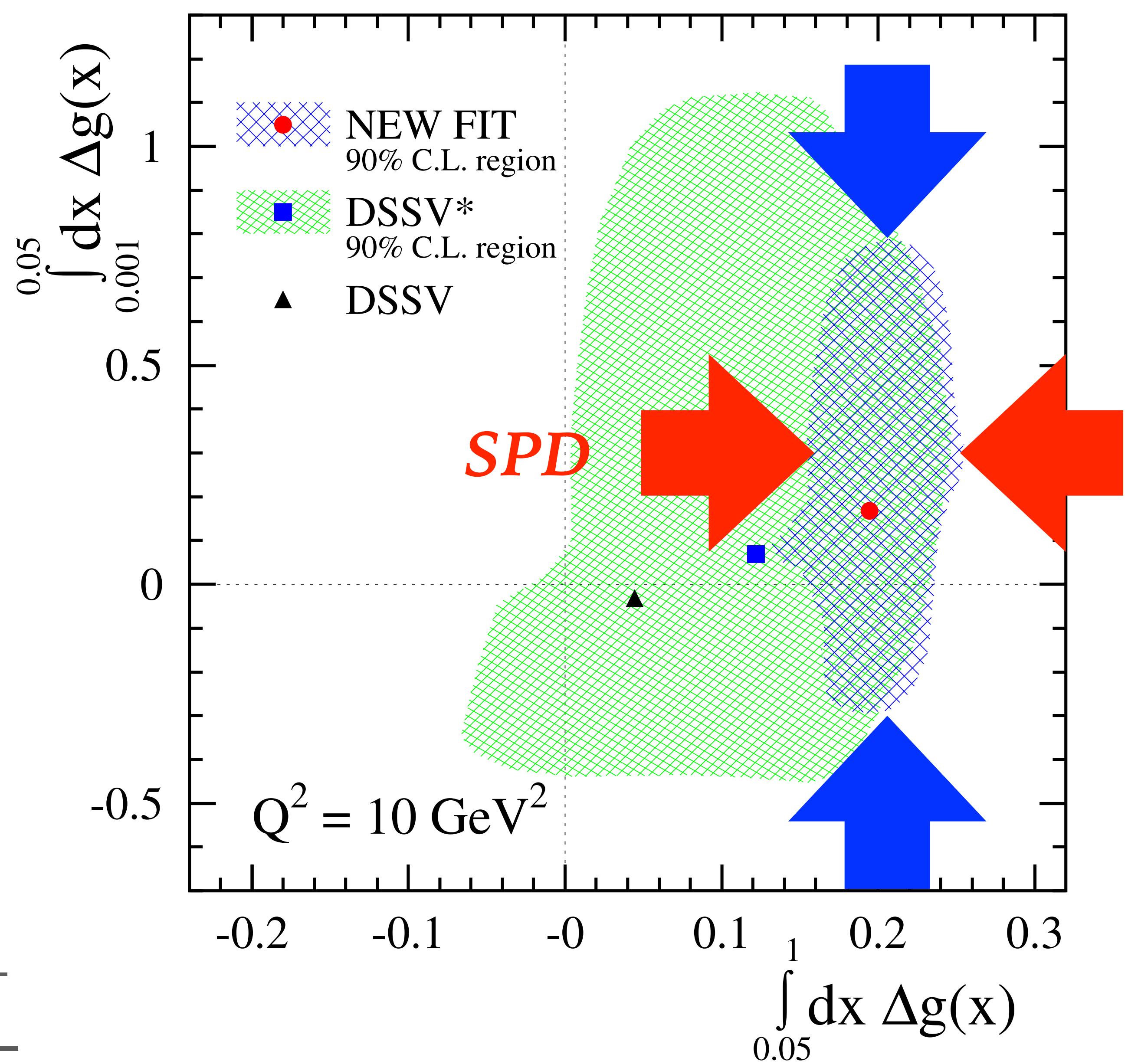
**⬅ SPD has a good opportunity!**

# Helicity gluon PDF Δg(x):

*accessible with SPD*




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




*SPD could help to reduce uncertainty of ΔG at large x*

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

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

# 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:**

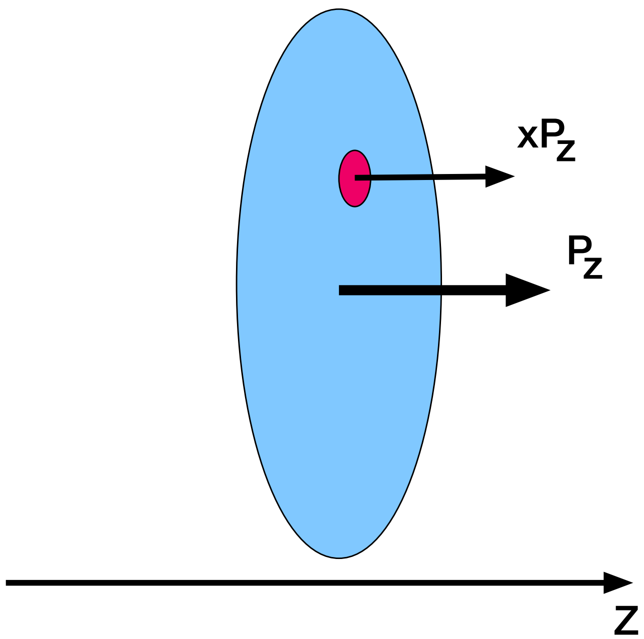
