Spin Physics Detector

Physics with Stage-1 SPD experiment at NICA

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SPD Detector Advisory Committee Meeting
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Main SPD physics goal

Spin Physics Detector (SPD) (http://spd.jinr.ru):
a universal particle physics facility at NICA collider

➥ **Main SPD goal:**
understanding of the strong interactions using both polarized and unpolarized pp- and dd- collisions at √s up to 27 GeV with high-luminosity

To this end, it will be studied (un)polarized 3D quark-gluon structure of proton and deuteron with emphasis of gluon PDF(x) and TMD(x,kT) at high x

- SPD physics program is complementary to the other intentions to study gluon content of nuclei (RHIC, AFTER@LHC, LHC-spin, EIC) and mesons (COMPASS++/AMBER, EIC)

➥ **In addition, it will be carried out a comprehensive program, at the initial period of SPD data taking, for a broad range of particle and nuclear physics**

Parton distribution function (PDF)
Transverse momentum distribution (TMD)

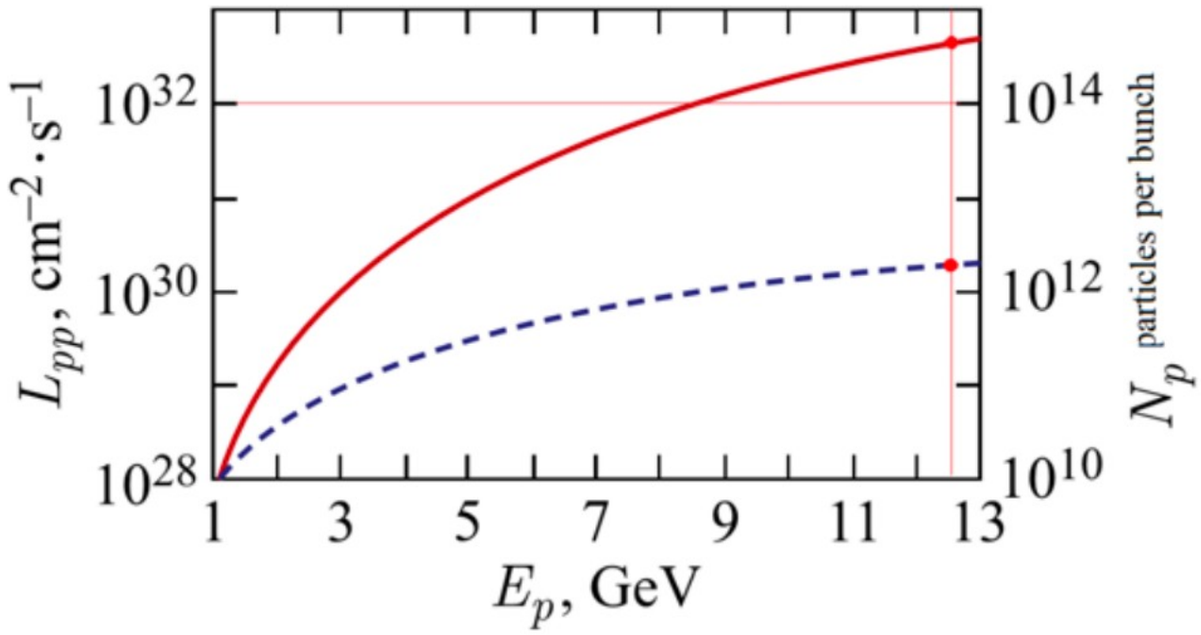
SPD at NICA (JINR, Dubna)

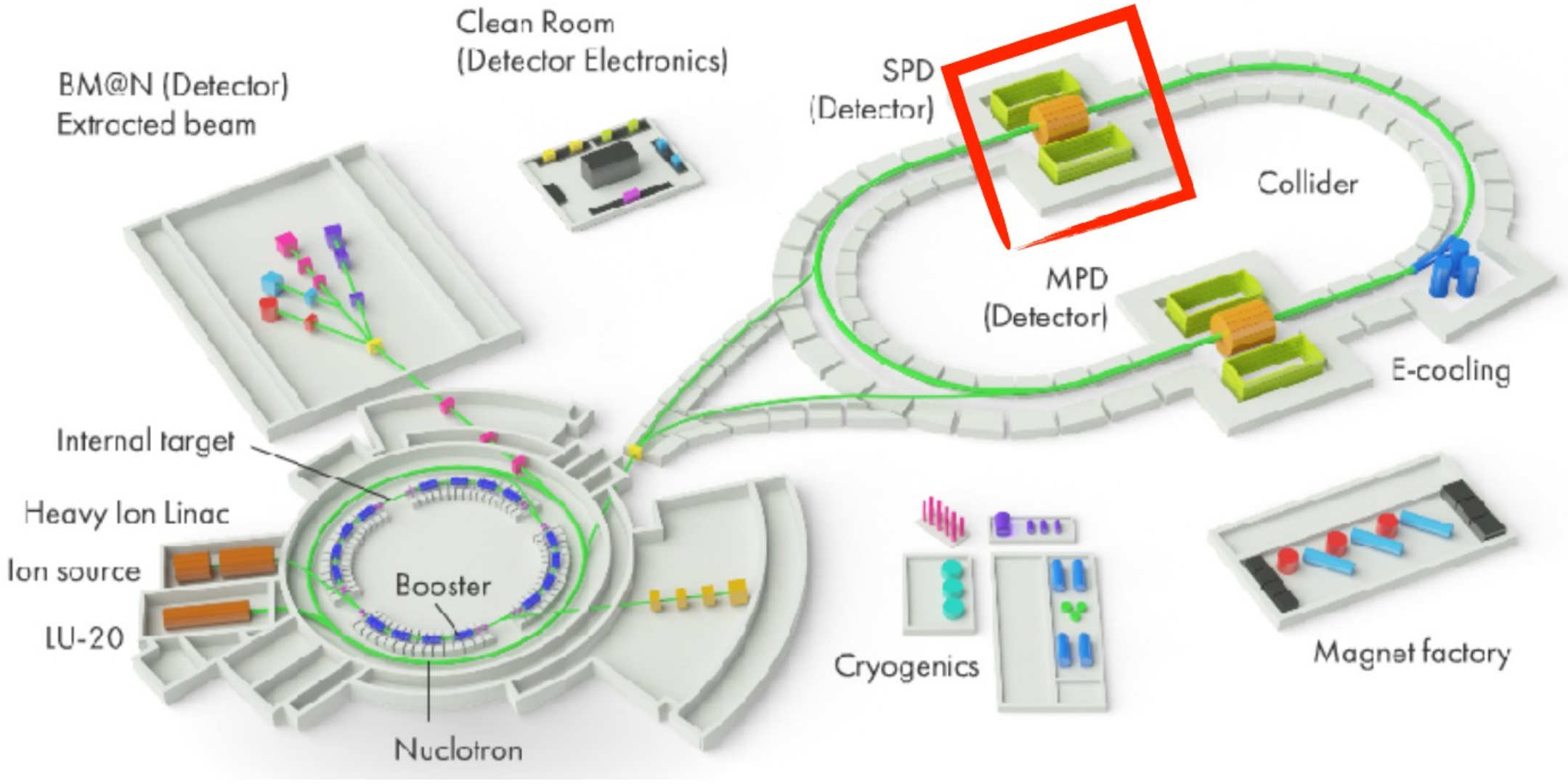
NICA:
Nuclotron-based Ion Collider fAcility

$$p^{\uparrow}p^{\uparrow} : \sqrt{s} \leq 27\ GeV$$
$$d^{\uparrow}d^{\uparrow} : \sqrt{s} \leq 13.5\ GeV$$
$$d^{\uparrow}p^{\uparrow} : \sqrt{s} \leq 19\ GeV$$

