Development of experimental research program for multi-quark systems at high p_T on Nuclotron

HighPt@Nuclotron

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Status EOI(expression of interest)

Russia:
Omsk (Omsk State Transport University: Sosnovskiy Yu.M., Kurmanov R.S.)
Omsk (Dostoevsky Omsk State University: Potudanskaya M.G., Strunin V.I.)
Mexico:
Morelia (Michoacan University of San Nicolás de Hidalgo: Diaz A.-R.)
Japan:
Osaka (Research Center for Nuclear Physics, Osaka University**:** Hosaka A.)
China:
Beijing (University of Chinese Academy of Sciences: Olsen S.)
Beijing (Center High Energy Physics, Tsinghua University: Bingsong Z.)

Введение

Создание ускорительной базы ЛФВЭ ОИЯИ:

- 1993*: под руководством акад.* ***А.М. Балдина*** *создан* ***Нуклотрон – первый в мире СП*** *синхротрон тяжелых ионов (****4,5 АГэВ****) на основе передовой технологии* ***«Дубненских» СП магнитов,*** *востребованных как для* ***ускорительных центров,*** *так и для* ***прикладных*** *целей;*

- 2009: *решением* ***КПП ОИЯИ*** *началась реализация проекта* ***NICA – Nucloton based Ion Collider fAcility:***

- 2016: *подписано Соглашение между* ***ОИЯИ и Правительством РФ*** *о создании и эксплуатации* ***Комплекса NICA***

- 2018: Мегасайенс проект **Комплекс NICA** вошел в состав Национального проекта **РФ НАУКА**

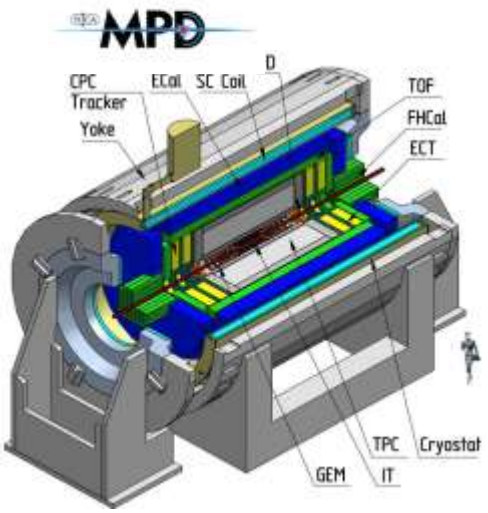
NICA Nuclotron-based Ion Collider fAcility

Экспериментальные установки

*Разработана научная программа **NICA**, нацеленная на исследование: **КХД** диаграммы в мало изученной области **большой барионной плотности**, где **КХД** на решетке не эффективна; **спиновой структуры** нуклонов; а также широкого спектра прикладных работ.*

2018: *Начато формирование международных научных коллабораций*

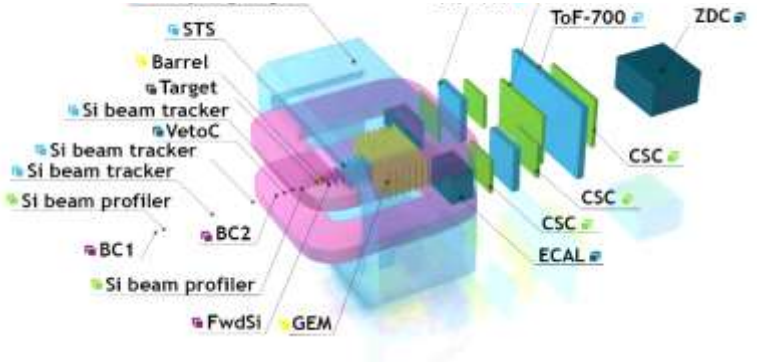
Multi Purpose Detector (MPD) Collaboration:



***12** стран + **ОИЯИ**, **39** центров; **> 500** участников; завершается создание детектора, подготовка к набору данных*

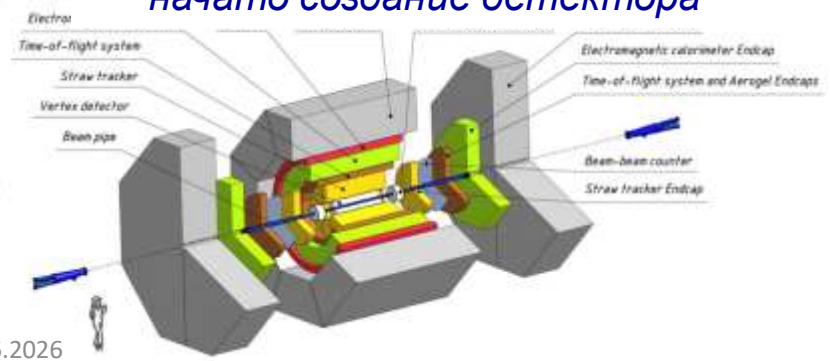
Baryonic Matter at Nuclotron (BM@N) :

***5** стран +**ОИЯИ**, **13** центров, >**220** участников; начаты эксперименты*



Spin Physics Detector (SPD) Collaboration:

***12** стран+**ОИЯИ**, **35** центров, **> 300** участников; начато создание детектора*

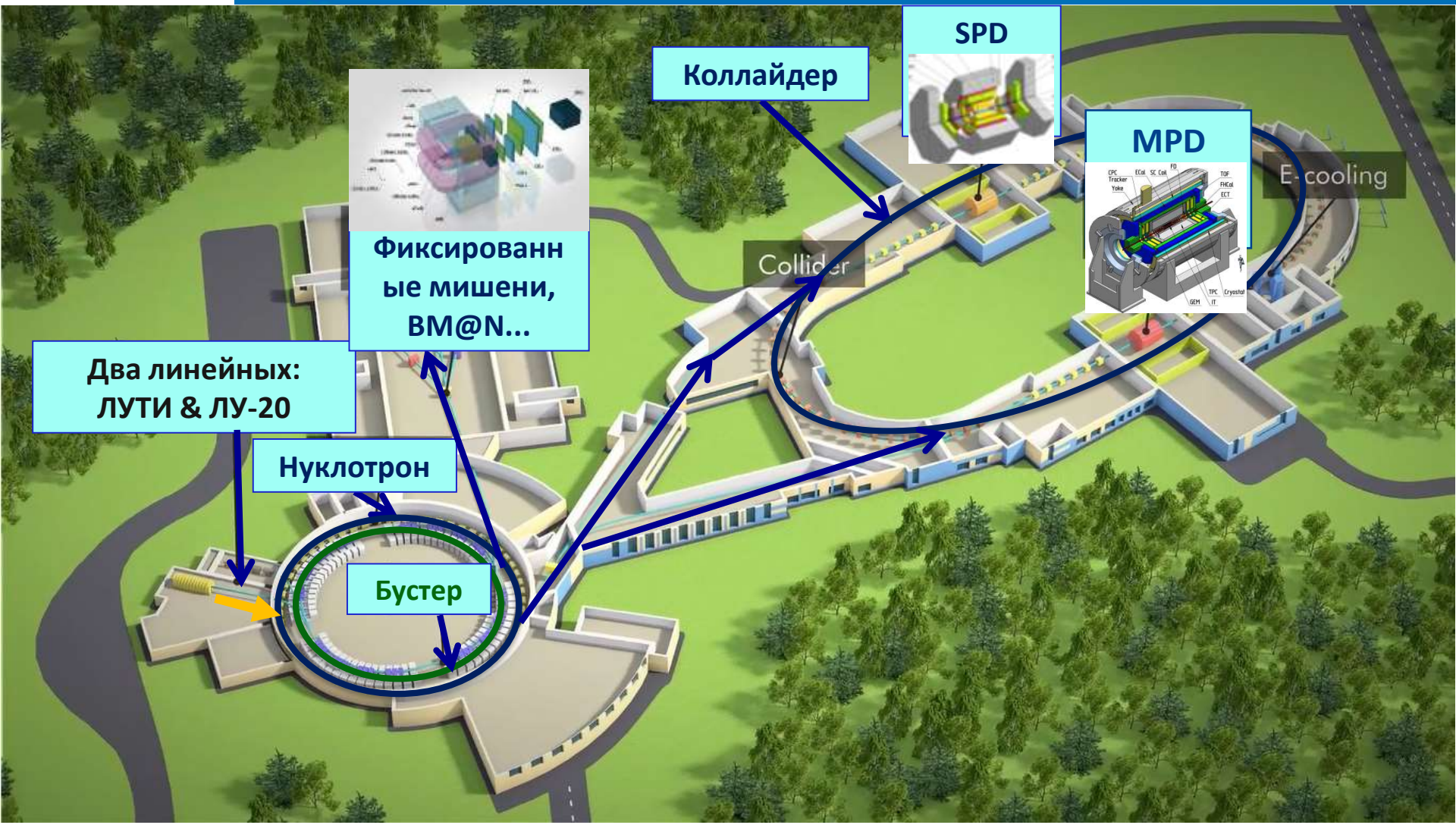


Коллаборация **ARIADNA**

*для прикладных и инновационных работ: **6** стран, **27** центров, > **185** участников; начаты исследования*

Комплекс NICA

Nuclotron-based Ion Collider fAcility



Motivation: Nuclotron is a good choice for rare processes with $p_T > 1$ GeV/c investigations

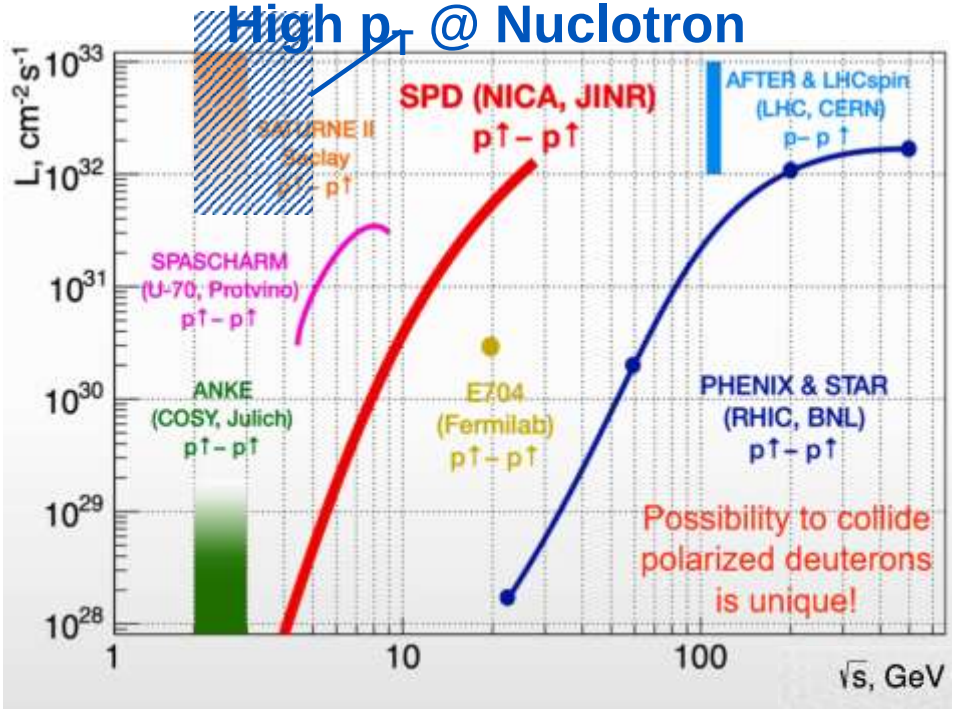
Maximal E_p	12 GeV
Maximal E_A(q/A=0.5)	6 GeV
Intensity (p) per spill 2 sec	up to 10^{10}
Time to fill the NICA rings	0.5 h
Collisions on NICA	3 h
Polarized beams	p↑, d↑, ^{3}He↑

Between NICA cycles Nuclotron will give beams to fixed target experiments

+ Polarized and cryogenic targets

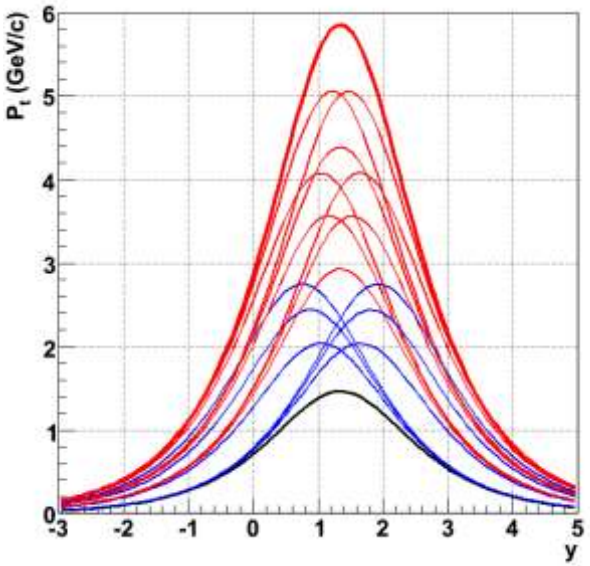
MPD + BM@N

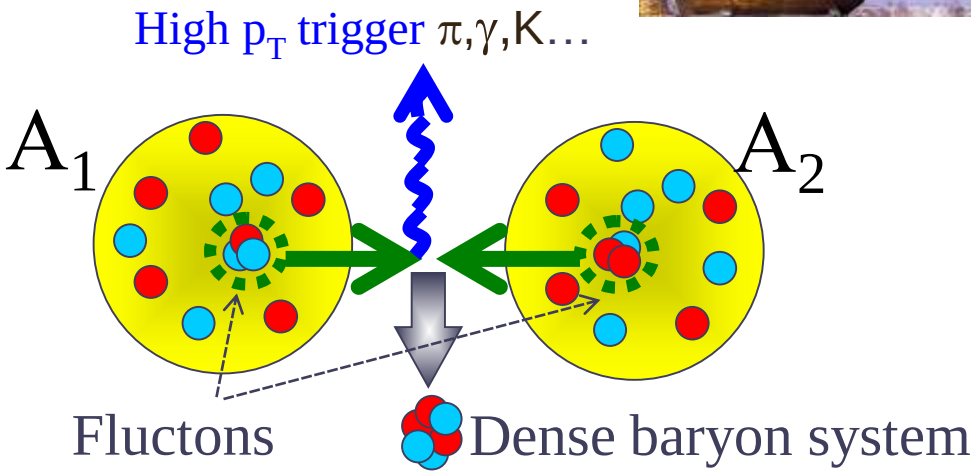
SPD + ? (High p_T @ Nuclotron)



Why high p_t?