- ► **Generalized parton distributions (GPDs): G(x, b, n; logQ$^2$)**
  **b - impact parameter, n – unit vector**

- ► **Unintegrated over kT PDF: Φ(x, kT, n; logQ$^2$) (two theory approaches):**

  - ➥ **Unintegrated collinear PDF (uPDF)**

  - ➥ **Transverse momentum distribution (TMD)**

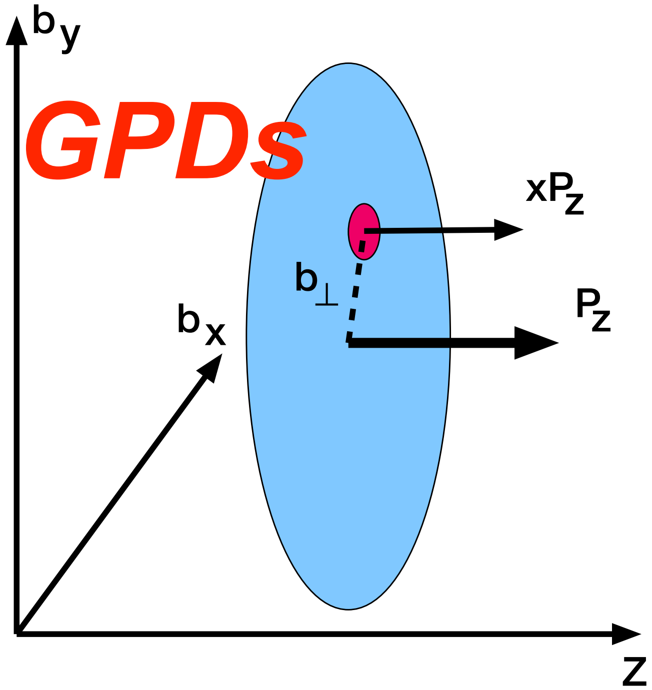
# SPD: towards 3D-structure of nucleon




Collinear approximation

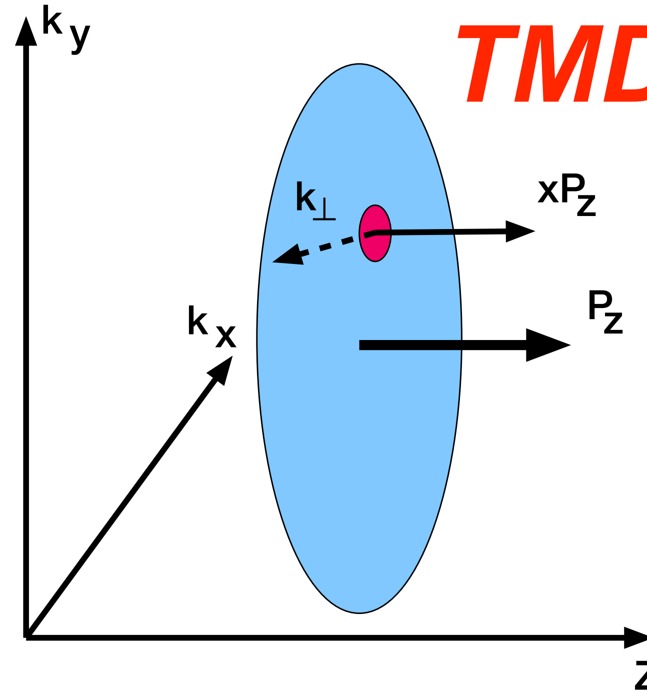
(common PDF)

