# NA61/SHINE experiment for neutrino physics

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# The NA61/SHINE Experiment

"The SPS Heavy Ion and Neutrino Experiment"

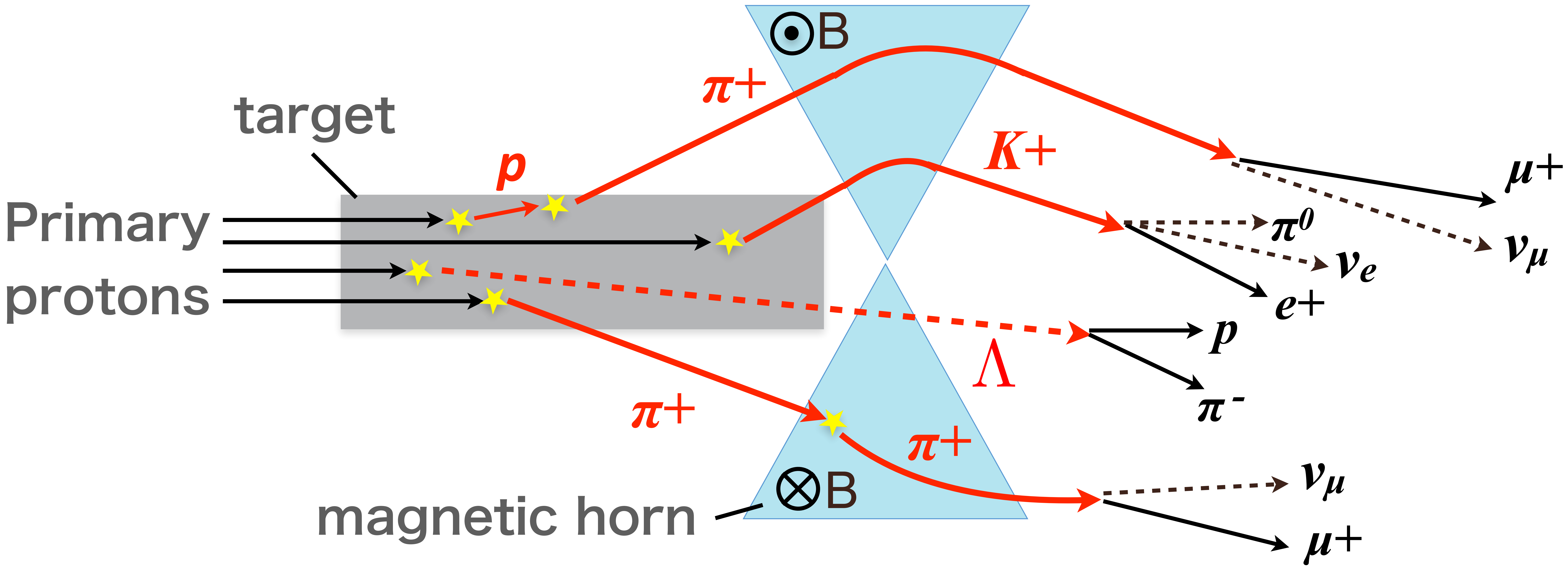
Over 150 physicists from 30 institutions and 15 countries

# Physics program

## Multi-purpose experiment

- Neutrino: Hadron production measurements
- Strong interaction physics
  - Search for the critical point
  - Study the onset of deconfinement
  - Study open-charm production mechanism
- Cosmic-ray physics
  - Hadron production measurements to improve air-shower model predictions
  - Study (anti-)deuteron production mechanism for the AMS and GAPS
  - Nuclear fragmentation cross sections to understand cosmic-ray flux

# How to produce neutrino beam



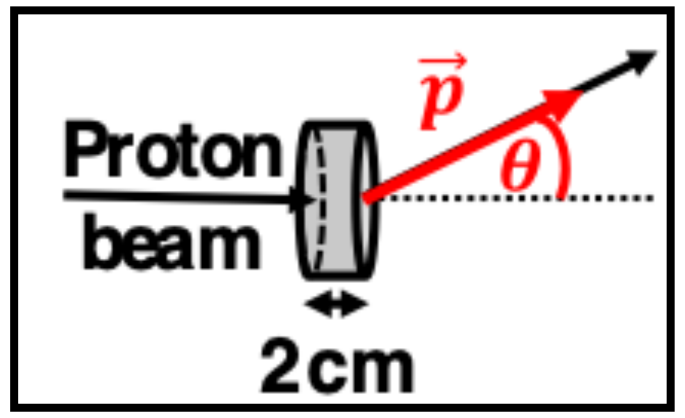

- Primary interactions in the target ( $p + \mathrm{Be/C} \rightarrow \pi^{\pm}, \mathrm{K}^{\pm}$ )
- Secondary interactions with beamline materials ( hadrons + C/Be/Al/Ti/Fe/$H_2O$ etc. )
- Neutral hadron decay ( $p + \mathrm{Be/C} \rightarrow \mathrm{V}^0 + \mathrm{X}$ )

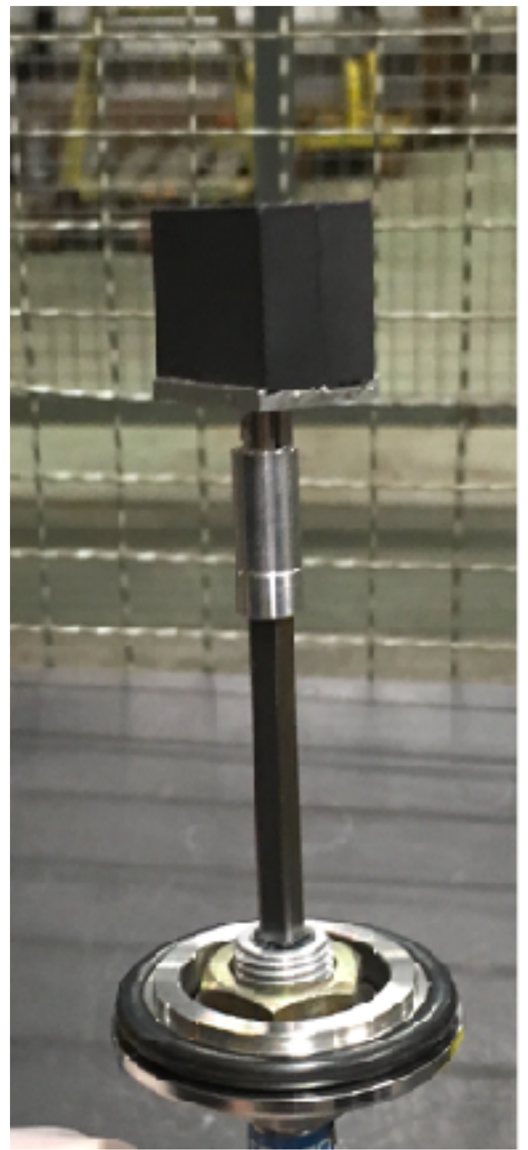
# History of neutrino program

1. 2006 – 2010: $p$+C at 31GeV/$c$ for T2K
2. 2015 – 2018: various interactions at 30–120 GeV/$c$ for NuMI and LBNF
3. 2022 – 2025: various interactions at 30–120 GeV/$c$ for T2K/HK, LBNF/DUNE

