Report from the NA61/SHINE experiment

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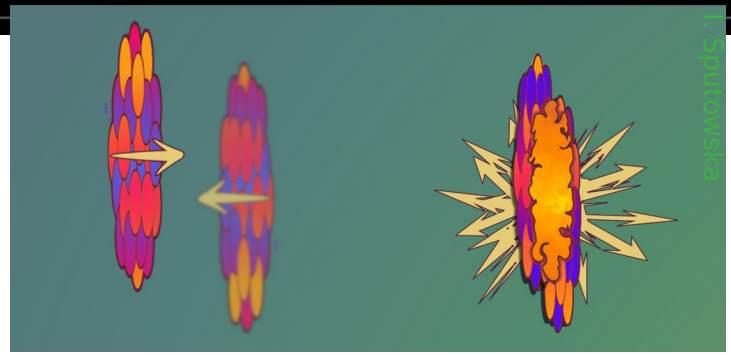
for the NA61/SHINE Collaboration

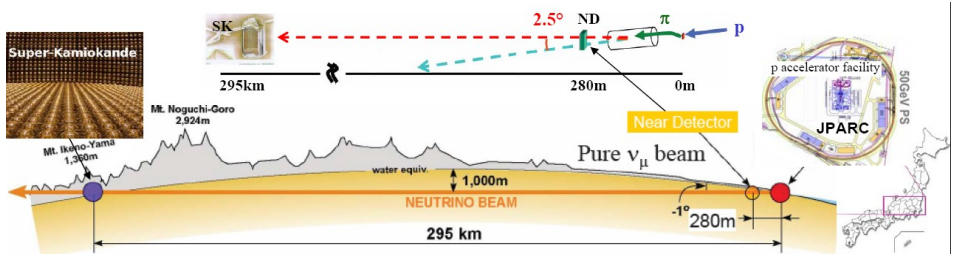
SPSC Open Session
November 22, 2022

NA61/SHINE - Research program



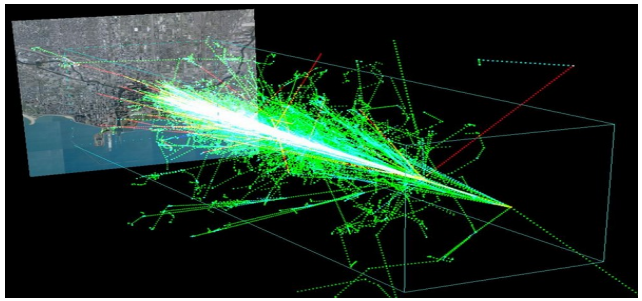
Strong interactions physics

- search for the critical point of strongly interacting matter
- study of the properties of the onset of deconfinement
- heavy quarks: direct measurement of open charm at SPS energies



Neutrino and cosmic ray physics

- hadron measurements for the J-PARC neutrino program
- hadron measurements for the Fermilab neutrino program
- measurements for cosmic ray physics (Pierre-Auger and KASCADE experiments) for improving air shower simulations
- measurements of nuclear fragmentation cross sections of intermediate mass nuclei needed to understand the propagation of cosmic rays in our Galaxy



Detector upgrade: completed

… data taking in progress

- Measurements of charm hadron production for heavy ion physics
- Measurements of nuclear fragmentation cross section for cosmic ray physics
- Measurements of hadron production induced by proton and kaon beams for neutrino physics

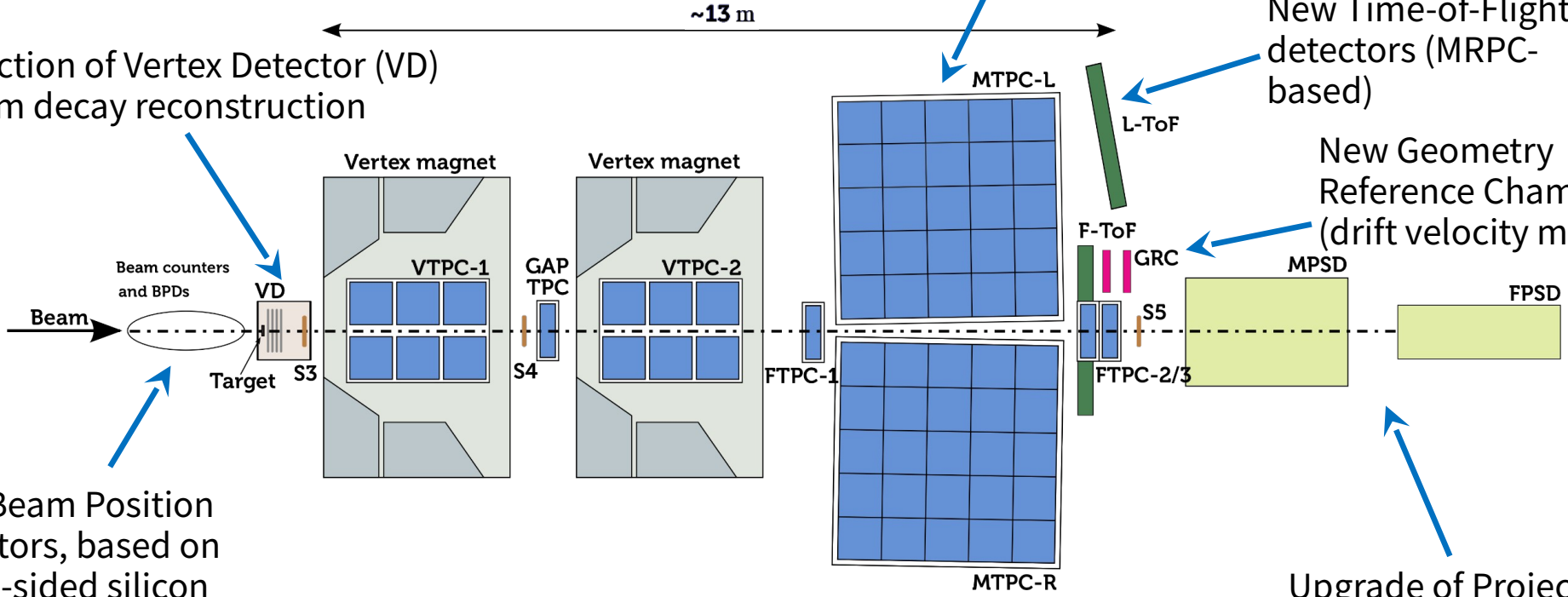
NA61/SHINE

Replacement of the TPC read-out electronics to increase data rate to 1 kHz

New Time-of-Flight detectors (MRPC-based)

Construction of Vertex Detector (VD) for charm decay reconstruction

New Geometry Reference Chamber (drift velocity meas.)



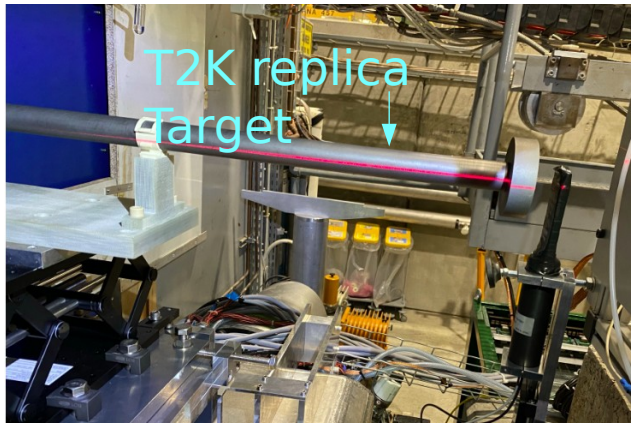
New Beam Position Detectors, based on single-sided silicon strip detectors

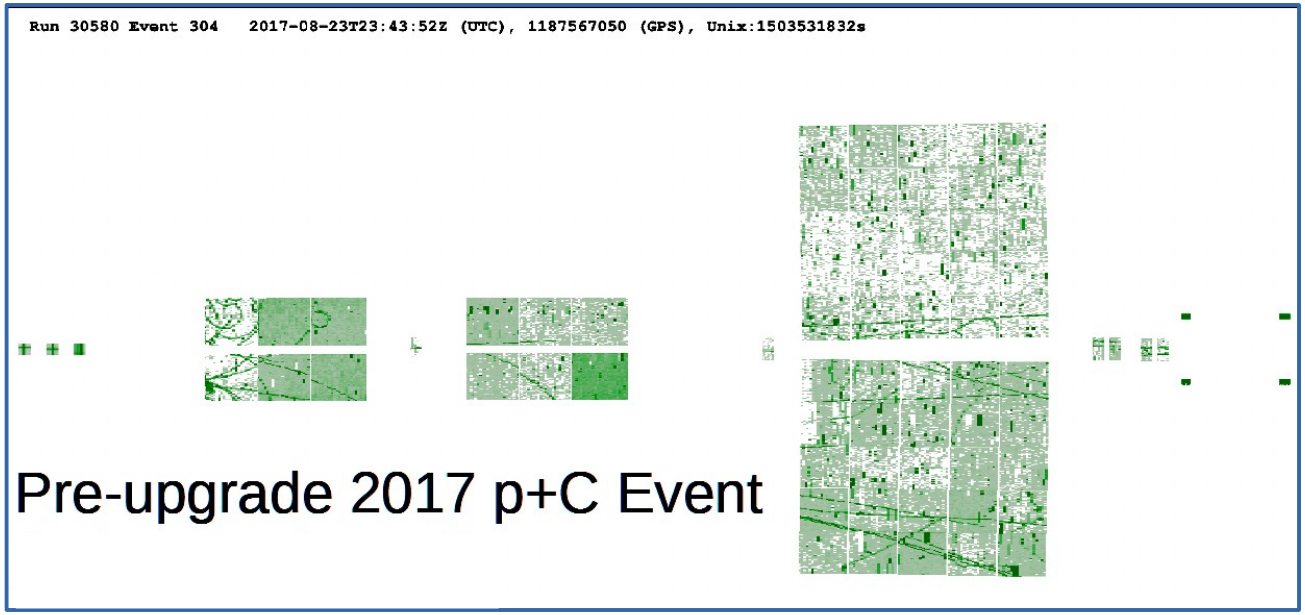
New trigger and data acquisition system

New read-out system based on the DRS4 chip (full waveform is measured and stored)

Upgrade of Projectile Spectator Detector (two detectors, new electronics)

