

NA61/SHINE Project

Extension for 2025-2029

JINR participation (Theme 1087: Research on Relativistic Heavy and Light Ion Physics. Experiments at the Accelerator Complex Nuclotron-M/NICA at JINR and CERN SPS)

Project leader: A. Malakhov

Deputies: A.Dmitriev, A.Zaitsev

JINR Management (1 person):

V.Matveev

VBLHEP (9 persons):

M.Buryakov, A.Dmitriev, V.Golovatyuk, V.Kireyeu, R.Kolesnikov, A.Malakhov, G.Melkumov, M.Rumyantsev, A.Zaitsev

DNLP (5 persons):

A.Krasnoperov, G.Lykasov, V.Lyubushkin, B.Popov, V.Tereshenko

Institute of Physics and Technology of MAS, Ulaanbaatar, Mongolia (6 persons):

B.Baatar, Ts.Baatar, N. Khishigbuyan, M. Sovd, B. Otgongerel, M. Urangua

Sofia University "St. Kliment Ohridski", Bulgaria (4 persons):

M.Bogomilov, D.Kolev, S.Ileeva, R.Tsenov

The American College, Madurai, India (2 persons):

N. Marimuthu, S. Sanila



- 1 Introduction
 - Collaboration
 - NA61/SHINE physics program
 - NA61/SHINE facility
- 2 NA61/SHINE highlights
 - Strong interactions
 - Neutrinos
 - Cosmic rays
- 3 Activities of the JINR group in the NA61/SHINE experiment in 2022-2024
 - Light cluster formation in midrapidity region in PbPb collisions
 - Development of the self-similarity approach to describe hadron production in pp and AA collisions
 - Upgrade of the NA61/SHINE detector: ToF system
 - Other activities
- 4 Future plans of JINR group
- 5 Manpower, publications and thesis's
- 6 Required resources
- 7 Summary

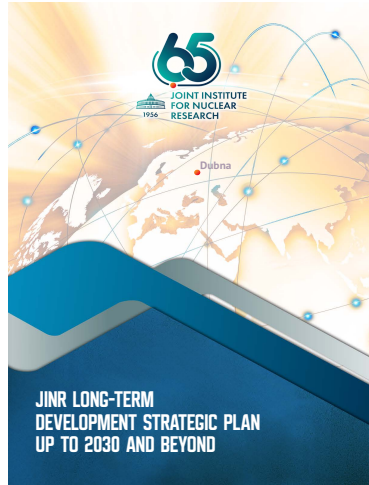
- Azerbaijan:** National Nuclear Research Center, Baku
- Bulgaria:** Faculty of Physics, University of Sofia, Sofia
- France:** LPNHE, University of Paris VI and VII, Paris
- Germany:** Karlsruhe Institute of Technology, Karlsruhe
- Hungary:** Wigner Research Centre for Physics of the Hungarian Academy of Sciences, Budapest
Eötvös Loránd University, Budapest
- Japan:** Institute for Particle and Nuclear Studies, Tsukuba
Okayama University, Okayama
- Norway:** University of Bergen, Bergen
University of Oslo, Oslo
- Poland:** Jan Kochanowski University in Kielce
Institute of Nuclear Physics, Polish Academy of Sciences, Cracow
National Centre for Nuclear Research, Warsaw
Jagiellonian University, Cracow
AGH – University of Science and Technology, Cracow
University of Silesia, Katowice
University of Warsaw, Warsaw
University of Wrocław, Wrocław
Warsaw University of Technology, Warsaw
- Russia:** Institute for Nuclear Research, Moscow
Joint Institute for Nuclear Research, Dubna
National Research Nuclear University (Moscow Engineering Physics Institute), Moscow
St. Petersburg State University, St. Petersburg
- Serbia:** University of Belgrade, Belgrade
- USA:** Fermilab, Batavia
University of Notre Dame, Notre Dame
University of Colorado, Boulder
University of Hawaii at Manoa, Honolulu

148 participants,
29 institutions,
11 countries



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“4. Study of the physics of strongly interacting matter, including the search for a critical point, the study of deconfinement, collective flows and the formation of an open charm in the NA61 experiment at SPS (CERN) — 2024–2030.”

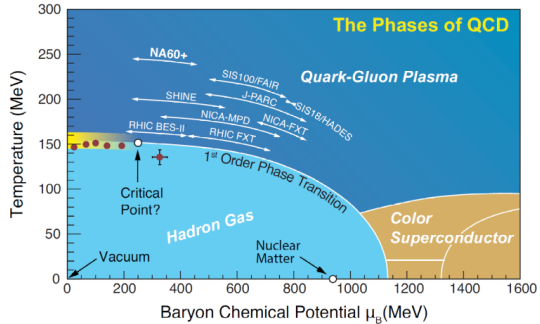
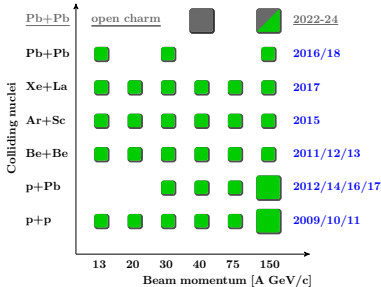


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“JINR has been an important player with its participation in the heavy-ion programme at the CERN SPS first in WA98 and NA49/NA61, then in ALICE. These activities have been the motivation and source for the Mega-Science project NICA.”

