Spin Physics Detector

SPD NICA

Экперимент SPD
на коллайдере NICA

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НИЦ «Курчатовский Институт»

SPD at NICA (JINR, Dubna)

NICA:
Nuclotron-based Ion Collider fAcility

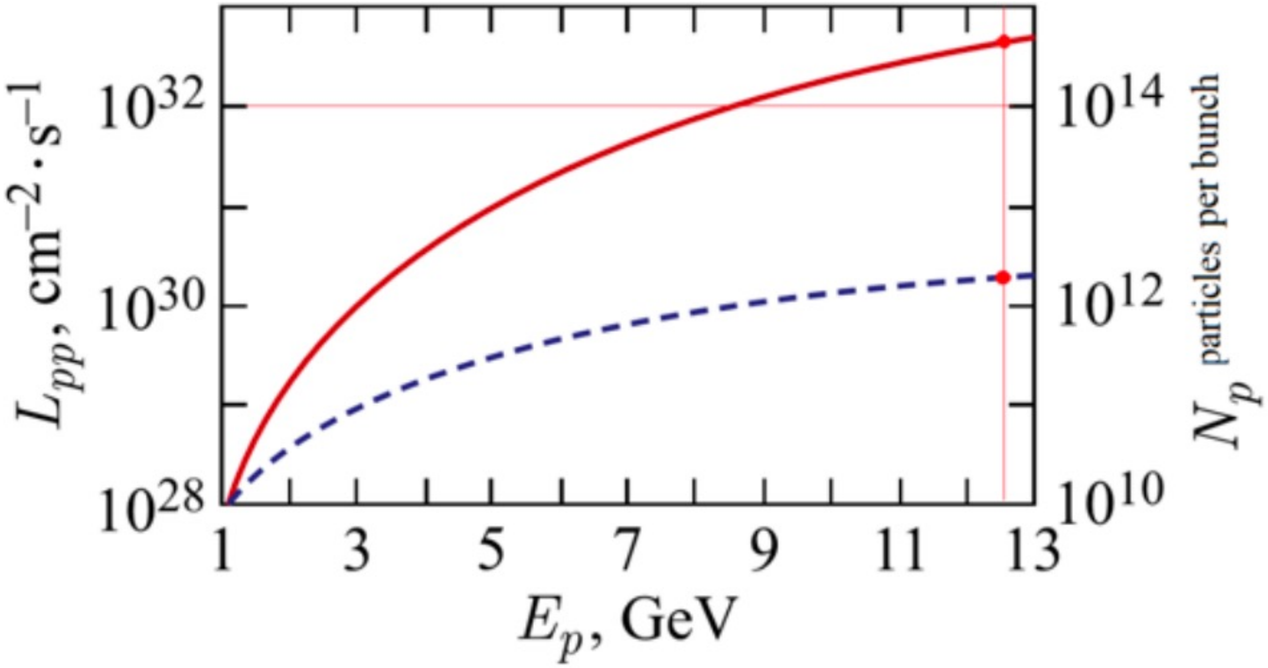
$p^{\uparrow}p^{\uparrow} : \sqrt{s} \leq 27\ GeV$

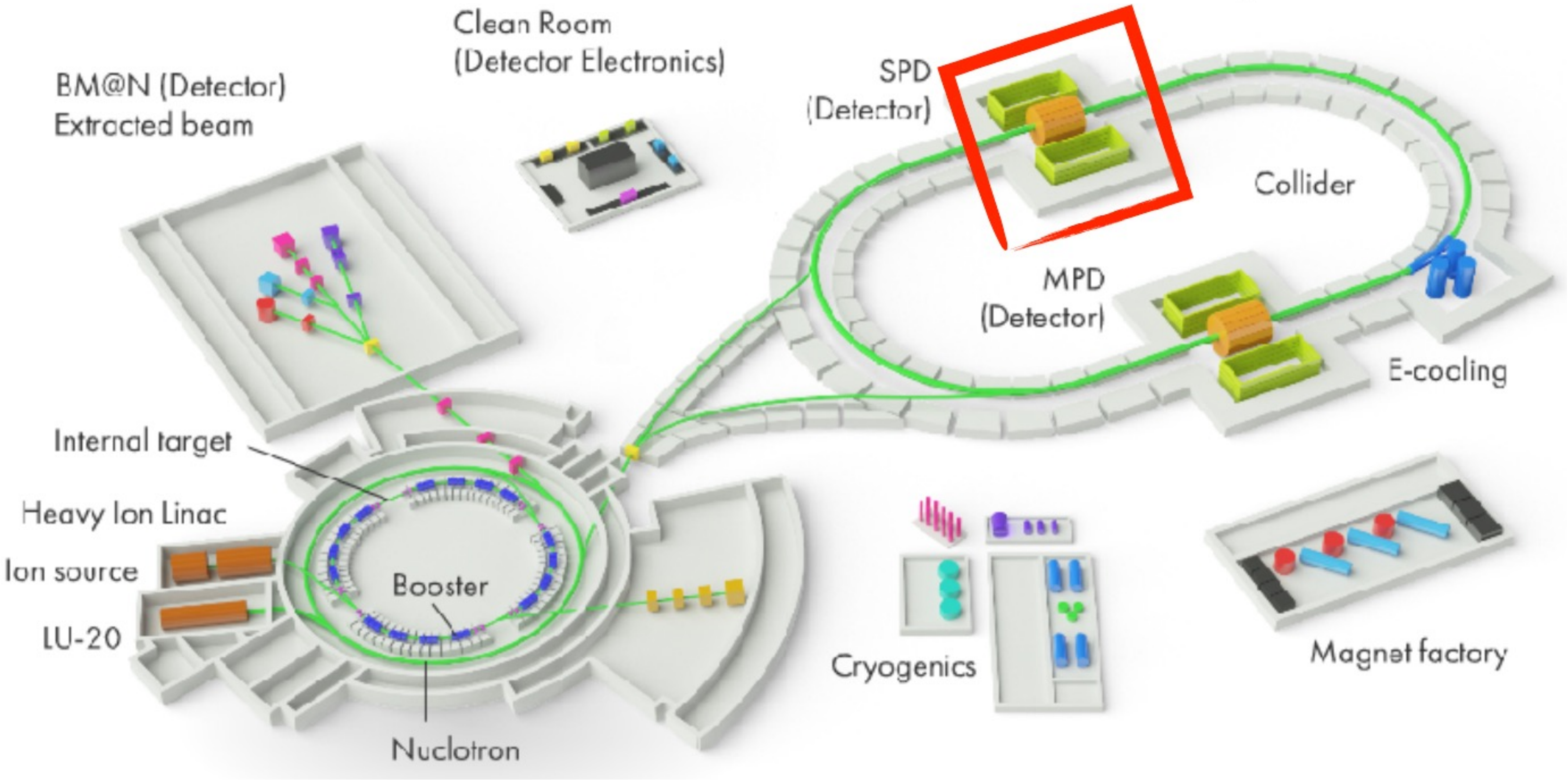
$d^{\uparrow}d^{\uparrow} : \sqrt{s} \leq 13.5\ GeV$

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

U, L, T

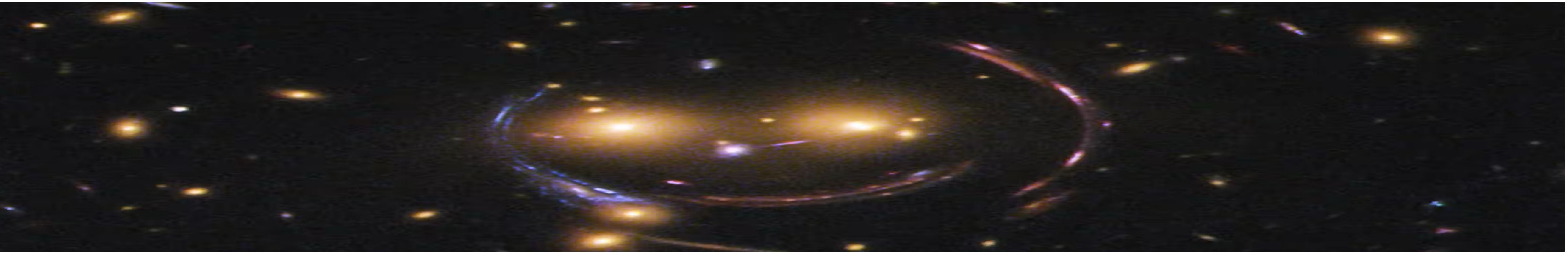
$|P| > 70\%$





ОИЯИ (Дубна): Ускорительный Комплекс NICA

Why nucleon structure?



- proton mass -> the visible Universe mass

Electroweak Higgs boson provides:
current quark masses ~ m_U=3 MeV, m_D=7 MeV ➥ 2% proton mass

➥ quark-gluon dynamics of nucleon structure provides:
~ 98% of the mass of the visible Universe!

- nucleon size ~ 1 Fm:
naïve quark model ➥
huge neutron electric dipole moment (EDM)
exceeding 10^12 observed value!

Why Spin?

Spin: pure quantum characteristics

spin: no classical analog

➥ **quantum entanglement,**
quantum computers, ….

spin observables

➥ **hadron wave functions**
process amplitudes

“proton spin crisis” :
naïve quark model (valence quarks)
➥ **only 1/3 of proton spin !**

Spin physics: very high energy?

Spin effects in QCD: size value

naïve expectations

➥ **current quark: few MeV**

$m_q/m_N \sim 1\%$

Spontaneous symmetry breaking

➥**constituent quark mass: few hundred MeV**

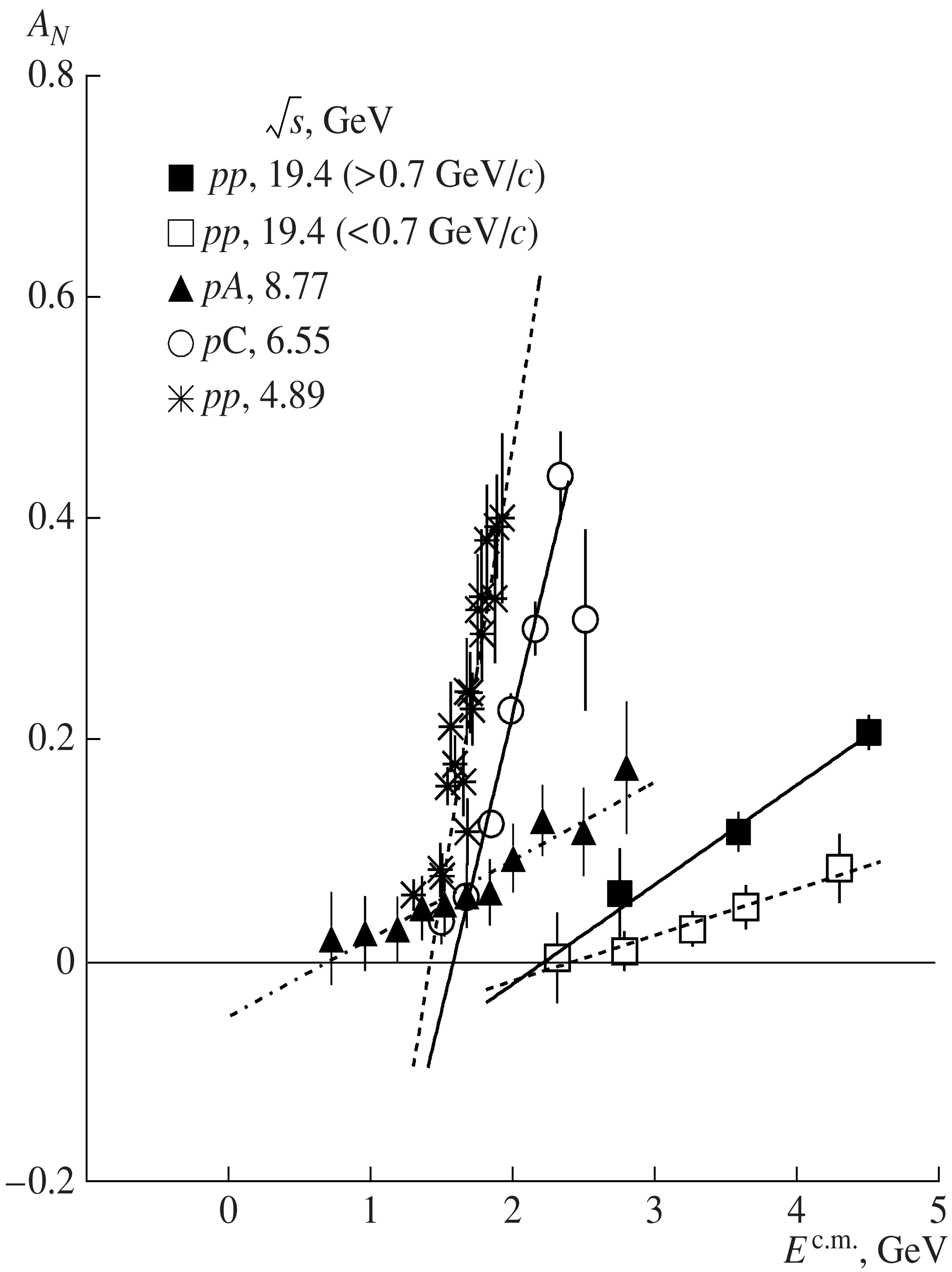
$m_Q/m_N \sim 40\%$

polarized PDF evolution:

