REPORT FROM THE NA61/SHINE EXPERIMENT

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NA61/SHINE research program

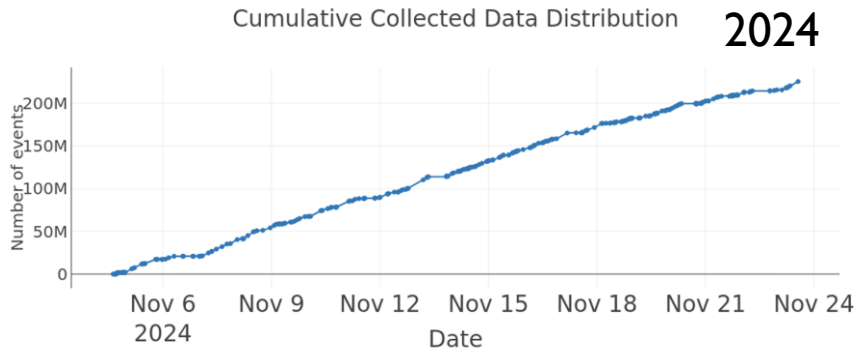
- **This presentation:**
  - data taking
  - detector status
  - strong interaction physics
- **Next presentation:**
  - measurements for neutrinos and cosmic rays
  - beam request for 2025

- **Strong interaction physics**
  - search for the critical point of strongly interacting matter
  - study of the properties of the onset of deconfinement
  - heavy quarks: direct measurement of open charm at SPS energies
- **Neutrino and cosmic-ray physics**
  - hadron measurements for the J-PARC neutrino program
  - hadron measurements for the Fermilab neutrino program
  - measurements for cosmic-ray physics (Pierre-Auger and KASCADE experiments) for improving air shower simulations
  - measurements of nuclear fragmentation cross-sections of intermediate-mass nuclei needed to understand the propagation of cosmic rays in our Galaxy
  - measurements of production cross sections of deuterons, anti-deuterons, and antiprotons in p+p to understand cosmic anti-nuclei

2024 Data-taking summary

Strong interaction physics:

- Charge symmetry
  - π^++ C at 158 GeV/c ≈ 30M events
  - π^- + C at 158 GeV/c ≈ 30M events
  - Memorandum: CERN-SPSC-2024-022
- Open charm
  - Pb+Pb at 150 *A* GeV/c up to now ≈ 200 M events - data taking ongoing



Neutrino and cosmic-ray physics:

- p + LBNF/DUNE prototype target at 120 GeV/c
  - Two settings
    - Full magnetic field ≈ 114 M events
    - Half magnetic field ≈ 124 M events

Status of data-taking for open charm in Pb+Pb at 150 A GeV/c

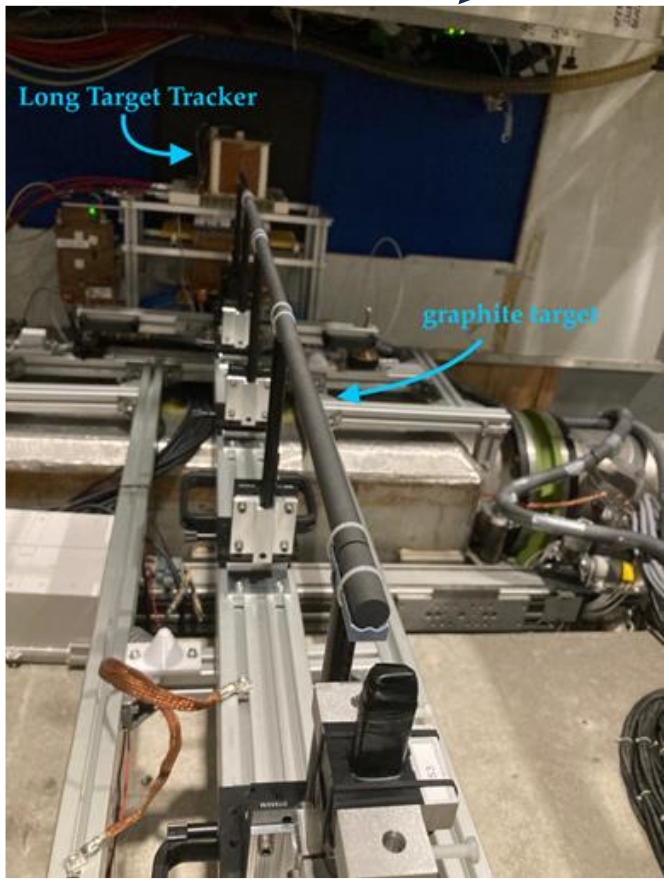
- 2022: 30M collisions (2 weeks)
- 2023: 150M collisions (4 weeks)
- 2024: ≈ 120M collisions (3 weeks)
- 2025+2026: ≈ 240M collisions (expected number of weeks is 6)
- In total ≈ 540M collisions
- Data-taking rate ≈ 40M collisions per week

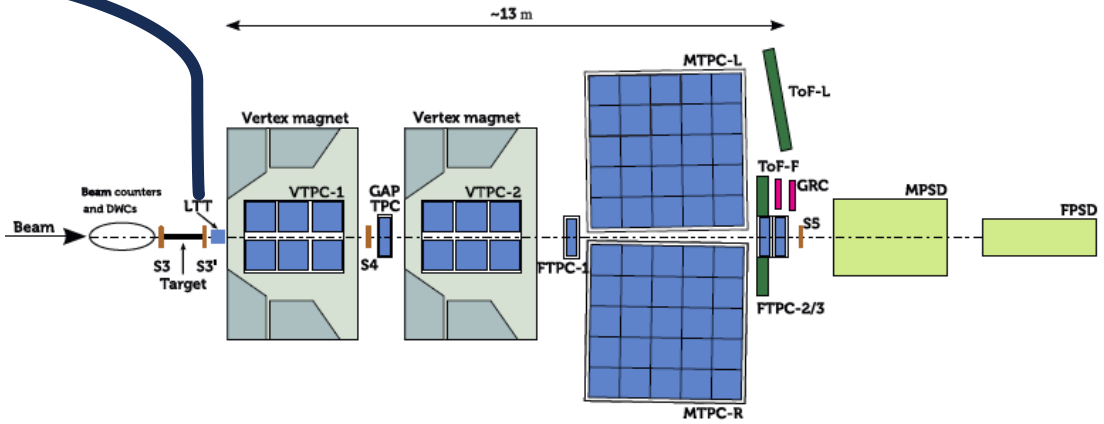
Expected number of reconstructed charm mesons in centrality selected Pb+Pb collisions assuming 500M minimum bias events

	0–10%	10–20%	20–30%	30–60%	60–90%
$\#(D^0 + \overline{D^0})$	31k	20k	11k	13k	1.3k
$\#(D^+ + D^-)$	19k	12k	7k	8k	0.8k
$\langle W \rangle$	327	226	156	70	11

CERN-SPSC-2022-005

Detector





LBNF/DUNE prototype target

- five cylindrical sections of IG510 graphite, each with a diameter of 16 mm,
- total length of 150 cm

Long Target Tracker

- small size TPC chamber (10cm × 12cm × 20cm)

DAQling software framework

- New data acquisition system prepared in collaboration with CERN EP-DT-DI department

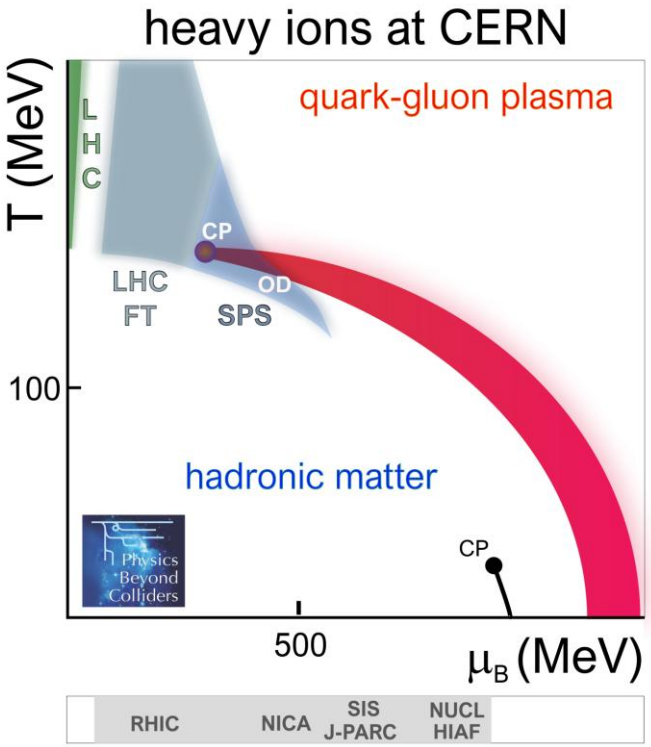
New results for strong interaction physics

Strong interaction program

Critical structures:

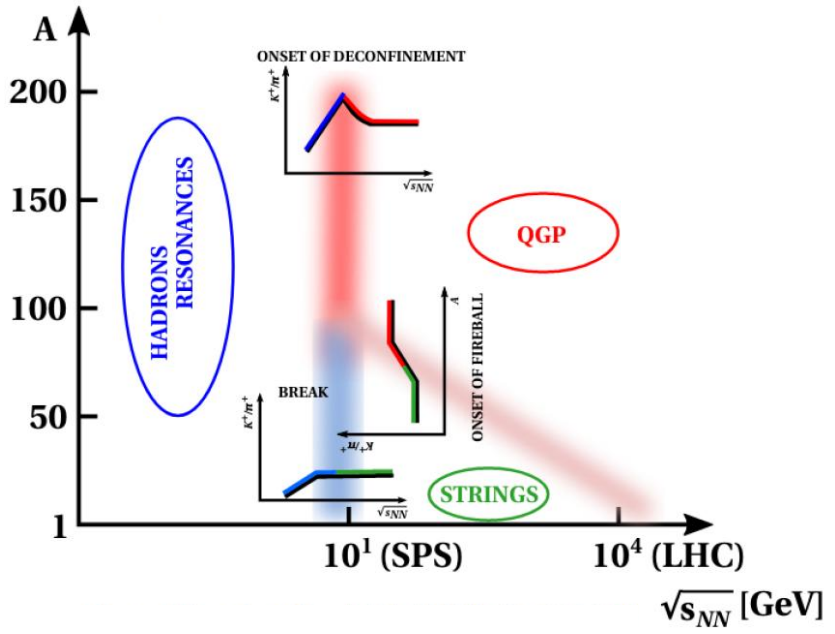
- **Onset of deconfinement**
  - beginning of QGP creation in heavy-ion collisions with an increase in collision energy
- **Critical Point**
  - The endpoint of first-order phase transition line that has properties of second-order phase transition
- **Onset of fireball**
  - The transition from non-equilibrium strings to QGP with increasing masses of colliding nuclei

Phase diagram of strongly interacting matter



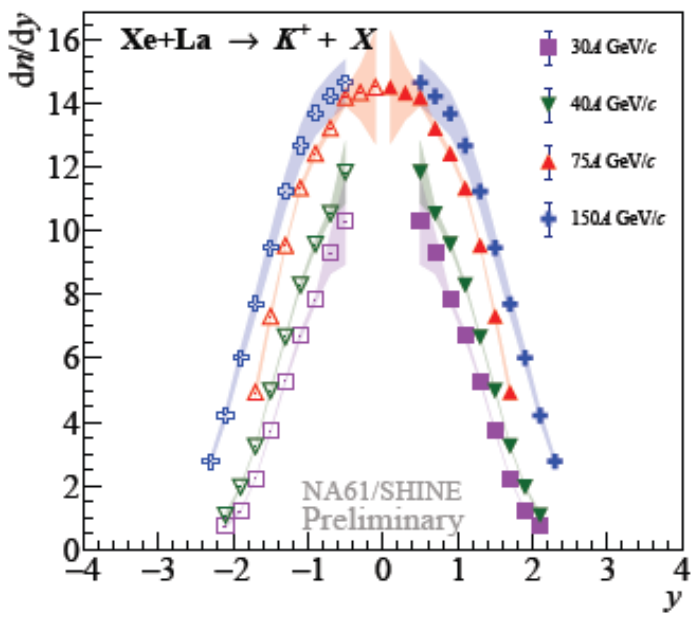
CERN-PBC-REPORT-2018-003

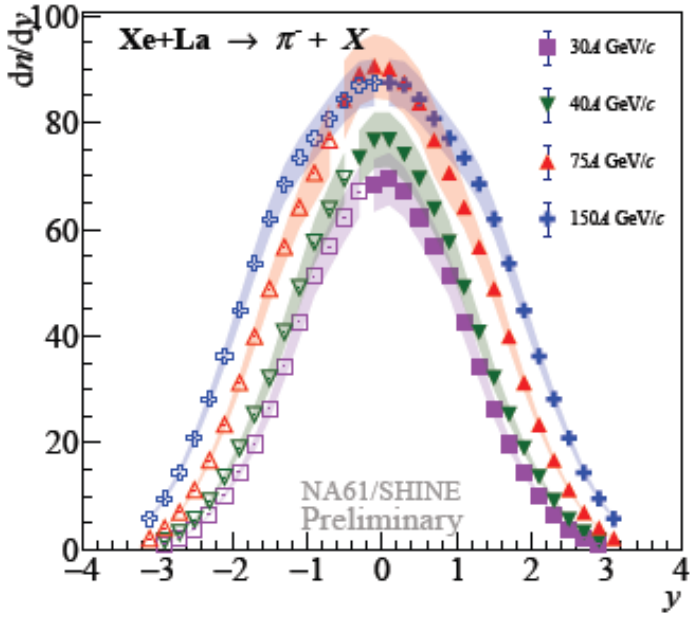
Diagram of the high-energy nuclear collisions



Universe **2023**, *9*(2), 106;

Results on π^-, K^+, and K^- production in 0–10% central Xe+La collisions at 30*A*, 40*A*, and 75*A* GeV/*c*



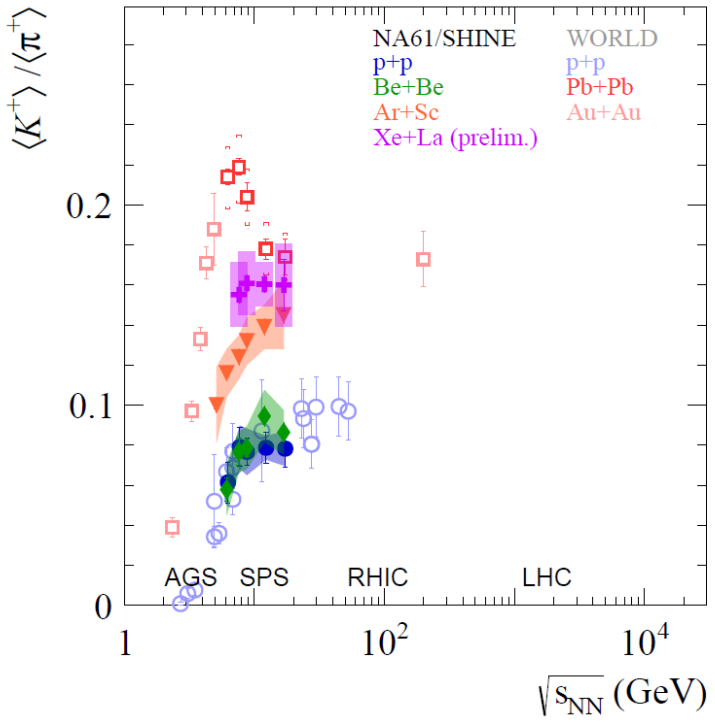


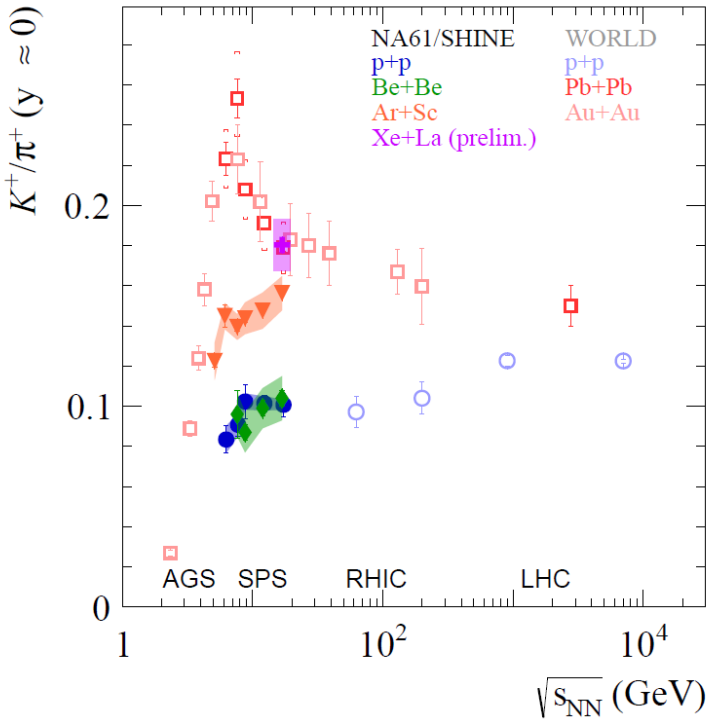
Completing analysis of data recorded in Run 2

