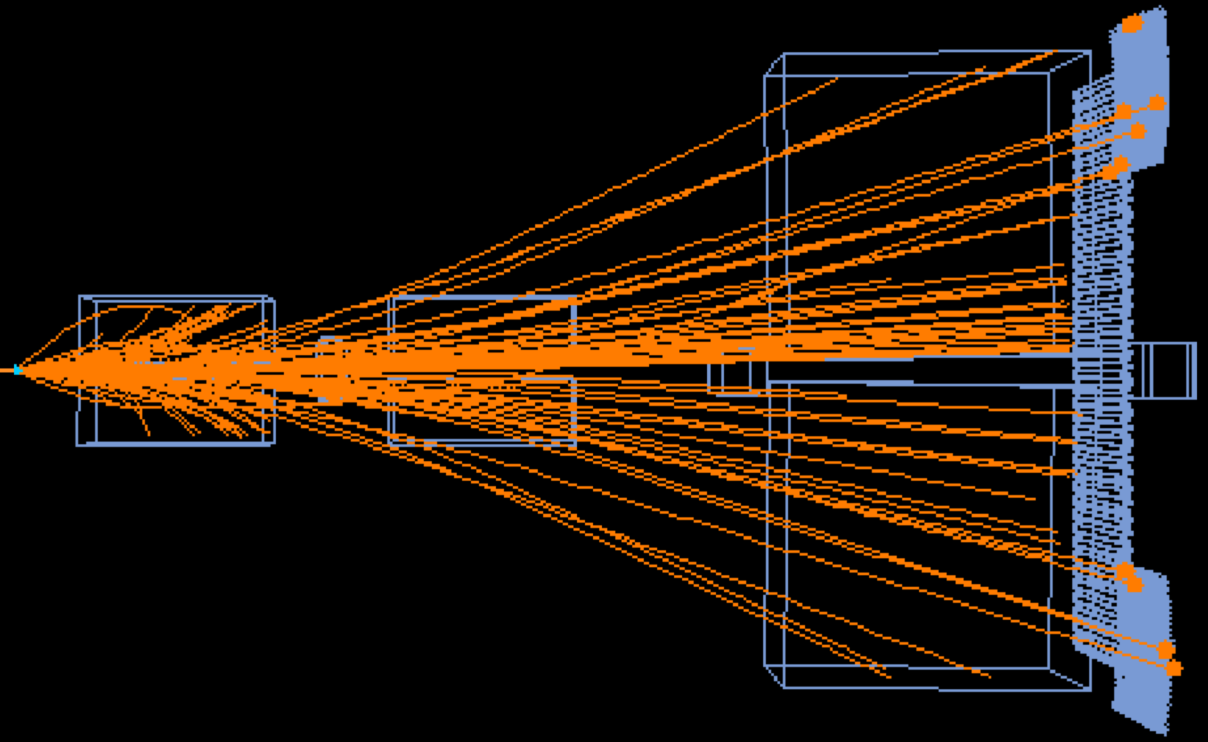
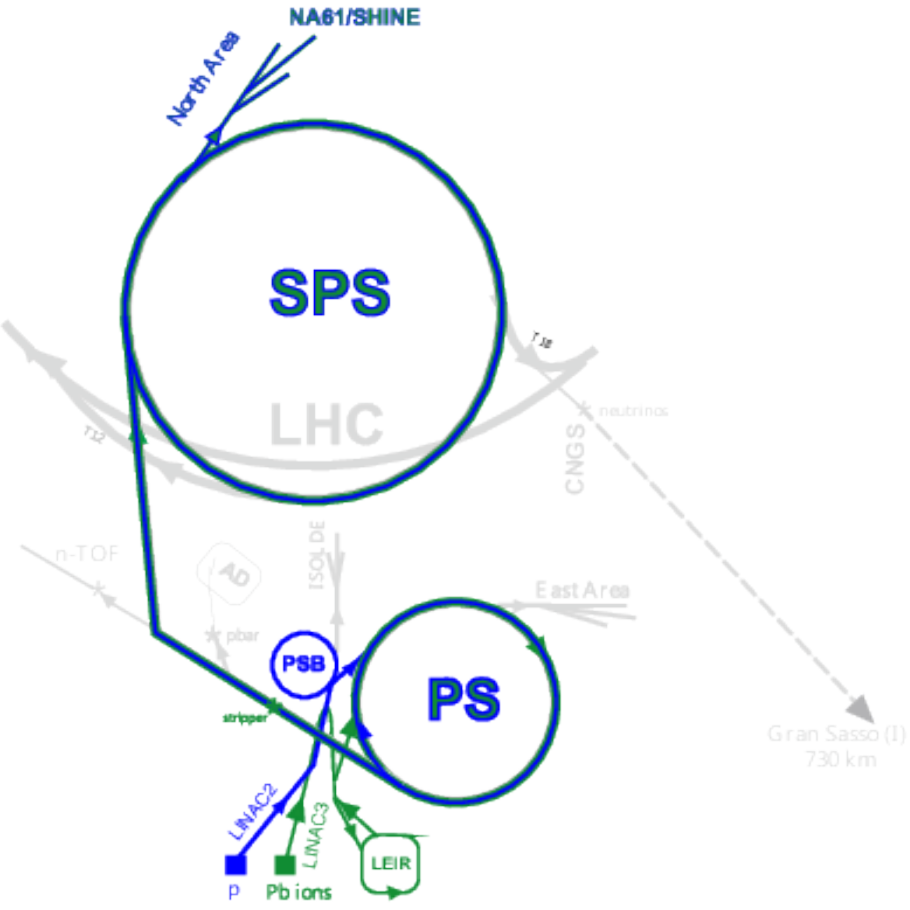
Future physics program and prospects

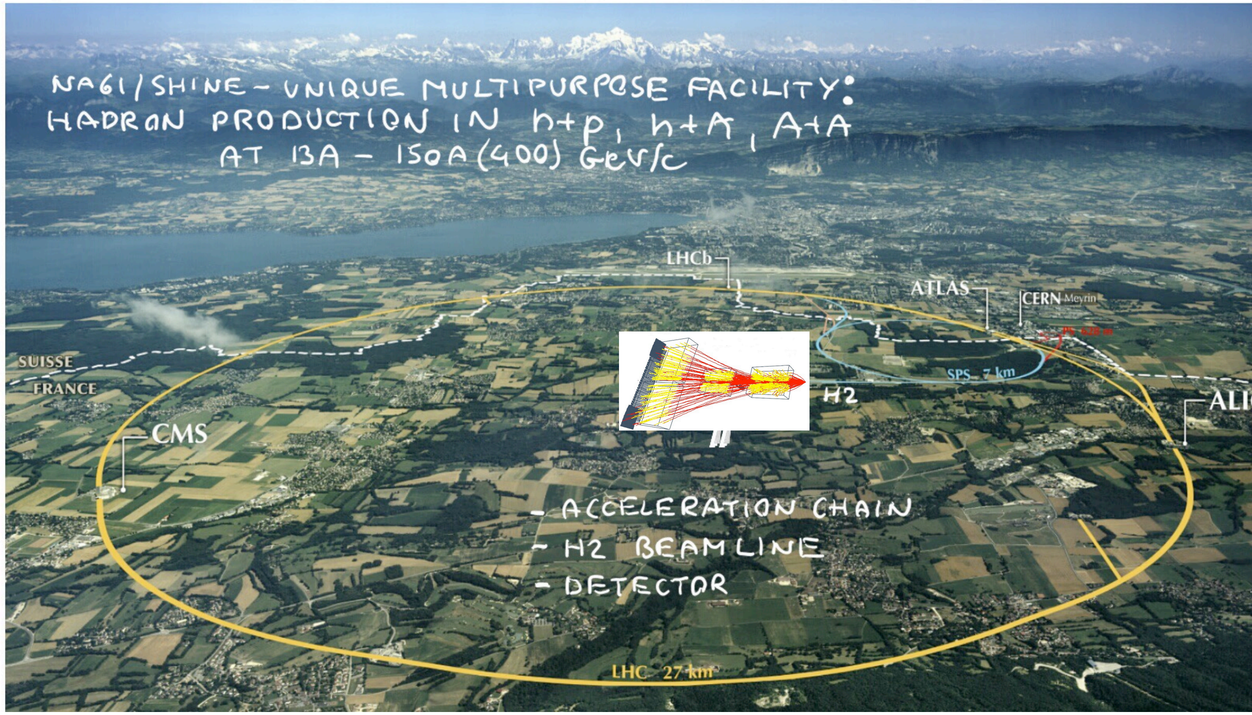
for the NA61/SHINE large acceptance particle spectrometer at the CERN SPS



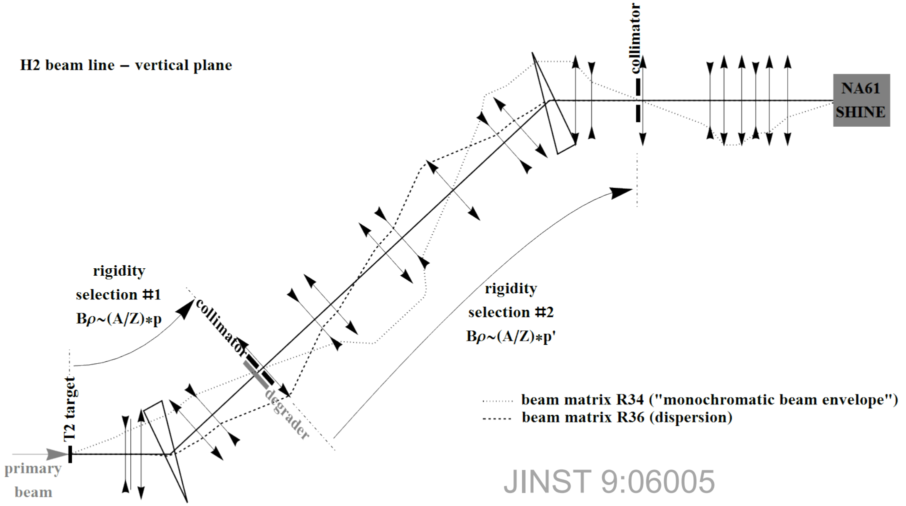
Andrey Seryakov
for the NA61/SHINE collaboration
20th ZIMÁNYI SCHOOL WINTER WORKSHOP ON HEAVY ION PHYSICS
ZOOM, 07/12/2020, andrey.seryakov@cern.ch

