Cold dense baryonic matter

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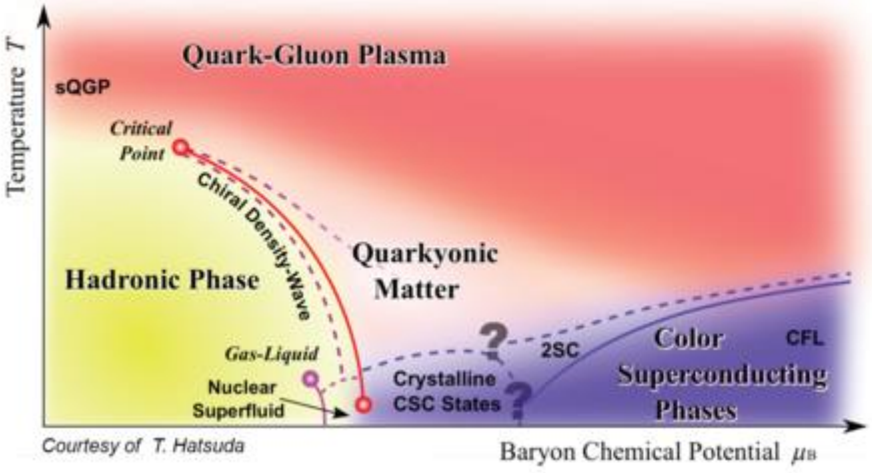
Motivation

Perturbative aspects of QCD have been tested to a few percent. In contrast,
non-perturbative aspects of QCD
(hadronization, confinement, etc)
have barely been tested. The study of the quark matter at different temperature and baryon density is part of effort to consolidate the grand theory of particle physics.

The Compressed Baryonic Matter Experiment

The goal of the research program on nucleus-nucleus collisions at FAIR is the investigation of highly compressed nuclear matter. Matter at very high densities exists in neutron stars and in the core of supernova explosions. In the laboratory, super-dense nuclear matter can be created in the reaction volume of relativistic heavy-ion collisions. The baryon density and the temperature of the fireball reached in such collisions depend on the beam energy. In other words, by varying the beam energy one may, within certain limits, produce different states and phases of strongly interacting matter.



Courtesy of T. Hatsuda

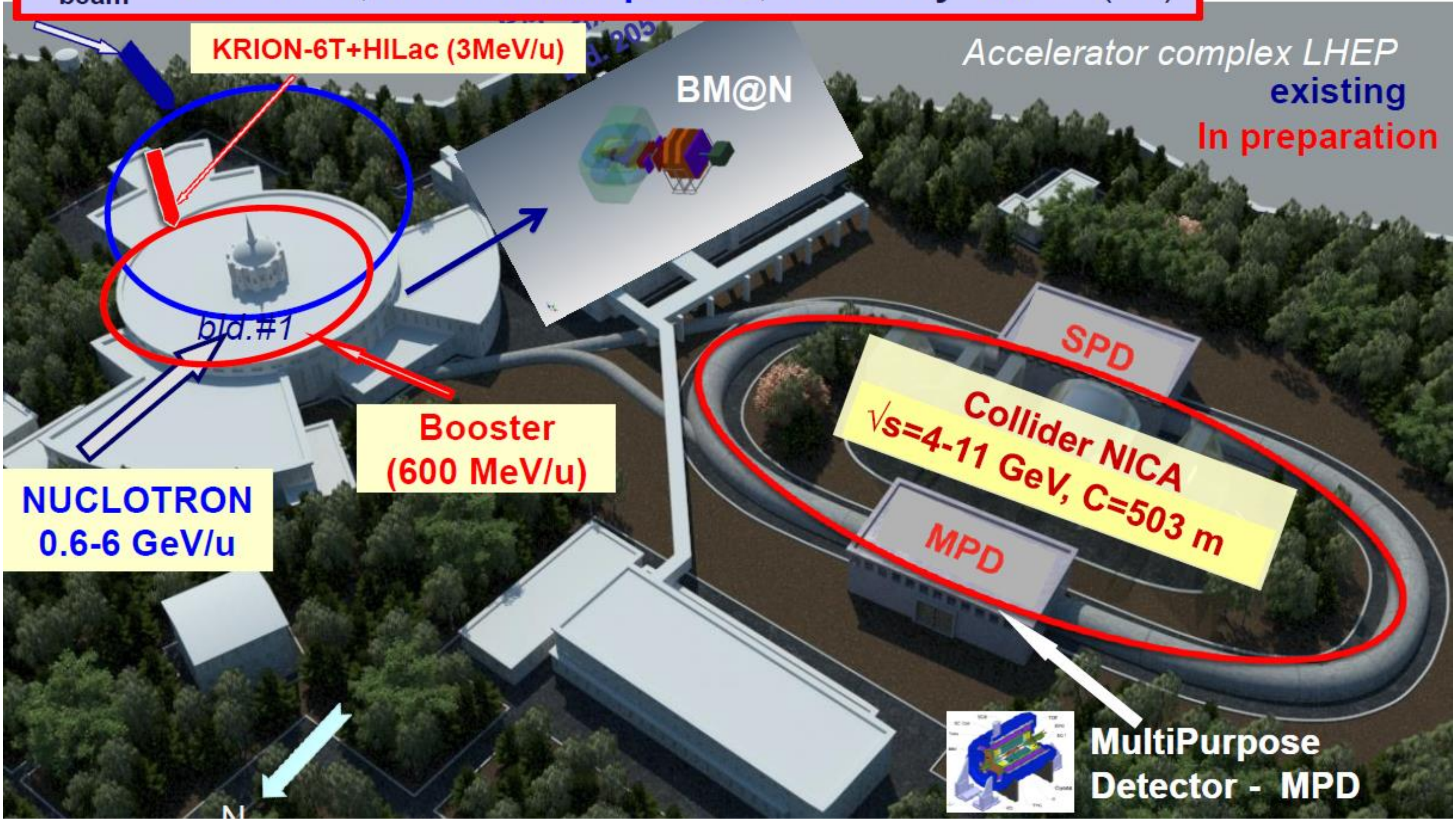
Mapping the phase diagram of strongly interacting matter

... hadronic phase is represented by the white area in figure 1. At very high temperatures the hadrons melt and their constituents, the quarks and gluons, form a new phase of matter, the so called quark-gluon plasma. This "deconfinement" phase transition from hadronic matter to quark-gluon matter takes place at a temperature of about 170 MeV (at net baryon density zero). Such conditions did exist in the early universe a few microseconds after the big bang and can be created in heavy ion collisions at ultra-relativistic energies as provided by the Relativistic Heavy Ion Collider (RHIC) in Brookhaven and by the Large Hadron Collider (LHC) at CERN. In highly compressed cold nuclear matter - as it may exist in the interior of neutron stars - the baryons also lose their identity and dissolve into quarks and gluons. The critical density at which this transition occurs, however, is not known. The same is true for the entire high-density area of the phase diagram. At very high densities and low temperatures, beyond the deconfinement transition, a new phase is expected: the quarks are correlated and form a color superconductor.

Complex **NICA**

Parameters of Nuclotron for BM@N experiment:

E_{beam} = **1-6** GeV/u; ***beams****: from* **p** to **Au**; **Intensity~10^7** c^{-1} (Au)

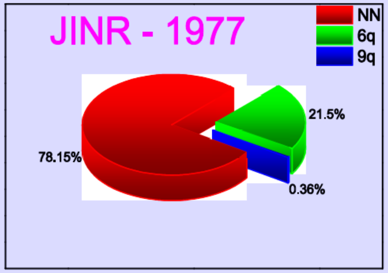


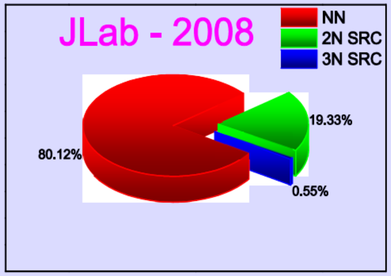
RNP – program at JINR

V.V.B., V.K.Lukyanov, A.I.Titov, PLB, 67, 46(1977)

eA – program at JLab

R.Subedi et al., Science 320 (2008) 1476-1478
e-Print: arXiv:0908.1514 [nucl-ex]





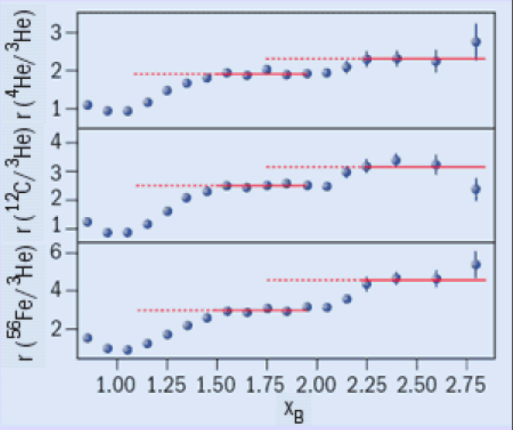
Phys.Rev.Lett. 96 (2006) 082501

Measurement of 2- and 3-Nucleon Short Range Correlation Probabilities in Nuclei

K.S. Egiyan,[1] N.B. Dashyan,[1] M.M. Sargsian,[10] M.I. Strikman,[28] L.B. Weinstein,[27] G. Adams,[30] P. Ambrozewicz,[10]
M. Anghinolfi,[16] B. Asavapibhop,[22] G. Asryan,[1] H. Avakian,[34] H. Baghdasaryan,[27] N. Baillie,[38] J.P. Ball,[2]

$$r(A,{}^3\mathrm{He}) = \frac{A(2\sigma_{ep}+\sigma_{en})}{3(Z\sigma_{ep}+N\sigma_{en})}\frac{3\mathcal{Y}(A)}{A\mathcal{Y}({}^3\mathrm{He})}C^A_{\mathrm{rad}}, \qquad (2)$$

where Z and N are the number of protons and neutrons in nucleus A, σ_{eN} is the electron-nucleon cross section, $\mathcal{Y}$ is the normalized yield in a given (Q^2, x_B) bin [30] and C^A_{rad} is the ratio of the radiative correction factors for A and ^{3}He ($C^A_{\mathrm{rad}} = 0.95$ and 0.92 for ^{12}C and ^{56}Fe respectively). In our Q^2 range, the elementary cross section correction factor $\frac{A(2\sigma_{ep}+\sigma_{en})}{3(Z\sigma_{ep}+N\sigma_{en})}$ is 1.14 ± 0.02 for C and ^{4}He and 1.18 ± 0.02 for ^{56}Fe. Fig. 1 shows the resulting ratios integrated over $1.4 < Q^2 < 2.6$ GeV^2.



- No rescattering

$$\boldsymbol{x}_B = Q^2/2m_N U$$

Probing Cold Dense Nuclear Matter,
R.Subedi et al.,arXiv:0908.1514v1[nucl-ex]

The protons and neutrons in a nucleus can form strongly correlated nucleon pairs. Scattering experiments, where a proton is knocked-out of the nucleus with high momentum transfer and high missing momentum, show that in ^{12}C the neutron-proton pairs are nearly twenty times as prevalent as proton-proton pairs and, by inference, neutron-neutron pairs. This difference between the types of pairs is due to the nature of the strong force and has implications for understanding cold dense nuclear systems such as neutron stars.