GPDs



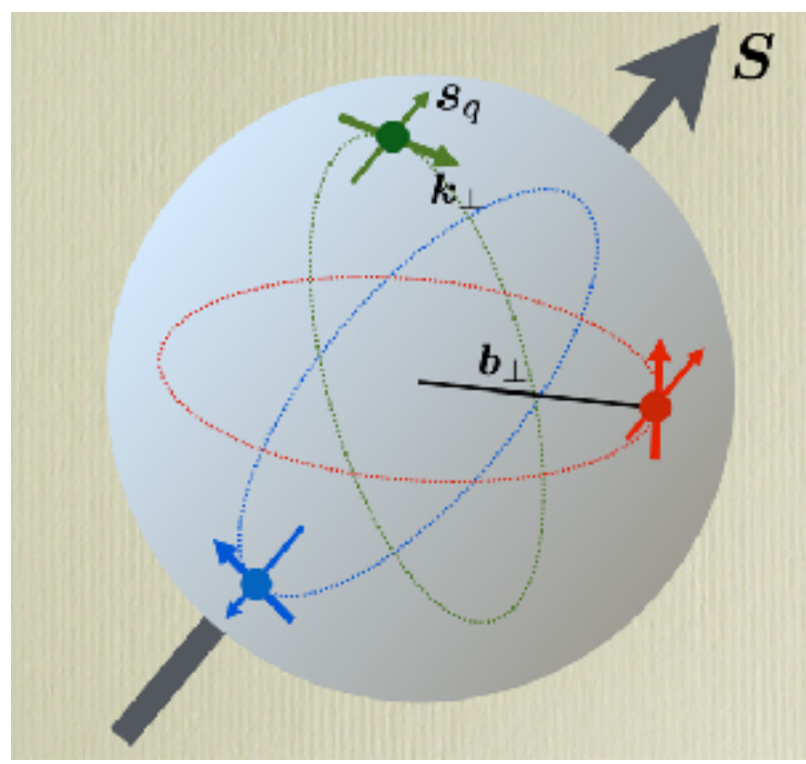

Generalized Parton Distributions

TMD PDFs




Transverse Momentum Dependent PDFs

3D structure of nucleon




connection to orbital moment

13

# 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

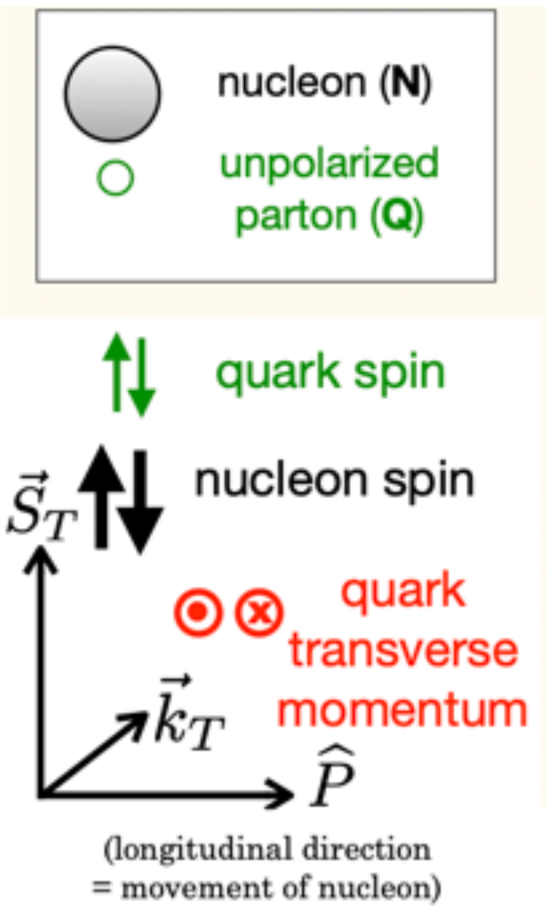
and time-odd functions (spin-orbital correlations):