➥ **twist-2 & twist-3 (1/Q)**

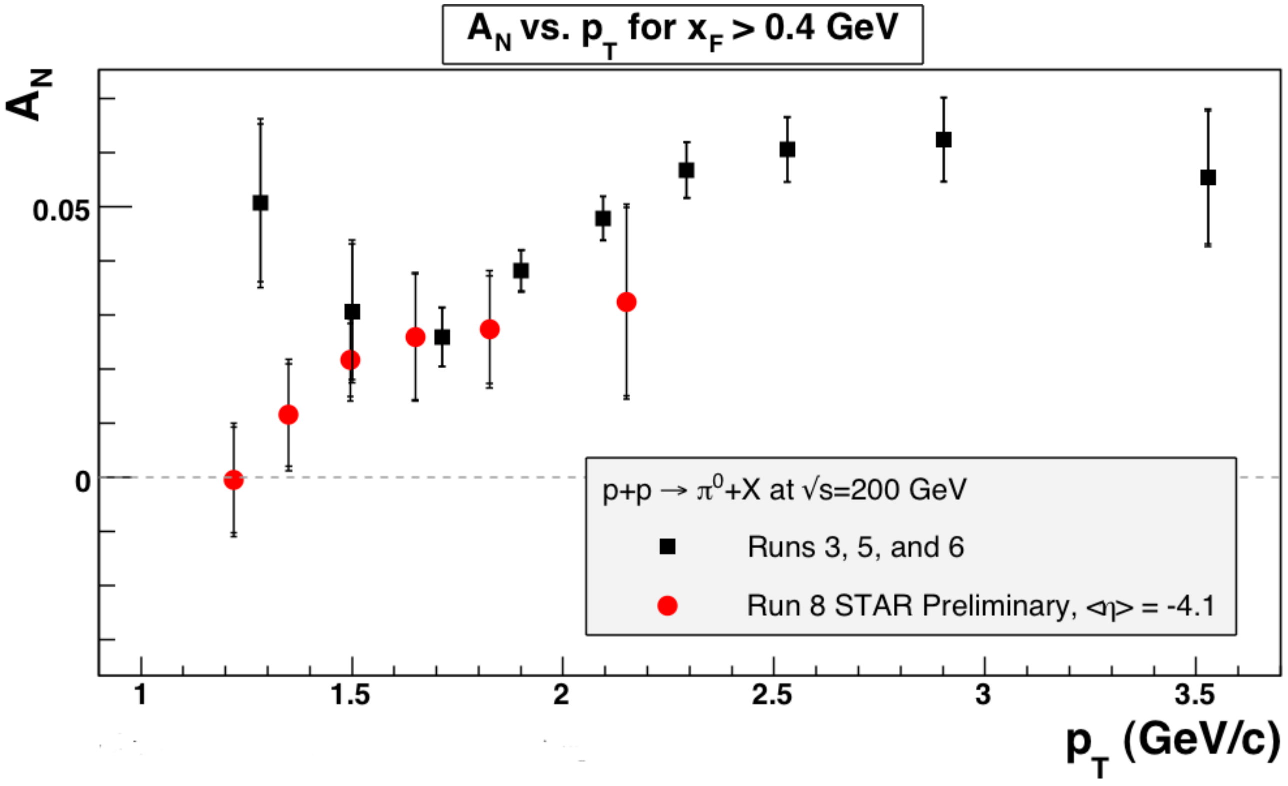
NICA energies: optimal for spin physics!

NICA energies: optimal for spin physics



Single-spin asymmetry A_N as a function of $E^{c.m.}$ for reactions of the type $p^{\uparrow}p(A) \to \pi^{+}X$

RHIC: √s=200 GeV **E_{CM} = 100 GeV**



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

A. Arbuzov et al. ,Prog. Part. Nucl.Phys. 119 (2021) 103858 e-Print: 2011.15005 [hep-ex]

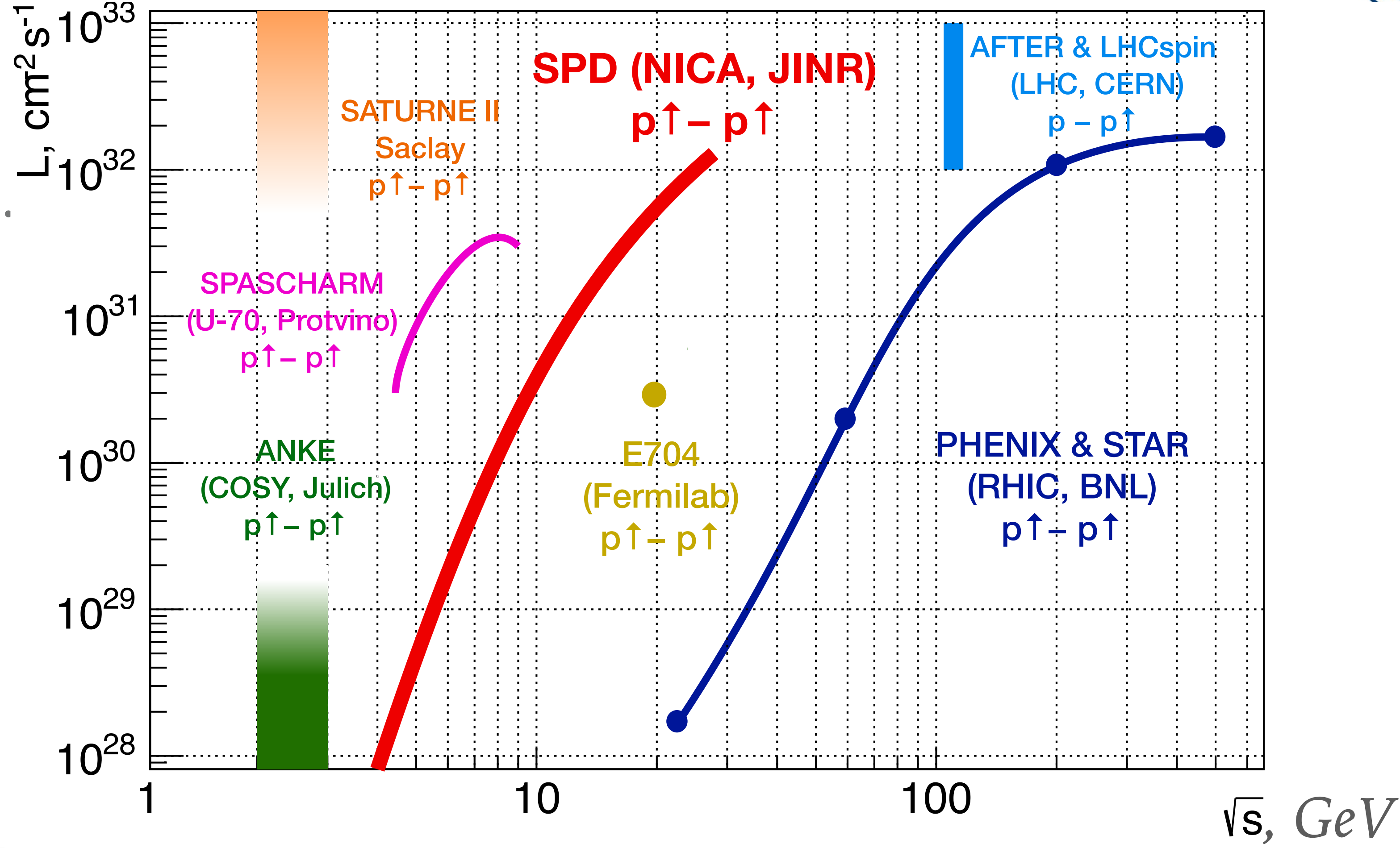
➥ **Запланирована программа в начальный период работы SPD для широкой области исследований ядерной физики и физики частиц**

V.V. Abramov et al., Phys. Part. 52 (2021) 1044, e-Print: 2102.08477 [hep-ph]

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

SPD in World landscape of polarized physics

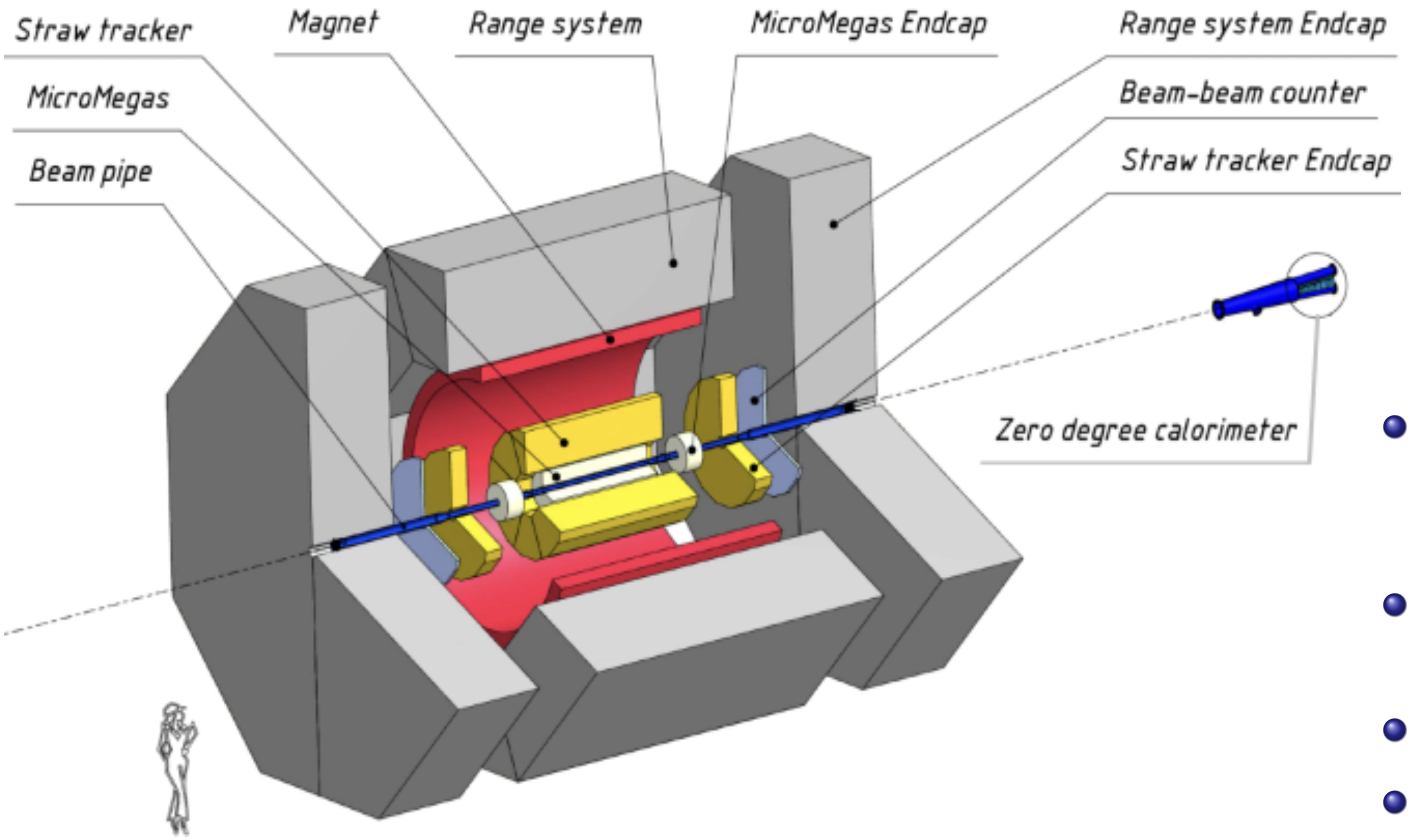
p↑ p↑-mode ➡️



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}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!

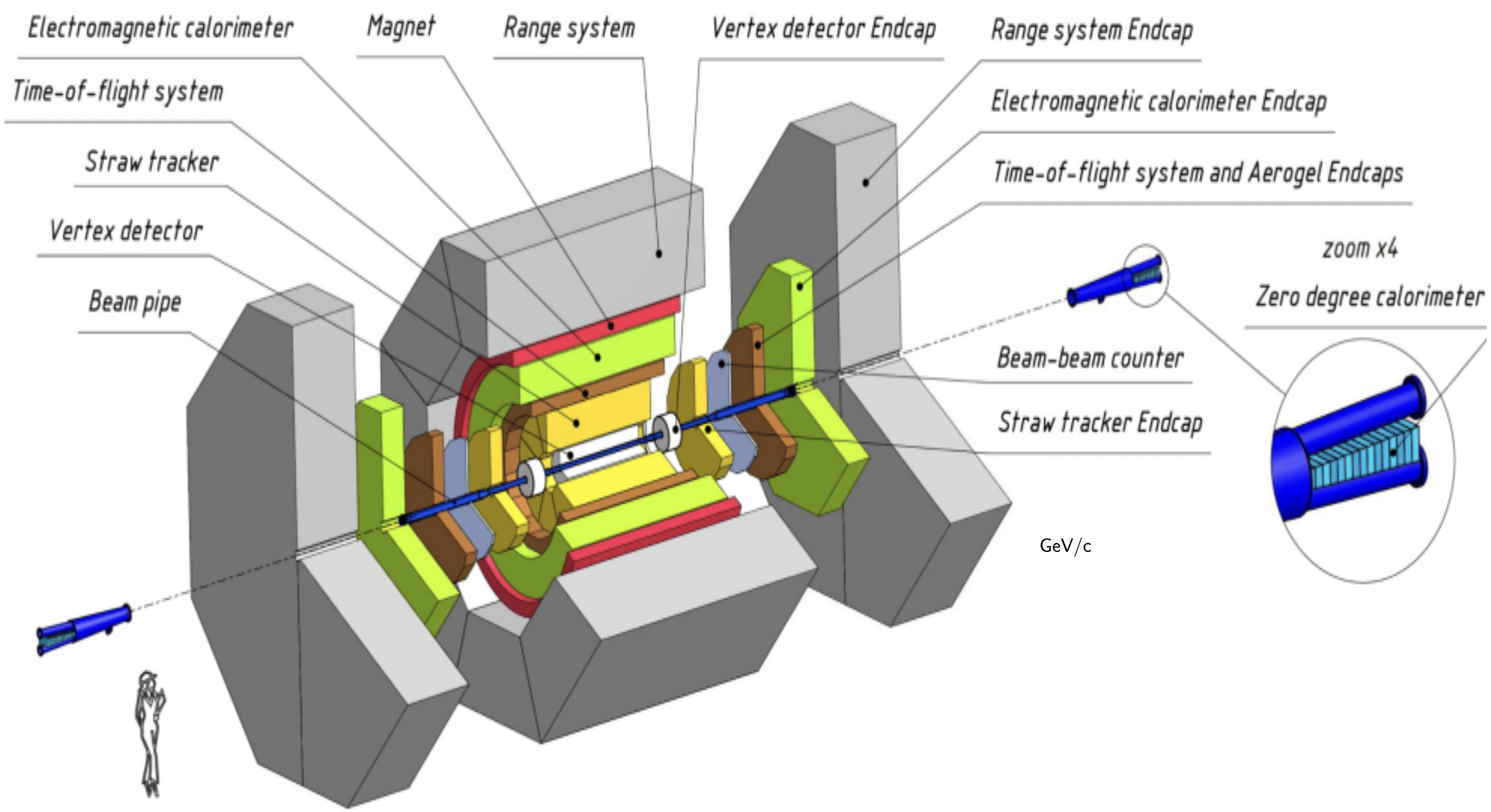
SPD detector at the Stage I



- 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, $\delta(\frac{dE}{dx}) = 8.5\%$

