



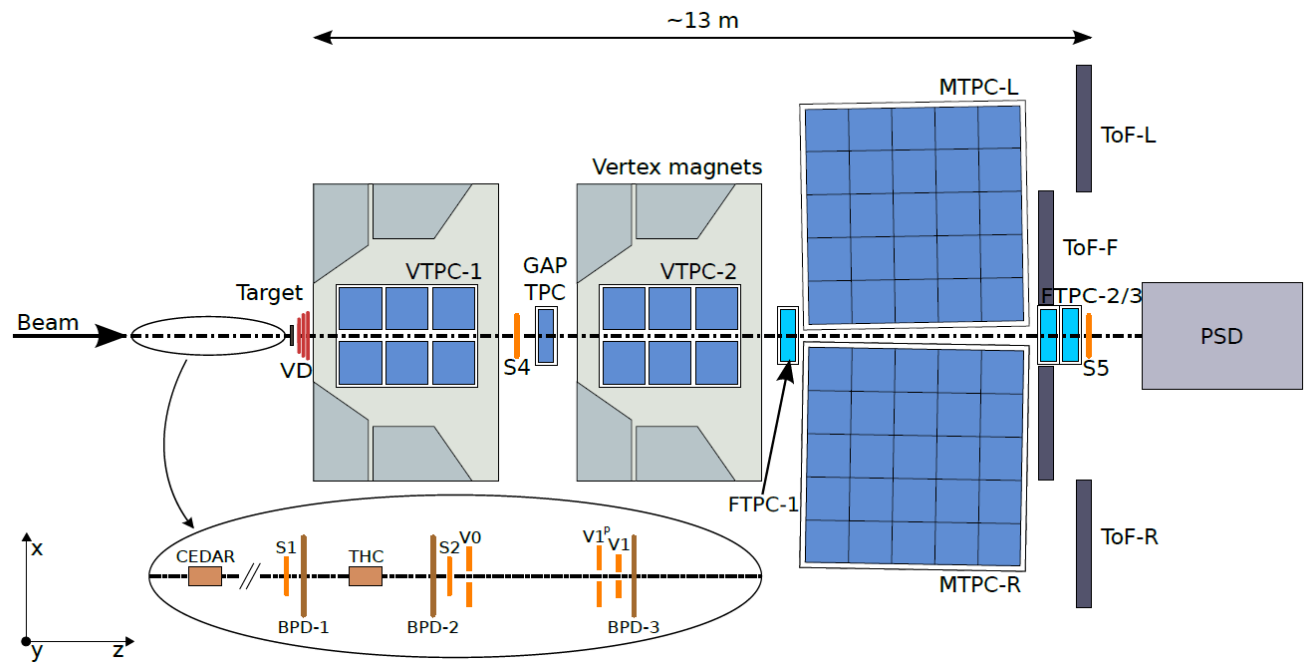
**Report from the NA61/SHINE
experiment at the CERN SPS**

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for the NA61/SHINE collaboration

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NA61/SHINE experiment

Fixed target experiment located at the SPS accelerator



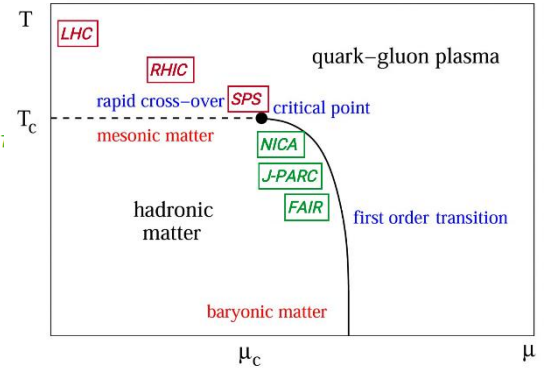
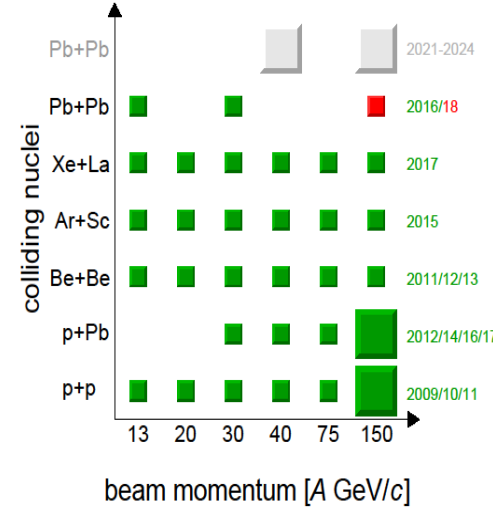
Beams:

- ions (Be, Ar, Xe, Pb)
 $p_{\text{beam}} = 13A - 150A \text{ GeV}/c$
- hadrons (π , K, p)
 $p_{\text{beam}} = 13 - 400 \text{ GeV}/c$
- $\sqrt{s_{NN}} = 5.1 - 16.8 (27.4) \text{ GeV}$

Large acceptance hadron spectrometer – coverage of the full forward hemisphere, down to $p_T = 0$

Research program: strong interactions physics

NA61/SHINE experiment performs scan in **collision energy and system size** to study the phase diagram of strongly interacting matter.



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

Research program: neutrino and cosmic ray physics

➤ Precision data on hadron production for neutrino experiments:

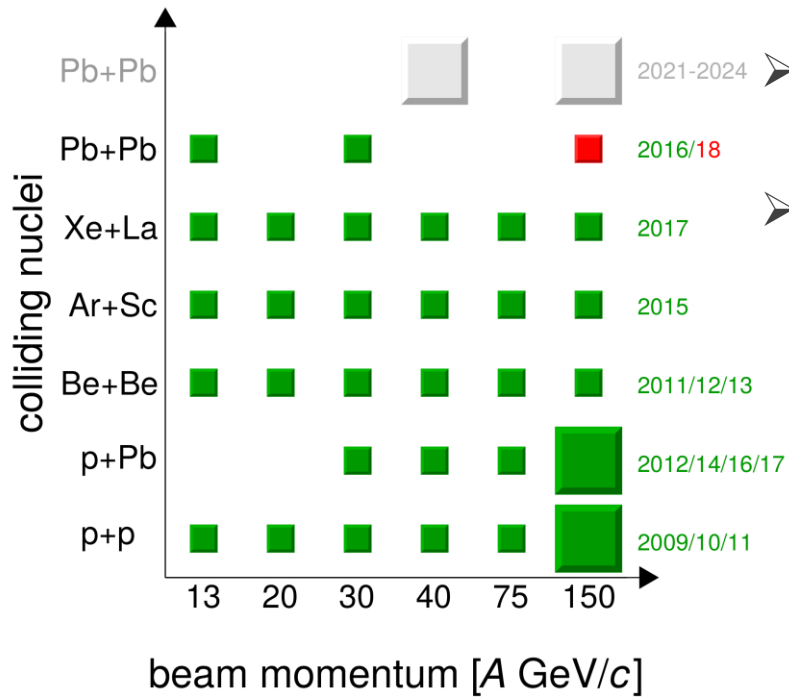
- reference measurements of $p+C$ interactions for the T2K experiment for computing neutrino fluxes from the T2K beam targets
- reference measurements of $h+A$ measurements for the Fermilab neutrino program

➤ Precision data for cosmic ray experiments:

- reference measurements of $p+C$, $p+\pi$, $p+p$, and $\pi+C$ interactions for cosmic-ray physics (Pierre-Auger and KASCADE experiments) for improving air shower simulations
- reference measurement of nuclear fragmentation cross sections of intermediate mass nuclei needed to understand the propagation of cosmic rays in our Galaxy (background for dark matter searches with space-base experiments as AMS)

Data taking 2017/18

Data taking in autumn 2017



➤ October 2017: p+Pb at 40 GeV/c
4.3M events recorded

➤ Oct-Dec 2017: **Xe+La at 13A-150A GeV/c**

beam	target	beam momentum	number of events
Xe	La	13A GeV/c	3.0M
Xe	La	19A GeV/c	3.9M
Xe	La	30A GeV/c	5.1M
Xe	La	40A GeV/c	4.0M
Xe	La	75A GeV/c	2.6M
Xe	La	150A GeV/c	4.9M