CLAS e-A→e-X @~4 AGeV

JLAB Phys Seminar Dec05 K. Egiyan

Having these data, we know almost full (≈99%) nucleonic picture of nuclei with $A \leq 56$

Fractions Nucleus	Single particle (%)	2N SRC (%)	3N SRC (%)
^{56}Fe	**76** ± 0.2 ± 4.7	**23.0** ± 0.2 ± 4.7	**0.79** ± 0.03 ± 0.25
^{12}C	**80** ± 02 ± 4.1	**19.3** ± 0.2 ± 4.1	**0.55** ± 0.03 ± 0.18
^{4}He	**86** ± 0.2 ± 3.3	**15.4** ± 0.2 ± 3.3	**0.42** ± 0.02 ± 0.14
^{3}He	**92** ± 1.6	**8.0** ± 1.6	**0.18** ± 0.06
^{2}H	**96** ± 0.8	**4.0** ± 0.8	-----

Using the published data on (p,2p+n) [PRL,90 (2003) 042301] estimate the isotopic composition of 2N SRC in ^{12}C

$a_{pp}(^{12}C) \approx$ 4 ± 2 %

$a_{2N}(^{12}C) \approx 20 \pm 0.2 \pm 4.1$ % → $a_{pn}(^{12}C) \approx 12 \pm 4$ %

$a_{nn}(^{12}C) \approx$ 4 ± 2 %

Probing Short Range Correlations

BM@N Project

List of organizations and participants

Russia: Joint Institute for Nuclear Research – JINR (Dubna) the BM@N collaboration

Israel: Tel Aviv University

Germany: TUD and GSI

USA: MIT and ODU

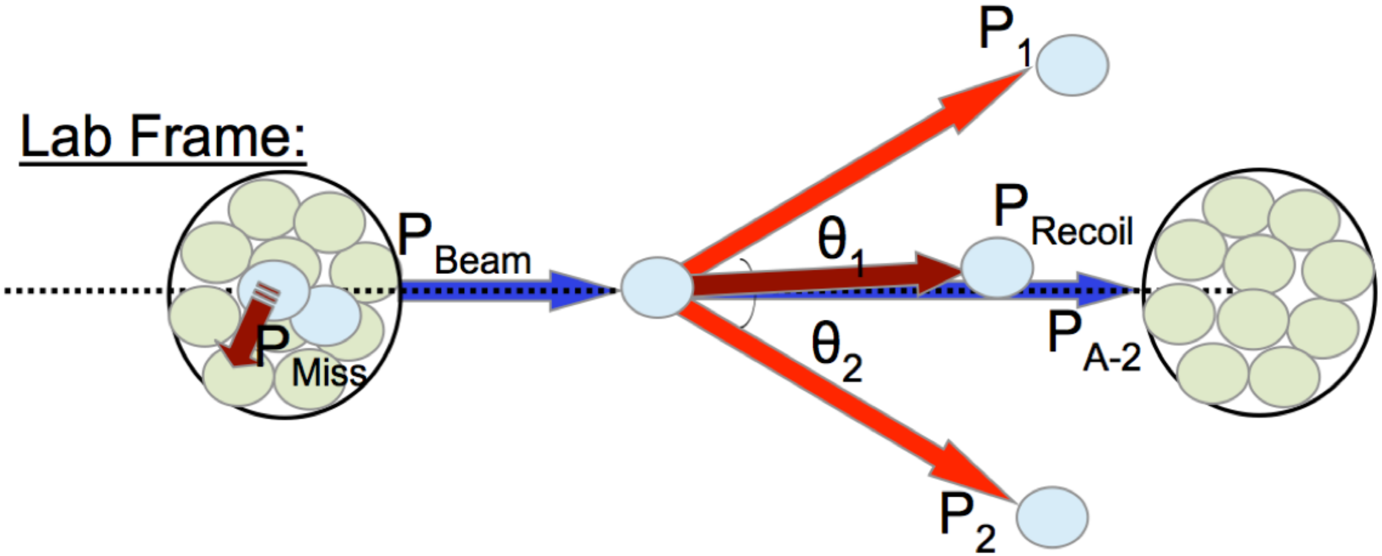
Spokespersons:

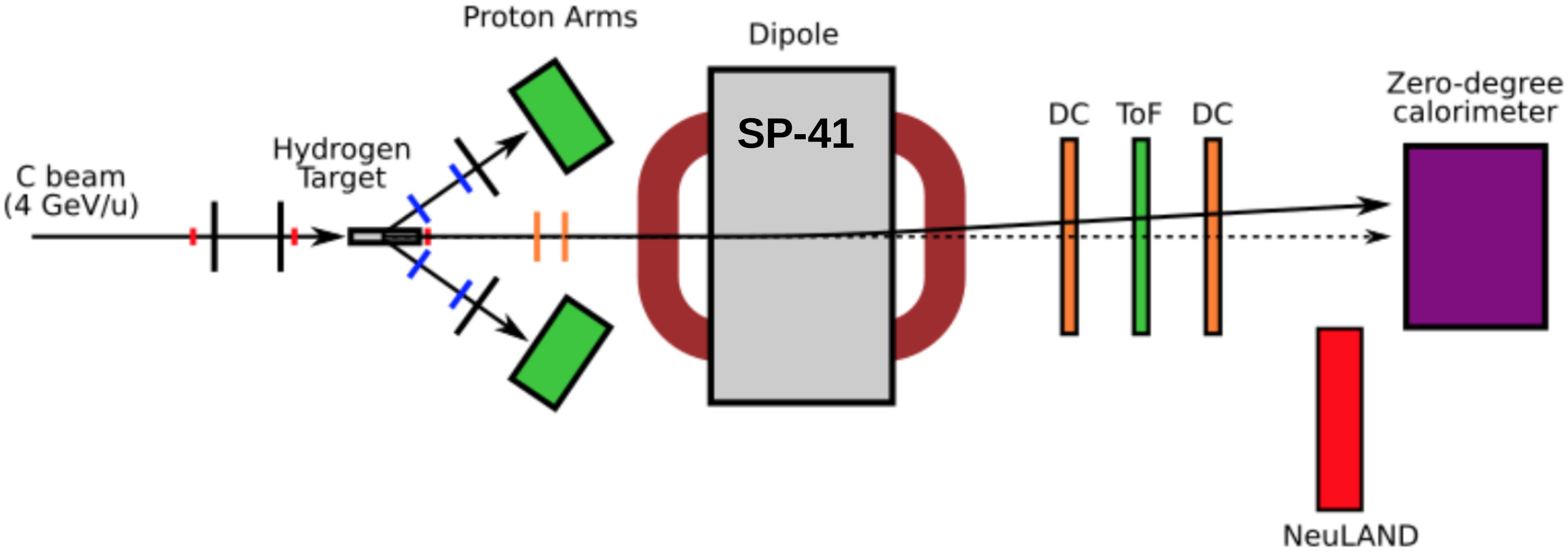
Or Hen (MIT), Thomas Aumann (TUD, GSI), Mikhail Kapishin (Dubna), Eli Piasetzky (TAU),

Coordinators:

Georgios Laskaris (MIT and TAU), Anatoly Litvinenko (Dubna), Maria Patsyuk (MIT)

Kinematics


Lab Frame:
P_{Beam}
P_{Miss}
P_1
θ_1
P_{Recoil}
θ_2
P_{A-2}
P_2


Proton Arms
Dipole
SP-41
Zero-degree calorimeter
DC
ToF
DC
Hydrogen Target
C beam (4 GeV/u)
NeuLAND

Femtoscopy aspect of this study:
Up to what degree SRC is isolated from A-2? →
How long live A-2 system? →
Fragments correlation study at small relative velosity

What is proposed to measure:

*Correlation function of two fragments (p,d,t,3He,4He) at small relative velocity

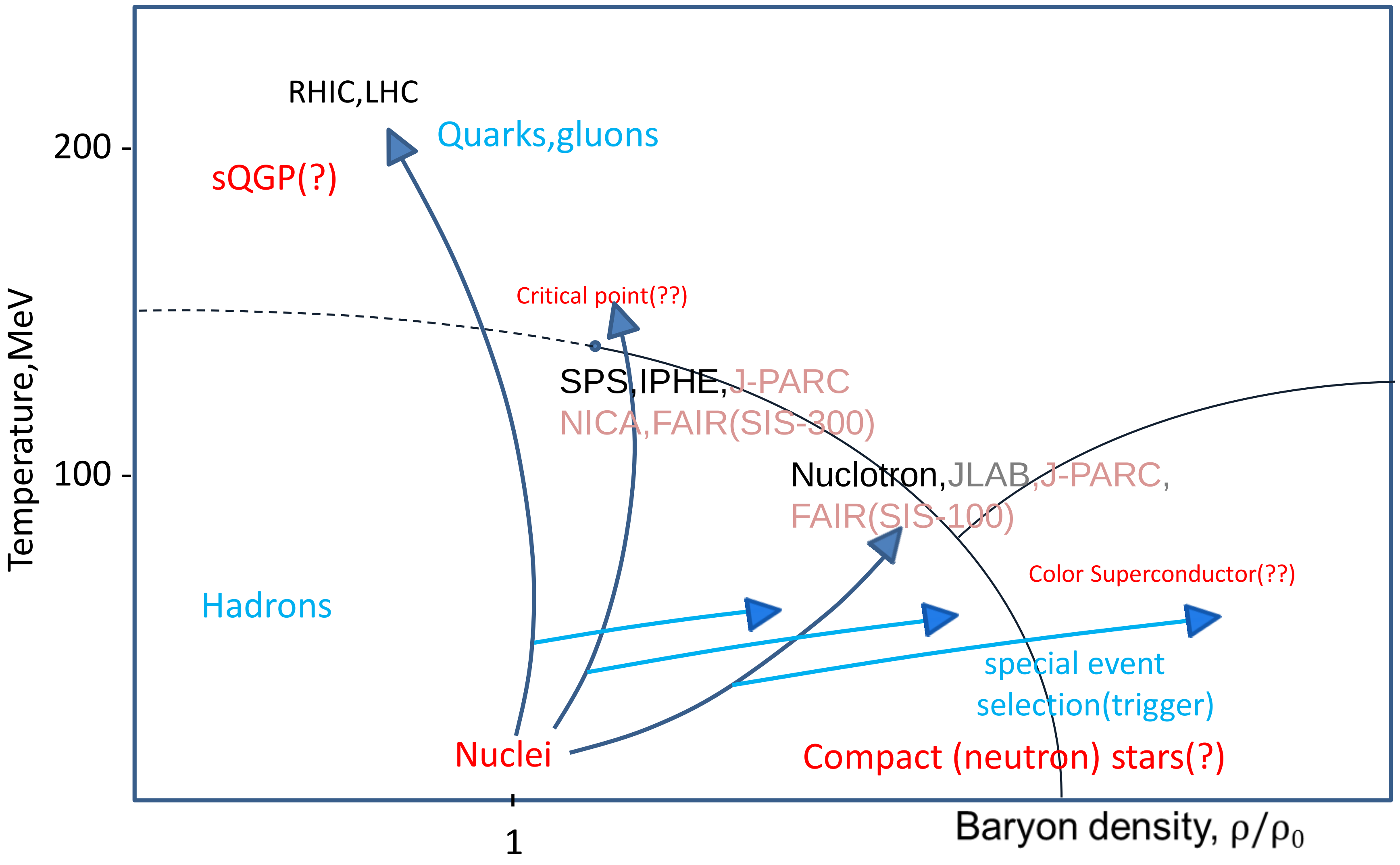
*approximation: p_z/nucleon≈p_{zbeam}/nucleon, relative velocity ≈ transverse relative velocity

*transverse relative velocity from tracks position at DC

*mixing procedure for background

Expected results:
Two(at least) possible model:
1.”Izolated” flucton(as supposed in proposal)→ ct» r_C
2.”Nonizolated” flucton(due to energy-momentum conservation) → ct ~ r_C