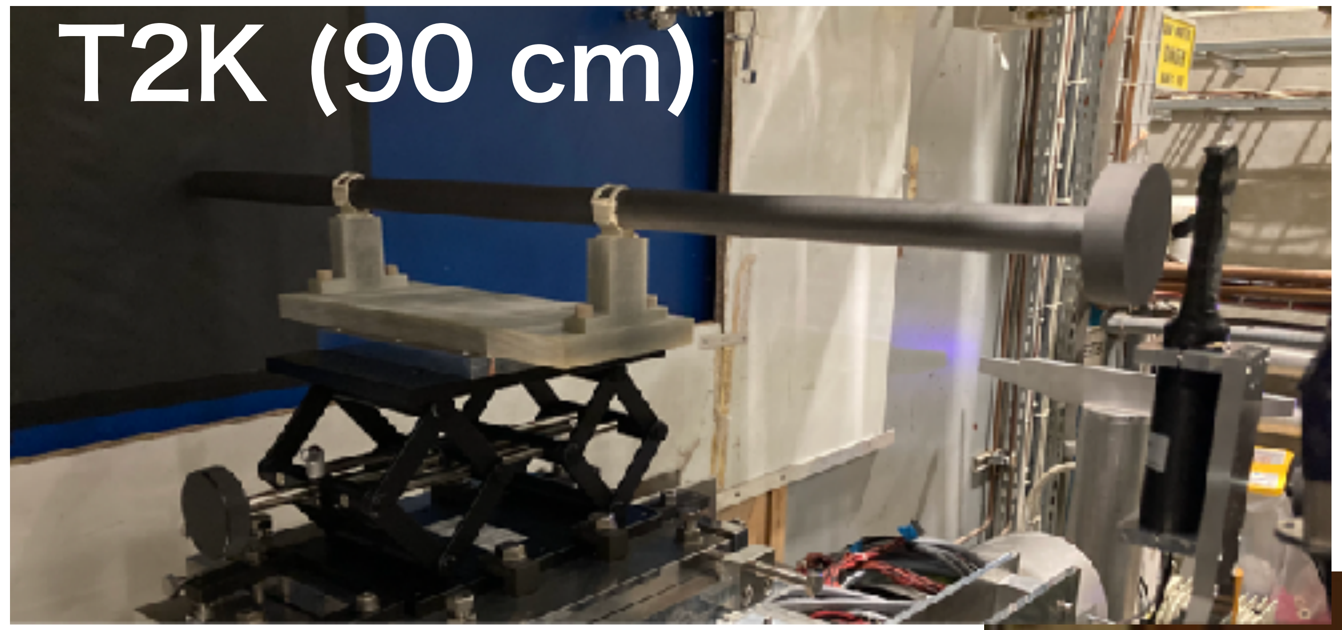
## Two kinds of targets

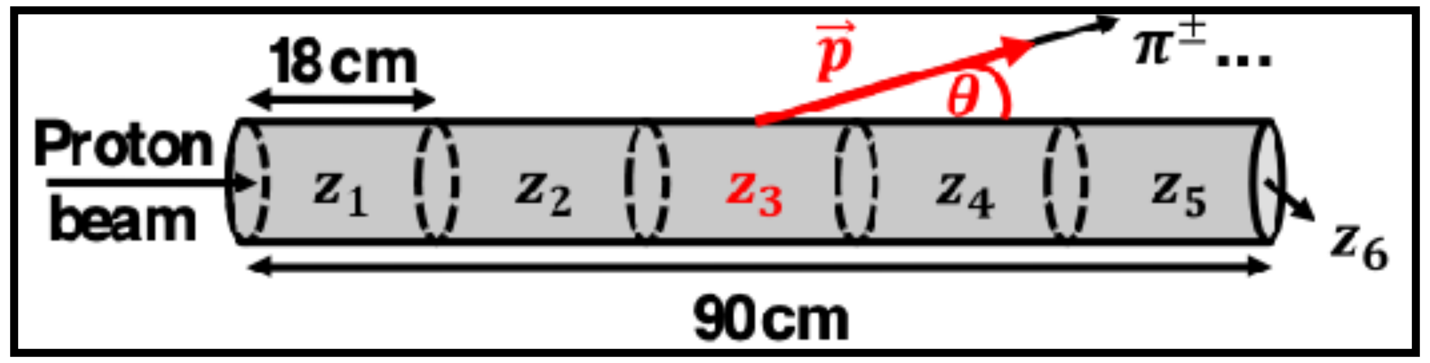
**Thin target:**
**A few % of nuclear interaction length to study single interactions**



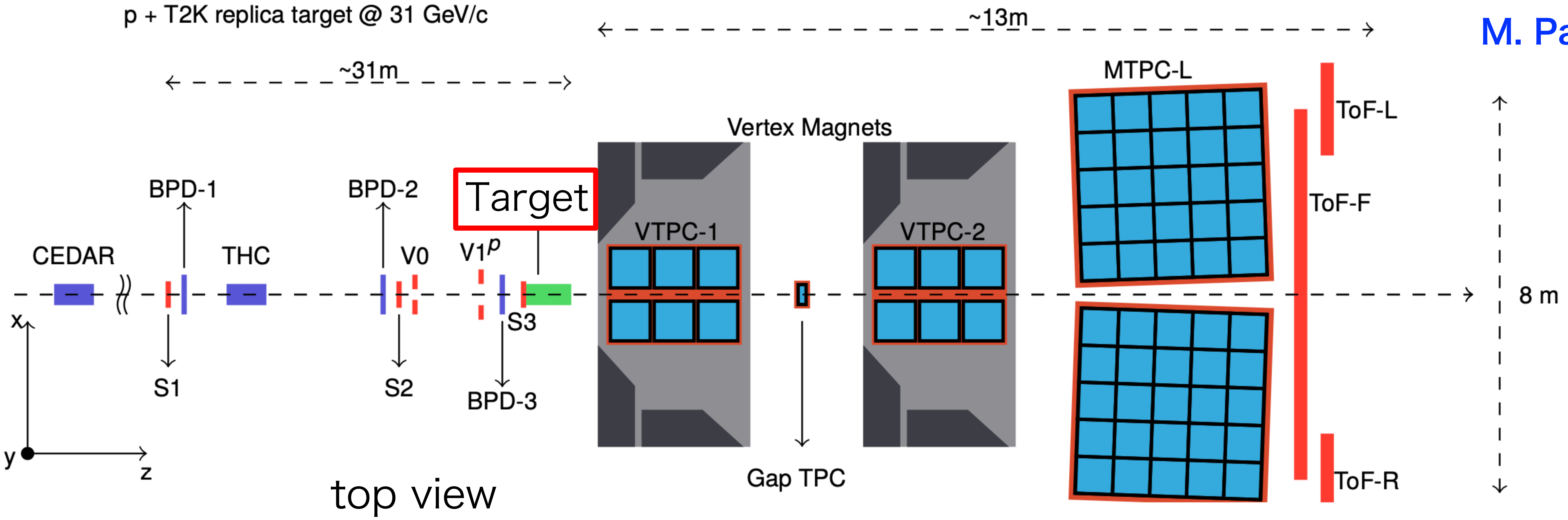
**Replica target: Same geometry and material as in real neutrino beamline**