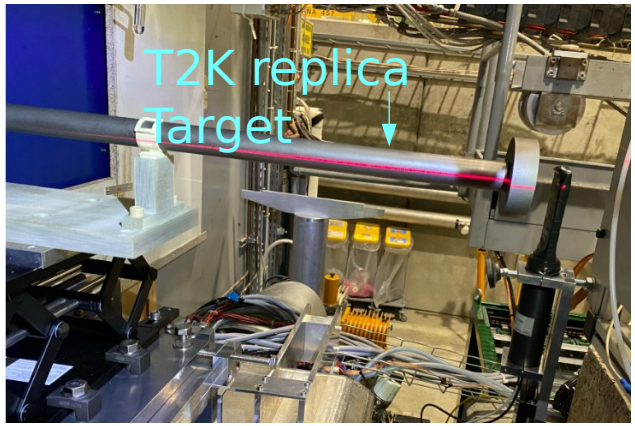
Summer 2022 data: 31 GeV/*c* protons on T2K replica target

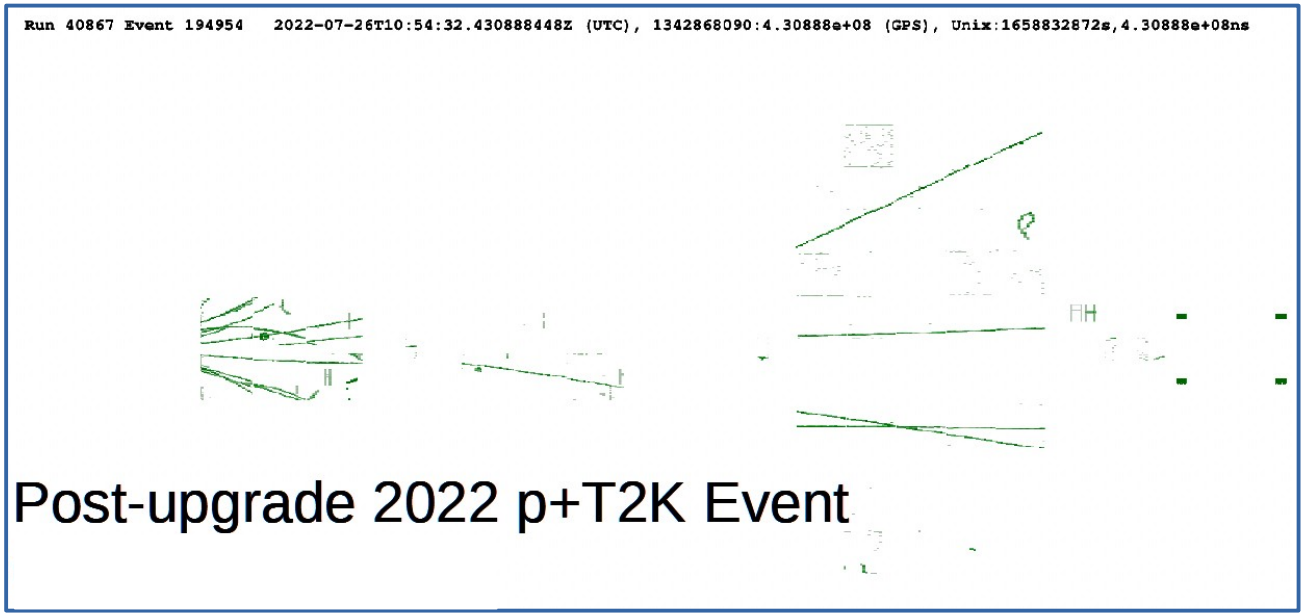




- First **physics running** after detector upgrade with a replica of target used to generate neutrinos in the beamline at J-PARC for T2K
- **Very low noise** observed
- Stable operation at **1.6 kHz**
- Over **180 million events** collected in 3 weeks (compared to 10 million in 5 weeks in previous T2K target running)

Summer 2022 data: 31 GeV/*c* protons on T2K replica target





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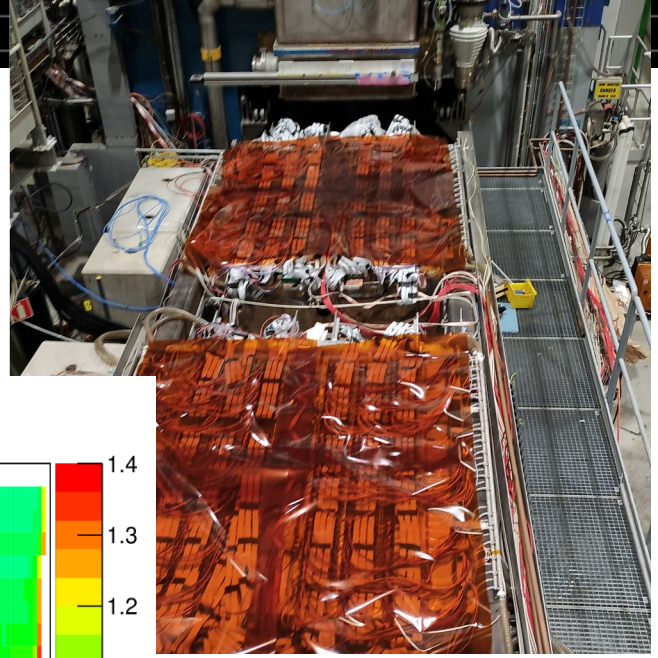
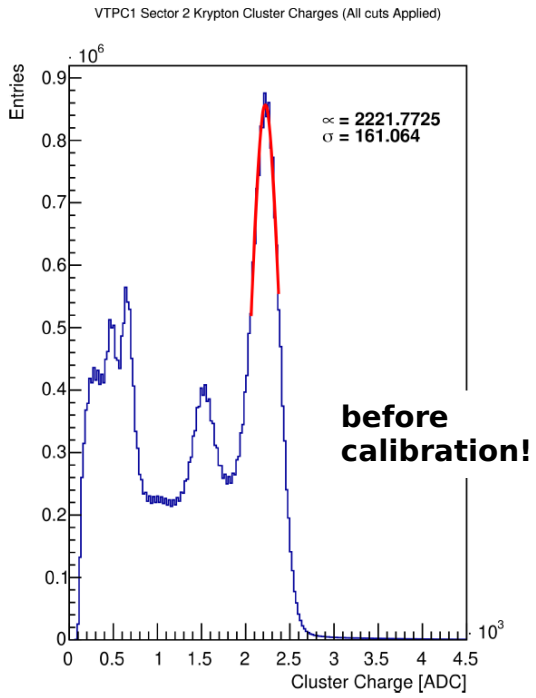
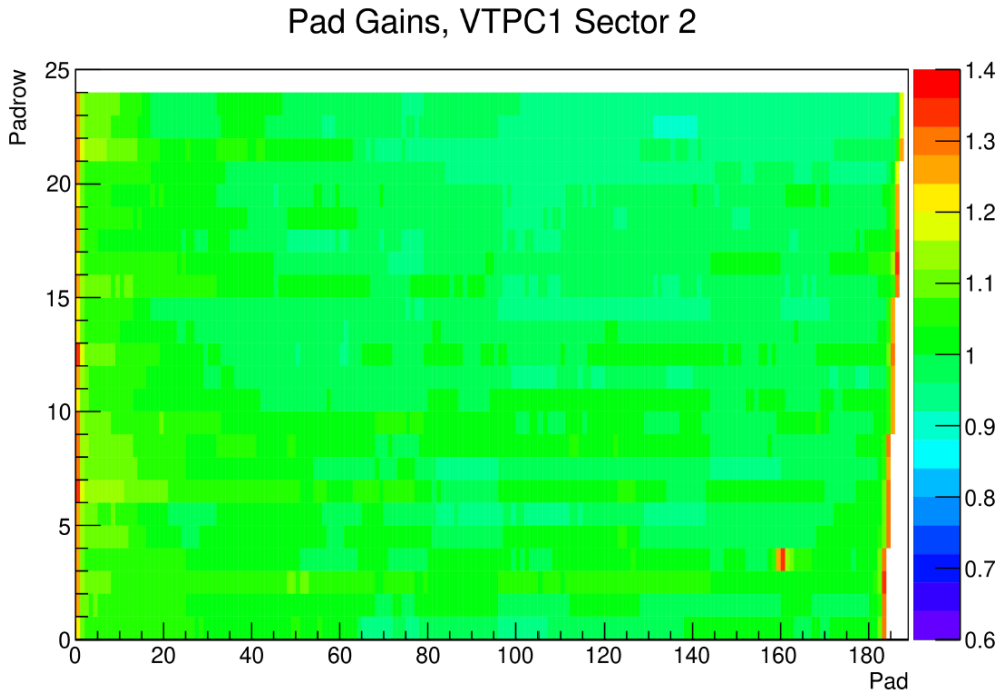
Time Projection Chambers

- **New read-out electronics** (based on former ALICE TPC read-out)
- ^{83}Kr gas allows measurement and calibration of TPC response