Scheme of A_1+A_2 process, A_i: d(up to 2N+2N),He,C,...



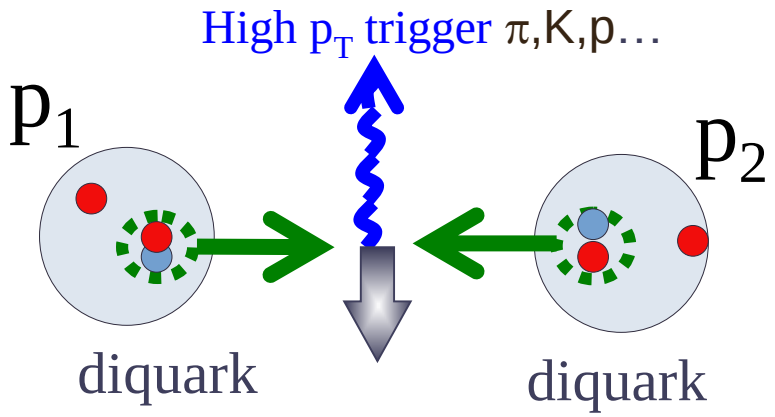


Trigger particle kinematical limits for different subprocesses: 1N+1N(black line)
1N+Flucton(2N,3N,4N)&Flucton+1N(blue lines)
Flucton+Flucton(red lines)
(6AGeV fixed target)

$p_t(max)(iN+iN)\sim ip_t(max)(N+N)$

Why high p_t?

Scheme of p_1+p_2 process



The same logic for PP:
p_t(max)(diquark+diquark)>p_t(max)(quark+quark)

Diquarks

Anomaly at p_T=2 GeV/C seen in p/π also

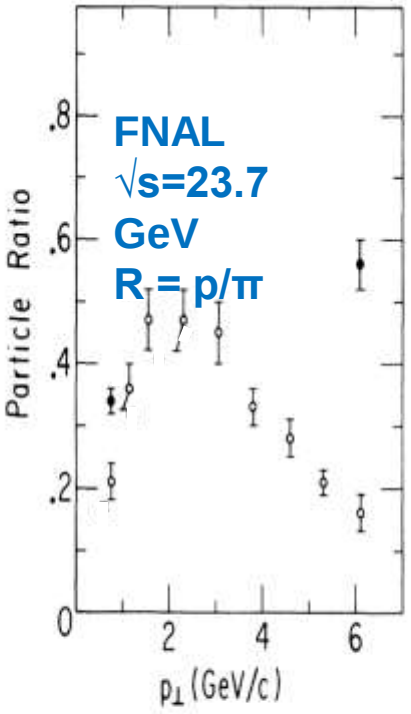
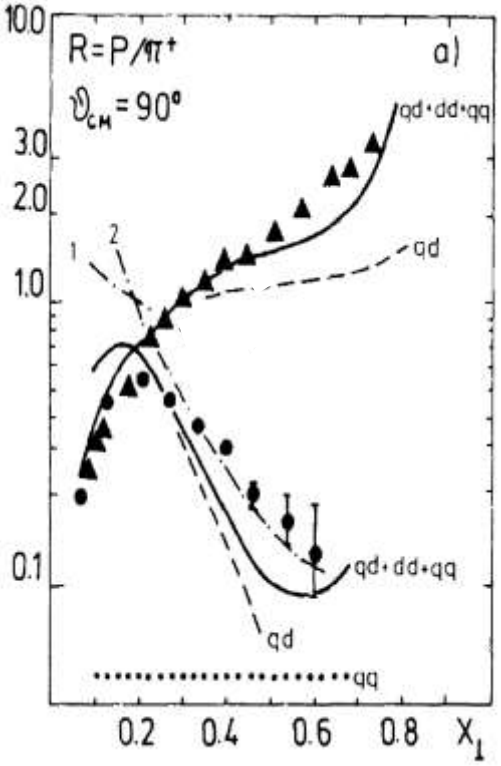


FIG. 20. Comparison of the cross-section ratio p/π^+ measured on tungsten at $\sqrt{s}$ =23.7 GeV (closed circles), with that obtained by extrapolation to A =1 (open circles). Ratios obtained from the British-Scandinavian collaboration (Ref. 23) at $\sqrt{s}$ =23.4 GeV are also plotted (closed squares).

FNAL Cronin et. Al. Phys Rev d11 (1975) 3105

Description of this anomaly using diquarks



V.T. Kim "Diquarks and dynamics of large-pT baryon production"

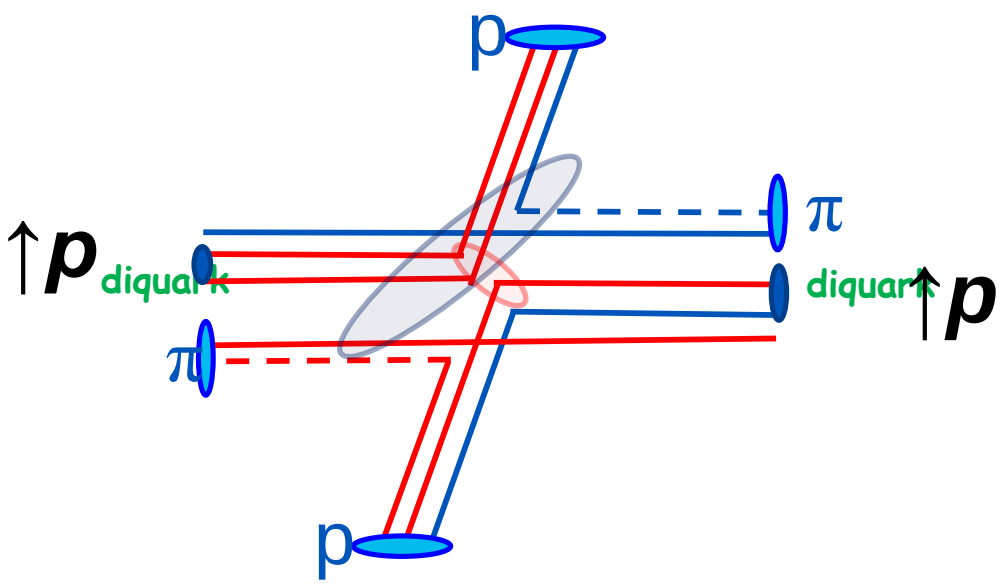
$x_\perp = 2p_\perp/\sqrt{s}$.

V.T. Kim Mod. Phys Lett A 3 9 (1988) 909

Measurements of A_{nn} in pp, πp and ππ scatterings would give indication on diquark spin

Hip$_T$aN

Exclusive reactions at high p_T



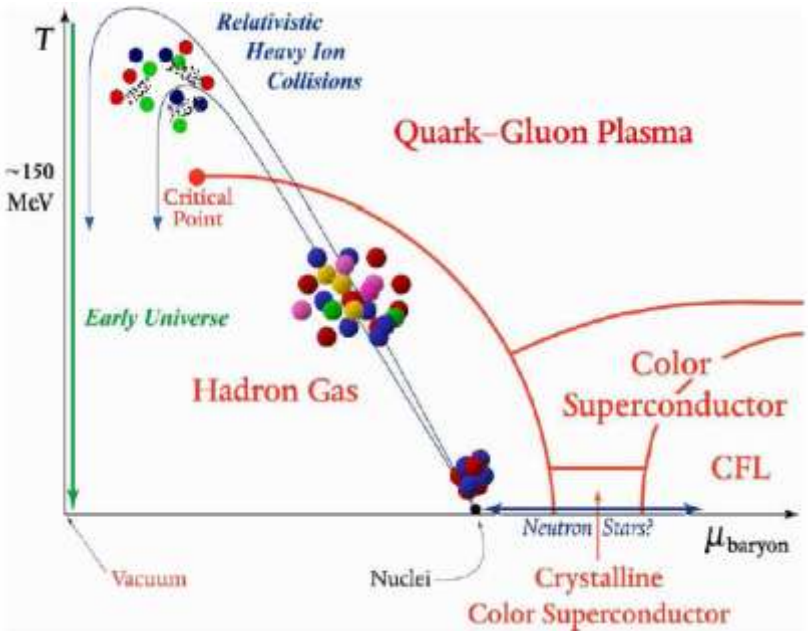
$A_{n(pp)} \to 0$ Diquark (S=0)

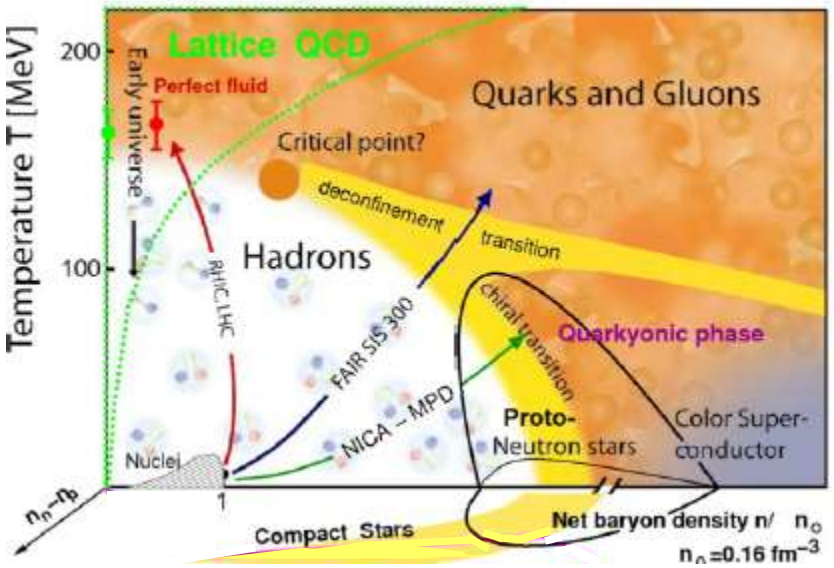
$A_{nn(pp)} \neq 0 \rightarrow$ dd (S_d=1)

$A_{nn(\pi p)} \neq 0 \rightarrow$ qd (S_d=1)

$A_{nn(\pi\pi)} \neq 0 \rightarrow$ qq

Phase diagram of nuclear matter

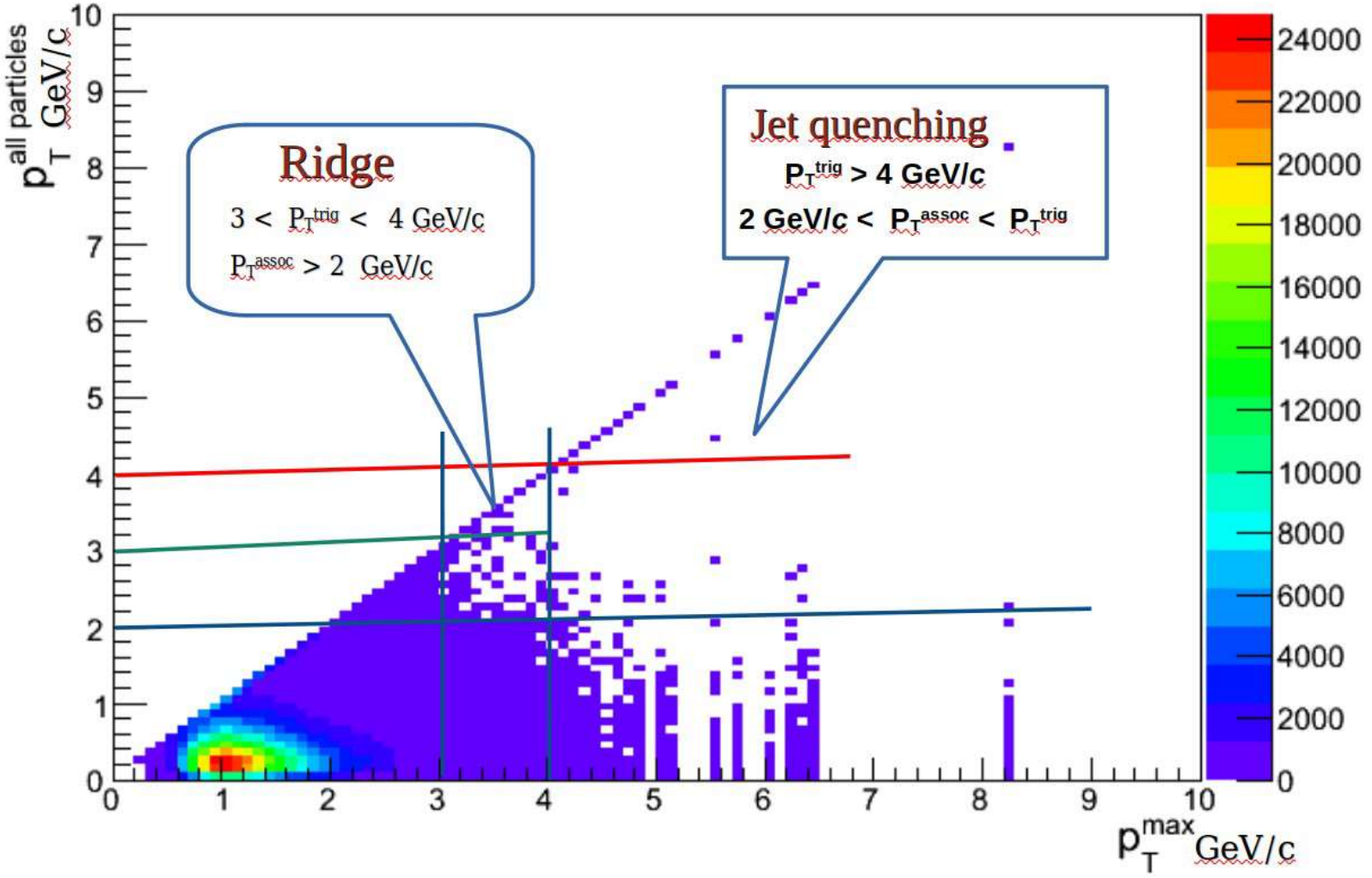




*ρ/ρ_0»1, T/T_0«1(DenseColdMatter): rich structure of the QCD phase diagram - new phenomena are expected!