2D scan is completed

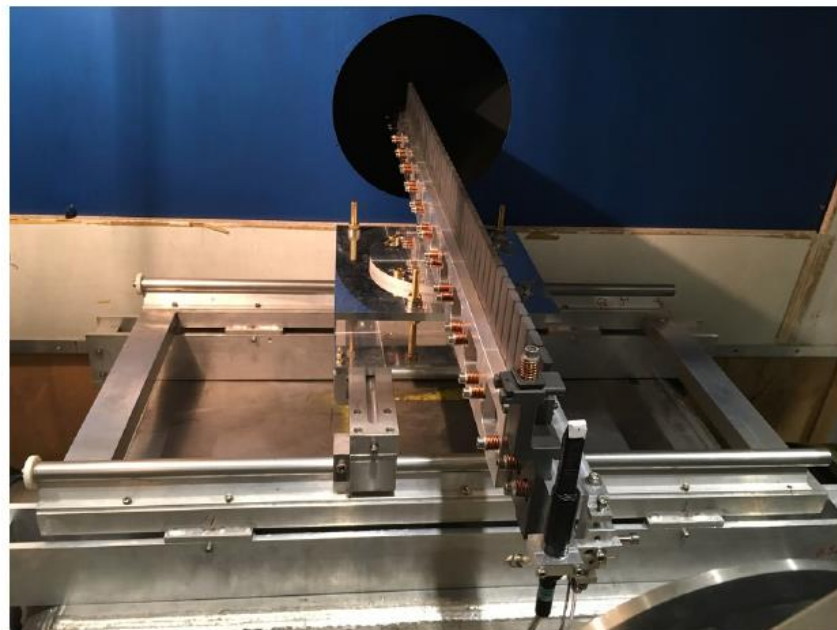
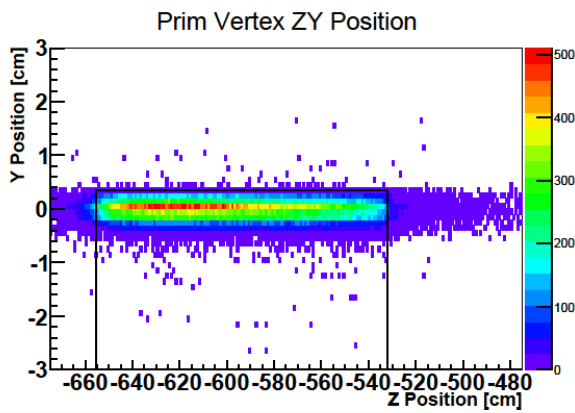
Data taking in 2018

July – August 2018, data taking with

p+(1.3-metre-long replica of the NOvA target) at 120 GeV/c

- **15 million events recorded** – will be continued this autumn.
- The data are intended to improve **flux predictions for the NOvA and MINERvA** experiments.

Beam



Facility and software modifications

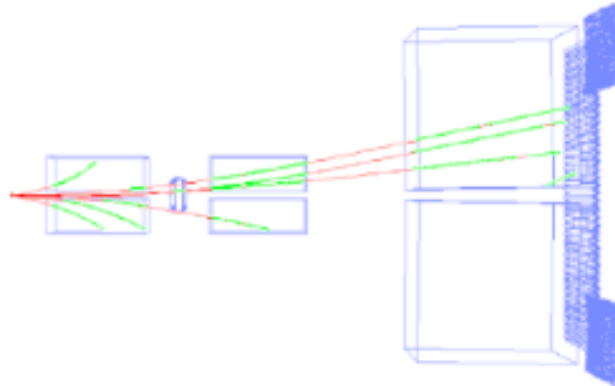
Summary of facility modifications

- The **NOvA target replica** was constructed by Fermilab and delivered to NA61/SHINE. The target consists of a series of contoured graphite fins held in place by an aluminum frame.
- The **Forward PSD calorimeter** needed for the data-taking with increased beam intensity after 2020 was installed and test with protons from 10 to 200 GeV/c.
- Several **modifications of beam and trigger counters** were introduced. They lead to about **20% decrease of the background** of off-target interactions.



Summary of software modifications

- A significant progress was reached in development of the [new SHINE reconstruction software](#). The software is routinely used for the off-line data quality assessment.
- NA61/SHINE software infrastructure changes follow the CERN IT infrastructure development plan.



New results:

- First indication of critical point
- New results on Onset of Fireball
- First elliptic and directed flow measurement
- New results from neutrino program
- Further new physics results

First indication of critical point Proton Intermittency

Proton intermittency as signal of CP

Second order phase transition \rightarrow scale invariance \rightarrow characteristic dependence of fluctuations on size δ of subdivision intervals of momentum space Δ

$M = \Delta/\delta$ – numer of intervals

$$F_2(M) \equiv \frac{\sum_{i=1}^M \langle N_i(N_i - 1) \rangle}{\sum_{i=1}^M \langle N_i \rangle^2}$$

Where:

N_i – particle number in bin i ,

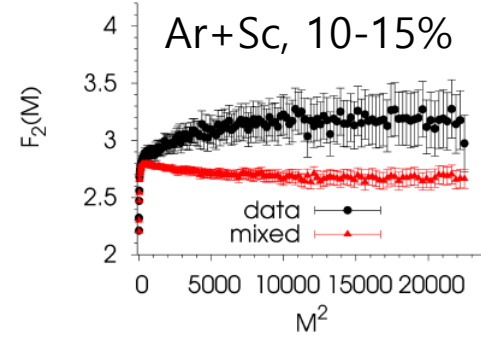
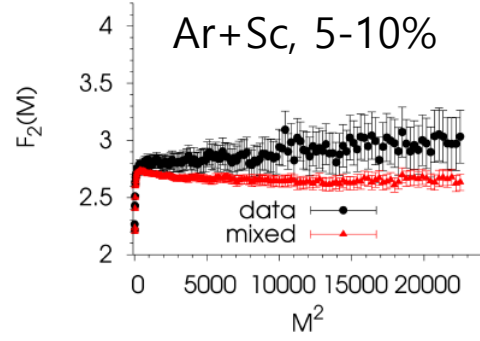
$\langle \dots \rangle$ - averaging over events

At critical point power law dependence is expected

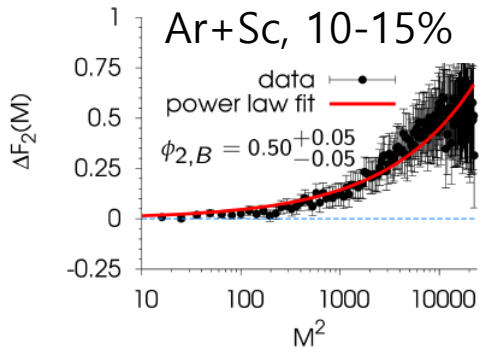
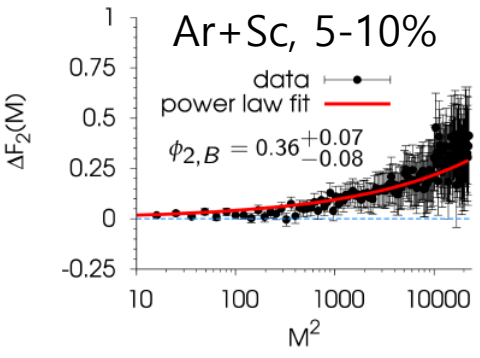
$$F_2(M) = F_2(\Delta)M^{\phi_2}$$

Proton intermittency

Ar+Sc and Be+Be at 150A GeV/c

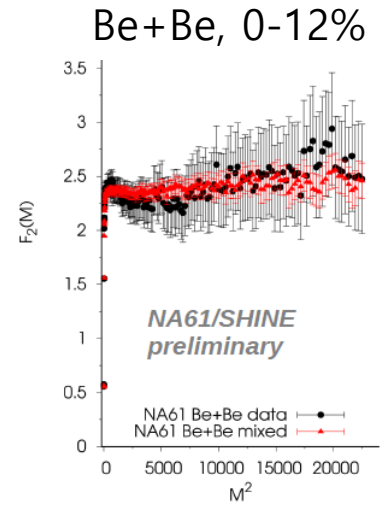


NA61/SHINE preliminary



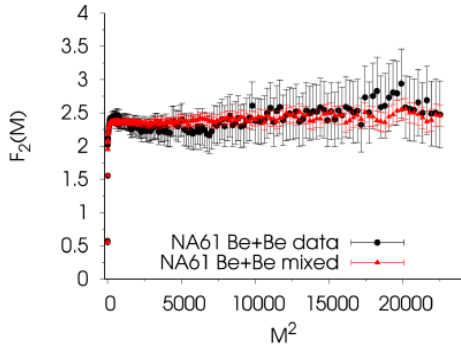
Indication of intermittency effect in mid-central Ar+Sc

