Recent results of the NA61/SHINE experiment

SHINE – SPS Heavy Ion and Neutrino Experiment

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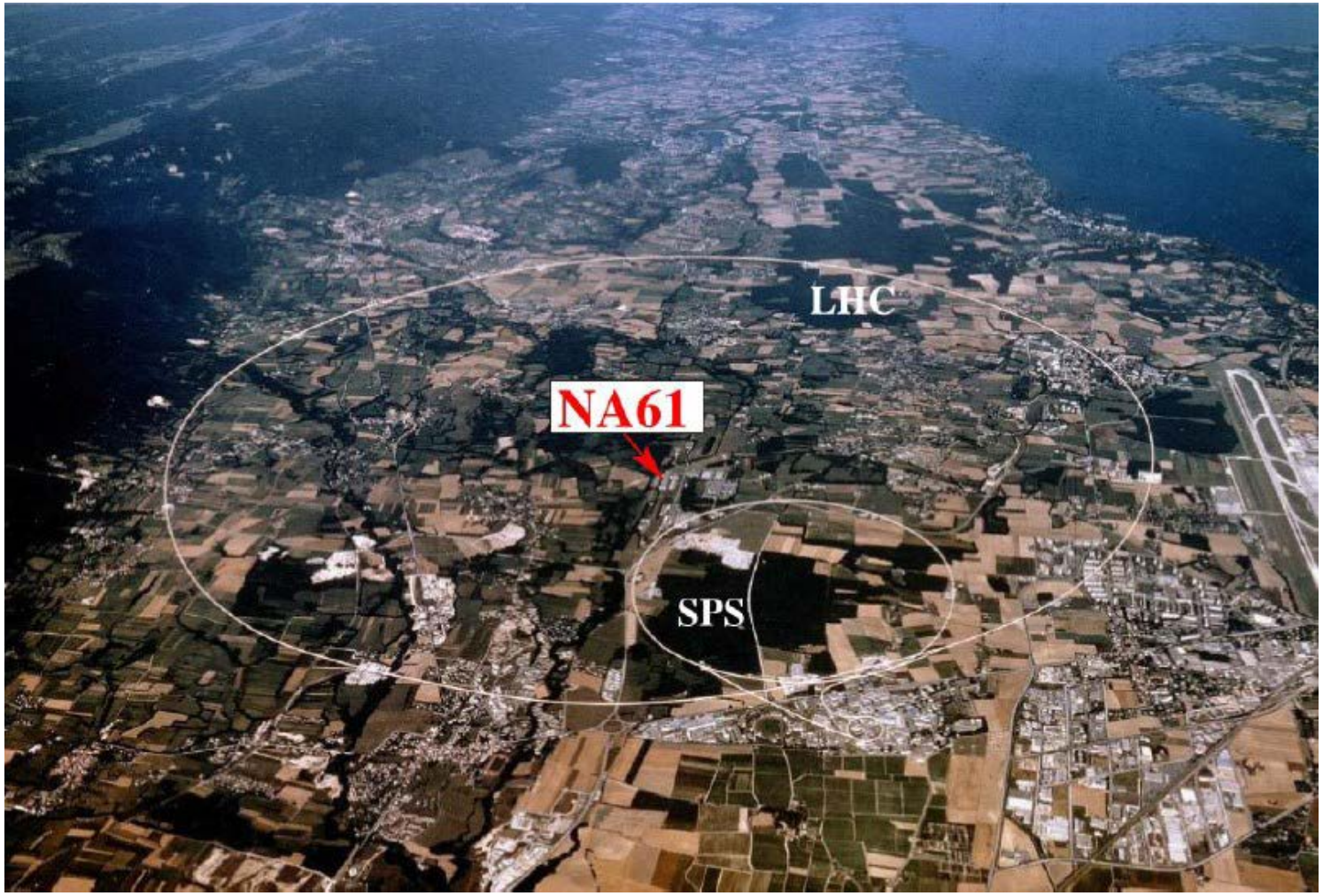
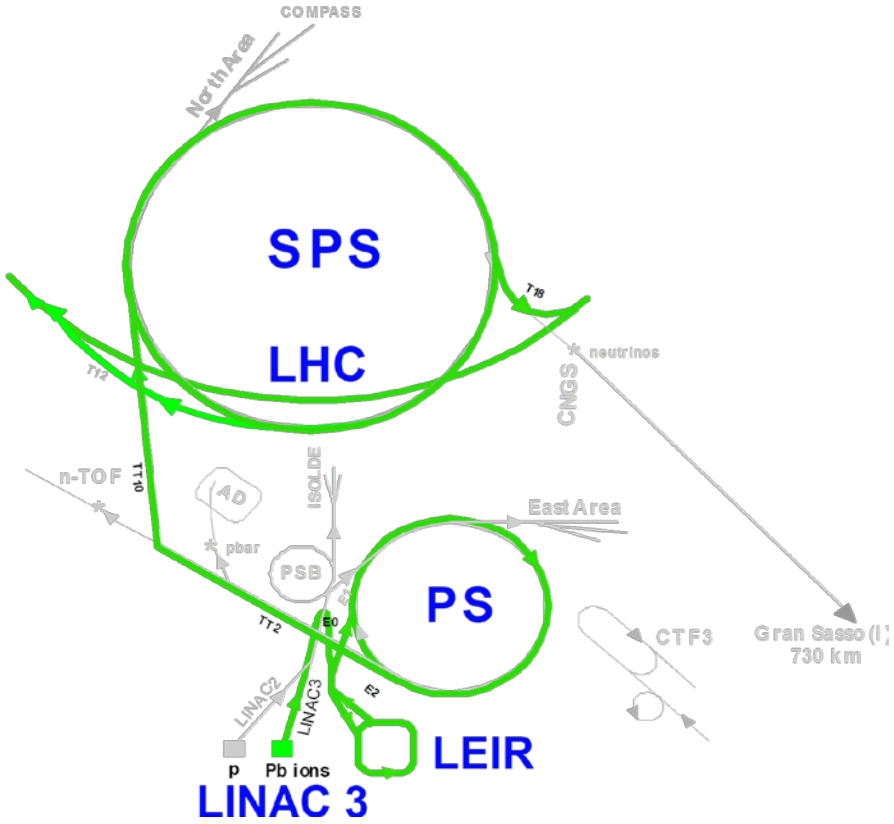
The NA61/SHINE experiment at CERN

- Facility
- Neutrinos
- Cosmic-rays
- Strong interactions

NA61/SHINE experiment at the CERN



NA61/SHINE
Acceleration chain and beams

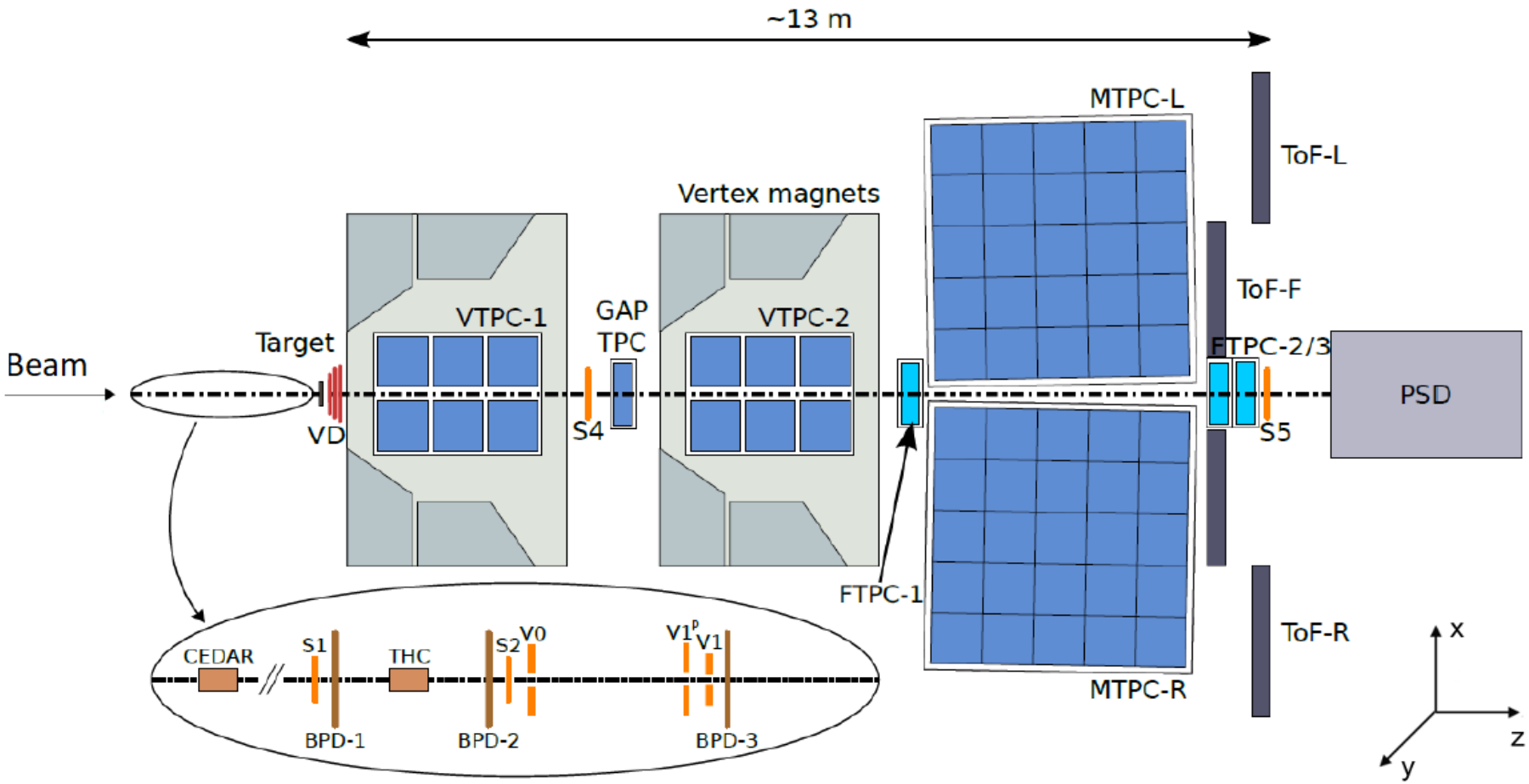


Beams: Unprecedented variety of masses and momenta

Primary beams:
- **Protons at 400 GeV/c**
- **Ions (Ar, Xe, Pb) at 13A – 150A GeV/c**

Secondary beams:
- **Hadrons ($\pi^{+/-}$, $K^{+/-}$, $p/\bar{p}$) at 13 - 400 GeV/c**
- **Ions (Be, C) at 13A - 150A GeV/c**

