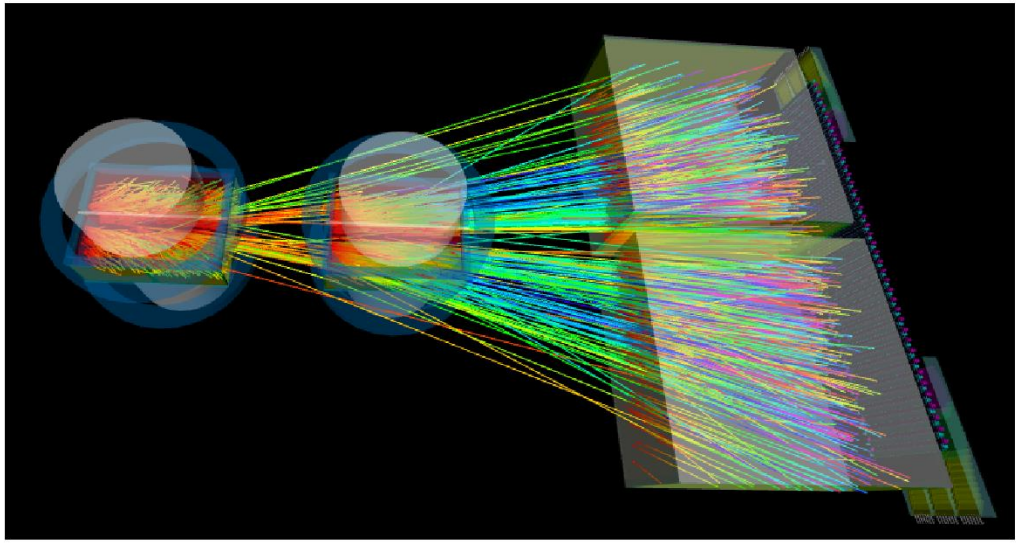
NA61/SHINE experiment - past, present, and future

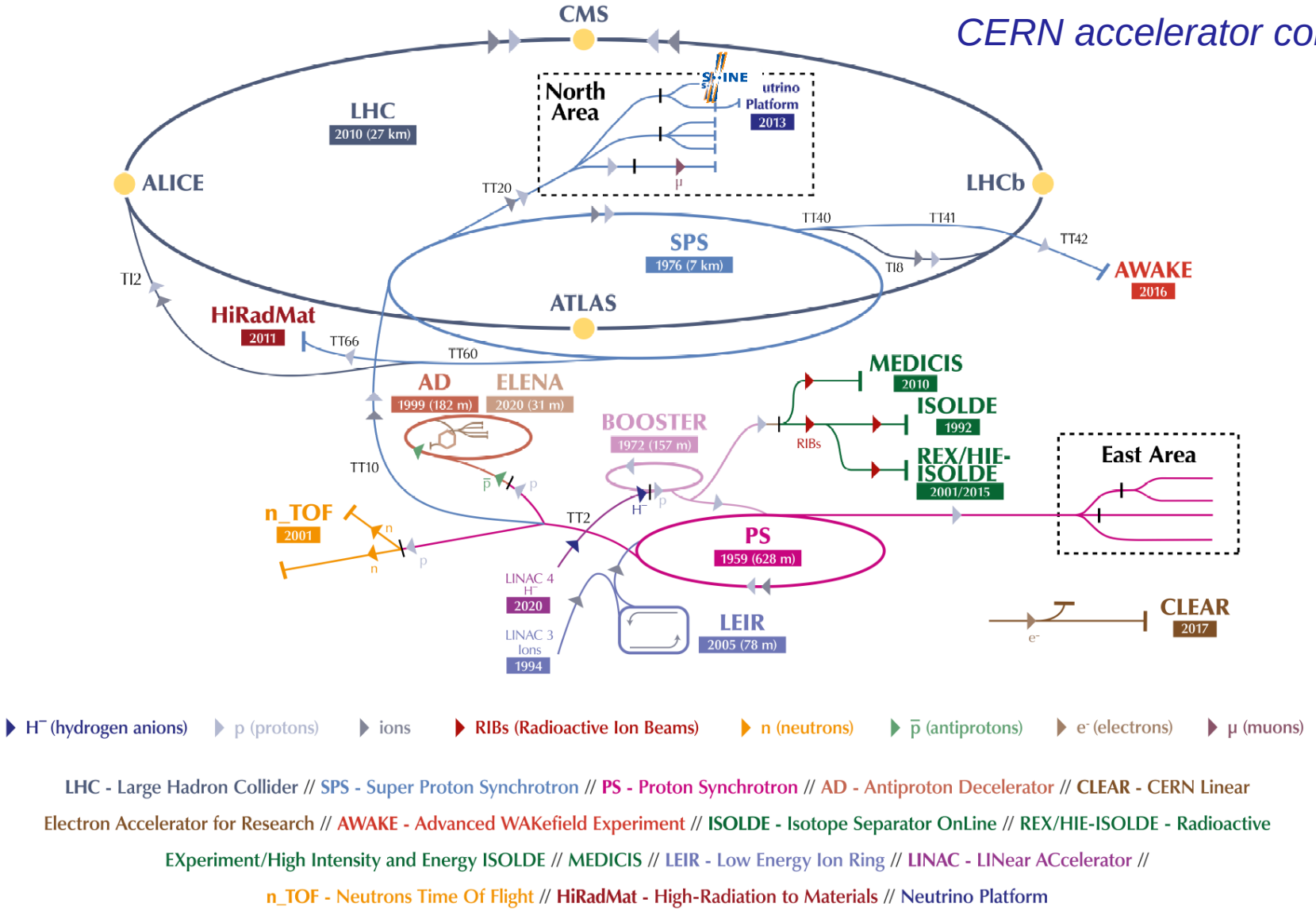


Grzegorz Stefanek
Jan Kochanowski University

HISTORY

NA61/SHINE Experiment - PAST

CERN accelerator complex.



LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

NA61/SHINE is a fixed target experiment on the H2 beam line from the SPS accelerator.

NA61/SHINE Experiment - PAST

Milestones:

Expression of Iterest:	***CERN-SPSC-2003-031, SPSC-EOI-001***	***(November 21, 2003)***
Letter of Intend:	***CERN-SPSC-2006-001, SPSC-I-235***	***(January 6, 2006)***
Proposal:	***CERN-SPSC-2006-034, SPSC-P-330***	***(November 3, 2006)***
Approval by the CERN Research Board:		***(February and June 2007)***
Pilot data taking:		***(autumn 2007)***
First status report:	***CERN-SPSC-2008-018, SPSC-SR-033***	***(July 2008)***
Memorandum of Understanding for Collaboration:		***(October 2008)***

and the acronym of the experiment

(SHINE – SPS Heavy Ion and Neutrino Experiment)

Regular data-taking from 2009

The collaboration was built by **25 institutions** from **15 countries** including 5 from Poland

Jan Kochanowski University

Jagiellonian University

Warsaw University of Technology

University of Warsaw

Sołtan Institute for Nuclear Studies

with the total **number of participants about 100**.

NA61/SHINE Experiment - PAST

Physics goals (2007):

NA61 physics goals (I):

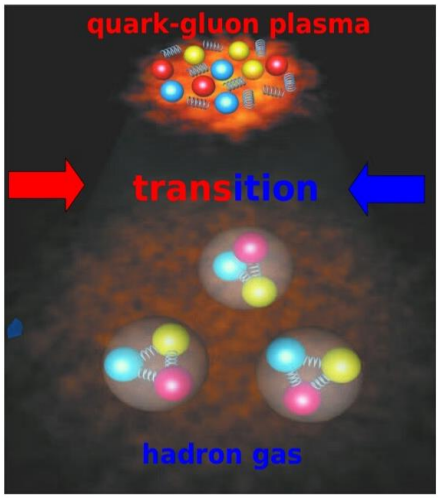
Physics of strongly interacting matter

Search for the critical point of strongly interacting matter

Precision measurements:

Study the properties of the onset of deconfinement in nucleus-nucleus collisions

Measure hadron production at high transverse momenta in p+p and p+Pb collisions as reference for Pb+Pb results



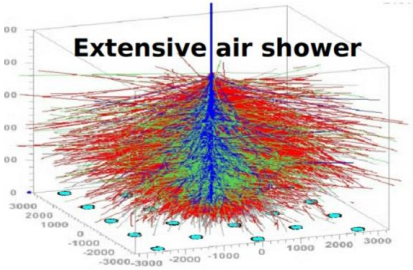
NA61 Physics goals (II):

Data for neutrino and cosmic ray experiments

Precision measurements:

Measure hadron production in the T2K target needed for the T2K (neutrino) physics

Measure hadron production in p+C interactions needed for T2K and cosmic-ray, Pierre Auger Observatory and KASCADE, experiments



To reach these goals the NA49 detector was upgrade to:

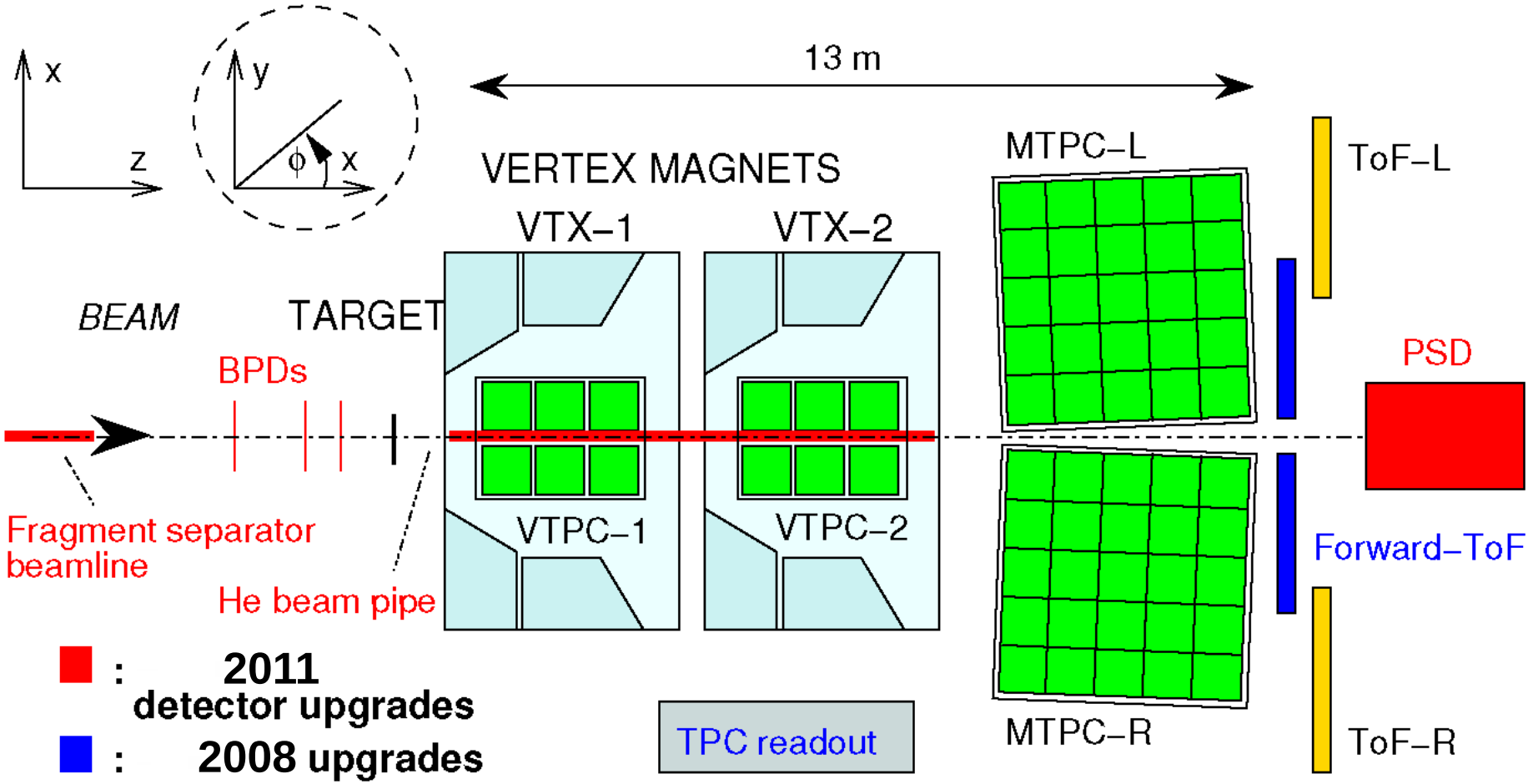
- **extend the measurements to the region with a low polar angle**
- **increase statistics of events (event rate)**
- **obtain cleaner spectra**
- **more precisely determin centrality**

The costs of the upgrades were about 2-2.5 MCHF.