**Diagram study not finished-additional new phenomena can be found

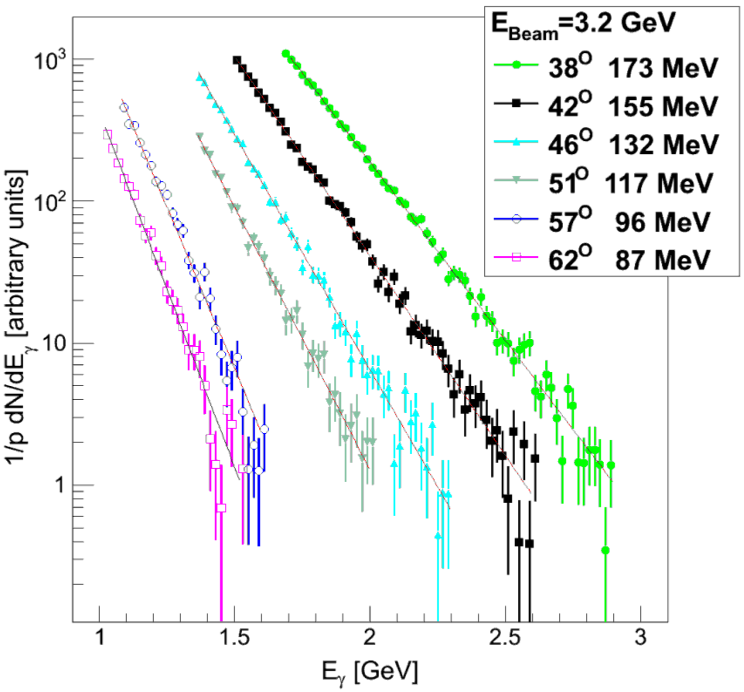
See, for example L.McLerran, “Happy Island”, arXiv:1105.4103 [hep-ph] and ref. therein.

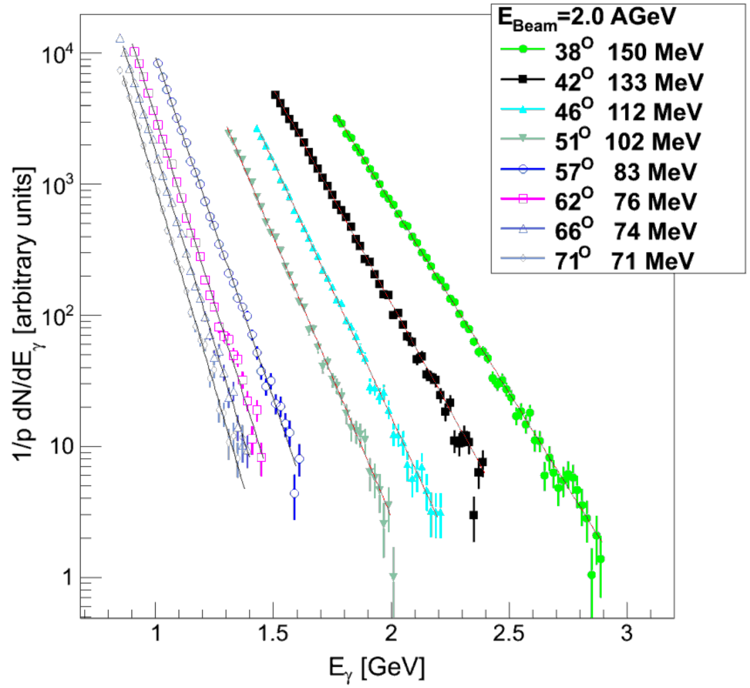


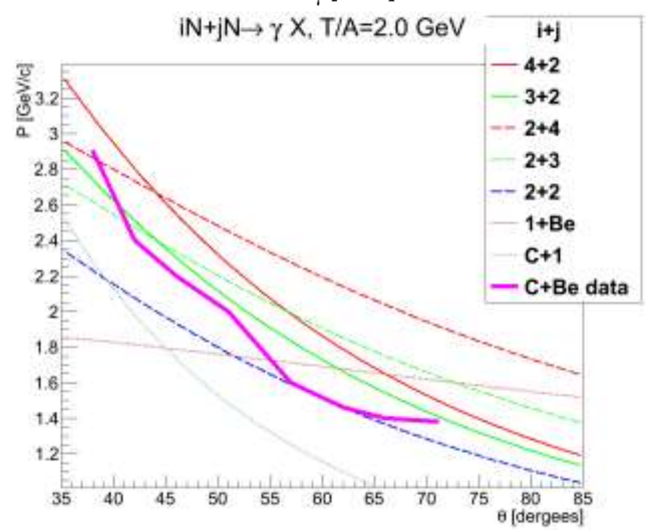
STAR AuAu $\sqrt{s_{NN}}$=200 GeV;
O.Rogachevsky, VBLPHE-seminar,08.04.2026

Why Nuclotron?

FLINT DATA: Photon spectra CBe→γX







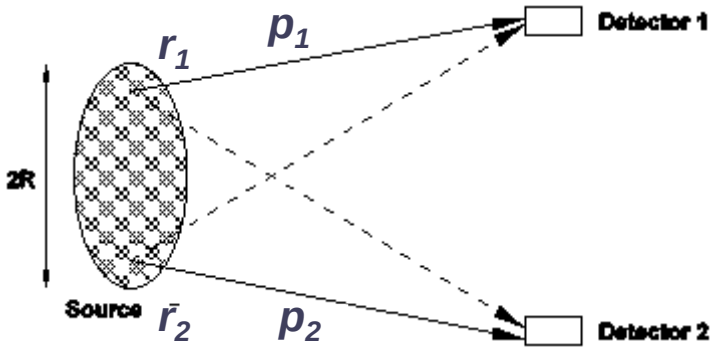
FLINT have got data for flucton-flucton interaction up to 6 nucleons kinematical region, which cannot be explained neither p+Be nor C+p interactions

Six nucleons system: n!n¡p!p¡+??

Does we already see phase transition?

Femtoscopy

Bose-Einstein statistics of identical bosons leads to short-range correlations in momentum space

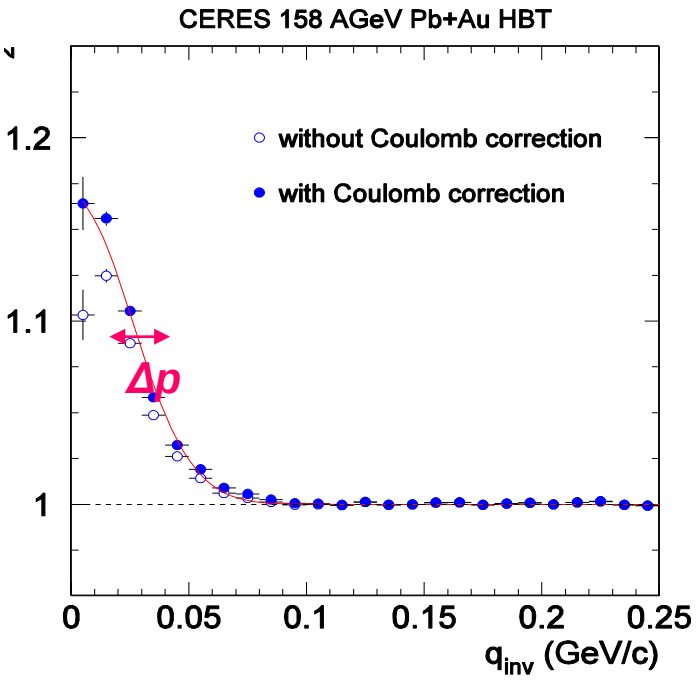


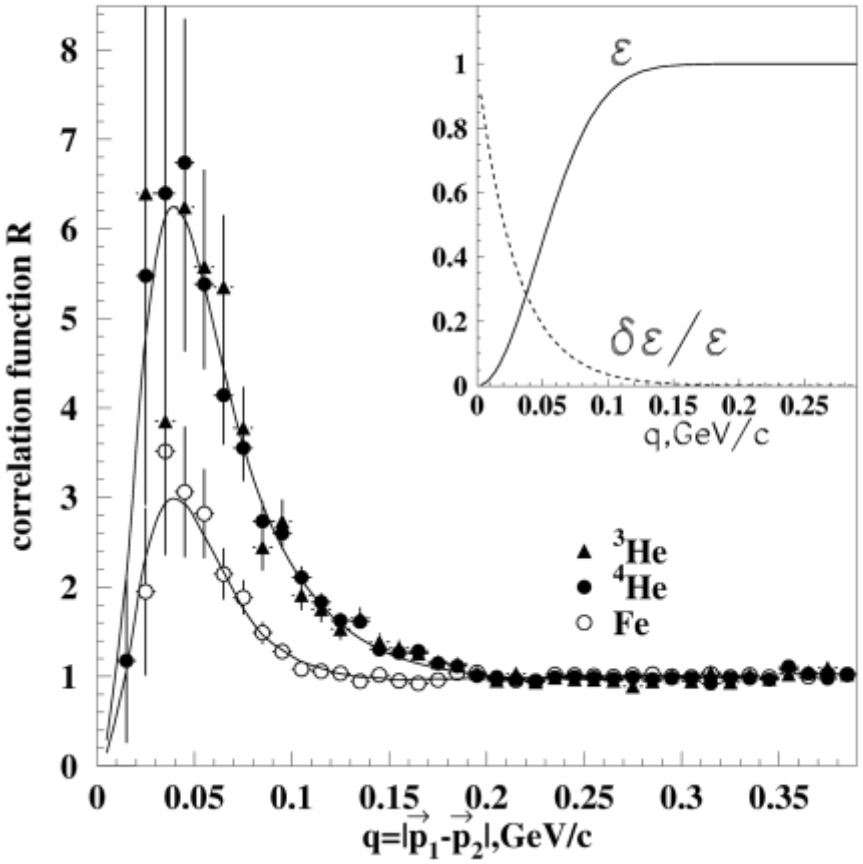
$$R\ (\vec{p}_1, \vec{p}_2) = \frac{P_2(\vec{p}_1, \vec{p}_2)}{P_1(\vec{p}_1) \cdot P_1(\vec{p}_2)}$$

First application with photons: size of stars (R. Hanbury-Brown, R.Q. Twiss, 1956)

In heavy-ion reactions: pions, kaons, protons(Interferometry+strong FSI+Coulomb)…

$$\Delta r = \frac{\hbar c}{\Delta p} = \frac{197\ \text{MeV/c}}{\Delta p}\ \text{fm}$$