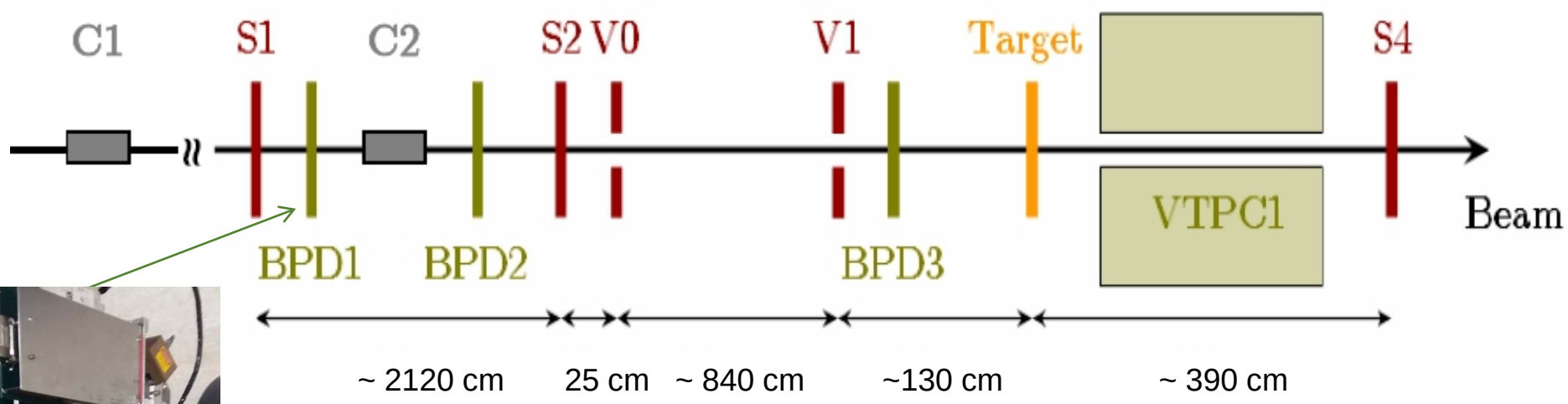
NA61/SHINE facility

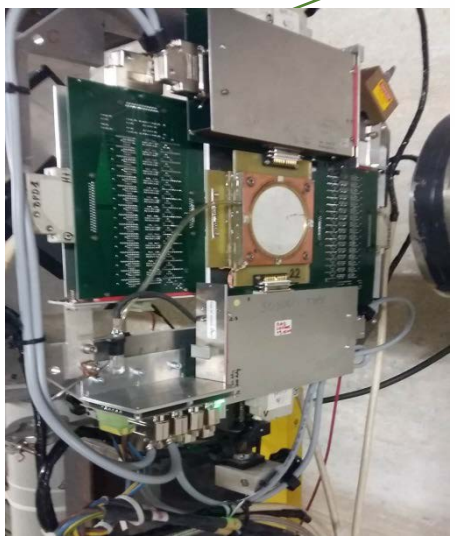


NA61/SHINE facility paper:
JINST 9 (2014) P06005

NA61/SHINE facility

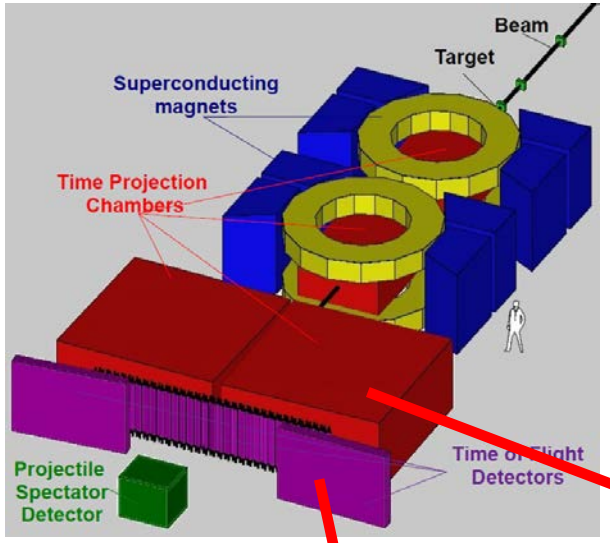
Beam and trigger counters



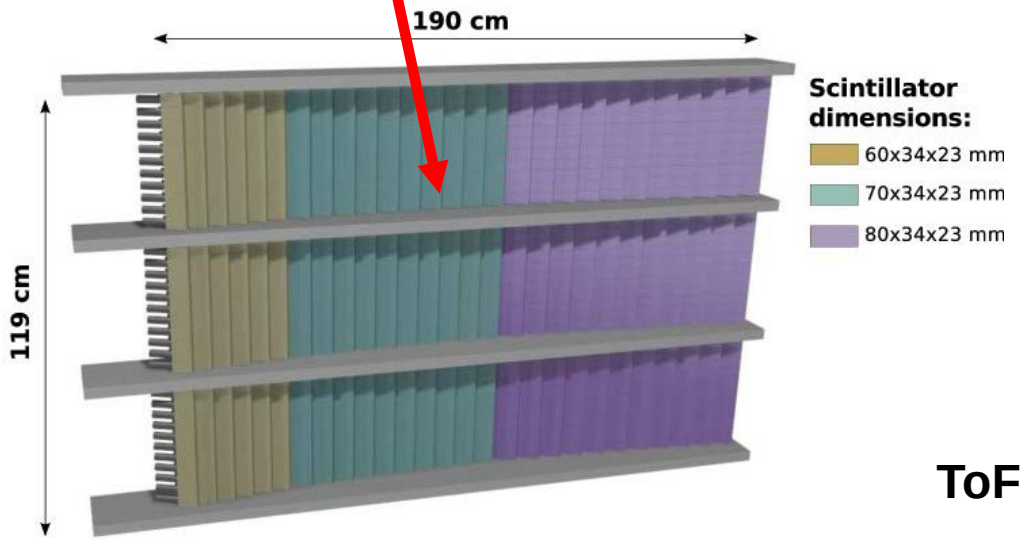


C1 and C2 - hadron identification,
S1, S2, V0, V1, BPD1/2/3 - determination of projectile trajectory,
S4 - selection of projectile+target interactions

NA61/SHINE facility

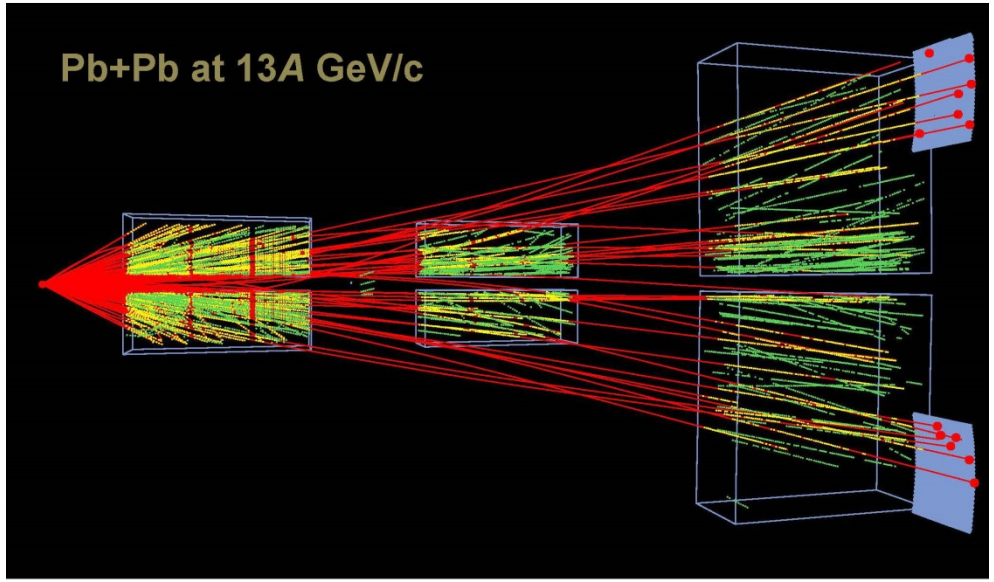


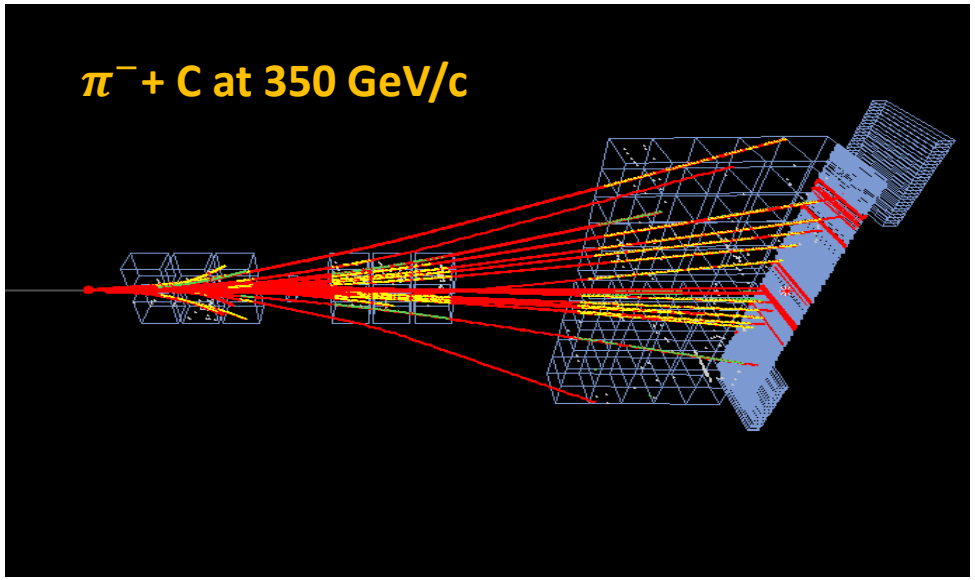
Time Projection Chambers (TPC)