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

SPD detector at the Stage II



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

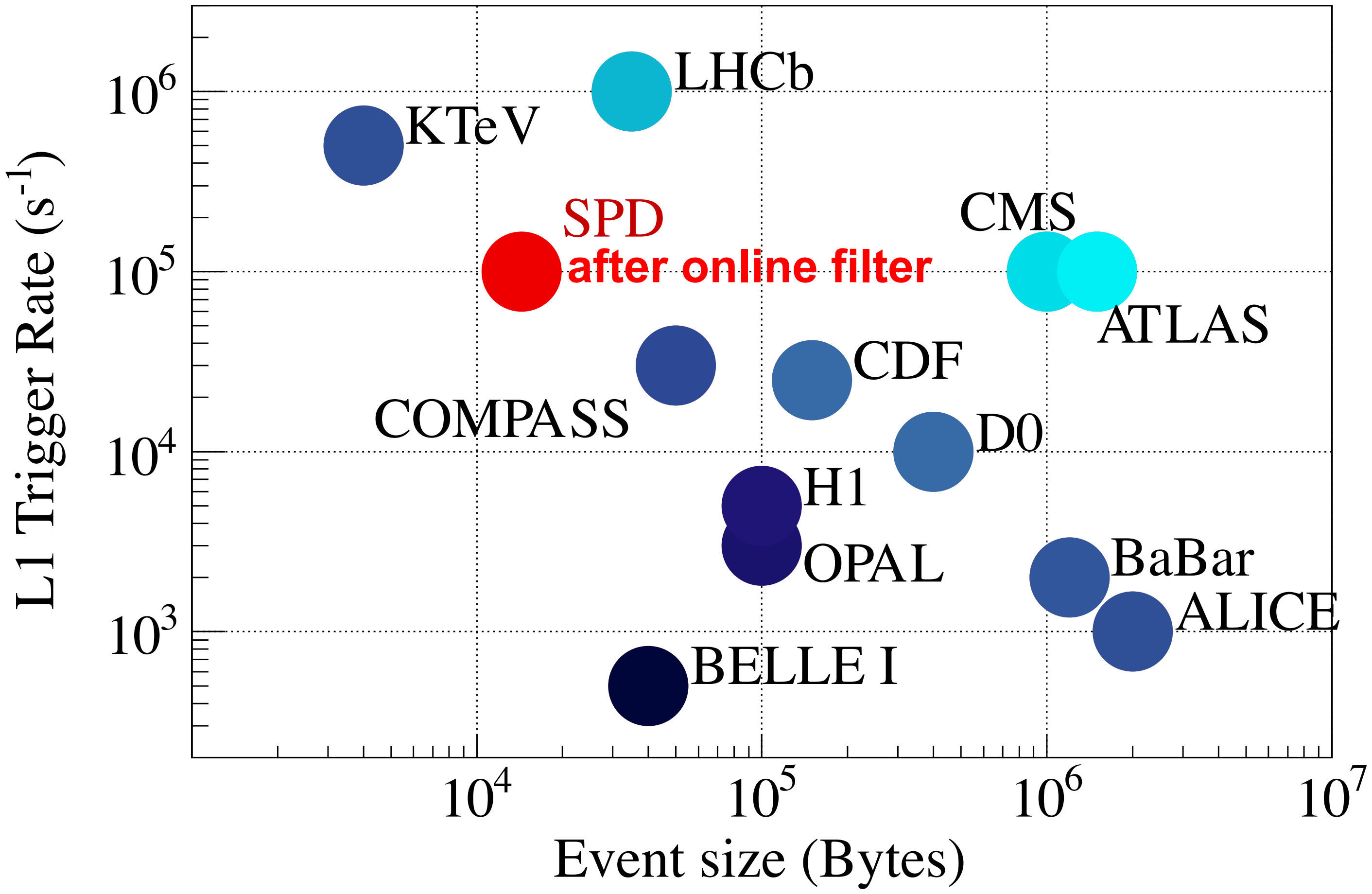
SPD detector data flow

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 at the Stage 2!
Comparable in data rate with ATLAS and CMS at LHC RUN1

SPD Tier-1:
NRC KI, Moscow ?
NRC KI - PNPI, Gatchina ?

SPD data rate after online filter



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 SPD Collaboration is established
Two SPD-physics papers were published

2023 SPD Technical Design Report (TDR): under review
http://spd.jinr.ru/wp-content/uploads/2023/03/TechnicalDesignReport_SPD2023.pdf

the 1st SPD Phase: included to the JINR 7-year Plan 2024-2030

SPD Collaboration: established in July 2021

Spin Physics Detector

The NICA-SPD Collaboration, July 2021

SPD Collaboration: established in July 2021

SPD Spokespersons:

Alexey Guskov (JINR, Dubna) Victor Kim (NRC KI - PNPI) Gatchina)

SPD Collaboration Board Chair:

Egle Tomasi-Gustafsson (CEA, Saclay)
deputy: Armen Tumasyan, (ANNL, Yerevan)

SPD Coordinators:

Hardware: Alexander Korzenev (JINR)
Software: Alexey Zhemchugov (JINR)
deputy: Danila Oleynik (JINR)
Software: Igor Denisenko (JINR)
deputy: Amaresh Datta (JINR)

36 organizations from 15 countries ~ 400 participants

SPD Collaboration: established in July 2021

Signed MoU (15+3):

NRC “Kurchatov Institute” - PNPI, Gatchina
Alikhanov National Science laboratory (Yerevan Physics Institute), Yerevan
Samara National Research University, Samara
Peter the Great Saint Petersburg Polytechnic University, St. Petersburg
Saint Petersburg State University, St. Petersburg
Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow
Lebedev Institute of Physics RAS, Moscow
Institute for Nuclear Research RAS, Moscow
Institute of Nuclear Physics (INP RK), Almaty
Tomsk State University, Tomsk
National Research Nuclear University MEPhI, Moscow
Belgorod State University, Belgorod
Institute of Nuclear Problems, Belorussian State University, Minsk
Budker Institute of Nuclear Phsycis RAS, Novosibirsk
Higher School of Economics, Moscow
* Higher Institute of Technologies and Applied Sciences, Havana
* NRC “Kurchatov Institute”, Moscow
* VINS, Belgrade

SPD Collaboration Meetings

2023: Dubna (April)
Samara (October)
2024: Almaty (May)
Dubna (October)

36 organizations from 15 countries ~ 400 participants

ЗАКЛЮЧЕНИЕ

► Spin Physics Detector (SPD) – универсальный детектор на коллайдере NICA:
Детальное изучение поляризованной и неполяризованной (глюонной) структуры протона и дейтрона в pp- и dd- соударениях при высокой светимости до √s < 27 ГэВ

► 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 …

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

► Широкая программа на 1-й Стадии SPD:
- поиски экзотических резонансов (глюболы, пента- и тетра- кварки), …
- многокварковые флуктоны и малонуклонные корреляции …

► Большой поток данных (сравним с экспериментами БАК в RUN1)

► SPD TDR: *http://spd.jinr.ru* проходит международную экспертизу (утверждение: июнь 2024?)

► 1-я Стадия SPD включена в 7-летний план ОИЯИ 2024-2030

► SPD R&D: оптимизация физических сигналов, оптимизация дизайна,
изготовление и тестирование прототипов,
подготовка к производству

РЕЗЕРВНЫЕ СЛАЙДЫ

SPD Physics highlights

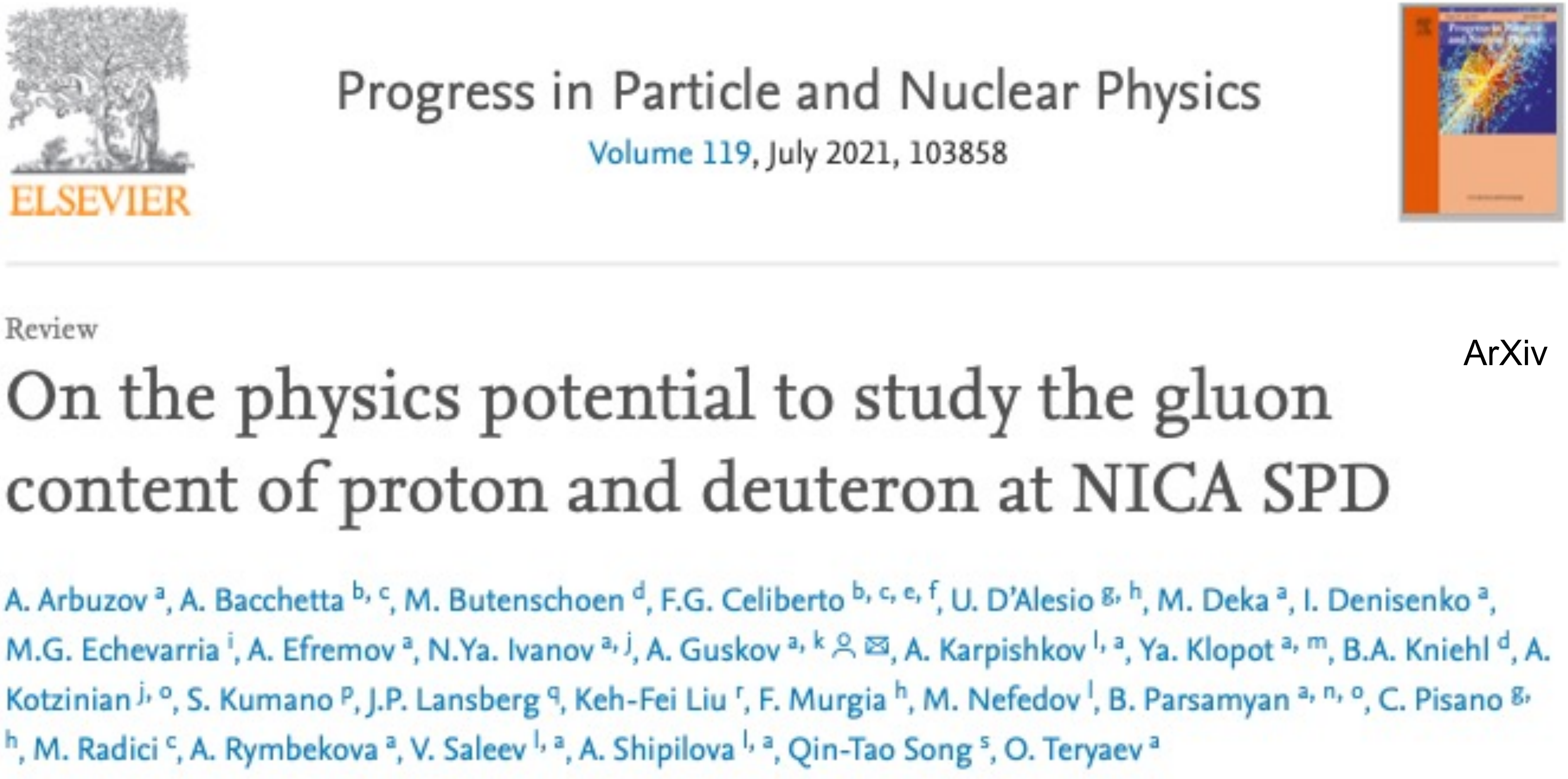
► Spin Physics Detector (SPD) at NICA (http://spd.jinr.ru):
a universal setup for comprehensive study of
polarized and unpolarized gluon content of proton and deuteron
in polarized and unpolarized high-luminosity pp- and dd- collisions at $\sqrt{s} \leq 27$ GeV

► 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

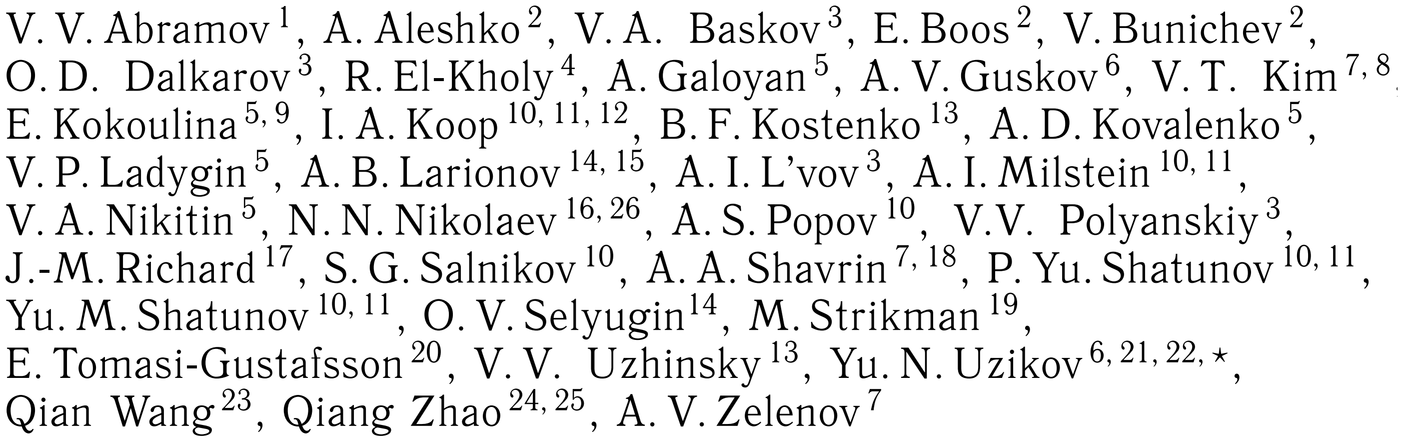
Review

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]

ArXiv e-Print: 2011.15005 [hep-ex]

