Alikhanov Institute for Theoretical and Experimental Physics
Russian Federation State scientific center

Dense Cold Matter

1. Motivation
2. Kinematical trigger
3. Experimental status
4. Detector for DCM study

A.Stavinskiy,DCM,ISSNP-2013,8/11/2013,Protvino

1. Motivation

I. Particle physics

The QCD (Quantum Chromodynamics) dynamics of the hadronization process are not yet fully understood, but are modeled and parameterized in a number of phenomenological studies, including the Lund **string** model and in various long-range QCD approximation schemes

Hadronization a) in vacuum (particle physics)

b) in artificial gluon matter (**Gluodynamics**)

c) in quark matter → **dense baryonic matter**

II. Nuclear physics

Strong interacting QGP is one of the most remarkable discovery for the last years. Important itself this discovery also

1)Provides new energy scale for physics ~200MeV(the temperature of the plasma).

2)Break the tendency of the study of particle interaction at the maximum available energy→

Critical point, Chiral transition, Quarkyonic phase etc...

1. Motivation

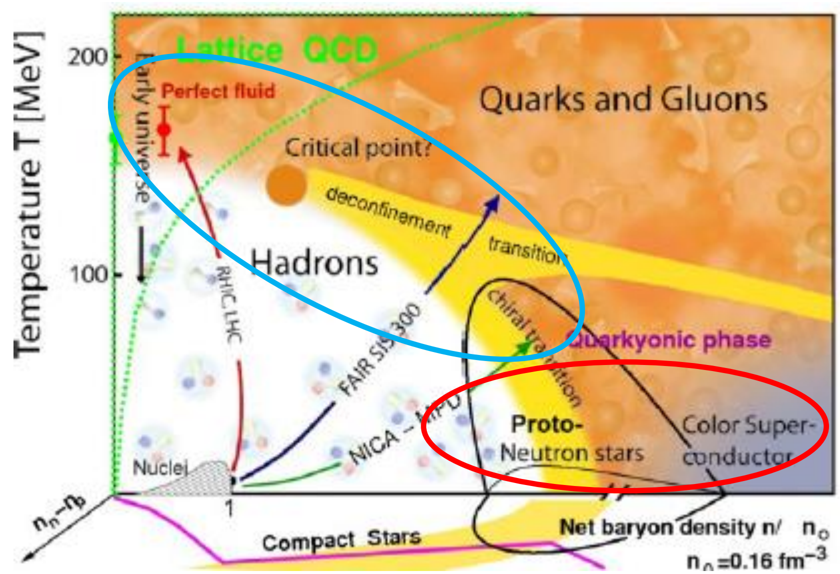
current region of the experiments

$\rho/\rho_0 \gg 1, T/T_0 \ll 1$
(DenseColdMatter – (below-DCM)
proposed region for the study of

*rich stucture of the QCD phase diagram, new states of matter
**diagram study not finished
additional new phenomena can be found

See, for example L.McLerran, “Happy Island”, arXiv:1105.4103 [hep-ph] and ref. therein

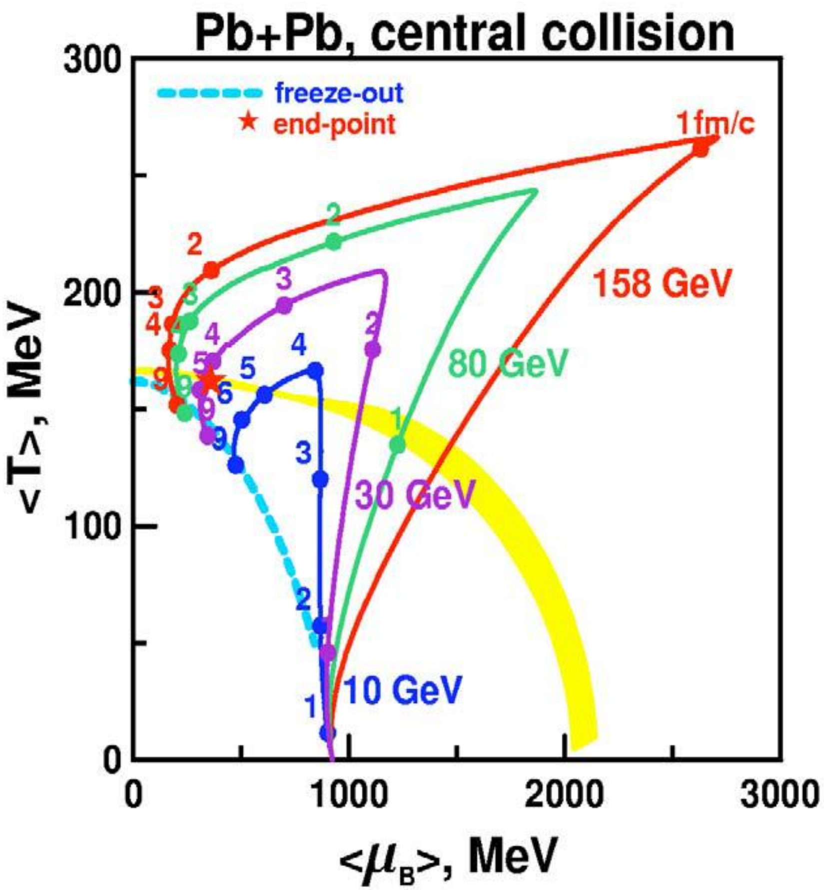
Phase diagram of nuclear matter



1. Motivation

How the new state of matter is created in the lab?

Y. Ivanov, V. Russkikh, V.Toneev, Phys. Rev. C73 (2006) 044904



The QGP can be created by heating matter up to a temperature of 2×10^{12} K, which amounts to 175 MeV per particle. This can be accomplished by colliding two large nuclei at high energy (note that 175 MeV is not the energy of the colliding beam). Lead and gold nuclei have been used for such collisions at CERN and BNL, respectively. The nuclei are accelerated to ultrarelativistic speeds and slammed into each other. When they do collide, the resulting hot volume called a "fireball" is created after a head-on collision. Once created, this fireball is expected to expand under its own pressure, and cool while expanding. By carefully studying this flow, experimentalists put the theory to test.

*Region $\rho/\rho_0 \gg 1$, $T/T_0 \ll 1$(DenseColdMatter) hardly accessible experimentally by standard way

2. Kinematical trigger (Fluctons or Short Range nucleon Correlations(SRC))

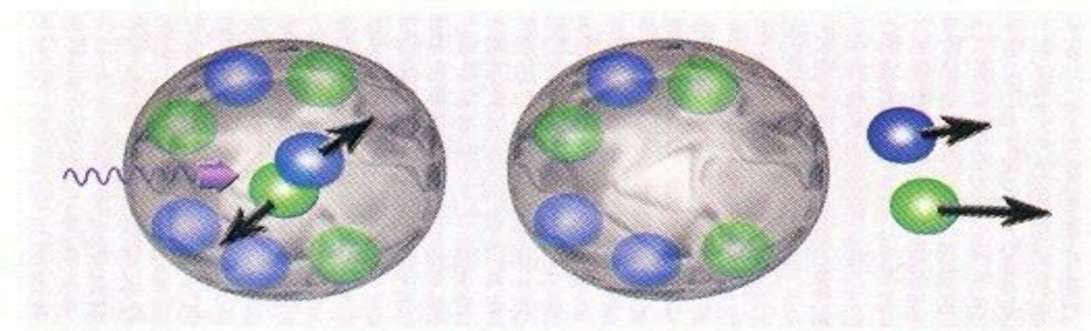


Fig. 1. Scattering of a virtual photon off a two-nucleon correlation, x > 1.5, before (left) and after (right) absorption of the photon.

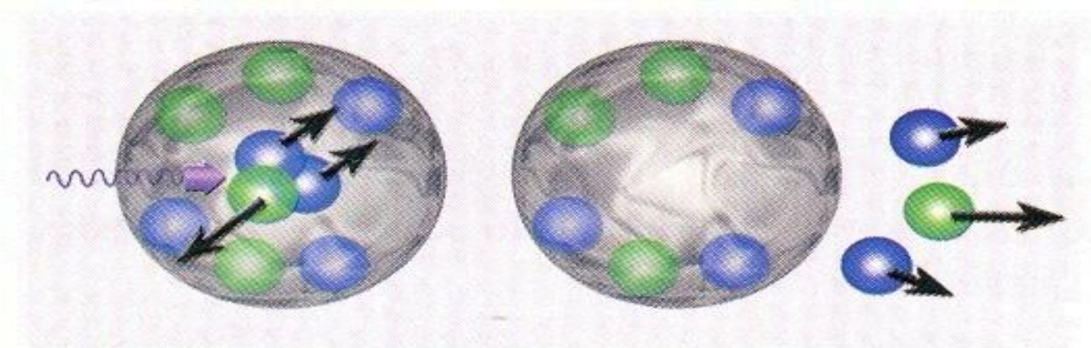


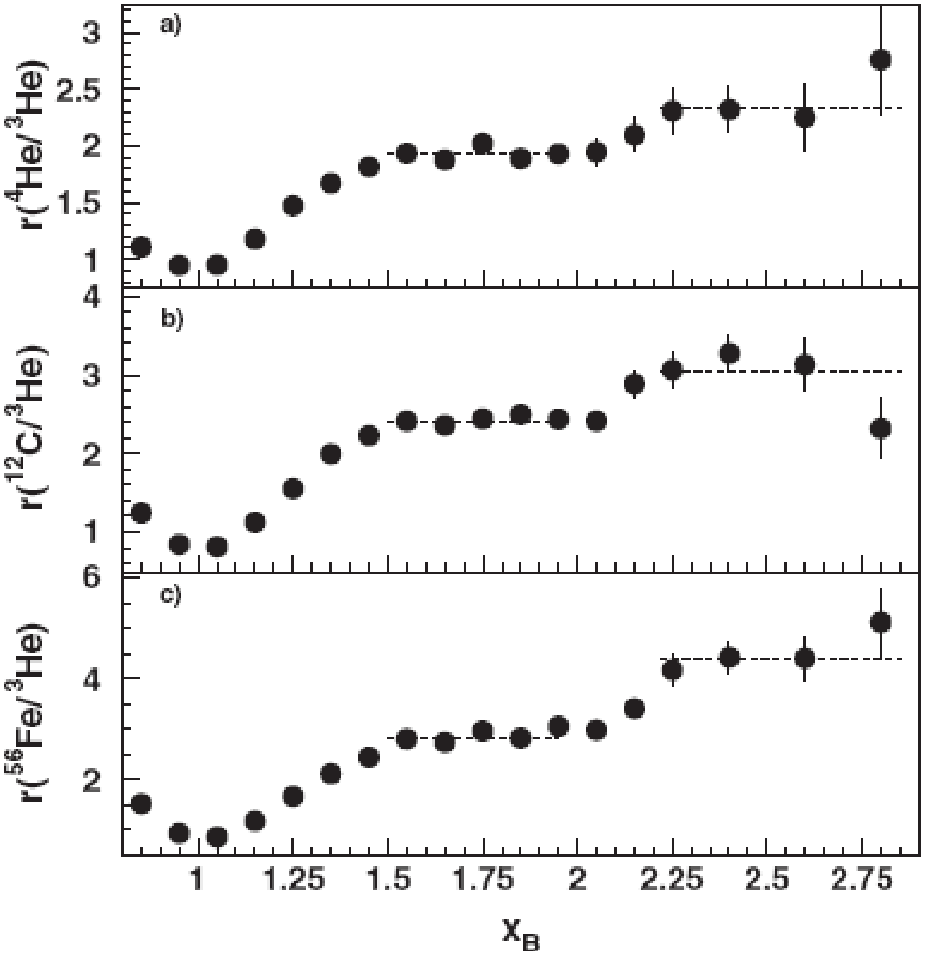
Fig. 2. Scattering of a virtual photon off a three-nucleon correlation, x > 2, before (left) and after (right) absorption of the photon.

