Multi-messenger studies of nuclear short-range correlations (SRC)

Maria Patsyuk (JINR)

Joint 20th International Workshop on Hadron Structure and Spectroscopy and 5th workshop on Correlations in Partonic and Hadronic Interactions

NICA

TSINGHUA UNIVERSITY 1911

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

Hen Lab Laboratory for Nuclear Science @ MIT

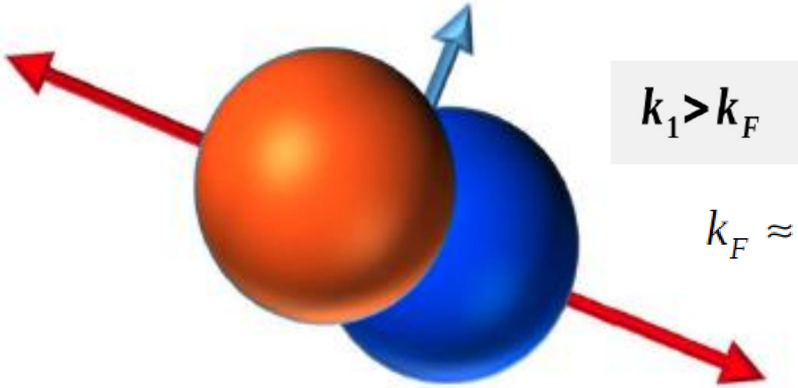
JINR

Short-Range Correlations (SRCs) – close proximity nucleon pairs

Short-range, short-lived,
highly correlated nucleon pairs

High momentum of correlated nucleons,
low pair momentum

r ~ R



$k_1 > k_F \quad k_2 > k_F \quad k_1 \simeq k_2$

$k_F \approx 250$ MeV/c

Position-space

Momentum-space

SRC Experiments and results

2018:
Nature 560, 617 (2018)
Phys. Rev. Lett. 121, 092501 (2018)
Phys. Lett. B 785, 304 (2018)
Phys. Lett. B 780, 211 (2018)

2019:
Nature 566, 354 (2019)
Phys. Rev. Lett, 122, 172502 (2019)
Phys. Lett. B 797, 134890 (2019)
Phys. Lett. B 797, 134792 (2019)
Phys. Lett. B 793, 360 (2019)
Phys. Lett. B 791, 242 (2019)

2020:
Nature 578, 540 (2020)
Phys. Rev. Lett. 124, 212501 (2020)
Phys. Rev. Lett. 124, 092002 (2020)
Phys. Lett. B 805, 135429 (2020)
Phys. Lett. B 811, 135877 (2020)
Phys. Lett. B 800,135110 (2020)

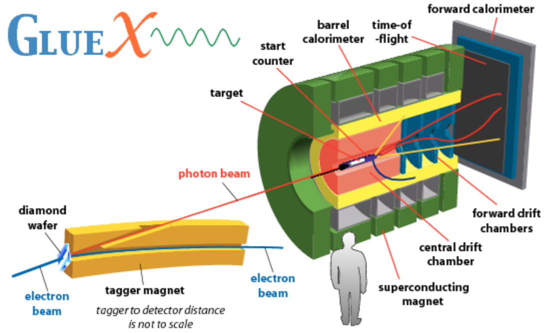
2021:
Nature Physics 17, 693 (2021)
Nature Physics 17, 306 (2021)
Phys. Lett. B 820, 136523 (2021)
Phys. Rev. Research 3, 023240 (2021)
Phys. Rev. C Lett. 103, L031301 (2021)

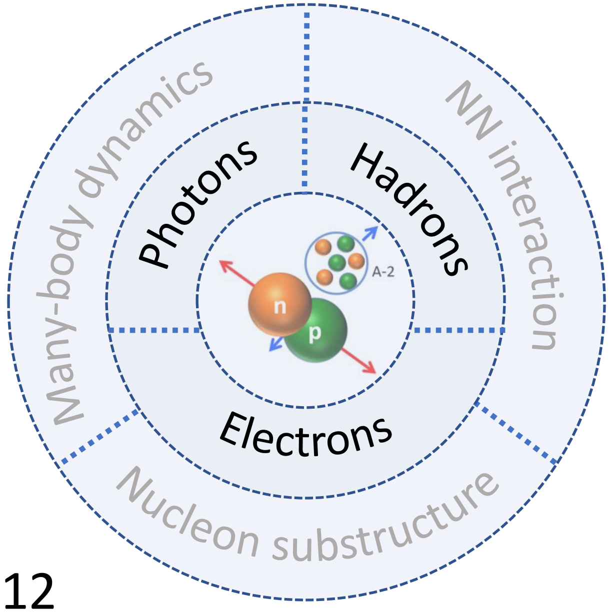
2022:
Phys. Rev. C 105, 034001 (2022)

2023:
Phys. Rev. C 107, L061301 (2023)
Nucl. Instrum. Meth. A 1052, 168238 (2023)

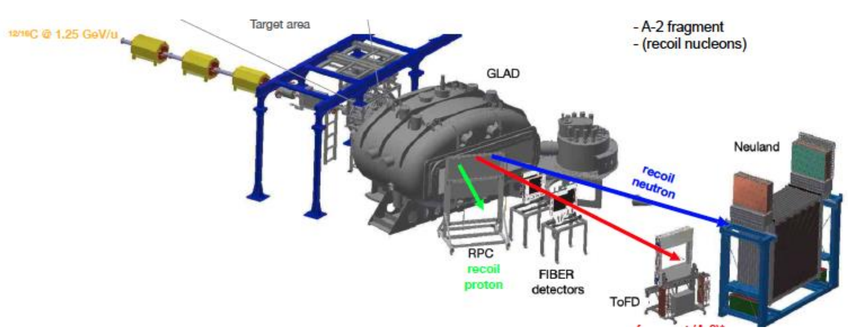
2024:
Nucl. Phys. A 1047, 122874 (2024)
JHEP 02, 123 (2024)
Phys. Rev. C 109, 054001 (2024)
Phys. Lett. B 855m 138790 (2024)