Polish groups participated in the construction of new detectors.

NA61/SHINE Experiment - PAST

Detector upgrades:



■ : **2011 detector upgrades**

■ : **2008 upgrades**

↑

Detector upgrades →

Event rate ↑ x10

Spectator energy resolution ↑ x10

Delta – electrons background ↓ /10

NA61/SHINE Experiment – PAST/PRESENT

CERN/LHC timeline (past and present)

2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
LHC start	RUN1				Long shutdown 1			RUN2			Long shutdown 2			RUN 3

NA61/SHINE timeline (past and present)

2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
NA61 PHASE 1 Upgrade and pp, pC data taking	NA61 PHASE 1 AA and pA data taking									Major upgrade			PHASE 2

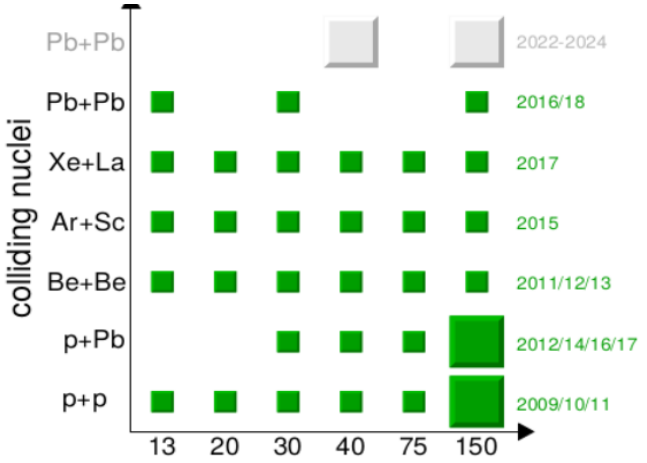
Now we are in RUN 3 of LHC and PHASE 2 of NA61/SHINE

Collected data:

PHASE 1 of NA61/SHINE was realized in the years **2009 - 2018**.

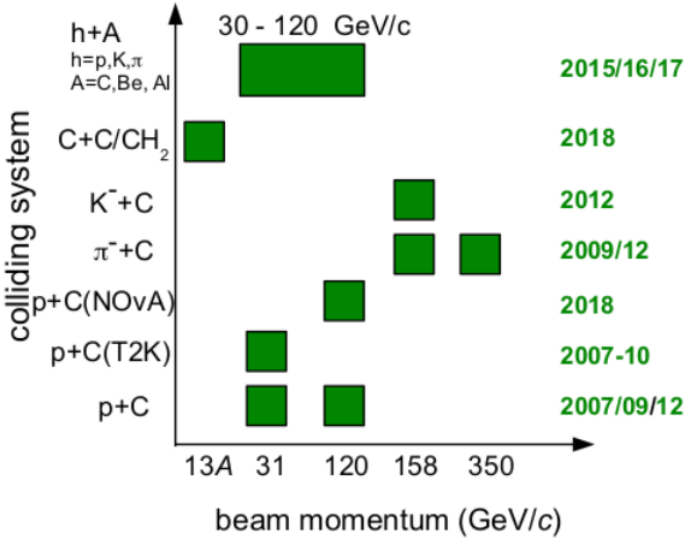
Data for the Strong Interaction (SI) program consists of p+p, p+Pb, Be+Be, Ar+Sc, Xe+La and Pb+Pb data samples collected at 6 beam momenta per nucleon with statistics of several million events per data sample (statistics is several times larger than in the NA49 experiment).

The 2007 program was extended by the pilot data for charm measurements using a Small Acceptance Vertex Detector.



Data for Neutrino and Cosmic Ray (NP, CP) programs was collected with light targets (C, Be) using different projectiles p, K,π.

The 2007 program was extended by additional measurements for the NOvA experiment and C+C, C+CH_2 (methylene) collisions for cosmic ray program.



Publication statistics:

Published papers 2007-2022 (final results): 45

- SIP, spectra/yields – 14
- SIP, correlations/fluctuations – 8
- NP - 13
- CP - 1
- General – 5
- Hardware – 4

Most of the papers published in Eur. Phys. J. C

Max. number of citations – 288

Conference papers (preliminary results) – 204

2022:

NA61/SHINE collaboration – ~150 participants from 31 institutions (9 polish)
+ 30 from 6 institutions with limited membership

RESULTS

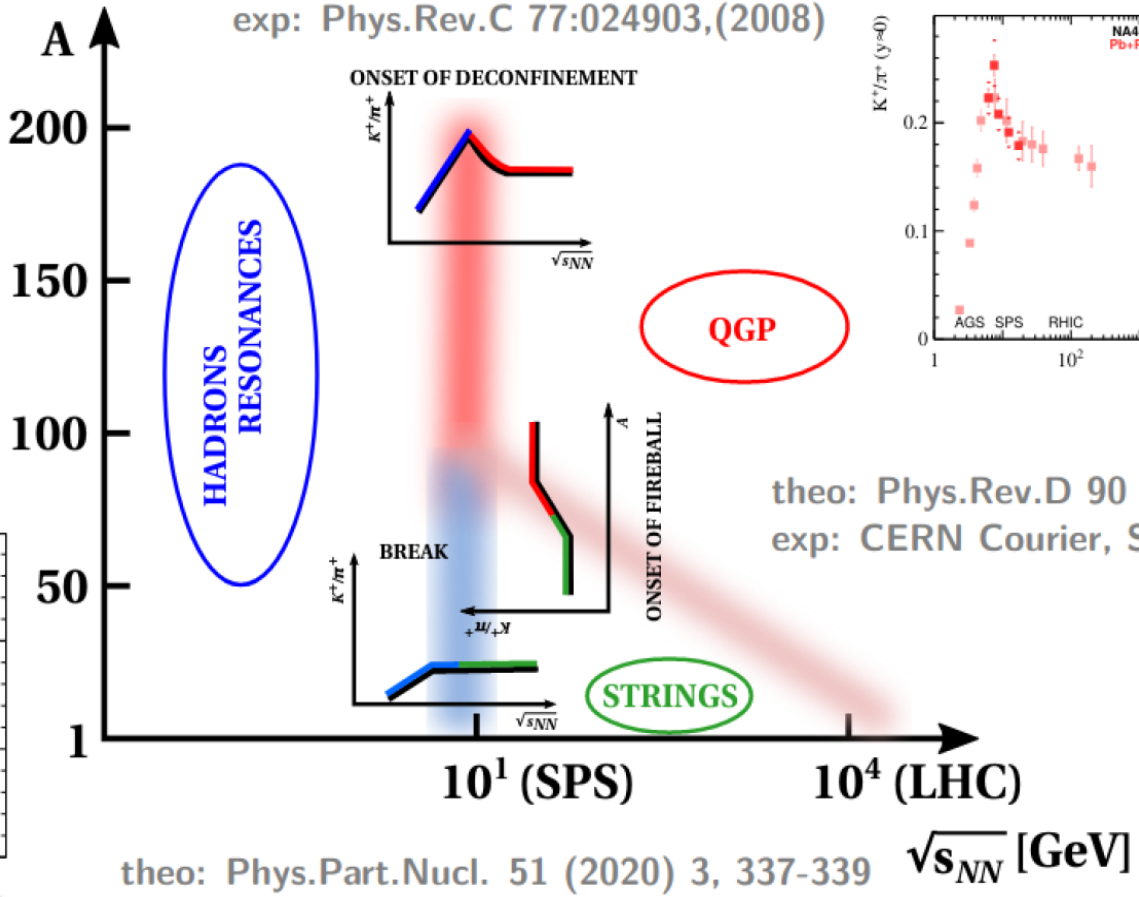
Marek,
Quark confinement and Hadron Spectrum

Main results:

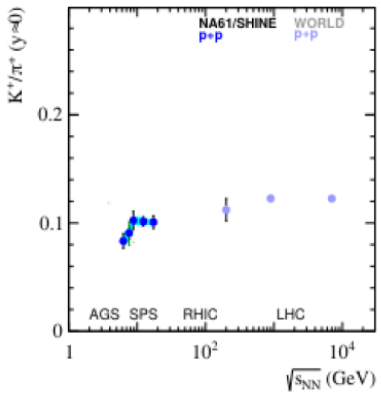
Strong Interaction Program (onsets):

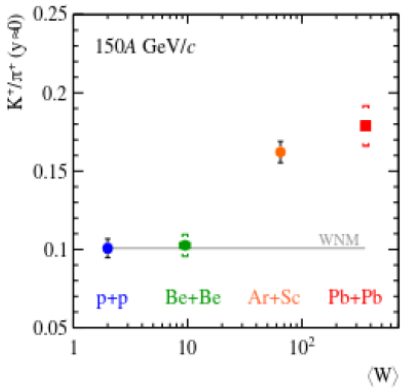
Diagram of high-energy nuclear collisions

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



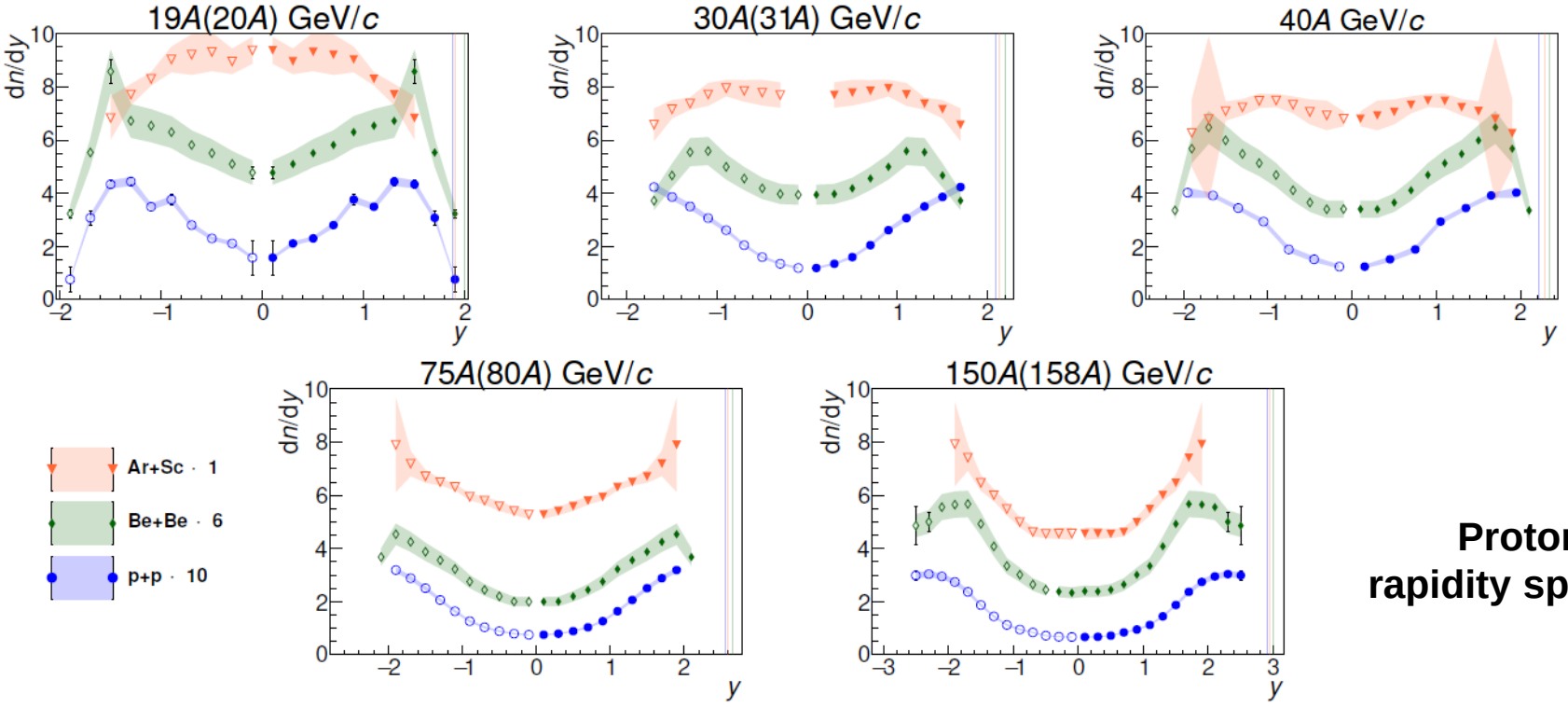


theo: Phys.Part.Nucl. 51 (2020) 3, 337-339
exp: Phys.Rev.C 102 (2020) 1, 011901

Oleksandra,
Quark Confinement and Hadron Spectrum

Main results:

Strong Interaction Program (onsets and spectra):



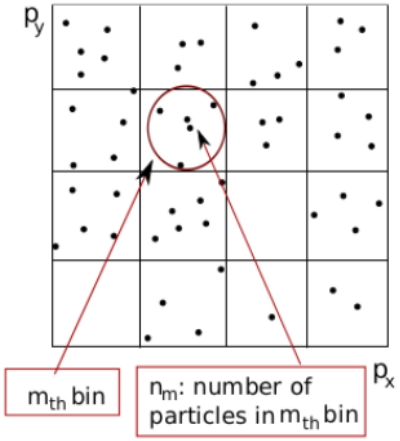
Proton rapidity spectra

”Peak-dip” transition for 10% of most central Ar+Sc collisions.

„Dip” observed for smaller systems.

Main results:

Strong Interaction Program (critical point):

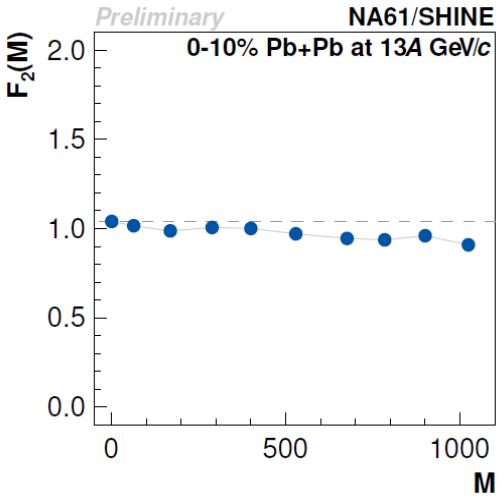


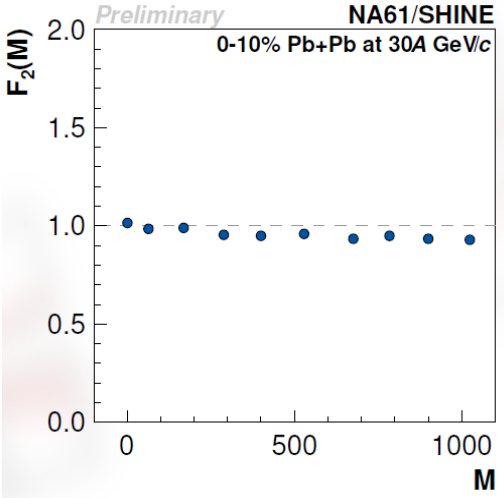
$$F_r(M) = \frac{\left\langle \frac{1}{M}\sum_{m=1}^{M} n_m(n_m-1)\ldots(n_m-r+1) \right\rangle}{\left\langle \frac{1}{M}\sum_{m=1}^{M} n_m \right\rangle^r}$$

preserves power law $F_r(M) \sim M^{\phi_r}$

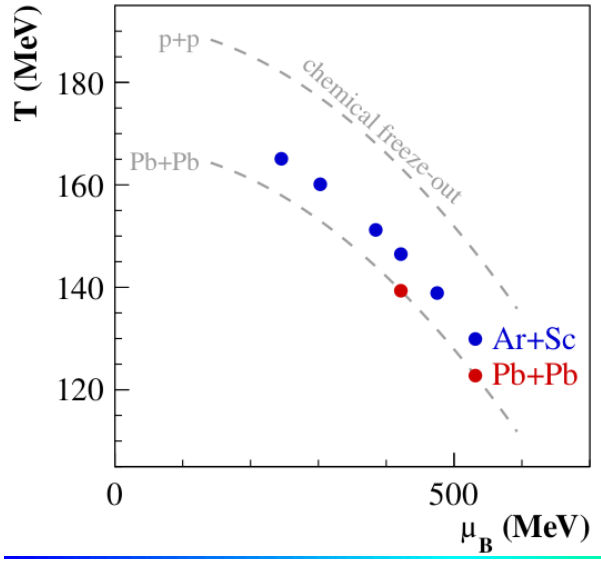
expected $\varphi_2 = 5/6$

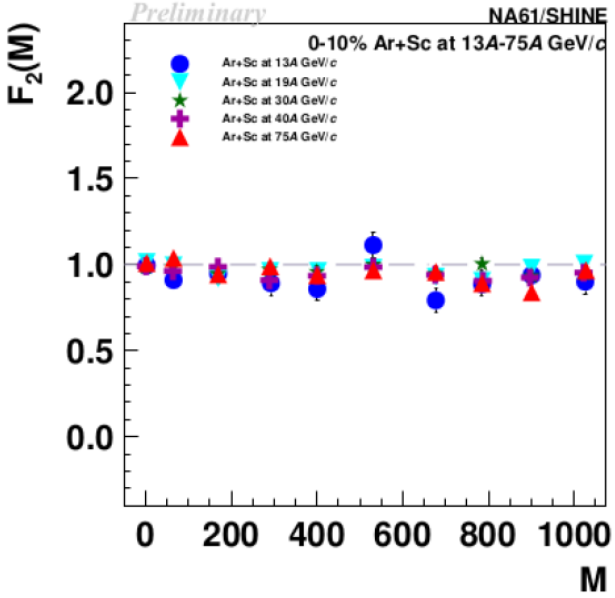
proton intermittency





No indication of CP signal

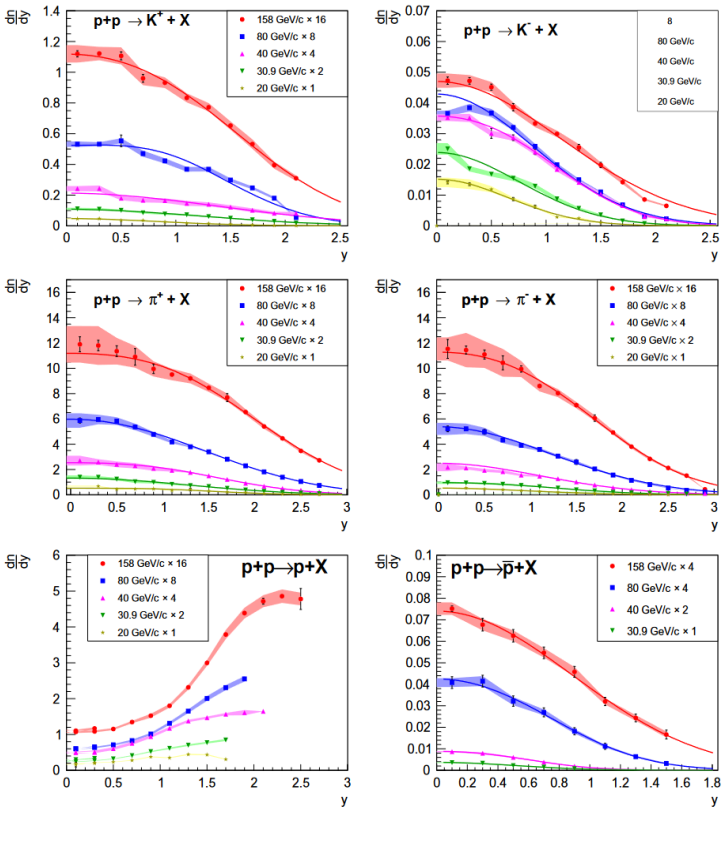




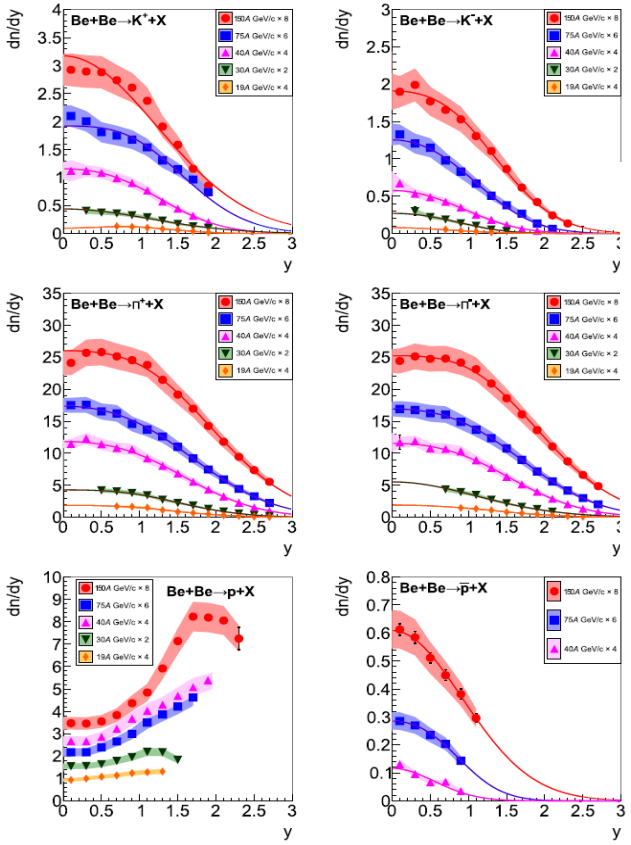
Main results:

Strong Interaction Program (π, K and p spectra/yields):

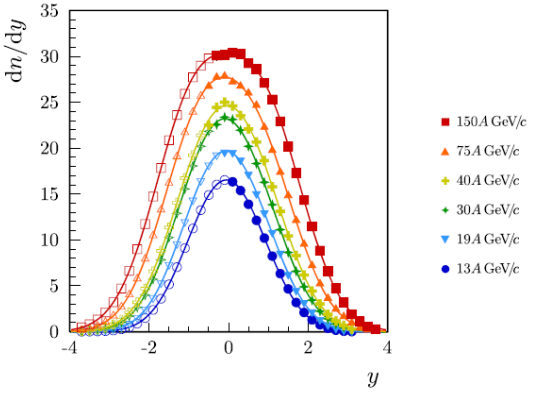
p+p



Be+Be



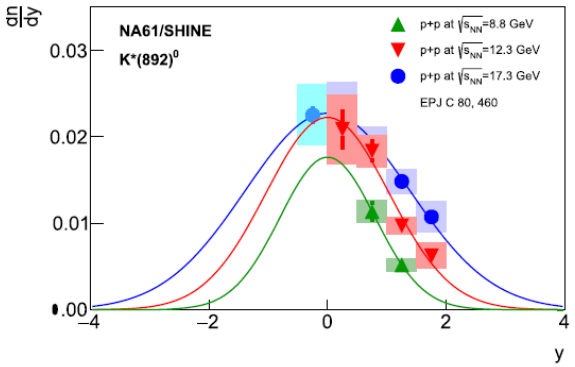
Ar+Sc (π-)