Figure from: M.Strikman, CERN Courier Nov.2,2005

2.Kinematical trigger

CLAS $e^-A \rightarrow e^-X$ @~4 AGeV

•No rescattering



	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

dramatic decreasing
of the cross sections with N

K.S. Egiyan et al. Phys. Rev. Lett. 96, 082501 (2006)

$$x_B = Q^2/2m_N U$$

2. Kinematical trigger

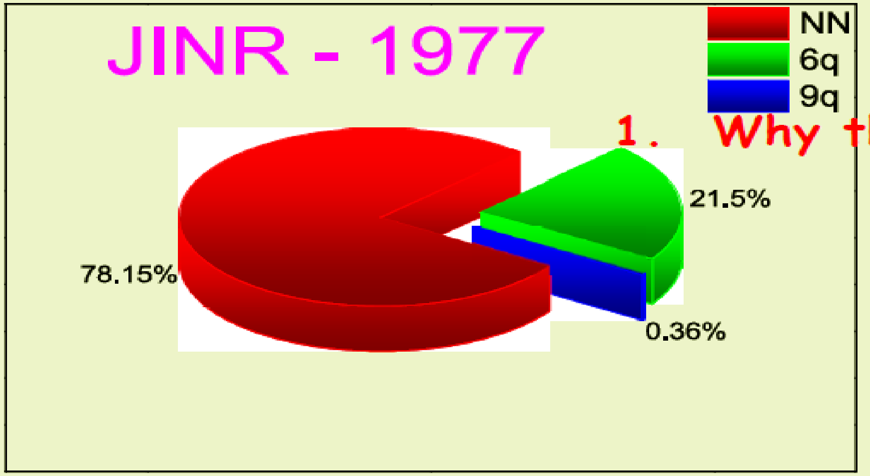
^{12}C – structure

RNP – program at JINR

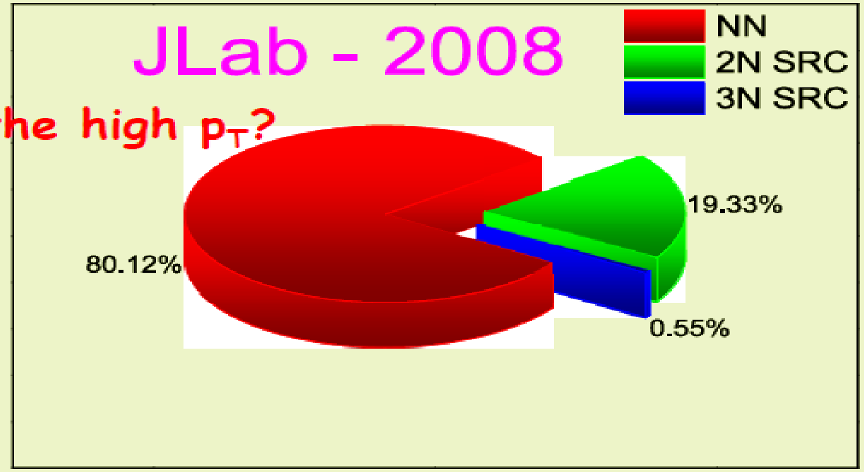
V.V.B., V.K.Lukyanov, A.I.Titov, PLB, 67, 46(1977)

eA – program at JLab

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



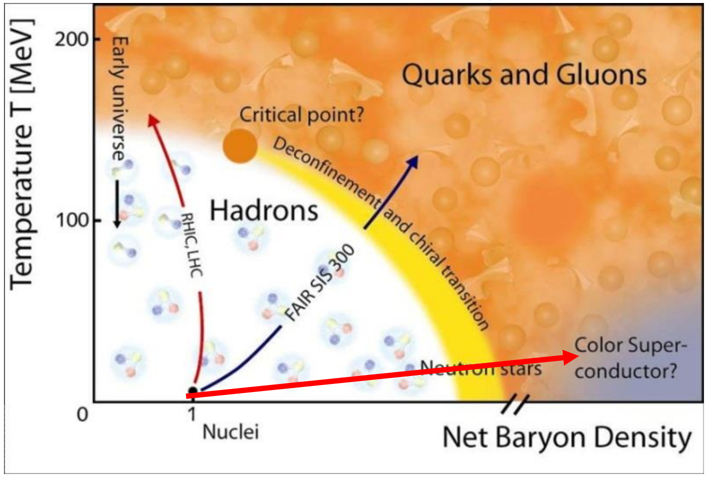
1. Why the high p_T?



See, also Burov et al.,EPAN 15,6, p.1249-1295(1984).

2. Kinematical trigger

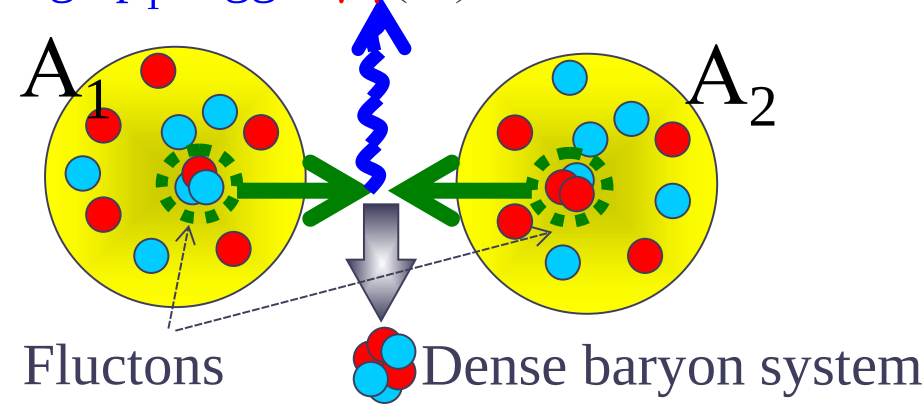
Phase diagram*



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

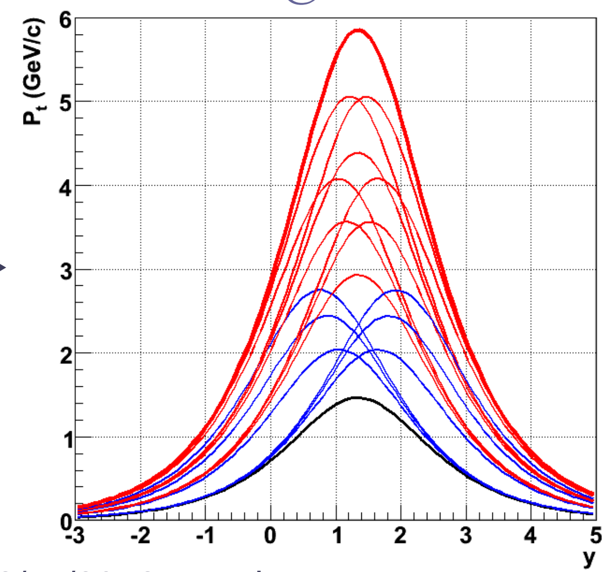
Scheme of process

High p_T trigger $\gamma,\gamma(\pi^o),\pi^\pm,K^\pm\ldots$



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

He+He @ 6 AGeV



2.Kinematical trigger

1) K.S. Egiyan et al. Phys. Rev. Lett. 96, 082501 (2006): $W_3/(W_2)2$~ 1/(6±2)
2) R. Subedi et al., Probing Cold Dense Nuclear Matter, arXiv:0908.1514v1 [nucl-ex] 11 Aug 2009: W(pp+nn)/W(np) ~ 1/(10±2)

Our estimate **$W_n \sim (W_2)^{(n-1)} (1/8)^{(n-2)}$**

σ (3N+3N(He+He)) ~ σ(He+He)*$(W_3)^2$ ~$2*10^{-6}$b
σ (4N+4N(He+He)) ~ σ(He+He)*$(W_4)^2$ ~$2*10^{-9}$b

"DCM": baryonic droplet with $<P_{NDCM}>$ < 0.4GeV/c in the droplet rest frame

T_0=2GeV/nucleon, p_N~0.80GeV/c, $(P_{NDCM}/ P_N)^{3(n-1)}$~$3*10^{-5}$,(n=6) σ(DCM-6N)~60pb

Beam(He): 10^9sec $^{-1}$; target(He):0.1; run:1000hours
6n droplet- $2*10^5$ events($<P_{NDCM}>$ < 0.3 GeV/c- 6000 events)

2. Kinematical trigger

Kinematical cooling for cumulative trigger

$dS = d^4p_1 \ldots d^4p_n \delta(p_i^2 - m_i^2)\delta^4(\sum_1^n p_i - P_n)\text{ɱ}^2$

Nonrelativistic n particles:

$dS \sim T_n^{(3n-5)/2}\ \text{ɱ}^2$

Cumulative trigger:

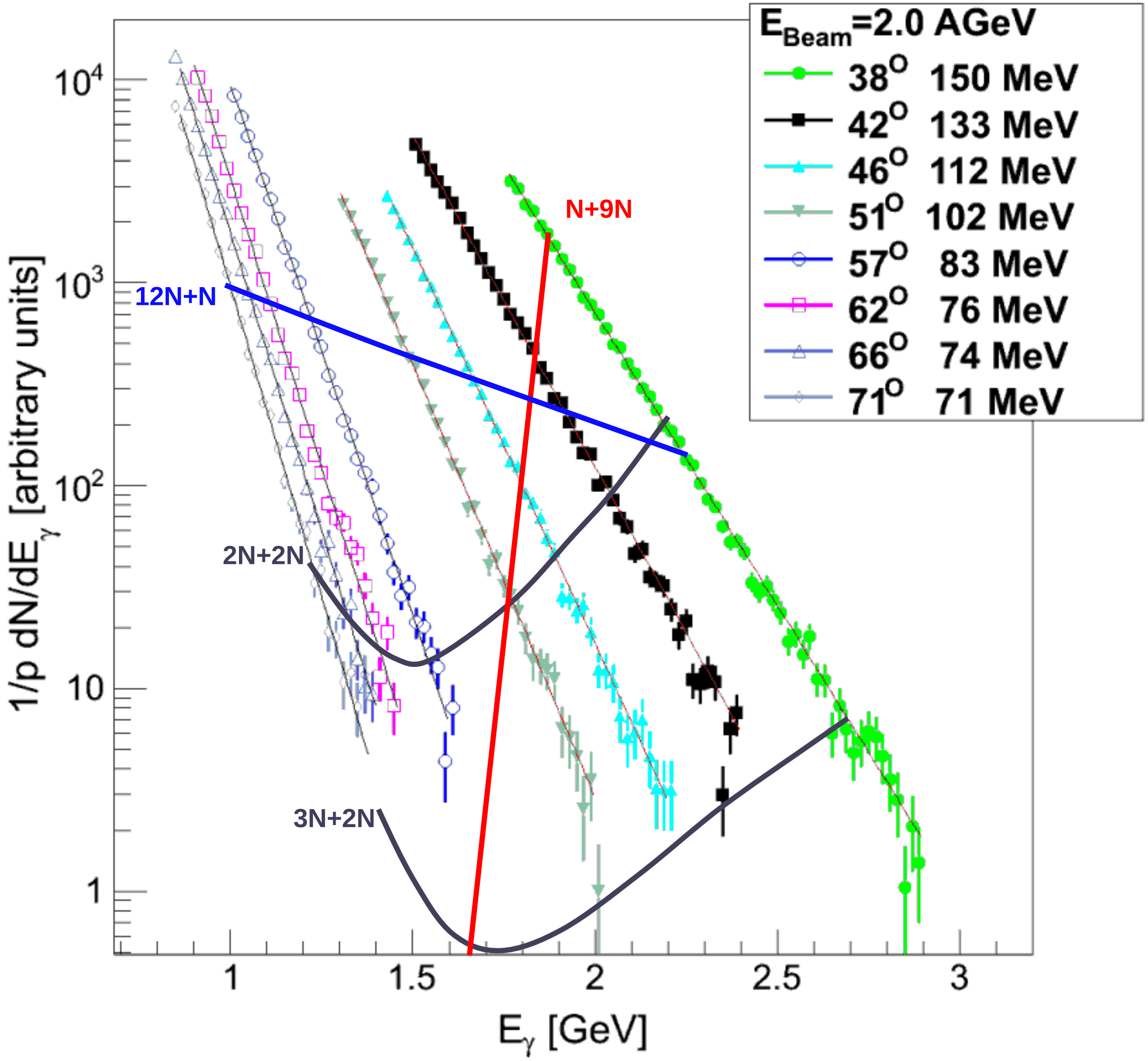
$\text{ɱ}^2 \sim \exp\{-T_n/T_*\}$(neglecting for dramatic decreasing of the cross sections with N)

$T_0 \sim (3n-5)T^*/2n \rightarrow 3T^*/2 \sim 60\text{MeV}$, $p \sim 300\text{-}400\text{MeV}/c$

