The physics of neutrino flux:

The NA61/SHINE neutrino program

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NA61/SHINE Neutrino Program

- Neutrino beam physics
- NA61/SHINE neutrino program
- Current and new results
- Upcoming data sets
- New opportunities

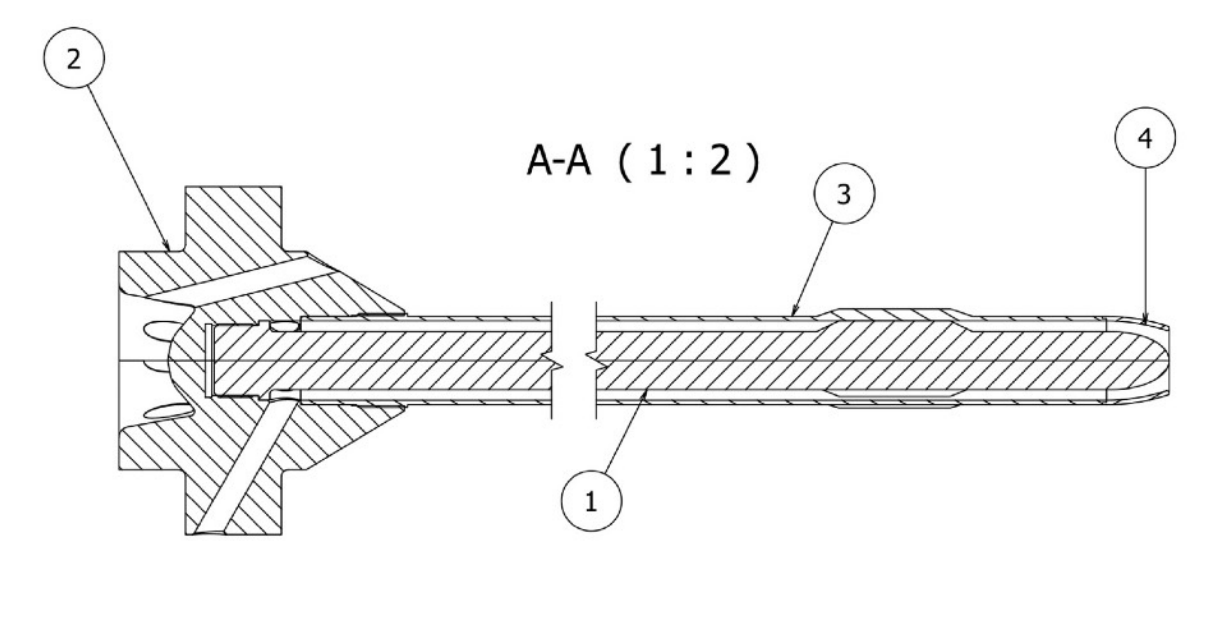
Neutrino beam physics

- Modern long-baseline 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

Targets

- Target must be ~2 λ_0 in beam direction, to maximize interactions
- Should be wide enough to contain the primary beam, but narrow enough to allow interaction products with average p_T to escape the side
- Target material is generally selected to be low-A, since lighter nuclides tend to produce shorter-lived radioactive isotopes with lower gamma energies. Also, want to maximize interactions while minimizing multiple scattering: low λ_0/X_0 ratio preferred.
- Targets must handle very high beam power deposition! Modern targets need dedicated cooling; future targets may need to be liquid or powder-jet as solids may not be able to survive thermal shock.