- First possible evidence for CP signal in NA61/SHINE
- No intermittency signal in Be+Be

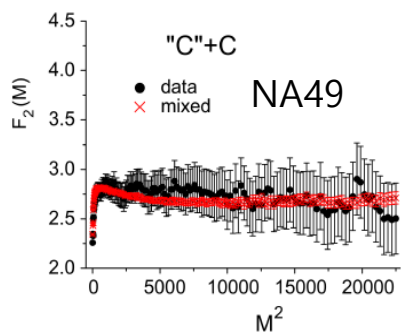


Proton intermittency at 150/158A GeV/c

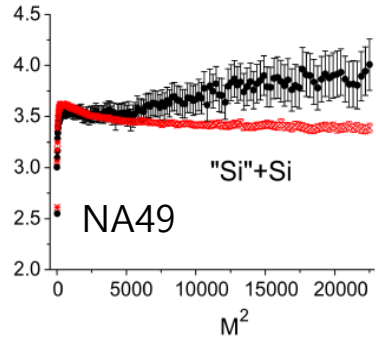
Be+Be, 0-12%



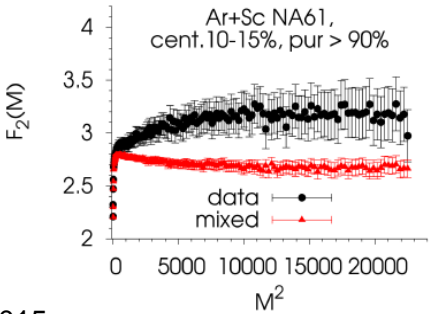
"C"+C, 0-12%



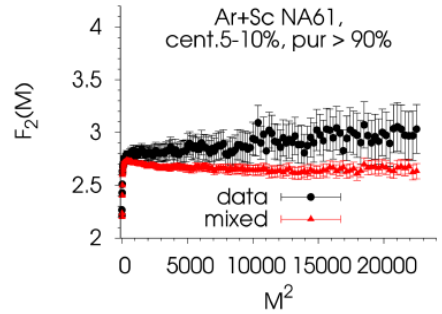
"Si"+Si, 0-12%



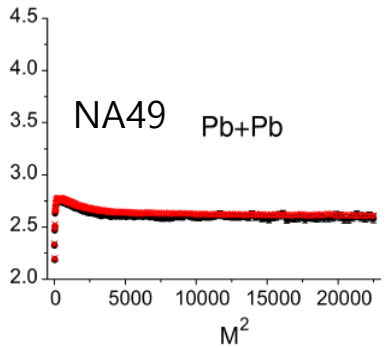
Ar+Sc, 10-15%



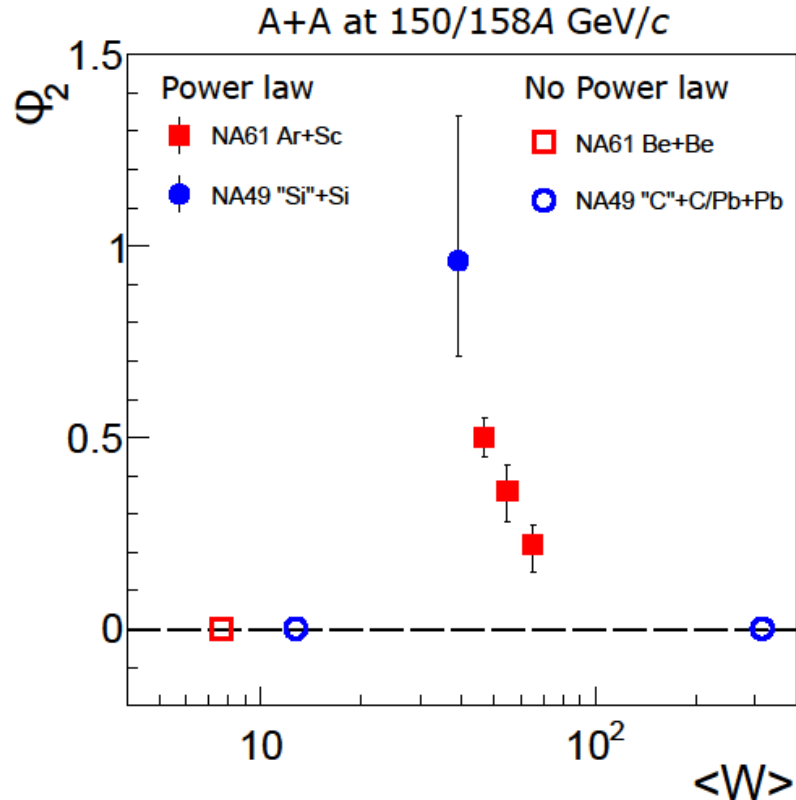
Ar+Sc, 5-10%



Pb+Pb, 0-10%



Proton intermittency



At critical point power law dependence is expected

$$F_2(M) = F_2(\Delta) (M^2)^{\phi_2}$$

First possible evidence for CP signal in NA61/SHINE

Only statistical uncertainties shown

New results on onset of fireball Spectra in Be+Be

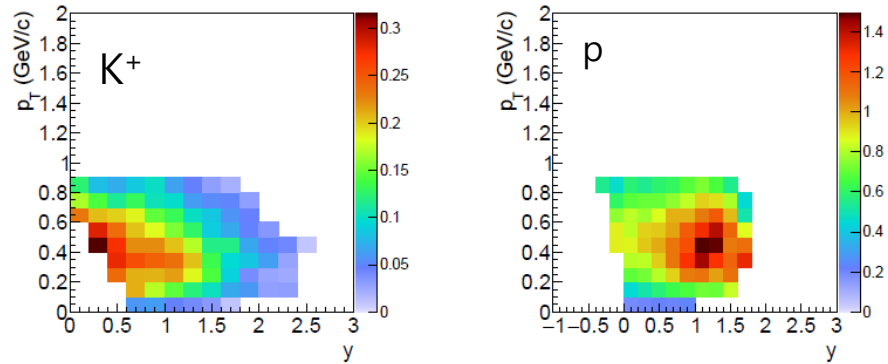
Identified charged hadrons in 0-20% central Be+Be

Double differential spectra

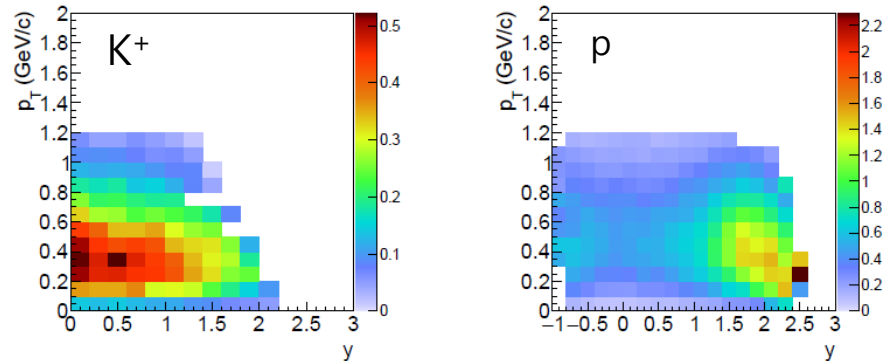
$d^2n/(dp_T dy)$ of π^\pm , K^\pm and
protons in rapidity and transverse
momentum for central (0-20%)

Be+Be collisions obtained using
dE/dx method

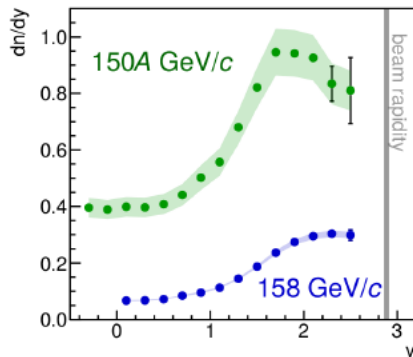
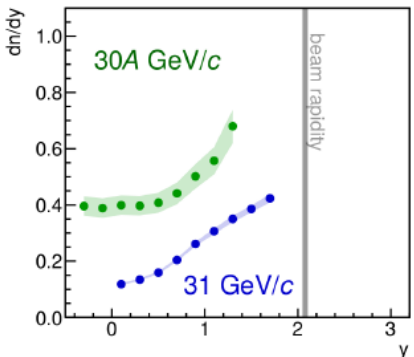
Be+Be at 30A GeV/c