UNIQUE BEAM LINE





primary and secondary beams

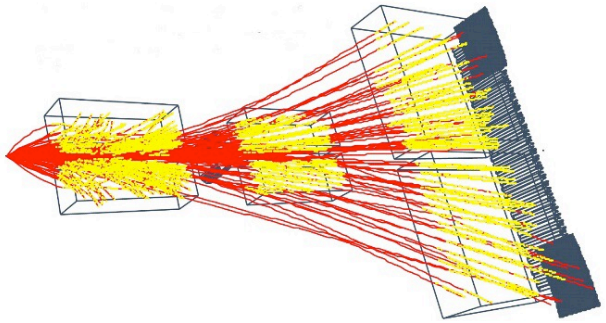


JINST 9:06005

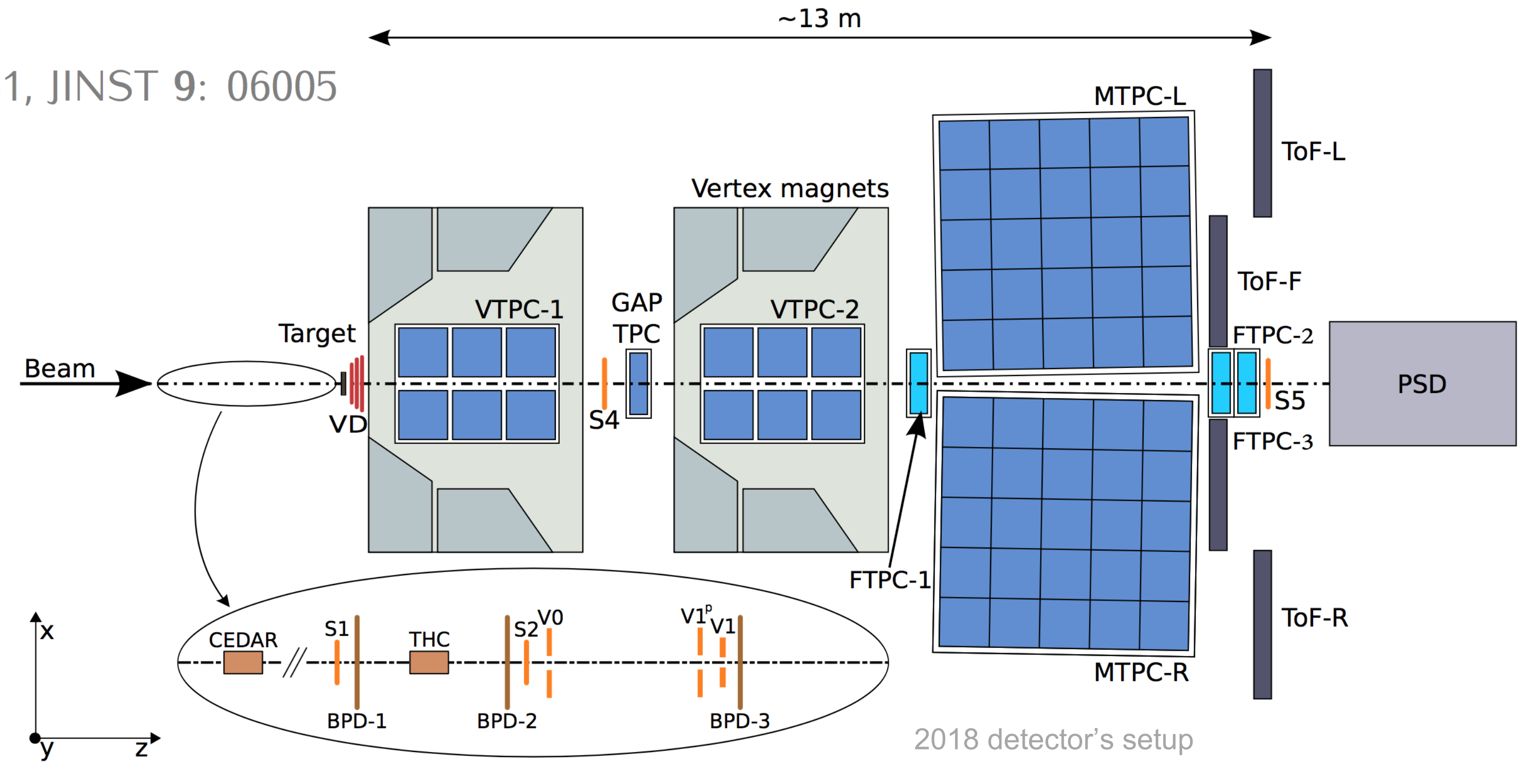
- hadrons (p, pi, …)
  13 – 400 GeV/c

- ions (Be, Ar, Pb …)
  13 – 150*A* GeV/c

LARGE ACCEPTANCE DETECTOR



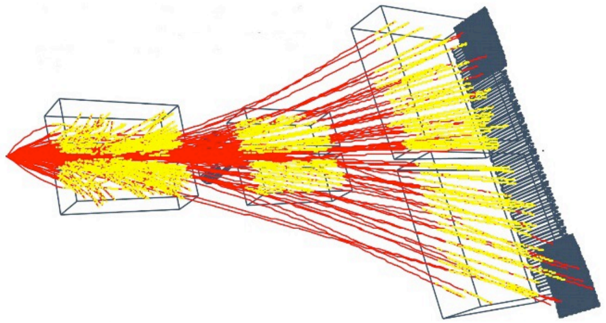
NA61, JINST 9: 06005



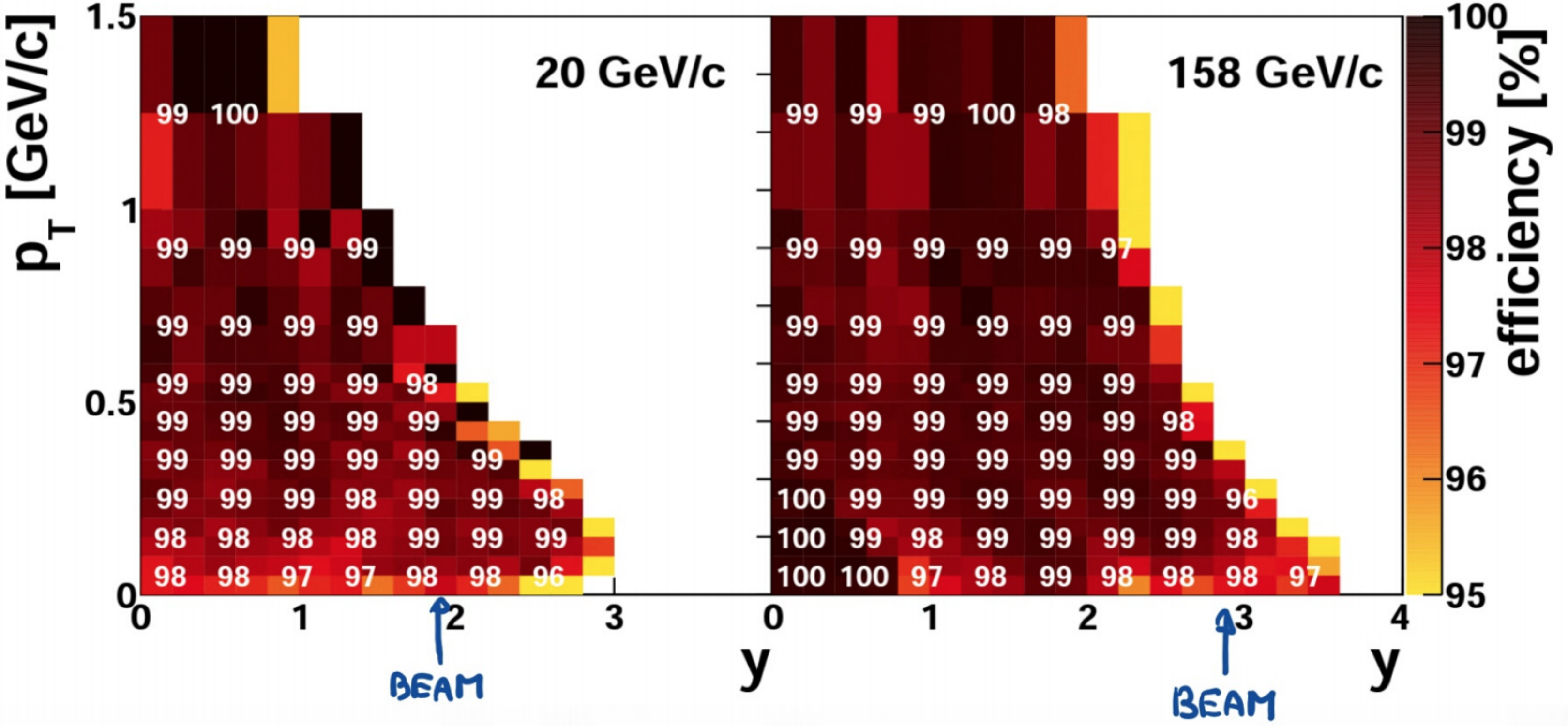
2018 detector's setup

- Fixed target experiment
- Large forward acceptance
- High tracking efficiency
- Good particle identification