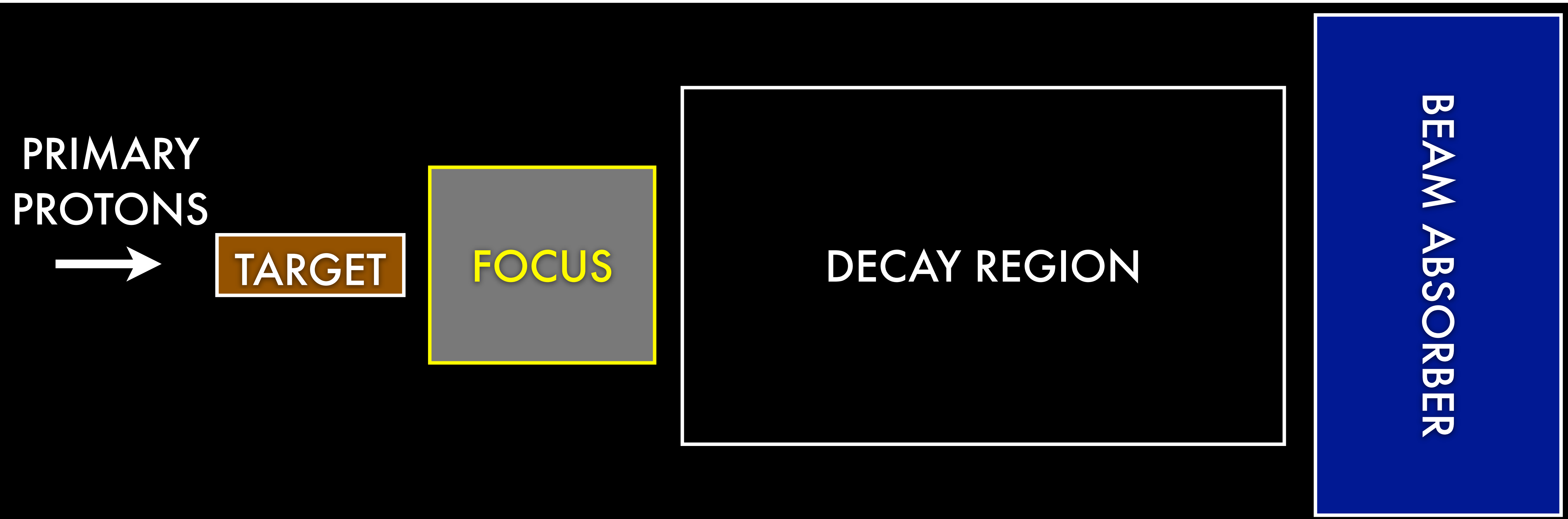
Targets



T2K target
(for illustration)

- Graphite target, like most modern beams
- 90 cm long: ~2 λ0 in beam direction, to maximize interactions
- 2.6 cm diameter
- Primary beam radius is large (6mm) to reduce local intensity and thermal shock
- Target cooled by very high velocity helium gas in closed loop

