Report from NA61/SHINE experiment - physics of strong interactions and detector upgrade

Seweryn Kowalski

for the NA61/SHINE Collaboration

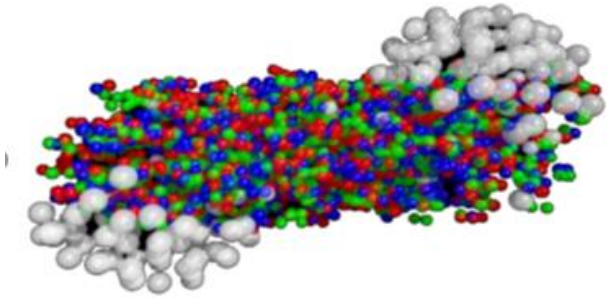
SPSC Open Session

October 12, 2021

NA61/SHINE - Research programme

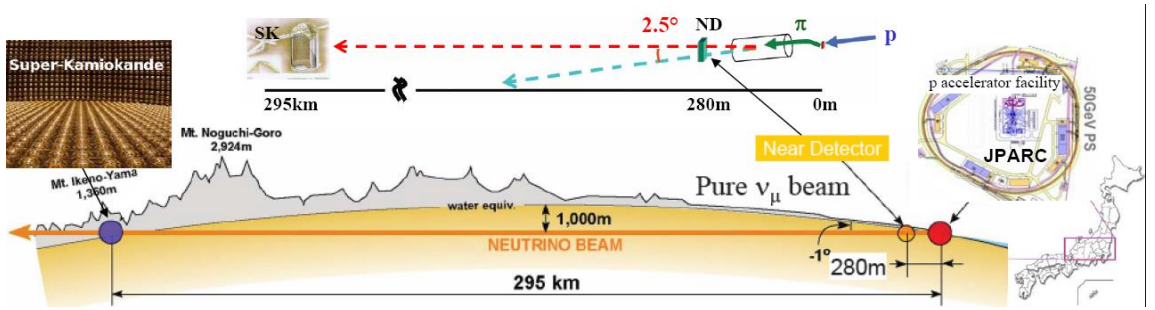
Strong interactions physics

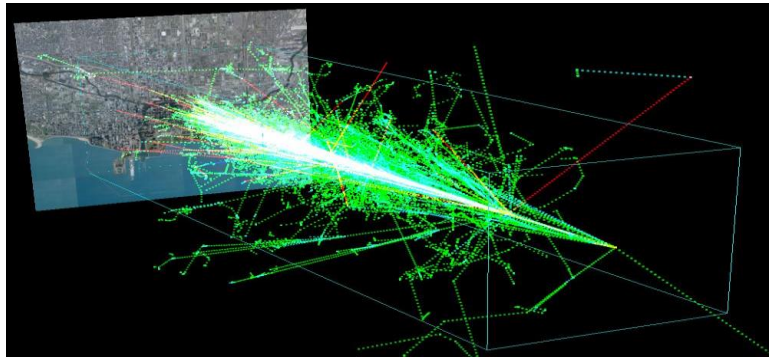
- search for the critical point of strongly interacting matter
- study of the properties of the onset of deconfinement
- heavy quarks: direct measurement of open charm at SPS energies



Neutrino and cosmic ray physics:

- hadron measurements for the J-PARC neutrino programme
- hadron measurements for the Fermilab neutrino programme
- 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





Selected new results: strong interactions physics

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

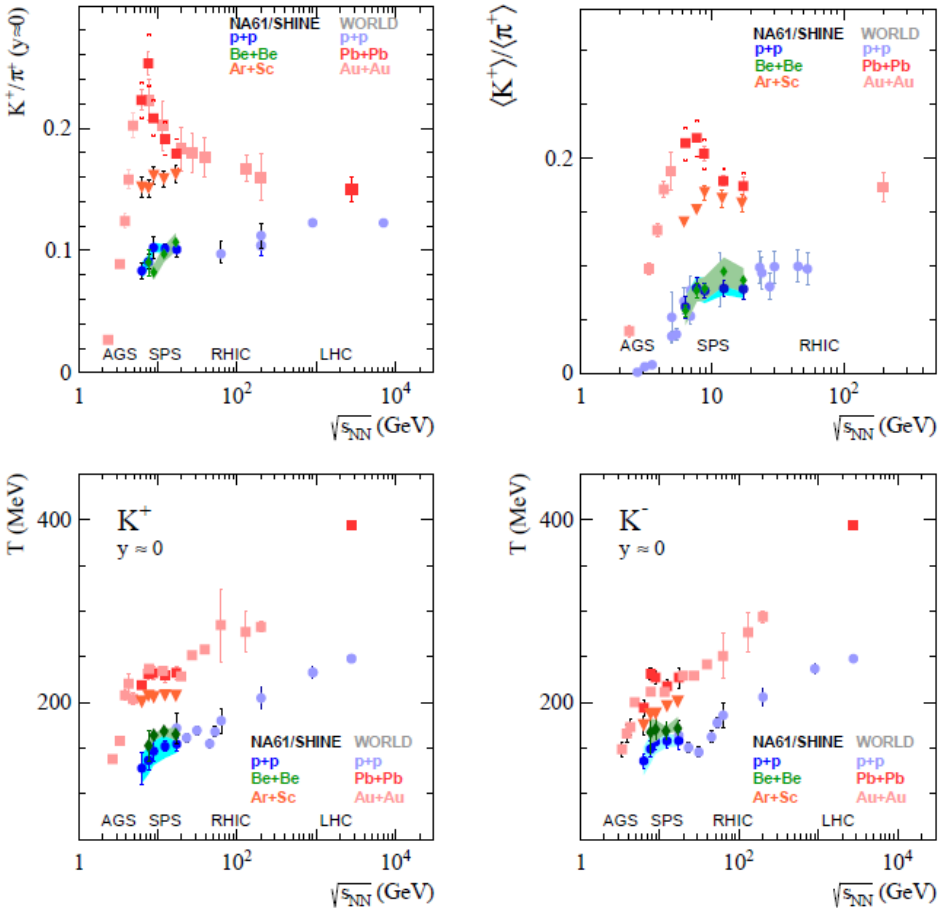
The search for the critical point (CP)

