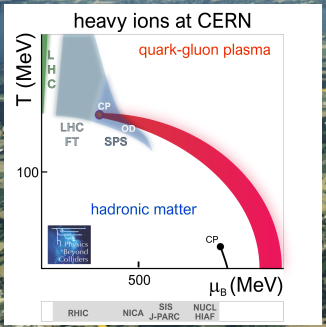
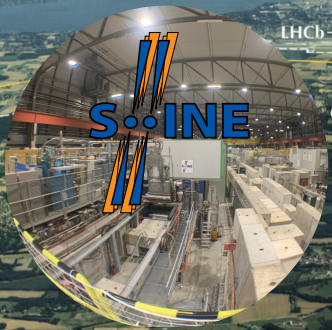
NA61/SHINE ++
strong interactions program

Maja Maćkowiak-Pawłowska (WUT)
for the NA61/SHINE Collaboration

NA61/SHINE - UNIQUE MULTIPURPOSE FACILITY:
Hadron production in hadron-nucleus and nucleus-nucleus collisions at high energies





LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
BEAMLINE
ACCELERATORS
ALIC
LHC 27 km

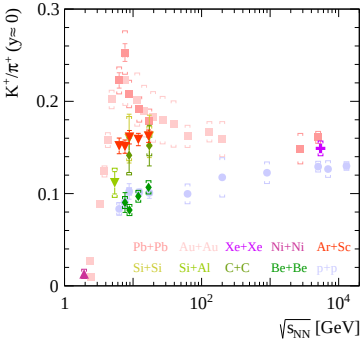
NA61/SHINE++

- **Energy scan with light and medium mass ions to study the diagram of strongly interacting matter**
- Measurements of heavy hadron resonances in large statistic p+p interactions
- Measurements with antiproton beams
- Measurements of hadron emission from the LBNF and HYPER-K replica targets
- Data for flux predictions in neutrino experiments using very low energy beams

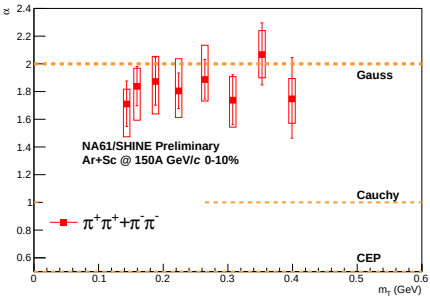
NA61/SHINE: Heavy-ions current status

Present results on nucleus-nucleus collisions:

- p+p and Pb+Pb/Au+Au in broad energy range
- Be+Be, Ar+Sc and Xe+La in the SPS energy range

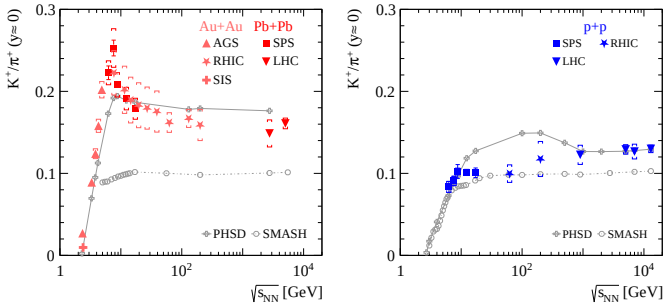


Onsets



No CEP indications

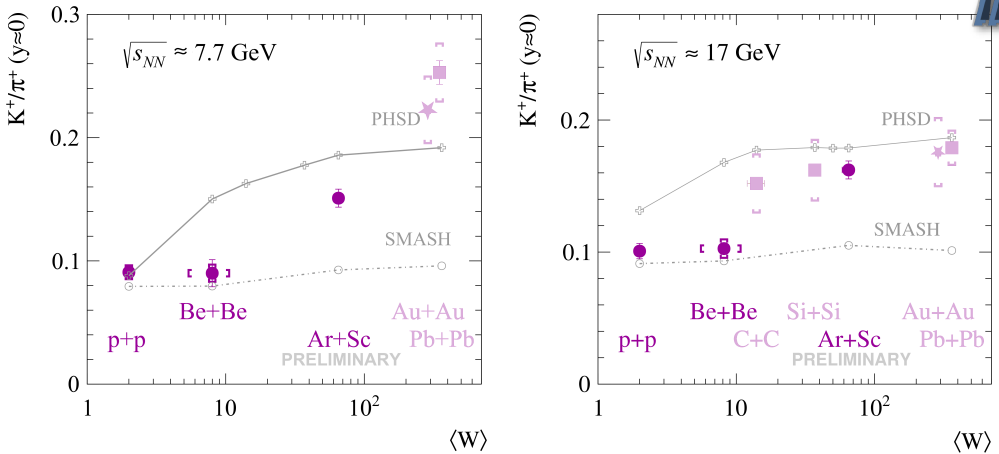
Heavy-ions and p+p



Small and heavy systems can be roughly described with the existing most popular models:

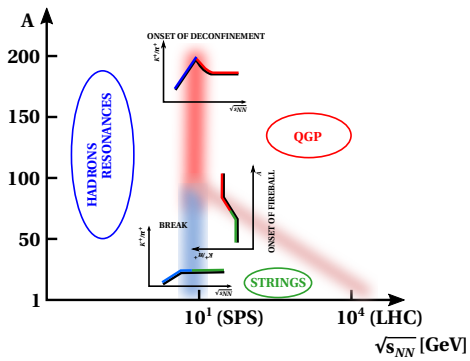
- Pb+Pb/Au+Au by PHSD, which includes transition to the QGP phase at high enough energy density,
- p+p by SMASH in lower energies and PHSD in higher energies via string production

Intermediate systems

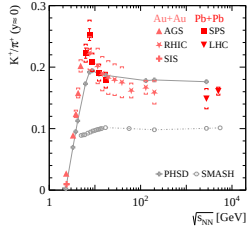


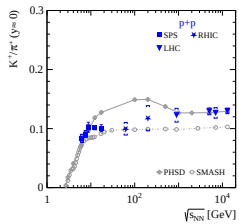
Existing models fail to describe the system size dependence

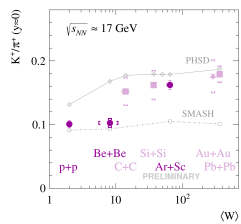
Possible interpretation of the data



arXiv:2205.06726

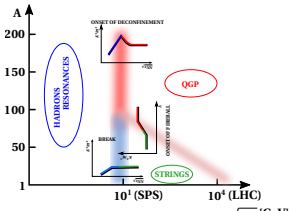






post-LS3 program

Possible explanations - references



Onset of strings:

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

Onset of deconfinement:

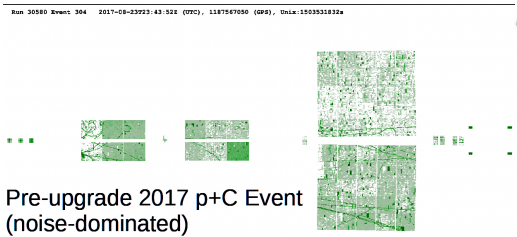
- SMES: Acta Phys.Polon. B30 (1999) 2705; PHSD: PRC, 78, 034919, 200; and NPA, 831, 215–242, 2009

Onset of QGP fireball:

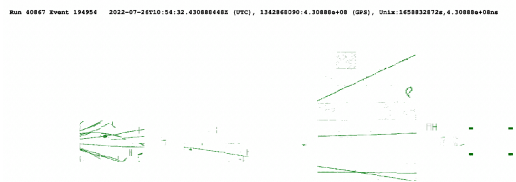
- colour ropes: NPB, 245, 449–468, 1984.
- string fusion: NPB, 390, 542–558, 1993; PLB, 287, 154–158, 1992; EPJA, 51, 4, 44, 2015; Phys. Rep., 599, 1–50, 2015; and PRD, 103, 9, 094029, 2021.
- core fragmentation: PRL., vol. 98, p. 152301, 2007.
- string melting: PRC, 72, 064901, 2005.
- percolation: EPJC, 32, 547–553, 2004; and PLB, 640, 96–100, 2006.
- **AdS/CFT duality:** PRC, 90, 1, 014901, 2014; PRD, 90, 2, 025031, 2014; PRC, 92, 1, 014011, 2015