Be+Be at 150A GeV/c

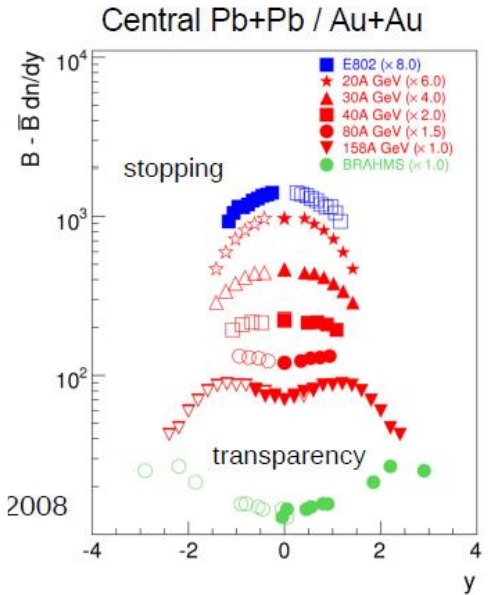


Rapidity distribution of protons



Proton rapidity distribution measured in:

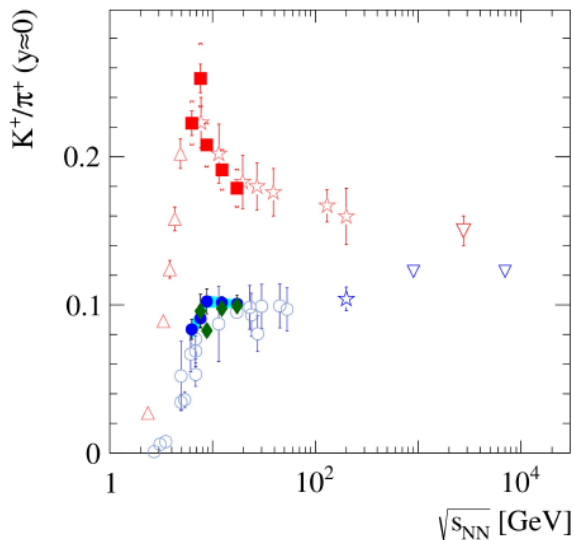
- p+p
- Be+Be (preliminary)



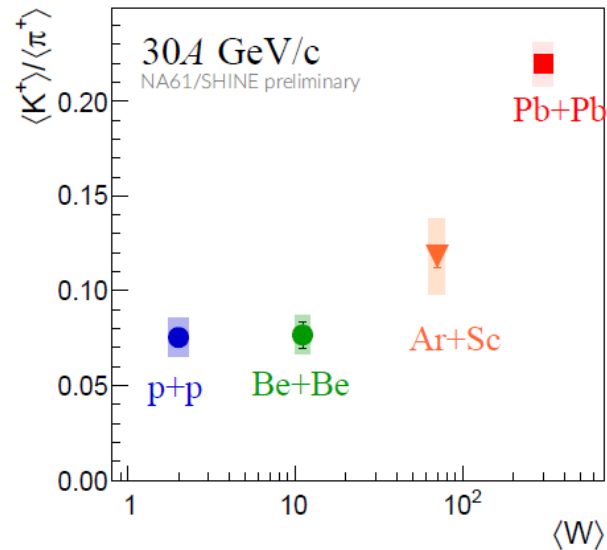
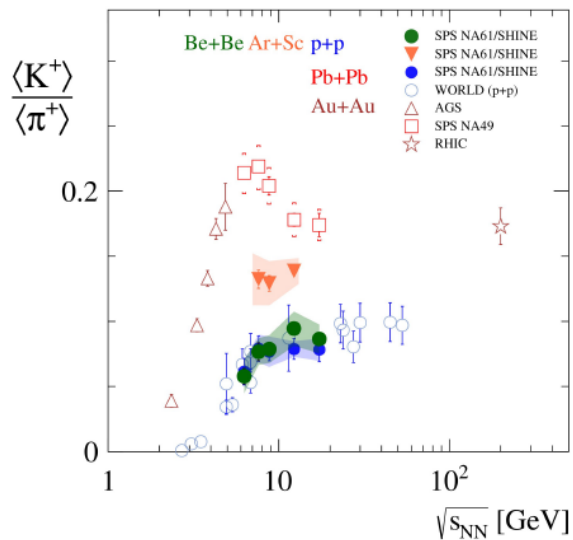
- **Shape of distributions** is qualitatively **similar in Be+Be and p+p**
- Proton, net-proton and net-baryon **spectra in Pb+Pb are qualitatively different**

K^+/π^+ ratio in 0-20% central Be+Be

“Horn” at mid-rapidity



“Horn” in 4π acceptance



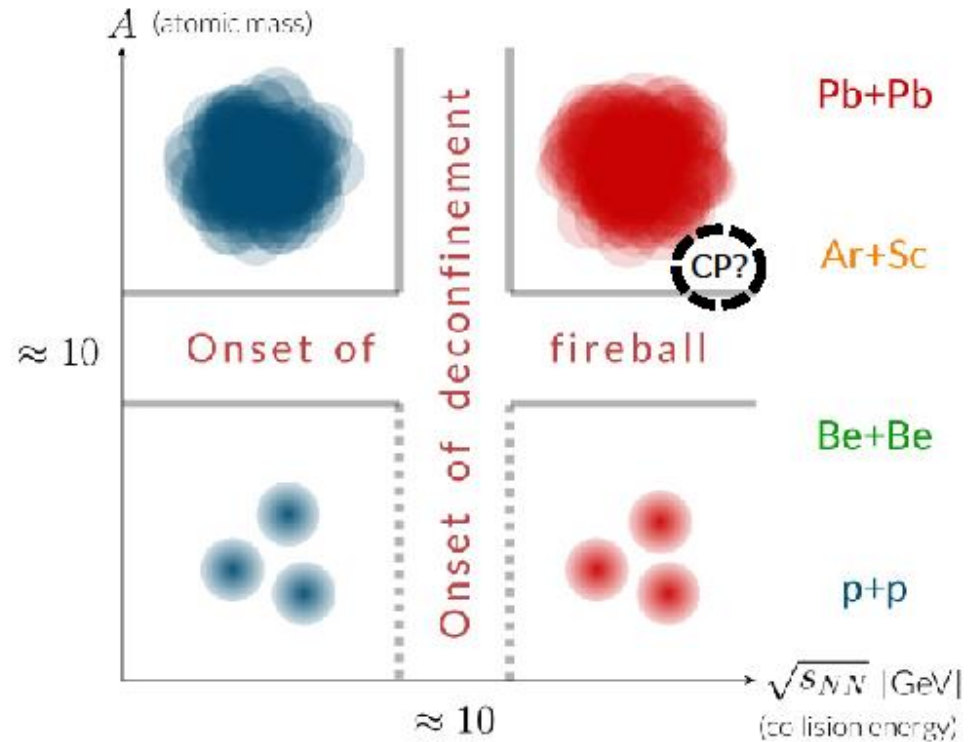
Be+Be results are **close to p+p** at mid-rapidity and in 4π acceptance

Two onsets

Two onsets in nucleus-nucleus collisions

Onset of deconfinement \equiv
beginning of QGP formation

Onset of fireball \equiv beginning of
formation of a large cluster which
decays statistically

