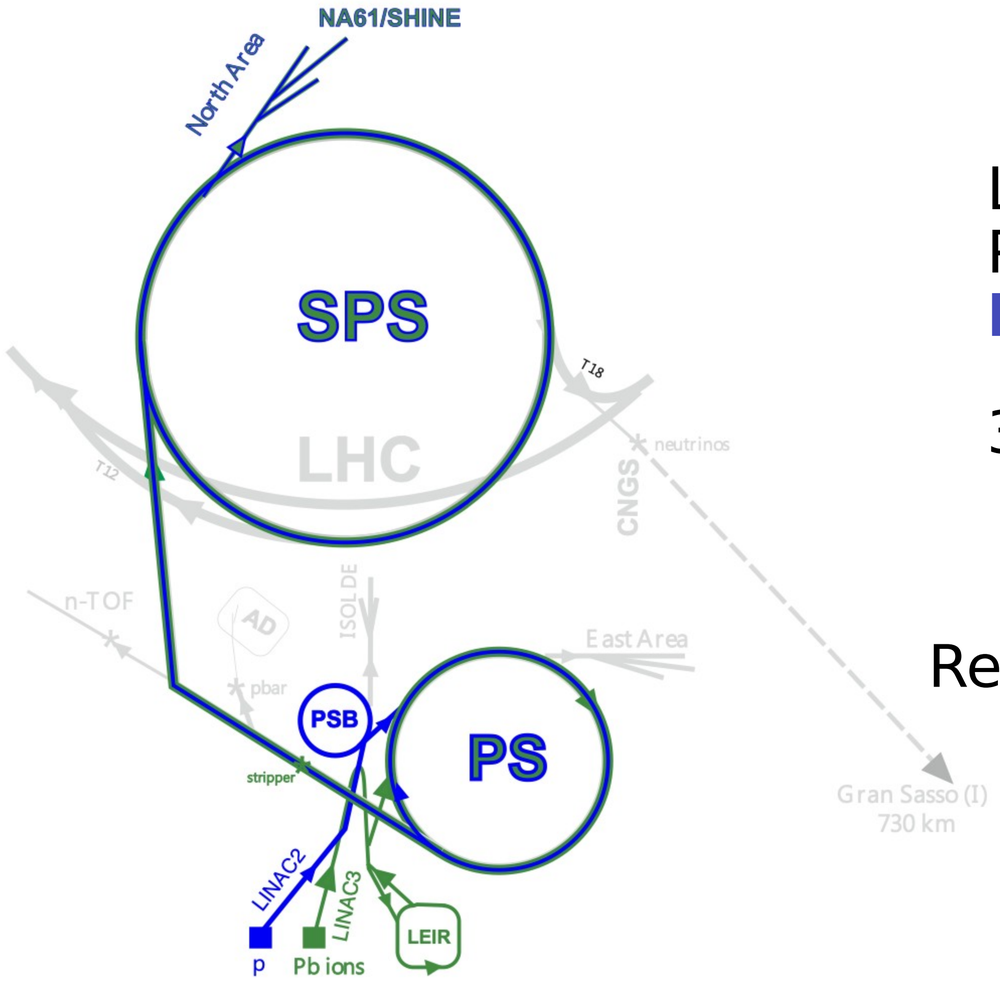
NA61/SHINE at CERN SPS

IRN “Neutrino”, October,10 2024

Boris Popov
on behalf of the NA61/SHINE Collaboration

NA61/SHINE experiment



JINST 9 P06005 (2014)

Located in **N**orth **A**rea of CERN, at the Super Proton Synchrotron: **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment

3 main scientific goals:

- **Strong interaction**

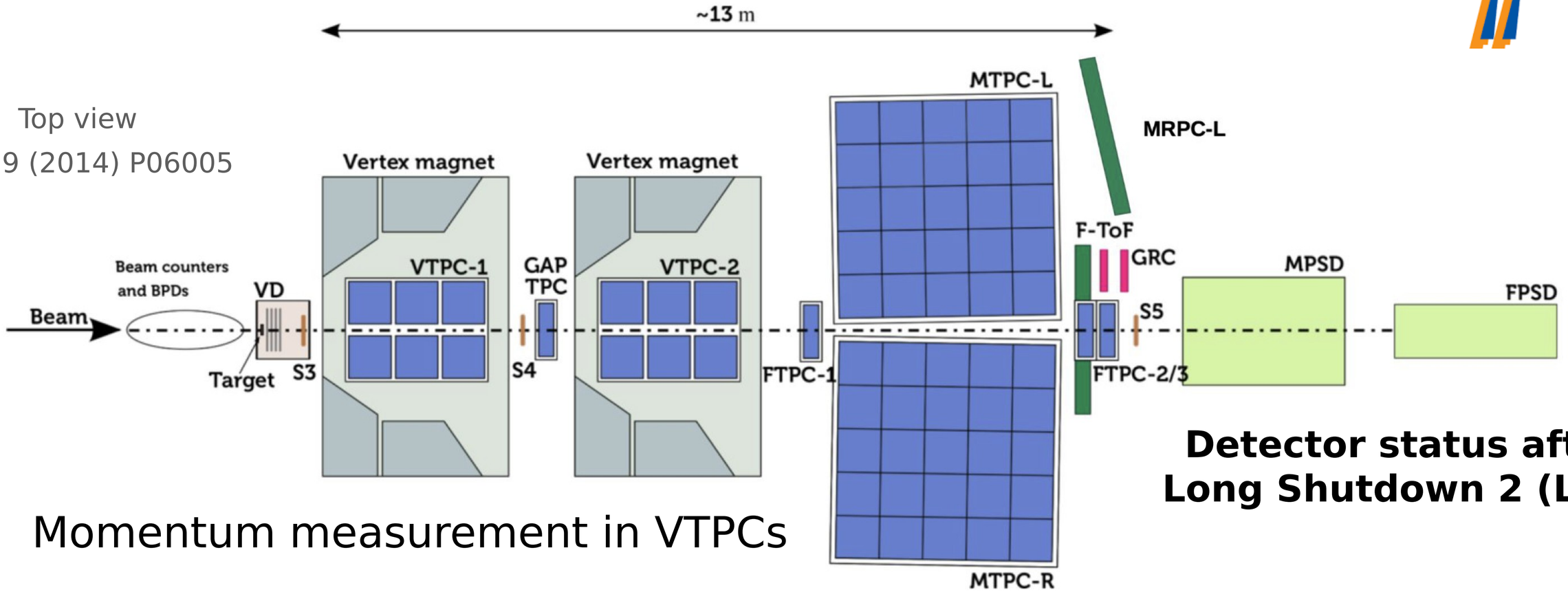
Reference measurements for

- **accelerator neutrino experiments**
- cosmic ray induced air showers, cosmic rays propagation in our Galaxy

NA61/SHINE spectrometer

Top view

JINST 9 (2014) P06005



Detector status after Long Shutdown 2 (LS2)

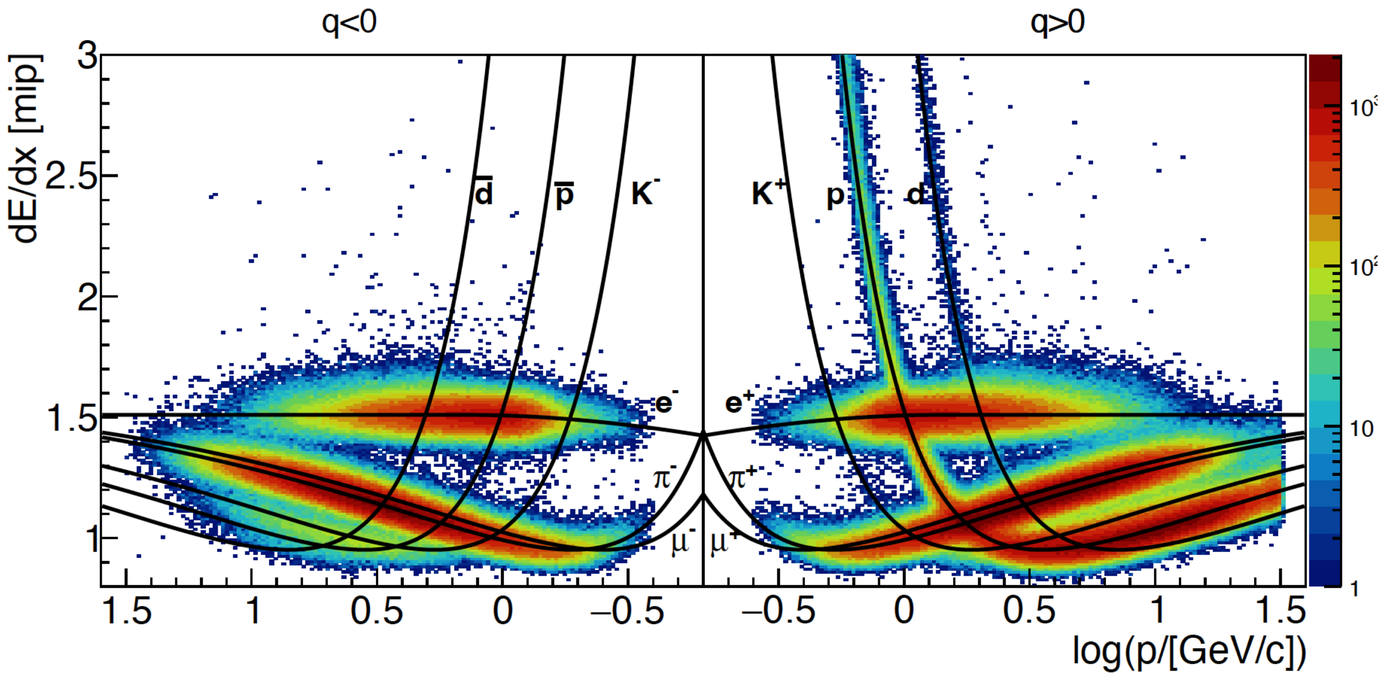
Momentum measurement in VTPCs

dE/dx measurement in TPCs (for PID)

TOF panels and MRPC (for PID)

Projectile Spectator Detector (MPSD+FPSD):
determination of collision centrality

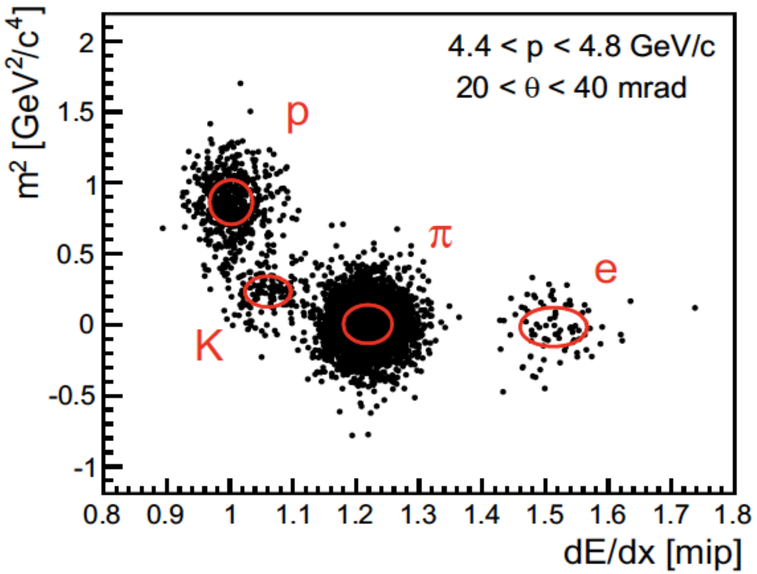
dEdX and tof analysis



PID with ionization energy losses dE/dx in the TPCs

TOF measurement is also used to estimate particle mass

An example of combined ToF-dE/dx analysis

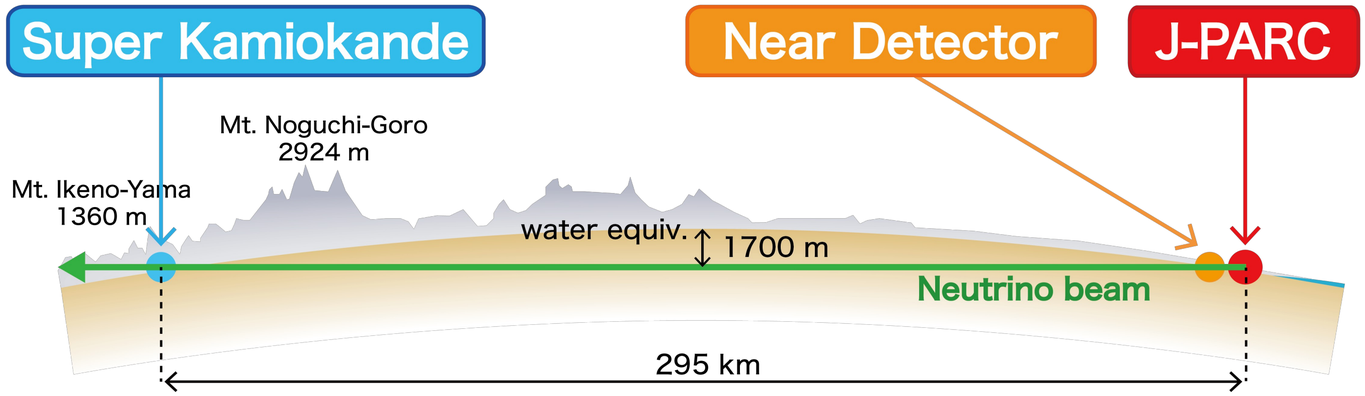


Result of tof-dEdX analysis for positively charged particles in a given {p,θ} bin

Hadron production measurements for accelerator neutrino experiments

Long baseline neutrino oscillation experiments

Example: T2K



Long baseline neutrino oscillation experiments (T2K, NOvA) are key tools to:

- **Precisely measure** neutrino oscillation parameters
- Potentially **discover CP violation** in neutrino oscillation

It is important to **reduce systematic uncertainties** for the future generation (Hyper-Kamiokande, DUNE) that will accumulate statistics much faster

Principle:

A beam of ν_μ or $\bar{\nu}_\mu$ is **produced at an accelerator facility** (e.g.: J-PARC)

The **systematic effects** (flux, interaction cross section) are constrained with **Near Detectors** measurements

The **oscillation** ($\nu_\mu \rightarrow \nu_e$ / $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance and ν_μ / $\bar{\nu}_\mu$ disappearance) is measured at the **far detector** (e.g.: Super-Kamiokande)

Accelerator neutrino beam

Magnetic horn

Decay volume

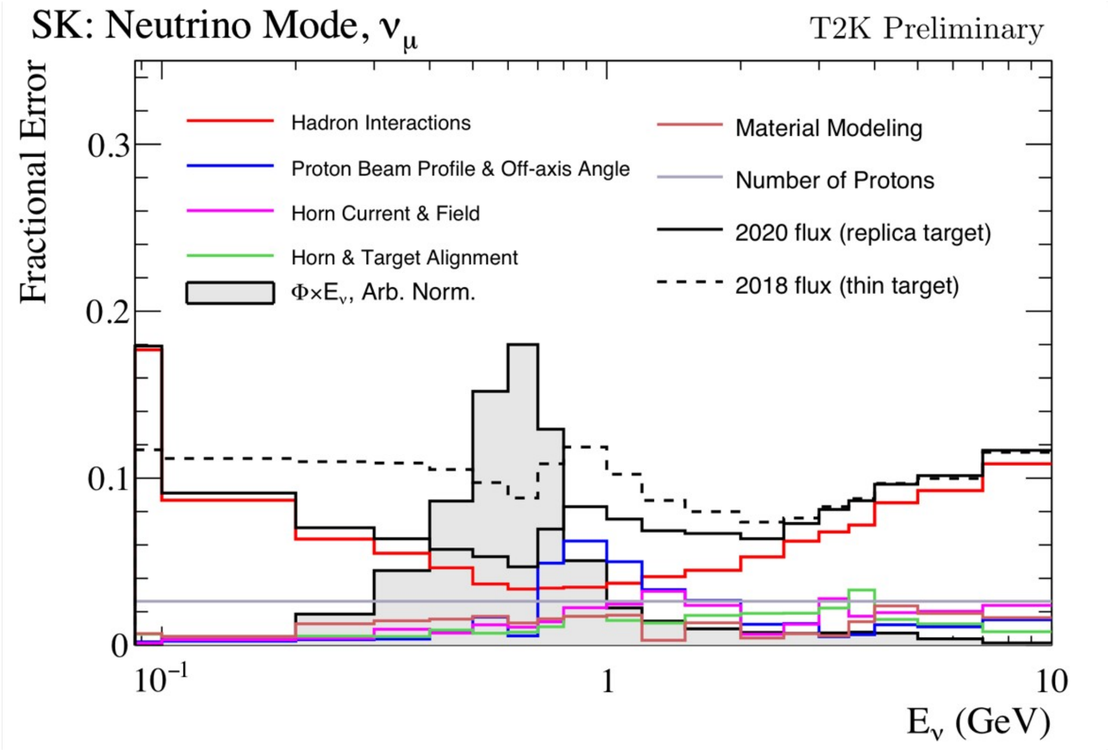
Proton beam → Long target → **Charged hadrons**

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

or

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

Current direction in the horn selects the hadrons charge



Caption

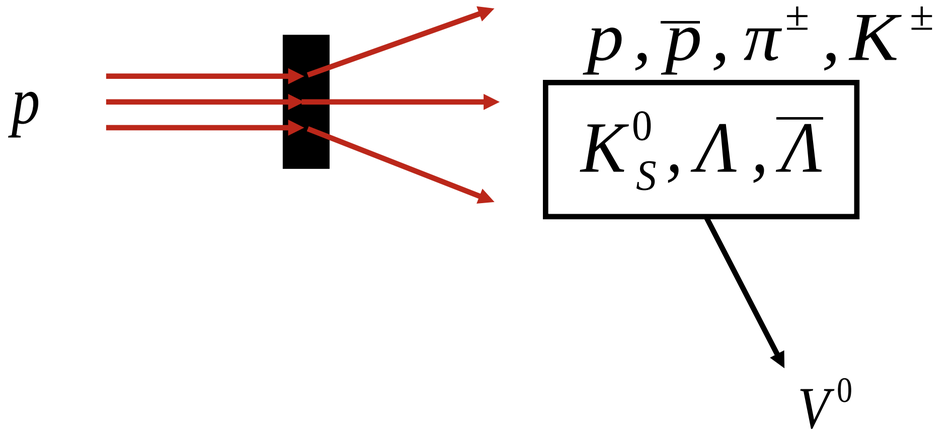
Main source of uncertainty in neutrino flux comes from the hadron interactions uncertainty in the simulation models (e.g.: FLUKA or GEANT4 physics lists) >20% !

Thin and long target measurements

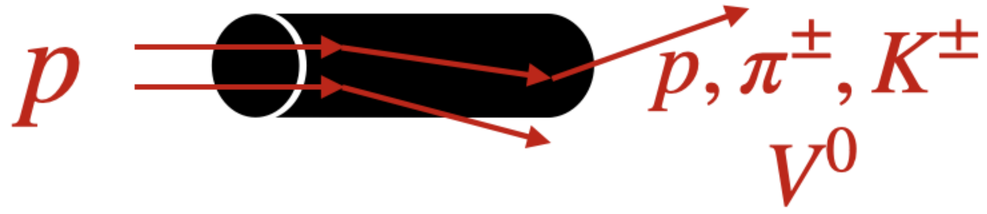
NA61/SHINE hadron production measurements provide inputs to **improve hadronic models** (FLUKA, GEANT4 etc.) and to **re-weight neutrino flux simulations**.

Production **cross section** and differential **hadrons yields** are measured for collisions:

1. On thin targets:



2. On long (replica) targets:



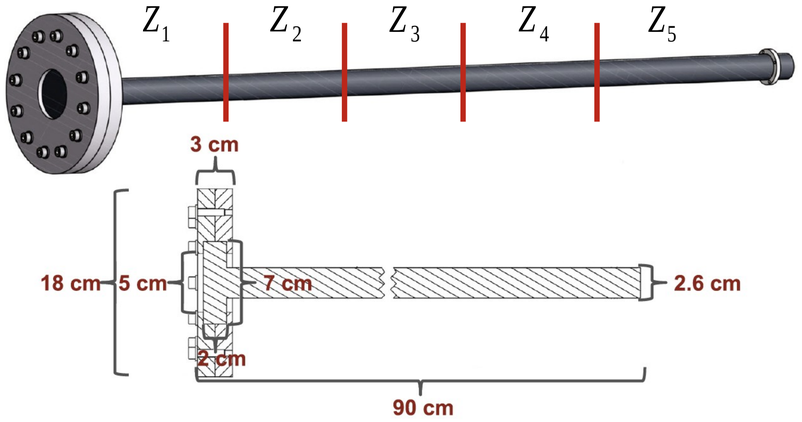
Decay into two oppositely-charged hadrons in the spectrometer

Results for T2K

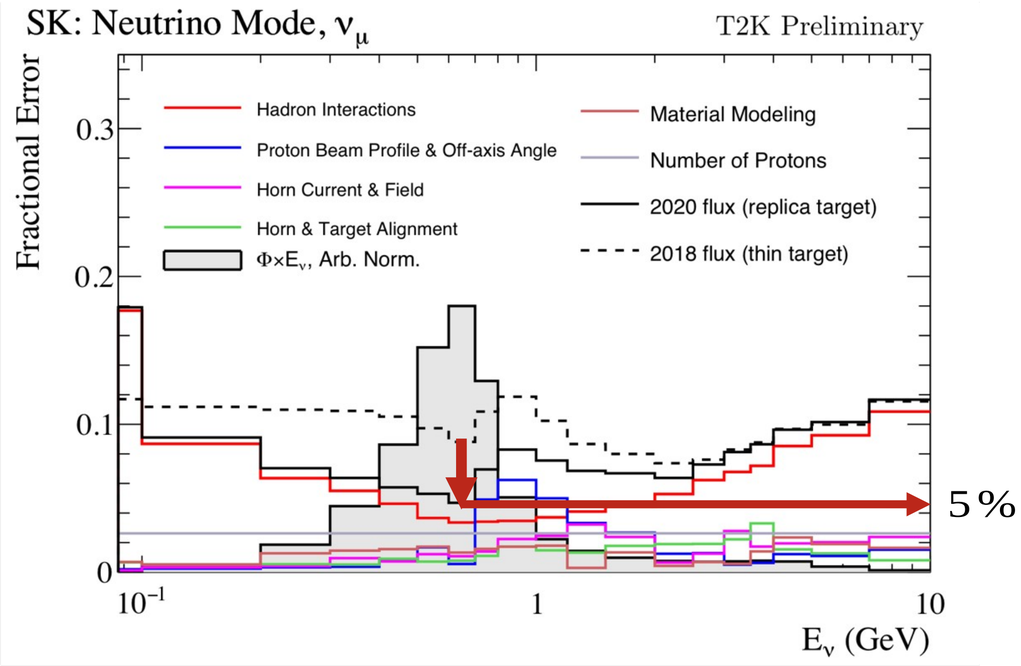
2007-2010 data-taking

31 GeV/c proton beam (T2K) collision on a 2cm graphite target (Eur. Phys. J. C. 76 84 (2016))

31 GeV/c proton beam collision on a 90cm T2K replica graphite target: Eur. Phys. J. C. 79 100 (2019)



Hadrons yields were measured per $\{p,\theta\}$ bin for each Zi section of the target.

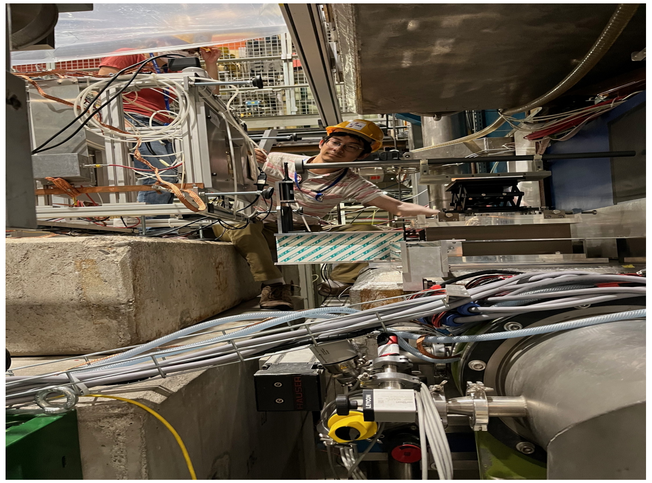


Including tuning on NA61/SHINE thin and replica target results reduced T2K flux uncertainty **down to 5%** at the flux peak!

2022: T2K replica target

2022: **New T2K replica target data**, after the upgrade

- >**10 times more statistics** than 2010
  - ~14M events with same Magnetic Field as 2010
  - ~150M events with **twice higher MF**



Statistics will allow **K^0_s yield** measurement (source of ν_e / $\bar{\nu}_e$ **contamination** in ν_μ / $\bar{\nu}_\mu$ beams)

Higher MF data will allow study of **high momentum charged kaon production** (constrain **higher energy part of neutrino flux**)

Thin targets measurements

Production and inelastic cross section:

Long baseline experiments @FNAL

p+C/Be/Al at 60 GeV/c and 120 GeV/c Phys. Rev. D. 100, 112001 (2019): essential to constrain **primary interactions** in neutrino experiments target & surrounding material

π^+ / K^+ +C/Al at 60 GeV/c and 31 GeV/c Phys. Rev. D. 98, 052001 (2018): essential to constrain **re-interactions of hadrons** in neutrino experiments target & surrounding material

Multiplicity:

Charged hadrons production in p+C at 120 GeV/c Phys. Rev. D. 108, 072013 (2023)

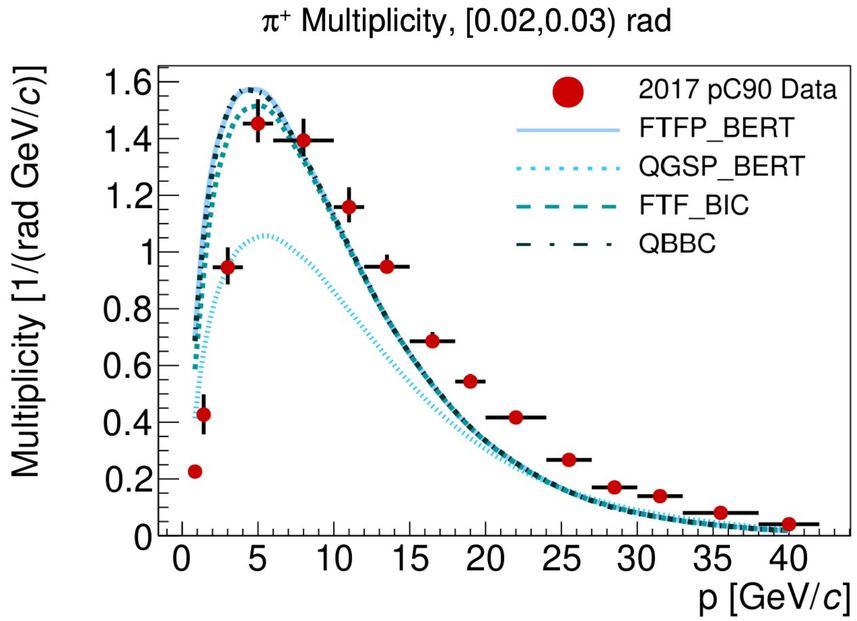
V0 production in p+C at 120 GeV/c Phys. Rev. D. 107, 072004 (2023)