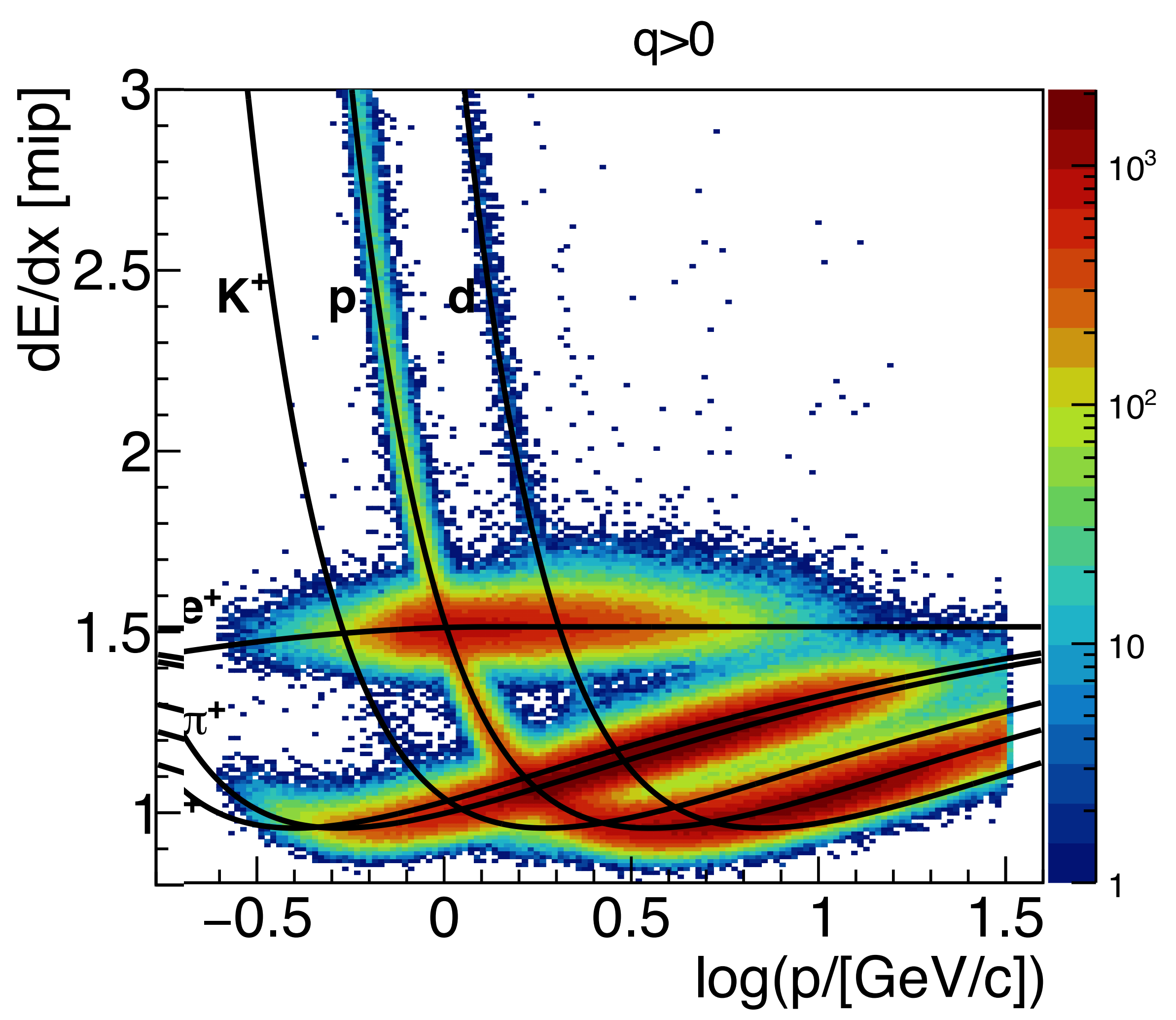




NuMI (120 cm)

# NA61/SHINE experimental facility




M. Pavin, doctoral thesis (2017)




## Large acceptance spectrometer for charged particles

- TPCs for tracking and d$E$/dx
- 2 dipole magnets up to 1.5 T field
- Time-of-flight detectors placed downstream

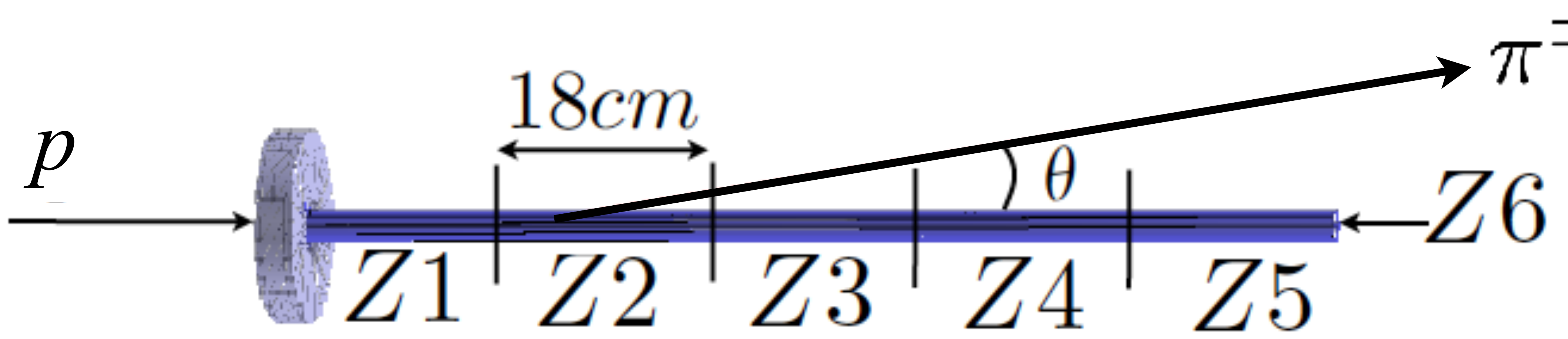
**Momentum measurement with particle identification**

# Results in NA61/SHINE

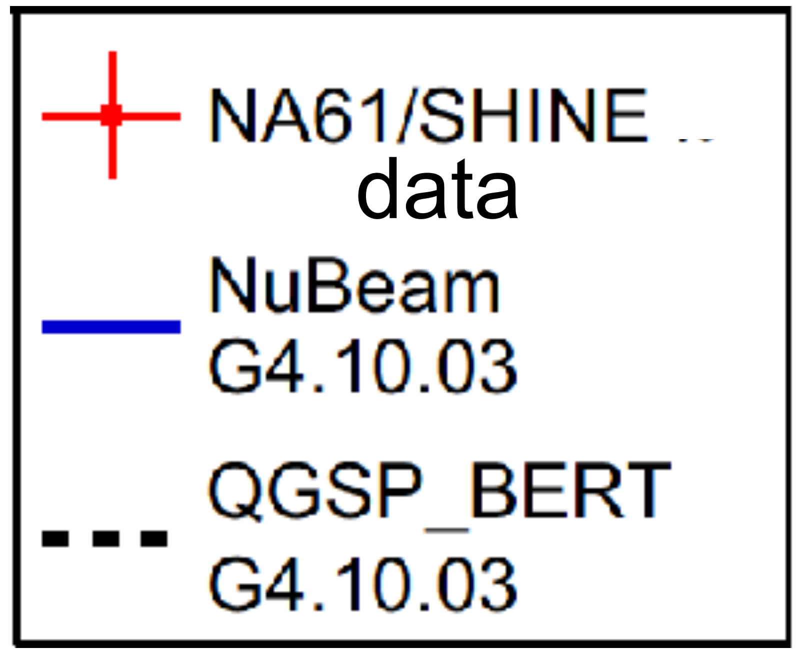
# Phase 1 (2006–2010)

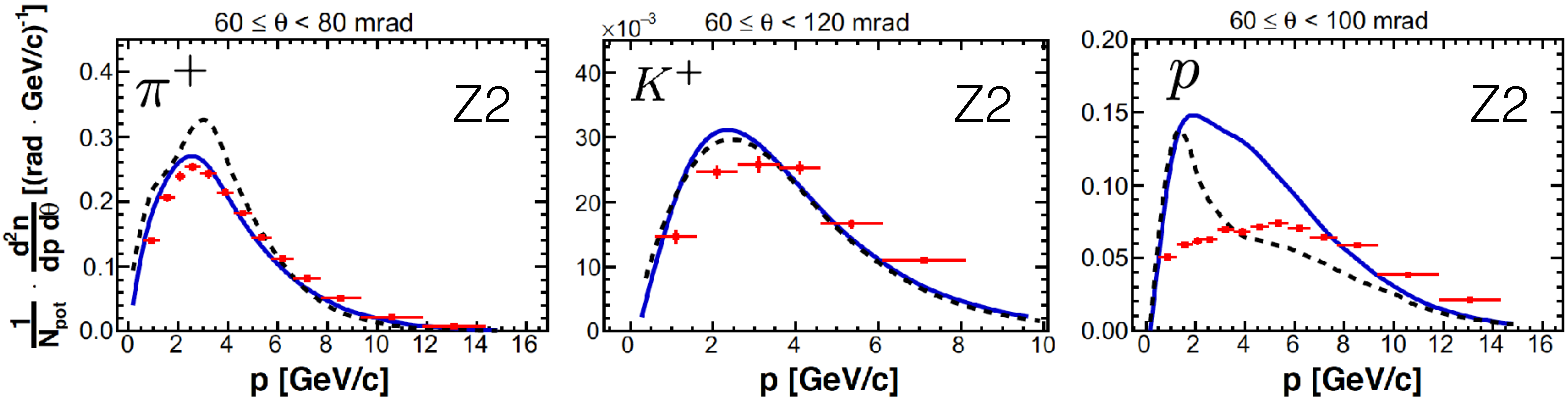
NA61/SHINE, Eur. Phys. J. C79, no2 100 (2019)

## For T2K




$p$ + T2K replica at 31 GeV/$c$




(15 θ-bins for 0 < θ < 380 mrad (Z1-Z5)
10 θ-bins for 0 < θ < 300 mrad (Z6))