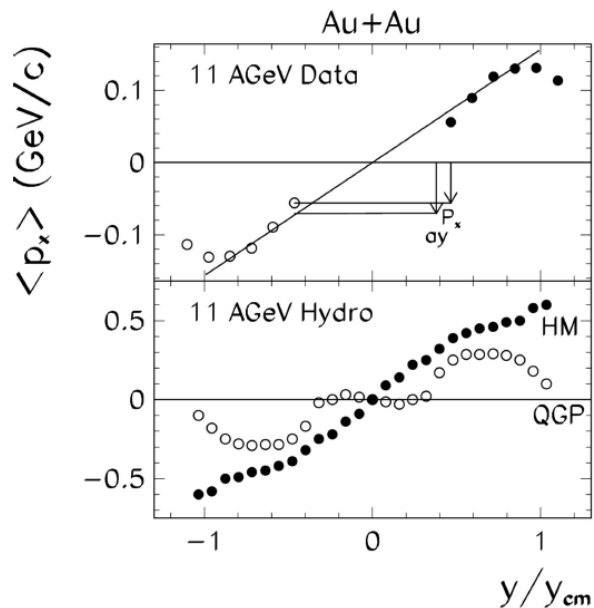


First elliptic and directed flow measurement in Pb+Pb at 30A GeV/c

Directed flow and the onset of deconfinement

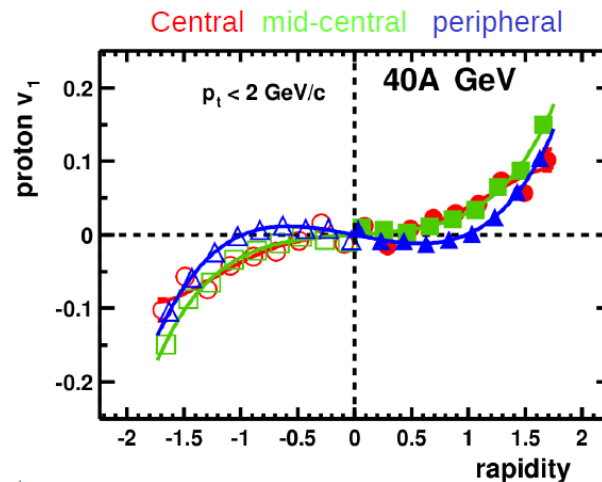
Directed flow v_1 is considered to be **sensitive to 1st order phase transition** (softening of EOS). Expected: **non-monotonic behavior** (positive \rightarrow negative \rightarrow positive) of proton dv_1/dy as a function of beam energy - “collapse of proton flow”

Predictions of hydrodynamical model:



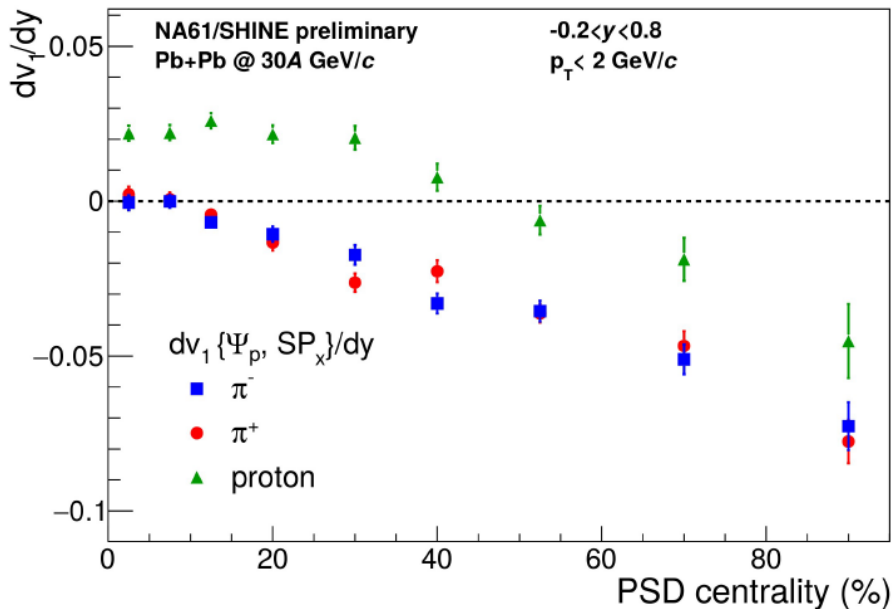
$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle$$

Directed flow measured by NA49 at middle SPS energy (“anti-flow” of protons at mid-rapidity):



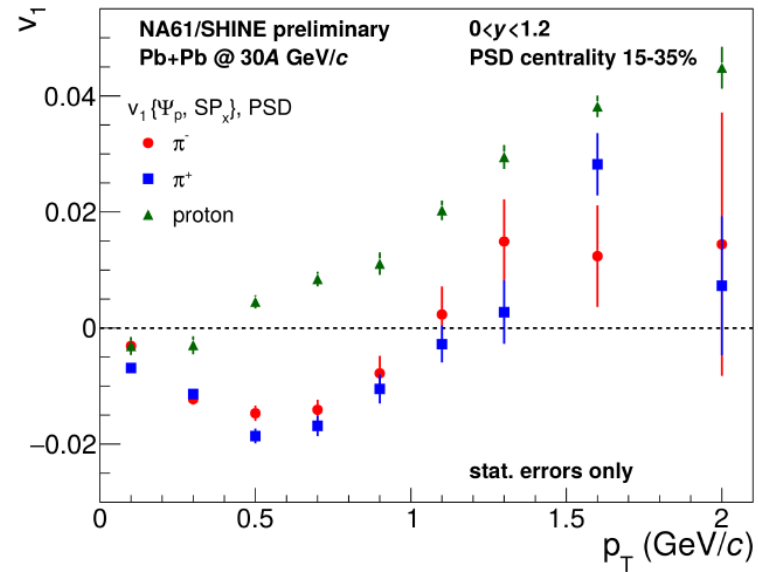
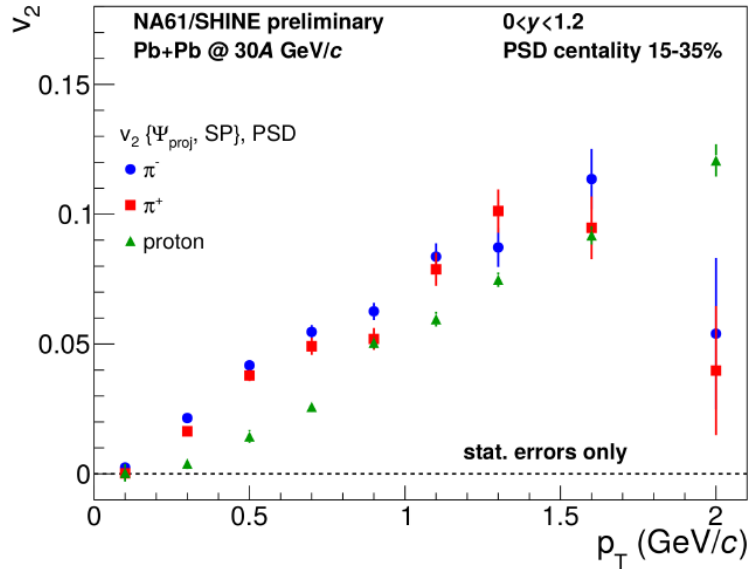
Centrality dependence of dv_1/dy in Pb+Pb at $\sqrt{s_{NN}} = 7.6$ GeV

- NA61 fixed target setup → tracking and particle identification over wide rapidity range
- Flow coefficients are measured relative to the **spectator plane estimated with Projectile Spectator Detector (PSD)** → unique for NA61



- Slope of pions v_1 is always negative
- Slope of protons v_1 changes sign for centrality of about 50%

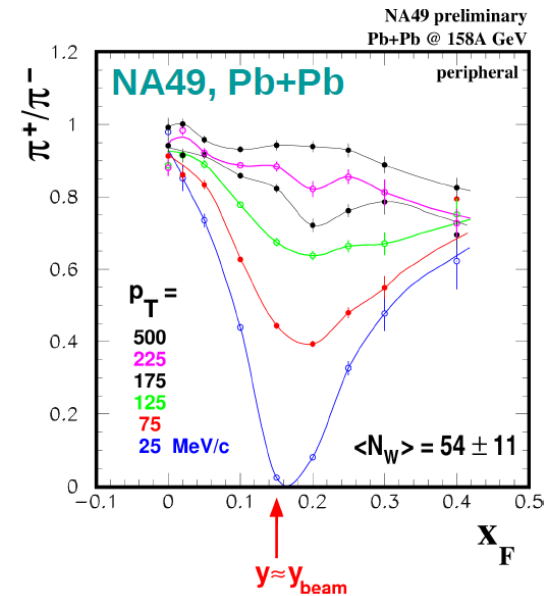
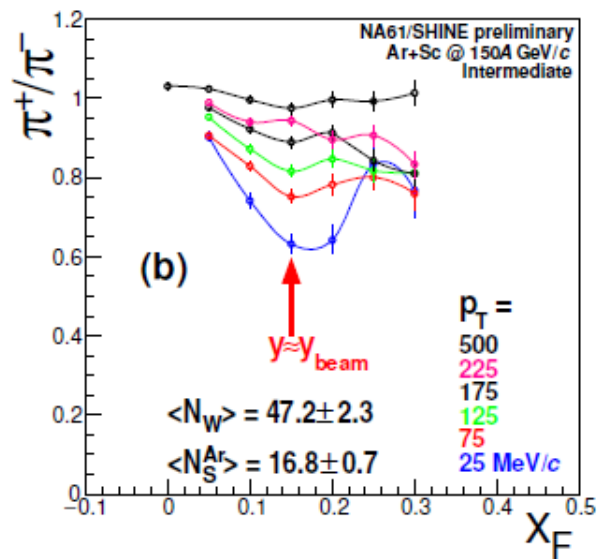
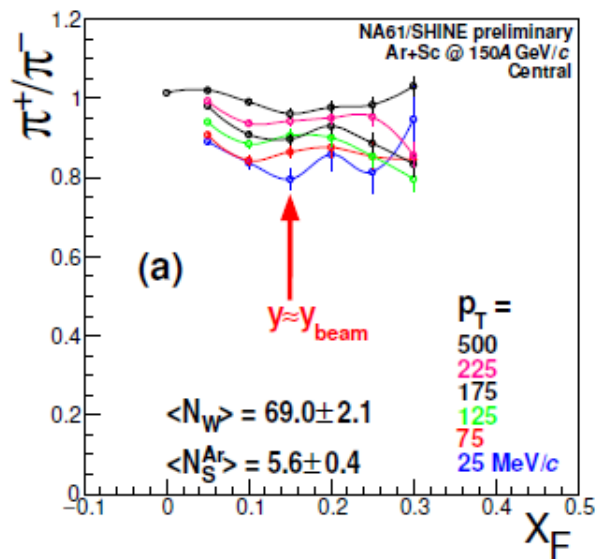
Particle type dependence of elliptic and directed flow