LARGE ACCEPTANCE DETECTOR

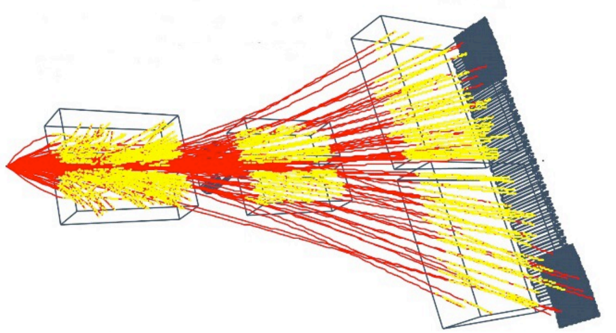


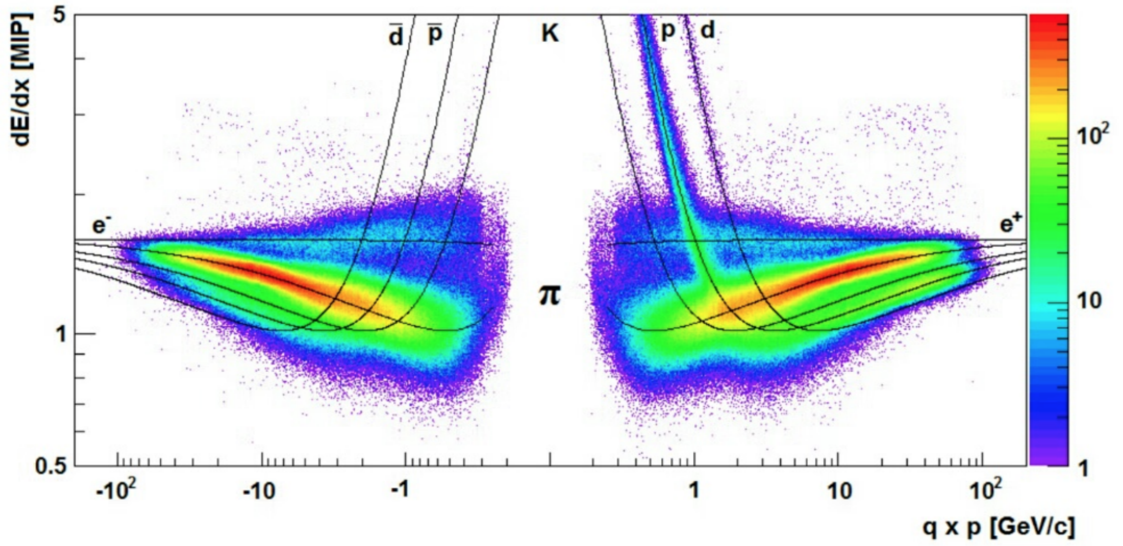
Eur.Phys.J. C74 (2014) no.3, 2794

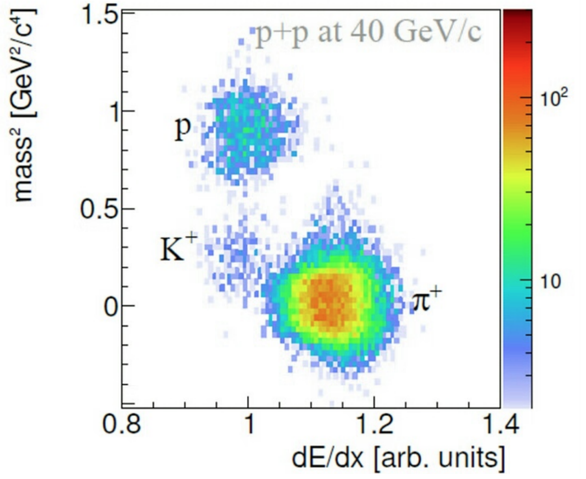


- Fixed target experiment
- Large forward acceptance
- High tracking efficiency
- Good particle identification

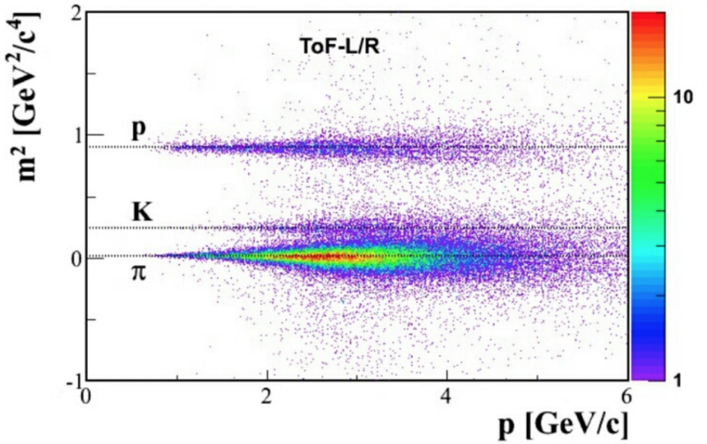
LARGE ACCEPTANCE DETECTOR





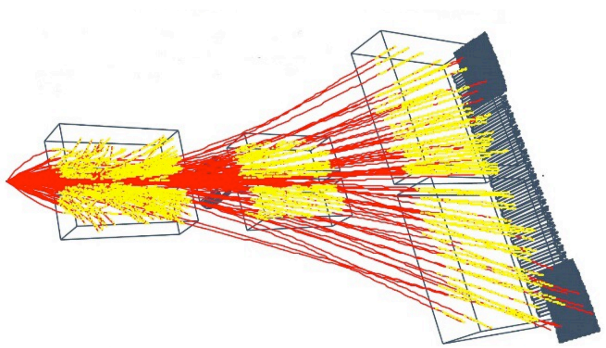


- Fixed target experiment
- Large forward acceptance
- High tracking efficiency
- Good particle identification



$\sigma(\mathrm{ToF}) \approx 100\mathrm{ps}$

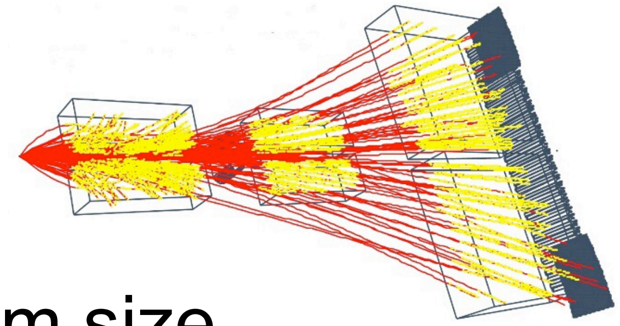
$\frac{\sigma(\mathrm{dE/dx})}{\mathrm{dE/dx}} \approx 4\%$



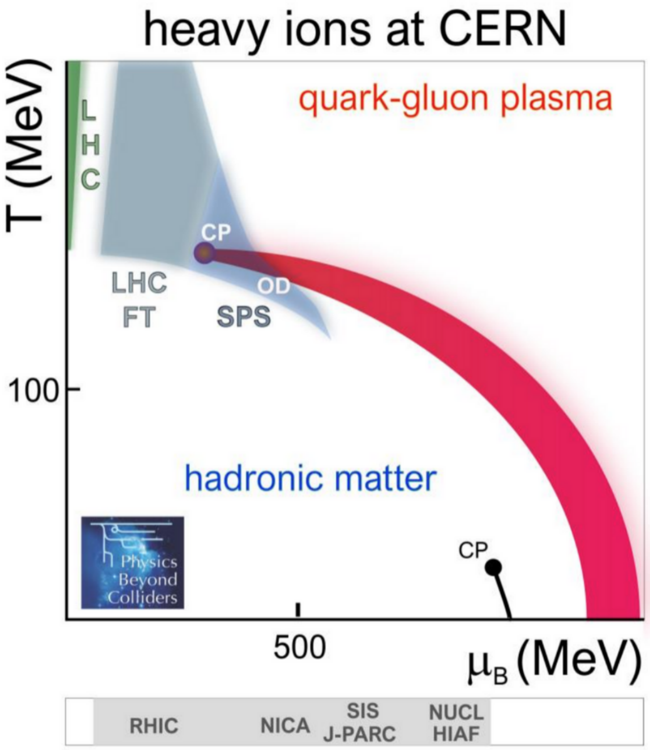
PHYSICS OUTLINE

- Strong interactions
- Measurements for cosmic rays physics
- Measurements for neutrino experiments

STRONG INTERACTIONS

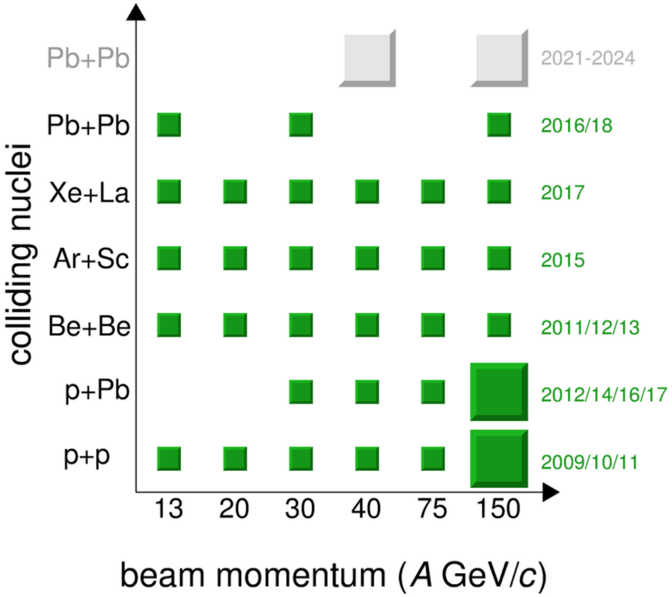


Search for the critical point



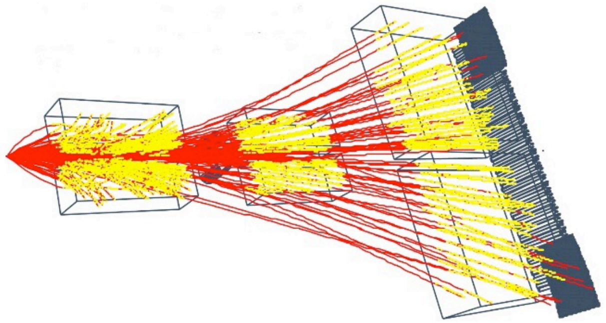
2018: energy and system size scan program is completed

What is next?

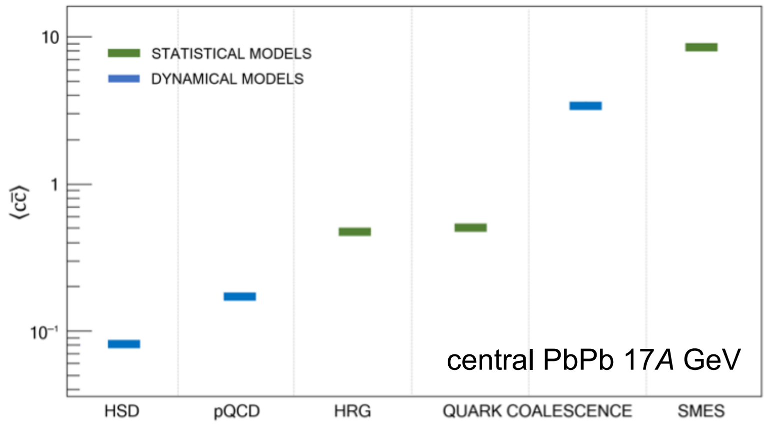


The data is being analyzed.
No signal of the critical point so far.

CHARM PHYSICS (2021-2024)



- What is the mechanism of open charm and J/ψ production?
- How does the onset of deconfinement impact open charm production?
- How does the formation of quark gluon plasma impact J/ψ production?



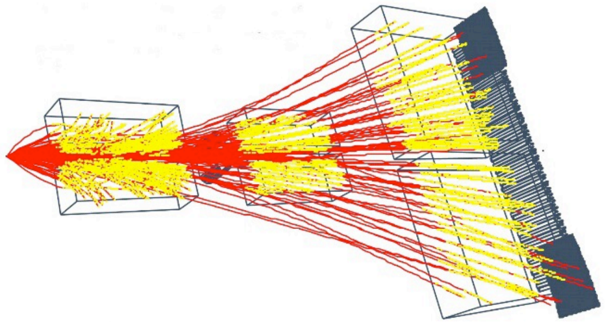
HSD:
Linnyk, Bratkovskaya, Cassing, IJMP E17 1367.
pQCD:
Gavai *et al.* IJMP A 10 2999.
Braun-Munzinger, J. Stachel, PL B 490, 196.
HRG, Quark Coalesc. Stat.:
Gorenstein, Kostyuk, Stoecker, Greiner, PL B 509, 277.
Quark Coalesc. Dyn.:
Levai, Biro, Csizmadia, Csorgo, Zimanyi, JP G 27, 703.
SMES:
Gazdzicki, Gorenstein, APP B30, 2705.