Strong interactions physics:

- study the properties of the **onsets of deconfinement and fireball**
- search for the **critical point** of strong interacting matter
- direct measurements of **open charm**



Neutrino and cosmic ray physics:

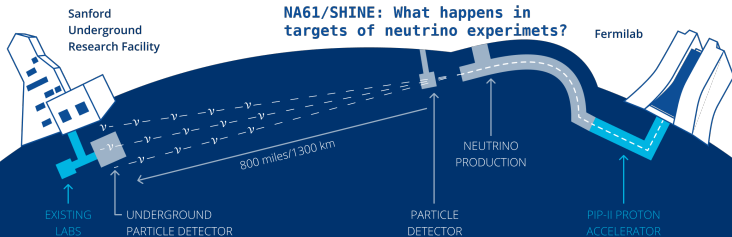
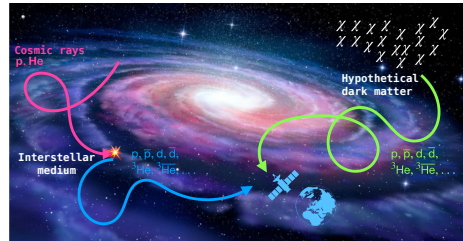
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Strong interactions physics:

-

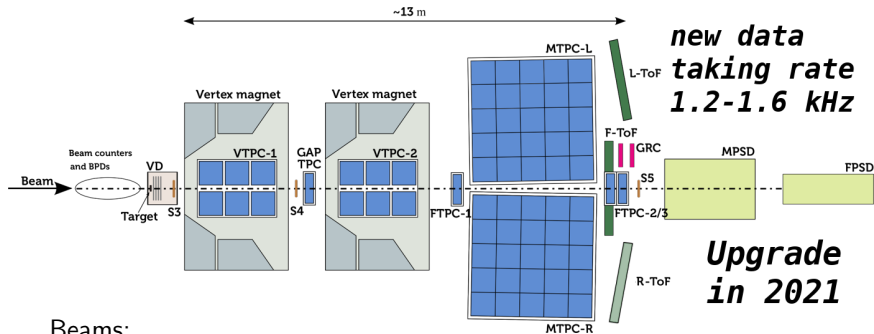
Neutrino and cosmic ray physics:

- **measurement for the J-RAPC (T2K) and Fermilab (NuMI and DUNE) neutrino experiments**
- **measurements of nuclear fragmentation cross sections and hadron production to improve air shower simulations and understand the cosmic ray propagation in Galaxy**



NA61/SHINE: What happens in targets of neutrino experiments?

Fixed target experiment located at the H2 beam line of CERN – North Area



Beams:

- ions (Be, Ar, Xe, Pb)
 $p_{beam} = 13A-150A \text{ GeV}/c$

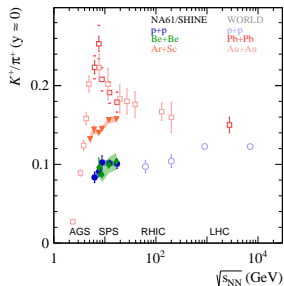
- hadrons (π , K , p)
 $p_{beam} = 13-400 \text{ GeV}/c$

- $\sqrt{S_{NN}} = 5.1-17.3(27.4) \text{ GeV}$

- new TPC readout electronics (contribution)
- new Vertex Detector (VD)
- new Time-of-Flight system (L-ToF)
- new Beam Position Detectors (BPDs)
- new Geometry Reference Chambers (GRC)
- upgrade of the Projectile Spectator Detector (PSD)
- new DAQ and trigger systems (contribution)

