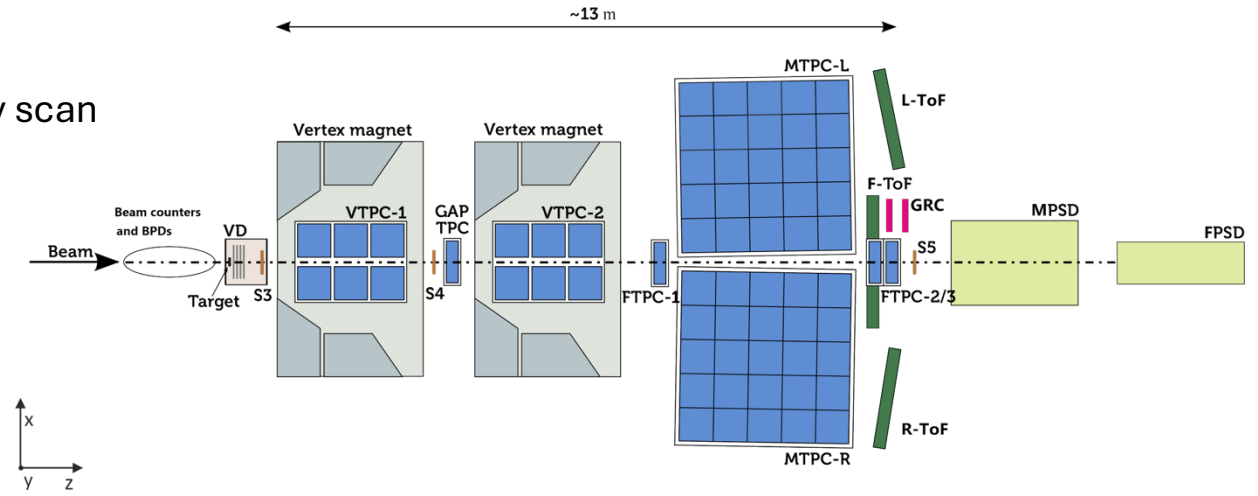
NA61/SHINE beyond LS3

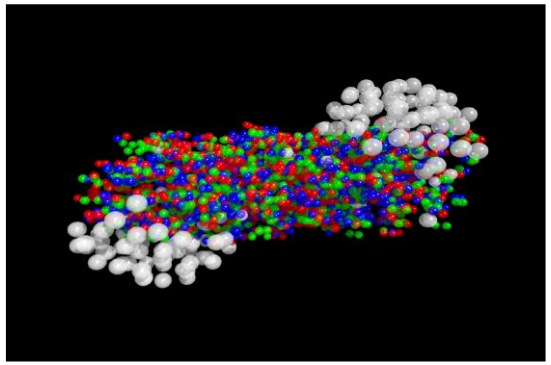
Seweryn Kowalski for the
NA61/SHINE Collaboration

Why NA61/SHINE beyond LS3?

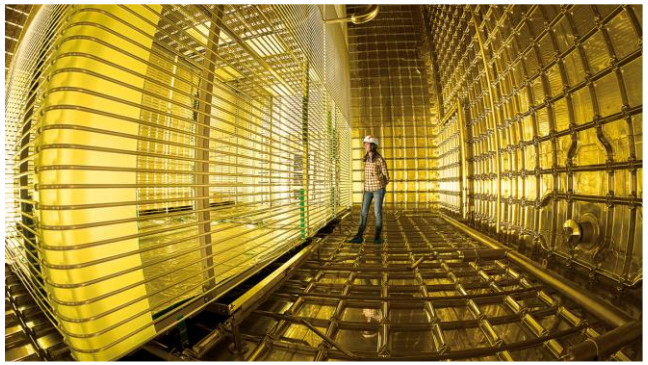
- **Strong interactions**
  - Complete the light-ion system-size and collision-energy scan
  - Isospin-symmetry violation
  - Towards charm correlations
- **Neutrinos**
  - Hyper-K / DUNE / SBND
  - Atmospheric neutrinos
- **Cosmic rays**
  - Antimatter production
  - Nuclear fragmentation
- **Space radiation**
  - Cross-section measurements



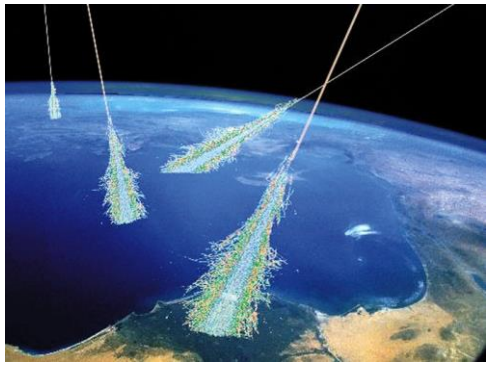
A unique multi-purpose fixed-target experiment exploiting the flexibility of the SPS



