Some aspects of BM@N physical program

A.Stavinskiy[1,2] for BM@N collaboration

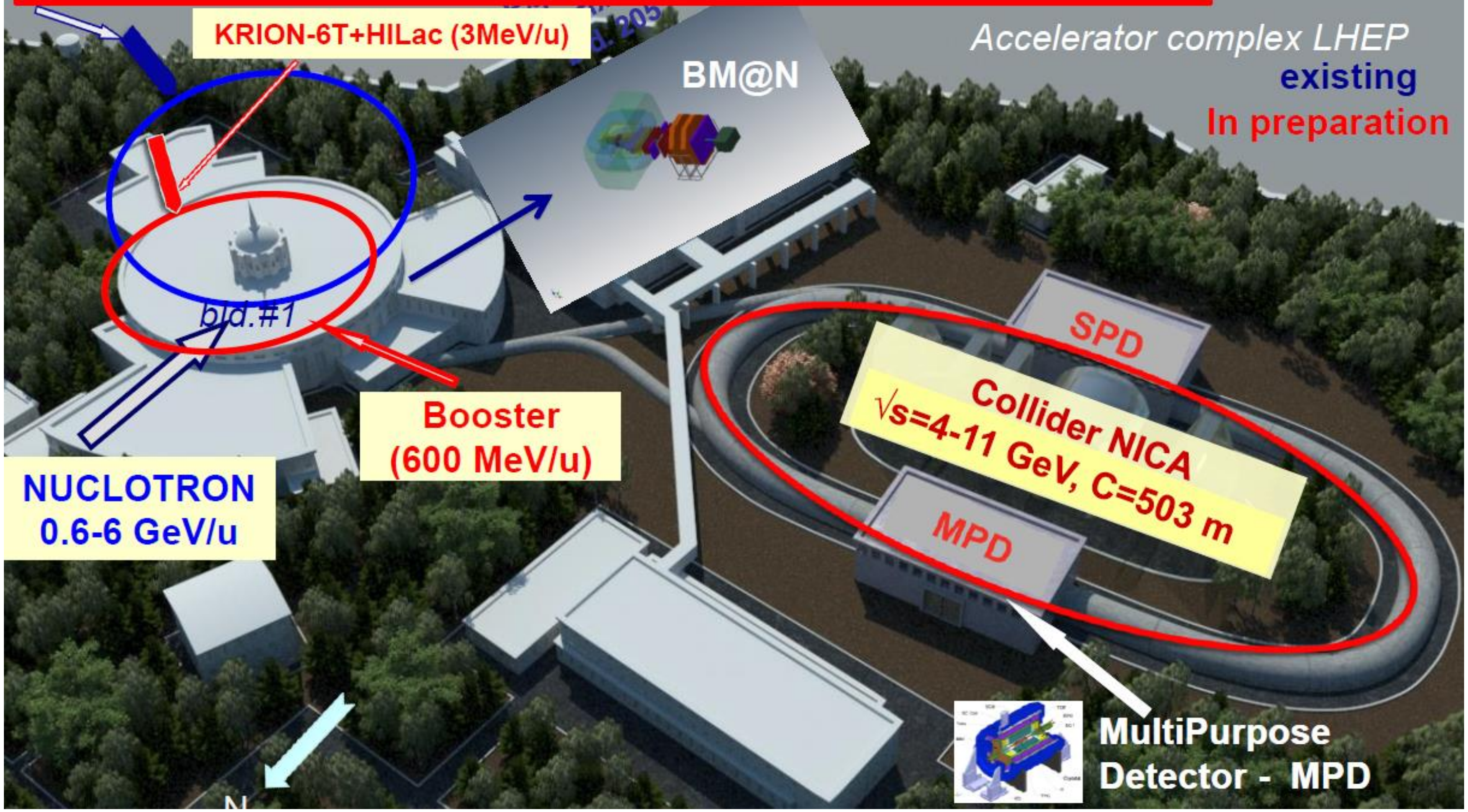
1.NRC “Kurchatov Institute” - ITEP (Moscow)
2.JINR

Baryonic Matter at Nuclotron (BM@N)

JINR (Dubna), IHEP (Protvino), INR RAS (Troitsk), ITEP (Moscow), SINR MSU, MEPHI, Plovdiv Uni, WUT (Warsaw), Goethe Uni (Frankfurt), MoU with GSI (Darmstadt) + SRC team

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)



1. Strange baryons at BM@N

Physics possibilities at the Nuclotron

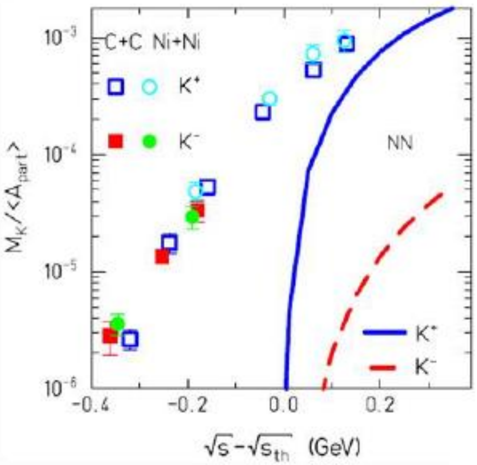
I. In A+A collisions at Nuclotron energies:

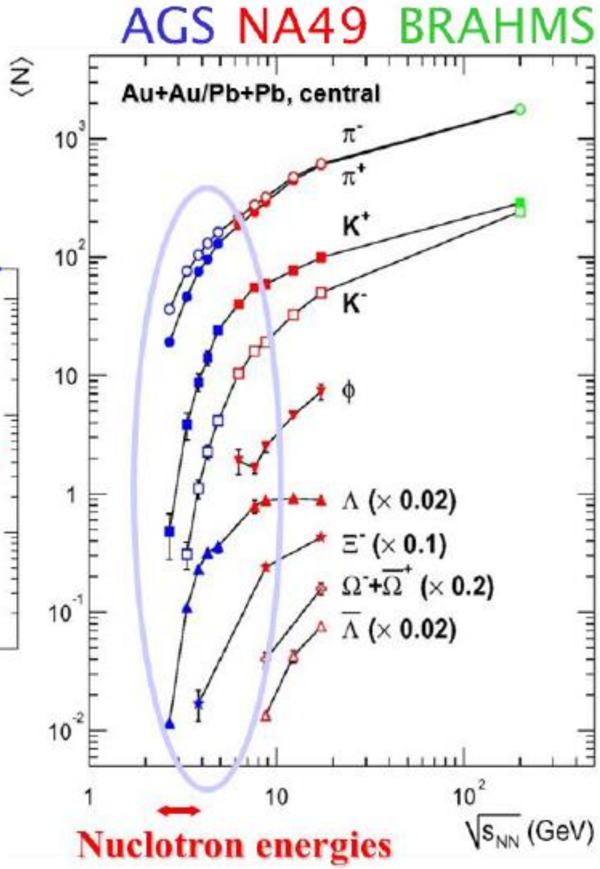
❑ Opening thresholds for strange and multi-strange hyperon production

➔ strangeness at threshold

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

▶ Collective flows v_1, v_2





Nuclotron energies

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

Strange baryons:Λ,Ξ^-. Why no $\Sigma(\Sigma^-,\Sigma^0,\Sigma^+)$?

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

3AGeV: $K^+ + K^0$ (13625) ~ $\Lambda+\Sigma$(13035).

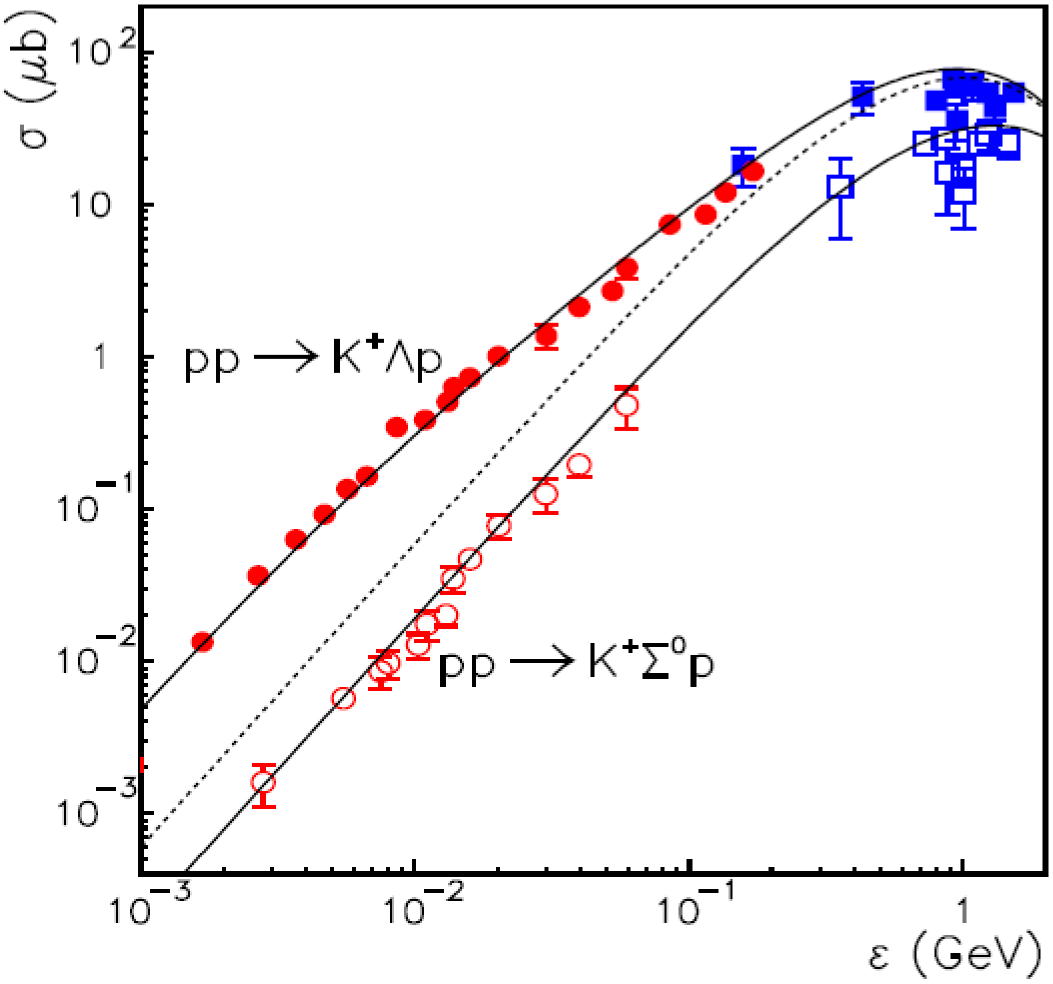


Fig. 1. Total cross sections for the $pp \to K^+ \Lambda p$ (closed symbols) and $pp \to K^+ \Sigma^0 p$ (open symbols) reactions as a function of the excess energy ϵ. Results from COSY [1,2,11,13,14] are indicated by circles, while the squares are data from Ref. [25]. The solid lines are our results 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 ?