Decisive contribution
of the JINR group

Onset of deconfinement

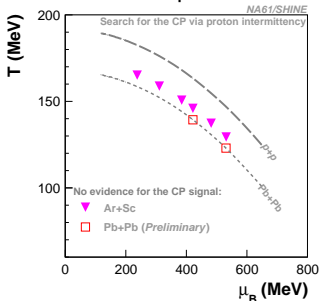


Unexpected collision energy
dependence for
small/medium size ions

p+p: Eur.Phys.J. C77 (2017) 10, 671
Be+Be: Eur.Phys.J. C81 (2021) 1, 73

Key results 1

Critical point

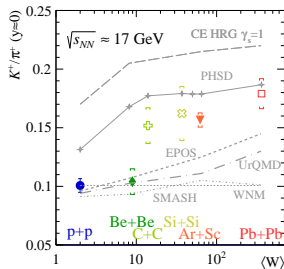


No evidence

Values calculated from Becattini,
Manninen, Gazdzicki, Phys. Rev. C73
2006

Ar+Sc: OD,OF: Eur.Phys.J. C84 (2024) 3
CP: arxiv.org/pdf/2401.03445

Onset of fireball



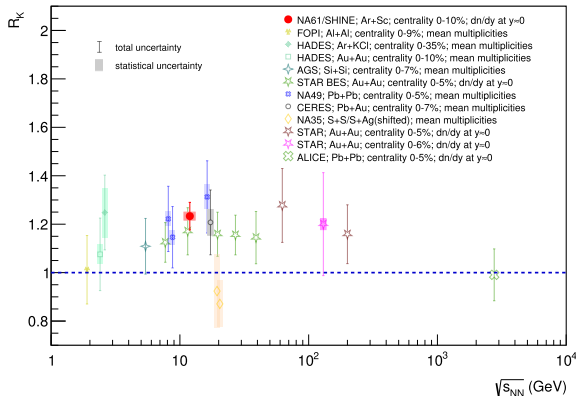
Unexpected system size
dependence for
small/medium size ions

Pb+Pb: Phys. Rev. C66 (2002) 054902

Decisive contribution
of the JINR group

Key results 2

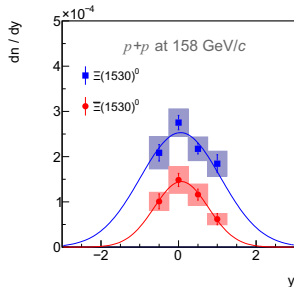
Anomaly excess of K^\pm/K_s^0 in Ar+Sc@75A GeV/c



$$R_K = \frac{K^+ + K^-}{2K_s^0} \text{ significantly higher than 1}$$

Ar+Sc: [arXiv:2312.06572 \[nucl-ex\]](https://arxiv.org/abs/2312.06572)
[arXiv:2312.07176 \[nucl-th\]](https://arxiv.org/abs/2312.07176)

$\Xi(1530)^0$ production in
 $p+p@158$ GeV/c



The only results in $p+p$ at
SPS energy

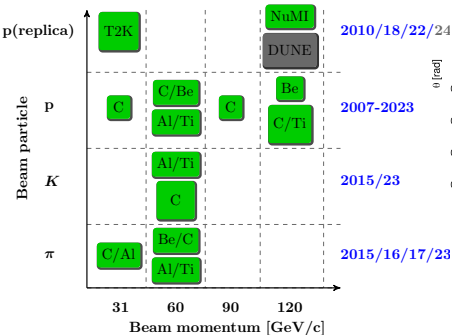
$p+p$: [Eur.Phys.J.C 81 \(2021\) 10, 911](https://doi.org/10.1007/s00285-021-01611-1)

Decisive contribution
of the JINR group

Key results

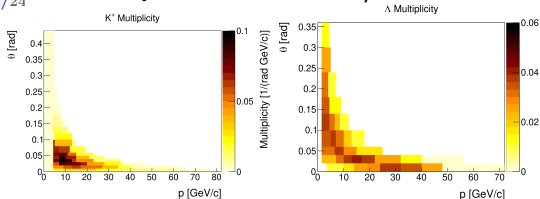
B.Popov is a
convener of WG for JPAC

Collected systems:



Last results for FNAL:

$p + C$ at 120 GeV/c



Multiplicity measurements for
 $\pi^\pm, K^\pm, K_S^0, p, \bar{p}, \Lambda, \bar{\Lambda}$

$p+C$: [Phys.Rev.D 108 \(2023\) 072013](#)
[Phys.Rev.D 107 \(2023\) 072004](#)

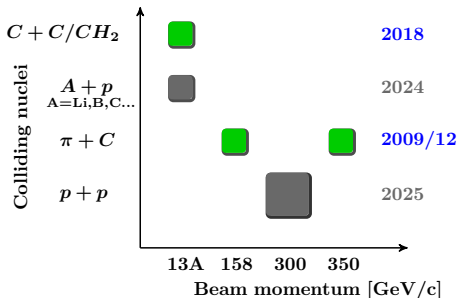
NA61/SHINE data decisively reduce the uncertainties of final results in neutrino experiments

Contribution
of the JINR group

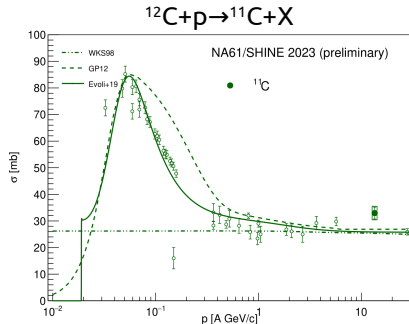
Key results

- Extensive air showers:
 - $p + C$ and $\pi + C$ interactions
 - synergy with neutrino program