2D scan in collision energy and size of colliding nuclei

K^+ to π^+ ratio

The onset of deconfinement & onset of QGP fireball

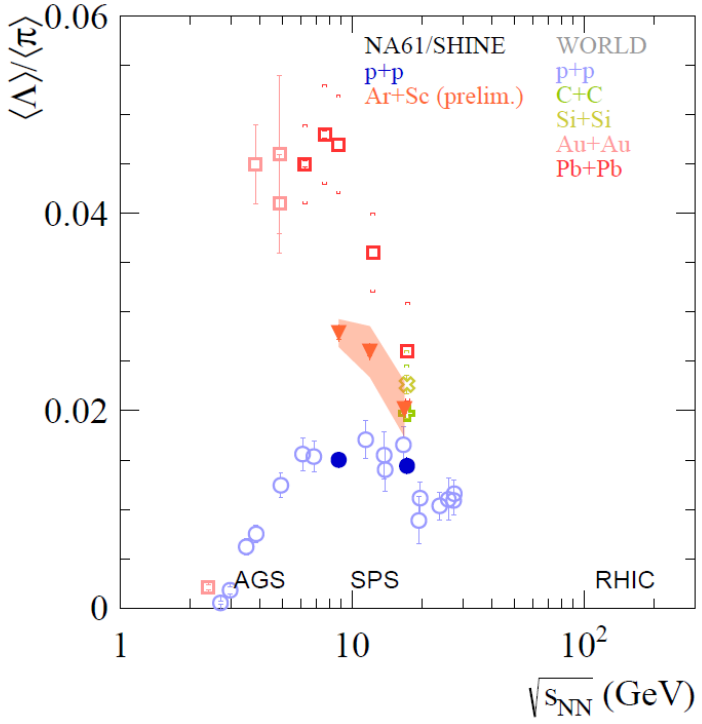


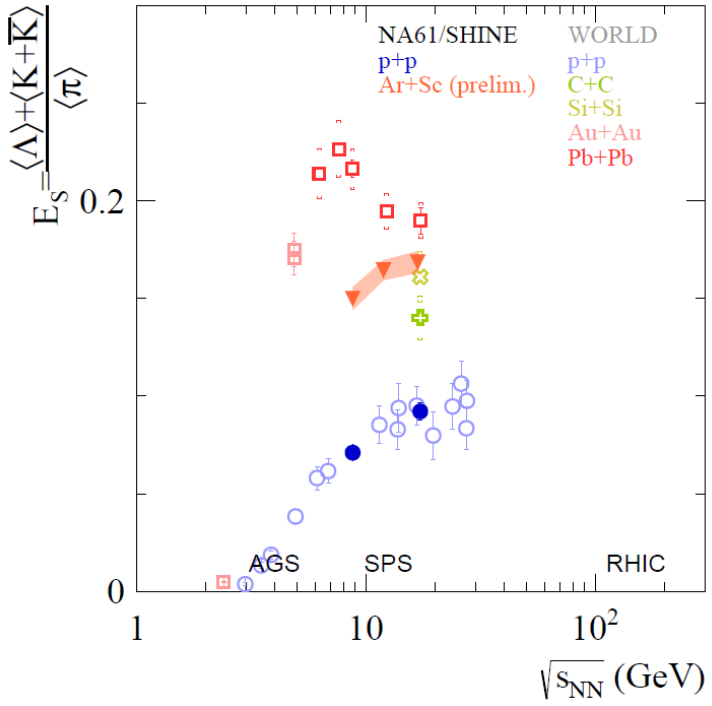


No indication of the Pb+Pb horn in Xe+La

Λ production in 0–10% central Ar+Sc collisions at 40A and 150A GeV/c

The onset of (QGP) deconfinement & onset of fireball

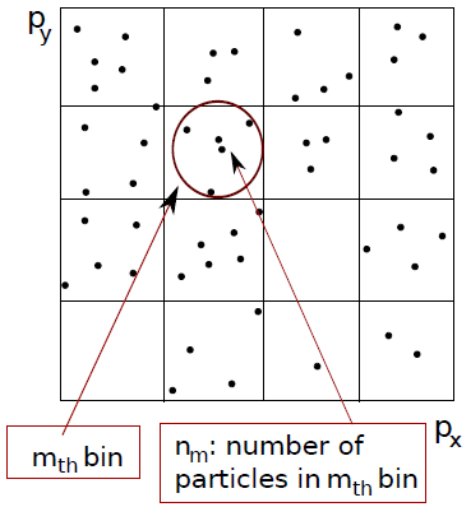




- **A similar decline of the Λ/π ratio in Ar+Sc to the one observed in Pb+Pb**
- **No maximum observed in $E_S \sim \frac{K^+}{\pi^+}$ in Ar+Sc contrary to the one observed in Pb+Pb**

Proton and charged hadron intermittency

Critical Point



$$F_r(M) = \frac{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m(n_m-1)\ldots(n_m-r+1) \right\rangle}{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m \right\rangle^r}$$

If the system freezes out near CP, its properties are expected to be different from those of an ideal gas. Such a system represents a simple fractal and $F_r(M)$ follows a power-law dependence

$$F_r(M) = F_r(\Delta) \cdot (M^D)^{\varphi_r}$$

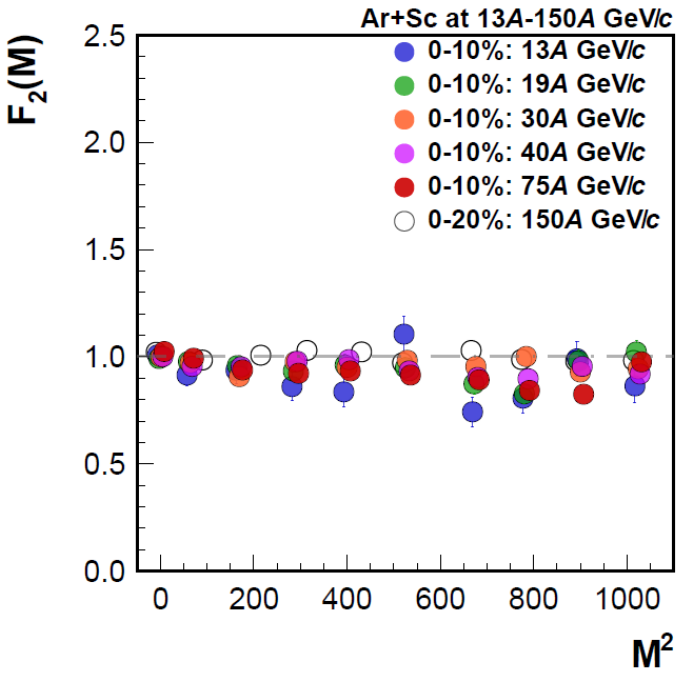
NA61/SHINE used in intermittency analysis:

- Statistically independent points
- Cumulative variables

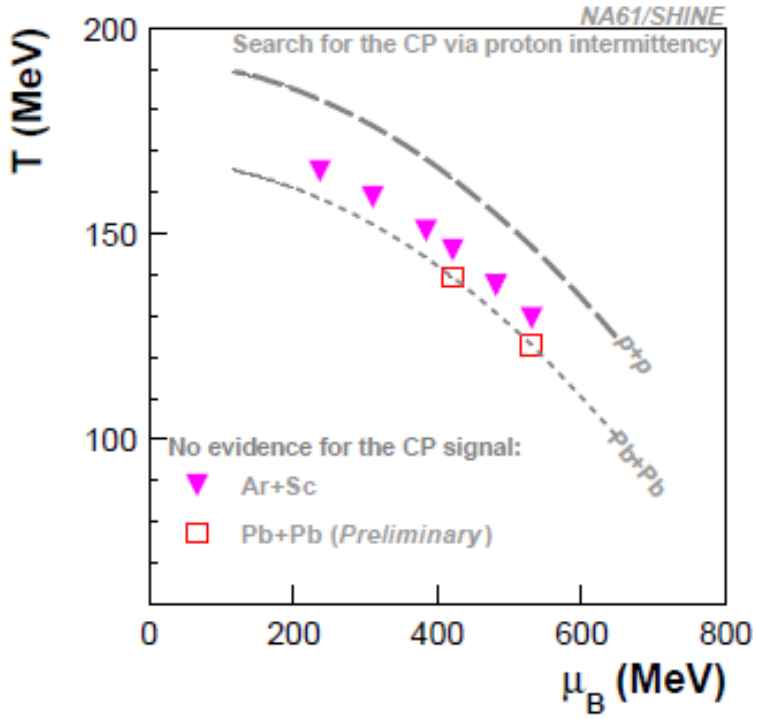
NA61/SHINE: Eur.Phys.J.C 83 (2023) 9, 881; arxiv:2401.03445

Proton intermittency in 0–10% central Ar+Sc collisions at 13A–75A GeV/c

Critical Point



Calculated for number of subdivisions in cumulative transverse momentum space for $1^2 \leq M^2 \leq 32^2$



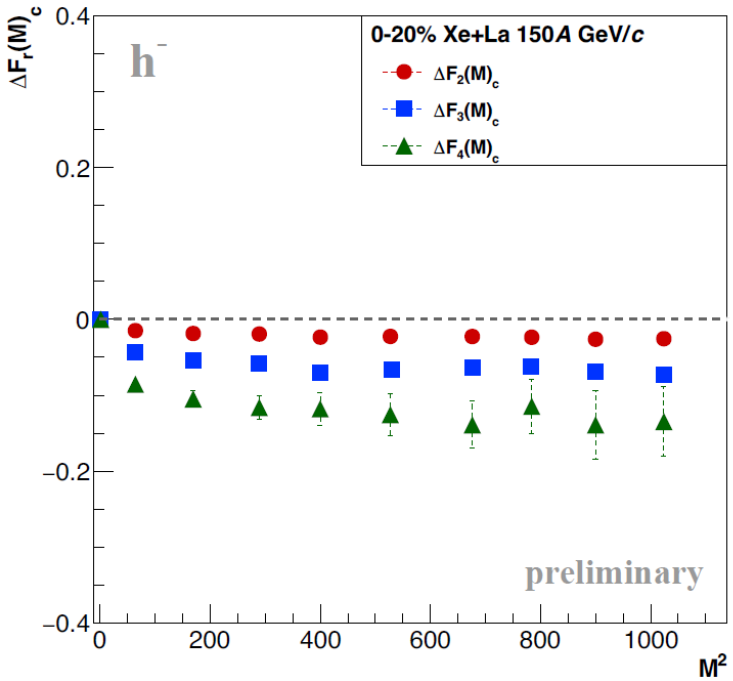
No signal indicating critical point in Ar+Sc and Pb+Pb collisions

NA61/SHINE Eur. Phys. J. C 84 no. 7, (2024) 741, arXiv:2401.03445

h^- intermittency in 0–20% central Xe+La collisions at 150*A* GeV/*c*

Critical Point

$$\Delta F_r(M)_c = F_r(M) - F_r(1)$$

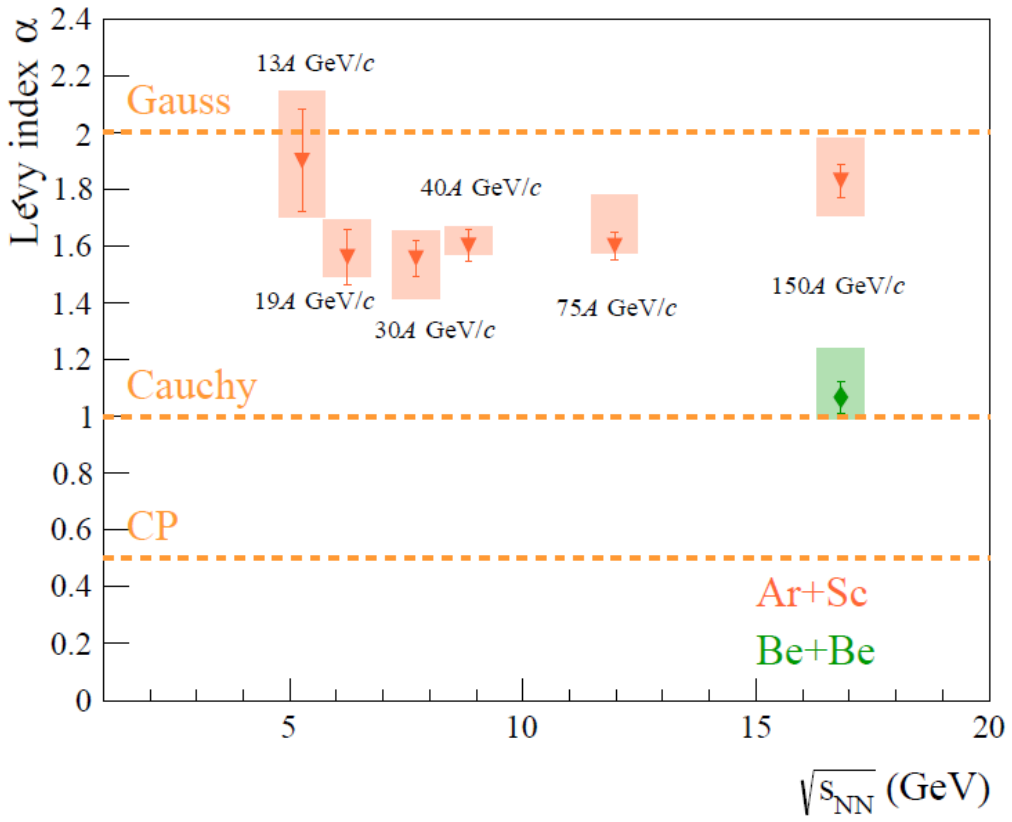


$$1^2 \leq M^2 \leq 32^2$$

No signal indicating the critical point in cumulative p_T independent bin analysis

Femtoscopy analysis in 0–10% central Ar+Sc collisions at 13A–75A GeV/c

Critical Point

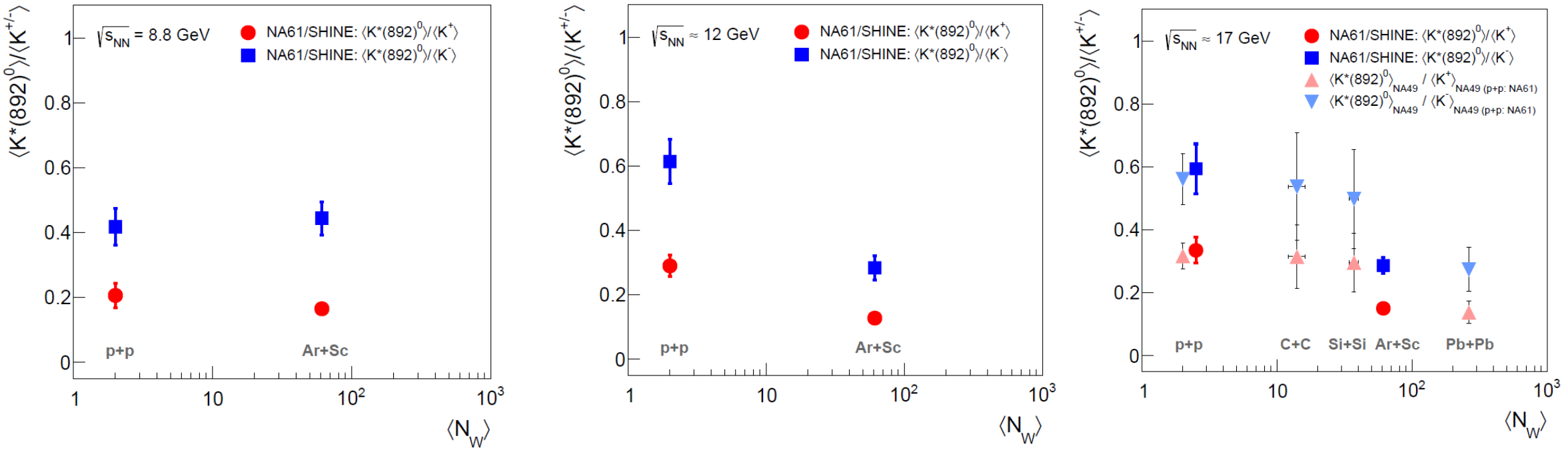


- Bose-Einstein correlations (femtoscopy) reveal the space-time structure of hadron production
- The Lévy parameter α describes the shape of the source and is sensitive to the system freezing out at the CP
- The new Ar+Sc results are between Gaussian and Cauchy, far from the CP (α=0.5)

No indication of critical point (α far above from the CP prediction)

NA61/SHINE: Eur.Phys.J.C 83 (2023) 10, 919 (Be+Be); Universe 9 (2023) 7, 298

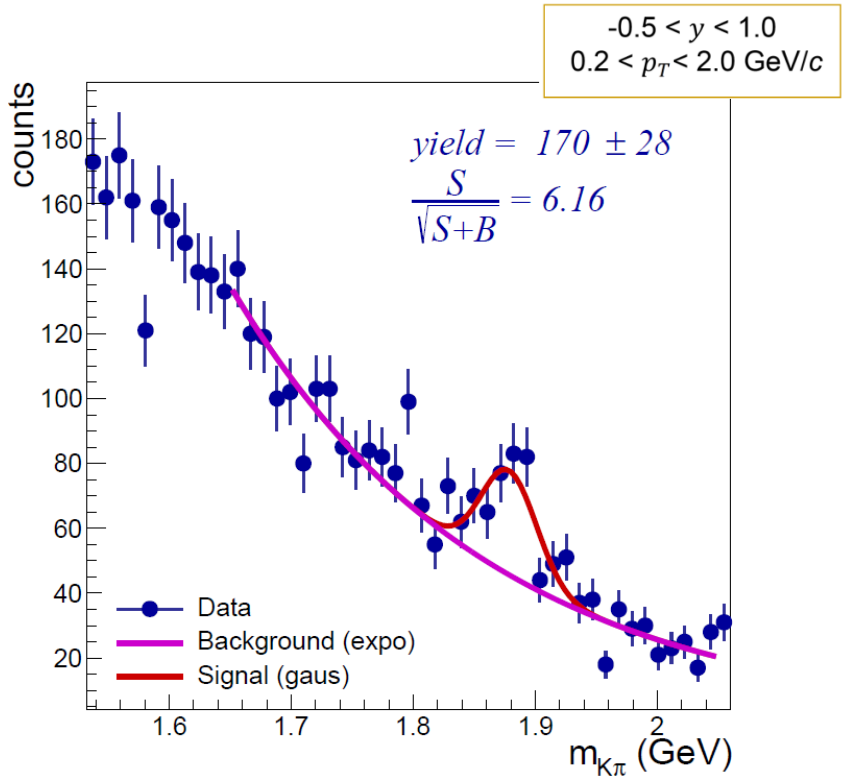
K*(892)^0 production in 0–10% central Ar+Sc collisions at 40A, 75A, and 150A GeV/c

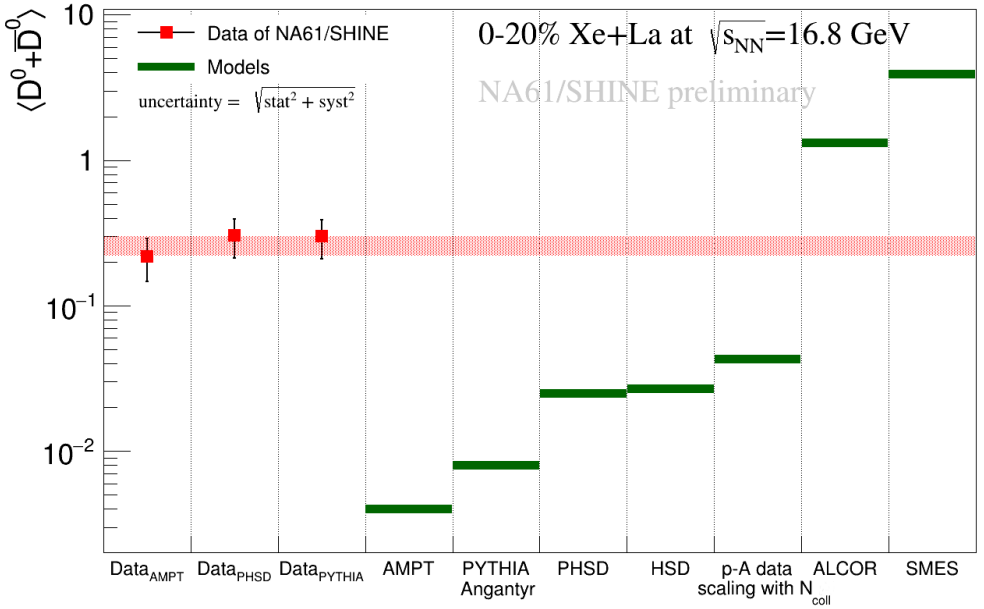


The decrease of K^*/K ratio from p+p to Ar+Sc ≈ Pb+Pb at $\sqrt{s_{NN}} \approx 17$ GeV