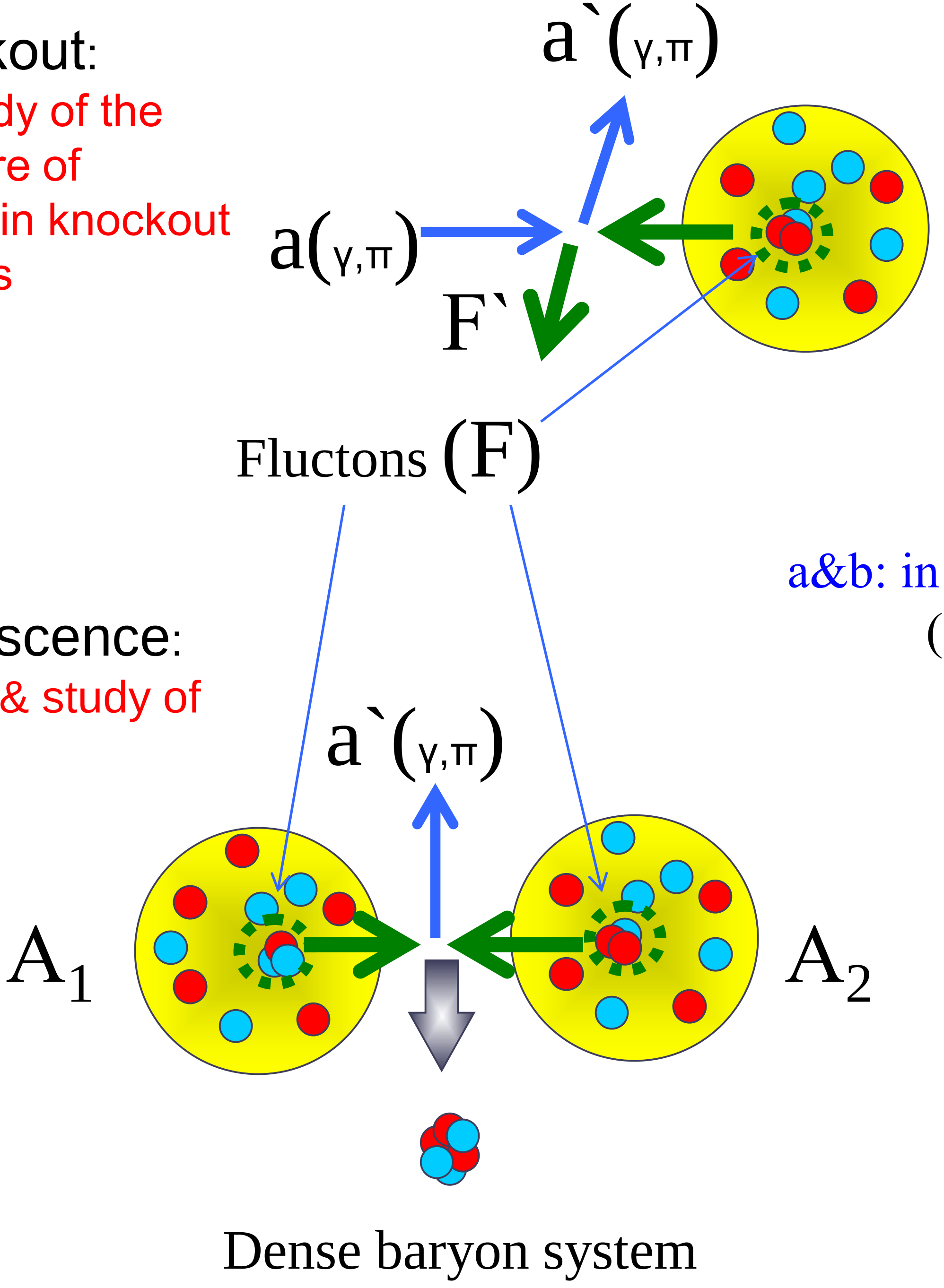
Phase diagram of nuclear matter



S.S. Shimansky, in Proc. of the VIII Intern. Workshop on Relativistic Nuclear Physics:from Hundreds of MeV to TeV, May 23-28, 2005 , 297 (Dubna, 2006); nucl-ex/0604014.

a) Knockout:

the study of the structure of flucton in knockout process



a`(γ,π)

a(γ,π)

F`

Fluctons (F)

b) Coalescence:

search for & study of DCM

a`(γ,π)

A_1

A_2

Dense baryon system

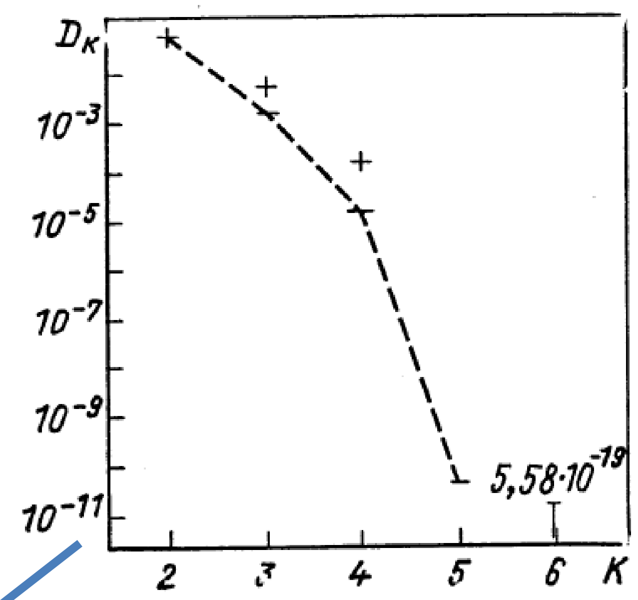
a&b: in both cases high p_T trigger

(π,γ,γ(π^o),…)

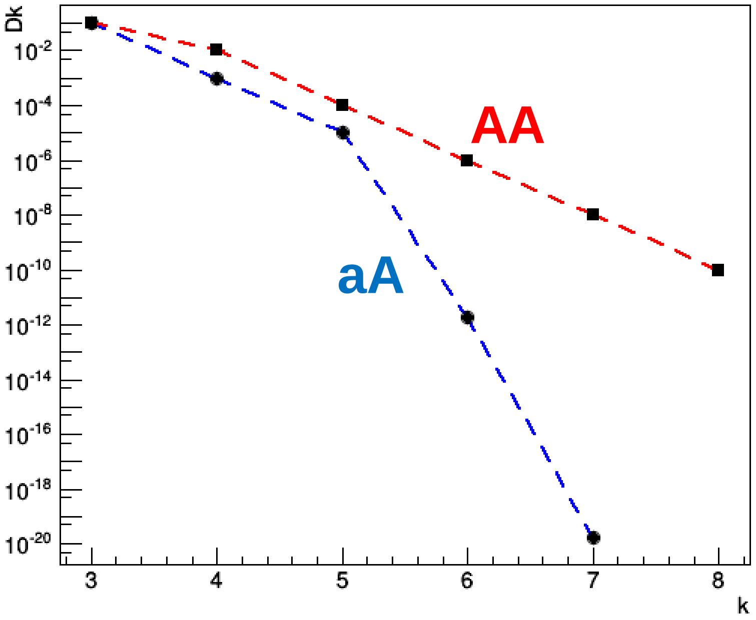
A_1,A_2: He,Be,C,…

Why AA ?

	a_{2N}, %	a_{3N}, %	$(a_{2N})^2$, %
^{3}He	8.0±1.6	0.18±0.06	0.64
^{4}He	15.4±3.3	0.42±0.14	2.4
^{12}C	19.3±4.1	0.55±0.17	3.7



Flucton probability as a function of number of nucleons.
V.K.Luk'yanov,A.I.Titov,
PEPAN,1979,vol.10(4),p.815

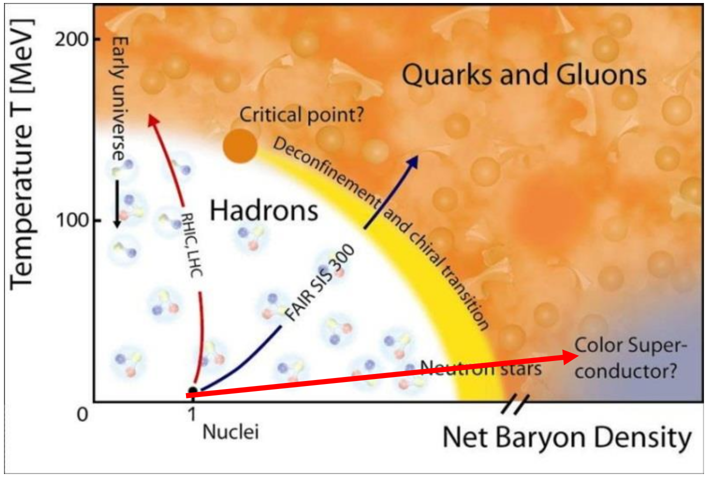


dramatic decreasing of the cross sections with N:
----> max N~4

Flucton+flucton probability as a function of total number of nucleons.

FLINT experiment @ ITEP

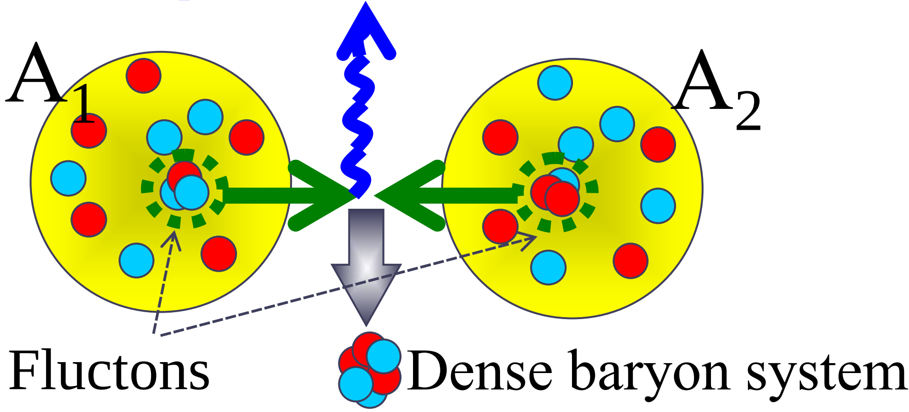
Phase diagram*



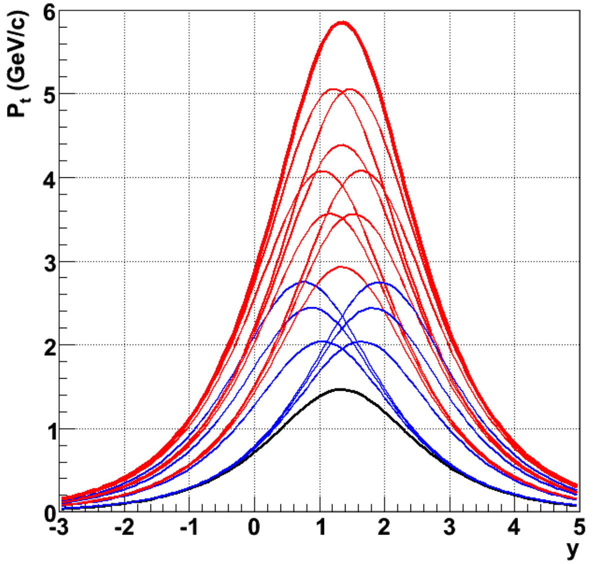
*http://www.gsi.de/forschung/fair_experiments/CBM /