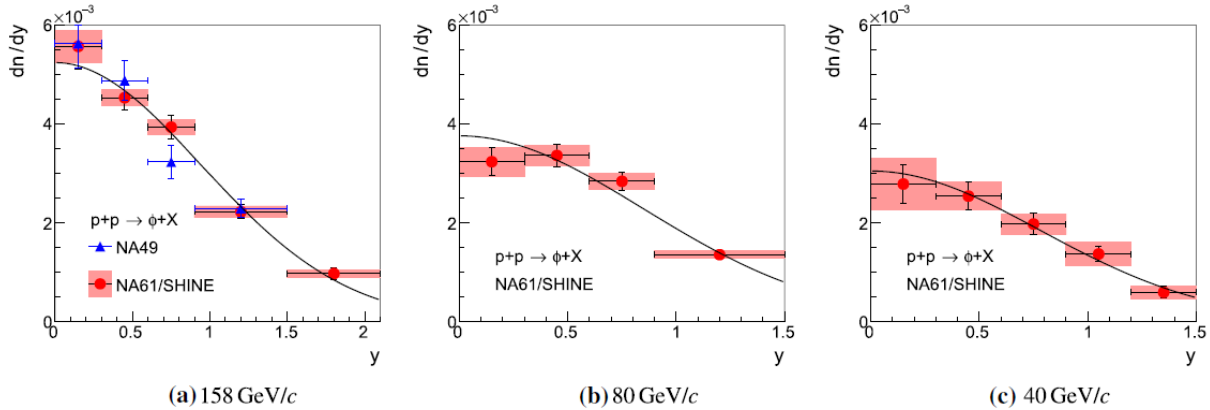
Main results:

Strong Interaction Program (spectra/yields, pp data):

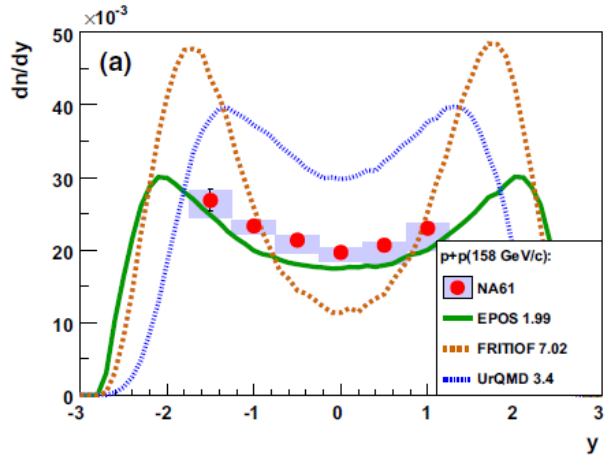
K* mesons



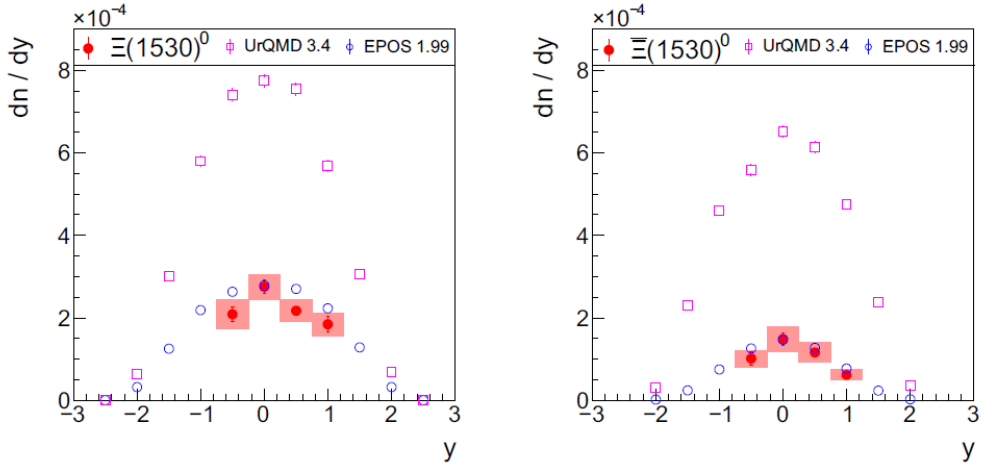
φ mesons



Λ hyperons



Ξ, anti-Ξ (p+p 158 GeV/c)

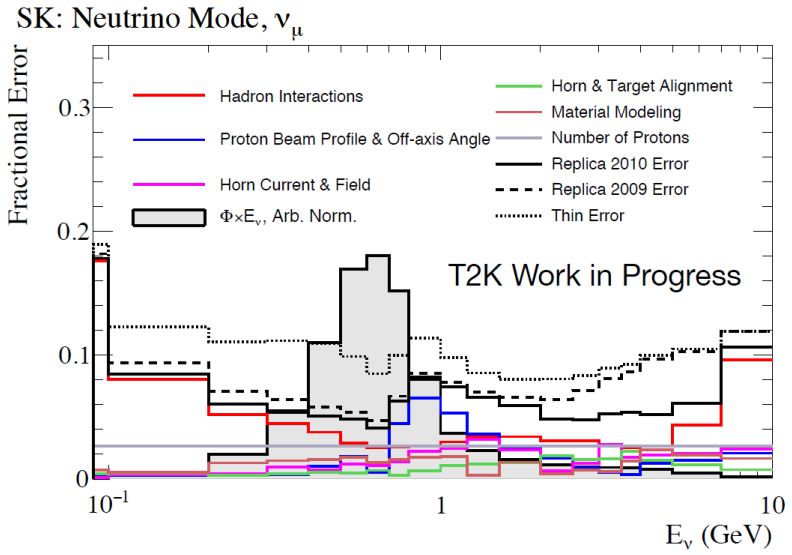


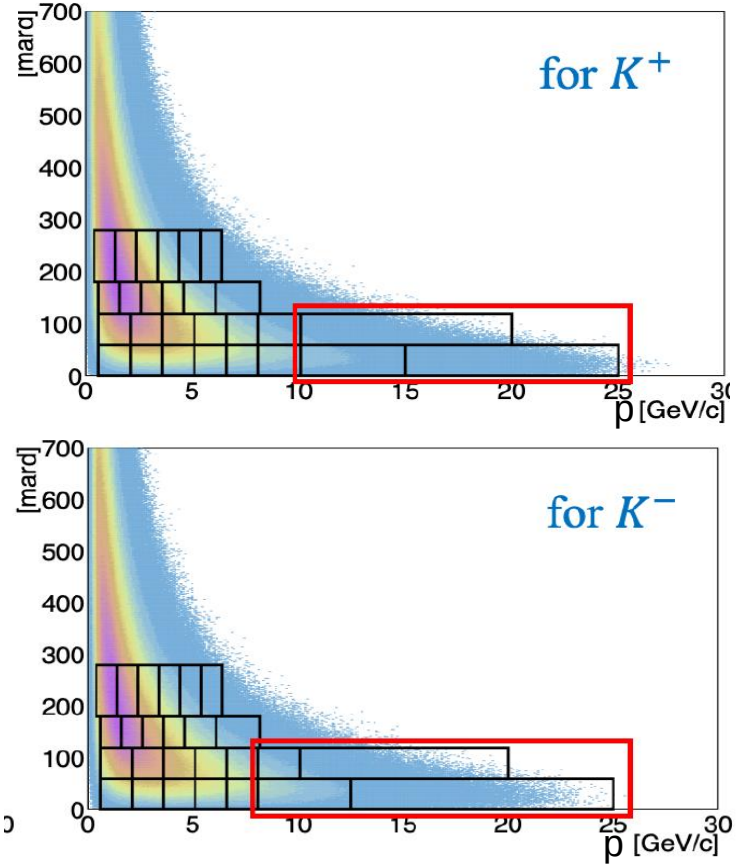
Main results:

Neutrino Program (hadron spectra and production cross sections in p/π+C/Be interactions):

Improve knowledge of the neutrino flux produced in accelerator-based neutrino beams.

Measurements of total cross sections and differential spectra of hadron yields from thin and replica neutrino beam targets.





Possible further improvement with high statistics data, for example, using kaons with high momentum. →

Main results:

Neutrino Program (hadron spectra and production cross sections in p/π+C/Be interactions):

Improve knowledge of the neutrino flux produced in accelerator-based neutrino beams.

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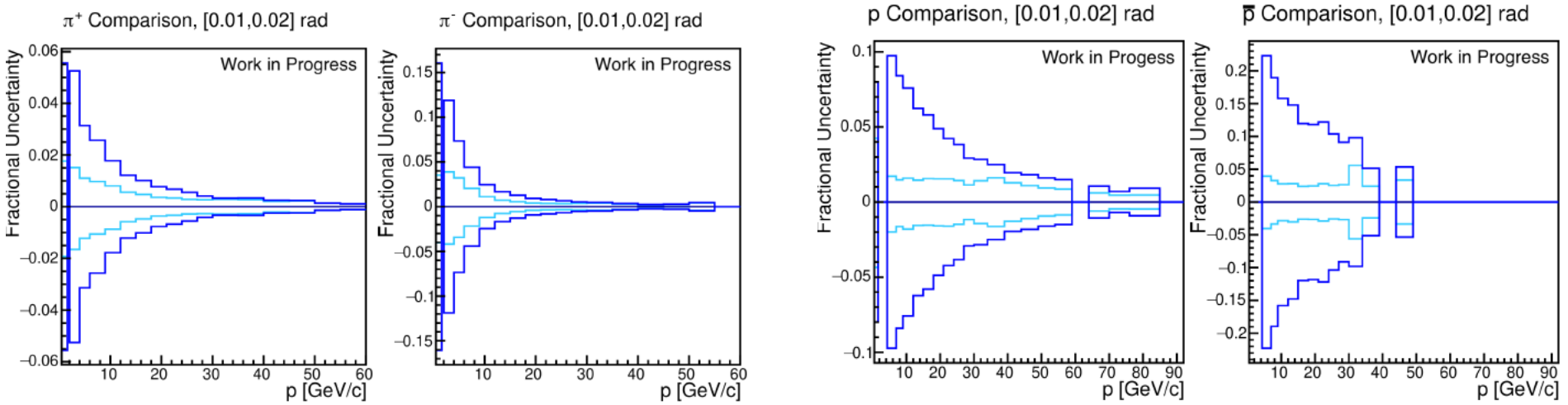
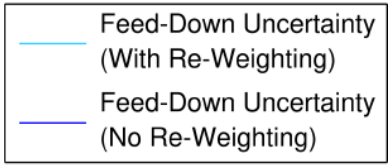


Improvement of feed-down correction from decay of neutral particles.