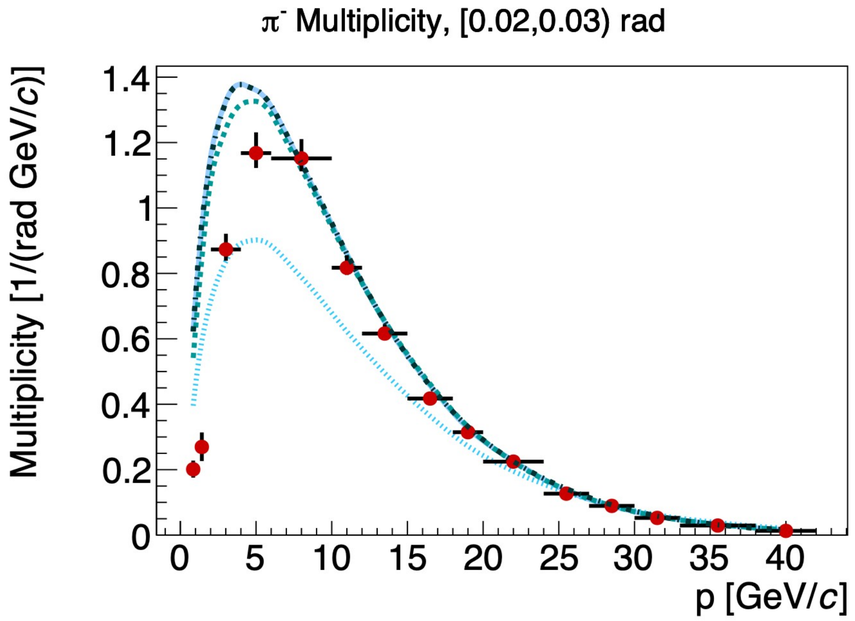
Thin targets measurements

Analyses in progress:

Neutral and charged hadrons yields in p+C at 60 GeV/c

Neutral and charged hadrons yields in p+C at 90 GeV/c: final results prepared for publication



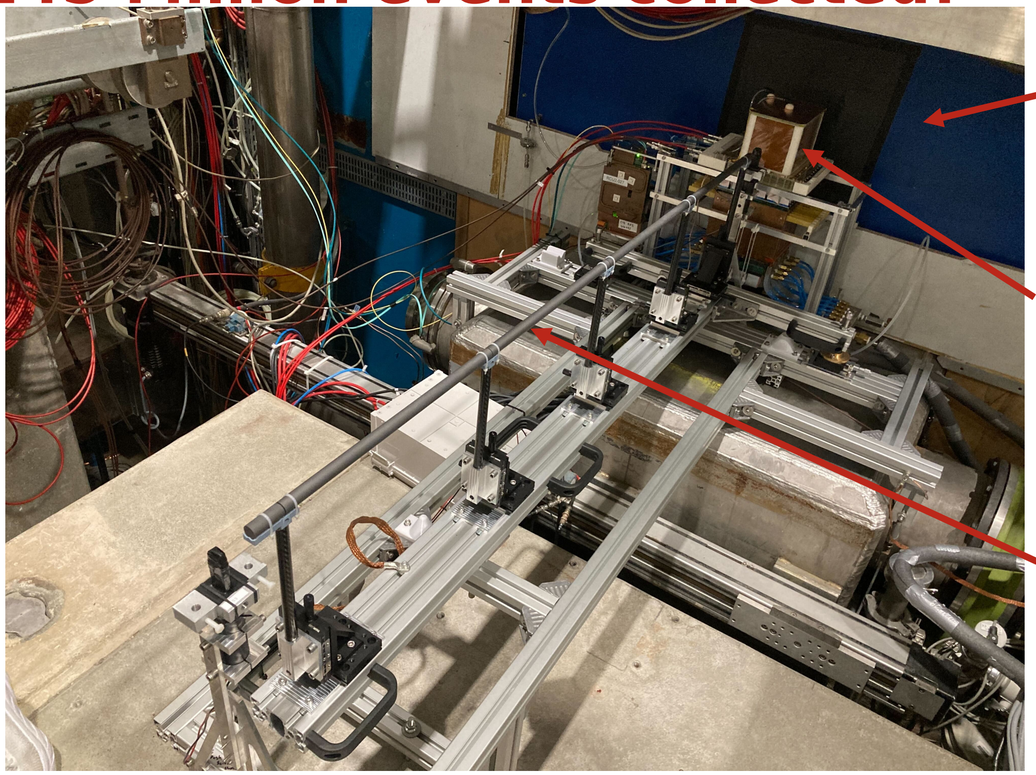


NuMI and LBNF targets

2018: **p+NuMI target at 120 GeV/c**, data calibration in progress

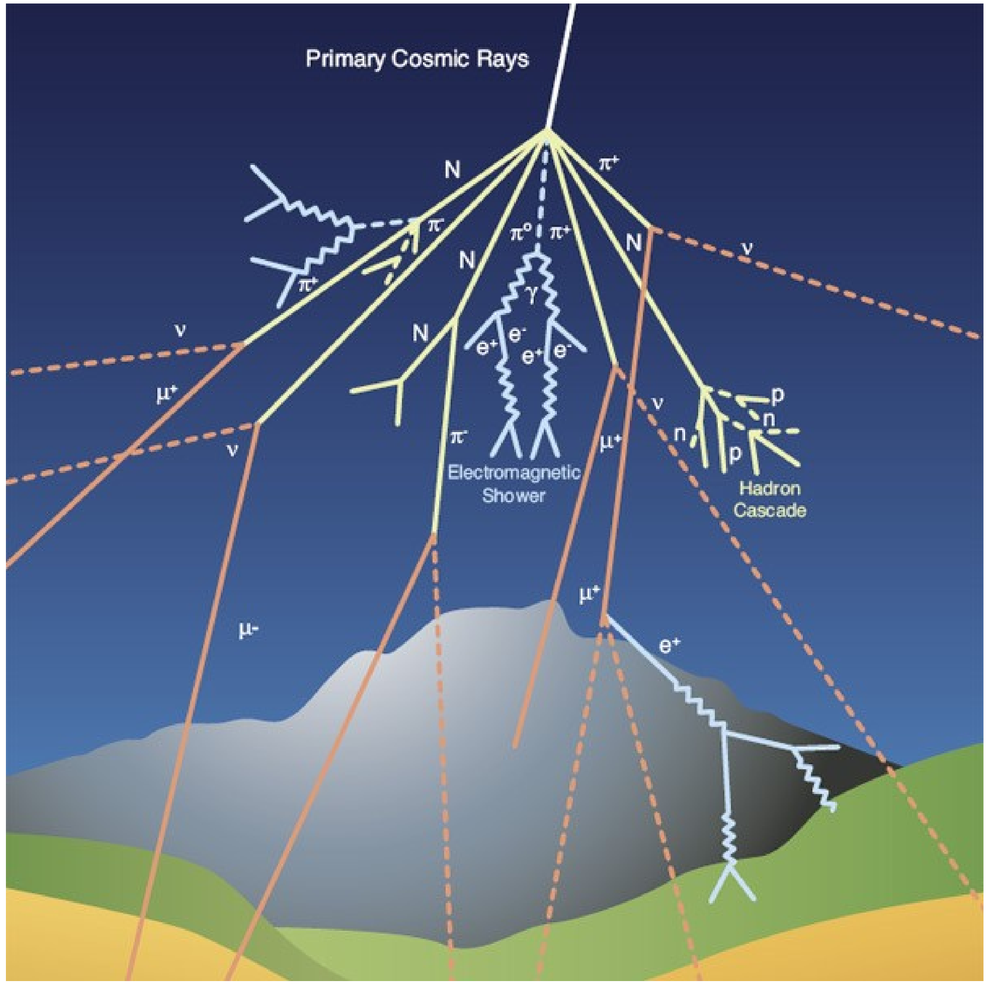
2024: **LBNF/DUNE prototype target** newly taken data

245 Million events collected!



NuMI replica target

Cosmic-Ray program



From https://home.cern/fr/science/physics/cosmic-rays-particles-outer-space

Cosmic ray induced air shower mostly hadronic (pions)

NA61/SHINE provided precision data for the tuning of air shower simulations

PHYSICAL REVIEW D **107,** 062004 (2023)

Measurement of hadron production in π^--C interactions at 158 and 350 GeV/c with NA61/SHINE at the CERN SPS

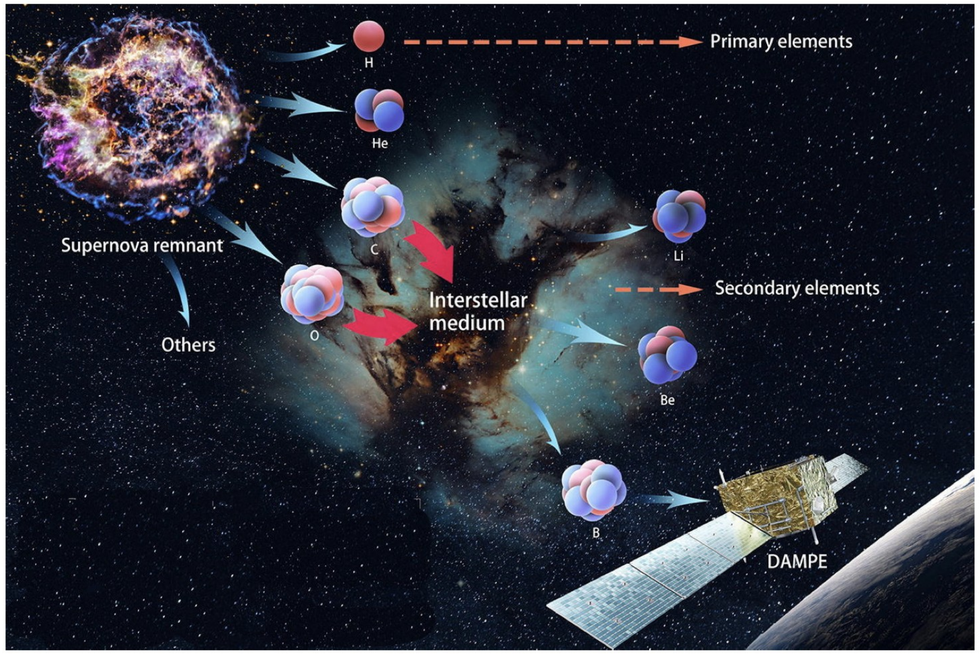
Eur. Phys. J. C (2017) 77:626
DOI 10.1140/epjc/s10052-017-5184-z

THE EUROPEAN PHYSICAL JOURNAL C

Measurement of meson resonance production in π^-+ C interactions at SPS energies

Close to air

Cosmic-Ray program



Sci.Bull. 67 (2022) 2162

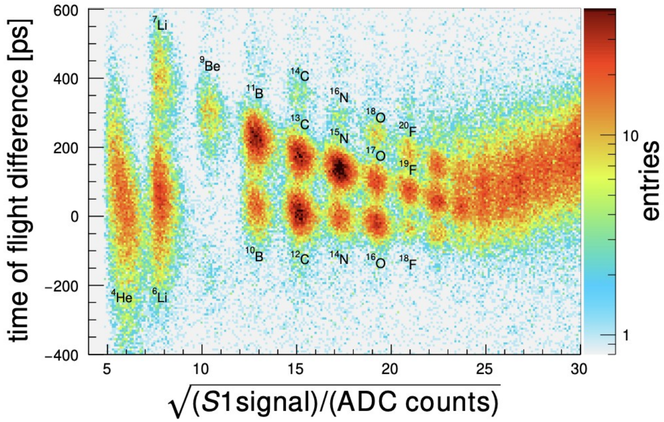
- CR-grammage X (**"target thickness"**) from secondary nuclei
  e.g. boron/carbon flux ratio (B/C)
- halo size (**"target length"**) from unstable secondaries
  e.g. $^{10}\mathrm{Be}/\,^{9}\mathrm{Be}$ → need to know fragmentation cross sections!

Credit: Michael Unger

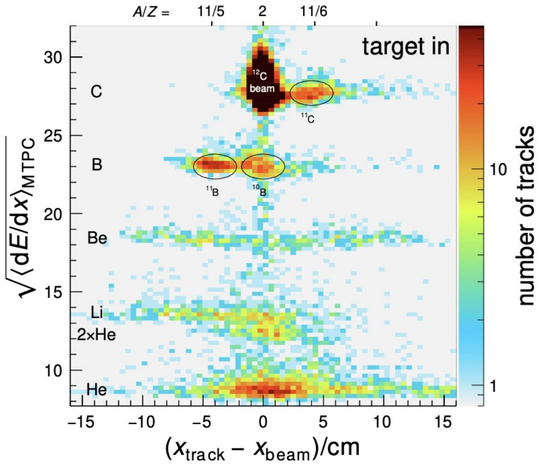
NA61/SHINE Pilot Run on Fragmentation, Dec 2018

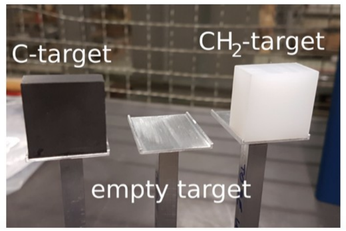
13.5 A GeV/c fragmented Pb beam

SPS beam-fragment identification



reaction-fragment identification





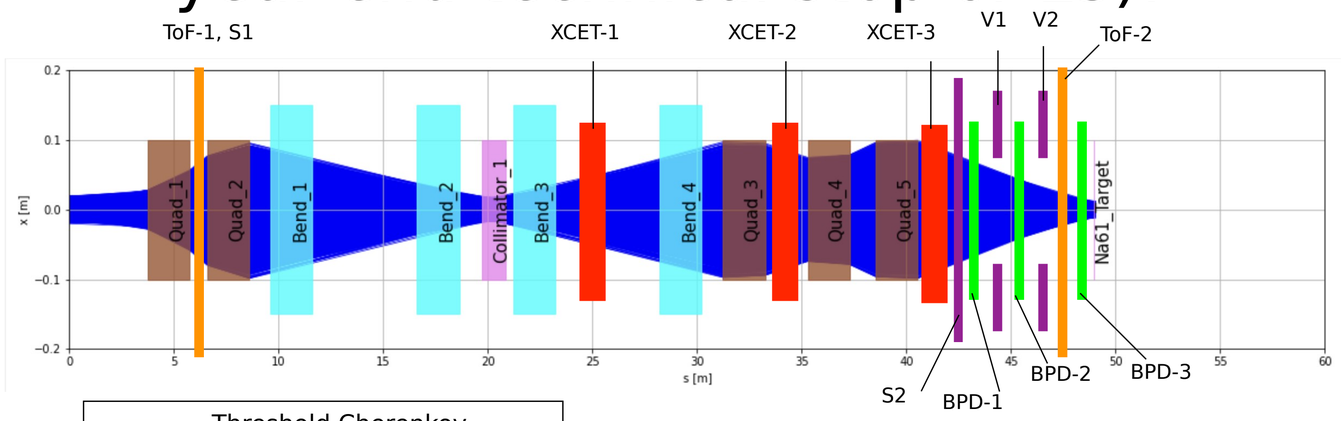
- 2.5 days data taking at 13.5 AGeV/c
- events after upstream ^{12}C selection:
  - 1.7×10^5 CH_2-target
  - 1.5×10^5 C-target
  - 0.4×10^5 empty-target