Scheme of process

High p_T trigger $\gamma,\gamma(\pi^o)$,…



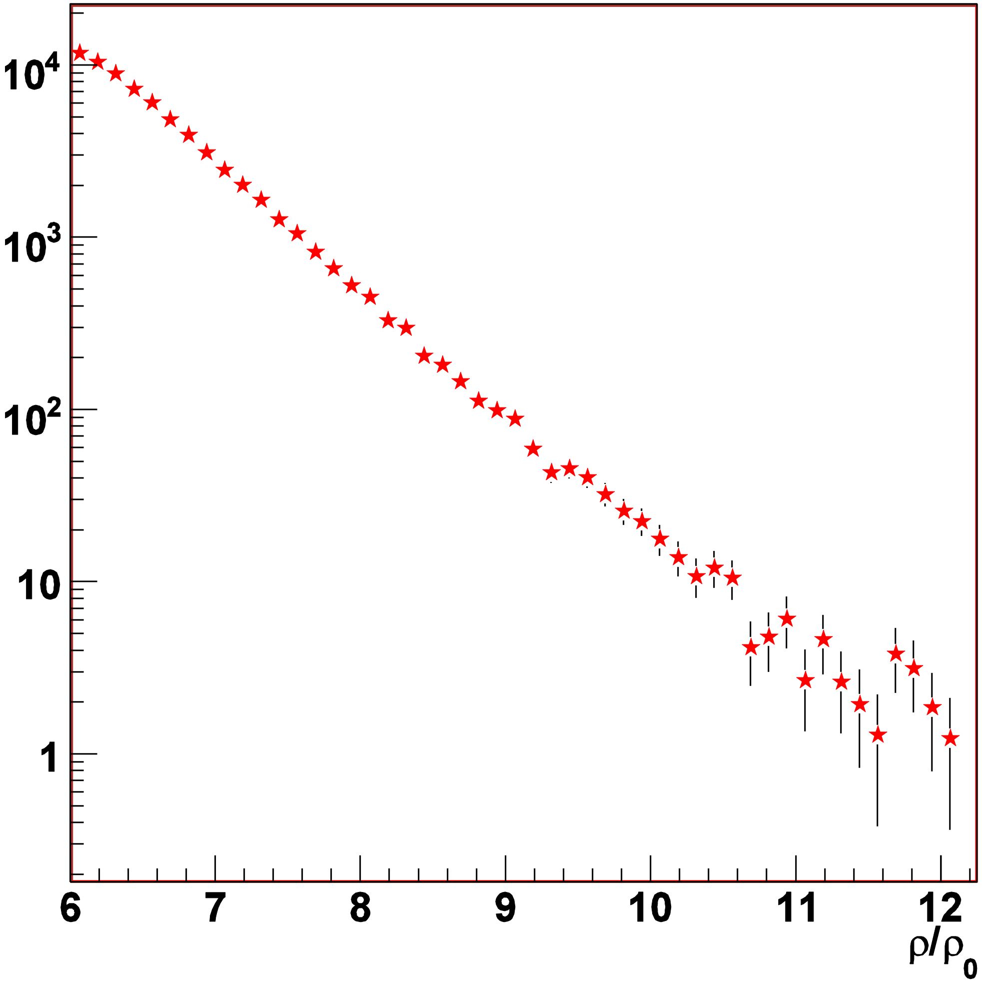
He+He @ 6 AGeV



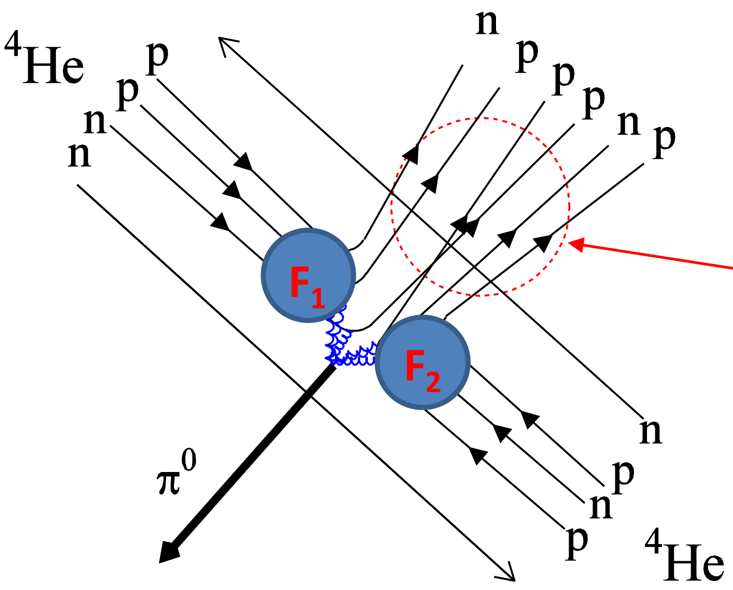
Kinematical limits for different subprocesses:
1N+1N(black line)
1N+Flucton(2N,3N,4N)&Flucton+1N(blue lines)
Flucton+Flucton(red lines)

An estimate of baryon density

r_f~1.5fm



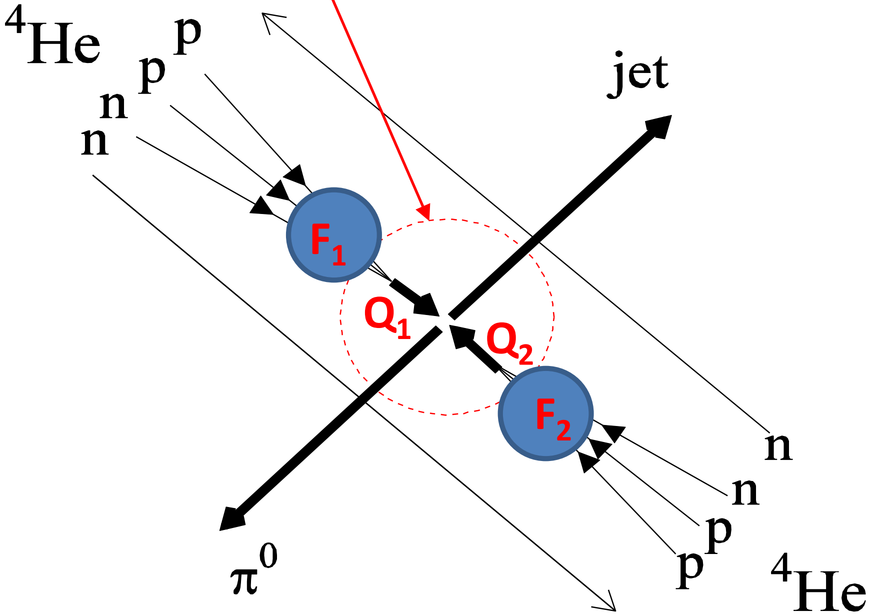
BM@N<->SPD



F_1-flucton
Q_i(q,2q)-light cumulative quark objects

Cold dense barionic system

Sqrt (s)~ 10 GeV(SPD)



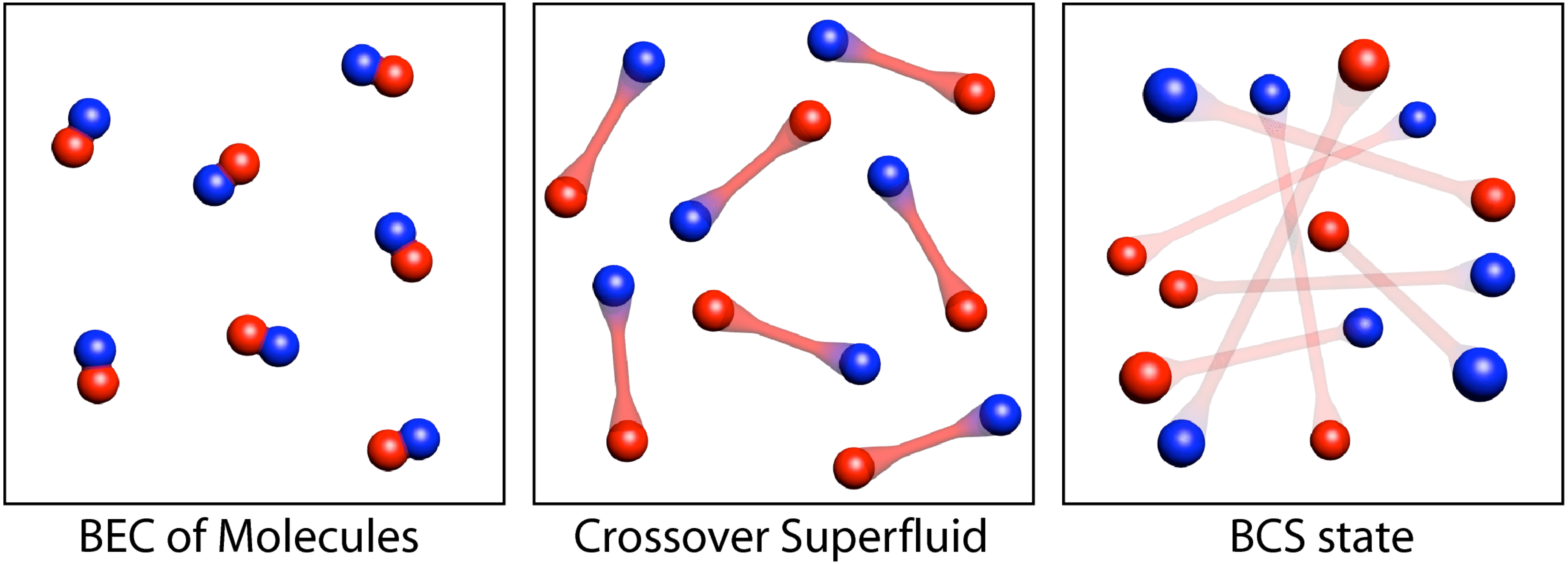
Sqrt (s)~ 3 GeV(BM@N)

E»1GeV(no FSI)

Model baryon=quark+diquark:
“ diquark: T=S=1 or 0.”
И.Ю.Кобзарев, Б.В.Мартемьянов, М.Г.Щепкин
УФН 162, вып.4,1992,стр.1-41
See, also, Anisovich A.V., et al., Int. J. Modern Phys. A, 25:15 (2010);
arXiv:1001.1259[hep-ph]
(**Quark**-**Diquark Systematics of Baryons)**

Does the theory of DCM really exist?