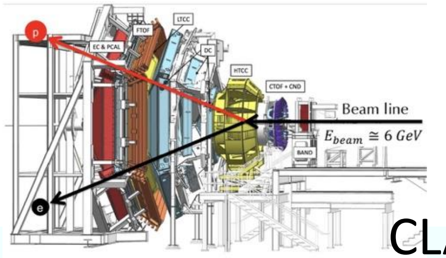
Jefferson Lab Hall D GlueX



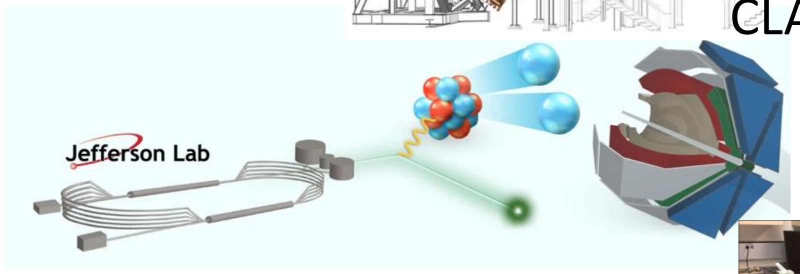


R3B

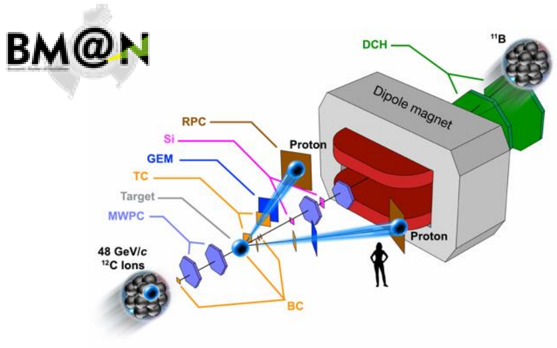




CLAS 12

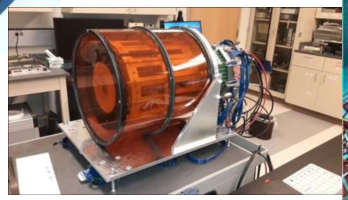


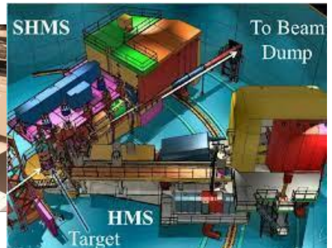
JINR



Jefferson Lab Halls A, B, C

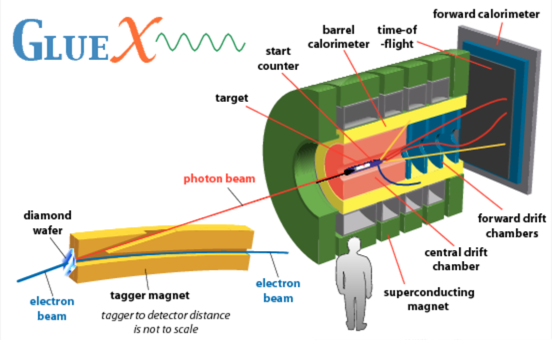
ALERT

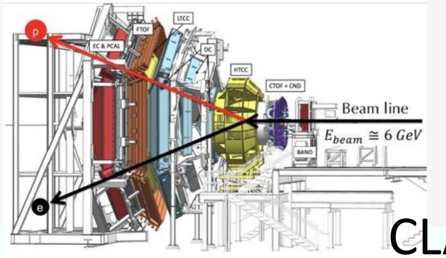




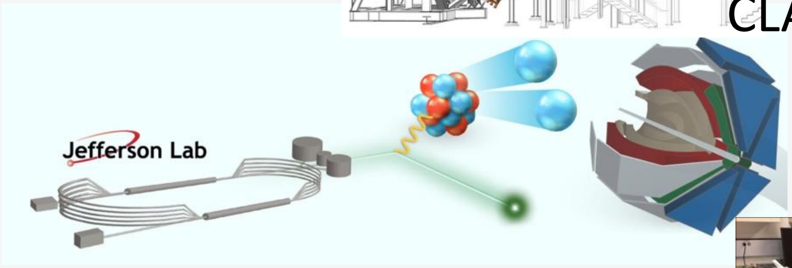
SRC studies with leptons

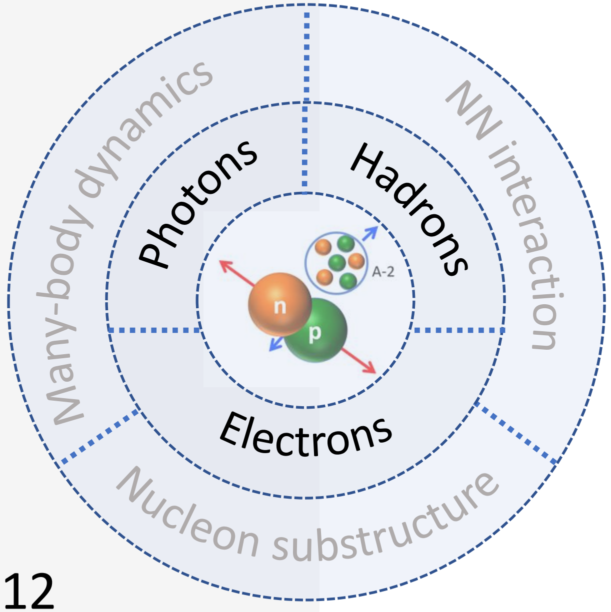
Jefferson Lab Hall D GlueX





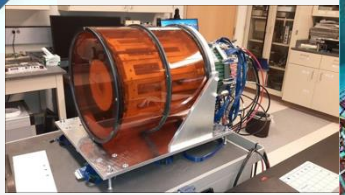
CLAS 12

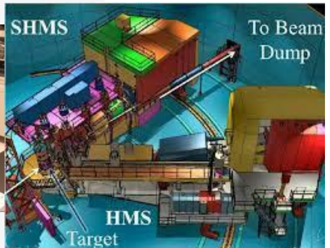




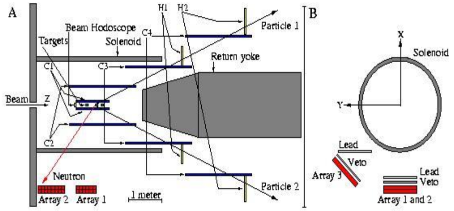
Jefferson Lab
Halls A, B, C

ALERT

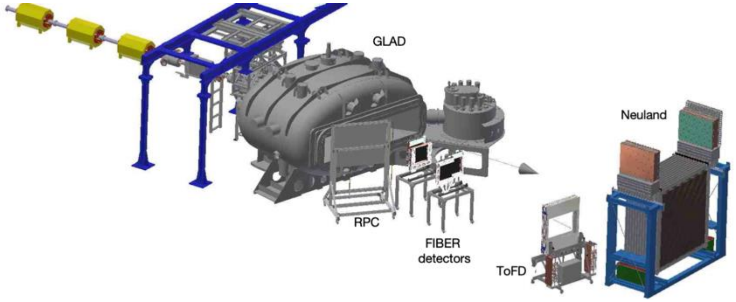




SRC studies with hadrons

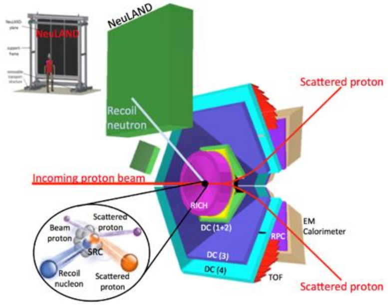


EVA/BNL

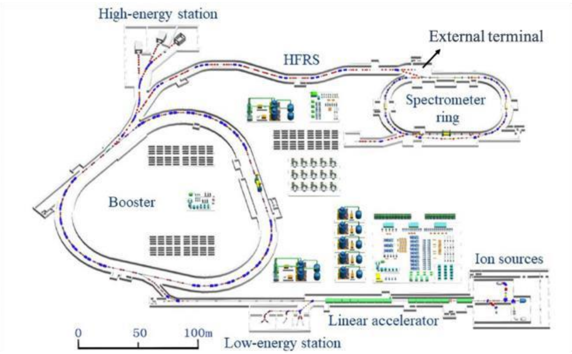


R3B

HADES

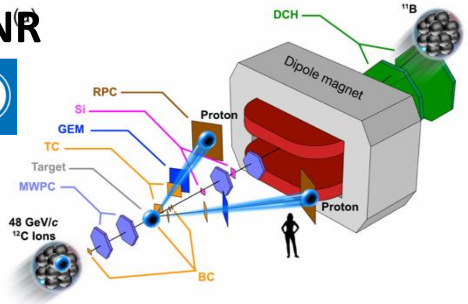


HIAF

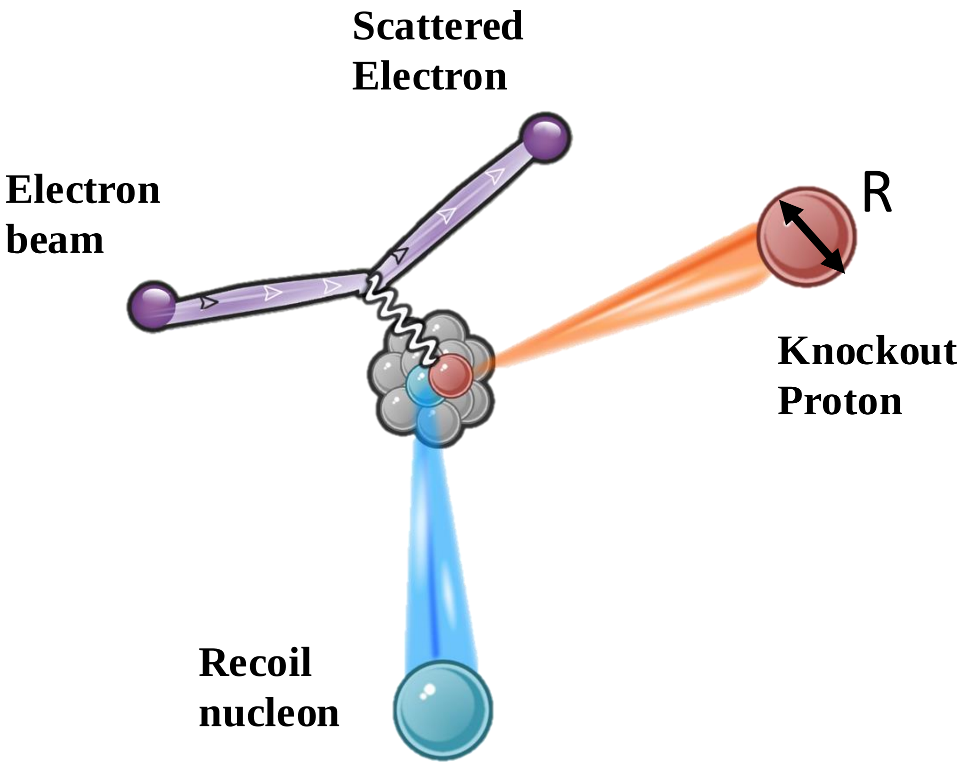


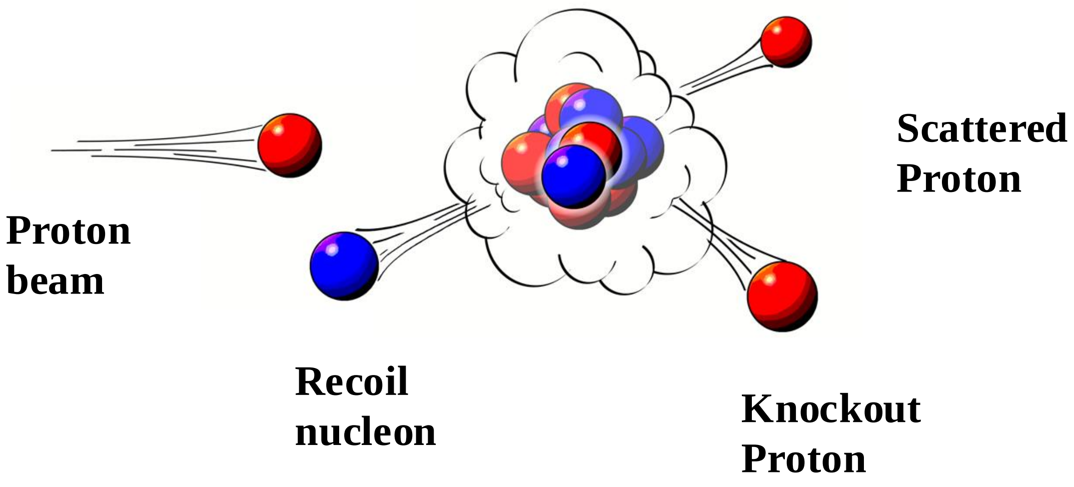
JINR

NICA



Study SRC with hard scattering

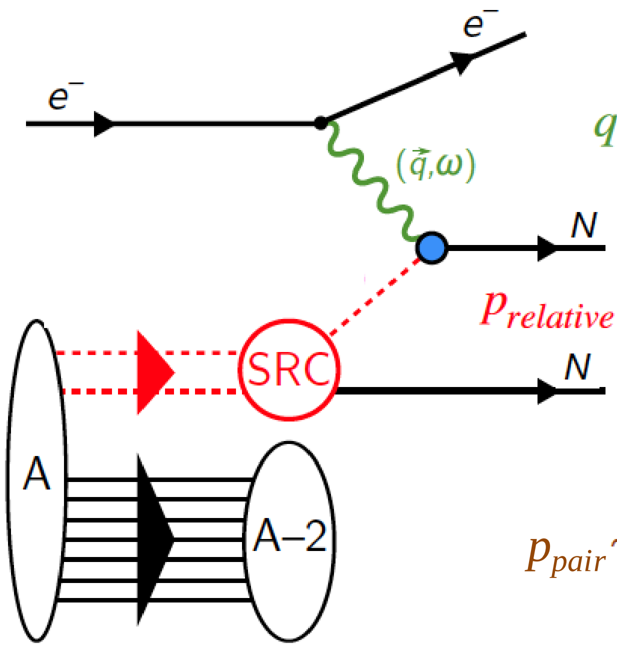




High energy: small de Broglie wavelength $\lambda < R$

Large momentum transfer q $q \cdot R < 1$

Scale Separation: $q \gg p_{relative} \gg p_{cm}$



$q > 1.5$ GeV/c

$p_{relative} \sim$ 300-700 MeV/c

$p_{pair} \sim$ 100-150 MeV/c

hard scattering

PRC 92 (2015), PLB 780 (2018), PLB 791 (2019), PLB 792 (2019), JPG 47 (2020), Nature Physics 17 (2021), PRC 104 (2021), PRC 53 (1996), PRL 119 (2017)

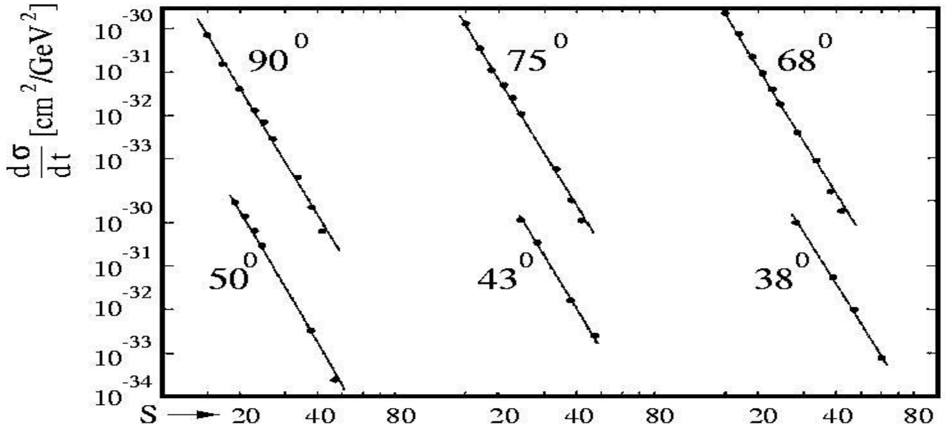
Elementary eN cross section	Nuclear Contacts	Two-body wave function	Center of mass motion

$$\sigma_{eA} = \sigma_{eN}(q) \cdot \sum_{NN-pairs} \cdot C_A^{NN} \cdot |\phi(p_{relative})|^2 \cdot n(p_{pair})$$