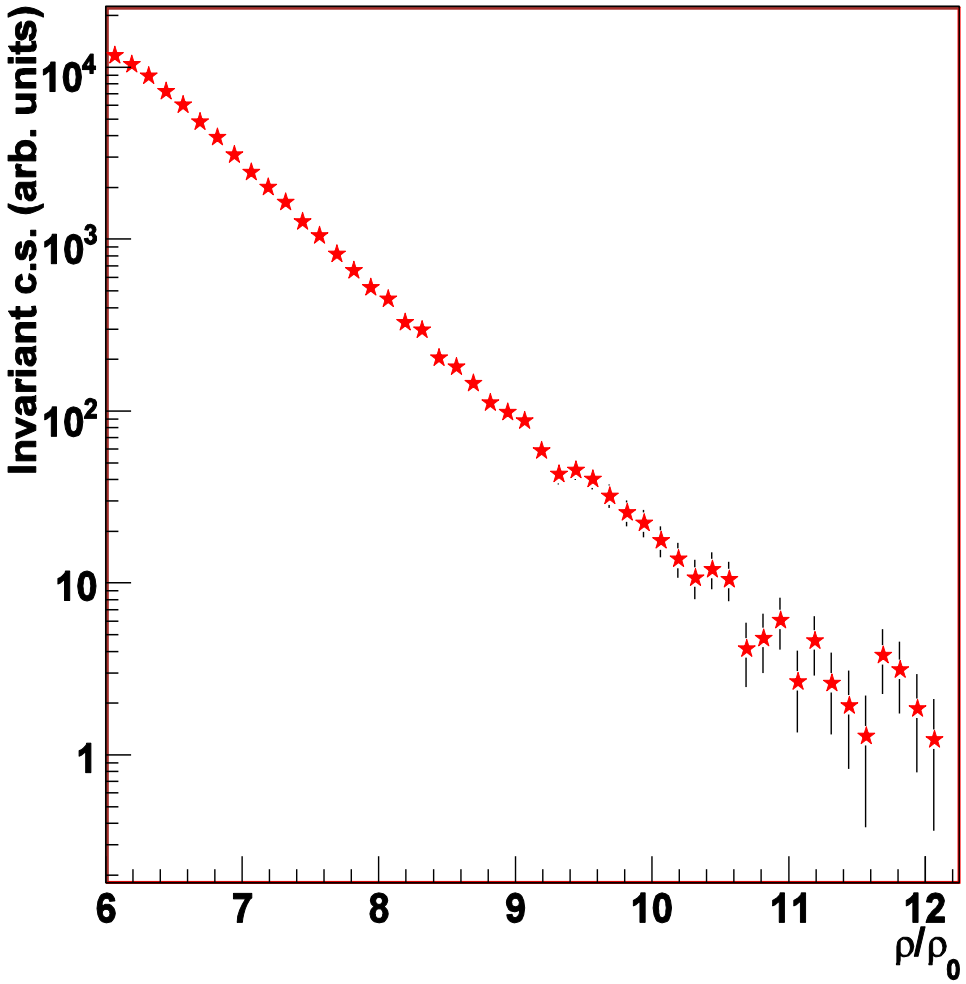


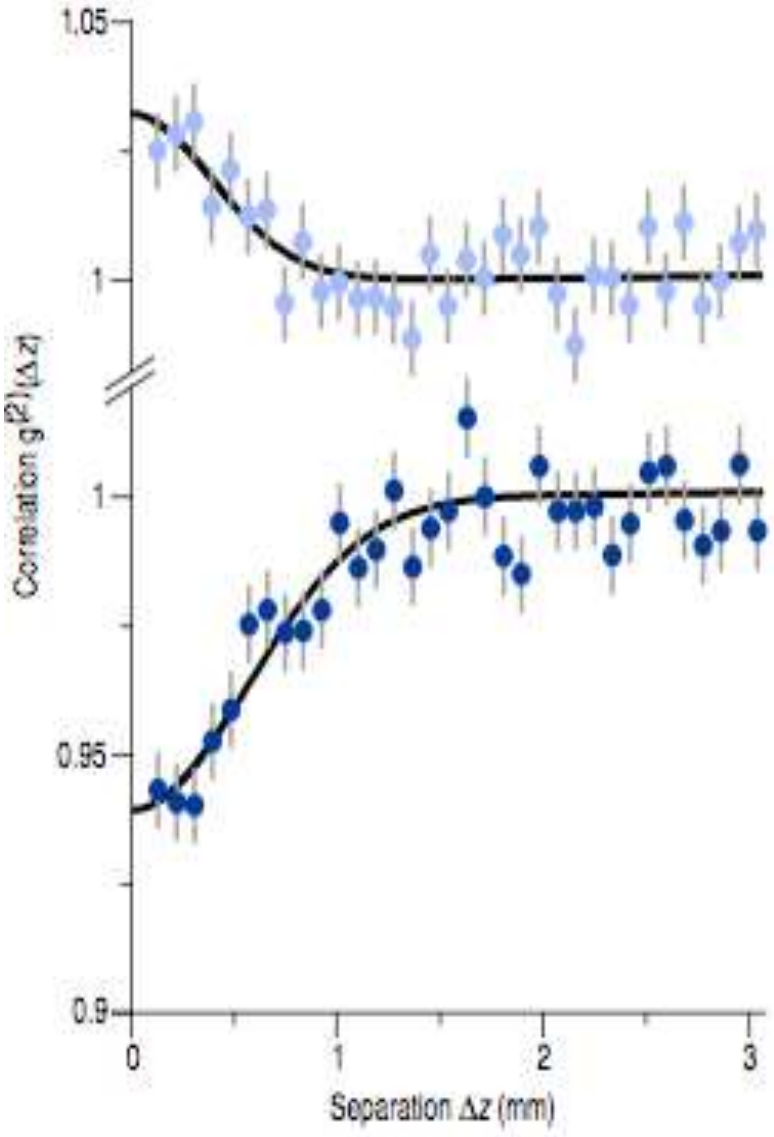
r_f~1-1.5fm

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

An estimate of baryon density

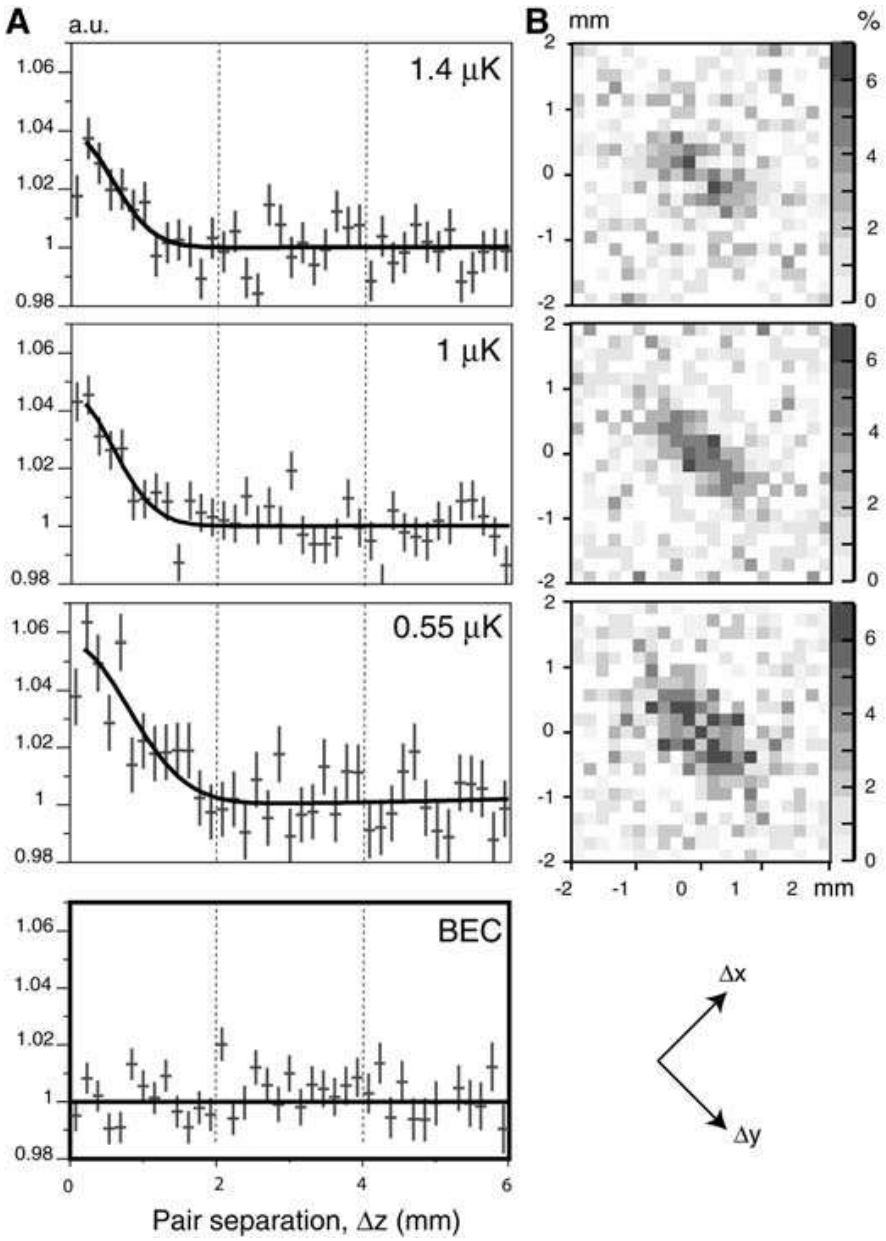
r_f~1.5fm





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)



Hanbury Brown Twiss Effect for Ultracold Quantum Gases

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

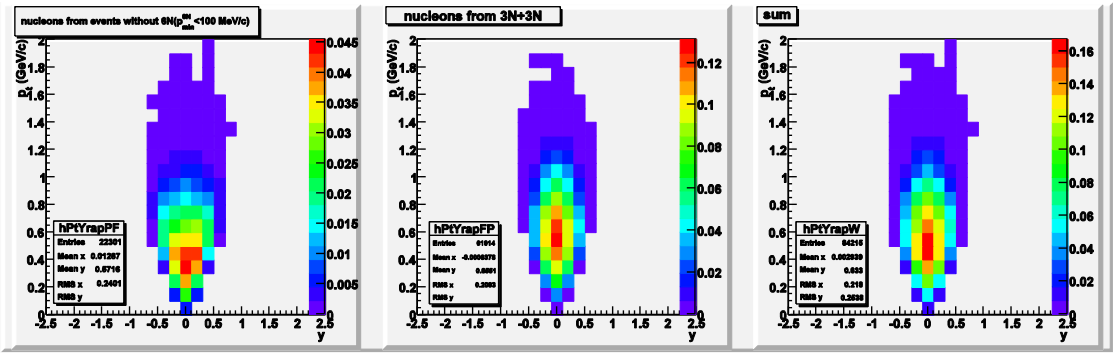
We have studied two-body correlations of atoms in an expanding cloud above and below the Bose-Einstein condensation threshold. The observed correlation function for a thermal cloud shows a bunching behavior, whereas the correlation is flat for a coherent sample. These quantum correlations are the atomic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

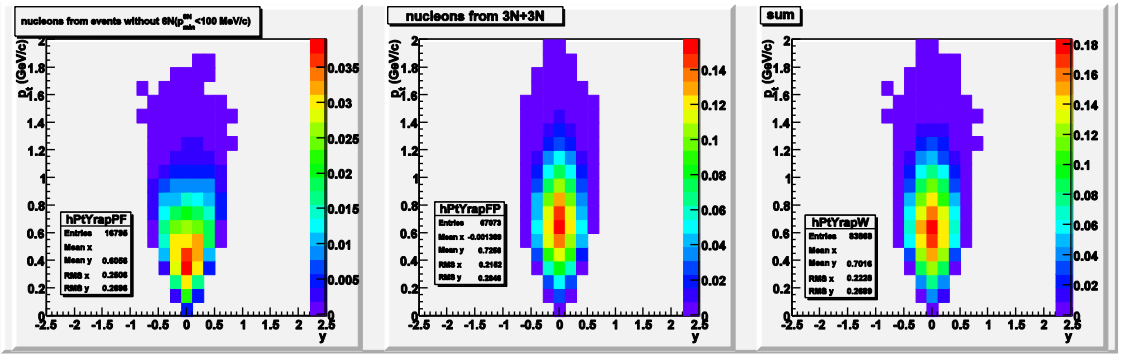
Science,v.310,p.648(2005)

Background and signal, σ_{smear}= 340 MeV/c

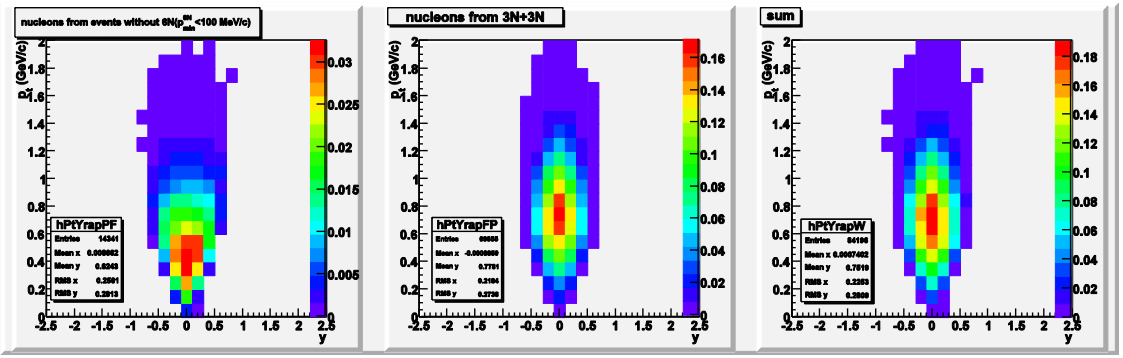
T/A=2.0



T/A=3.2



T/A=4.0



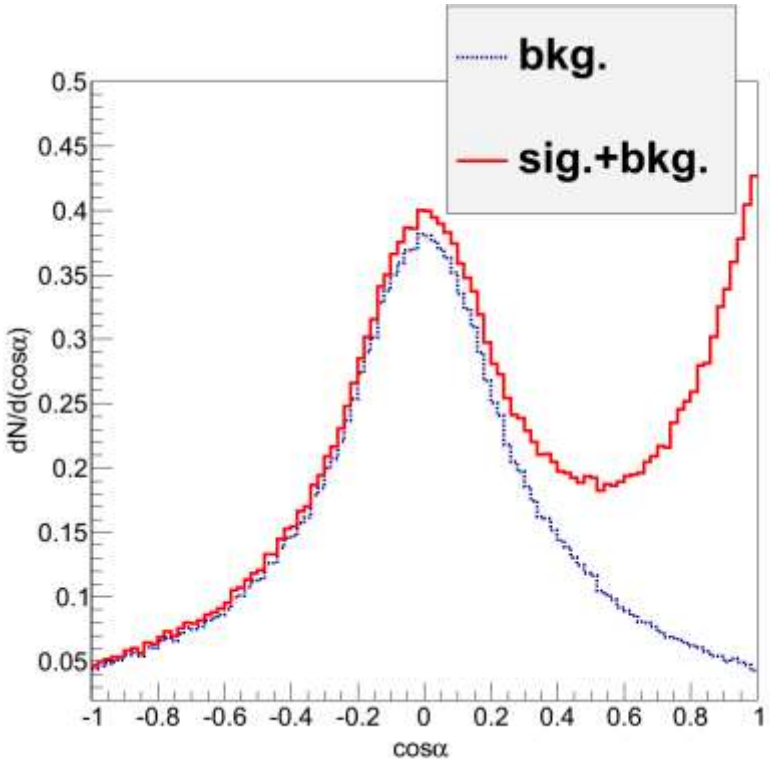
An idea to estimate the background:

- select UrQMD events with the number of nucleon-participants, $N_{prod} \geq 6$
- among N_{prod} find 6N with minimal momentum, p_{min}
- select events with $p^{6N}_{min} < p_{cut}$ (=100 MeV/c)
- remove this 6N from each event, rest nucleons - background
- add the π^0+6N system, these 6N – signal
- momentum of a nucleon from the signal is smearing with a parameter σ_{smear}=340 MeV/c ($\sigma_x=\sigma_y=\sigma_z=\sigma_{smear}$.).