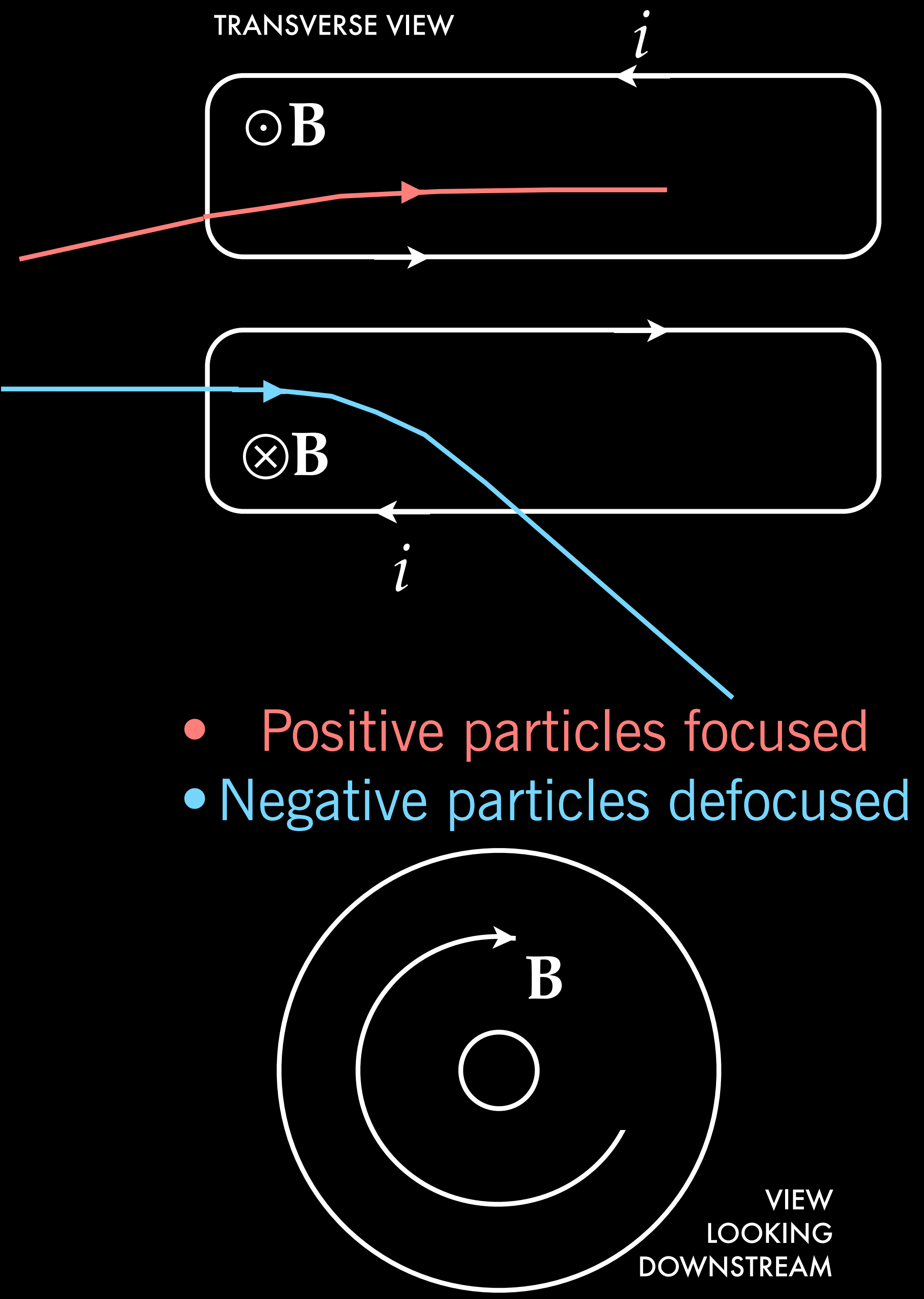
CONVENTIONAL BEAMS: Basic components



- After leaving target, charged particles may be focused before entering decay volume
    - Several focusing schemes possible
    - Focusing not strictly necessary: 1962 two-flavor neutrino discovery experiment used unfocused mesons.

Horns

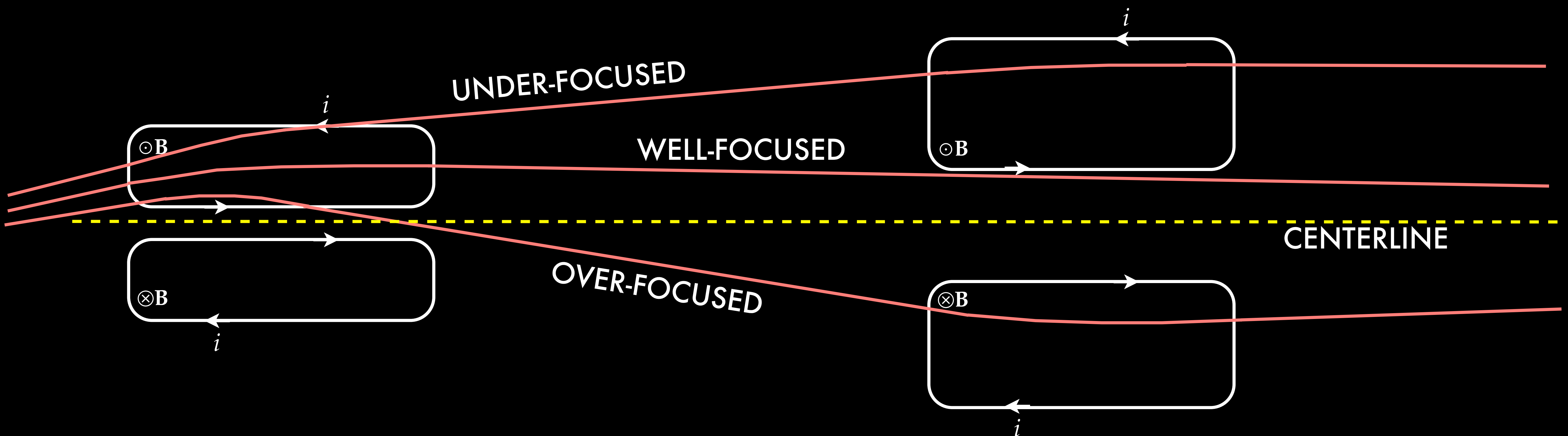
- Horns first proposed by Van der Meer (1961)
- At the most basic level:
  - Two coaxial conductors: a toroidal field exists in the region radially between inner and outer conductors
  - Inner conductor is thin enough (2-3 mm) for most pions to pass through
  - Conductor currents are 100-300 kA so water cooling, pulsed operation necessary to prevent melting
  - Generally made of aluminum alloy



Multi-horn systems

- A single horn generally reduces the angular spread of the beam by a factor of ~2. The resulting beam, observed from far enough downstream, looks again like a point source of pions with an angular spread ⇒ it can be focused further by adding another horn.

