

Future light-ion program at SPS

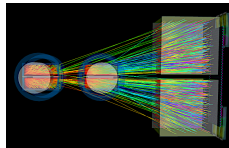
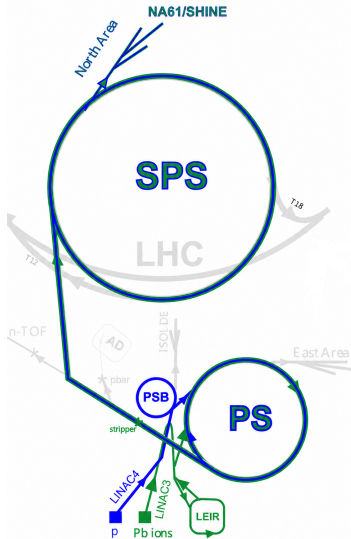
Maja Maćkowiak-Pawłowska
for the NA61/SHINE Collaboration



**Faculty
of Physics**

WARSAW UNIVERSITY OF TECHNOLOGY

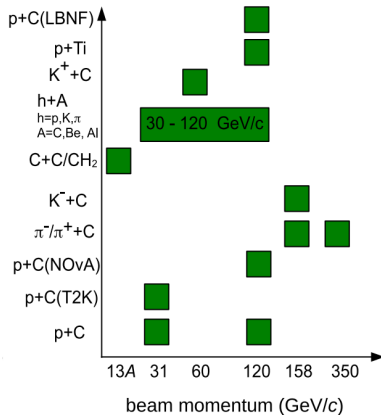
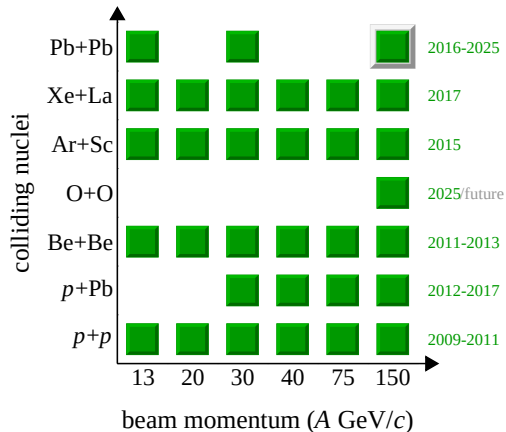
SPS Heavy Ion and Neutrino Experiment – NA61/SHINE



Physics program:

- **Strong interactions:** study of **onset of deconfinement (OD)**, **isospin-symmetry breaking (IB)**, **search for CP (CP)**, **open charm production (OC)**
- **Cosmic rays:** fragmentation cross-section measurements, hadron production for reference measurements
- **Neutrinos:** reference measurements for accelerator neutrino experiments (T2K, NO ν A, DUNE)

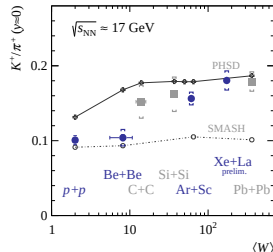
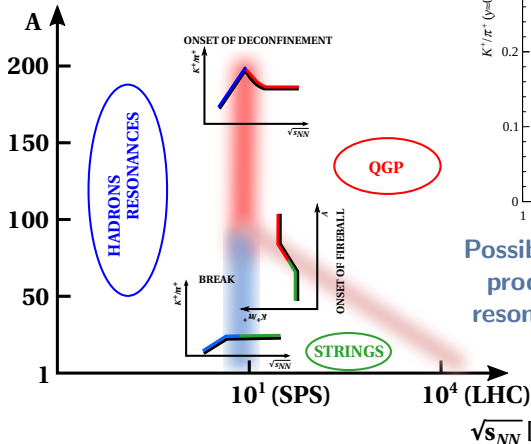
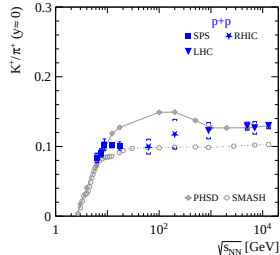
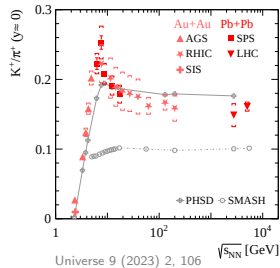
Wide variation of studied systems and energies