Lattices just started (see, for example):
Unitary Fermions on the Lattice
With: Michael Endres, Jong-Wan Lee, Amy Nicholson
Major outstanding problem in LGT: QCD at finite fermion number
BEC-Bose-Einstein condensation


BEC of Molecules
Crossover Superfluid
BCS state

Conclusions

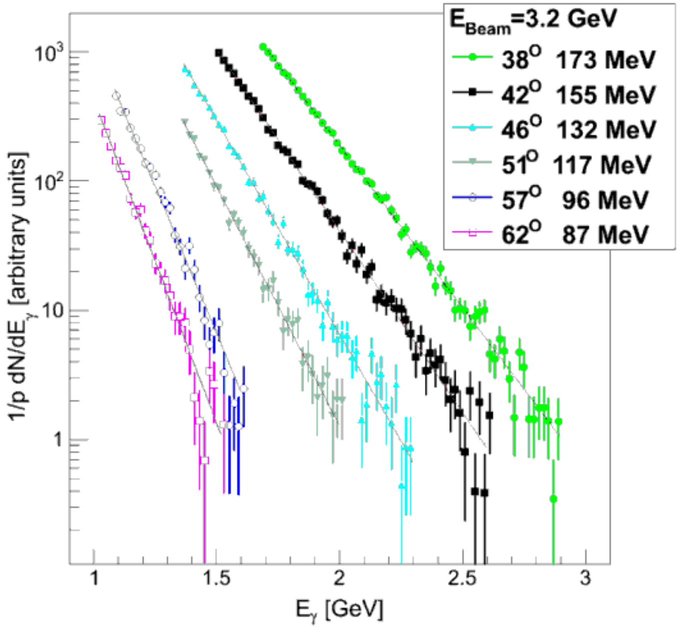
1. Cold and dense part of phase diagram is important to study for: QCD check, color superconductivity, neutron stars

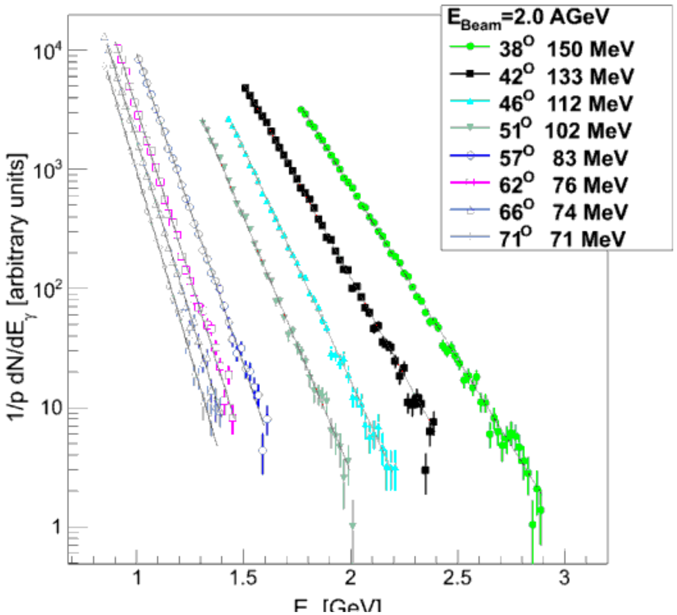
2. It is accessible in the lab using high P_T trigger ($P_T \approx P_{beam}$)

3. Both BM@N and SPD experiments have an unique room for this study.

Extra slides

FLINT DATA: Photon spectra CBe→γX

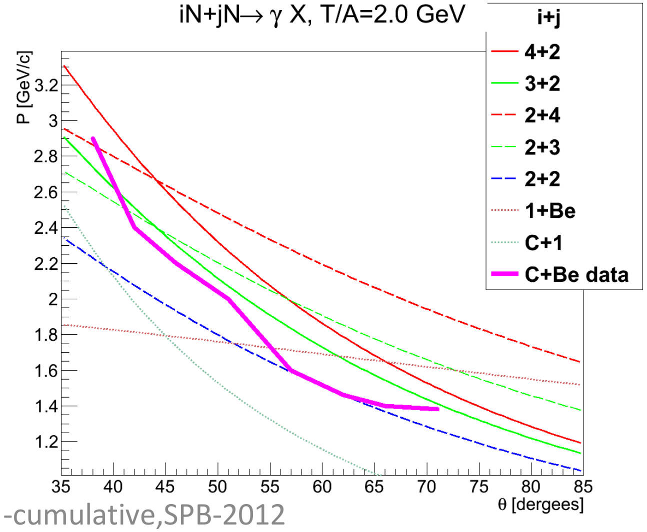




FLINT have got data for flucton-flucton interaction up to 6 nucleons kinematical region, which cannot be explained neither p+Be nor C+p interactions

Six nucleons system: n!n¡p!p¡+??

Does we already see phase transition?



Experimental program

1). Search for and the study of new state of matter at high density and low temperature corner of phase diagram

- search for the dense baryonic droplet in correlation measurements with high p_t cumulative trigger
- femtoscopy measurements for the dense baryonic droplet
- izotopic properties of the droplet
- strangeness production in the droplet
- fluctuations
- search for an exotic in the droplet

2) Dense cold matter contribution in ordinary nuclear matter and its nature SRC,flucton,…

- nuclear fragmentation
- hard scattering

Proposed measurements:

1.Trigger's particles: γ, π, K^-,K^+,p, d, …(p_t /E_0~1)
2. Recoil particles: nucleon, multinucleon systems,
nuclear fragments, exotic states
3. Measurement values: <N(p_t ,y)> vs X_{trig} and E_0(2-6GeV/nucleon);
-ratios(p/n, ^{3}He/t,…);correlations between recoil particles

Femtoscopy aspect of this study:
Up to what degree SRC is isolated from A-2? →
How long live A-2 system? →
Fragments correlation study at small relative velocity

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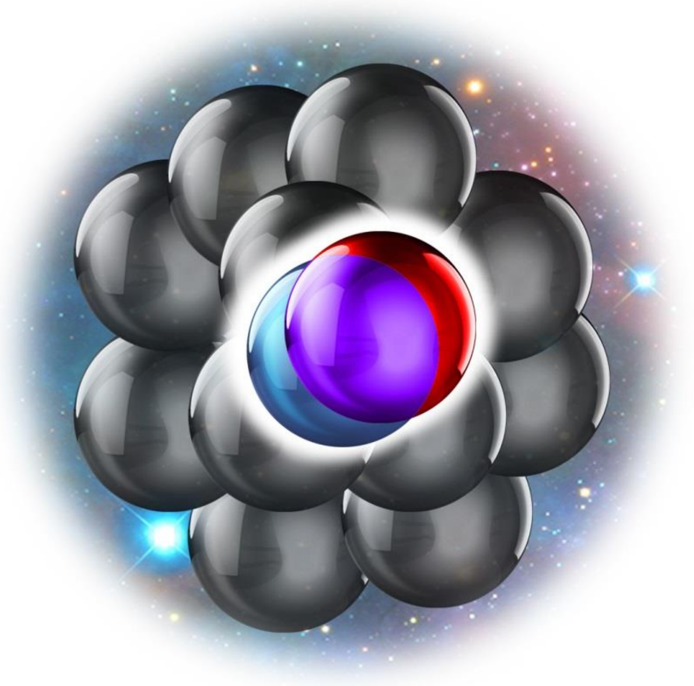
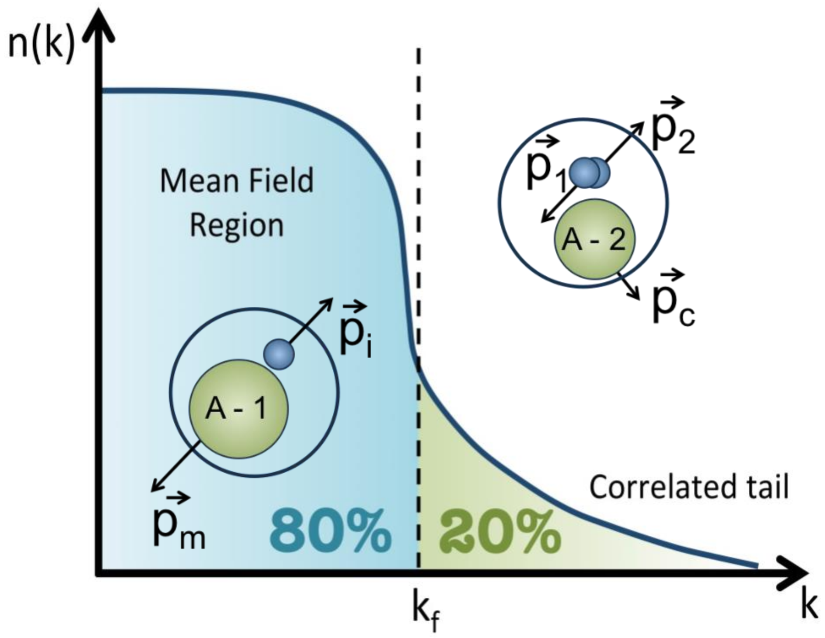
2N-Short Range Correlations



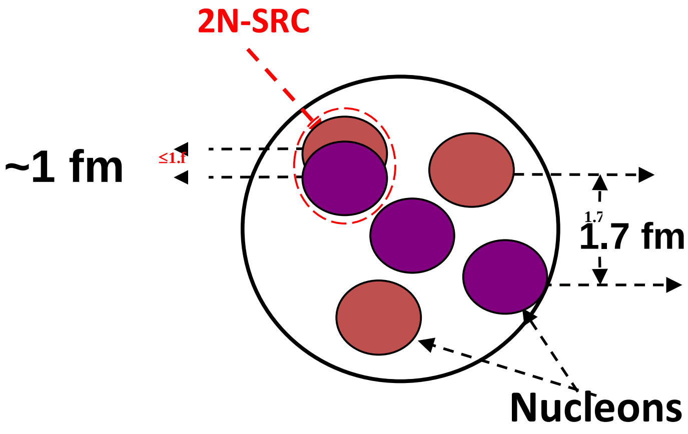


Occasionally nucleons are at close proximity in the nucleus

Each individual nucleon has high momentum

Low center of mass momentum of the pair relative to k_F

What SRC can teach us?

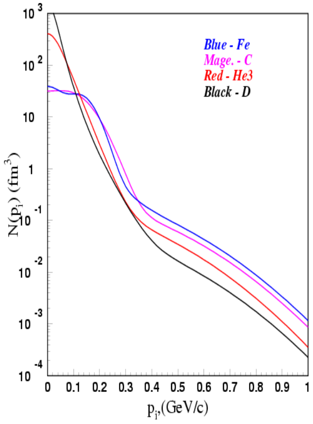


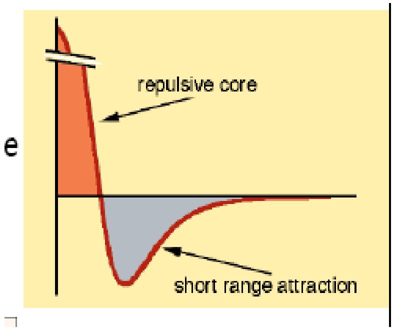
- High momentum component of the nuclear wave function

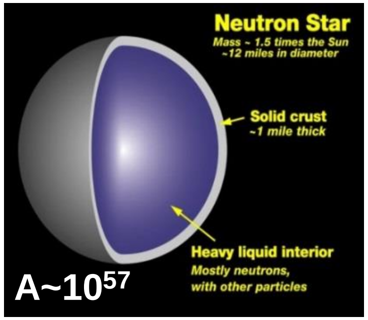
- **The strong short-range force between nucleons (tensor force, repulsive core, 3N forces)**

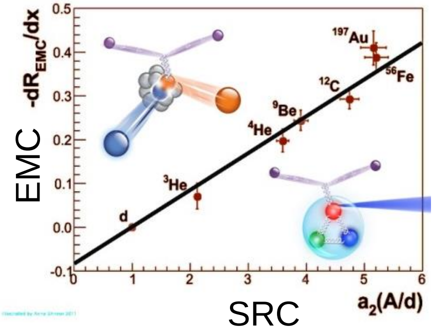
- Cold dense nuclear matter (from deuteron to neutron stars)

- **Nucleon structure modification in medium (EMC and SRC)**



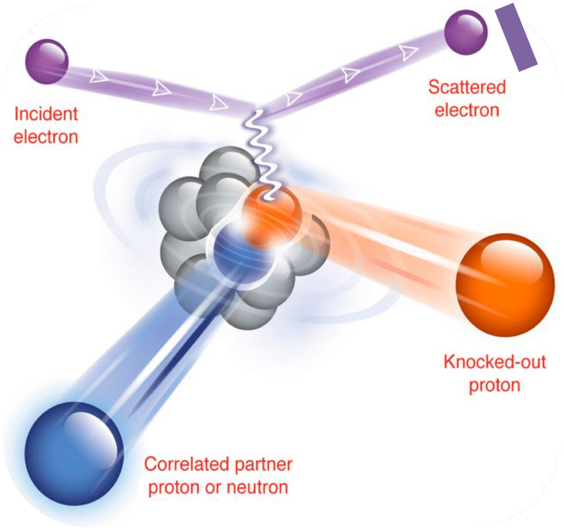


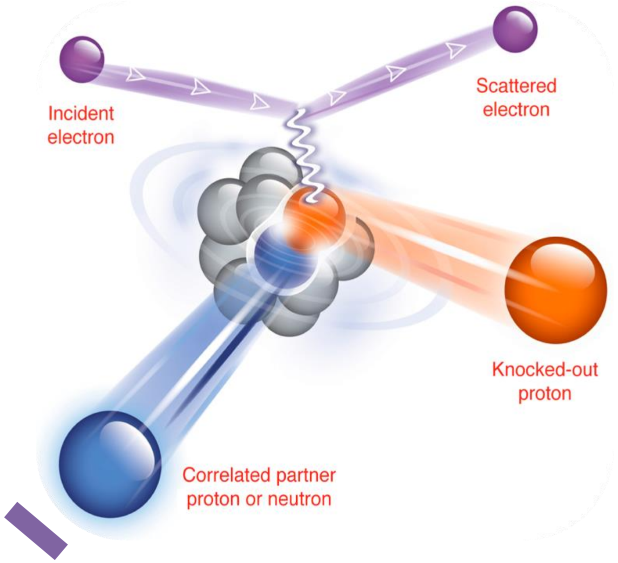




How to study SRC? - Break up the pair!