First data-taking after LS2

- 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

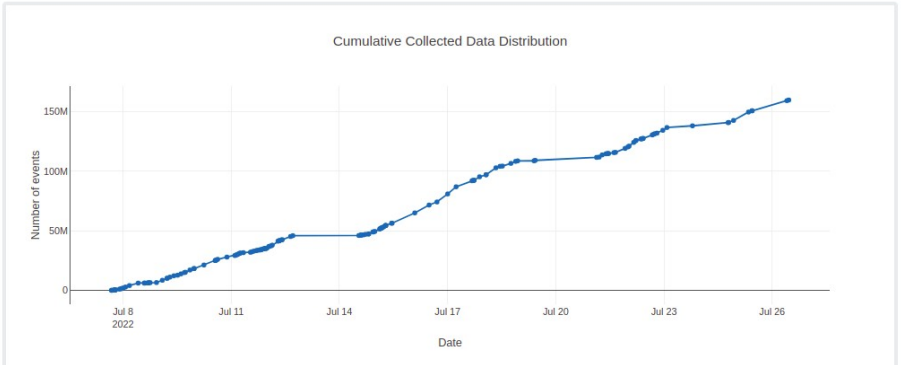


Pre-upgrade 2017 p+C Event (noise-dominated)



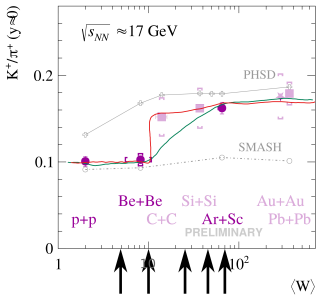
Post-upgrade 2022 p+T2K Event (track-dominated)

Success of the detector upgrade



The same detector set-up is planned for the post-LS3 measurements

Proposal to **measure** collisions of **light** and **intermediate** mass nuclei



+

p_{beam} (A GeV/c)	$\sqrt{s_{NN}}$ (GeV)	^{10}B # days	^{16}O # days	^{24}Mg # days	^{40}Ar # days
13	5.1	7	7	7	7
30	7.6	7	7	7	7
150	16.8	7	7	7	7

- $\sim$ 100M events per reaction
- ^{16}O beam already in 2024?

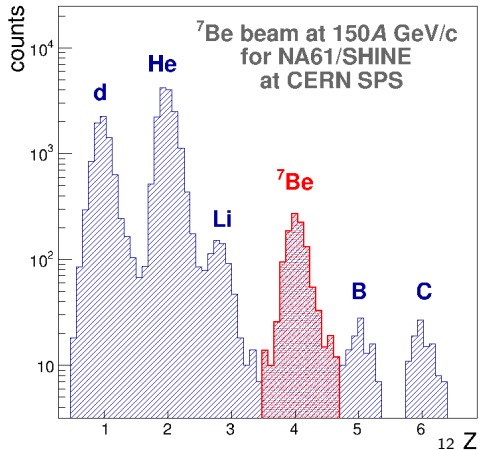
Primary vs secondary beams

Note, LHC and NA60++ request Pb beam.
Can NA61++ use fragmented Pb instead of primary beam?

Experience shows the superiority of primary over secondary beams

In case of secondary beams, beam identification and separation between isotopes becomes a problem.

Fraction of Be/all≈ 3-5%



Primary and secondary beams - future

- Primary beams of ^{10}B, ^{16}O, ^{24}Mg and ^{40}Ar are considered
  - there is presently **no separate source test stand** for source or beam developments $\rightarrow$ all tests have to be done on operational source.
    - need of extended beam diagnostics at source
- Secondary ^{4}He beam under consideration
  - \+ possibility to separate He from d and Li
  - \- no separation ^{4}He from ^{3}He?

NA61++ and NA60++ post LS3 requests

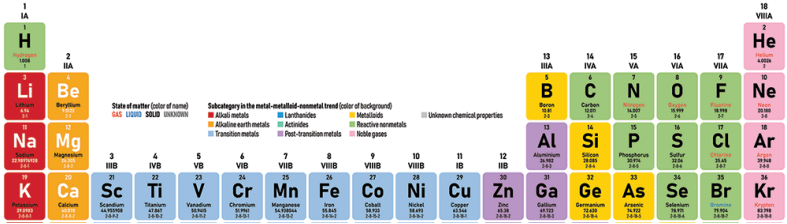
	NA61++	NA60++
objective	phase diagram studies	charmonia and open-charm production
beams	^{10}B (primary)/^{4}He(secondary), ^{16}O, ^{24}Mg(primary), ^{40}Ar(primary)	Pb

