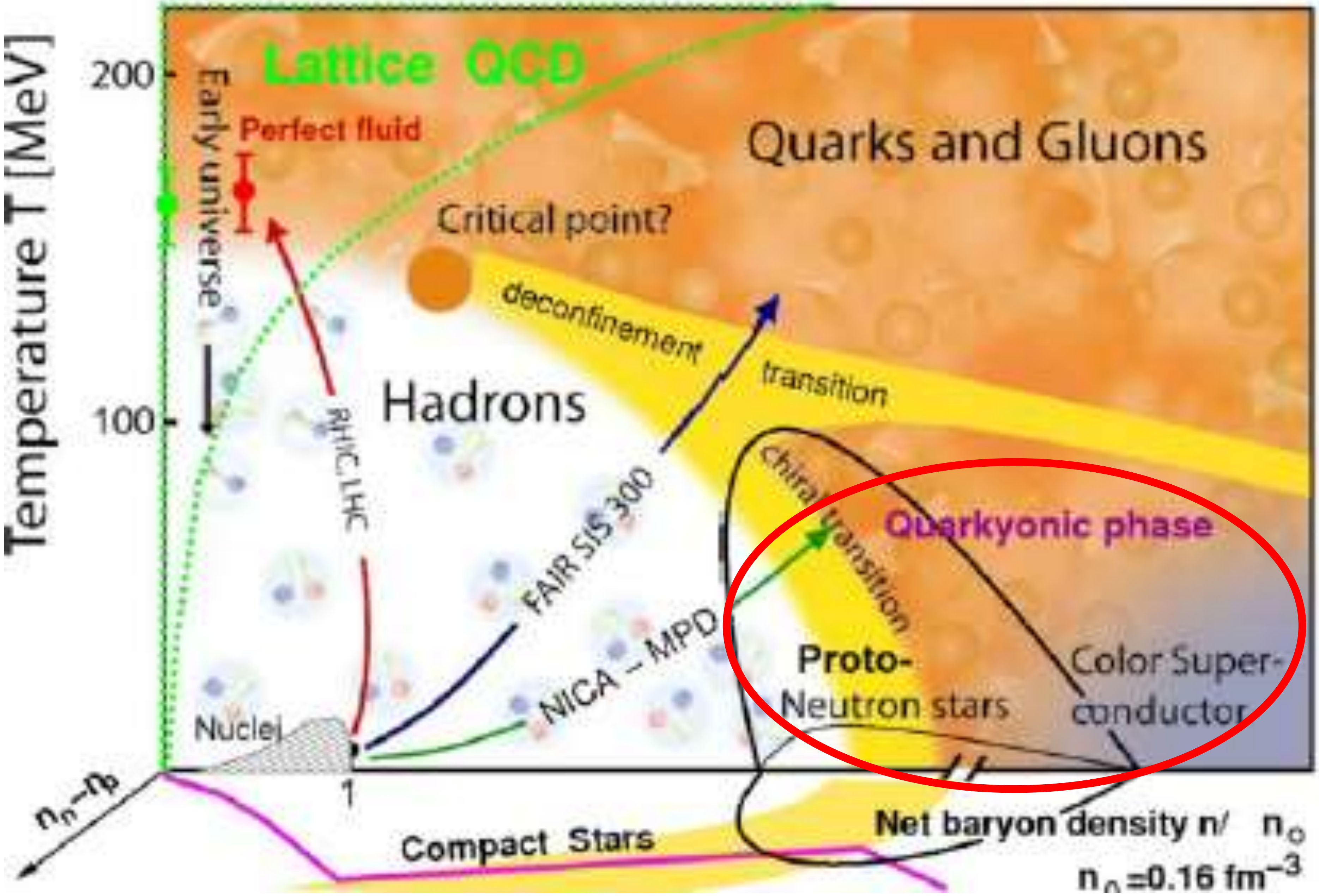
Cold and dense baryonic matter @ Nuclotron-NICA

A.Stavinskiy(ITEP,JINR)


SPD
(Detector)
E-cooling
MPD
(Detector)
BM@N (Detector)
Extracted beam
Collider
Injection Complex
Nuclotron
Booster



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

Relativistic nuclear physics at NICA-Nuclotron energy range

- Rare nontrivial fluctuations in ordinary nuclear matter (fluctons)
- Phase transitions at high μ and low(or moderate)T
- The propeties of new states of matter (cold and dense baryonic matter)
- Exotic structures (diquarks, …)
- Hadronization in nuclear matter

General conditions(1)

- in contrast to hot nuclear matter created in multiply high energy collisions cold and dense baryonic matter probably cannot be prepared without fluctuation →

 -not needed very high initial energy ($\sqrt{s_{NN}}$<10 GeV)

 -not needed heavy nuclear (A_1,A_2:1÷50)

General conditions(2)

- “cold”→ (δp→0), “dense” → (δx→0), but
- cold and dense matter must be in accordance with Pauli blocking* →

  -bosonisation of constituents could be a solution

  -diquark is probable candidate for important constituent

*The **Pauli** exclusion principle is the quantum mechanical principle which states that two or more identical fermions (particles with half-integer spin) cannot occupy the same quantum state within a quantum system simultaneously.This principle was formulated by Austrian physicist Wolfgang **Pauli** in 1925

General conditions(3)

- For cold matter “strangeness” is “small parameter”. It can be used both for simplification of theoretical analysis and for experiment →

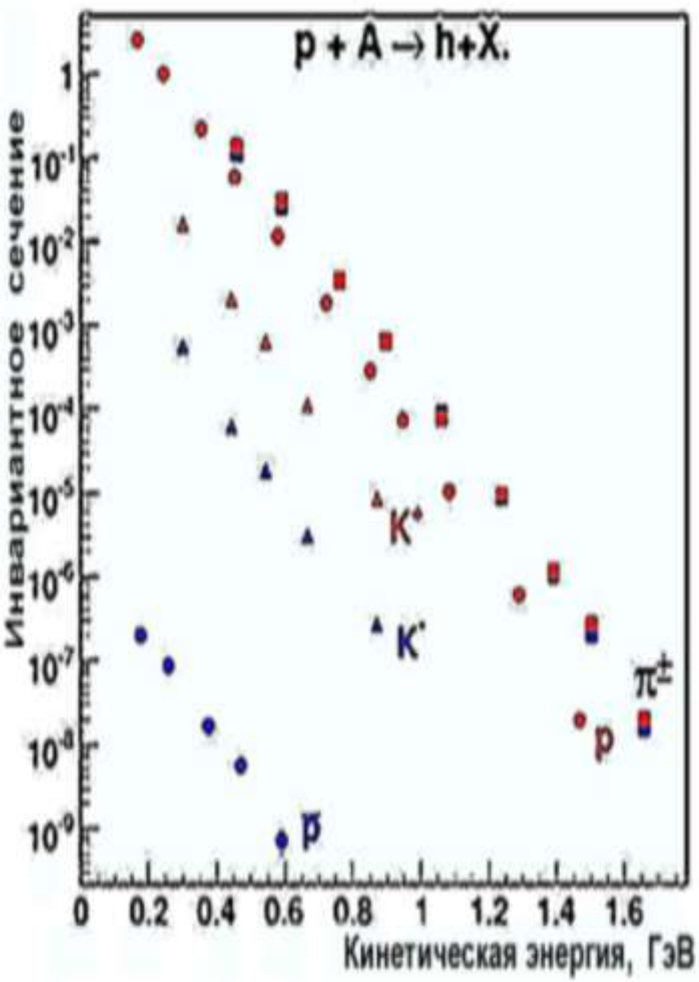
  -(as an example :slight excess of neutrons in dense and cold matter could be transformed into large value of Σ^-/Σ^+ ratio)