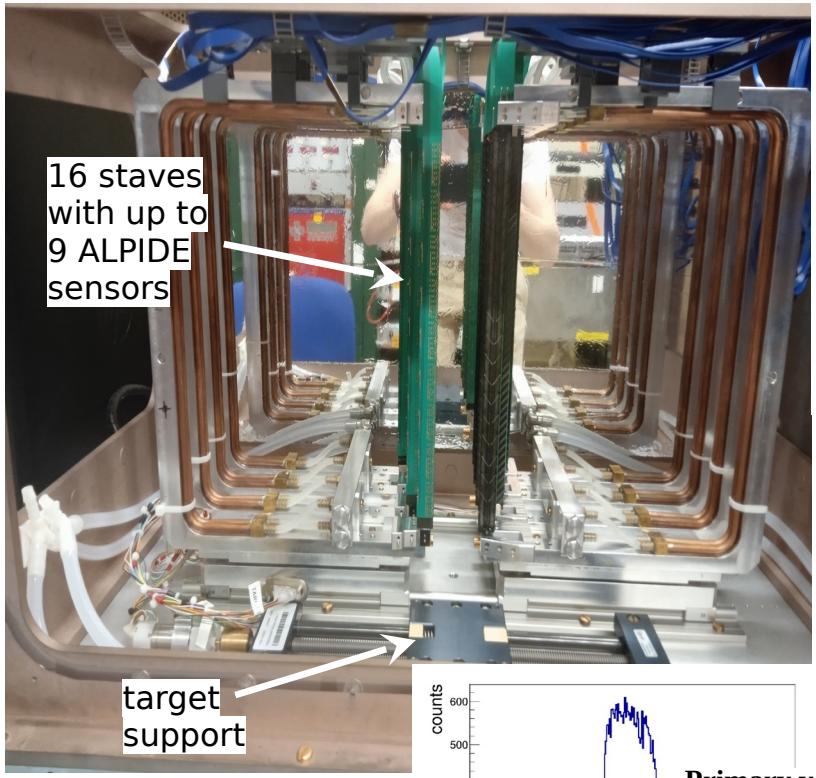


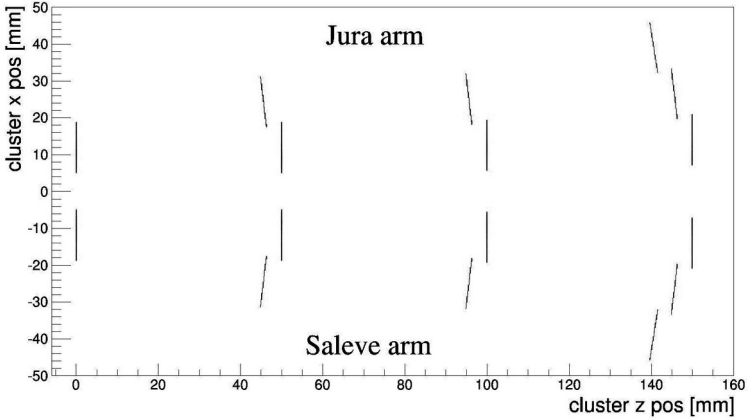


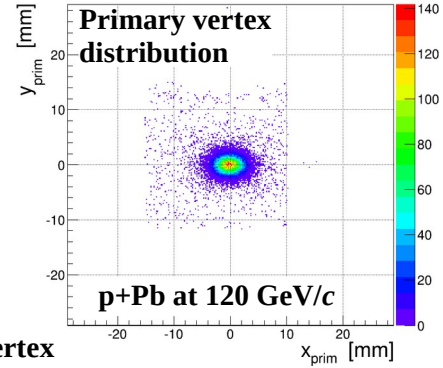


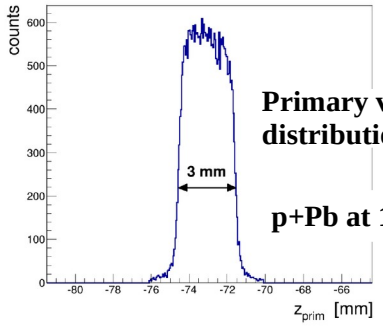
- **Uniformity of electronics** is **2x** better than before
- Best Kr decay spectrum ever

Vertex Detector









Primary vertex distribution

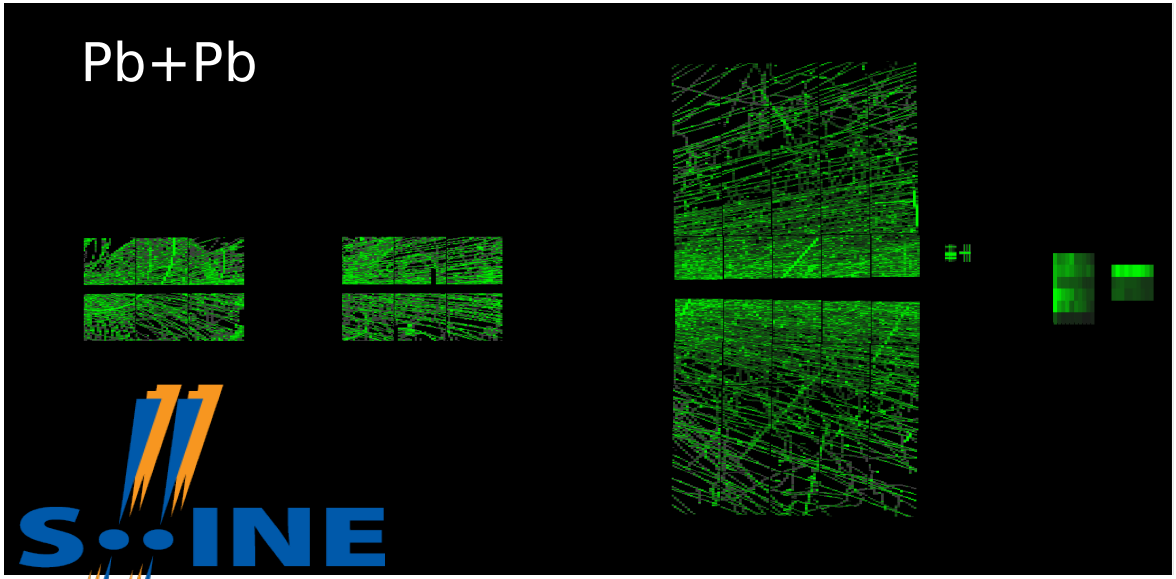
p+Pb at 120 GeV/*c*

We got significant help from ALICE-ITS:
Paolo Martinengo,
Antonello Di Mauro,
Giuseppe De Robertis

Synergy between NA61/SHINE and ALICE

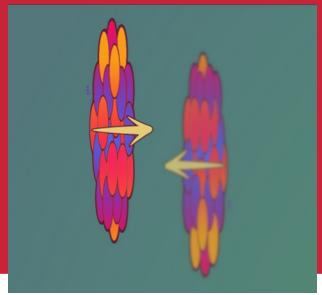
- **Key element** of NA61/SHINE charm program
- Active area **4.5 x** larger than prototype SAVD detector
- Fast (10 μs) **ALPIDE** pixel sensors, developed for ALICE-ITS and adapted to NA61/SHINE
- **Tested** on a 120 GeV/*c* proton beam on a 3 mm Pb target

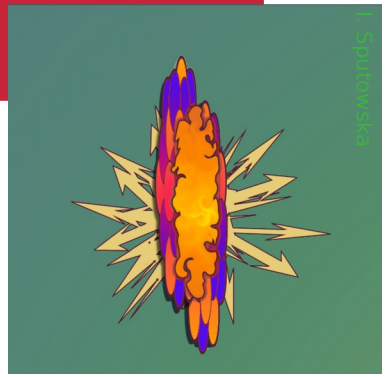
November 2022: data taking with Pb beams



- Out of the requested 9 weeks, four weeks were originally allocated in 2022. This was finally reduced to **two weeks**, about 6% of the FT running period
- Commissioning of the entire detector is presently **complete**
- Physics data taking for the NA61/SHINE charm program is **ongoing**
- Due to reduction of beam time, data taking for cosmic-ray physics **had to be canceled**

New results on strong interaction physics





The study of the onsets of deconfinement (OD)
and fireball (OF)

The search for the critical point (CP)

Others (O)

New results on strong interactions

Published:

(O) $\Xi(1530)^0$ and $\bar{\Xi}(1530)^0$ production in inelastic p+p collisions at 158 GeV/*c*, **Eur. Phys. J. C 81 (2021) 911**

(O,OD) K^0_s production in inelastic p+p collisions at 158 GeV/*c*, **Eur. Phys. J. C 82 (2022) 96**

(O) $K^*(892)^0$ production in inelastic p+p collisions at 40 and 80 GeV/*c*, **Eur. Phys. J. C 82 (2022) 322**

Preliminary:

(O,OD) K^0_s production in inelastic p+p collisions at 80 GeV/*c*

(OD,OF) rapidity spectra of protons in 0-10% central Ar+Sc collisions at 13*A*-150*A* GeV/*c*

(O,CP) femtoscopy analysis in 0-10% central Ar+Sc collisions at 150*A* GeV/*c*

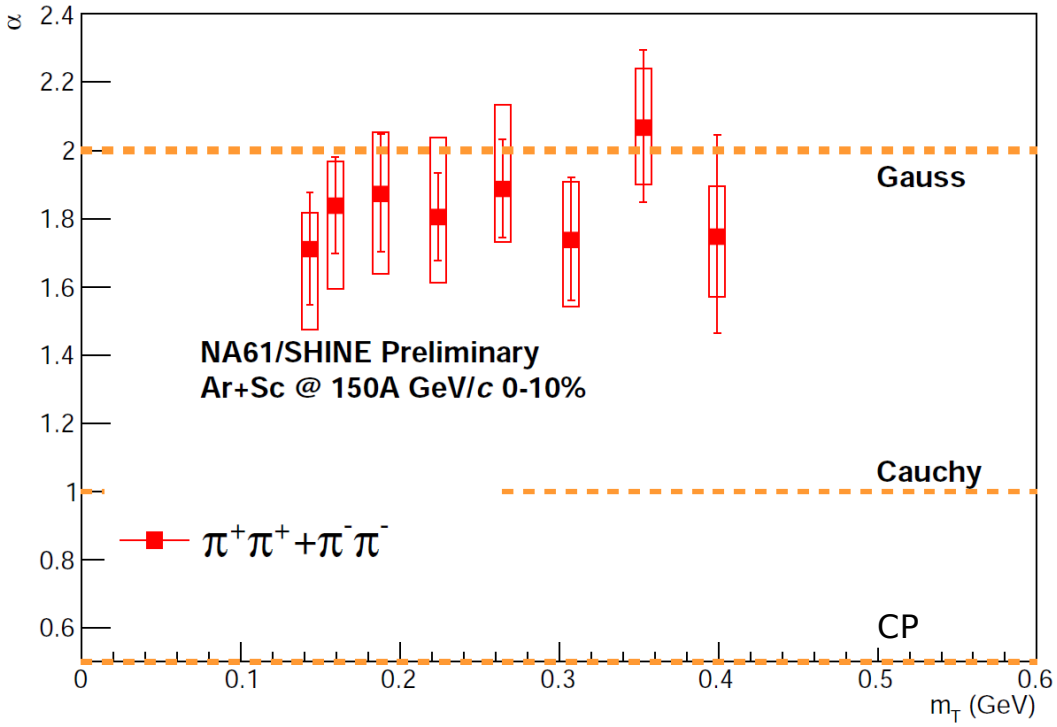
(CP) proton intermittency in 0-10% central Pb+Pb collisions at 13*A* GeV/*c*

(CP) proton intermittency in 0-10% central Ar+Sc collisions at 13*A*-75*A* GeV/*c*