3. Experimental status

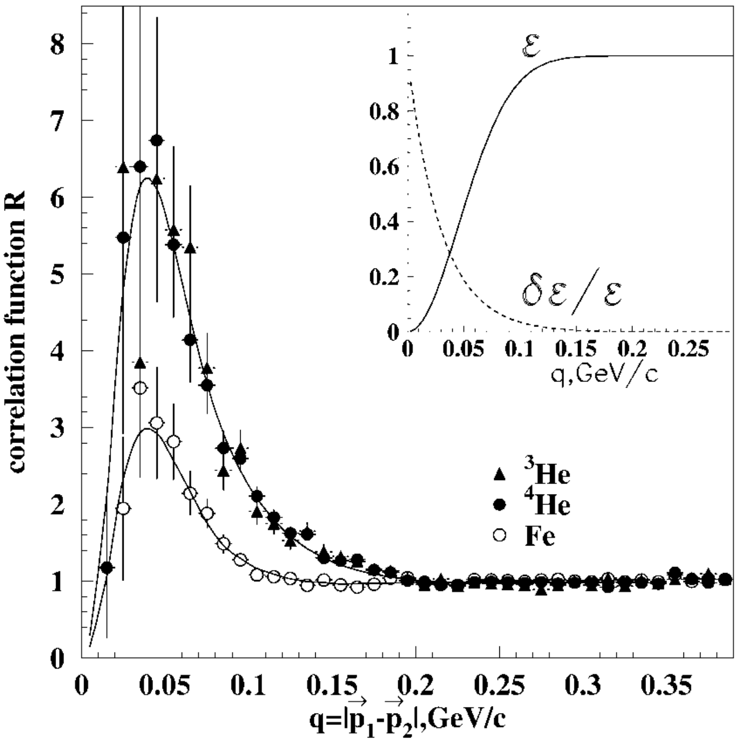
FLINT DATA: Photon spectra

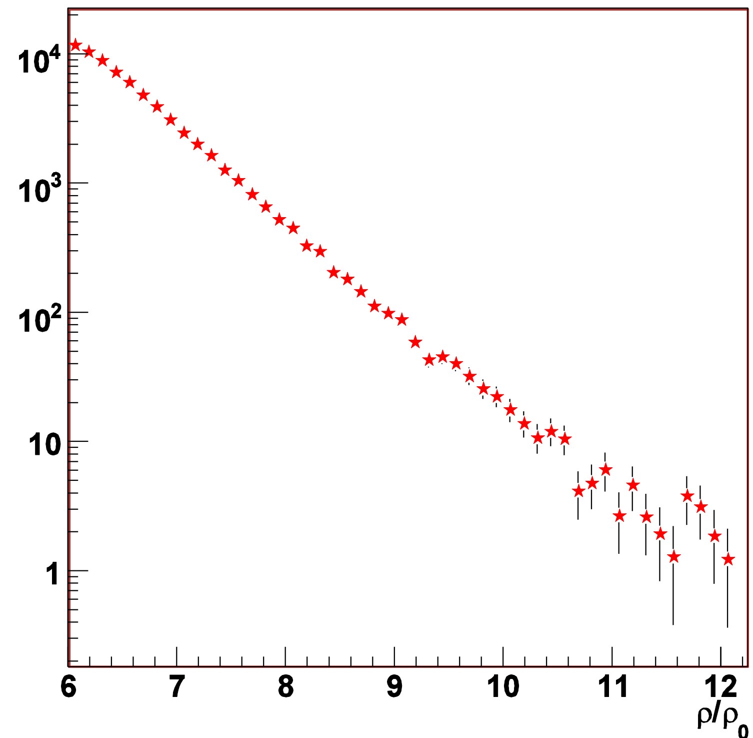
CBe→γX



3. Experimental status

An estimate of baryon density@FLINT experiment





CLAS:r_f~1-1.5fm

A.S.et al., Phys.Rev.Lett. 93,192301 (2004)

3. Experimental status

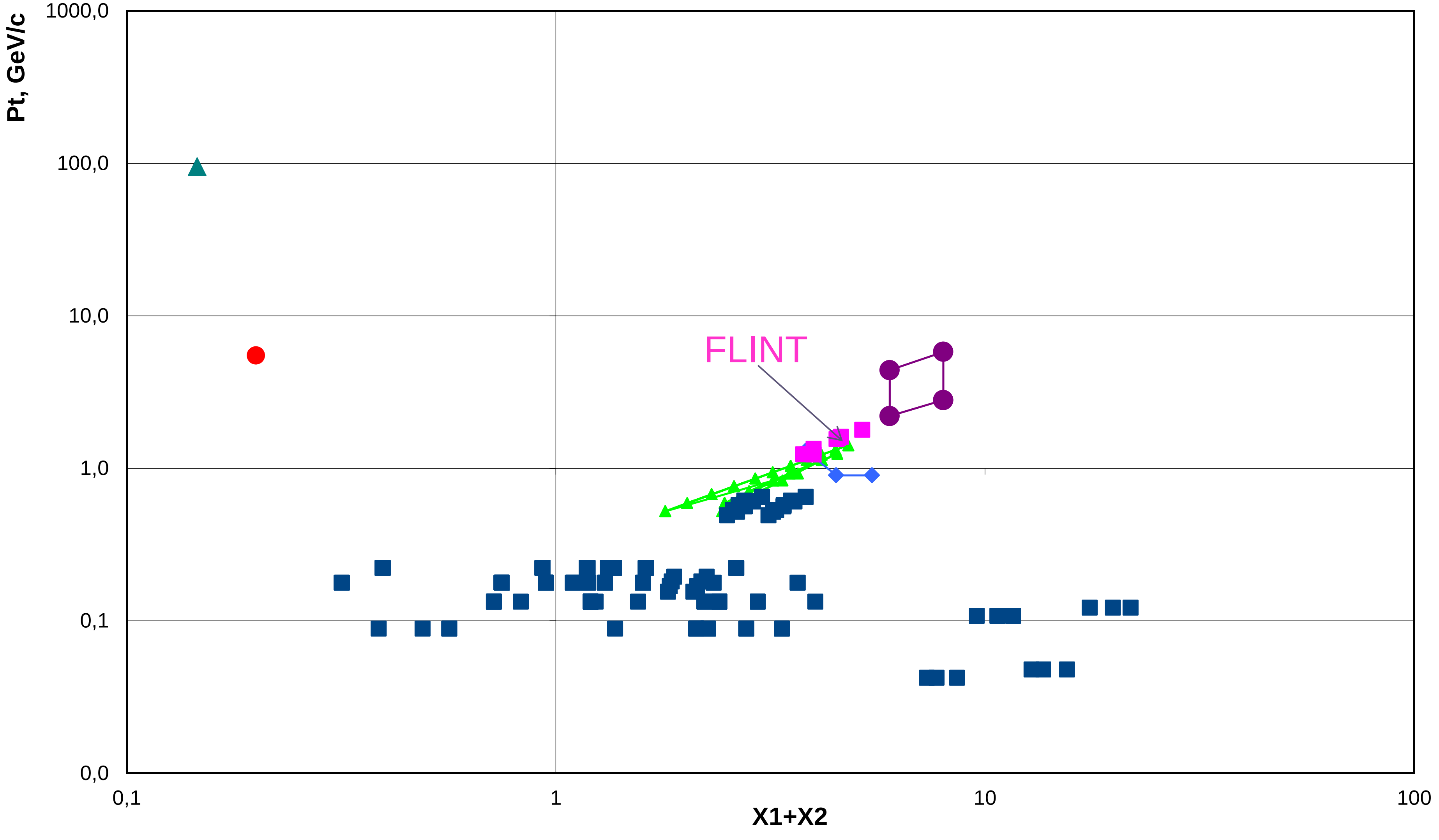
pp(ALICE, arXiv:1007.0516[hep-ex],K.Aamodt et al.)

$dN_{ch}/d\eta$	R_{inv}(fm)	Description
3.2	~0.9	Without hydro (arXiv:1106.1786[hep-ph] M.Nilsson et al.)
7.7	~1.1	
11.2	~1.2	With hydro (arXiv:1010.0400[nucl-th],K.Werner ety al.)

Criterium: r»l

	number of particles	Size(r), fm	free path, (l)fm
Heavy Ions:	1000	10	1
flucton-flucton	10	1	0.1

3. Experimental status



Search for and study of cold dense baryonic matter
(Letter of intent)

O.A.Chernishov [1],A.A.Golubev[1], V.S.Goryachev[1], A.G.Dolgolenko[1], M.M.Кats[1],
B.O.Кerbikov[1], S.M.Кiselev[1], Yu.T.Kiselev[1], A.Kogevnikov [1], К.R.Mikhailov[1],
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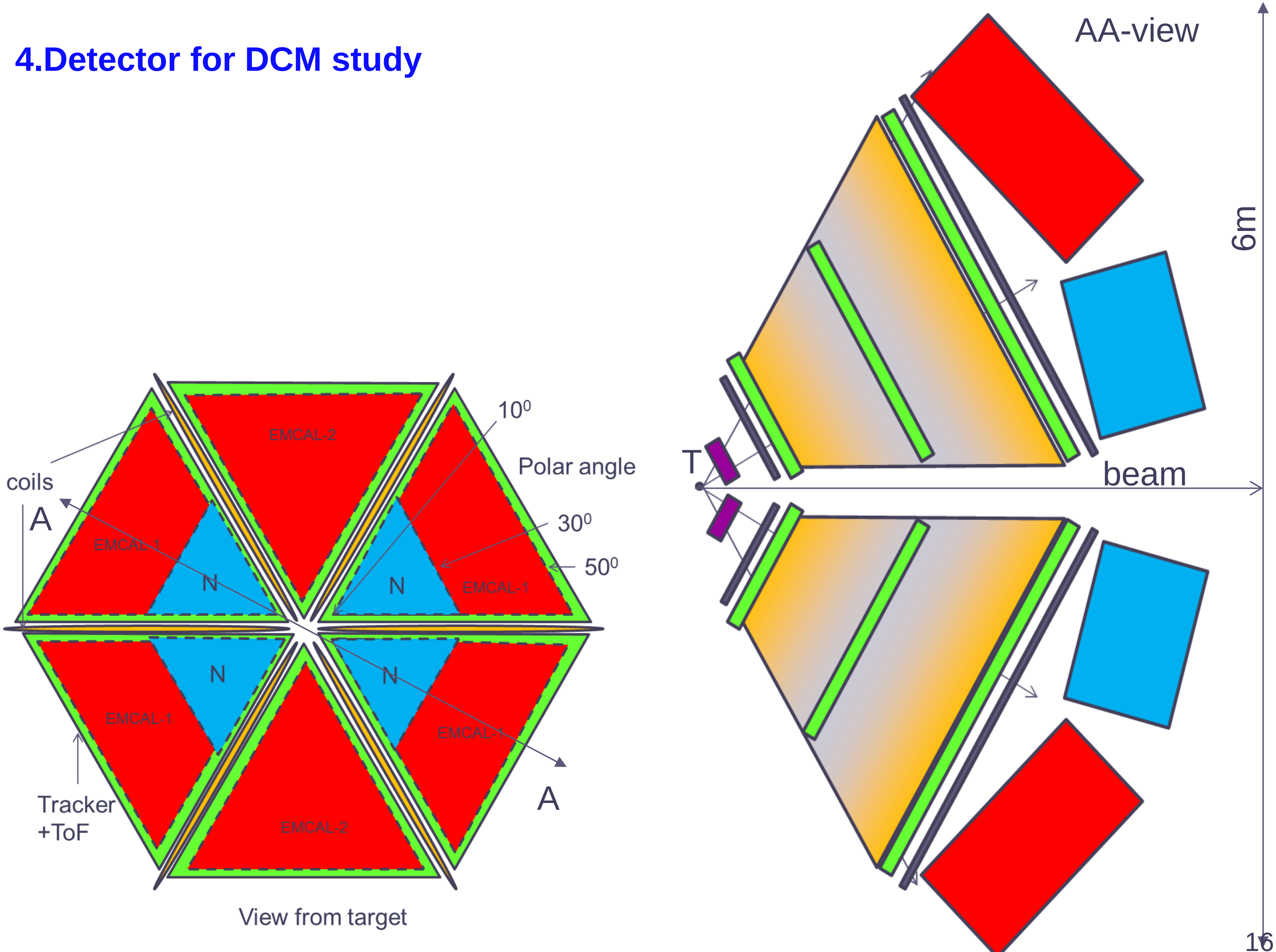
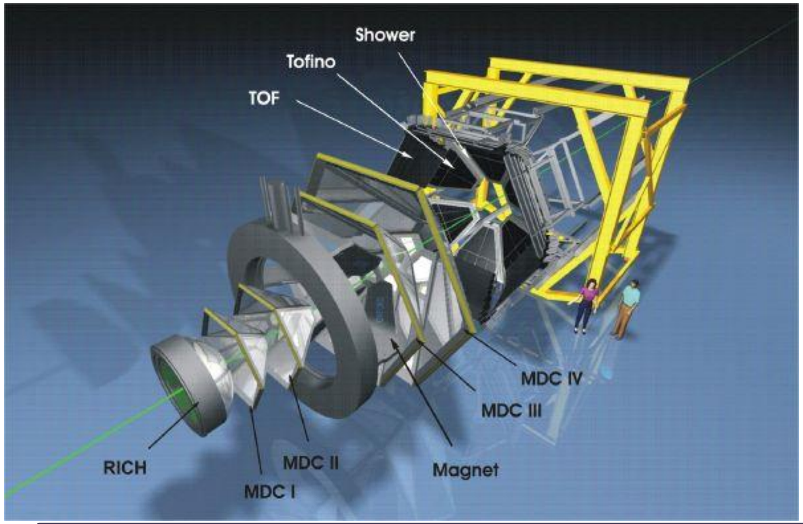
A. Кoloyvar[2], V.Кondrat'ev[2], V.A.Murzin[3], V.A. Oreshkin[3], D.P. Suetin[6] ,
G. Feofilov[2],A.A.Baldin[4], V.S.Batovskaya[4], Yu.T. Borzunov[4], A.V. Кulikov[4],
A.V. Кonstantinov[4], L.V.Malinina[4,7],G.V.Mesheryakov[4],A.P.Nagaitsev[4], V.K. Rodionov[4],
S.S.Shimanskiy[4], O.Yu.Shevchenko[4] , A.V.Gapienko[5], V.I.Krishkin[5] , I.N.Dorofeeva[7],
M.M.Merkin[7], AA.Ershov[7], N.P.Zotov[7]