- Charm yield as a signal of deconfiniment

[Poberezhnyuk, Gazdzicki, Gorenstein, ACTA PHYS POL B 9 48(2017)]

To answer these questions $< c\bar{c} >$ produced in A+A collisions has to be known.
Up to now corresponding experimental data does not exist and only NA61/SHINE can perform it in the near future.

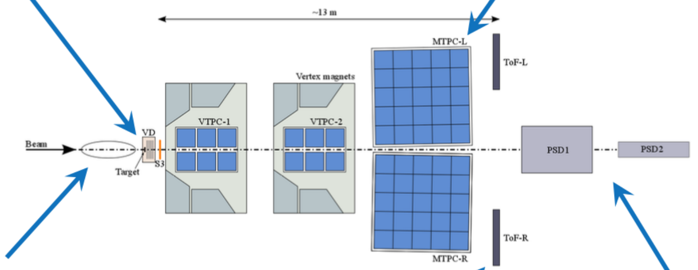
UPGRADE 2020



Detector configuration for Pb+Pb 2020+

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

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



New trigger and data
acquisition system

New Time-of-Flight
detectors (stage 2)

Upgrade of Projectile
Spectator Detector

Universe 2019, 5, 24; doi:10.3390/universe5010024

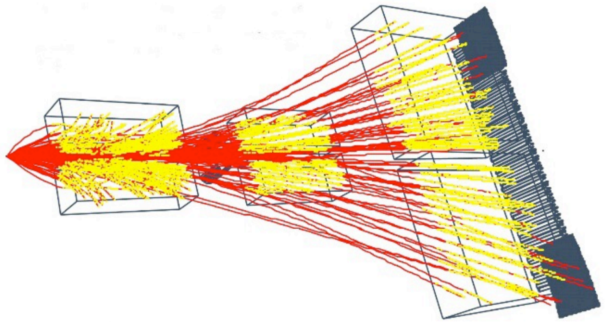
Heavy ions – future measurements

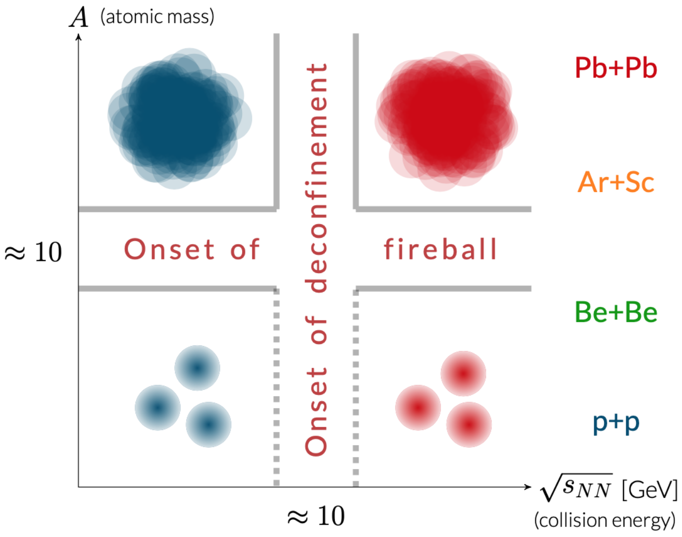
(the table was made before the pandemic)

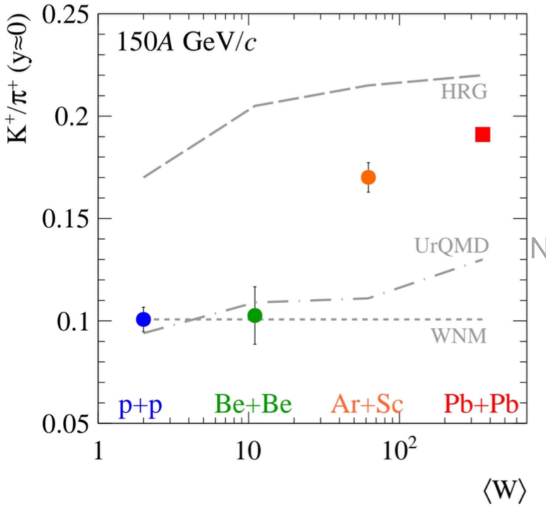
Year	Reaction	Number of events	D^0 & antiD^0	D^+ & D^-
2021	Pb+Pb 150*A* GeV/c	250M	38k	23k
2022	Pb+Pb 150*A* GeV/c	250M	38k	23k
2023	Pb+Pb 40*A* GeV/c	250M	3.6k	2.1k

HSD, N of measured

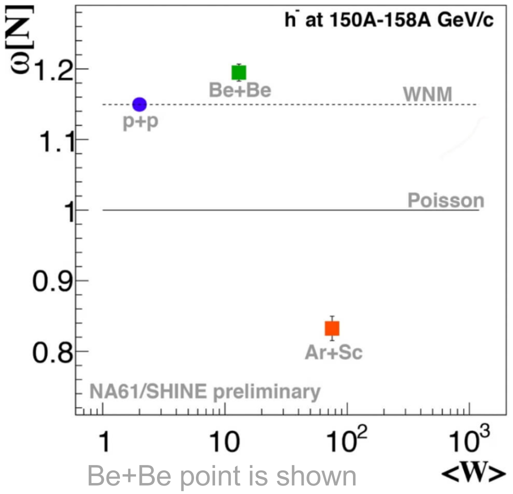
ONSET OF FIREBALL







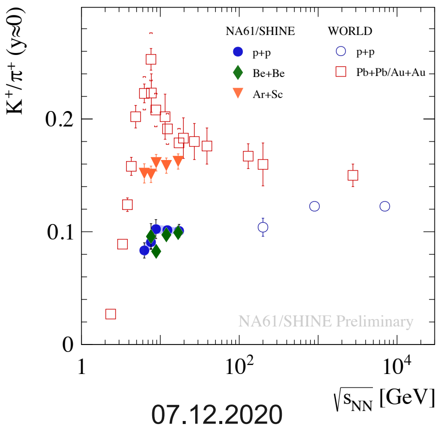
DOI: 10.22323/1.311.0050



Be+Be point is shown without systematic uncertainties

Ions in 2026-2029*	
A	Possible candidate
~ 5	4He
~ 15	16O (test in 2023!)
~ 30	30P
~ 40	40Ca

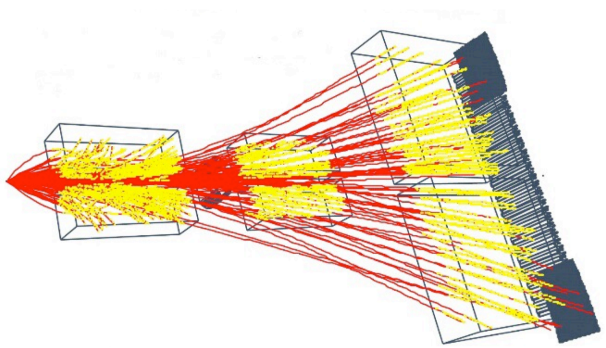
*proposal after LS3



- Unobvious system size dependence
- A clear difference between behavior of Be+Be and Ar+Sc, Ar+Sc and Pb+Pb

pp: Phys.Rev.C 102 (2020) 1, 011901
Be+Be: arXiv:2010.01864
Ar+Sc: preliminary

MEASUREMENTS FOR COSMIC RAYS PHYSICS



Current programs:

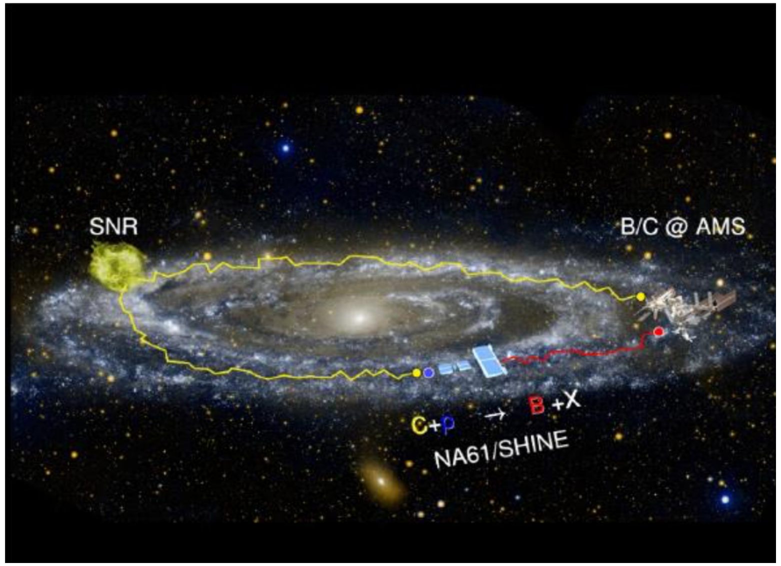
- Hadron production measurements to improve air-shower model predictions
  for example: Eur.Phys.J.C 77 (2017) 9, 626
- Studying the (anti-)proton and (anti-)deuteron production to reduce background uncertainties for the AMS and GAPS experiments
  for example: Phys. Rev. D 98, 023012 2018, Phys. Rev. D 102, 063004 (2020), JCAP 08 (2020) 035

Future (2021-2022)

- <u>Nuclear fragmentation cross sections to understand cosmic-ray flux</u>

DARK MATTER SEARCH

Cosmic-ray nuclei:
- Primary (p, He, C, N, O, Fe) ← supernova remnants
- Secondary ($e+$, $\bar{p}$, d, Li, Be, B) ← primary + interstellar p & d



Studding the ratios (e.g. B/C)

⇩

characteristics of propagation of cosmic rays
- effective diffusion coefficient
- column depth of material
- time CR spend in the Galaxy before escaping

⇩

Propagation model

⇩

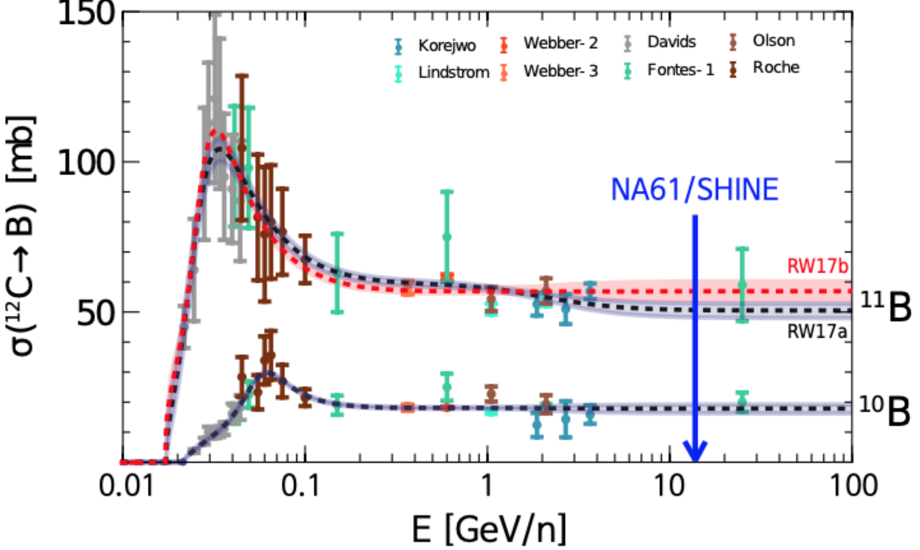
Secondary cosmic-ray antimatter flux

⇩

Search for dark matter annihilation

COSMIC RAYS FUTURE MEASUREMENTS

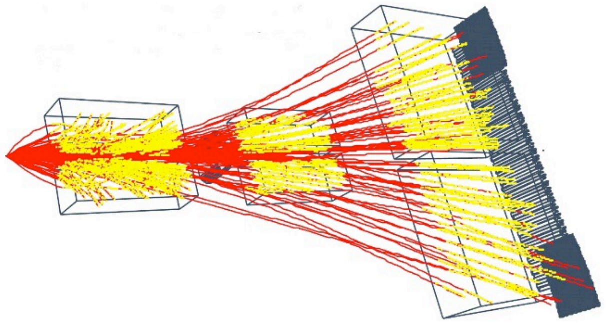
A. Reinert and M. W. Winkler
arXiv:1712.00002 [astro-ph.HE].