ToF wall

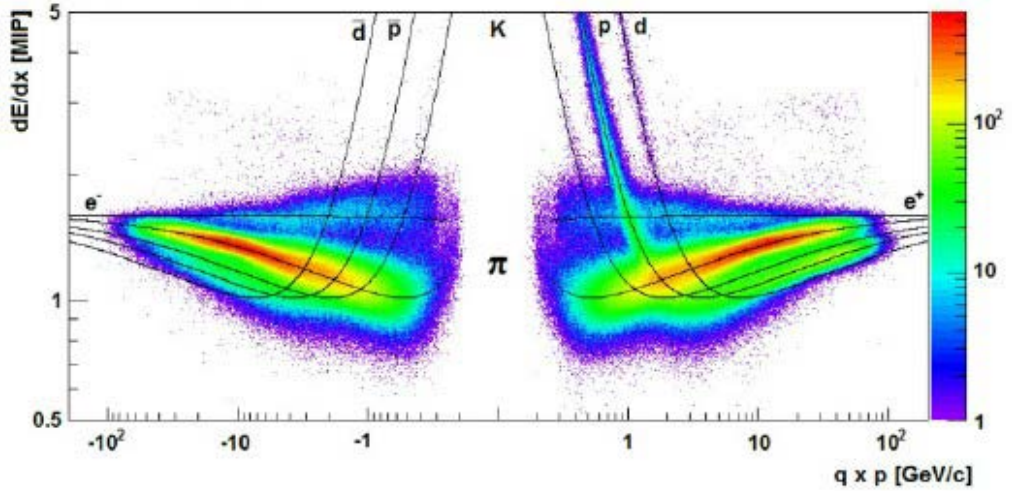
NA61/SHINE facility

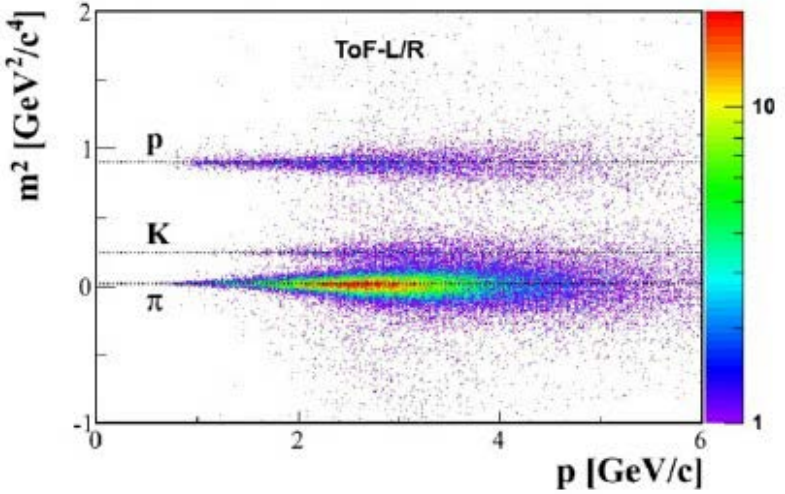


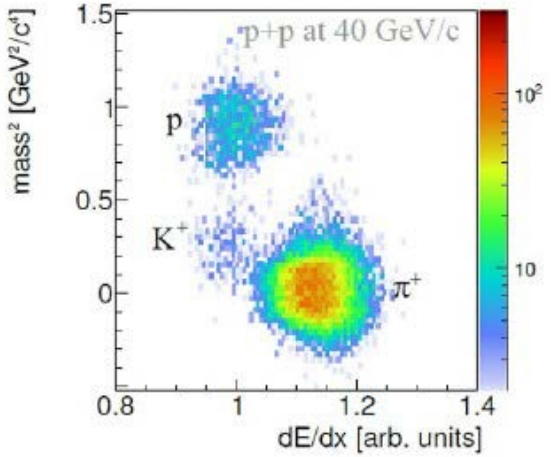


Precise measurements of produced particles properties :
electric charge, mass, momentum vector

NA61/SHINE Performance







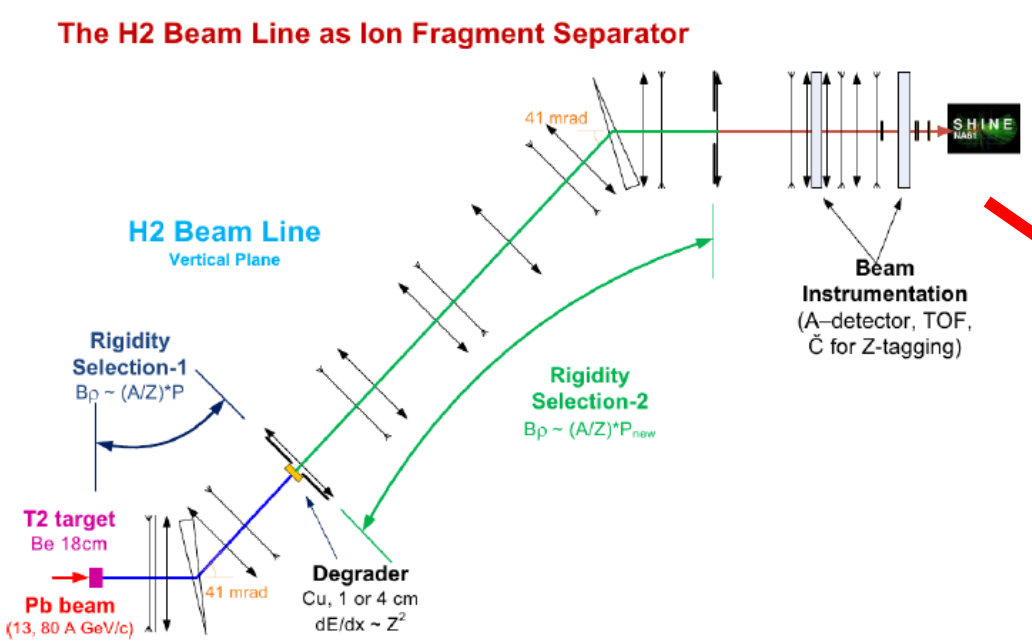
$$\sigma(p)/p^2 \approx 10^{-4}(GeV/c)^{-1}$$

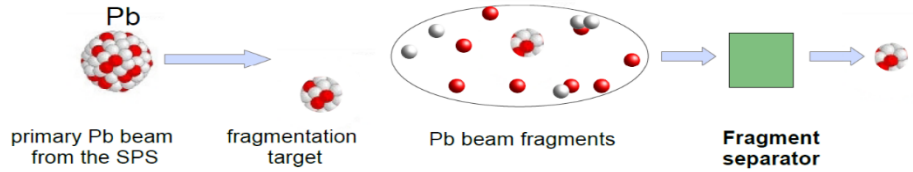
$$\sigma(dE/dx) \approx 4\%$$

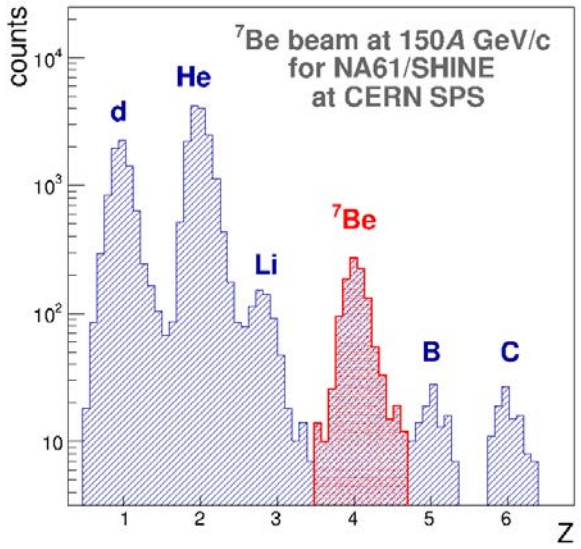
$$\sigma(ToF) \approx 100\,ps$$

NA61/SHINE facility

Secondary Ion Beam







The H2 beam line basically consists two spectrometers with 0.04% resolution that are used to separate the ion fragments corresponding to a selected magnetic rigidity : Bρ

Cherenkov Z-detector spectrum

NA61/SHINE facility

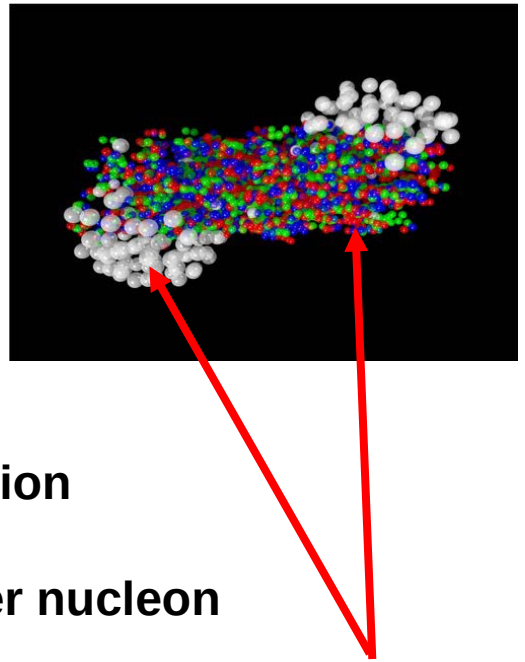
Projectile Spectator Detector (PSD)

Number of participants gives information on:

- **Centrality of nucleus-nucleus collisions**
- **Reaction plane orientation**

Number of participants:

$$N_p = A - \frac{E_S}{E_A}$$

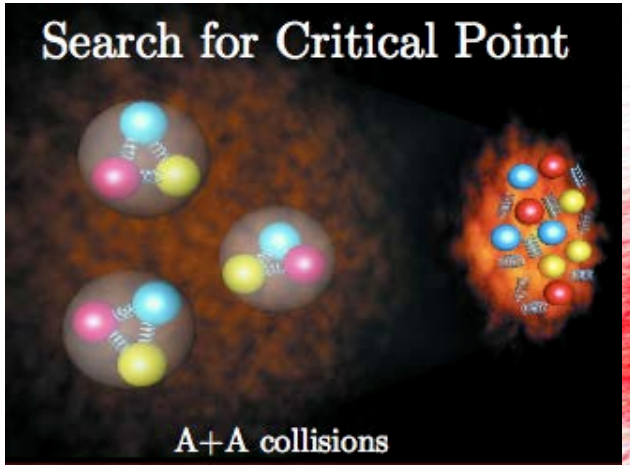


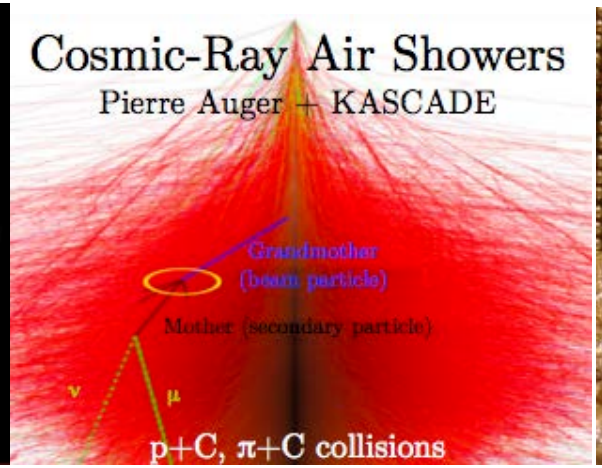
A – mass number of ion

E_A **– beam energy per nucleon**

E_S **– energy carried by the non-interacting nucleons (projectile spectators) measured by PSD**

NA61/SHINE
Physics program



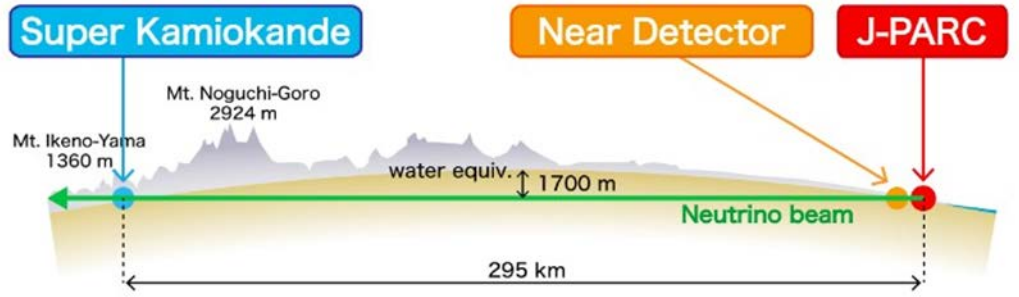


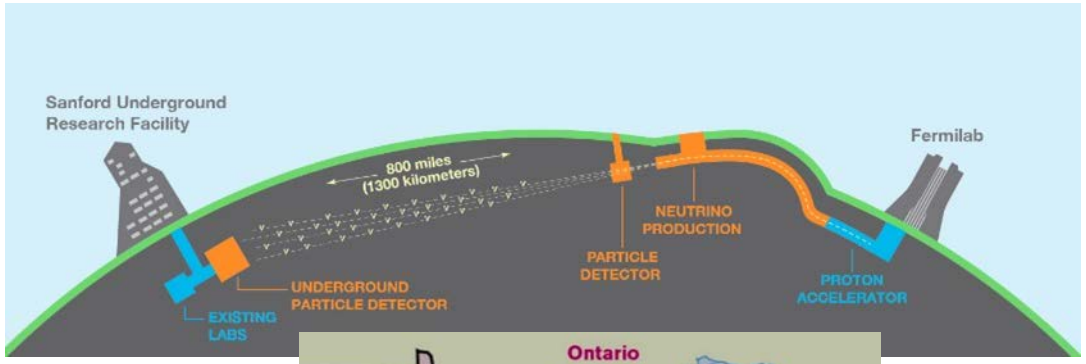
Long-Baseline Neutrino Oscillation Experiments