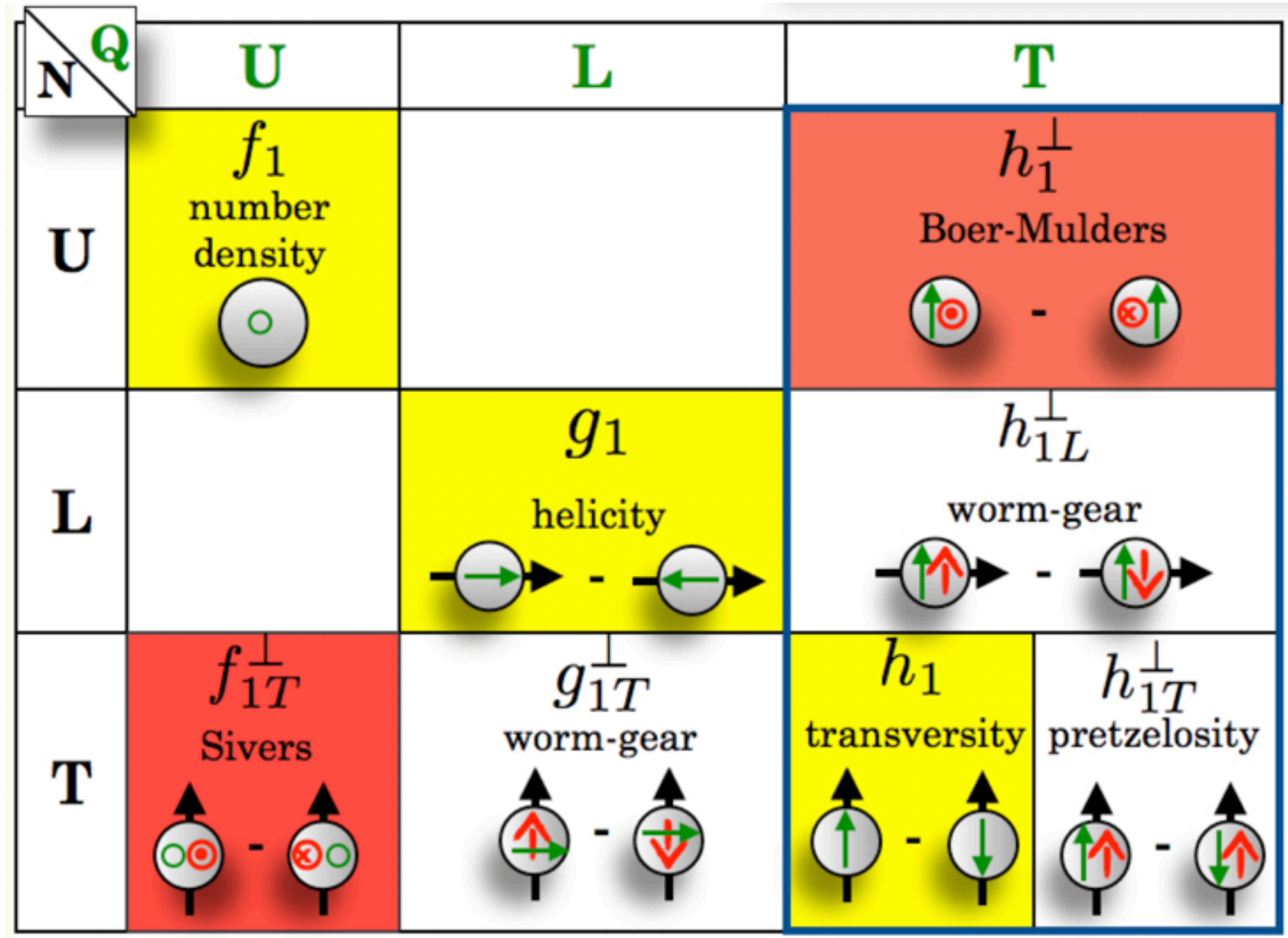
$f^{\perp q}_L(x, kT)$ ⬅ unpolarized quarks in T-polarized N ⬅ Sivers f.
$h^{\perp q}_T(x, kT)$ ⬅ T-polarized quarks in unpolarized N ⬅ Boer-Mulders f.