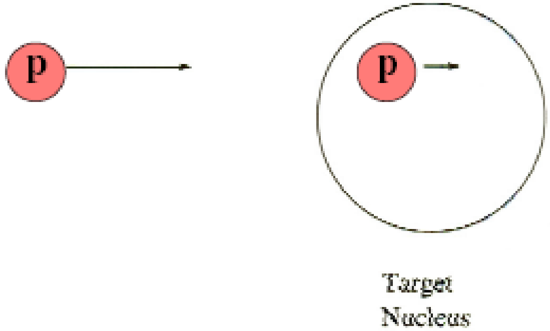
Advantage of hadronic probes

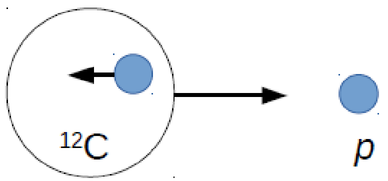
$$\frac{d\sigma}{dt} \propto s^{-10}$$

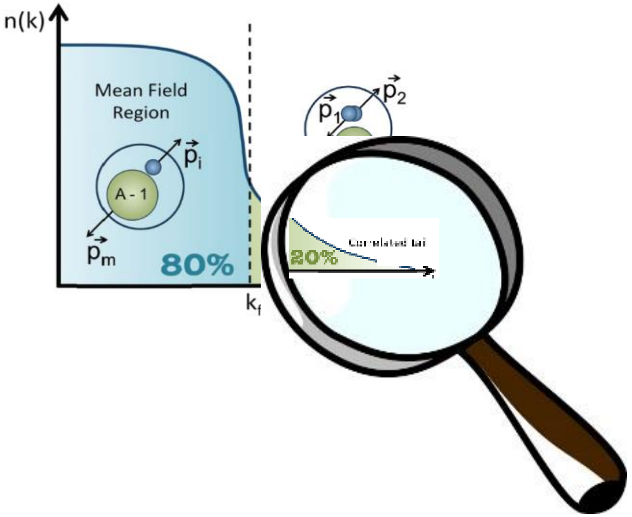
pp elastic scattering



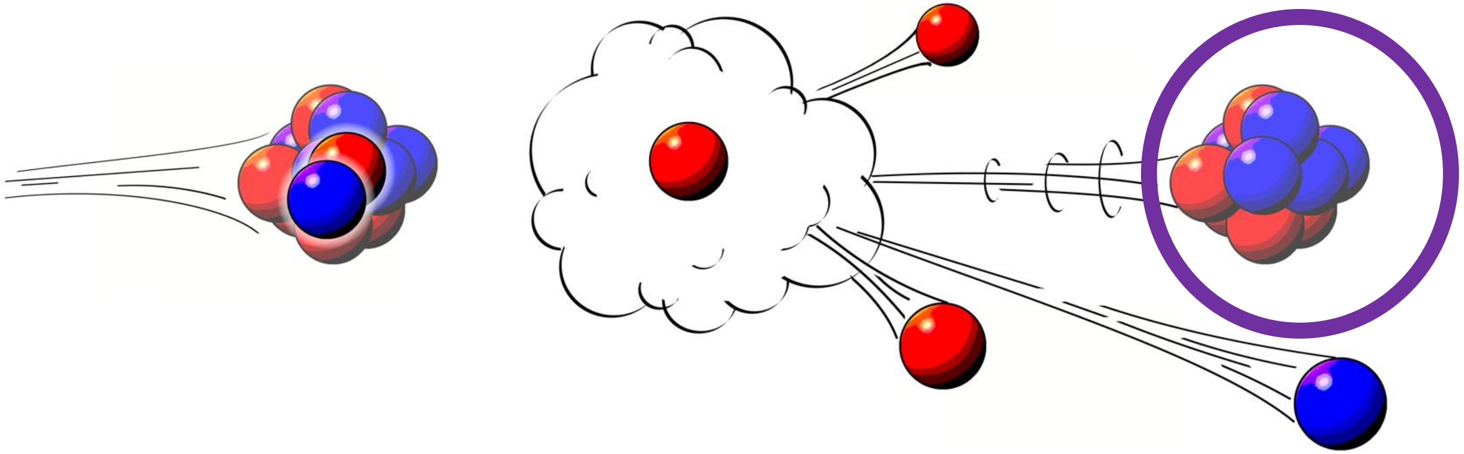
QE pp scattering have a very strong preference for reacting with high-momentum nuclear protons (lower s)







Advantages of inverse kinematics



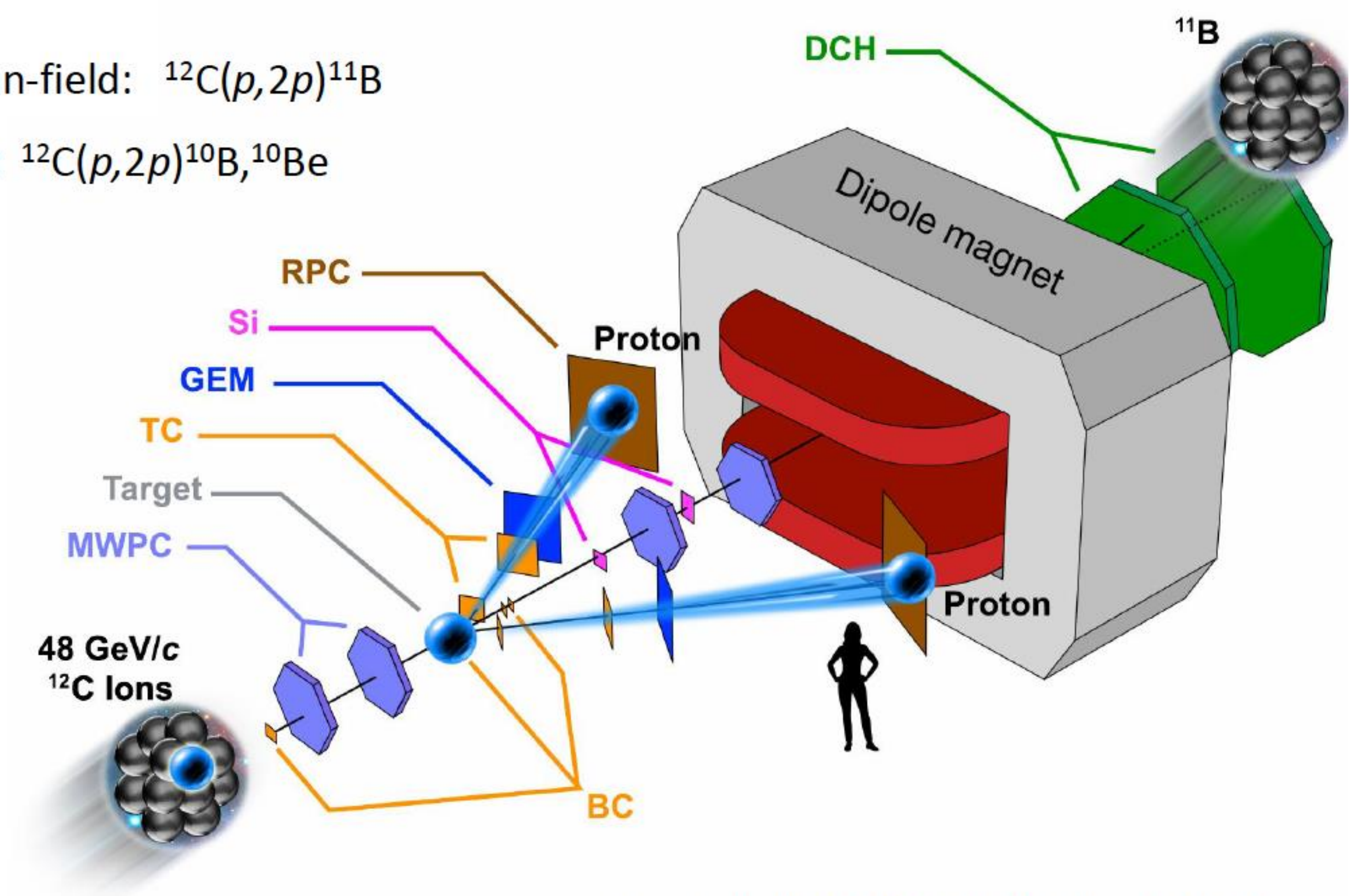
Exotic unstable very asymmetric nuclei

Fully exclusive measurement
Suppress rescattering
More information on initial ground state
More information on reaction mechanism

Experiment with hadronic probes at BM@N/JINR in inverse kinematics

Mean-field: $^{12}C(p,2p)^{11}B$

SRC: $^{12}C(p,2p)^{10}B,^{10}Be$



M. Patsyuk, JK et al. (BM@N), Nat. Phys. 17 (2021).

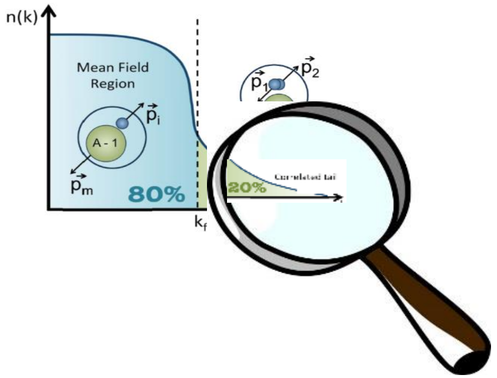
See talk by Timur Atovullaev on Friday Oct 4th at 9.50

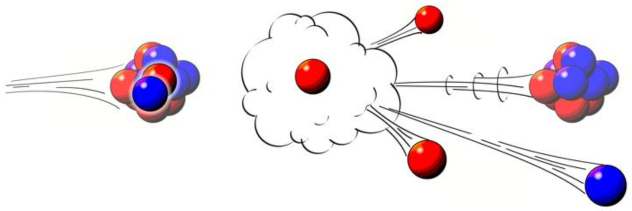
Why pA (summary)

* Large cross section , high beam intensity ➔ **superior SRC statistic**

* Selects high momentum nucleons (SRC pairs)