Results: in the region of maximum

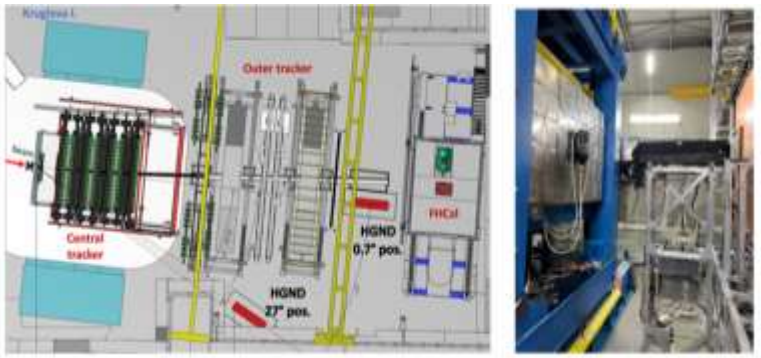
T/A (GeV)	S/B
2.0	~ 0.12/0.045 = 2.7
3.2	~ 0.14/0.035 = 4
4.0	~ 0.18/0.03 = 6

Background and signal, σ_{smear}= 340 MeV/c (continued)



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

URQMD CC, 10^5ev	2 AGeV/c	3AGeV/c	4AGeV/c
P	271 961	266 605	266 161
N	271 720	266 368	266 624
π^0	43 878	64 268	85 051
π^+	37 929	55 837	74 365
π^-	37 969	55 702	74 208
K^0	230	1 121	2 398
K^+	235	1 110	2 304
Λ	225	951	1 922
Σ^0	86	468	927
Σ^+	66	372	788
Σ^-	83	362	785
antiK^0	2	45	130
K^-	3	33	130



HGND prototype on BM@N experiment

Highly granulated neutron detector HGND

- allows to measure neutrons in the range ~0.3 – 3 GeV
- Opens possibility to measure Σ+-

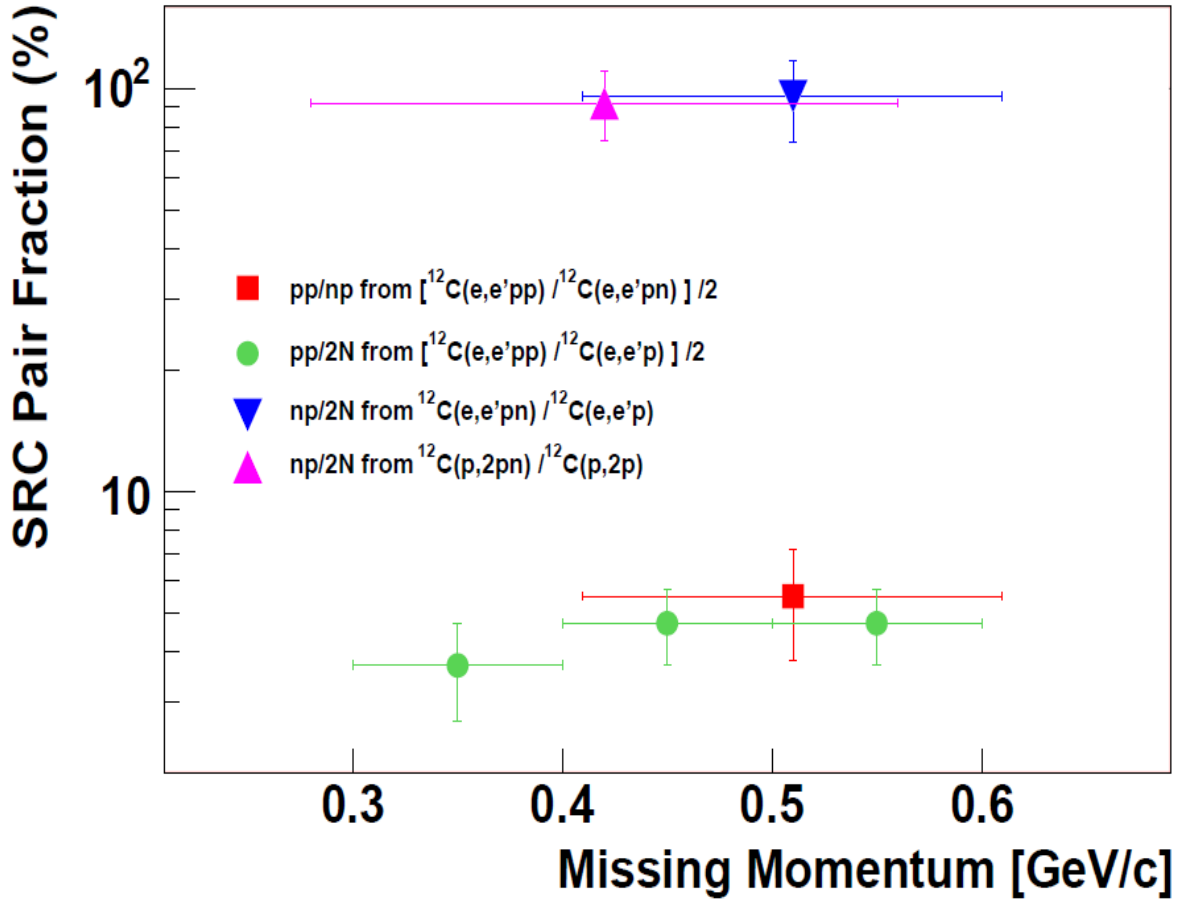
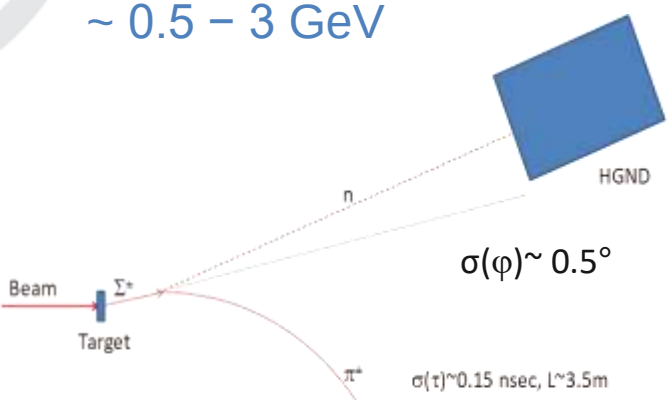


Figure 2: The fractions of correlated pair combinations in carbon as obtained from the (e,e'pp) and (e,e'pn) reactions, as well as from previous (p,2pn) data. The results and references are listed in Table 1.

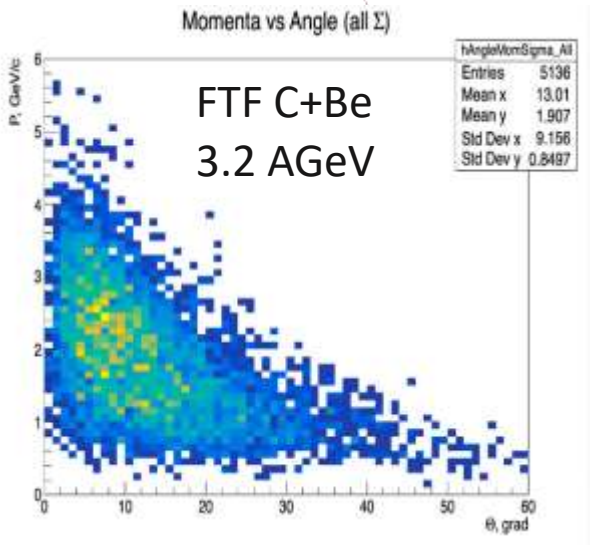
R. Subedi et al., Probing Cold Dense Nuclear Matter, arXiv:0908.1514v1 [nucl-ex] 11 Aug 2009{http://arxiv.org/abs/0908.1514v1}.

Neutron detector is important not only for neutron registration, but also for hyperons

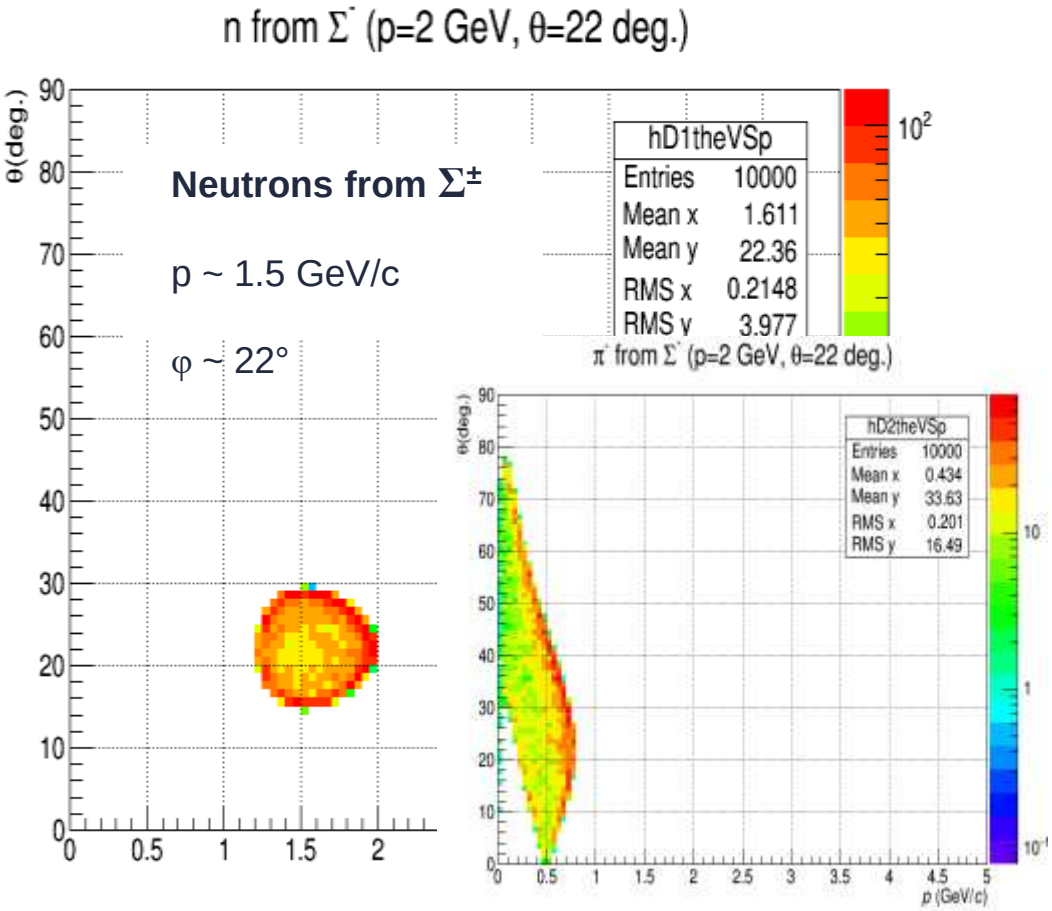
E_{kin} of neutrons @ midrapidities is
~ 0.5 – 3 GeV



σ(φ)~ 0.5°



FTF C+Be
3.2 AGeV



Neutrons from $\Sigma^{\pm}$

p ~ 1.5 GeV/c

φ ~ 22°

Ratio Σ^+/Σ^-

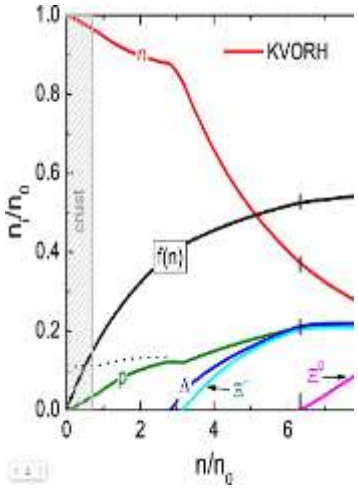
Systematics in Σ^+/Σ^- can be minimized by reversing the magnet

Strangeness in dense nuclear matter and neutron stars

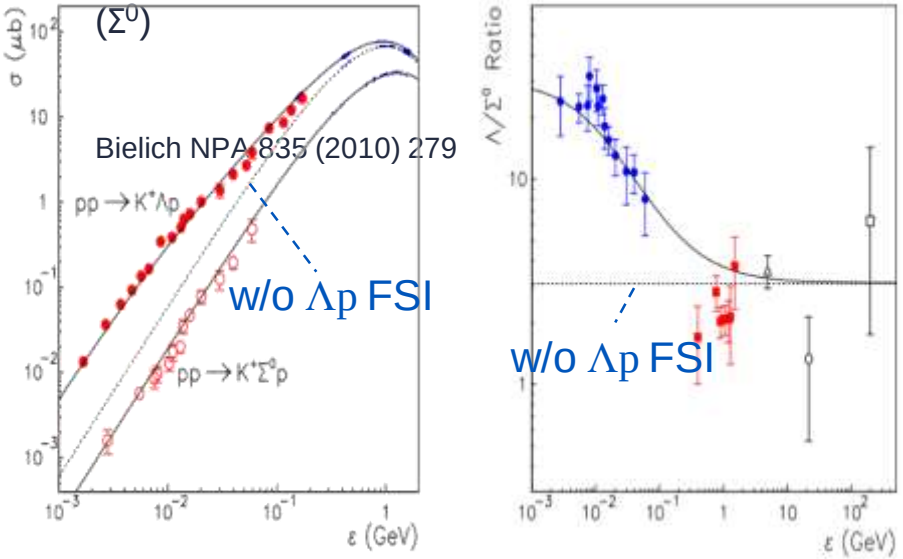
With the increase of density in nuclear stars, the role of Pauli blocking increases

Way out 1* : production of Σ^- (also for compensation of p^+ electrical charge)

Way out 2 : (with furthe ion of Λ: $n \rightarrow \Lambda^0$ (Σ^0)



K.A. Maslov , E.E. Kolomeitsev, D.N. Voskresensky PL B748 2015 369



Bielich NPA 835 (2010) 279

A. Sibirtsev et.al. Eur. Phys. J. A 29, 363–367 (2006)

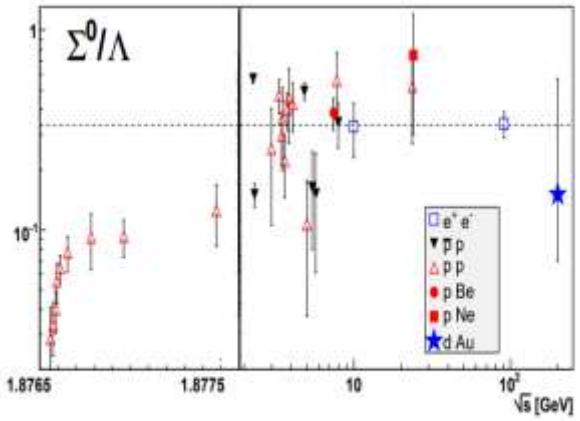


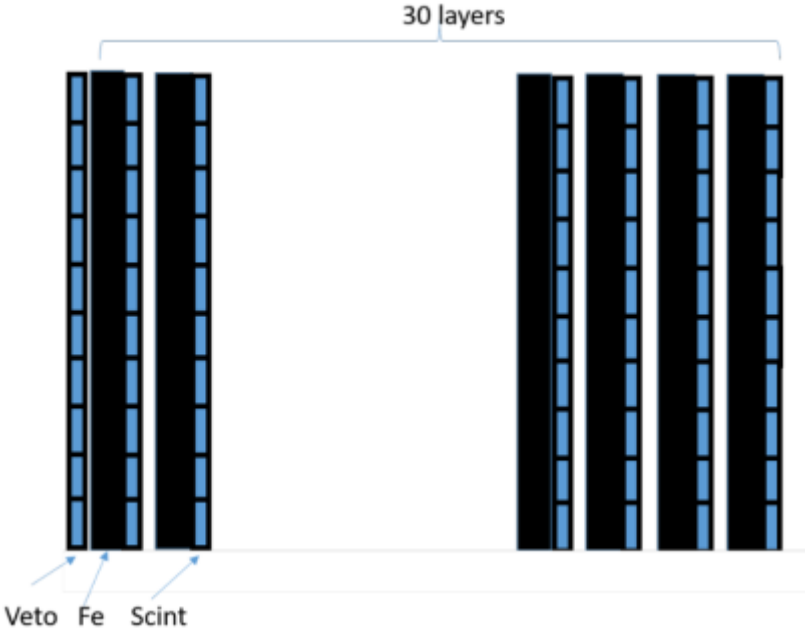
Figure 4: Σ^0/Λ results versus collision $\sqrt{s}$ ($\sqrt{s_{NN}}$ for p/d+A) [1]. Meson-nucleon reaction results are excluded for clarity, but exist only at intermediate energies and lie in the same range. The dashed line is the ratio of isospin degeneracy factors (1/3).