U, L, T

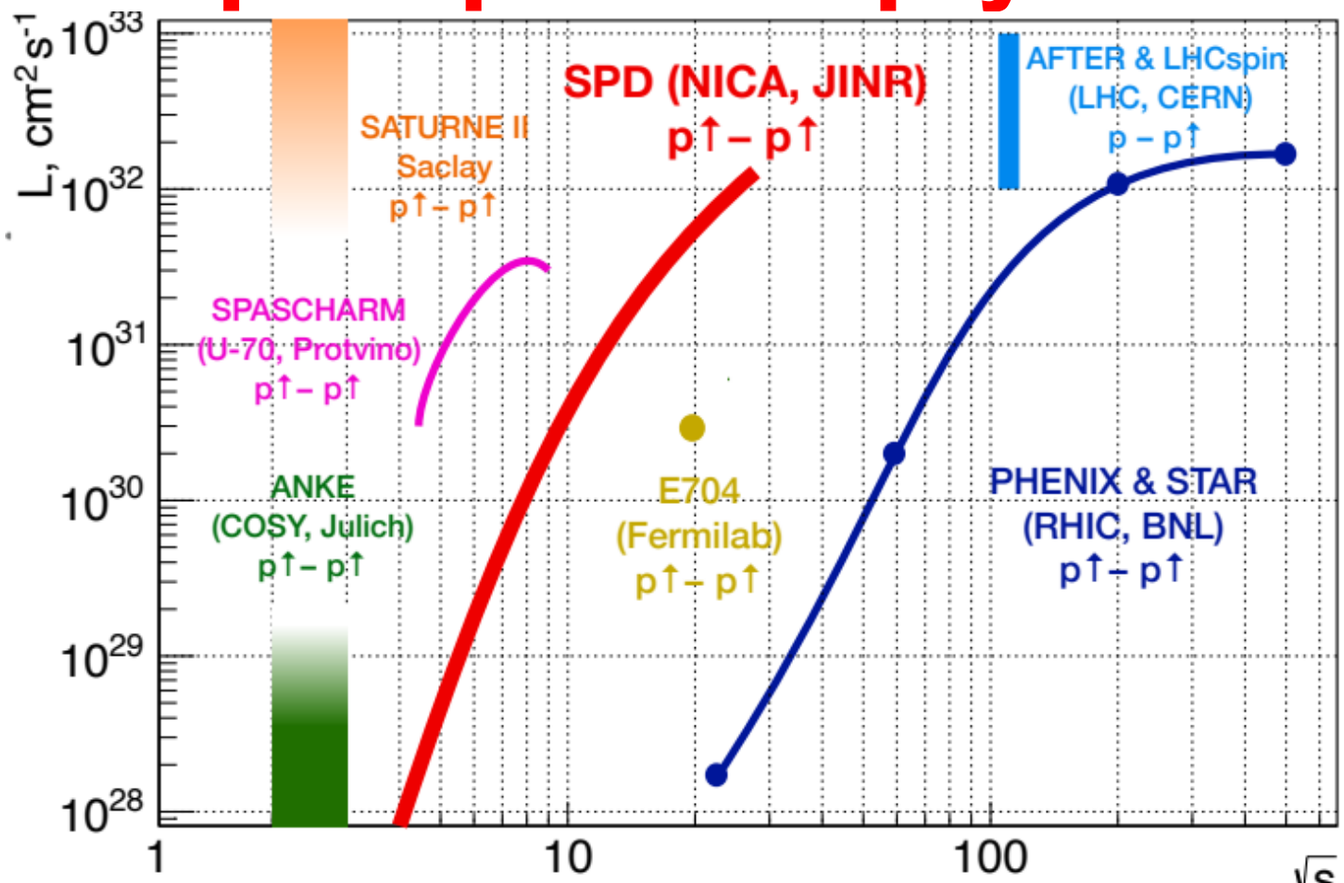
|P|>70%





SPD in World landscape of polarized physics

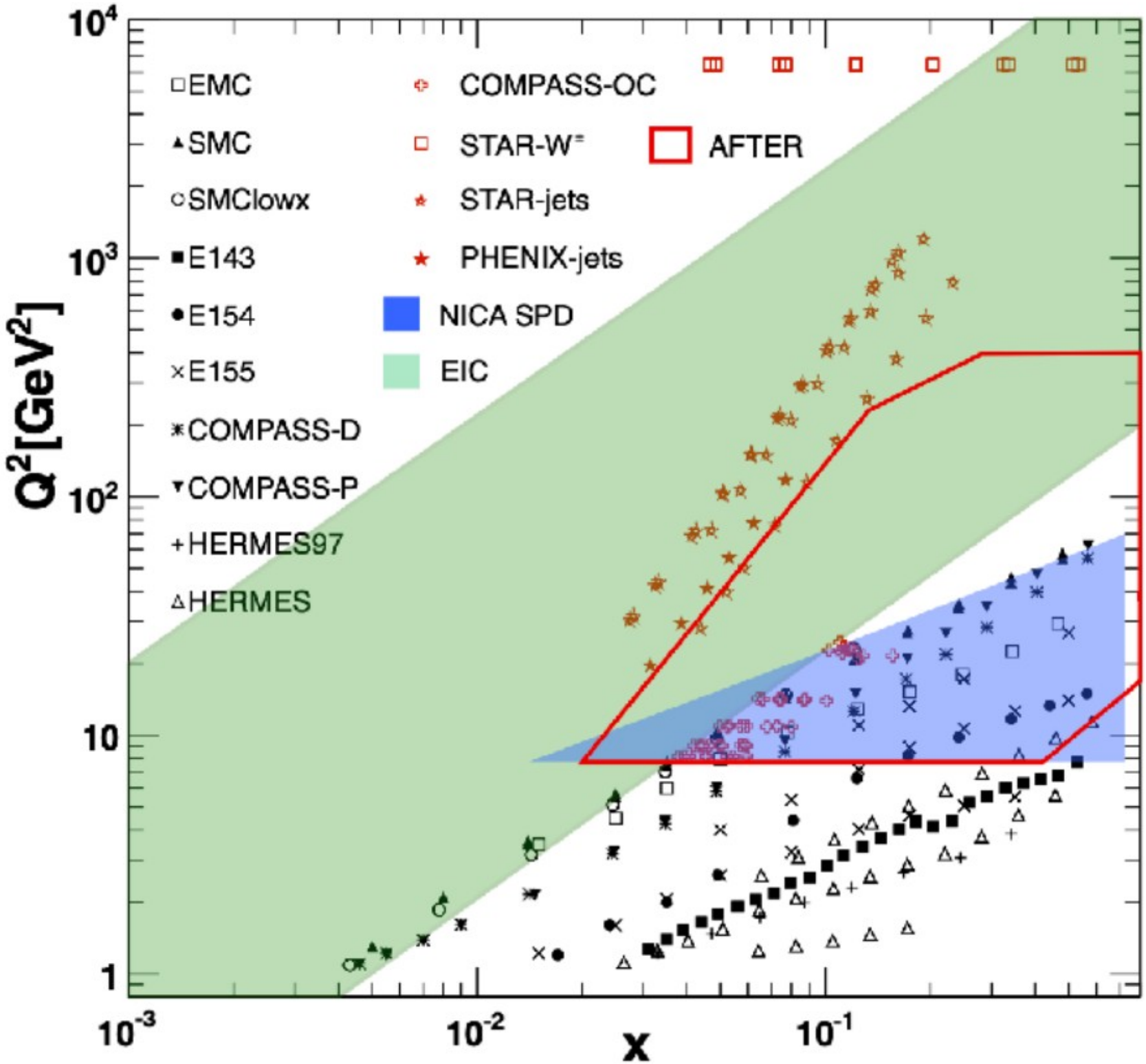
p↑ p↑-mode



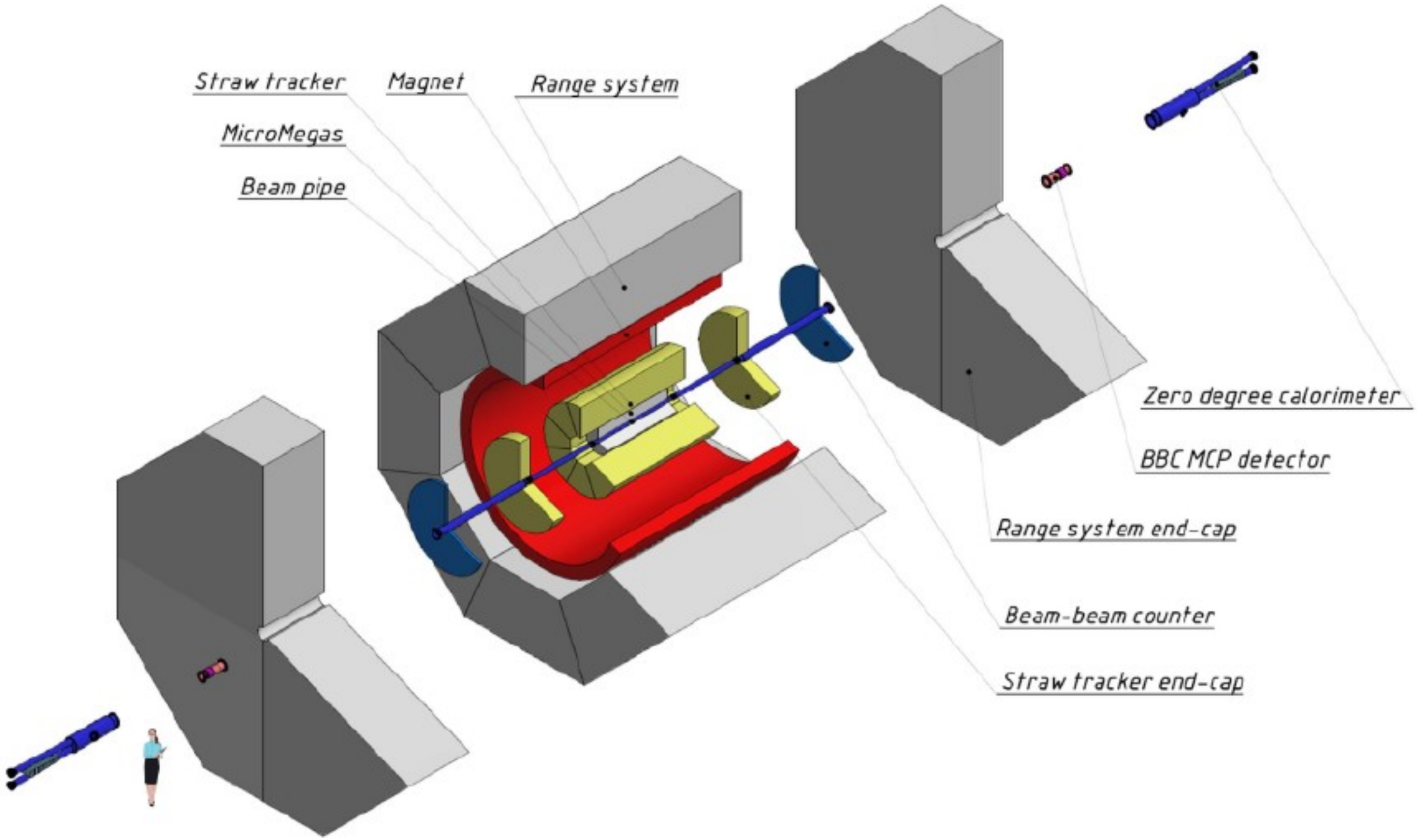
Experimental facility	SPD @NICA	RHIC	EIC	AFTER @LHC	LHCspin
Scientific center	JINR	BNL	BNL	CERN	CERN
Operation mode	collider	collider	collider	fixed target	fixed target
Colliding particles & polarization	$p^{\uparrow}$-$p^{\uparrow}$ $d^{\uparrow}$-$d^{\uparrow}$ $p^{\uparrow}$-d, p-$d^{\uparrow}$	$p^{\uparrow}$-$p^{\uparrow}$	$e^{\uparrow}$-$p^{\uparrow}$, $d^{\uparrow}$, $^3He^{\uparrow}$	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!