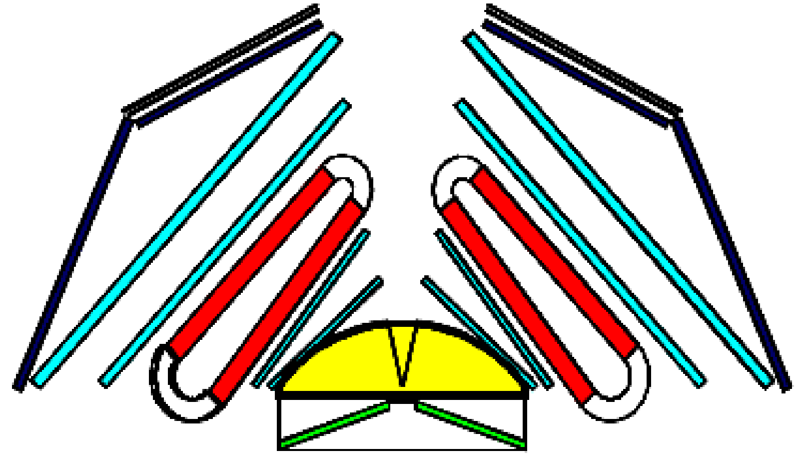
1). ITEP NRC KI , Moscow, 2). SPbSU, S.Peterburg, 3). PINP NRC KI, S.Peterburg,
4). LPHE,JINR,Dubna, 5). IHEP NRC KI, Protvino , 6). SPbSPU, S.Peterburg,
7).MSU,Moscow

4.Detector for DCM study



HADES@GSI





Shown above is a schematic view of the HADES detector system. The system is divided into 6 identical sectors surrounding the beam axis; the picture above shows a two-dimensional slice to demonstrate HADES' large angular acceptance, which stretches between 16 and 88 degrees. HADES is comprised of the following components:
A diamond START detector, composed of two identical 8-strip diamond detectors of octagonal shape placed 75 cm downstream respectively 75 cm upstream of the HADES target.

A Ring Imaging Cherenkov (RICH) gas radiator for electron identification, covering the full azimuthal range. The high angular resolution of a RICH is needed to assure that the lepton identification can be assigned to the corresponding lepton track.

Two sets of Multiwire Drift Chambers (MDC) before and after the magnetic field region for tracking. Besides precise determination of lepton trajectories, event characterization via charged particle momentum and angular distributions is obtained from these detectors.

A superconducting toroidal magnet with 6 coils in separate vacuum chambers. The coil cases are aligned with the frames of the MDC's to reduce dead space in the spectrometer. The magnet provides the momentum kick necessary to obtain charged particle momenta with a resolution of about 1%.

A multiplicity/electron trigger array consisting of granular pre-shower detectors at forward angles below 45° and two walls of scintillators: the time-of-flight wall (TOF) at angles above 45° and the TOFINO wall at angles below 45°.

Experimental program:

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

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- 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

3) Modification of particles properties in nuclear matter

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

4.Detector for DCM study

I: $^3He+^3He \rightarrow a+X$, Q1+Q2 ~ 3-4,

Does np-flucton represent dominant contribution into the process?
(Combinatorial factor pp/np=1/2 for ^3He is trivial,
Coulomb corrections for He are small)

$$\frac{^3He+^3He \rightarrow \pi^+ +X}{^3He+^3He \rightarrow \pi^- +X} = 1 \text{ in case of np dominance, and } >1 \text{ for pp contribution}$$

Background measurements: ^4He+d

II: $^3He+^3He \rightarrow a+X$, Q1+Q2→6 , X→6N

Does dense cold matter
is izosymmetrical one?

a - π^+ X→pppnnn

a - π^- X→pnnnnn

$$\frac{^3He+^3He \rightarrow \pi^+ +X}{^3He+^3He \rightarrow \pi^- +X} >1(\text{model:}\sim 2)$$

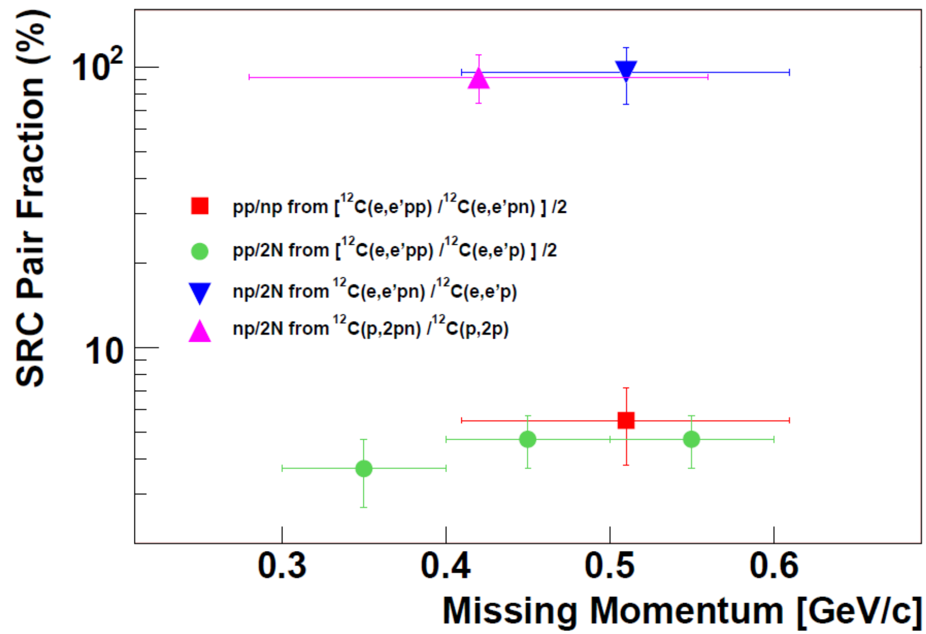

Figure 2: The fractions of correlated pair combinations in carbon as obtained from the (e,e'pp) and (e,e'pn) reactions, as well as from previous (p,2pn) data. The results and references are listed in Table 1.

R. Subedi et al., Probing Cold Dense Nuclear Matter,
arXiv:0908.1514v1 [nucl-ex] 11Aug2009
{http://arxiv.org/abs/0908.1514v1}.
See also preprint ITEP,11-89,1989

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2. Dense Cold Matter(4)

Condensed matter(not an analog in the state of matter but for the statistical properties of the system):

Advances in atom cooling and detection have led to the observation and full characterisation of the atomic analogue of the HBT effect

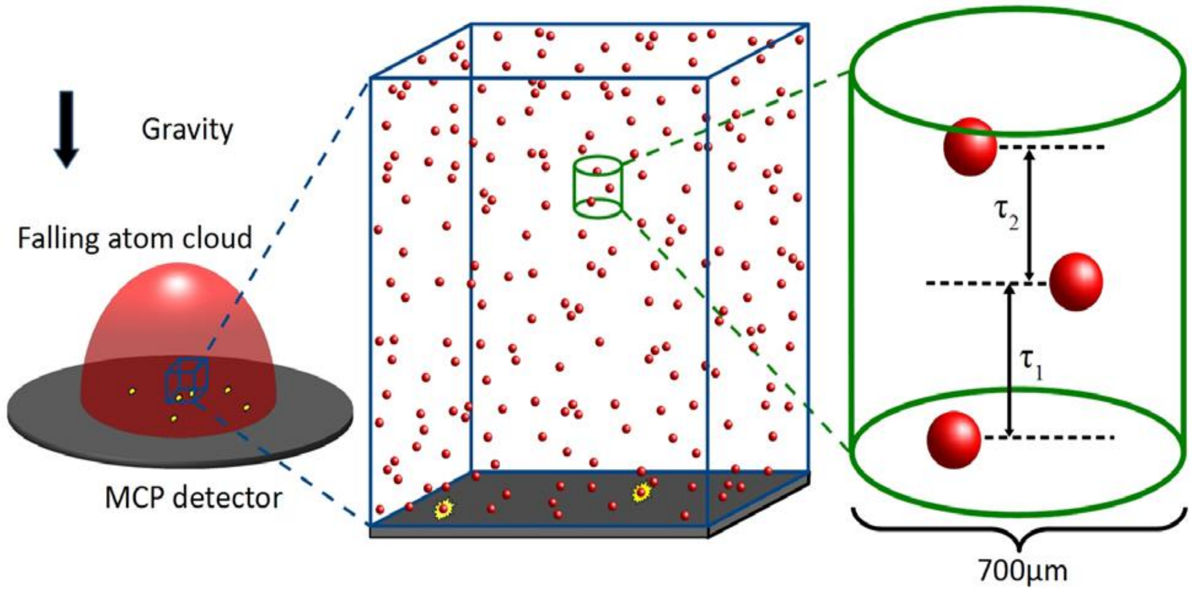
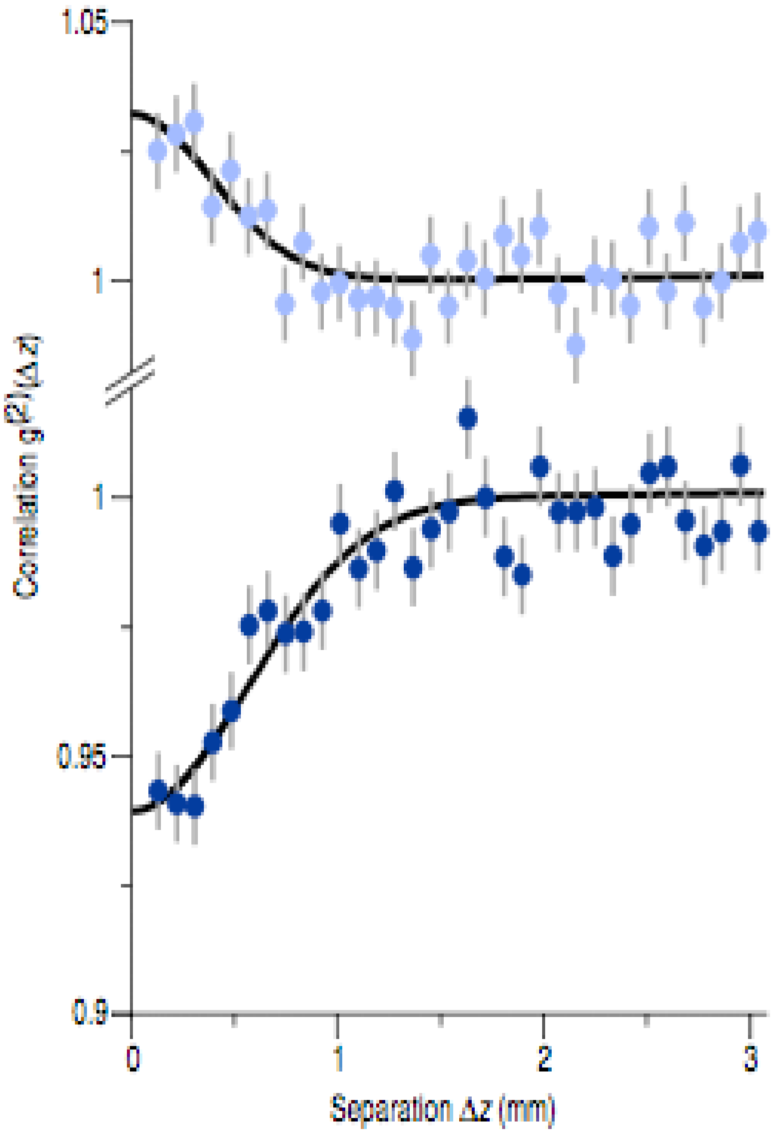


Fig.2-K.G.H. Baldwin, *Contemp. Phys.* **46**, 105 (2005).