FSI depend on interaction point sizes (~$1/r^2$)

Λ/Σ (E→0) = 30, but Λ/Σ (E >> 0) = 3 for pp.

Lack of data for AA

G. Van Buren (for the STAR Collaboration) arXiv:nucl-ex/0512018

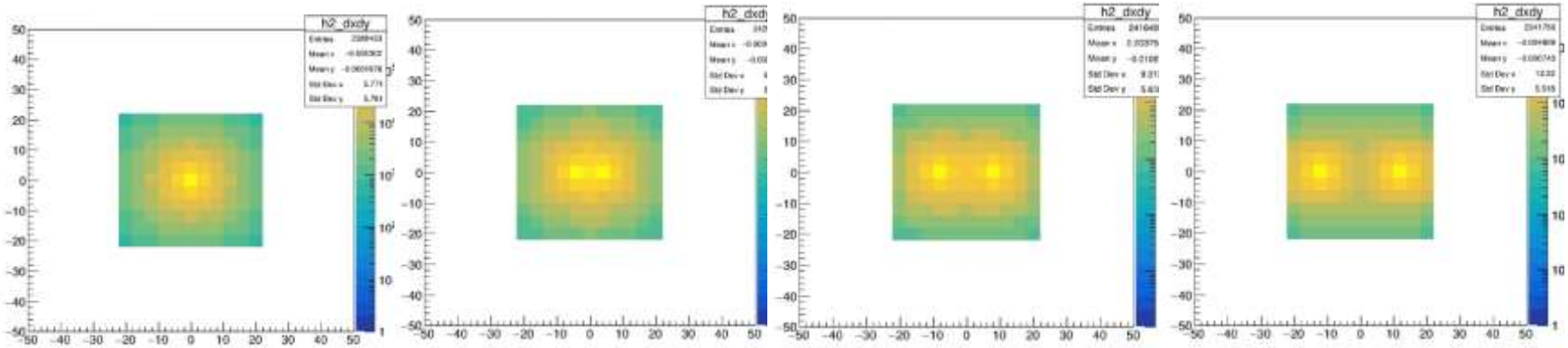


Simulated structure of HighGranularityNeutronDetector:

Structure of Scint. layer:
array of 11x11 scintillator cells 4 x 4 cm2

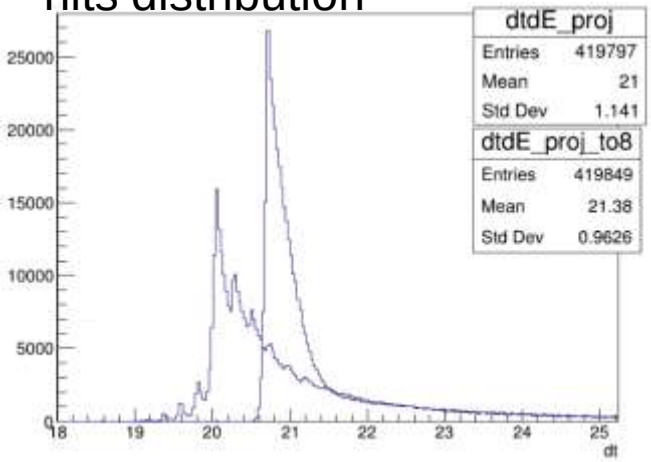
- Transverse size of one layer: 44 x 44 cm2,
- number of layers: – 15 + Veto,
- structure of layer: 3 cm Cu (absorber) + 2.5cm Scint. + 0.5cm (SiPM+FEE)
- size of scintillation detectors (cells): 4x4x2.5 cm3, total number of cells: 1936
- light readout: one SiPM with sensitive are 6 x 6 mm2 per cell
- total length of the HGN: ~ 95 cm (~3 λin)

BOX-generator for simulations



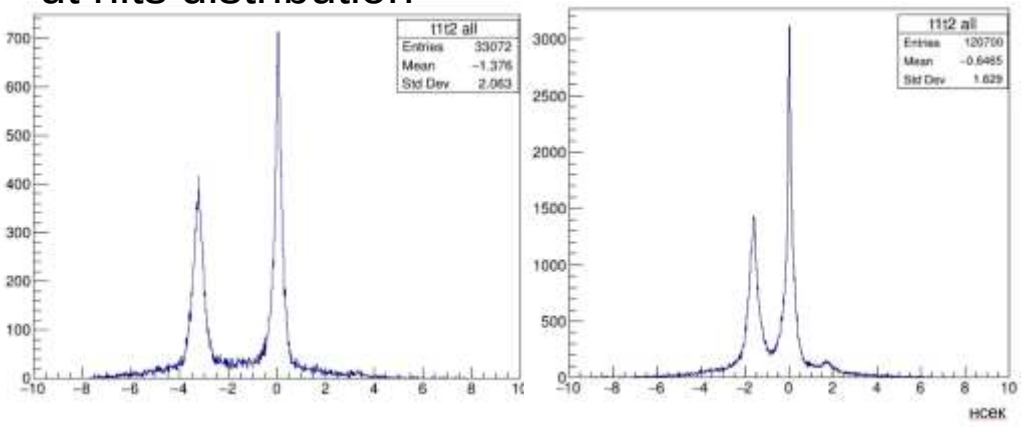
2 Neutron T=1GeV, x-y hits distribution

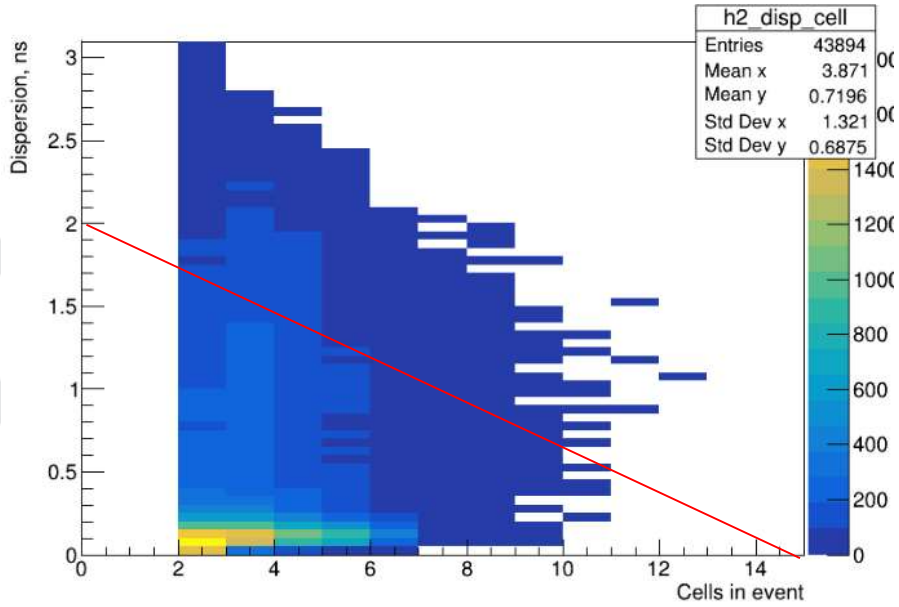
1 Neutron T=1GeV, ToF(L=4m) hits distribution



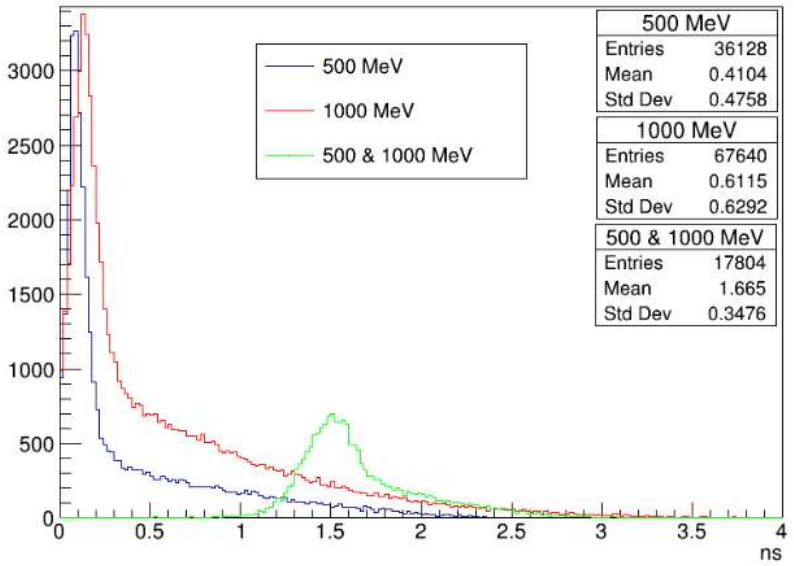
$t_c = t * d_c/d$

2 Neutron: T=1GeV and T=0.5GeV(left), T=1Gev and T=2GeV(right); ToF(L=4m) dt hits distribution

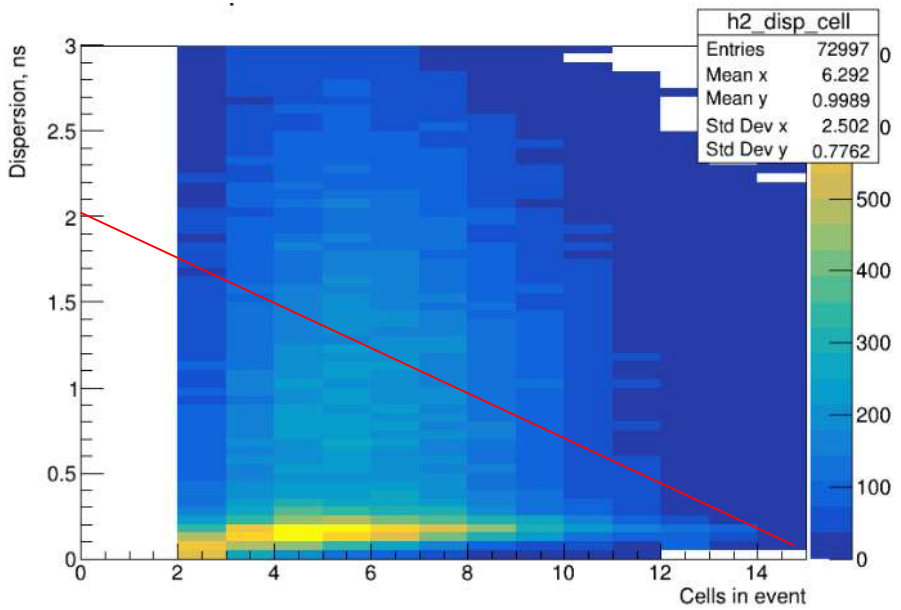




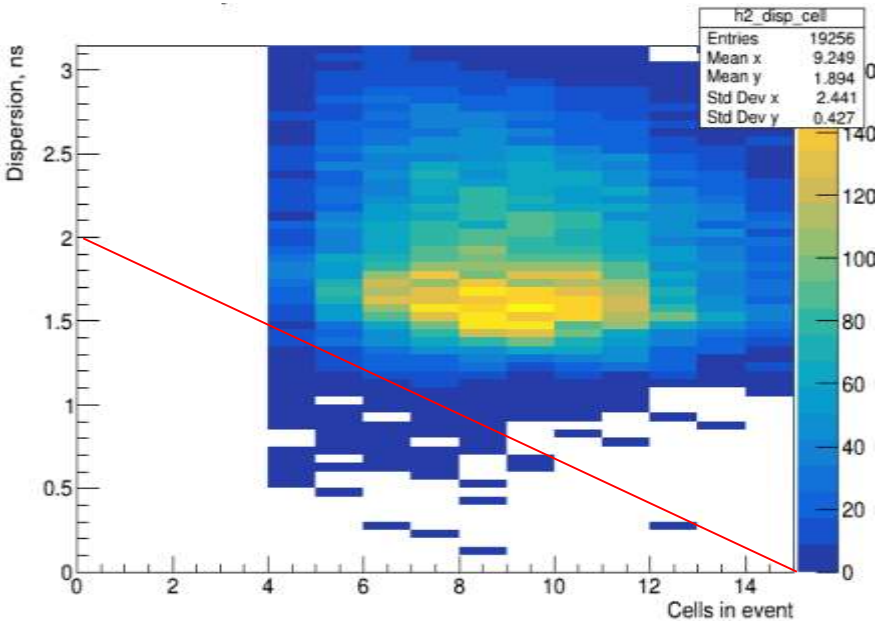
1N,T=0.5GeV



$D=\mathrm{sqrt}(\Sigma(t_i-t)^2/(n-1))$



1N,T=1GeV



2N,T=0.5GeV and 1GeV

Experimental setup (vesion 0.0)

Targets

p, d, He^3,… (incl. polarized)
JINR

Vertex detector

JINR

TOF and Tracker

TOF: Δt < 100ps
Tracker: straw(?)