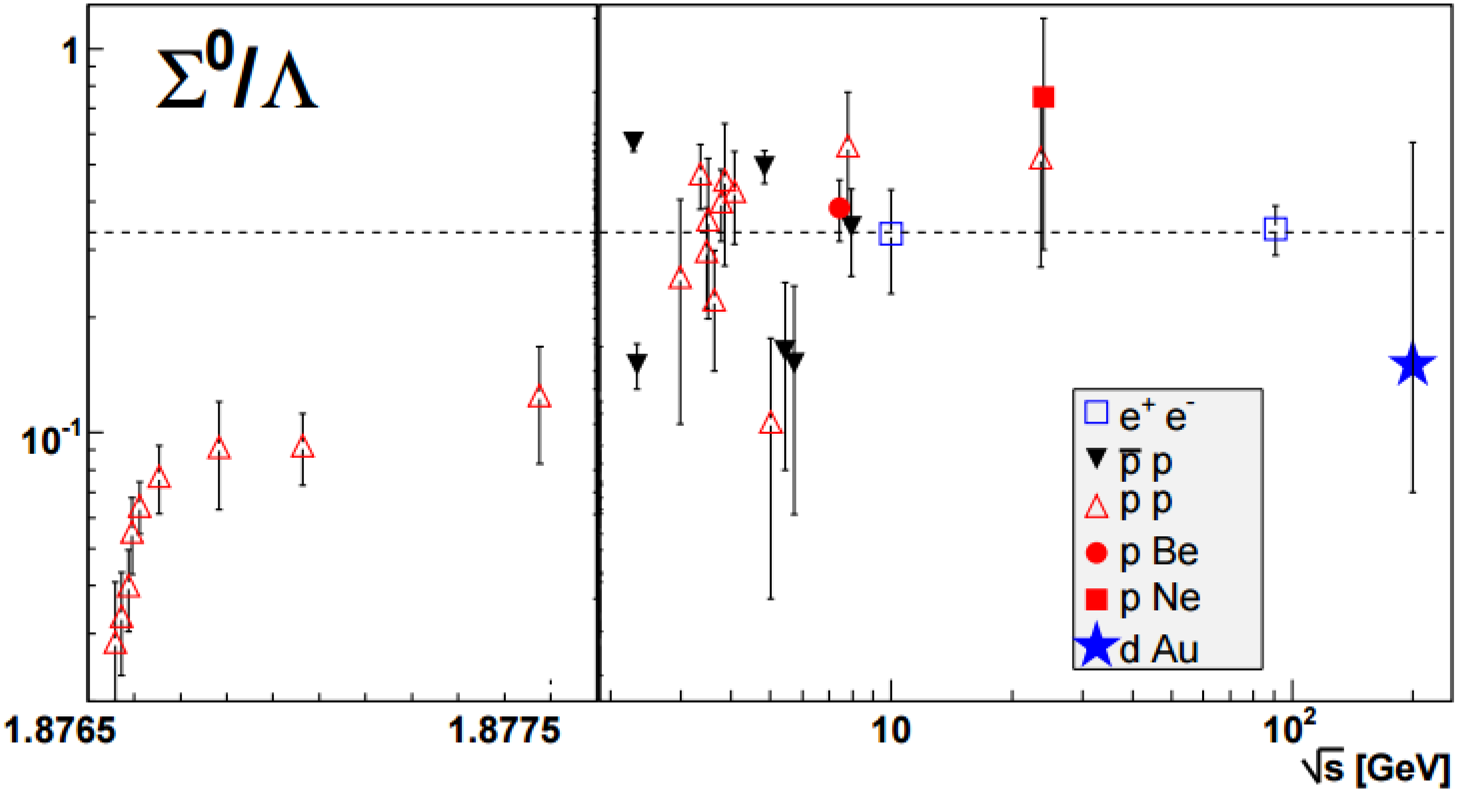


Figure 4: Σ^0/Λ results versus collision $\sqrt{s}$ ($\sqrt{s_{\mathrm{NN}}}$ for p/d+A) [1]. Meson-nucleon reaction results are excluded for clarity, but exist only at intermediate energies and lie in the same range. The dashed line is the ratio of isospin degeneracy factors (1/3).

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!

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)**

Femtoscopy.

Λ: $\Sigma(1385) \rightarrow \Lambda\pi$(87%), $\Sigma\pi$(12%), $\Sigma^0 \rightarrow \Lambda\gamma$(100%), $\Xi^0 \rightarrow \Lambda\pi^0$(99.5%), $\Xi^- \rightarrow \Lambda\pi^-$(99.9%)

P: $\Lambda \rightarrow p\pi^-$(64%), $\Sigma^+ \rightarrow p\pi^0$ (52%), $\Sigma^0 \rightarrow \Lambda\gamma$(100%)$\rightarrow p\pi^-$(64%)

To mesure Λp, better to know $\Xi^0 p$, $\Xi^- p$, $\Sigma(1385)p$, $\Sigma^0 p$, $\Sigma^+\Lambda$, $\Lambda\Lambda$, $\Sigma^0\Lambda$ interactions.

$a_{pp}(^1S_0)$=-7.8 fm; $a_{np}(^1S_0)$=-23.7 fm; $a_{nn}(^1S_0)$=-16.4 fm.

$a_{p\Lambda}(^1S_0)$=-2.7 fm; $a_{\Sigma+p}(^1S_0)$=-3.85 fm; $a_{\Lambda\Lambda}(^1S_0)$=-0.88 fm[1]

[1] Th.A.Rijken, M.M.Nagels, Y.Yamamoto,
Progress of Theoretical Physics Suppl.N0.**185**(2010),14

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.

Λ in deuteron and carbon beams

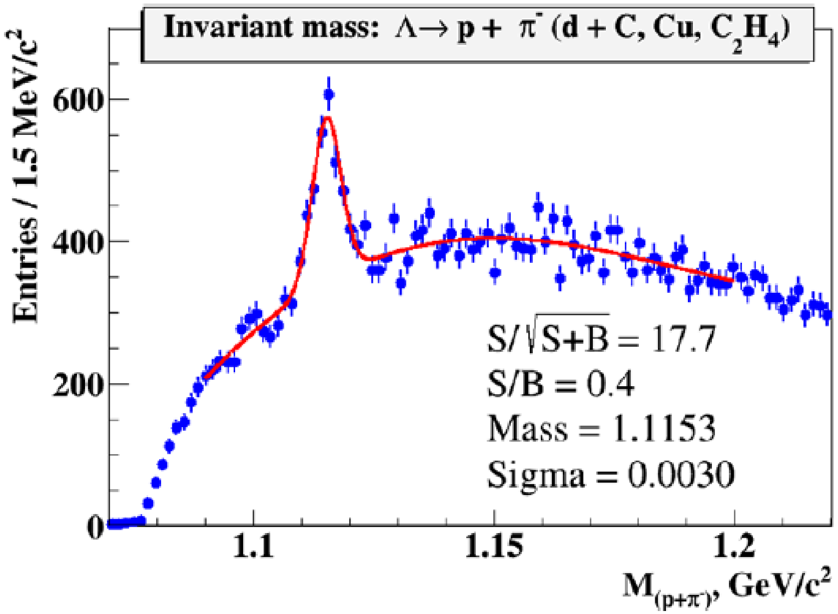
d (C) + A → X

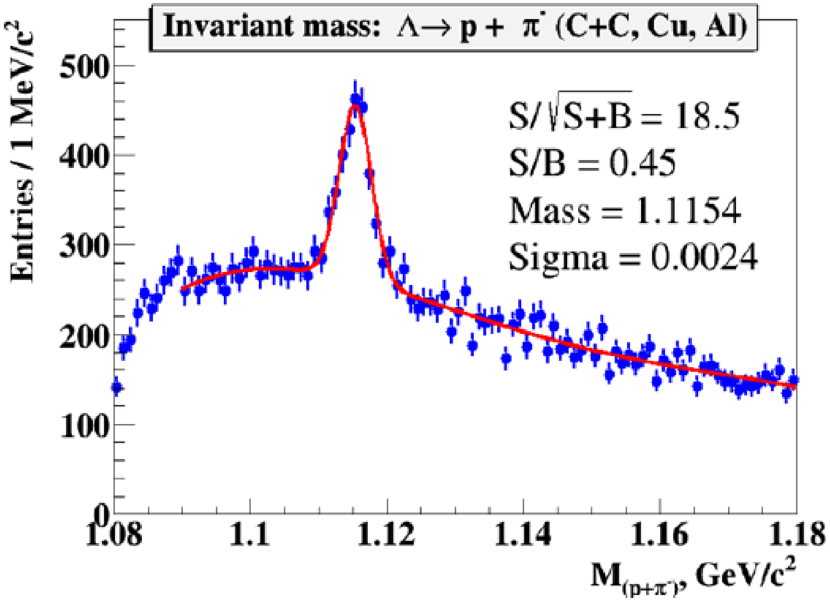
G.Pokatashkin, I.Rufanov,
V.Vasendina and A.Zinchenko

Λ signal width of 2.4 - 3 MeV

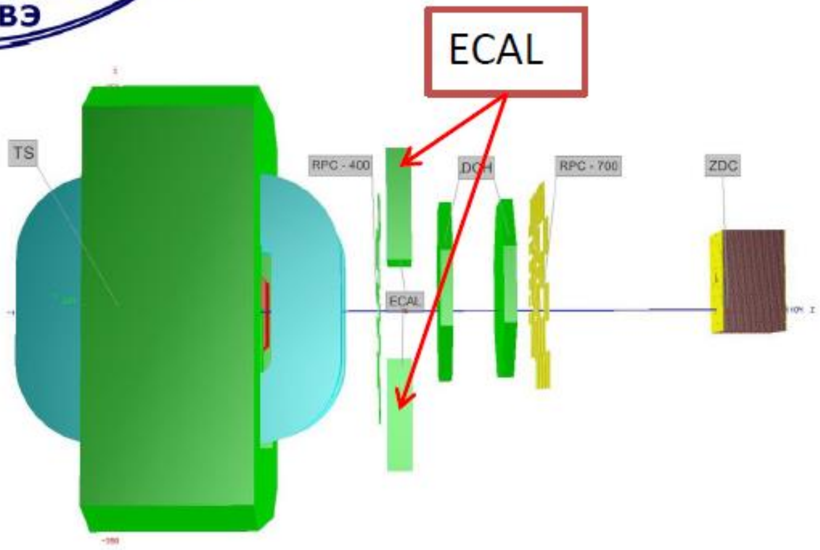
Deuteron Data

Carbon beam run, 4 AGeV

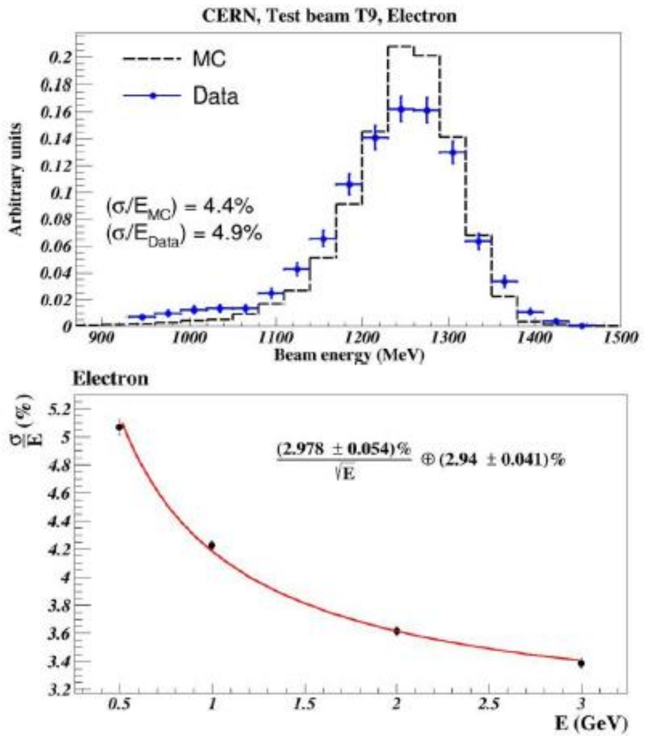


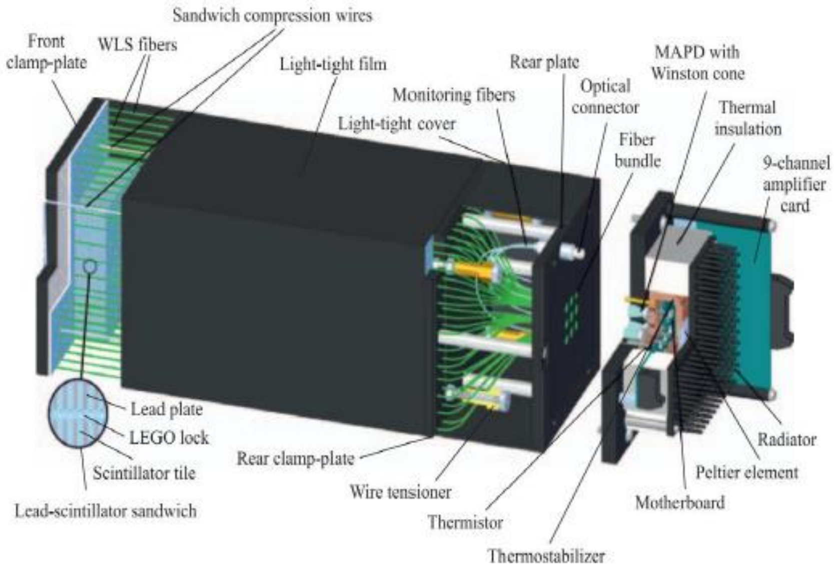


Electromagnetic calorimeter (optional)



Energy resolution





Design of the Shashlyk type calorimeter module

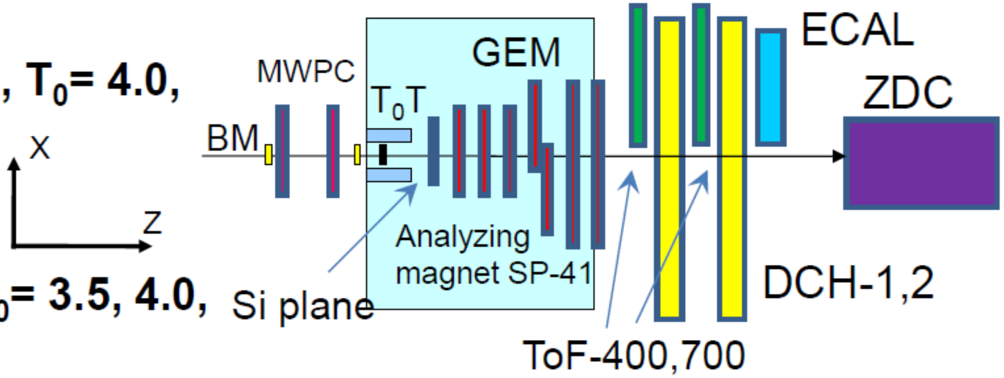
Parameters	
Transverse size, mm²	40x40
Module size, mm²	120x120
Number of layers	220
Lead absorber thickness, mm	0.3
Polystyrene scintillator thickness, mm	1.5
Moli'ère radius, mm	26
Radiation length, X_0	11.8