- Propagation in Galaxy:
 - d, \bar{d} and \bar{p} production in $p + p$
 - nuclear fragmentation in $C + C/CH^2$

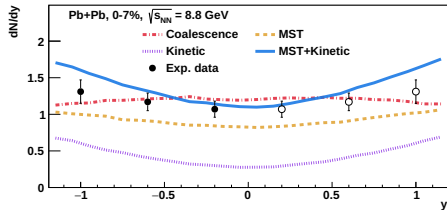
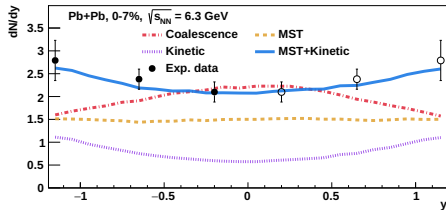


$\pi^- + C$: [Phys.Rev.D 107 \(2023\) 062004](#)

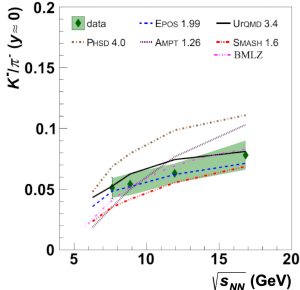
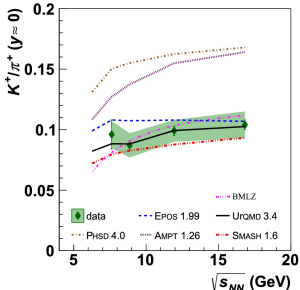


Unique results which cannot be described by the models needed to interpret high precision data on cosmic rays

● Light cluster formation in midrapidity region in PbPb collisions



Pb+Pb: [arXiv:2304.12019](https://arxiv.org/abs/2304.12019) [nucl-th]



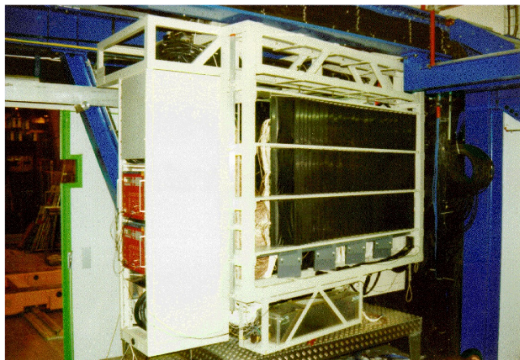
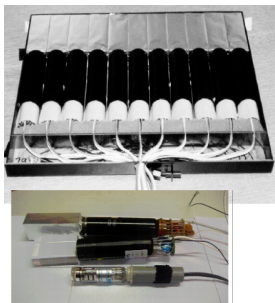
- Development of the self-similarity approach to describe hadron production in pp and AA collisions (BMLZ model)

p+p: [Eur.Phys.J.A 57\(2021\) 3,91](https://arxiv.org/abs/2011.00011)

Be+Be: [Eur.Phys.J.A 58\(2022\) 6,112](https://arxiv.org/abs/2011.00011)

Ar+Sc: [arXiv:2402.03260](https://arxiv.org/abs/2402.03260) [hep-ph]

\bar{B}/B : [J.Exp.Theor.Phys. 135\(2022\) 2,209](https://arxiv.org/abs/2011.00011)

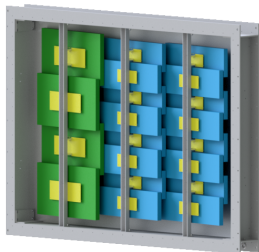


The previous NA49/61 ToF-LR:

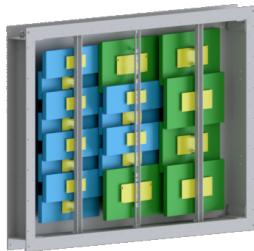
- 891 scintillator counters per wall
- ToF-L (JINR contribution) put into operation in 1995-96
- time resolution: ~ 75 ps
- significant degradation of all parts of ToF → the detector disassembling in 2018

previous ToF-L: JINR Rapid Communications 5 (1997) p.69

ToF-R
(possible commissioning in 2024+)



ToF-L
(commissioned in 2021)



- MRPCs with gas module (16+4 detectors)
- modification of HV and gas systems
- LV system
- Front-end electronics (~ 2000 ch)
- DRS4 readout
picoTDC readout
- **Time resolution up to**
 $\sigma_{\text{ToF}} \approx 36$ ps

ToF-R: Nucl.Instrum.Meth.A 1064 (2024) 169235?

- MRPCs with gas module (12+6 detectors)
- Closed-loop gas system for two modules
- HV & LV systems
- Front-end electronics (1728 ch)
- DRS4 readout
- Time resolution: ~ 50 ps

ToF-L: Nucl.Instrum.Meth.A 1034 (2022) 166735
Phys. Part. Nuclei Lett. 21 (2024) 2, 5?