Caption for figure 1: The experimental setup. A cold cloud of metastable helium atoms is released at the switch-off of a magnetic trap. The cloud expands and falls under the effect of gravity onto a time resolved and position sensitive detector (micro-channel plate and delay-line anode), that detects single atoms. The inset shows conceptually the two 2-particle amplitudes (in black or grey) that interfere to give bunching or antibunching: S1 and S2 refer to the initial positions of two identical atoms jointly detected at D1 and D2.

T.Jeltes et al., Nature,**445**,402(2007)

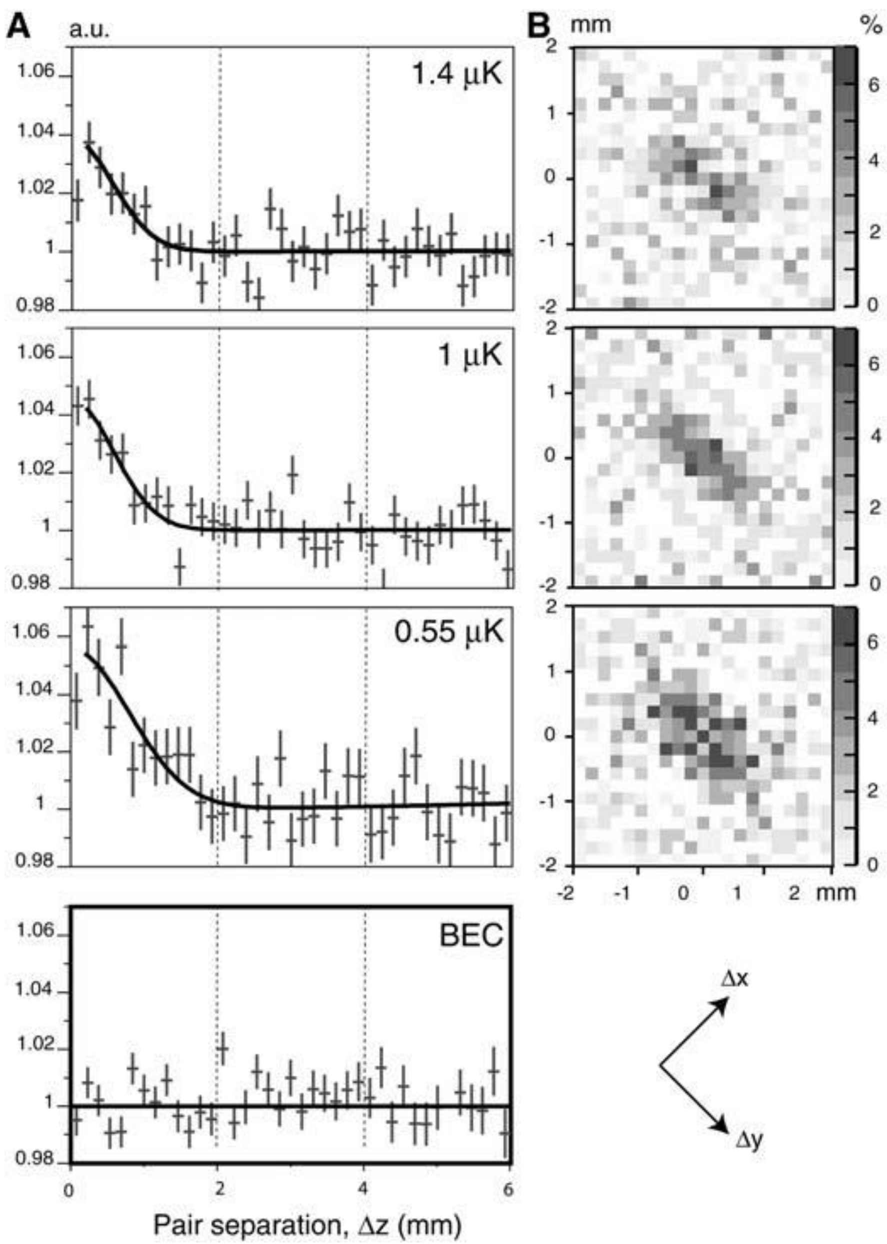
2. Dense Cold Matter(5)



Caption for figure 2: Normalised correlation functions for 4He* (bosons) in the upper graph, and 3He* (fermions) in the lower graph. Both functions are measured at the same cloud temperature (0.5 μK), and with identical trap parameters. Error bars correspond to the root of the number of pairs in each bin. The line is a fit to a Gaussian function. The bosons show a bunching effect; the fermions anti-bunching. The correlation length for 3He* is expected to be 33% larger than that for 4He* due to the smaller mass. We find 1/e values for the correlation lengths of 0.75±0.07 mm and 0.56±0.08 mm for fermions and bosons respectively.

T.Jeltes et al.,Nature,**445**,402(2007)

2. Dense Cold Matter(6)



Hanbury Brown Twiss Effect for Ultracold Quantum Gases

M. Schellekens,R. Hoppeler,A. Perrin,J. Viana Gomes,D. Boiron, A. Aspect, C. I. Westbrook

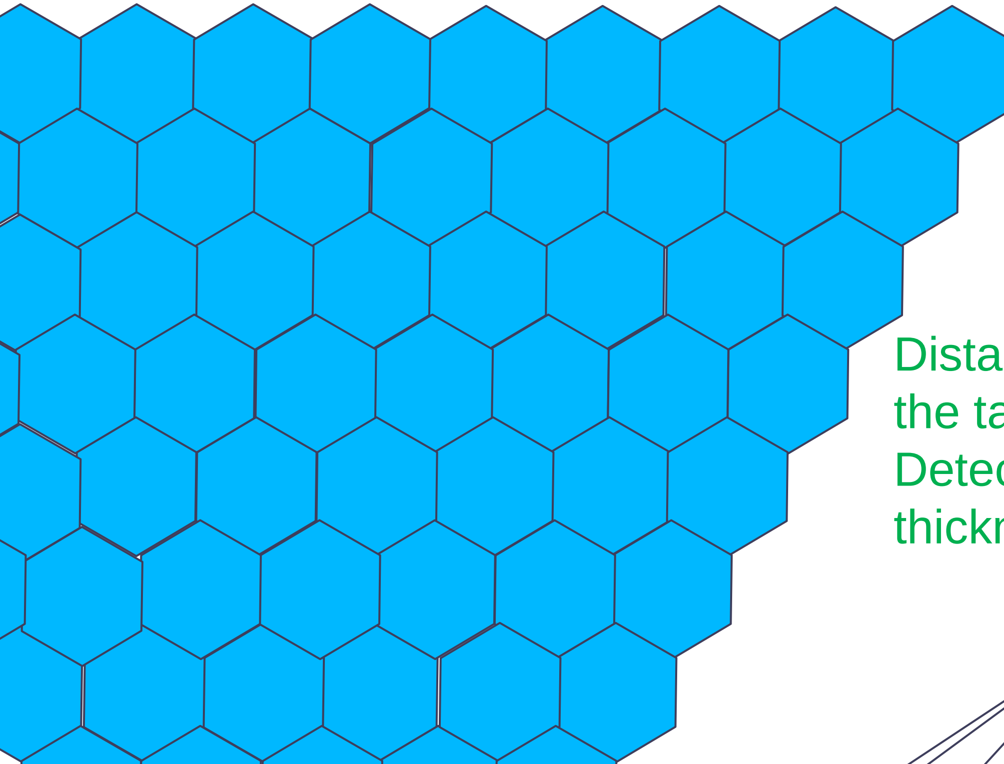
We have studied two-body correlations of atoms in an expanding cloud above and below the Bose-Einstein condensation threshold. The observed correlation function for a thermal cloud shows a bunching behavior, whereas the correlation is flat for a coherent sample. These quantum correlations are the atomic analog of the Hanbury Brown Twiss effect.

Fig. 2. (A) Normalized correlation functions along the vertical (z) axis for thermal gases at three different temperatures and for a BEC. For the thermal clouds, each plot corresponds to the average of a large number of clouds at the same temperature. Error bars correspond to the square root of the number of pairs. a.u., arbitrary units. (B) Normalized correlation functions in the Dx j Dy plane for the three thermal gas runs. The arrows at the bottom show the 45- rotation of our coordinate system with respect to the axes of the detector. The inverted ellipticity of the correlation function relative to the trapped cloud is visible.

Science,v.310,p.648(2005)

4. Detector for DCM study

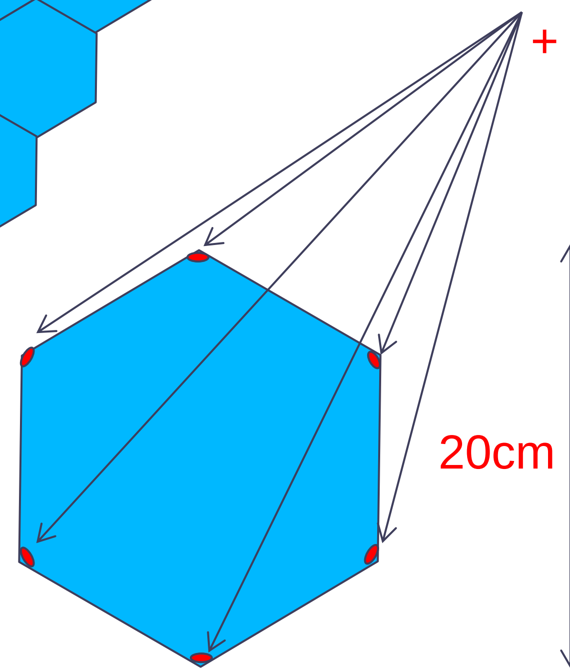
Neutron detector supermodule(78 detectors)