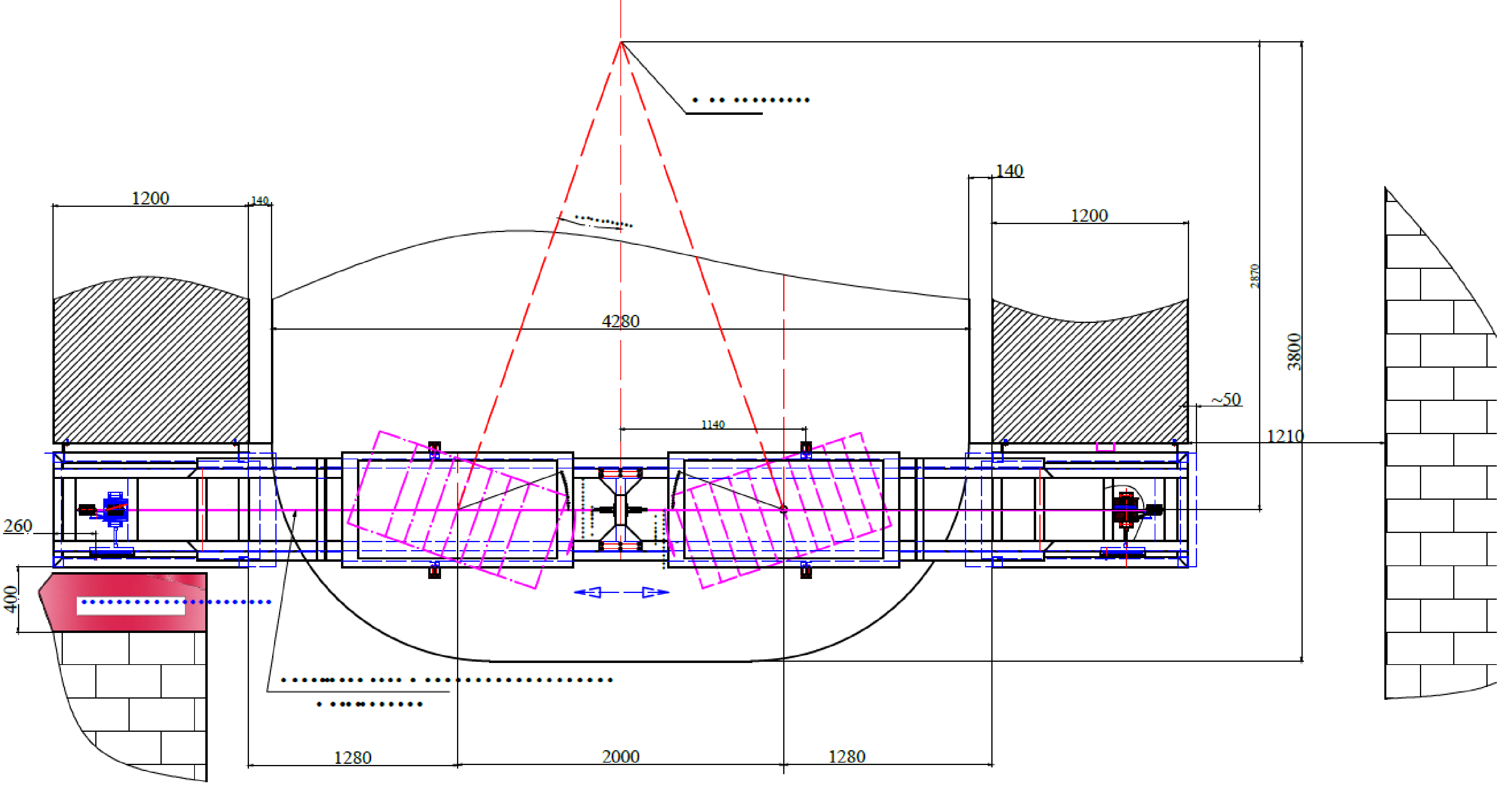
I.Tyapkin

BM@N in technical runs with deuteron and carbon beams

Deuteron beam, T_0= 4.0, 4.6 GeV/n

Carbon beam, T_0= 3.5, 4.0, 4.5, (5.14) GeV/n

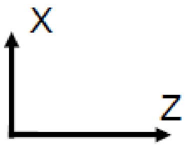




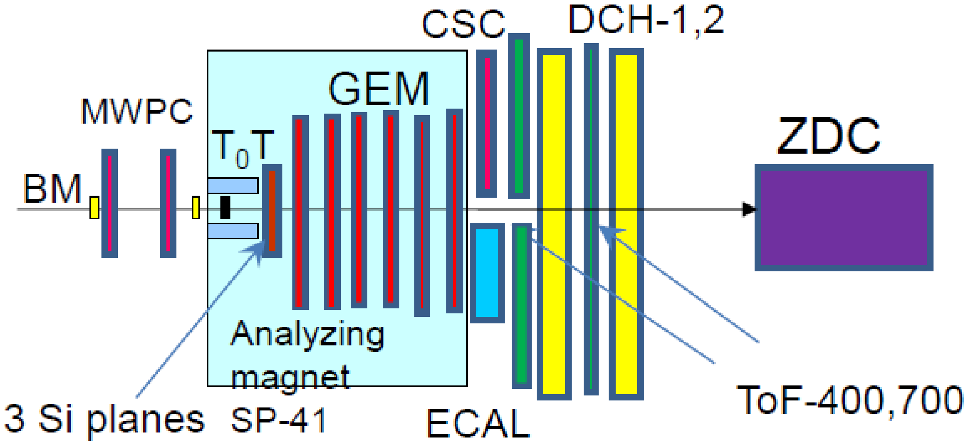
V.Semyachkin,A.S.

BM@N run with Ar and Kr beams in March 2018

Ar beam, T_0= 3.2 GeV/n



Kr beam, T_0= 2.3 (2.9) GeV/n



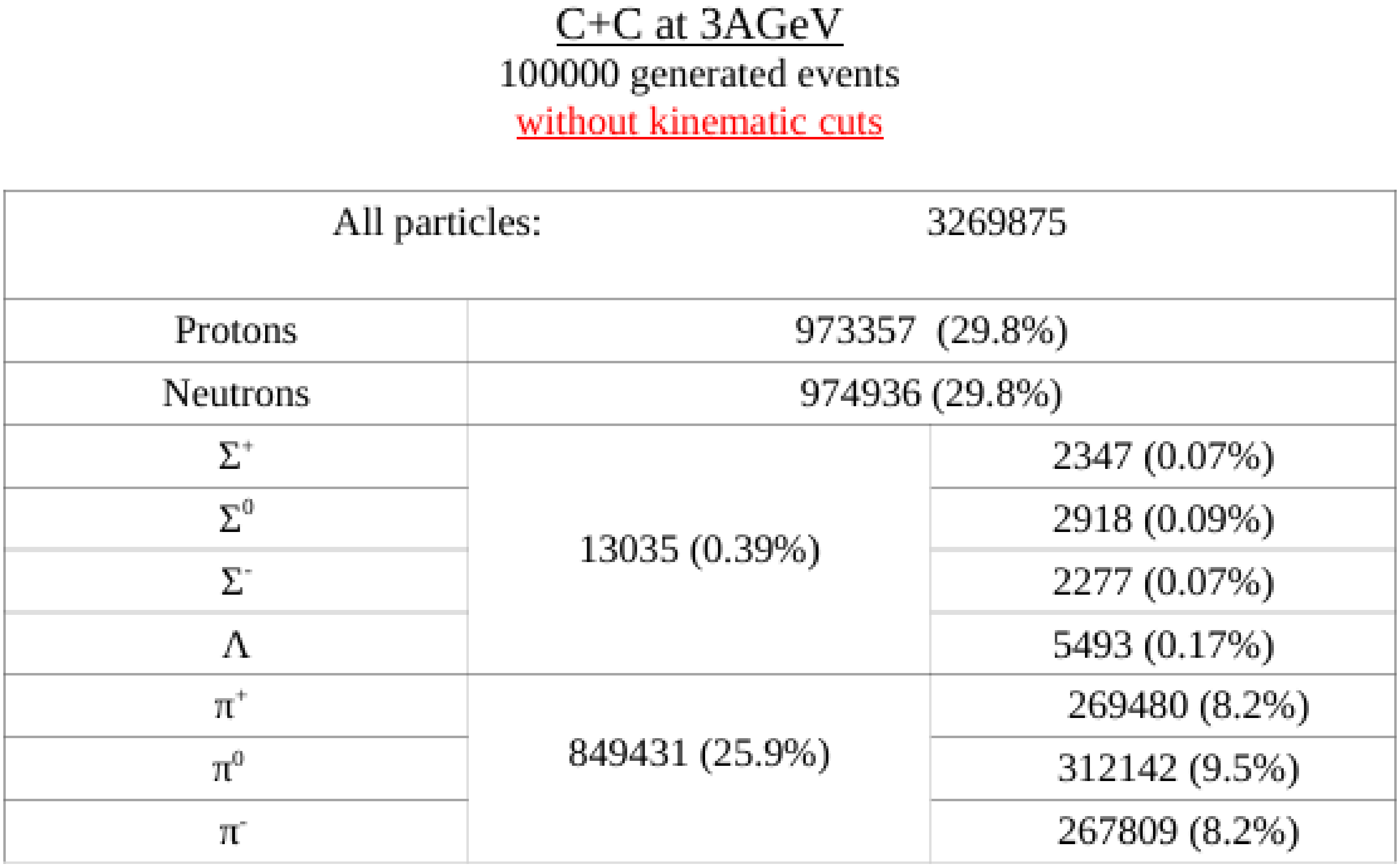
- Central tracker inside analyzing magnet → 6 GEM detectors 163 x 45 cm^2 and 3 forward Si strip detectors for tracking
- Full ToF-400, ToF-700, T0 + Trigger barrel and Si detectors, full ZDC, part of ECAL, CSC and DCH chambers as outer tracker

Program:

- Measure inelastic reactions Ar (Kr) + target → X on targets Al, Cu, Sn, Pb

→ Hyperon production measured in central tracker (Si + GEM)
→ Charged particles and nuclear fragments identified with ToF-400,700
→ Gamma and multi-gamma states identified in ECAL
→ 130 M events in Ar beam, 50 M events in Kr beam

+ analyze data from previous technical runs with Deuteron and Carbon beams of 3.5 - 4.6 GeV/n performed in December 2016 and March 2017



C+C at 3AGeV

100000 generated events

without kinematic cuts

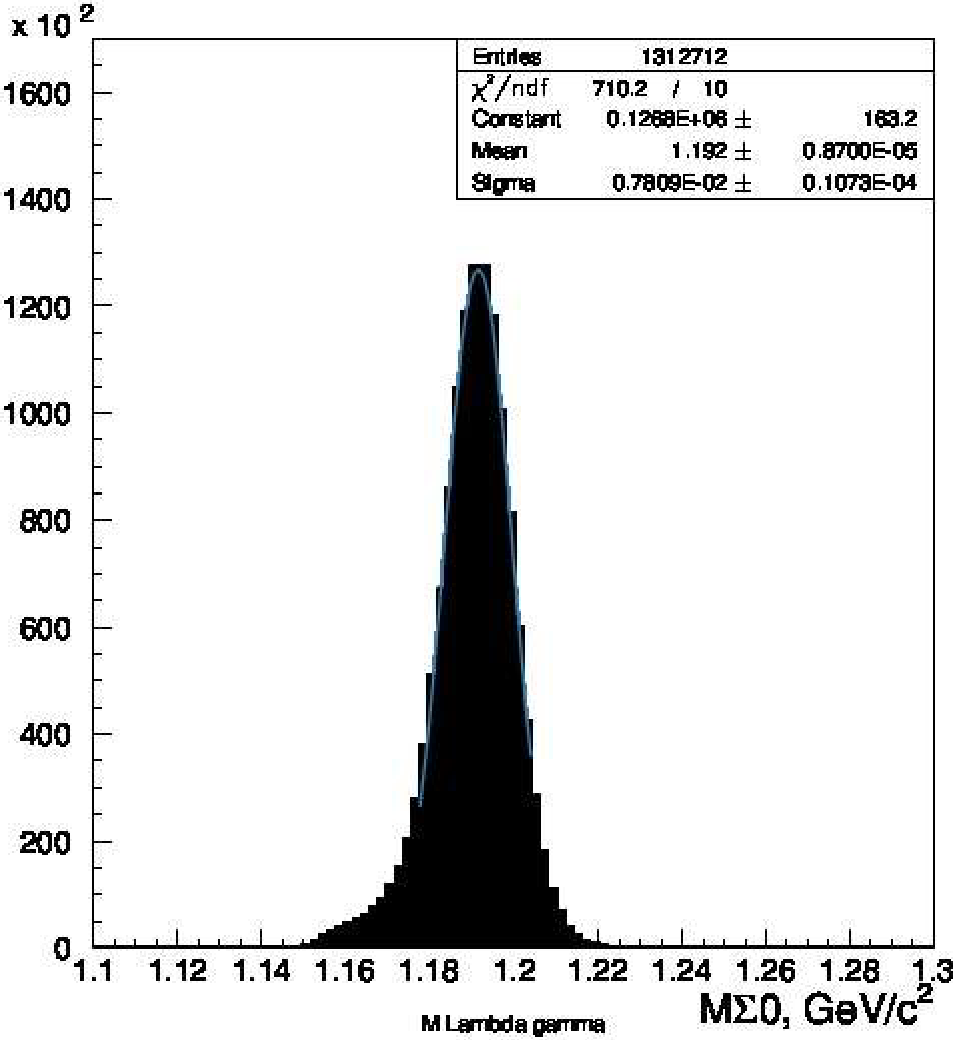
All particles:	3269875	
Protons	973357 (29.8%)	
Neutrons	974936 (29.8%)	
Σ^+	13035 (0.39%)	2347 (0.07%)
Σ^0		2918 (0.09%)
Σ^-		2277 (0.07%)
Λ		5493 (0.17%)
π^+	849431 (25.9%)	269480 (8.2%)
π^0		312142 (9.5%)
π^-		267809 (8.2%)

Photon(ECAL Acceptance) ~ 1%;
Λ~1/10; δM_Σ~ 10 MeV, Rate estimate ~ 0.3 sec^{-1}
(N.Zhigareva,A.S.)

