NA61/SHINE long-term plans

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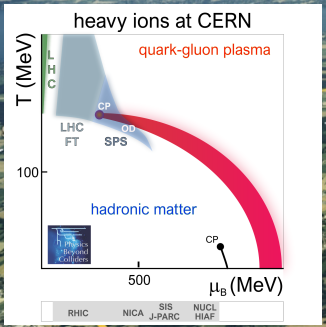
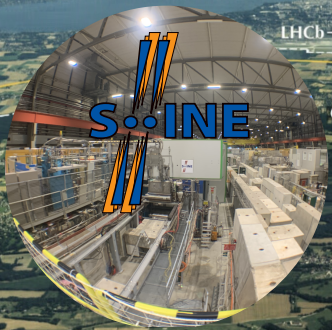
for the NA61/SHINE Collaboration

Detailed information is given in the NA61/SHINE status report 2020

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 2021-2024 (2025?)

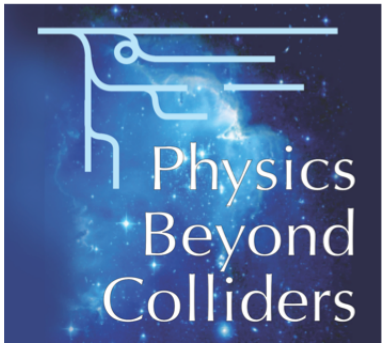
Beam request submitted to SPSC

- **STRONG INTERACTIONS:** measurements of charm hadron production in Pb+Pb collisions
- **COSMIC-RAYS:** measurements of nuclear fragmentation cross section
- **NEUTRINO:** measurements of hadron production induced by hadron beams

CERN-SPSC-2021-027

NA61++ 2027+

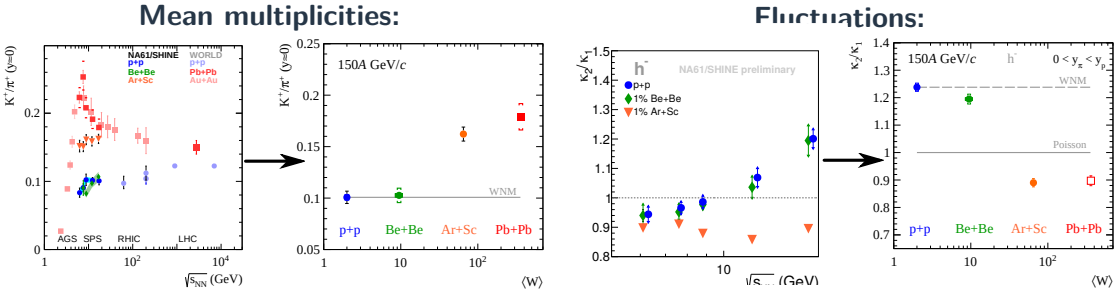
- Energy scan with light and medium mass ions to study the onset of fireball
- Measurements of heavy hadrons resonances in large statistics p+p interactions
- Measurements of hadron emission from the LBNF and HYPER-K replica targets
- Data for flux predictions in neutrino experiments using very low energy beams



CERN-SPSC-2020-023

Energy scan with light and medium mass ions to study the onset of (QGP) fireball

Current NA61/SHINE results



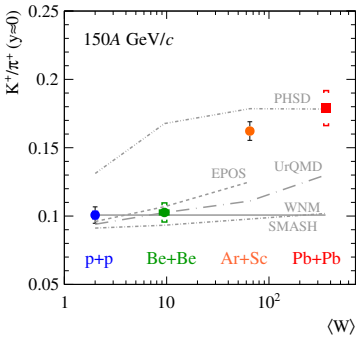
$$p+p \approx \text{Be+Be} \neq \text{Ar+Sc} \leqslant \text{Pb+Pb}$$

- Beginning of creation of strongly interacting matter with increasing nuclear mass number. Transition from **non-equilibrium** strings and resonances to **equilibrium** hadron gas or quark gluon plasma.