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



# Gluon TMD with SPD

Unpolarized gluons at high x in proton and deuteron

Gluon helicity

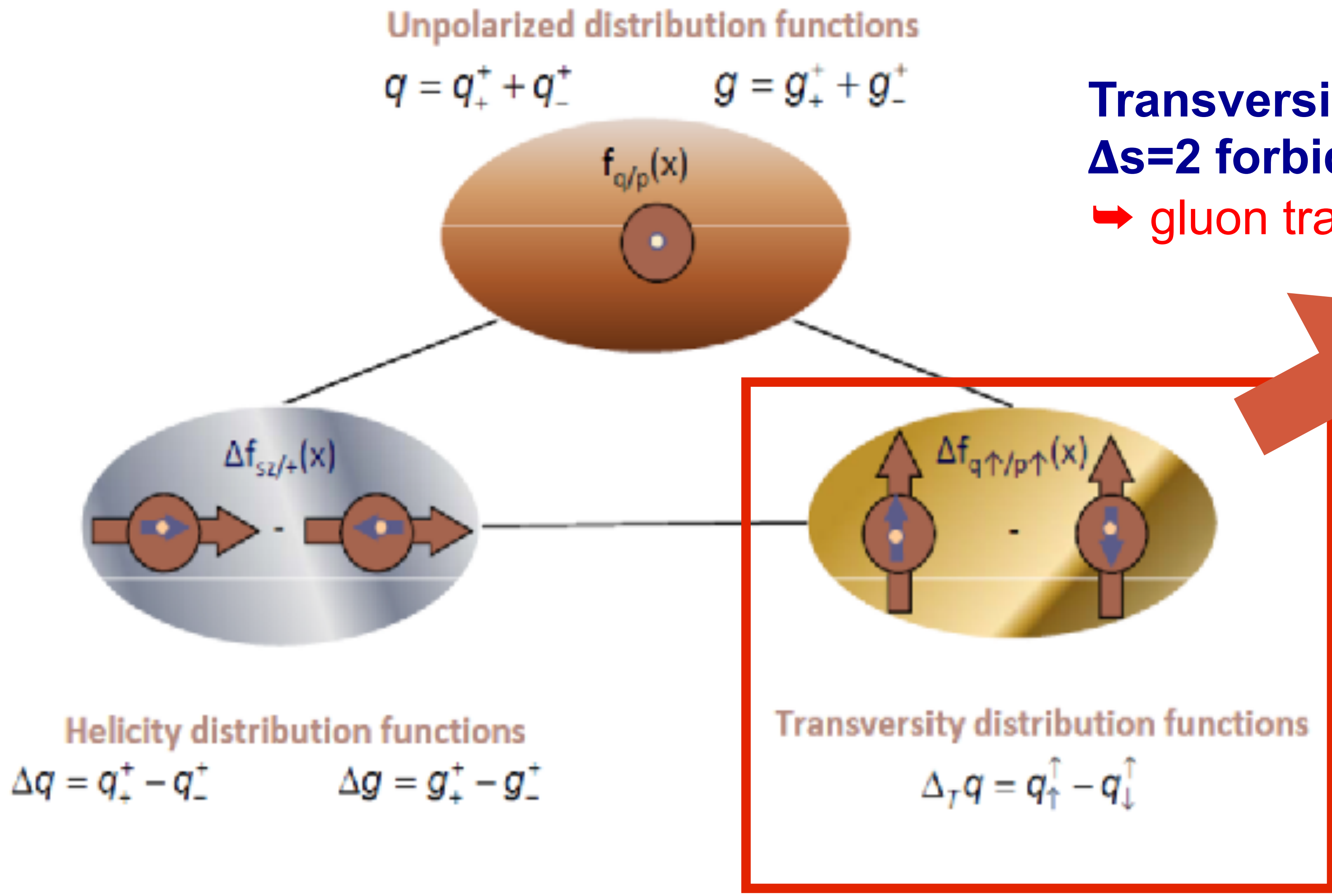
Gluon Boer-Mulders function

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

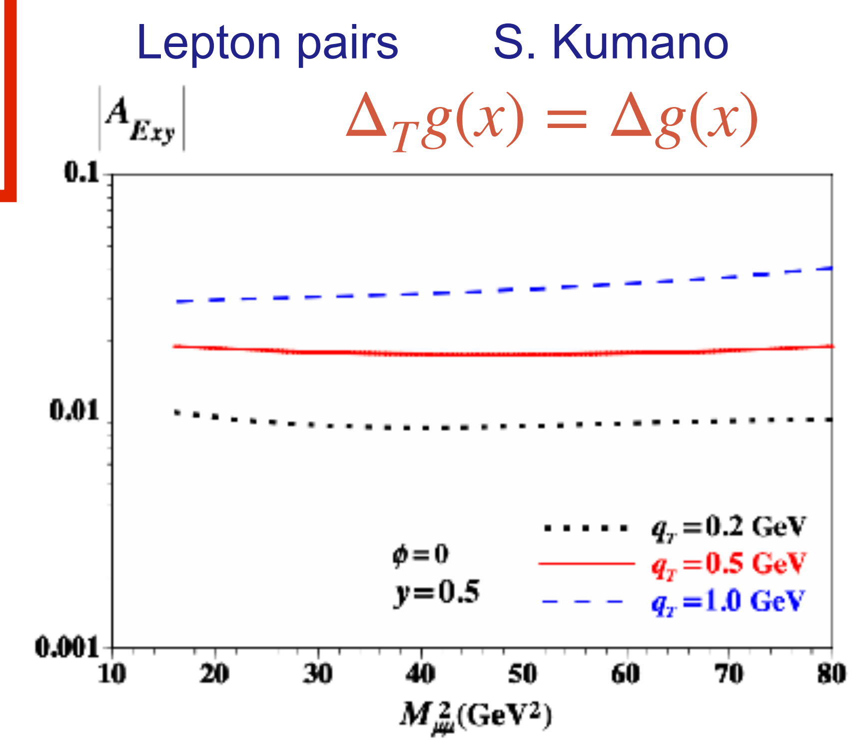
Gluon Sivers function

Gluon transversity in deuteron

# Gluon transversity of deuteron



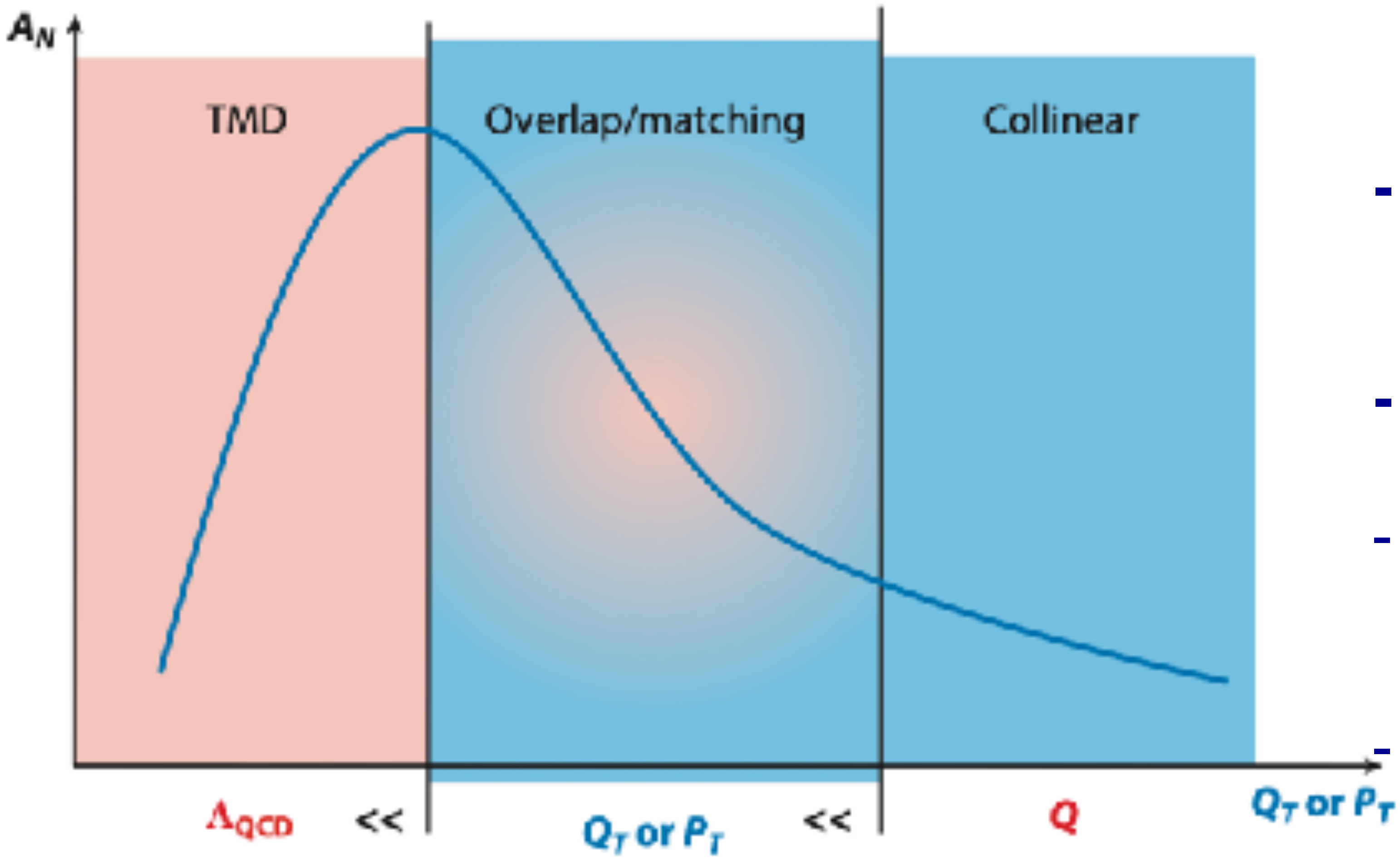

**Transversity comes from spin-flip:**
**Δs=2 forbidden for spin-½ nucleon in LO**
➥ gluon transversity in nucleon ≈ 0