Distance from the target 240cm; Detector thickness 20cm

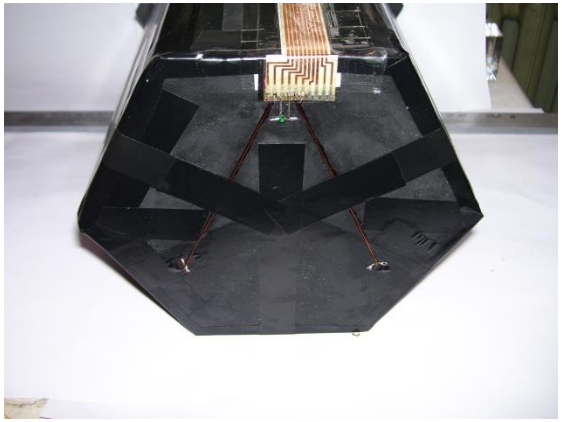
180cm

Fiber + SiPM

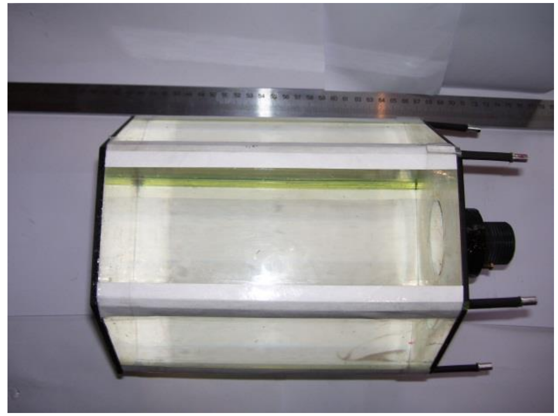


20cm

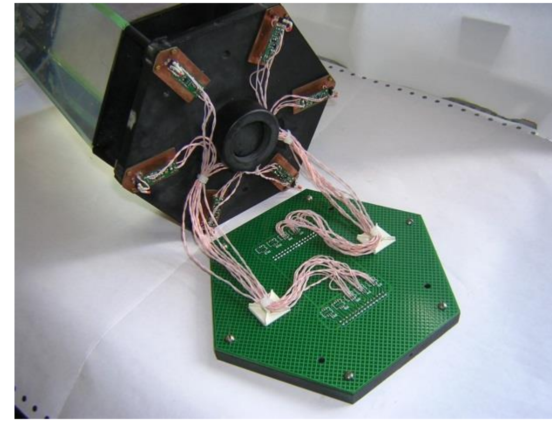
4. Detector for DCM study



Front



Side



Back

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4.Detector for DCM study

*search for an exotic in the droplet

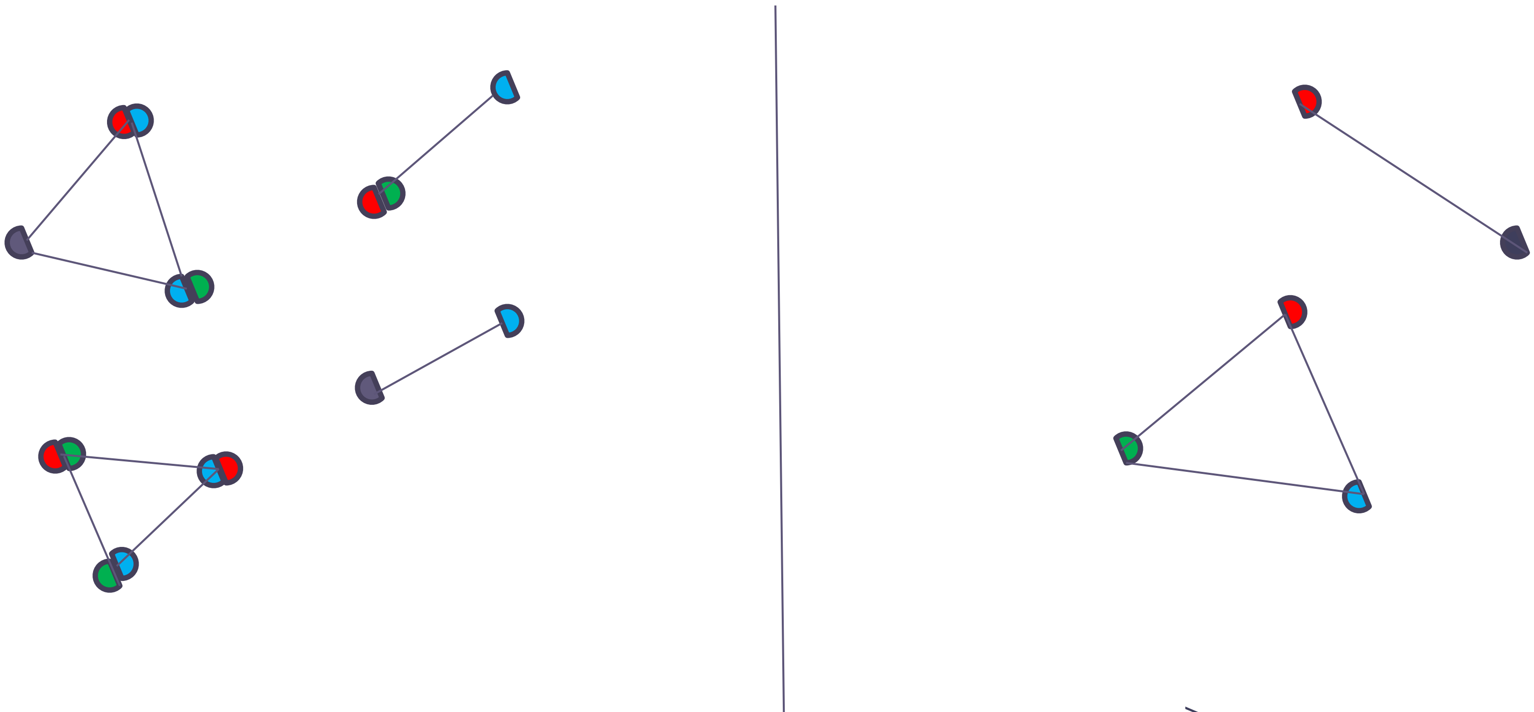
Reaction: $^{4}He(2GeV/nucleon)+^{4}He \rightarrow K^{-}BX$

Trigger's particle: K^{-} ($p>2GeV/c$, $30^{0}<\vartheta<60^{0}$)

$B \rightarrow B_{1}\ldots B_{n-1}\Theta^{+}$; $\Theta^{+} \rightarrow K_{s}p$; $K_{s} \rightarrow \pi^{+}\pi^{-}$

1event=1fb, (CLAS Upper limit for Θ^{+} - 0.7nb(PRD74(2006)032001),

see also I.G.Alekseev et al.,preprint ITEP 2-05,2005(EPECUR))



$\rho \gg \rho_0$(Dense Cold Matter)

$\rho_0 \geq \rho$

Conclusions

1)Dense cold corner of phase diagram is accessible
in the laboratory, at least for relatively small systems

2)Wide new physical program for the study

3)Light ions high intensity (10^{10} sec^{-1}) beams(He,C)
at initial energy 2-3 GeV/nucleon and light fixed targets(^3He, ^4He)
are optimal for the proposed study

4)Detector for the proposed study looks like already existing
ones in the same initial energy range (CLAS,HADES etc…) +
+ some specific detectors for the identifications of neutrons

Extra slides

Simulations (S.M.Kiselev,ITEP)

Our goal: using the high momentum π^0 as a trigger, study the baryon system produced in 4N+4N → π^0+8N

An instrument: collisions of light nuclei (e.g. $^4He+^4He$ and C+Be at T/A=2.0 GeV)

An idea to estimate the background:

- select events with the number of nucleon-participants, $N_{prod} \geq 8$
- among N_{prod} find 8N with minimal momentum, p_{min}
- select events with $p^{8N}_{min} < p_{cut}$ (=100 MeV/c)
- remove this 8N from each event, rest nucleons - background
- add the π^0+8N system, these 8N – signal
- momentum of a nucleon from the signal is smearing with a parameter σ_{smear}: $\sigma_x=\sigma_y=\sigma_z=\sigma_{smear}$= 170 MeV/c. momentum non conservation ΔP due to the removing+adding procedure should be close to zero.

Input info

UrQMD1.3 generator

• 10^6 min. bias $^4He+^4He$ and 10^5 C+Be events at T/A=2 GeV ($b<R_1 + R_2$)

$4N+4N \leftrightarrow \pi^0+8N$ in an $^4He+^4He$ or C+Be event:

• π^0 will be detected at $\theta_{c.m.}=90^0$ → p_{cumul} = 2.78 GeV/c for T/A=2.0,

($p_x=0$, $p_y = - p_{cumul}$, $p_z=0$)

• the momentum of every N of the 8N system,

($p_x=0$, $p_y = p_{cumul}/8$, $p_z=0$)

is smearing with $\sigma_x = \sigma_y = \sigma_z = \sigma_{smear}$ (= 170 MeV/c)

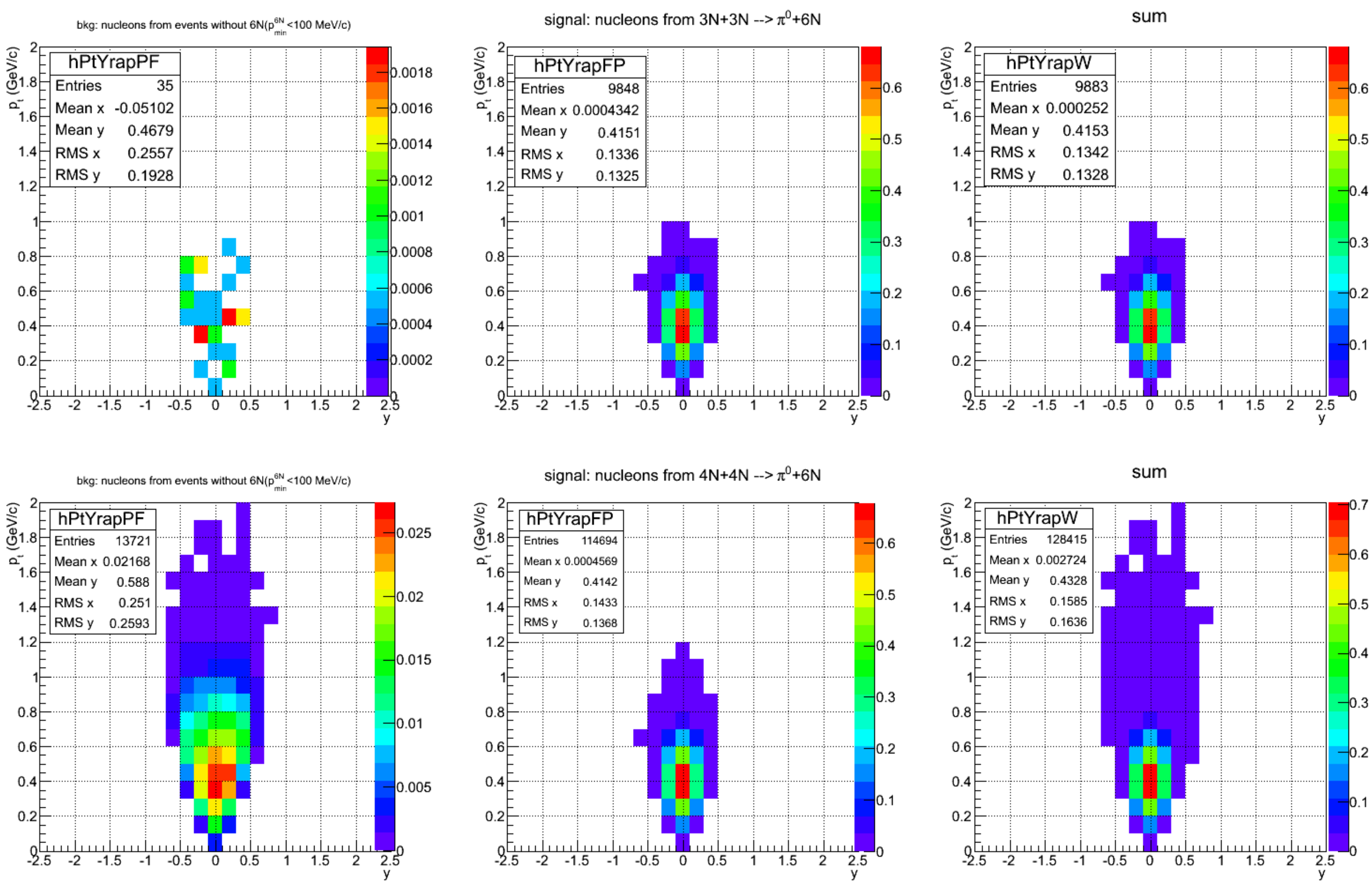
Do N_{cycles} (= 1000) to select the 8N system with minimal ΔP

•our “detector” covers the cone with 45^0 around the y axis

Background and signal 3N+3N

$^4He+^4He$

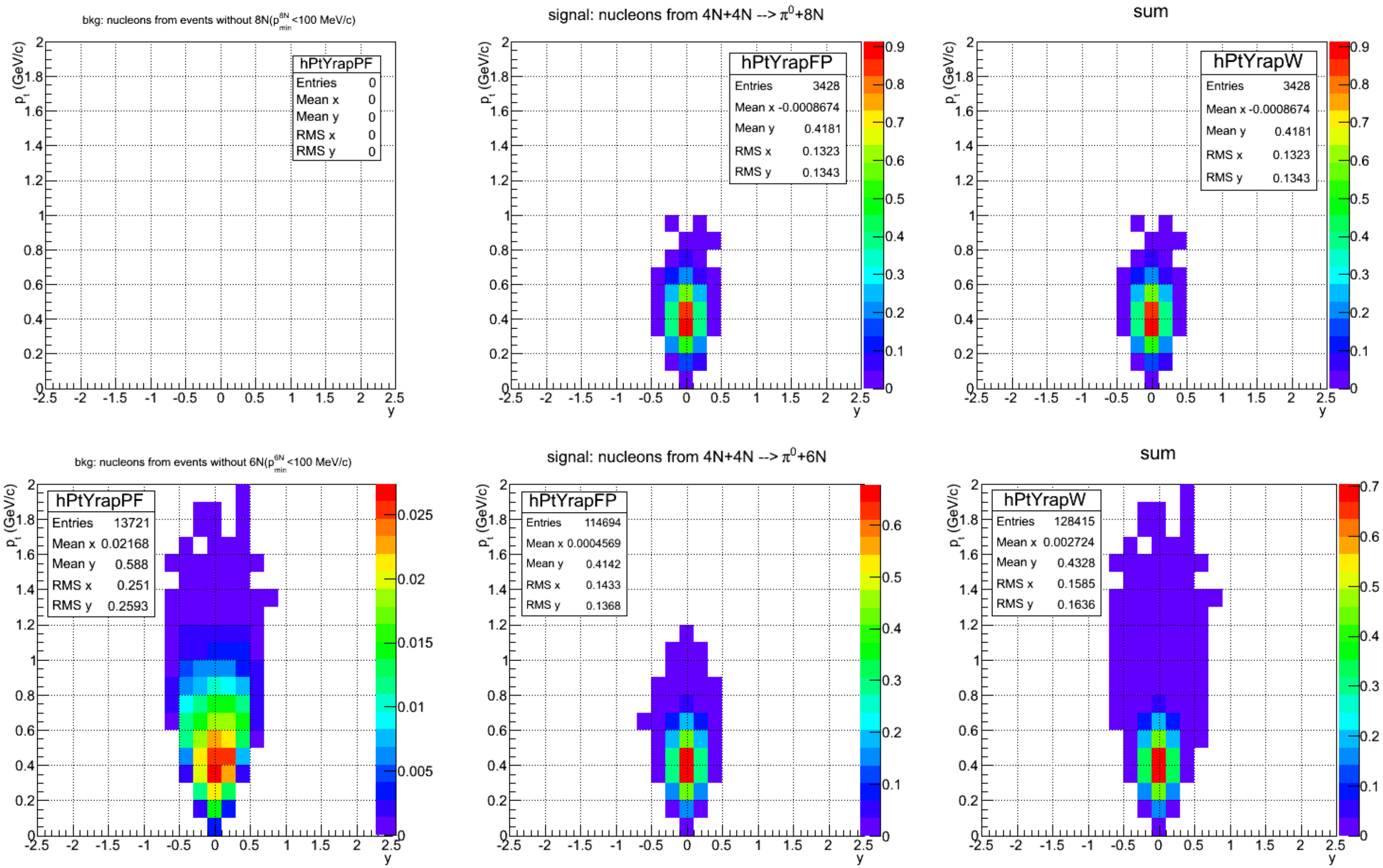
C+Be



Background and signal 4N+4N

^{4}He+^{4}He

C+Be



reminder: for 3N + 3N

select the 'signal area':