No K* suppresion in Ar+Sc at $\sqrt{s_{NN}} \approx 8.8$ GeV

D^0+ $\overline{D}^0$ production in 0–20% central Xe+La collisions at 150A GeV/c

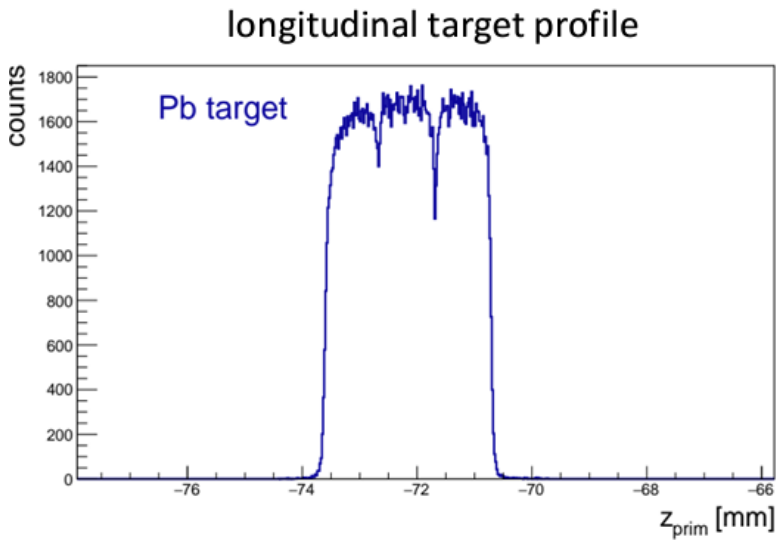


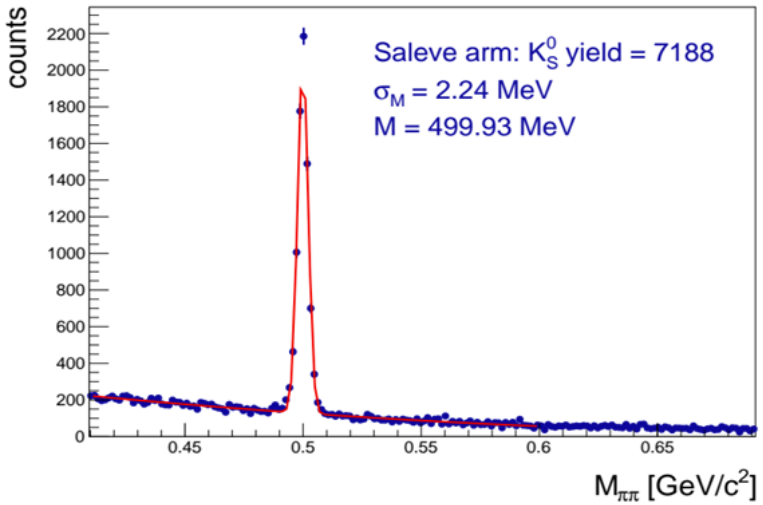


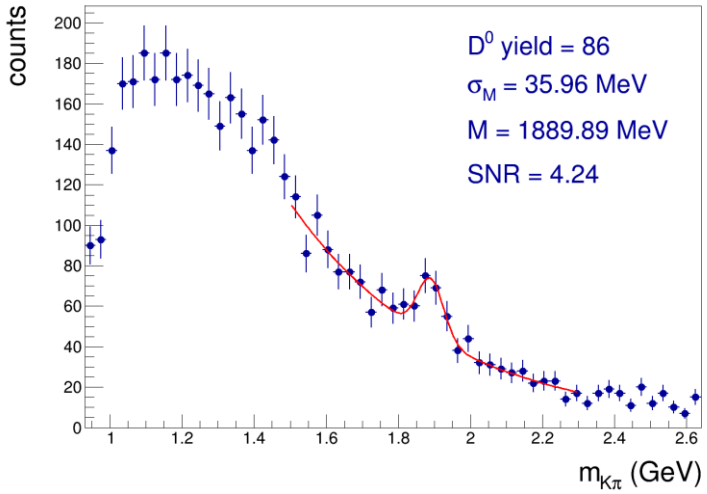
Correction made with:	Yield in 4π $\langle D^0 + \overline{D}^0 \rangle$
AMPT	**0.218** ± 0.039(stat) ± 0.060(syst)
PHSD	**0.303** ± 0.054(stat) ± 0.074(syst)
PYTHIA/Angantyr	**0.300** ± 0.052(stat) ± 0.075(syst)

First-ever direct measurement of open charm in nucleus-nucleus collisions at SPS energies

D^0+ $\overline{D}^0$ signal in Pb+Pb collisions at 150*A* GeV/*c* (2022 data)







Initial analysis has low efficiency - improvements are being made rapidly

Effort is currently put into improving the calibration

List of publications

- Two-pion femtoscopic correlations in Be+Be collisions at$\sqrt{s}_{NN}$ = 16.84 GeV measured by the NA61/SHINE at CERN: European Physical Journal C, ISSN 1434-6044, e-ISSN 1434-6052
- K0S meson production in inelastic p+p interactions at 31, 40 and 80 GeV/c beam momentum measured by NA61/SHINE at the CERN SPS: European Physical Journal C, ISSN 1434-6044, e-ISSN 1434-6052
- Measurements of higher-order cumulants of multiplicity and net-electric charge distributions in inelastic proton–proton interactions by NA61/SHINE: European Physical Journal C, ISSN 1434-6044, e-ISSN 1434-6052
- Measurements of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ spectra in $^{40}Ar+^{45}Sc$ collisions at 13A to 150A GeV/c European Physical Journal C, ISSN 1434-6044, e-ISSN 1434-6052
- Search for a critical point of strongly-interacting matter in central ^{40}Ar + ^{45}Sc collisions at 13 A-75 A GeV/c beam momentum European Physical Journal C, ISSN 1434-6044, e-ISSN 1434-6052

NA61/SHINE

Neutrino and cosmic ray physics; beam request

Neutrino beam physics

- Modern accelerator-based oscillation experiments use “conventional” beams: primary protons strike a target, secondary mesons enter a decay region, and they decay in flight to neutrinos upstream of a beam stop
- All have common properties:
  - Predominantly ν_μ, with ν_e contamination at the ~1% level from muon, kaon decays.
  - Even “narrow-band” beams tend to have tails to high energy
  - Fluxes have significant systematic errors

Understanding the flux

- Use Monte Carlo techniques to simulate the beam, but this is generally a very complicated and challenging environment. **Uncertainties can be large: 20-50% with standard simulation tools.**
- Monte Carlo must simulate:
  - Interaction of proton in target
  - Production of pions, kaons in target
  - Propagation of particles through horn (scattering, interactions, field)
  - Propagation through decay volume and loss in beam absorber
  - Meson decays to neutrinos, muons

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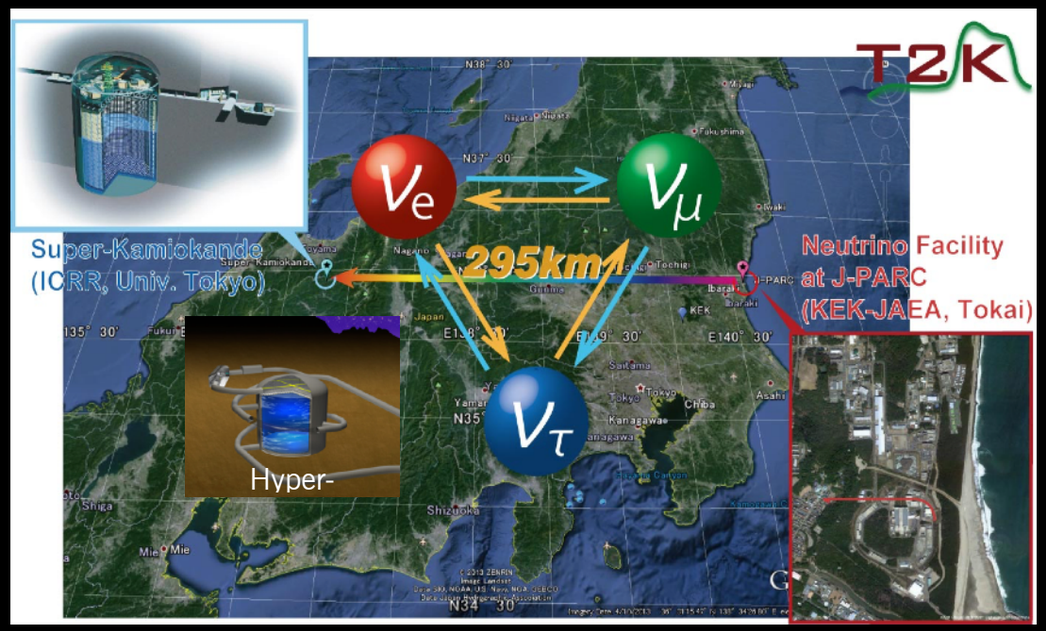
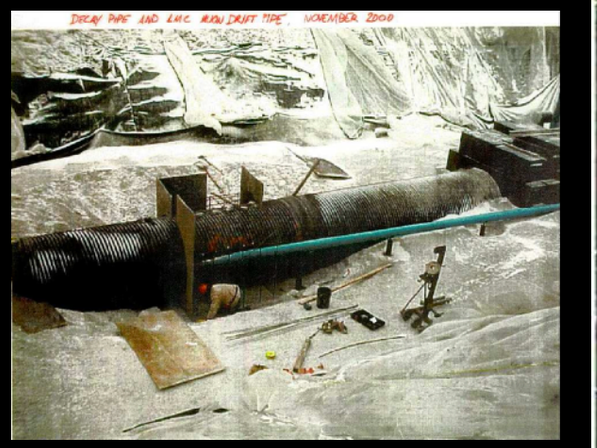
All of these require knowing hadron interaction physics!