Current predicted secondary cosmic-ray antimatter flux (~10 GeV) has uncertainty ~ 20%

Planned data (2021)

reaction	N_{inter}	A/Z
$^{16}\mathrm{O}+\mathrm{H}$	250k	2
$^{12}\mathrm{C}+\mathrm{H}$	150k	2
$^{16}\mathrm{O}+\mathrm{He}$	100k	2
$^{14}\mathrm{N}+\mathrm{H}$	40k	2
$^{10}\mathrm{B}+\mathrm{H}$	5k	2
$^{11}\mathrm{B}+\mathrm{H}$	5k	2
$^{12}\mathrm{C}+\mathrm{He}$	5k	2
$^{13}\mathrm{C}+\mathrm{H}$	5k	11/5
$^{15}\mathrm{N}+\mathrm{H}$	5k	13/6
$^{20}\mathrm{Ne}+\mathrm{H}$	5k	15/7
$^{24}\mathrm{Mg}+\mathrm{H}$	5k	2
$^{28}\mathrm{Si}+\mathrm{H}$	5k	2
$^{7}\mathrm{Li}+\mathrm{H}$	5k	7/3
	$\Sigma = 0.6\mathrm{M}$	

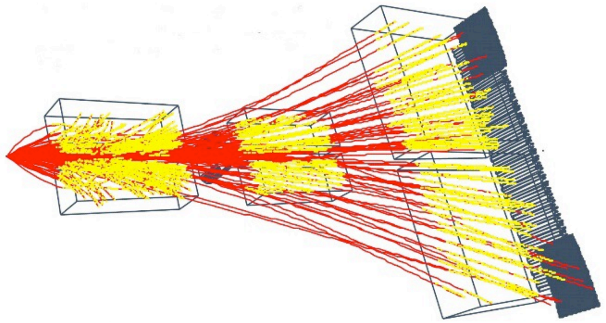


X+Li, Be, B, C, N

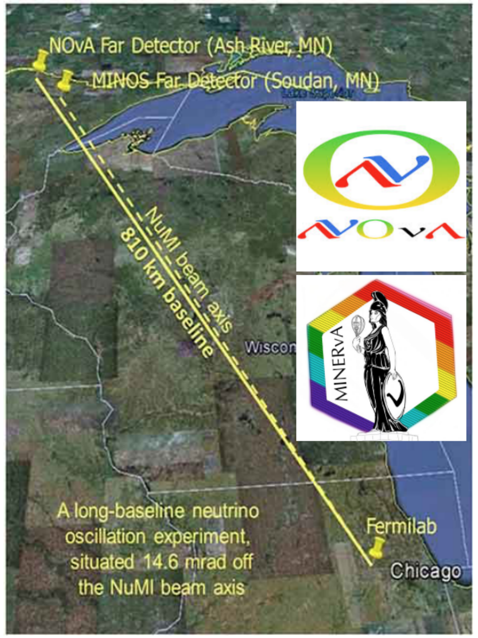
With our measurements we expect to reduce it to ~1%

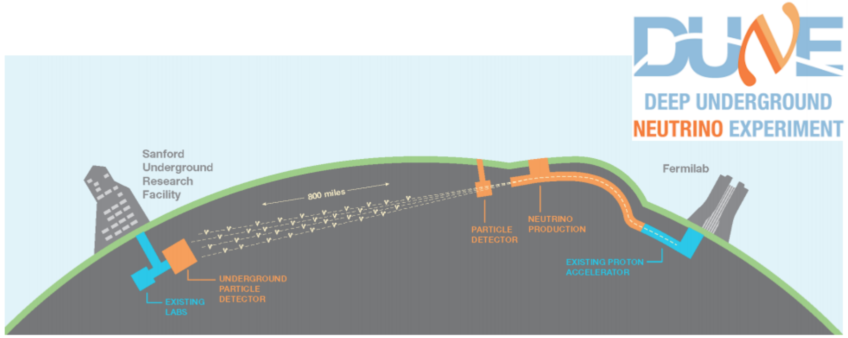
CERN SPSC-P-330-ADD-10

UNDERSTANDING NEUTRINO FLUX PRODUCED IN NEUTRINO BEAMLINES



J-PARC beamline (30 GeV proton beam)
experiments: T2K, T2HK



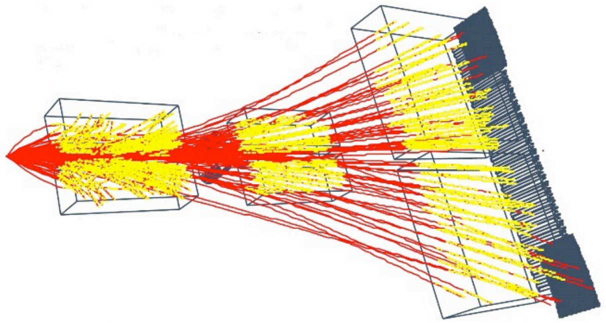


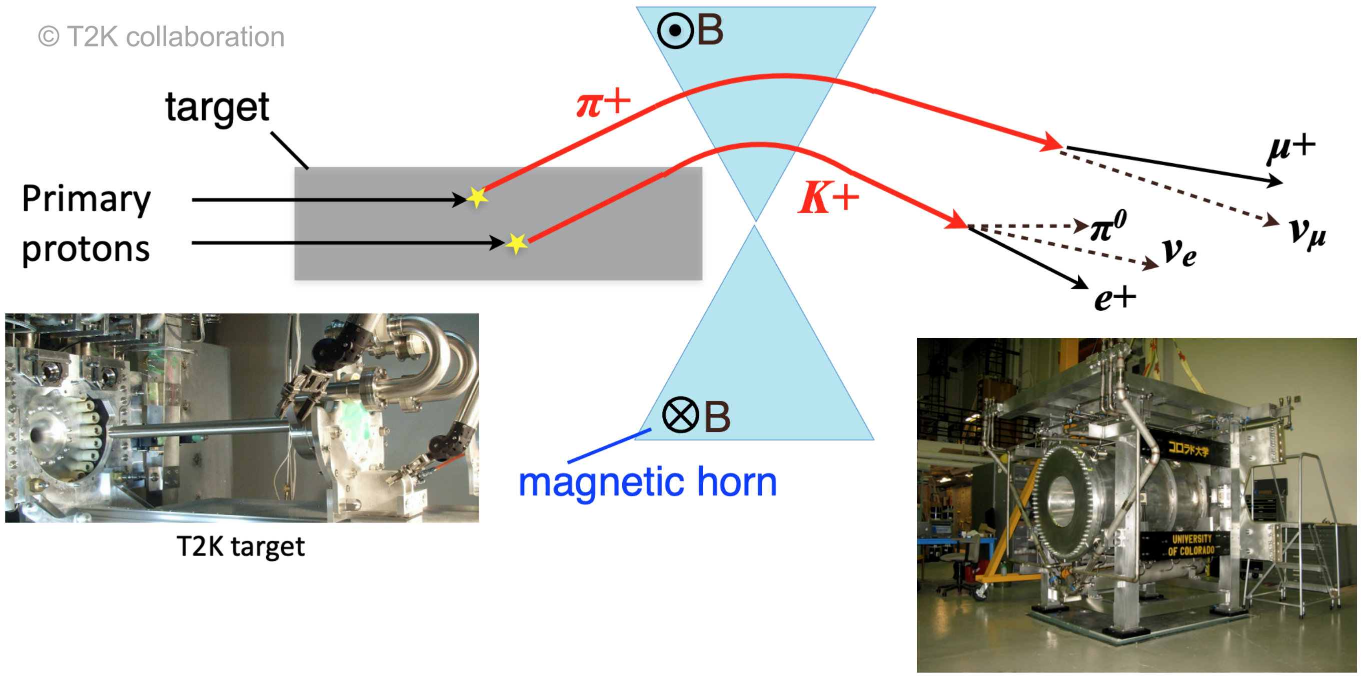
LBNF beamline (60 - 120 GeV proton beam not yet determined)
experiment: DUNE

NuMI beamline (120 GeV proton beam)
experiments: NOvA (and MINERvA)

3

HOW TO PRODUCE A NEUTRINO FLUX





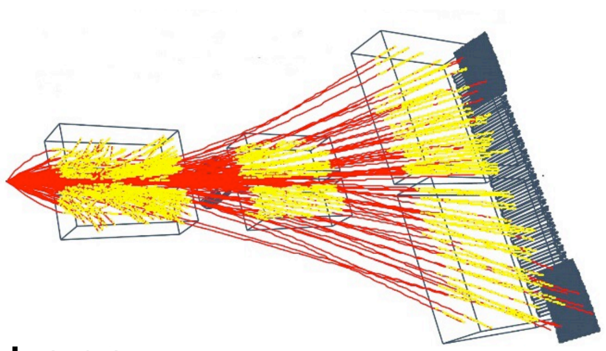
T2K target

T2K magnetic horn

Hadron production is a complex process:

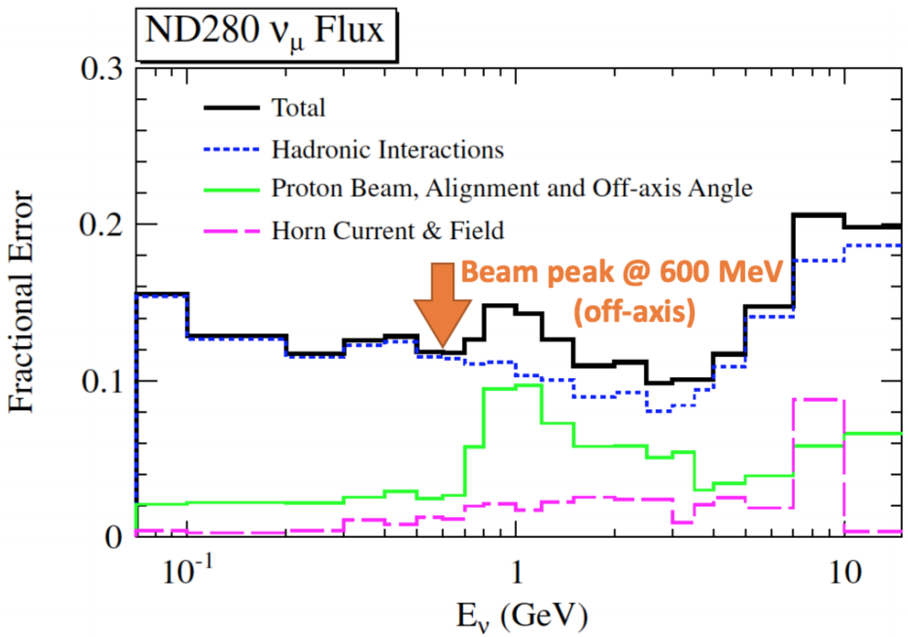
- Secondary interactions in the target (hadrons + C/Be)
- Secondary interactions with horn or beamline materials (hadrons + X)
- Neutral hadron decay (p + C / Be —> V0 + X)

WHY TO MEASURE?