$y = 0 \pm 0.3$,

$p_t = 0.4 \pm 0.2$ GeV/c

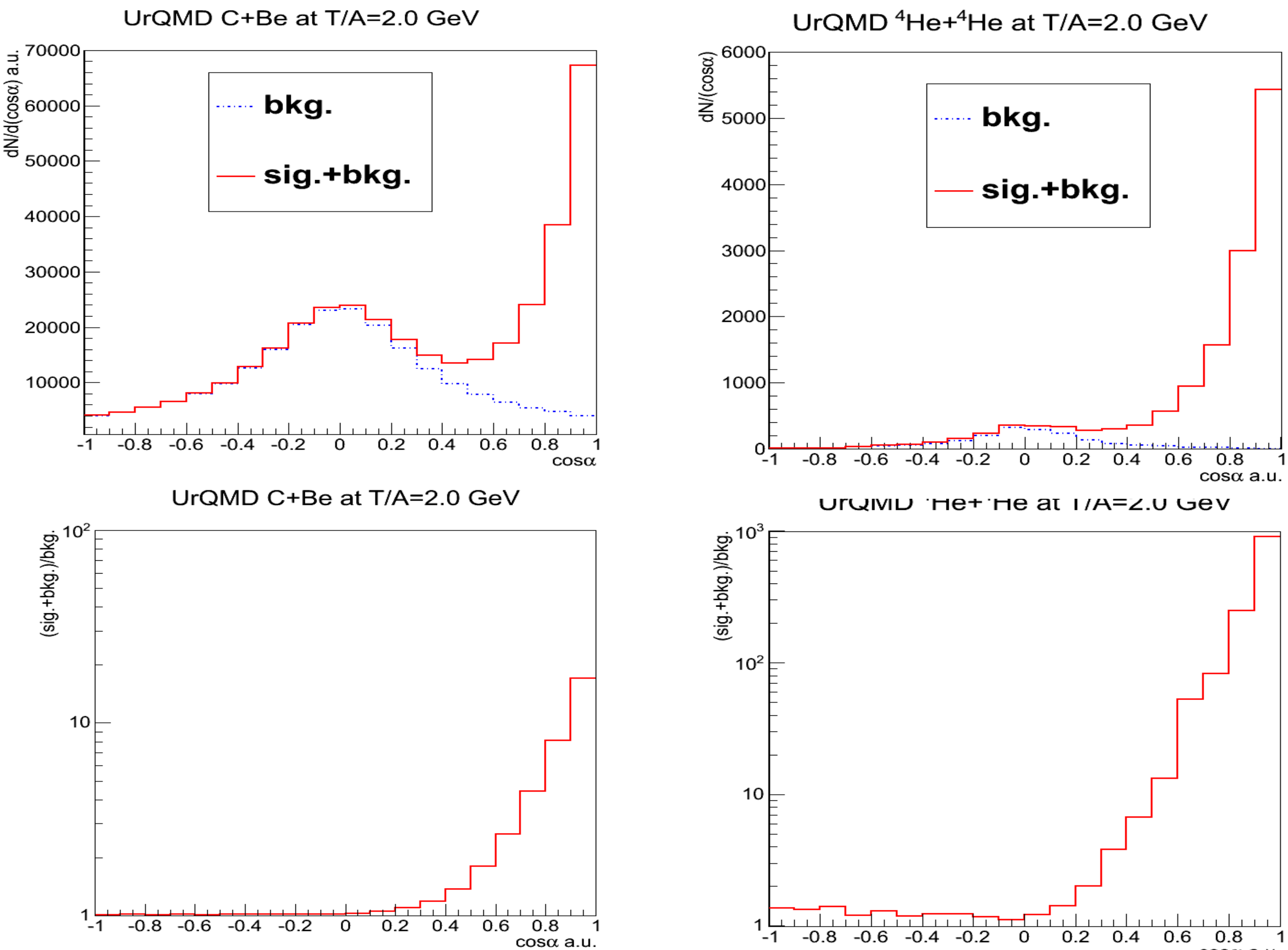
system	$<N_{sig}>/<N_{bkg}>$
^{4}He+^{4}He	5.33/0 = ∞
C+B	5.25/0.22 = 24

system	$<N_{sig}>/<N_{bkg}>$
^{4}He+^{4}He	4.043/0.0077 = 525
C+B	4.56/0.75 = 6

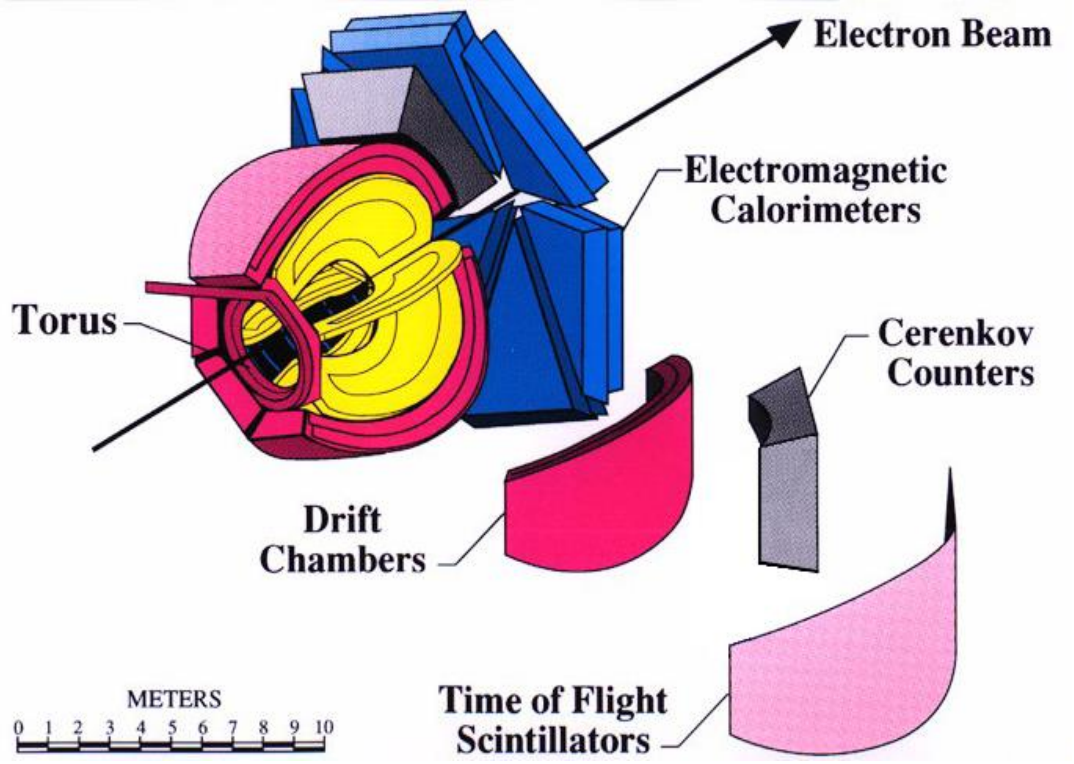
En example:

search for the dense baryonic droplet in correlation measurements with high p_t cumulative trigger

α-angle between trigger particle and baryon (cms);



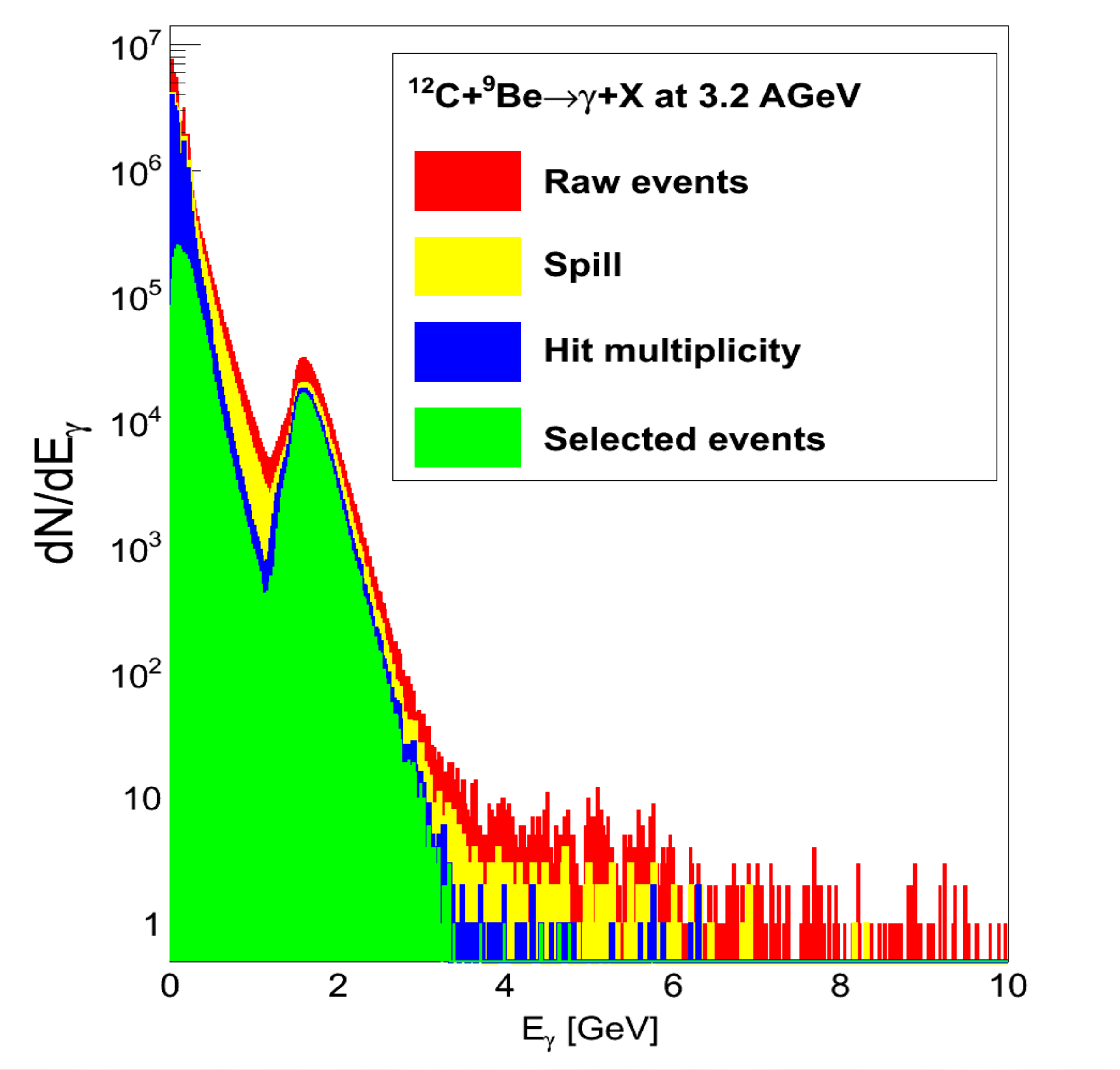
CLAS



Performance

- $L = 10^{34}\ cm^{-2}\ s^{-1}$
- $\int B\,dl = 2.5$ T m
- $\delta p/p \sim 0.5\text{–}1\ \%$
- $\sim 4\pi$ acceptance
- Best suited for multiparticle final states
- Bremsstrahlung Photon Tagger ($\delta E_\gamma/E_\gamma \sim 10^{-3}$)