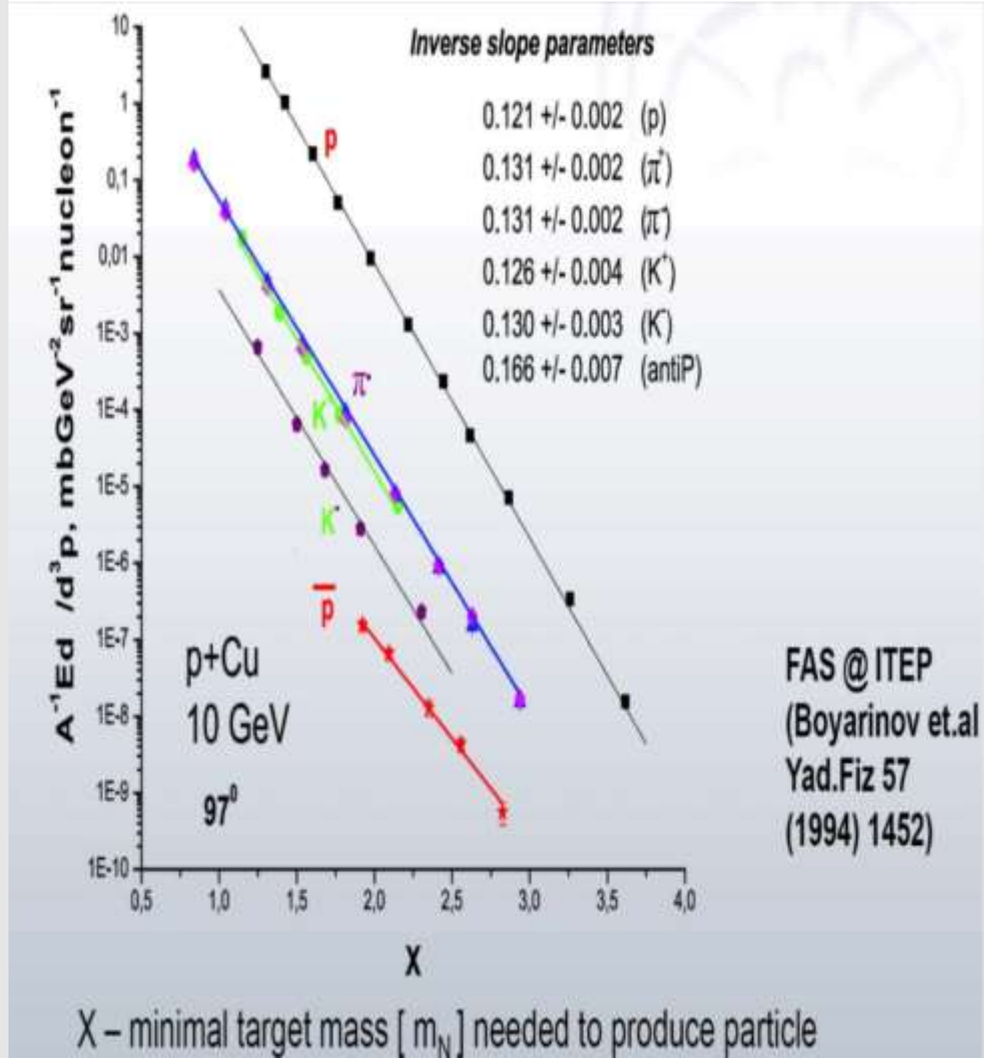
General conditions(4)

- In the cold and dense nuclear matter all degrees of freedom are important, including spin and isospin one →

  -the state of matter depends not only on temperature and density but also on spin and isospin

Experimental & theoretical background(1), cold&dense





Experimental & theoretical background(2), cold&dense

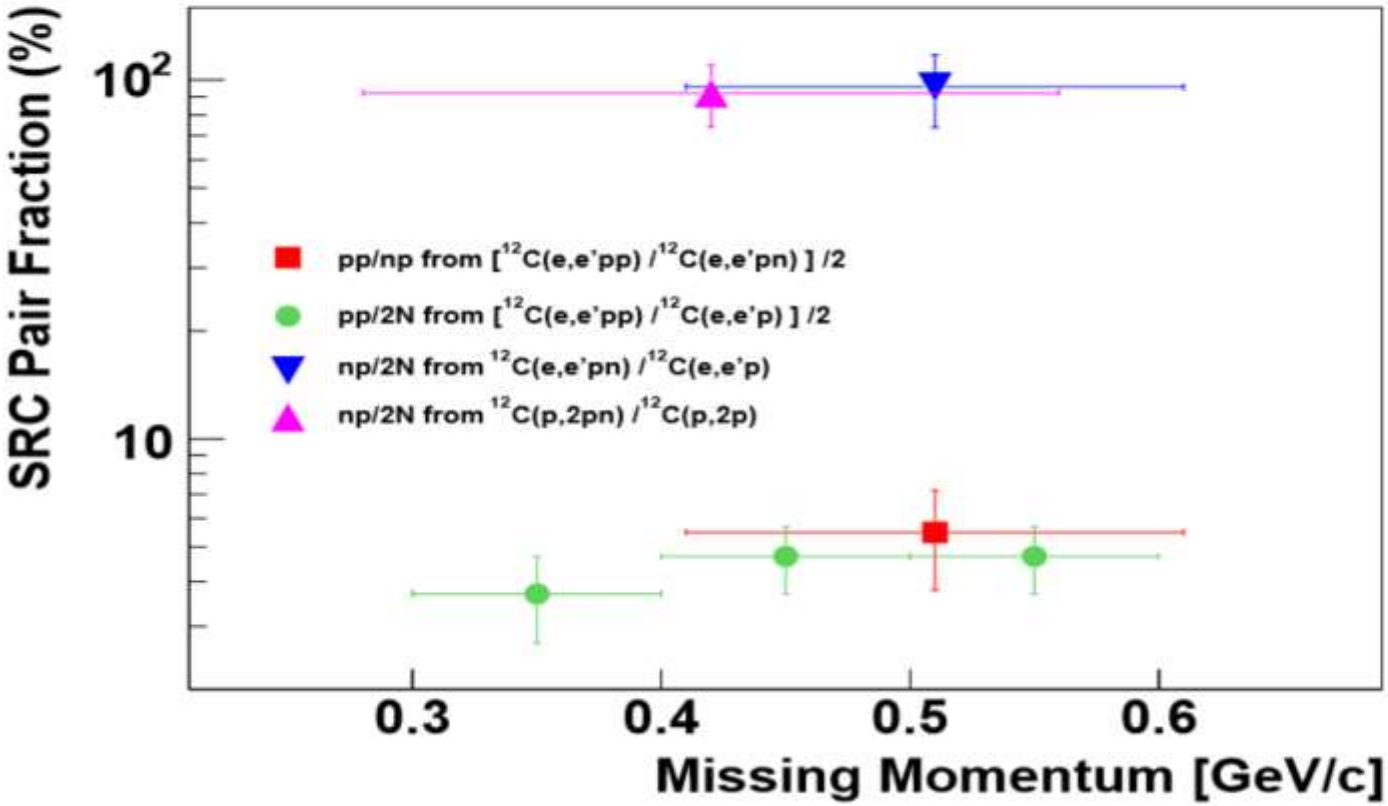
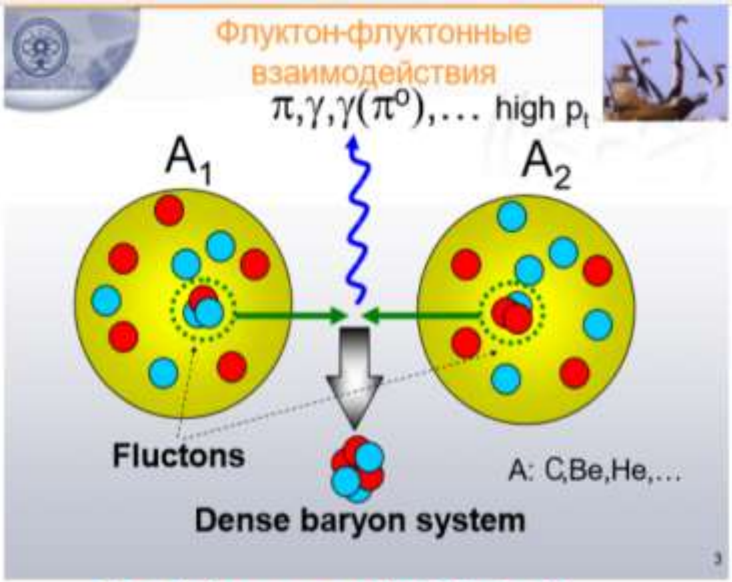