Hadron production is the leading uncertainty source of flux predictions

J-PARC beamline (T2K flux)



T2K: Phys. Rev. D87, 012001 (2013)

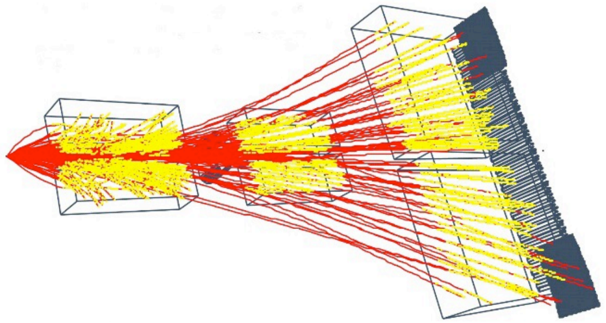
We rely on hadronic interaction models for the neutrino flux predictions FLUKA (J-PARC/T2K), Geant4 FTFP_BERT (NuMI experiments)

However, hadron production prediction is difficult… e.g. five interaction models in Geant 4 —> variations neutrino flux prediction ~40% at the focusing peak

Leonidas Aliaga (Ph.D Thesis, 2016)

Need to constrain neutrino flux uncertainty coming from hadron production

STRATEGY



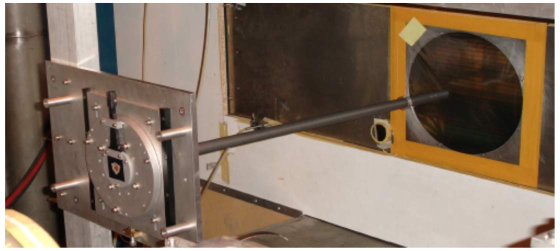
Thin target: a few % of nuclear interaction length (λ) to study single interactions

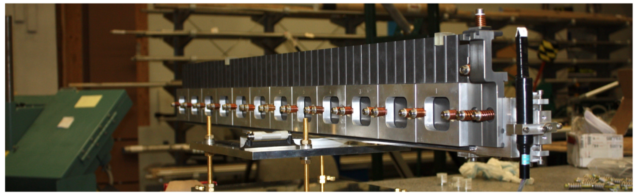
- Total cross sections (inelastic and production cross sections)
- Measurement of differential cross section

Replica (thick) target: same geometry and material as real neutrino beamline

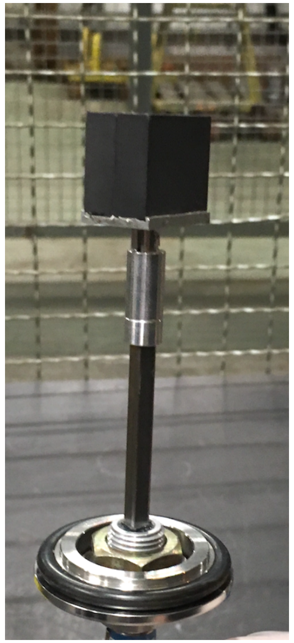
- Measurement of differential particle yields
- Measurements of total production cross section via beam attenuation in the target

T2K replica graphite target
(90 cm, 1.9 λ)





NuMI replica graphite target
(120 cm, 2.5 λ)



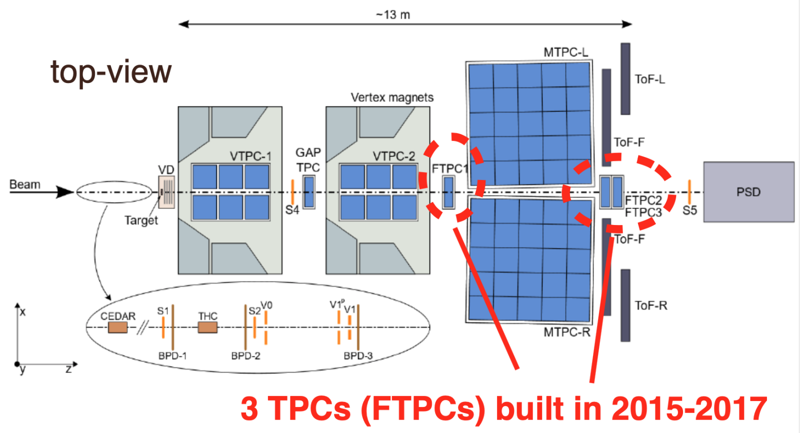
Thin graphite target
(1.5 cm, 3.1% of λ)

DATA TAKINGS

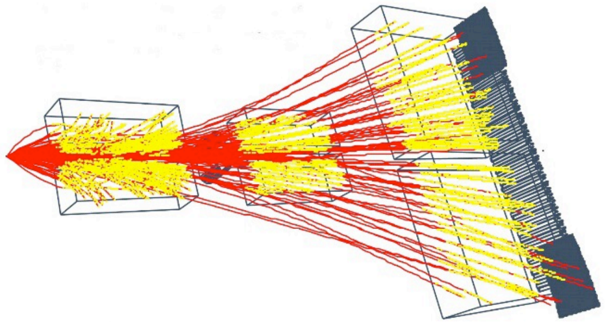
Collected data:

Measurements for T2K (2007-2010):
with proton beam at 30 GeV

Measurements for Fermilab (2015-2018): with various beam types and energies



Future plans (2021-2023):



Thin Target

- Uncovered materials

—> With various nuclear targets (Al, Fe, Ti, Water, etc...)

- Uncovered phase-space

—> T2K/Hyper-K: low momentum (1-5 GeV/c) hadrons

—> DUNE: and re-interactions (30-60 GeV/c)

- Improved precision

—> More statistics to reduce statistical uncertainty

Replica Target

- New replica targets

—> Hyper-K and DUNE targets are under development

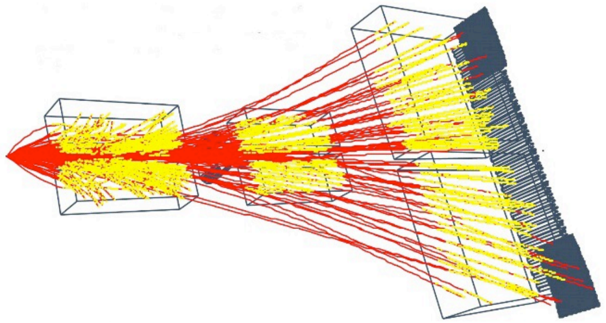
- Improved precision

—> More statistics for T2K and NuMI replica target data

—> Target tracking detector will be necessary

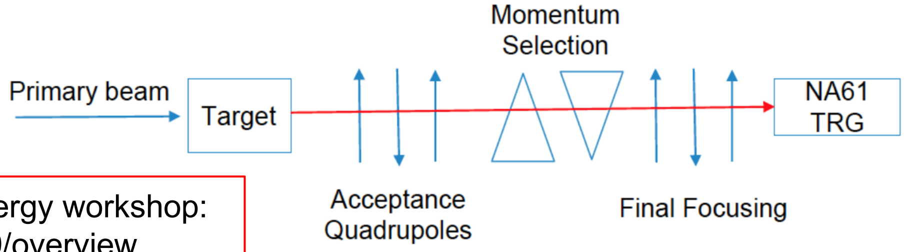
Review of our neutrino program:
USNA61 https://npc.fnal.gov/2019-2020-season/

(VERY) LOW-ENERGY BEAMLINE



We are designing a new low-E beamline at CERN SPS H2-beamline

- Low-Energy = 1-13 GeV/c —> the lowest momentum achievable now is 13 GeV/c



9-10.12.2020 NA61/SHINE low energy workshop:
https://indico.cern.ch/event/973899/overview

Possible physics cases:

<u>Shot BaseLine Neutrino@Fermilab:</u>

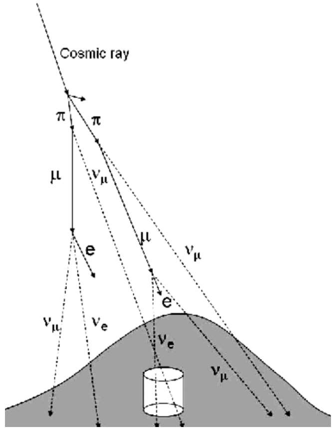
- proton 8 GeV on beryllium target
  - SBND
  - MicroBoone
  - ICERUS

<u>Atmospheric neutrinos</u>

- Measurements to improve flux predictions
  - DUNE; Super-K; Hyper-K

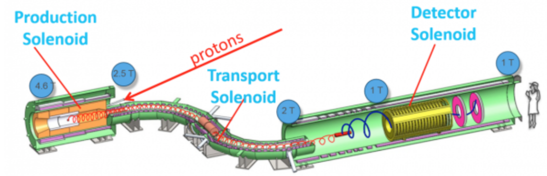
<u>T2K / Hyper-K</u>

- Measurements of unconstrained interactions
  - pion beam: 1-6 GeV
  - proton beam: > 4 GeV
  - kaon beam: 1-10 GeV



<u>Muon-to-electron conversion</u>

- Measurements to understand hadron production on target
  - Mu2e (FNAL); COMET (J-PARC)