**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!**

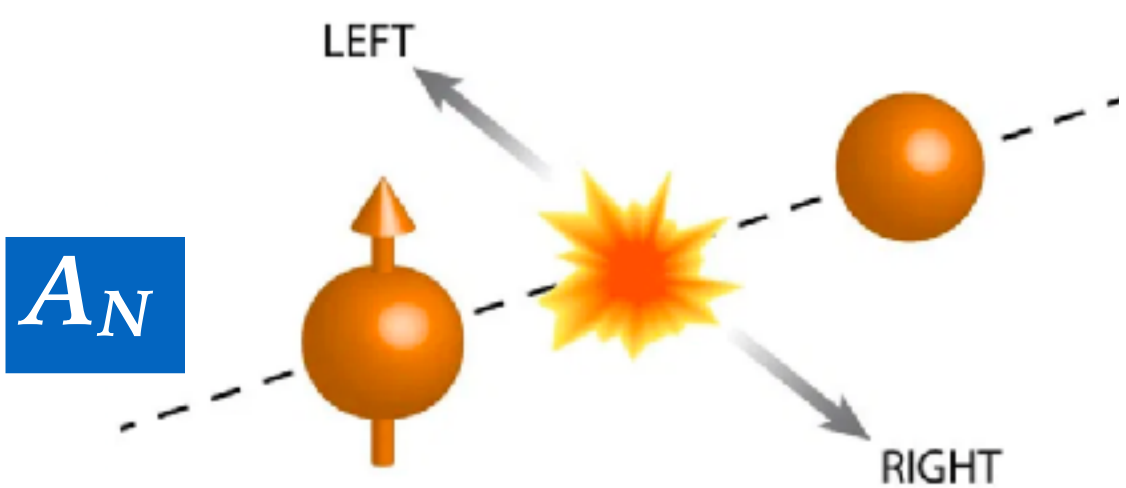
# Gluon TMD effects: gluon Sivers function




- 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



# SPD Physics at the initial Stage I

**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**
- ► **Search for exotic states (glueball, penta- and tetra- quarks)**
- ► **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**
- ► **Large-pT hadron production to study multiparton scattering**
- ► **Antiproton production measurement for astrophysics and BSM search**
- ► **…**

# PNPI @ SPD

**ПИЯФ**

**В.Т. Ким, Е.В. Кузнецова, А.В. Зеленов, Д.Е. Соснов, М.Ю. Малышев, С.А. Буланова, А.В. Сергеев**
**О.Л. Федин, В.П. Малеев, С.Г. Барсов**
**В.Л. Головцов, Л.Н. Уваров**
**А.К. Кирьянов**

**► Физика:**
- поиск экзотических резонансов: глюболы, пента- и тетра- кварки
- многопартонные взаимодействия
- дикварковые степени свободы
- МК генератор ULYSSES