- Strong interaction (charm) program:
 - 30M in target in 2022
 - 150M in target in 2023

realistic goal is 440M in 2025
- Neutrino program:
 - 160M with T2K replica target in 2022
 - 264M with thin targets for DUNE in 2023
- Cosmic ray program:
 - Close co-operation in preparation for high-statistics antimatter measurements in $p + p$ at 300 GeV/c
- Data reconstruction and software development for the runs since 2022:
 - Development and maintenance of the DRS4 calibration software
 - Geant4 model for new ToF detector
 - New algorithm for MRPC signal classification using ML

Software: [JINST 19 P02038?](#)
- Upgrade of the trigger system

Hardware & data taking:

- ToF-L and overall facility maintenance during data taking
- ToF-R commissioning
- Participation in trigger R&D

Software:

- Service and further development of calibration software
- Reconstruction chain in the SHINE framework

Data analysis:

- the study of the light nucleus formation (d , t , ^3He , ..) in nucleus-nucleus interactions
- the study of hyperon and hypernuclei production in $Be + Be$, $Ar + Sc$, $Xe + La$, $Pb + Pb$ collisions
- analysis of anti-matter production in relativistic interactions
- the study of open charm production in heavy ion collisions
- measurement of hadron production for neutrino and cosmic ray physics
- further development of theory models for better understanding the collected data

NA61/SHINE Management positions(4):

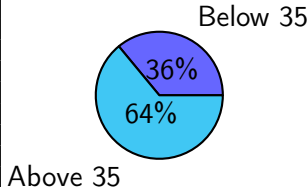
Dmitriev A. - Dep. tech. coordinator (1)

Malakhov A. - Collaboration board member (2)

Popov B. - Resource coordinator (3) and convener of neutrino analysis for JPAC (4)

Nº	Name	Lab	Category	FTE
1	Matveev V.	Directorate	scientific staff	0.1
1	Buryakov M.	VBLHEP	engineer	0.2
2	Kolesnikov R.	VBLHEP	engineer	0.5
3	Dmitriev A.	VBLHEP	scientific staff	0.7
4	Golovatyuk V.	VBLHEP	scientific staff	0.1
5	Kireyeu V.	VBLHEP	scientific staff	0.3
6	Malakhov A.	VBLHEP	scientific staff	0.3
7	Melkumov G.	VBLHEP	scientific staff	0.7
8	Rumyantsev M.	VBLHEP	scientific staff	0.2
9	Zaitsev A.	VBLHEP	scientific staff	0.5
10	Krasnoperov A.	DLNP	scientific staff	0.1
11	Lykasov G.	DLNP	scientific staff	0.3
12	Lyubushkin V.	DLNP	scientific staff	0.1
13	Popov B.	DLNP	scientific staff	0.9
14	Tereshenko V.	DLNP	scientific staff	0.1
Σ FTE				5.1

Age distribution:



* – PhD degree

* – doctorate degree

- Two (2) PhD thesis were defended since 2021.
Three (3) more are planned.
- 25 papers were published by JINR members for the last three years:
 - 11 of them are collaboration papers with JINR contribution
 - Five (5) are detector and methodological papers
 - Nine (9) are theory and analysis papers

Item	Full cost (k\$)	2025	2026	2027	2028	2029
1. International cooperation	400	80	80	80	80	80
2. Materials	500	100	100	100	100	100
3. Equipment and third-party company services	50	10	10	10	10	10
Total budget:	950	190	190	190	190	190

- The unique results for heavy ion, neutrino and cosmic ray physics have been obtained. The future investigation is needed for:
 - search of the CP;
 - study of the QCD phase transition region;
 - new charm program;
 - further reduction of the flux uncertainties for neutrino oscillation measurements and etc.
- A huge amount of the joint work has been carried out for the NICA and NA61 projects¹:
 - theoretical research – models, simulations;
 - detectors – MRPCs, electronics.
- The resources are rather modest, but justified by the physical tasks of the NA61/SHINE experiment.

¹*prof. V.V.Burov (†): JINR participation in the experiment NA61 is very important since the research programme in this experiment lies in the main stream of the long-range programme in the field of relativistic nuclear physics at JINR.*

Thank you for your attention!