UrQMD



ProtoDUNE
(CERN-PHOTO-202308-195-28)

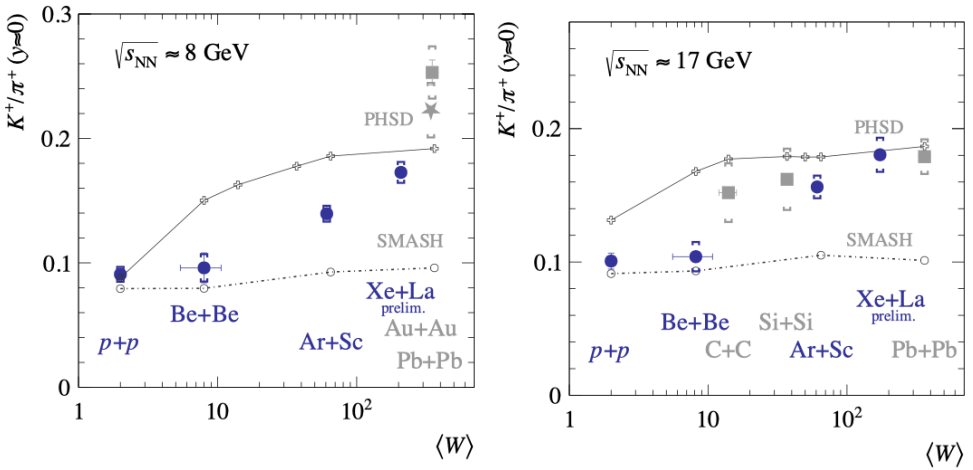


NASA
(in NA61/SHINE since 2024)

One light-ion program - two major physics questions

What have we learned?

CERN-SPSC-2026-020 (SPSC-P-330-ADD-16)
and references therein

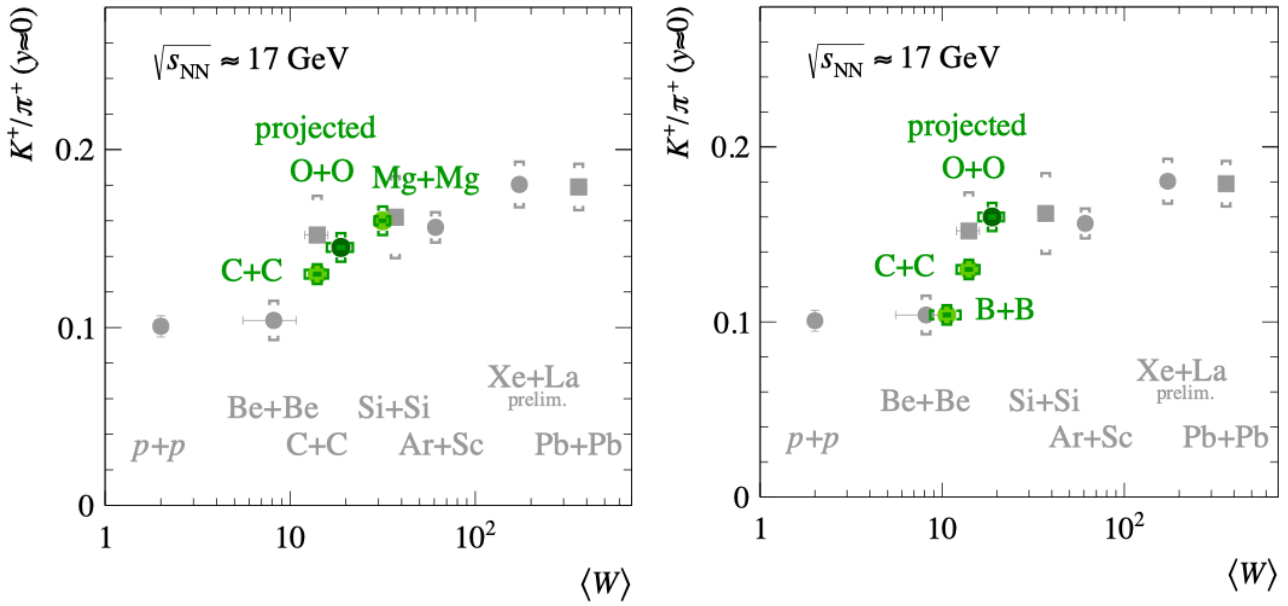


System-size dependence reveals a non-trivial pattern

- NA61/SHINE performed a systematic scan of *p*+*p* → Be+Be → Ar+Sc → Xe+La → Pb+Pb at 13*A*-150*A* GeV/*c*
- The results indicate a rapid change of hadron-production properties with increasing system size
- The region between Be+Be and Ar+Sc remains particularly important
- Measurements of light nuclei are needed to resolve the structure of this transition

Where does the transition from string-dominated to QGP-dominated particle production occur?