**► Трековая система:**
- Считывающая система: оптимизация ASIC-решений
- Высоко- и низко- вольтные системы

**► Компьютинг и передача данных**

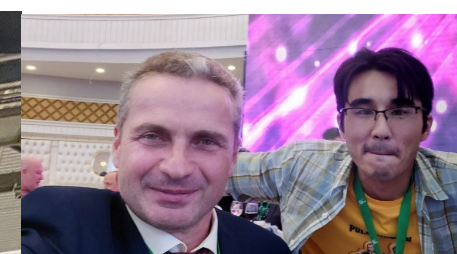
**► Фиксированная мишень 2024+**

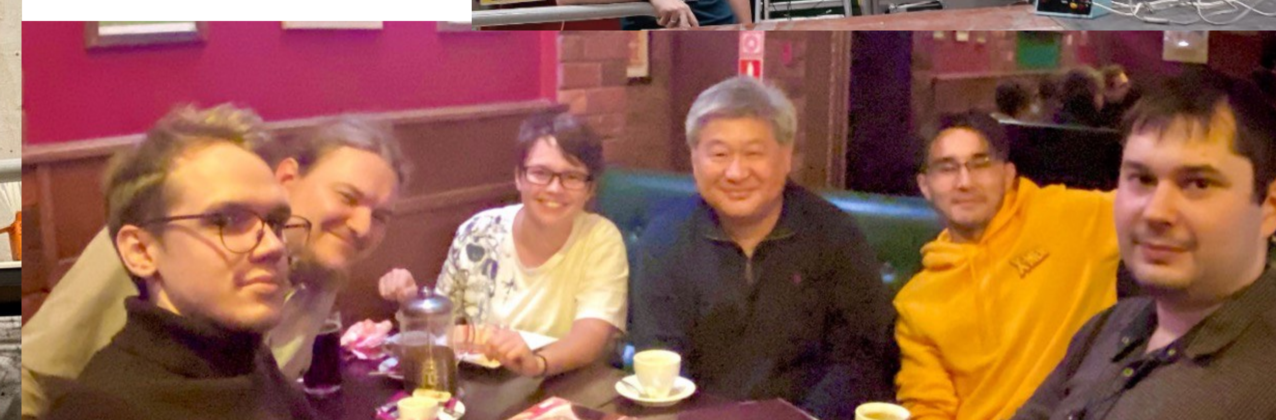
# Трековая система SPD: R&D

## Группа ПИЯФ (Е.В. Кузнецова) & Группа ОИЯИ (Т. Еник): Трековая система SPD: R&D тонкостенных трубок и ASIC решений

► **Стенд Трековой системы SPD/SHiP/Dune/RD51 на СПС ЦЕРН для определения требований к считывающей электронике**

**Сеансы тестовых измерений с ASIC: VMM3,VMM3a, Tiger**
- 2021 (октябрь),
- 2022 (апрель-май, май-июнь, июль, октябрь-ноябрь)
- идет обработка данных
- часть результатов включены в текущую версию SPD TDR



# Дополнительные возможности SPD

## Тестовая зона SPD:
## возможности SPD физики в моде фиксированной мишени

# ЗАКЛЮЧЕНИЕ

► Spin Physics Detector (SPD) – универсальный детектор на коллайдере NICA (http://spd.jinr.ru):
Детальное изучение поляризованной и неполяризованной (глюонной) структуры протона и дейтрона в pp- и dd- соудареениях при высокой светимости до $\sqrt{s} < 27$ ГэВ

► Дополняющие друг друга пробники: кварконии (J/Psi и высшие состоянии), открытый чарм и прямые фотоны

► SPD должен улучшить понимание 3D глюонной структуры:
- поляризованные глюонные распределения
- неполяризованные PDF и TMD при высоких x в протоне и дейтроне
- глюонная трансверсити (transversity) в дейтроне …

► Широкая программа на первой стадии SPD:
- поиски экзотических резонансов (глюболы, пента- и тетра- кварки), …
- многокварковые флуктоны и малонуклонные корреляции …

► Физическая программа SPD является дополняющей исследования на COMPASS++/AMBER, RHIC, AFTER@LHC, LHC-spin, EIC

► SPD CDR: arXiv:2102.00442

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

# С наступающим Новым Годом!