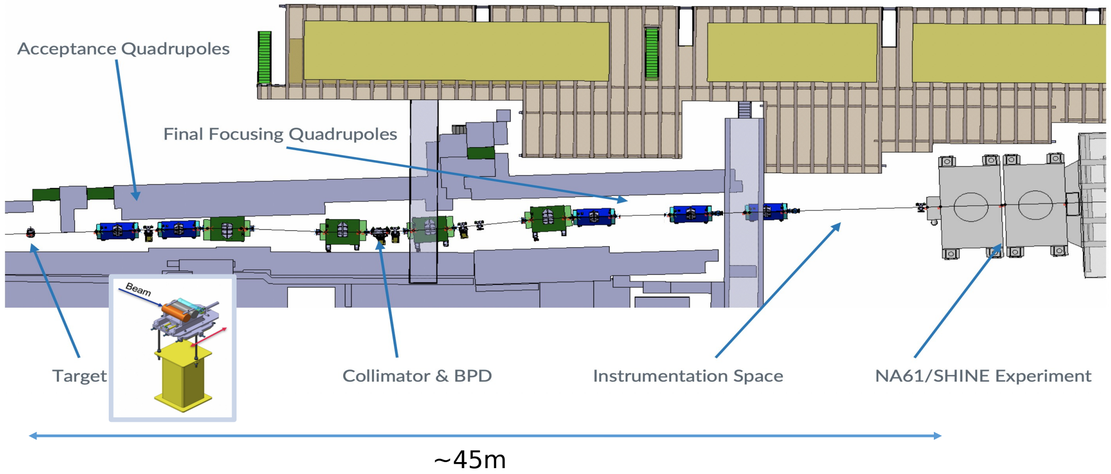
Credit: Michael Unger

Future prospects: low-energy beamline

Project of a new beamline to deliver low-energy (2-30 GeV/c) hadron beams

Design/feasibility studies complete. Propose construction soon (CERN year-end technical stop or LS)!





Threshold Cherenkov counter
Beam Profile Detector
TOF counter
Trigger and Veto counter

Detectors already available at CERN

Ongoing R&D

Well focused beam ($\sigma_{x/y}$<20mm) with good PID quality!

Y. Nagai et al.
SPSC-P-330-ADD-12 (2021)

SPSC-M-793 (2022)
SPSC-M-795 (2023)

Conclusions

NA61/SHINE experiment at CERN SPS has a **rich physics program**

Completed a **scan in colliding nuclei size - collision energy**, to better understand the onset of deconfinement and QGP fireball and search for CP: **many published results and more to come**!

Strong Interaction program extended to study **open charm production** in Pb+Pb collisions

Big success with a reduction of **T2K flux uncertainty down to 5%** thanks to NA61/SHINE results on T2K replica target

Recent **long (NuMI, T2K, LBNF/DUNE) target** and thin target data being analysed: **stay tuned!**

Plan of **low energy beamline** for the future of the neutrino program

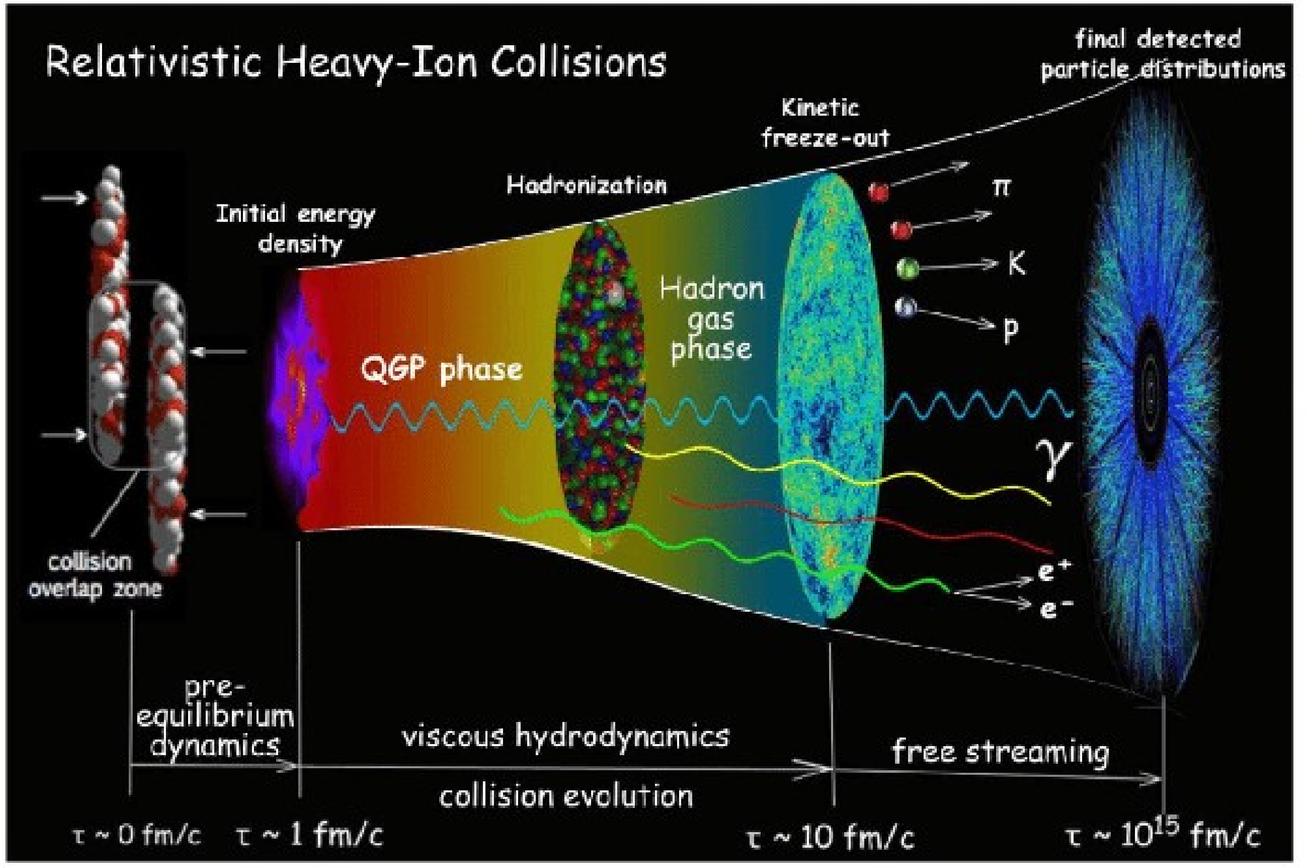
Other interesting applications in Cosmic Rays physics

French (LPNHE) contribution: data taking, calibration, analysis and coordination

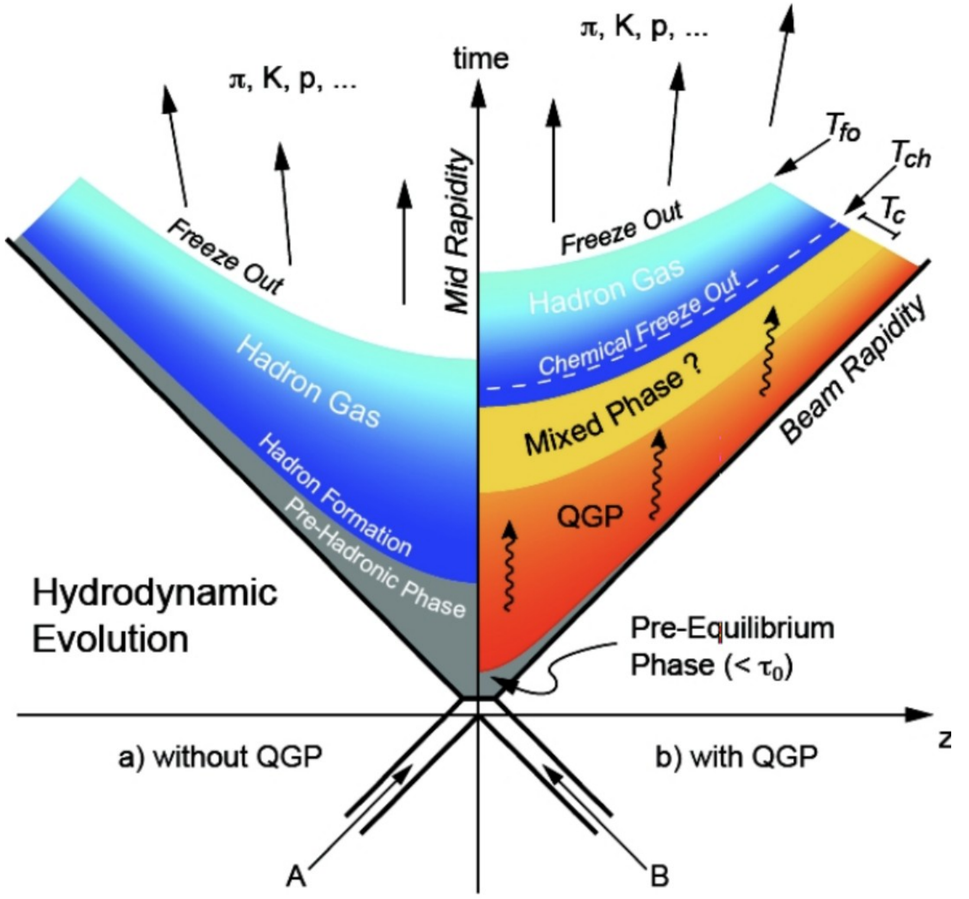
Thank you!

April 2024 Collaboration meeting in Sofia, Bulgaria

The strong interaction program

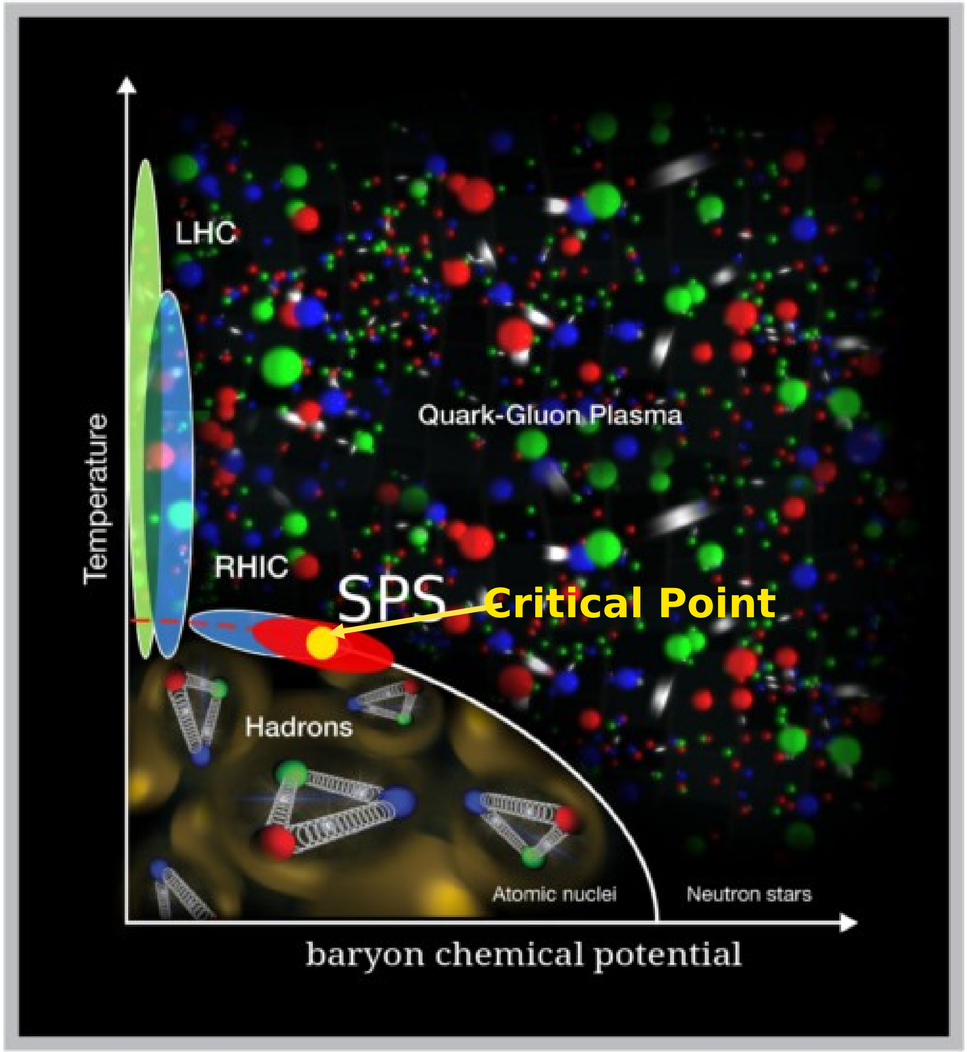


Rys. C. Shen, U. Heinz, Nucl. Phys. News 25 (2015) 2, 6-11

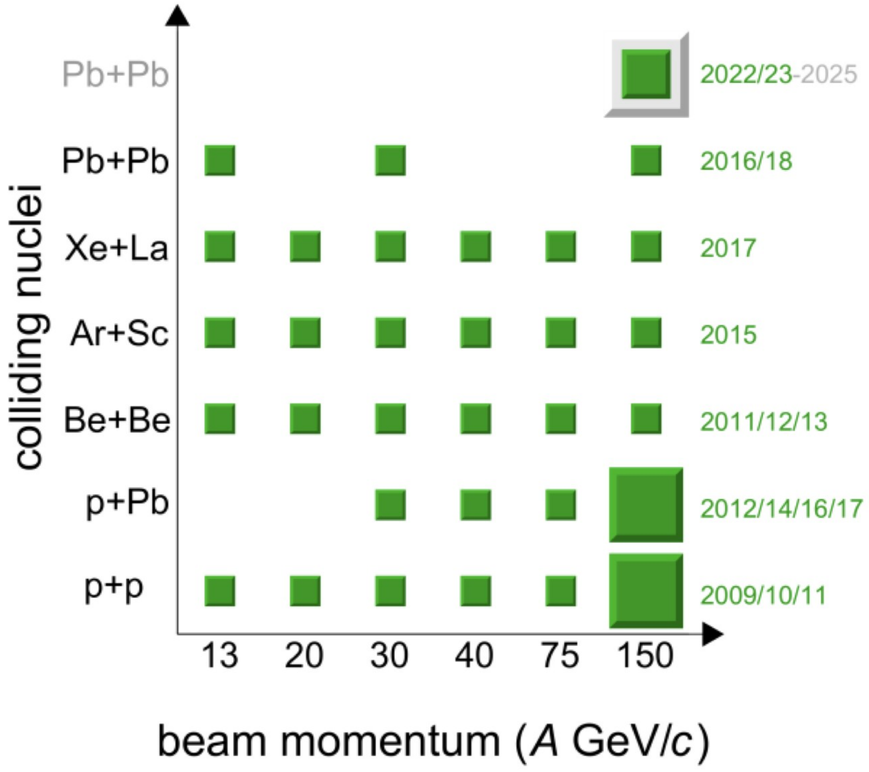


https://particlesandfriends.wordpress.com/2016/10/14/evolution-of-collisions-and-qgp