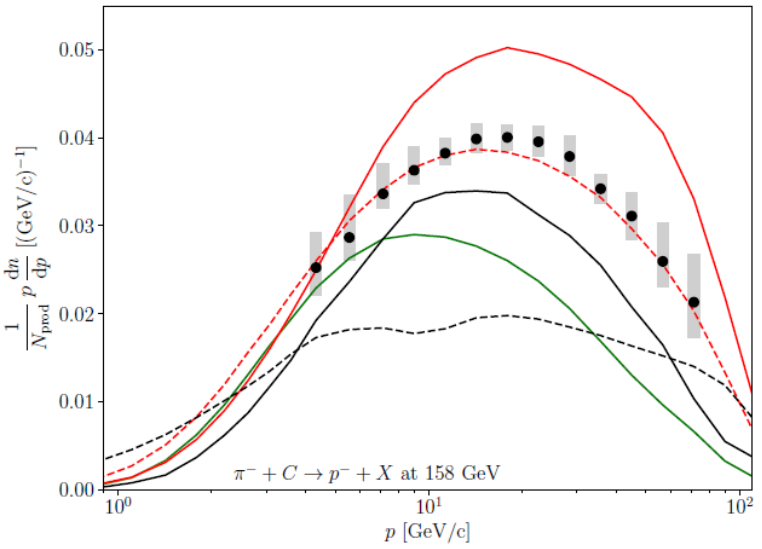


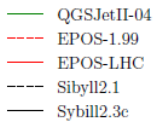
Main results:

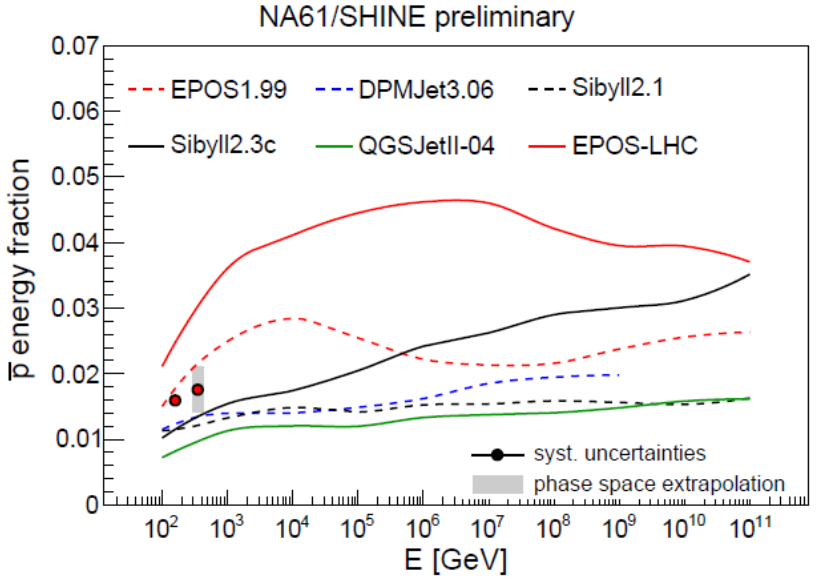
Cosmic Ray Program (hadron productions in p/π+C interactions):

Estimation of muon production in air showers; constraints on models for air shower simulations.

Estimation of the fraction of energy that remains in the hadronic cascade
→ measurement of antiproton production in π+C interactions at 158 and 350 GeV/c.







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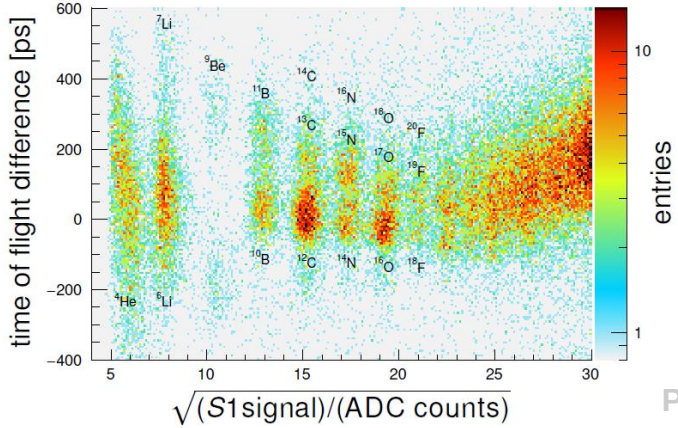
Other interesting results:

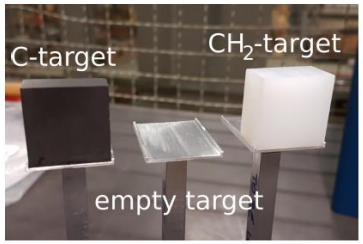
- Two-particle correlations in azimuthal angle and pseudorapidity in Be+Be collisions
- Search for pentaquarks in p+p interactions at 158A GeV
- EM effects in Ar+Sc collisions at 40A GeV
- Femtoscopy analysis in 10% most central Ar+Sc collisions at 150A GeV

Results of pilot data:

Cosmic Ray Program (pilot run for fragmentation measurements):

Measurement of total $^{10}B+^{11}B$ production cross section in C+p interactions at 13.5 A GeV/c and fragmentation cross section of C+p→^{11}C, to understand Boron production in Galaxy.





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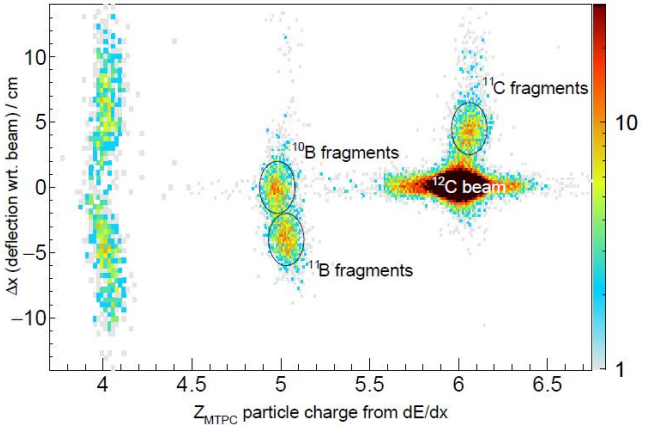
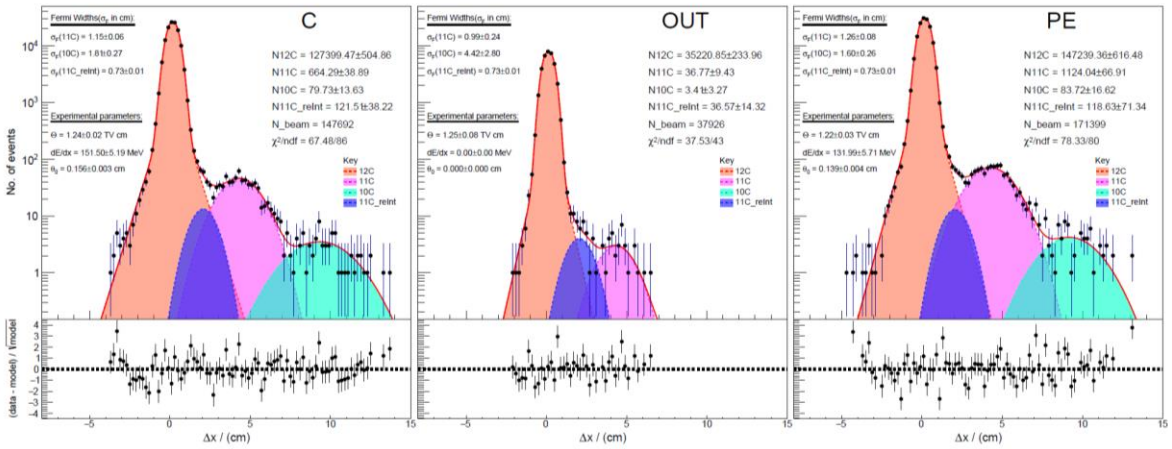
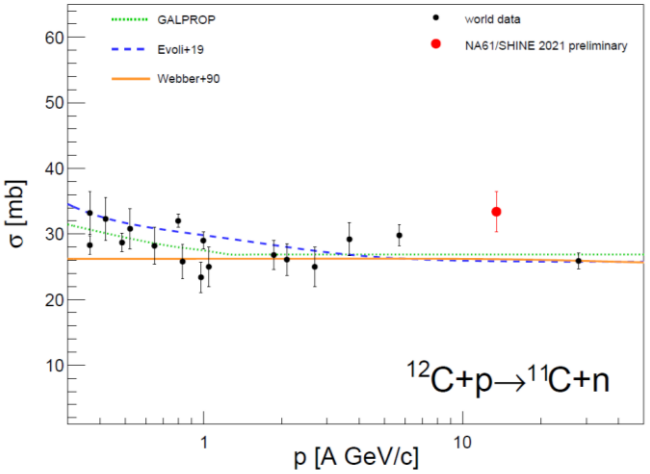


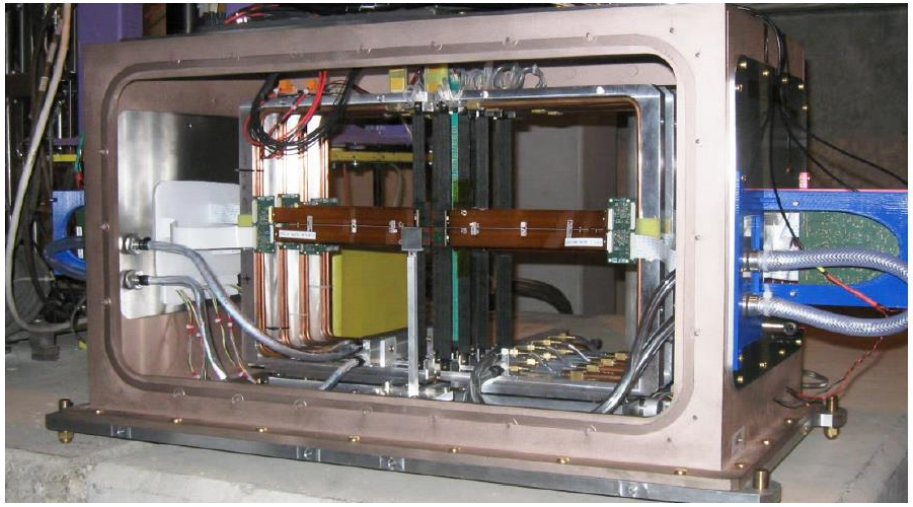




Results of pilot data:

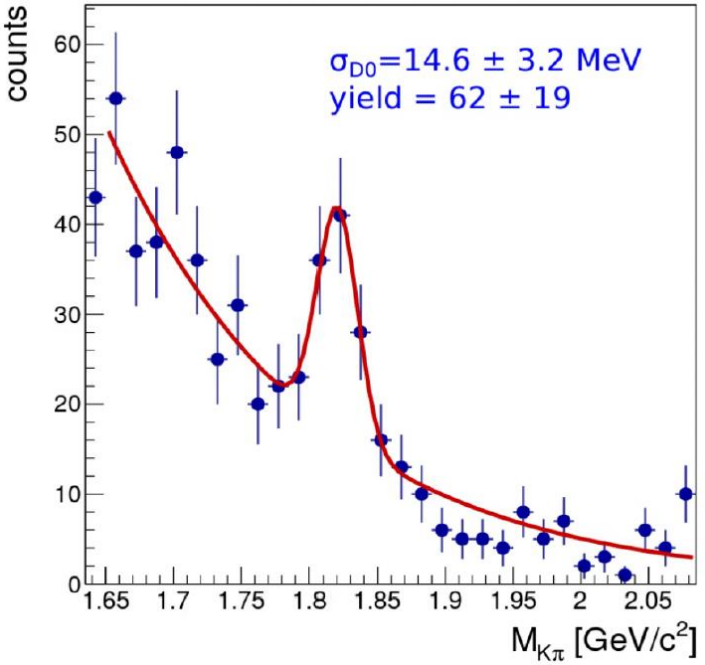
Strong Interaction Program (pilot run on charm measurement):

Small Acceptance Vertex Detector (2016-2018)



Based on technologies developed for ALICE and CBM.

Pb+Pb at 150A GeV/c



Indication of D^0 + anti-D^0 peak

Results of pilot data:

Strong Interaction Program (pilot run on charm measurement):

Estimation of the number of D charm mesons in the future data taking.

Reaction	days	events	$\#(D^0 + \overline{D}^0)$	$\#(D^+ + D^-)$
Pb+Pb at 150A GeV/c	84	500M	76k	46k
Pb+Pb at 40A GeV/c	42	250M	3.6k	2.1k

Centrality	0–10%	10–20%	20–30%	30–60%	60–90%	0–90%
$\#(D^0 + \overline{D}^0)$	31k	20k	11k	13k	1.3k	76k
$\#(D^+ + D^-)$	19k	12k	7k	8k	0.8k	46k

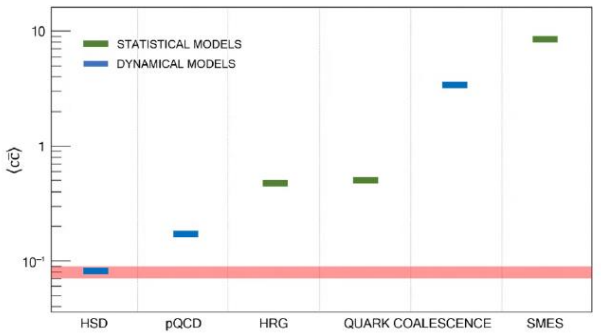
We need Vertex Detector with larger geometrical acceptance and high statistics of PbPb.