- Many prominent results over the past several years
- Active LB experiments:

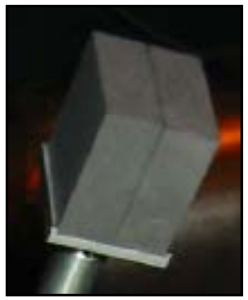
  - T2K, NOvA,…
- Future LB experiments:

  DUNE, Hyper-K,…
- Focus: discovery & precise parameter measurement
- Future experiments require tight control of systematic uncertainties



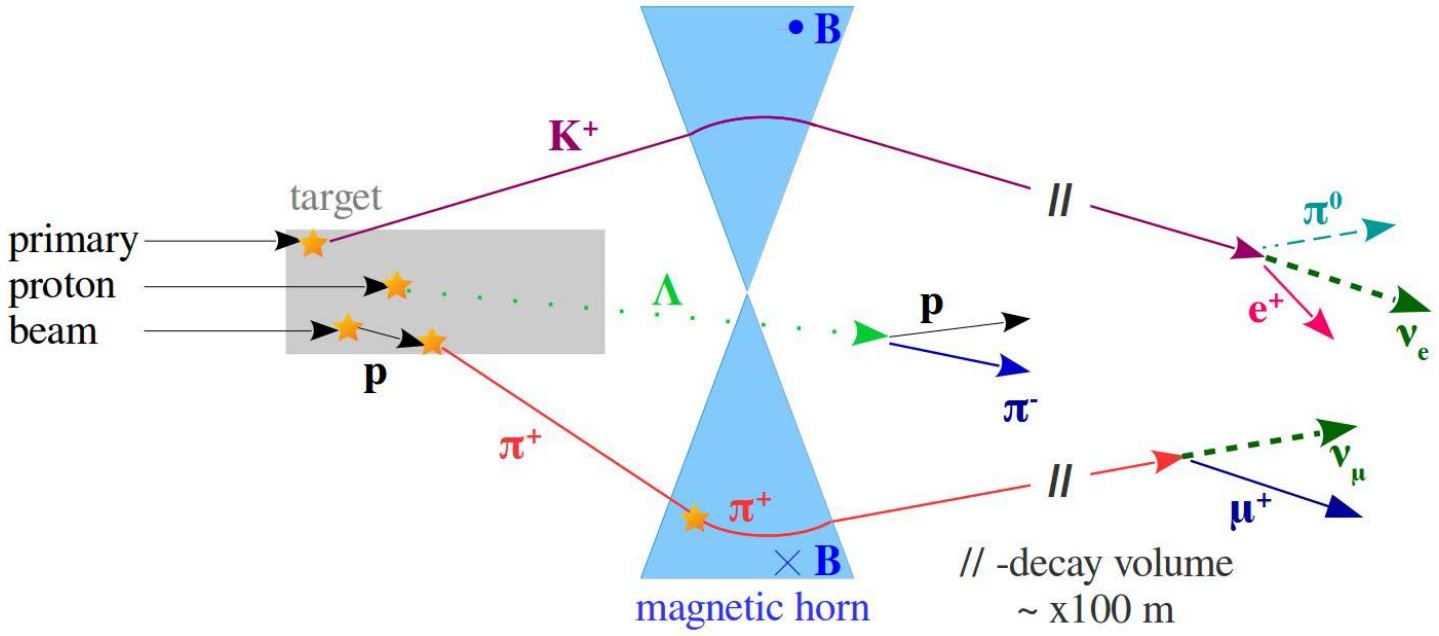


NA61/SHINE neutrino physics



Thin Carbon Target
length=2 cm
~0.04 λ_{int}

T2K replica Target
length = 90 cm, Ø=2.6 cm
~1.9 λ_{int}



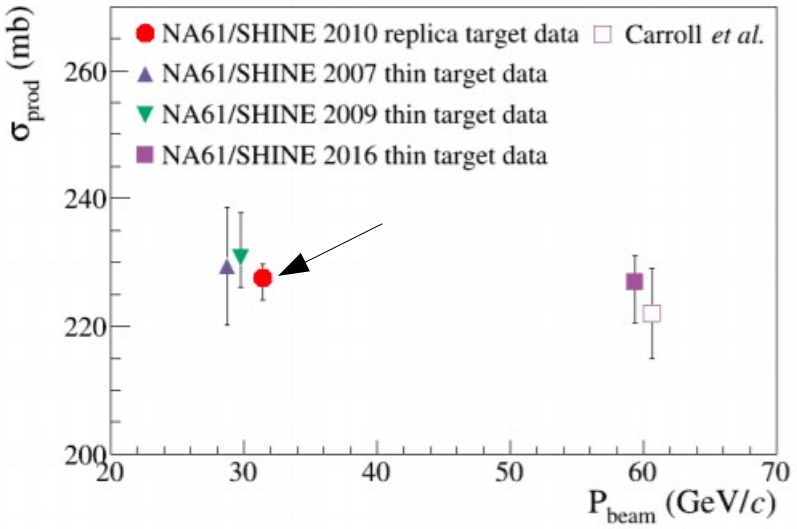
Important to study hadron production with the T2K replica target since ~ 30 – 50% of π, K from secondary interactions, which in general are very difficult to model.

Data for both targets required to model reliably the neutrino flux.

T2K Replica Target Production Cross-Section

- Production cross-section measured via beam attenuation in 90-cm T2K Replica Target
- Full magnetic field setting used for improved measurement of elastic and quasi-elastic protons
- Result consistent with 30 GeV/c proton-carbon thin-target measurement
  - Improved overall precision
- Will help reduce T2K flux prediction uncertainty

T2K Replica Target



Phys. Rev. D 103, 012006 (12 Jan. 2021)

Thin Target Results

Inelastic & production cross-section measurements

Used to weight hadron production to correct neutrino flux predictions

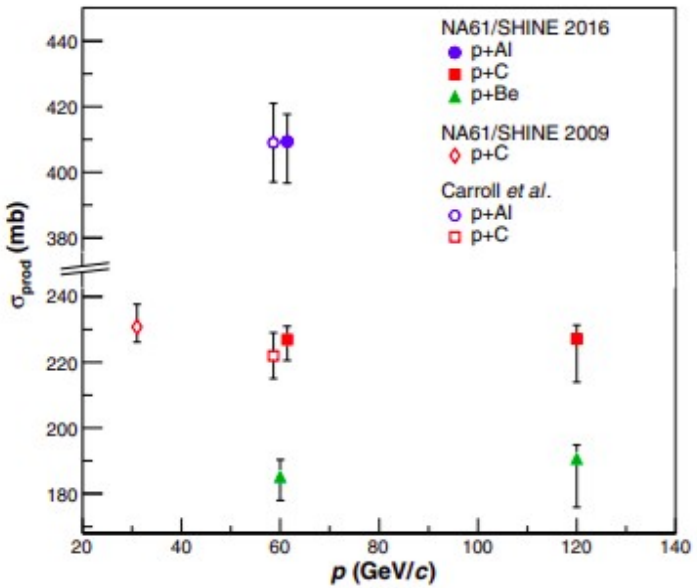
Phys. Rev. D 98, 052001 (2018):

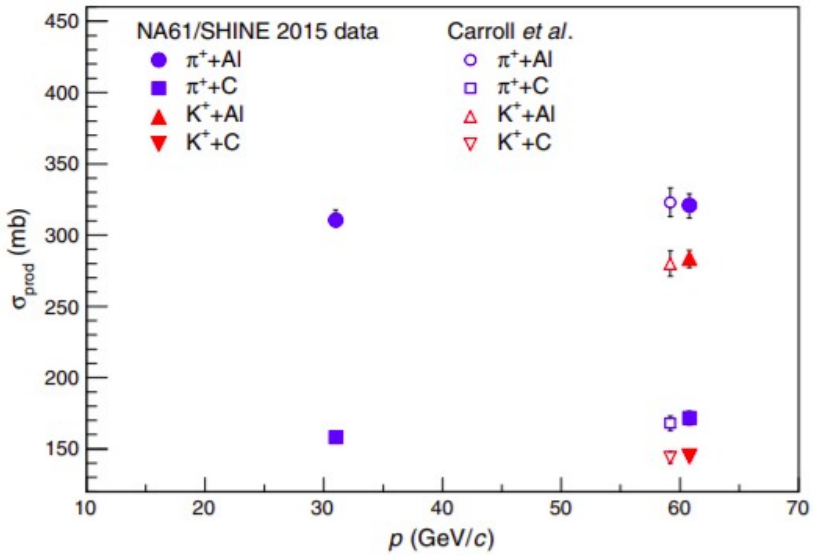
π^+ on C, Al (31 & 60 GeV/c)

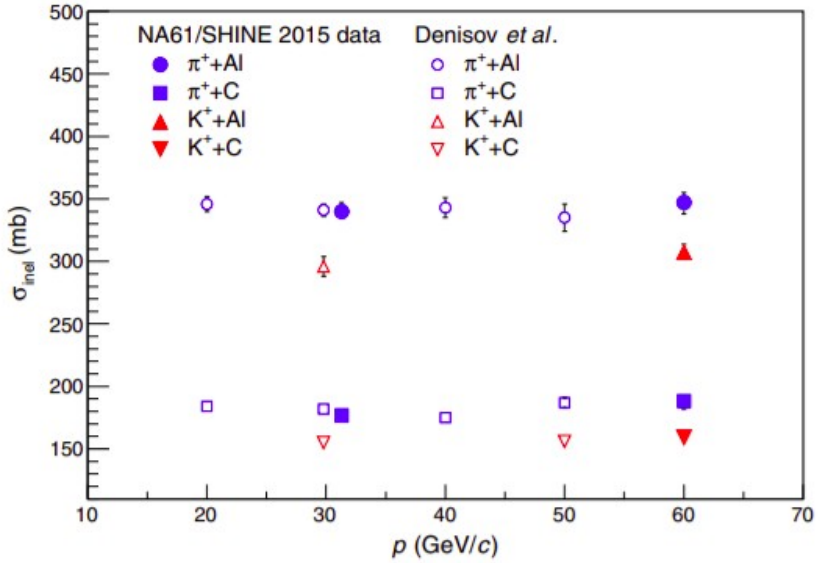
π^+ on Be (60 GeV/c) K^+ on C, Al (60 GeV/c)

Phys. Rev. D 100, 112001 (2019):