Others (O)

Selected new results: Strong Interaction Physics

- (OD, OF) Results on π^- production in central Be+Be collisions at 19A–150*A* GeV/c, Eur. Phys. J. C **80** no. 10, (2020) 961 [Erratum: Eur.Phys.J.C 81, 144 (2021)]
- (OD, OF) Results on π^+, π^-, K^+, K^-, p, and $\bar{p}$ in central Be+Be collisions at 19*A*–150*A* GeV/c, Eur. Phys. J. C **81** no. 1, (2021) 73
- (OD, OF) Results on π^- production in central Ar+Sc collisions at 13*A*–150*A* GeV/c Eur. Phys. J. C **81** no. 5, (2021) 397
- (OD, O) Final results on K_s^0production in inelastic p+p collisions at 158 GeV/c arXiv:2106.07535
- (O) Results on two-particle correlations in azimuthal angle and pseudorapidity in central Be+Be collisions at 19*A*–150*A* GeV/c Eur. Phys. J. C **80** no. 12, (2020) 1151
- (O) Final results on $\Xi(1530)^0$and $\bar{\Xi}(1530)^0$ production in inelastic p+p collisions at 158 GeV/c arXiv:2105.09144
- (CP) Results on multiplicity fluctuations of identified hadrons in inelastic p+p collisions at 31–158 GeV/c Eur. Phys. J. C **81** no. 5, (2021) 384
- (CP) Preliminary results on proton intermittency in Ar+Sc at 150AGeV/c and Pb+Pb at 30AGeV/c
- (CP) Preliminary results on the intermittency of negatively charged hadrons in Pb+Pb at 30AGeV/c
- (CP) Preliminary results on rapidity dependence of higher-order moments of multiplicity and net-charge in inelastic p+p collisions at 158 GeV/c

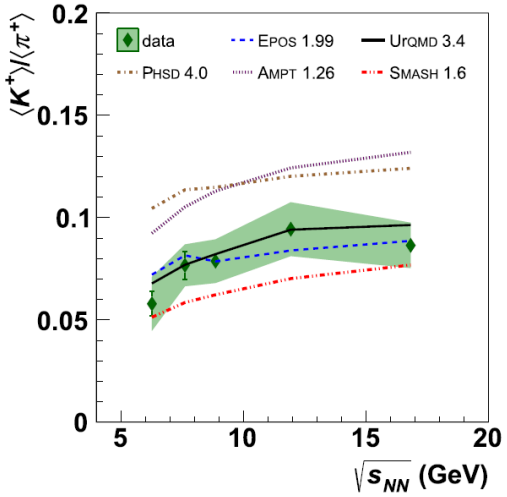
onset of deconfinement

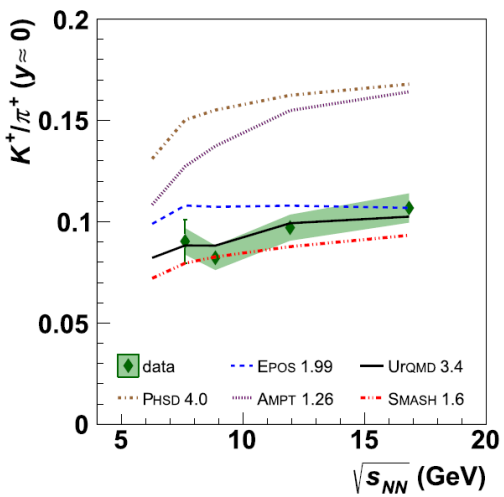


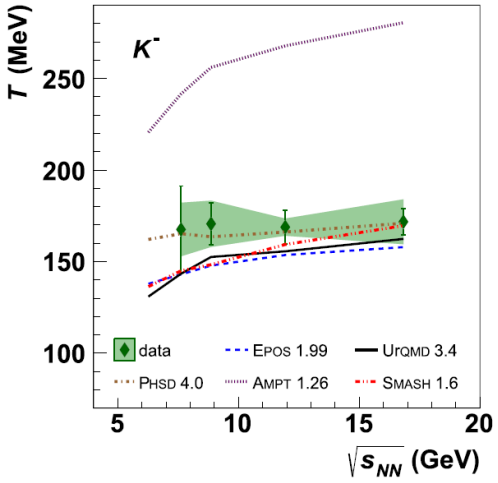
$p + p \approx Be + Be \neq Ar + Sc \leq Pb + Pb$

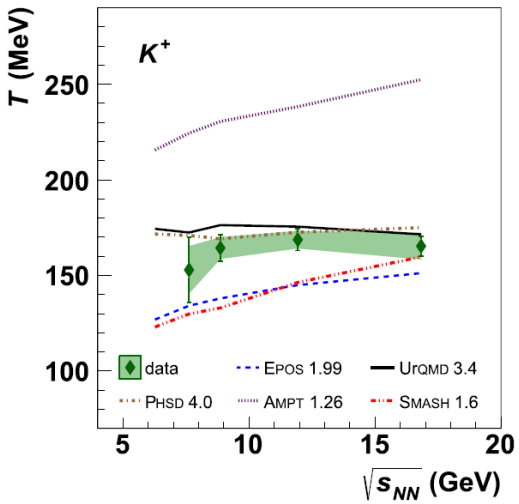
- Precise measurements of collision energy dependence for p+p, Be+Be, and Ar+Sc
- K^+/π^+ ratio in inelastic p+p interactions is different from the one in heavy-ion collisions
- No horn structure in Be+Be and Ar+Sc
- The collision energy dependence of the inverse slope parameter of m_T spectra T shows the so-called *step* structure

results on $\pi^+, \pi^-, K^+, K^-, p$, and $\bar{p}$ in central Be+Be collisions at 19A–150A GeV/c