$$\sqrt{s_{NN}} = 5.1 - 16.8(27.4)^1 \text{ GeV}$$

¹max. p beam momentum 400 GeV/c

OD: Different phases of strongly interacting matter



Possible domains of particle productions described by resonances, strings or QGP

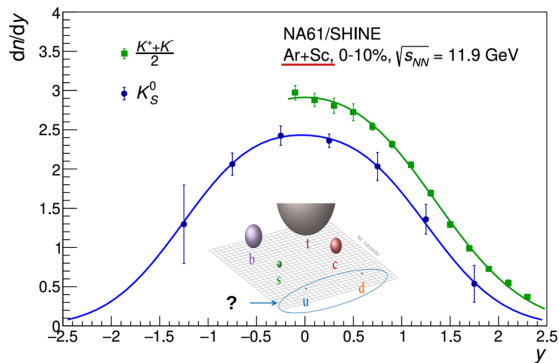
theo: APPB 46 (2015) 1991, PRD 90 (2014) 025031,

PPN 51 (2020) 337

exp: PRC 77 (2008) 024903, EPJC 84 (2024) 416,

PRC 102 (2020) 011901, Xe+La preliminary

IB: Excess of charged over neutral kaons



NA61/SHINE and others, Nature Commun. 16 (2025) 2849

- Ar+Sc – nearly charge symmetric (valence $u \approx d$ within 6%)
- We expect:

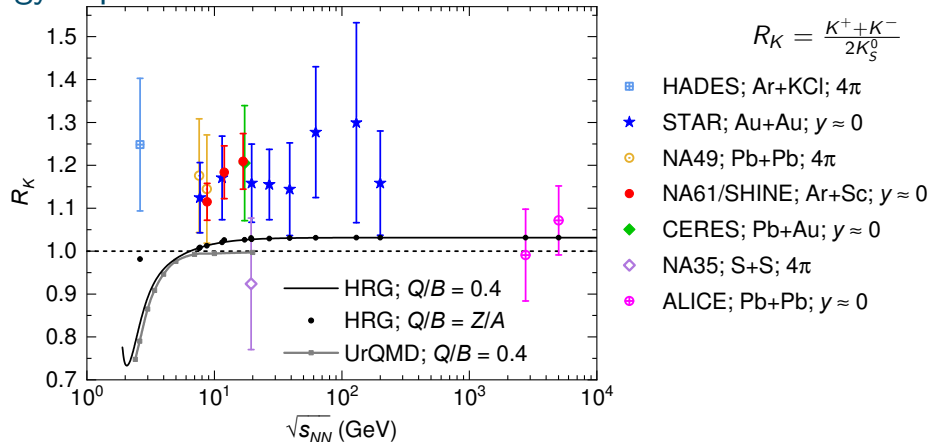
$$K^+(u\bar{s}) \approx K^0(d\bar{s}) \quad u \leftrightarrow d$$

$$K^-(\bar{u}s) \approx \bar{K}^0(\bar{d}s) \quad \bar{u} \leftrightarrow \bar{d}$$

$$\frac{K^+ + K^-}{2} \approx \frac{K^0 + \bar{K}^0}{2} = K_S^0$$
- Data – excess of charged over neutral kaons:

$$\frac{K^+ + K^-}{2} > K_S^0$$
- Unexpected violation of flavor symmetry between u and d quarks

IB: Energy dependence in ion+ion collisions



The charged-kaon yield at mid-rapidity exceeds the neutral-kaon yield by $\approx 20\%$. Also visible in hadron-nucleus collisions! NA61/SHINE, PRD 107 (2023) 062004