NEAR FUTURE PLANS

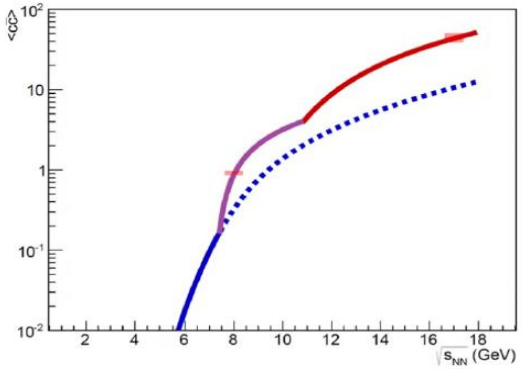
Physics goals (2021-2024/ 2022-2025):

Strong Interaction Program:

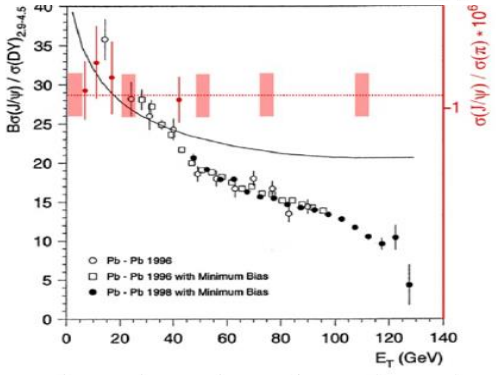
- Main goal: first ever open charm measurements at SPS. Open questions:
  - What is the mechanism of open charm production?
  - How does the onset of deconfinement impact open charm production?
  - How does the formation of quark-gluon plasma impact J/Ψ production?
- To answer these questions mean number of charm quark pairs $\langle c\bar{c} \rangle$ produced in the full phase space in A+A collisions has to be known.



$\langle c\bar{c} \rangle$ and models



$\langle c\bar{c} \rangle$ and onset of deconfinement



$\langle c\bar{c} \rangle$ $\langle J/\psi \rangle$ and QGP

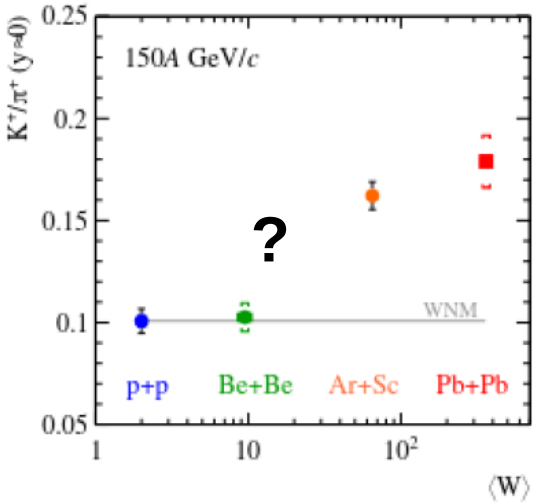
Open charm measurements are planned in Pb+Pb collisions at 150*A* and 40*A* GeV/*c*.

Physics goals (2021-2024/ 2022-2025):

Strong Interaction Program:

- Other goals:

  Measurements with primary oxygen beam at 13*A*, 30*A*, and 150*A* GeV/*c* for the onset of fireball studies.



Neutrino Program:

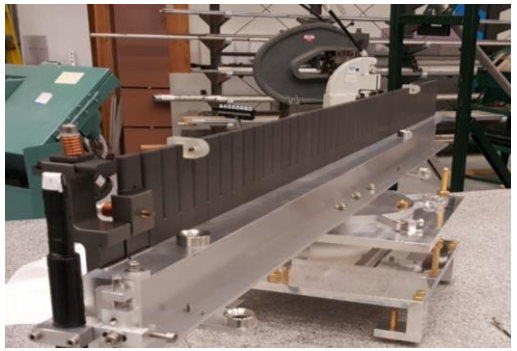
- **Cross-section measurements of the interaction of K^+ beam at 60 GeV/c on thin C target**

→ data for reducing flux uncertainties in the high-energy tail of the neutrino flux at DUNE

- **Cross-section measurements of the interaction of p beam at 120 GeV/c on a thin Ti target**

→ important data to constrain interactions in the LBNF target containment vessel (made of Ti)

- **Cross-section measurements of the interaction of the p beam at 120 GeV/c on LBNF/DUNE prototype target**

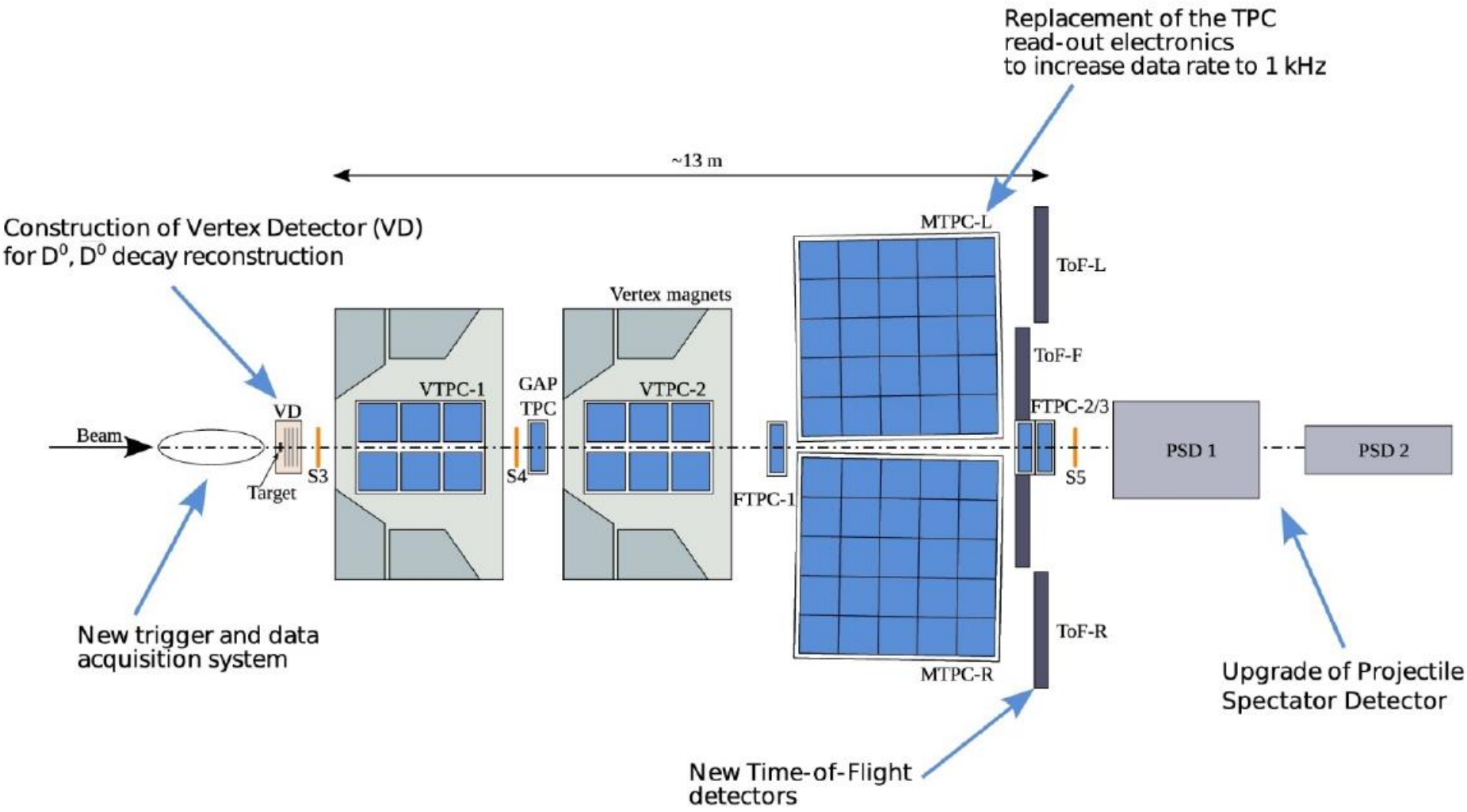


Cosmic Ray Program:

- **Nuclear fragmentation cross-section measurements with the light-ion beam at 13A GeV/c**

DETECTOR UPGRADE

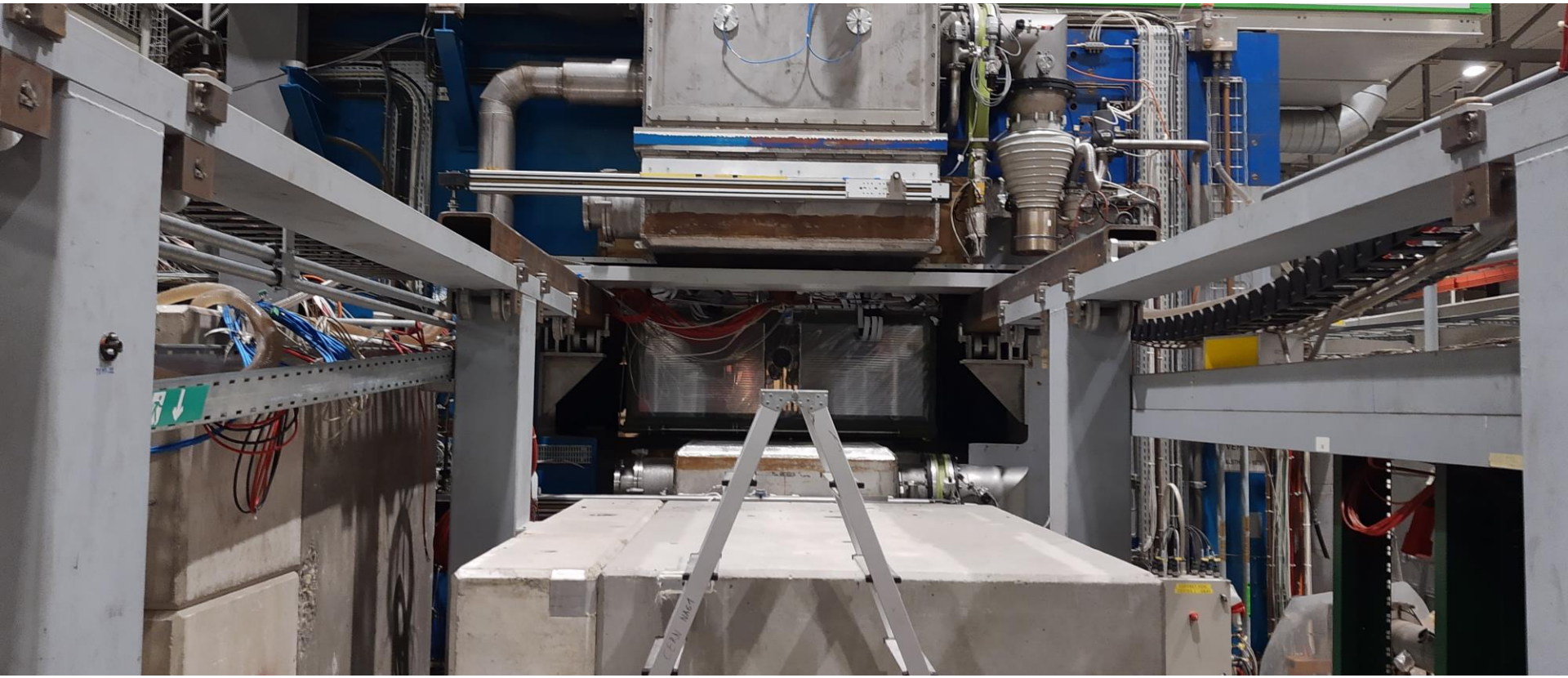
Major detector upgrade:



Detector upgrade finished in 2022 (except of TOF-R).