Hard scattering in direct kinematics





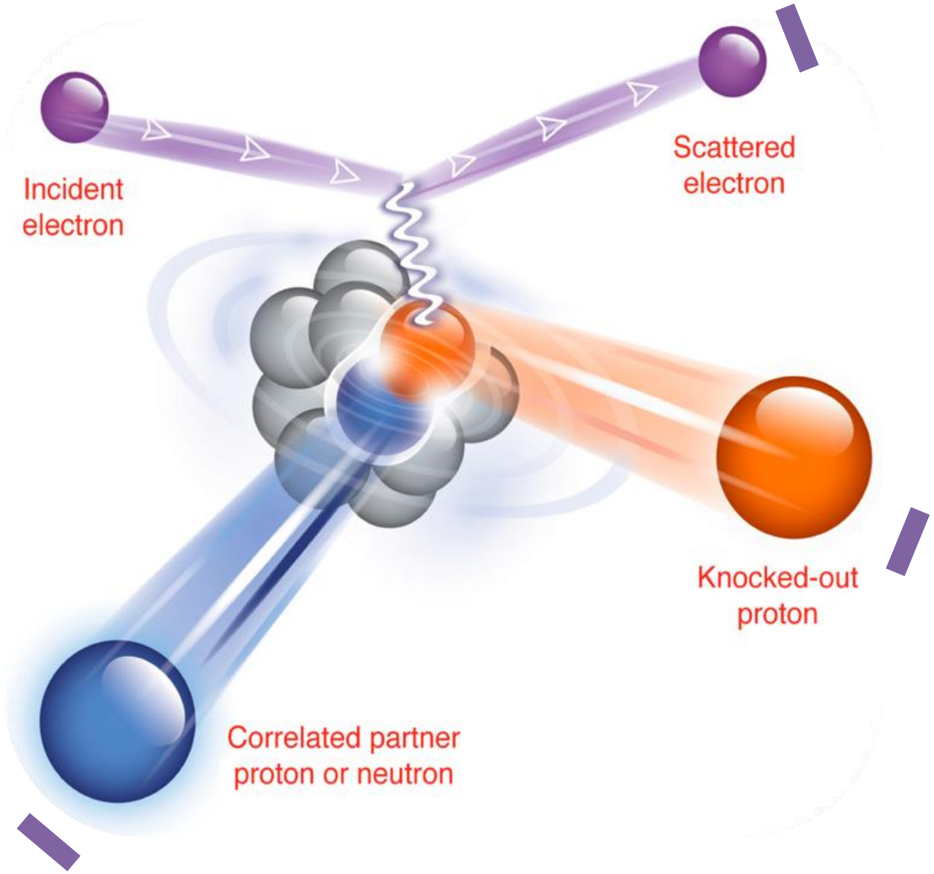
Inclusive measurement

Detect scattered probe A(e, e’) **OR** Recoil particle (cumulative kinematics):

JLab

Dubna and Yerevan

How to study SRC? - Break up the pair!



Exclusive measurement

Detect (3 particles):

scattered probe,

the knocked-out nucleon,

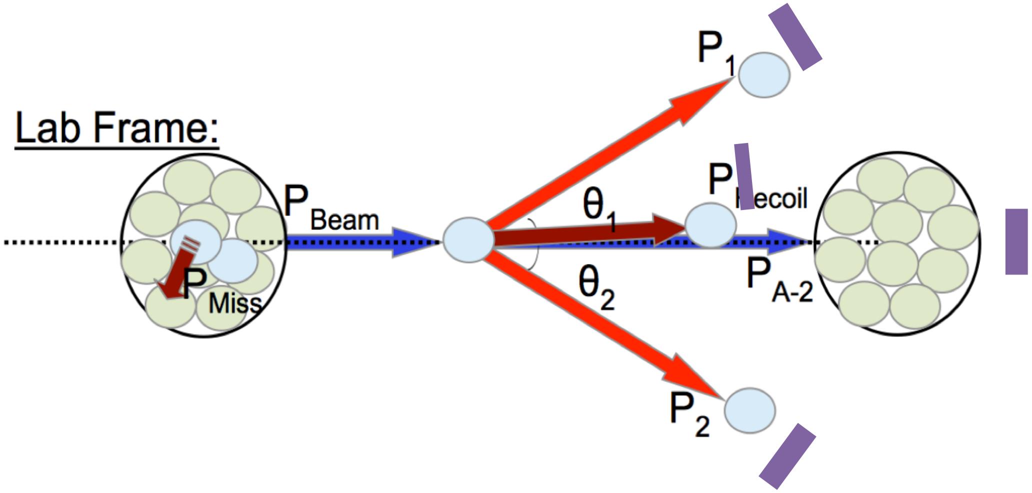
and the recoil

A(e, e’pp) - JLab
A(e, e’pn) - JLab
A(p, 2pn) – BNL

Also inverse kinematics:

p(^{12}C, 2p A-2) - Dubna

How to study SRC? - Break up the pair!



Inverse kinematics

Super exclusive measurement!

Detect (4 particles):