Primary beam energies for current and near future neutrino beams

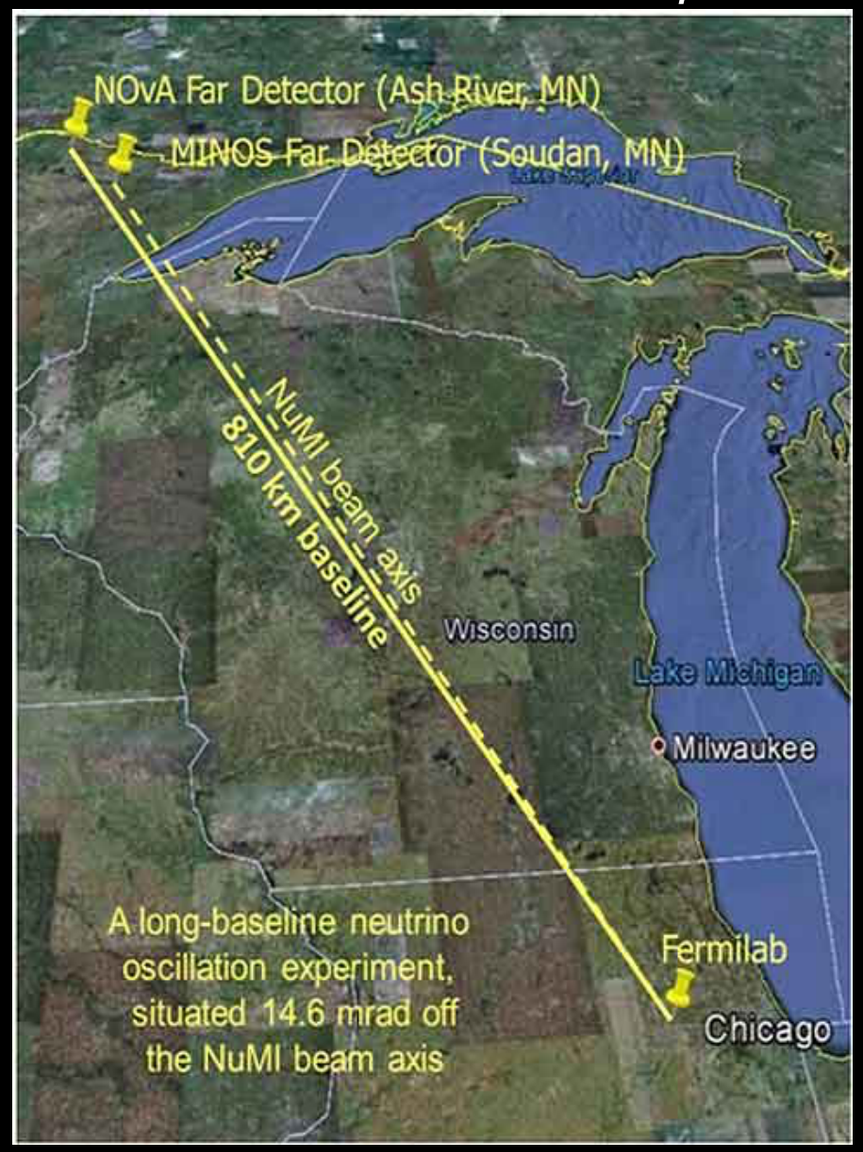
T2K, T2HK: 31 GeV/*c* *p*



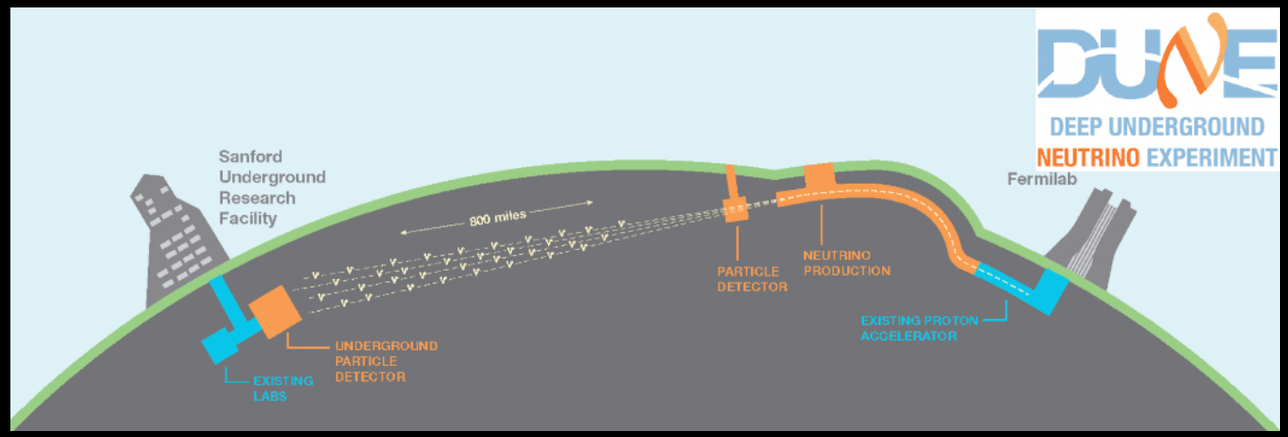


BNB: 8.9 GeV/*c* *p*

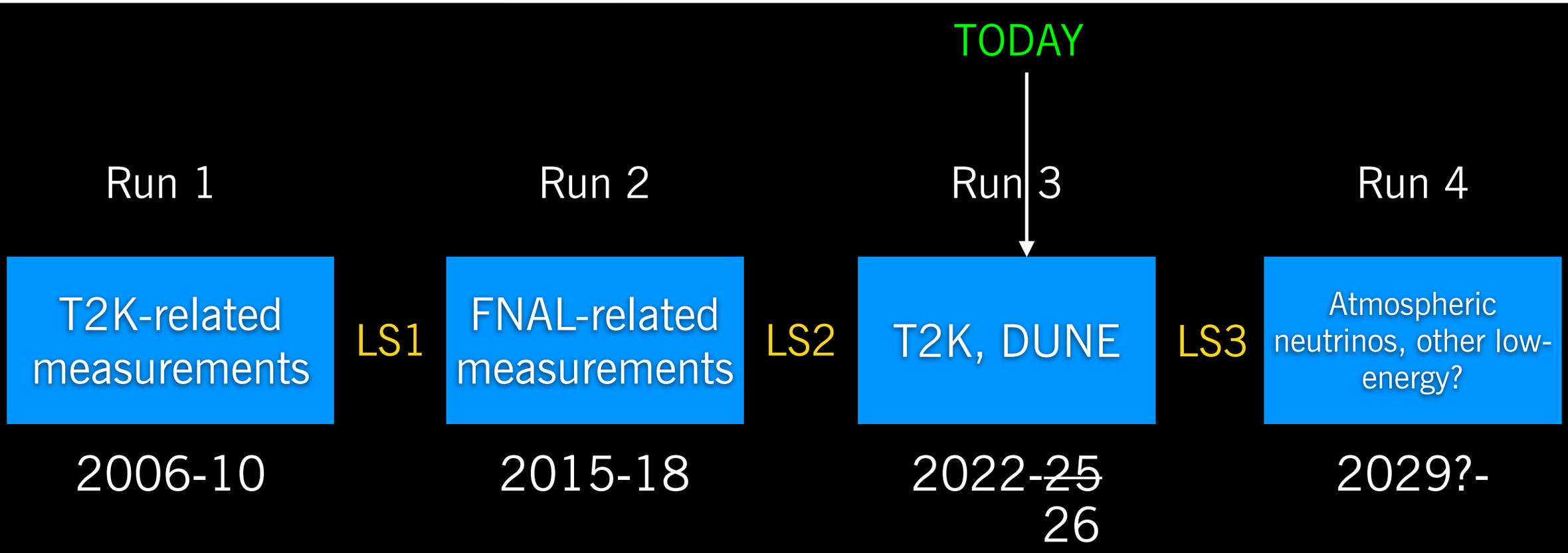
NuMI: 120 GeV/*c* *p*



LBNF/DUNE: 60-120 GeV/*c* *p*



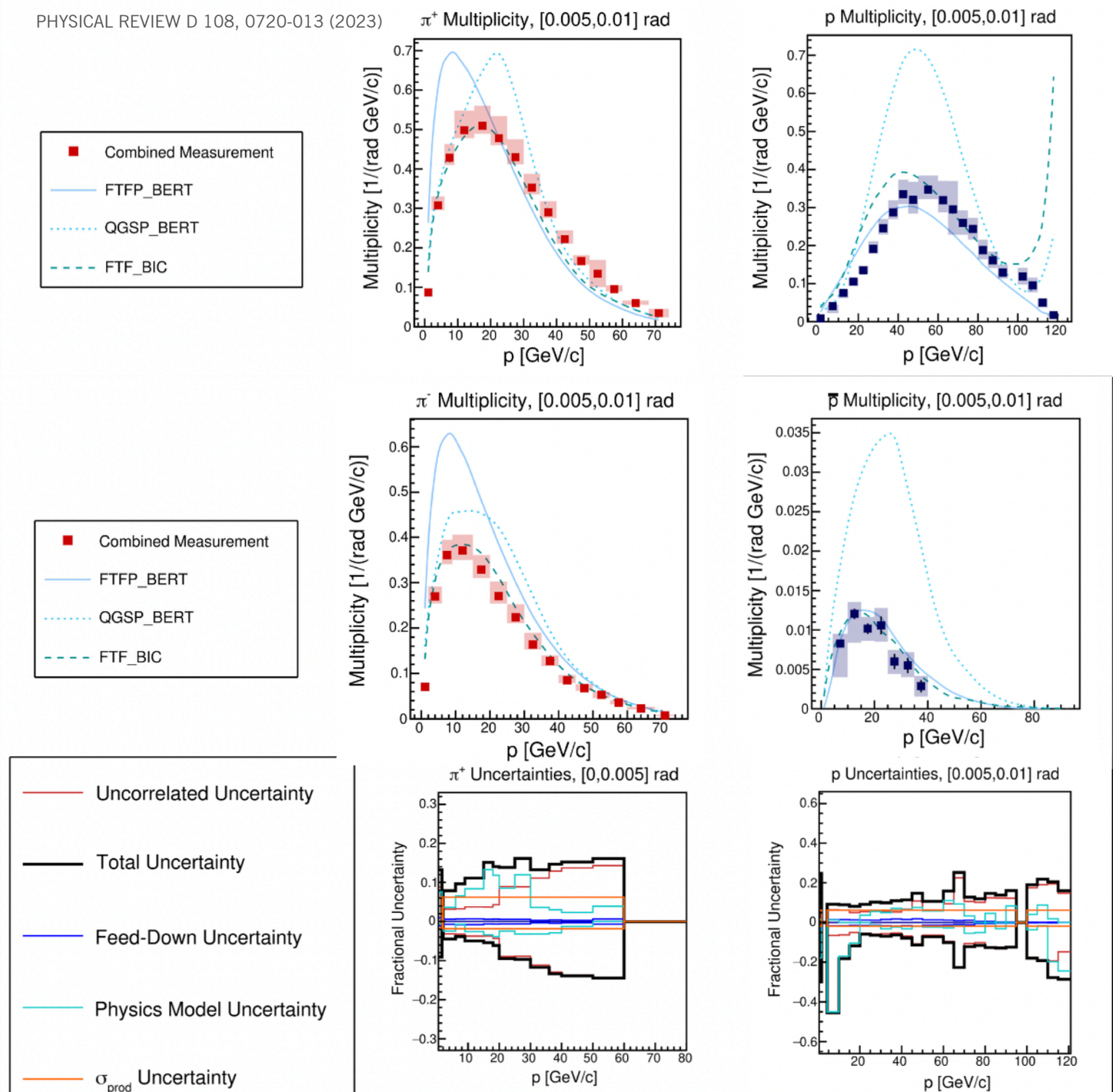
NA61/SHINE neutrino physics operational eras



- Multi-phase program of hadron production measurements dedicated for neutrino physics
- Major upgrades during each Long Shutdown
- Plans continue to evolve for future upgrades and operations

p+C @ 120 GeV Charged, neutral hadron multiplicities: published last year

- Measured multiplicities: π^+, π^-, p, $\bar{p}$, K^+, K^-, K^0_S, Λ, $\bar{\Lambda}$
- 2016, 2017 data sets combined
- Phys.Rev.D 108 (2023) 072013
- Phys.Rev.D 107 (2023) 072004
- Results will soon be used to reduce DUNE beam flux uncertainties



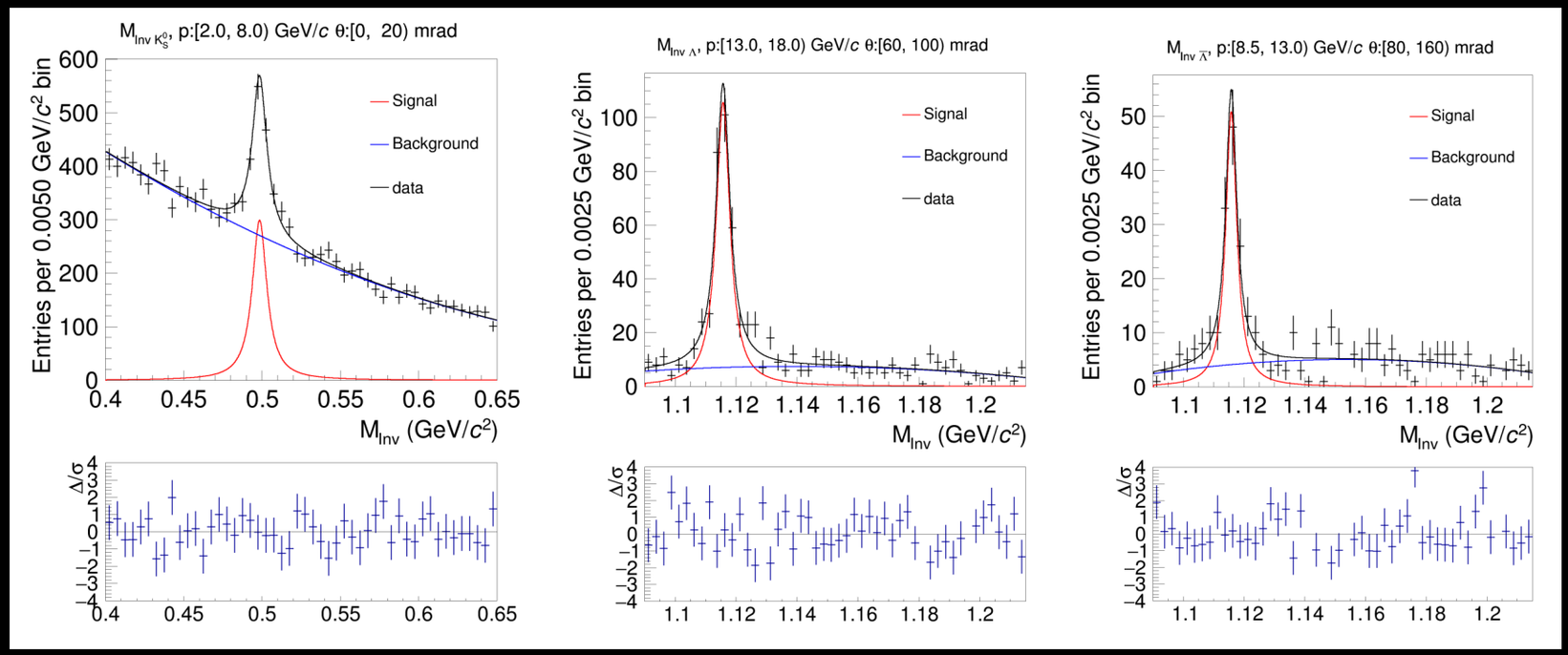
Intermediate energy interactions

- Production cross-sections at intermediate energies below the primary proton beam energy in neutrino experiments provide constraints for models to predict secondary interactions in targets and surrounding material
- NA61/SHINE took data with 90 GeV/*c* and 60 GeV/*c* protons
- 90 GeV/*c* analysis is complete: submitted to PRD in October
- 60 GeV/*c* analysis is at an advanced stage

p+C 90 GeV/c

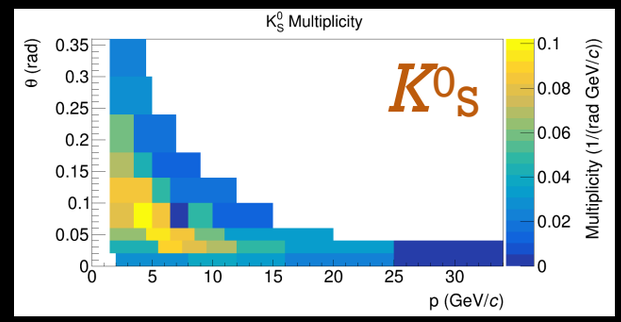
- Newest NA61 neutrino result: arXiv:2410.23098 [hep-ex]
- Differential multiplicities for the charged and neutral analysis of the p+C 90 GeV/*c* dataset

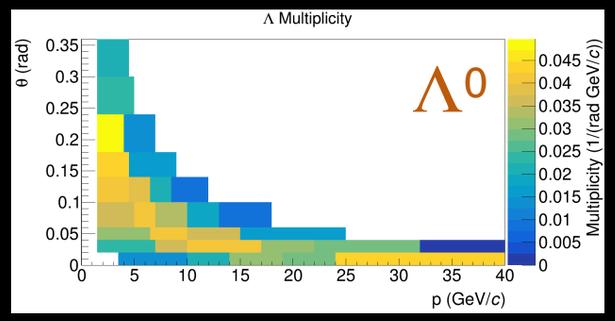
Invariant mass fits for reconstruction of K^0_S, Λ, $\bar{\Lambda}$

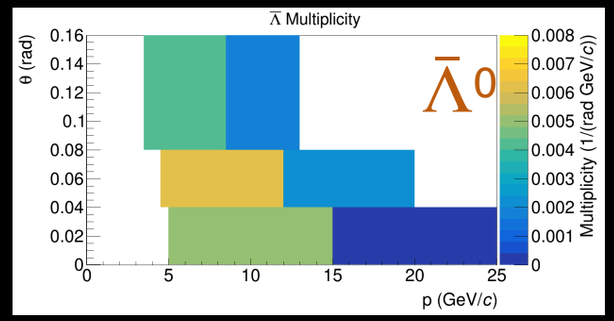


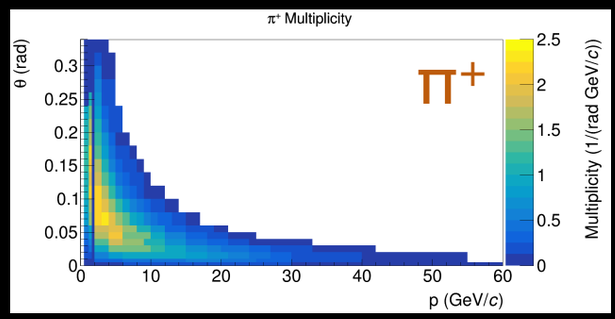
p+C 90 GeV/c

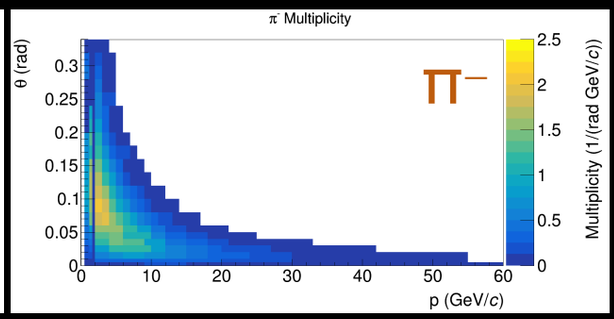
- Results on multiplicity of produced hadrons on thin carbon target

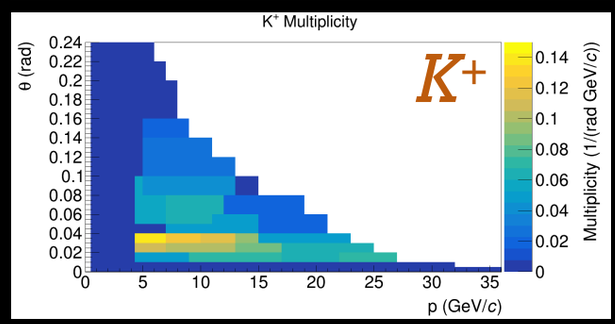


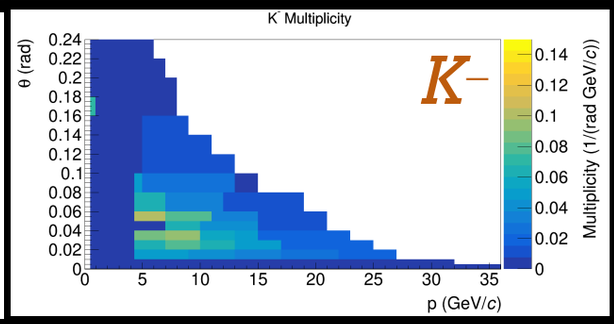










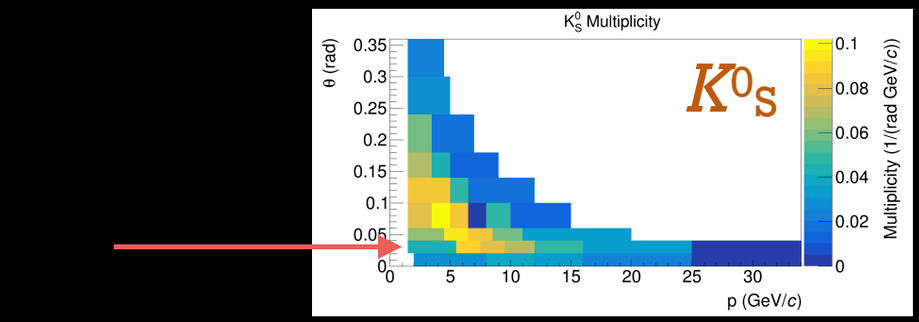


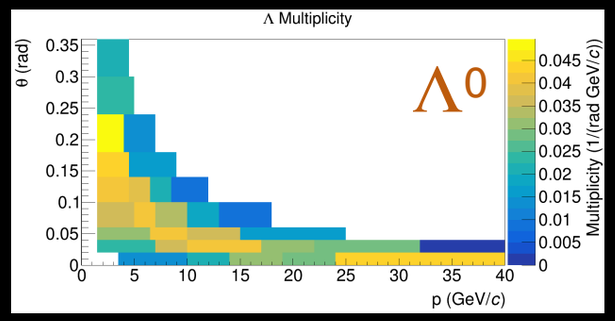
- arXiv:2410.23098 [hep-ex]

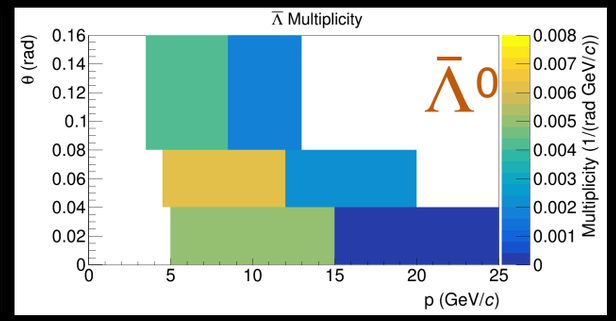
p+C 90 GeV/c

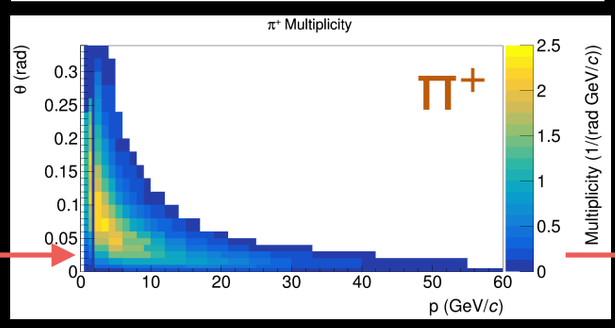
- Results on multiplicity of produced hadrons on thin carbon target

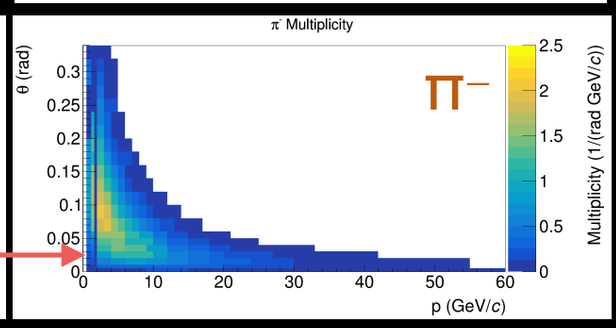
- Next: 1-D spectra with systematic errors for a specific angle bin