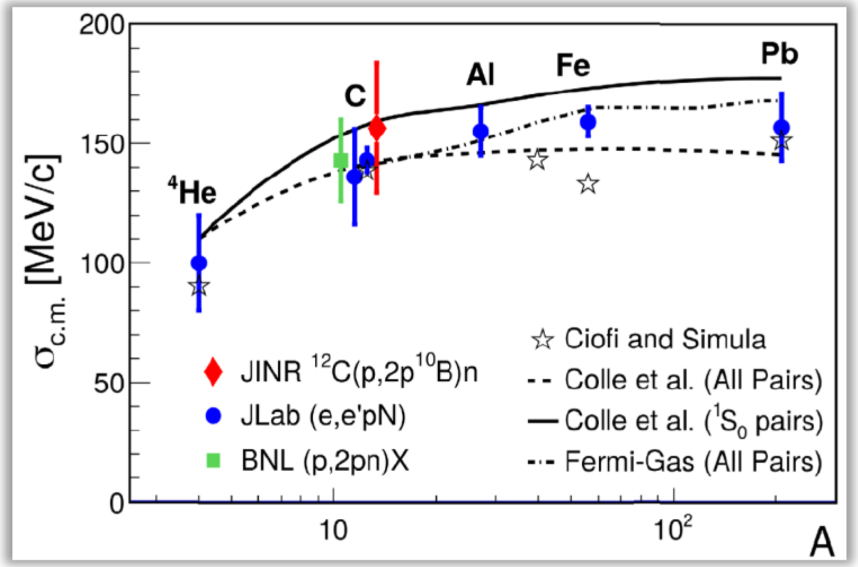
* Allows **inverse kinematics**:





- Fully exclusive (including A-2)
- Suppress rescattering
- More information on the ground state
- More information on the reaction mechanism

- Acess to exotic (very asymmetric) nuclei



* **Multimessenger study** pA with eA and γA

SRC studies with hadrons

Fragmnets tagging

(R3B, JINR, HIAF, ALERT@CLAS12)

Neutron-rich nuclei / isotopic chains

(R3B, CLAS12, HIAF)

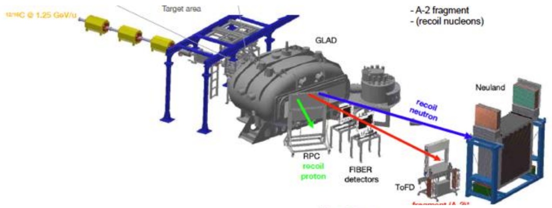
Polarized probes

(JINR)

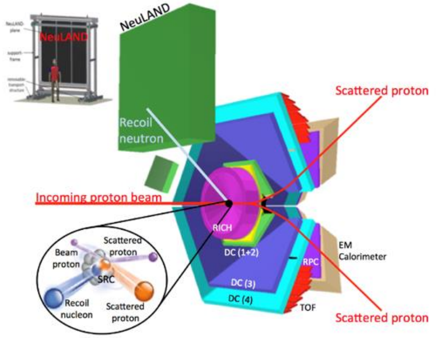
High statistics

(HADES, JINR, HIAF)

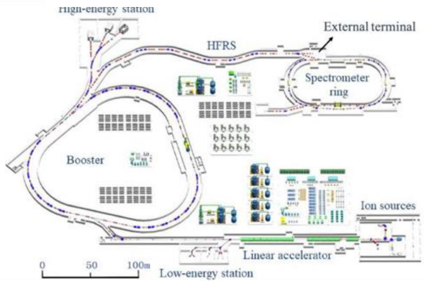
R3B



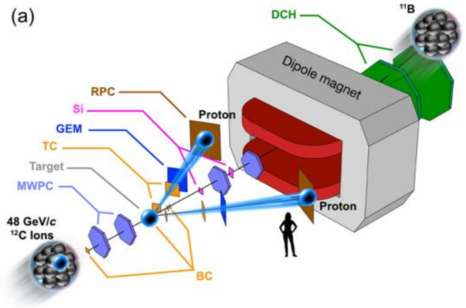
HADES



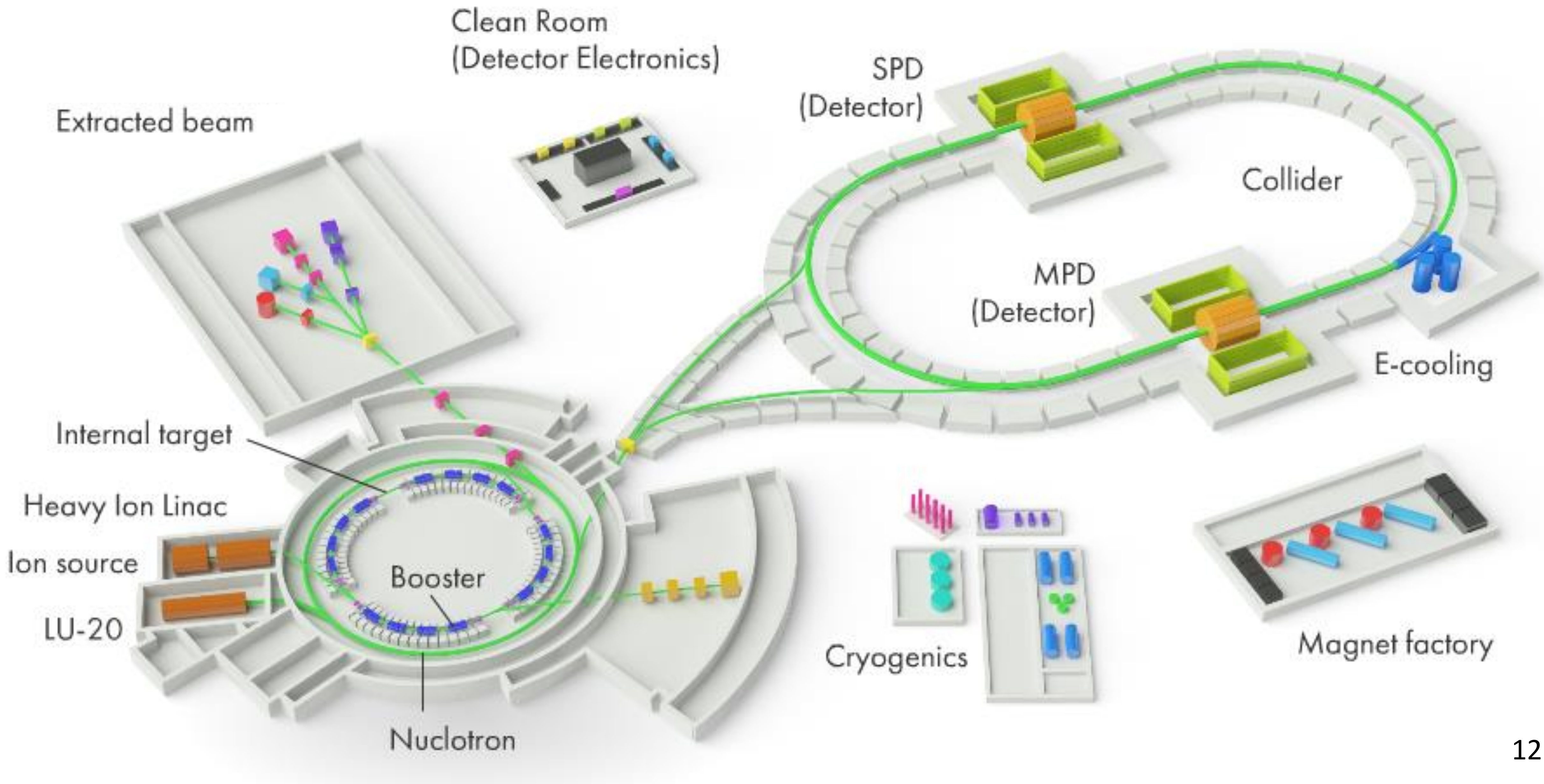
HIAF



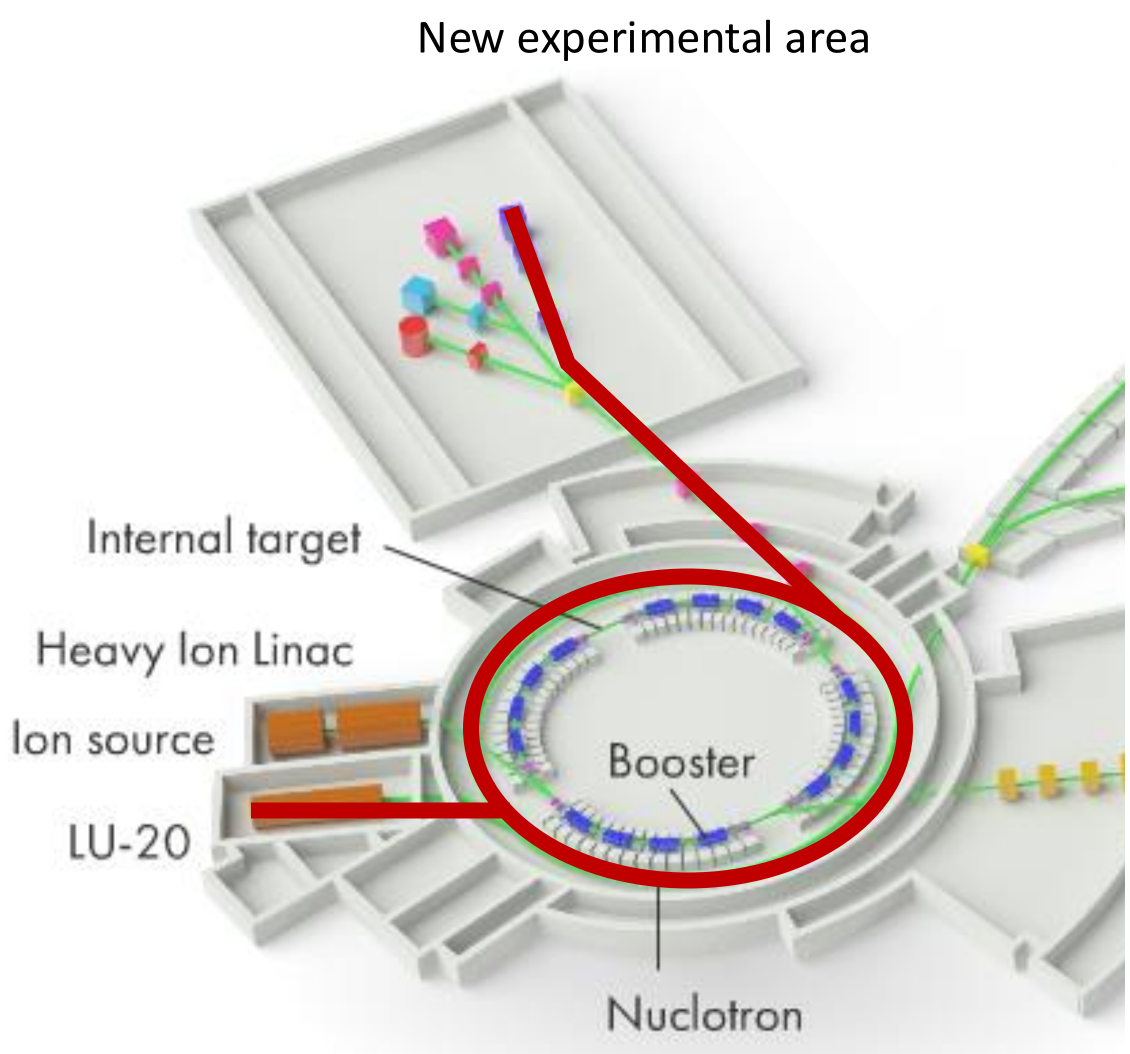
JINR



at Joint Institute for Nuclear Research (JINR)