TPC read-out electronics upgrade:

The main activity connected with TPC electronics upgrade are cabling and screwing.



The new electronics consist of:

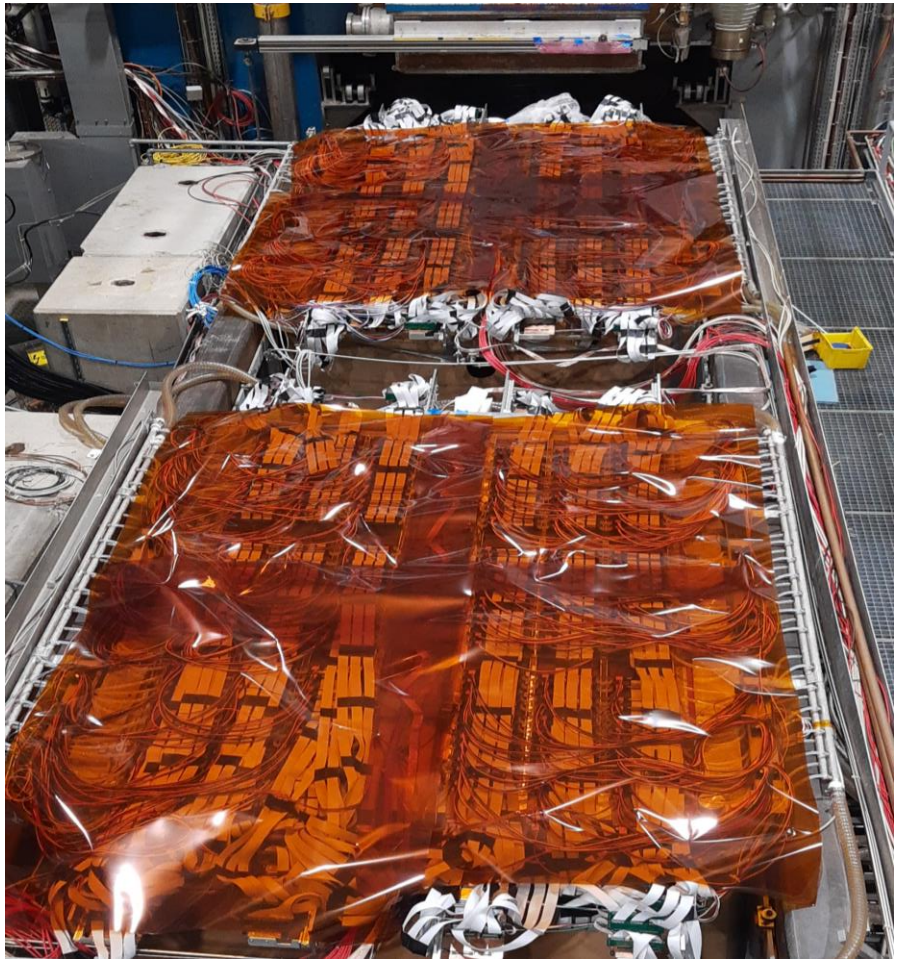
1478 Front-End Cards (FEDs)

TPC read-out electronics upgrade:

The new electronics consist of:

88 Readout Control Units (RCUs)

TPC read-out electronics upgrade:



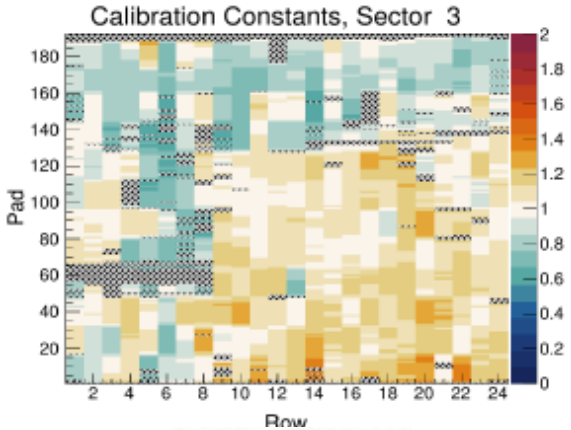
The new electronics consist of:

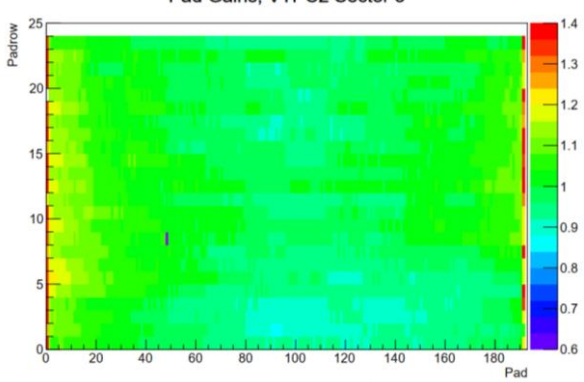
16 Common Readout Receiver Cards (C-RORCs)

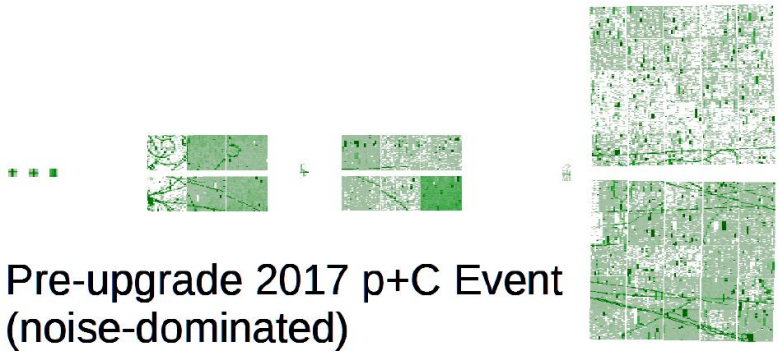
TPC read-out electronics upgrade:

Effects of replacement of readout electronics:

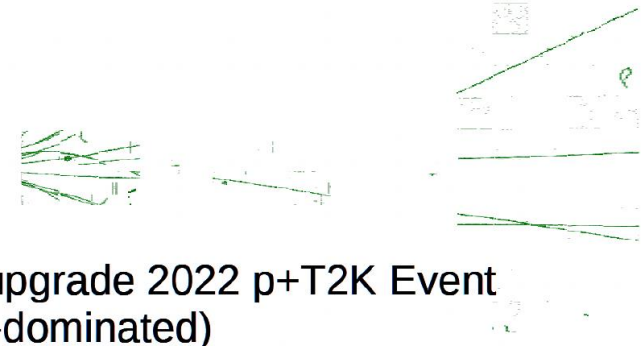
- Increase data rate up to1 kHz or even more
- Smaller number of malfunctioning channels
- More homogenous pad-by-pad gains
- Lower noise level





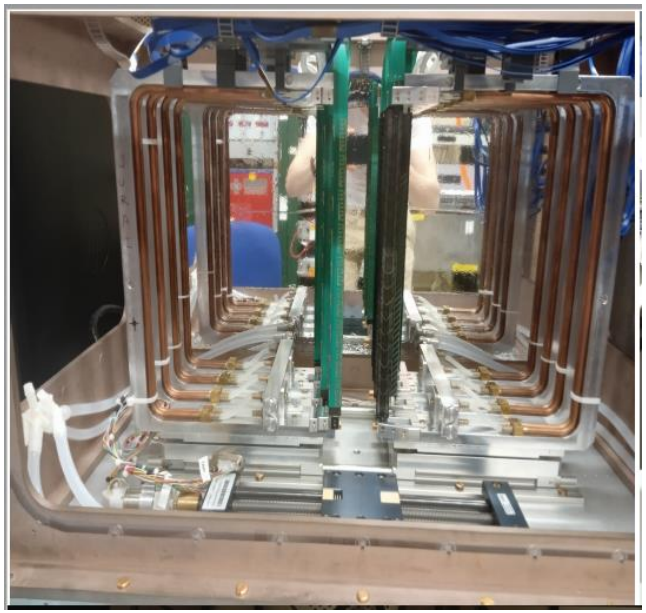


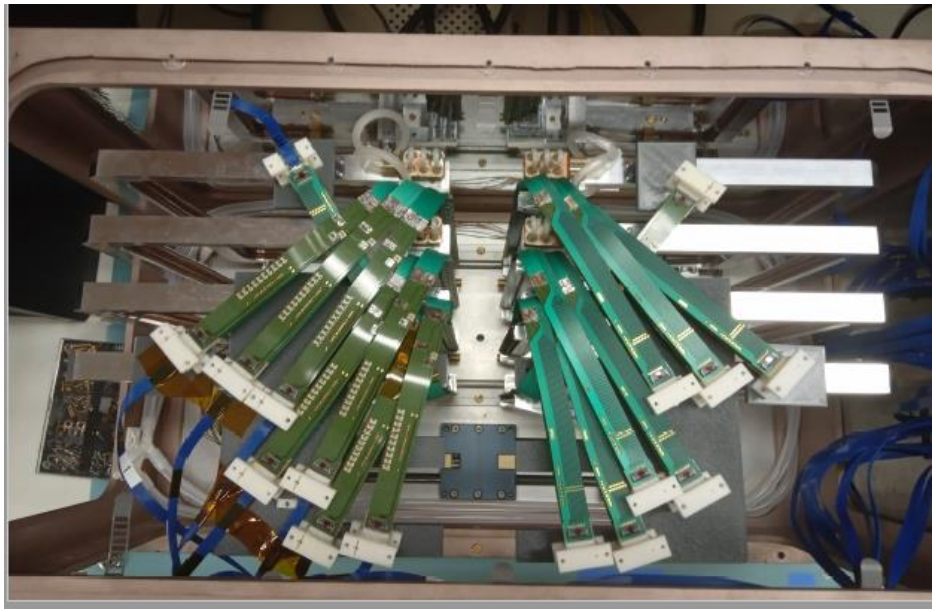
Pre-upgrade 2017 p+C Event
(noise-dominated)



Post-upgrade 2022 p+T2K Event
(track-dominated)

Large Acceptance Vertex Detector:





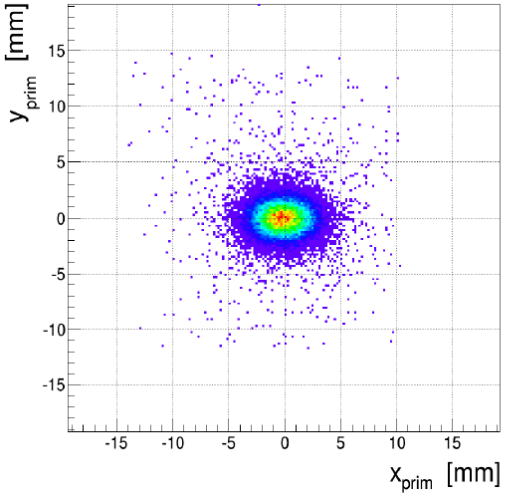
New Vertex Detector adapted to requirements:

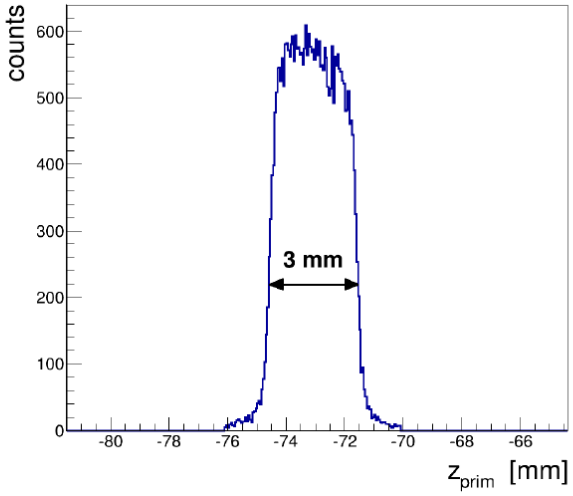
- data taking with a 1 kHz trigger rate – replacement of MIMOSA pixel sensors by faster (10 μs) ALPIDE-sensor-based modules (*staves*) developed within the ALICE-ITS project

- increase geometrical acceptance – 4 stations with 18 staves, active surface increased by a factor of more than 4.5.