Run-3 O+O results will determine the optimal ion sequence



Scenario 1
K^+/π^+ in O+O between Be+Be and Ar+Sc
→ C; Mg; O

Scenario 2
K^+/π^+ in O+O close to Ar+Sc
→ C; B; O

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

One light-ion program - two major physics questions

Unexpectedly large isospin-symmetry violation

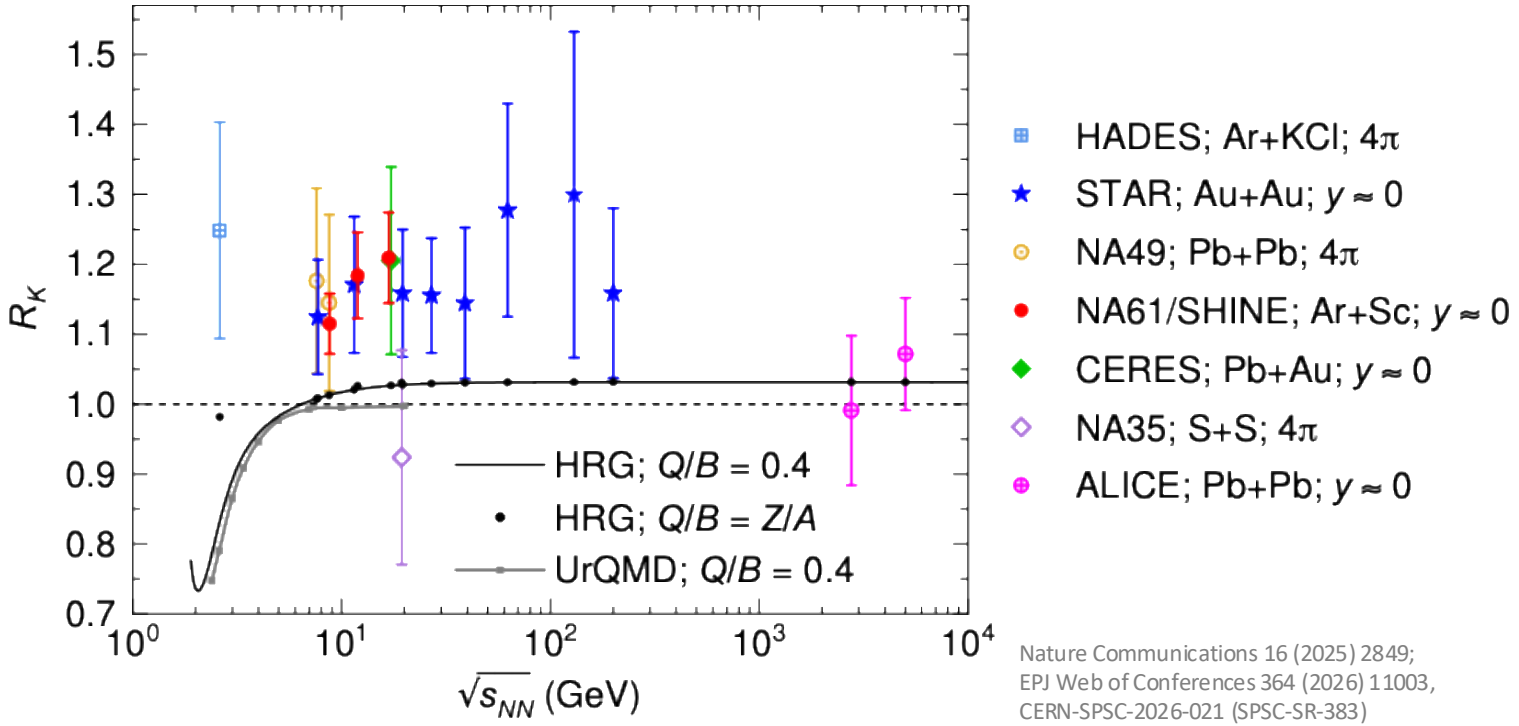
Isospin symmetry for collision of *Z*=*N* nuclei predicts

$$R_K = \frac{\langle K^+ \rangle + \langle K^- \rangle}{2\langle K_S^0 \rangle} = 1$$