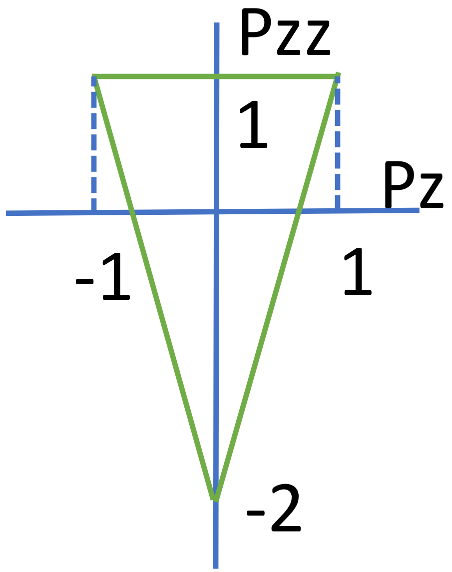


New SRC experiment with tensor-polarized deuteron beam



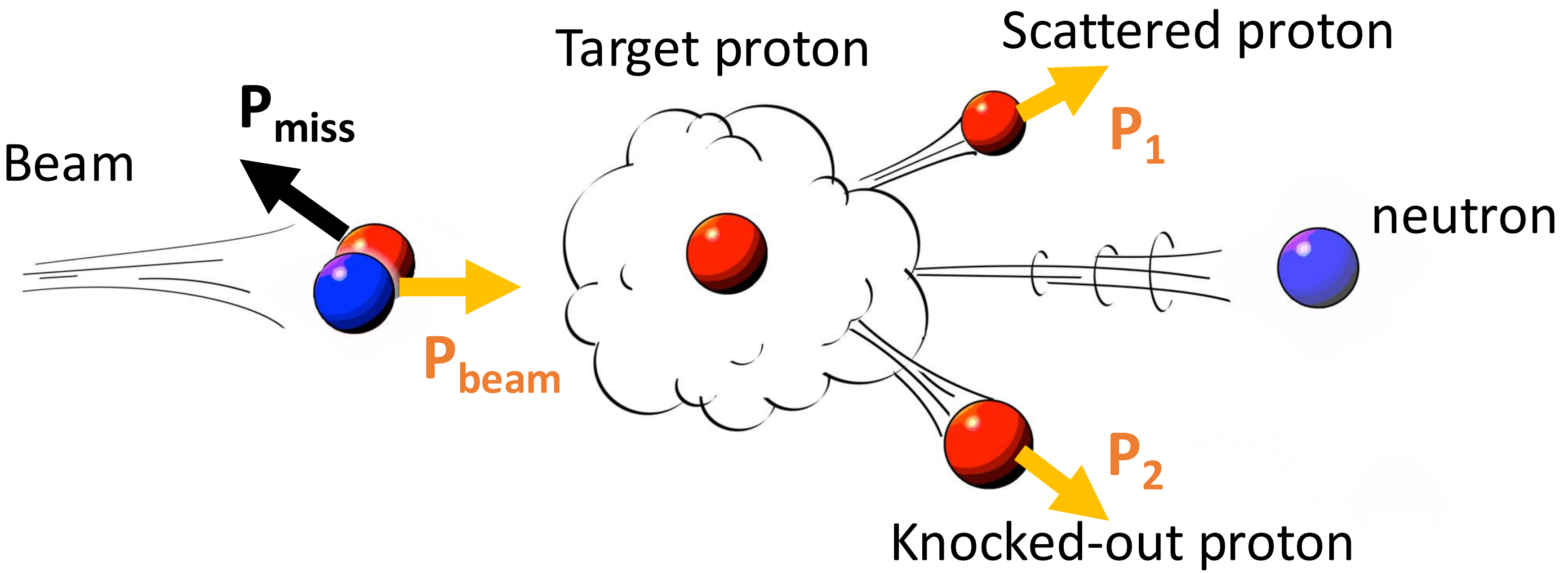
d beam, p < 5.5 GeV/c/nucleon, intensity 10^6 d/s

Various polarization configurations are available



Polarization can be changed every spill (σ_+ , σ_- , σ_0)

Quasi-free **(p,2p)** scattering

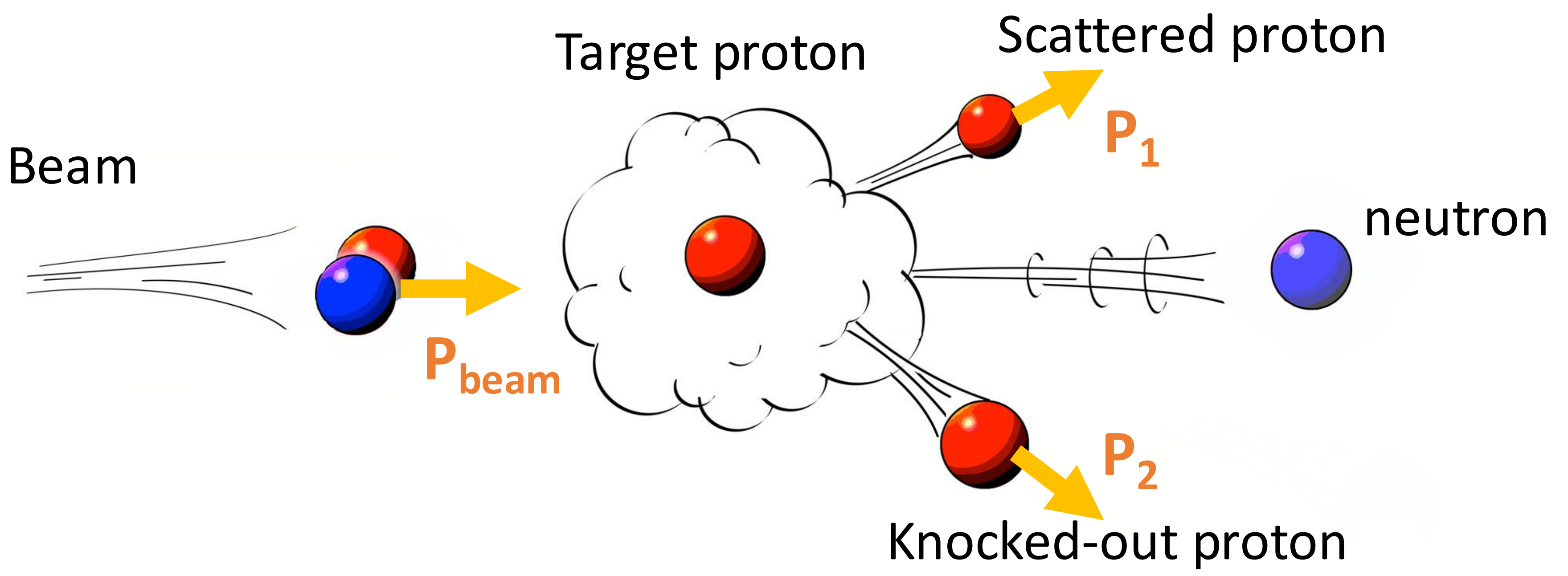


Reconstruct initial nucleon momentum $\mathbf{P_{miss}}$ from scattered particles

$$\mathbf{P_{miss}} = P_1 + P_2 - P_{beam}$$

~ 90° c.m. scattering

A_{zz} for hard quasi-free breakup of the deuteron: $\vec{d}$(p, 2p)n

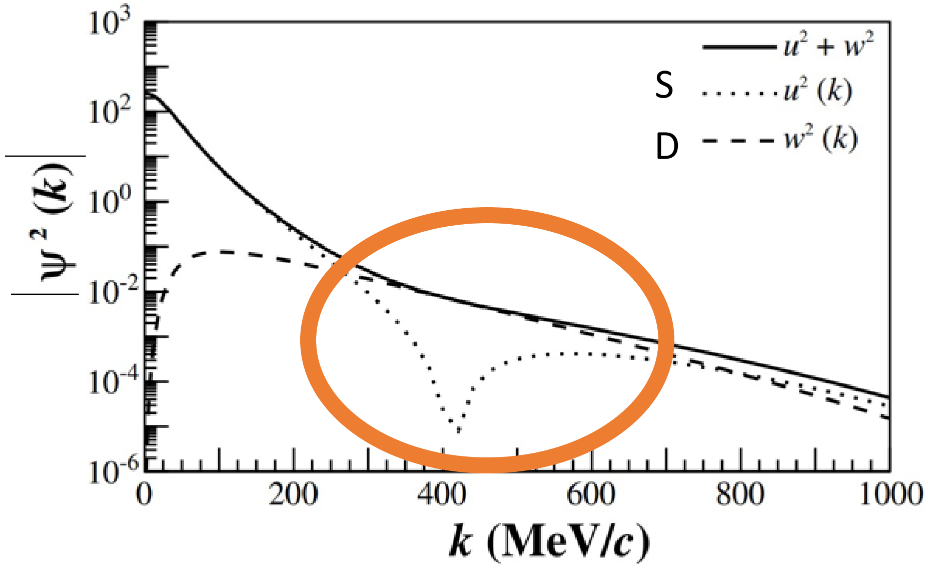


- |t| & |u| > 1 GeV^2
- $60^0 < \theta_{cm}$
- Two-arm acceptance: $20^0 < \theta_{lab} < 45^0$; $-20^0 <|\varphi_{lab}| < 20^0$
- $p_{miss} > 0.25$ GeV/c.

$$A_{zz} = \frac{(\sigma_- + \sigma_+ - 2\sigma_0)}{\sigma_{unpol}}$$

σ_-, σ_+, σ_0 – cross sections for different tensor polarization states

Tensor asymmetry has a better sensitivity to admixture of small w.f. component than σ

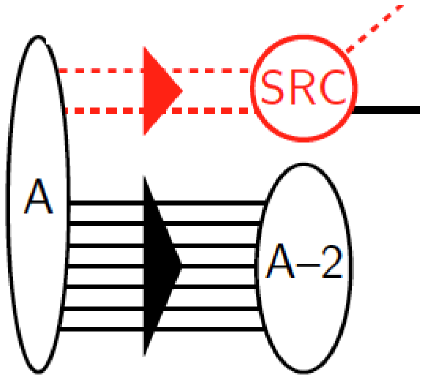


$$A_{zz} = \frac{(\sigma_- + \sigma_+ - 2\sigma_0)}{\sigma_{unpol}}$$

$$\sigma \sim u(k)^2 + w(k)^2$$

u(k) – S-wave, w(k) – D-wave

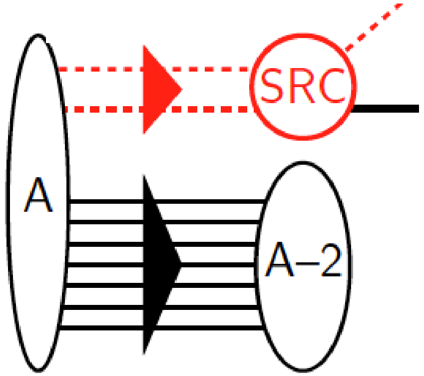
$$A_{zz} \sim \frac{\frac{1}{2}w^2(k) - u(k)w(k)\sqrt{2}}{u^2(k) + w^2(k)}$$



L. Frankfurt and M. Strikman, Phys.Rept. 160, 235 (1988)
V. G. Ableev, E. Strokovsky et. al, Pis'ma Zh. Exp. Teor. Fiz. 47, 11 (1988)

See talk by Misak Sargsian on Wed. Oct 2d at 14.45

What can we study?