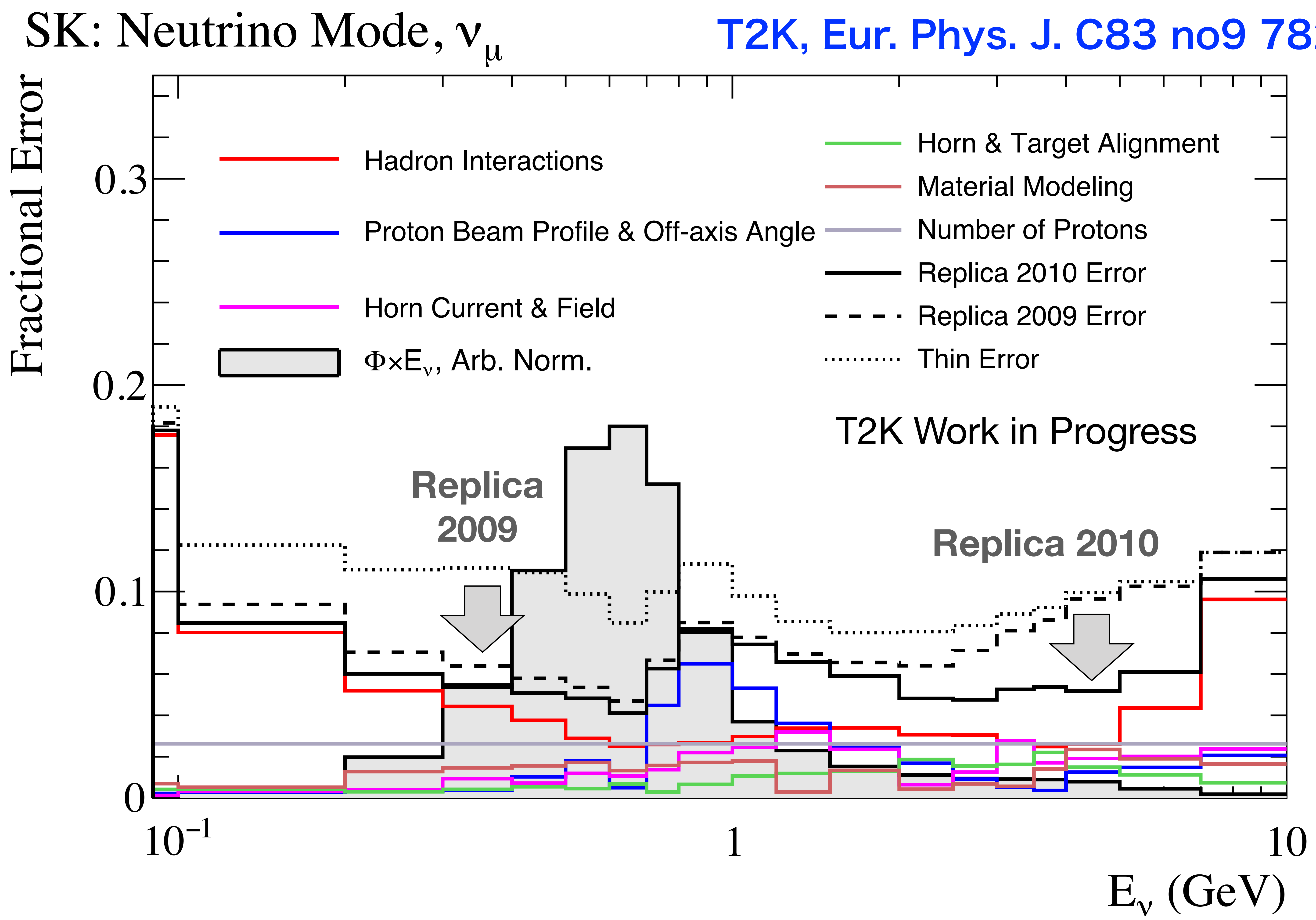
(4 θ-bins for 0 < θ < 280 mrad (Z1-Z5)
2 θ-bins for 0 < θ < 120 mrad (Z6))

(10 θ-bins for 0 < θ < 380 mrad (Z1-Z5)
8 θ-bins for 0 < θ < 260 mrad (Z6))

# T2K neutrino flux uncertainty

## with NA61/SHINE data (Phase 1)

T2K, Eur. Phys. J. C83 no9 782 (2023)

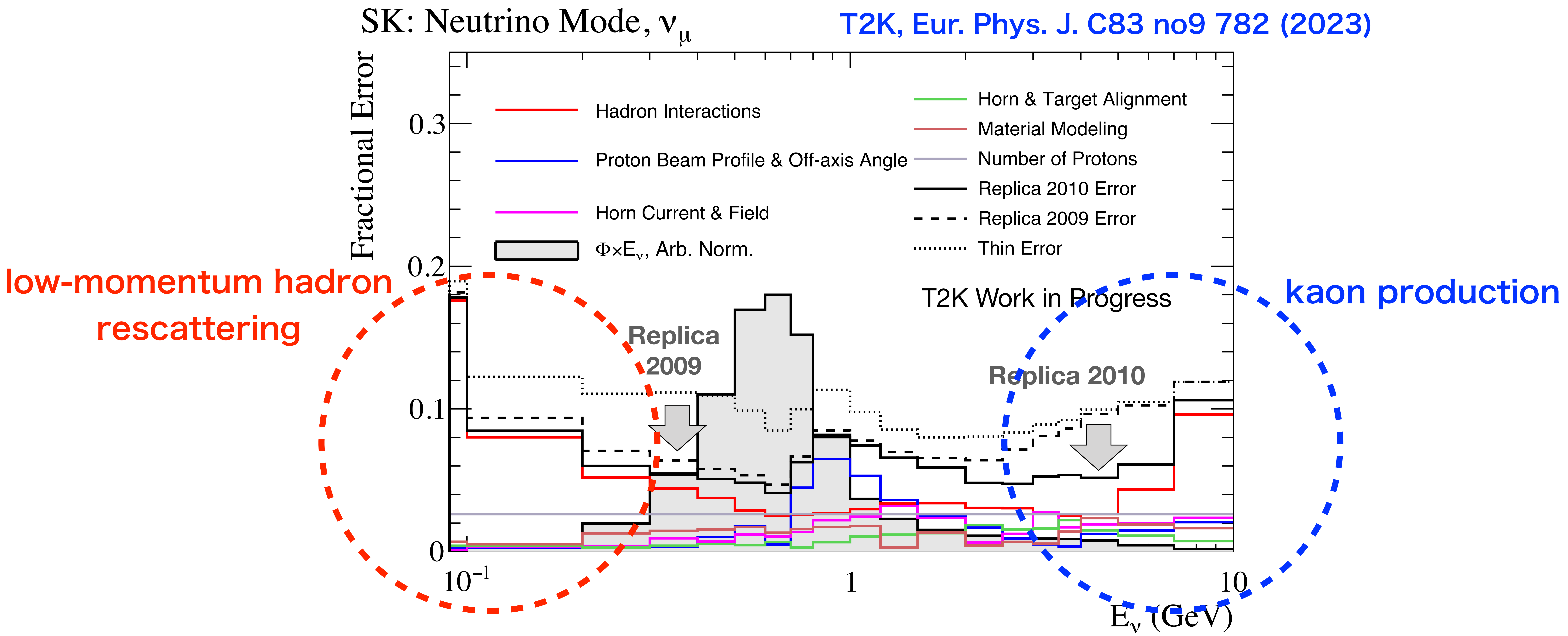



Improved uncertainty down to < 5%

# T2K neutrino flux uncertainty

## with NA61/SHINE data (Phase 1) → Future

T2K, Eur. Phys. J. C83 no9 782 (2023)