PDF kinematic range



SPD Layout at Stage-1



SPD setup: main parameters

	Stage I	Stage II
Maximum luminosity, 10^{32} cm^{-2} s^{-2}	up to 0.1	1
Interaction rate, MHz	up to 0.4	4
Magnetic field at IP, T	up to 1.0	1.0
Track momentum resolution $\frac{\delta p}{p}$ at 1 GeV/c, %	~1.7	~1.0
Photon energy resolution, %		$5/\sqrt{E} \oplus 1$
$D^0 \to K\pi$ vertex spatial resolution, μm		60 for MAPS 80 for DSSD
PID capabilities	dE/dx, RS	dE/dx, ECal, RS, TOF, FARICH
Number of channels, 10^3	177	XXX for MAPS) 608 for DSSD
Raw data flow, GB/s	up to 1	up to 20
Total weight, t	1236*	1240
Power consumption, kW	77	113 for MAPS 90 for DSSD

*ECal mock-up of similar weight will be used for the first stage

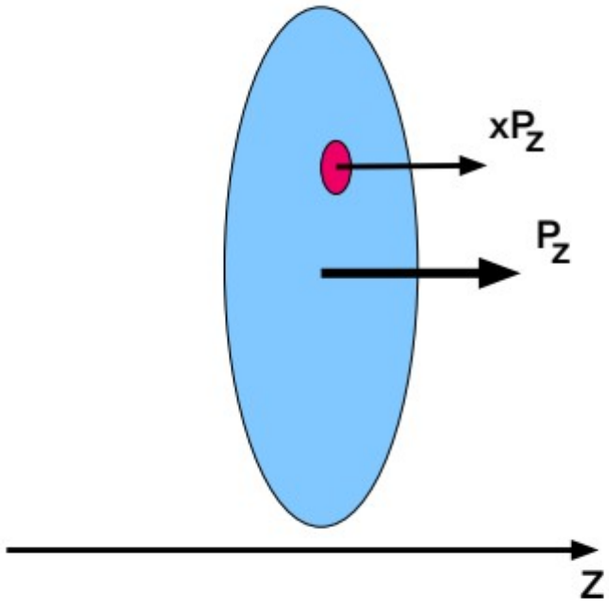
SPD Physics at the Stage-1: Highlights

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

Comprehensive and rich physics program for the fist period of data taking (Stage-1)

- Spin effects in hyperon production in (un)polarized pp-collisions
- Spin effects in pp-, pd- and dd- scattering
- Tests of factorization of various approaches: CF, TMD, GPD, etc.
- Multiquark correlations (SRC, fluctons, dibaryons) in dd and ion-ion collisions
- Hypernucleus production
- Charmonia production near threshold
- Large-pT hadron production to study diquark structure of proton
- Semi-inclusive large-pT hadron production to study multiparton scattering
- Central exotic resonance production: search for glueball, pentaquark, tetraquark)
- Antiproton production measurement for astrophysics and BSM search
- …

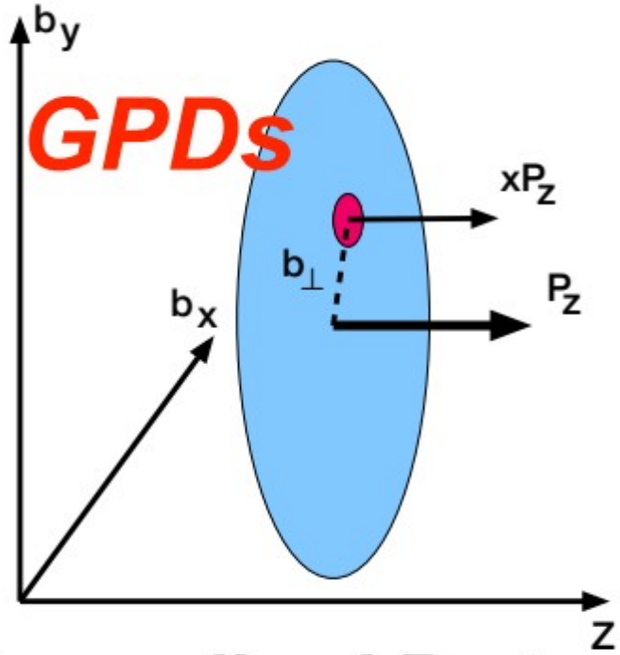
SPD: towards 3D-structure of nucleon



Collinear approximation

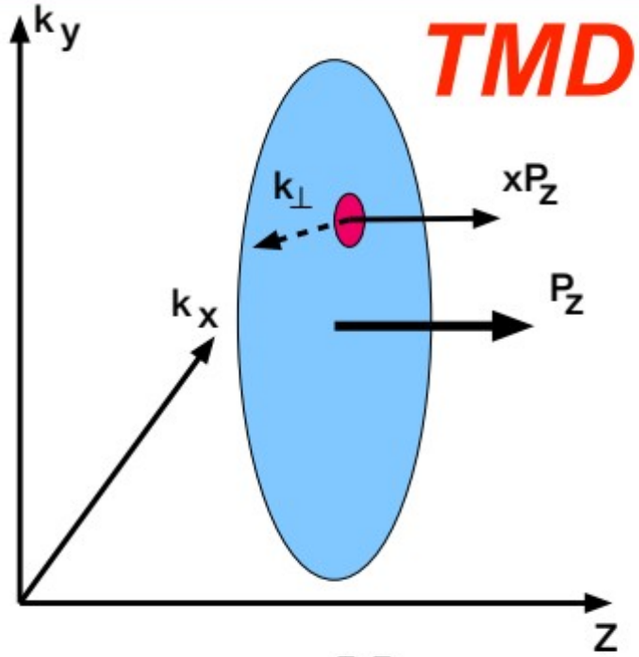
(common PDF)