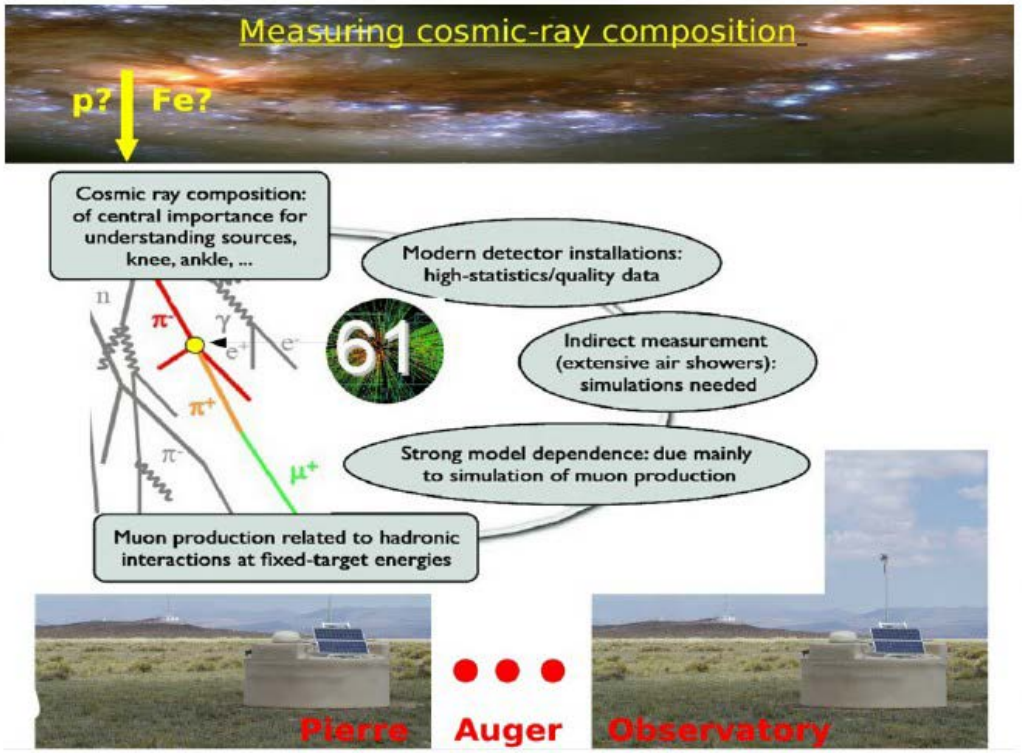
p on C, Be (60 & 120 GeV/c), p on Al (60 GeV/c)

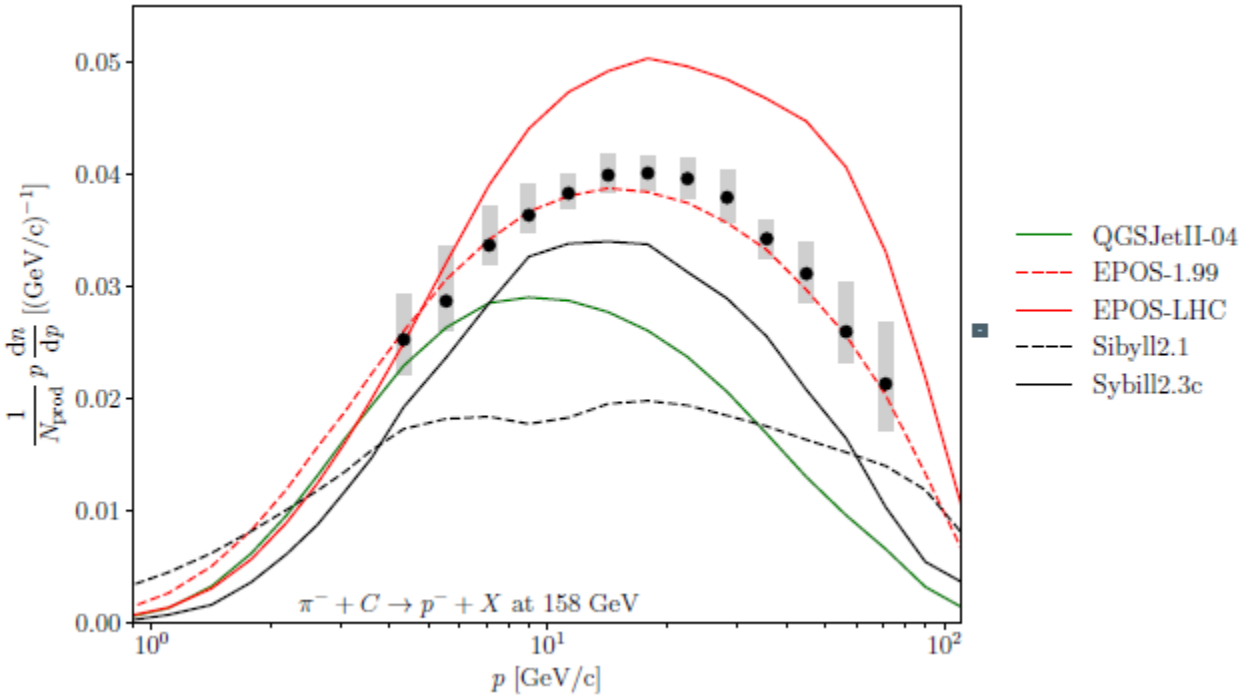






NA61/SHINE: Cosmic rays





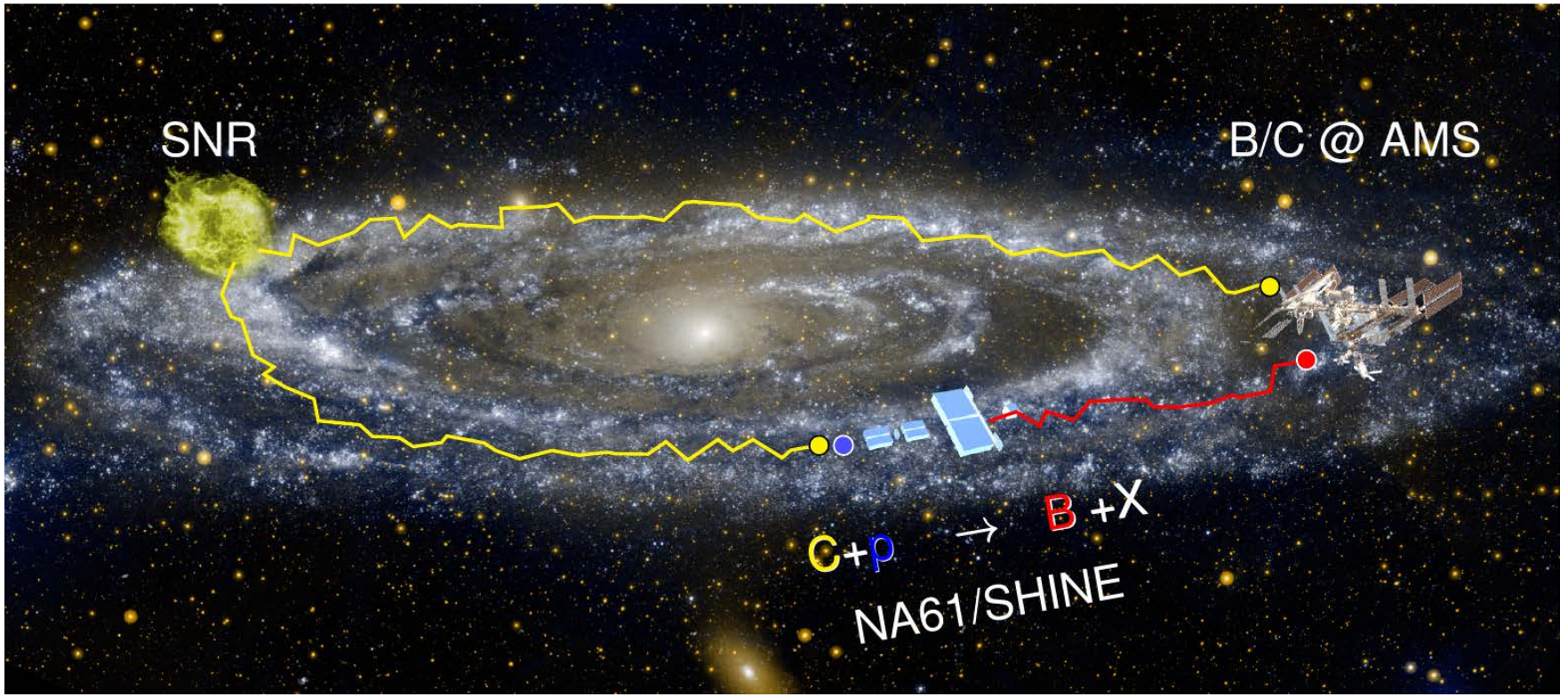
NA61/SHINE significantly improves precision of the world data

Production of $\bar{p}$ in π^- + C reaction at 158 GeV

Proposal of measurement of Nuclear Fragmentation Cross Sections (NFCS)

Motivation: NFCS of intermediate mass nuclei are needed to understand the propagation of cosmic rays in our Galaxy

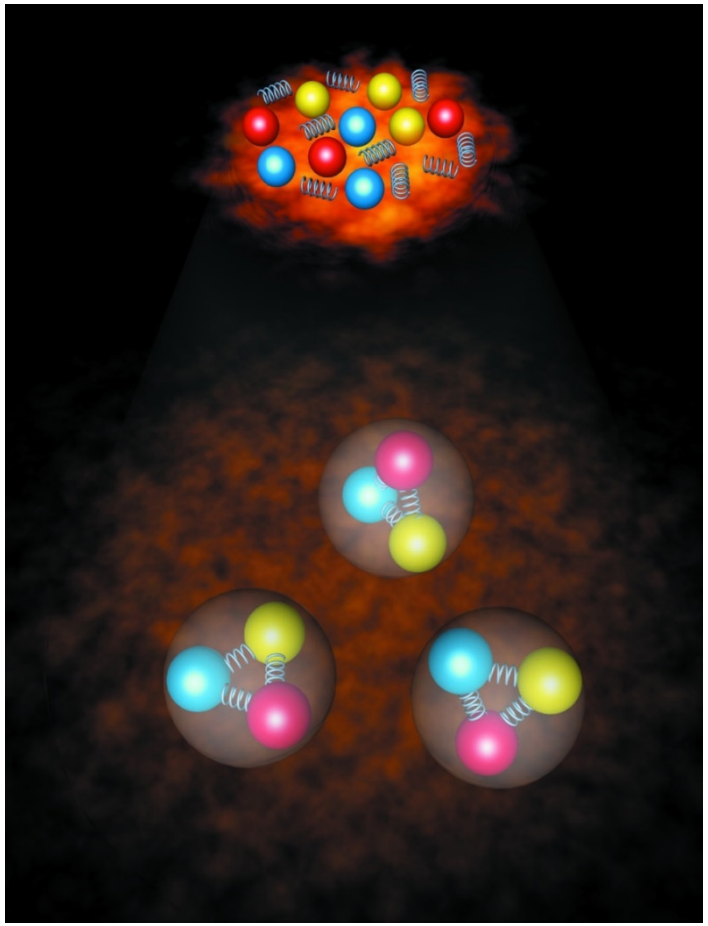
→ background for dark matter searches with space-based experiments as AMS