NA61/SHINE and others, Nature Commun. 16 (2025) 1, 2849; Y. Balkova and T. Šušša (for NA61/SHINE), EPJ Web Conf. 364 (2026), 11003; A. Tefelska (for NA61/SHINE), ICNFP 2026;

ALICE Pb+Pb 5.02 TeV based on PRC 101 (2020) 044907, PRC 114 (2026) 024909

NA61/SHINE light-ion program after LS3 – main goals:

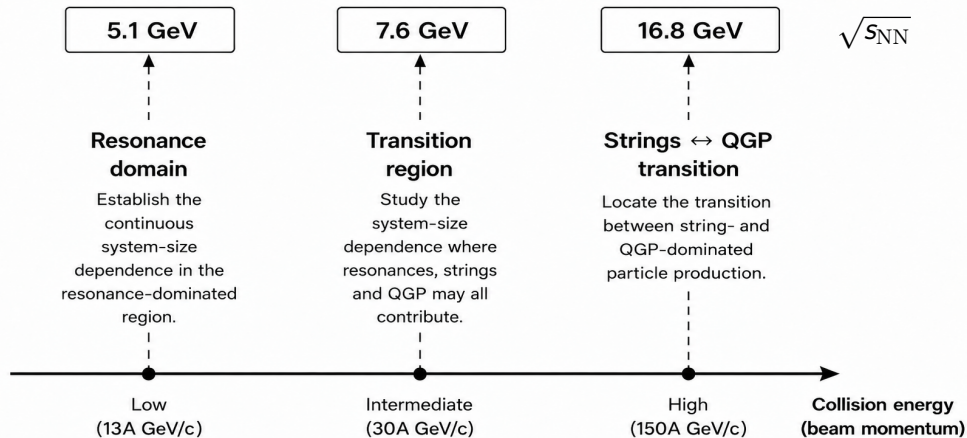
- Complete the systematic exploration of the system-size and collision-energy dependence of hadron production with light systems of C+C, Mg+Mg or B+B, and O+O
- Almost all suggested systems are symmetric ones:

$^{12}\text{C} + ^{12}\text{C}$	$^{16}\text{O} + ^{16}\text{O}$	$^{24}\text{Mg} + ^{24}\text{Mg}$	$^{11}\text{B} + ^{11}\text{B}$ (alternative)
C + C	O + O	Mg + Mg	B + B
A = 12 + A = 12	A = 16 + A = 16	A = 24 + A = 24	A = 11 + A = 11
Z = 6 + Z = 6	Z = 8 + Z = 8	Z = 12 + Z = 12	Z = 5 + Z = 5
$N = Z$ (N = 6, Z = 6)	$N = Z$ (N = 8, Z = 8)	$N = Z$ (N = 12, Z = 12)	$N \neq Z$ (N = 6, Z = 5)
Isospin symmetric systems ($N = Z$) — ideal for a clean isospin test			Alternative system selected according to O+O results.

- Three proposed beam momenta to be measured after LS3

For the proposal of new post-LS3 measurements see
SPSC-P-330-ADD-14 and **SPSC-P-330-ADD-16**

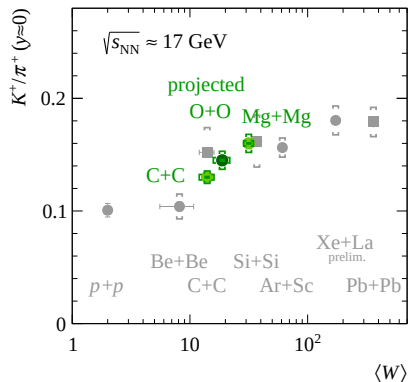
Why three energies (beam momenta)?