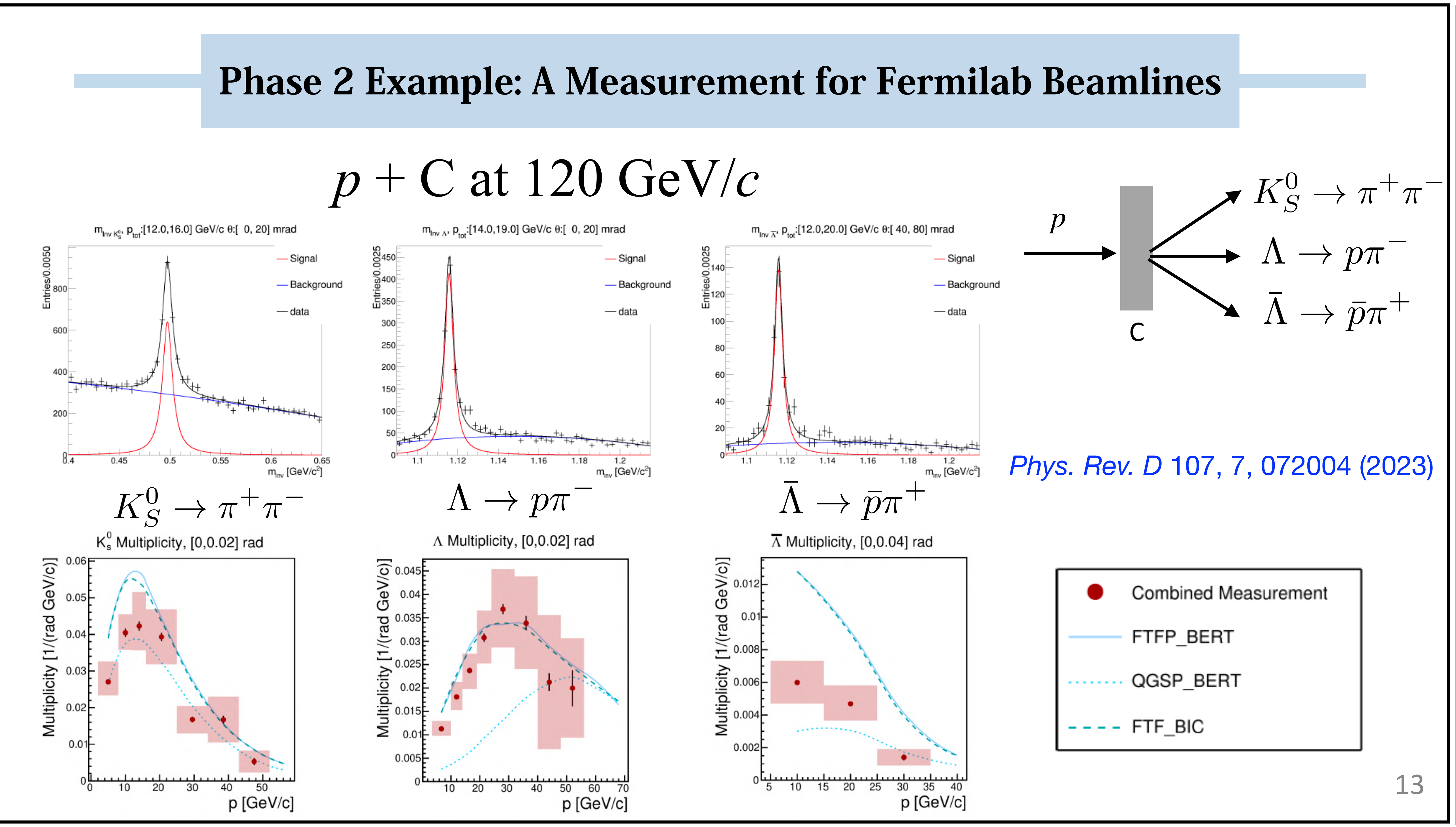


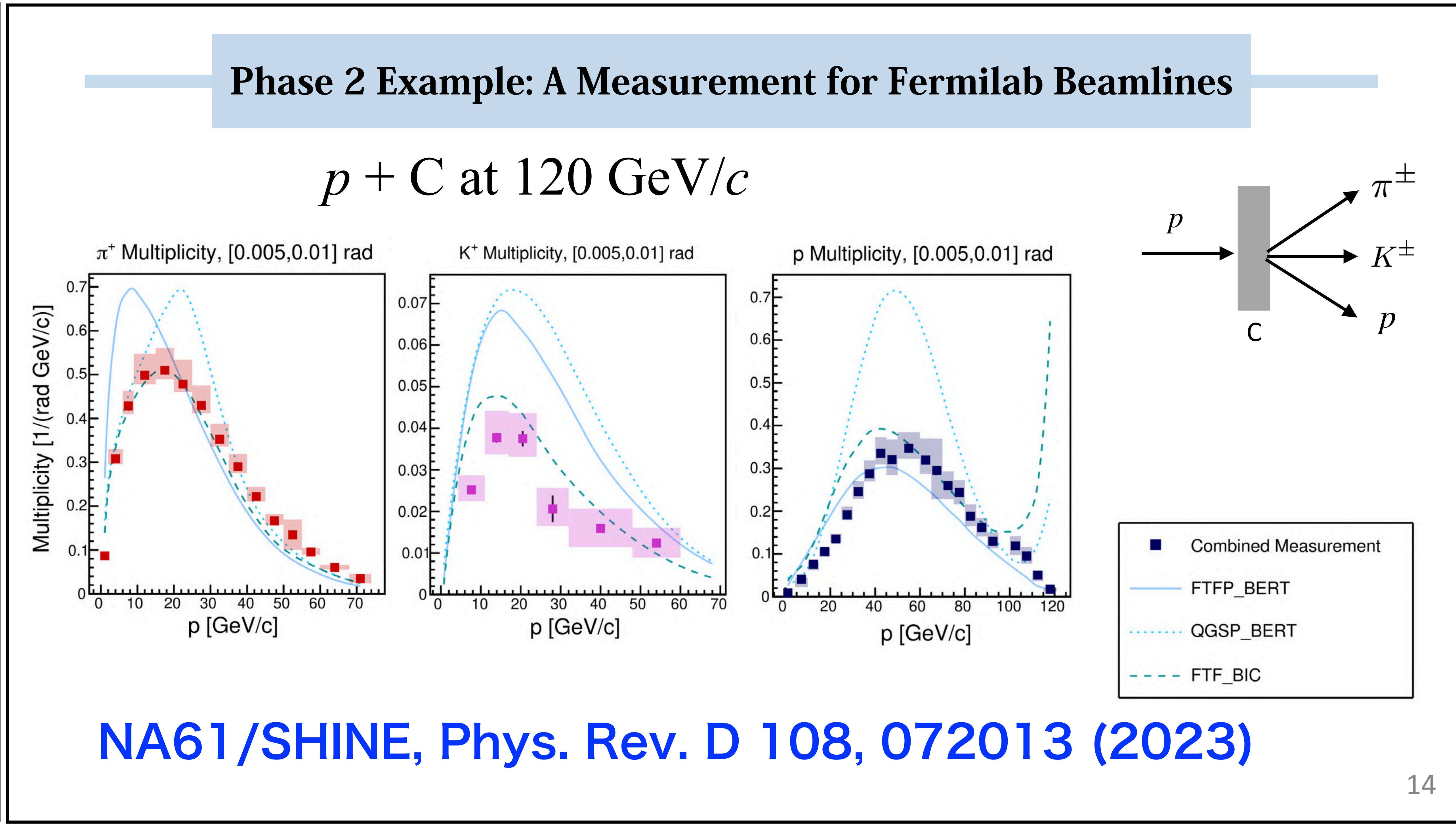

For further improvement, will take data at phase 3 and beyond

# Phase 2 (2015–2018)

## Various interactions for NuMI and LBNF

Y. Nagai at Neutrino Telescope 2023