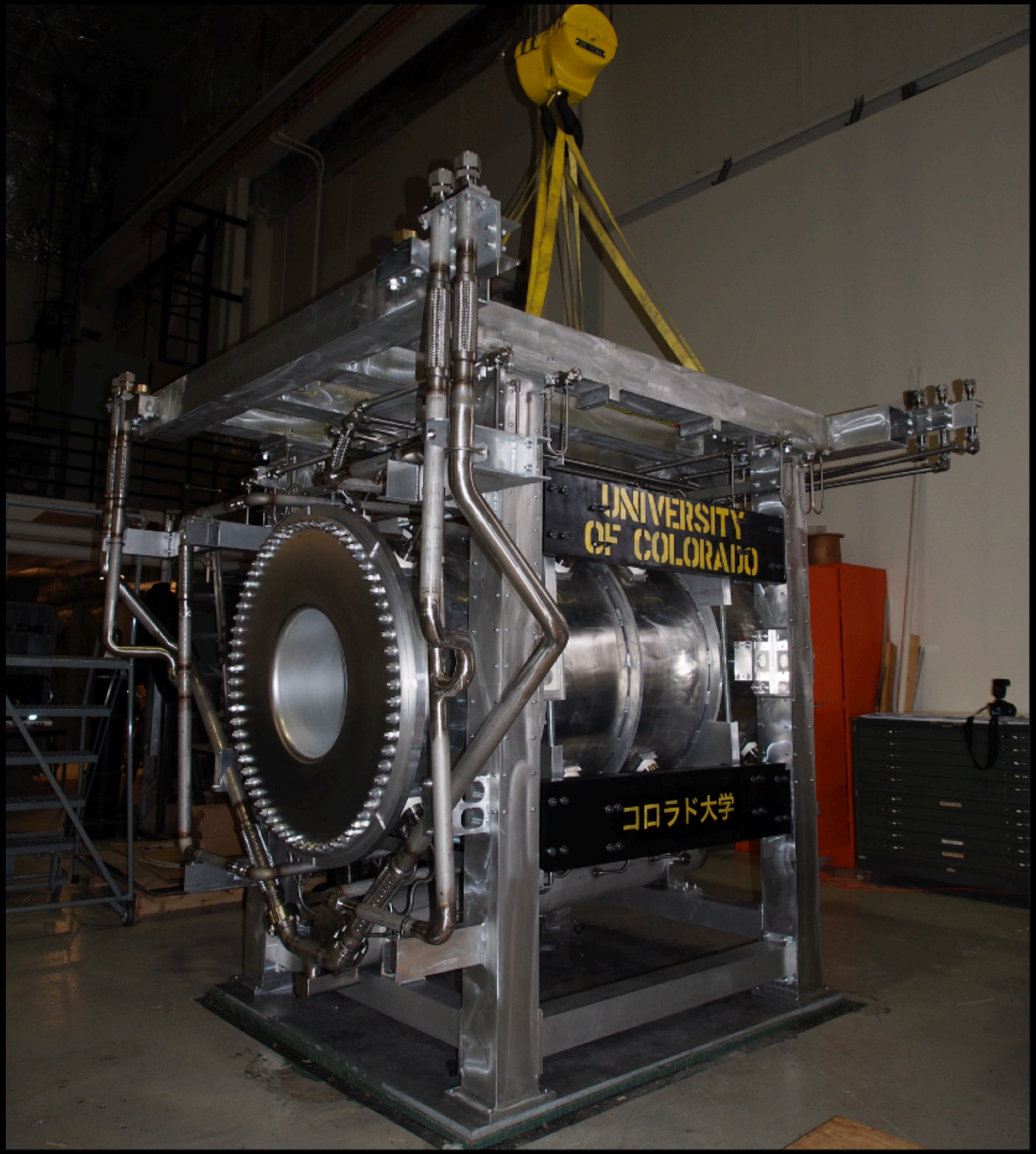
- Common for beams to be designed with two (or even three) horns in series. The downstream horns allow correction of both under- and over-focused particles:



Horns

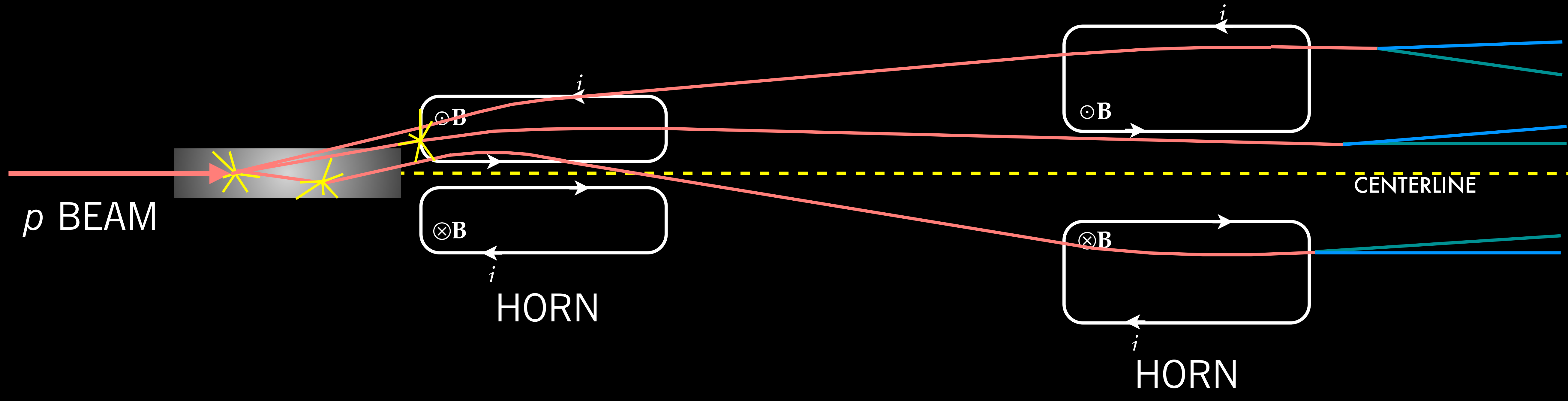
1960s

2010s



Flux from a neutrino beam

- Neutrino flux comes from:
  - Pions, kaons produced directly from primary p+C interactions
  - Also produced from re-interactions of secondary p,π in the target
- Secondary particles from target focused in a series of horns
  - Horns contain substantial amounts of aluminum, which also acts like a secondary target
- **All of these sources of mesons contribute significantly to the neutrino flux.**



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

All of these require knowing hadron interaction physics!

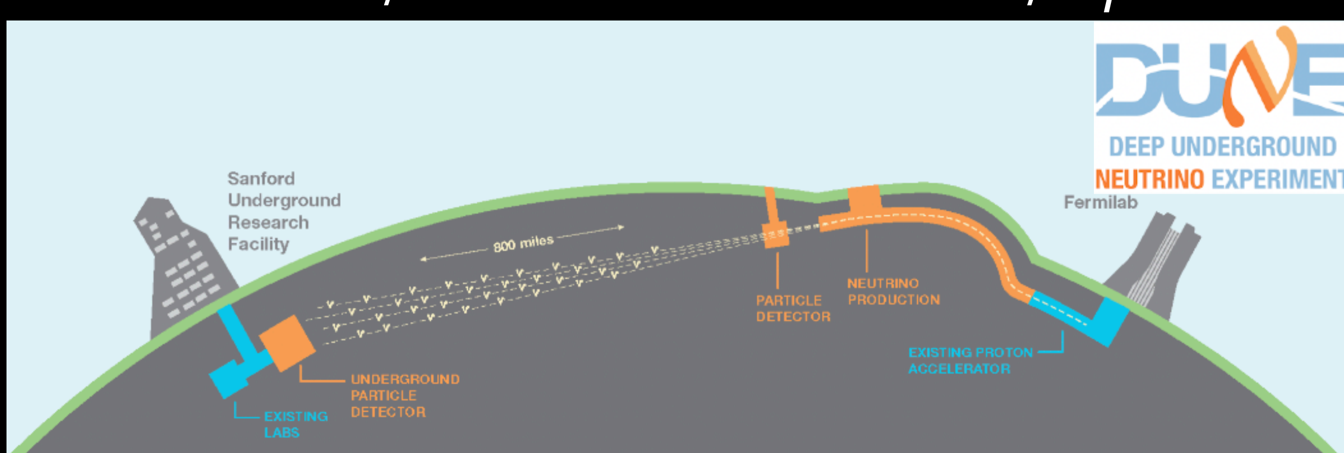
Primary beam energies for current and near future neutrino beams