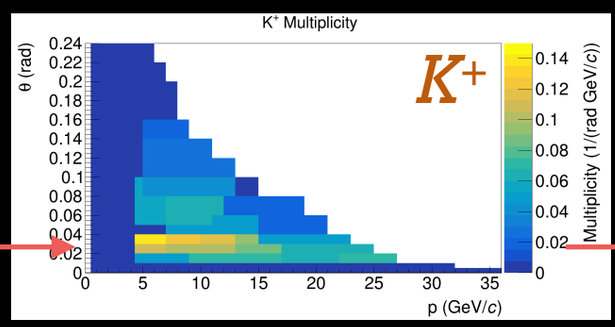


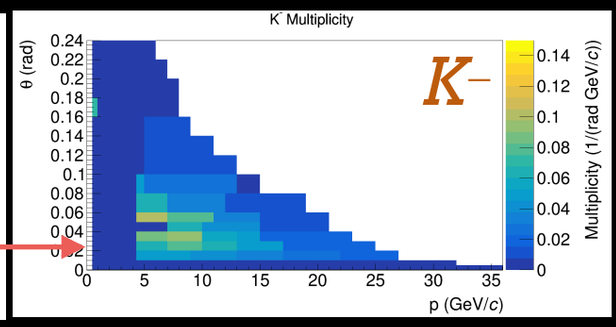








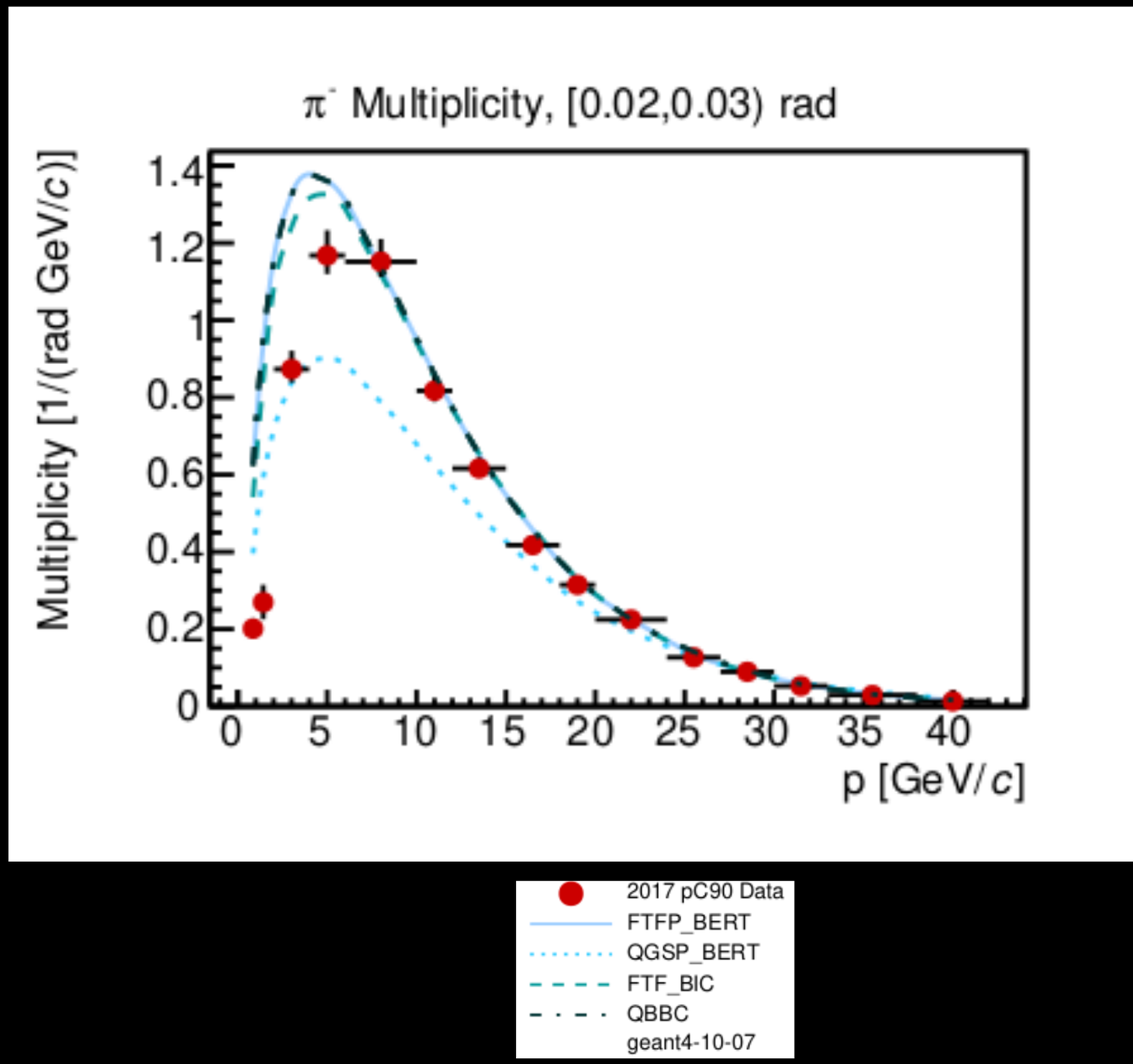




- arXiv:2410.23098 [hep-ex]

p+C 90 GeV/c

- Differential multiplicities for the charged and neutral analysis of the p+C 90 GeV/c dataset
- One angular bin for selected samples shown
- Have results on $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$, K^0_S, Λ, $\bar{\Lambda}$



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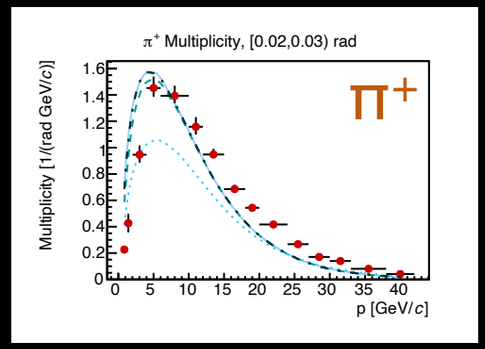
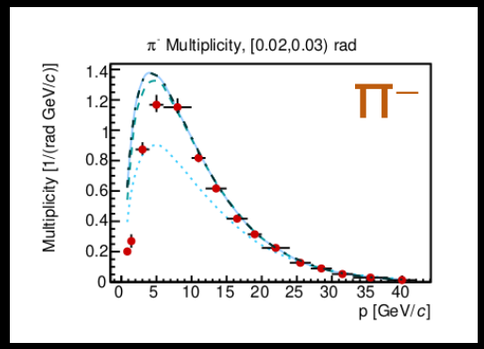
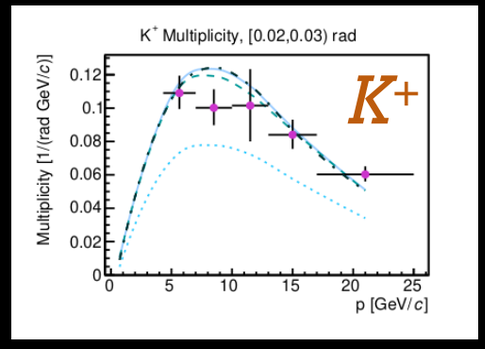
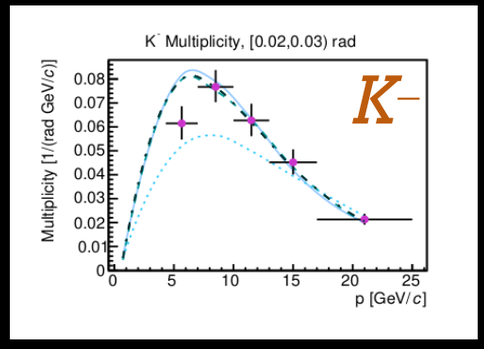
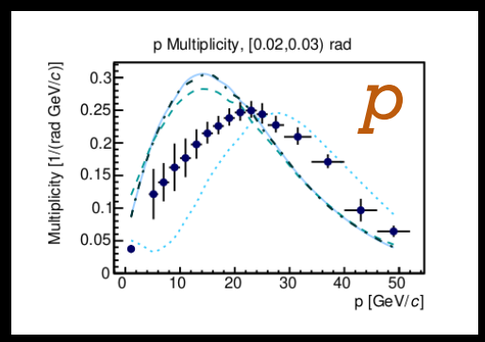
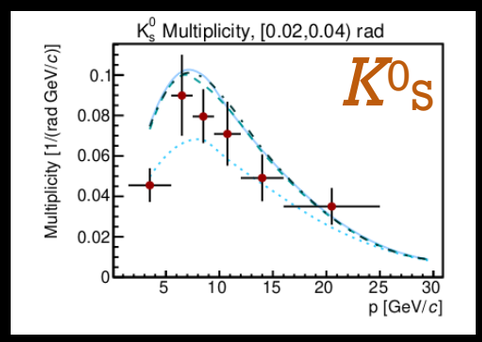


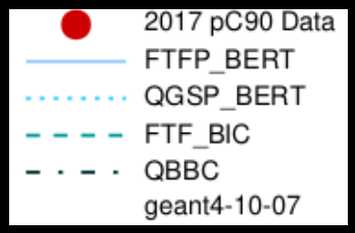






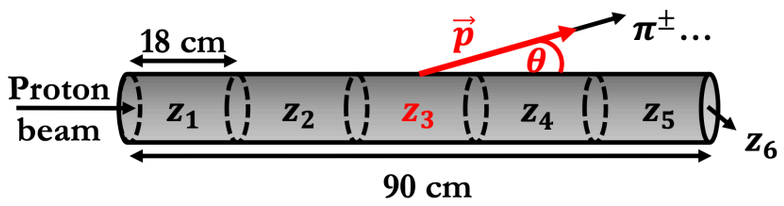


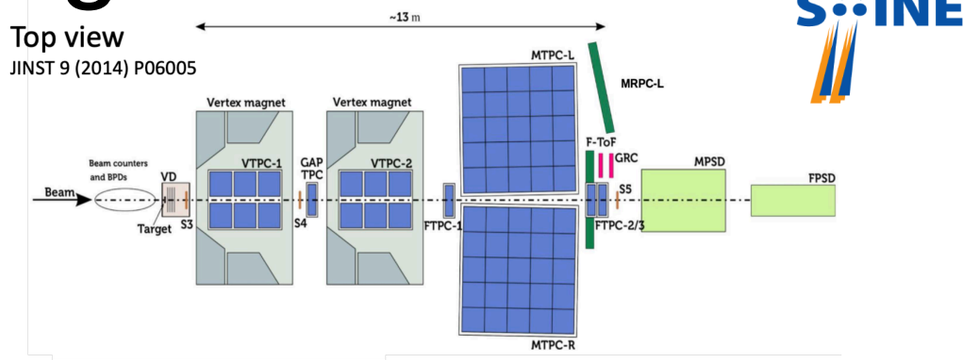




From T2K collaboration meeting this month: 2022 data

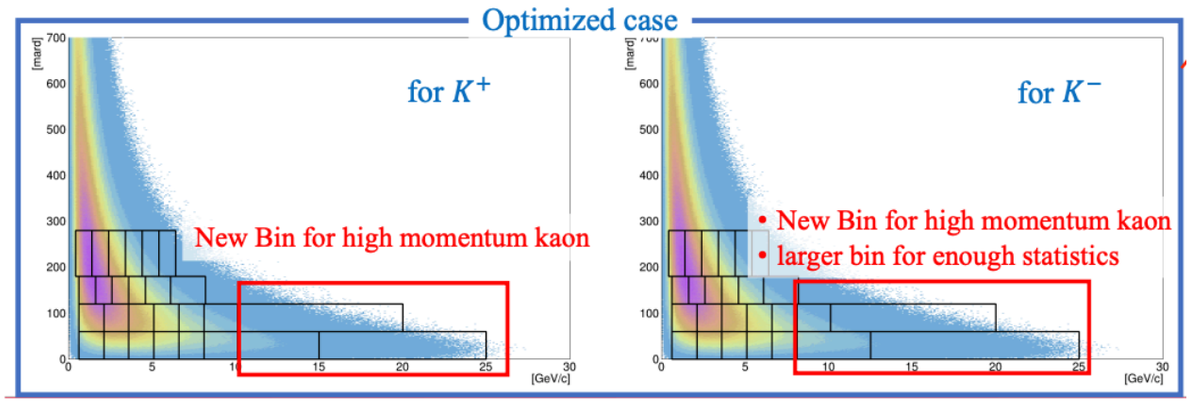
Long term outlook: more hadron production data from the NA61 replica-target dataset





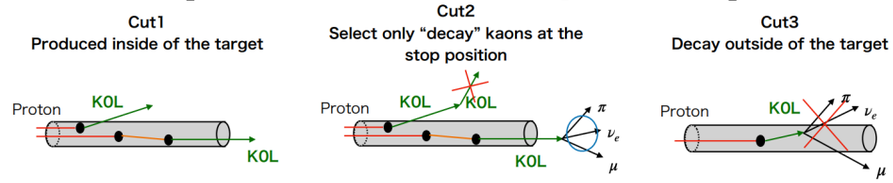
- More than 150M events were collected by NA61 in 2022 from the T2K replica target, which are being used to extract the K^0_S yields (constrains the wrong sign electron neutrino flux) and $K^{\pm}$ yields (further constraint on high energy flux tail)

$K^{\pm}$ Yields: Yuki Shiraishi and Amelia Camino



K^0_S Yields: Sakiko Nishimori and Claire Dalmazonne

MC to compare the K0L/K0S production



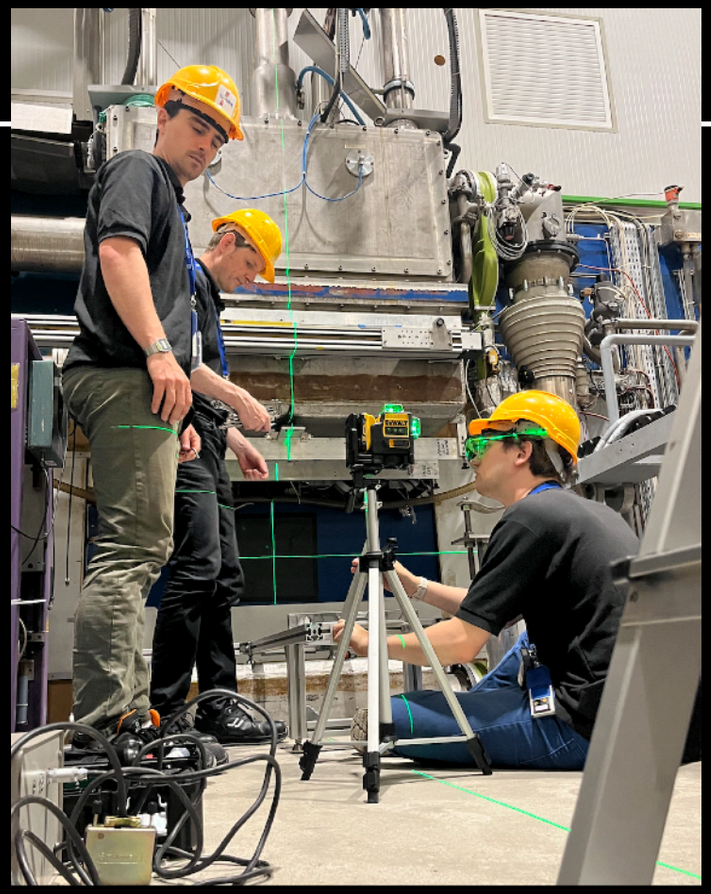
FTFP_BERT	Replica (90cm)			2cm		
	K0L	K0S	K0L/K0S	K0L	K0S	K0L/K0S
Cut1	204569	204274	100%	6756	6853	99%
Cut2	20175	185251	46 %	698	6752	-
Cut3	19888	93190	-	697	6051	-

99 %

- More than half of K0S are produced and decayed inside of the target. (Cut3/Cut1)
- Most K0L (~ 99 %) produced inside the target decay outside the target. (Cut3/Cut2)

—> Need to consider the difference!!

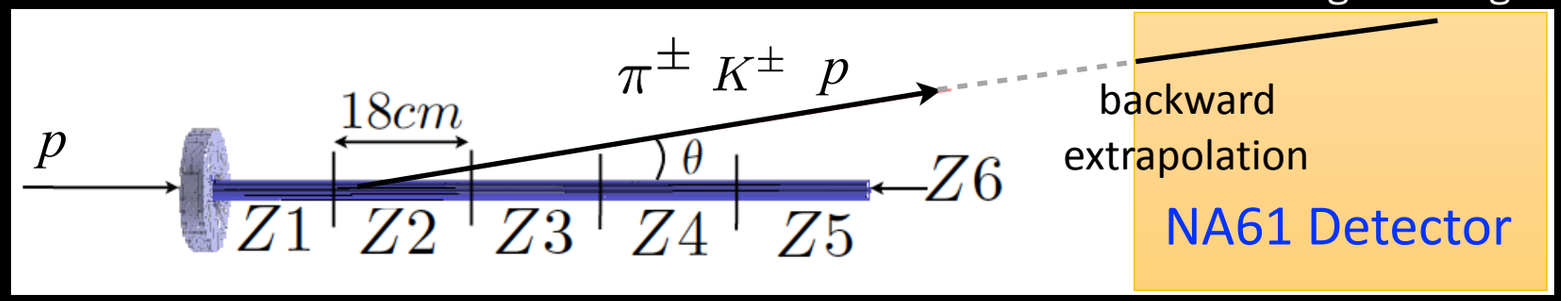
Data collection: now and near future



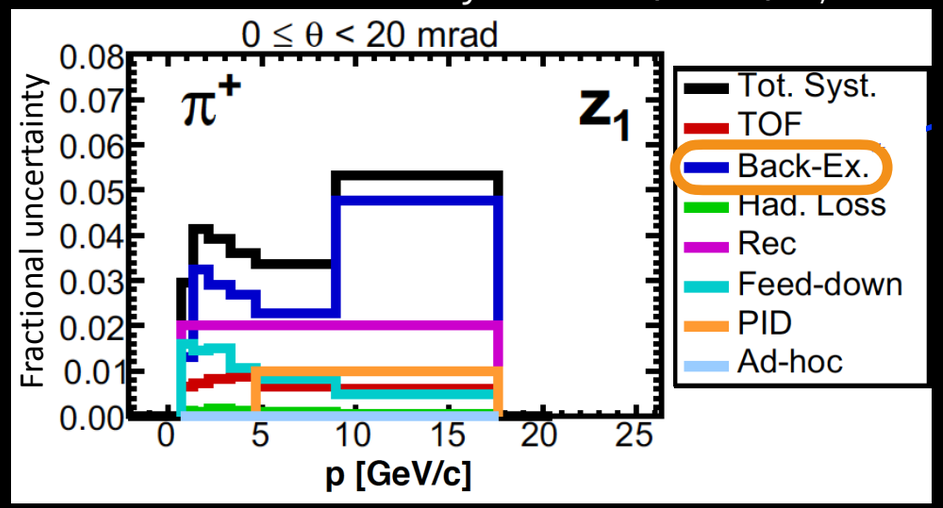
- LBNF/DUNE prototype target (2024)
- Target designed and built by RAL targetry group to expected dimensions of LBNF/DUNE target: 1.5 m long
- New TPC added to track particles exiting target
- Took 250M events summer 2024
- Planning to run with lower-density graphite target in 2025