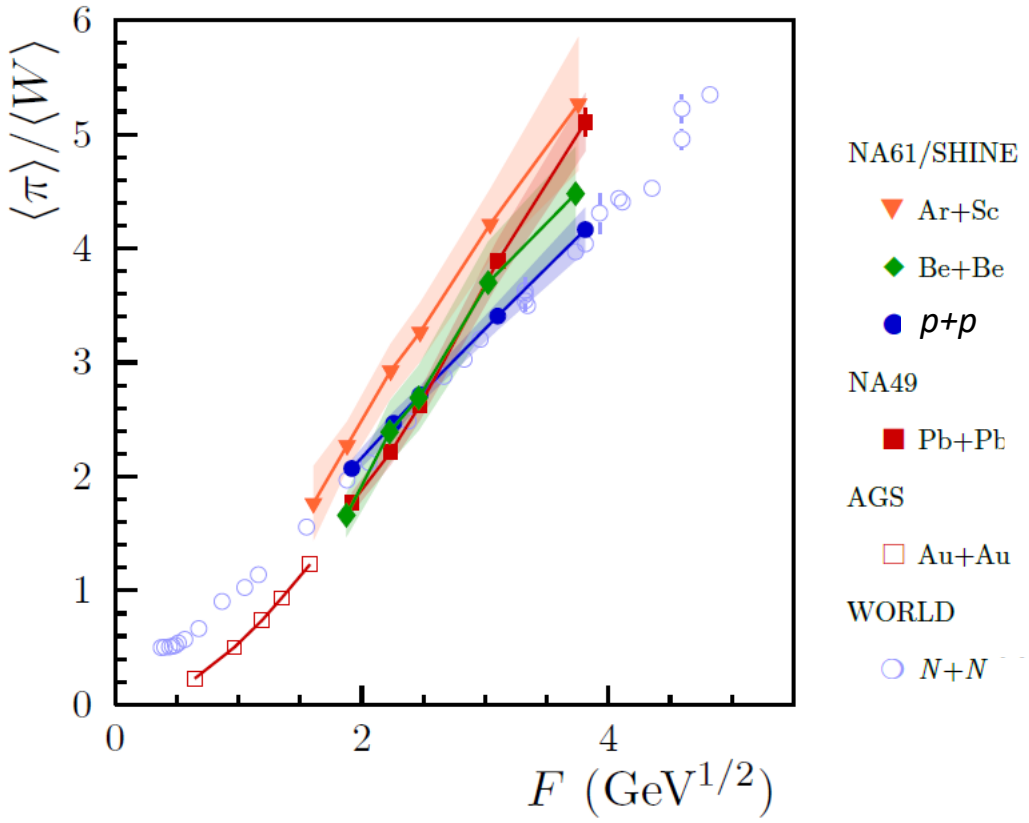


Be+Be collisions and onset of deconfinement

- NA61/SHINE – the only world data for Be+Be collisions
- No visible sharp break in K^+/π^+ and inverse slope parameter T in the accessible energy range.
- No model describes all measured quantities

Eur. Phys. J. C **81** no. 1, (2021) 73

Results on π^- production in central Ar+Sc collisions at 13A–150A GeV/c



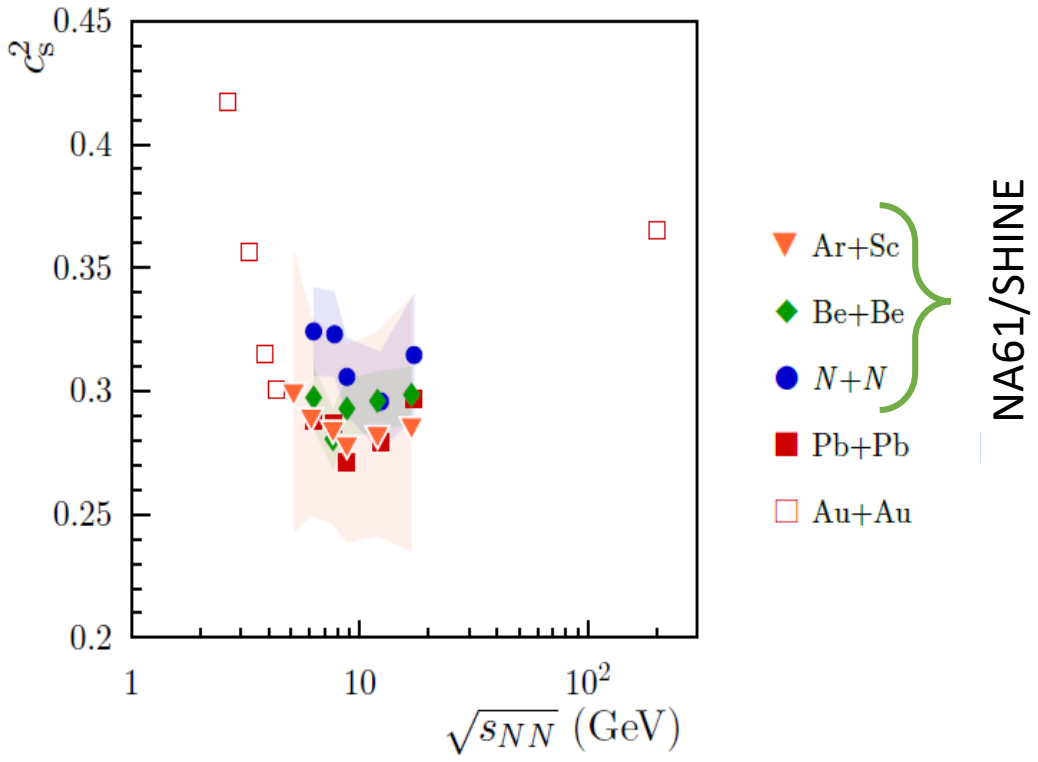
$$F = \left[(\sqrt{s_{NN}} - 2m_N)^3 / \sqrt{s_{NN}}\right]^{1/4},$$

update of the "kink" plot – pion multiplicity per number of wounded nucleons $\langle\pi\rangle/\langle W\rangle$

- The NA61/SHINE results
  - *N+N* interactions agree well with the world data
  - Be+Be collisions are mostly between measurements from *N+N* and Pb+Pb collisions.
  - Ar+Sc collisions seem to be systematically higher than the results for *N+N*, Be+Be and Pb+Pb collisions at the lower energies
  - Ar+Sc close to the Pb+Pb results at the highest energies.