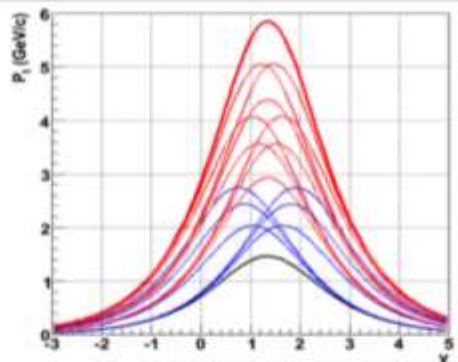
Figure 2: The fractions of correlated pair combinations in carbon as obtained from the (e,e'pp) and (e,e'pn) reactions, as well as from previous (p,2pn) data. The results and references are listed in Table 1.

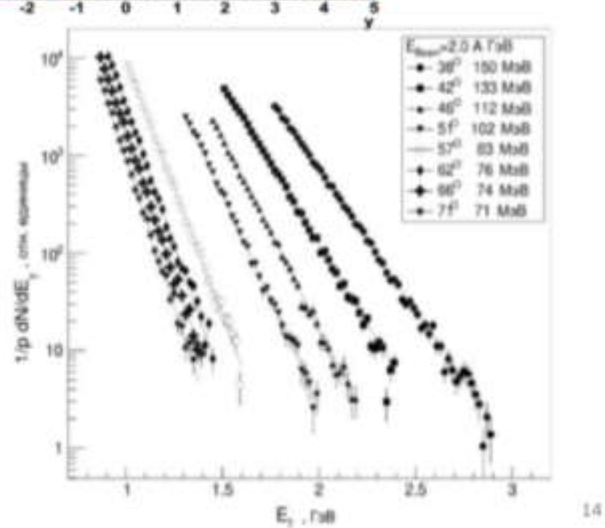
R.Subedi et al.,JLAB Hall A, arXiv:0908.1514 v1[nucl-ex]2009

Experimental & theoretical background(3), cold&dense



I.G.Alekseev et.al.(FLINT), ЯФ 71(2008)1;
A.Stavinskiy, EPJ Web Conf. 71 (2014) 00125;
K.R. Mikhailov et al., Phys.Atom.Nucl. 77 (2014) 576; ЯФ 77 (2014) 610





Experimental & theoretical background(4), cold&dense

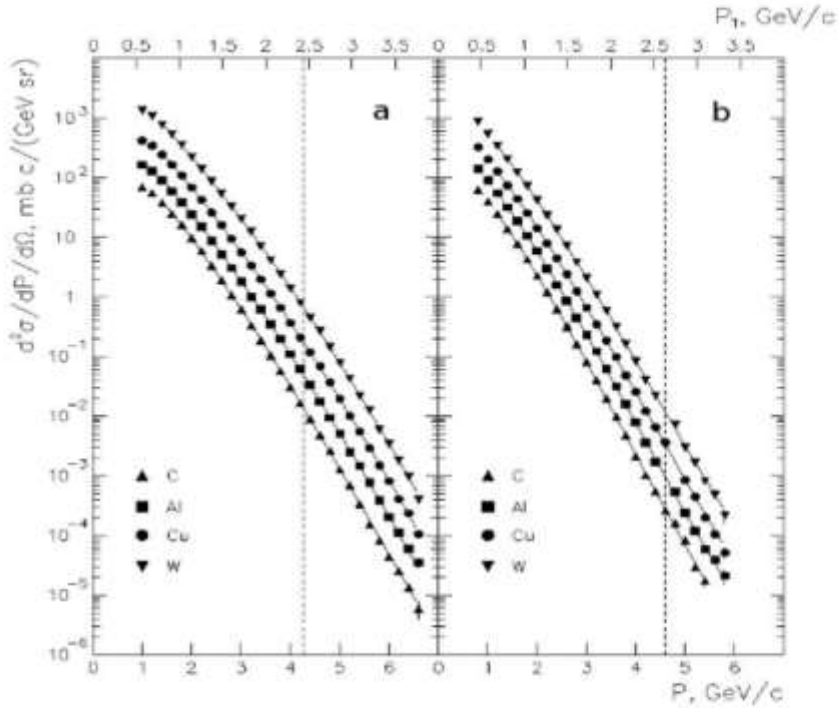


Fig. 2. Differential production cross sections for (a) positively and (b) negatively charged particles as functions of momentum. The upper horizontal axes show the transverse momentum. Vertical dashed lines show the kinematic thresholds for (a) elastic scattering of free nucleons, and (b) single π^--meson production in interaction of free nucleons. Curves are plotted for better data perception.

Ammosov et al., YaF 4(2013)773, High pt cumulative in pA at 50 GeV(IHEP)

Where we stand:

- Fluctons exist (it is not trivial high momentum component)

What would be possible next steps:

- Correlations with cumulative trigger
  - flucton properties
- From few nucleons fluctons to cold and dense matter

Experimental & theoretical background(5), cold&dense

SRC in inverse kinematics at JINR
A(p, 2p n A-2) : **detecting the nuclear remnant**

4 GeV/c ^{12}C beam on LH target

Probe universality

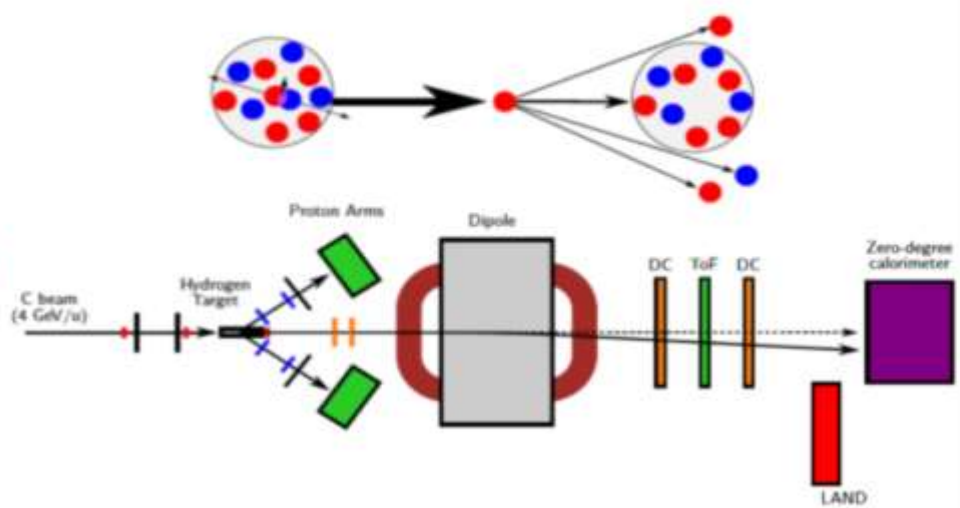
Detect 4 particles:

the scattered probe,

the knocked-out nucleon,

the recoil,

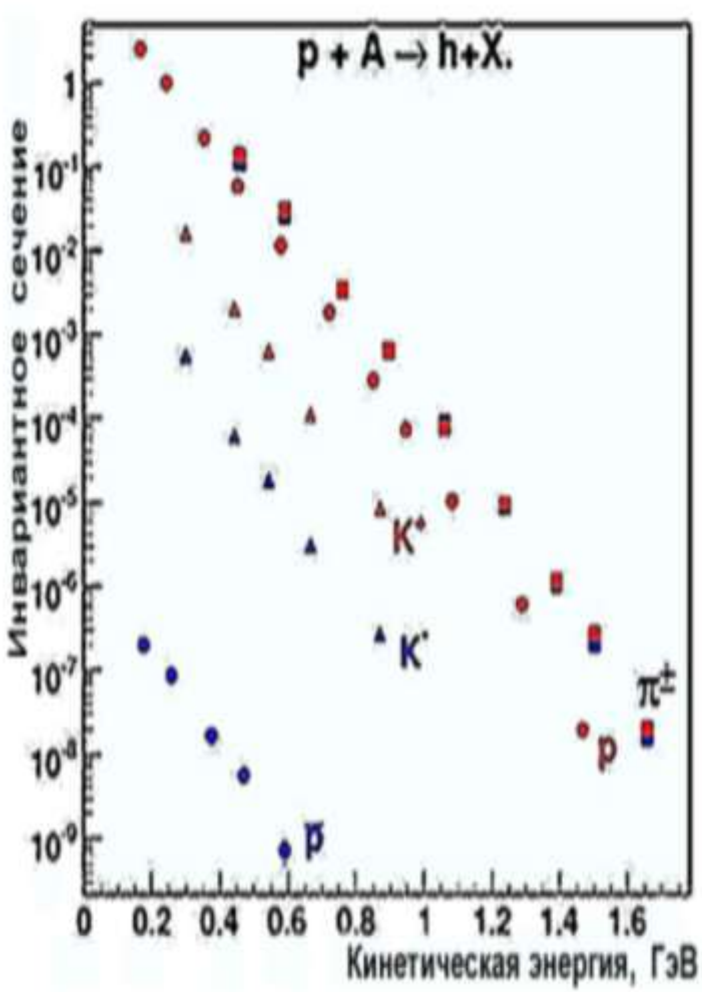
and the **A-2 system**!



(From M.Patsyuk presentation)

Experimental & theoretical background(6),strangeness

CC,UrQMD,10^5 ev.	2AGeV	3AGeV	4AGeV	10AGeV	30AGeV
All particles	2968383	3269875	3555732	4785049	6861519
P	980372	973357	964317	934470	899765
N	982267	974936	965797	937139	900696
Λ	1393	5493	10405	30537	57559
Σ^+	489	2347	4389	11135	17909
Σ^0	623	2918	5653	12424	19557
Σ^-	549	2277	4321	11209	18108
π^+	178772	269480	354107	714208	1286150
π^0	205822	312142	407661	796030	1418912
π^-	178205	267809	354088	713459	1286178
K^+	1607	6884	13574	45080	108427
K^0	1506	6741	13218	44376	108090
antiK^0	30	279	942	11760	51677
K^-	27	279	918	11516	51639



Experimental & theoretical background(7),strangeness

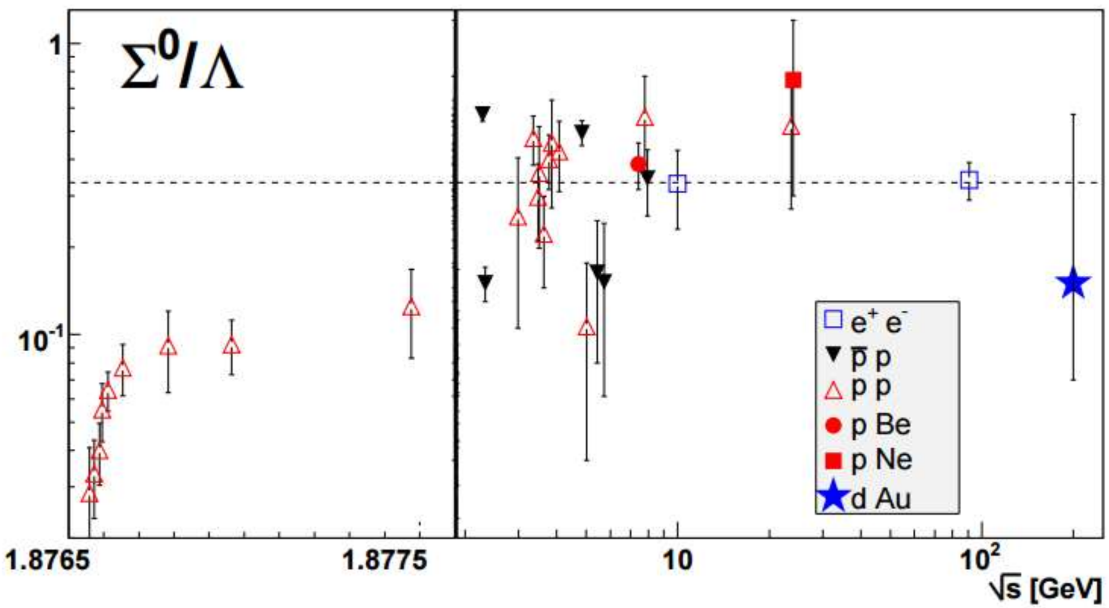


Figure 4: Σ^0/Λ results versus collision $\sqrt{s}$ ($\sqrt{s_{NN}}$ for p/d+A) [1]. Meson-nucleon reaction results are excluded for clarity, but exist only at intermediate energies and lie in the same range. The dashed line is the ratio of isospin degeneracy factors (1/3).

arXiv:nucl-ex/0512018, G.Van Buren for the STAR collaboration

FSI depends on the size of the interaction region(~$1/r^2$) , Λ/Σ (E→0) 3 for AA in contrast to Λ/Σ (E→0) 30 for pp? No data!