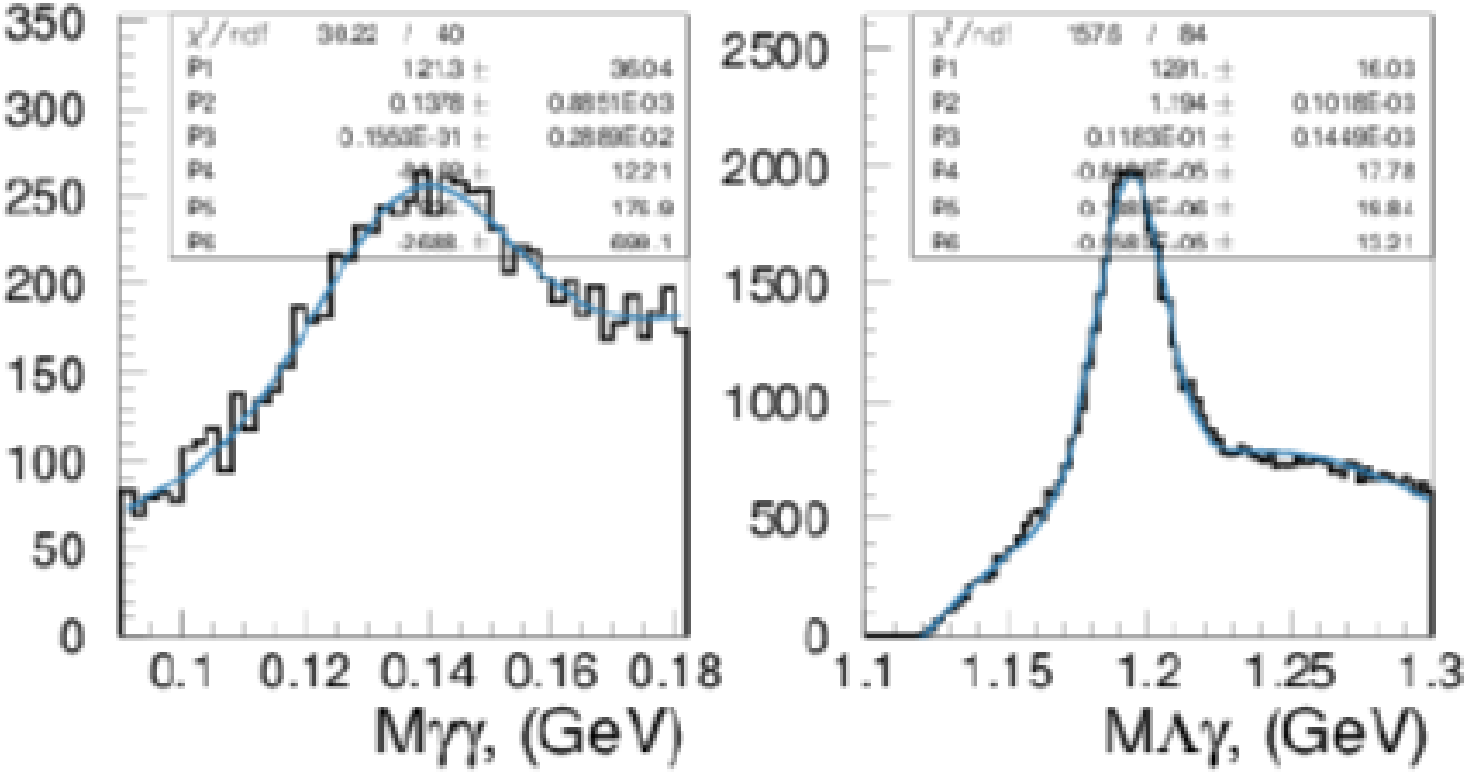
The UrQMD Model
(The Ultrarelativistic Quantum Molecular Dynamics model)
v. 3.4 (http://urqmd.org/documentation/)

Simulations show ~8MeV mass resolution for Σ0 and ~7MeV mass resolution for difference in Σ0 and Λ masses

Calorimeter has ~6.2% geometrical acceptance for γs from Σ0 decay and high ~99% reconstruction efficiency in the clean (no background) conditions



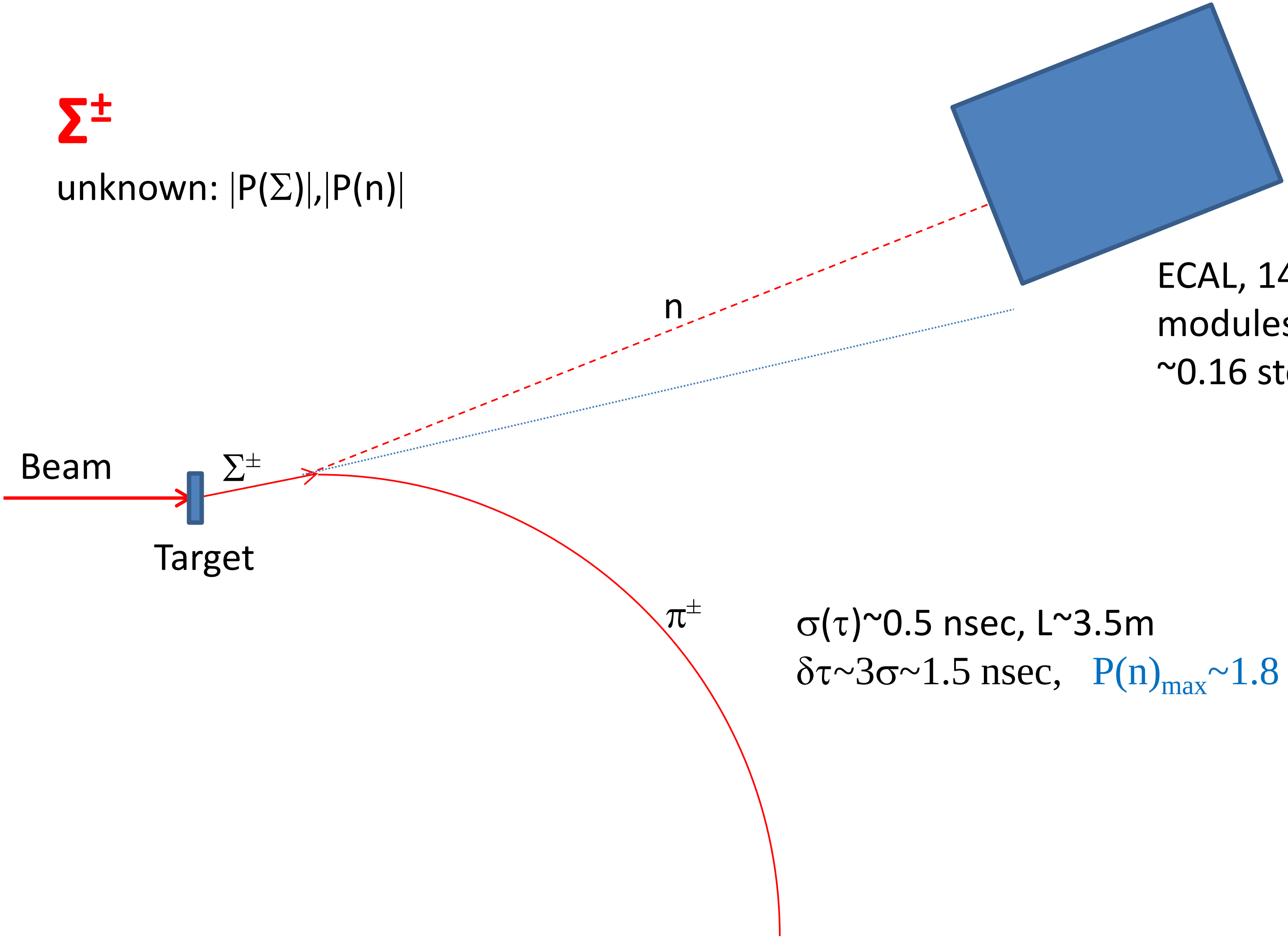
I.Larin,V.Tarasov



Simulation of π^0 and Σ^0 reconstruction; UrQMD, CC interaction, I.Larin, V.Tarasov(ITEP), JINR, BM@N meeting 27.12.2017

$\Sigma^{\pm}$

unknown: $|P(\Sigma)|, |P(n)|$



ECAL, 140 modules, ~0.16 ster.

$\sigma(\tau)$~0.5 nsec, L~3.5m

$\delta\tau \sim 3\sigma \sim 1.5$ nsec, $P(n)_{max} \sim 1.8$ GeV/c

2. Short range correlations at BM@N

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),

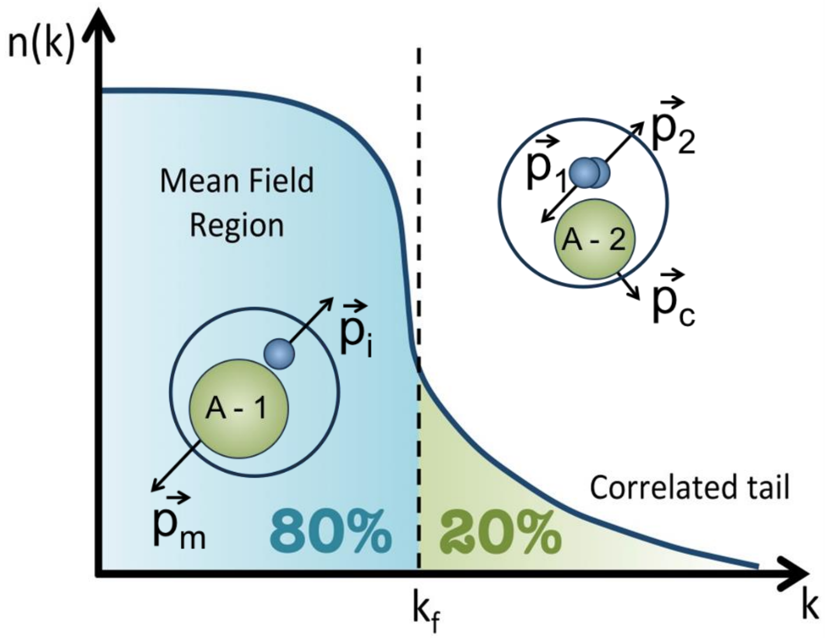
Coordinators:

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

The stability of atomic nuclei is a result of a delicate interplay between the long-range attraction that binds nucleons and the short-range repulsion that prevents the collapse of the system. In between, the dominant scalar part of the nucleon-nucleon (NN) force almost vanishes and the interaction is dominated by the tensor force, which depends on the spin orientations and the relative orbital angular momentum of the nucleons.

Already in a 1953 Scientific American journal article, Hans Bethe claimed that probably more man-hours had been devoted to understanding the nucleon-nucleon interaction and how it forms atomic nuclei than to any other scientific question in the history of mankind. Even today, more than 60 years later, our theoretical and experimental knowledge of the short-range part of NN interaction is very limited.