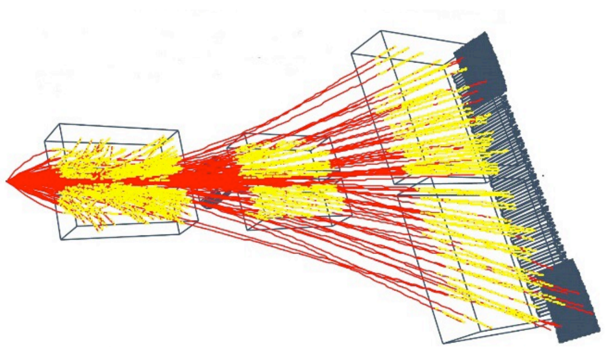


<u>JSNS2 (J-PARC E56) experiment</u>
(sterile neutrino)

- proton 3 GeV on mercury target

No data exist —> Hard to predict BG

CONCLUSIONS

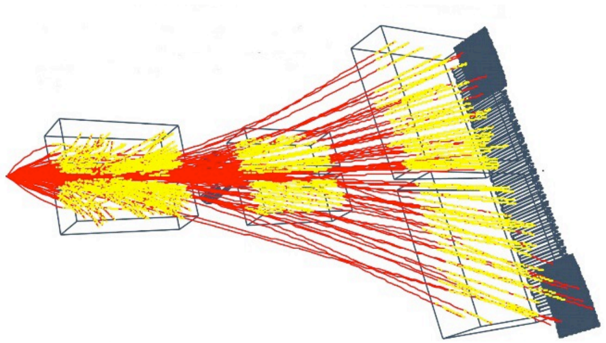


Due to the unique detector and the beam line the NA61/SHINE collaboration has a diverse physics program and plans:

- $< c\bar{c} >$ in Pb+Pb at 30 and 150A GeV/c – 2021-23
- Nuclear fragmentation cross sections for cosmic-ray flux – 2021-22
- Hadron production for current and future neutrino experiments – 2009-…
- Intermediate and light nuclei collisions – 2026-29

If you have any other projects in mind which can be accomplished in a frame of our setup, you are welcome to share it with us and we may collaborate.

THANK YOU



We are welcome new ideas and collaborators

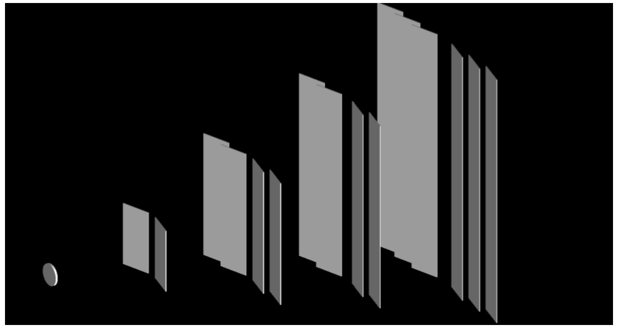
a.seryakov@cern.ch
https://shine.web.cern.ch/

SHINE.EXPERIMENT

BACKUP

Table 3: Comparison of basic parameters of MIMOSA and ALPIDE sensors.

	MIMOSA-26AHR	ALPIDE
Sensor thickness (μm)	50	50
Spatial resolution (μm)	3.5	5
Dimensions (mm^2)	10.6×21.2	13.8×30
Power density (mW/cm^2)	250	40
Time resolution (μs)	115.2	10
Detection efficiency (%)	>99	>99
Dark hit occupancy	$\lesssim 10^{-4}$	$\lesssim 10^{-6}$



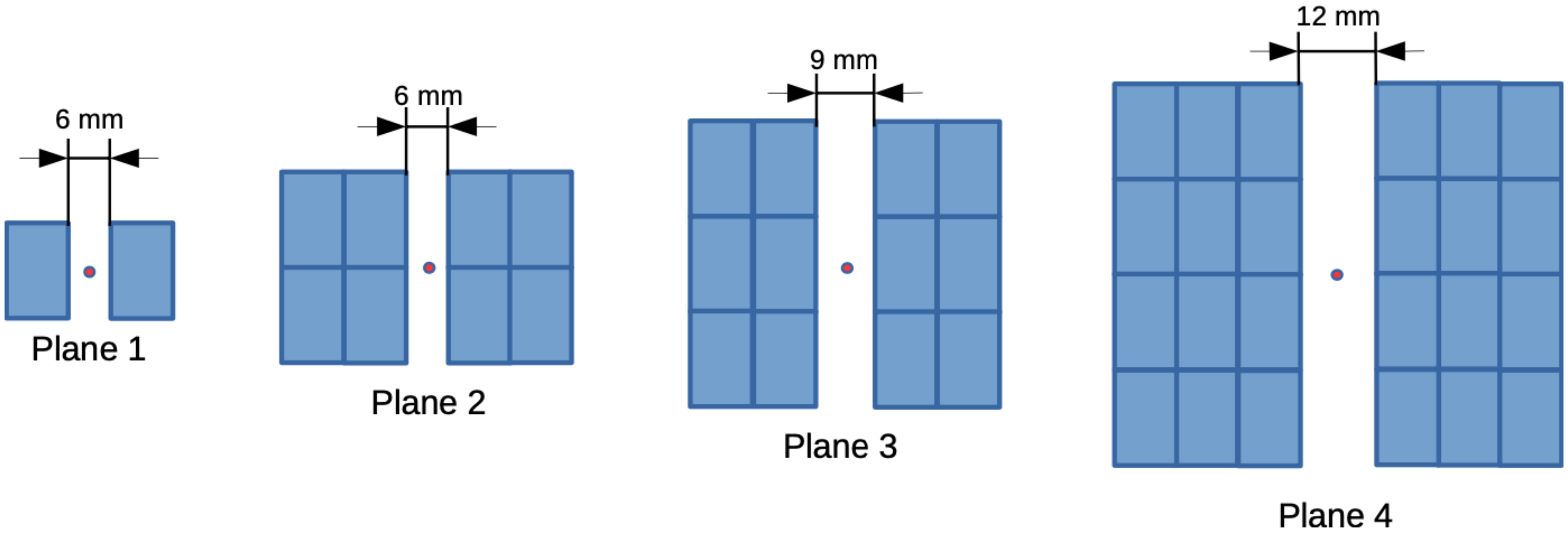


Figure 40: Schematic view of the VD layers based on ALPIDE sensors. From left to right: the first layer with two sensors, the second layer with 8 sensors, the third layer with 12 sensors and the fourth layer with 24 sensors. The total active area of the VD sensors is 190 cm^2.

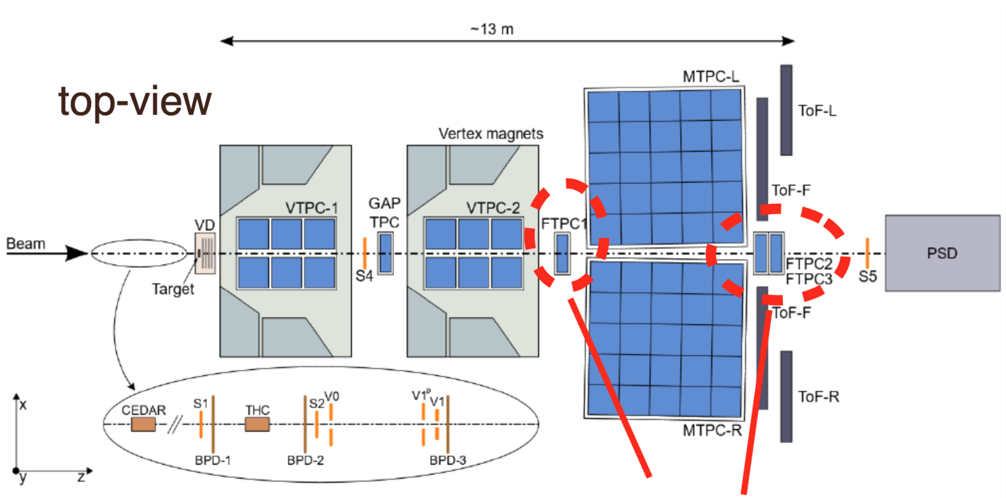
Measurements for Fermilab Neutrino Program

- Thin target: various interactions in 2015 - 2017

Data sets		
no magnetic field (2015)	with magnetic field (2016)	with magnetic field (2017)
p+C (31 GeV/c)	p+Al/Be/C (60 GeV/c)	p+C (90 GeV/c) **(with FTPCs)**
π^++Al/C (31 GeV/c)	p+Be/C (120 GeV/c)	p+Be/C (120 GeV/c) **(with FTPCs)**
π^++Al/C (60 GeV/c)	π^++Be/C (60 GeV/c)	π^++C (31 GeV/c) **(no FTPCs)**
K^++Al/C (60 GeV/c)		π^++Al (60 GeV/c) **(no FTPCs)**
(no FTPCs)	**(no FTPCs)**	π^-+C (60 GeV/c) **(with FTPCs)**

- Total cross-section
  - 2015 π^+ and K^+ beams (Phys. Rev. D98, 052001 (2018))
  - 2016 proton beams (Phys. Rev. D100, 112001 (2019))
  - 2016 π^+ beams (Phys. Rev. D100, 112004 (2019)) (with differential multiplicity analysis)

FTPC



3 TPCs (FTPCs) built in 2015-2017

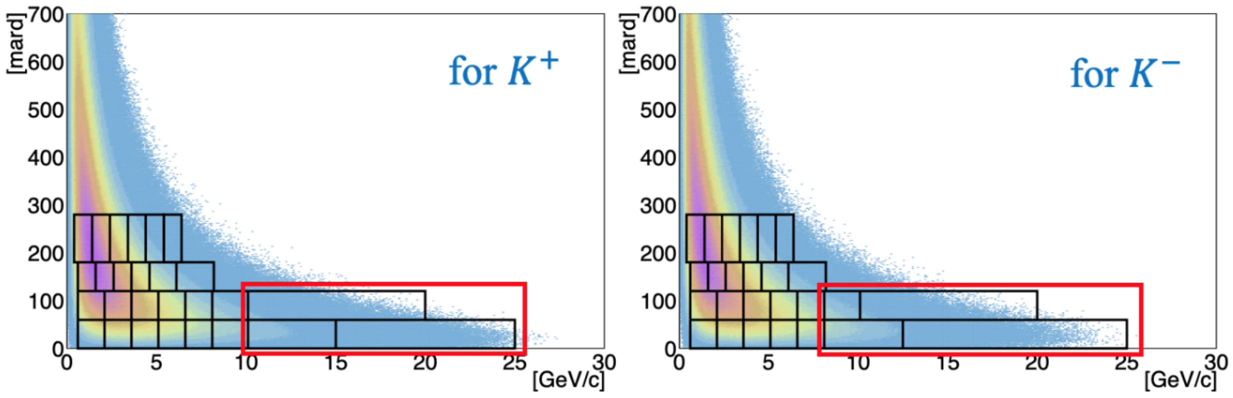


Figure 20: The momentum and angle distribution of the charged kaon exiting from the T2K target, whose contribute to neutrino at the far detector. Black lines outside the red box indicate the coverage of the NA61/SHINE replica 2010 data. We plan to expand the coverage in the high momentum region (red box) by accumulating higher statics data.