- Clear mass hierarchy of v_2 due to radial flow
- Difference between π^+ and π^- v_2 is small

- Significant mass dependence of v_1
- Difference between π^+ and π^- v_1 is sensitive to electromagnetic effects

Spectator-induced electromagnetic effects

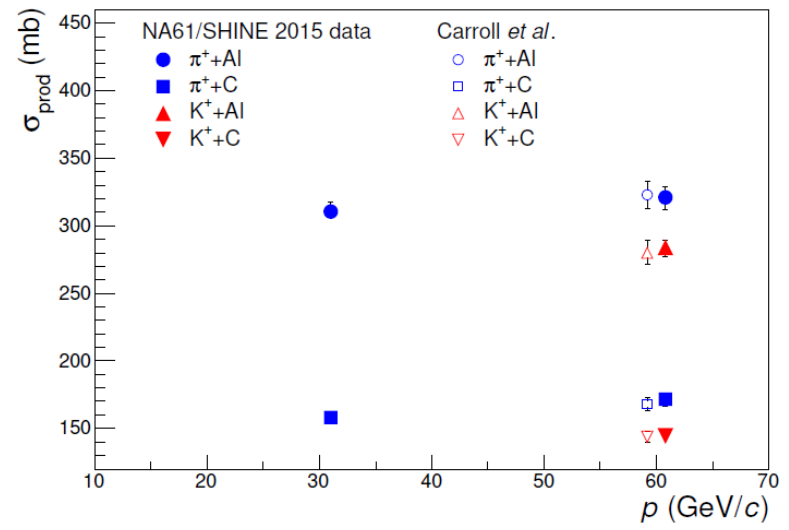
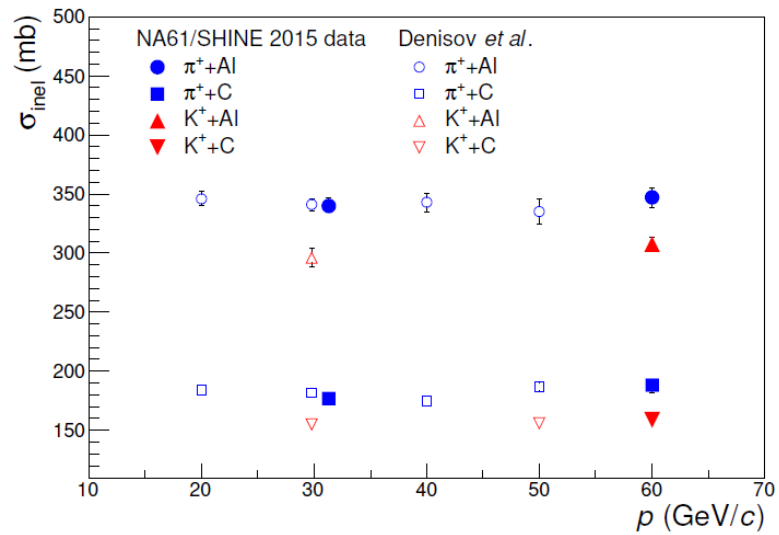


- Repulsion of π^+ is the strongest for pions with rapidities close to beam rapidity (spectators) and with low p_T
- **First observation of spectator induced EM effects in small systems at SPS**
- Similar effect seen in intermediate centrality Ar+Sc and peripheral Pb+Pb (NA49)

New results from neutrino program

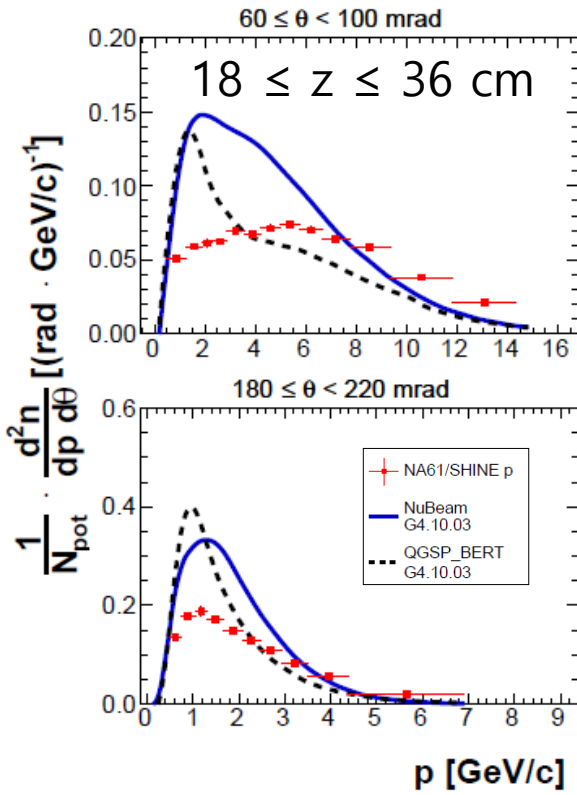
New production cross section measurements

$\pi^+ + C$, $\pi^+ + Al$, $K^+ + C$, and $K^+ + Al$ at 60 GeV/c and $\pi^+ + C$, $\pi^+ + Al$ at 31 GeV/c



The proposed future LBNF beamline for the DUNE experiment will provide protons beam with an energy 60-120 GeV/c.

Final T2K replica-target measurements



The double differential yields of π^\pm , K^\pm and protons emitted from the surface of a 90 cm-long carbon target (T2K replica) with 31 GeV/c protons

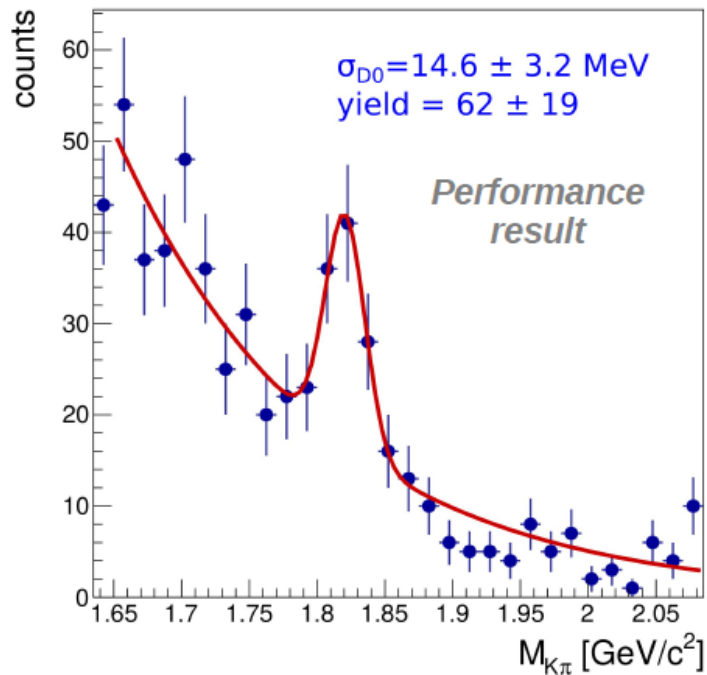
These new measurements are crucial for reducing the hadron production component of the T2K (anti)neutrino flux error.