1. Relativistic description of the bound system 

2. Ratio between S- and D-waves of the deuteron 

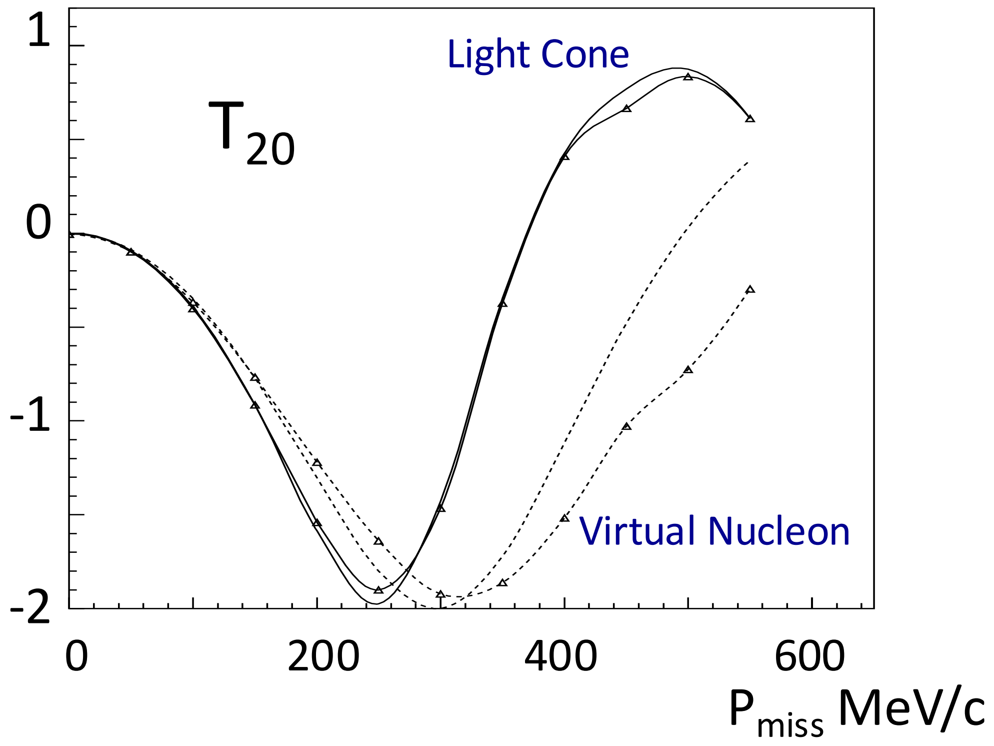
3. Final state interactions in the high-momentum region 

4. Non-nucleonic deuteron components in polarization measurements 

Relativistic description of the bound system

$$T_{20} \equiv \frac{1}{3}\left(\sigma(1,1) + \sigma(1,-1) - 2 \cdot \sigma(1,0)\right)$$

$$\theta_{ps} = 180^0$$



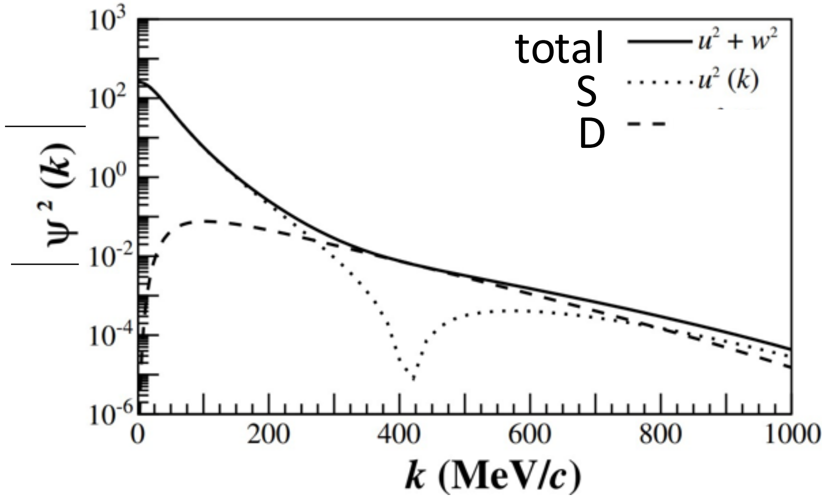
Curves with triangles Include FSI

M.Sargsian & M.Strikman, 2002

Work in Progress

Ratio between S- and D-waves of the deuteron

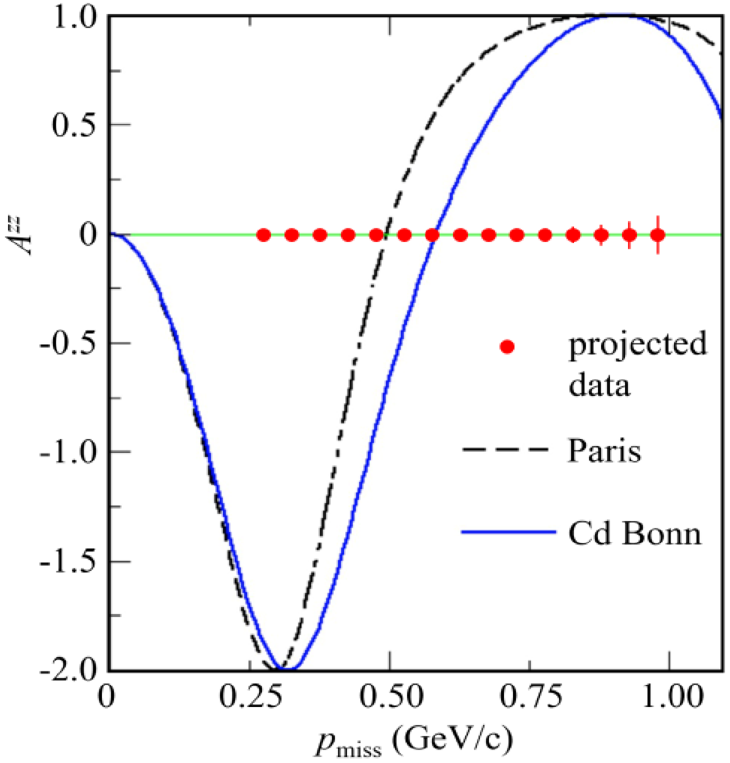
NN-potentials have different D-wave contribution



4.87% (e.g., CDBonn)

5.76% (e.g., **AV18**)

Yu. Uzikov

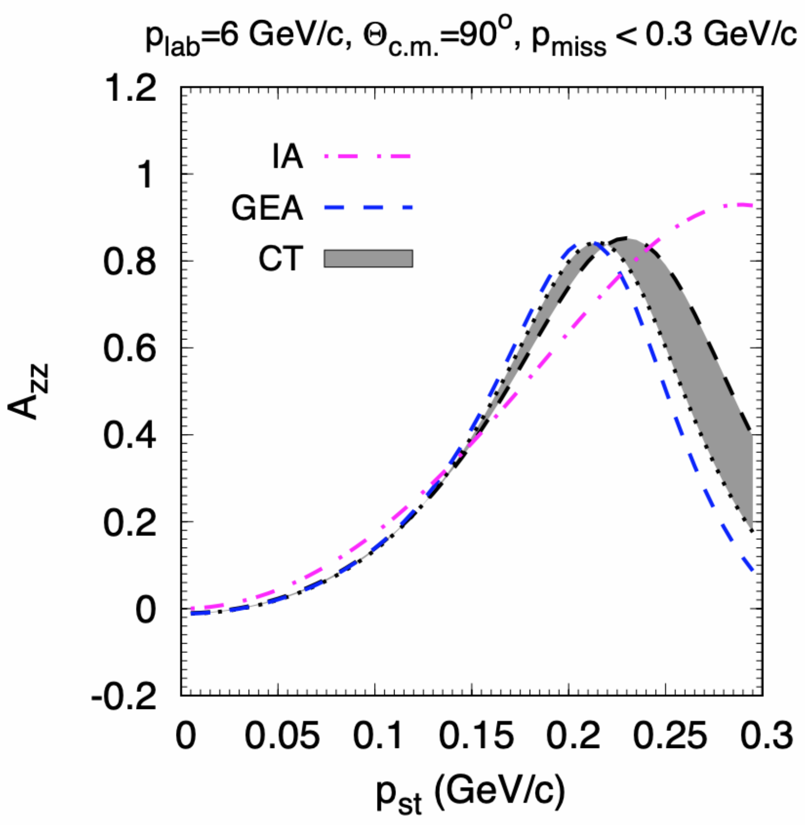


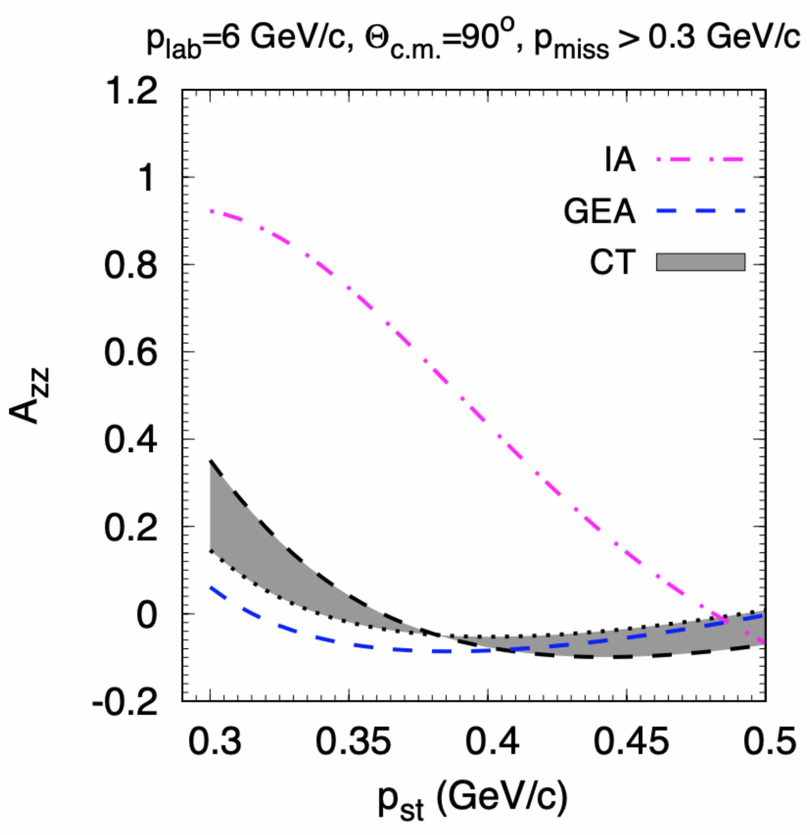
Leads to dramatic differences in relativistic description of the bound system!