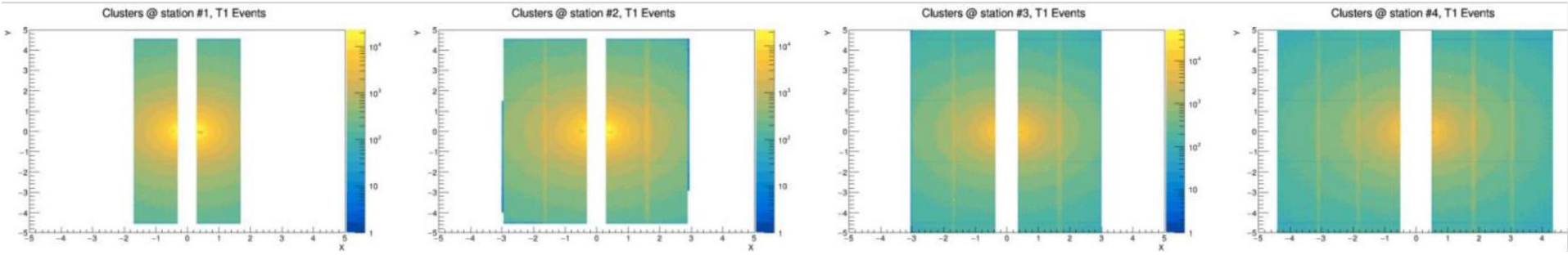
Large Acceptance Vertex Detector:

New Vertex Detector tested on a 120GeV/c proton beam interacting on a 3mm Pb target:





and used during data taking in November 2022



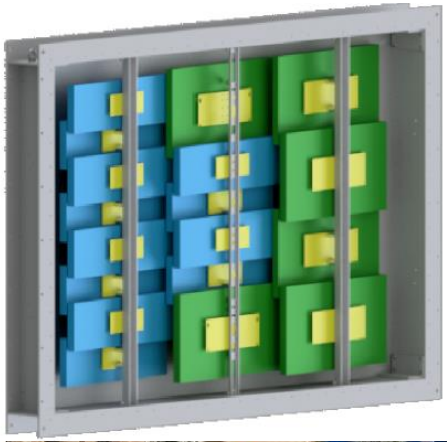
We expect 13k D^0+D^0bar decays in this data sample.

New or upgraded sub-detectors:

New silicon strip Beam Position Detectors

Fast Silicon Strip detectors working in the vacuum with electronically controlled scale-changing feature.

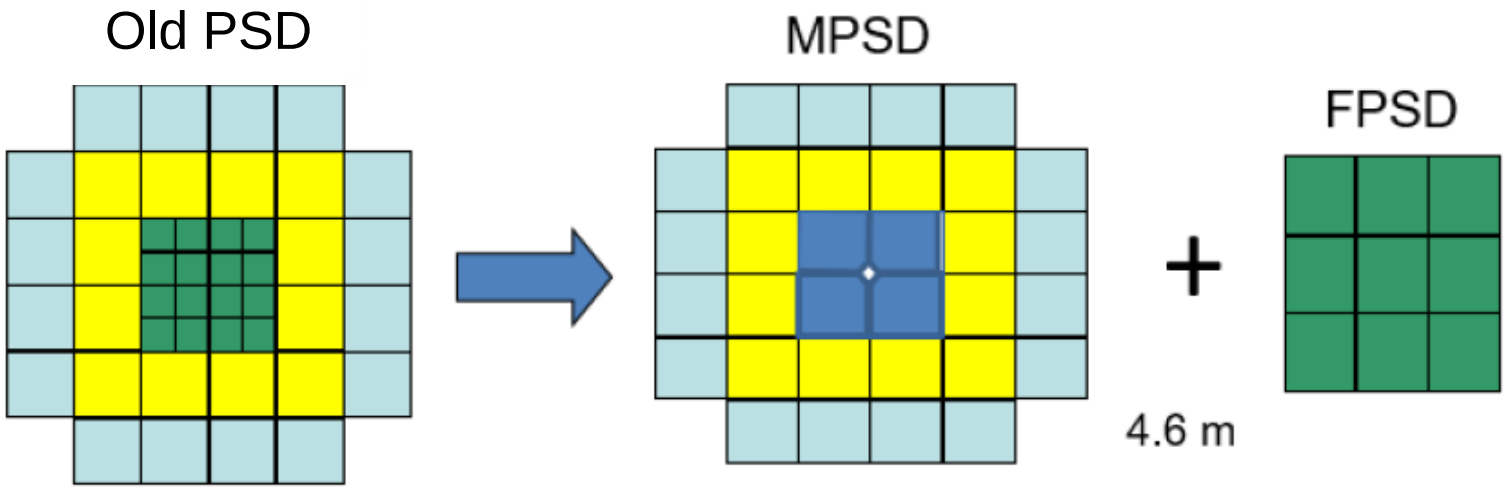
New TOF-L and TOF-R detectors



Multi-gap Resistive Plate Chambers (MRPC) →
(efficiency 95%, time resolution 50ps,
no degradation for high event rate)

New or upgraded sub-detectors:

New Projectile Spectator Detectors (PSD)



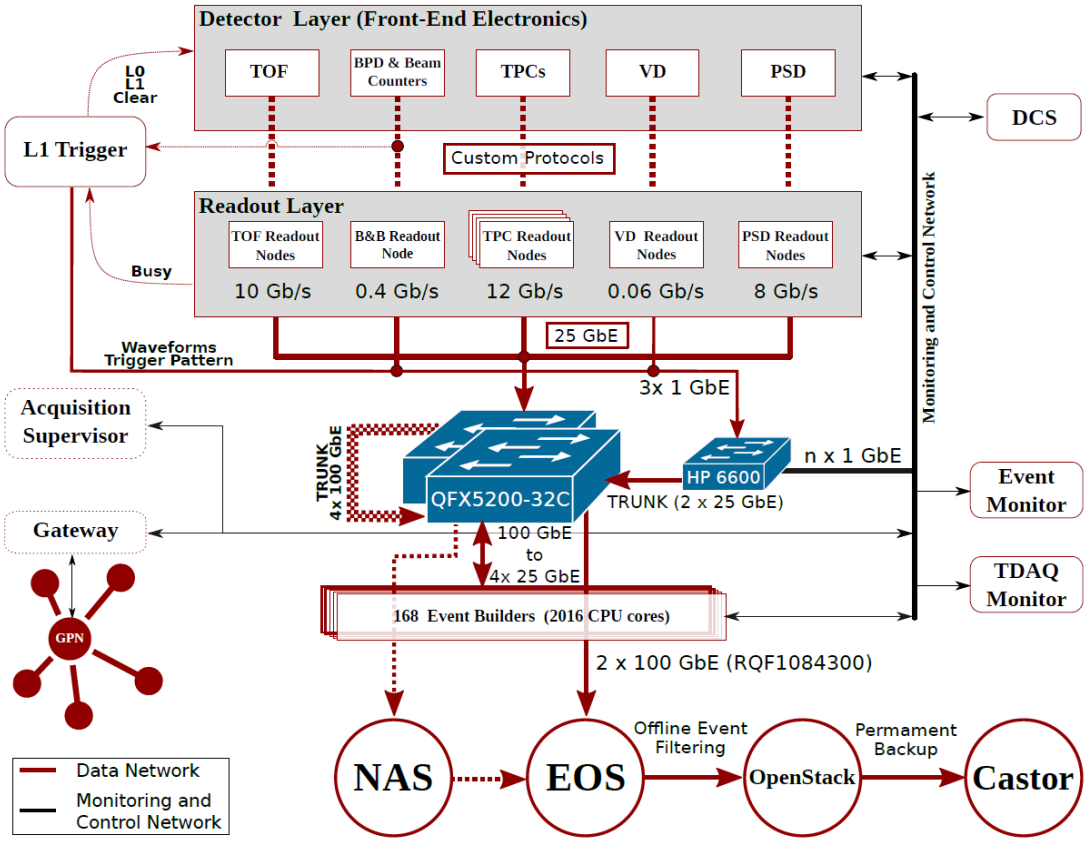
Motivation for PSD upgrade - connected with increase of lead ion beam intensity :

- Radiation hardness problems will lead to the deterioration of reliability and response of old PSD calorimeter
- PSD readout will be too slow at a high rate of heavy ion beam →faster photodetectors
- Radiation conditions → radiation alarm possible in the experimental area, concrete shielding required

New configuration decreases the shower leakage from 11% to 4% for Pb+Pb 150A GeV.

New DAQ system:

Oskar + MAESTRO grant



Requirements:

Speed – up to minimum 1kHz readout

Accommodation of 3MB per event with a new technique of data reduction

Remote Monitoring and Control – user-friendly web-based interface

Extendability – easy way to add new detectors

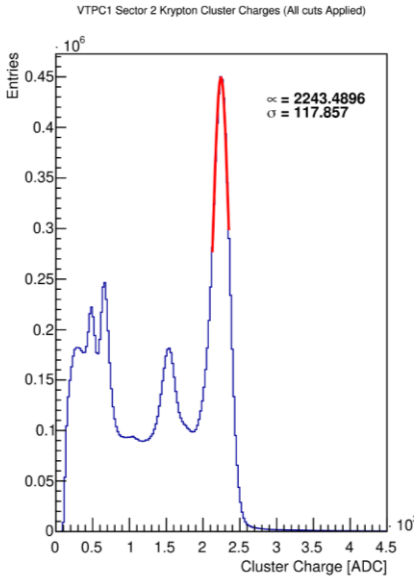
High readout speed: 1kHz x 3MB = 30GB/s = 240Gb/s
→ sub-event builders with 32GB RAM and 168 event builders with fast data network connection

Data taking with upgraded detector in 2022:

- **July 2022:** p+C collisions at 31 GeV/c with a full-scale replica target for the T2K experiment.
  180 million events were recorded over 3 weeks.
  Similar data collected in 2010 - 5 weeks and 10 million events collected

- **July/November 2022:** Kr calibration data collected for TPCs for measuring gain variations of electronic channels.

  The number of collected decays:
  min. 50 mln for VTPC1, VTPC2
  min. 100 mln for MTPCL, MTPCR
  with very clean decay spectrum



- **November 2022:** 58 mln of Pb+Pb collisions at 150A GeV/c was collected**.**
  Typical pre-upgrade data samples have statistics of less than 5 mln.

CERN/LHC timeline (future)

2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
RUN 3				Long shutdown 3			RUN 4				LS4		RUN5	

NA61/SHINE timeline (future)

2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
NA61 PHASE 2				Partial upgrade			NA61++ ??? data taking				???	

We are now in RUN 3 of LHC and PHASE 2 of NA61/SHINE

Physics goals (~2029-2032, NA61++):

Possible directions:

- Measurements using very low energy (VLE) beamline 1-20 GeV for many neutrino, cosmic ray and other experiments
- Systematic measurements of the onset of fireball with low and intermediate-mass nuclei (^{4}He, ^{16}O, ^{30}P, ^{40}Ca) at six beam momenta → require a significant improvement in the quality of the ion beams at low momenta
- Measurements of collisions of anti-protons with elementary and nuclear targets → understanding of baryon-stopping processes
- Critical measurements of hadron yields of LBNF and Hyper-Kaminokande replica targets as well as measurements with a thin target and very low beam momenta
- Measuremets of exotic resonances and exotic phenomena with the possible upgrade of slow VTPC1 detector to a much faster electronic one

Completely new experiment with new name? New collaboration? New spokesperson for sure

Workshop: NA61++: Physics opportunities from ions to pions, 15-17 Dec 2022 at CERN

CERN Indico: https://indico.cern.ch/event/1174830

Thank you