Deconfinement and Critical Point

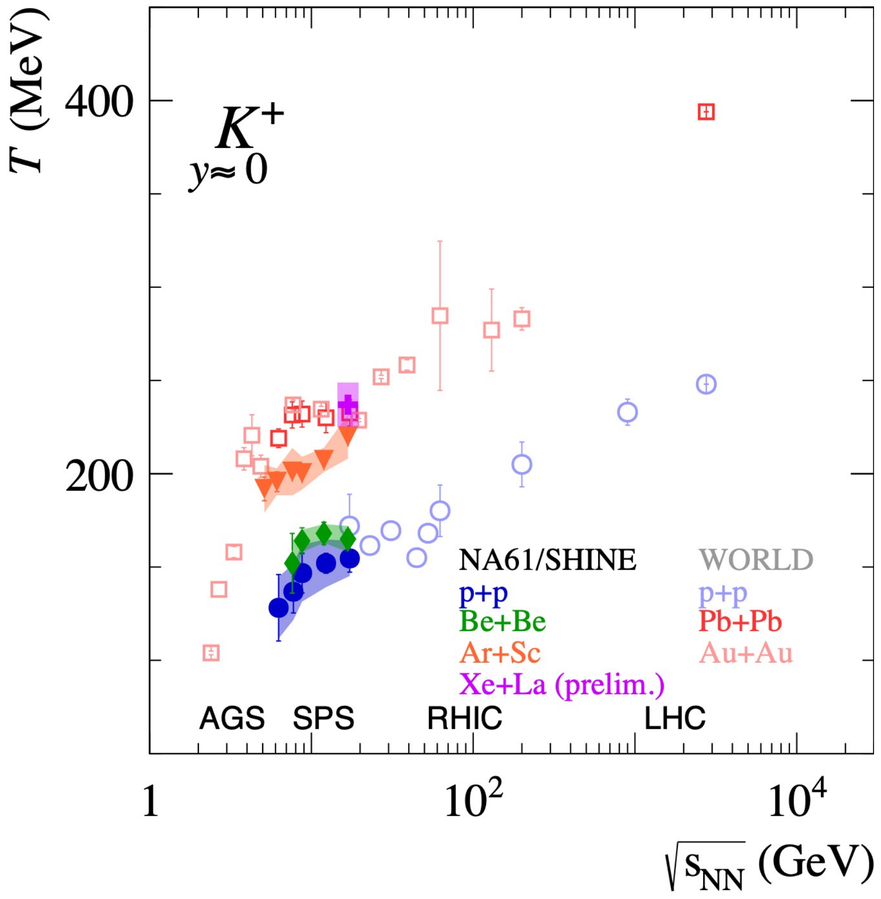


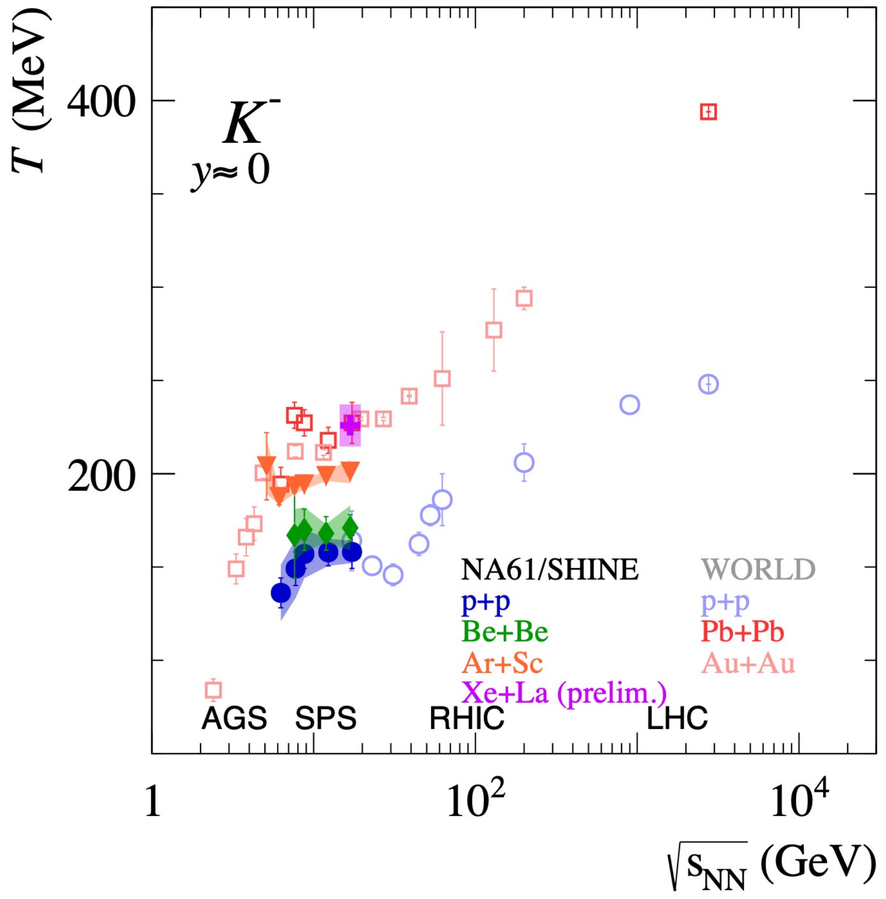
SPS energy range ideal for studying **onset of deconfinement** and to search for the **Critical Point**



Scan in collision energy and system (nuclei) size

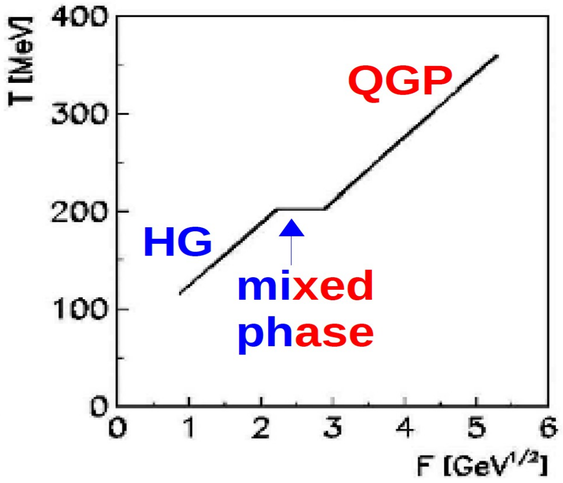
Onset of deconfinement





Eur. Phys. J. C 84 (2024) 4, 416 (Ar+Sc);
Eur. Phys.J. C 81 (2021) 1, 73 (Be+Be);
Eur. Phys. J. C 77 (2017) 10, 671 (p+p)

“step”

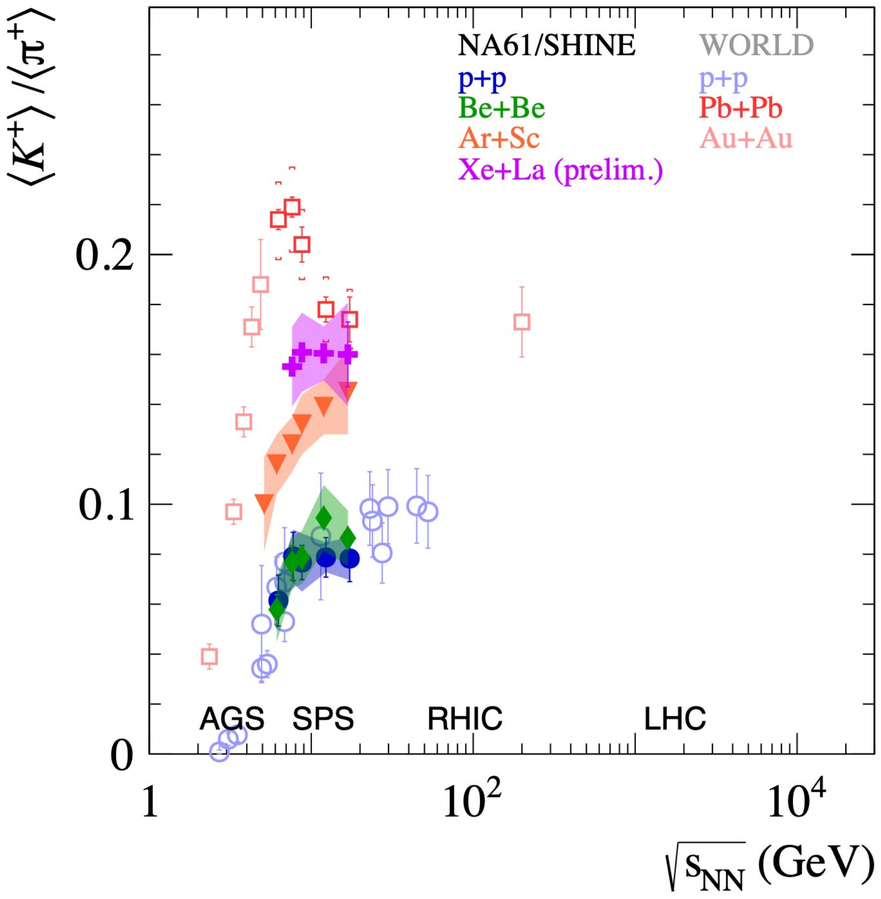


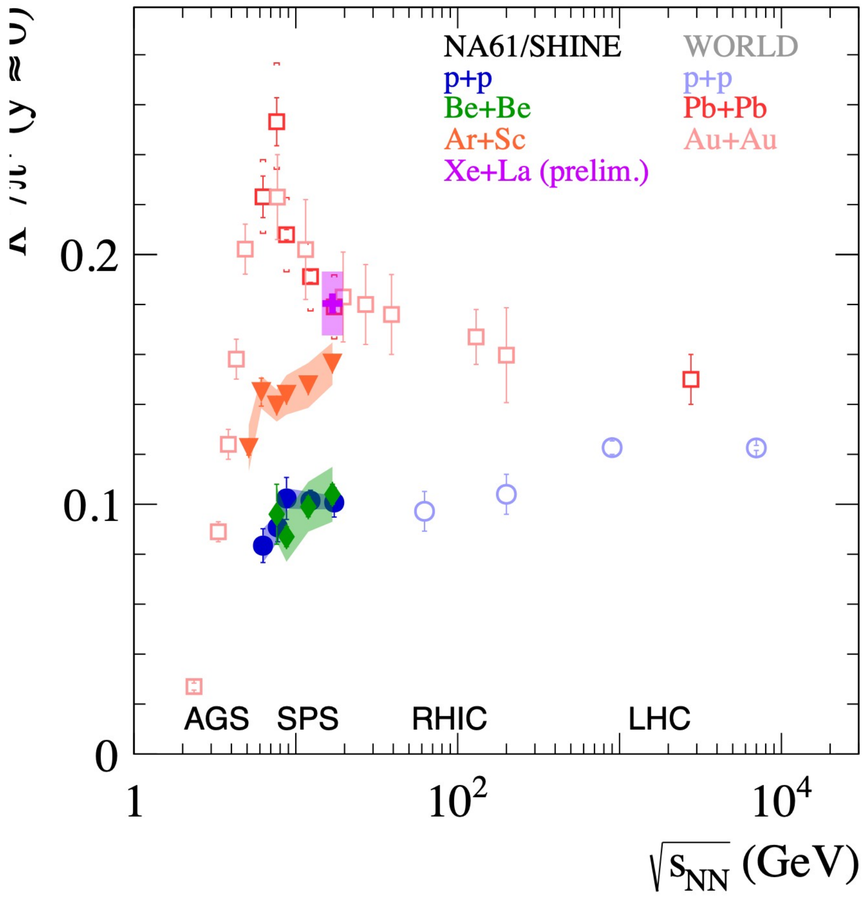
Prediction from the Statistical Model of the Early Stage (M. Gazdzicki, M. Gorenstein, Acta Phys. Polon. B 30 (1999) 2705)