NA61/SHINE: physics of strongly interacting matter

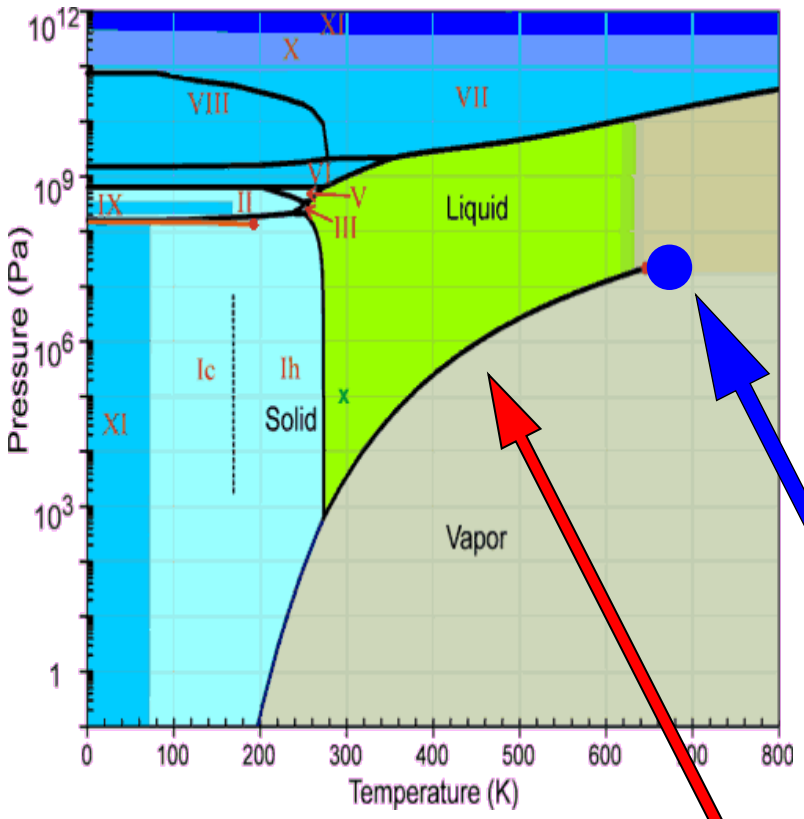
Phases of water
(electro-magnetic interactions)