Eur. Phys. J. C **81** no. 5, (2021) 397

Results on π^- production in central Ar+Sc collisions at 13A–150A GeV/c



width of the rapidity distribution - speed of sound

- The collision energy dependence of the rapidity distribution width is associated with the speed of sound c_S

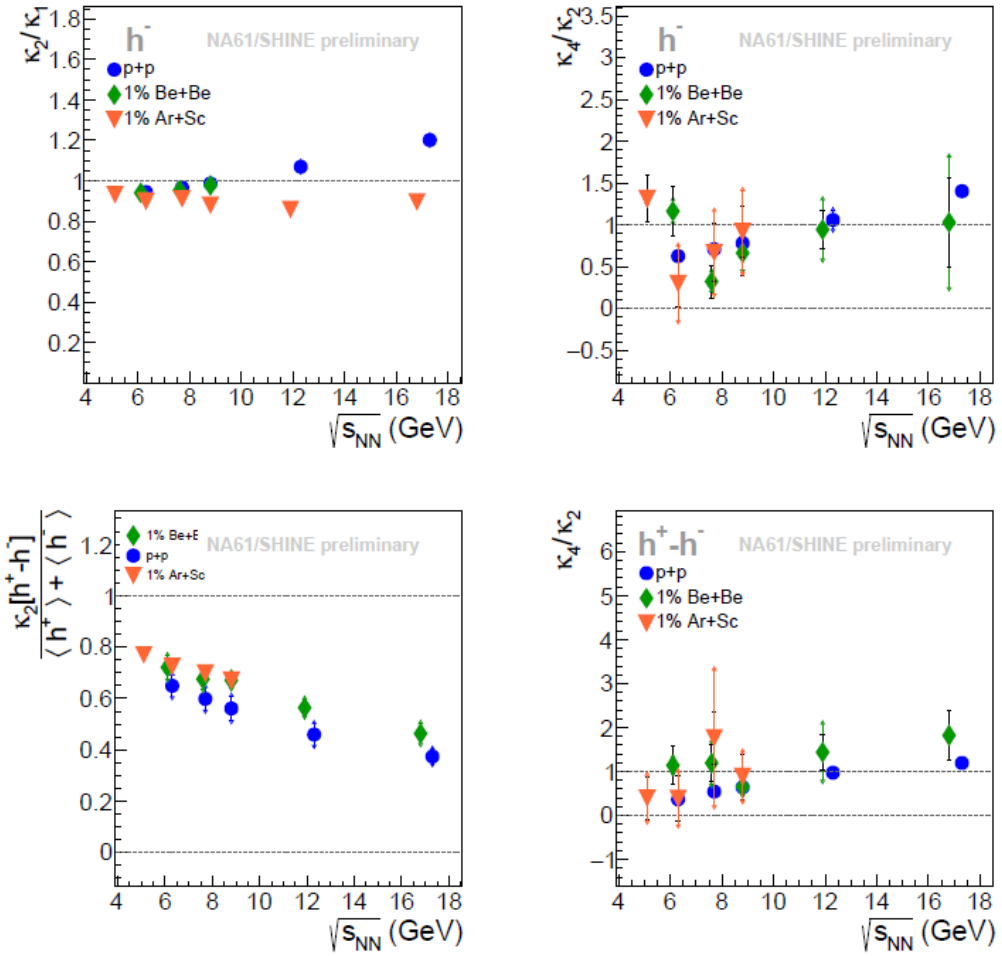
$$\sigma^2 = \frac{8}{3} \cdot \frac{c_s^2}{1 - c_s^4} \cdot \ln\left(\frac{\sqrt{s_{NN}}}{2m_p}\right)$$

E. V. Shuryak. *Yad.Fiz.*, 16:395–405, 1972.

- The dense matter produced in the collisions was predicted to show a minimum in the speed of sound energy dependence around the collision energy of the onset of deconfinement
- Confirmed by Pb+Pb (Phys. Rev. C **66** (2002) 054902, Phys. Rev. C **77** (2008) 024903) data in combination with results from central Au+Au (Acta Phys. Hung. A **4** (1996) 33–44 , Phys. Lett. B **567** (2003) 175–178) collisions
- The results of NA61/SHINE from *central* Ar+Sc, Be+Be collisions, and inelastic *N*+*N* reactions need to be extended to lower end energies for conclusion about a possible minimum

Eur. Phys. J. C **81** no. 5, (2021) 397

Preliminary results on rapidity dependence of higher-order moments of multiplicity and net-charge in inelastic p+p collisions at 158 GeV/c