Experimental & theoretical background(8),strangeness+femto

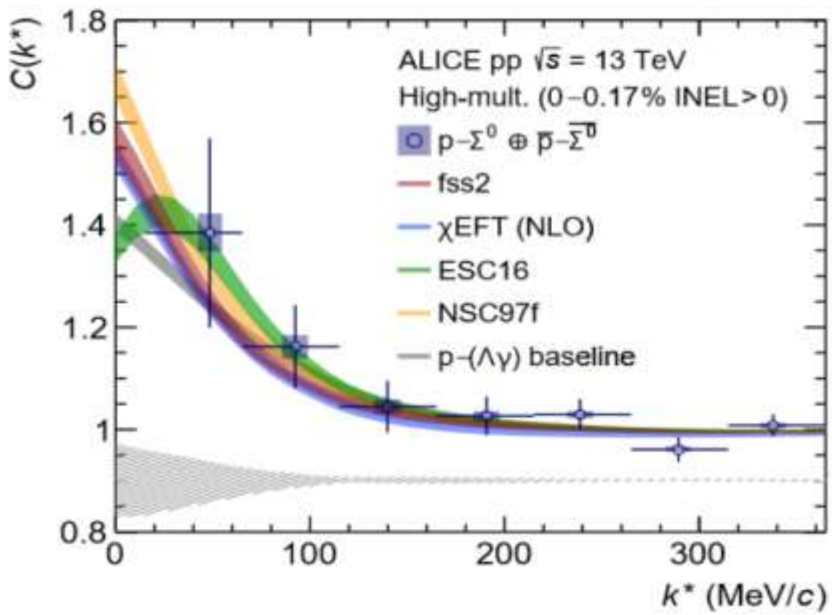
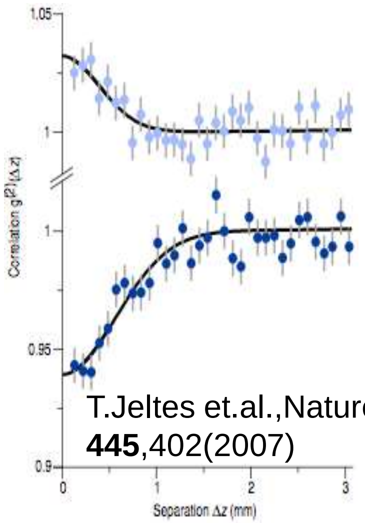


Figure 3: Measured correlation function of p–Σ^0 ⊕ $\overline{\text{p}}$–$\overline{\Sigma^0}$. Statistical (bars) and systematic uncertainties (boxes) are shown separately. The gray band denotes the p–($\Lambda\gamma$) baseline. The data are compared with different theoretical models. The corresponding correlation functions are computed using CATS [46] for χEFT [20], NSC97f [26] and ESC16 [23], and using the Lednický–Lyuboshits approach [51, 52] for fss2 [24]. The width of the bands corresponds to one standard deviation of the systematic uncertainty of the fit. The absolute correlated uncertainty due to the modeling of the p–($\Lambda\gamma$) baseline is shown separately as the hatched area at the bottom of the figure.

arXiv:1910.14407v3[nucl-ex]2020, ALICE collaboration

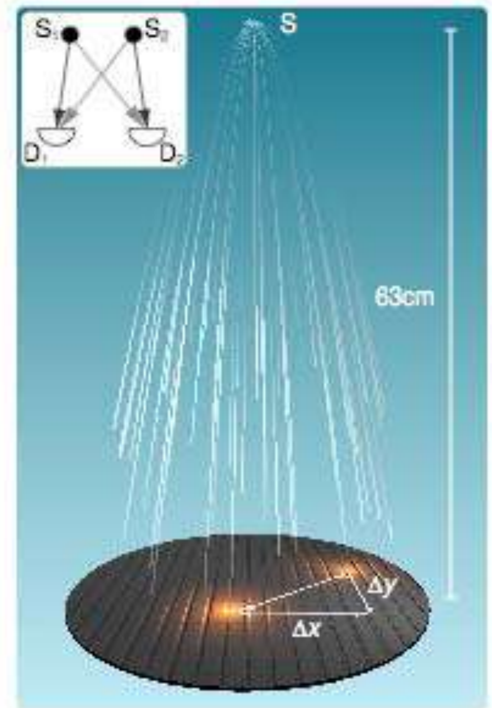
– **femtoscopy measurements for the dense baryonic droplet**

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

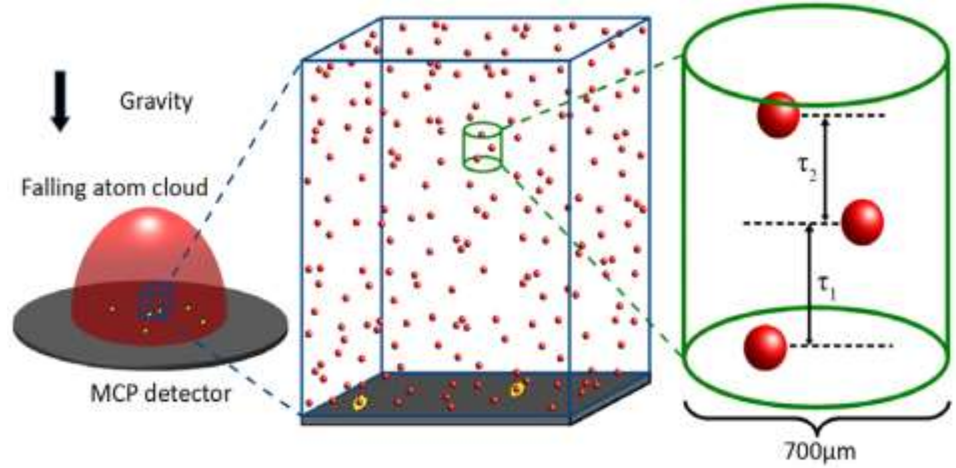


T.Jeltes et.al.,Nature, **445**,402(2007)

Caption for figure 1: Normalised correlation functior 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.The correlation length for 3He* is expected to be 33% larger than that for 4He* due tc 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 respectivel



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.



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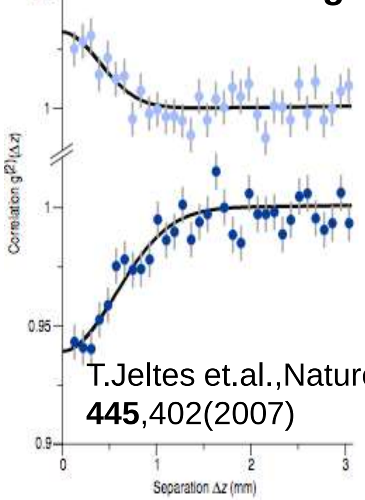

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Bose-Einstein Condensation(BEC)

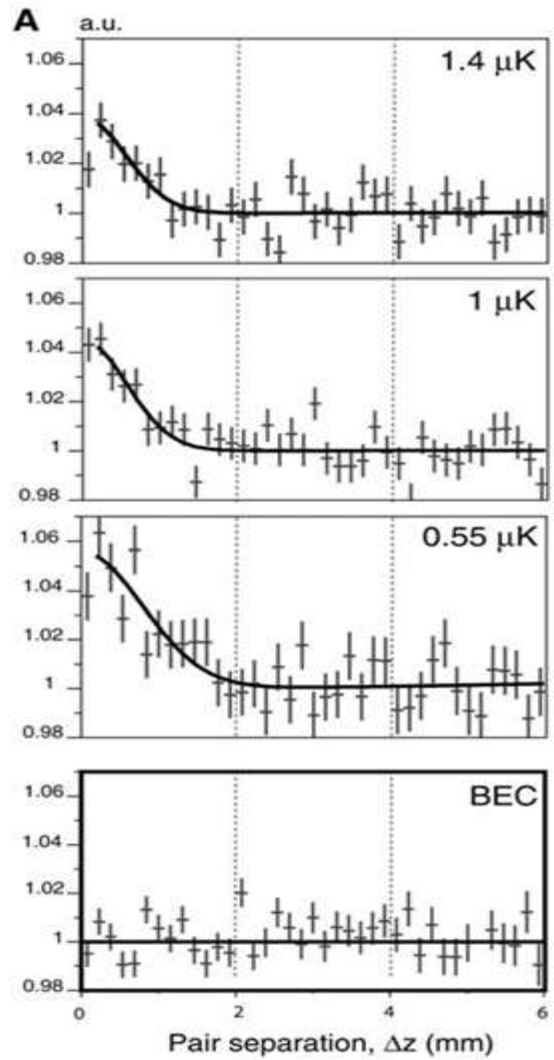


Fig. 2. (A) Normalized correlation functions along the vertical (z) axis for thermal gases at three different temperatures and for a BEC.