GPDs



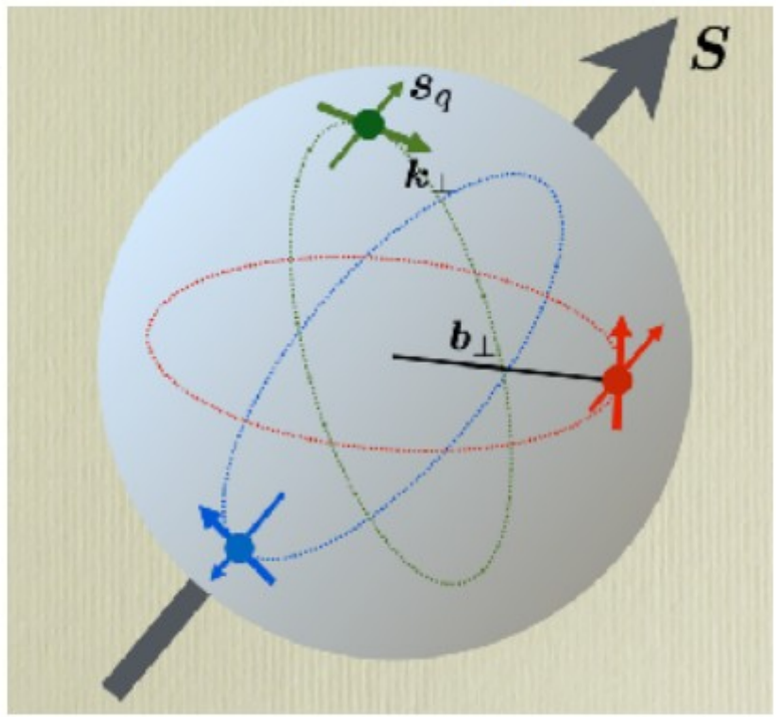
Generalized Parton Distributions

TMD PDFs



Transverse Momentum Dependent PDFs

3D structure of nucleon



connection to orbital moment

13

Parton Distribution Functions (PDFs): 1D 3D

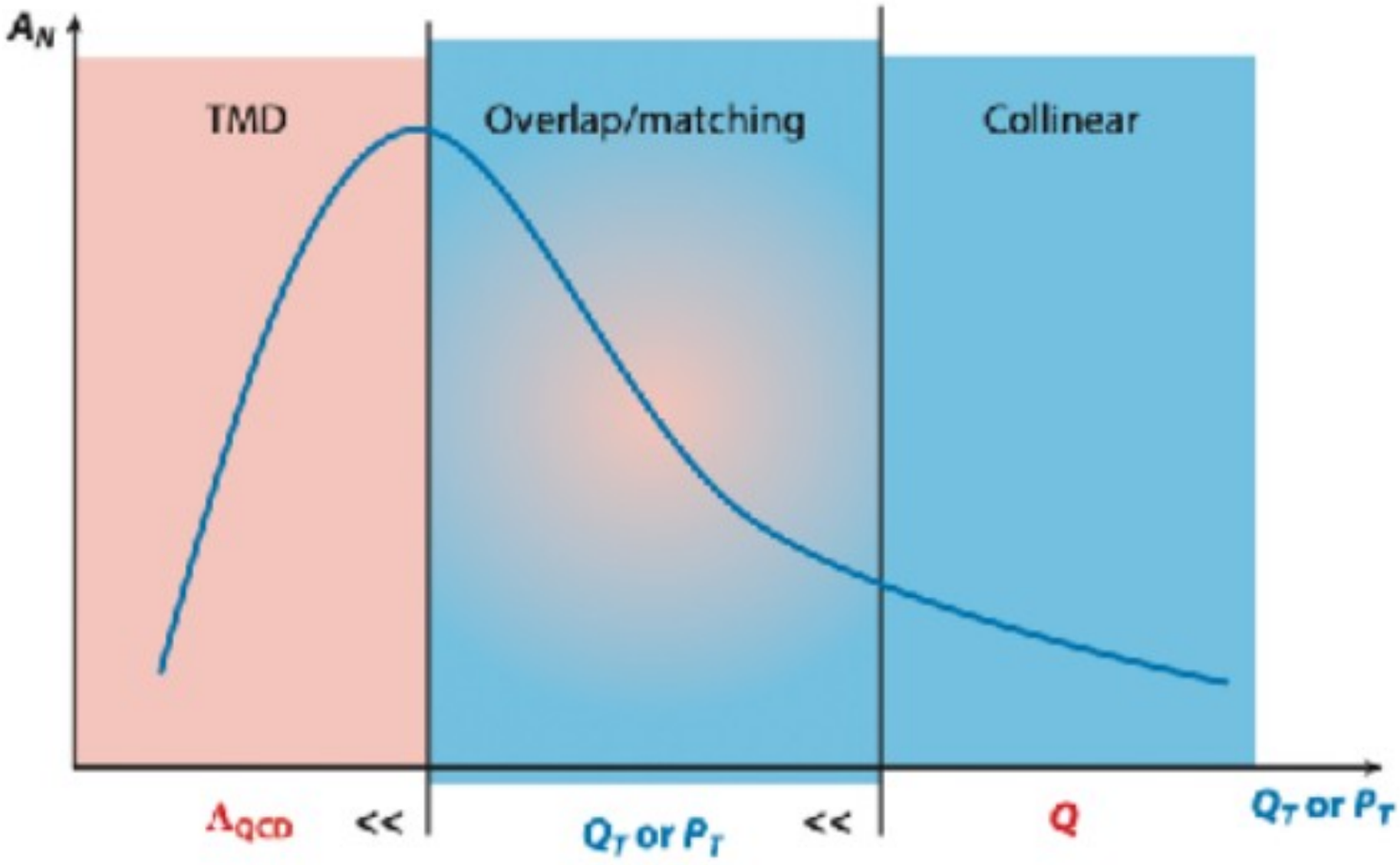
Parton 1D-distribitions:

Integrated over kT PDF: $f(x; \log Q^2)$ modulo $\log Q^2$ - DGLAP evolution

Extension to parton 3D-distribitions:

- **Generalized parton distributions (GPDs): $G(x, b, n; \log Q^2)$**
  b - impact parameter, n – unit vector
- **Unintegrated over kT PDF: $\Phi(x, kT, n; \log Q^2)$ (two theory approaches):**
  - **Unintegrated collinear PDF (uPDF)**
  - **Transverse momentum distribution (TMD)**

Gluon TMD effects: gluon Sivers function



TESTING FACTORIZATION:

- Collinear factorization
  twist-2 and twist-3

- TMD-factorization

STUDY:

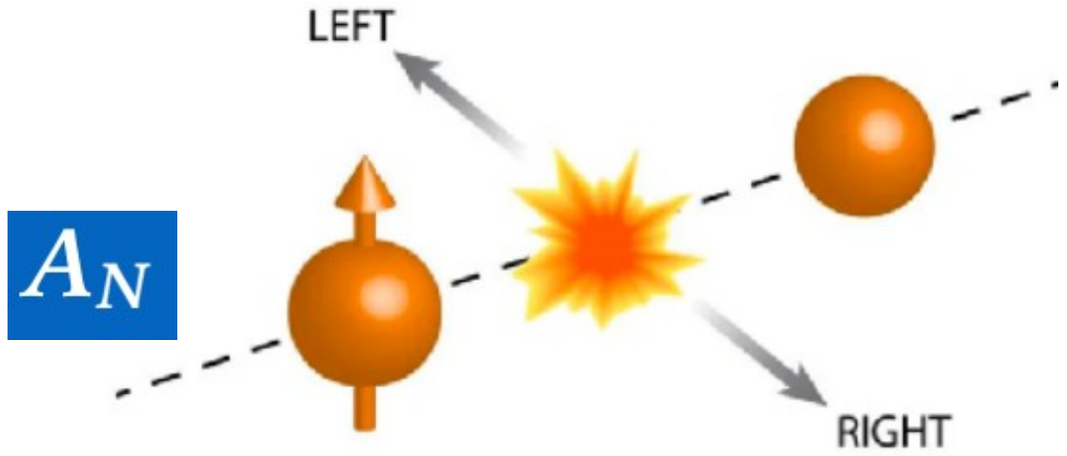
- Overlap/matching region
-TMD: nontrivial x and kT correlatio

Single Spin Asymmetry (SSA)

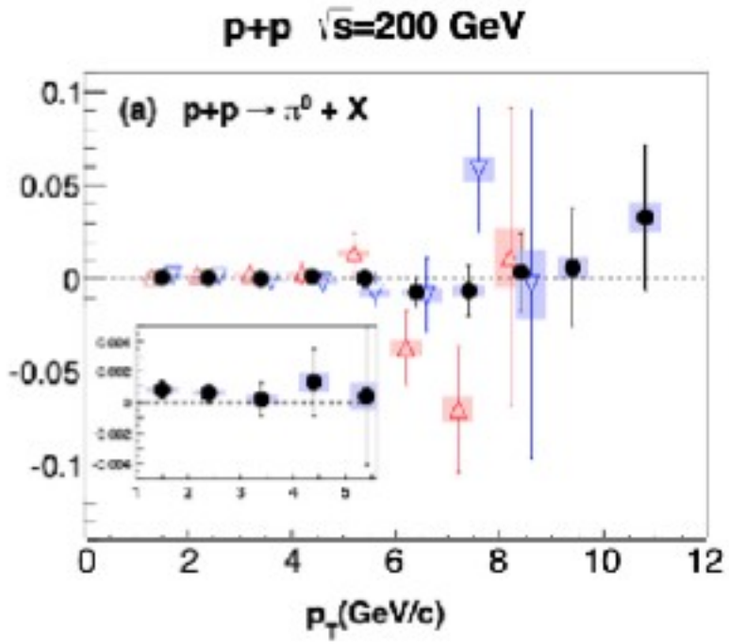
$$A_N = (d\sigma^{\uparrow} - d\sigma^{\downarrow})/(d\sigma^{\uparrow} + d\sigma^{\downarrow})$$

Sivers effect: L-R asymmetry of unpolarized kT-distribution in T-polarized nucleon