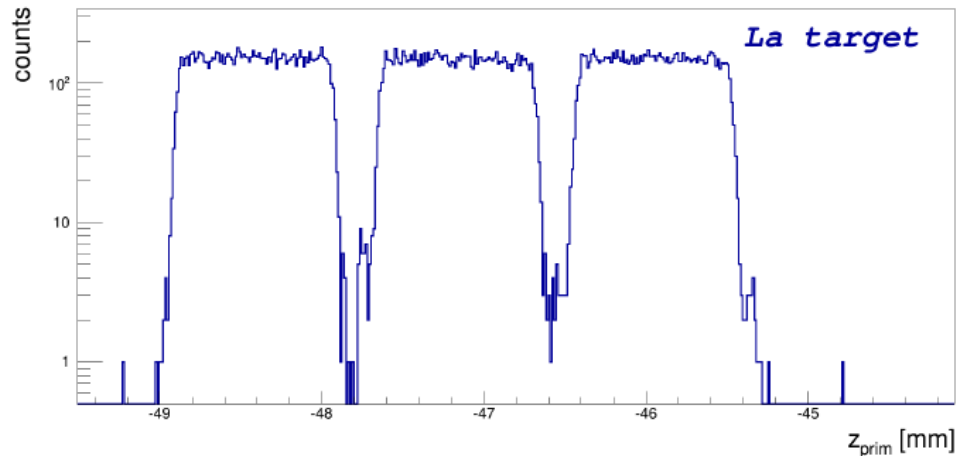
Further new physics results

Analysis of Vertex Detector data

Improved D_0 analysis of pilot Pb+Pb 2016 data



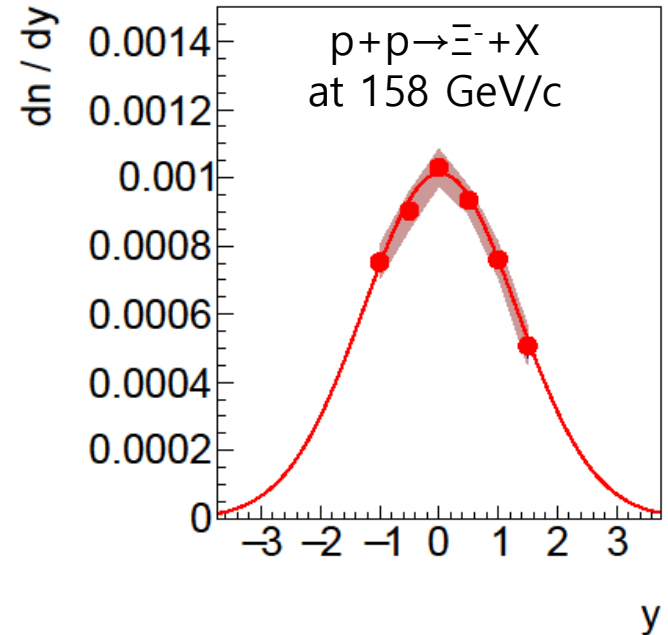
Vertex z distribution from Xe+La 2017 data



Vertex fit resolution in the beam direction on the level of $50 \mu\text{m}$.

Further new physics results

- $K^*(892)^0$ production in $p+p$ interactions at 158 GeV/c,
- Ξ^- production in $p+p$ interactions at 158 GeV/c,
- pseudo-rapidity dependence of multiplicity and transverse momentum fluctuations in $p+p$ interactions at 158 GeV/c,
- identified hadron spectra in π^-+C interactions at 150 and 350 GeV/c.



New measurements in 2021 – 2024

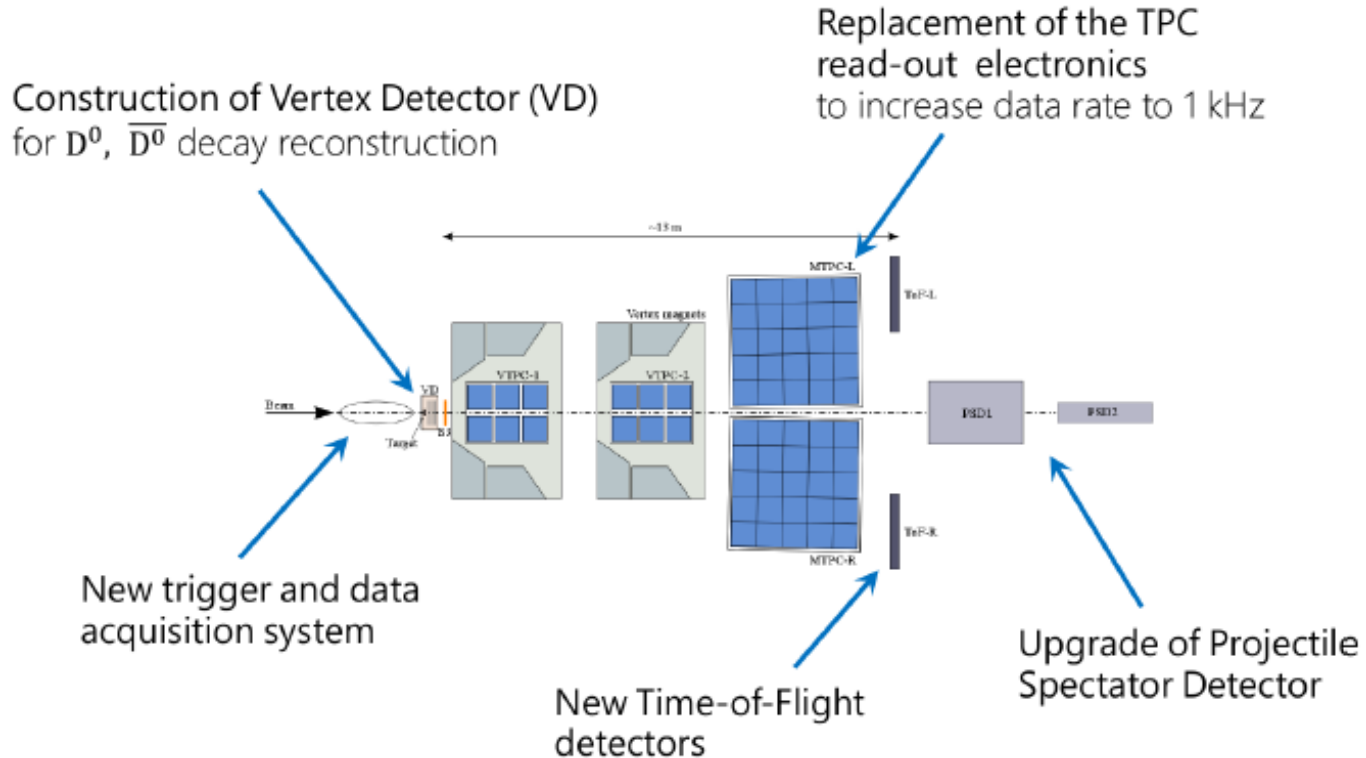
Addenda: SPSC-P-330-ADD-10

SPSC-P-330-ADD-11

Physics motivation

- Measurements of charm hadron production in Pb+Pb collisions for heavy ion physics:
 - What is the mechanism of charm production?
 - How does the onset of deconfinement impact open charm production?
 - How does the formation of quark-gluon plasma impact J/ψ production?
- Measurements of nuclear fragmentation cross section for cosmic ray physics:
 - Study the origin of Galactic cosmic rays.
 - Evaluate the cosmic-ray background for signatures of astrophysical dark matter.
- Measurements of hadron production induced by proton and kaon beams for neutrino physics:
 - Hadron production measurements for the currently used T2K replica target.
 - New target material (super-sialon) for T2K-II and Hyper-Kamiokande.
 - Possibility of measurements at low incoming beam momenta (below 12 GeV/c).
 - Hadron production measurements with prototypes of Hyper-Kamiokande and DUNE targets.