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

Opposite sign correlations

Our purpose here is to point out that if a manyboson or many-fermion system exhibits opposite sign correlations, then the state in question necessarily has a certain complexity. For example,
consider a fermion gas. If the gas exhibits any positive pair correlations when it has been prepared in a certain state, then that state cannot be represented by a simple Slater determinant wavefunction. In general, if one probes a many-boson or many-fermion state and finds that it exhibits opposite sign correlations, then, even without any model for the unknown state, one may infer that it is not a “free” state, i.e., it does not have the form of a grand canonical ensemble for noninteracting indistinguishable particles. We believe that opposite sign correlations can be observed in current experimental setups and may even have already been observed and passed unnoticed.

Ref.:Alex D. Gottlieb and Thorsten Schumm, arXiv:0705.3491 [quant-ph]

Experimental & theoretical background(11) diquarks

Modern Physics Letters A, Vol. 3, No. 9 (1988) 909–916

DIQUARKS AND DYNAMICS OF LARGE-$P_\perp$ BARYON PRODUCTION

V. T. KIM

Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, 101000 Moscow

Received 4 January 1988

In the framework of a diquark model of the nucleon, the strong scaling violation of the p/π^+-ratio in the pp-collisions from $\sqrt{s} = 11.5$ GeV (IHEP, Serpukhov) to $\sqrt{s} = 23.4$ GeV (FNAL) and to $\sqrt{s} = 62$ GeV (CERN ISR) is described. A fairly good description of the magnitude of cross sections for single protons and for symmetric-proton-pairs with large-$p_\perp$ is obtained. In the model with the dominating scalar (ud)-diquark, the yield relation $\Lambda^0/p \simeq K^+/\pi^+$ is predicted.

Experimental & theoretical background(12) diquarks

E»1GeV(no FSI)

Model baryon=quark+diquark:
“ diquark: I=S=1 or 0.”
И.Ю.Кобзарев, Б.В.Мартемьянов, М.Г.Щепкин
УФН 162, вып.4,1992,стр.1-41(in Russian)
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)**

Experimental & theoretical background(13) diquarks

From: Craig Roberts <cdroberts.phy.anl@gmail.com>

…independent of detailed information about the interaction used to describe quark-quark scattering.

The result is most easily seen when looking at Eqs. (A.1) in [[arxiv.org]https://arxiv.org/pdf/1705.03988.pdf]. There you will see that the isospin=0 Lambda contains two different arrangements of diquark correlations. However, the simple [ud] configuration is forbidden in the isospin=1 Sigma^0, which only contains [us]d+[ds]u. To be explicit, here are the flavour wave function components:
Lambda ... [ud]s, [us]d-[ds]u, {us}d-{ds}u
Sigma^0 ... [us]d+[ds]u, {us}d+{ds}u

Dynamics determines the relative strength of each term within a given baryon.
As you note below, depending on the assumed reaction mechanism, this difference in diquark content could affect the Lambda/Sigma production ratio in AA collisions.

Experimental & theoretical background(14) diquarks

TABLE I: Masses of light ground state diquarks (in MeV). S and A denotes scalar and axial vector diquarks antisymmetric [...] and symmetric {...} in flavour, respectively.

Quark content	Diquark type	Mass [14] our	[15] NJL	[16] BSE	[17] BSE	[18] Lattice
$[u,d]$	S	710	705	737	820	694(22)
$\{u,d\}$	A	909	875	949	1020	806(50)
$[u,s]$	S	948	895	882	1100	
$\{u,s\}$	A	1069	1050	1050	1300	
$\{s,s\}$	A	1203	1215	1130	1440	

D.Ebert et al.,Eur.Phys.J.C60,273(2009), arXiv:0812.2116[hep-ph](on light tetraquarks in the relativistic quark model)

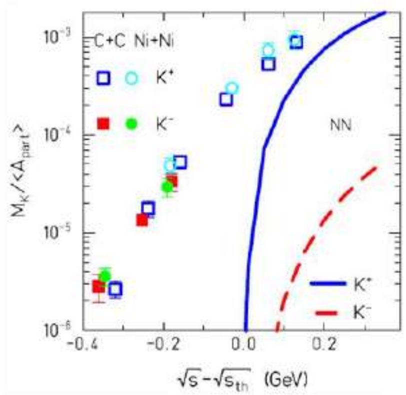
Experimental & theoretical background(15), BM@N

Physics possibilities at the Nuclotron

I. In A+A collisions at Nuclotron energies:

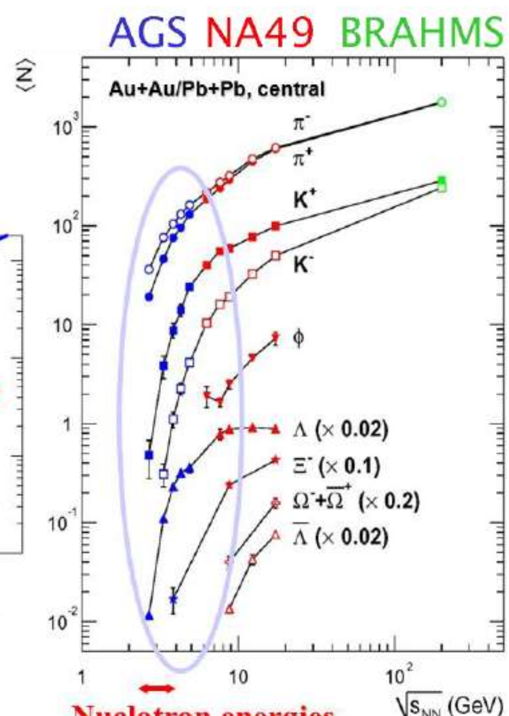
❑ Opening thresholds for strange and multi-strange hyperon production

➔ strangeness at threshold



➔ Need more precise data for strange mesons and hyperons, multi- variable distributions, unexplored energy range

▶ Collective flows v_1, v_2



II. In *p+p, p+n, p+A* collisions:

➔ hadron production in elementary reactions and 'cold' nuclear matter as 'reference' to pin down nuclear effects

Experimental & theoretical background(16),J-PARC

Studies of extremely dense matter in heavy-ion collisions at J-PARC
J-PARC-HI Collaboration
(H. Sako (JAEA, Ibaraki & Tsukuba U.) for the collaboration). 2019. 4 pp.
Published in **Nucl.Phys. A982 (2019) 959-962**

From general conditions to experiments

- To study of the rare fluctuations one needs high luminosity and acceptance
- Diquarks can be studied not only in AA but also in pp collisions
- Strangeness in cold nuclear matter – mainly kaons and light hyperons: $\Lambda, \Sigma^0, \Sigma^+, \Sigma^-, \ldots$

  (hyperons ID need neutron and photon ID)

Some of possible measurements

- Cumulative (for example high p_t) trigger at AA(including dd, CC, pA…)

    - to study fluctons

    - to select and to study cold and dense system

(including Λ/Σ^0,Σ^+/Σ^-,… ratios with and without cumulative trigger)

- Femtoscopy of phase transition
- Search for and the study of diquarks in high p_t process at dd and pp collisions

Methods(1)

- Luminosity.