Long-target tracker

image: Y. Nagai



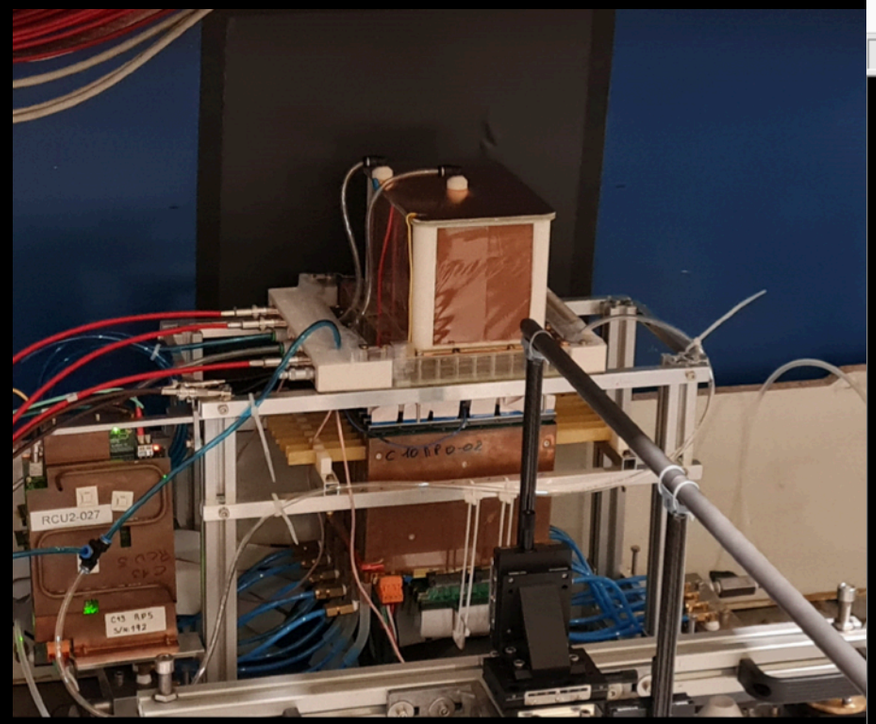
Eur.Phys.J.C 79 (2019) 2, 100

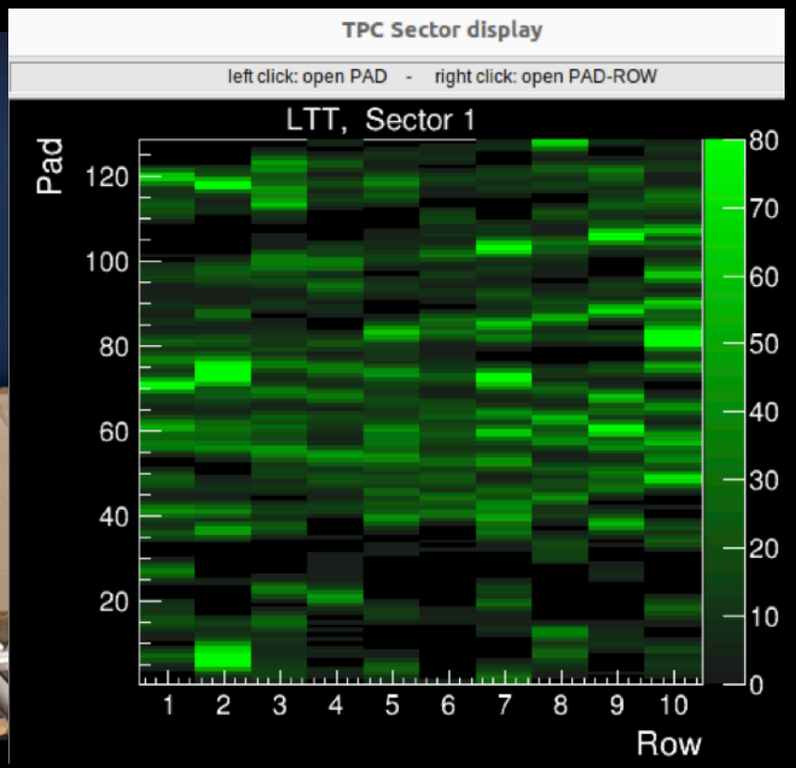


- A leading systematic error with the T2K replica target has been extrapolation of shallow-angle tracks backward to the target surface

- Additional small TPC built at KFKI/Wigner in Budapest

    - Sits at the end of the target to measure exit point of tracks more precisely

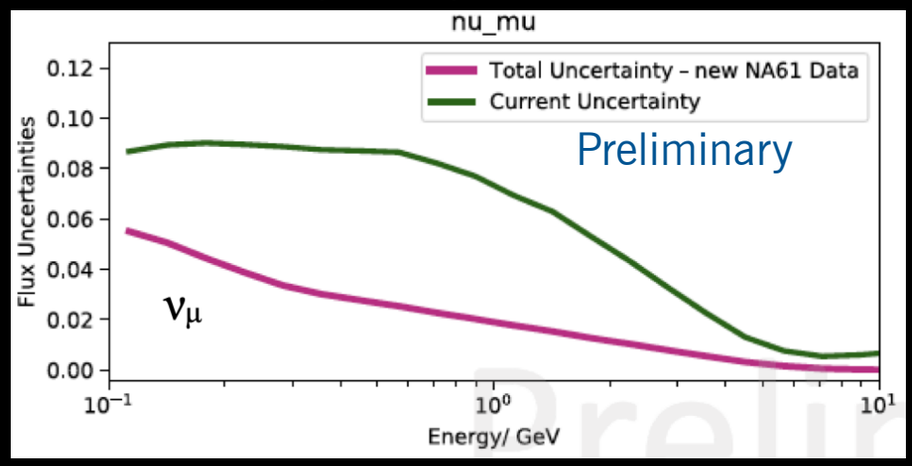




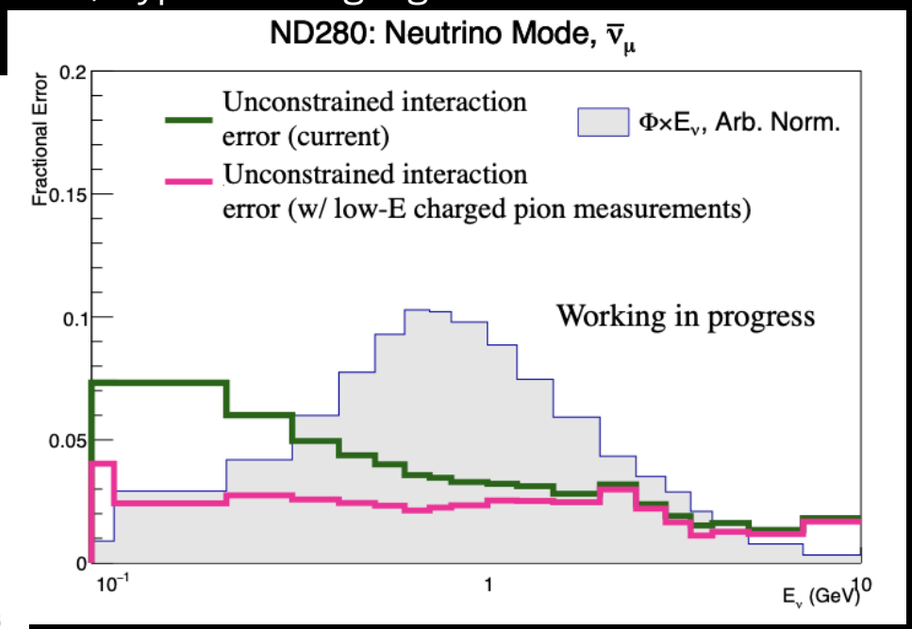
Neutrino program after 2025: low-energy beam

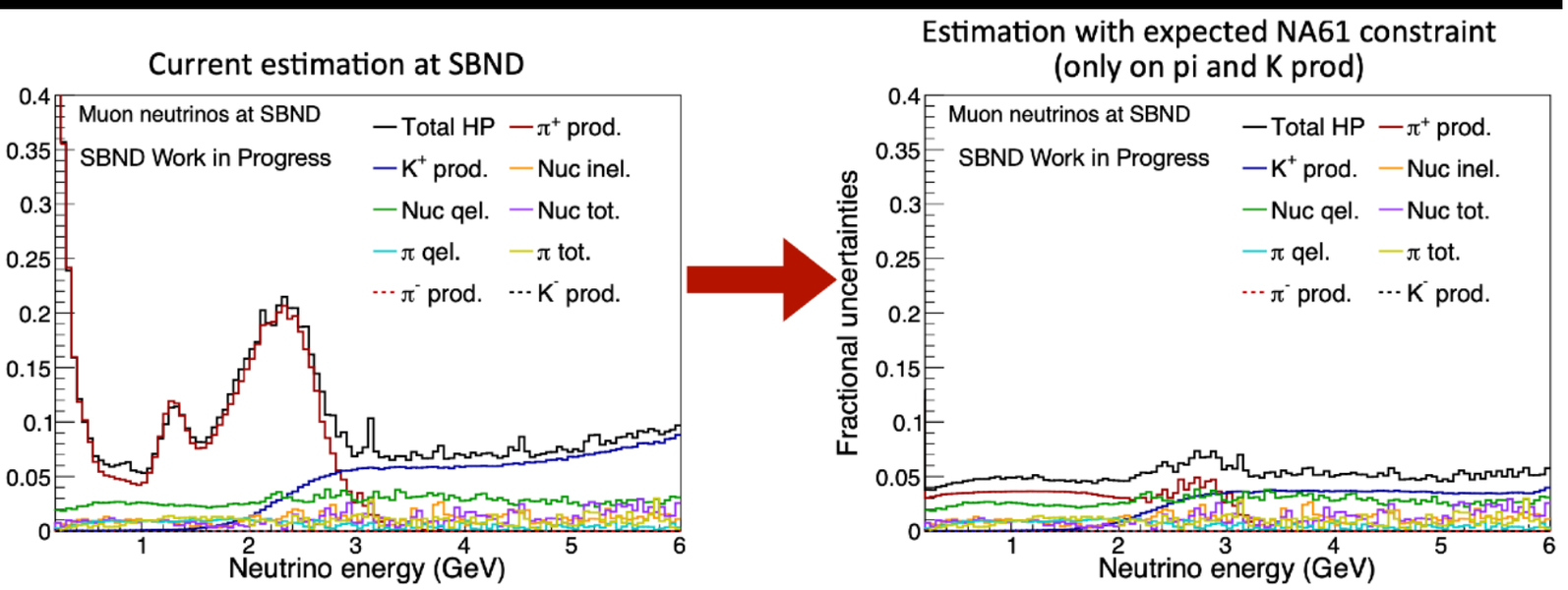
- Many groups are interested in hadron production with beams in the 1-20 GeV region, below the range the current H2 beam is capable of providing
  - Potential significant improvement in atmospheric neutrino flux prediction
  - FNAL Booster Neutrino Beam
  - T2K/HyperK secondary interactions
  - Spallation sources, cosmic rays, others…

L. Cook (Bartol Group) atmospheric neutrino flux

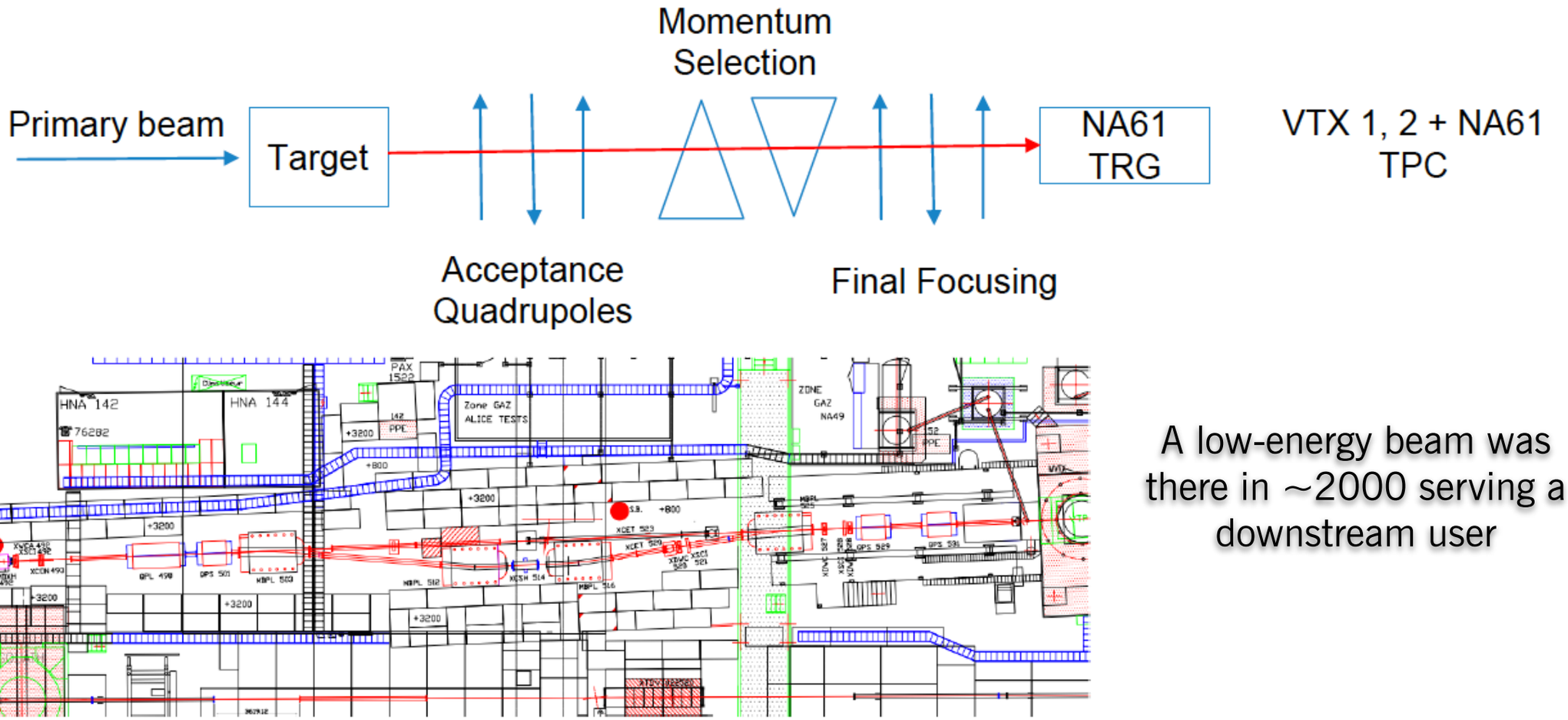


T2K/HyperK wrong-sign flux uncertainties





Low-energy beam for NA61/ SHINE



- Goal is to have beam available after (or even before) the next Long Shutdown
- Can switch easily between new low-energy beam and current higher-energy configurations

Low-energy beam for NA61/ SHINE

- A letter has been drafted to be submitted on behalf of the neutrino community
- Requests CERN allocate resources for construction of the low-energy beam
- Submitted today to DRC Joachim Mnich

November 25, 2024

Contact persons: Yoshikazu Nagai and Eric D. Zimmerman
Phone: +36 30 403 2854
Email: yoshikazu.nagai@cern.ch, edz@colorado.edu

Dr. Joachim Mnich
Director for Research and Computing
CERN
1211 Geneva 23
Switzerland

Dear Dr. Joachim Mnich (cc: CERN SPSC, CERN RB),

As representatives of experiments across the neutrino and other relevant scientific communities, we are writing this letter to seek authorization for the implementation of the low-energy (low-E) beamline project at the SPS H2 line and inquire whether CERN could assume the financial responsibility for the required facility modification and beamline development. As detailed in previous exchanges with the SPSC (SPSC-P-330-ADD-12 (2021), SPSC-M-793 (2022), SPSC-M-795 (2023)), the NA61/SHINE collaboration, alongside the H2 low-E Beamline Working Group, has accomplished comprehensive design and feasibility assessments for the low-E beamline deployment, as well as examining its scientific impacts within the neutrino and pertinent physics communities. These evaluations underscore a considerable impact on relevant physics cases, crucial for advancing future experimental endeavors.

It is also pertinent that the Short-Baseline Neutrino initiative promises to yield precise data regarding neutrino-argon interaction cross sections, which constitute a vital element for the DUNE experiment's scientific agenda. CERN has significantly invested in advancing liquid argon TPC technology, which forms the backbone of the DUNE experiment. The low-energy hadron beam initiative will thus augment and enhance CERN's commitments to neutrino physics in this particular aspect.

Comprehensive estimates of the expenses and schedule necessary for both facility upgrades and beamline construction have been developed with input from all pertinent experts at CERN. These estimates are compiled in the Engineering Change Request (ECR SPSX-L-EC-0009), which calculates the cost to reach up to 967.2 kCHF. The analysis indicates that a significant portion of these expenses are for capital investment in CERN's infrastructure. It is challenging for external funding bodies to allocate resources for such internal CERN infrastructure, though external in-kind contributions are expected for appropriate items such as beam instrumentation. Considering the significant scientific value for both neutrino research and the other relevant scientific communities, **we would urge CERN to cover these project costs for constructing the low-energy beamline branch at the SPS H2 line**.

The NA61/SHINE collaboration is currently in the process of planning an extension to its program including physics cases with low-energy beams. A comprehensive discussion regarding the necessity of low-energy hadron beams at the SPS H2 beamline took place during the NA61/SHINE++ workshop in December 2022. In light of these considerations, the collaboration is actively seeking new collaboration members to contribute to the physics initiatives involving low-E hadron beams. We maintain ongoing communication with several institutions to enable their initial participation in NA61/SHINE with limited membership status, transitioning to full membership once the low-E hadron beam project receives approval.

Low-energy beam for NA61/ SHINE

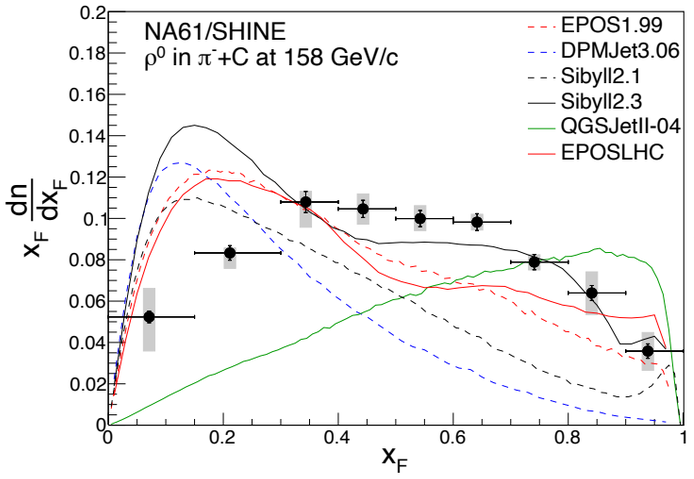
- Letter has been signed by spokespersons of the following collaborations:
  - DUNE
  - Hyper-Kamiokande
  - T2K
  - SBND
  - ICARUS
  - FLUKA
  - COMET
  - Honda atmospheric neutrino flux group
  - COMET
  - COHERENT
  - JSNS^2/JSNS-II
  - NA61/SHINE
- We hope that this strong support from the neutrino physics community will allow CERN resources to be freed up for the low-energy beam.