Backup slides

Beam time schedule in Run 3



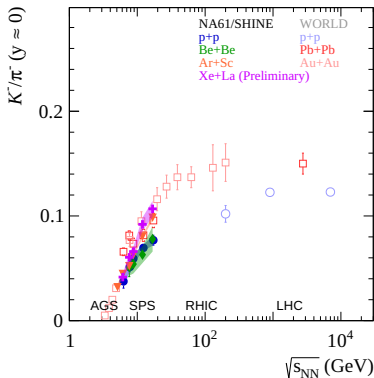
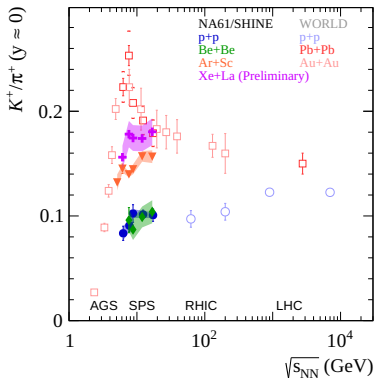
Measurements	Field	2022	2023	2024	2025
Charm measurements in $Pb + Pb$	SI	<u>30M events per two weeks</u>	<u>150M events per four weeks</u>	three weeks of Pb beam at 150A GeV/c	four weeks of Pb beam at 150A GeV/c
T2K replica-target measurements	N	<u>160M events per four weeks</u>			
Thin-target C and Ti X-section	N, CR		<u>264M events per six weeks</u>		
Nuclear fragmentation cross-section	CR			week of a secondary light-ion beam at 13A GeV/c	
DUNE replica-target measurements	N			four weeks of proton beam at 120 GeV/c	
High-statistics measurements of $p+p$	SI, CR				four weeks of proton beam at 300 GeV/c

Strengths	Weaknesses
<ul style="list-style-type: none"> * Modern facility with unique parameters * Relevance of the NA61/SHINE physics program to modern challenges of fundamental science * A large amount of experimental data collected for p+A and A+A interactions in a wide energy range from 13 to 158A GeV 	<ul style="list-style-type: none"> * Delay with facility upgrade * Reduced amount of the beam time * Time-consuming calibration procedure
Opportunities	Threats
<ul style="list-style-type: none"> * A new physics existence * The young people training for the NICA project * Development of new methods and technologies 	<ul style="list-style-type: none"> * Facility accident * Unsuccessful detectors delivery * Changes in the world situation

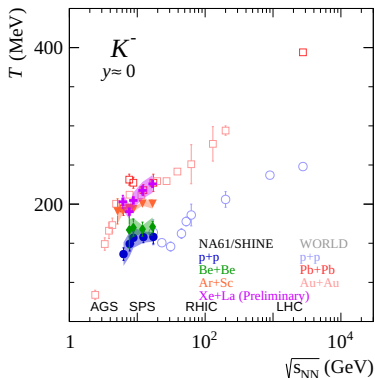
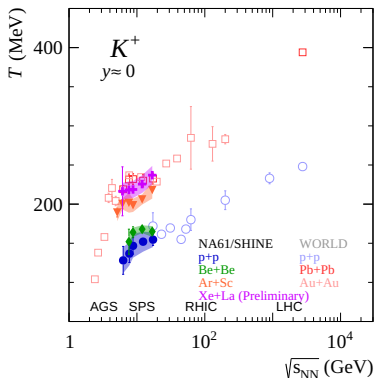
Plots related to Onset of Deconfinement and Onset of Fireball

according to the request of the PAC for PP at the 55th meeting

K^+/π^+ and K^-/π^- at $y = 0$ (horn)

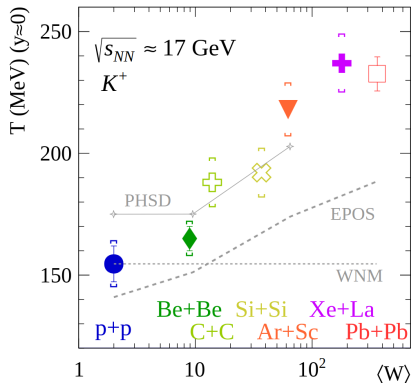
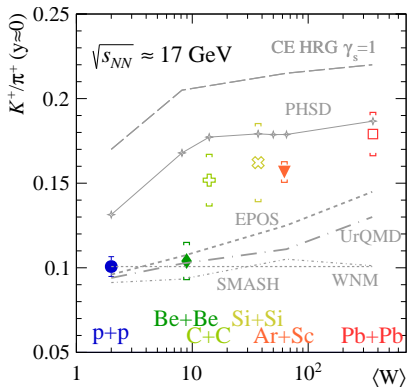


- Rapid change in the energy dependence of K^+/π^+ ratio in Pb+Pb collisions indicated the onset of deconfinement in the SPS energy range, as predicted within SMES
- Plateau-like structure visible in light systems (p+p and Be+Be)
- Ar+Sc systematically higher, Xe+La close to Pb+Pb at $\sqrt{s_{NN}} = 16.8$ GeV/c

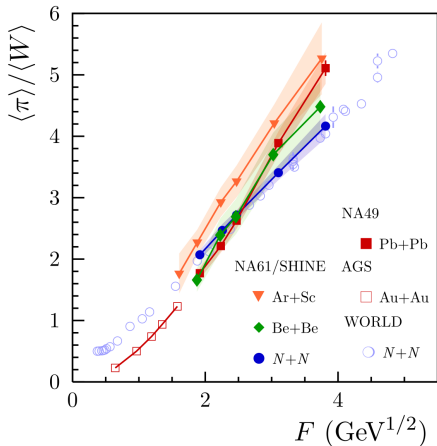


- Qualitatively similar energy dependence in pp, BeBe, ArSc, XeLa and PbPb
- Magnitude of T increases with the system size