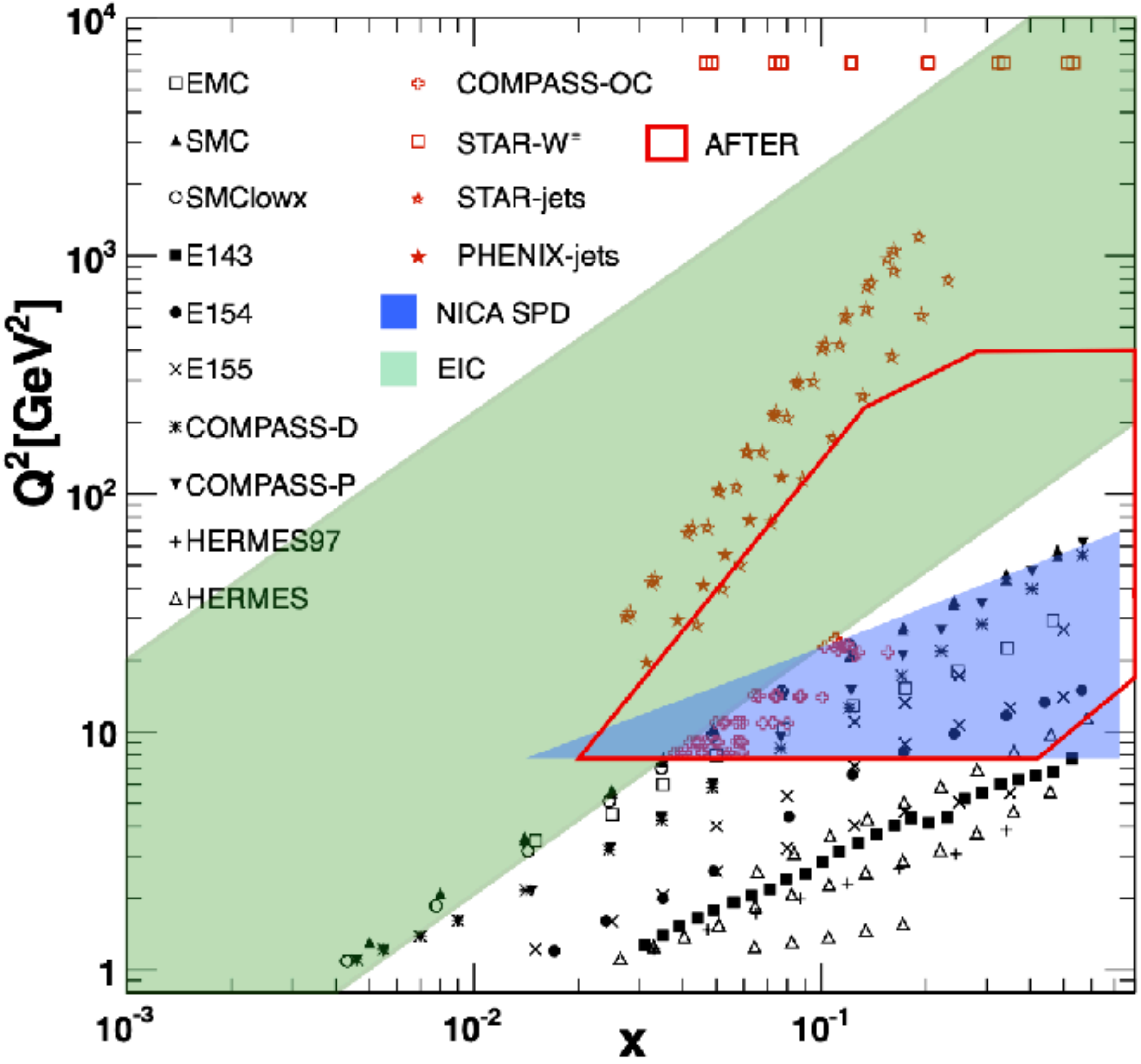
Possible studies at the first stage of the NICA collider operation with polarized and unpolarized proton and deuteron beams


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]

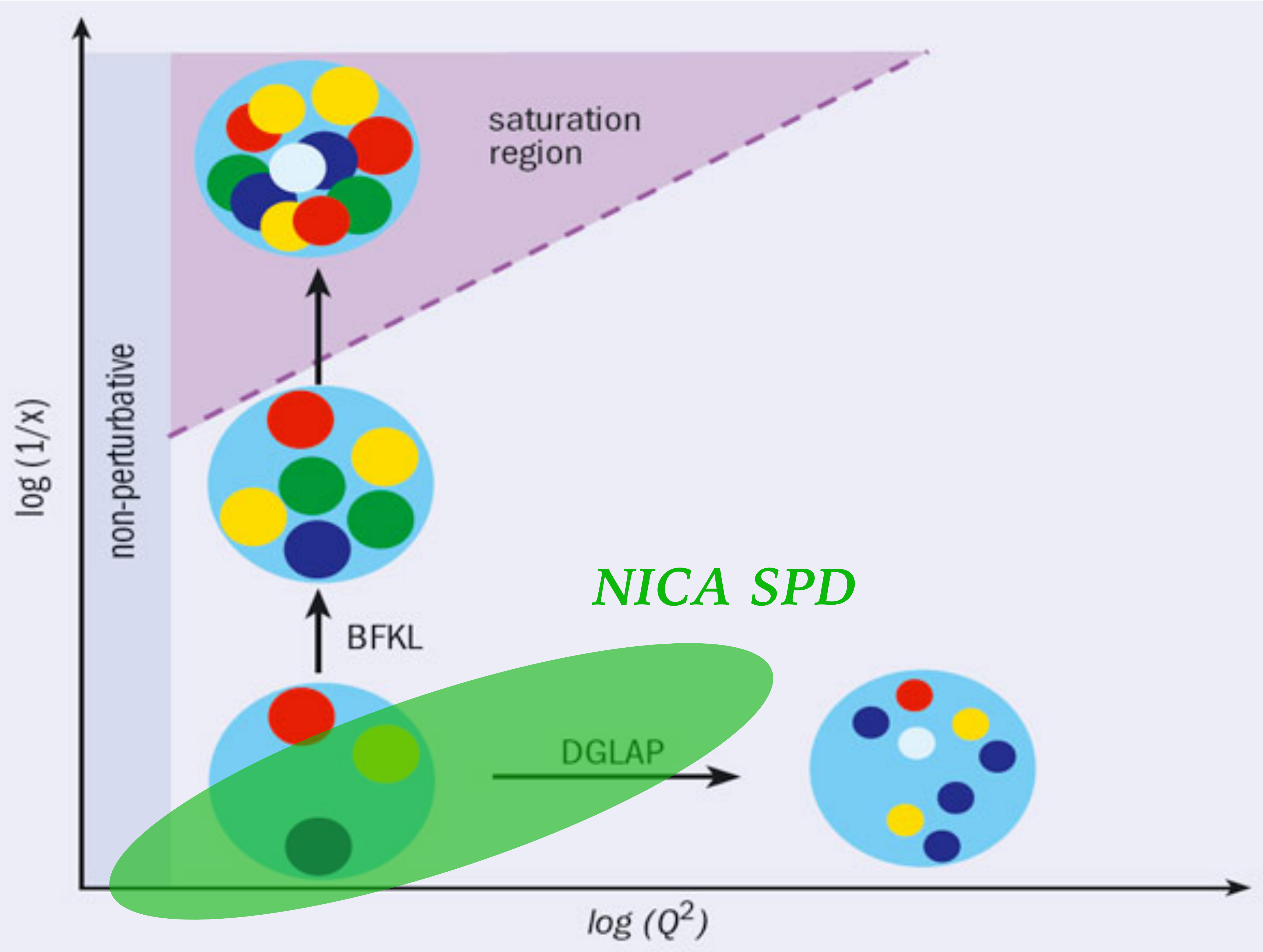
Phys. Part. Nucl. Vol.52, 2021, 1044

ArXiv e-Print: 2102.08477 [hep-ph]

PDF kinematic range

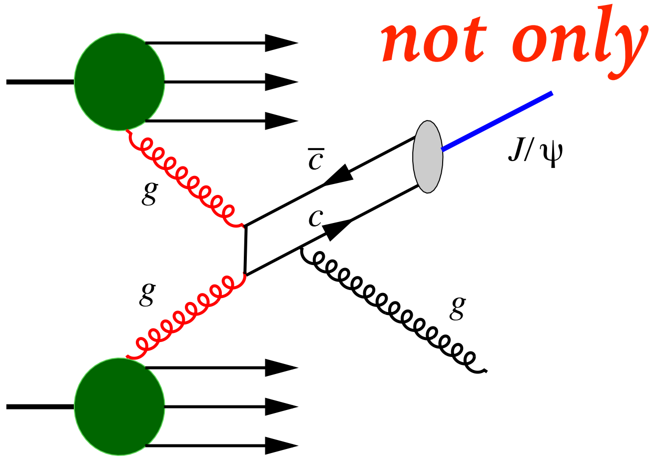


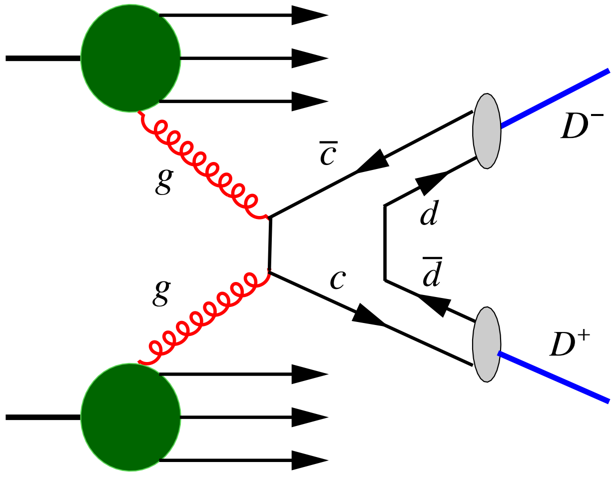
Dynamics kinematic range

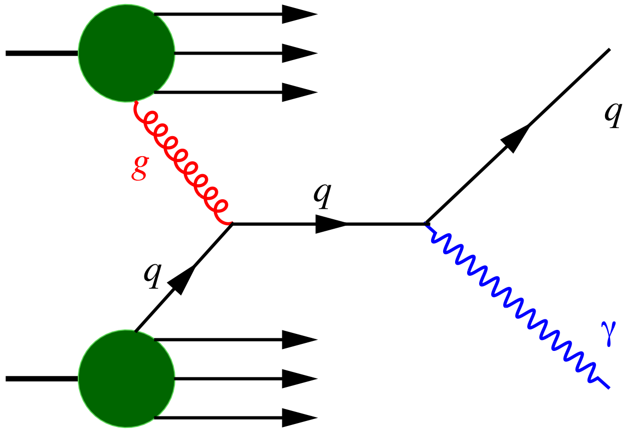


Gluon probes at SPD: charmonia, open charm, direct photons

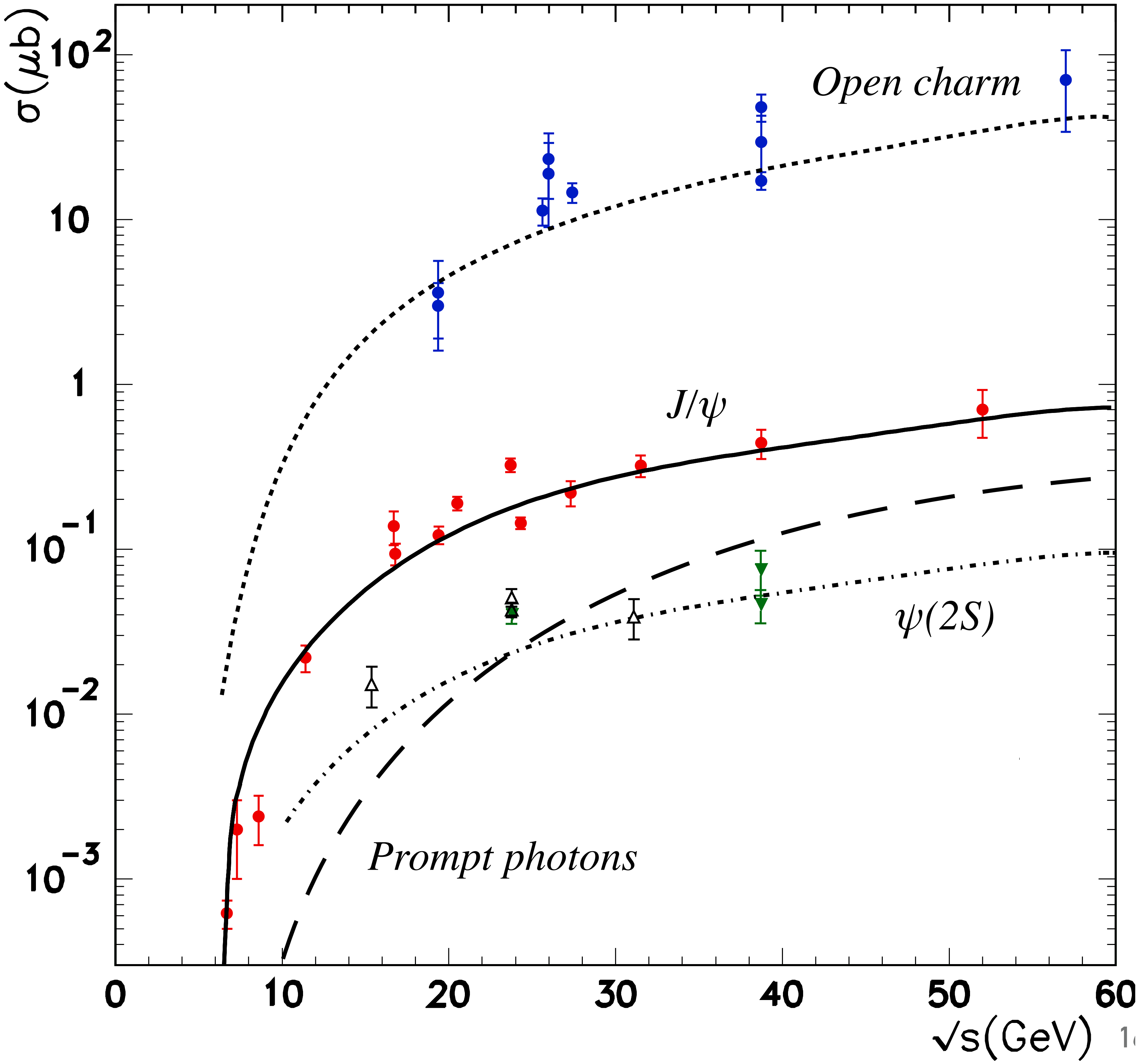
not only J/ψ!