SC toroidal magnet

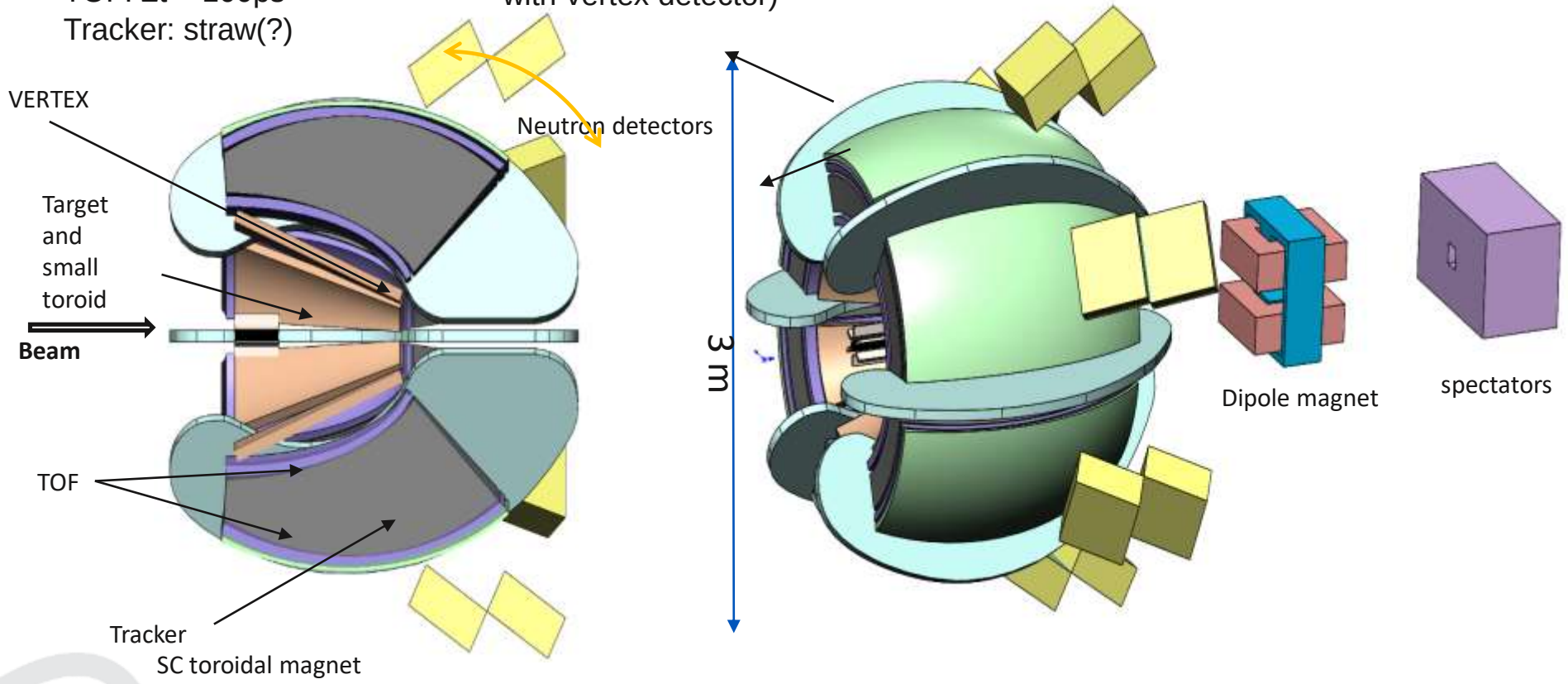
Budker INP RAS

Neutron Detector

- Accepatance ~0.25 sr (~40% full accepatance @ central rapidities)
- Time resolution < 150ps
- Δp/p < 2% ⇒ PID, tracking (together with vertex detector)

Dipole magnet and small angles detectors

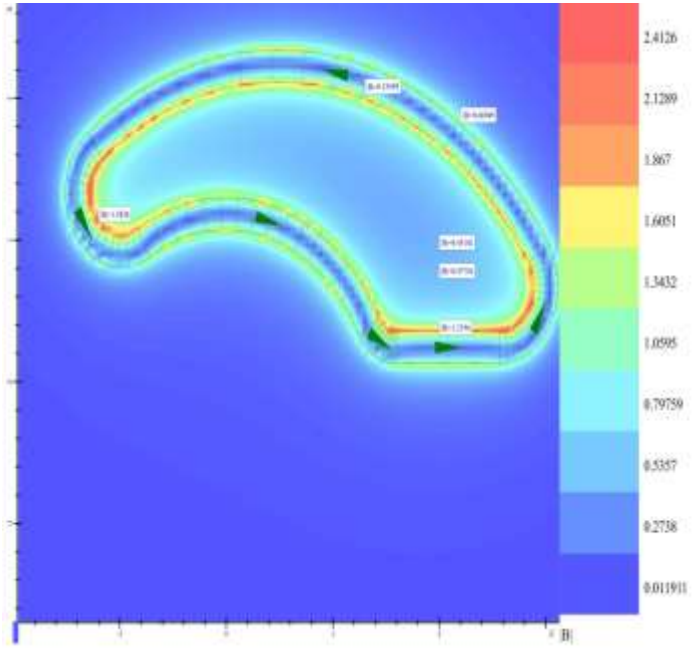
- Spectators registration
- ZDC



SC toroid. Cold vs. High temperature: pros&cons

Cold (He) SC toroid:

- Typical NbTi wires use
- State of art design
- Winding tooling is well established
- Maximum field 2 T is reached
- Larger coil section



magnetic field map

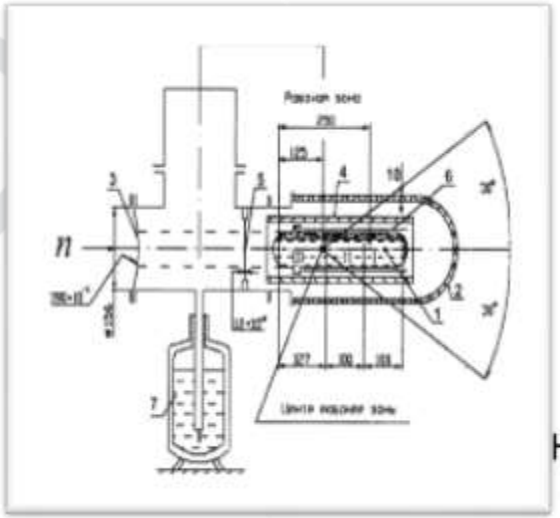
HTSC toroid:

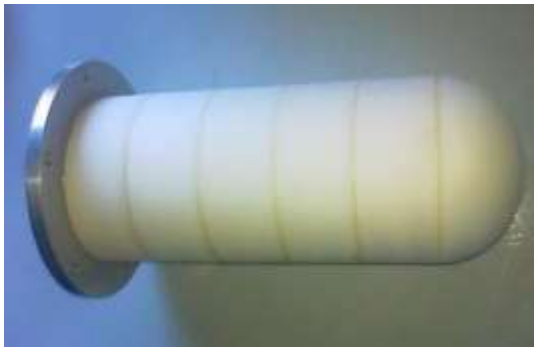
- Need selection for HTSC tapes for uniform and maximum parameters.
- Need work for cable assembling from original tapes
- Winding tooling is not well established
- A lot of design work is required
- Maximum field 2 T is reached only for 40 K temperature use (but cooling equipment for 40 K is commercially available in China for example)
- Maximum field 1.3-1.5 T may be reached for 77 K
- Coil section is smaller for about 30-40 %
- Smaller operation cost

HTSC cable

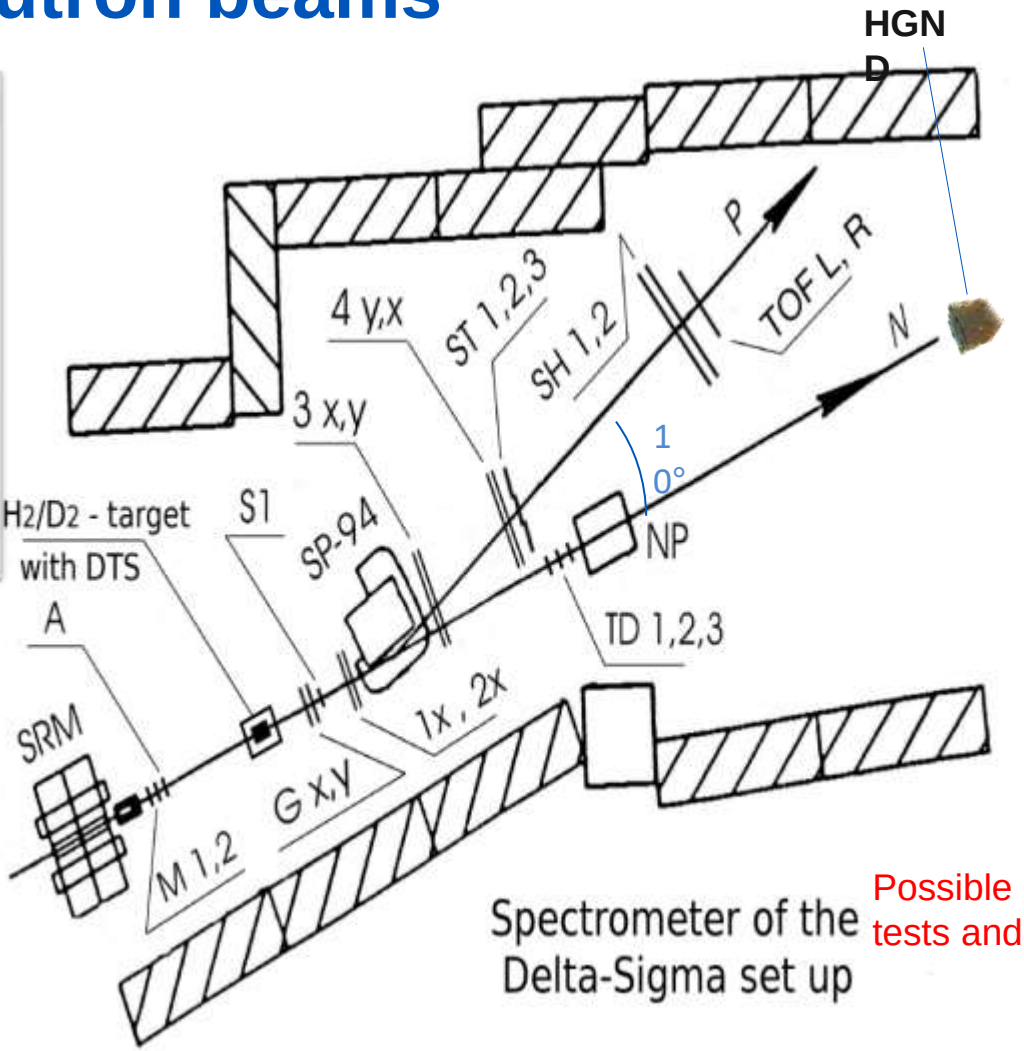
=> ***Needs development work for both toroid versions to compare and choose the appropriate one.***

Delta-Sigma experimental place @ Nuclotron neutron beams





H_2/D_2 Cryogenic target



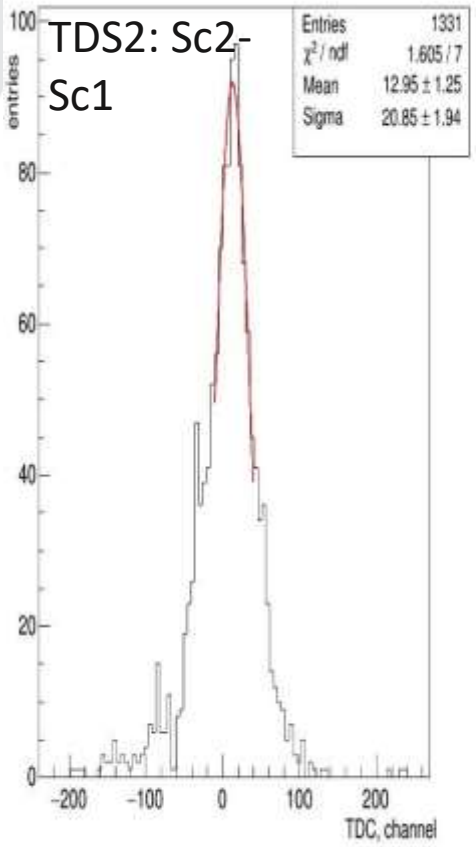
Spectrometer of the Delta-Sigma set up

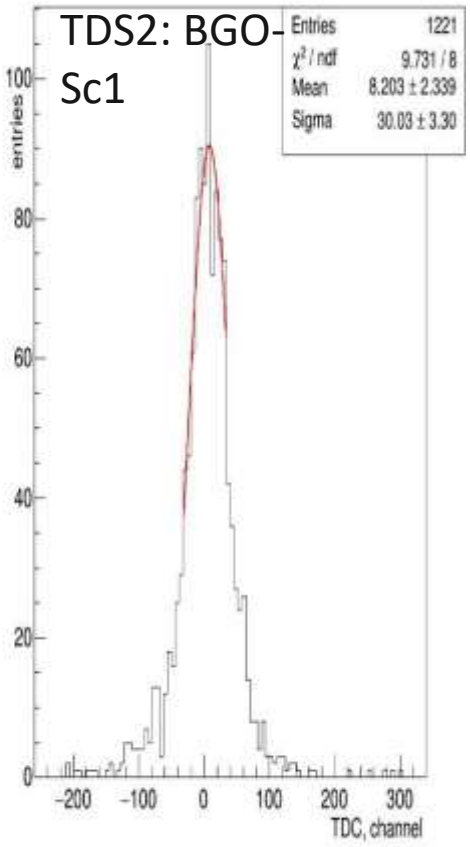
Possible place for HGND tests and calibration