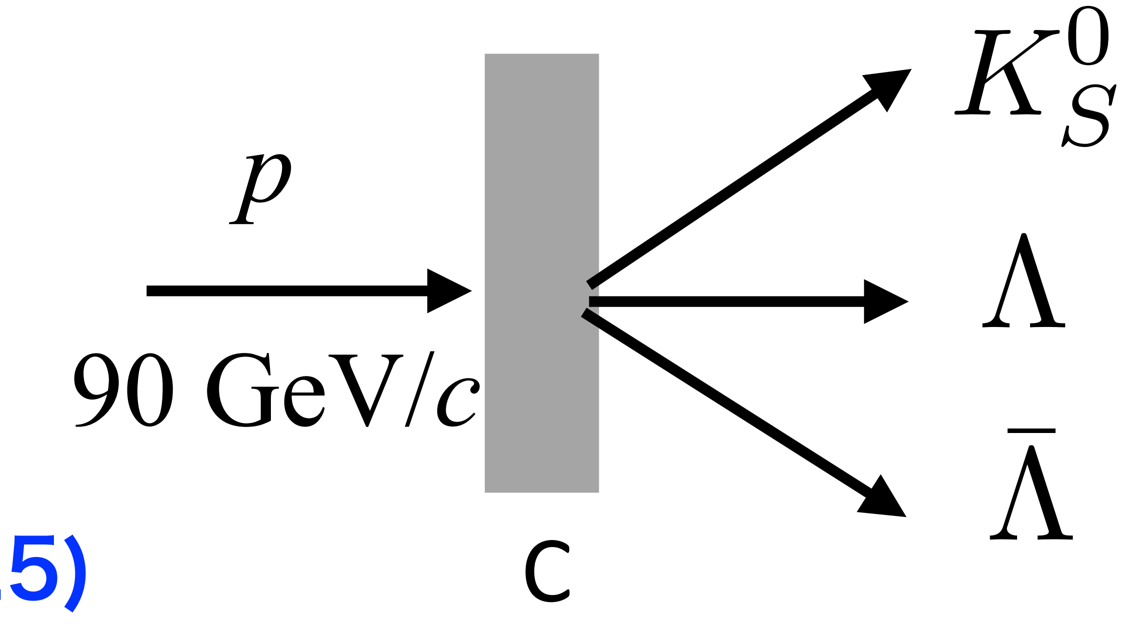


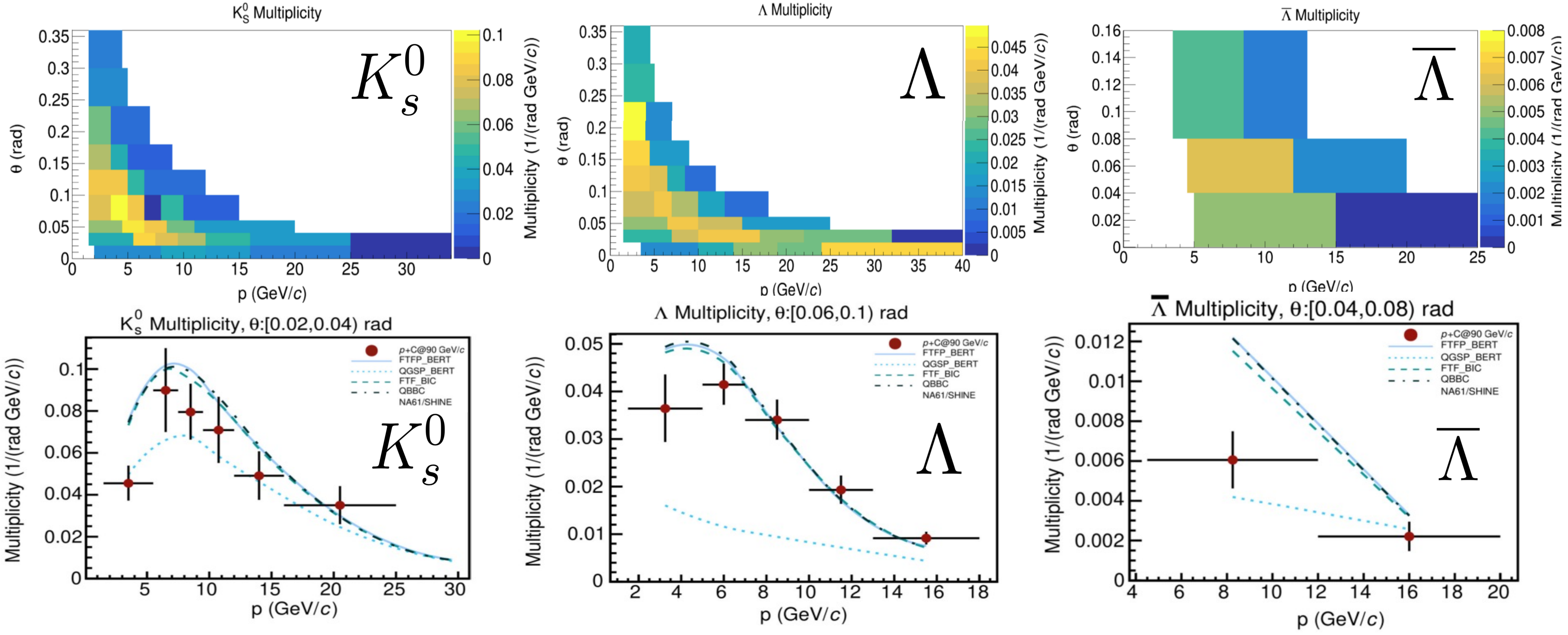



# Phase 2 (2015–2018)

## $p$+C at 90 GeV/$c$

NA61/SHINE, Phys. Rev. D112, 012011 (2025)



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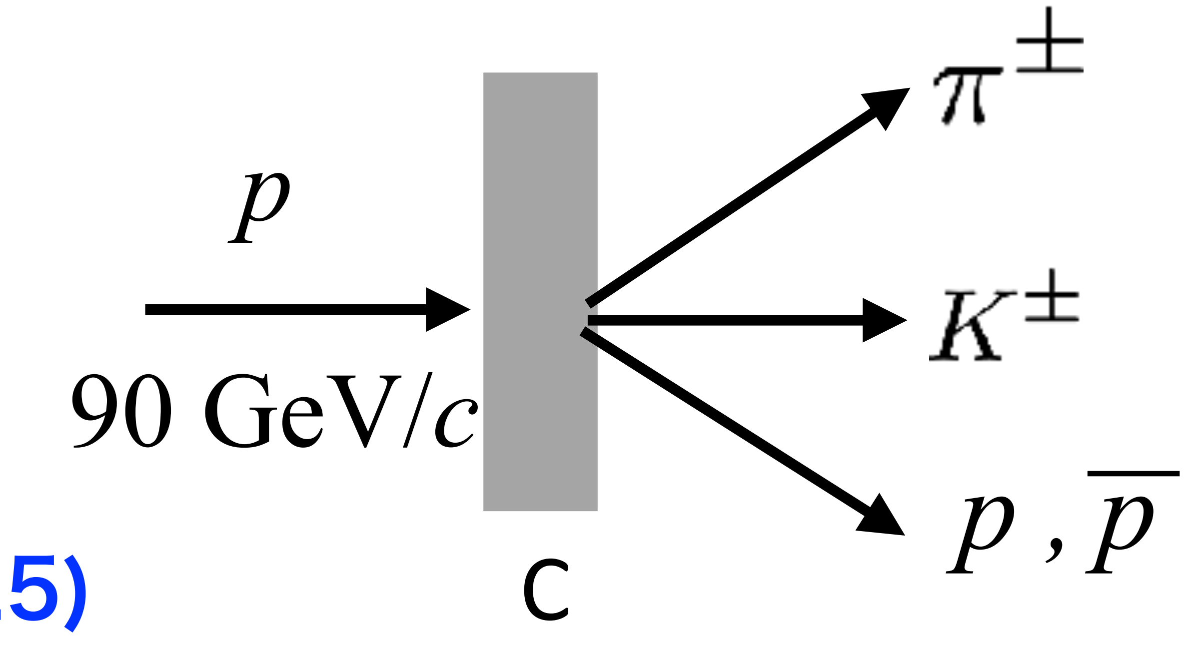