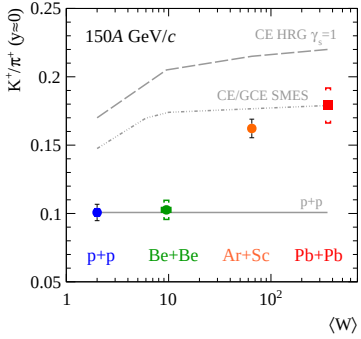
Data vs models

Multiplicities: K^+/π^+

dynamical models

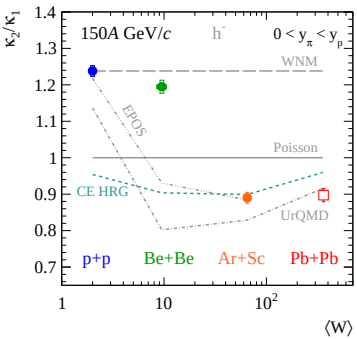


statistical models



Fluctuations:

various models

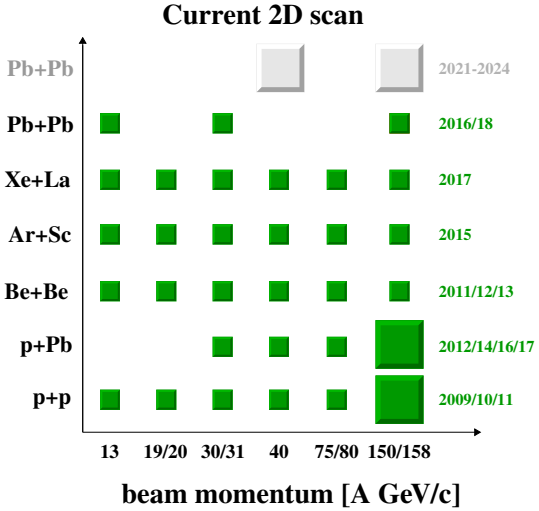


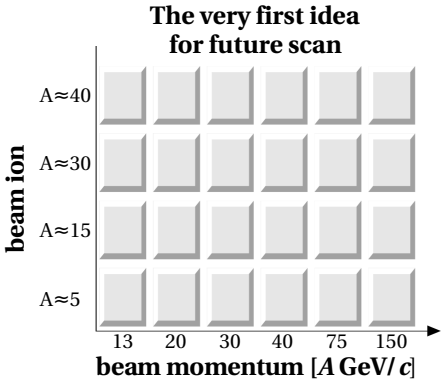
- None of actual models describe NA61/SHINE results

PHSD: Eur.Phys.J.A 56 (2020) 9, 223, arXiv:1908.00451 and private communication;
SMASH: J.Phys.G 47 (2020) 6, 065101 and private communication;
UrQMD and HRG: Phys. Rev. C99 (2019) 3, 034909
SMES: Acta Phys. Polon. B46 (2015) 10, 1991 - recalculated

p+p: Eur. Phys. J. C77 (2017) 10, 671
Be+Be: Eur. Phys. J. C81 (2021) 1, 73
Ar+Sc: NA61/SHINE preliminary
Pb+Pb: Phys. Rev. C66, 054902 (2002)
κ_2/κ_1: NA61/SHINE preliminary