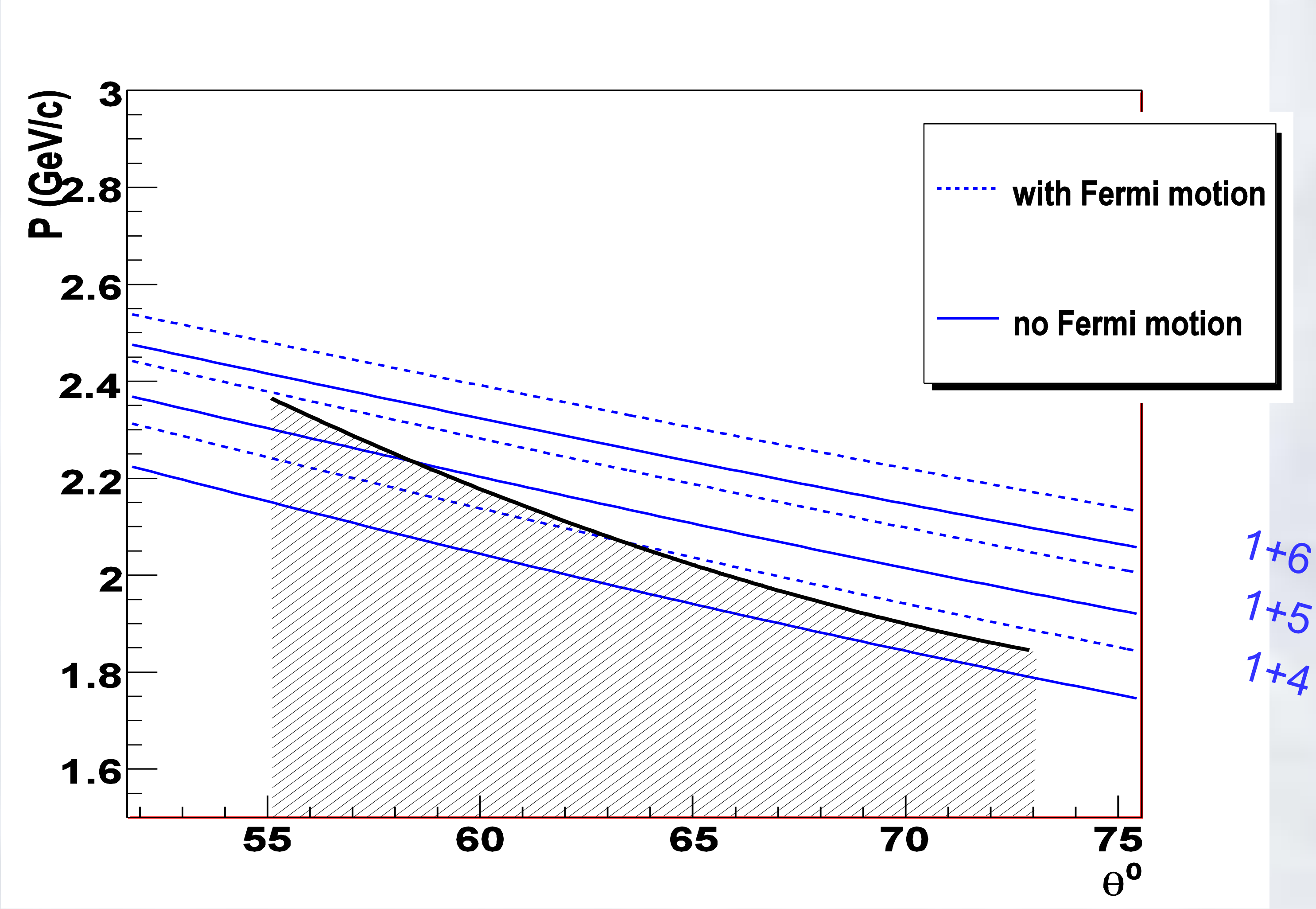
Data quality cuts



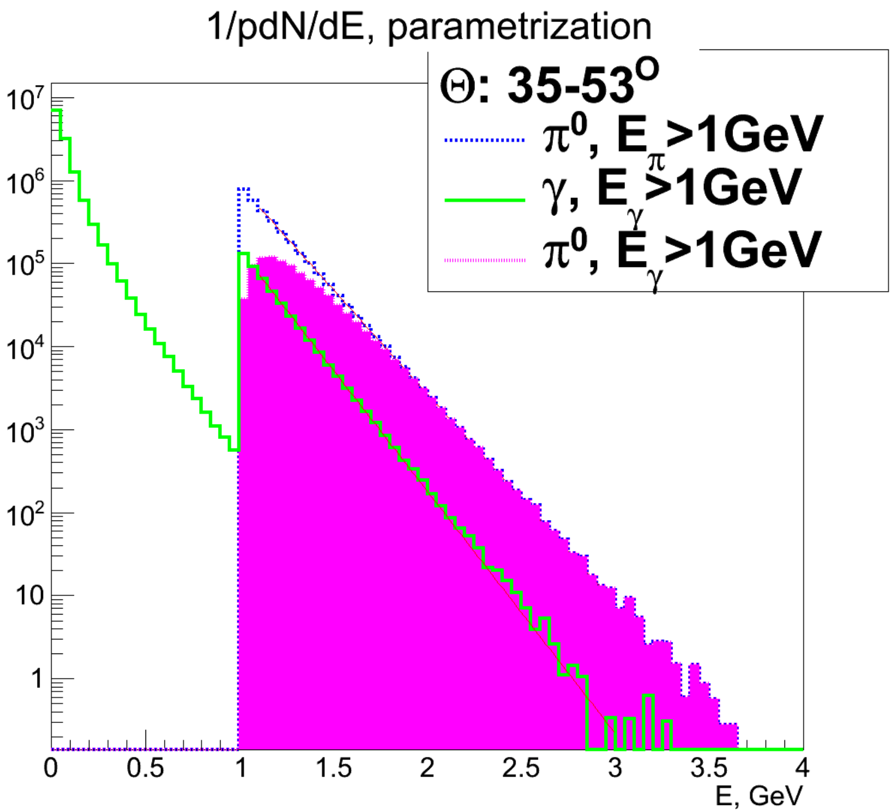
Three groups of cuts:

- Spill
- Hit Multiplicity
- Signal shape

Fermi motion



What is the difference between pion and photon cumulative number?



Using the empirical scaling for the beam energy dependence of the Lorentz-invariant cross sections

$$\sigma_I = E\frac{d^3\sigma}{d^3p} \tag{1}$$

found in [20] and parameterizing the angle dependence one can propose the following laboratory momentum dependence of the cross section for the reaction C+C $\rightarrow \pi X$

$$\sigma_I = Cexp(-\frac{p}{p_o}), \tag{2}$$

where C=3800 (mb GeV^{-2} c sr^{-1}) and

$$p_o = \frac{0.075\gamma}{1-\beta(cos\theta - cos45^0) - cos^2 45^0} \tag{3}$$

with β and γ are the Lorentz transformation factors which define the nucleon-nucleon c.m. frame relative to the laboratory frame and depend on the beam energy.

E_π-E_γ~0.3GeV → Q_π-Q_γ~1

C(2GeV/nucleon)+Be→π^0+X, $\pi^0 \rightarrow \gamma\gamma$

I: $^3He+^3He \rightarrow a+X$, Q1+Q2 ~ 3-4,

Does np-flucton represent dominant contribution into the process?
(Combinatorial factor pp/np=1/2 for ^3He is trivial,
Coulomb corrections for He are small)

$$\frac{^3He+^3He \rightarrow \pi^+ + X}{^3He+^3He \rightarrow \pi^- + X} = 1 \text{ in case of np dominance, and } >1 \text{ for pp contribution}$$

Background measurements: ^4He+d

II: $^3He+^3He \rightarrow a+X$, Q1+Q2→6 , X→6N

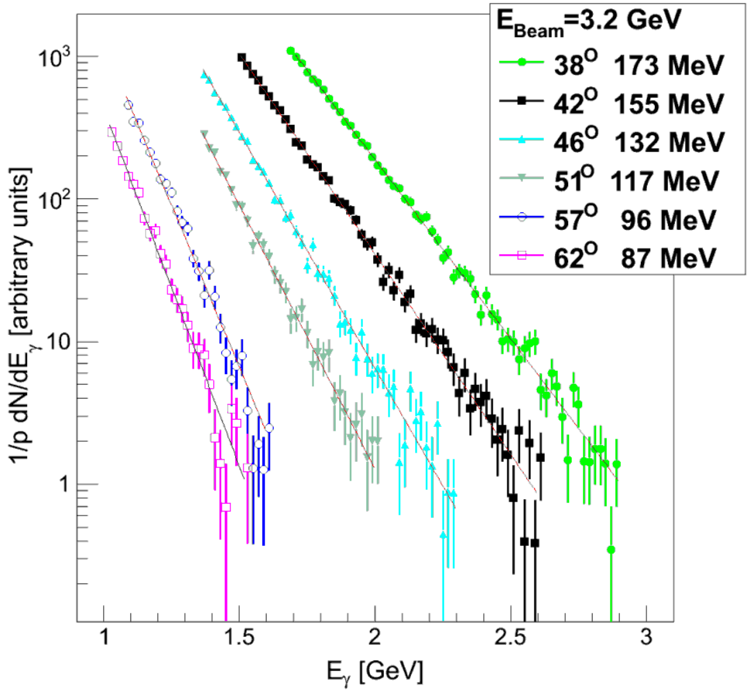
Does dense cold matter is izosymmetrical one?

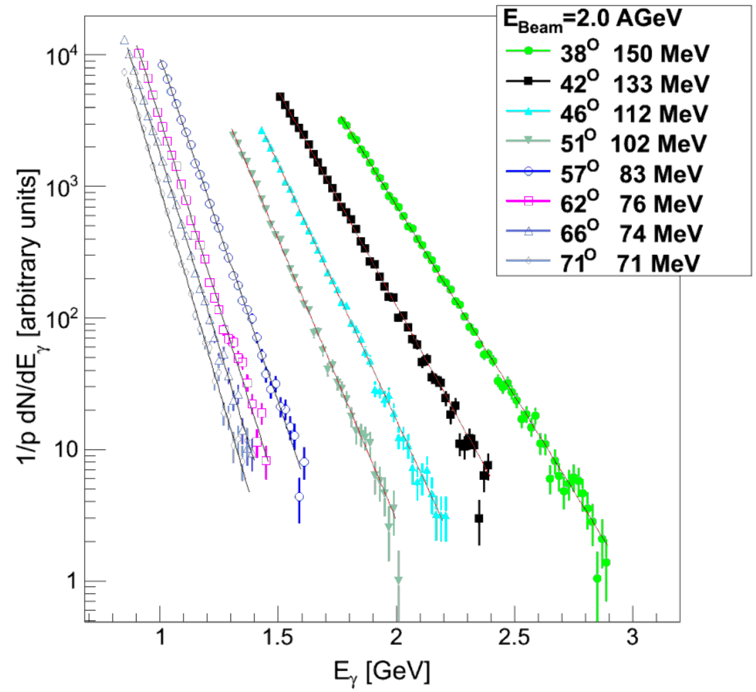
a - π^+ X→pppnnn

a - π^- X→pnnnnn

3. Experimental status

FLINT DATA: Photon spectra CBe→γX





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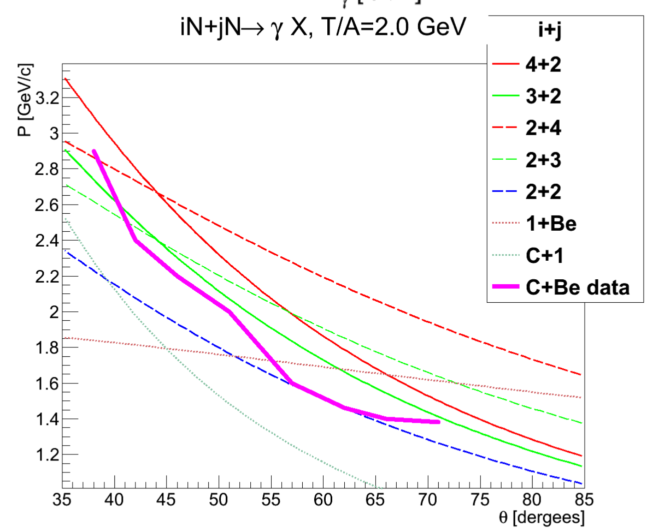
interaction up to 6 nucleons
kinematical
region, which cannot be explained
neither p+Be nor C+p interactions



Six nucleons system: n!n¡p!p¡+??
Does we already see phase transition?

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