Collins effect: due to fragmentation of polarized parton



Gluon Sivers function

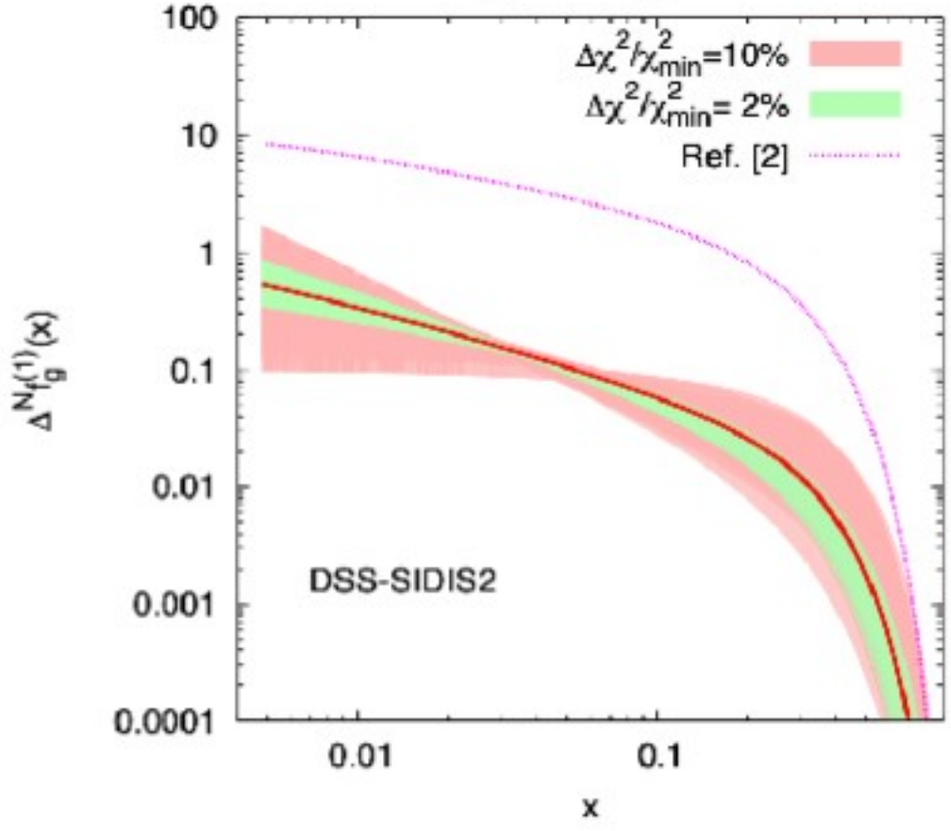


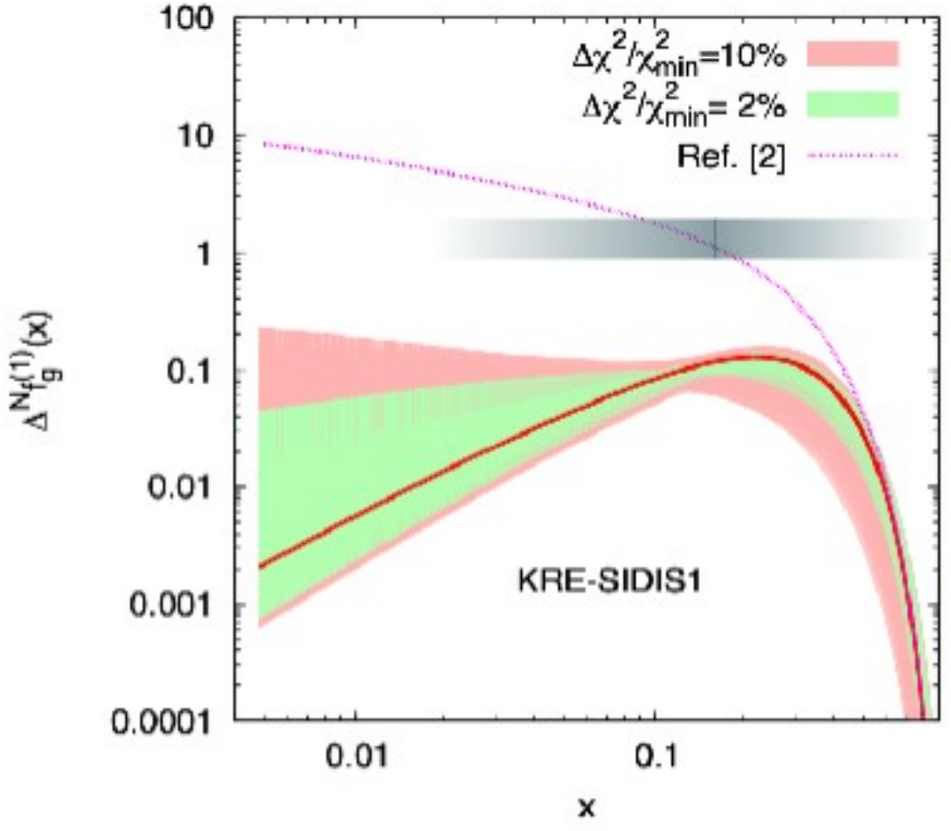
Phys.Rev.D 90 (2014) 1, 012006

PHENIX

First $k_\perp$-moment of the gluon Sivers function

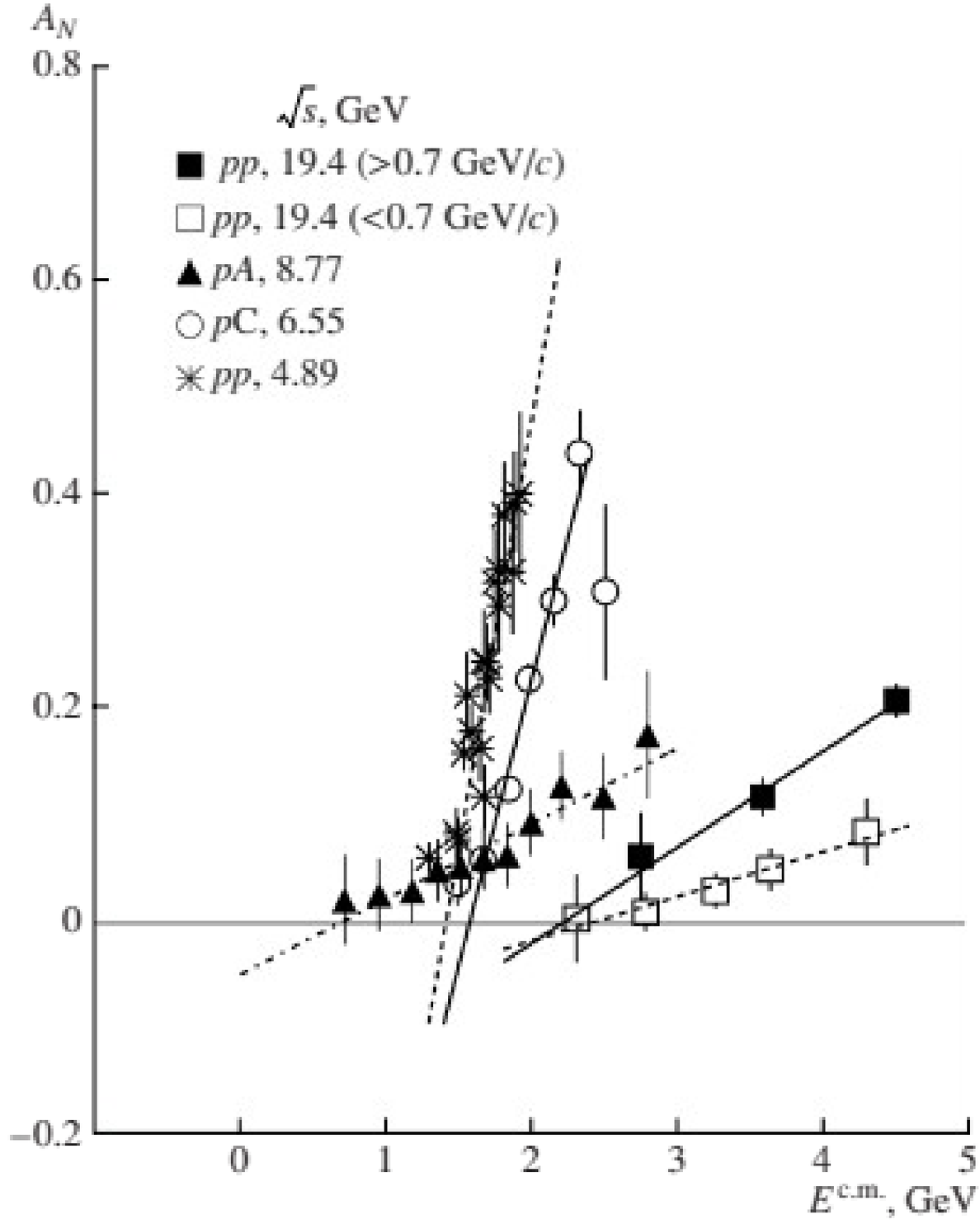
JHEP 09 (2015) 119





SPD

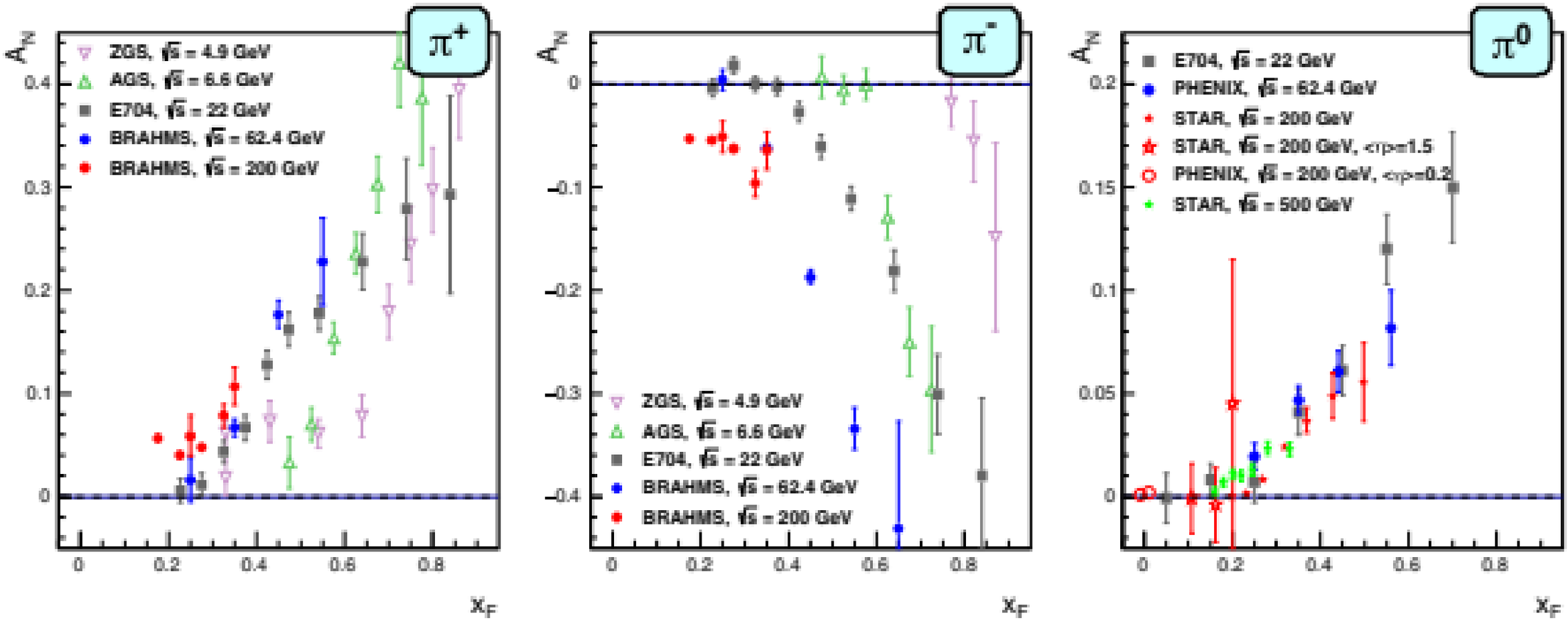
NICA energy range: fixed target at ZGS, AGS, U70, Tevatron