Complementary programs

Possible targets

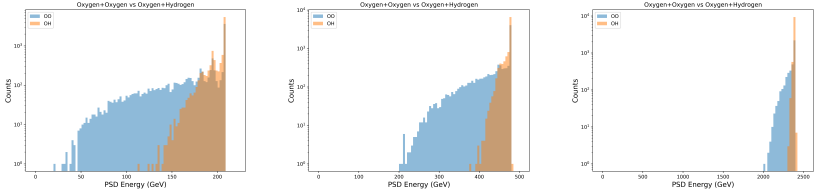
- For each beam ion candidate, the target with similar or a bit higher nuclear mass is desired.
- The solid/compact targets are in favor due to possibility of installation in VD.

projectile	$^{4}He/^{10}B$	^{16}O	^{24}Mg	^{40}Ar
target	^{4}He(liquid)/^{9}Be-^{12}C ^{7}Li	^{16}O(water) ^{19}F (LiF)	^{32}S ^{24}Mg	^{45}Sc ^{40}Ca



Water target for ^{16}O beam

- For 10% interaction probability $\sim$ 10 cm^3 of water is needed ($2.5x2.5x1.58$ cm^3),
- Water-tight container needed (bigger volume to eliminate interactions with walls?); can be installed in VD,
- clear separation of central O+O from O+H background:



- Fraction of O+O interactions below the energy deposited in O+H interactions estimated with RQMD.RMF model (SPSC-P-330-ADD-13):

oxygen beam (GeV/c)	13A	30A	150A
PSD upper cut(GeV)	120	380	2300
fraction (%)	12	16	17

Summary

- The physics case for studying the light and intermediate-mass nuclei collisions is study of the onset of fireball.
- Rough plan of the measurements was presented.
- Further beam/source studies are needed, and any input/improvement is most welcome!
- Next steps:
  - Decision on the continuation of NA61/SHINE or a new experiment's proposal in the first half of 2023
  - Addendum or LoI by summer 2023

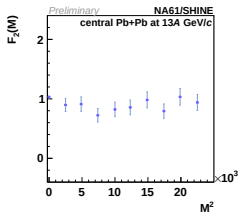
Thank you

NA61/SHINE would like to thank the CERN EP, BE, HSE and EN Departments for support

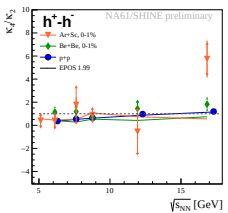
Search for the **critical point**

- **No indications** of **CP** so far→
- SPS energy range remains possible location of the CP
- Possible CP signatures improvement post-LS3:
  - higher-order moments of multiplicity and net-charges, e.g. stat. uncertainty of $\kappa_4/\kappa_2[net]$ for new data drops by 10 (30% → 3%)
  - intermittency - depending on the reaction σ_{stat} will drop 3-10 times
  - HBT correlations (for Be+Be current statistics is minimal for analysis)

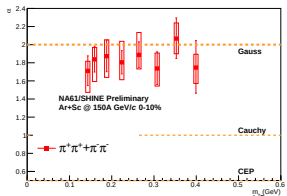
intermittency



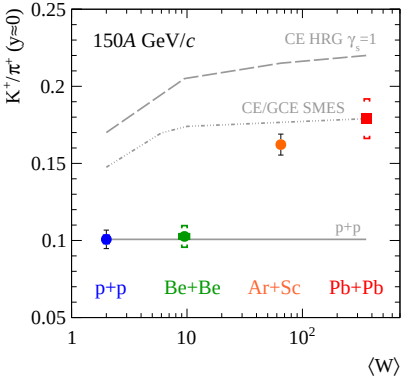
higher-order moments

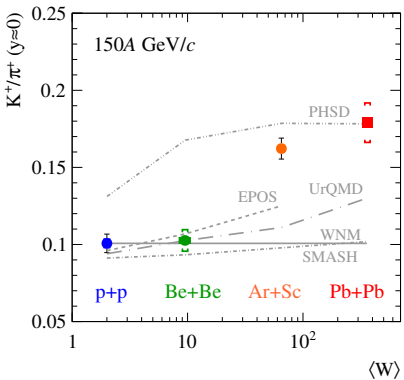


HBT correlations

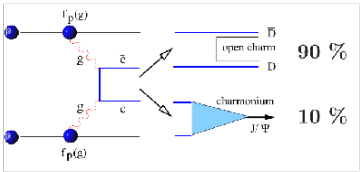


Model predictions

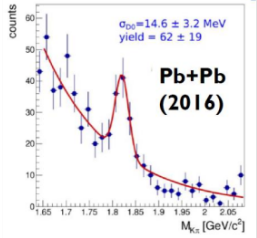




Strong interactions in 2021-2025

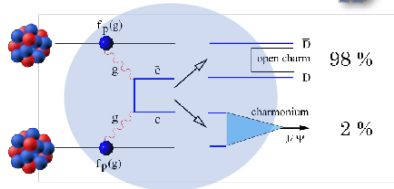


Open charm and J/ψ production within Matsui-Satz model [PL B178 416]



NA61/SHINE pilot measurements

Pb+Pb with QGP



- What is the mechanism of open charm production?
- How does the onset of deconfinement impact open charm production?
- How does the formation of quark-gluon plasma impact J/Ψ production?