(CP) higher-order moments of multiplicity and net-charge in 0-1% central Ar+Sc collisions at 75*A* and 150*A* GeV/*c*

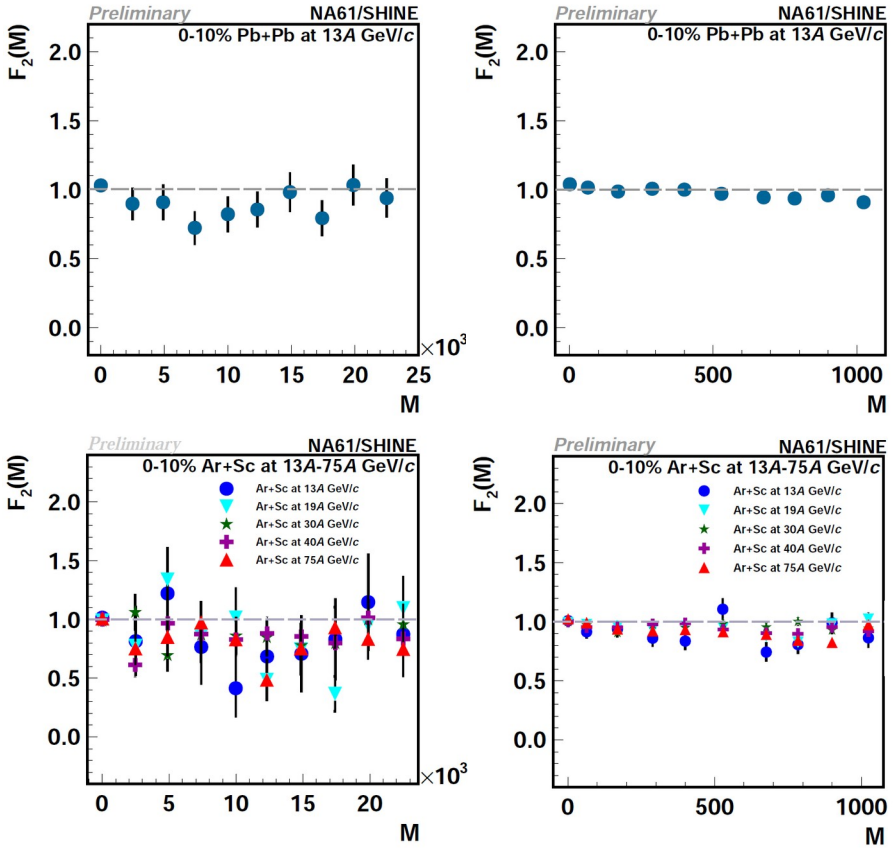
(*) Note: for more details, see CERN-SPSC-2022-034

Search for the Critical Point in NA61/SHINE (1): femtoscopy analysis in central Ar+Sc collisions at 150*A* GeV/*c*



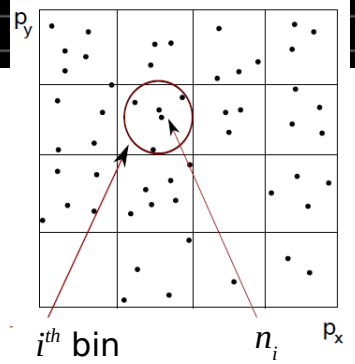
- Bose-Einstein correlations (femtoscopy) reveal the space-time structure of hadron production
- The Levy parameter α describes the shape of the source and is sensitive to the system freezing out at the CP
- The new Ar+Sc results are close to Gaussian, and **far from the CP**

Search for the Critical Point in NA61/SHINE (2): proton intermittency



Analysis made for:

- statistically independent data points
- cumulative quantities
- M=1 … 25000 bins in the (p_x, p_y) plane



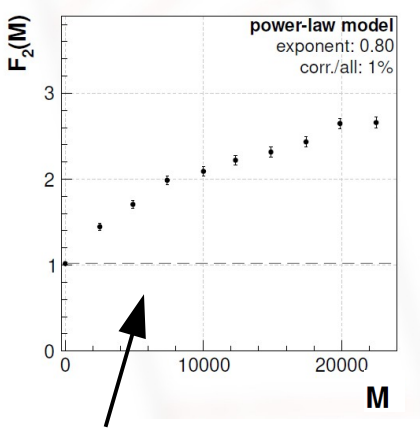
Second Scaled Factorial Moments of protons for Pb+Pb at 13*A* GeV/*c* and Ar+Sc at 13*A*-75*A* GeV/*c* show **no indication for power-law increase with bin size**

$$F_2(M) = \frac{\left\langle \frac{1}{M}\sum_{i=1}^{M} n_i(n_i-1) \right\rangle}{\left\langle \frac{1}{M}\sum_{i=1}^{M} n_i \right\rangle^2},$$

M – number of bins in the (p_x, p_y) plane

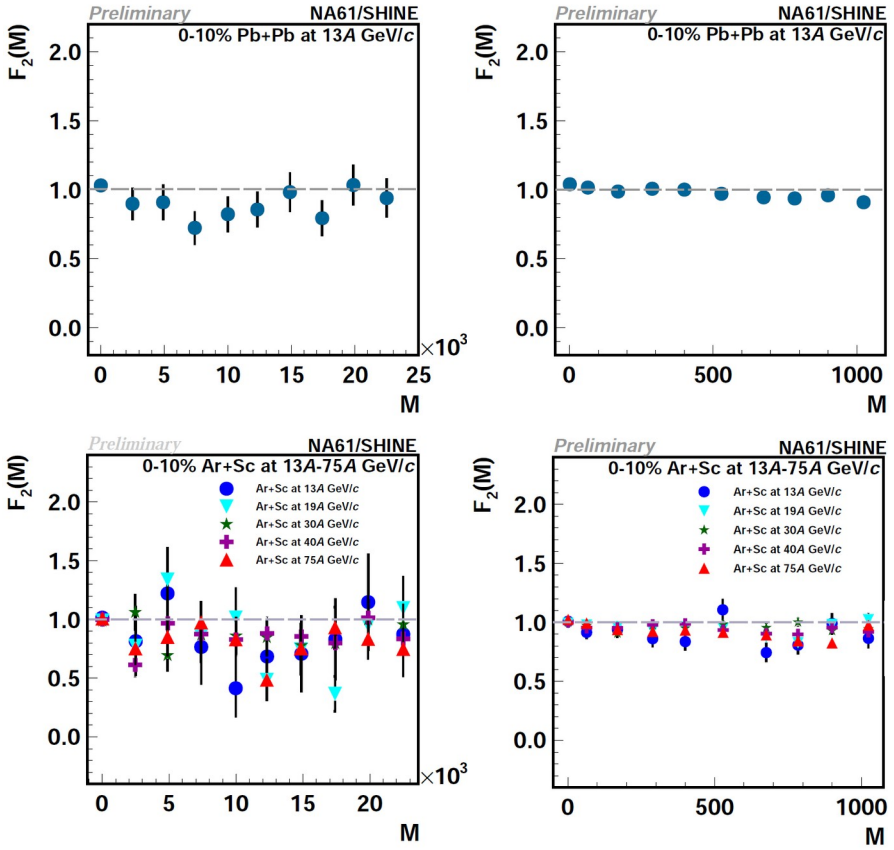
n_i - number of protons in the i^{th} bin

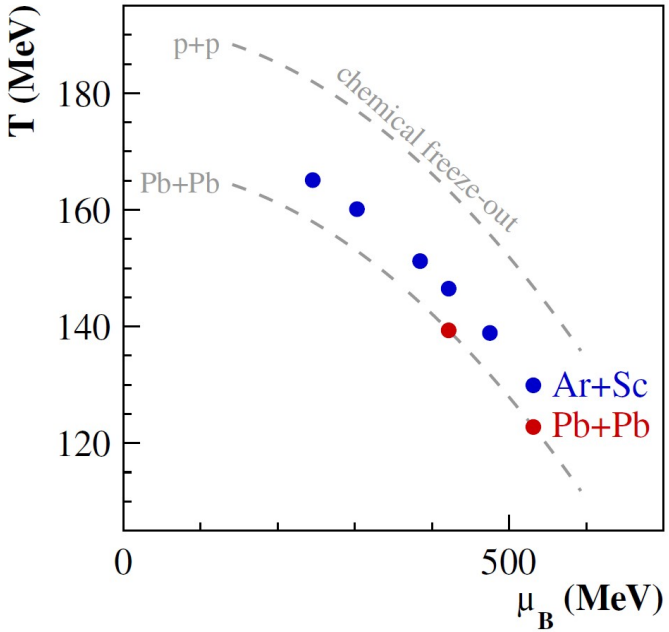
$\langle \ldots \rangle$ - averaging over events



If the system freezes-out in the vicinity of the critical point, **$F_2(M) \sim M^{\phi_2}$ should reveal a power-law dependence.**