NA61/SHINE observes

$$R_K = 1.184(61)$$

in central Ar+Sc collisions at $\sqrt{s_{NN}} = 11.9$ GeV

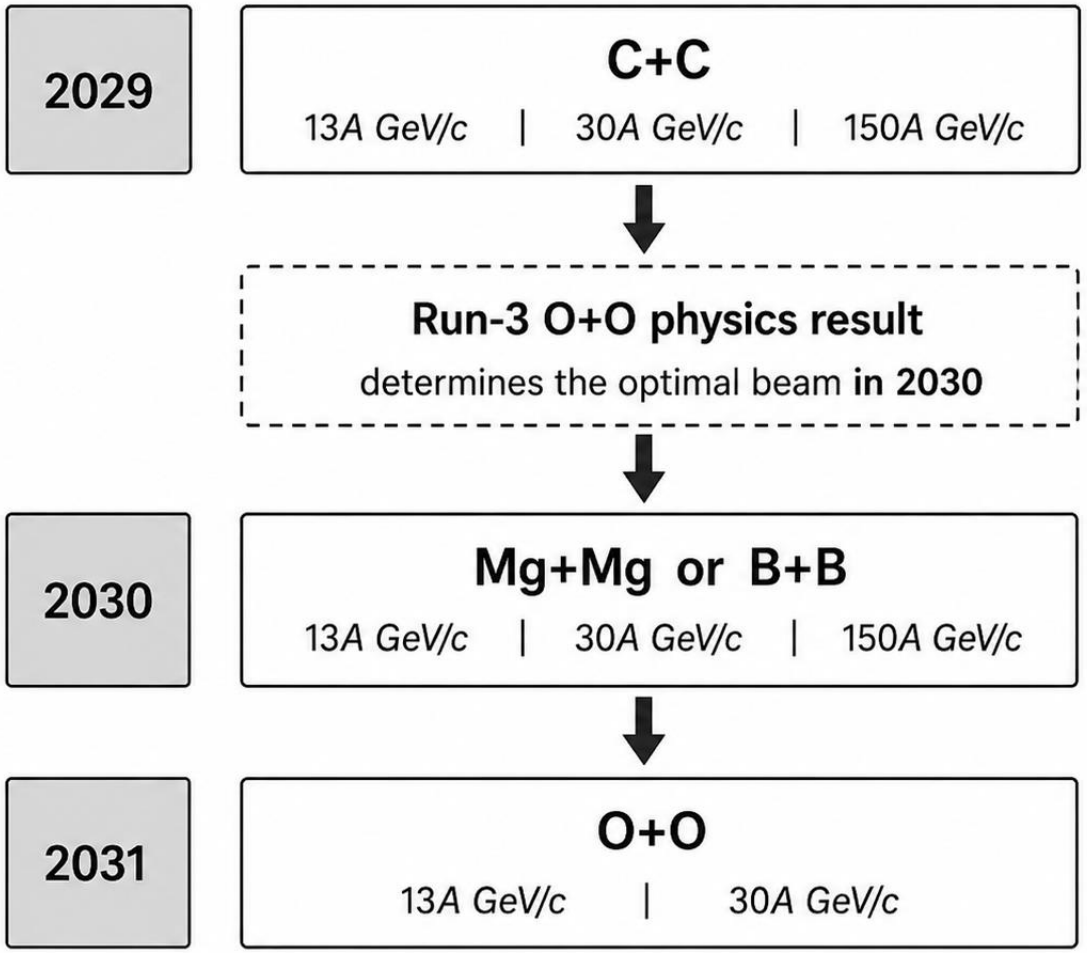


Nature Communications 16 (2025) 2849;
EPJ Web of Conferences 364 (2026) 11003,
CERN-SPSC-2026-021 (SPSC-SR-383)

Known isospin-breaking effects do not explain the observed excess

One measurement program addresses two fundamental questions

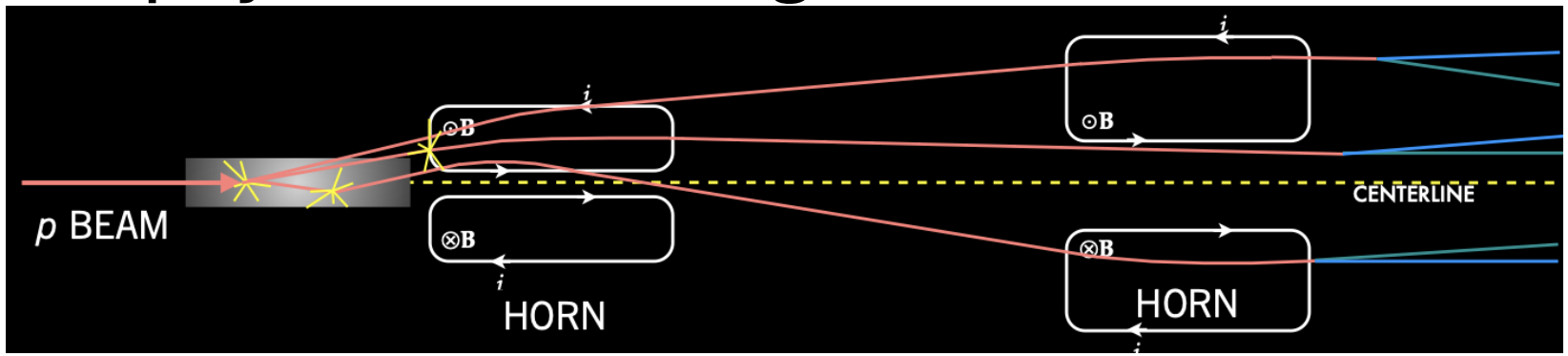
Strong interactions - completing the light-ion scan