K^+/π^+ and T vs the system size at 150A GeV/c (OF)

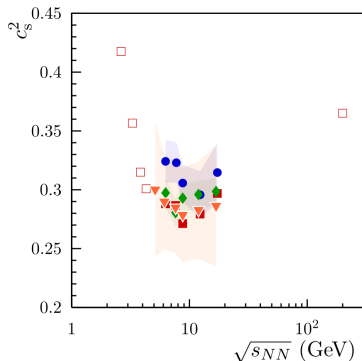
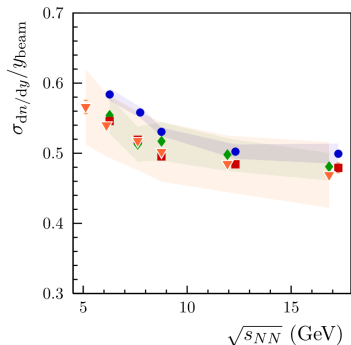


- Rich collection of results on system size dependence of particle production in SPS energy range
- None of the models reproduce K^+/π^+ ratio or T in the whole $\langle W \rangle$ range



- Ar+Sc results systematically higher than the results for N + N, Be+Be and Pb+Pb at the lower energies
- Ar+Sc close to the Pb+Pb results at the highest energies
- Be+Be results close to Pb+Pb at lower energies and between N+N and Pb+Pb at higher energies

$$F = \left[(\sqrt{s_{NN}} - 2m_N)^3 / \sqrt{s_{NN}} \right]^{1/4}$$



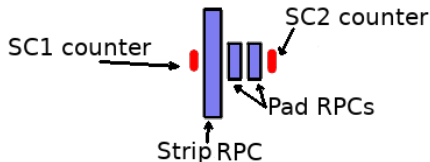
- The collision energy dependence of the pion rapidity distribution width is associated with the speed of sound c_s :

$$\sigma_y^2 = \frac{8}{3} \frac{c_s^2}{1 - c_s^4} \ln\left(\frac{\sqrt{s_{NN}}}{2m_p}\right)$$

- The results of NA61/SHINE from central Ar+Sc, Be+Be collisions, and inelastic N+N reactions need to be extended to lower energies for conclusion about a possible minimum

picoTDC test

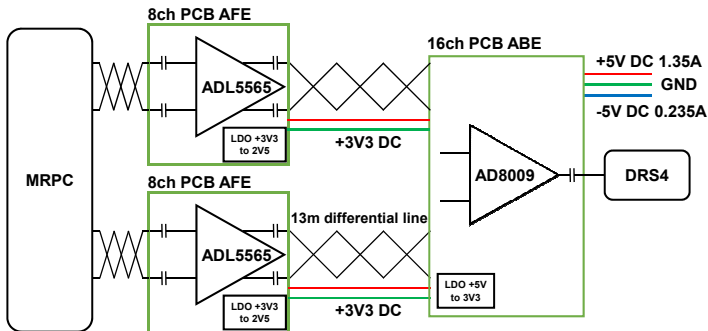
- HV - MPOD system
 - ± 6 kV (120 kV/cm) - PRPCs,
 - ± 5.75 kV (115 kV/cm) - MRPC
- $C_2H_2F_4$, $i-C_4H_{10}$ and SF_6 (90/5/5)
14 nl/h flow rate
- **A5203 FERS** readout(48ch):
16+16ch for pad RPCs ($\sim 15 \times 7.5$ cm²)
16ch (8 strips) for MRPC ($\sim 15 \times 10$ cm²)
- LV - lab.sources
 - 4.4 V/3.41A - analogue FEE (48ch)
 - 12 V/0.57A - picoTDC
- Front-end electronics:
Analogue FEE with comparator
NINO 160 mV threshold
- Two trigger sci-counters:
Forward PMT SC1 ($\sim 12.5 \times 10$ cm²)
Backward SiPM SC2 ($\sim 9.5 \times 9.5$ cm²)



Pb+Pb collisions at 150A GeV/c were registered!!!

Analogue front-end electronics - AFEC

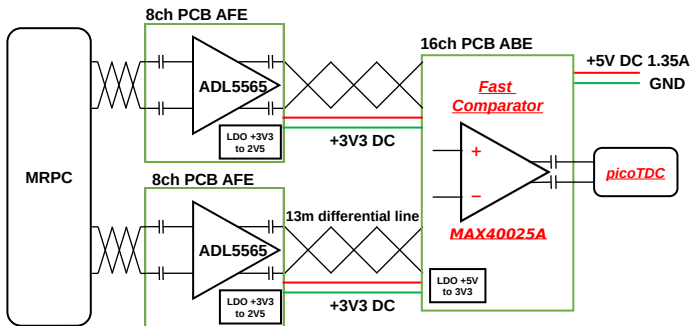
- The key idea is to modify front-end electronics for DRS4 readout, namely to replace the (Analogue Back-End) ABE part with fast comparator.