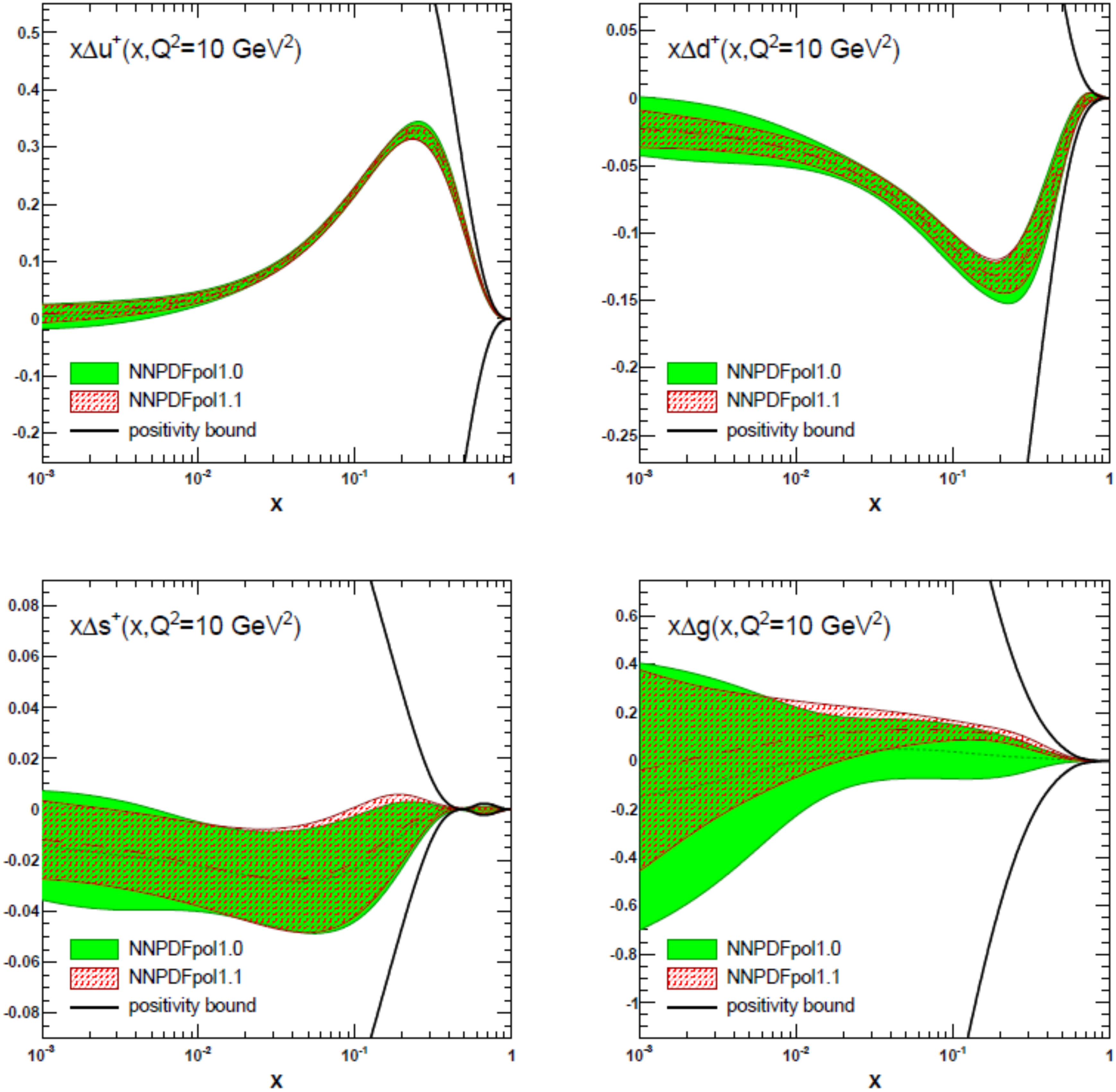




$$\sigma = PDF_1 \otimes PDF_2 \otimes \hat{\sigma}_{12}$$



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

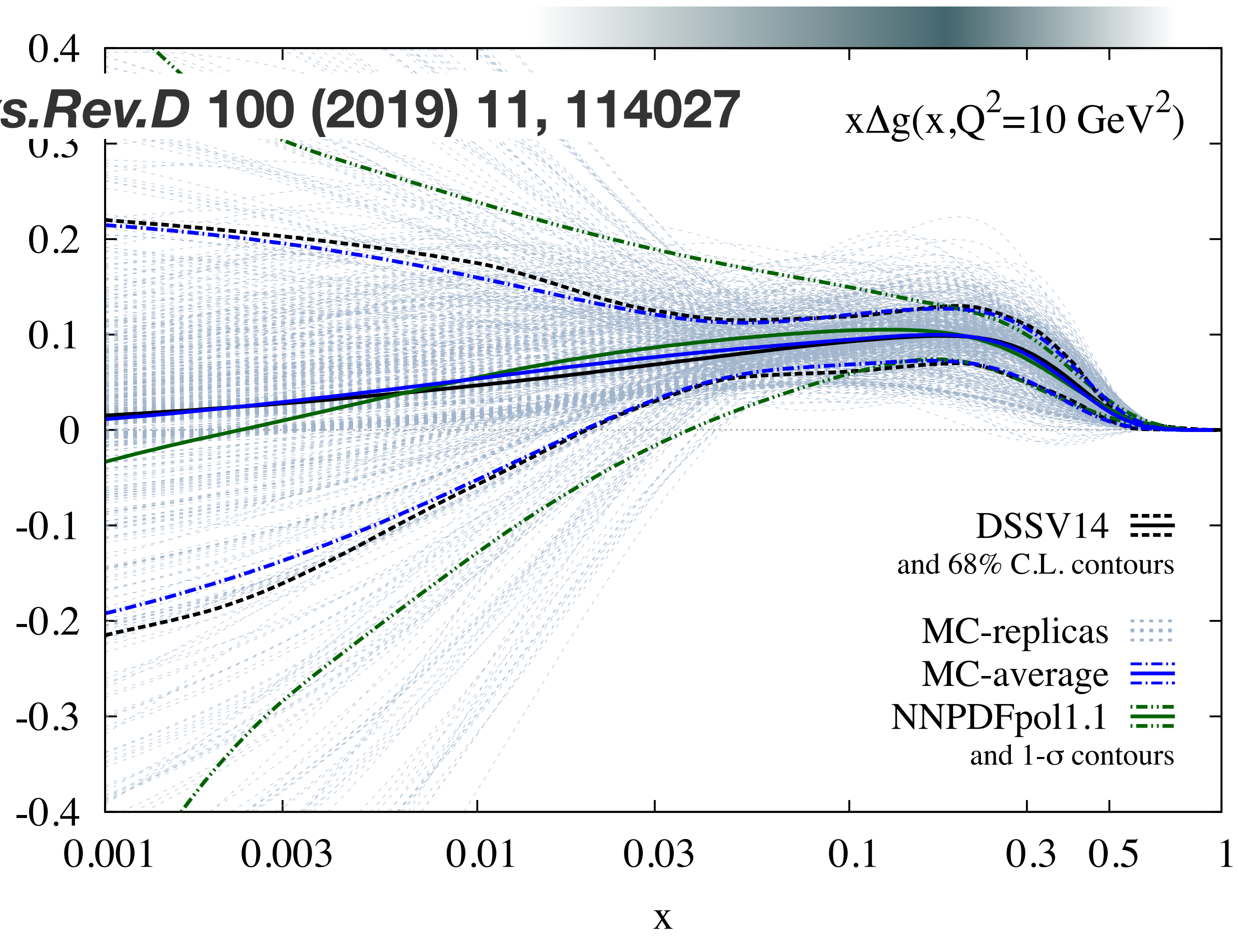
Gluon helicity PDF:
still rather high uncertainties!

Hadron collisions have a better
sensitivity to measure it.

⬅ SPD has a good opportunity!

Helicity gluon PDF Δg(x):