A focused three-year program completing the light-ion scan

Three energies – three systems – synergy for two physics cases

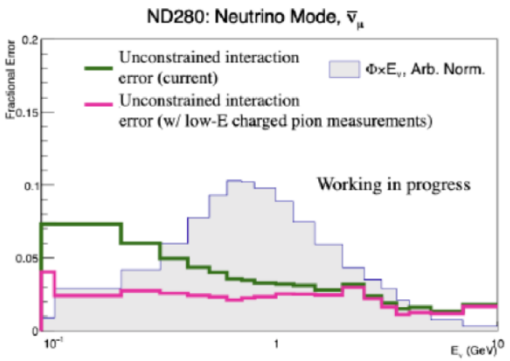
Neutrino physics - reducing flux uncertainties



primary proton → target → secondary hadrons → re-interactions → neutrino flux

low-energy secondary interactions = important remaining uncertainty

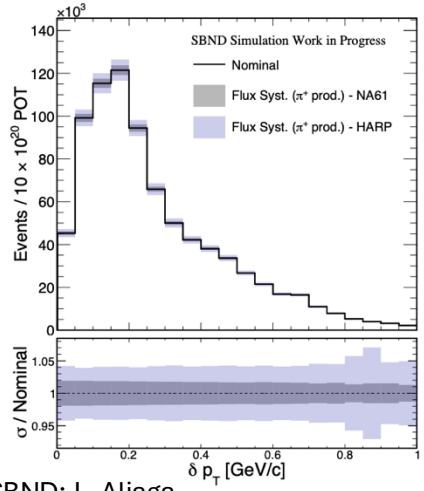
Hyper-K



Expected improvements of flux error (CERN-SPSC-2022-022)

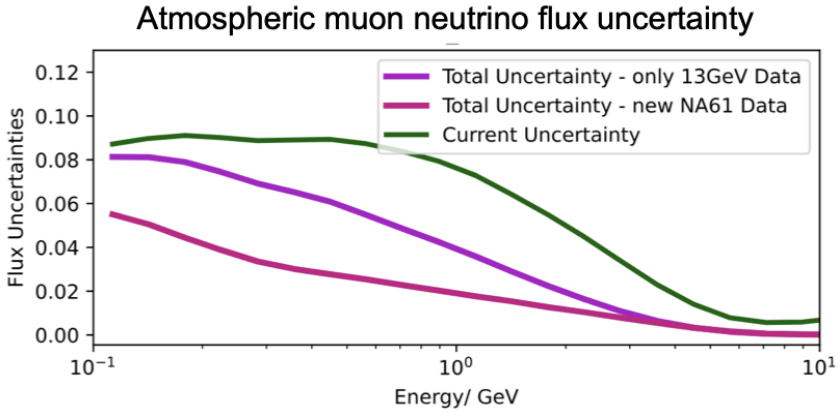
CERN-SPSC-2022-022 (SPSC-M-793)

DUNE



SBND: L. Aliaga

Atmospheric neutrinos



Y. Yang and L. Cook (Bartol flux group)

CERN-SPSC-2022-022 (SPSC-M-793)
CERN-SPSC-2025-024 (SPSC-P-374)

Precise neutrino measurements require precise hadron-production measurements

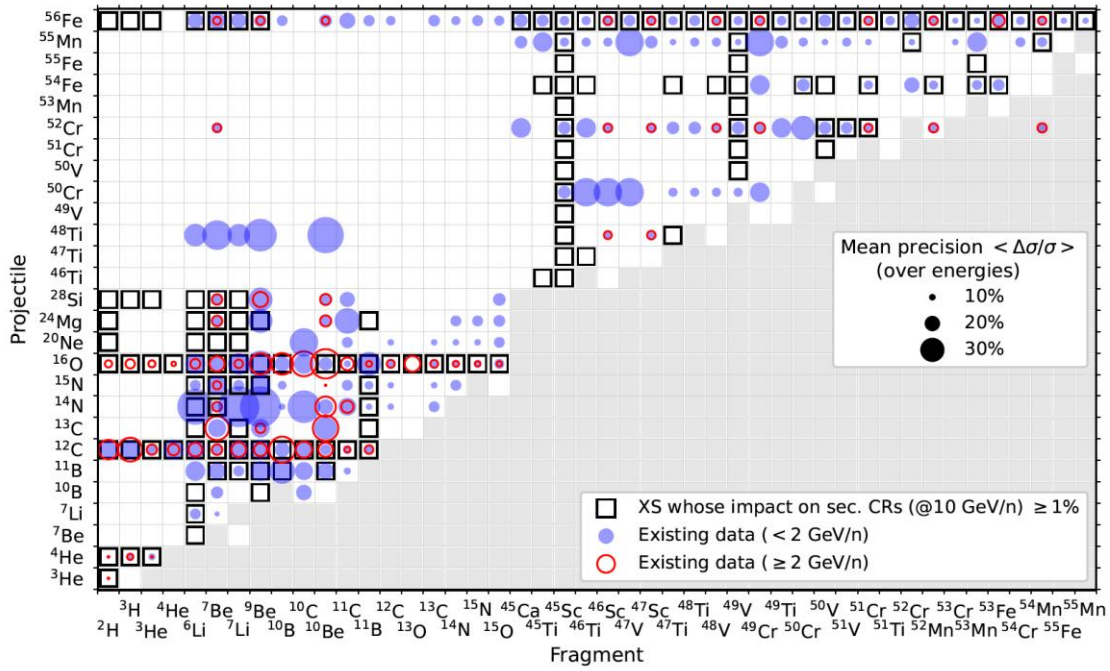
Cosmic rays and space radiation - nuclear physics limits the interpretation

