

# NA61/SHINE future plans

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# iviuitipurpose fixed-target sp









# Reasearch program

Strong interactions:

- study the onset of deconfinement
- search for the critical point
- measurements of open charm

#### Neutrino and cosmic ray physics:

- hadron production measurements for neutrino programs (J-PARC, Fermilab)
- hadron production measurements for cosmic-ray physics (Pierre-Auger, KASCADE, space cosmic ray experiments)







# Strong interactions program



beam momentum [ $A \operatorname{GeV}/c$ ]

# Data of NA61/SHINE Data of NA61/SHINE O-20% Xe+La at \$\sum\_{SNN}=16.8 \expression delta at

#### Green

system size - energy scan to search for CP, and study OD and hadron production at high  $p_T$ CERN-SPSC-2006-034 Measurements of  $D^0$  yields in A+A at SPS energies - first results from Xe+La A. Merzlava, SQM24

## **Results: Critical point search**





# **Results: Critical point search**





# **Results: Onset of deconfinement**



- Step-like structure in inverse slope parameter of  $p_{T}$  spectra of  $K^{+}$
- Sharp maximum at K<sup>+</sup>/π<sup>+</sup> ratio reflects strangeness to entropy the ratio which is different in the confined phase (hadrons) and the QGP (quarks, anti-quarks and gluons) Probe of the onset of deconfinement
   NA61/SHINE: EPJC 84 (2024) 4, 416 (Ar+Sc); EPJC 81 (2021) 1, 73 (Be+Be); EPJC 77 (2017) 10, 671 (p+p)

For WORLD see: EPJC 84, 416 (2024)



#### None of the models reproduces $K^+/\pi^+$ ratio and T system size ( $\langle W \rangle$ ) dependence

EPOS: Nucl. Phys. Proc. Suppl. 175-176 (2008) 81-87; PHSD: PRC
 78 (2008) 034919; Nucl. Phys. A 831, 3, (2009) 215 - 242; UrQMD:
 Prog.Part.Nucl.Phys. 41 (1998) 255-369; J.Phys. G25 (1999)
 1859-1896, HRG: Eur. Phys. J. C 65 (2010) 9-63,







- Unexpected violation of isospin (flavor) symmetry
- Cannot be described by known effects

## **Plans**

- Study the onset of fireball with light ions - Addendum with light-ion scan post-LS3 submitted to SPSC (SPSC-P-330-ADD-14); earlier request for O before LS3 (CERN-SPSC-2022-021)
- All ions are selected in close collaboration with the accelerator complex
- All initial target configurations selected
- O beam at 150A GeV/c in 2025 allows <sup>1</sup> <sup>1</sup> <sup>(w)</sup> <sub>(W)</sub> to start the study of the onset of fireball and charge-symmetry violation before LS3 continuation in Run4
- Extenstion of the charm program  $\rightarrow$  charm and anti-charm correlations shift of LS3 allows to consider it in Run4



## Planned light-ion data-sets SPSC-P-330-ADD-14

<b>р</b> ьеат (AGeV/c)	√ <i>s</i> <sub>NN</sub> (GeV)	<pre><sup>10</sup>B # days (# events)</pre>	<sup>16</sup> O # days (# events)	<sup>24</sup> Mg # days (# events)
13	5.1	7 (100M)	7 (100M)	7 (100M)
30	7.6	7 (100M)	7 (100M)	7 (100M)
150	16.8	7 (100M)	7 (100M)	7 (100M)

Dates: O beam before LS3 (150A GeV/c) and first years of Run 4, Mg, and B - first years of Run 4

The requested time includes setup time and one more day for possible stops in the beam delivery, longer supercycle, etc.

#### 12/17

# Physics performance

• System size dependence and the onset of fireball - OF



Considerable difference between light and heavy systems  $\implies$  onset of fireball

SPSC-P-330-ADD-14 was submitted as proposals to extend the ion program by light ion beams after LS3



# **Physics performance**

#### • hypothesis of large isospin violation







Assuming collisions of N = Z nuclei and the exact isospin symmetry one gets  $R_{\kappa} = 1$ . The proposed runs with O+O and Mg+Mg collisions post-LS3 may allow us to verify the hypothesis of a large isospin symmetry violation in kaon production.



# Charm and anti-charm correlations

Azimuthal angle correlation of charm hadrons produced in heavy ion collision  $\mu$  at top SPS energy (on average less than  $c - \bar{c}$  pair produced) is expected to be sensitive to space correlation (locality) at their origin

#### Directly accessible in NA61/SHINE++ via neutral D mesons.



M. Gazdzicki et al., arXiv:2305.00212 [hep-ph]

#### but

High event rate – **beyond 10 kHz** – is necessary for central Pb+Pb collisions at 150A GeV/c

A unique input constraining the diffusion of c quarks and testing the production locality of a  $c - \overline{c}$  pair.