T2K, T2HK: 31 GeV/*c p*

NuMI: 120 GeV/*c p*

BNB: 8.9 GeV/*c p*

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

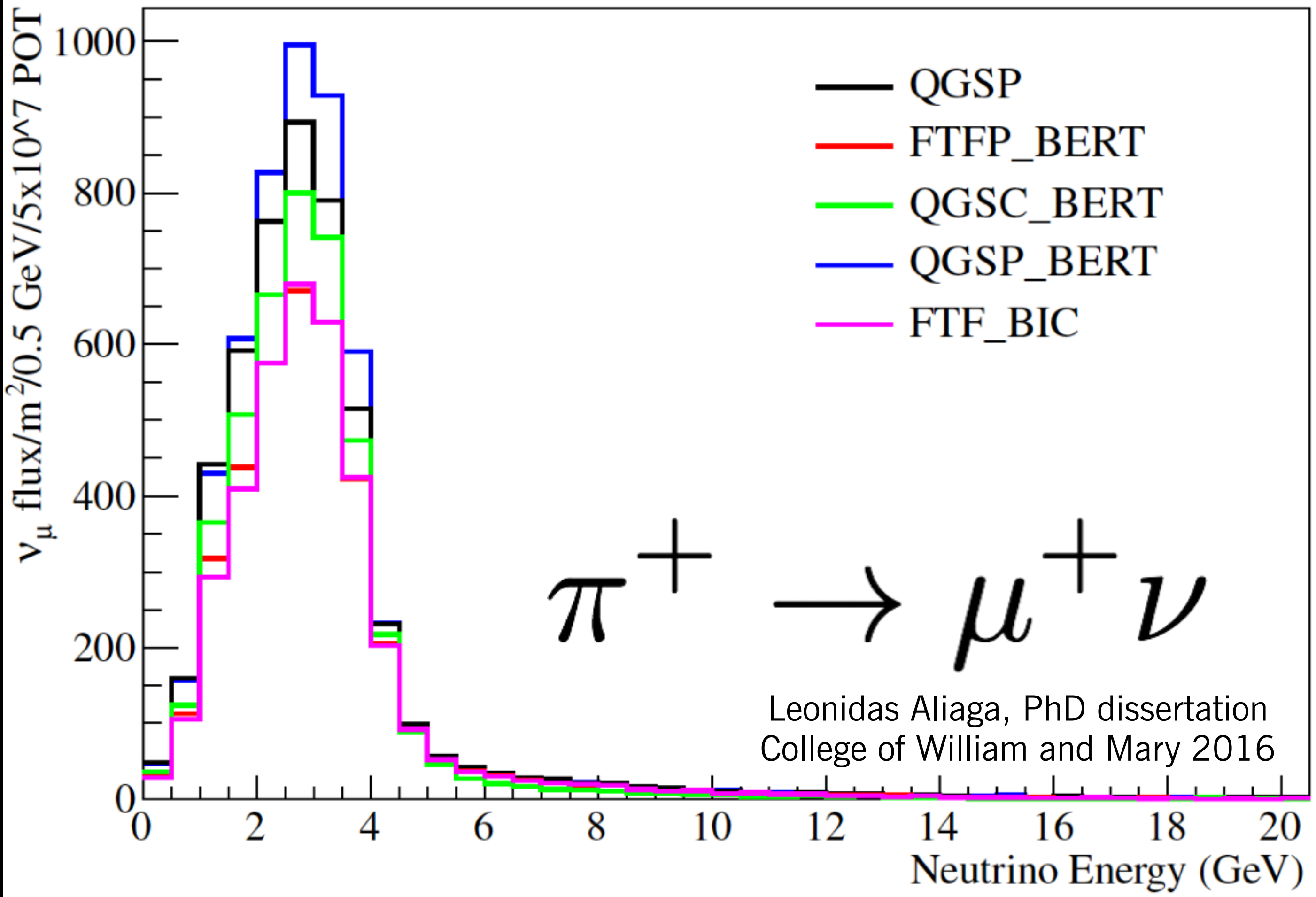


Understanding a neutrino beam

- Two complementary techniques needed to understand the beam well enough to do oscillation measurements
  - Near neutrino detector
    - Goal is cancellation of flux uncertainties in near/far ratio.
    - Not perfect for constraining flux, due to neutrino cross-section (don't cancel if detectors are different) and reconstruction uncertainties, and parallax effects due to being near an extended neutrino source
  - **Measurement of pion, kaon production and interactions**
    - Essential for measuring neutrino interaction cross-sections
    - Reduces oscillation systematic errors