Cosmic rays

- antiprotons
- antideuterons
- fragmentation Si–Fe

Space radiation

- Moon / Mars missions
- secondary particles in shielding
- transport codes disagree by **30–40%**
- lack of cross-section data



Phys. Rept. 1161 (2026) 1–81

overview of the available nuclear data for the H target and the missing cross section

Low-energy beamline opens a new physics domain

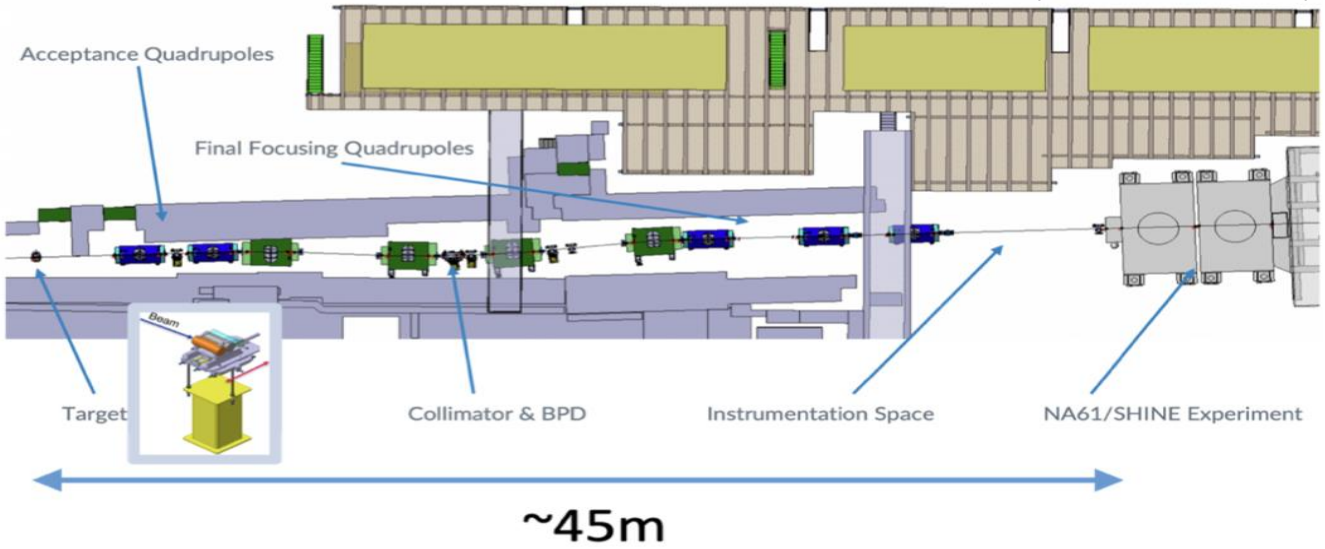
Low-energy beamline → broad physics impact

Neutrinos
- Hyper-K
- DUNE
- SBND
- atmospheric ν

Space radiation
- *p*+Al
- Moon/Mars radiation transport

The low-energy beamline is not a single-experiment facility - it enables several complementary physics programs

Adapted from CERN-SPSC-2021-028 (SPSC-P-330-ADD-12)