Transverse momentum/mass spectra were fitted with an exponential shape with an **inverse slope parameter**

reflects the **thermal freeze-out temperature** and the **radial flow velocity**

Onset of deconfinement





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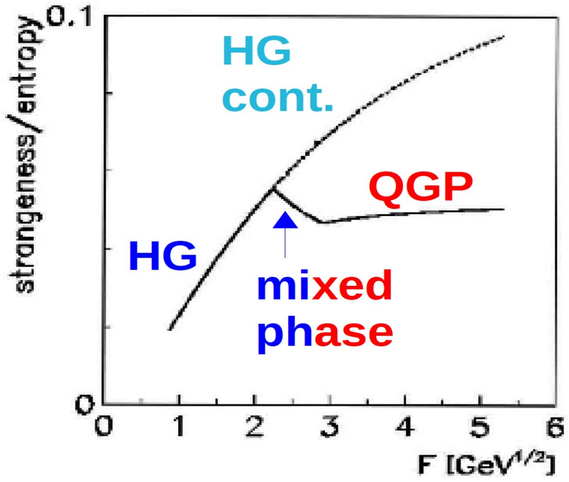
Eur. Phys. J. C 77 (2017) 10, 671 (p+p)

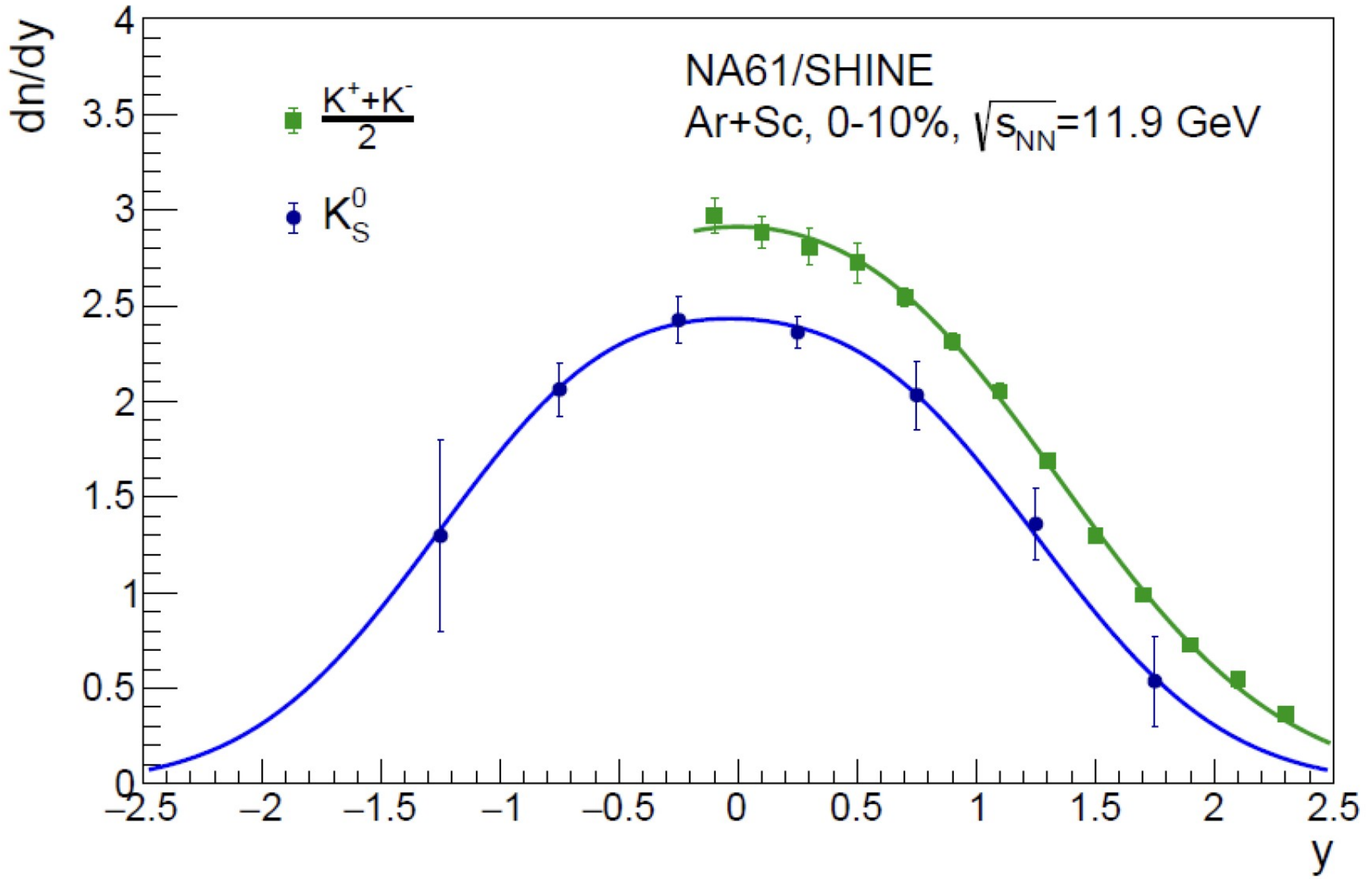
"horn"



Prediction from the Statistical Model of the Early Stages (M. Gazdzicki, M. Gorenstein, Acta Phys. Polon. B 30 (1999) 2705)

Good measure of the **strangeness to entropy ratio** which is expected to be different in the confined phase and the QGP: **probe of the onset of deconfinement**

Kaon puzzle



Eur. Phys. J. C. 84 (2024) 4, 416 (,)
arXiv:2312.06572 ()

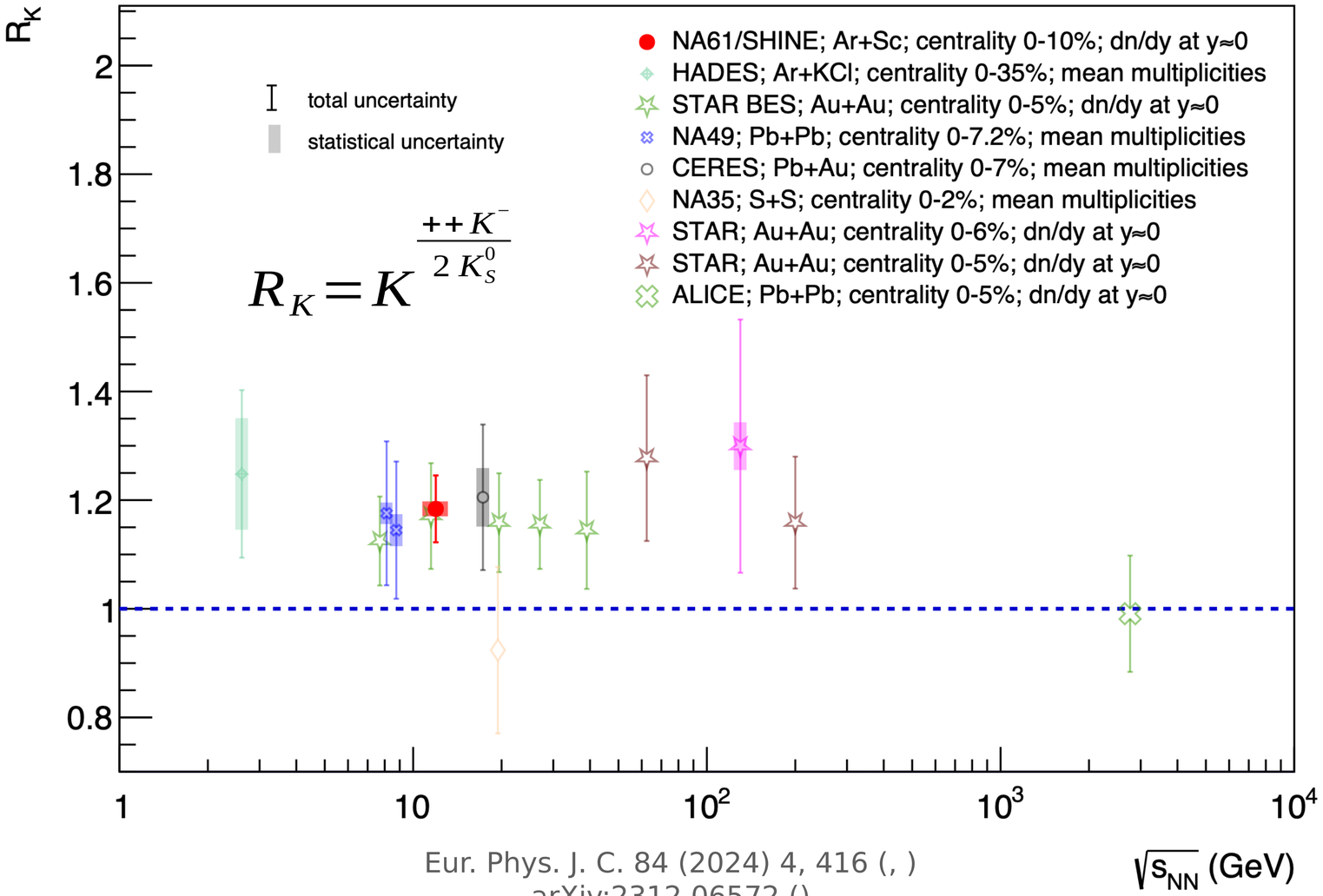
Ar+Sc is approximately **isospin symmetric** (valence u valence d)

Expected: and

Neglecting CP violation:

Data shows : **excess of charged** over neutral **kaons**

Kaon puzzle



Eur. Phys. J. C. 84 (2024) 4, 416 (,)
arXiv:2312.06572 ()

expected to be in case of isospin symmetry

We see an **excess of charged over neutral kaons** corresponding to additional per Ar+Sc collision

World data support NA61/SHINE result despite larger uncertainties

Open charm program

Motivations:

The **mechanism of charm production** in heavy ion collisions **is unknown**: various theoretical predictions greatly differ!!

Charm production is also expected to be different in a deconfined state: another good **probe of onset of deconfinement**!

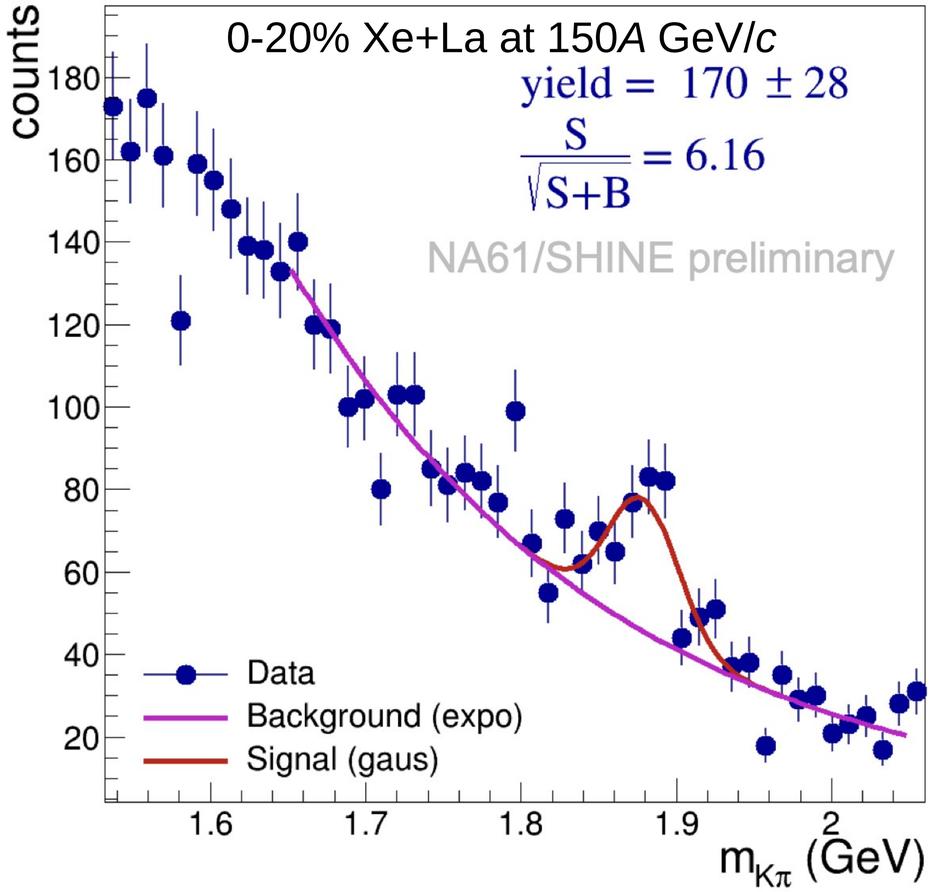
Precise measurement needed to **interpret existing results on**