2N-Short Range Correlations

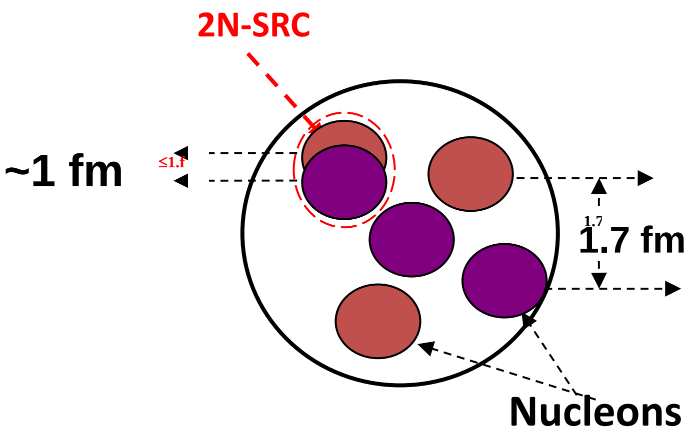


Occasionally nucleons are at close proximity in the nucleus

Each individual nucleon has high momentum

Low center of mass momentum of the pair relative to k_F

What SRC can teach us?

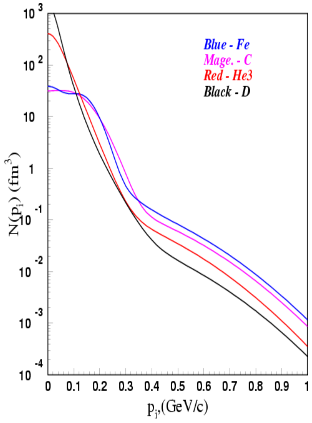


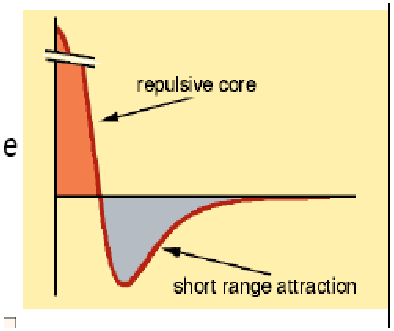
- High momentum component of the nuclear wave function

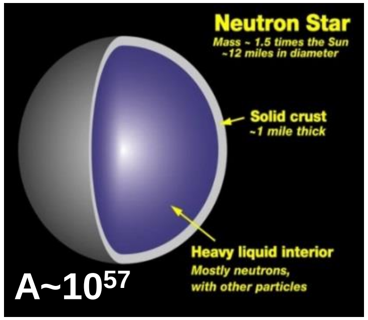
- **The strong short-range force between nucleons (tensor force, repulsive core, 3N forces)**

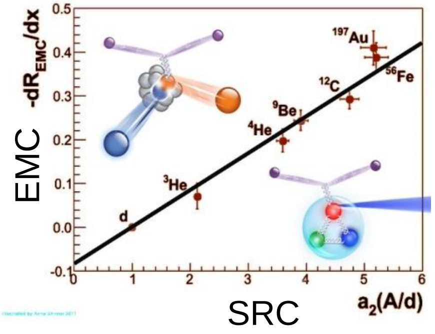
- Cold dense nuclear matter (from deuteron to neutron stars)

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









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].

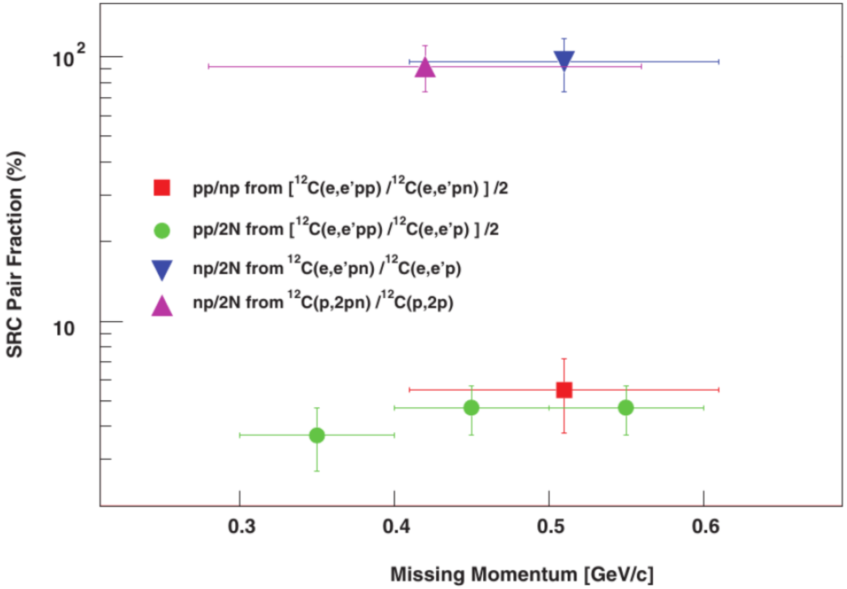
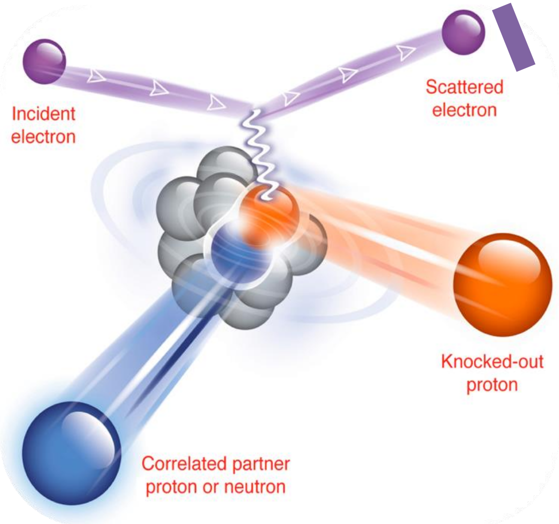
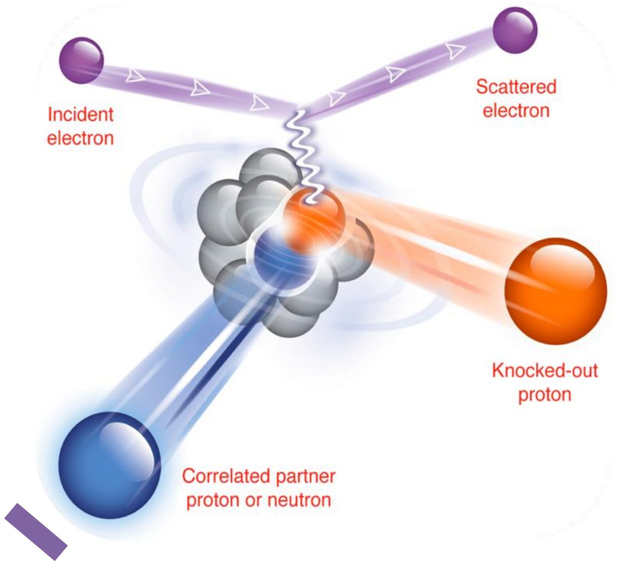


Figure 1: The fractions of correlated pair combinations in carbon as obtained from the ^{12}C(e, e’pp) and ^{12}C(e, e’pn) reactions measured at JLab [1,2] as well as from previous, ^{12}C(p,2pn) data from BNL [3,4].

How to study SRC? - Break up the pair!

Hard scattering in direct kinematics





Inclusive measurement

Detect scattered probe A(e, e’)

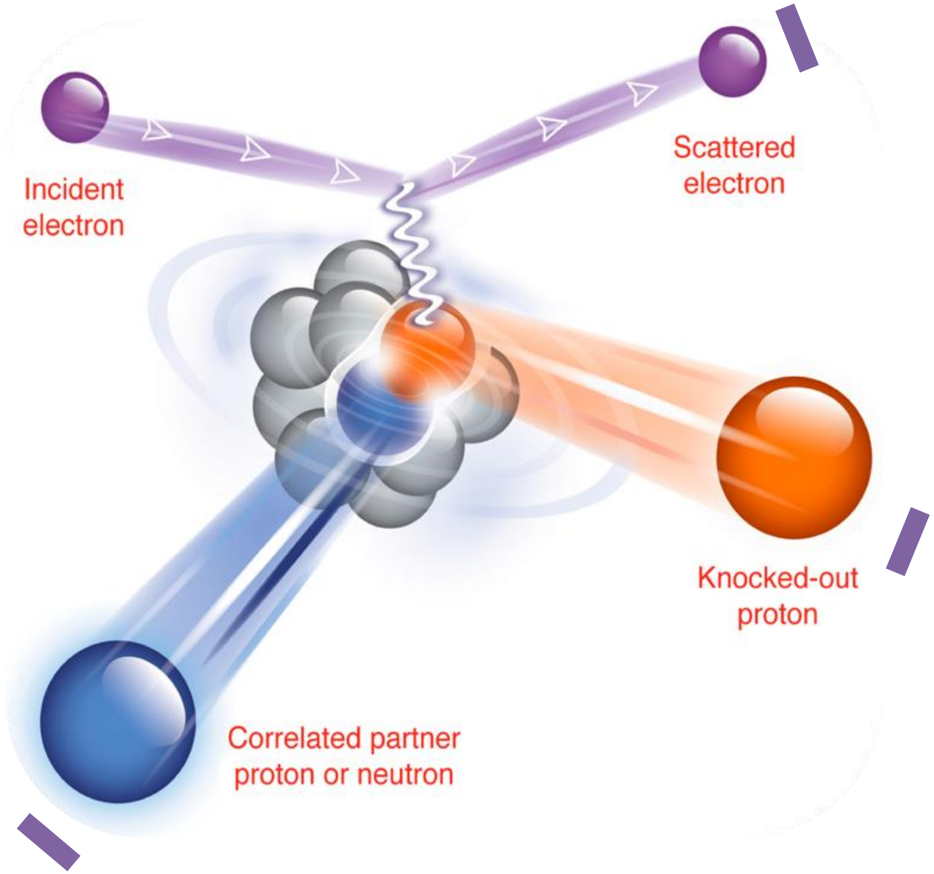
OR

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

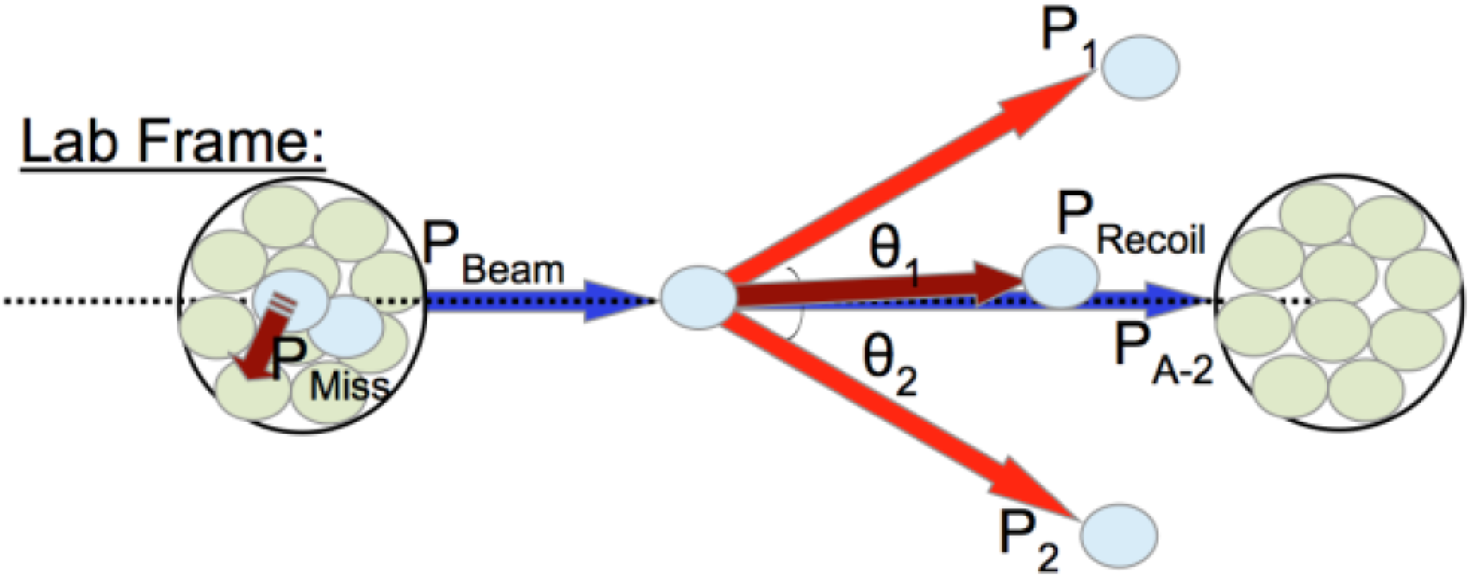
A(e, e’pp) - JLab
A(e, e’pn) - JLab
A(p, 2pn) – BNL

Also inverse kinematics:

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

2 Experimental Setup

The typical kinematics of a scattering off a SRC-pair is shown in figure 7. A proton (P_{miss}) from the SRC-pair in the carbon nucleus is scattered from a proton inside the target. The two leading protons have a large angle with respect to each other in the lab system. The short-range correlated nucleon emerges forward. The A-2 system moves along the beam direction after the scattering. We plan to detect the leading protons, the A-2 system, and possibly the recoil neutron or proton for np-SRC and pp-SRC pairs respectively.