Measure A_{ZZ} -> constrain S/D ratio for deuteron ?

Impact of FSI

A. Larionov



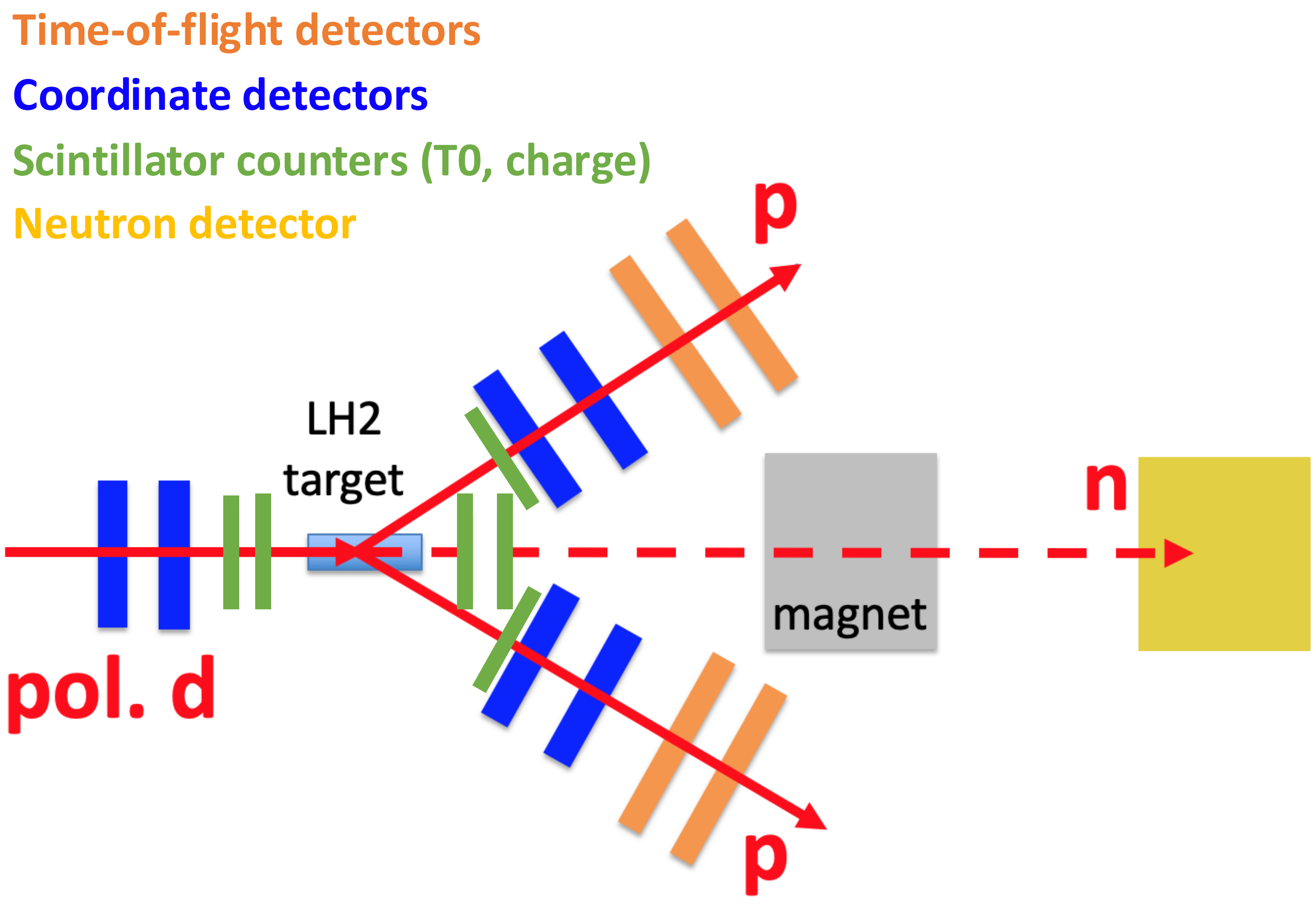


IA = Impulse Approximation

GEA = Generalized Eikonal Approximation

See talk by Alexey Larionov later today

Hard quasi-free breakup of the deuteron: $\vec{d}$(p, 2p)n



Two-arm spectrometer like 2022

A polarimeter separately or incorporated into the setup

Expected trigger rate < 5kHz based on single arm trigger

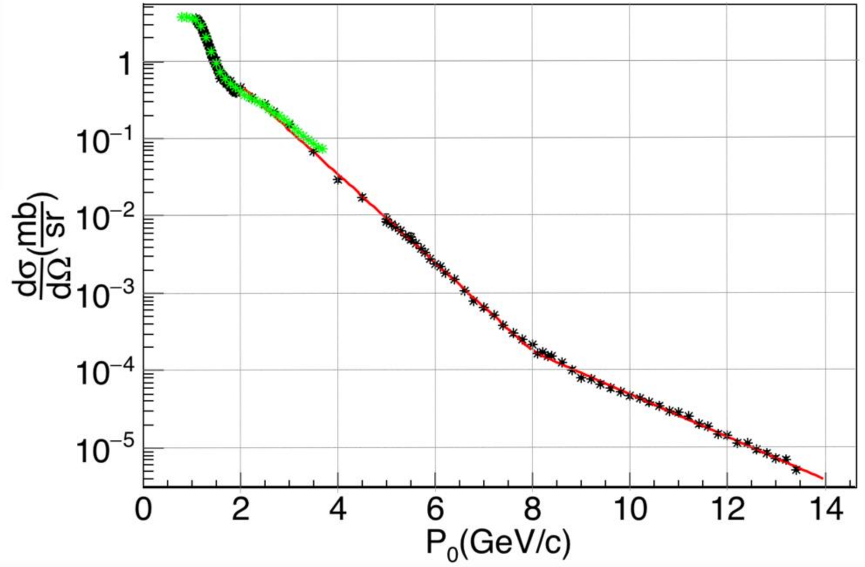
Applied for RSF-NSFC grant 2025-2027

SRC event rate estimation

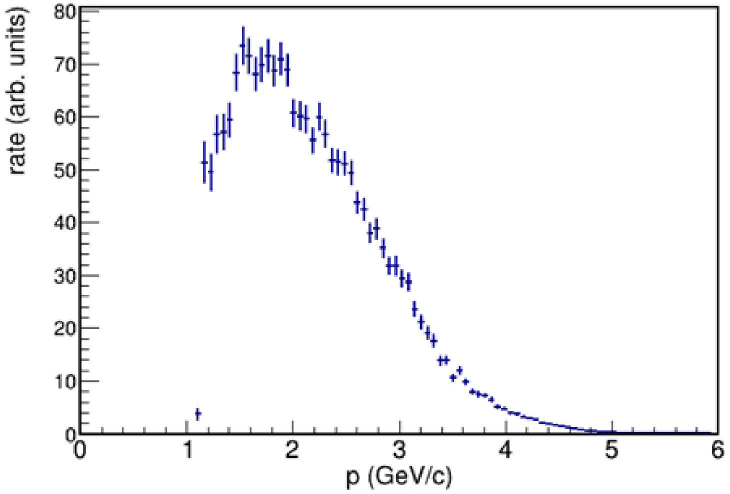
J. Kahlbow

GCF-based simulation
Focus on the deuteron high-momentum tail:

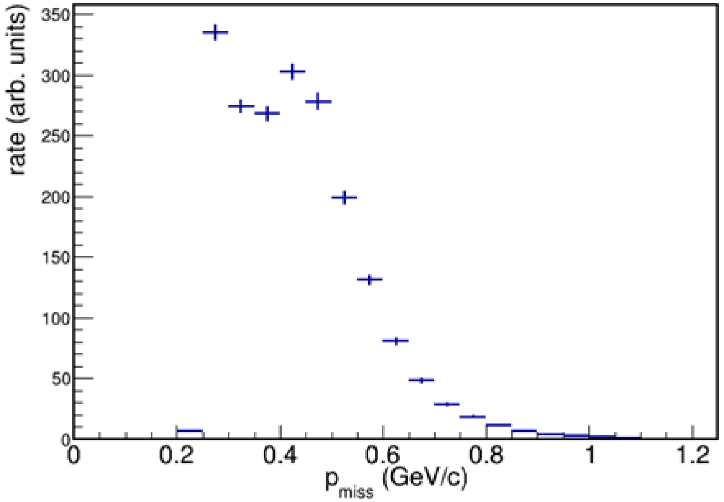
- $|t|$ & $|u| > 1\ GeV^2$
- $60^0 < \theta_{cm}$
- Two-arm acceptance: $20^0 < \theta_{lab} < 45^0$; $-20^0 <| \varphi_{lab}| < 20^0$
- $p_{miss} > 0.25$ GeV/c.