Detector upgrade during LS2



- Design of TPC electronics adapters is ready and **will be tested this year.**
- Design of Vertex Detector is almost completed. Discussion about technology transfer with ALICE is ongoing.
- The Forward PSD was **installed** and **tested** with proton beam this year.
- New DAQ and trigger test bench is under construction.
- New ToF detector based on MRPC is under consideration. Tests of prototype are performed **this year.**

- **2D scan in system size and collision energy was completed in 2017 with Xe+La data.**
- **NOvA replica target was installed** and 15 million events were registered in 2018.
- Many new/final physics results were released.
- **In particular, proton intermittency in Ar+Sc collisions at 150A GeV/c may be the first NA61/SHINE indication of the QGP critical point.**
- The data taking plan for 2021 – 2024 and the detector upgrade strategy were presented in **Addenda:** SPSC-P-330-ADD-10, SPSC-P-330-ADD-11.

Backup slides

Publication drafts under preparation

- N- p_T fluctuations in p+p, Be+Be and Ar+Sc
- N- E_F fluctuations in p+p, Be+Be and Ar+Sc
- Hadron spectra produced in π^+ +C at 158 and 350 GeV/c
- Φ production in p+p at 40, 80 and 158 GeV/c
- $\Delta\eta/\Delta\phi$ correlations in Be+Be
- K^* production in p+p at 158 GeV/c
- π^- spectra from Ar+Sc
- π^- spectra from Be+Be
- Cross sections and centrality determination in Be+Be
- Identified hadrons in Ar+Sc
- Identified hadrons in Be+Be

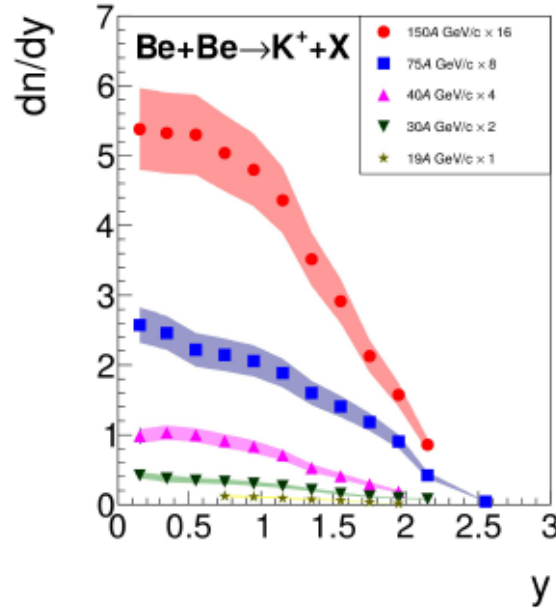
Conferences Oct. 2017 – Oct. 2018



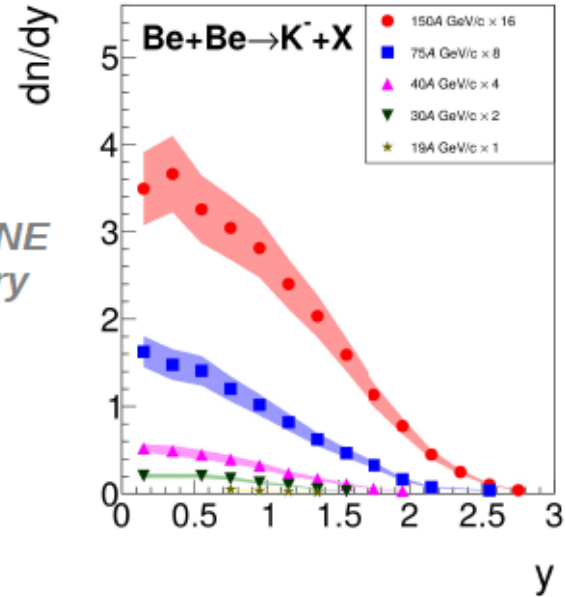
NA61/SHINE presented around 75 talks and 15 posters at **34 conferences.**

K^\pm rapidity spectra in 0-20% central Be+Be

Almost full forward hemisphere is covered

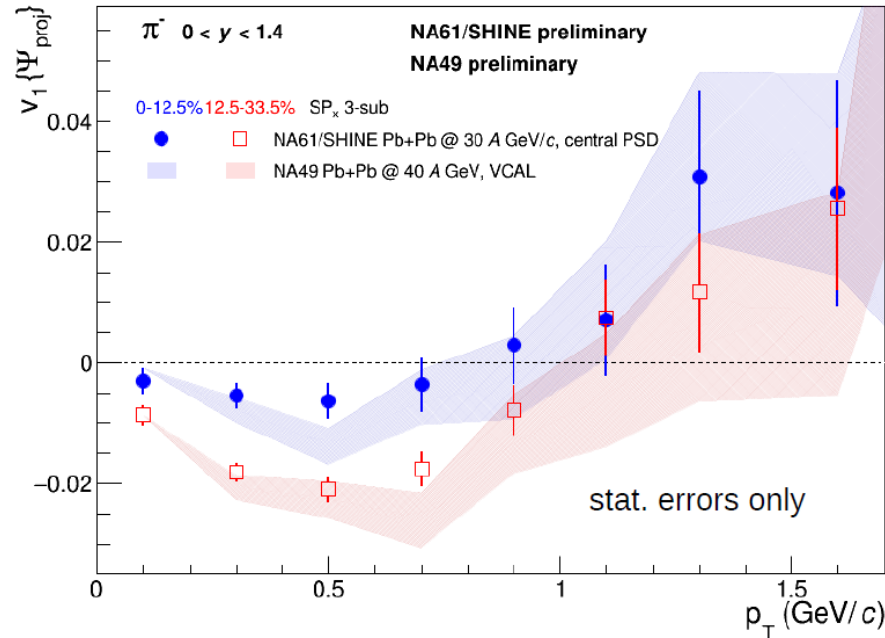


NA61/SHINE
preliminary

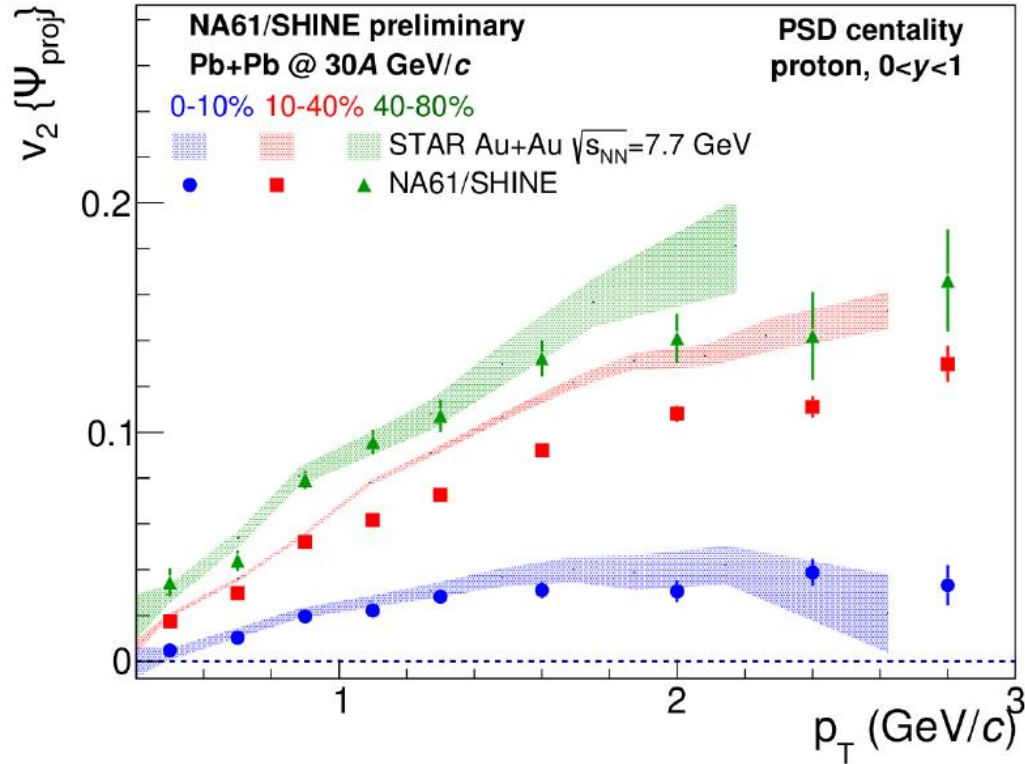


v_1 comparison with NA49 data

- Similar results to new NA49 analysis of pions relative to the spectator plane



v_2 comparison with Star data



STAR Collaboration PRC 88 (2013) 014902

- Similar results for central and peripheral
- Tension for mid-central collisions could be due to different centrality estimators:
 - ✓ Particle multiplicity at midrapidity (STAR)
 - ✓ Projectile spectators (NA61/SHINE)