the scattered probe,

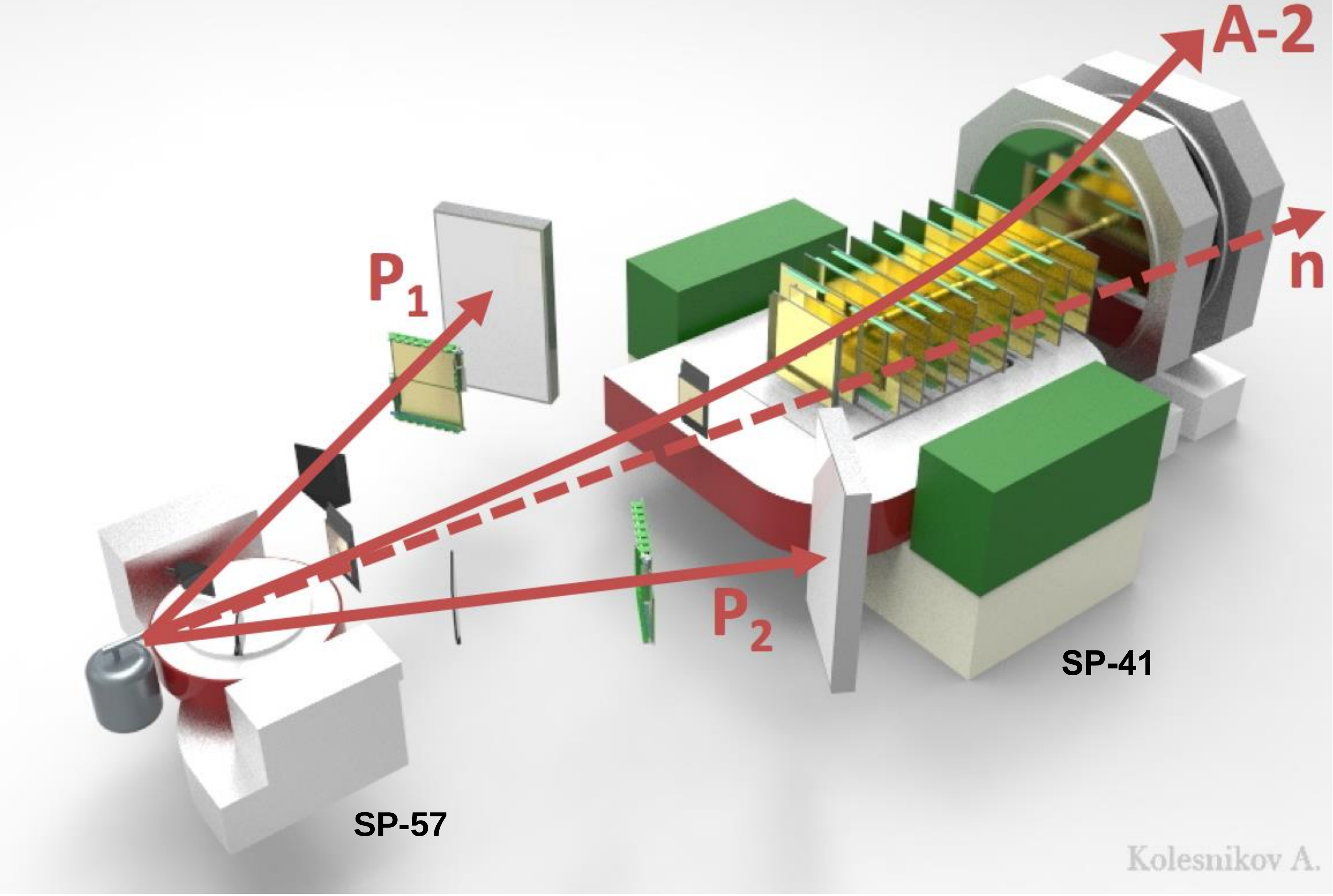
the knocked-out nucleon,

the recoil,

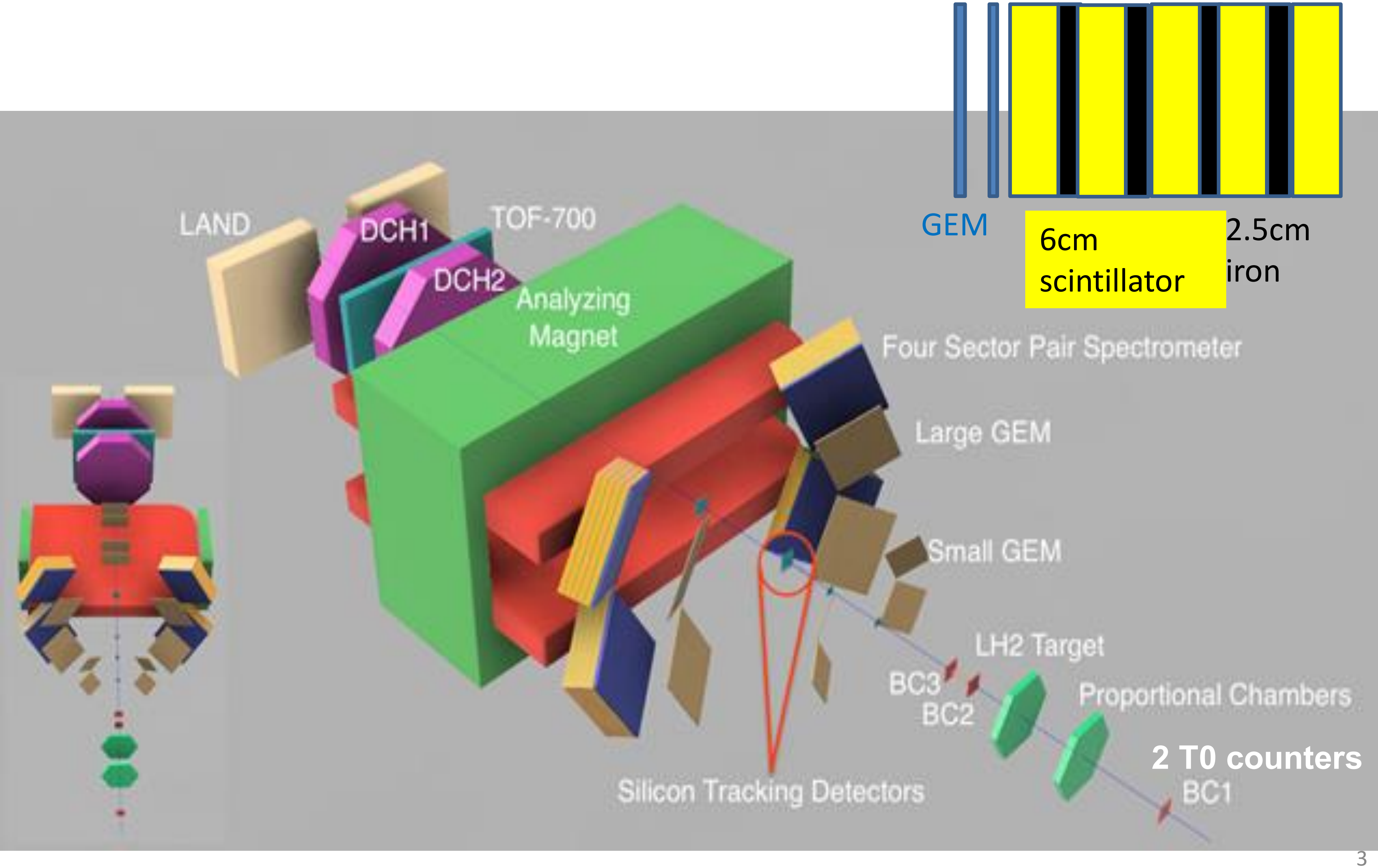
and the A-2 system!

A(p, 2p n A-2) – Dubna

Experimental setup



Ideas for the future



2 T0 counters

Recent high-momentum-transfer triple-coincidence 12C(e, e’pN) and 12C(p, 2pn) measurements [1-4] have shown that nucleons in the nuclear ground state form nucleon pairs with large relative momentum and small center-of-mass (CM) momentum, where large and small are relative to the Fermi momentum of the nucleus (kF). We refer to these pairs as short-range correlated (SRC) pairs [5-7]. In the range of missing-momentum (the knocked-out proton’s pre-scatter momentum in the absence of re-interactions) from 300– 600 MeV/c, these pairs were found to dominate the nuclear wave function, with neutron-proton (np) pairs nearly 20 times more prevalent than proton-proton (pp) pairs, and by inference neutron-neutron (nn) pairs (see figure 1). The strong preference for np pairs is due to the dominance of the tensor part of the NN interaction at the probed sub-fm distances [8-10]. These observations were also confirmed in recent measurements on heavier nuclei reaching all the way up to 208Pb [16].

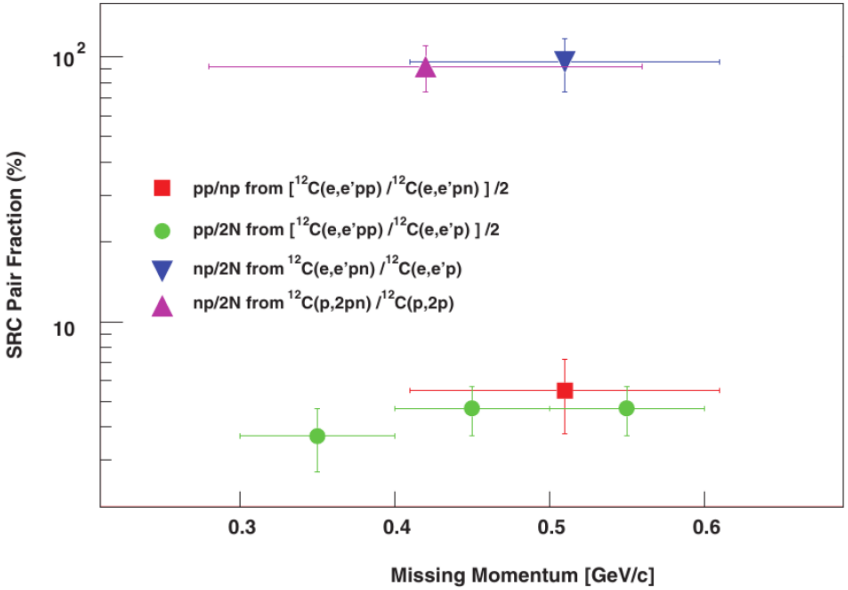
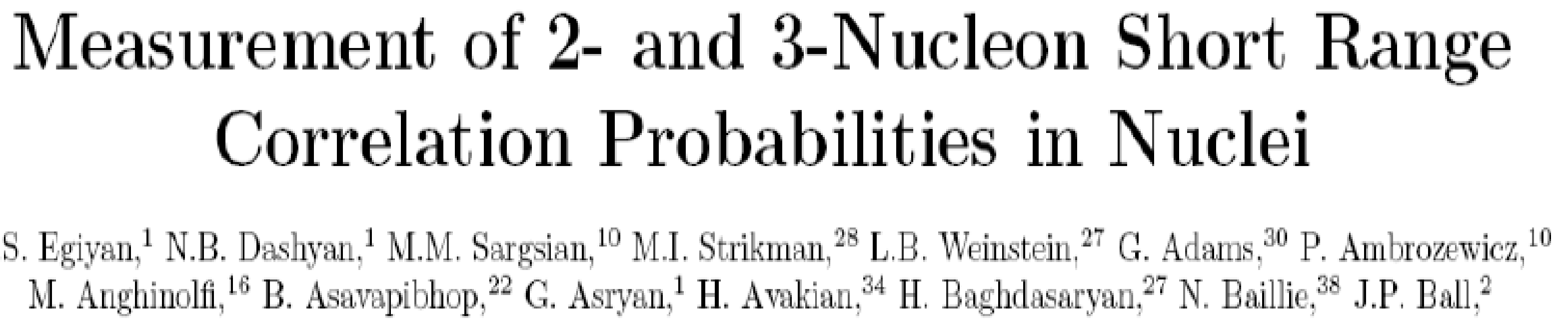


Figure 1: The fractions of correlated pair combinations in carbon as obtained from the ^{12}C(e, e’pp) and ^{12}C(e, e’pn) reactions measured at JLab [1,2] as well as from previous, ^{12}C(p,2pn) data from BNL [3,4].

JLAB

Phys.Rev.Lett. 96 (2006) 082501



Measurement of 2- and 3-Nucleon Short Range Correlation Probabilities in Nuclei

K.S. Egiyan,[1] N.B. Dashyan,[1] M.M. Sargsian,[10] M.I. Strikman,[28] L.B. Weinstein,[27] G. Adams,[30] P. Ambrozewicz,[10]
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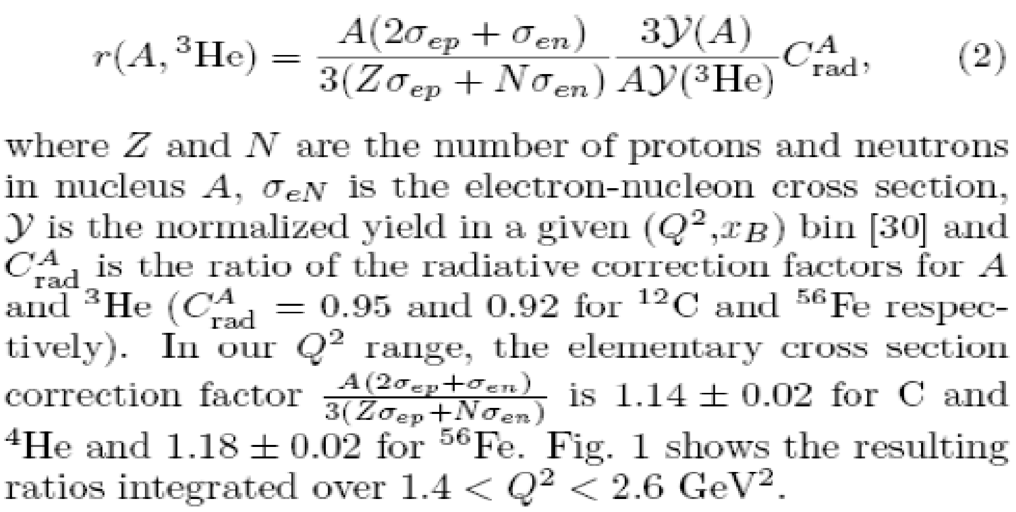
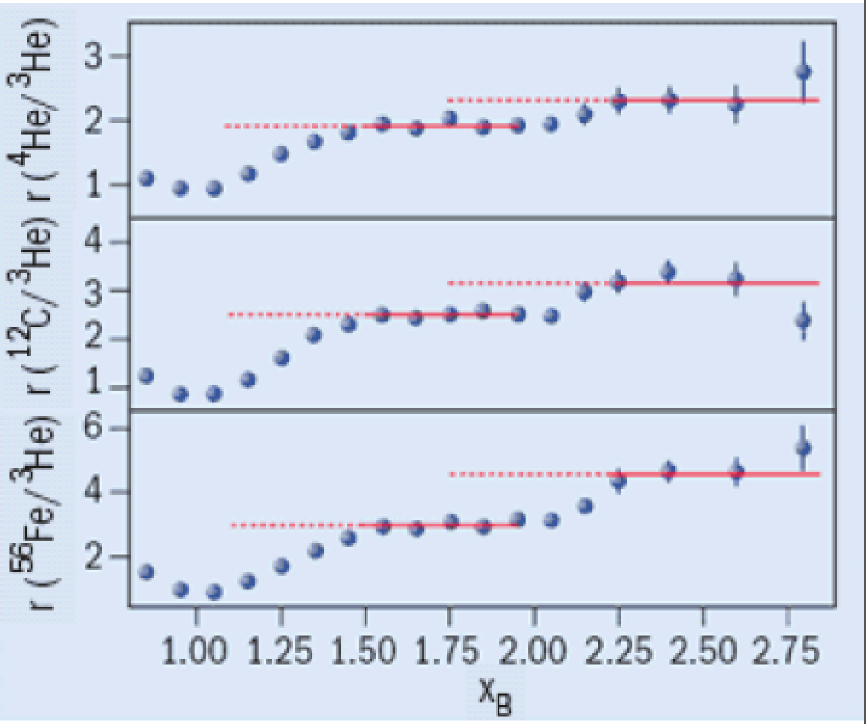


$$r(A,{}^3\mathrm{He}) = \frac{A(2\sigma_{ep}+\sigma_{en})}{3(Z\sigma_{ep}+N\sigma_{en})}\frac{3\mathcal{Y}(A)}{A\mathcal{Y}({}^3\mathrm{He})}C^A_{\mathrm{rad}}, \qquad (2)$$

where Z and N are the number of protons and neutrons in nucleus A, σ_{eN} is the electron-nucleon cross section, $\mathcal{Y}$ is the normalized yield in a given (Q^2, x_B) bin [30] and C^A_{rad} is the ratio of the radiative correction factors for A and ^{3}He ($C^A_{\mathrm{rad}} = 0.95$ and 0.92 for ^{12}C and ^{56}Fe respectively). In our Q^2 range, the elementary cross section correction factor $\frac{A(2\sigma_{ep}+\sigma_{en})}{3(Z\sigma_{ep}+N\sigma_{en})}$ is 1.14 ± 0.02 for C and ^{4}He and 1.18 ± 0.02 for ^{56}Fe. Fig. 1 shows the resulting ratios integrated over $1.4 < Q^2 < 2.6$ GeV^2.