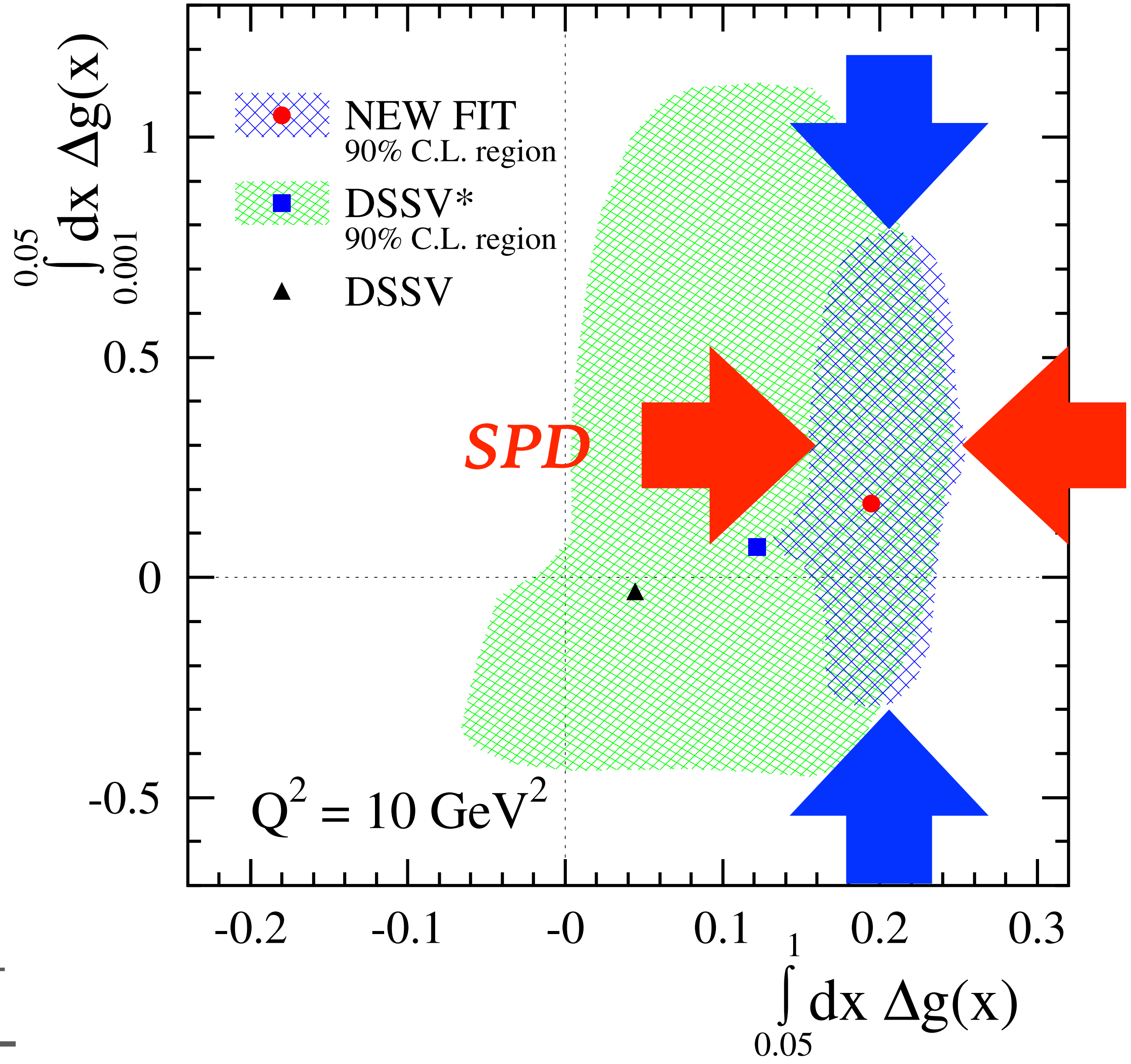
accessible with SPD



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

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

EIC



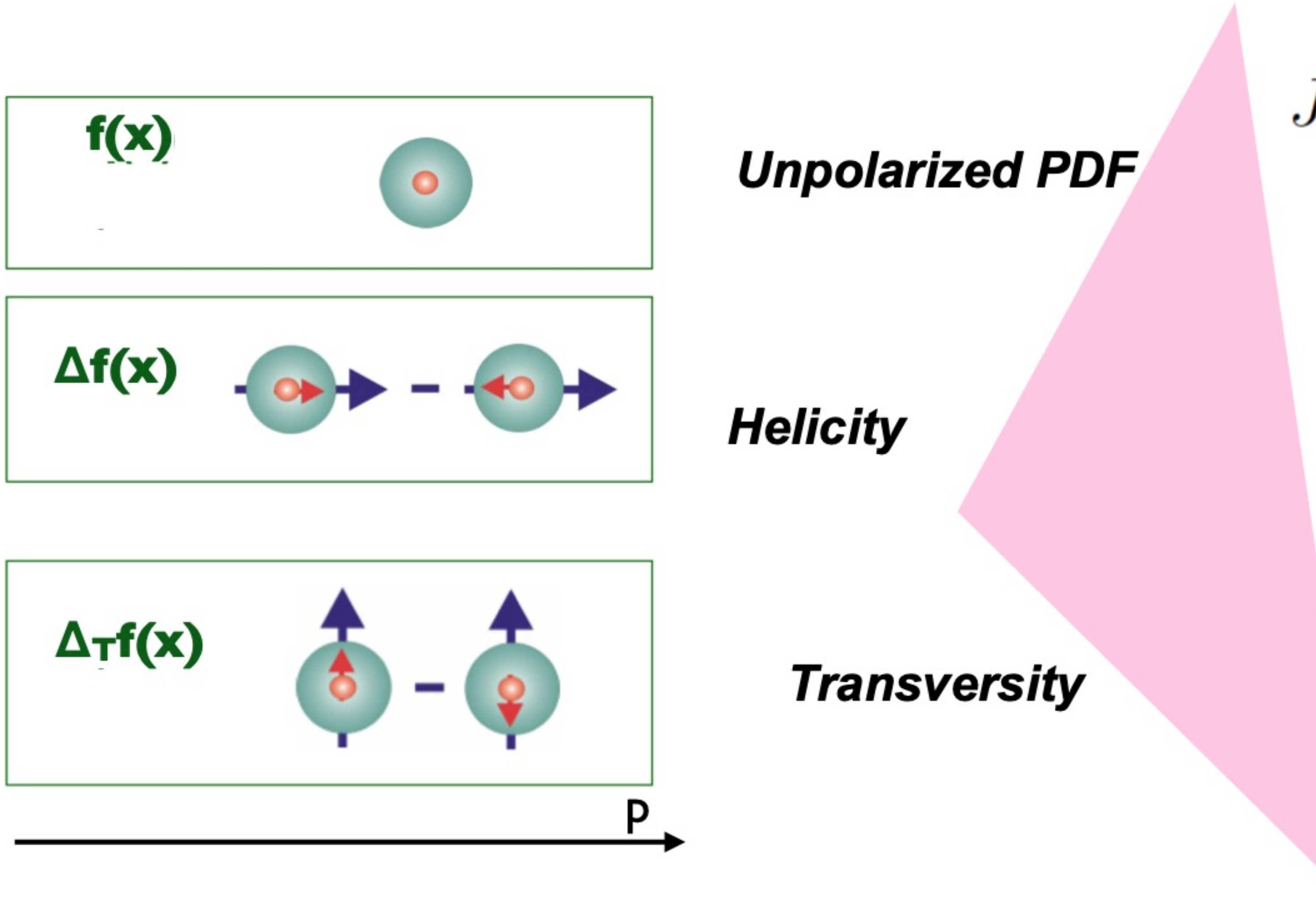
SPD

SPD could help to reduce uncertainty of ΔG at large x

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

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

Spin of proton



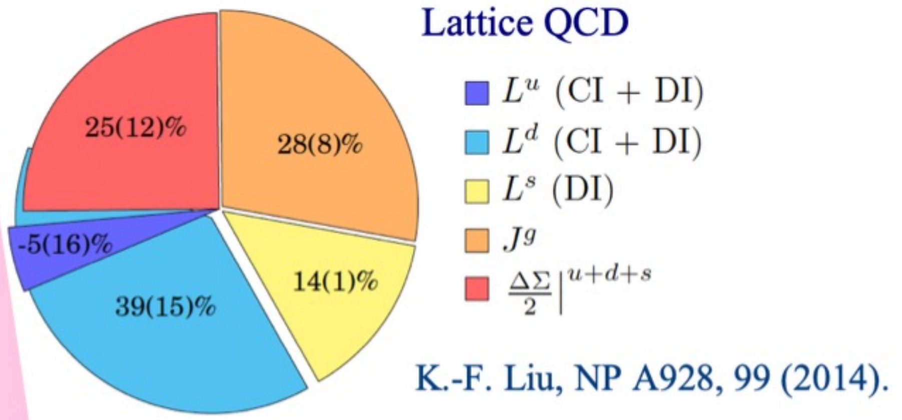
Unpolarized PDF

Helicity

Transversity

$$J = \overset{\sim 30\%}{\frac{1}{2}\Delta\Sigma} + \underset{\sim 10\text{-}20\%}{\Delta G} + \boxed{\overset{?}{L_q} + \overset{?}{L_g}}$$

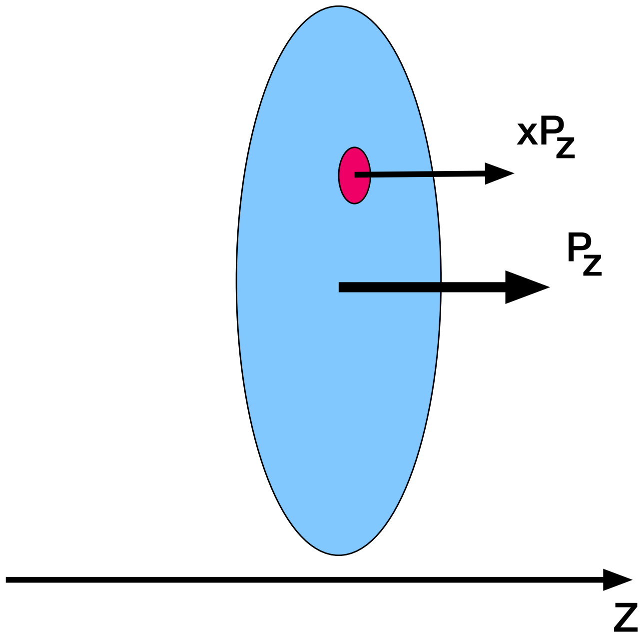
Lattice QCD



K.-F. Liu, NP A928, 99 (2014).

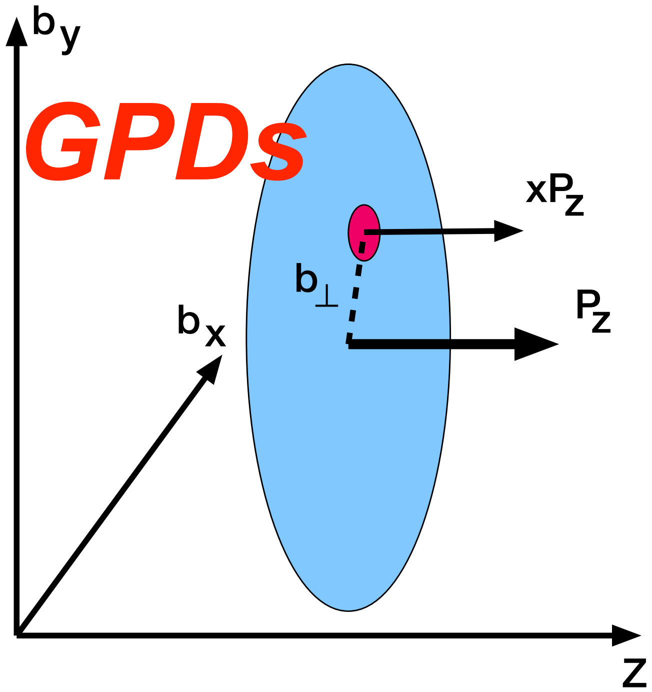
To access angular momenta info about 3D structure is needed!

SPD: towards 3D-structure of nucleon



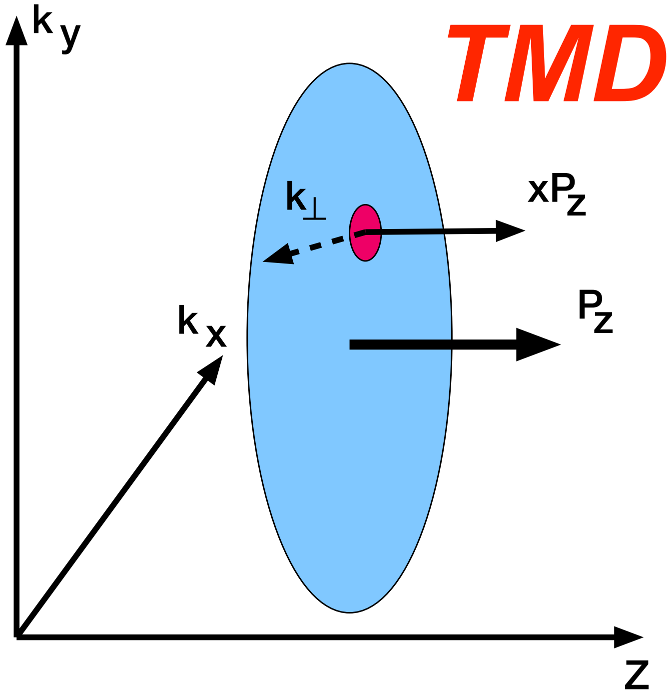
Collinear approximation

(common PDF)



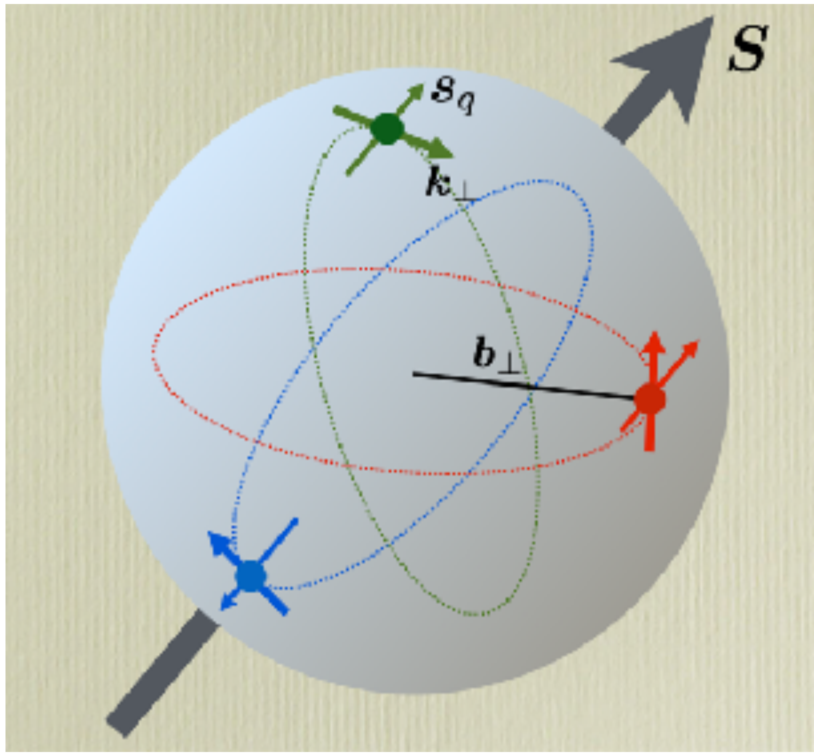
GPDs

Generalized Parton Distributions



TMD PDFs

Transverse Momentum Dependent PDFs



3D structure of nucleon

connection to orbital moment

Parton Distribution Functions (PDFs): 1D ➡ 3D

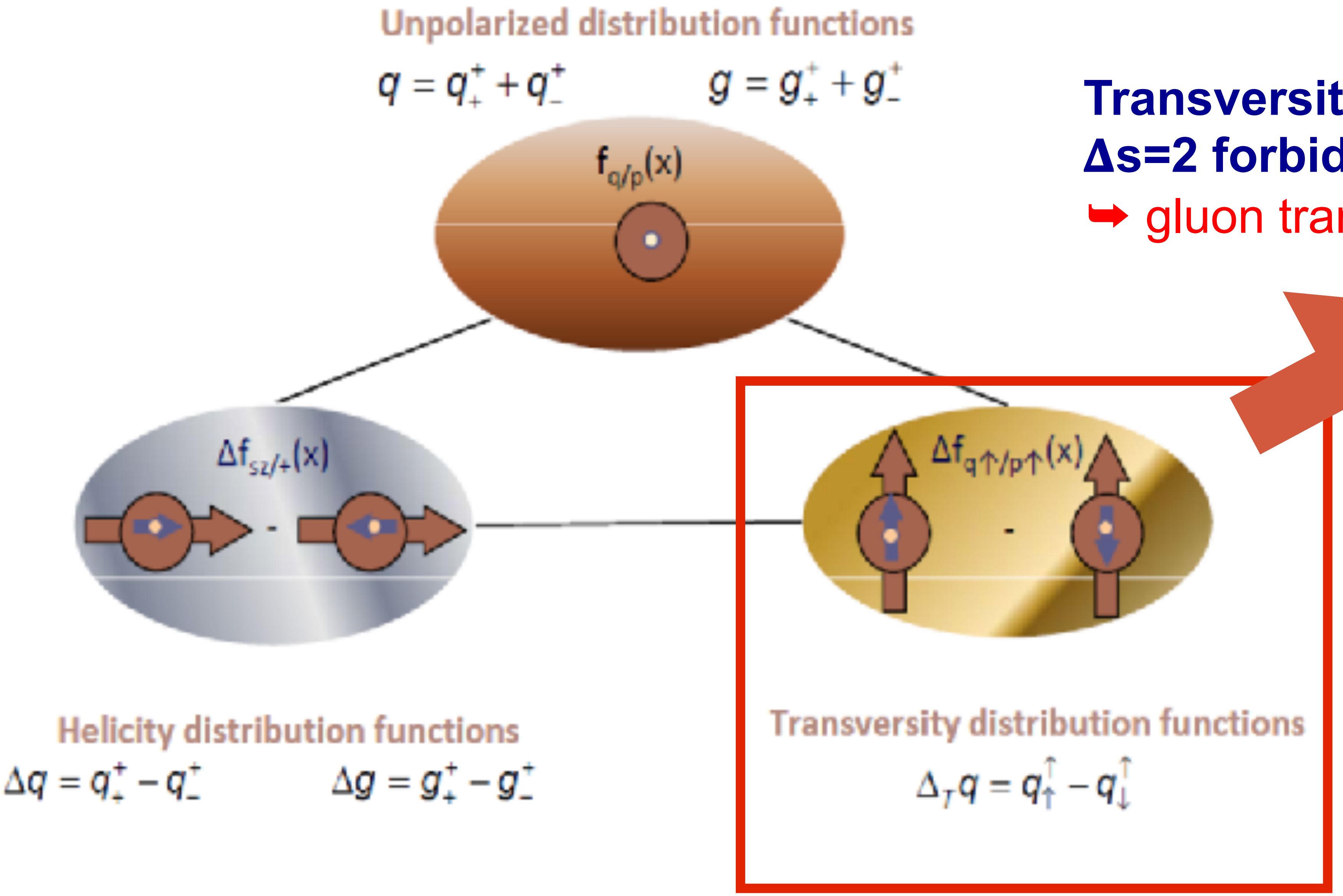
Parton 1D-distribitions:

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)