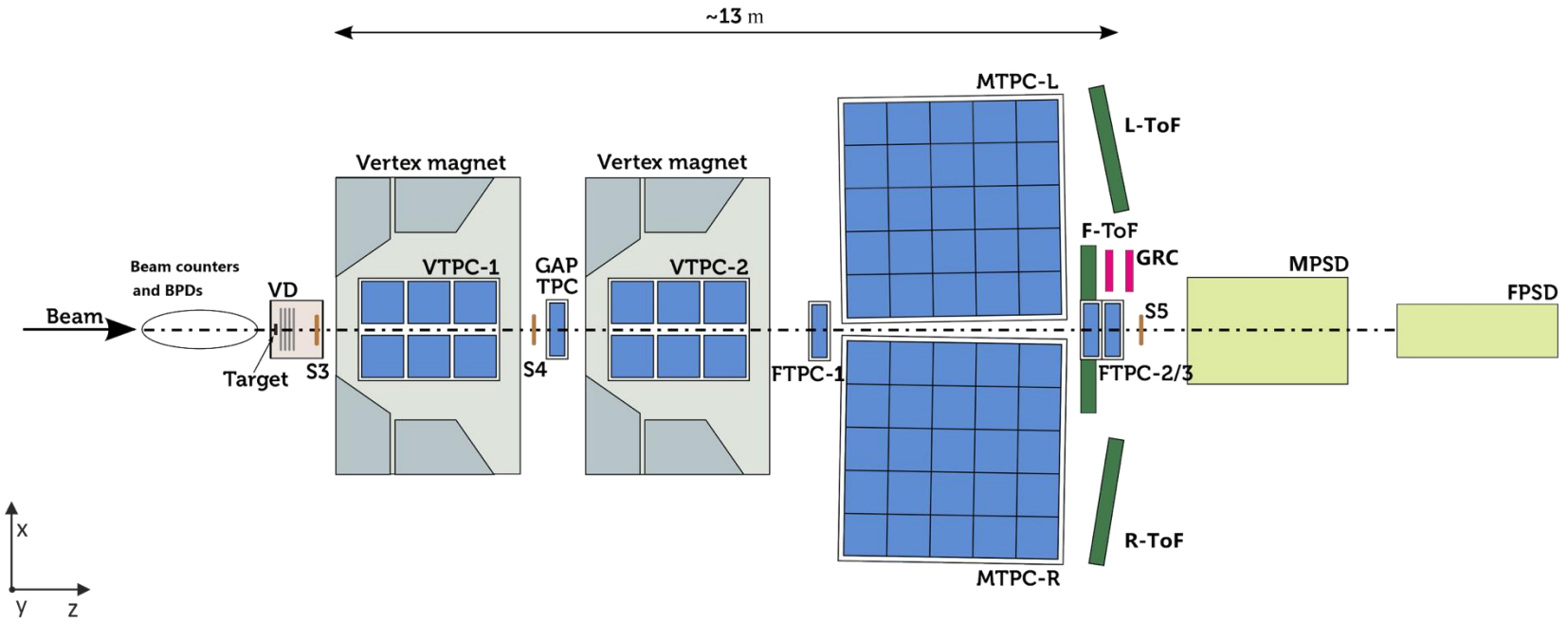
Experimental capabilities and path towards Run 5

Post-LS3

- existing detector for light ions
- existing SPS beams
- new low-energy beamline

Towards Run 5

- fast tracking system
- silicon pixels + possible MPGDs
- up to **10 kHz**
- charm–anticharm correlations



Two realistic running scenarios

OPTIMISTIC

2029 → 2030 → 2031 → 2032 → 2033

Low-E beamline: **from 2030**

~8 weeks/year neutrino program

Cosmic rays: antimatter + fragmentation

Light ions: 2029–31

Charm correlation: 2032–33

PESSIMISTIC

2029 → 2030 → 2031 → 2032 → 2033

Low-E beamline: **from 2031**

~4 weeks/year neutrino program

Cosmic rays: reduced / delayed

Light-ion statistics reduced

Charm correlation → Run 5

in either scenario, the low-energy beam is essential for most of the neutrino physics program

Different schedules — the same long-term physics goals

Year	Collision system	Beam momentum	Requested statistics	Estimated beam time
2029 (late autumn)	C+C	150 A GeV/c	100 M central events	~1.5 weeks
	C+C	30 A GeV/c	100 M central events	~1.5 weeks
	C+C	13 A GeV/c	100 M central events	~1.5 weeks
	The program for 2030 depends on the results of the O+O analysi			
2030 Option 1	Mg+Mg	150 A GeV/c	100 M central events	~1.5 weeks
	Mg+Mg	30 A GeV/c	100 M central events	~1.5 weeks
	Mg+Mg	13 A GeV/c	100 M central events	~1.5 weeks
2030 Option 2	B+B	150 A GeV/c	100 M central events	~1.5 weeks
	B+B	30 A GeV/c	100 M central events	~1.5 weeks
	B+B	13 A GeV/c	100 M central events	~1.5 weeks
2031	O+O	30 A GeV/c	100 M central events	~1.5 weeks
	O+O	13 A GeV/c	100 M central events	~1.5 weeks
2032/2033	Pb+Pb	150 A GeV/c	250 M central events	~2 weeks commis + 4 weeks