# NA61/SHINE upgrade - LS3

For measurement of  $c - \bar{c}$  correlations in central Pb+Pb collisions at 150A GeV/cNA61/SHINE considers replacing one of (slow) TPC with the Large Acceptance Silicon Tracker (**LAST**) • R&D in progress

- TDR in preparation
- Earliest by the end of LS3 (2029)
- Possible data-taking at the end of Run4

Planned two modes of operation:

- $\bullet\,$  fast: only LAST for the charm and anti-charm correlations in central Pb+Pb at 150A GeV/ $c\,$
- $\bullet\,$  slow:  ${\sim}1\,$  kHz LAST+TPC for light-ion, neutrino, and cosmic-ray programs which require large acceptance hadron measurements



# Summary

- precision studies of the onset of fireball of strongly interacting matter with O (2025/Run4), Mg (Run4), and B (Run4) beams
- verification of the hypothesis of large isospin violation with N=Z nuclei (the simplest case) - O and Mg
- charm and anti-charm correlations in central Pb+Pb collisions at 150*A* GeV/c

	SIS18/	SIS100		SPS		RHIC	LHC
	HADES	CBM	NA61/	SHINE	NA60+	STAR	ALICE / ALICE3
Domains of	Properties of dense		Onsets of deconfinement and fireball			Properties of dense	
heavy-ion physics	hadronic matter		Critical point			quark-gluon plasma	
$\sqrt{s_{NN}}$ (GeV)	1.9 - 4.9	2.7 - 4.9	5.1-	17.3	6.3-17.3	3-200	2760 - 5440
Start date	running	2028	runni	ng	>2029	running	running / 2035
			light ions	Pb+Pb			
Bulk properties	+	+	+	+		+	+
E-by-E fluctuations	+	+	+	+		+	+
Resonances	+	+	+	+	+	+	+
Open charm			+	+	+	only top energy	+
$c-\bar{c}$ correlations				+	+		+
Quarkonium	+	+			+	+	+
Dileptons	+	+			+	+	+





# Thank you<sup>a</sup>

 $^{a}MMP$  supported by WUT ID-UB

NA61/SHINE would like to thank the CERN EP, BE, HSE, and EN Departments for support  $\frac{17}{17}$ 



# Light-ion beams in the past

Primary ion beams:

• Ar (2015)

8 weeks of Ar (9/2/15-6/4/2015) with 6 momenta (in parallel, in SPS, with protons for LHC)

• Xe (2017)

NA61/SHINE requested Xe beam went up to LHC with many interesting results

• Pb (2016-...)

Secondary ion beams:

• Be (2011), C (2018)

Beamline not designed for  $\leq$  60 GeV/c: at low beam momenta large and diverging beam spot







# Secondary beam quality in the past

Fragmented beam: a wide spectrum of ions  $\longrightarrow$  low ratio of wanted ions and large beam spot already at the level of target





# Detector after LS2

2017-08-23723-43-528 (UTC) 1187567050 (GPS) Unix-1503531832

- Large acceptance Vertex Detector
- Significant increase in the TPC raw data quality (new electronics):
  - Noise reduction
  - Cluster shape improvement
- New DAQ performed better than expected - up to 1.6 kHz event rate for p+C interactions



Pre-upgrade 2017 p+C Event

(noise-dominated)

# Possible explanations

#### **Onset of strings**:

- PHSD: WC and ELB, PRC, 78, 034919, 200; and NPA, 831, 215-242, 2009;
- SMASH: JW, PRC, 94, 5, 054905, 2016 and JM, SR, and HE, J. Phys. G, 47, 6, 065101, 202
- UrQMD: SAB, Prog. Part. Nucl. Phys., 41, 255–369, 1998 and VYV, DVA, and MIG, NPA, 936, 1–5, 2015