Monte Carlo generators

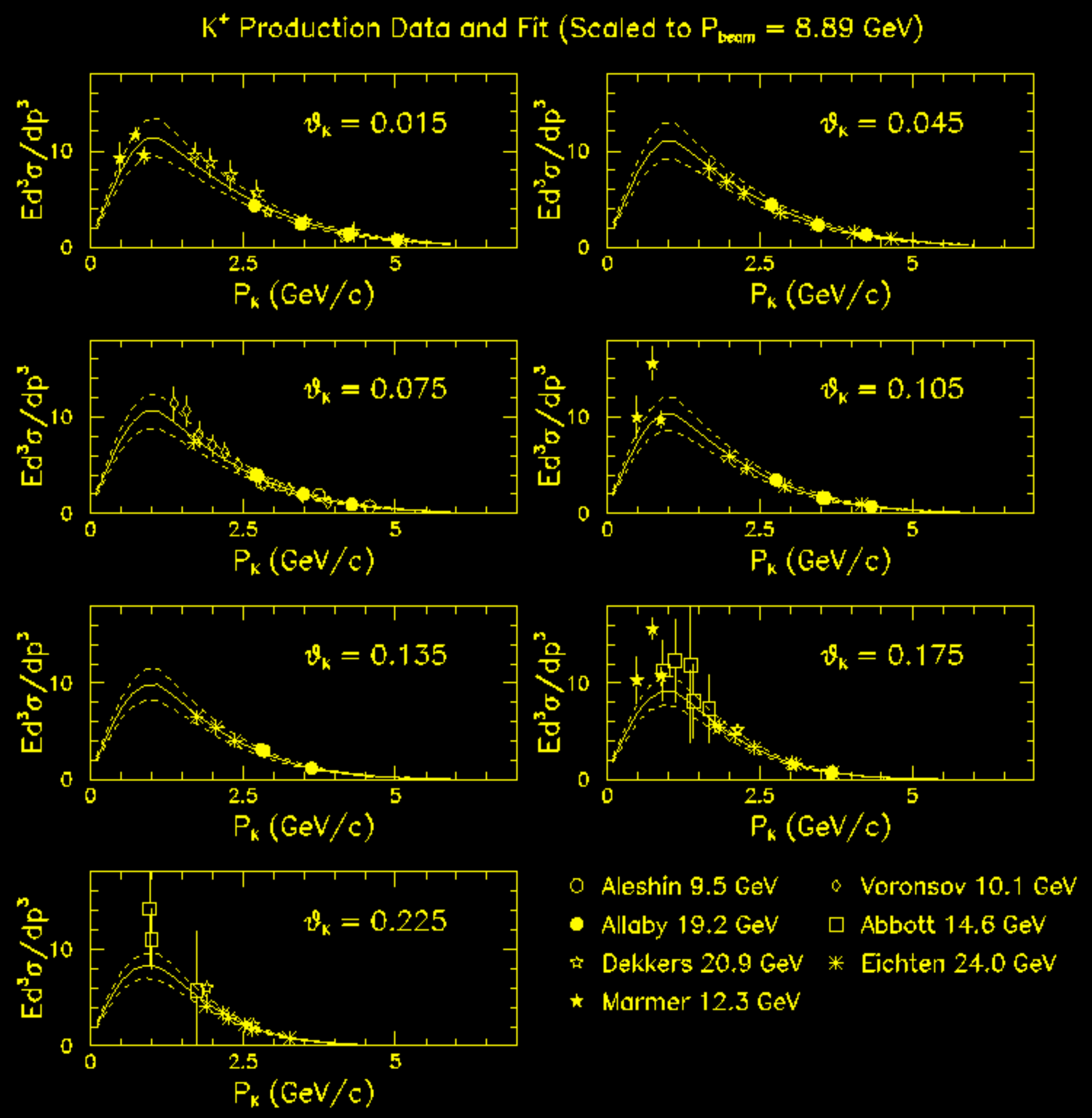
- Neutrino experiments use hadronic interaction generators including FLUKA, GEANT4 with various physics lists
- But these generators have **very large** disagreements with one another: 20%+ is common, or even factors of two for kaon production!
- Very important to have constraints on the hadronic processes



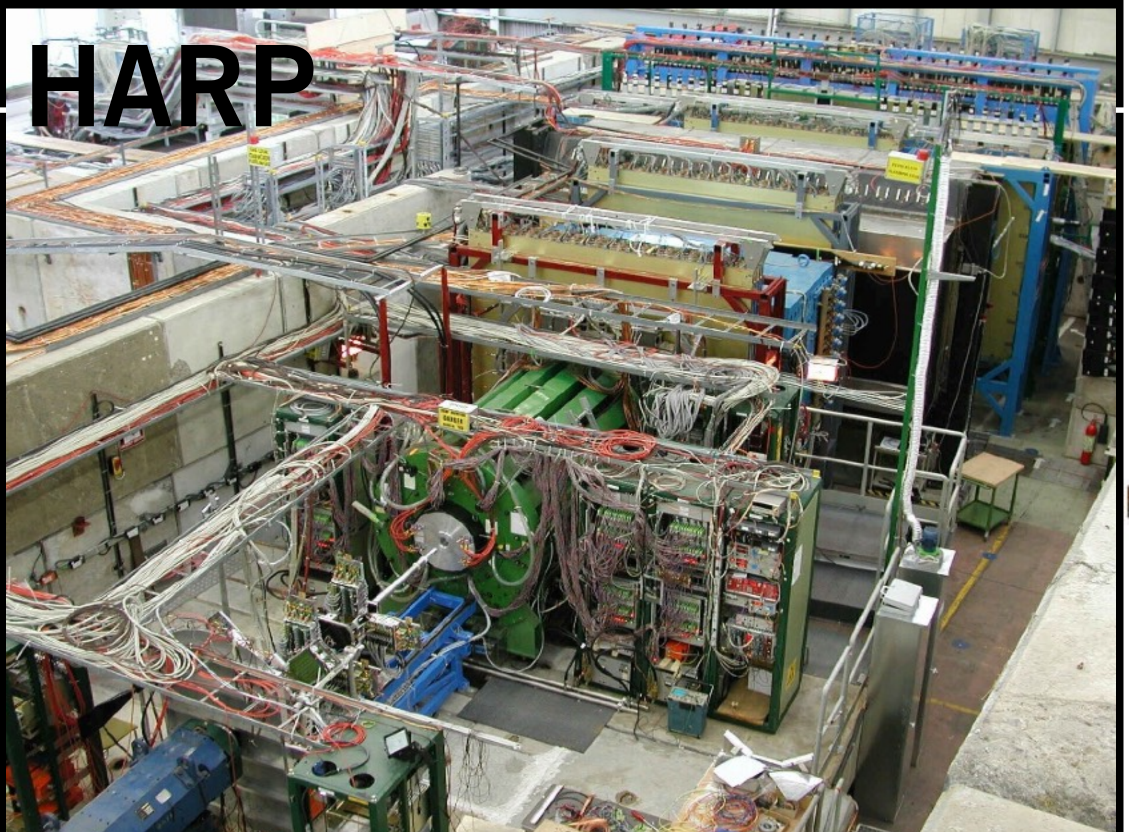
Flux of FNAL's NuMI neutrino beam with different physics generators