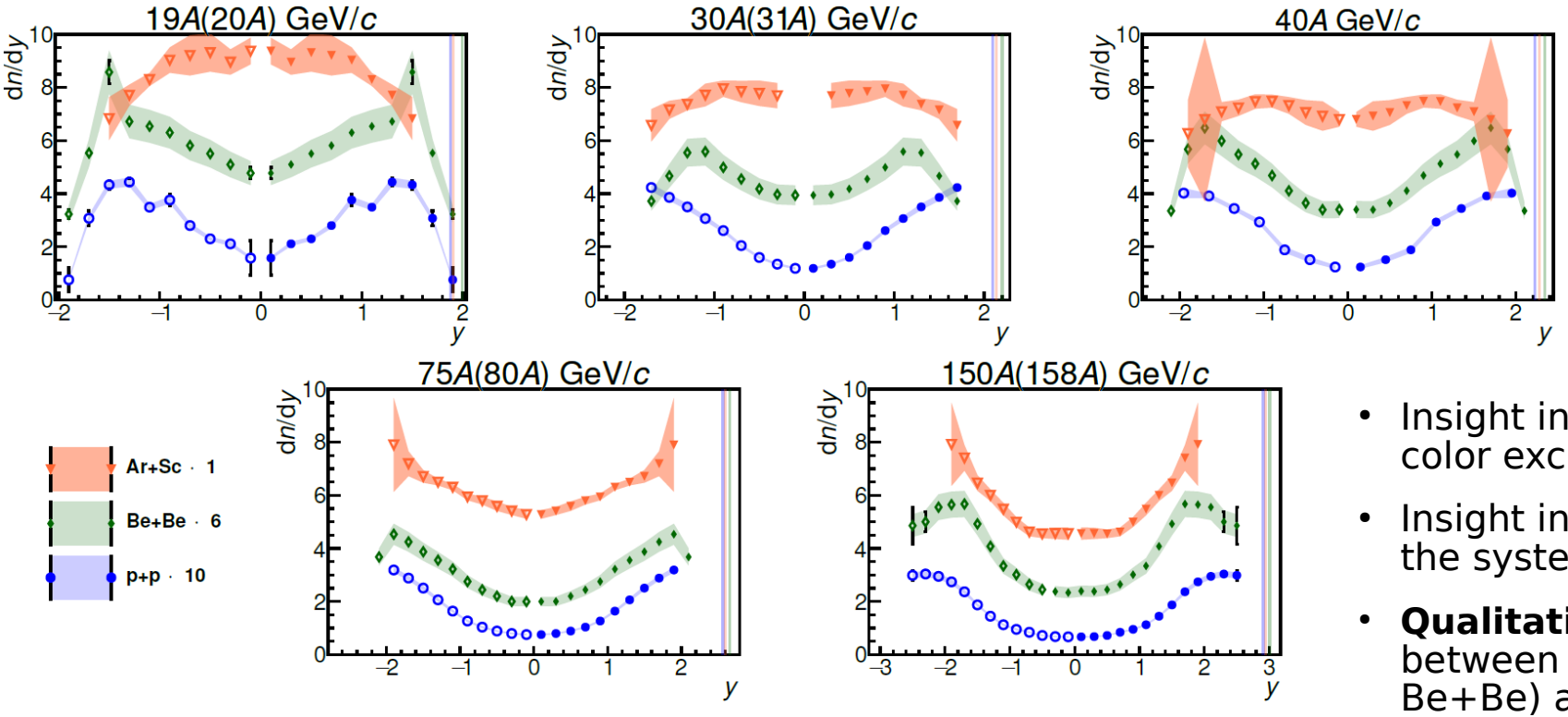
Search for the Critical Point in NA61/SHINE (3): compilation of results on proton intermittency





- Phase diagram indicating chemical freeze-out conditions for the analyzed systems
- Points are shown for the data sets where preliminary results on proton intermittency, obtained using cumulative variables and statistically independent data samples show **no indication for the CP**

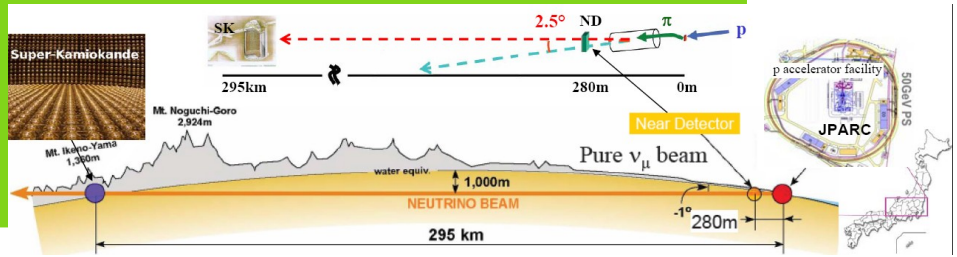
Preliminary rapidity spectra of protons in 0-10% central Ar+Sc collisions at 19*A*-150*A* GeV/*c*



- Insight into the nature of color exchange
- Insight into the EoS of the system
- **Qualitative difference** between small (p+p, Be+Be) and intermediate (Ar+Sc) systems

p+p data: NA61/SHINE, EPJ C 77 (2017) 671
Be+Be data: NA61/SHINE, EPJ C 81 (2021) 73

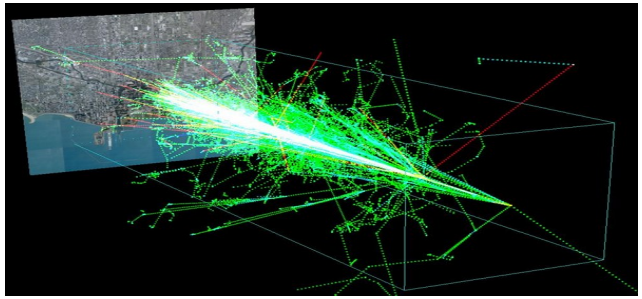
New results on neutrino and cosmic-ray physics from NA61/SHINE



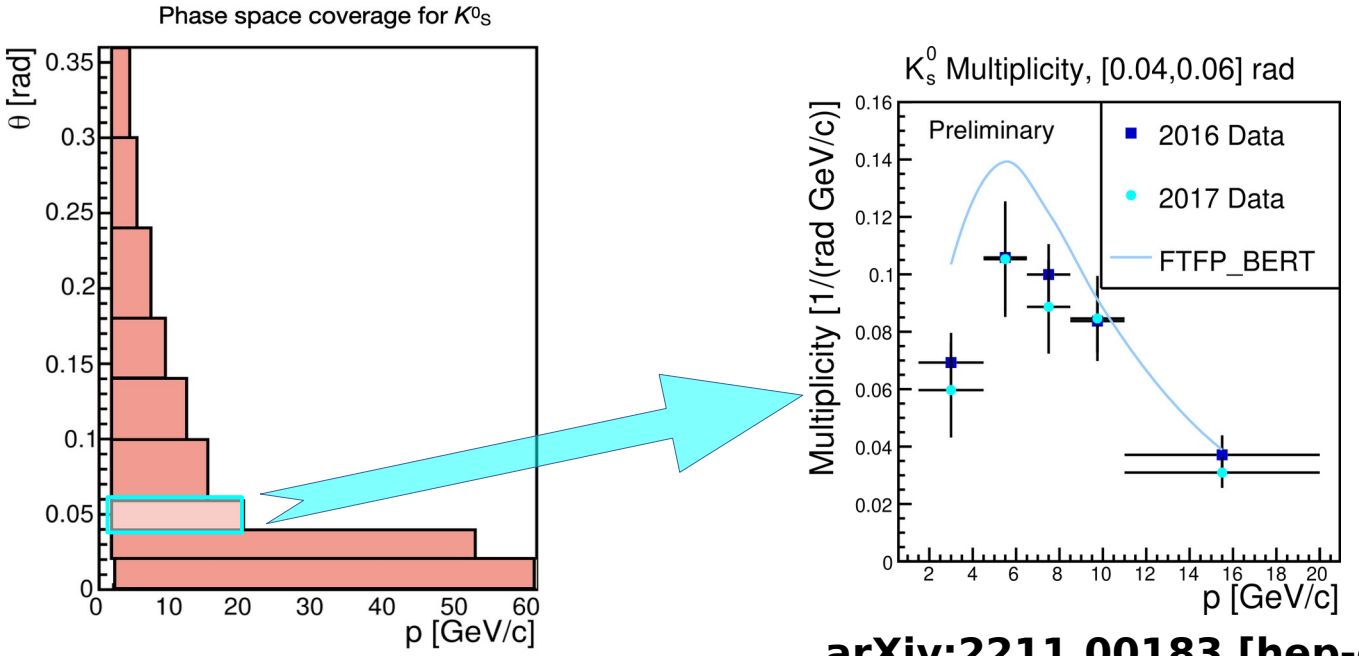
Neutral Hadrons from p+C @ 120 GeV/*c*

π^-+C Interactions at 158 and 350 GeV/*c*

Nuclear fragments from C+p @ 13.5*A* GeV/*c*



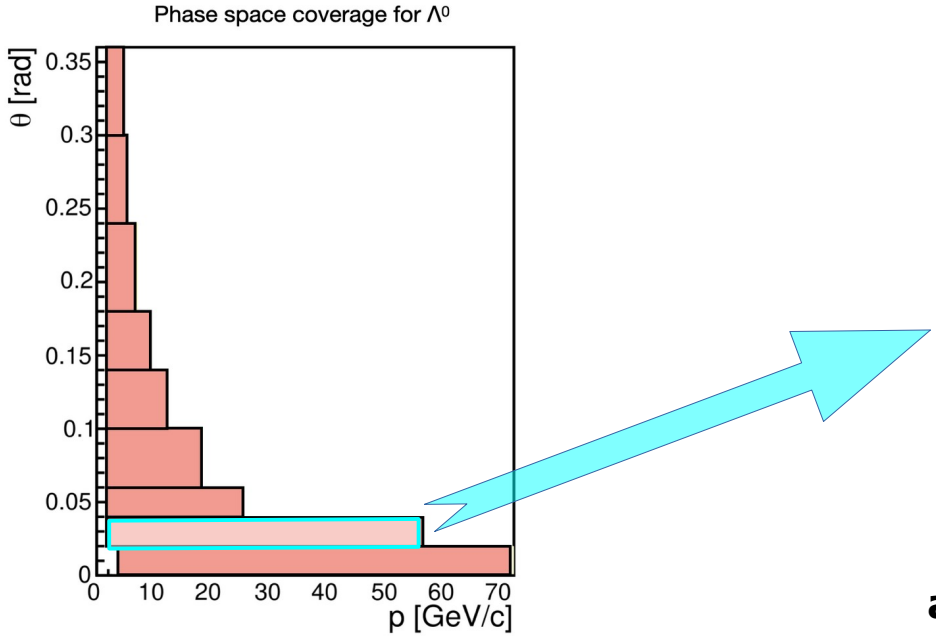
New Neutrino Result: Neutral Hadrons from p+C @ 120 GeV/*c*

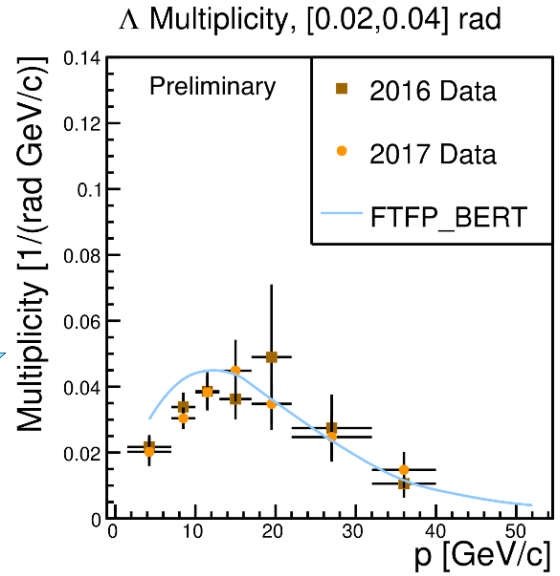


arXiv:2211.00183 [hep-ex]