Phases of strongly interacting matter

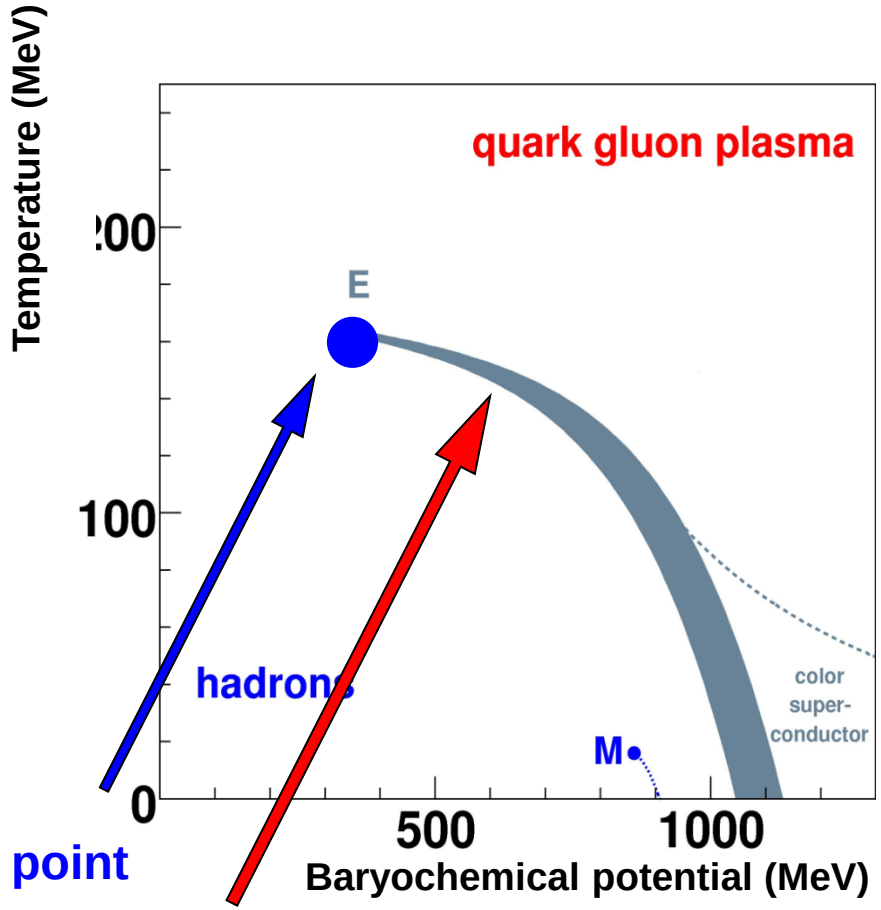


Physics of strongly interacting matter in NA61/SHINE

water

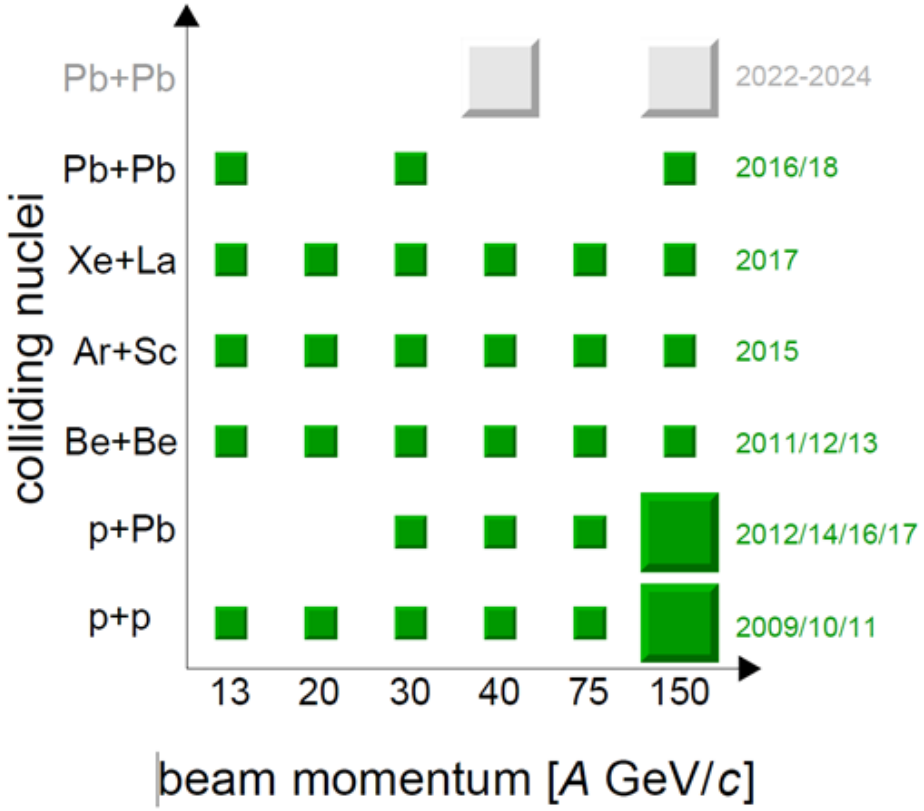


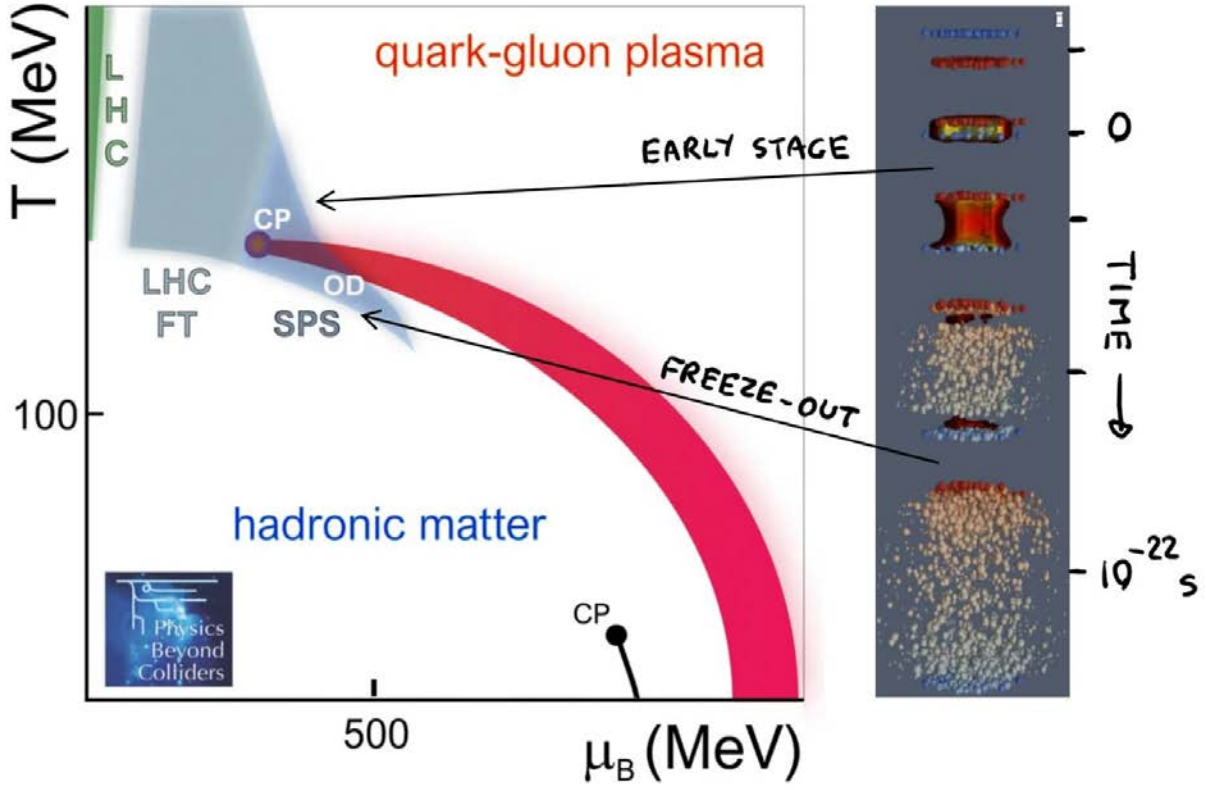
strongly interacting matter



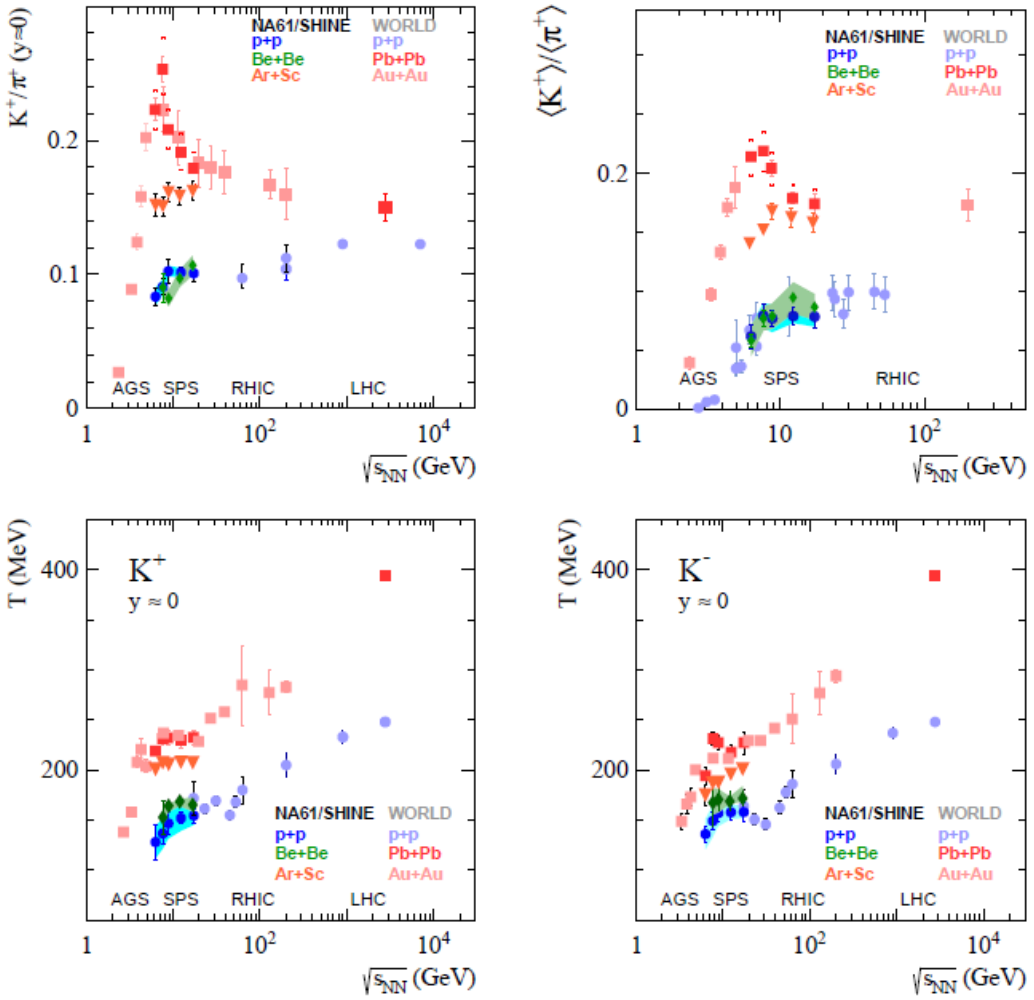
1st order phase transition

NA61/SHINE: collected data





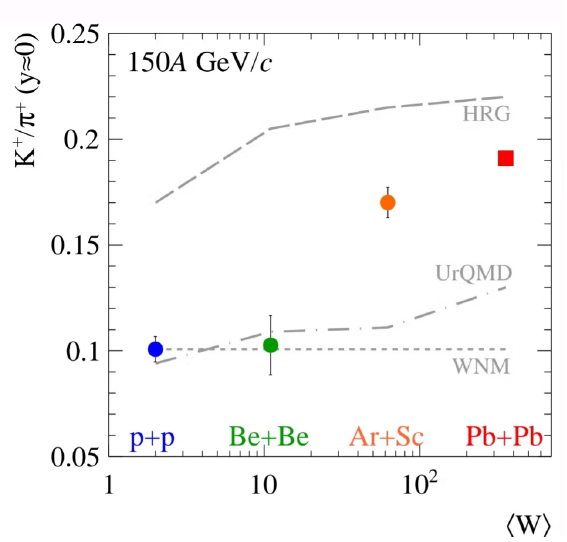
Onset of deconfinement

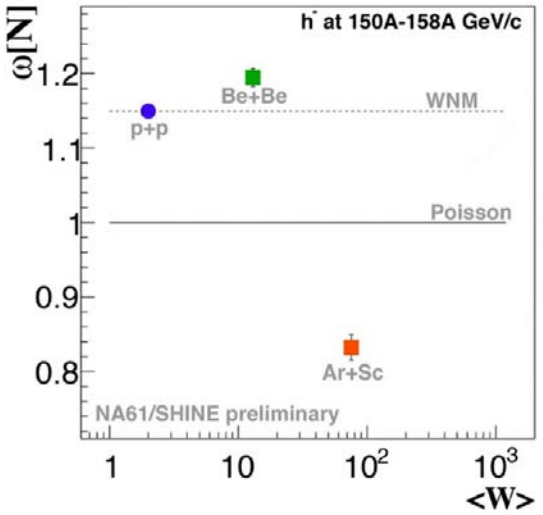


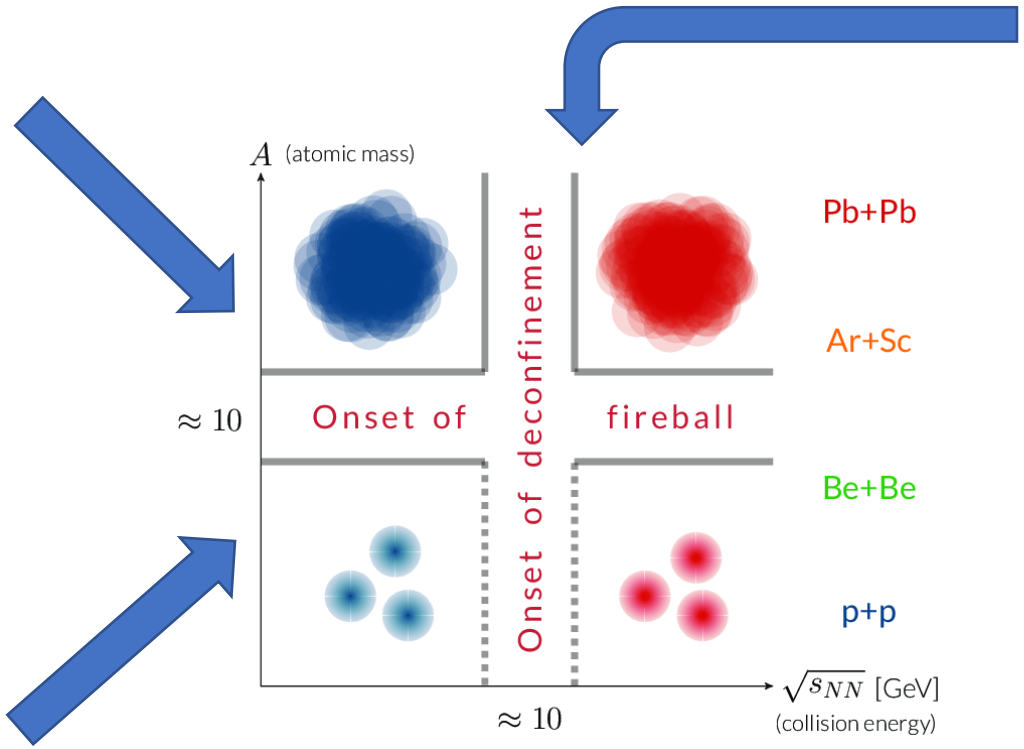
$$p+p \approx Be+Be \neq Ar+Sc \leq Pb+Pb$$

- Precise measurements on collisions 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 T in heavy-ion collisions shows the so-called *step* structure

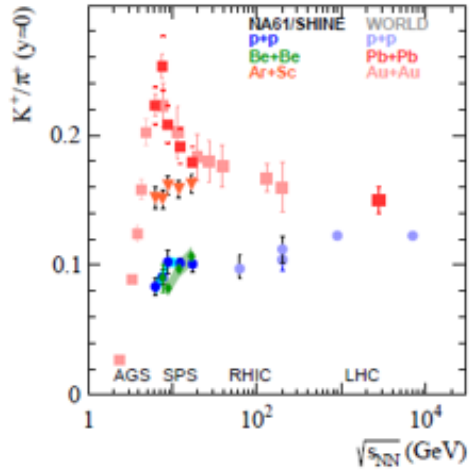
Uniqueness of heavy ion results from NA61/SHINE







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

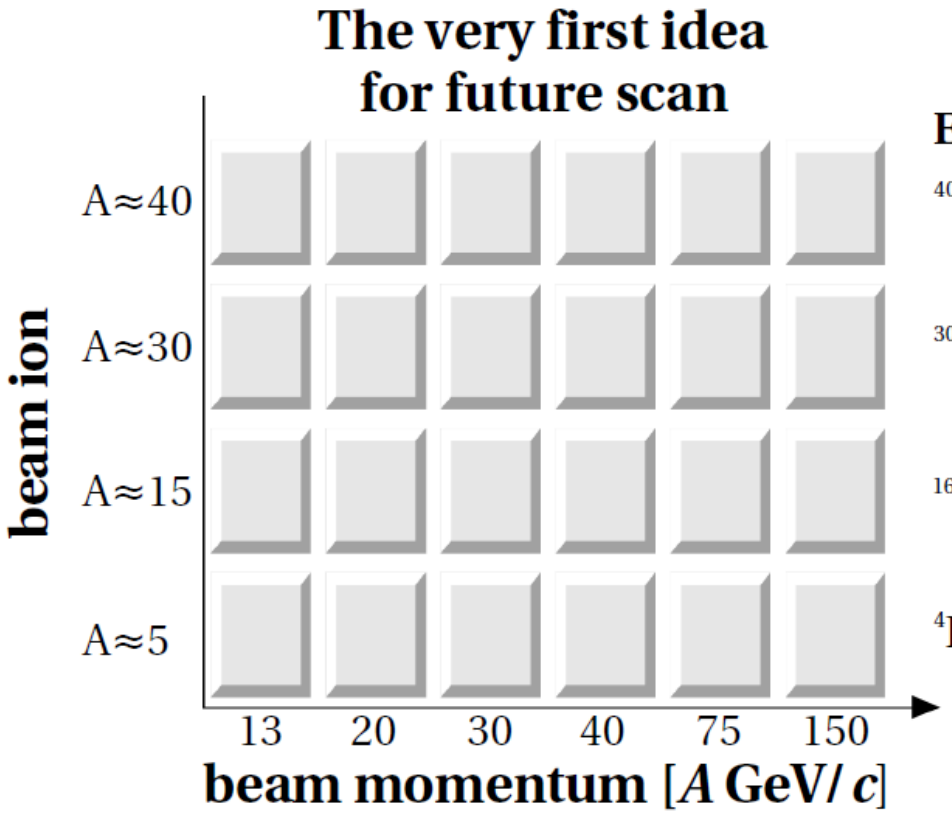


- Two onsets in nucleus-nucleus collisions
- Onset of deconfinement - beginning of QGP formation
- Onset of fireball - beginning of formation of a large cluster which decays statistically

$\omega[N]$ – *scaled variance*

WNM – wounded nucleon model

Onset of fireball - measurements after LS3



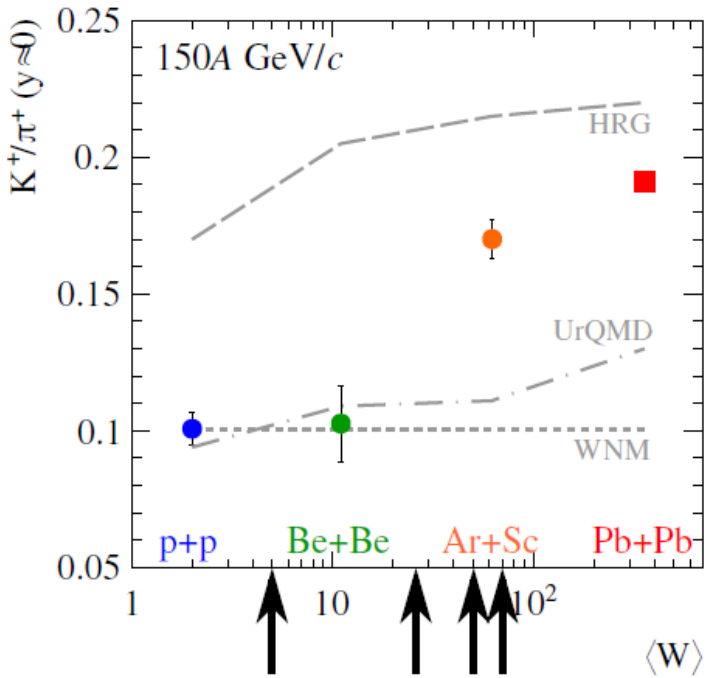
Example ion:

^{40}Ca Synergy with Gamma Factory

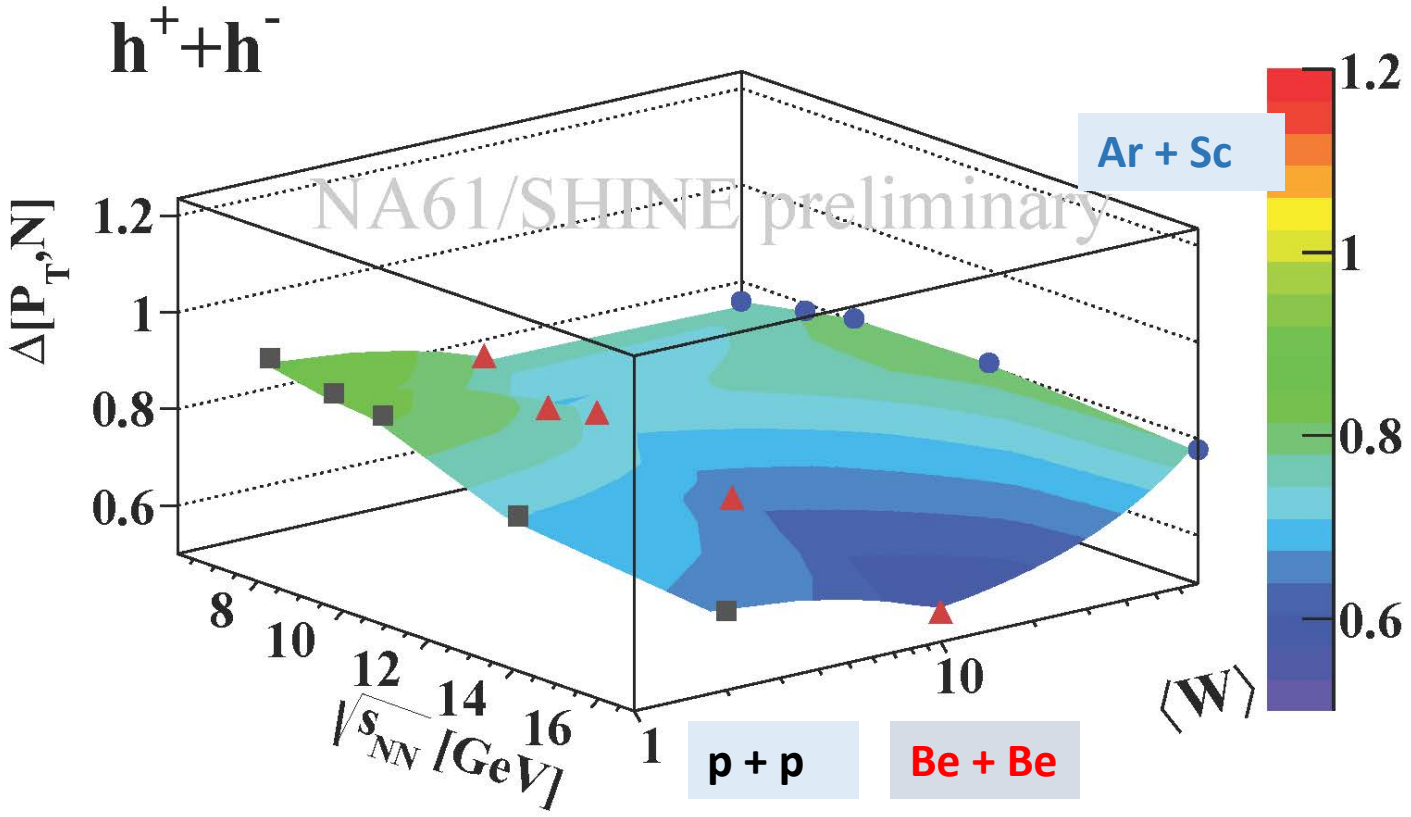
^{30}P

^{16}O Synergy with Cosmic-Ray LHC

^{4}He

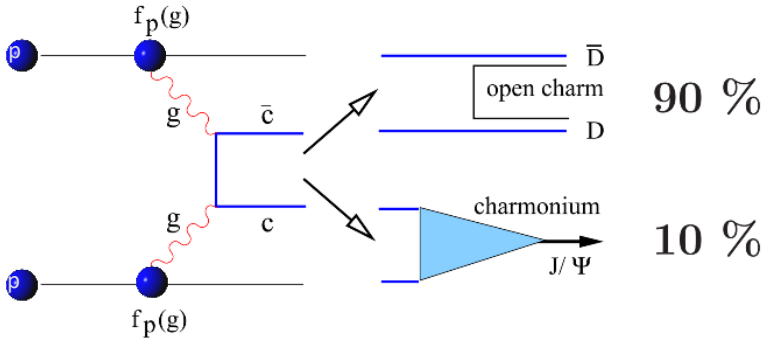


Search for critical point

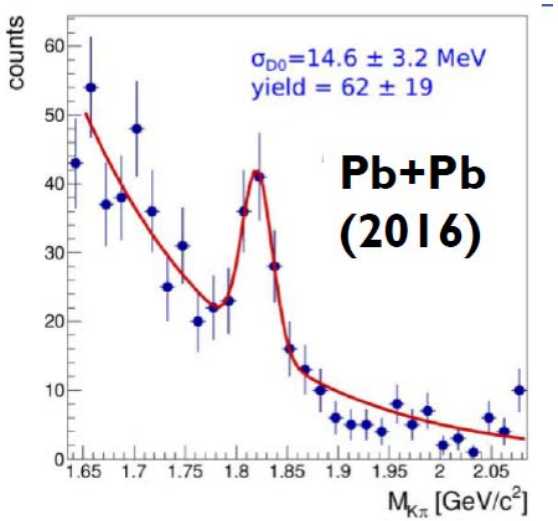


Up to now no evidence for expected „hill" of fluctuations

Charm production and the onset of deconfinement

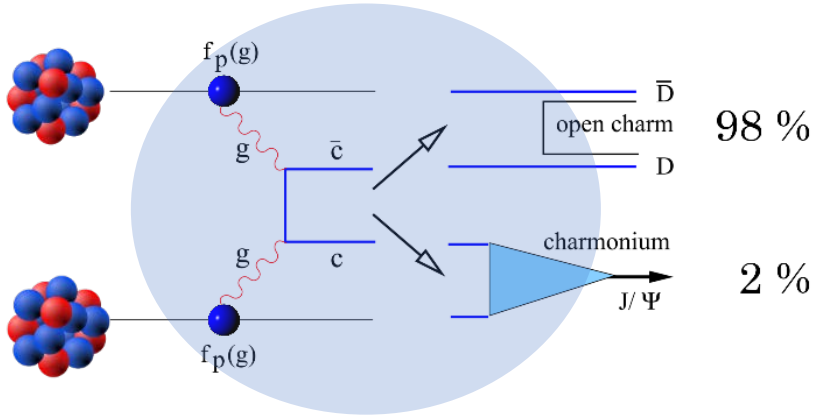


Open charm and J/ψ production within Matsui-Satz model
[PL B178 416]



NA61/SHINE pilot measurements
open charm signal in Pb+Pb at 150 A GeV/c

Pb+Pb with QGP



- 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?

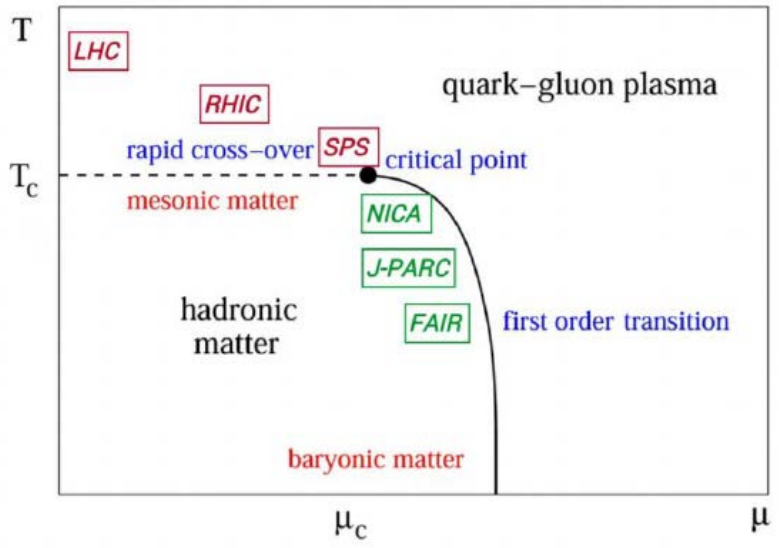
Medium reduces probability of J/ψ production

$$P(c\bar{c} \to J/\psi) \equiv \frac{< J/\psi >}{< c\bar{c} >} \equiv \frac{\sigma_{J/\psi}}{\sigma_{c\bar{c}}}$$

$$P_{\text{vacuum}}(c\bar{c} \to J/\psi) \quad > \quad P_{\text{medium}}(c\bar{c} \to J/\psi)$$

Uniqueness of NA61 open charm program

Landscape of present and future heavy ion experiments



Only NA61/SHINE is able to measure open charm production in heavy ion collisions in full phase space in the near future

- LHC and RHIC at high energies: measurements of open charm are performed in a significantly limited acceptance; this limitation is due to the collider kinematics and related to the detector geometry
- RHIC BES collider ($\sqrt{s_{NN}} = 7.7\ GeV\ - 39\ GeV$): measurement not considered in the current program, this may likely be due to difficulties related to collider geometry and kinematics as well as the low charm production cross-section
- RHIC BES fixed-target ($\sqrt{s_{NN}} = 3\ GeV\ - 7.7\ GeV$): not considered in the current program
- NICA ($\sqrt{s_{NN}} =< 11\ GeV$): measurements during stage 2 (after 2023) are under consideration
- J-PARC-HI ($\sqrt{s_{NN}} \lesssim 6\ GeV$): under consideration, may be possible after 2025
- FAIR SIS-100 ($\sqrt{s_{NN}} \lesssim 5\ GeV$): not possible due to the very low cross-section at SIS-100, systematic charm measurements are planned with SIS-300 (($\sqrt{s_{NN}} \lesssim 7\ GeV$) which is part of the FAIR project, but not of the start version

Beyond approved program 2026 - 2029

- **Detailed 2D scan to study onset of fireball region**
- **Measurements of hadron production from the LBNF and HYPER-K replica targets**
- **Measurements with anti-proton beams**
- **Data for flux predictions at neutrino experiments using Very Low Energy beams**

Summary

- 2D scan measurement in system size and the collision energy was completed
- NA61/SHINE delivers reach information about the onset of deconfinement in the light and medium-size system
- The onset of Fireball - unexpected system size dependence
- So far, no convincing indication of the critical point
- NA61/SHINE will measure open charm production in 2022- 2024

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COLLABORATION