Why Nuclotron at JINR?

P_F(~200 MeV/c) «P_{SRC} (~800 MeV/c) «$P_{beam/nucleon}$(~4GeV/nucleon)

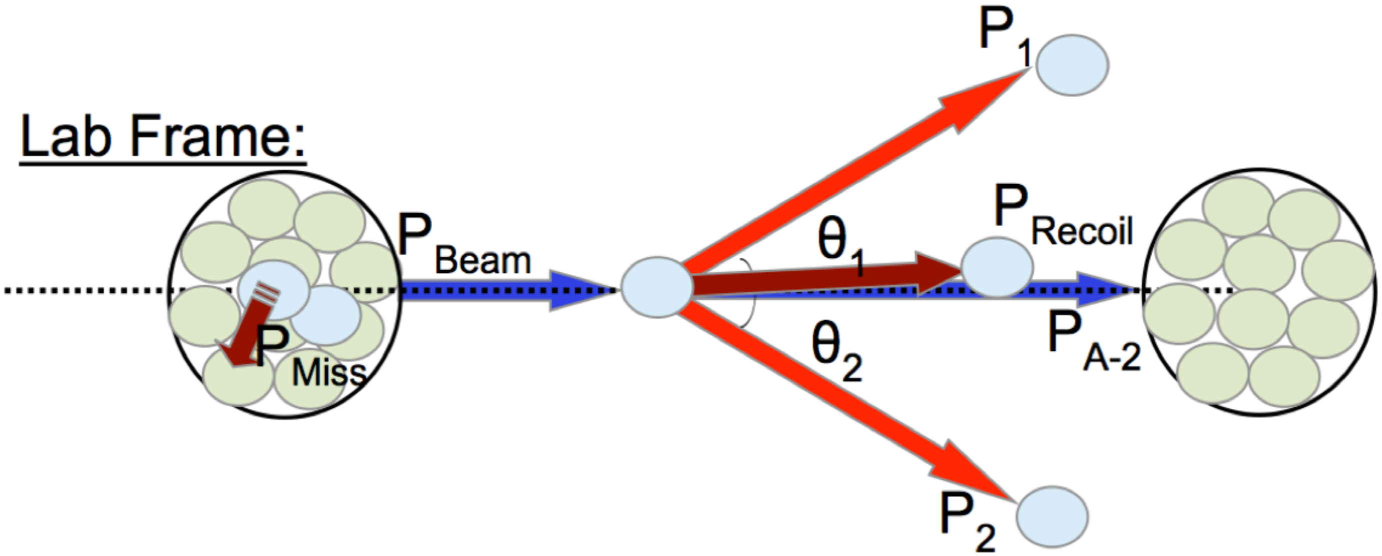
The experiment proposed here intends to:

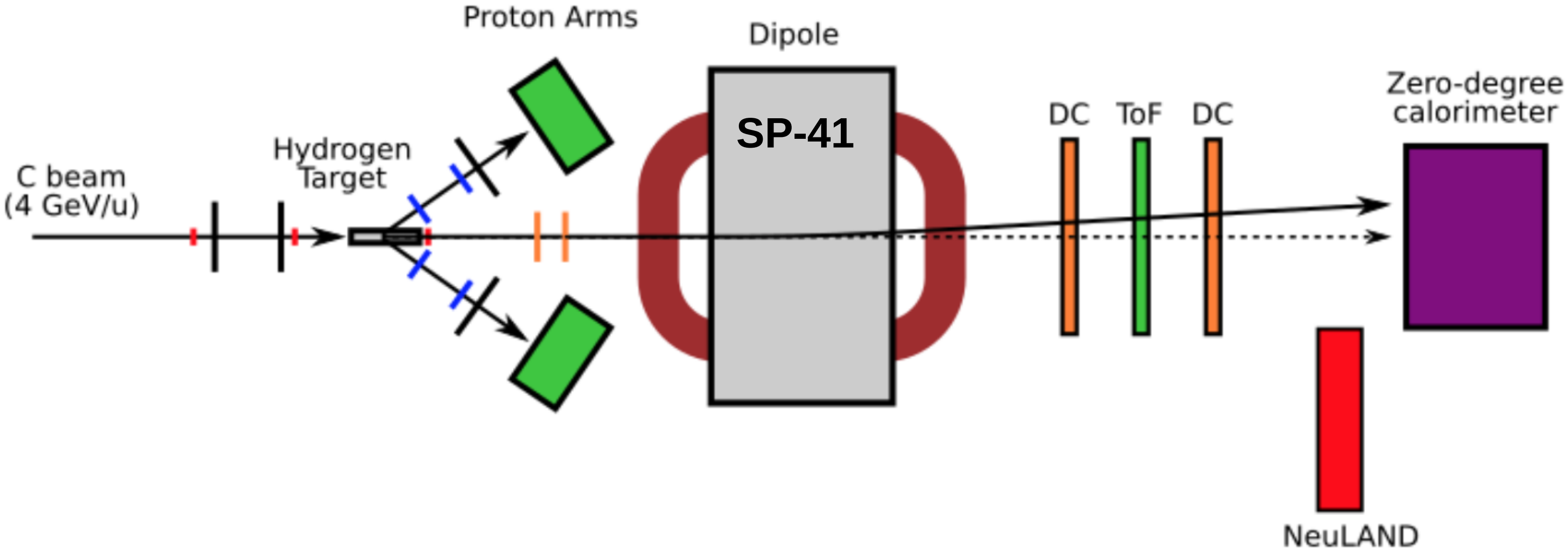
(A) verify the previous phenomenological findings with different reaction/kinematics and

(B) allow a first observation of the A-2 system left after the hard breakup of the SRC pair from the 12C nucleus.

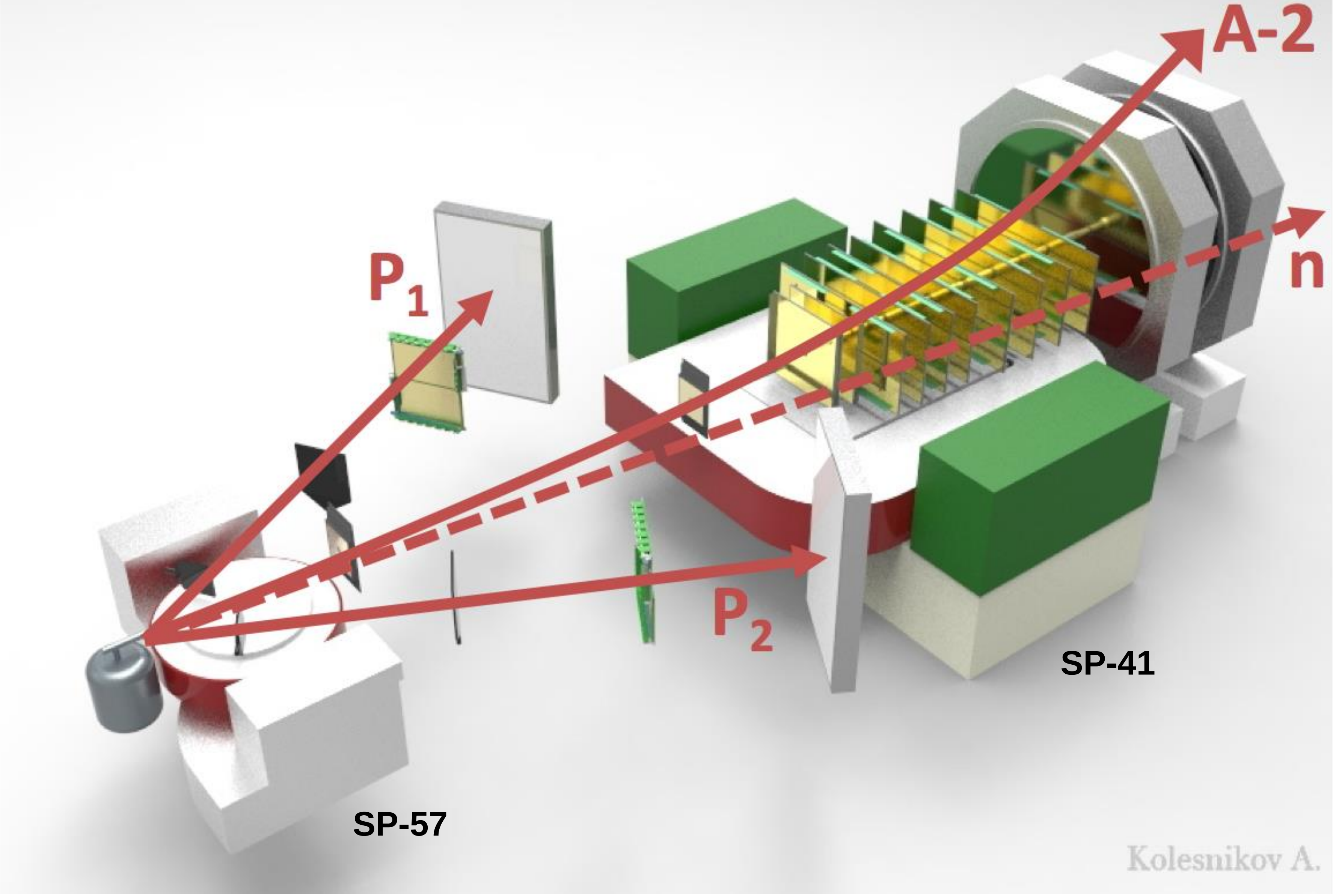
The use of a nuclear beam and a hard knockout reaction in inverse kinematics can be a breakthrough in SRC research and can open the way to the development of a new experimental program. In particular, these will enable future studies of SRCs in nuclei far from stability using radioactive beams and will make accessible detailed information on the origin and formation process of SRC pairs through direct measurements of the A-2 system (with gamma spectroscopy and other techniques).

Kinematics


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


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

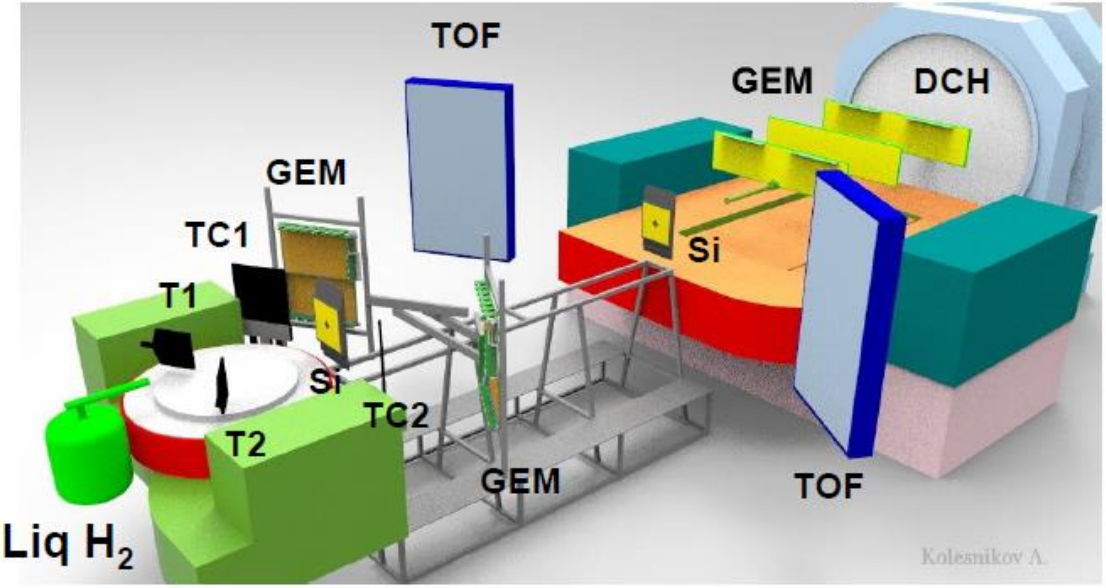
Experimental setup



BMN & SRC set-up

Talk of E.Piasetzky

Cuts
$\|\theta_{1,2}-30^o\|<6.5^o$
$\|\Delta\varphi_{1,2}\|<7.5^o$
$\|s,t,u\|>2\ (GeV/c)^2$
$P_{miss} > 0.275$ GeV/c



Trigger:
T0 · T1 · T2 · TC1 · TC2

T0 +Target + T1

Signal rates for 14 days of data taking

Within LAND acceptance

$^{12}C + p \rightarrow {}^{10}B + pp$ np SRC

$^{12}C + p \rightarrow {}^{10}Be + pp$ pp SRC

$^{12}C + p \rightarrow 2p + {}^{10}_{5}B + n$ np SRC

$^{12}C + p \rightarrow 2p + {}^{10}_{4}Be + p$ pp SRC

→ First SRC @ BMN run in March 2018: collected 8 M events

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

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:

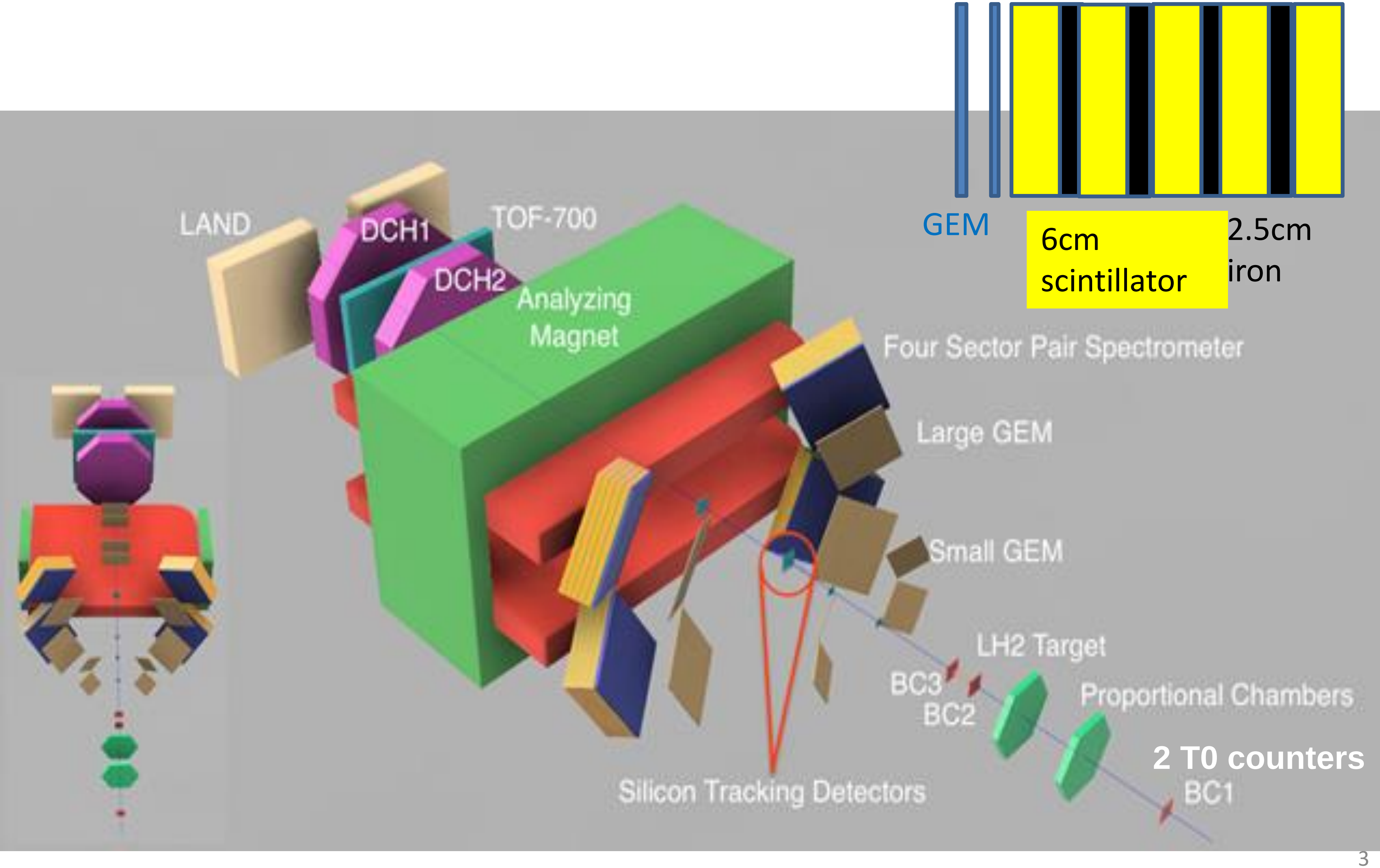
Two(at least) possible model:

1.”Izolated” flucton(as supposed in proposal)→ ct» r_C

2.”Nonizolated” flucton(due to energy-momentum conservation) → ct ~ r_C

Thank you for the attention and
welcome to collaboration!

Ideas for the future



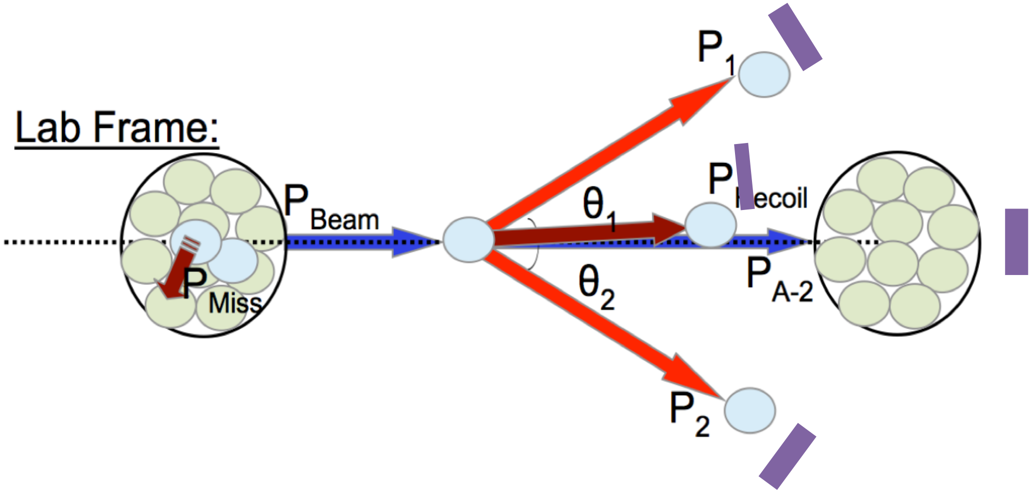
GEM

6cm
scintillator

2.5cm
iron

2 T0 counters

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

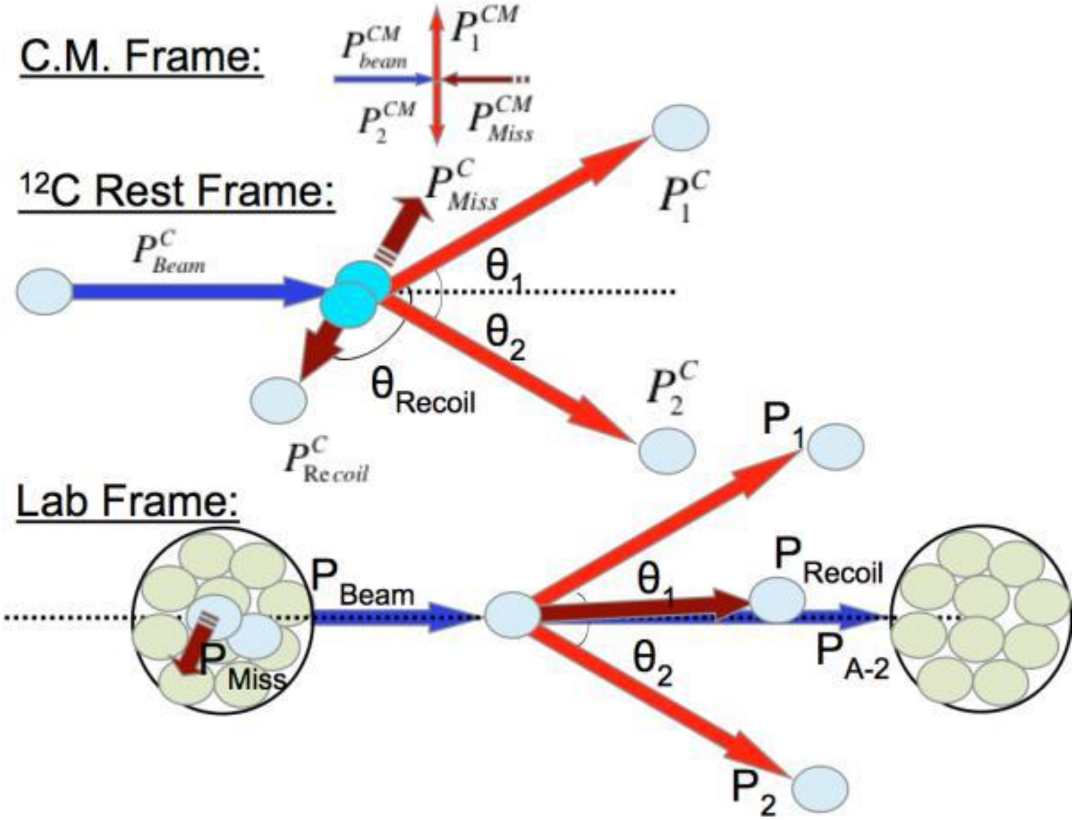
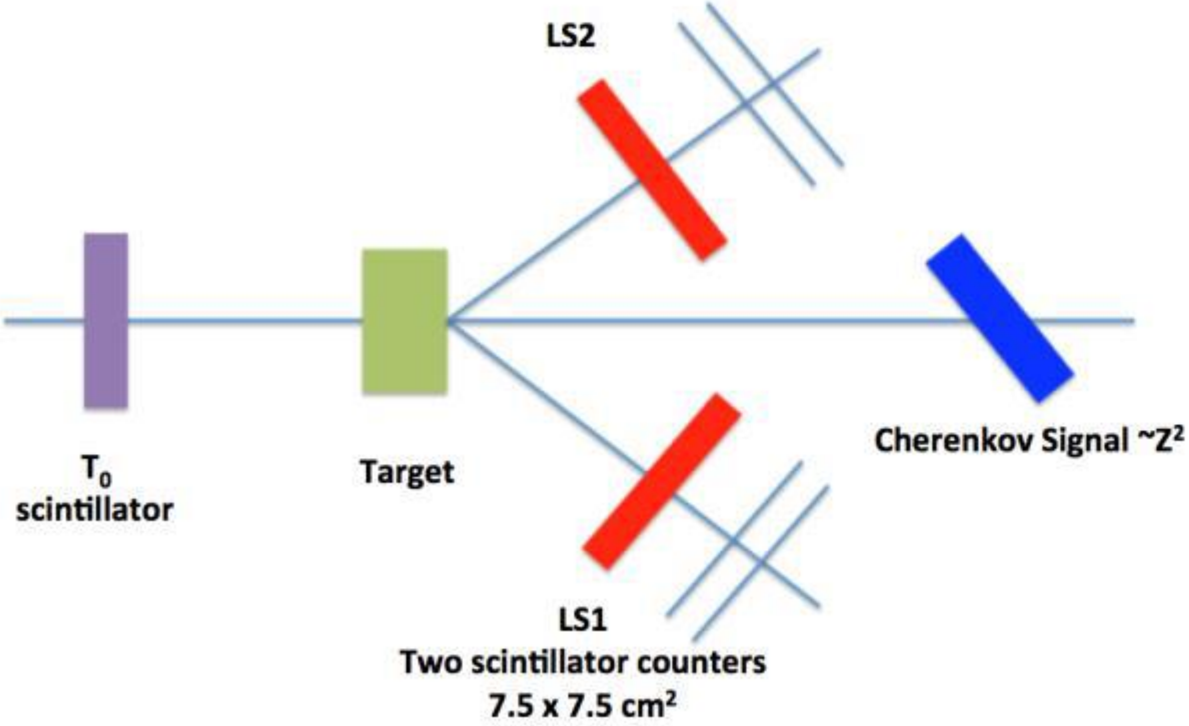


Figure 15: (Top) Two protons scattering at θcm=90o in their C.M. frame. The momenta of the particles after scattering are P1(C.M.) and P2(C.M.).
(Middle) Proton beam scattering off of an SRC-pair inside a stationary nucleus. The beam proton scatters from a proton within the SRC-pair with initial momentum Pmiss, knocking it from the nucleus. The short-range-correlated partner recoils backward with momentum Precoil.
(Bottom) An SRC-pair in a moving carbon nucleus scattering off of a stationary proton target. An SRC-proton in the carbon nucleus knocks a proton out of the target. The short-range-correlated partner is boosted forward with momentum Precoil. The A-2 nucleus continues along the beam direction (PA-2).