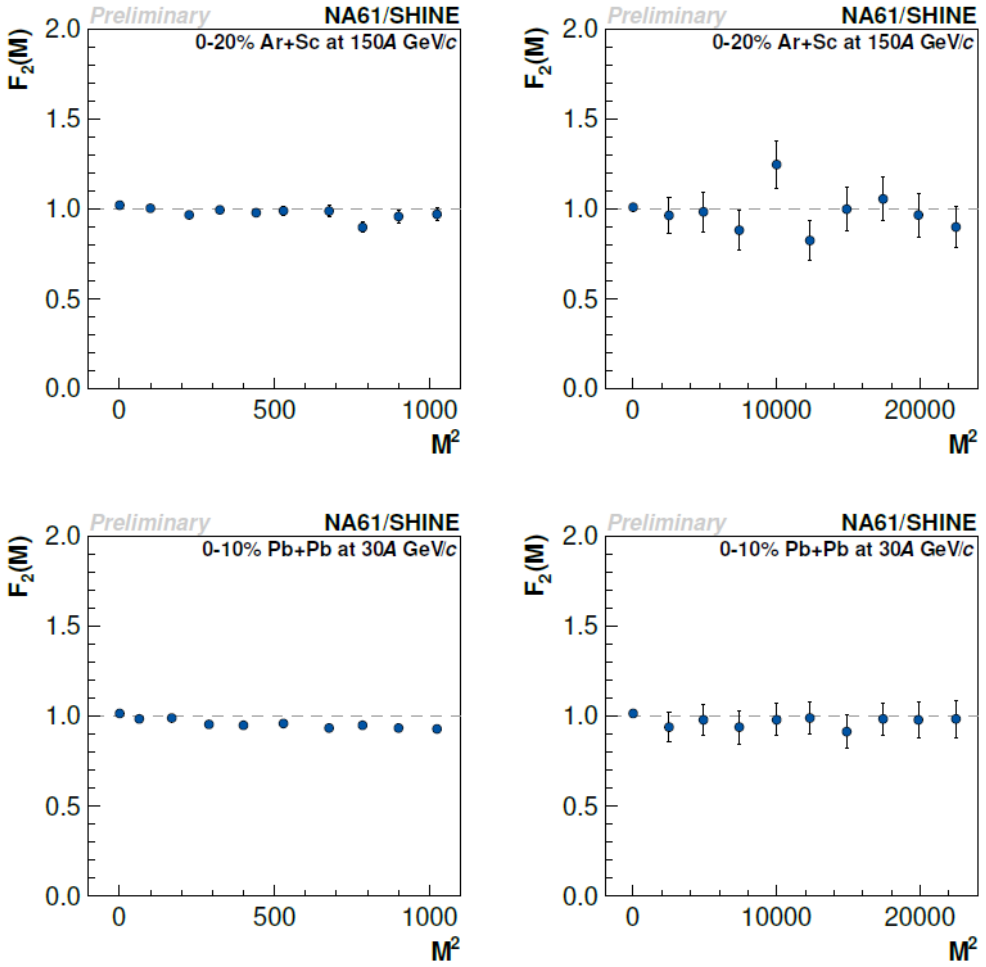
net-charge fluctuations measured by higher order moments

- p+p≈Be+Be
- Considerable difference between p+p and Ar+Sc interactions is visible for the second-order cumulant ratio
- This difference does not remain for higher-order moments
- No structure indicating critical point

$$\kappa_1 = \langle N \rangle$$
$$\kappa_2 = \langle (\delta N)^2 \rangle = \sigma^2$$
$$\kappa_3 = \langle (\delta N)^3 \rangle = S\sigma^3$$
$$\kappa_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2 = K\sigma^4$$

N - multiplicity, $\delta N = \langle N - \langle N \rangle \rangle$,
σ - standard deviation, S - skewness
K - kurtosis

Preliminary results on proton intermittency in Ar+Sc at 150AGeV/c and Pb+Pb at 30AGeV/c



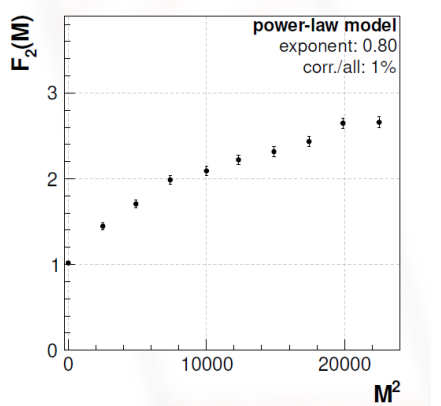
- Results for:
  - statistically independent points
  - cumulative quantities
  - M = 1 … 32 bins in $p_x \; and \; p_y$
- second scaled factorial moments of protons for Ar+Sc at 150*A* GeV/*c* and Pb+Pb at 30*A* GeV/*c* shows no indication for power-law increase with a bin size

$$F_r(M) = \frac{\left\langle \frac{1}{M}\sum_{i=1}^{M} n_i(n_i-1)\ldots(n_i-r+1) \right\rangle}{\left\langle \frac{1}{M}\sum_{i=1}^{M} n_i \right\rangle^r},$$

M – subdivision intervals of the momentum space

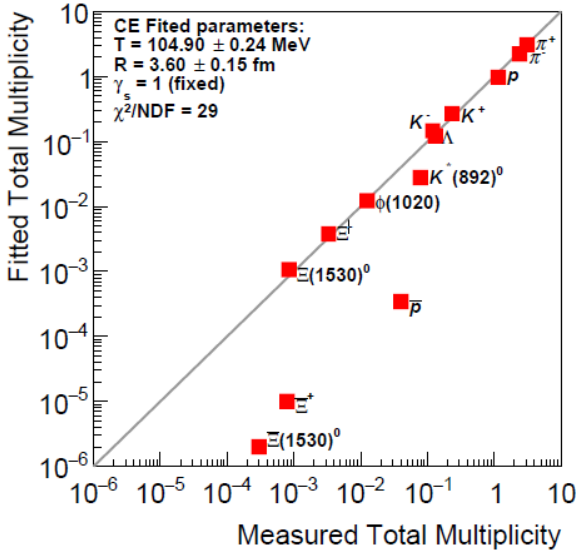
n_i - number of the particle in i^{th} bin

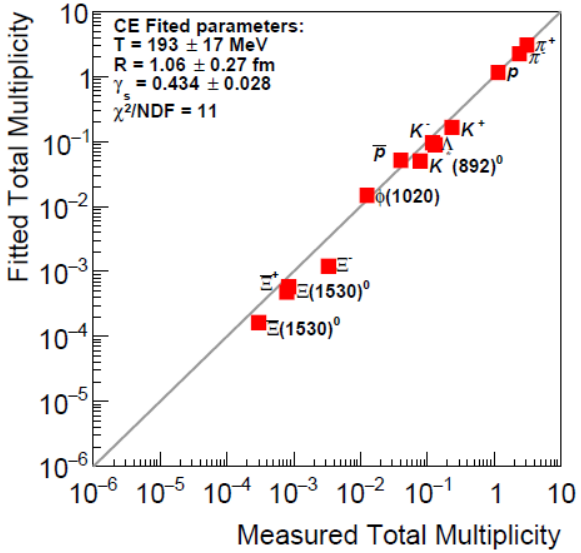
<…> averaging over events



If the system freezes-out in the vicinity of the critical point, $F_2(M)$ should reveal a power-law dependence.