Gluon transversity of deuteron



Unpolarized distribution functions

$q = q_+^+ + q_-^+$ $g = g_+^+ + g_-^+$

Helicity distribution functions

$\Delta q = q_+^+ - q_-^+$ $\Delta g = g_+^+ - g_-^+$

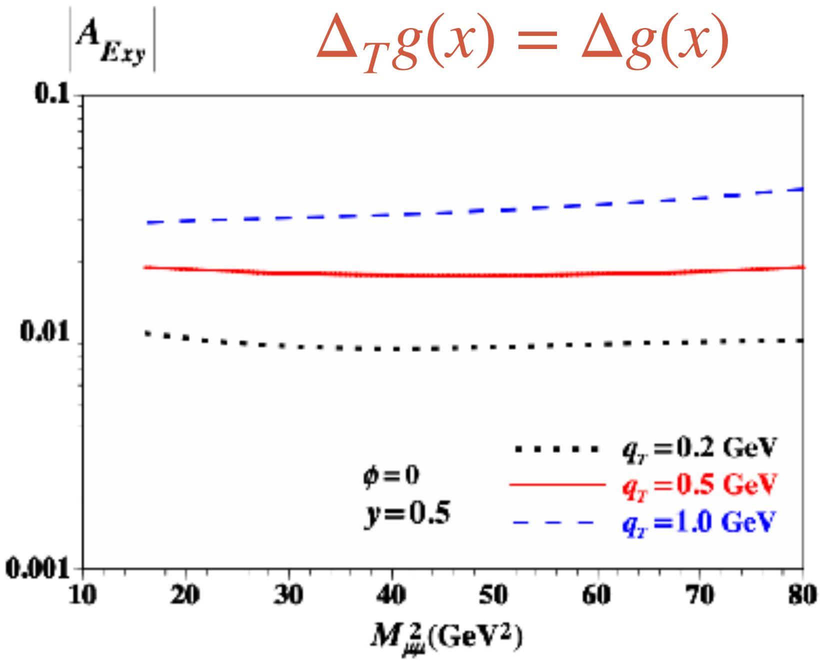
Transversity distribution functions

$\Delta_T q = q_\uparrow^\uparrow - q_\downarrow^\uparrow$

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

Lepton pairs S. Kumano

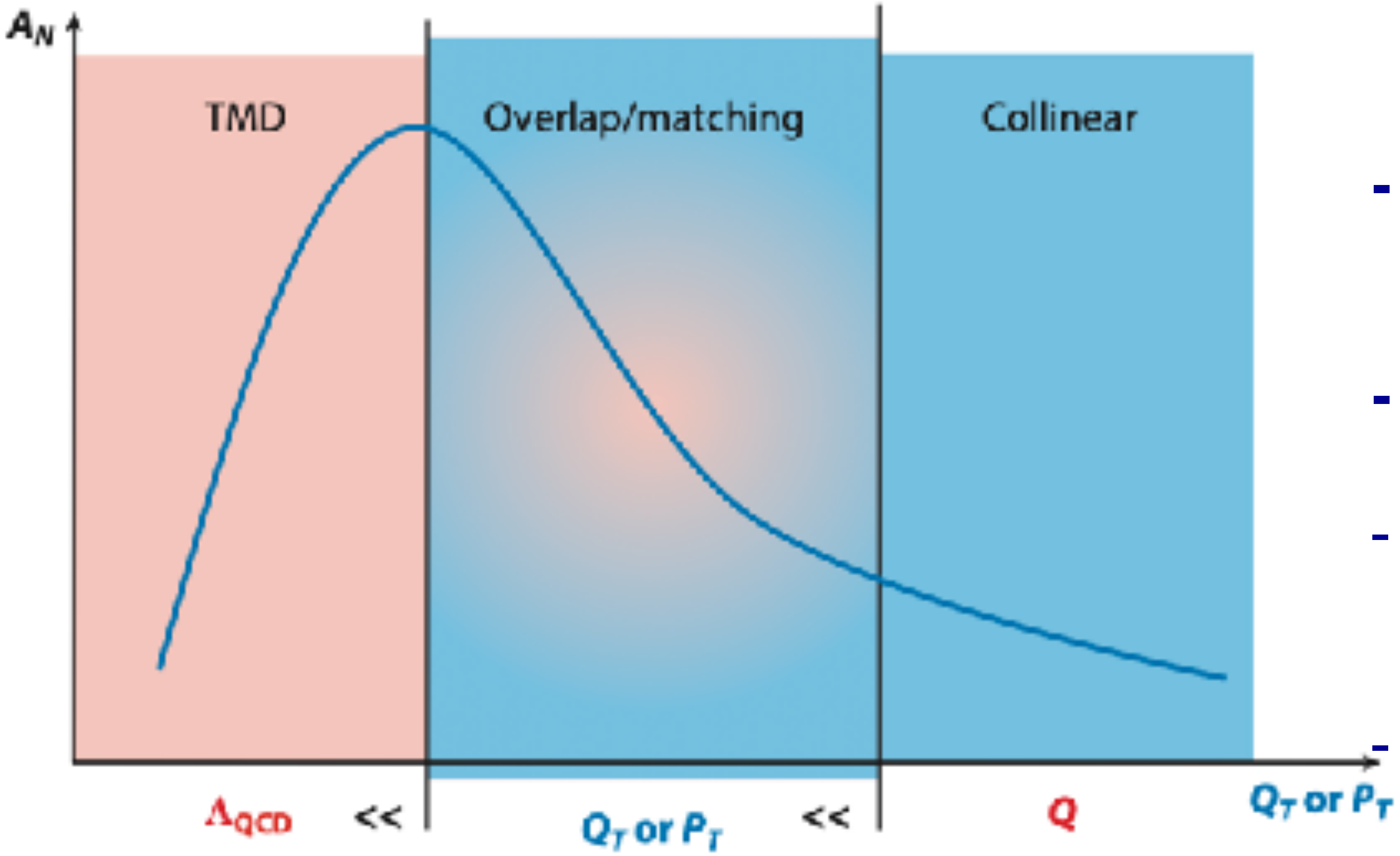
$\Delta_T g(x) = \Delta g(x)$



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

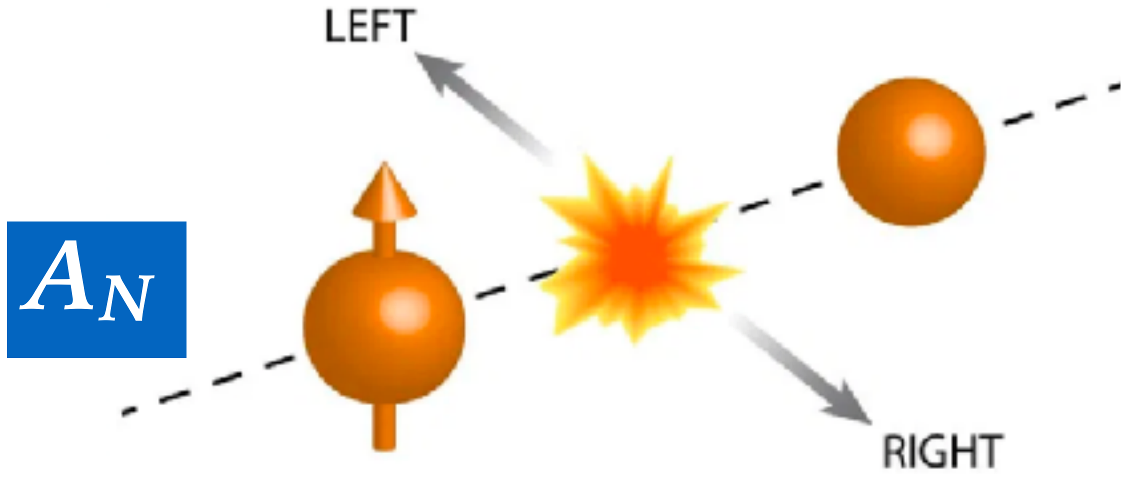
- TMD-factorization

- 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



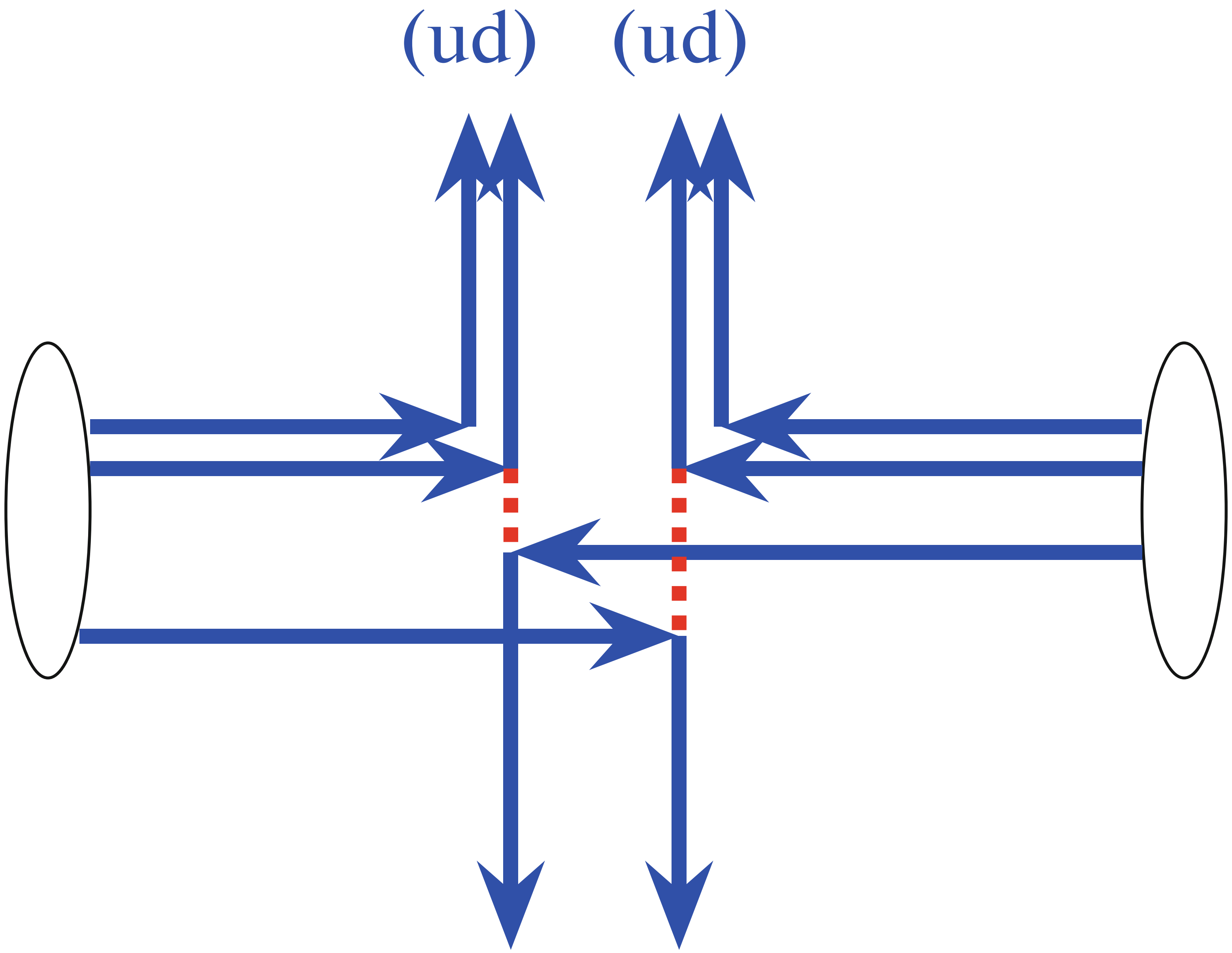
SPD Physics at the initial Stage I

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:

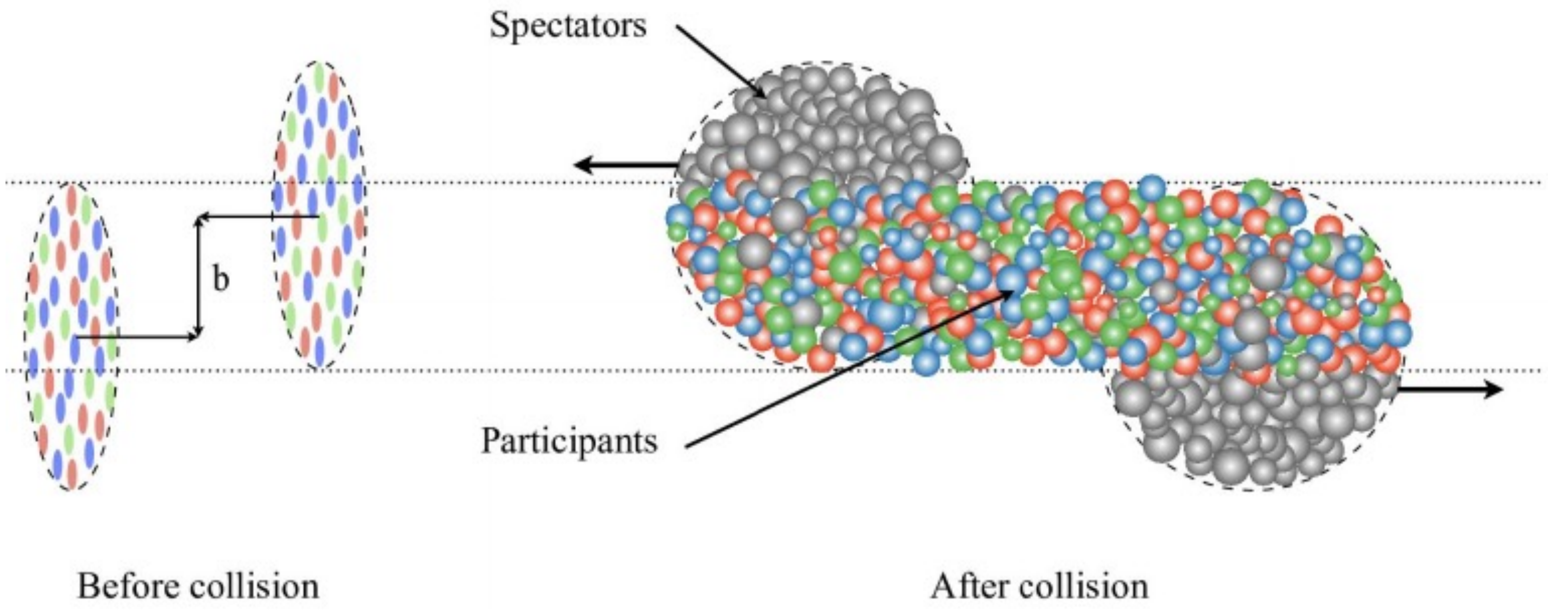
- ► **Spin effects in pp-, pd- and dd- (quasi)elastic scattering**
- ► **Spin effects in hyperon production**
- ► **Search for exotic states (glueball, penta- and tetra- quarks)**
- ► **Multiquark correlations (SRC) in deuteron and light nuclei**
- ► **Dibaryon resonances**
- ► **Hypernucleus production**
- ► **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**
- ► **…**