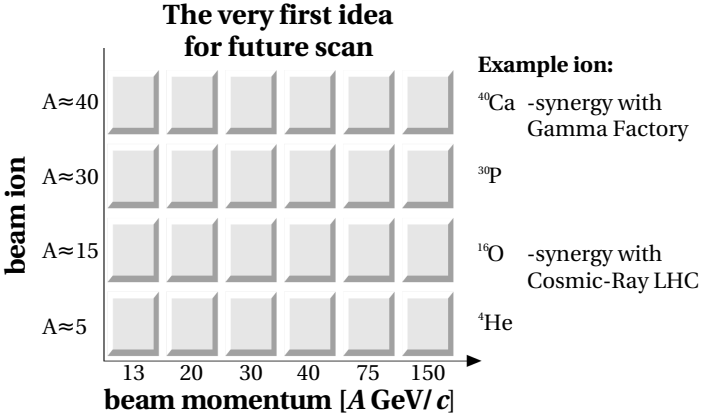
Onset of fireball

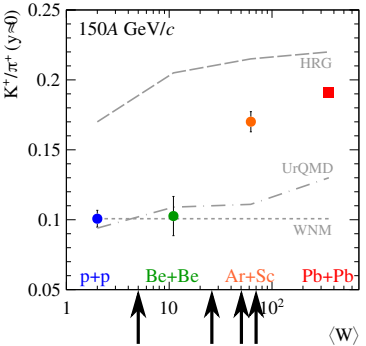




Onset of fireball

- Ion beam request for the Run 4 period

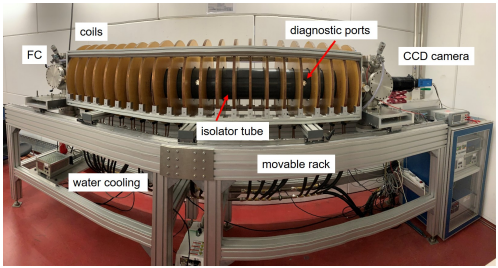




Improvement of the beam-line

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

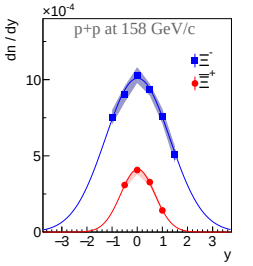
- Ongoing efforts for improvement of the low energy ion beam emittance in SPS and in H2 beam-line in collaboration with BE-OP and BE-EA
- Ongoing efforts in investigating new innovative focusing techniques based on electrostatic lenses ("Gabor-lenses")
- First tests are planned before LS3

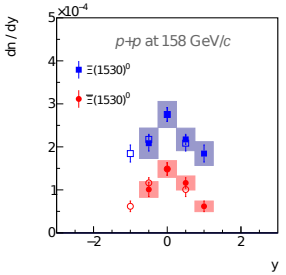


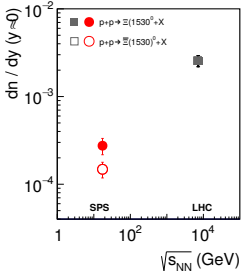
Measurements of heavy hadrons and resonances in large statistics p+p interactions

Multi-strange particles in NA61/SHINE

- **Large statistics of p+p interactions at 158 GeV/c gathered in 2009-2011 allowed to obtain unique results on the production of multi-strange hadrons**







- 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

- **Study of heavy baryons and resonances requires a large-statistics data sample**

Eur.Phys.J.C 81 (2021) 911

Heavy particles-there is more

Baryon resonance particles

Λ particles			Σ particles			Ξ and Ω particles			Charmed particles			Bottom particles		
Λ	$\frac{1}{2}^+$	****	Σ^+	$\frac{1}{2}^+$	****	Ξ^0	$\frac{1}{2}^+$	****	Λ_c^+	$\frac{1}{2}^+$	****	Λ_b^0	$\frac{1}{2}^+$	***
$\Lambda(1405)$	$\frac{1}{2}^-$	****	Σ^0	$\frac{1}{2}^+$	****	Ξ^-	$\frac{1}{2}^+$	****	$\Lambda_c(2595)^+$	$\frac{1}{2}^-$	***	$\Lambda_b(5912)^0$	$\frac{1}{2}^-$	***
$\Lambda(1520)$	$\frac{3}{2}^-$	****	Σ^-	$\frac{1}{2}^+$	****	$\Xi(1530)$	$\frac{3}{2}^+$	****	$\Lambda_c(2625)^+$	$\frac{3}{2}^-$	***	$\Lambda_b(5920)^0$	$\frac{3}{2}^-$	***
$\Lambda(1600)$	$\frac{1}{2}^+$	***	$\Sigma(1385)$	$\frac{3}{2}^+$	****	$\Xi(1620)$		*	$\Lambda_c(2765)^+$		*	Σ_b	$\frac{1}{2}^+$	***
$\Lambda(1670)$	$\frac{1}{2}^-$	****	$\Sigma(1480)$		*	$\Xi(1690)$		***	$\Lambda_c(2880)^+$	$\frac{5}{2}^+$	***	Σ_b^*	$\frac{3}{2}^+$	***
$\Lambda(1690)$	$\frac{3}{2}^-$	****	$\Sigma(1560)$		**	$\Xi(1820)$	$\frac{3}{2}^-$	***	$\Lambda_c(2940)^+$	$\frac{3}{2}^-$	***	Ξ_b^0, Ξ_b^-	$\frac{1}{2}^+$	***
$\Lambda(1710)$	$\frac{1}{2}^+$	*	$\Sigma(1580)$	$\frac{3}{2}^-$	*	$\Xi(1950)$		***				$\Xi_b(5935)^-$	$\frac{1}{2}^+$	***
$\Lambda(1800)$	$\frac{1}{2}^-$	***	$\Sigma(1620)$	$\frac{1}{2}^-$	*	$\Xi(2030)$	$\geq \frac{5}{2}$?	***	$\Sigma_c(2455)$	$\frac{1}{2}^+$	****	$\Xi_b(5945)^0$	$\frac{3}{2}^+$	***
$\Lambda(1810)$	$\frac{1}{2}^+$	***	$\Sigma(1660)$	$\frac{1}{2}^+$	***	$\Xi(2120)$		*	$\Sigma_c(2520)$	$\frac{3}{2}^+$	***	$\Xi_b(5955)^-$	$\frac{3}{2}^+$	***
$\Lambda(1820)$	$\frac{5}{2}^+$	****	$\Sigma(1670)$	$\frac{3}{2}^-$	****	$\Xi(2250)$		**	$\Sigma_c(2800)$		***	Ω_b^-	$\frac{1}{2}^+$	***
$\Lambda(1830)$	$\frac{5}{2}^-$	****	$\Sigma(1690)$		**	$\Xi(2370)$		**				$P_c(4380)^+$		*
$\Lambda(1890)$	$\frac{3}{2}^+$	****	$\Sigma(1730)$	$\frac{3}{2}^+$	*	$\Xi(2500)$		*	Ξ_c^+	$\frac{1}{2}^+$	***	$P_c(4450)^+$		*
$\Lambda(2000)$		*	$\Sigma(1750)$	$\frac{1}{2}^-$	***				Ξ_c^0	$\frac{1}{2}^+$	***			
$\Lambda(2020)$	$\frac{7}{2}^+$	*	$\Sigma(1770)$	$\frac{1}{2}^+$	*	Ω^-	$\frac{3}{2}^+$	****	$\Xi_c'^+$	$\frac{1}{2}^+$	***			
$\Lambda(2050)$	$\frac{3}{2}^-$	*	$\Sigma(1775)$	$\frac{5}{2}^-$	****	$\Omega(2250)^-$		***	$\Xi_c'^0$	$\frac{1}{2}^+$	***			
$\Lambda(2100)$	$\frac{7}{2}^-$	****	$\Sigma(1840)$	$\frac{3}{2}^+$	*	$\Omega(2380)^-$		**	$\Xi_c(2645)$	$\frac{3}{2}^+$	***			
$\Lambda(2110)$	$\frac{5}{2}^+$	***	$\Sigma(1880)$	$\frac{1}{2}^+$	**	$\Omega(2470)^-$		**	$\Xi_c(2790)$	$\frac{1}{2}^-$	***			