Final results on $\Xi(1530)^0$ and $\bar{\Xi}(1530)^0$ production in inelastic p+p collisions at 158 GeV/c





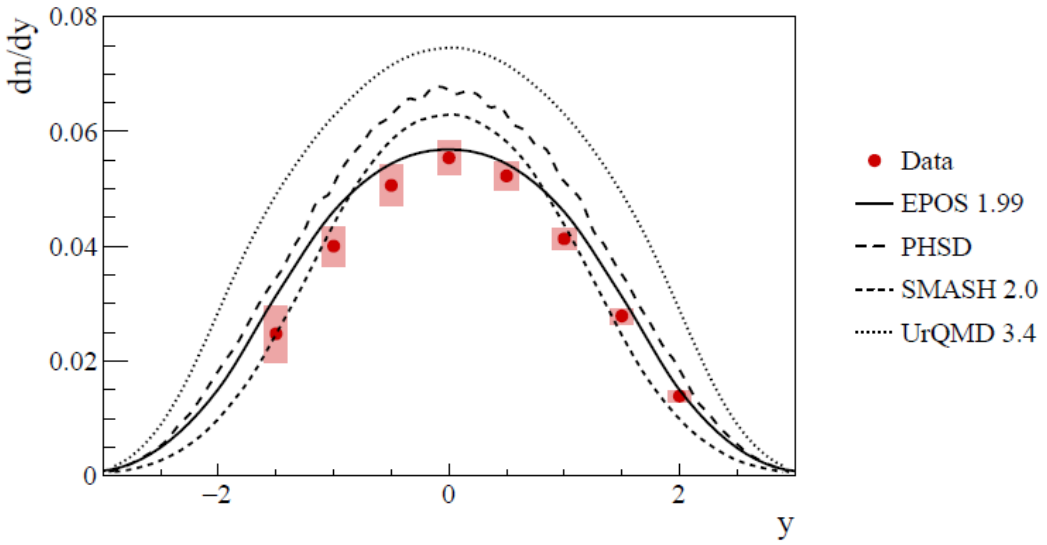
HRG model in the CE formulation and p+p data

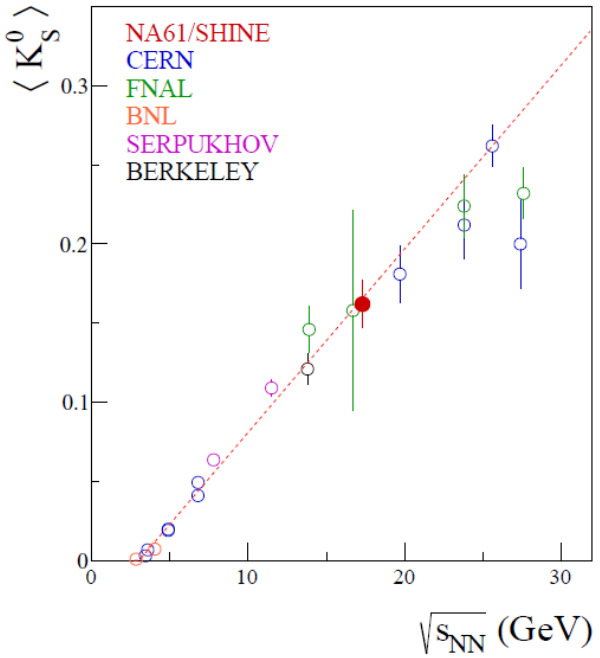
- Fit by different variants of the HRG model (THERMAL-FIST1.3 Comput.Phys.Commun.244(2019)295):
  - Canonical Ensemble with fixed γ_s=1
  - Canonical Ensemble with fitted strangeness saturation parameter γ_s

- Significant discrepancies of the fitted parameters
- The statistical model fails when γ_s is fixed
- The fit with free γ_s finds γ_s =0.434±0.028 and reproduces the measurements well -> suppression of strange particle production in *p+p* collisions at CERN SPS energies

arXiv:2105.09144

Final results on K_s^0 production in inelastic p+p collisions at 158 GeV/c





- The EPOS1.99 model describes the experimental data fairly well while all other models overpredict the K_s^0 yield by 10–20%
- The measured values are seen to rise linearly with collision energy
- The NA61/SHINE result follows the observed trend

arXiv:2106.07535

Detector upgrade

Measurements of charm hadron production in Pb+Pb collisions for heavy ion physics

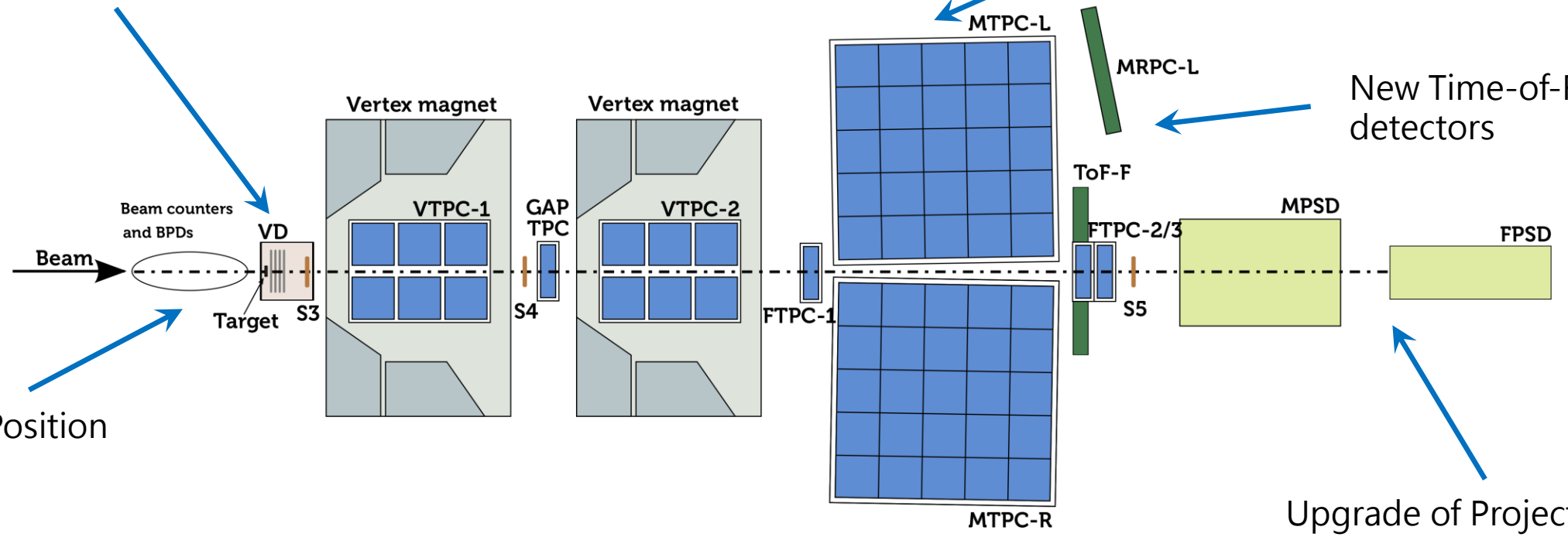
Measurements of nuclear fragmentation cross section for cosmic ray physics