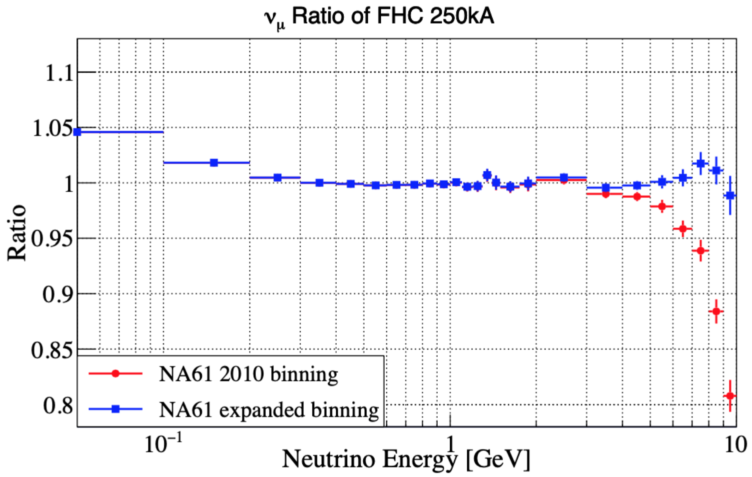
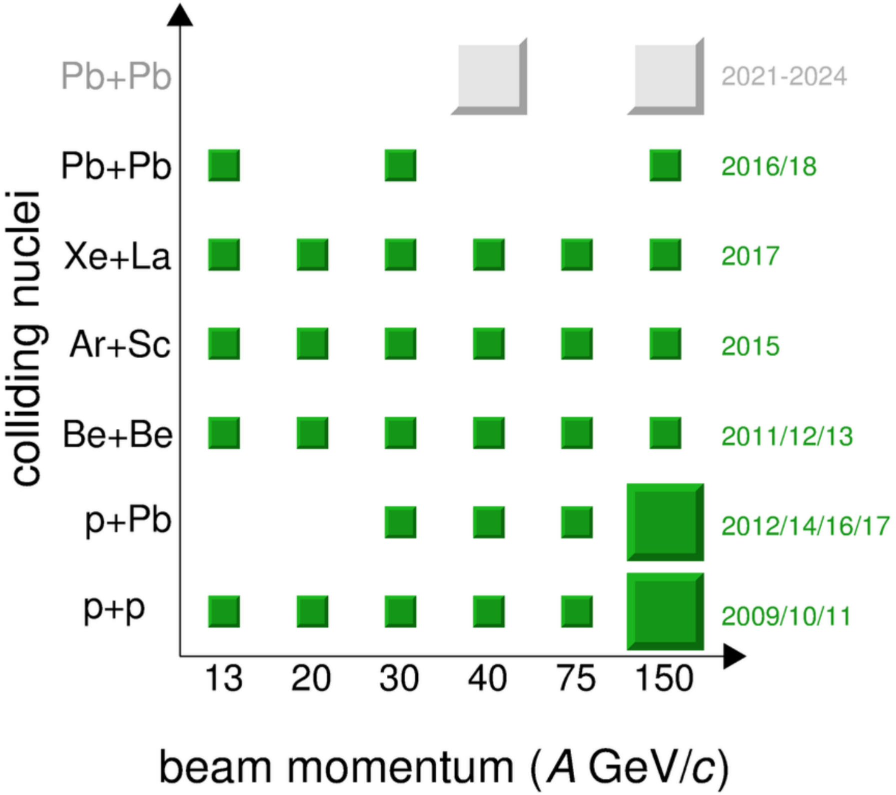
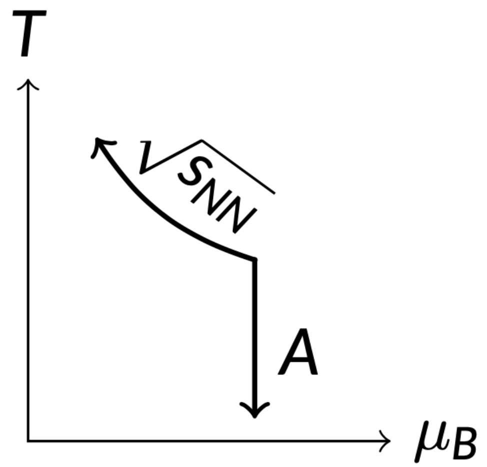


Figure 21: The expected improvement of the T2K flux prediction with new replica target data. This plot shows a ratio of nominal neutrino flux to one calculated with hadrons covered by the NA61/SHINE data. The red dots represent the ratio in case the 2010 replica target coverage. If the production of the high momentum charged kaon is measured, it is expected that the ratio will become to the blue dots and an improvement of the T2K/Hyper-K flux prediction at the neutrino energy more than 4 GeV is expected.

SEARCH FOR THE CRITICAL POINT AT CERN

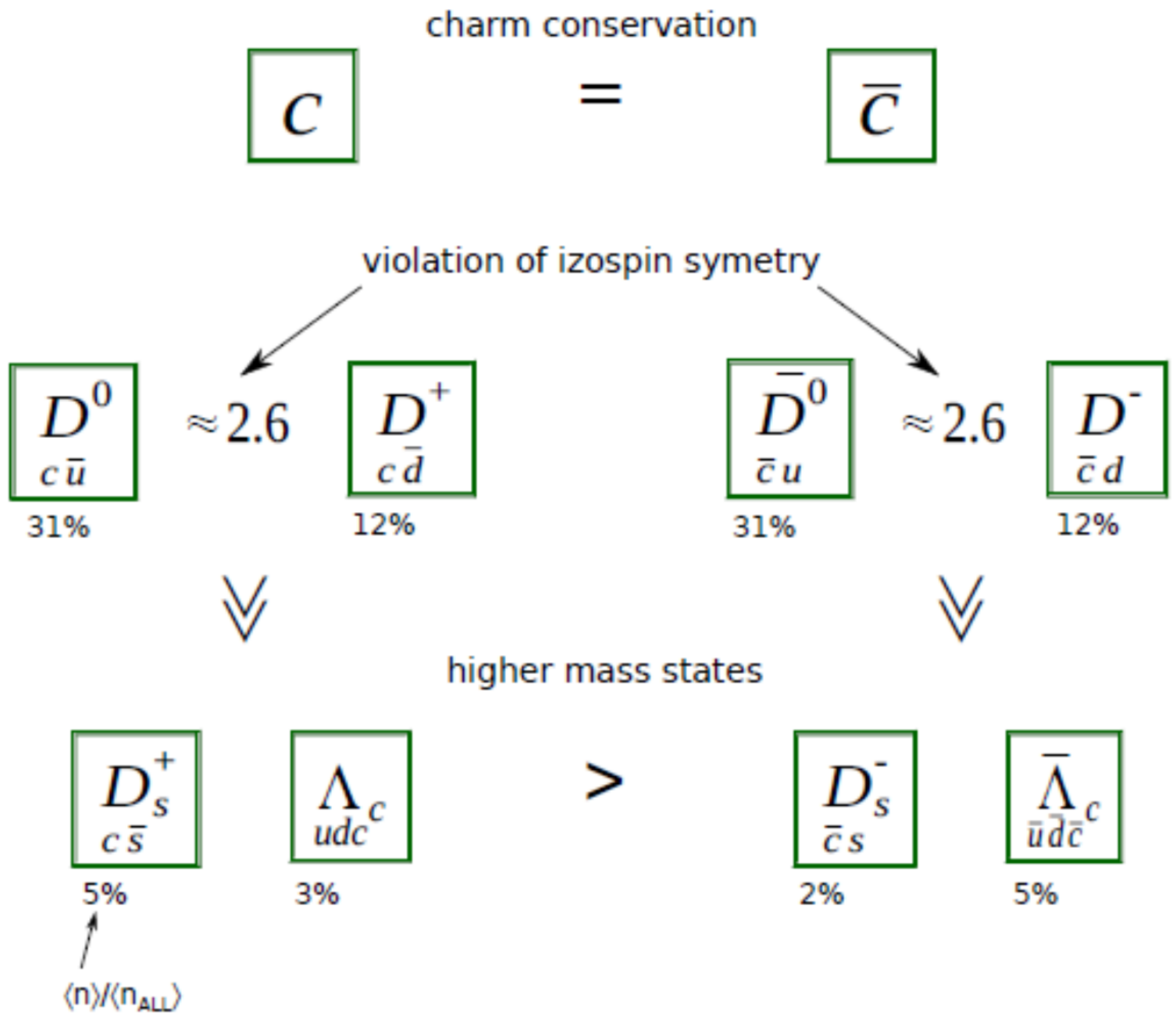


NA61/SHINE experiment:
<u>Energy and system size scan program</u>



Becattini, Manninen, Gaździcki
Phys. Rev. C 73, 044905 (2006)

0-20% Pb+Pb at 158 GeV/c



PHSD, Elena Bratkovskaya & Taesoo Song, private communication

Figure 6.4 presents a compilation of present and future facilities and their regions of coverage in the phase diagram of strongly interacting matter. Charmed hadron measurement capabilities are summarized below:

(i) LHC and RHIC at high energies ($\sqrt{s_{\mathrm{NN}}} \gtrsim 200\,\mathrm{GeV}$): measurements of open charm are performed within a limited acceptance due to collider kinematics and related to the detector geometry [40, 41, 42, 43].

(ii) RHIC BES collider ($\sqrt{s_{\mathrm{NN}}} = 7.7 - 39\,\mathrm{GeV}$): measurement not considered in the current program, this may be likely due to difficulties related to collider geometry and kinematics as well as the low charm production cross-section [44, 45].

(iii) RHIC BES fixed-target ($\sqrt{s_{\mathrm{NN}}} = 3 - 7.7\,\mathrm{GeV}$): not considered in the current program [46].

(iv) NICA ($\sqrt{s_{\mathrm{NN}}} < 11\,\mathrm{GeV}$): measurements during the stage 2 (after 2023) are under consideration [47, 48].

(v) J-PARC-HI ($\sqrt{s_{\mathrm{NN}}} \lesssim 6\,\mathrm{GeV}$): under consideration, may be possible after 2025 [49, 50].

(vi) FAIR SIS-100 ($\sqrt{s_{\mathrm{NN}}} \lesssim 5\,\mathrm{GeV}$): not possible due to the very low cross-section at SIS-100, systematic charm measurements are planned with SIS-300 ($\sqrt{s_{\mathrm{NN}}} \lesssim 7\,\mathrm{GeV}$) which is agreed-on part of FAIR, but not of the start version (timeline is unclear) [51, 52].

NA61/SHINE is planning to perform charm production measurements in heavy ion collisions in full phase space and may be the first to do so in the near future. Comparison with other facilities shows the uniqueness of these measurements.

Aleksandra Snoch, Master thesis, 2018 https://edms.cern.ch/document/2067629/1