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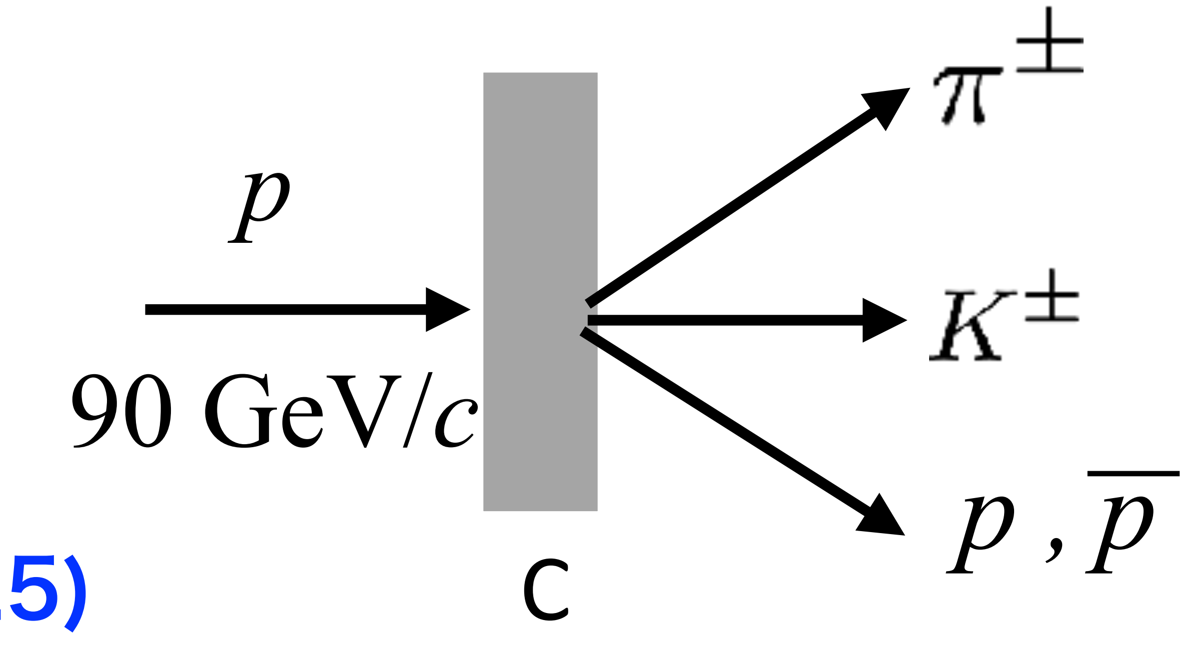
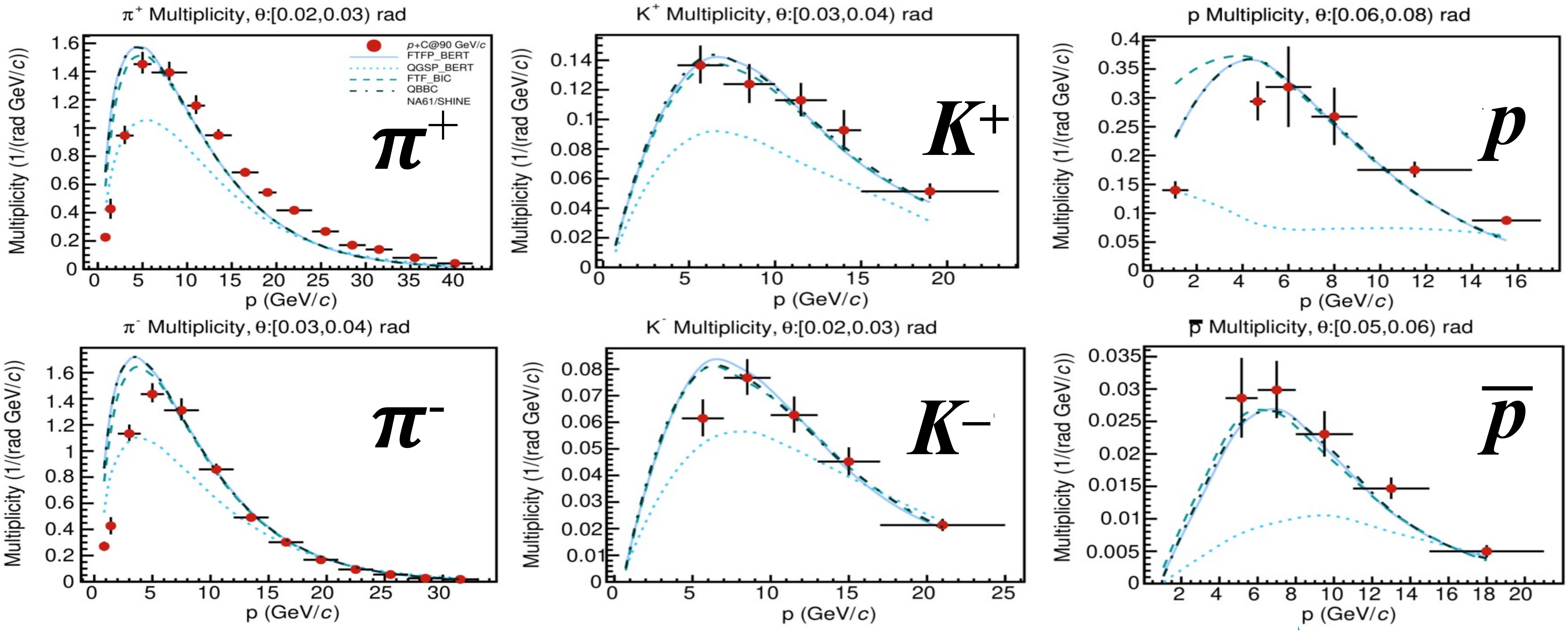
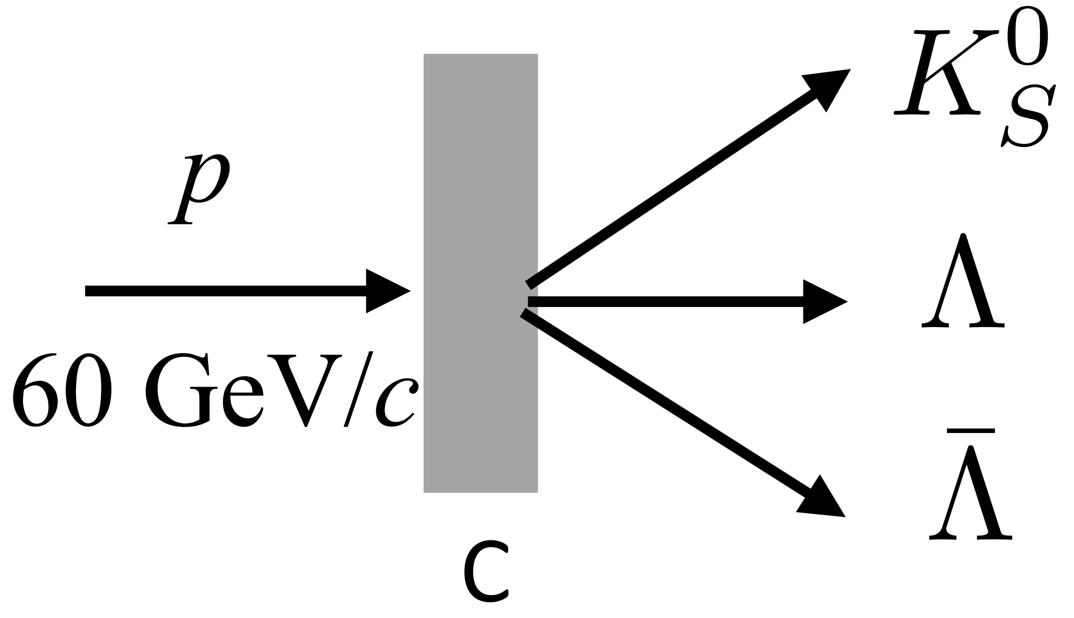


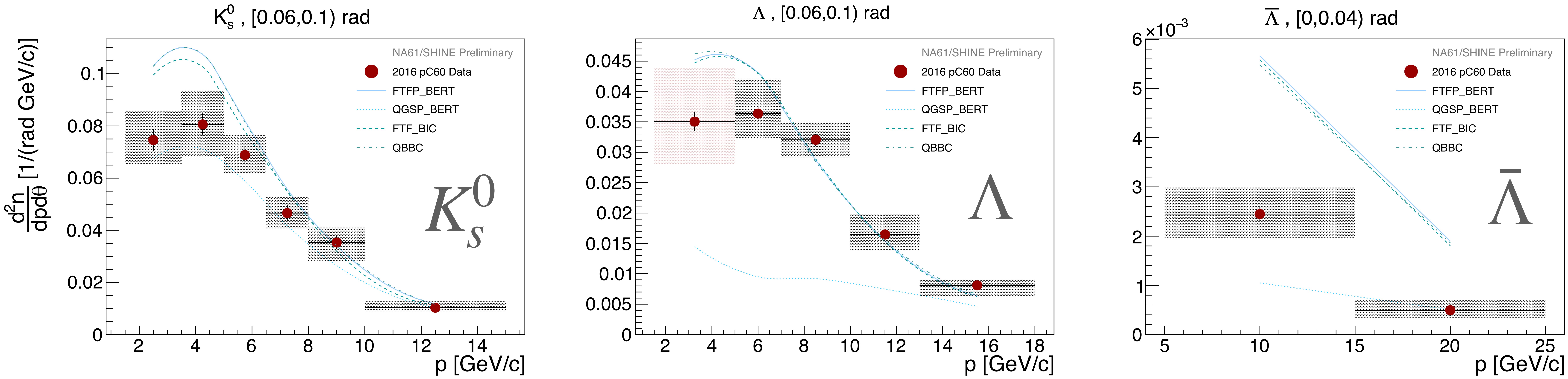



# Phase 2 (2015–2018)

## *p*+C at 60 GeV/*c*




## NA61/SHINE preliminary



# Phase 3 (2022–2025)

## Ongoing and planned

- T2K replica target run at 31GeV/$c$ (2022)
  - 18 times more data than the previous T2K dataset
  - Forward charged kaons (primary uncertainty at high-energy region)
  - $K^0{}_S$ production (primary uncertainty of wrong-sign $\nu_e$)
- Fermilab neutrino data (2023–2025)
  - Kaons on thin graphite targets and protons on thin titanium (2023)
  - 120 GeV/$c$ protons on LBNF/DUNE replica target (2024, 2025)