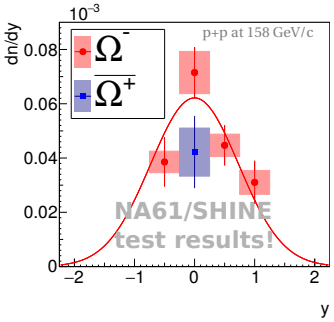
- Many poorly known meson and baryon states.
- SPS energies well suited for their measurements

$K^*(892)$

$I(J^P) = \frac{1}{2}(1^-)$

$895.50 \pm 0.92 \pm 2.6$	[9] ADUSZKIEW...20A NA61 158 pp
$48.8 \pm 1.8 \pm 2.0$	[8] ADUSZKIEW...20A NA61 158 pp

Large-statistics data sample needed



- Study of Ω already suffers form having only ∼60M events

Assuming

- average SPS super cycle: 40 s flat top: 4.8 s
- typical data taking efficiencies summarized in NA61/SHINE Addendum 2018, Sec 9.3
- 1 kHz read-out rate

We could achieve 600M p+p interactions over a month of the data taking

Measurements for flux predictions in neutrino experiments

Measurements of hadron production for neutrino and cosmic-ray physics

- **NA61/SHINE will continue to support needs of neutrino and cosmic ray communities after LS3 in the scope of:**
  - hadron yields measurements with use of LBNF and Hyper-Kamiokande replica targets
  - hadron production using low-energy hadron beams (1-20 GeV/c), where existing hadron production data is sparse, but high statistics of high-quality data is needed
- **Addendum to NA61/SHINE proposal submitted to SPSC** CERN-SPSC-2021-028

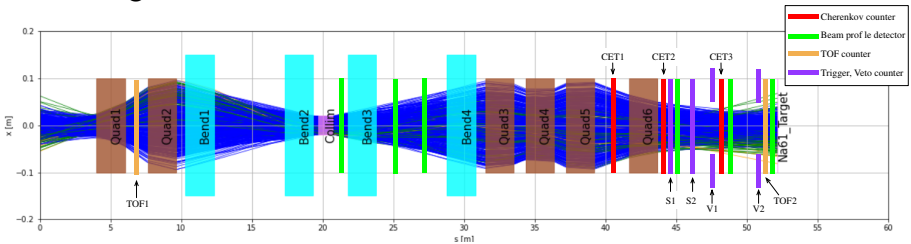
Needs for measurements employing low-E beams