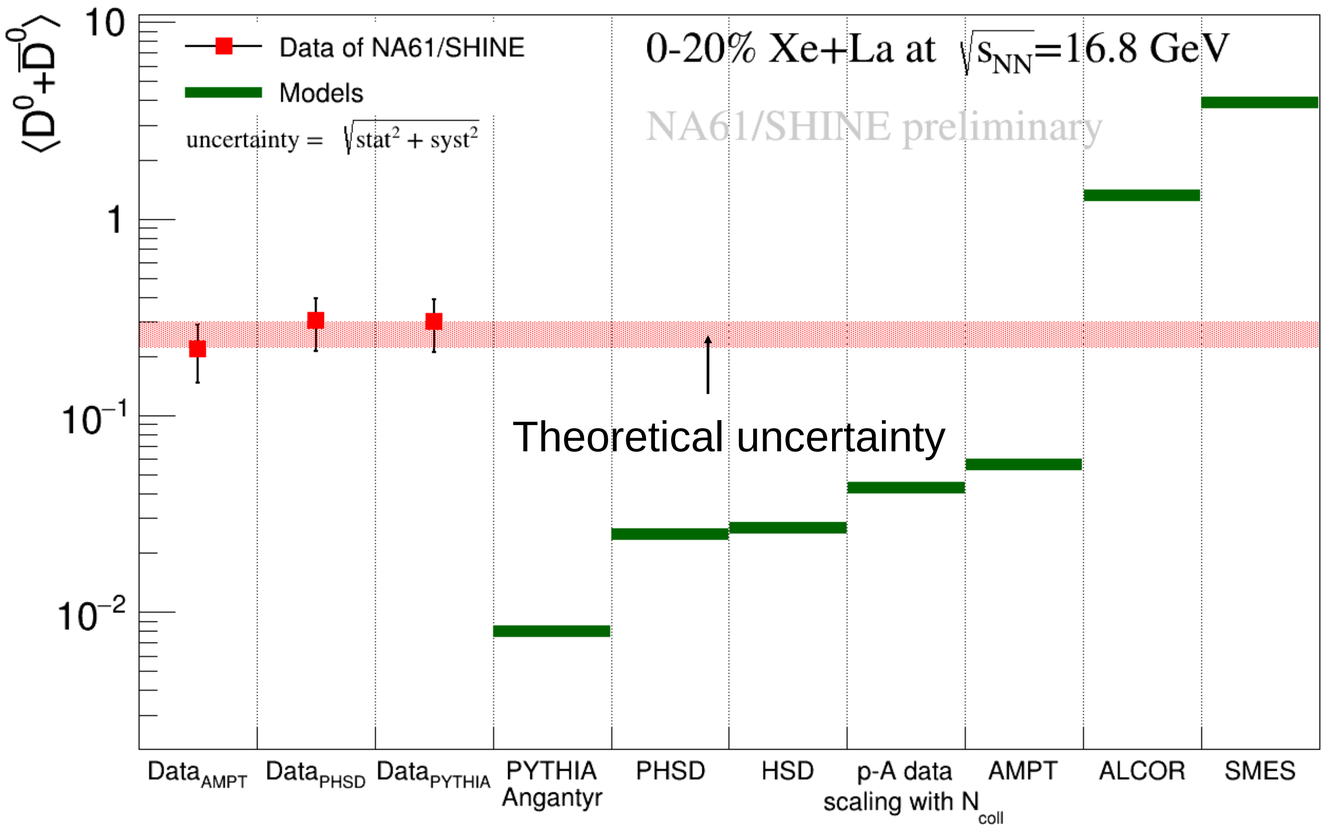
Challenge:

Open charm production at SPS mostly carried by **mesons** (low yield, short-lived particle): need precise tracking and good primary and secondary vertex resolution

Open charm program

First direct measurement of open charm production in A+A collisions at SPS energies: **measurement** of with significance !





Summary for SI program

NA61/SHINE has a rich SI program with various analyses of the data taken from 2009 of the **scan in size of colliding nuclei and collision energy**

Pursuing the study of the **onset of deconfinement and QGP fireball**

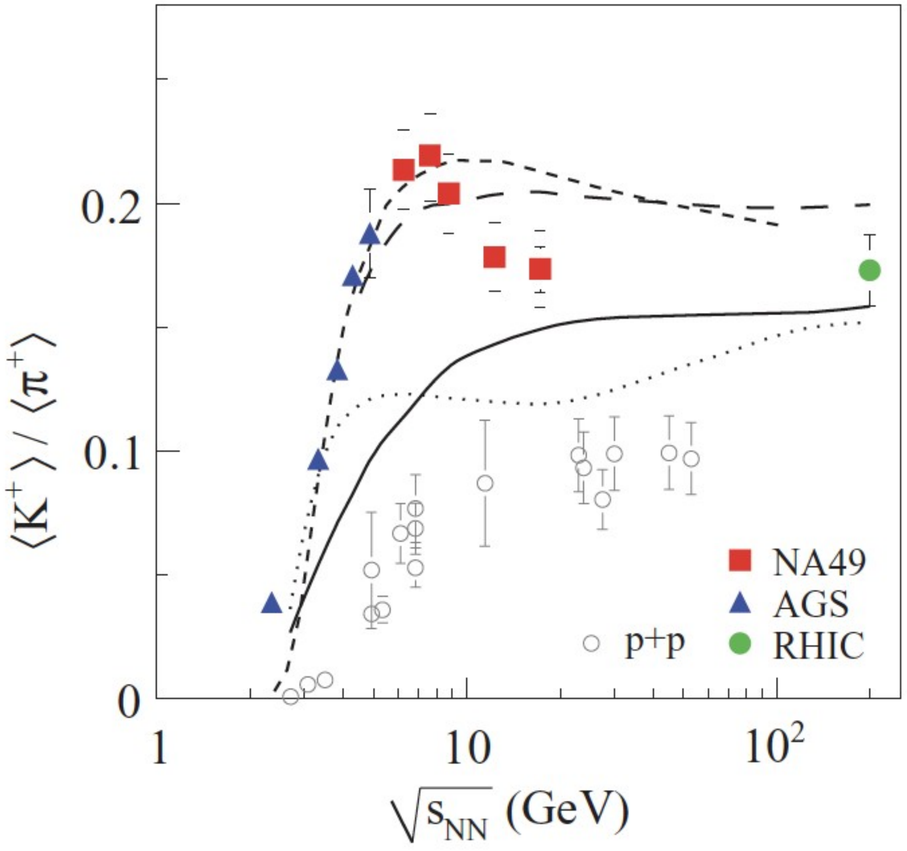
Actively **looking for signs of CP** with various types of analysis: femtoscopy, intermittency analyses …

First measurement of open charm production in heavy ion collisions **at SPS energies**: further measurements to come with post LS2 data

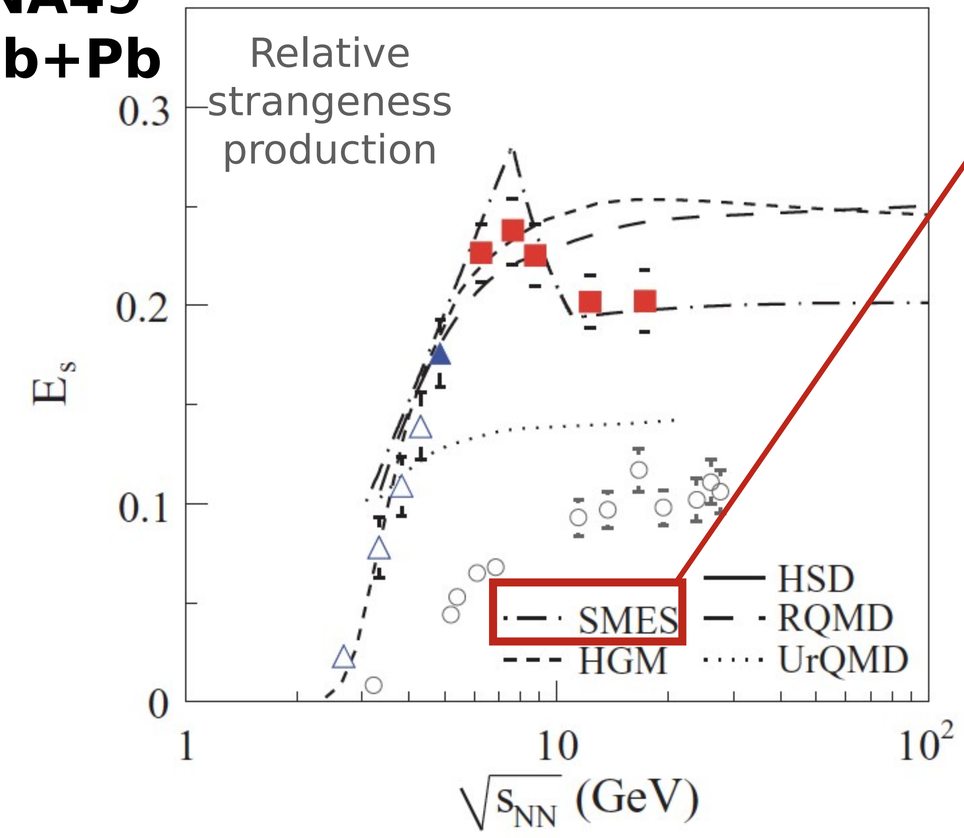
Possible future **plans**: Continue scan with B+B, O+O, Mg+Mg

Onset of deconfinement

A QGP in the initial stage of the collision is expected to impact hadron production: e.g., the evolution of **strangeness production with collision energy**



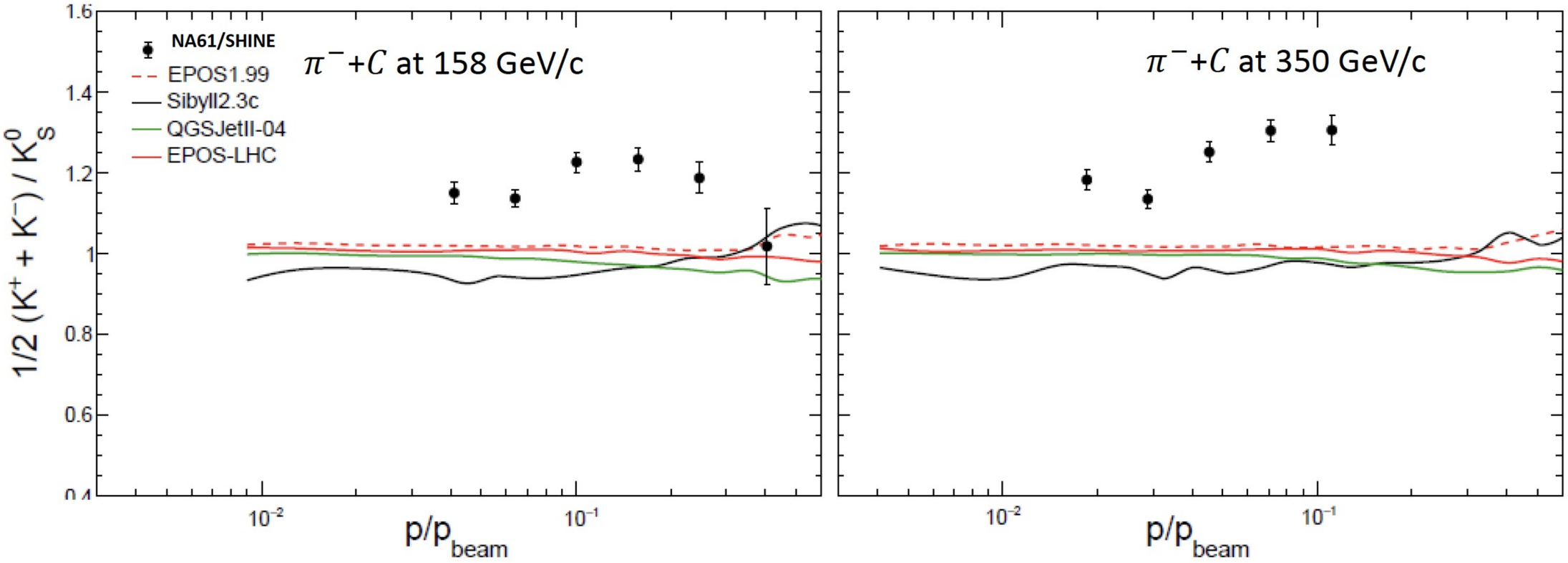
NA49 Pb+Pb



Statistical Model of the Early Stage: includes onset of deconfinement at low SPS energies

PHYSICAL REVIEW C 77, 024903 (2008)

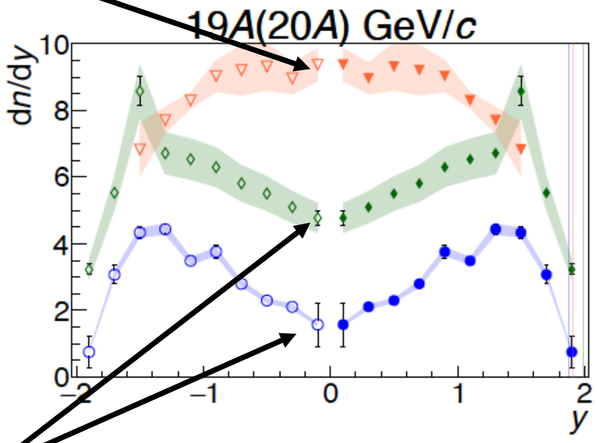
Kaon puzzle

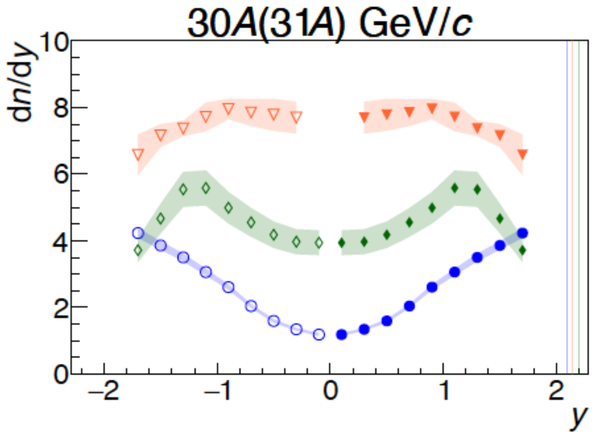


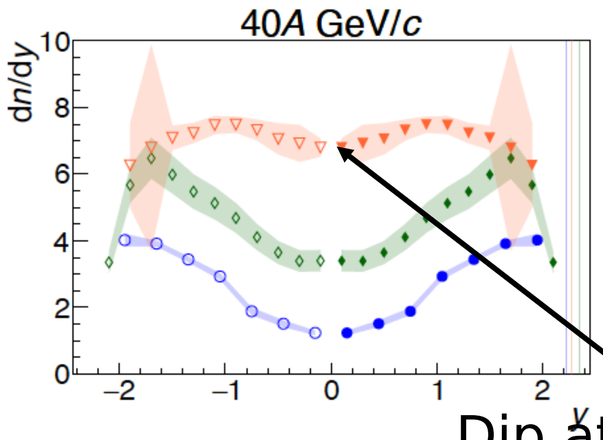
Models also fail to reproduce charged over neutral kaon ratio in small asymmetric systems like .