Cosmic-ray physics in NA61/ SHINE

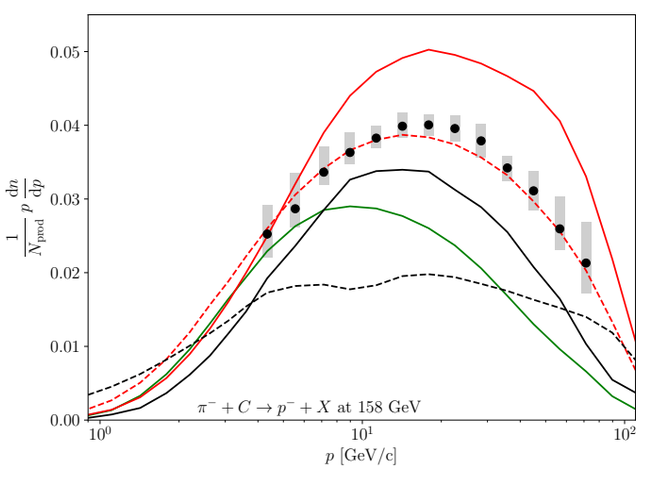
- Long-standing program within NA61/SHINE to make measurements of physics processes important to cosmic ray studies
  - Hadroproduction in ultrahigh-energy air showers
  - $\bar{p}$ production in the galaxy
  - Antinuclei in the galaxy
  - Cosmic-ray propagation in the galaxy

Large $p+p$ data set requested 2025

Nuclear fragmentation data to be collected late 2024



NA61/SHINE EPJ **C77** (2017) 626



NA61/SHINE PRD **107** (2023) 062004

- forward ρ^0 can replace $\pi^0 \rightarrow \gamma\gamma$
- $\bar{p}$ is proxy for baryon production (p, $\bar{p}$, n, $\bar{n}$)

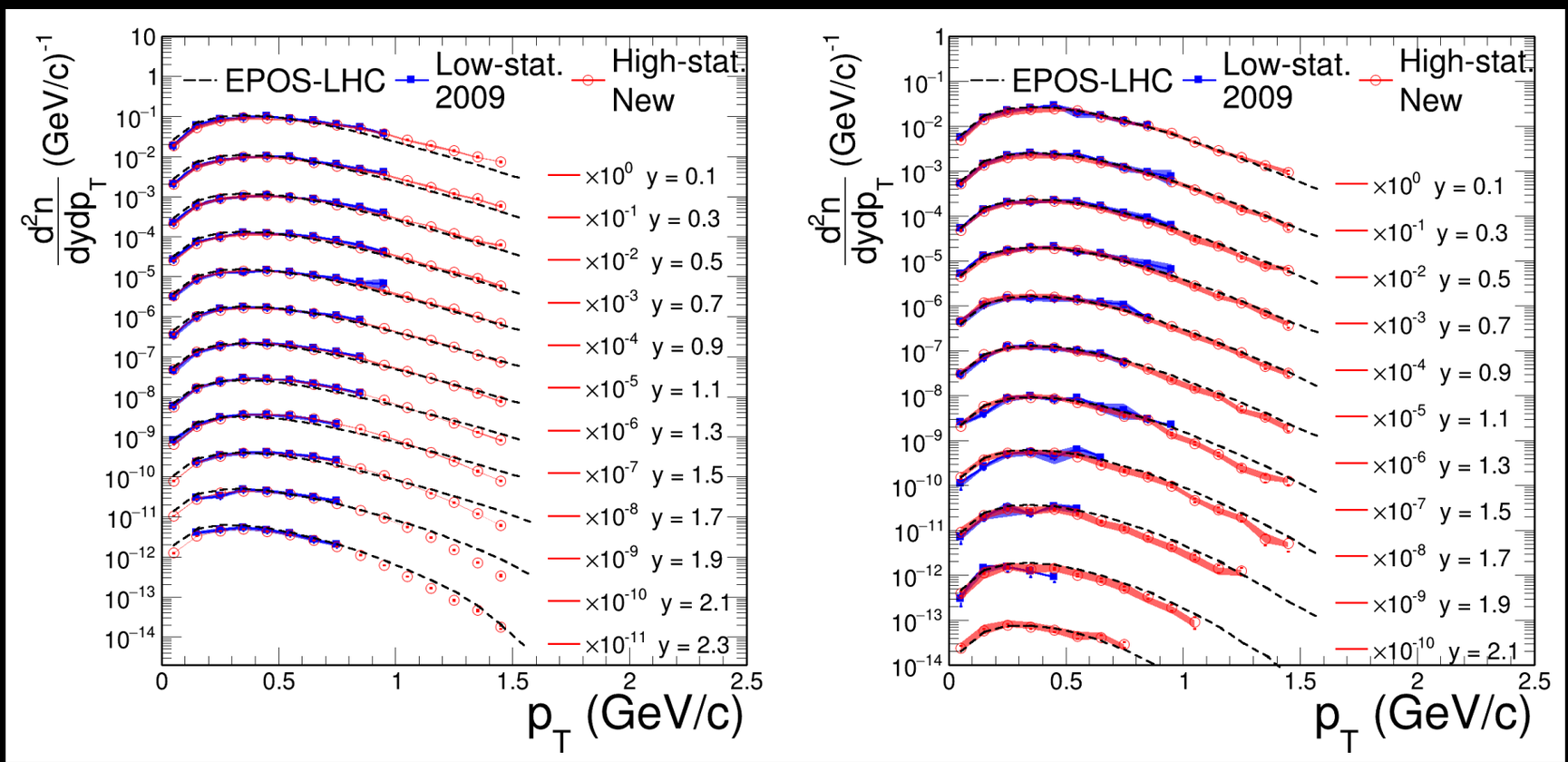
Hadron and deuteron production in p+p interactions

- Understand nucleus production in cosmic-ray p+p collisions in interstellar hydrogen
- Models of production are based on different physics (thermal and coalescence); data can shed light on the validity of the models
- Analysis of p, $\bar{p}$, d from 2009-2011 158 GeV/c p+p data sets, extending rapidity range to y_p=2.3 and $y_{\bar{p}}$=2.1

Hadron and deuteron production in p+p interactions

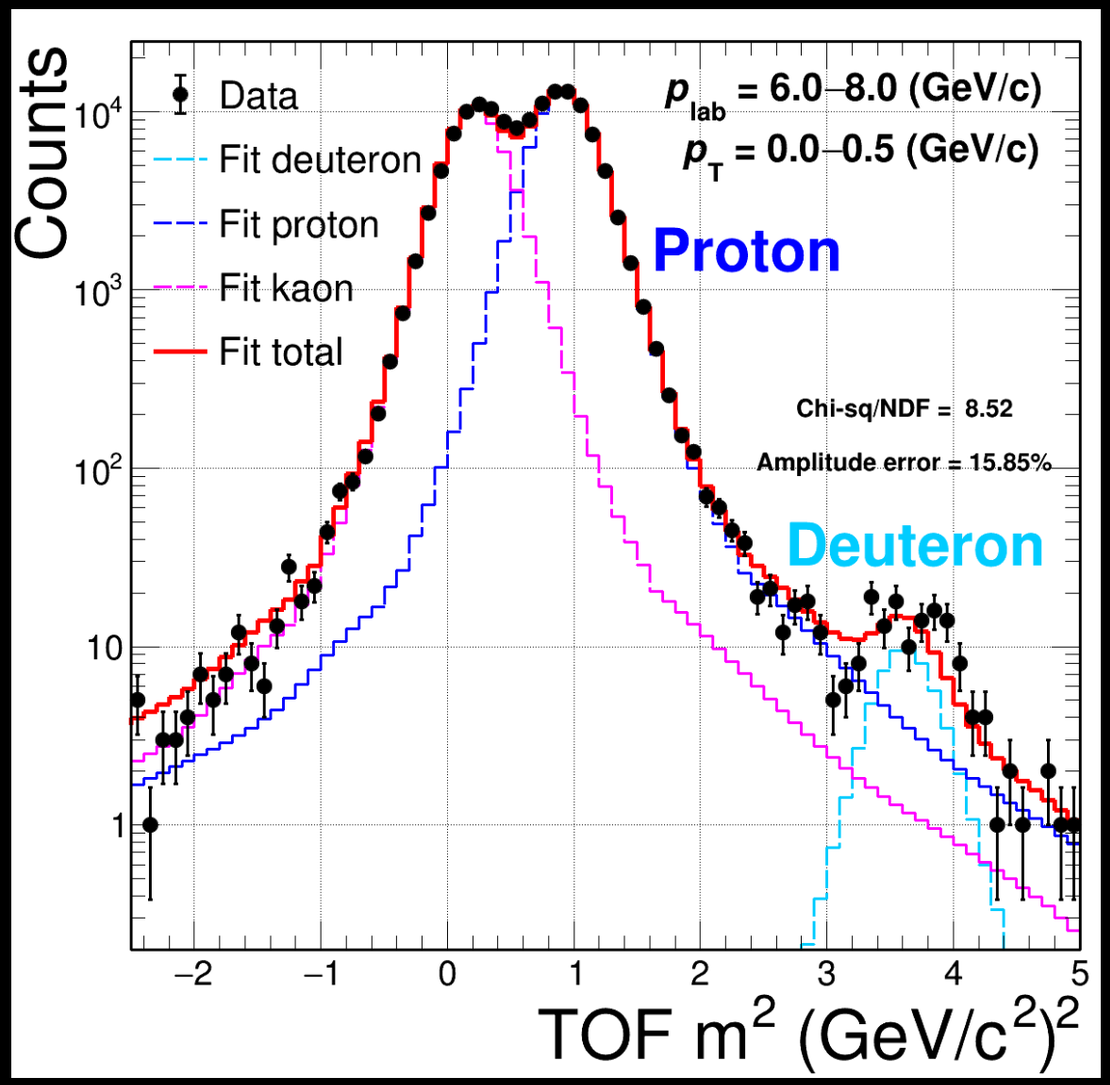
PROTONS

ANTIPROTONS



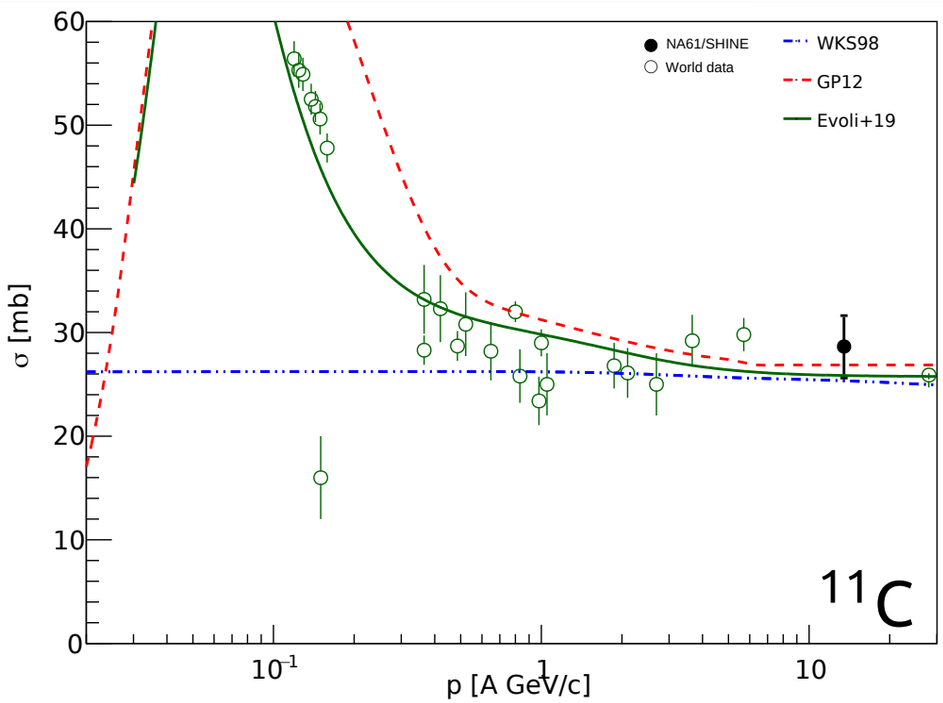
- Transverse momentum distribution of p, $\bar{p}$ production in p+p at 158 GeV/c
- New preliminary data points in red; EPOS-LHC model for comparison

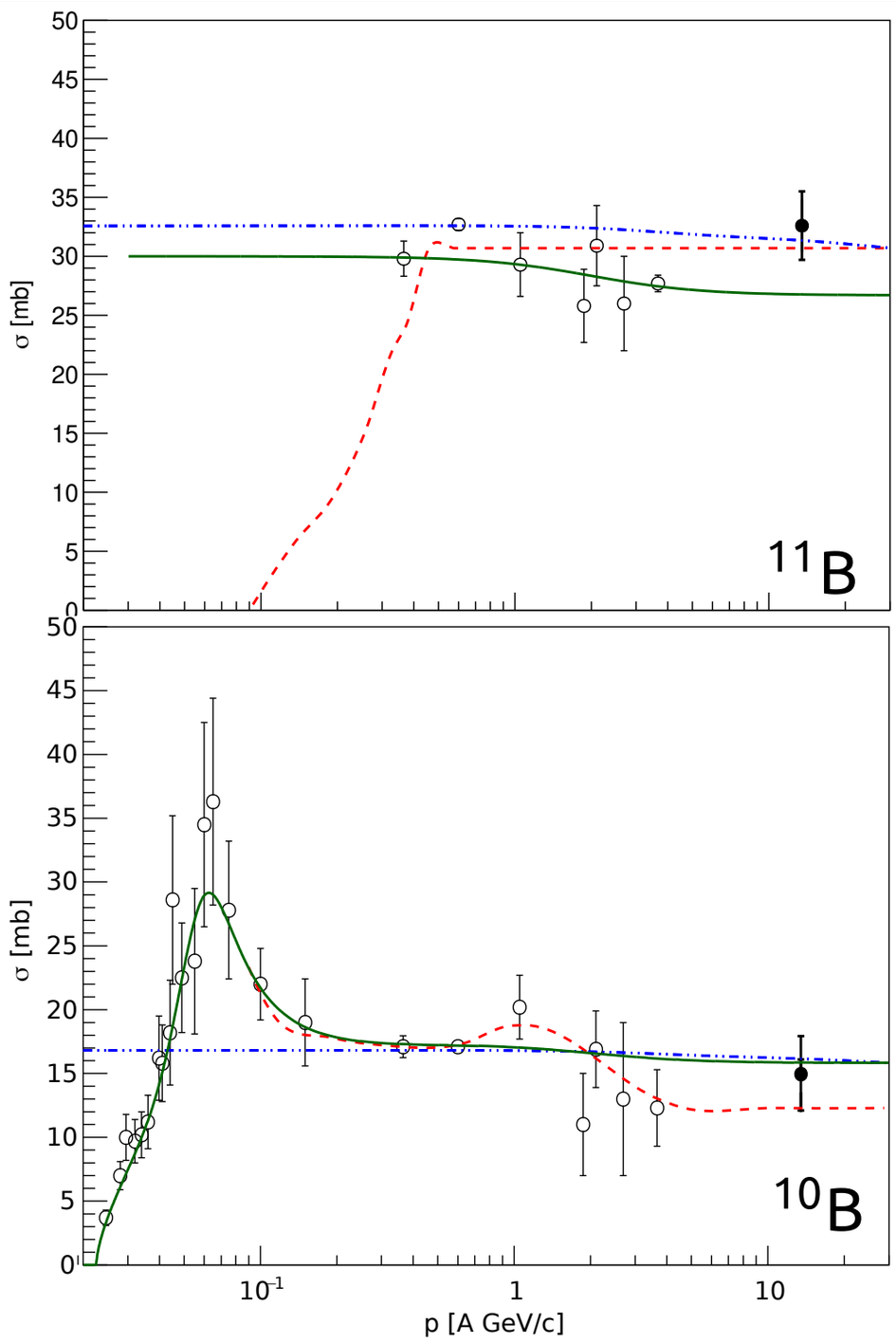
Hadron and deuteron production in p+p interactions



- Clear ability to identify deuterons using TOF
- Requesting new high-statistics 300 GeV/*c* data next year for precise measurement
- See CERN-SPSC-2024-028/ SPSC-P-330-ADD-15

Fragmentation pilot run results



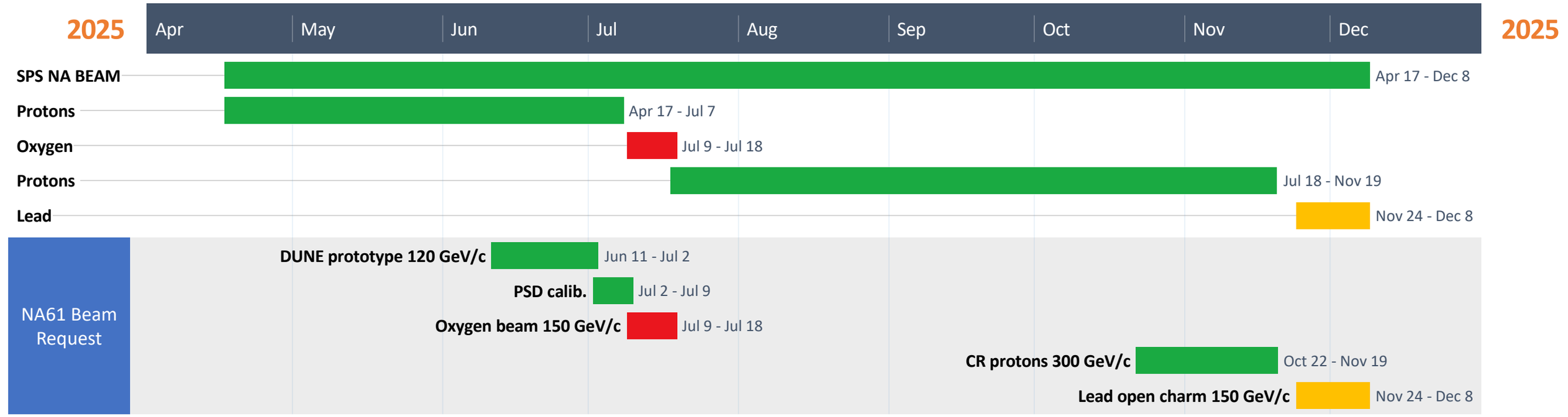


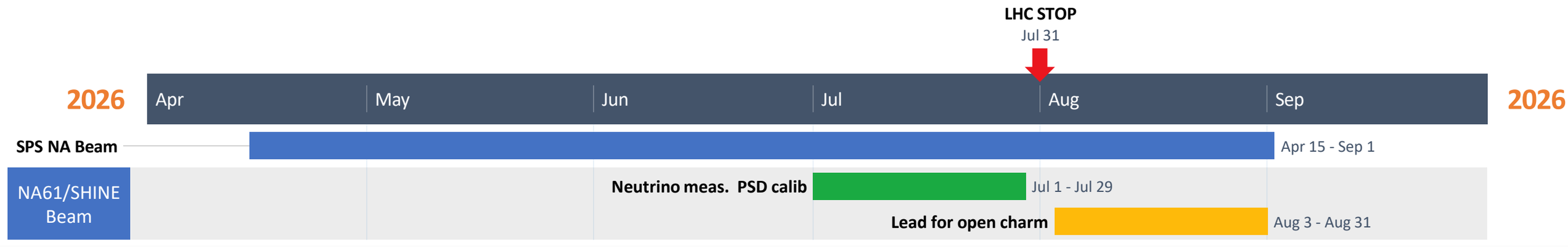
- pilot run succesful
- precision of pilot result limited by statistical uncertainty

$$\sigma_{C+p \rightarrow B} = 77 \pm 5 \text{ mb}$$

- e-Print: 2410.18273 [nucl-ex]
  - Submitted to *Phys. Rev. C*
- Shows that we can go to high energies where cross section is expected to flatten before logarithmic rise
- Coming high-statistics physics run to measure projectiles Li to F