Front-end amplifier for DRS4

Analogue front-end electronics - AFEC

- The key idea is to modify front-end electronics for DRS4 readout, namely to replace the (Analogue Back-End) ABE part with fast comparator.



Front-end with fast comparator for picoTDC



Front view



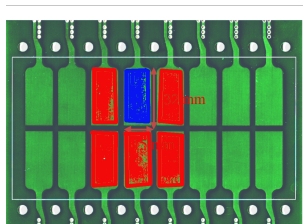
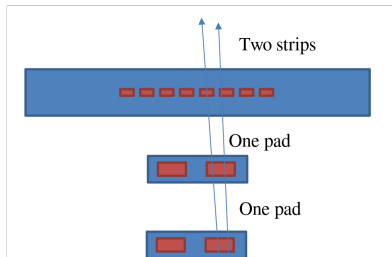
Back view

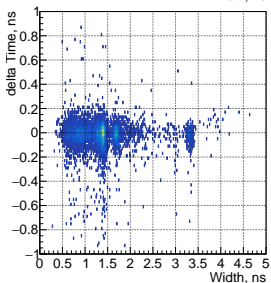
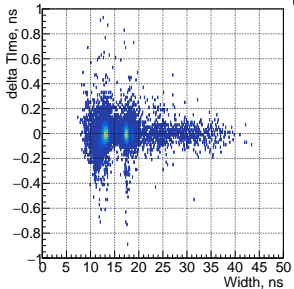
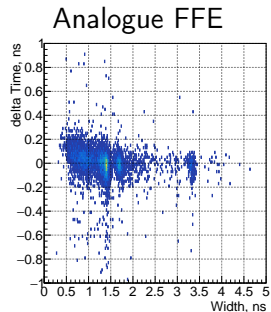
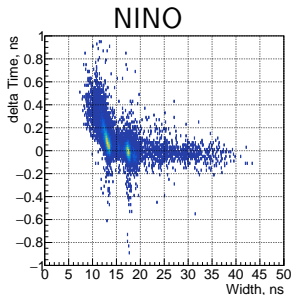
Event selection

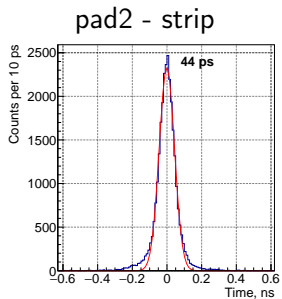
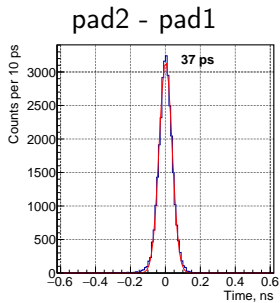
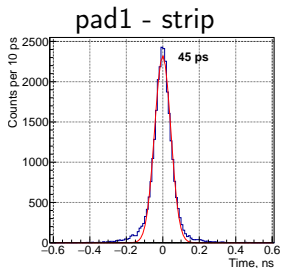
- 1 Time cut on pad detectors (time < 78 ns);
- 2 **Low amplitude cut on pad detectors !!! Affect on PRPCs time resolution and efficiency**
- 3 No hits on nearest pads (distance to nearest hit > 3.9 mm – circle selection);
- 4 Fixed pads and strips
(strip – #5 for analogue or #6 for NINO, both pads – #3);

Efficiency calculation. Fixed strip ± 1

Time calculation. TA-correction + three equation system

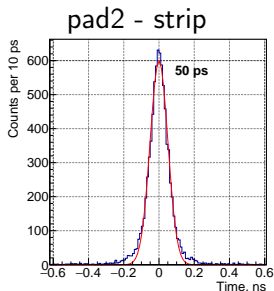
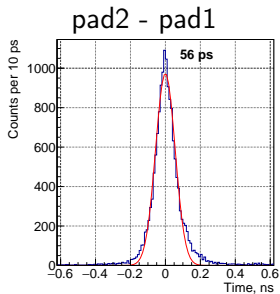
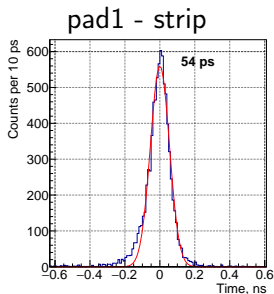






$$\sigma_{strip} \approx 36.1 \pm 0.66 \text{ ps}$$

$$\text{eff} = 97\%$$



$$\sigma_{strip} \approx 51.77 \pm 2.91 \text{ ps}$$

$$\text{eff} = 70\%$$

Thank you for your attention!