Measurements of hadron production induced by proton and kaon beams for neutrino physics

Detector upgrade

Construction of Vertex Detector (VD) for D^0, $\overline{D^0}$ decay reconstruction

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



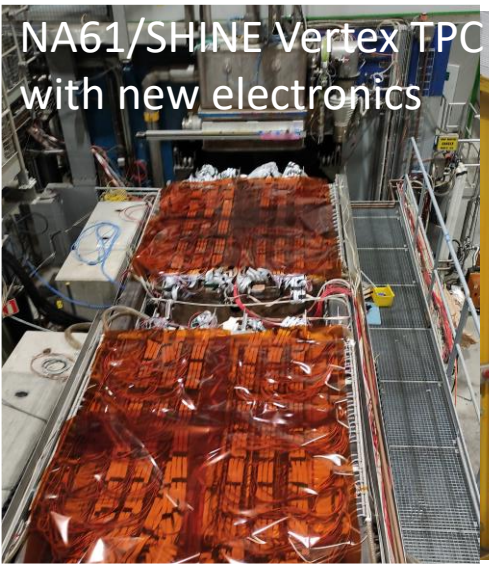
New Time-of-Flight detectors

New Beam Position Detector

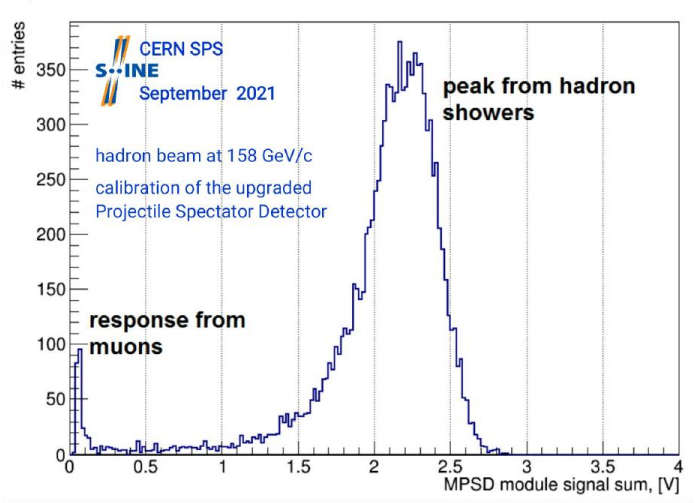
New trigger and data acquisition system

Upgrade of Projectile Spectator Detector

Achieved milestones of the NA61/SHINE detector upgrade



- Two test periods with hadron beam during summer 2021
- The successful test of the new subsystems:
  - Data acquisition system:
    - Fully scalable, with local data buffer
  - Trigger system
  - The readout system is based on the DRS4 chip, where the full waveform will be measured and stored.
  - PSD calorimeter with new readout electronic
  - Beam Position Detectors based on the single-sided silicon detector
- The successful installation of the new components:
  - Installation of the new electronics on Vertex Time Projection Chambers
  - Installation of the new Time of Flight System based on Multi-gap Resistive Plate Chambers



Upgrade status

Due to the ''synergy'' of the Covid-related obstacles (shortage of electronic components, delayed production of hardware and travel restrictions) not all detectors are fully upgraded.

During the October/November beam period, we will continue with the commissioning, calibration of upgraded detectors and plan the first physics measurements of the total cross sections for neutrino experiments.

We expect completion of the upgrade by April 2022 followed by final commissioning with hadron and Pb beams in spring 2022.

Subsystems ready by the end of 2021:

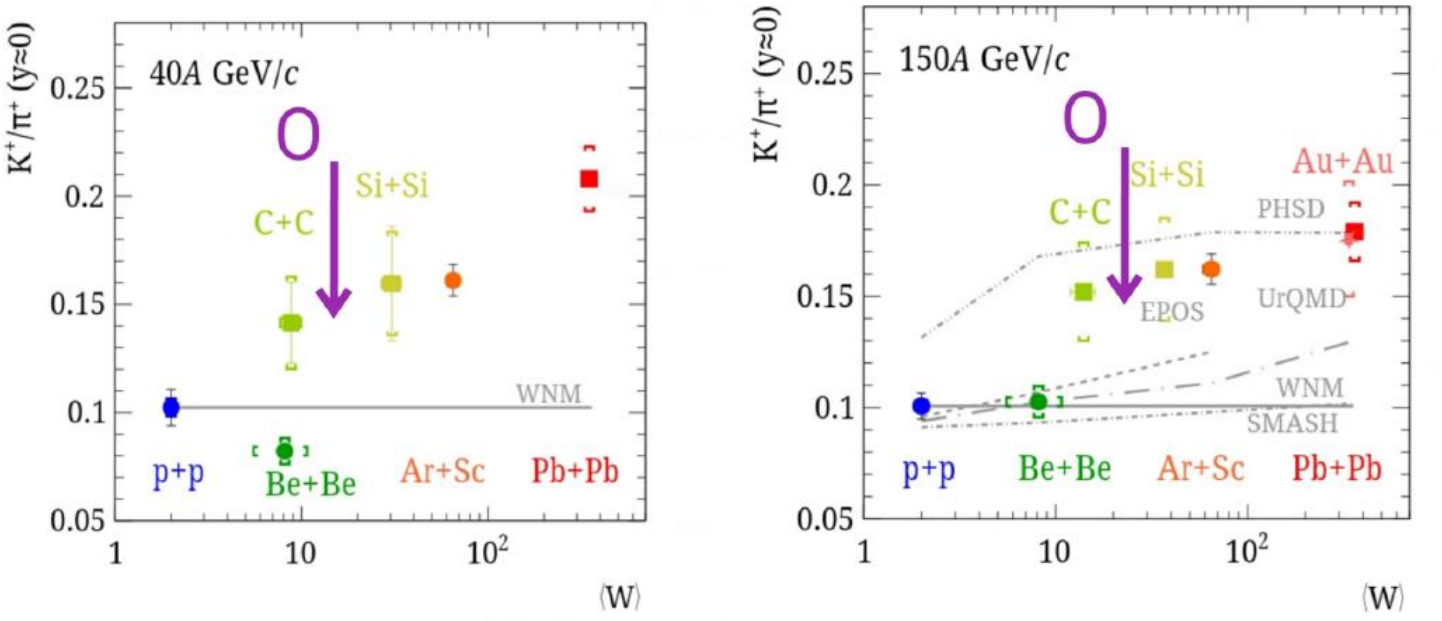
- Trigger and Data Acquisition System
- Calorimeters: MPSD, FPSD
- Time o Flight Detectors
- Beam Potion Detector
- Vertex detector
- TPC: VTPC, FTPCs, GTPC

Subsystems ready by spring 2022

- MTPC
- Full DRS readout

Onset of fireball - measurements

high-statistics measurements with oxygen beam



- hadron production properties change rapidly when increasing the nuclear mass of colliding nuclei between Be and Ar
- an unexpected phenomenon has been discovered: the onset of fireball
- relatively low-statistics results of NA49 obtained with secondary C and Si beams

Summary

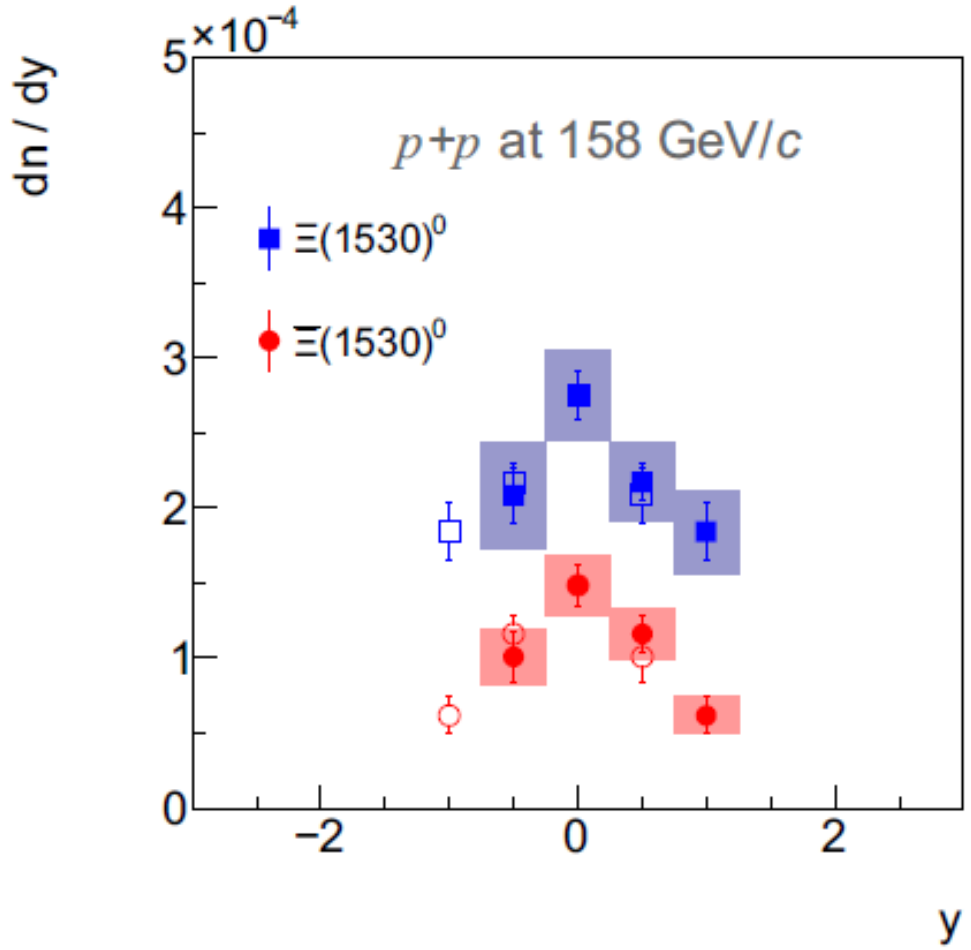
- Measurements within the 2D scan in system size and the collision energy are completed
- NA61/SHINE delivers reach information related to the onset of deconfinement in the light and medium-size system
- A significant wealth of promising results (analysis), still no smoking gun evidence of critical point:
  - net-charge fluctuations measured by the higher-order moments
  - second scaled factorial moments of protons
- NA61/SHINE will measure open charm production in 2022- 2024

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

Thank you

seweryn.kowalski@us.edu.pl

Rapidity spectra of $\Xi(1530)^0$ and $\bar{\Xi}(1530)^0$ produced in inelastic p+p interactions at 158 GeV/c



Corrected double-differential spectra d2*n*/d*y*d*p*T of negatively charged pions produced in the 5%most *central* Ar+Sc collisions at beam momenta of 13*A*, 19*A*, 30*A*, 40*A*, 75*A* and 150*A* GeV/*c*