HGND with active absorber (BGO) Cosmic rays test

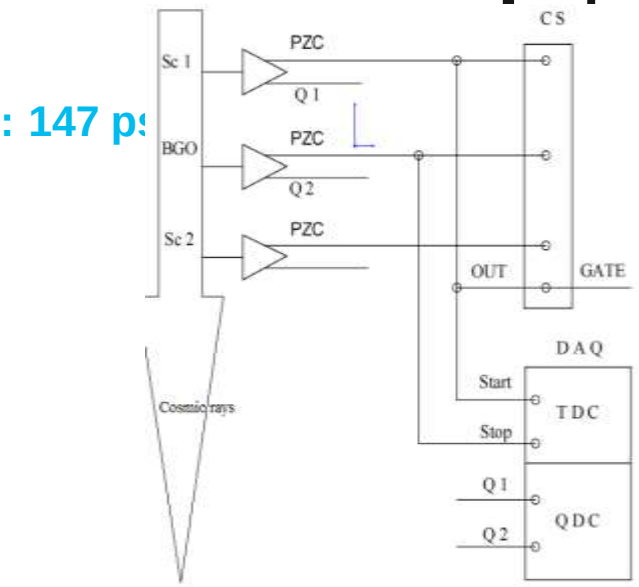
Hip_TaN

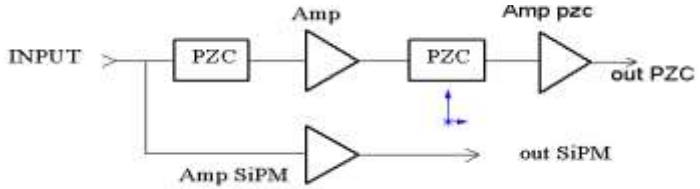
Time resolution for BGO crystal: 147 ps

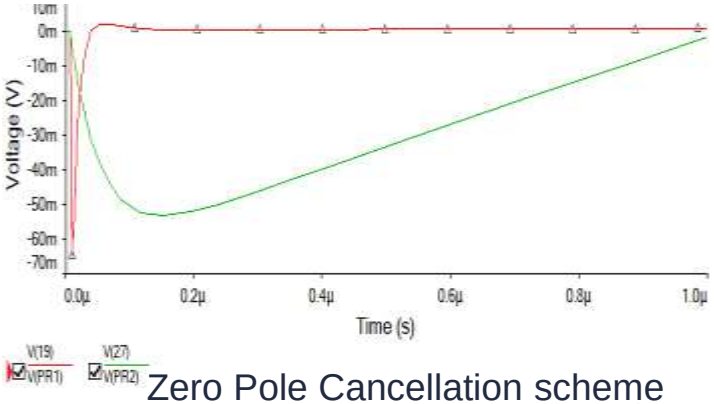




35psec







Zero Pole Cancellation scheme

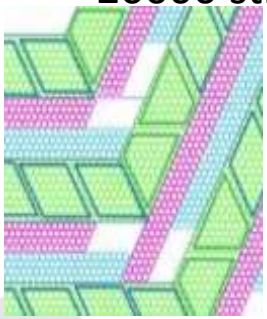
Straw tubes based tracking detector

HiptaN

SPD straw tracker

"Straw Tracker of the future Spin Physics Detector at NICA collider"
V. Bautin, T. Enik et. al. PoS TIPP2023 (2025) 125)

- Main tracker system of SPD ~2m long, D~1.6 m
- Straw diameter 10 mm, thickness 36 um PET
- Spatial resolution of 150 um
- Barrel is made of 6 modules with up to 30 double-layers, with the ZUV orientation (0,+/-2°)
- Endcaps are made of 12 double-layers with the XYUV orientation
- Rate O(100 kHz)
- ~20000 straws



The straw tracker are using of in the different experiments

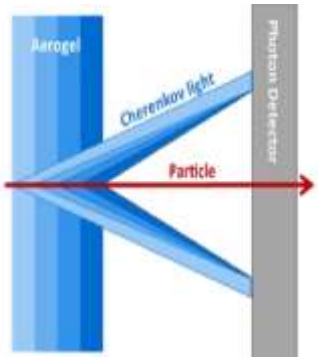
Straw winding

- ATLAS
- LHCb
- PANDA
- CBM
- COMPASS
- Mu2e
- NA64
- SVD-2
- GLUEX
- COZY-TOF
- ..

Straw welding

- NA62
- SPD
- KEDR
- COMET
- SHiP
- DUNE
- OKA
- VES
- SPASCH ARM
- ..

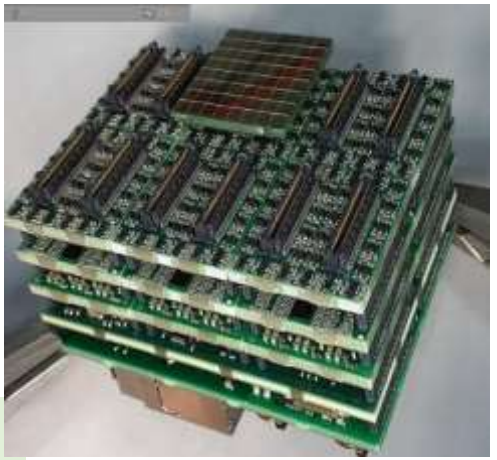
Aerogel based Cherenkov detectors for future HEP experiments A.Barnyakov et. al.



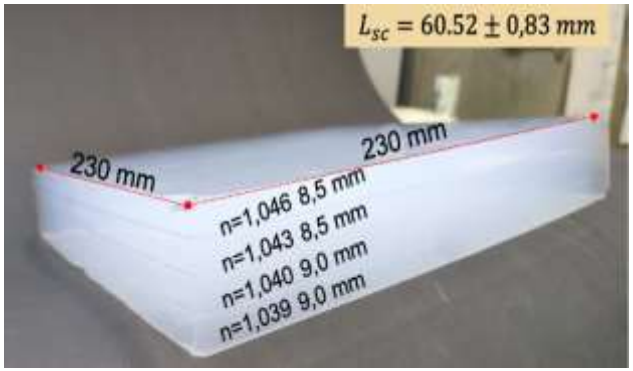
FARICH for reliable π/K and μ/π separation

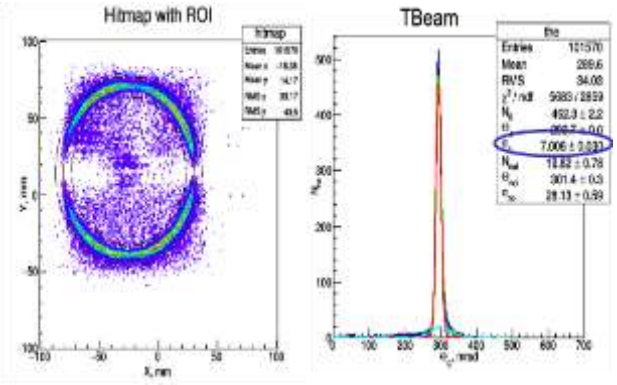
The technique has been developed since 2004

The most crucial issue now is position-sensitive photon detectors and FEE+DAQ issues.



- π/K–separation up to 8.5 GeV/c
- μ/π–separation up to 1.7 GeV/c
- K/p–separation from 3 to 14 GeV/c





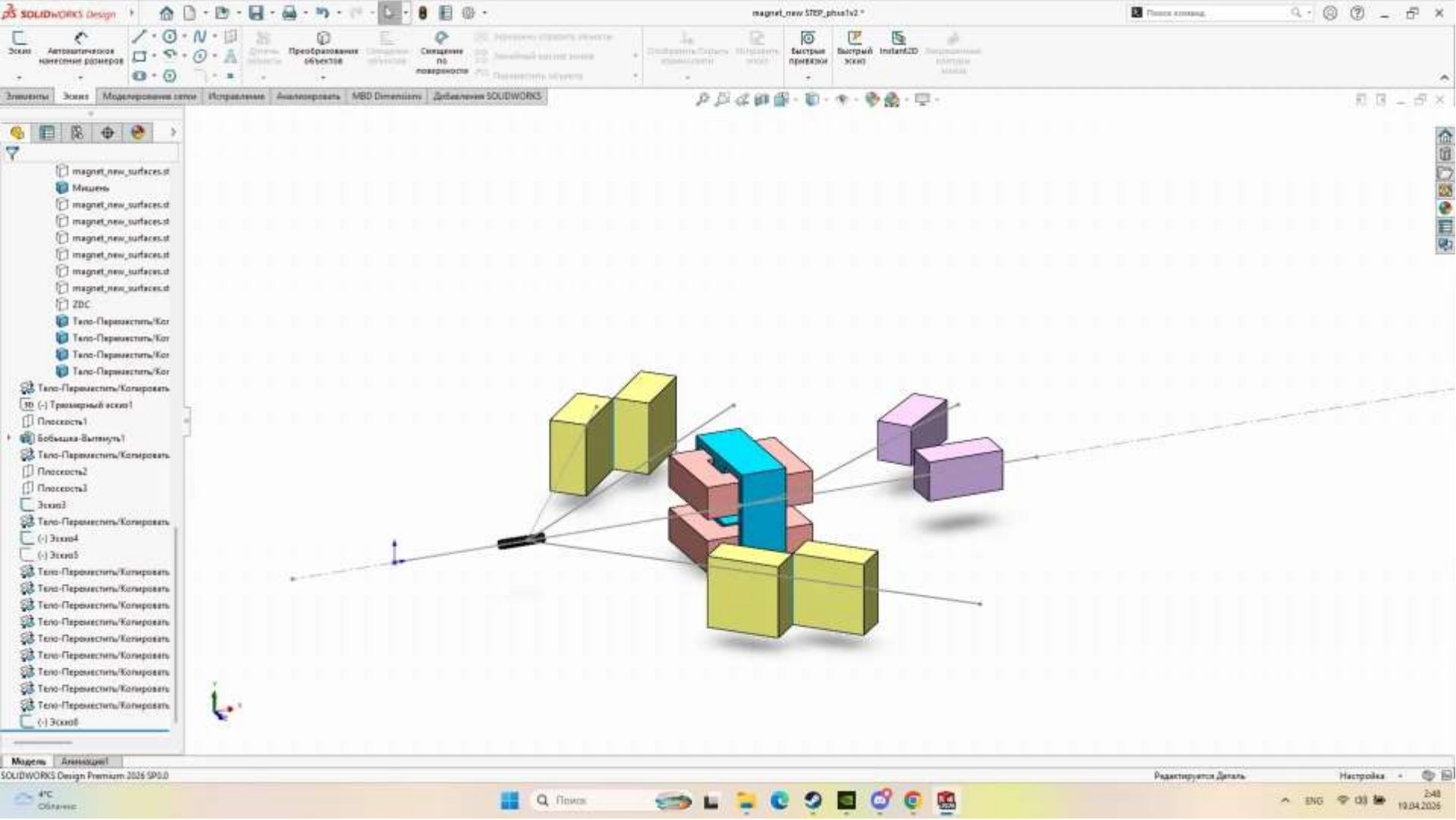
A.Yu. Barnyakov, et al., Nucl. Instr. and Meth. A 553 (2005) 70–75

A.Yu. Barnyakov, et al., Int. J. of Mod. Phys. A 39, No. 26n27, 2442012 (2024)

A.Yu. Barnyakov, et al., Phys. Part. Nucl. 56, No. 3 (2025) 652–655

Very promising progress in focusing aerogels production was achieved in 2022-2023. Several the largest 4-layer tiles of the focusing aerogel were produced in Novosibirsk

The beam test results are in good agreement with simulation. The expected (required) angle resolution for single Chrenkov photon was obtained experimentaly.



Hiptan, stage 1

Conclusions

Hip$_T$aN

- A new experimental program **Hip$_T$aN** is presented. Investigation of rare processes in high p_T region on fixed targets at Nuclotron is the main goal of the project.
- Unique properties of Nuclotron complex (high intensity, polarized beams, polarized targets) together with the development of new neutron detector open unique possibilities to study npQCD problems and cold dense baryonic matter
- Experimental setup for investigations at high p_T is proposed
  - Modular and comprehensive
  - 3m SC toroid: cold and high temperature versions discussed
  - High Granularity Neutron Detector
    - Algorithms of signal/noise separation
    - Active BGO absorber
  - Straw tubes tracker
  - Aerogel

Extra slides

Markus Greiner1, Cindy A. Regal1 & Deborah S. Jin2
NATURE ,426, p.537,2003 |

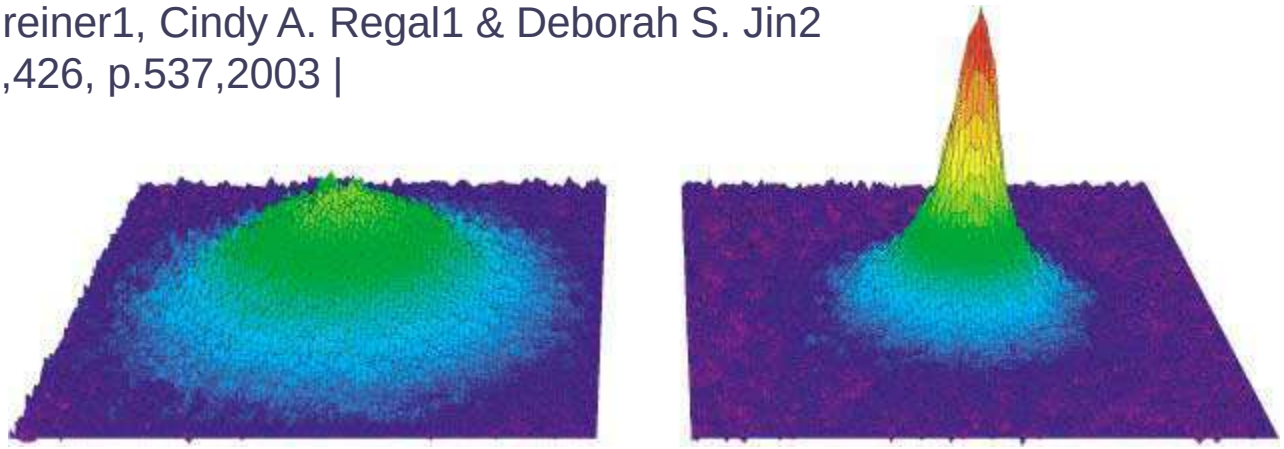


Figure 1 Time-of-flight images of the molecular cloud, taken with a probe beam along the axial direction after 20 ms of free expansion. Data are shown for temperatures above and below the critical temperature for Bose–Einstein condensation. Surface plot of the optical density for a molecule sample created by applying a magnetic-field sweep to an atomic Fermi gas with an initial temperature of 0.19TF (0.06TF) for the left (right) image. The total molecule number was 470,000 (200,000) for the left (right) picture. The surface plots are the averages of ten images.

Rate estimate for DCM trigger (preliminary)

Estimated possible data sample (based on ITEP experimental data):

Nuclotron:10^6sec*10^8int/sec*0.4ster ~10^5events (CC) for Q1+Q2~6

NICA: 10^6sec*10^5int/sec*10ster ~1/40 Nuclotron-rate

CBM@SIS100: 10^6sec*10^8int/sec*1.2ster ~3 Nuclotron-rate

Fermi motion