  -Probability of 3N short range correlations(SRC or fluctons) in nuclear matter of the order of $0.5*10^{-2}$(*). It means that for the study of 3N+3N interactions only $\sim 10^{-5}$ of inelastic interactions can be used

  -Particles from different beam-beam interactions provides background for correlation meagurements→

  the luminosity $\sim 10^{30}$ -$10^{32} cm^{-2} s^{-1}$ looks close to optimal

*Egiyan et al.(CLAS)2006,Phys.Rev.Lett.96,082501

Methods(2)

- Particle ID.

  -both charge and neutral (n,γ) particle ID in central rapidity interval in the momentum range from few hundreds MeV to few GeV
- Momentum resolution (mainly for femtoscopy)~20MeV/c

The unique SPD detector properties:

- about full solid angel $\delta\Omega \sim 4\pi$;
- registration about all kinds of particles;
- the luminosity ~ 10^{30} cm^{-2} s^{-1};
- PID – close to full energy range and high momentum resolution;
- polarized proton and deuteron beams;
- the presence of tagging stations to detect spectator neutrons and protons which will allow to investigate the full set of isotopic states of nucleon-nucleon interactions (pp, pn and nn) in the polarization mode;
- pp-, pd-, dd-, pA-, dA- and AA-interactions (A-light nuclear beams).

Thanks for the attention!

Backup

Σ^+ DECAY MODES Fraction ($\Gamma i/\Gamma$)

$p\pi^0$ (52 %)

$n\pi^+$ (48 %)

Σ^0 DECAY MODES Fraction ($\Gamma i/\Gamma$)

$\Lambda\gamma$ (100 %)

Σ^- DECAY MODES Fraction ($\Gamma i/\Gamma$)

$n\pi^-$ (100 %)

To identify Σ one needs detectors for γ and n.

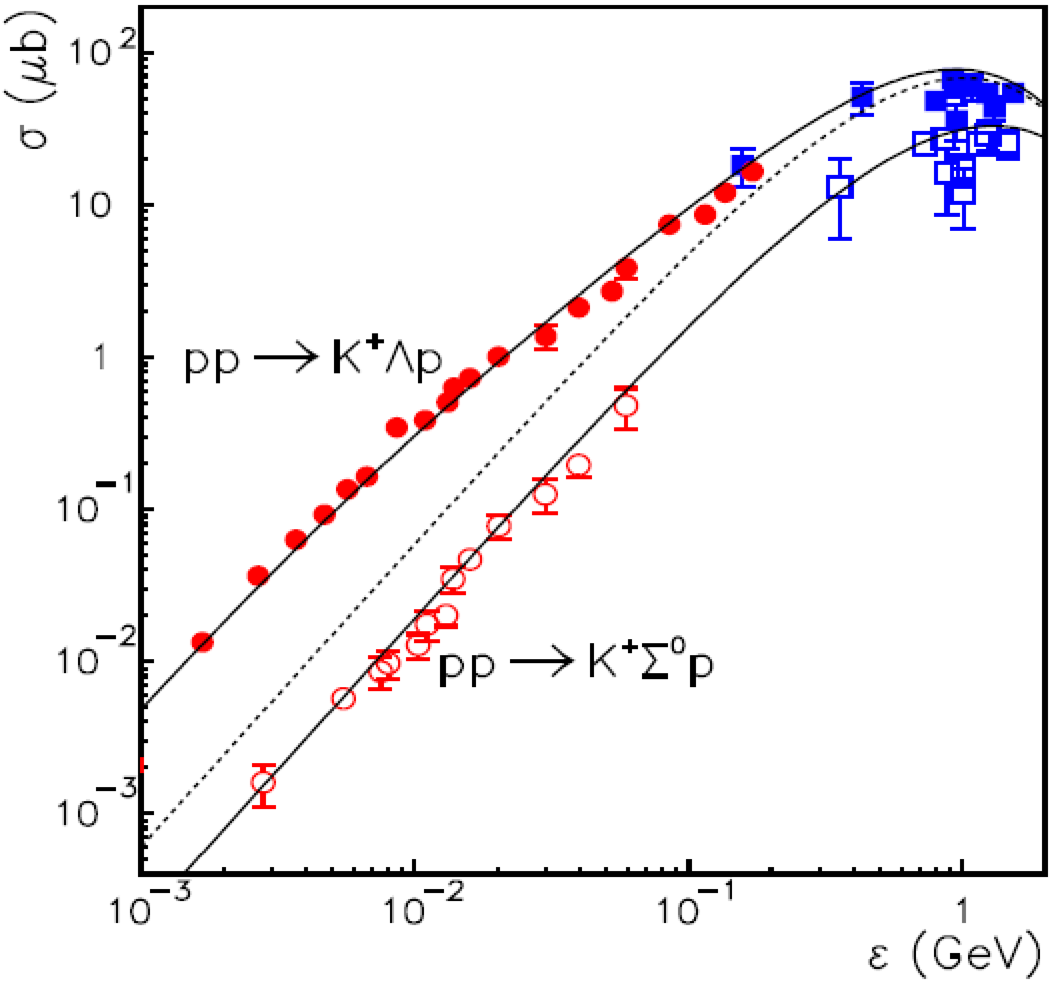
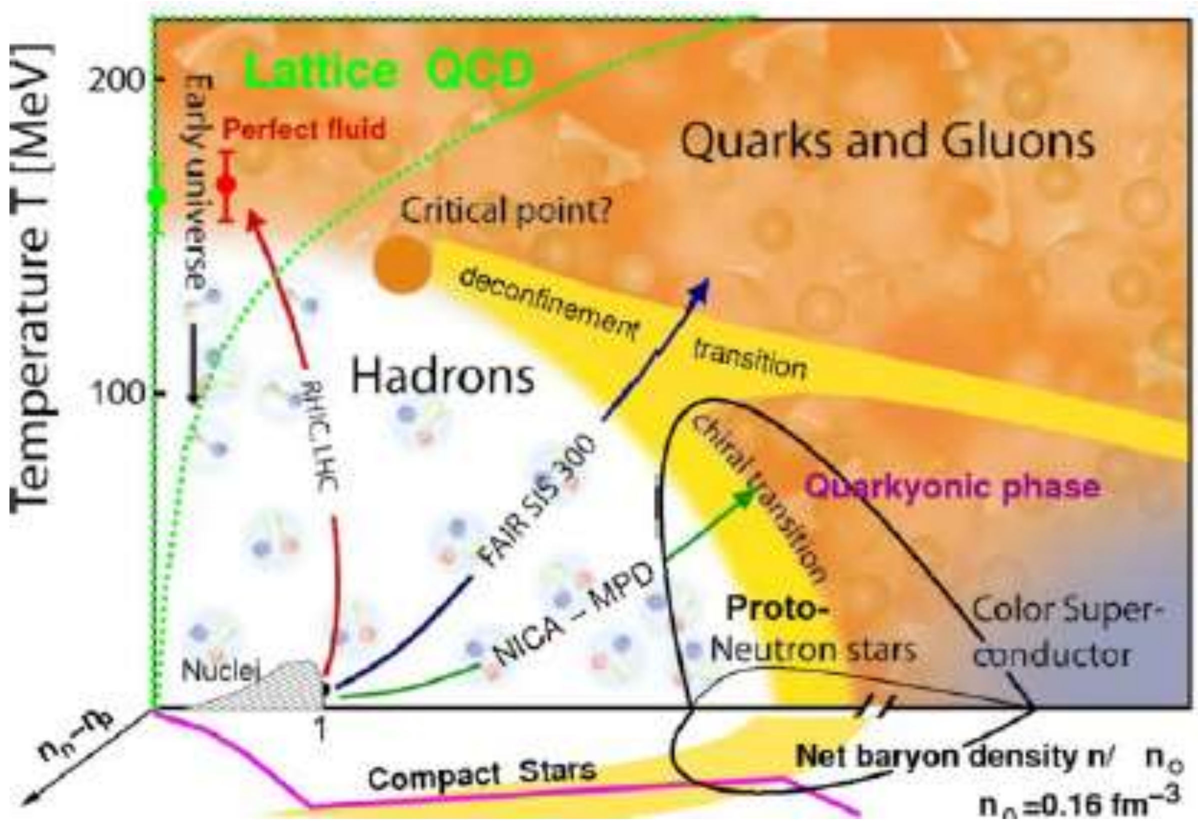