- Neutrino beamlines for current and future long-baseline experiments at Fermilab use (and likely will use) 120 GeV/*c* protons
- First results on **production of K^0_s, Λ, $\bar{\Lambda}$** submitted to PRD
- Results in a single angular bin for K^0_s shown above

New Neutrino Result: Neutral Hadrons from p+C @ 120 GeV/*c*



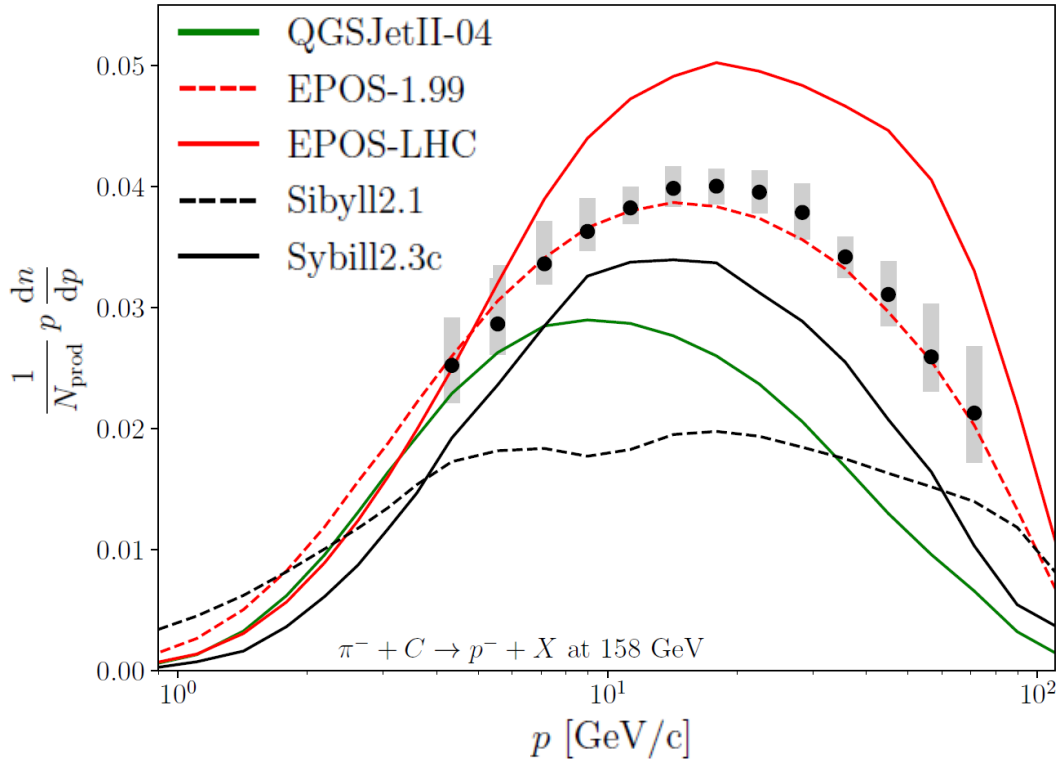


arXiv:2211.00183 [hep-ex]

- Results in a single angular bin for Λ^0 are shown above
- Results for production of charged hadrons (π^+,π^-, K^+,K^-, p) should be released soon

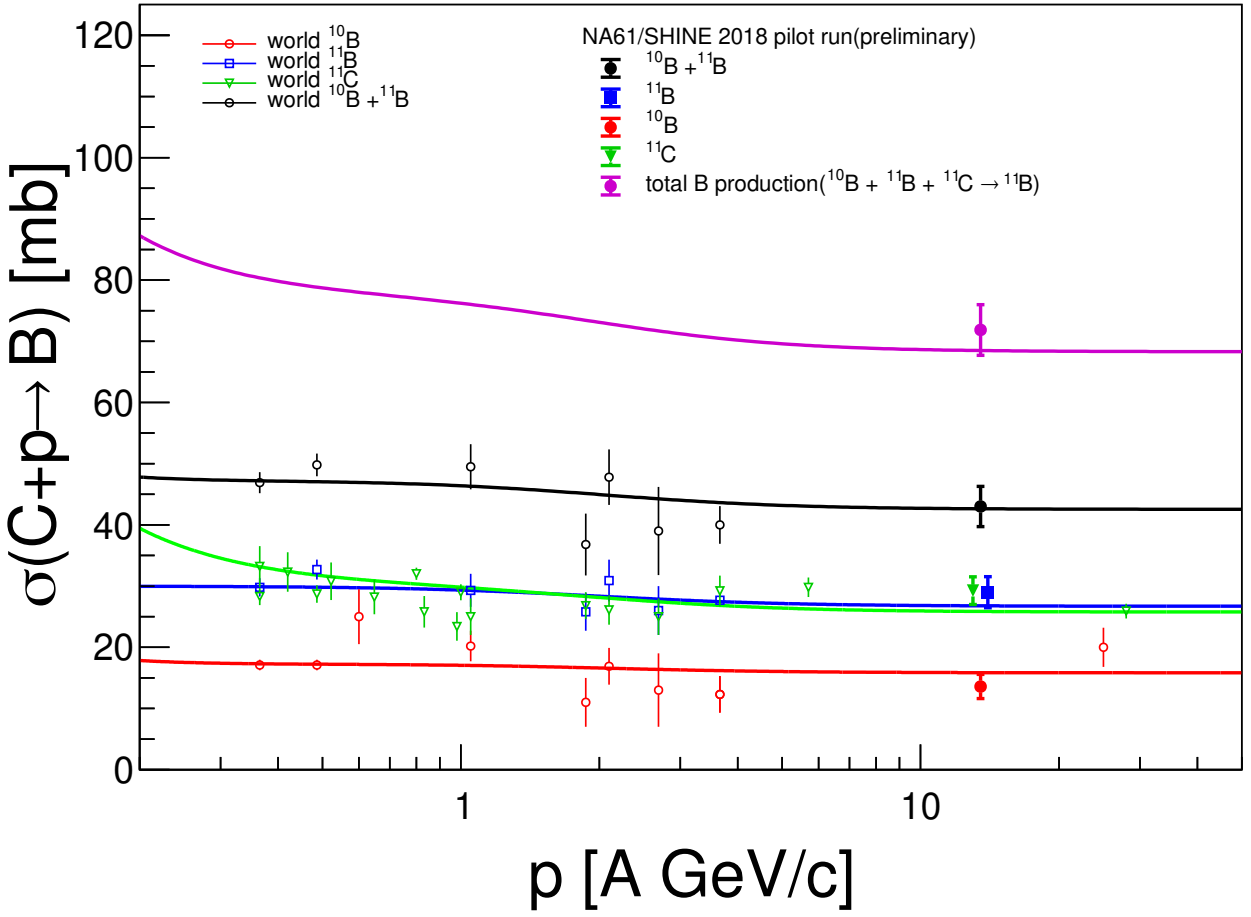
New Cosmic-Ray Result: π^-+C Interactions at 158 and 350 GeV/*c*

- Measurement of hadron production in π^-+C interactions, submitted to PRD: **arXiv:2209.10561 [nucl-ex]**
- Production cross section and spectra of **$\pi^\pm$, $K^\pm$, p, $\bar{p}$, Λ, $\bar{\Lambda}$ and K^0_s**
- **Unique data set** to tune hadronic interaction models for air shower simulations at ultra-high energies
- Constraints on muon production in air showers to understand the "**muon puzzle**" at ultra-high energies

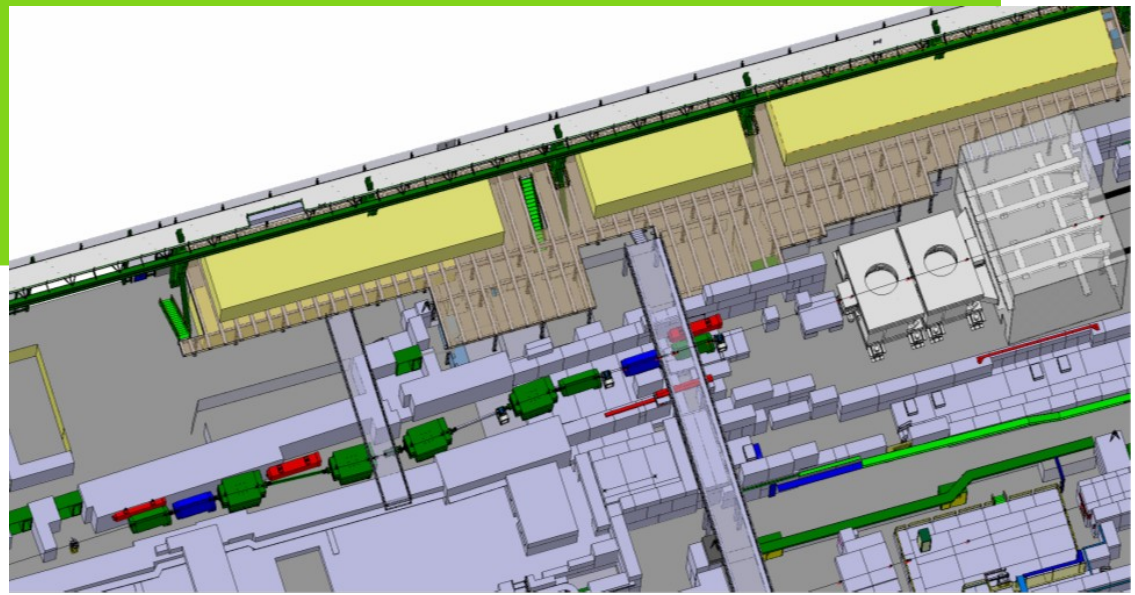


New Cosmic-Ray Result: Nuclear fragments from C+p @ 13.5*A* GeV/*c*

- Pilot run taken to measure the nuclear fragments produced in C+p reactions at 13.5*A* GeV/*c*
- New preliminary results in 2022 on the **isotopic yields of ^{11}C, ^{11}B and ^{10}B** from a pilot run in 2018
- Good agreement with previous studies
- Preparing for upcoming run with higher statistics