data-based pp cross-section



Momentum of protons in the arms



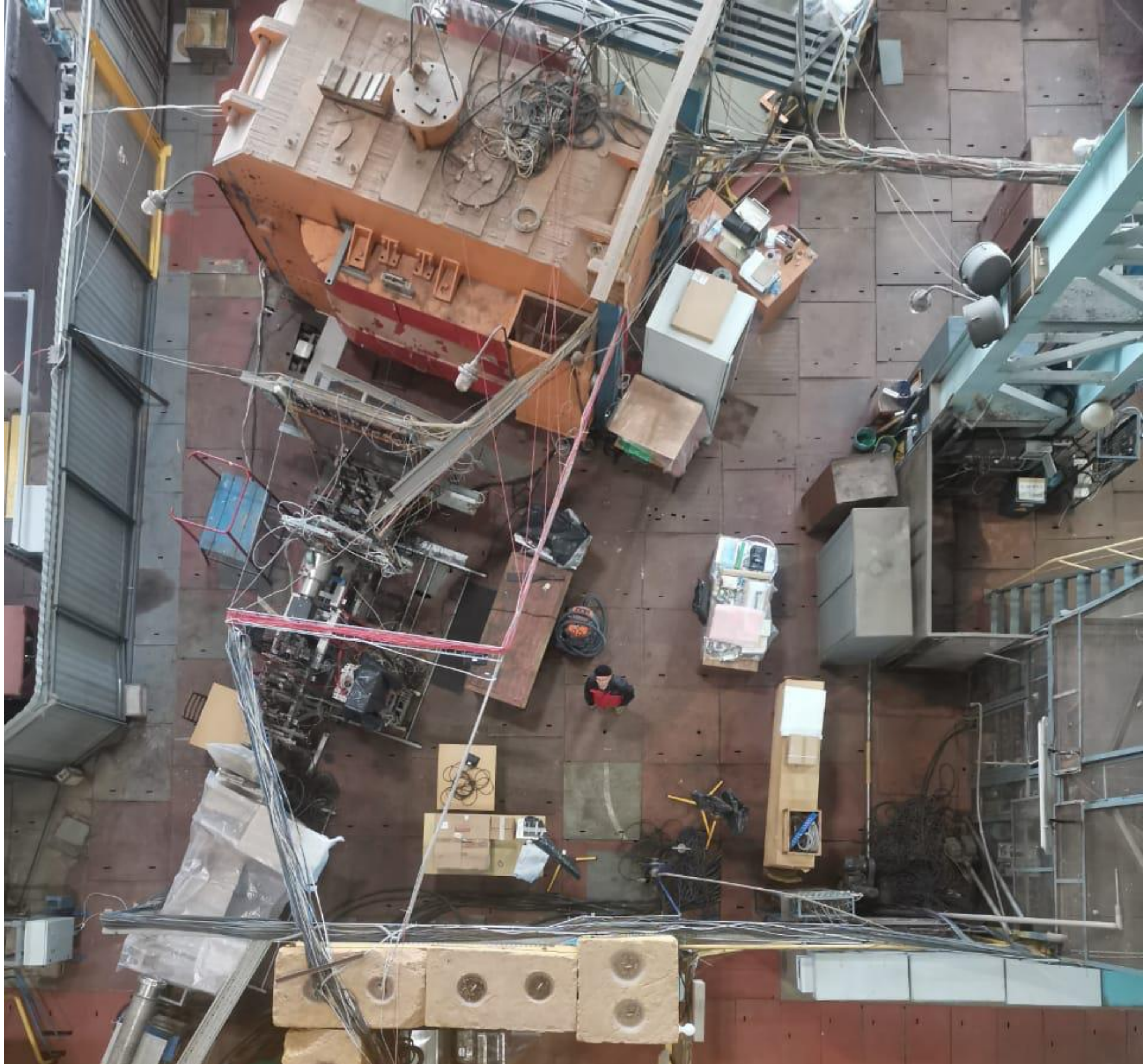
urQMD generator:

At 10^6 deuteron/s
~200 coincidence triggers/s (4/5 with pions)

Trigger rate below the DAQ limit

Experimental area

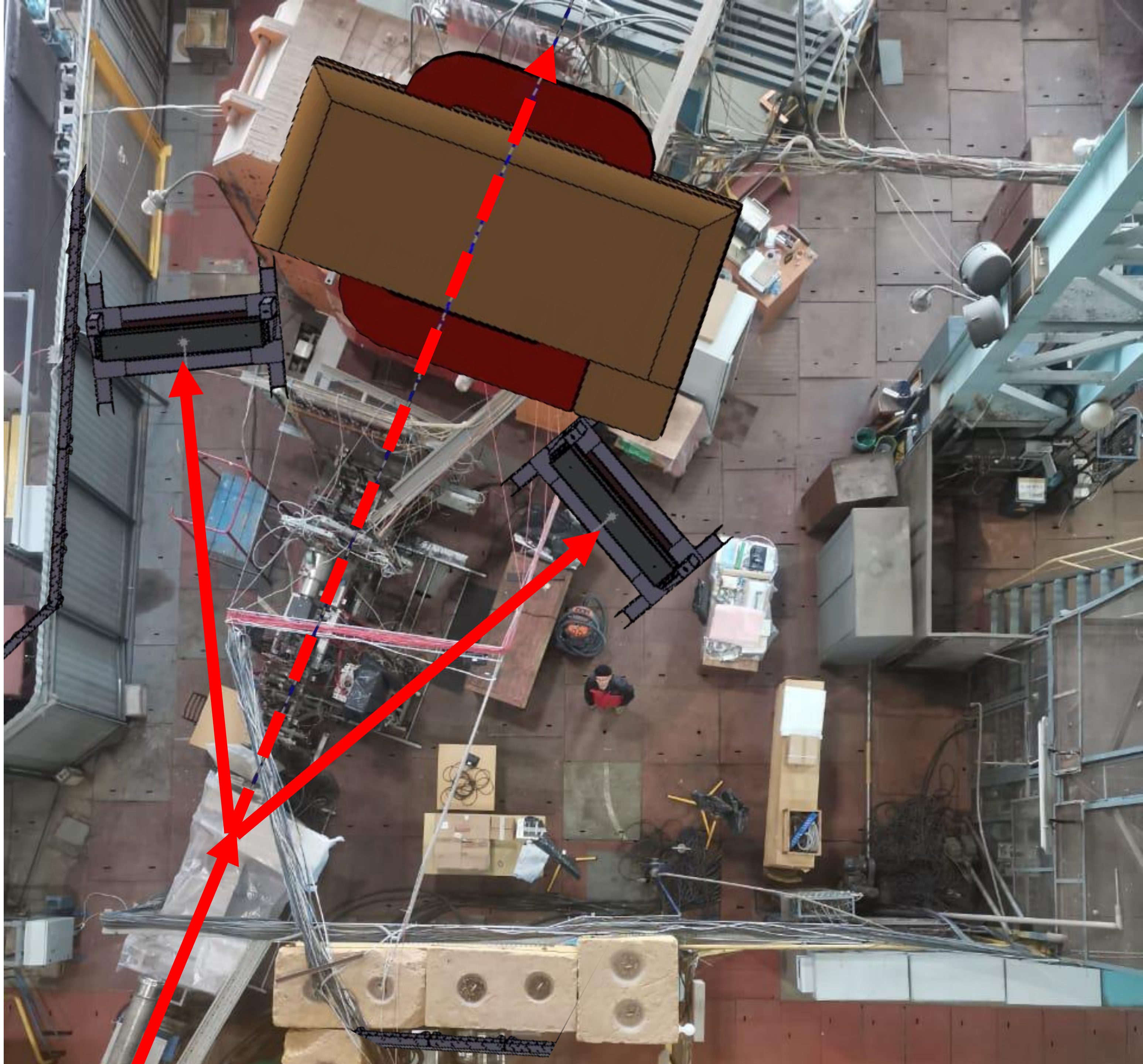
- CBM magnet will come in 1-2 years



First SRC experiment with polarized probes coming in a couple of years

We welcome new members/groups to

Gain practical experience
Work with the polarization
Test detectors/electronics



Summary:

- $\vec{d}$(p, 2p)n exclusive measurement in SRC kinematics aiming at A_{ZZ} at high P_{miss}

- Two-arm spectrometer, JINR LH target + DAQ, new MWDC from China

- Can be done in the next couple of years complementing the world-wide SRC effort

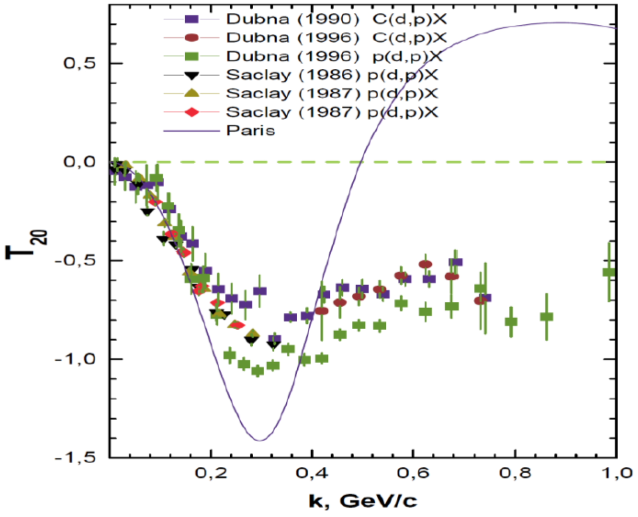
  (ALERT with polarized target at JLab - 2025)

Thank you!

Current world data on T_{20}

Fragmentation of polarized d measured along the beam

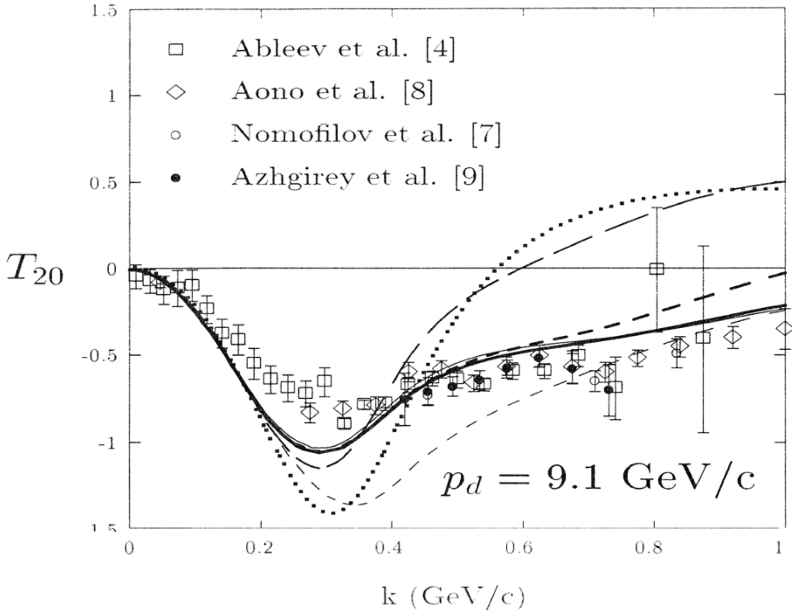
Backward elastic dp and inclusive d breakup at 0 degrees (d,p)X



$$T_{20} = 2\frac{n^- - n^+}{|\rho_{20}^+|n^- + |\rho_{20}^-|n^+} \qquad (1)$$

where n^+ and n^- are the numbers of protons for the "+" and "−" states of polarization, normalized to the corresponding monitor values.

L. S. Azhgirey Phys. Lett. B 387 (1996)



Curves show results of calculations with the Nijm-I deuteron wave function in the framework of multiple scattering: with (bold solid line) and without quark exchange (short-dashed line); and IA: with (long dashed line) and without quark exchange (dotted line).

Kobushkin, Phys. Lett. B 421 1998