Fig. 1. Total cross sections for the $pp \to K^+ \Lambda p$ (closed symbols) and $pp \to K^+ \Sigma^0 p$ (open symbols) reactions as a function of the excess energy ϵ. Results from COSY [1,2,11,13,14] are indicated by circles, while the squares are data from Ref. [25]. The solid lines are our results for the Λ and Σ^0 reaction channels, respectively. The dashed line is obtained by switching off the Λp final-state interaction.

arXiv:hep-ph/0608098, A.Sibirtsev et al.

No FSI for Σ ?



Let's consider cold and dense fermion rich system with u/d≠1.

"cold" means small internal energy per degree of freedom E « m_π

"dense" means δpδx ~ ħ

N_n must to be ~ N_P due to Pauli blocking

Strong deviation ∑-(dds)/∑+(uus) ratio from 1 could be a solution

Σ+(uus)/Σ-(dds) ratio is ideal instrument for the study of electromagnetic effects

Coulomb correction in classical approximation(Gyalassy M.,Kaufmann S.K.,Nucl.Phys.1981,A362,p.503), see also discussion in L.S.Vorobiev,G.A.Lexin, A.S.(Yad.Fiz. 1996,v.59, n.4, p.694)

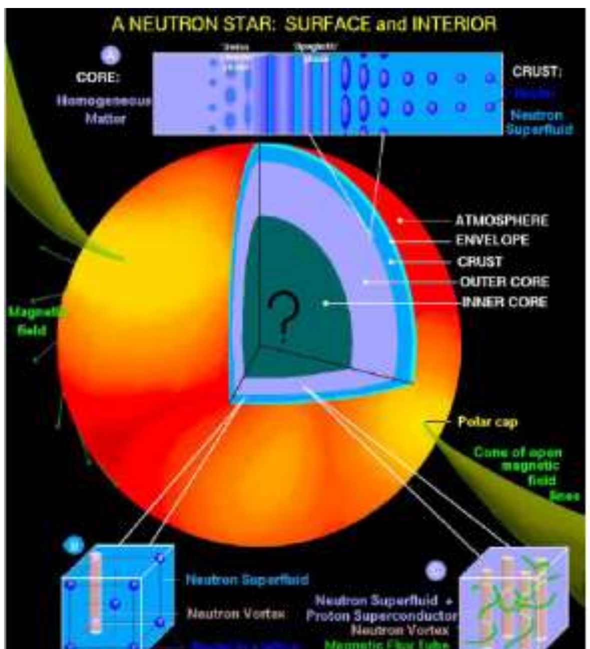
$V \sim Z_1 * Z_2 e^2/r$; $r \sim 2fm$, $Z_2 = \pm 1$, $0 < Z_1 < Z_{A1} + Z_{A2}$

$\delta V_{\Sigma+\Sigma-}$ (max) ~ 0.3 Mev(p+p), 2MeV(C+C), 6Mev(Ar+KCl), 11Mev(Kr+Cu), 28MeV(Au+Au)

For comparison: $M_{\Sigma+\ (1189,37)} - M_{\Sigma-(1197,45)}$ ~ 8 MeV

An example of dense cold matter: Neutron star

Under the effect of the gravitational collapse of a core heavier than 1.4 solar masses, the matter is forced into a degenerate state: electrons are unable to remain in their orbits around the nuclei (they would have to traver faster than light in order to obey the Pauli exclusion principle) and they are forced to penetrate the
atomic nuclei. So they fuse with protons, and form neutrons. Pauli's principle, that we've seen before, forbids two neutrons having the same state to stay in the same place . This principle
creates a degeneracy pressure fighting against gravity, and so allows the remnant of the star to find an equilibrium state.The result of this process is a so called 'neutron star', whose diameter is about 10 to 20 kilometers, weighting as much as the Sun.



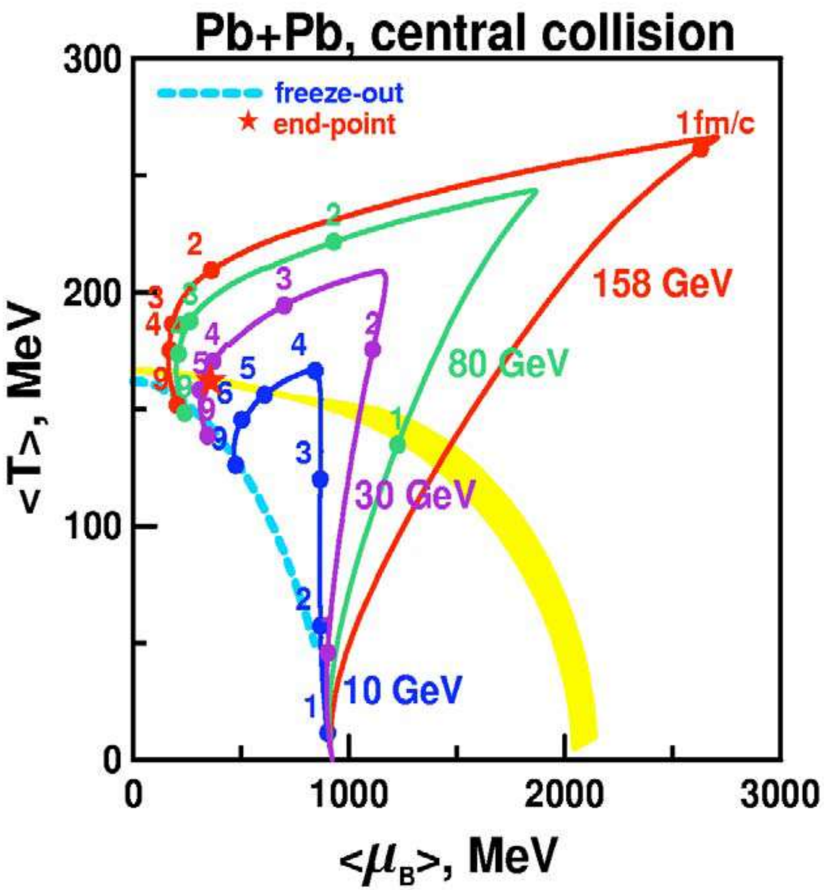
Only in the most primitive conception, a neutron star is constituted from neutrons.
At the densities that exist in the interiors of neutron stars, the neutron chemical potential, μ_n, easily exceeds the mass of the so that neutrons would be replaced with hyperons. This would happen for neutron Fermi momenta correspond to densities of just $\sim 2\rho_0$, with $\rho_0 = 0.16\ \mathrm{fm}^{-3}$ the baryon number density of infinite nuclear matter.(F.Weber et.al.,astro-ph/0604422)

*strangeness enhancement in DCM

**exotic(dibaryons, pentaquarks,...)

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