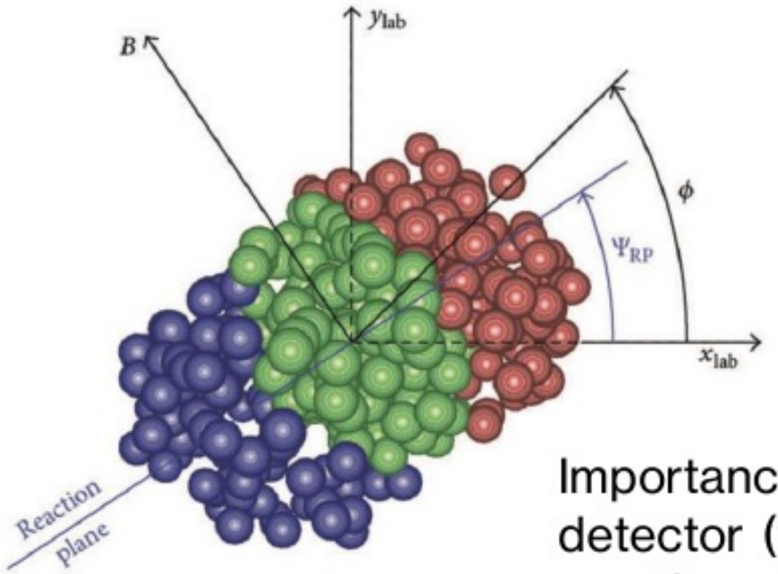
SPD Physics at the initial Stage: exotic states pentaquark, dihyperon, etc. production



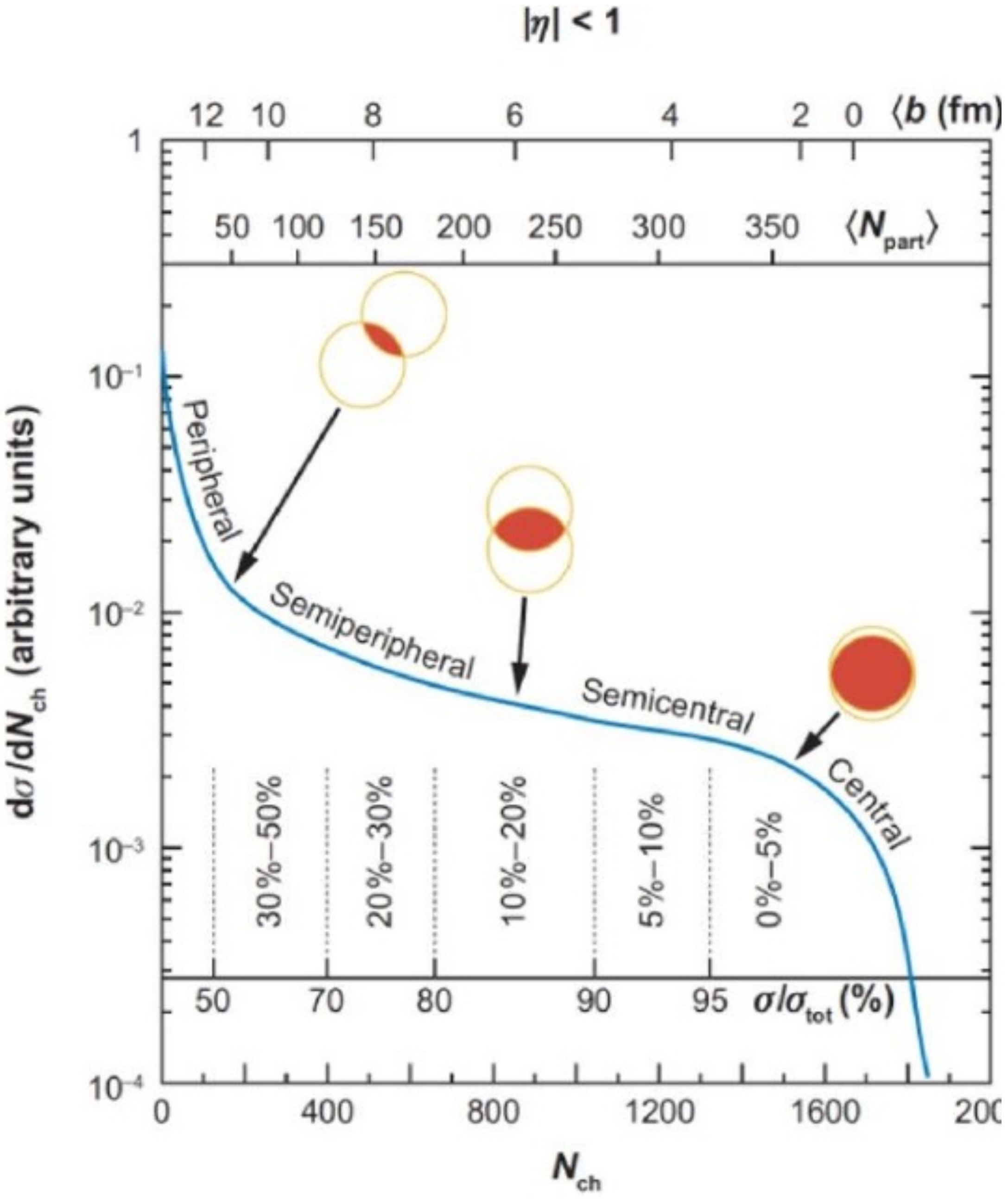
A. Efremov, V. Kim 1987
V. Abramov et al 2021

SPD Physics at the Stage-1: ion-ion collisions

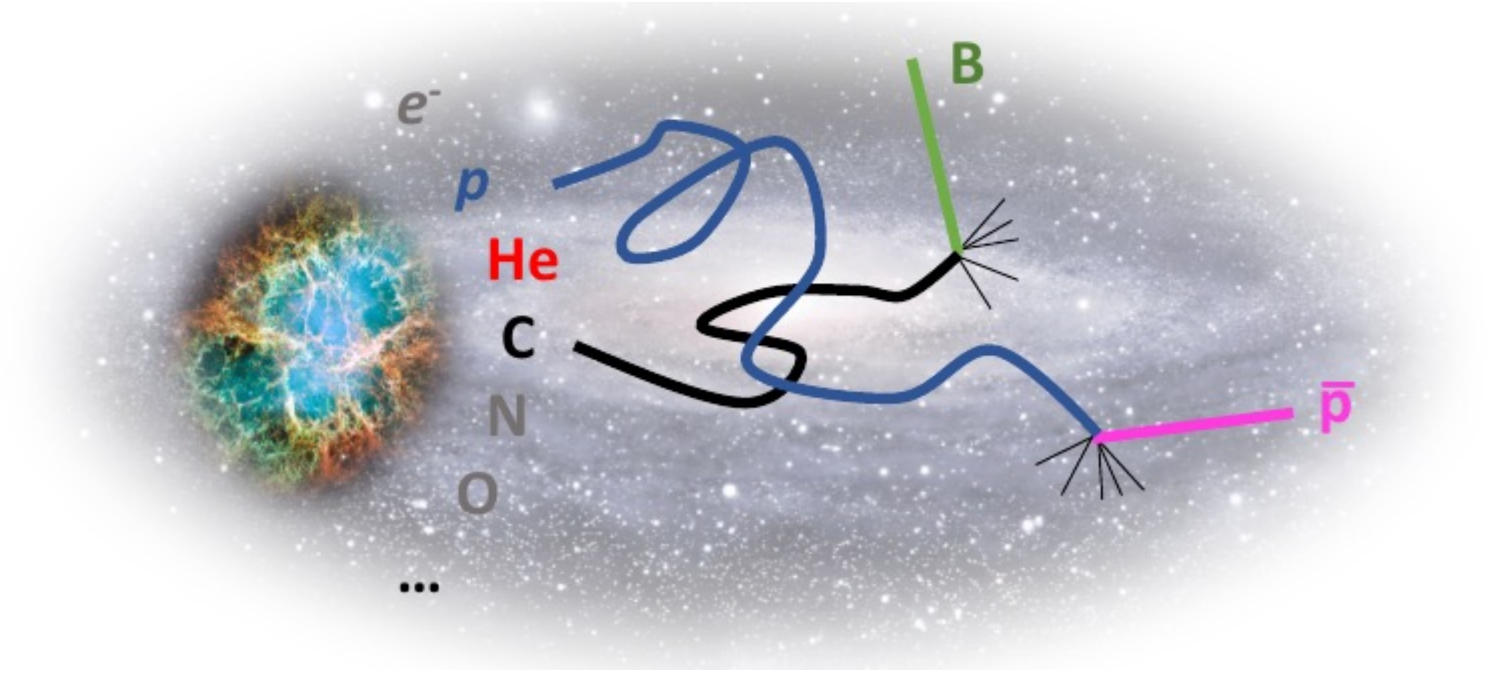




Importance of granular BBC detector (to reconstruct reaction plane angle)



SPD Physics at the Stage-1: antiproton production



ASTROPHYSICS

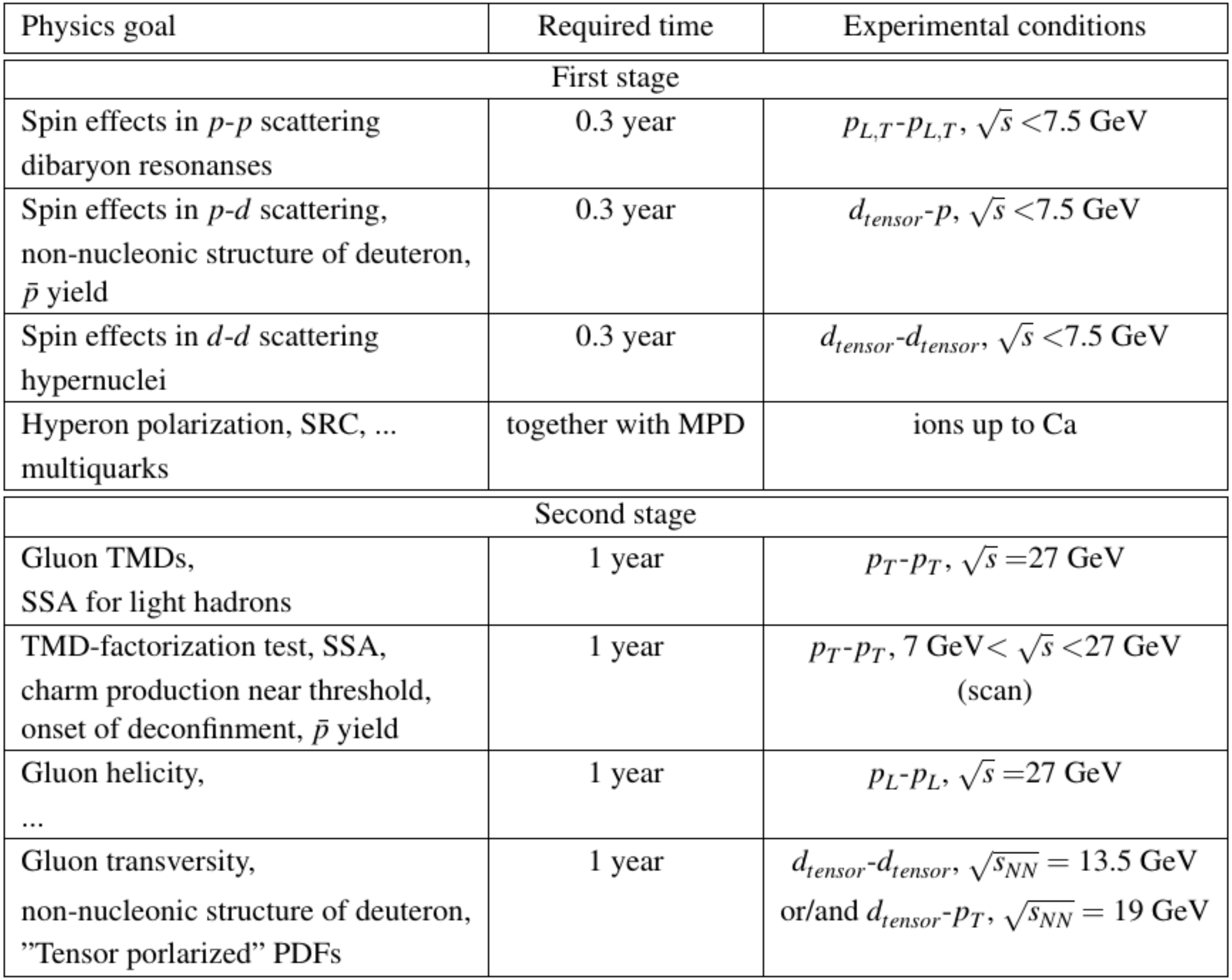
AMS-02 in International Space Station

AMS-02 search for Dark Matter:
antiproton flux precision ~5%

Contemporary high energy physics experiments
antiproton production ~25%

Precision antiproton production measurements needed:
energy range 5 GeV < ECM < 100 GeV with precision ~5%

SPD Experiment: 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 R&D: Трековая система

Группы ОИЯИ (Дубна), ПИЯФ (Гатчина) и ИЯФ РК (Алматы)
рук: Т.Л. Еник (ОИЯИ) и Е.В. Кузнецова (ПИЯФ)
R&D тонкостенных трубок и ASIC решений для считывающей электроники

- ► **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 (1 сеанс), 2022 (3 сеанса) 2023 (3 сеанса)
- часть результатов включены в текущую версию SPD TDR

Spin: challenging delicate properties

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

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

“Polarisation data has often been the graveyard of fashionable theories. If theorists had their way they might well ban such measurements altogether out of self-protection.”

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

V. Mochalov (NRC KI - IHEP)