NA61 Beam request for 2025 and 2026





Beyond LS3

- Strong Interactions
  - Light/medium ions (addendum CERN-SPSC-2023-022)
  - Charm correlations after tracking upgrade under discussion
- Neutrino/cosmic-ray physics:
  - Major program on atmospheric neutrino flux, other low-energy physics topics with low-energy beam
  - Retain capability for long-target measurements as needed for DUNE, Hyper-K

NA61/SHINE organizational changes

- As of December 1, Marek Gazdzicki will step down as spokesperson after serving since the collaboration was formed
- New spokespersons
  - Seweryn Kowalski (University of Silesia)
  - Eric D. Zimmerman (University of Colorado)
- New deputy spokespersons:
  - Katarzyna Grebieskow (Warsaw University of Technology)
  - Yoshikazu Nagai (Eötvös Lorand University)

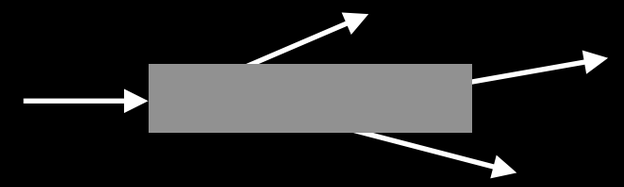
Acknowledgments

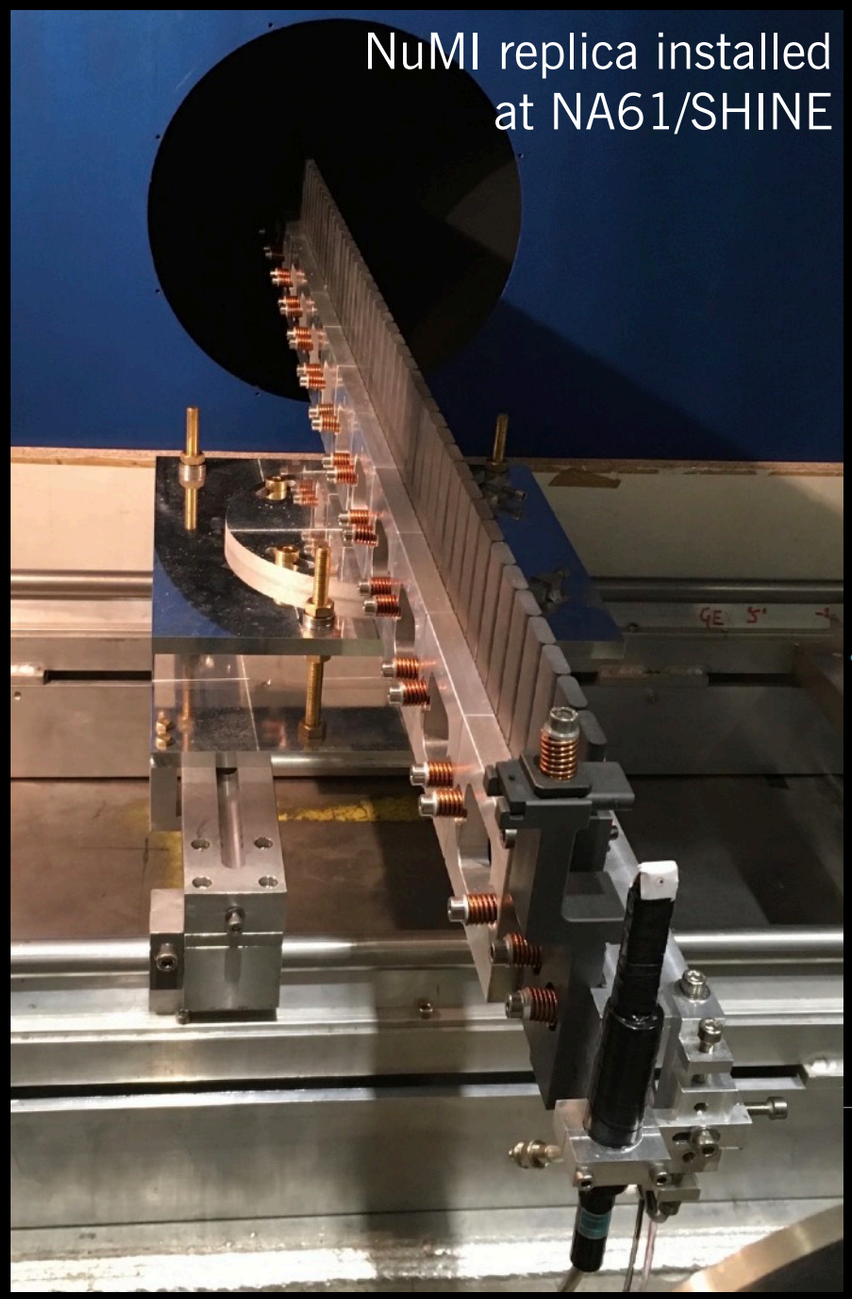
- We would like to thank the CERN EP, BE, HSE and EN Departments for the strong support of NA61/SHINE.

Speaker supported by US Department of Energy

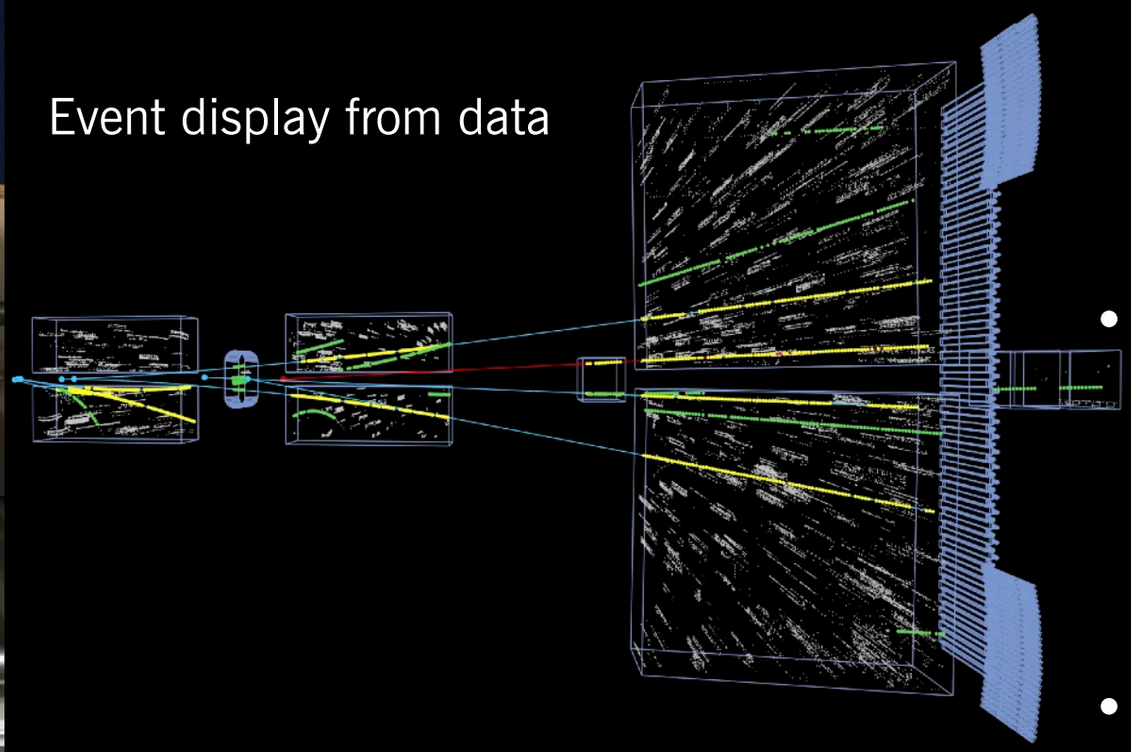
BACKUP

Analysis in progress: NuMI replica target





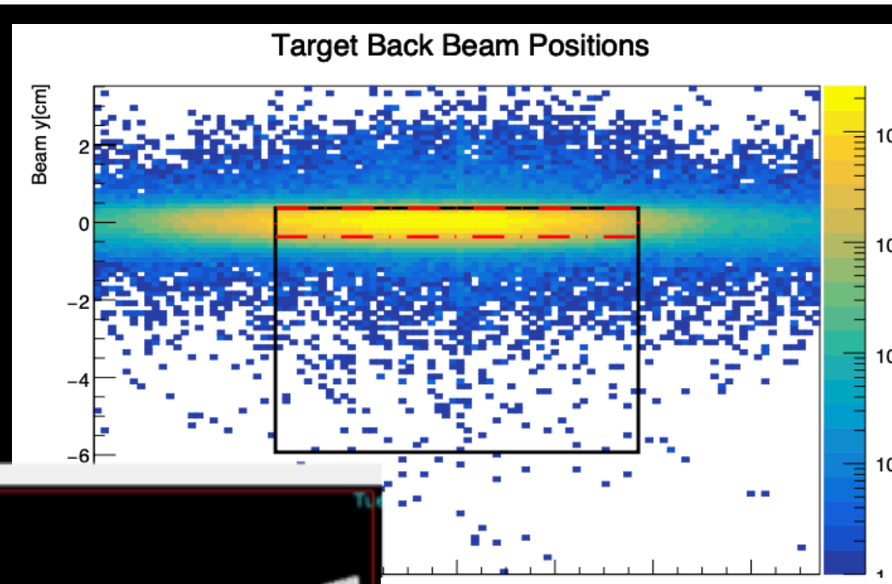
Event display from data



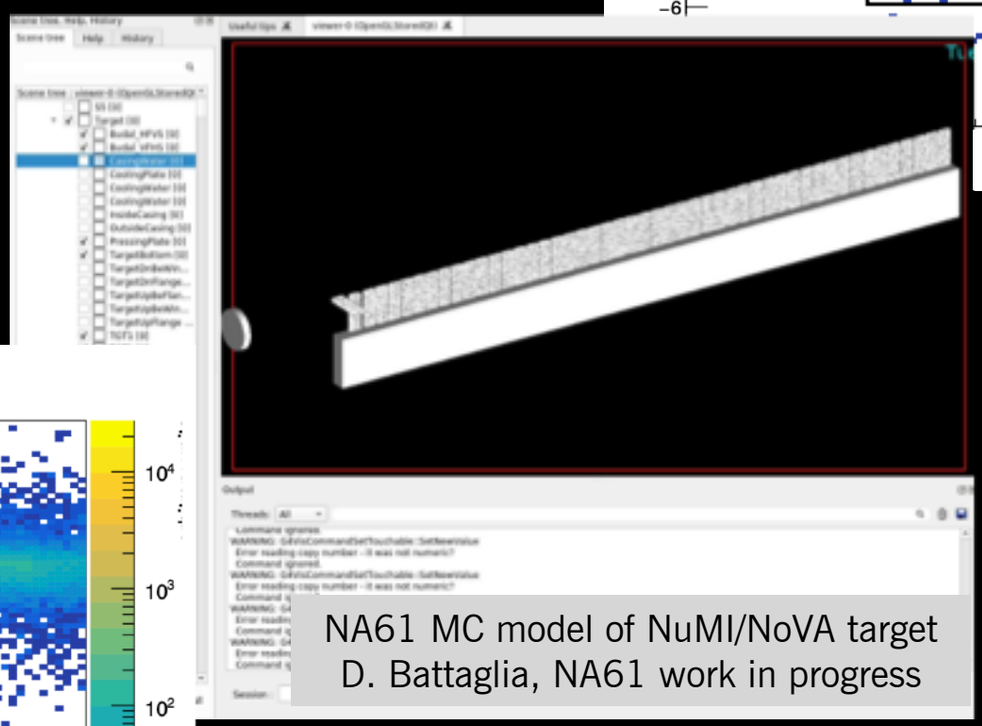
- Took high statistics (18M events) in 2018 with 120 GeV/c protons
- Analysis underway on hadron yields from this target
- Calibration in progress for this data set

NuMI target analysis

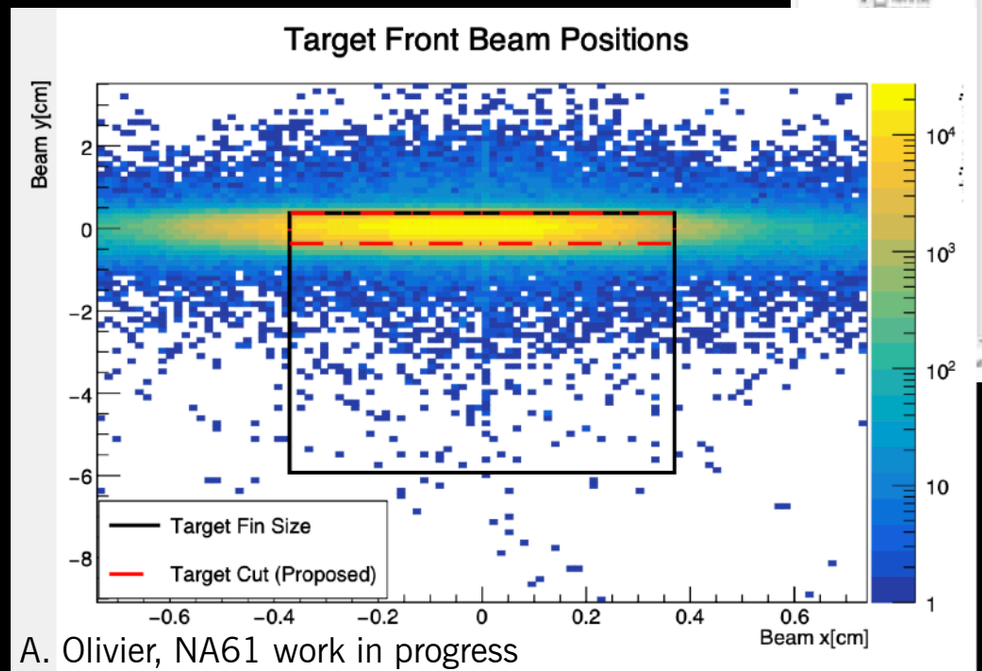
- Calibration of detectors underway
- Complicated geometry of the target, with azimuthal dependence
- NA61 acceptance is not uniform due to dipole analysis magnet!



A. Olivier, NA61 work in progress



NA61 MC model of NuMI/NoVA target
D. Battaglia, NA61 work in progress



A. Olivier, NA61 work in progress

PPFX: Package to Predict FluX

L. Ren

- Developed by the MINERvA collaboration for the NuMI beam
- Experiment-independent neutrino flux determination package for the Neutrinos at the Main Injector (NuMI) beam
  - MINERvA Collaboration, Phys. Rev. D 94, 092005, Leonidas Aliaga Soplin, PhD thesis
- Provides hadron production corrections and propagate uncertainties
- Uses external hadron production data

PPFX: Package to Predict FluX

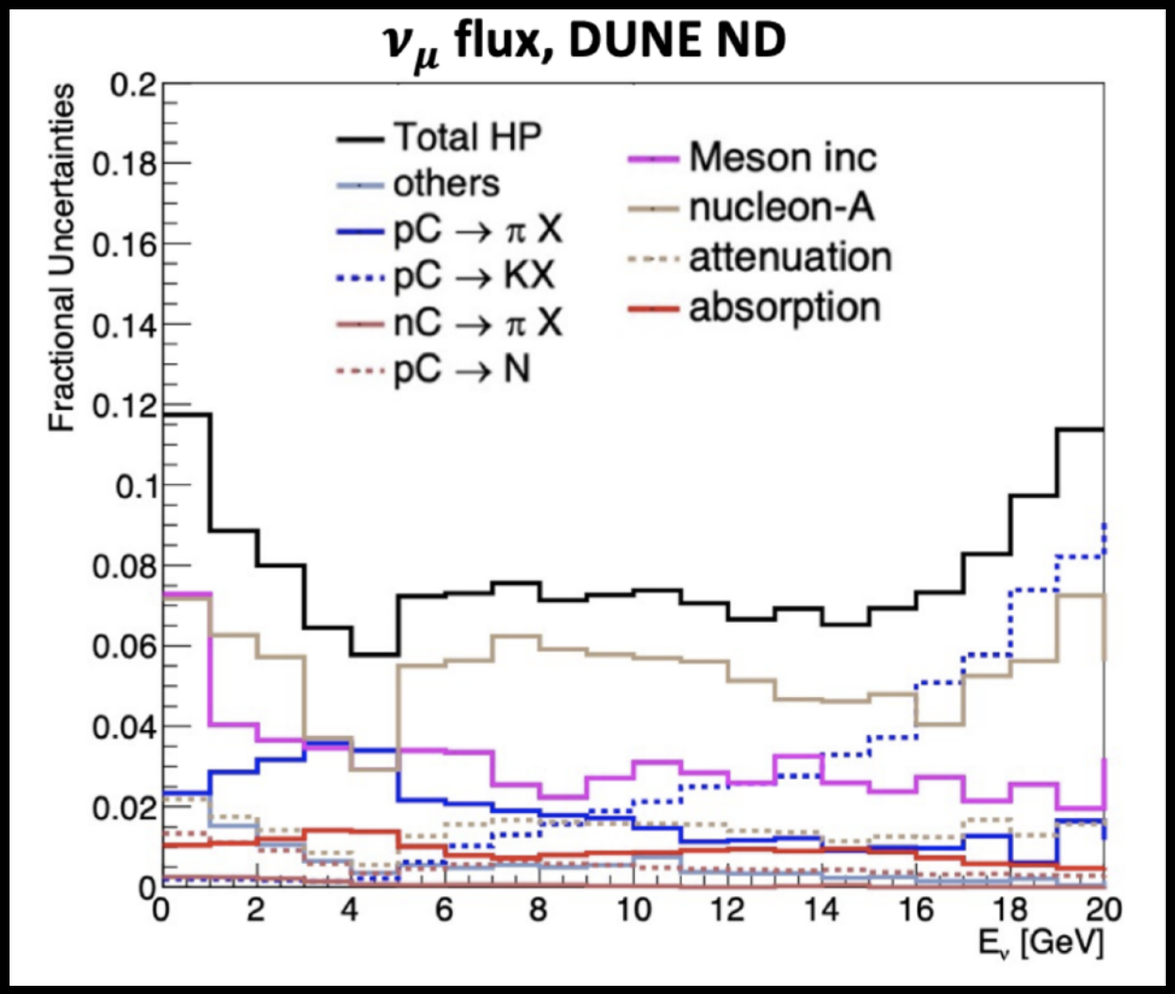
L. Ren

Total hadron production uncertainty includes:

- Pion production (proton + carbon)
- Kaon production (proton + carbon)
- Pion production (neutron + carbon)
- Nucleon production (proton + carbon)
- Meson incident interactions
- Nucleon incident interactions
- Absorption outside the target
- Absorption inside the target
- Others not covered by below categories

NA61 p+C 120 GeV/c results can address the red items

Current PPFX uncertainty using data sets scaled to NuMI parameters



Expect updated PPFX predictions in a few months!