Proton rapidity spectra

Flat at mid-rapidity

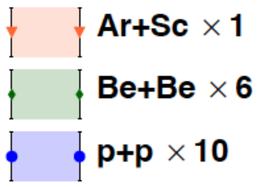


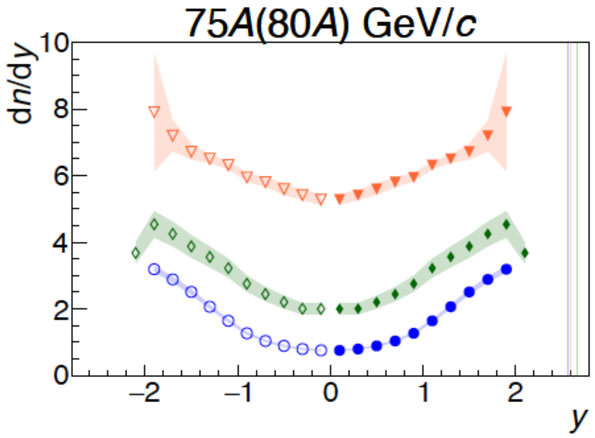


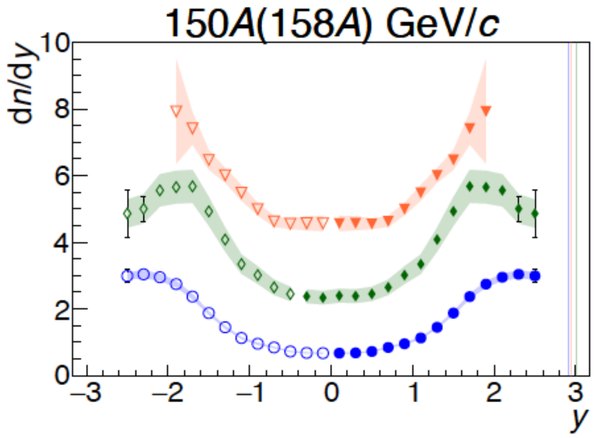


Dip at mid-rapidity

Dip at mid-rapidity starts appearing For Ar+Sc collisions





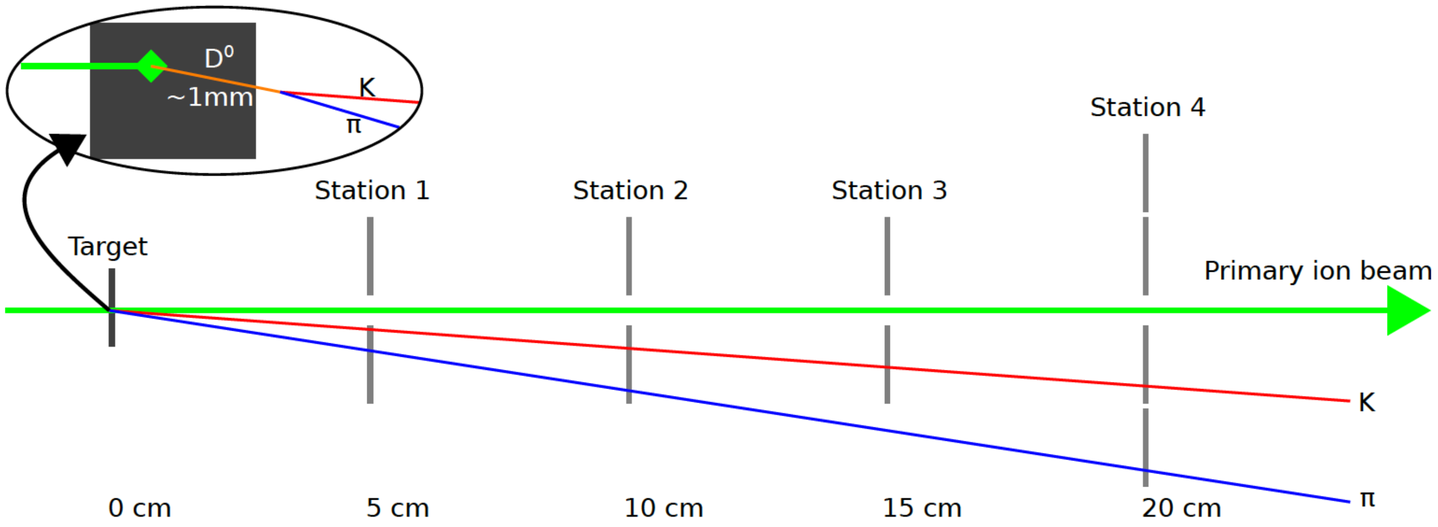


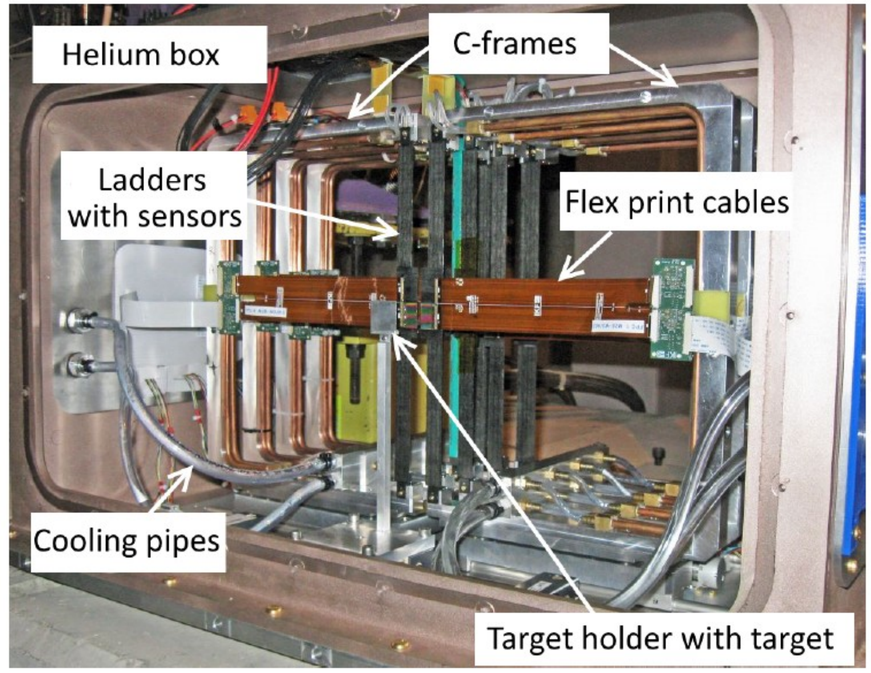
arXiv:2211.13987v1 (2022)

Open charm program

Small Acceptance Vertex Detector installed in 2016: used in Pb+Pb and Xe+La data-takings. **Upgrade** during LS2: **VD, higher acceptance**.

Allowed the **first-ever direct measurement of open charm production** in A+A collisions at SPS energies.

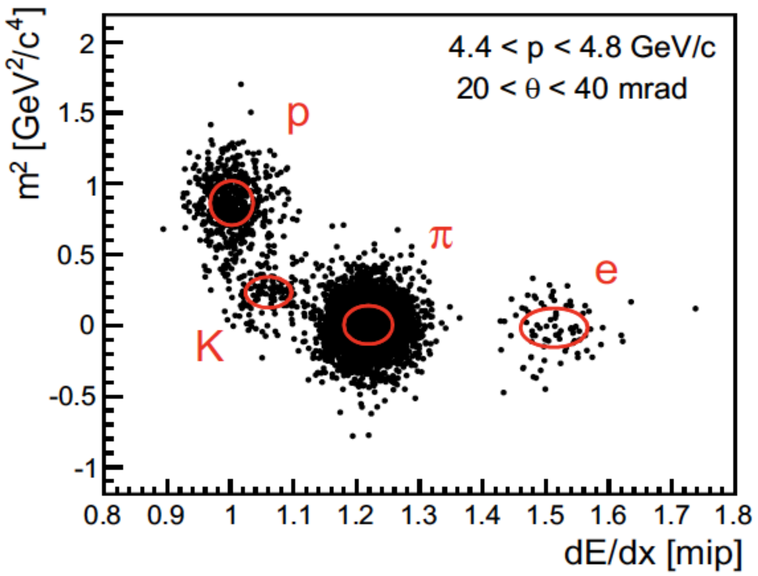




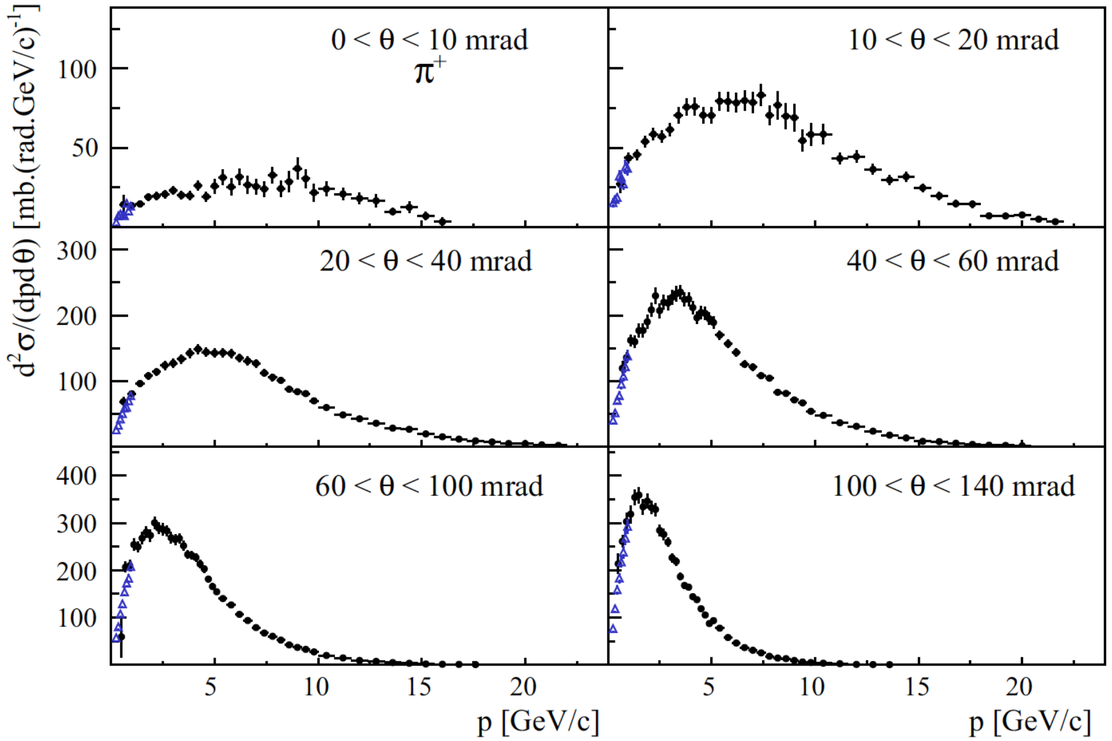
Results for T2K

2007-2010 data-taking

31 GeV/c proton beam collision on a 2cm graphite target.
Measured mesons () spectra and total cross-section:
Eur. Phys. J. C76 (2016) 84

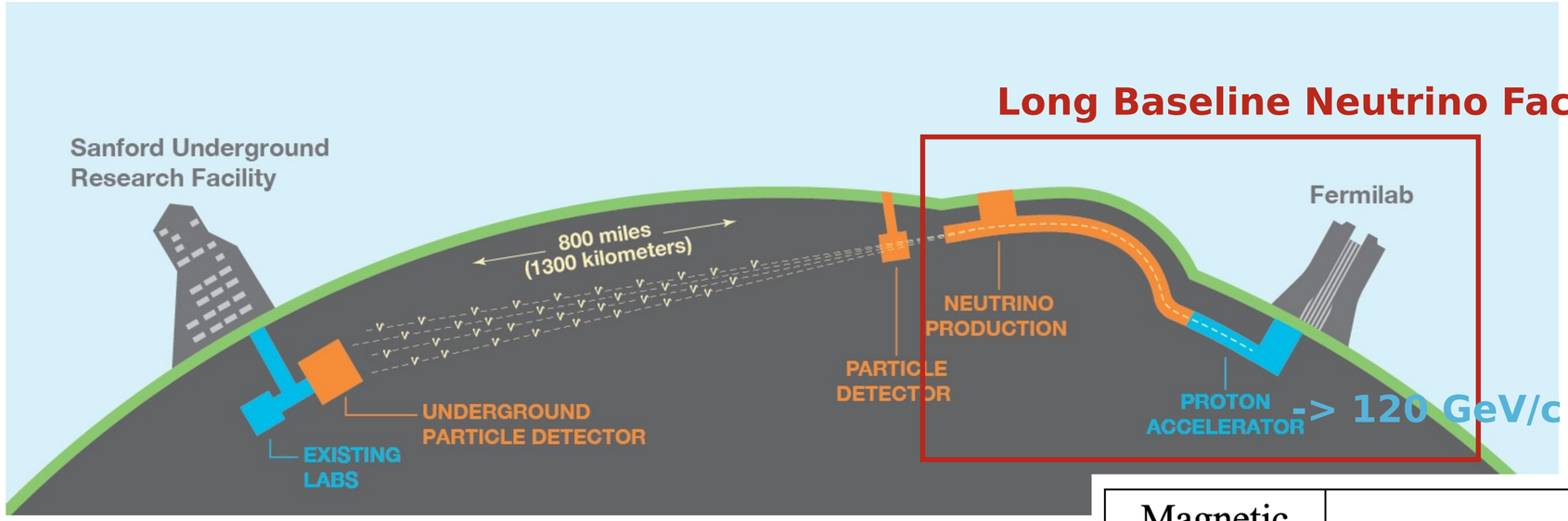


Result of tof-dEdX analysis for positively charged particles in a given bin



LBNF/DUNE data

Summer 2024



Magnetic field	80 GeV		158 GeV	
Target position	IN	OUT	IN	OUT
# of events	124,695,725	4,022,413	114,344,965	2,139,034
Total	245,202,137			

Future prospects: Low-Energy beamline

Conducted two beam tests (March and December 2023) at KEK ARTBL beamline

Silicon-based BPD

- Successfully reconstructed 2D beam profile (3 GeV electron beam, near MIP signal)

Time-of-Flight detector

- Two candidates: plastic scintillator (5mm thick) and GAGG inorganic crystal (0.5mm thick)
- Timing resolution is under evaluation