Year	Collision system	Beam momentum	Estimated beam time	Main physics goal
2029 (late autumn)	π + C	15 GeV/c	~4 weeks	Secondary interactions in the target for both J-PARC and Fermilab experiments
	π + Al	15 GeV/c		
2030	p + N_2	5 GeV/c	~8 weeks	Atmospheric neutrinos (ν runs at 3, 5, 8, and 12 GeV/c)
	p + N_2	8 GeV/c		
	p + Be	8.9 GeV/c		SBND at Fermilab
	π + C, Al, Be, water, Fe	8 GeV/c		Secondary interactions in the target and beamline for both J-PARC and Fermilab experiments (needs pions from 1–4 GeV; measurements on all targets at higher and lower energies may continue in later years)
2031	π + C, Al, Be, water, Fe	3 GeV/c	~8 weeks	Secondary interactions in the target and beamline for both J-PARC and Fermilab experiments (measurements on all targets at higher and lower energies may continue in later years)
	π + C, Al, Be, water, Fe	5 GeV/c		
	p + N_2	3 GeV/c		Atmospheric neutrinos (ν runs at 3, 5, 8, and 12 GeV/c)
	p + Hg / W	3.8 GeV/c		Future spallation neutron source R&D and JSNS² sterile neutrino search
2032	K + C, Al, Be, water, Fe	12 GeV/c	~8 weeks	Secondary interactions in the target and beamline for both J-PARC and Fermilab experiments (needs kaons; measurements on all targets at lower energies may continue in later years)
	p + N_2	12 GeV/c		Atmospheric neutrinos (ν runs at 3, 5, 8, and 12 GeV/c)
2033	p + LBNF/DUNE target	40–120 GeV/c	~8 weeks	DUNE primary beam energy
	p + Hyper-K prototype	31 GeV/c		Hyper-K
Measurements subject to beam-time availability	p + BNB replica	8.9 GeV/c	~8 weeks	SBND at Fermilab
	p + C downstream target	8.9 GeV/c		Backward production measurements for the COMET experiment

Year	Collision system	Beam momentum	Requested statistics	Estimated beam time	Main physics goal
2029 (late autumn)	C+C	150 A GeV/c	60 M central events	~1 week	Diagram of high-energy nuclear collisions; isospin-symmetry violation
	C+C	30 A GeV/c	60 M central events	~1 week	
	C+C	13 A GeV/c	60 M central events	~1 week	
	The program for 2030 depends on the results of the O+O as				
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	Mg+Mg	30 A GeV/c	60 M central events	~1 week	
	Mg+Mg	13 A GeV/c	60 M central events	~1 week	
2030 Option 2	B+B	150 A GeV/c	60 M central events	~1 week	
	B+B	30 A GeV/c	60 M central events	~1 week	
	B+B	13 A GeV/c	60 M central events	~1 week	Diagram of high-energy nuclear collisions; isospin-symmetry violation
2031	O+O	30 A GeV/c	60 M central events	~1 week	Diagram of high-energy nuclear collisions; isospin-symmetry violation
	O+O	13 A GeV/c	60 M central events	~1 week	Diagram of high-energy nuclear collisions; isospin-symmetry violation
Run 5	Pb+Pb	150 A GeV/c	>500 M central events	TBE	Charm–anticharm correlations

Year	Collision system	Beam momentum	Estimated beam time	Main physics goal
2029 (late autumn)	π + C	15 GeV/c	~4 weeks	Secondary interactions in the target for both J-PARC and Fermilab experiments
2030	π + C	30 GeV/c	~4 weeks	Secondary interactions in the target for Fermilab experiments
2031	p + N_2	8 GeV/c	~4 weeks	Atmospheric neutrinos
	p + Be	8.9 GeV/c		For SBND at Fermilab
2032	π + C, Al	5 GeV/c	~4 weeks	Secondary interactions in the target and beamline for both J-PARC and Fermilab experiments (needs pions 1–4 GeV, may take place on all higher energies in later years, also needs Be, water and Fe target runs)
	p + N_2	5 GeV/c		Atmospheric neutrinos (ν runs at 3, 5, 8, 12 GeV/c)
2033	p + Hyper-K prototype	31 GeV/c	~4 weeks	Hyper-K

Year	Beam	Targets	Beam momentum	Main physics applications	Estimated beam time
2030	p	H_2	70 GeV/c	Antiproton and antideuteron production	~ 4 weeks
2031	Pb fragments: Si–Fe, He	H_2	13 A GeV/c	Nuclear-fragmentation cross sections	~ 2 weeks
	p	Al	2 GeV/c and 10 GeV/c	Space-radiation transport and shielding studies	~ 2 weeks

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2031	p	H_2	70 GeV/c	Antiproton and antideuteron production	~ 2 weeks
2033	Pb fragments: Si–Fe, He	H_2	13 A GeV/c	Nuclear-fragmentation cross sections	~ 2 weeks
	p	Al	2 GeV/c and 10 GeV/c	Space-radiation transport and shielding studies	~ 1 week

Summary

NA61/SHINE beyond LS3

- **Complete the light-ion scan** and address the unexpected isospin-symmetry violation
- **Provide essential hadron-production data** for next-generation neutrino experiments
- **Deliver unique cosmic-ray, fragmentation and space-radiation measurements**
- **Prepare NA61/SHINE for charm correlations in Run 5**

A coherent and flexible physics program for the SPS after LS3