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

A_N in NICA energy range:
fixed target at ZGS, AGS, U70, Tevatron & collider RHIC

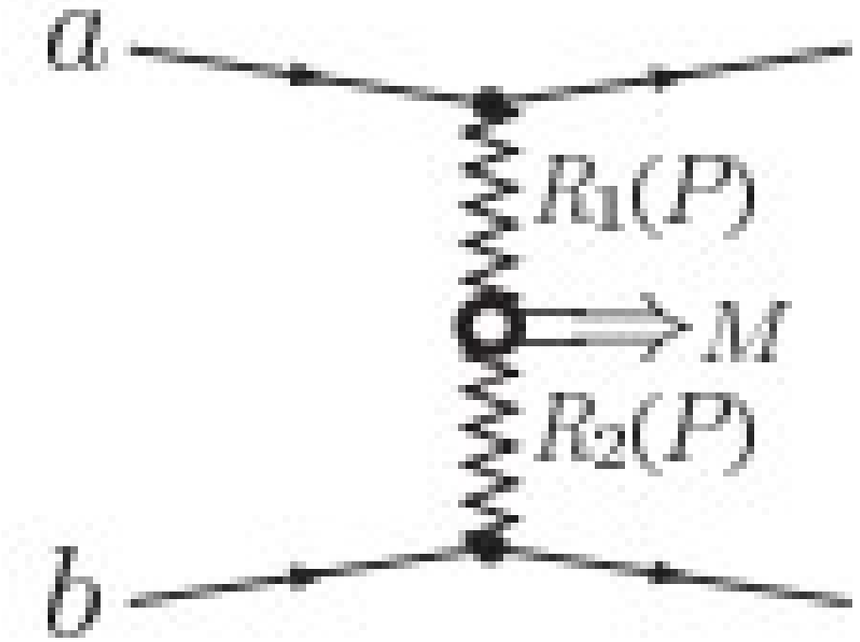
$$A_N = (d\sigma^{\uparrow} - d\sigma^{\downarrow})/(d\sigma^{\uparrow} + d\sigma^{\downarrow})$$

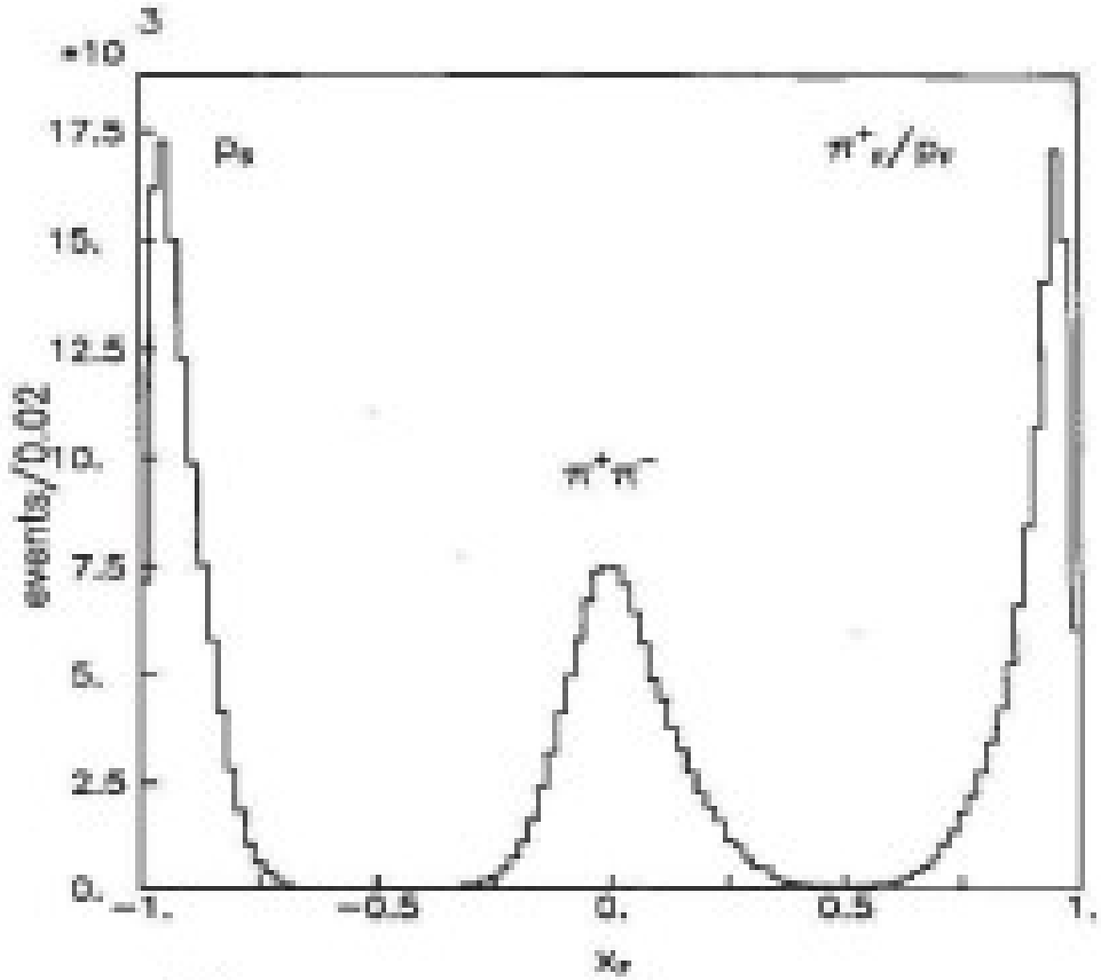


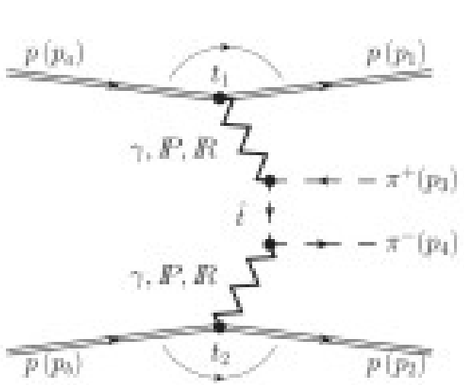
E.C. Aschenhauer, U. D'Alesio, F. Murgia, Eur. Phys. J. A 52 (2016) 6

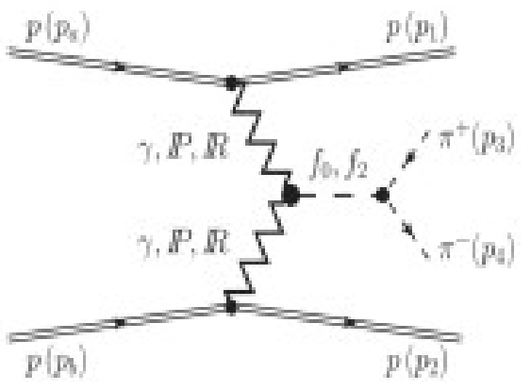
A_N in NICA energy range: effects can be higher