#### **Onset of QGP fireball:**

- colour ropes: TSB, HBN, and JK, NPB, 245, 449-468, 1984.
- string fusion: MB and CP, NPB, 390, 542–558, 1993; MAB. and CP, PLB, 287, 154–158, 1992; MAB, CP, and VVV, EPJA, 51, 4, 44, 2015; MAB, JDdD, ASH, CP, RPS, and BKS, Phys. Rep., 599, 1–50, 2015; and JER, BD, and CP, PRD, 103, 9, 094029, 2021.
- core fragmentation: KW, PRL., vol. 98, p. 152301, 2007.
- string melting: ZWL, CMK, BAL, BZ, and SP, PRC, 72, 064901, 2005.
- percolation: SD, SF, and HS, EPJC, 32, 547–553, 2004; and CH, FP, and RS, PLB, 640, 96–100, 2006.
- AdS/CFT duality: TK and ES, PRC, 90, 1, 014901, 2014; TK and ES, PRD, 90, 2, 025031, 2014; II, AR, and ES, PRC, 92, 1, 014011, 2015





10<sup>1</sup> (SPS)

STRINGS

104 (LHC)

√SNN [GeV]

CT OF DECONTRACTOR

A

200

150

100

50

# Search for QCD critical point: femtoscopic correlations

Measurements suggest Gaussian  $\longrightarrow$  Lévy-stable source distribution

$$\mathcal{L}(lpha, {\sf R}, {\sf r}) = rac{1}{(2\pi)^3} \int d^3 q e^{iqr} e^{-rac{1}{2}|q{\sf R}|^lpha}$$

- From generalization of Gaussian, power-law tail: $\sim r^{-(d-2+\alpha)}$
- The shape of the correlation function with Lévy source:  $C(q) = 1 + \lambda e^{-(qR)^{\alpha}}$ , where  $\alpha = 1 \longrightarrow$  exponential and  $\alpha = 2 \longrightarrow$  Gaussian
- We expect spatial power-law correlations at the CP ( $\sim r^{-(d-2+\eta)}$ )  $\longrightarrow$ Lévy-exponent  $\alpha$  identical to correlation exponent  $\eta$ <sub>Csorgo, Hegyi, Zajc, EPJC36 (2004) 67</sub>



NA61/SHINE, Eur.Phys.J.C 83 (2023) 10, 919

• Fit function: Bowler-Sinyukov C(q) = $1 - \lambda + 1(1 + e^{-|qR|^{\alpha}) \cdot \lambda \cdot K(q)}$ Y.Sinyukov et al., Phys. Lett. B432 (1998) 248, M.G. Bowler, Phys. Lett. B270 (1991) 69 Search for QCD critical point: proton intermittency

Second factorial moment as the function of momentum bin size



#### $CP \longrightarrow scale invariance \longrightarrow power-law form of correlation function for large distances$ $<math>\Leftrightarrow$ small momentum transfer $\Delta \vec{k}$

Wosiek ,Acta Phys. Polon.B 19,863-869; Bialas and Hwa,PLB 253,436-438; Diakonos et al., PoS (CPOD2006)010; Hatta and Stephanov, PRL91, 102003



$$\begin{split} F_2(M) &= \big\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i (n_i - 1) \big\rangle \Big/ \big\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_m \big\rangle^2, \\ \text{where } \langle ... \rangle \text{ indicates averaging over events} \\ \text{power-law dependence on M: } F_2(M) \sim (M^2)^{\phi_2} \end{split}$$

Expected intermittency index  $\phi_2$  at CP is 5/6 assuming the 3-D Ising universality class of QCD.

## Targets

- $\bullet\,$  Study of the onset of fireball and isospin symmetry in light systems requires symmetric reactions with preferable N = Z
- $\bullet$  All considered systems allow for a short target  $\longrightarrow$  allows for data-taking with Vertex Detector

#### **Planned targets**

- ullet water ightarrow
- magnesium (solid)
- boron (solid)





# NA61/SHINE future plans

- precision studies of **the onset of fireball** of strongly interacting matter with O, Mg, and B beams
- verification of the hypothesis of large isospin violation with N=Z nuclei (the simplest case) - O and Mg

			s	INE
()≈0)	$\sqrt{s_{NN}}$	≈ 17 GeV		
$K^{+}/\pi^{+}$	0.2	projected		·
	-	O+O	i+tvig ● , ●	<del>ال</del> ا •
	0.1 •	ι <b>€</b> ♥' <sub>B+B</sub>		-
	- p+p	Be+Be Si+S C+C A	Xe+L Si Au- Ar+Sc Pl	a +Au b+Pb
	0	10	102	i
	1	10	10-	$\langle W \rangle$

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E-by-E fluctuations	+	+	+	+		+	+
Resonances	+	+	+	+	+	+	+
Open charm			+	+	+	only top energy	+
$c - \bar{c}$ correlations				+	+		+
Quarkonium	+	+			+	+	+
Dileptons	+	+			+	+	+



SPSC-P-330-ADD-14

M. Gazdzicki et al., arXiv:2305.00212 [hep-ph]