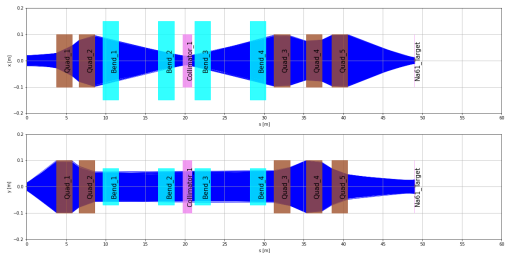
Medium reduces probability of J/Ψ production

$$P(c\bar{c} \to J/\psi) \equiv \frac{\langle J/\psi \rangle}{\langle c\bar{c} \rangle} \equiv \frac{\sigma_{J/\psi}}{\sigma_{c\bar{c}}}$$

$$P_{vacuum}(c\bar{c} \to J/\psi) > P_{medium}(c\bar{c} \to J/\psi)$$

Low-Energy Beamline Project

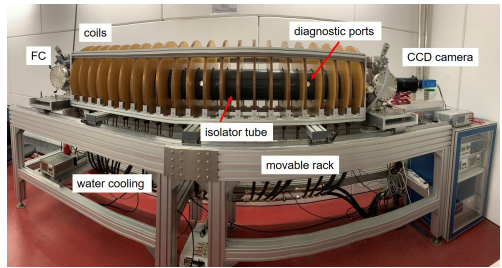
- A new tertiary low-E (1-20GeV) hadron beamline at CERN SPS H2 (same as NA61/SHINE)
- Positive evaluation from the SPSC committee - first data-taking planned in 2024 (depending on funding)
  CERN-SPSC-2021-028; CERN-SPSC-2022-022



Improvement of the beam-line

Large emittance of the low-momentum (below 40A GeV/c) ion beams is always a factor reducing the data-taking efficiency

- Ongoing efforts for improvement of the low energy ion beam emittance in SPS and in H2 beam-line in collaboration with BE-OP and BE-EA
- Ongoing efforts in investigating new innovative focusing techniques based on electrostatic lenses ("Gabor-lenses")
- First tests are planned before LS3

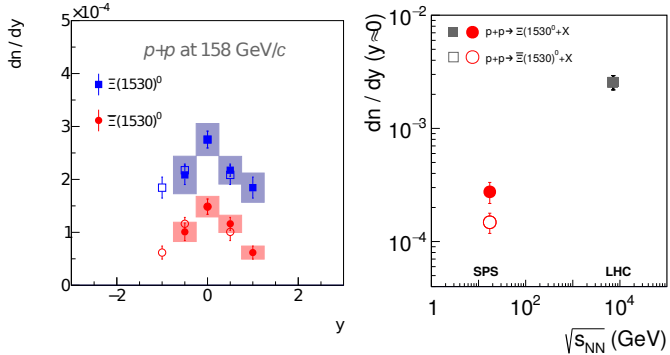


Summary

- **Status and plans for 2022-2025:**
  - The detector upgrade is completed.
  - First physics data taking in spring 2022

- **Ideas for 2027+:**
  - **Study of the diagram of high-energy nuclear collisions - energy scan with low and medium mass ions**
  - **Measurements of heavy hadrons and resonances in large statistics p+p interactions**
  - **Measurements with anti-proton beams**
  - **Hadron emission study using replica targets from the LBNF and HYPER-K**
  - **Measurements to improve quality of flux predictions in neutrino experiments using very low energy beams**

Multi-strange particles in NA61/SHINE -there is more



- The only results on $\Xi^0(1530)$ production in $p+p$ in the SPS energy range
- Other existing results on $\Xi^0(1530)$ production only by ALICE at $\sqrt{s_{NN}} = 7$ TeV

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- Study of exotic baryons requires a large-statistics data sample