LS2

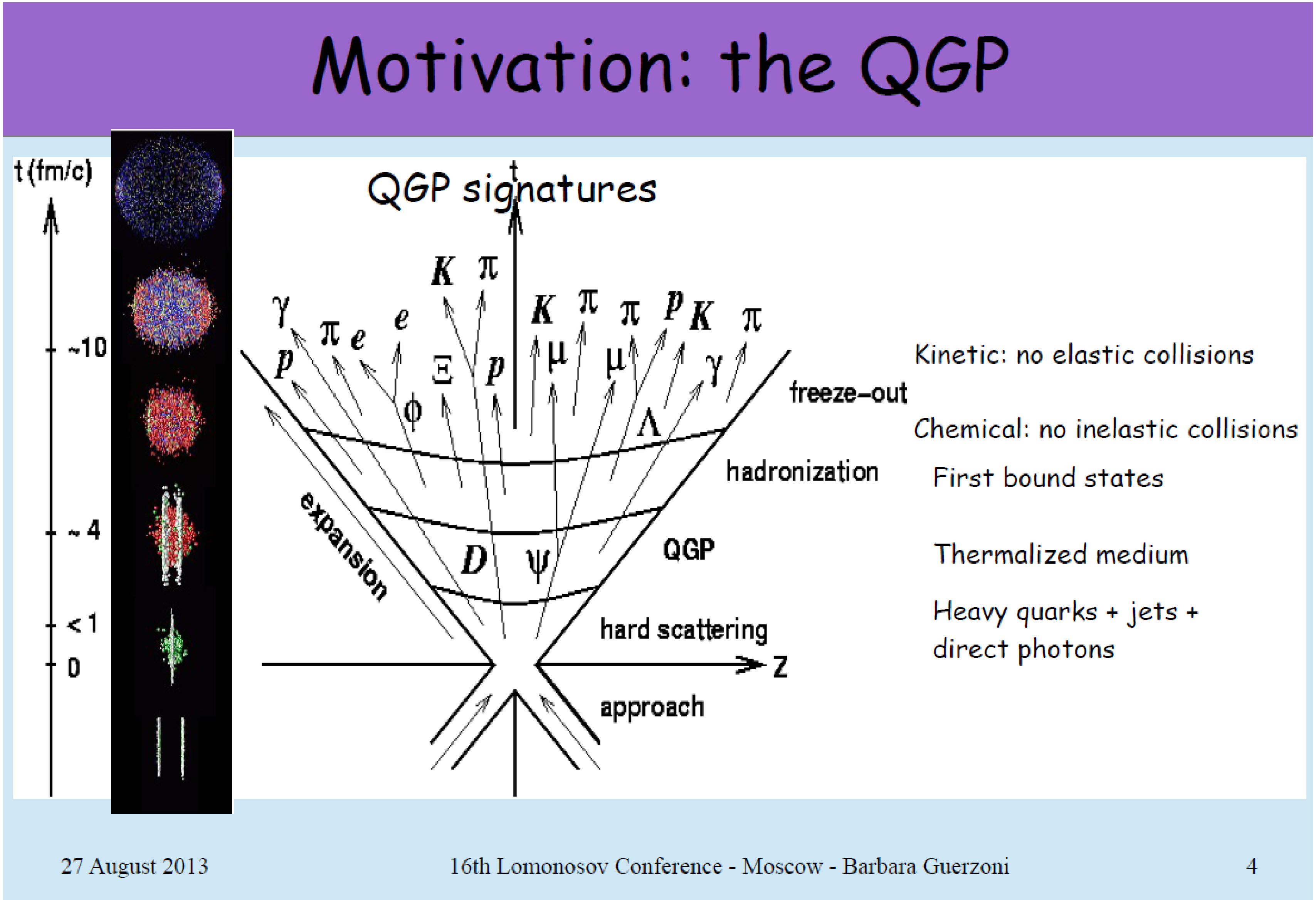
T_0
scintillator

Target

Cherenkov Signal ~Z^2

LS1
Two scintillator counters
7.5 x 7.5 cm^2

2 GEM detectors of the size 41 x 66 cm^2



Motivation: the QGP

Kinetic: no elastic collisions

Chemical: no inelastic collisions

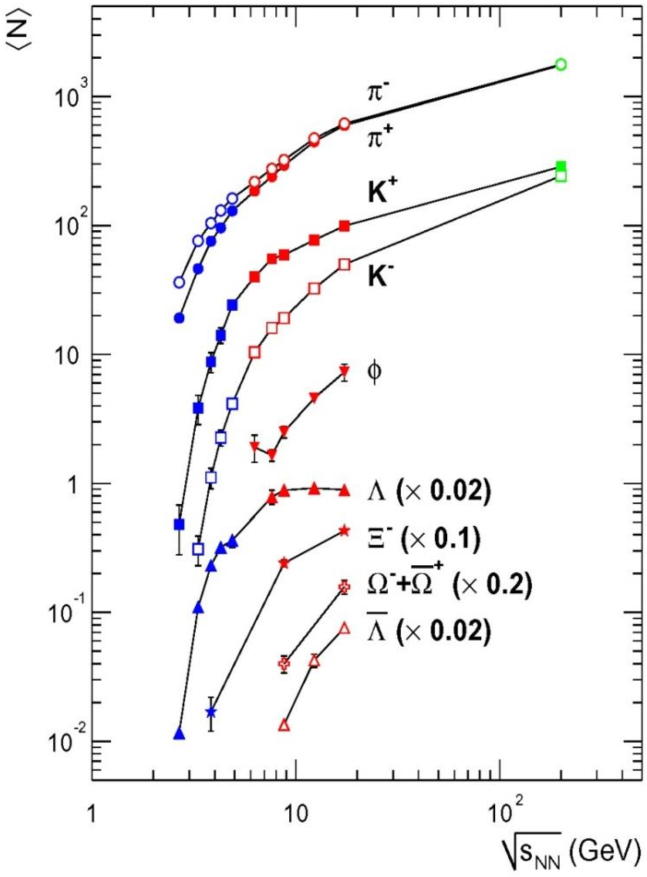
First bound states

Thermalized medium

Heavy quarks + jets + direct photons

Strange baryons:Λ,Ξ^-. Why no $\Sigma(\Sigma^-,\Sigma^0,\Sigma^+)$?

AGS NA49 BRAHMS



$K^+(\Lambda+\Sigma) \rightarrow K^+/K^-(\Lambda+\Sigma\ )$

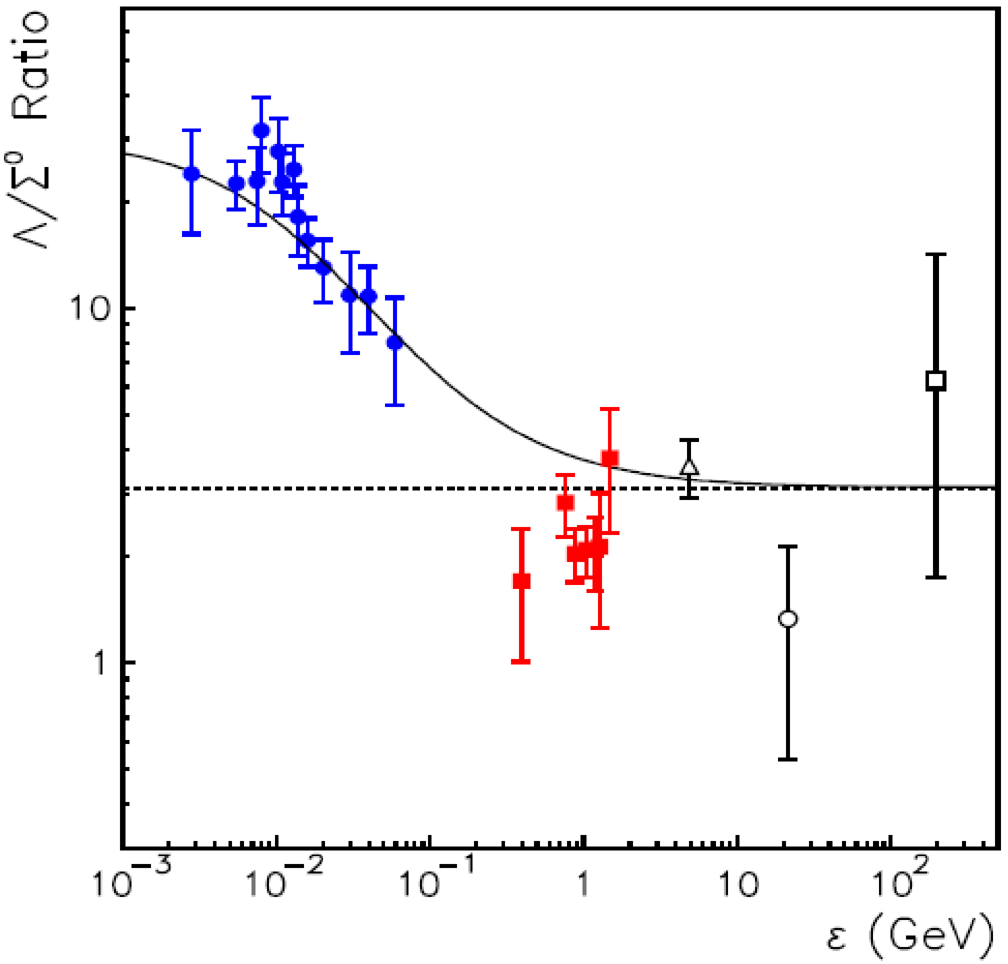


Fig. 3. The Λ/Σ^0 cross section ratio as a function of the excess energy ϵ. The solid circles show the ratio obtained for the $pp\to K^+\Lambda p$ and $pp\to K^+\Sigma^0 p$ reactions at COSY [2]. Solid squares are pp results from Ref. [25]. The open triangle and open circle are ratios measured in p Be [28] and p Ne [29] collisions, respectively. The open square is the result from a d Au experiment [30]. The curves are cross section ratios based on the $pp\to K^+\Lambda p$ results with Λp FSI (solid line) and without FSI (dashed line).

"It is interesting to observe that the ratios for nuclear targets, measured at high energies, are roughly in line with the results from high-energy pp collisions. Unfortunately, the new and still preliminary STAR result is afflicted by large uncertainties and, thus, precludes any firm conclusion concerning a possibly larger ratio with respect to that found in the pp interactions. Several authors have pointed out that the experimental ratio of around 3 coincides with the ratio of the isospin multiplicity of the Λ and Σ's [2,28,30]. But we are not aware of any deeper reason why those two quantities should be connected."

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

$a_{pp}(^1S_0)$=-7.8 fm; $a_{np}(^1S_0)$=-23.7 fm; $a_{nn}(^1S_0)$=-16.4 fm.

$a_{p\Lambda}(^1S_0)$=-2.7 fm; $a_{\Sigma+p}(^1S_0)$=-3.85 fm; $a_{\Lambda\Lambda}(^1S_0)$=-0.88 fm[1]

[1] Th.A.Rijken, M.M.Nagels, Y.Yamamoto,
Progress of Theoretical Physics Suppl.N0.**185**(2010),14

Measurements of Short Range Correlations (SRCs) in nuclei probe the tensor part of the NN force and even start to approach the repulsive part by studying the isospin decomposition of SRC pairs.

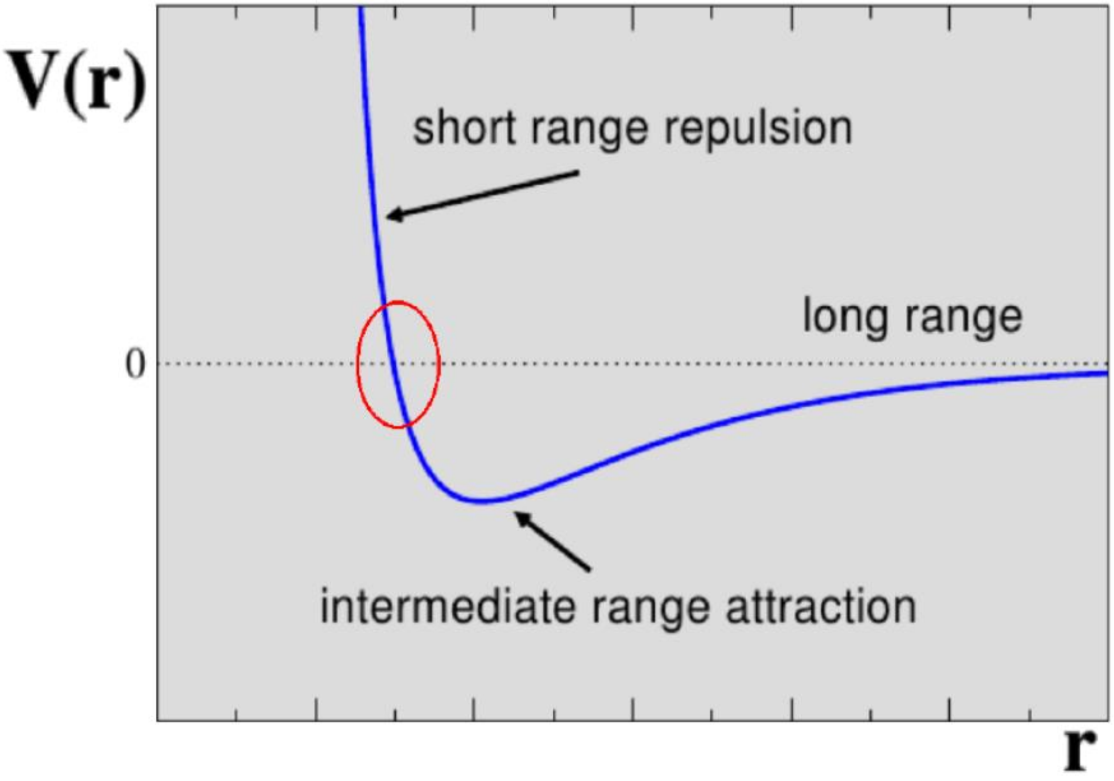


Figure 3: Schematic presentation of scalar part of the NN potential as function of distance between nucleons. Red ellipse present the region, were we expect to measure the effect of the tensor part of the force.