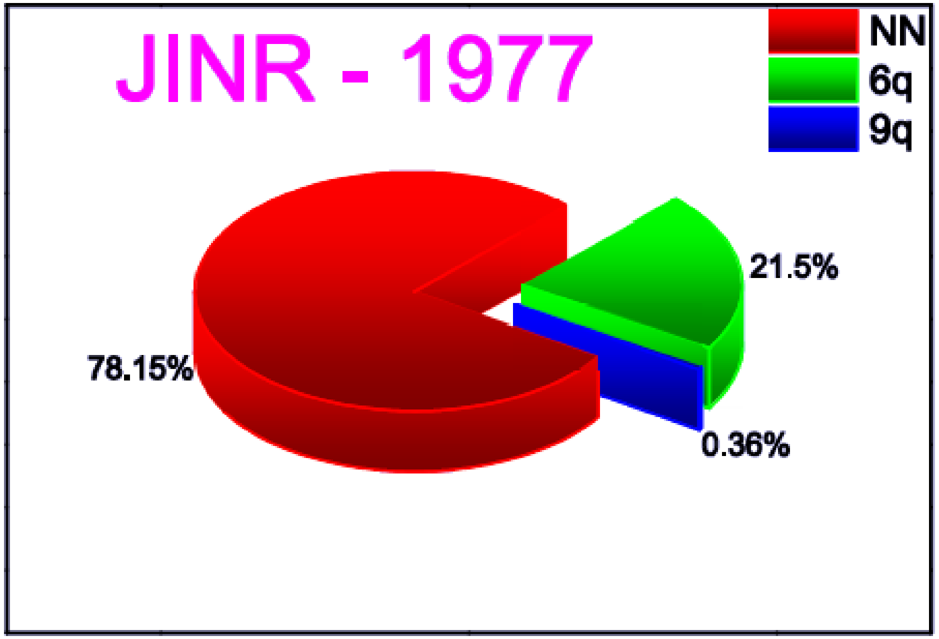
- No rescattering

$$x_B = Q^2/2m_N\upsilon$$

Leptonic and hadronic probes give same result

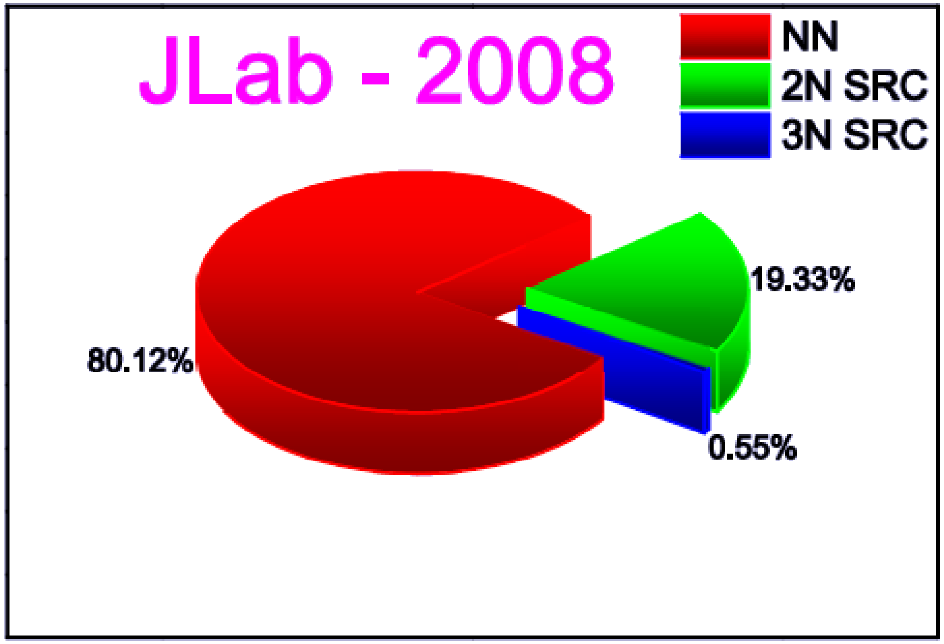
RNP – program at JINR

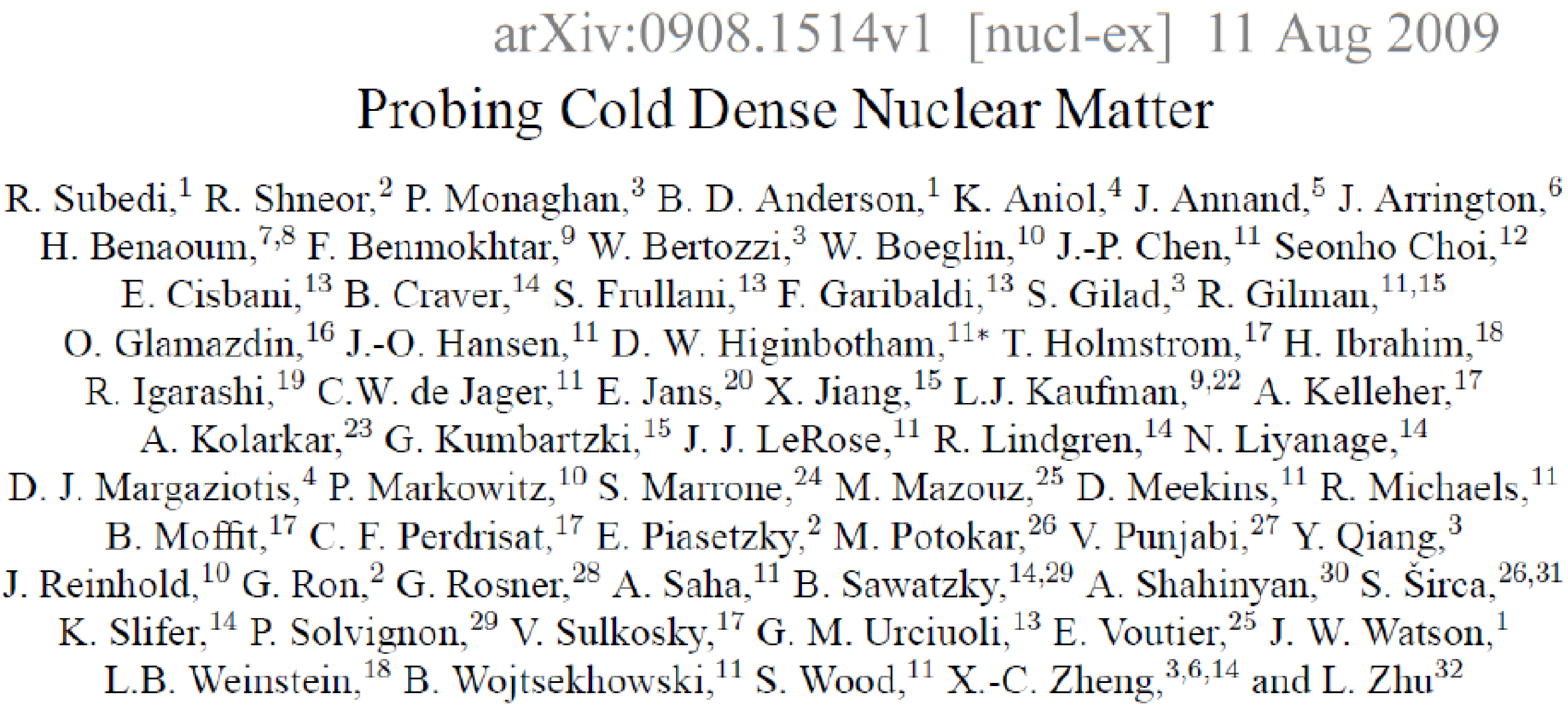
V.V.B., V.K.Lukyanov, A.I.Titov, PLB, 67, 46(1977)



eA – program at JLab

R.Subedi et al., Science 320 (2008) 1476-1478
e-Print: arXiv:0908.1514 [nucl-ex]





arXiv:0908.1514v1 [nucl-ex] 11 Aug 2009

Probing Cold Dense Nuclear Matter

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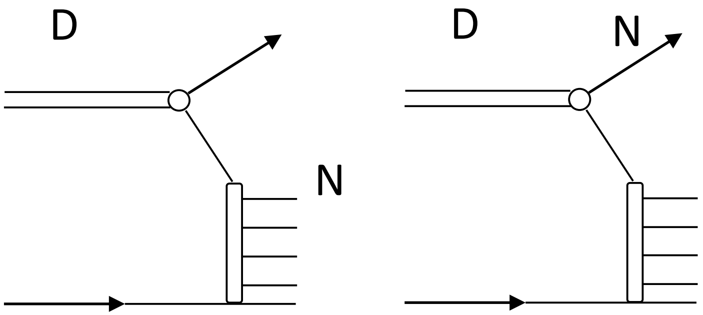
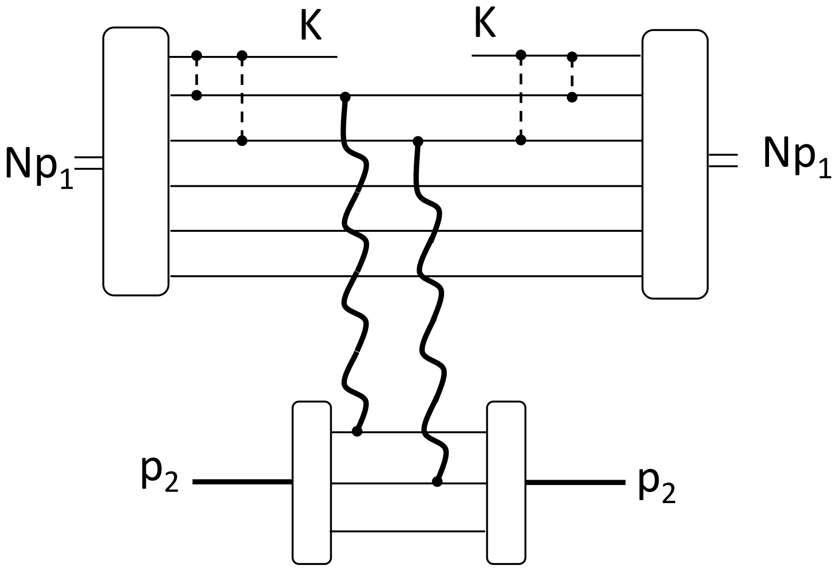
The protons and neutrons in a nucleus can form strongly correlated nucleon pairs. Scattering experiments, where a proton is knocked-out of the nucleus with high momentum transfer and high missing momentum, show that in ^{12}C the neutron-proton pairs are nearly twenty times as prevalent as proton-proton pairs and, by inference, neutron-neutron pairs. This difference between the types of pairs is due to the nature of the strong force and has implications for understanding cold dense nuclear systems such as neutron stars.

Cumulative particle production



L. Frankfurt and Strikman Phys. Let. 76B,3 (1978)



M. Braun and V. Vechernin, Nucl. Phys. B **427**, 614 (1994)