SPD Physics at the initial Stage: exotic states in central diffraction







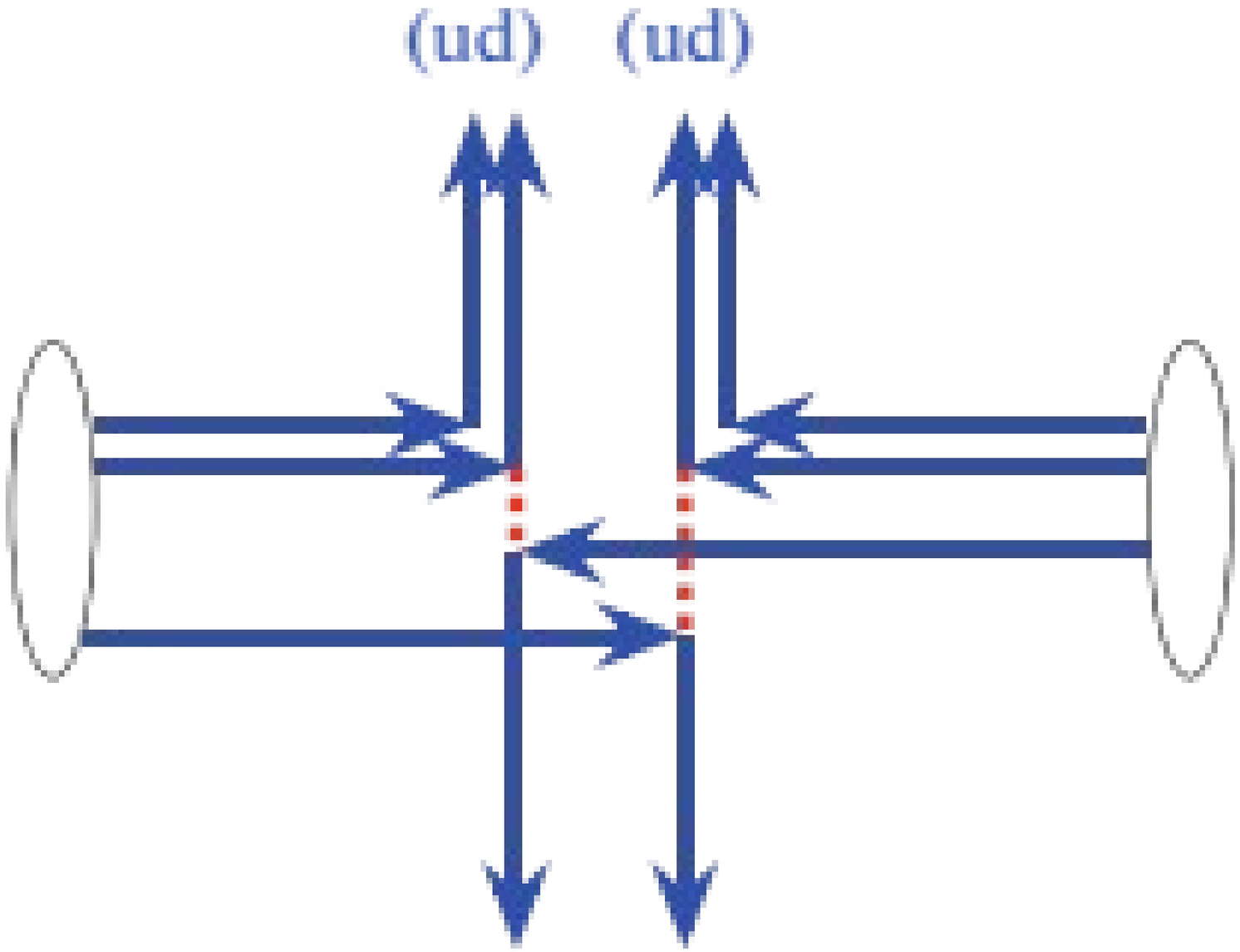


Non resonant production of 2 pions

Resonance production of 2 pions

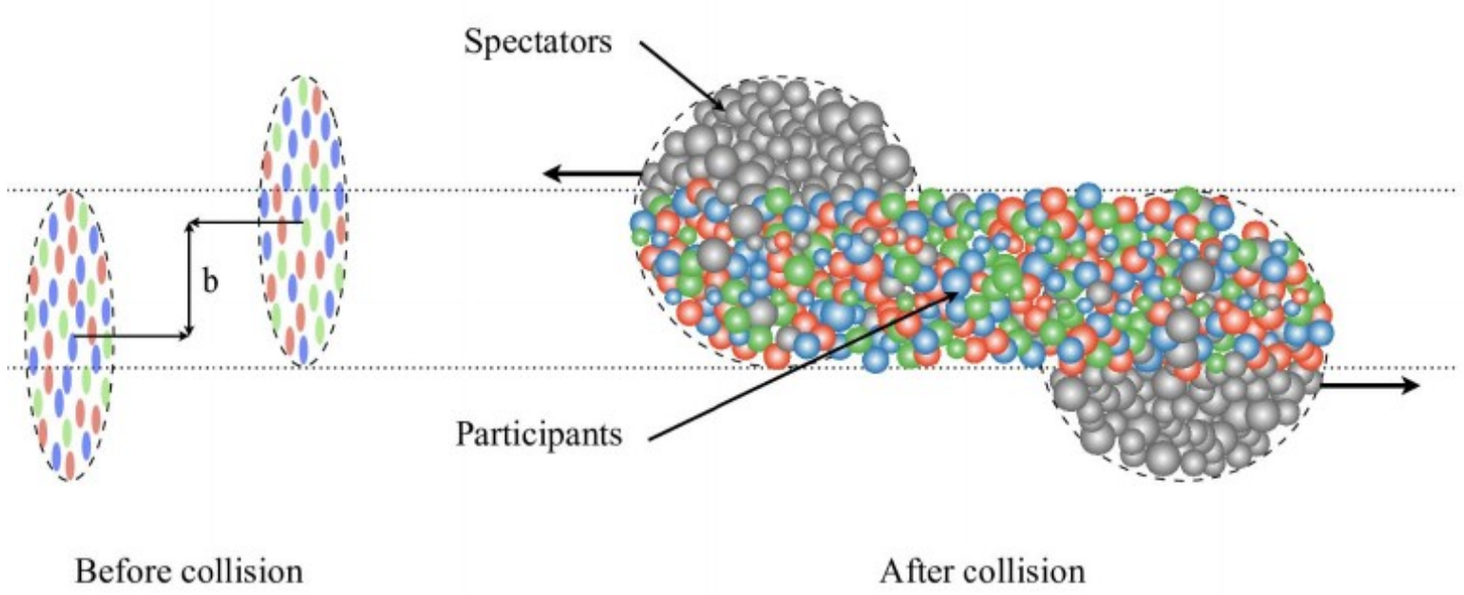
A.V. Sarantsev 2023

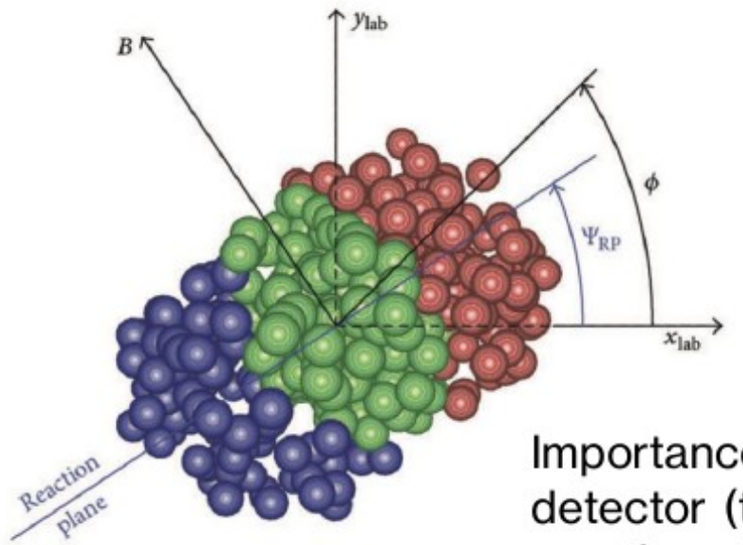
SPD Physics at the initial Stage: exotic states pentaquark, dihyperon, etc. production



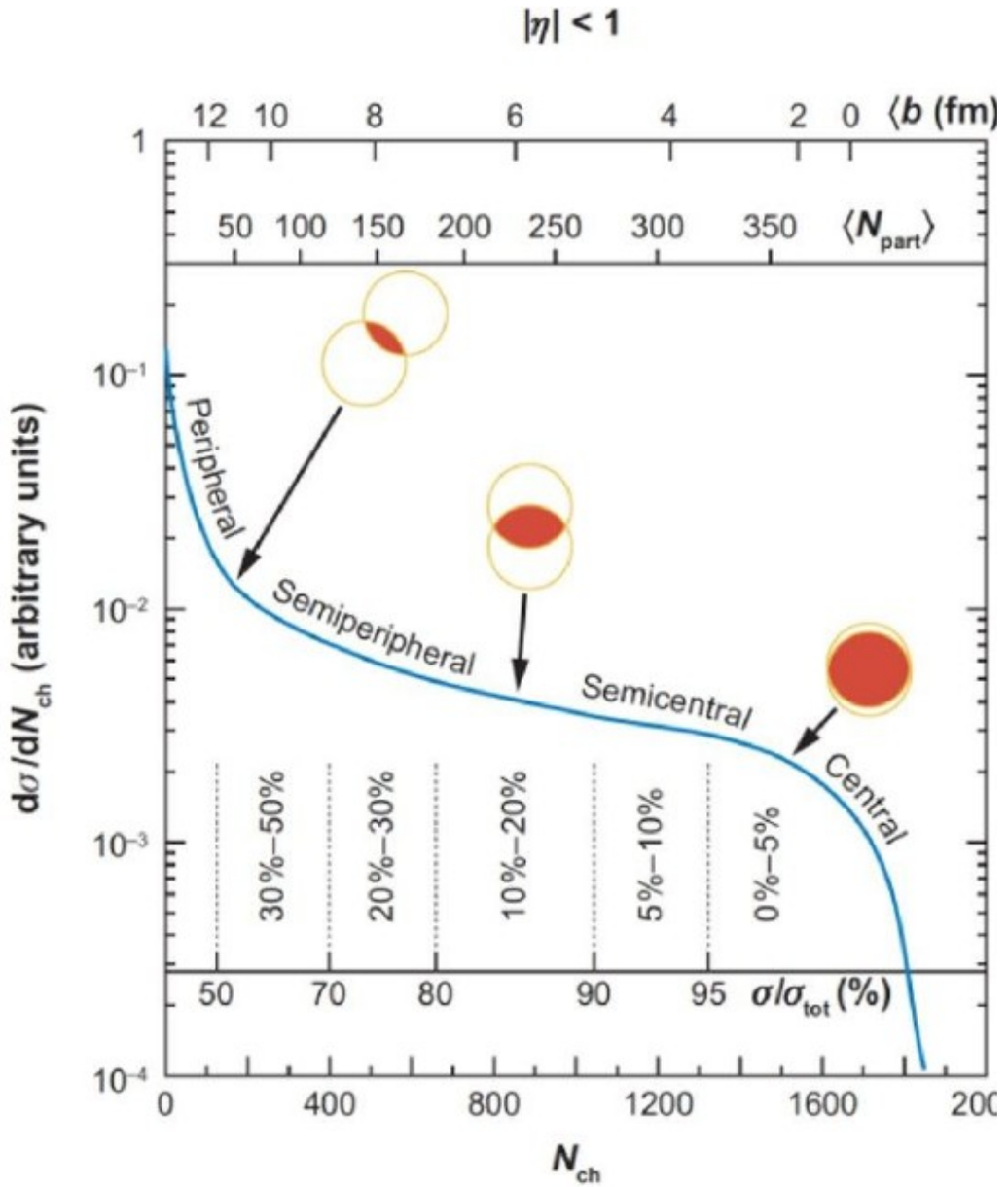
A. Efremov, V. Kim 1987
V. Abramov et al 2021