# Future prospects

# Low-Energy (< 20 GeV/$c$) beamline project

## Possible physics targets

- Accelerator neutrino experiments
  - study secondary hadron scatterings not covered by current data
- Atmospheric neutrino experiments
  - study cosmic-ray proton scatterings
- Spallation neutron source neutrino experiments
  - measurement of hadron production on $p$+Hg
- Muon experiments
  - measurement of hadron production on $p$+X at 8 GeV (X=C, W, or heavy materials)

# Low-Energy (< 20 GeV/$c$) beamline project

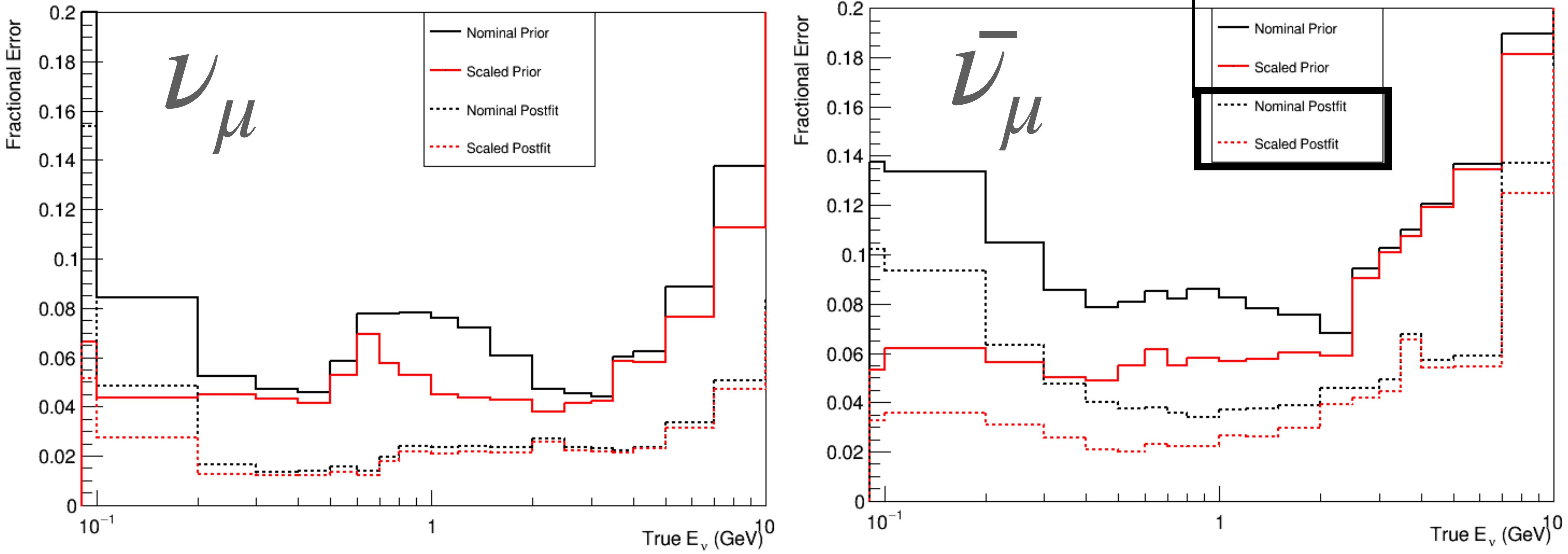
## Improve neutrino flux uncertainty

### T2K/HK flux uncertainty

- Measurements of secondary hadron interactions both for accelerator and atmospheric neutrinos

Current uncertainty
With Low-E data

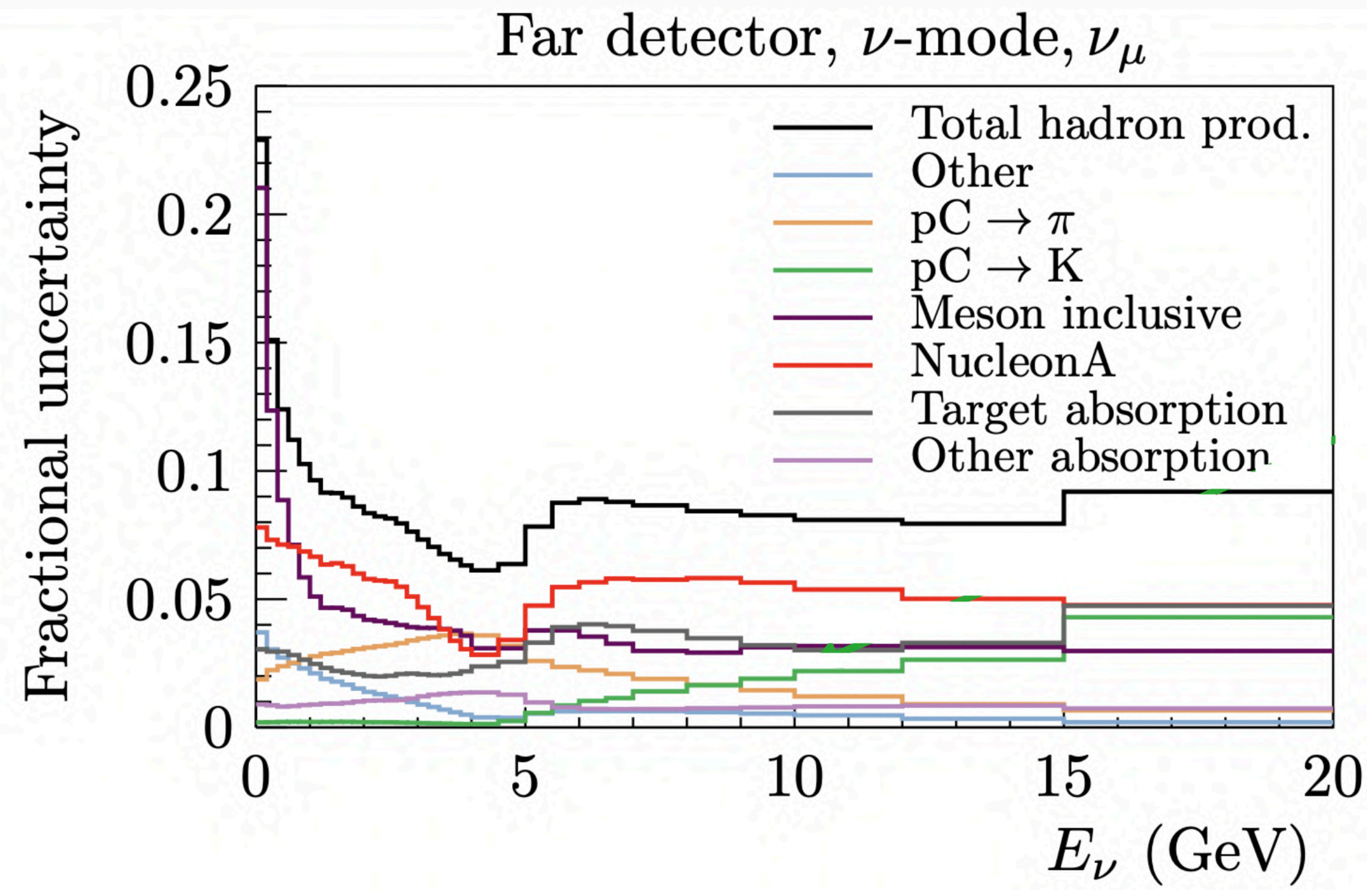
Hyper-K (neutrino-focusing mode)




Work in progress

### DUNE flux uncertainty

- Need to understand the broad energy range
- Aiming at below 2~3% at last




Laura Fields (NA61++/SHINE Workshop, 2022)

SPSC-M-793: https://cds.cern.ch/record/2810696

# Summary

- NA61/SHINE has provided critical data to improve neutrino flux predictions by precise hadron production measurements
- Additional data taking, including low energy hadron interactions, are ongoing for further improvement
- Low-energy beamline is now considered and studied. It is promising for understanding the hadron interactions in various experiments. We are aiming at the first beam after CERN's Long-Shutdown 3 (2028~)