- **Accelerator-based neutrino experiments:** to reduce the leading uncertainty on neutrino flux prediction (that is hadron production)
  Requirement: [T2K/Hyper-K] low-E secondary hadron interactions measurements (1-10 GeV/c pions, kaons, protons); [SBN] p+Be at 8 GeV/c
- **Atmospheric neutrino experiments:** to understand low-E hadron production for sub-GeV neutrino flux (0.1-1 GeV neutrinos)
  Requirement: low-E proton beam (1-20 GeV/c) on nitrogen or carbon target
- **Spallation neutron source neutrino experiments:** to understand pion production rate from mercury target
  Requirement: [JSNS2 at J-PARC] 3 GeV/c proton on a mercury target; [SNS at ORNL] 1 GeV/c proton on a mercury target

Very Low Energy beam-branch idea

NA61/SHINE with the strong support of BE-EA experts is advancing on studies for the implementation of a **Very Low Energy** (VLE) beam-line still before LS3:

- simulation of an intermediate (secondary) target for low-E beam production
- investigation of various options for particle identification in the beam-line
- investigation on beam-line designs aiming to maximize acceptance, minimize beam-line length and cost



CERN-SPSC-2021-028

Milestones

- **Now:**
  - main focus on completion of the upgrade and preparation to the approved physics programme
  - gathering the ideas for 2027+ physics programme
  - initial studies within working groups
  - discussion of the collaboration format (NA61/SHINE or a new collaboration)
- **2022:**
  - open workshop on NA61/SHINE future
- **2023:**
  - formulation of a letter of intend for 2027+ physics programme

Thank you

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

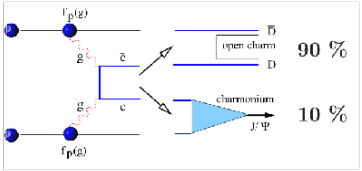
Summary

- **Status and plans for 2021-2024:**
  - The detector upgrade is ongoing.
  - Readiness for physics data taking in spring 2022
  - Beam request under discussion with SPSC

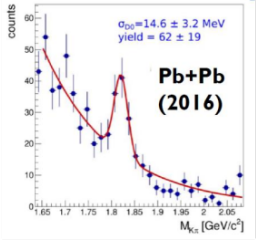
- **Ideas for 2027+:**
  - **Study of the onset of fireball - energy scan with low and medium mass ions**
  - **Measurements of heavy hadrons and resonances in large statistics p+p interactions**
  - **Measurements with anti-proton beams**
  - **Hadron emission study using replica targets from the LBNF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

Additional slides

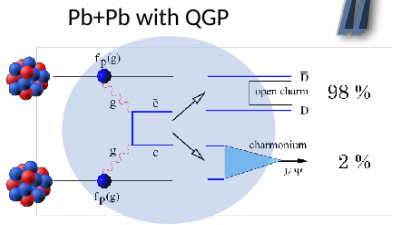
Strong interactions in 2021-2024



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



NA61/SHINE pilot measurements



- 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?

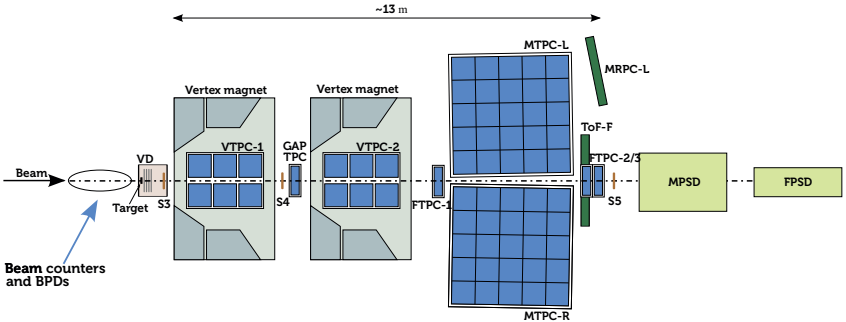
Medium reduces probability of J/Ψ production

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

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

NA61/SHINE's status

- Work on the upgrade is ongoing. Full readiness of the NA61/SHINE detector foreseen for spring 2022..



- **First physics data taking in 2022 - beam request submitted to SPSC.**