System size $\times$ collision energy $\rightarrow$ two-dimensional mapping of the collision diagram

Optimal program determined by O+O

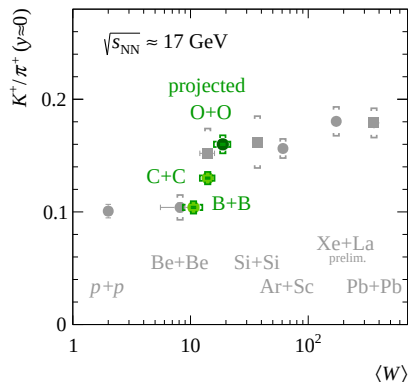
- Taken in 2025, O+O at 16.8 GeV ($\sqrt{s_{NN}}$) will determine the optimal ion sequence



Scenario 1

K^+/π^+ in O+O between Be+Be and Ar+Sc $\rightarrow$
C, Mg, O

See **SPSC-P-330-ADD-16** and references therein

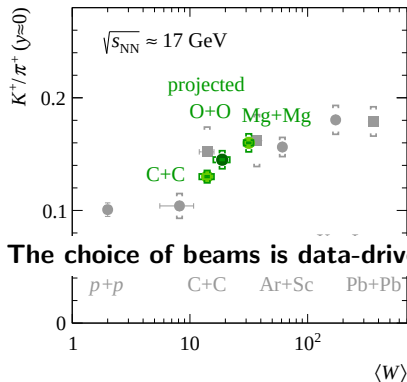


Scenario 2

K^+/π^+ in O+O close to Ar+Sc $\rightarrow$
C, B, O

Optimal program determined by O+O

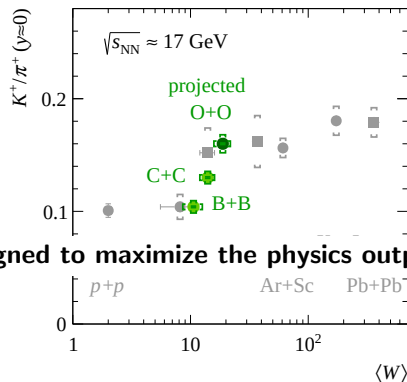
- Taken in 2025, O+O at 16.8 GeV ($\sqrt{s_{NN}}$) will determine the optimal ion sequence



The choice of beams is data-driven and designed to maximize the physics output

Scenario 1

K^+/π^+ in O+O between Be+Be and Ar+Sc $\rightarrow$
C, Mg, O



Scenario 2

K^+/π^+ in O+O close to Ar+Sc $\rightarrow$
C, B, O

Physics landscape

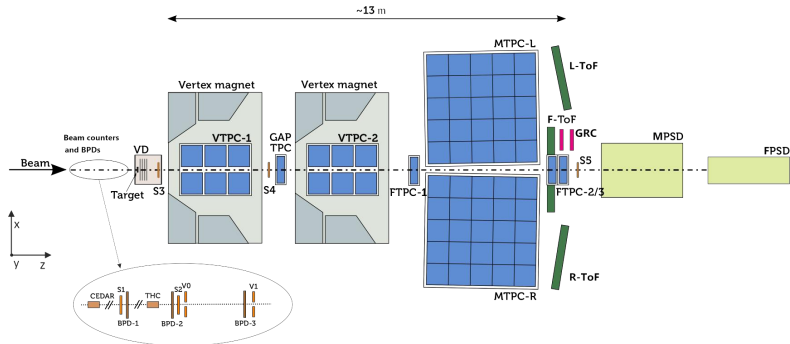
- **CERN SPS** ($\sqrt{s_{NN}}$ 5–17 GeV) enters its **Long Shutdown 3** (until 2029)
- **Two ion experiments** will operate after LS3 at SPS: **NA61/SHINE** and **NA60+/DiCE** (only Pb)
- **STAR at BNL RHIC**: operation ended in 2026 ($\sqrt{s_{NN}}$ 3–200 GeV).
- **CBM at SIS100/FAIR**: physics program is expected to start in 2028/29. However, the maximum $A+A$ collision energy, $\sqrt{s_{NN}} \leq 5$ GeV, is below the onset-of-deconfinement region (~ 8 GeV)
- **MPD at NICA**: physics program is expected to start in 2027, with collision energies up to 11 GeV. Its collider-mode measurements would be complementary to the NA61/SHINE fixed-target program

SPS therefore, remains uniquely positioned to perform a systematic light-ion system-size and collision-energy scan in this energy range

Thank you!