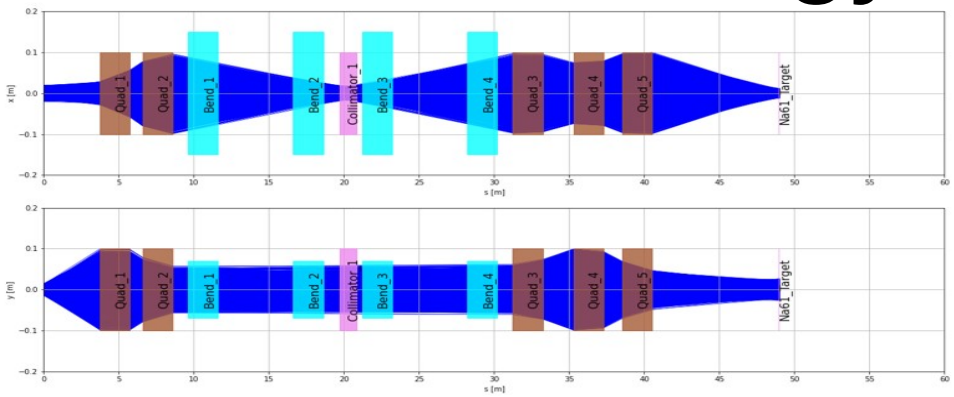
A new very-low-energy beam for NA61/SHINE



Charged Hadrons from ~2-20 GeV/*c*

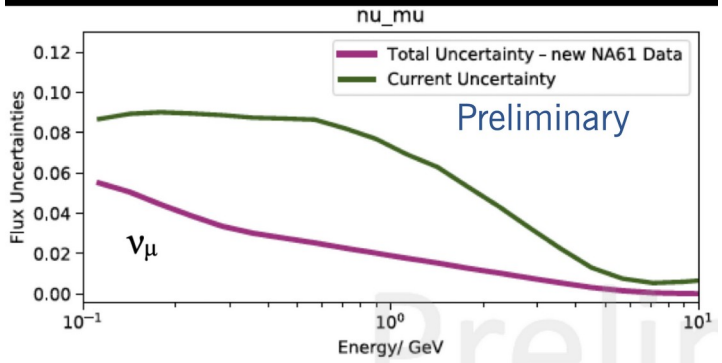
Opens up many new physics opportunities beyond current program

Low-Energy Hadron Beam

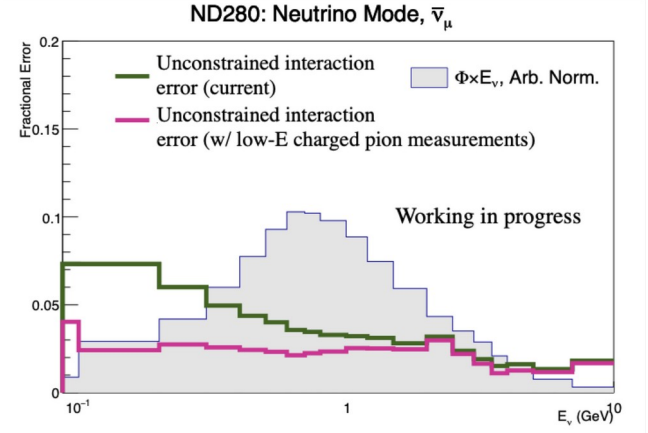


- Discussed in addendum CERN-SPSC-2021-028.
- Potential improvement to T2K/Hyper-K flux estimates
- Very significant reduction in atmospheric neutrino flux errors
- Potential measurements relating to FNAL SBN, spallation sources, muon experiments

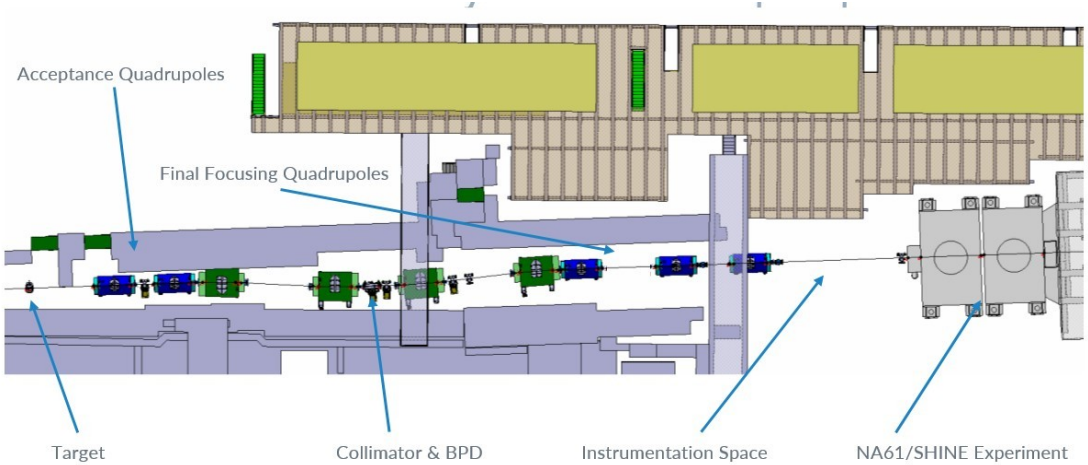
L. Cook (Bartol Group) atmospheric neutrino flux



T2K/HyperK wrong-sign flux uncertainties



Low-Energy Hadron Beam



- June 2022 SPSC feedback: “The SPSC recognizes the scientific value of the improvements that the low energy beam line could bring to the knowledge of the neutrino cross sections and recommends that the corresponding technical feasibility be studied in detail.”
- **Technical design work has continued, resource requests for installation during 2023-24 YETS**

Summary of beam requests from NA61/SHINE

Physics with secondary hadron beams

Physics with lead beams

Physics with oxygen beams

Physics with very-low-energy hadrons

Physics with secondary hadron beams:

- **July 2023:** four weeks of a K^+ beam at 60 GeV/*c* for thin-target graphite cross-section measurements
- **August 2023:** two weeks of a proton beam at 120 GeV/*c* for thin-target titanium cross-section measurements
- **September 2023:** one week of hadron beams at different momenta for PSD calibration

Physics with lead beams:

- **September 2023:** one week of a secondary (fragmented) light-ion beam at 13*A* GeV/*c* for nuclear fragmentation cross-section measurements
- **September-October 2023:** 6 weeks of Pb beam at 150A GeV/c for charm hadron measurements in Pb+Pb collisions (*)

(*) Note: NA61/SHINE was originally allocated **4** weeks of Pb beam data taking in 2022;
NA61/SHINE also requested **5** weeks of Pb beam data taking in 2023;
However, NA61 was finally granted only **2** weeks of Pb beam in 2022.

2024-2025

Physics with secondary hadron beams:

- **2024**: four weeks of a 120 GeV/*c* proton beam for measurements on an LBNF/DUNE prototype target

Physics with lead beams:

- **2024**: five weeks of Pb beam at 150*A* GeV/*c* for charm hadron measurements in Pb+Pb collisions
- **2024**: *optional (in case the oxygen beam is not available) one week of a secondary light-ion beam at 13A GeV/c for nuclear fragmentation cross-section measurements for cosmic-ray physics*
- **2025**: six weeks of Pb beam at 40*A* GeV/*c* for charm hadron measurements in Pb+Pb collisions

Physics with oxygen beams:

- **2024**: 12, 8 and 8 days of primary and fragmented oxygen beams at 13*A* GeV/*c*, 30*A* GeV/*c* and 150*A* GeV/*c*, respectively

Physics with very-low-energy hadrons:

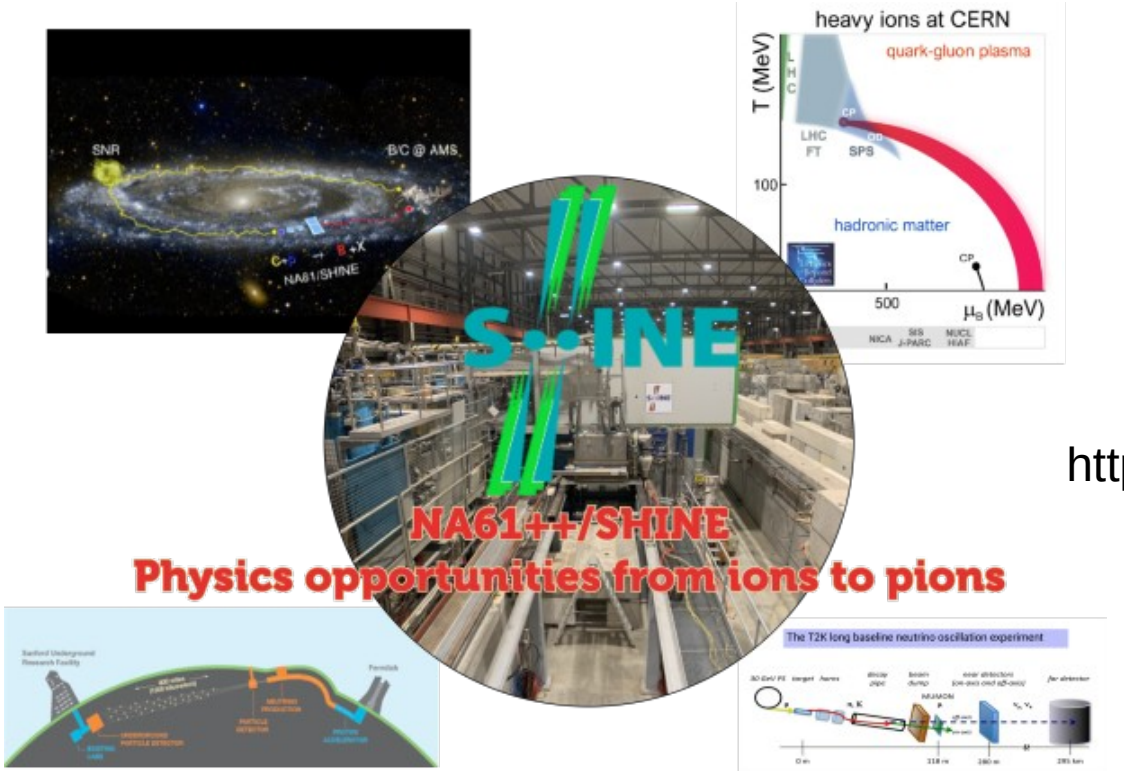
- **2024**: one week pilot run to characterize beam
- **2025**: several weeks physics data – studies ongoing to refine beam request