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

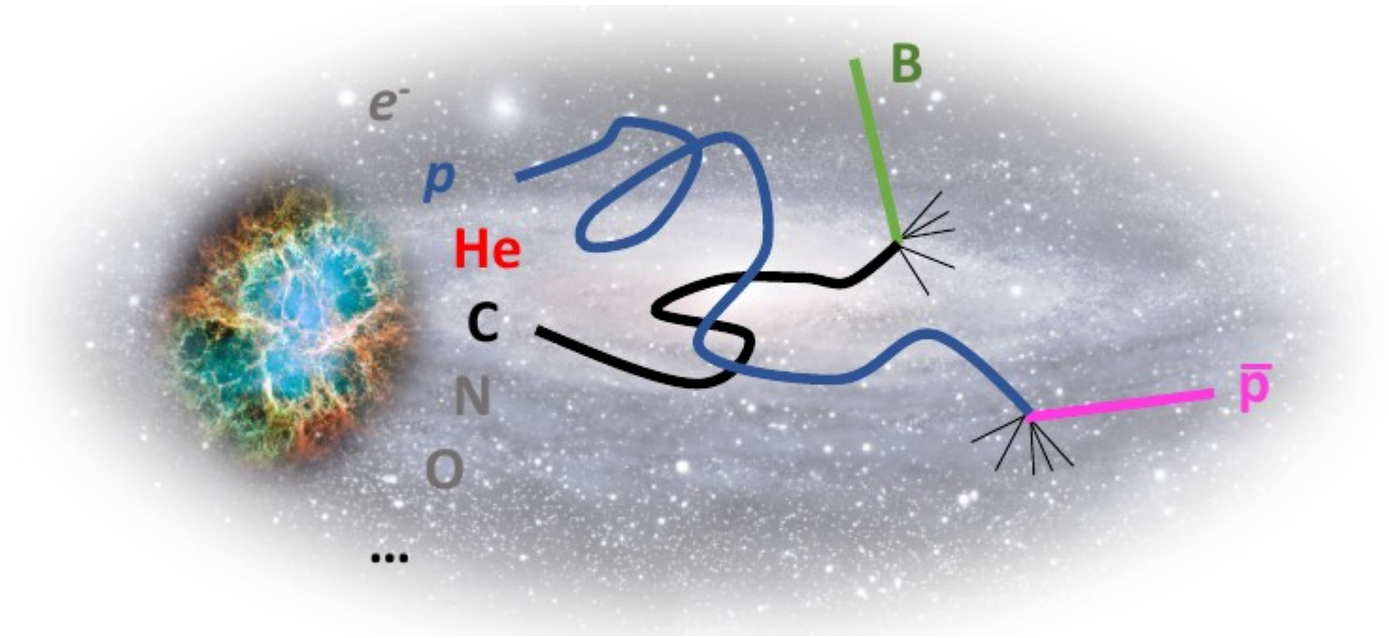




Importance of granular BBC detector (to reconstruct reaction plane angle)



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

Summary

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

Comprehensive and rich physics program for the fist period of data taking (Stage-1)

- ► **Spin effects in hyperon production in (un)polarized pp-collisions**
- ► **Spin effects in pp-, pd- and dd- scattering**
- ► **Tests of factorization of various approaches: CF, TMD, GPD, etc.**
- ► **Multiquark correlations (SRC, fluctons, dibaryons) in dd and ion-ion collisions**
- ► **Hypernucleus production**
- ► **Charmonia production near threshold**
- ► **Large-pT hadron production to study diquark structure of proton**
- ► **Semi-inclusive large-pT hadron production to study multiparton scattering**
- ► **Central exotic resonance production: search for glueball, pentaquark, tetraquark)**
- ► **Antiproton production measurement for astrophysics and BSM search**
- ► **…**

SPD physics a the Stage-1:

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

BACKUP

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 at the Stage-2: 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 (the Stage-1) (can be performed even at reduced energy and luminosity)**

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

$g^g_L(x, kT)$ L-polarized (chiral) quarks in L-polarized N helicity

$g^g_T(x, kT)$ 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):

$f^{\perp g}_L(x, kT)$ 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:

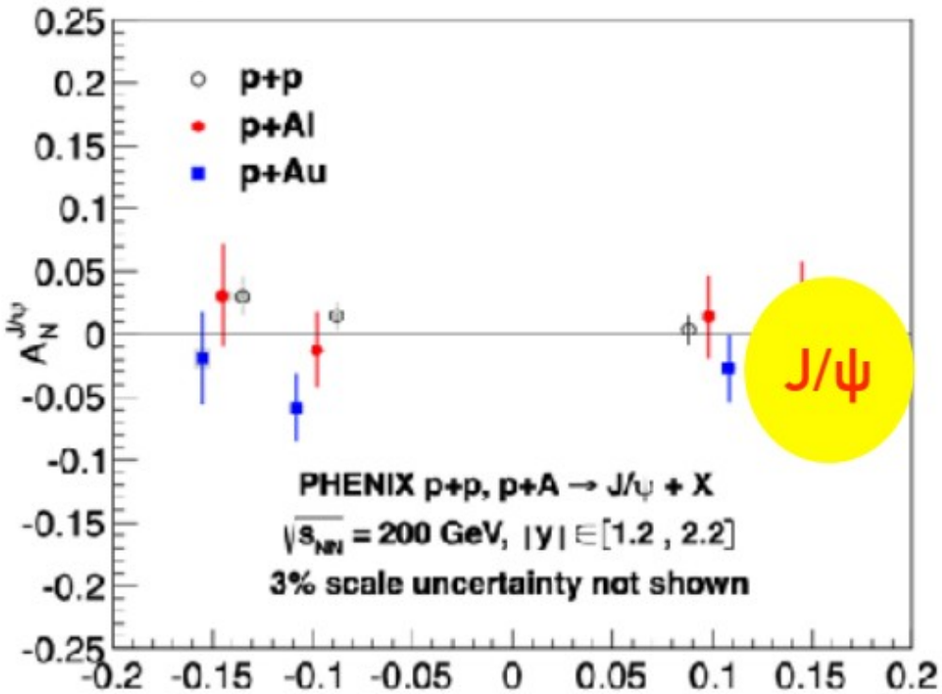
$f^q(x) = q(x) = q_{L=+}(x) + q_{L=-}(x)$

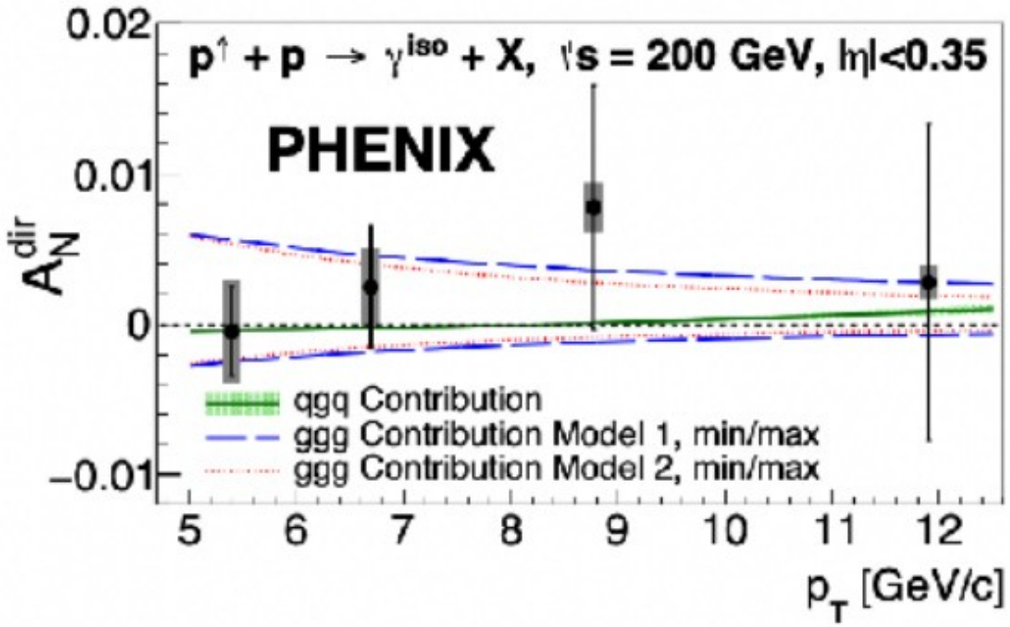
$g^q_L(x) = \Delta q(x) = q_{L=+}(x) - q_{L=-}(x)$ helicity (chirality)

$h^q_T(x) = \delta q(x) = q_{T=+}(x) - q_{T=-}(x)$ transversity

Gluon induced TMD effects: A_N at RHIC ($\sqrt{s}$=200 GeV)

Phys.Rev.D 98 (2018) 1, 012006





μ from HF

Phys.Rev.D 95 (2017) 11, 112001