Backup

NA61/SHINE detector

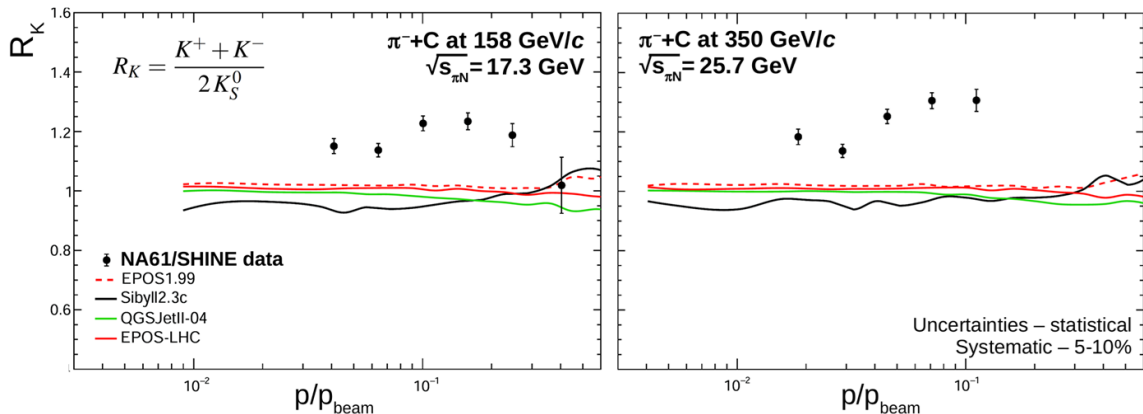


data rate:
Pre-LS2 ~ 100 Hz
Post-LS2 ~ 1000 Hz

- Large acceptance: full forward hemisphere, down to $p_T = 0$ for charged hadrons; partial coverage of the backward hemisphere for neutral hadrons
- Charged particle identification: dE/dx , tof
- Centrality: Projectile Spectator Detectors
- Ion (Be, O, Ar, Xe, Pb) and hadron (π , K , p) beams, various targets including liquid hydrogen and water

IB: Hadron-nucleus interactions

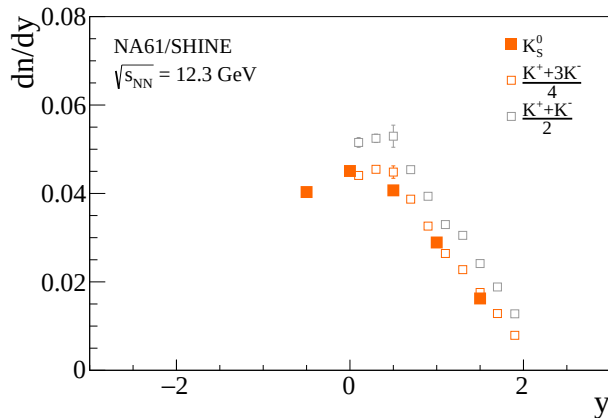
Ratio of charged over neutral kaons as a function of $x_F(lab) = p/p_{beam}$



NA61/SHINE, PRD 107 (2023) 062004

$R_K \approx 1.2 - 1.3$ not reproduced by models

IB: Proton-proton interactions



NA61/SHINE, EPJC 84 (2024) 8, 820

- The $p+p$ system is highly charge-asymmetric (valence u, u, d)
- A significant charged-over-neutral kaon excess is observed:
$$\frac{K^+ + K^-}{2} > K_S^0$$
- Can be understood by Quark Coalescence:
$$\frac{K^+ + 3K^-}{4} \approx K_S^0$$

EPJC 83 (2023) 10, 928