Summary

- The LS2 upgrade of the detector was successfully completed
- First physics data after LS2 were recorded: 180 million p+T2K replica target events
- First Pb beam data taking for the NA61/SHINE **open charm program** is **happening this week; compensation next year for the loss of Pb beam in 2022 is critical for the success of the program**
- New physics results, final and preliminary, were released:
  - so far, no convincing evidence for critical point in Ar+Sc and Pb+Pb collisions
  - hadron production in p+C interactions
  - nuclear fragmentation in C+p reactions
- Opportunities for new measurements with the low-energy beams under development

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

NA61++ open workshop, Dec 15-17, 2022



- Workshop to be held at CERN
- Planning for physics beyond LS3
- Please register at https://indico.cern.ch/event/1174830/

The NA61/SHINE Collaboration

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Backup

Papers

New results on strong interaction physics:

1. NA61/SHINE Collaboration, Measurements of $\Xi(1530)^0$ and $\overline{\Xi}(1530)^0$ production in proton-proton interactions at $\sqrt{s_{NN}}$=17.3 GeV in the NA61/SHINE experiment, **Eur. Phys. J. C 81 (2021) 911**
2. NA61/SHINE Collaboration, K^0_s meson production in inelastic p+p interactions at 158 GeV/*c* beam momentum measured by NA61/SHINE at the CERN SPS, **Eur. Phys. J. C 82 (2022) 96**
3. NA61/SHINE Collaboration, $K^*(892)^0$ meson production in inelastic p+p collisions at 40 and 80 GeV/*c* beam momenta measured by NA61/SHINE at the CERN SPS, **Eur. Phys. J. C 82 (2022) 322**

New results on neutrino and cosmic ray physics:

4. NA61/SHINE Collaboration, Measurements of K^0, Λ and $\overline{\Lambda}$ production in 120 GeV/*c* p+C interactions, **arXiv:2211.00183 [hep-ex],** submitted to Phys. Rev. D
5. NA61/SHINE Collaboration, Measurement of Hadron Production in π^-C Interactions at 158 and 350 GeV/*c* with NA61/SHINE at the CERN SPS, **arXiv:2209.10561 [nucl-ex],** submitted to Phys. Rev. D

Selected NA61/SHINE documents submitted to the SPSC

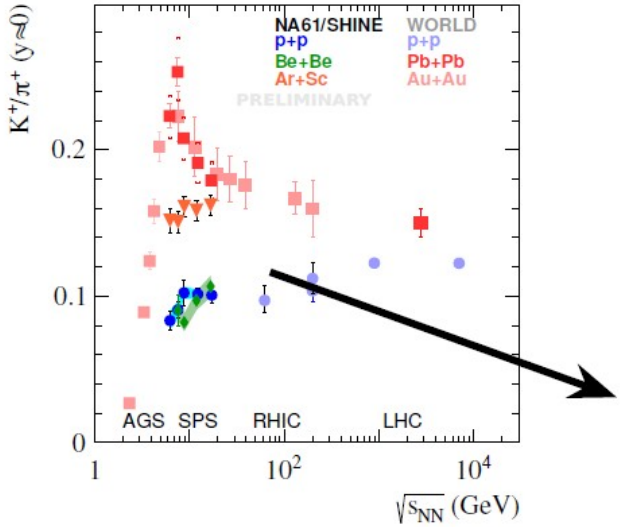
In the reported period:

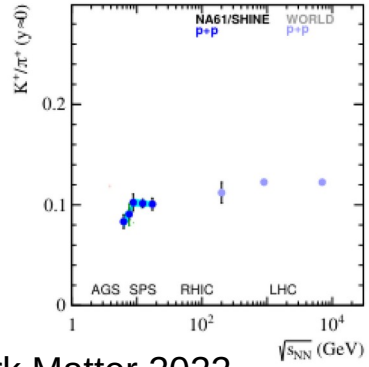
- Open Charm Measurements: Pb-beam schedule and detector upgrade (memorandum), CERN-SPSC-2022-005
- Addendum to the NA61/SHINE Proposal: Request for oxygen beam in Run 3 (addendum), CERN-SPSC-2022-021
- Additional Information concerning the Low Energy Beam project" (memorandum), CERN-SPSC-2022-022

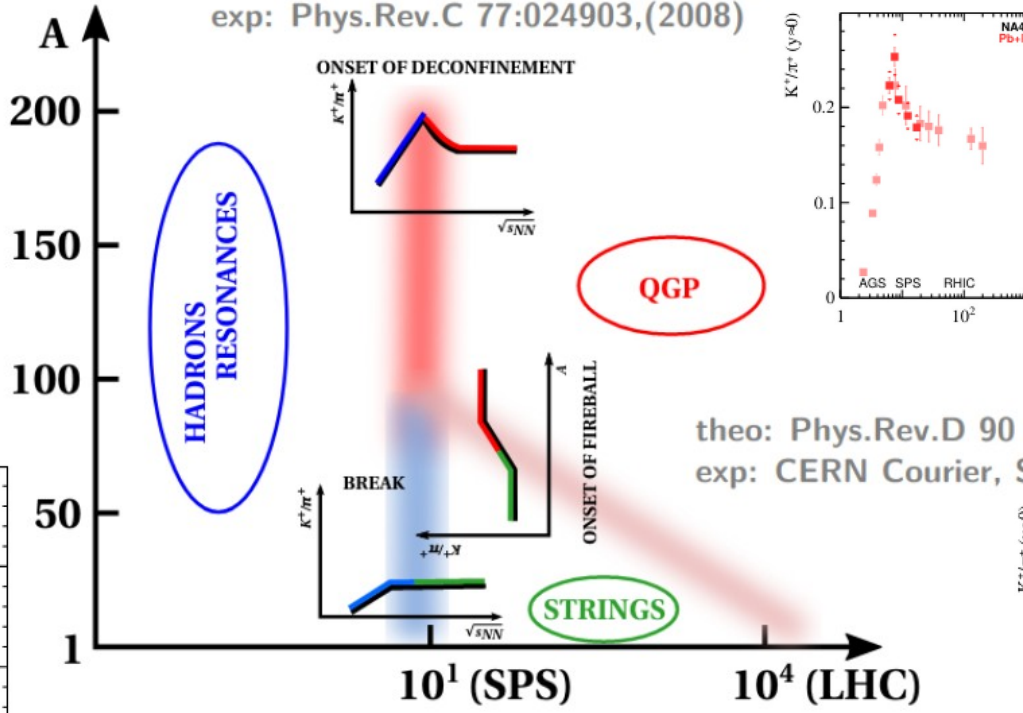
Other:

- Study of Hadron-Nucleus and Nucleus-Nucleus Collisions at the CERN SPS: Early Post-LS2 Measurements and Future Plans, CERN-SPSC-2018-008
- Reply to the SPSC questions on Addendum CERN-SPSC-2018-008 entitled Study of Hadron-Nucleus and Nucleus-Nucleus Collisions at the CERN SPS: Early Post-LS2 Measurements and Future Plans, CERN-SPSC-2018-019
- Report from the NA61/SHINE experiment at the CERN SPS, CERN-SPSC-2020-023
- Addendum to the NA61/SHINE Proposal: A Low-Energy Beamline at the SPS H2, CERN-SPSC-2021-028

Selected NA61/SHINE results on the Onsets of Deconfinement and Fireball

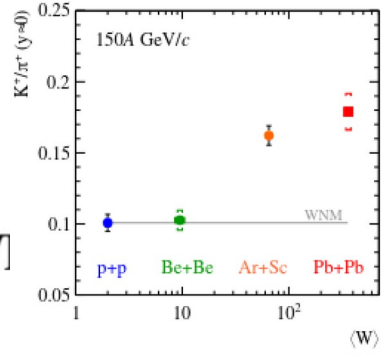






theo: Acta Phys.Polon.B 46 (2015) 10, 1991
exp: Phys.Rev.C 77:024903,(2008)

theo: Phys.Rev.D 90 025031 (2014)
exp: CERN Courier, Sep 23rd, 2019



theo: Phys.Part.Nucl. 51 (2020) 3, 337-339
exp: Phys.Rev.C 102 (2020) 1, 011901

Slide taken from
A. Marcinek, Quark Matter 2022

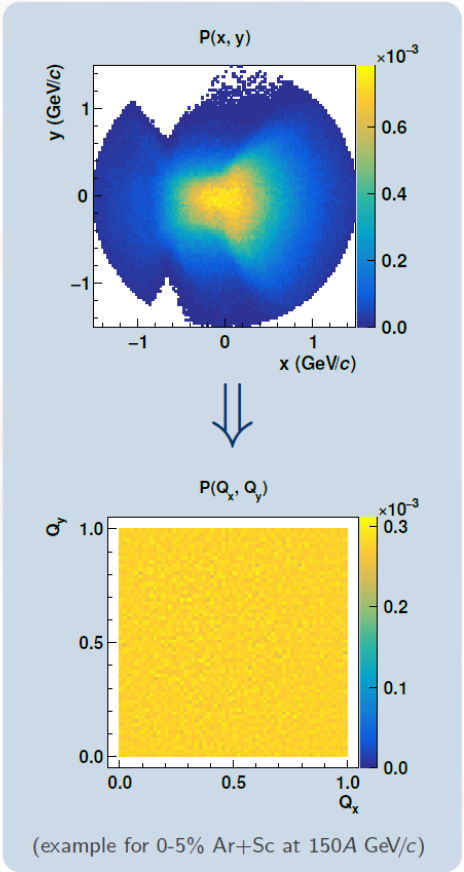
Cumulative variables in intermittency analysis

Instead of using p_x and p_y, we use cumulative variables:

$$Q_x = \int_{x_{min}}^{x} \rho(x)dx \Big/ \int_{x_{min}}^{x_{max}} \rho(x)dx$$

$$Q_y = \int_{x_{min}}^{y} \rho(x)dx \Big/ \int_{x_{min}}^{x_{max}} \rho(x,y)dy$$

- Transforms any distribution into a uniform distribution (0,1)
- Removes the dependence of $F_2(M)$ on the shape of the single-particle distribution
- The intermittency index of an ideal power-law system described in two dimensions in momentum space was proven to remain approximately invariant after the transformation



For more details, see H. Adhikary, XVth Quark Confinement and Hadron Spectrum, Stavanger, Norway, Aug 2022

Bialas, Gazdzicki, PLB 252 (1990) 483
Antoniou, Diakonos, https://indico.cern.ch/event/818624