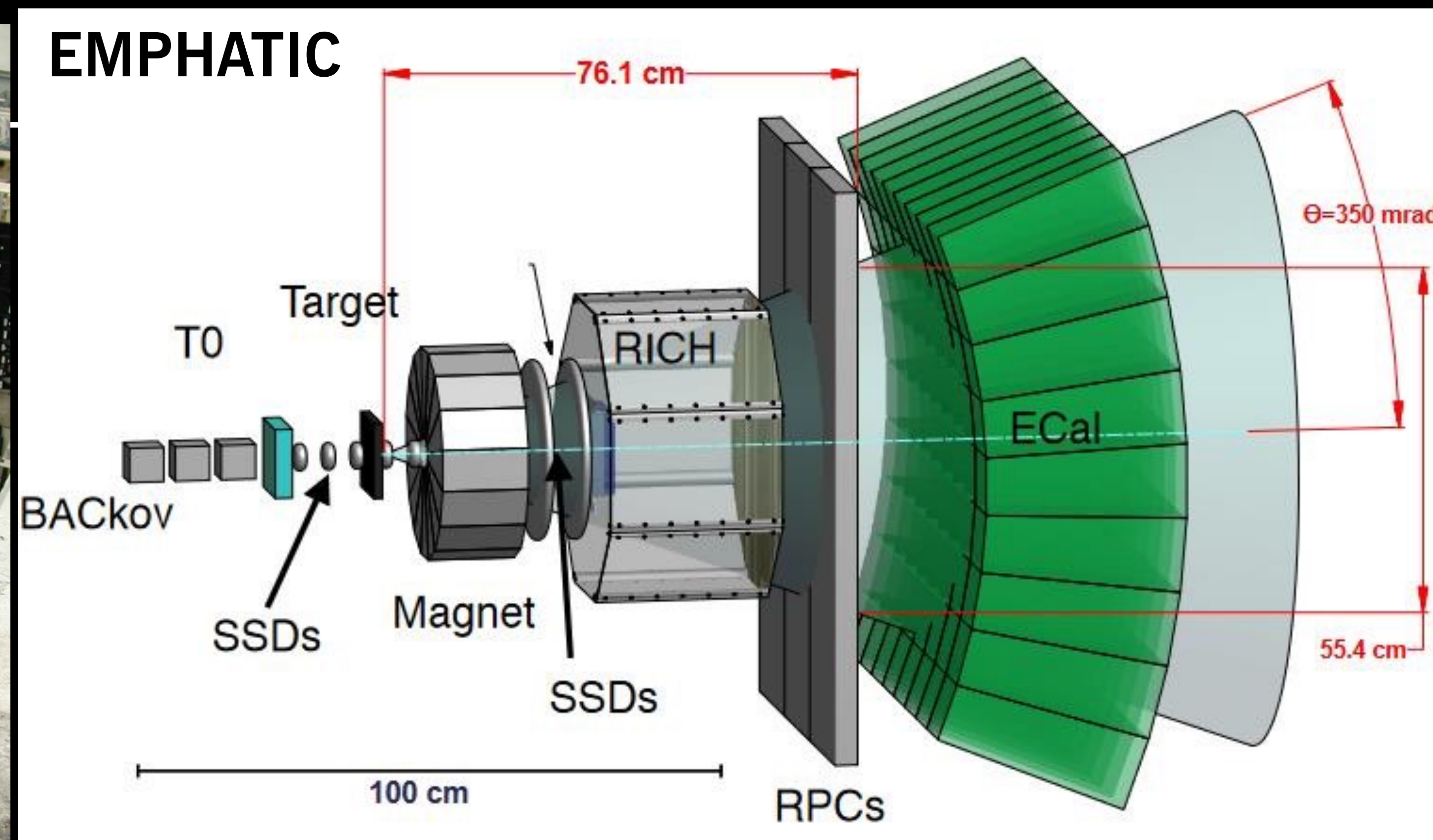
External measurements of meson production

- Until recently, depended on fits to multiple measurements at different labs with different beam energies
- These measurements were made many years ago for other purposes, and had varying applicability to neutrino beams
- Significant issues with combining systematic errors across very different experiments
- Model dependence in extrapolating from different energies, target nuclei

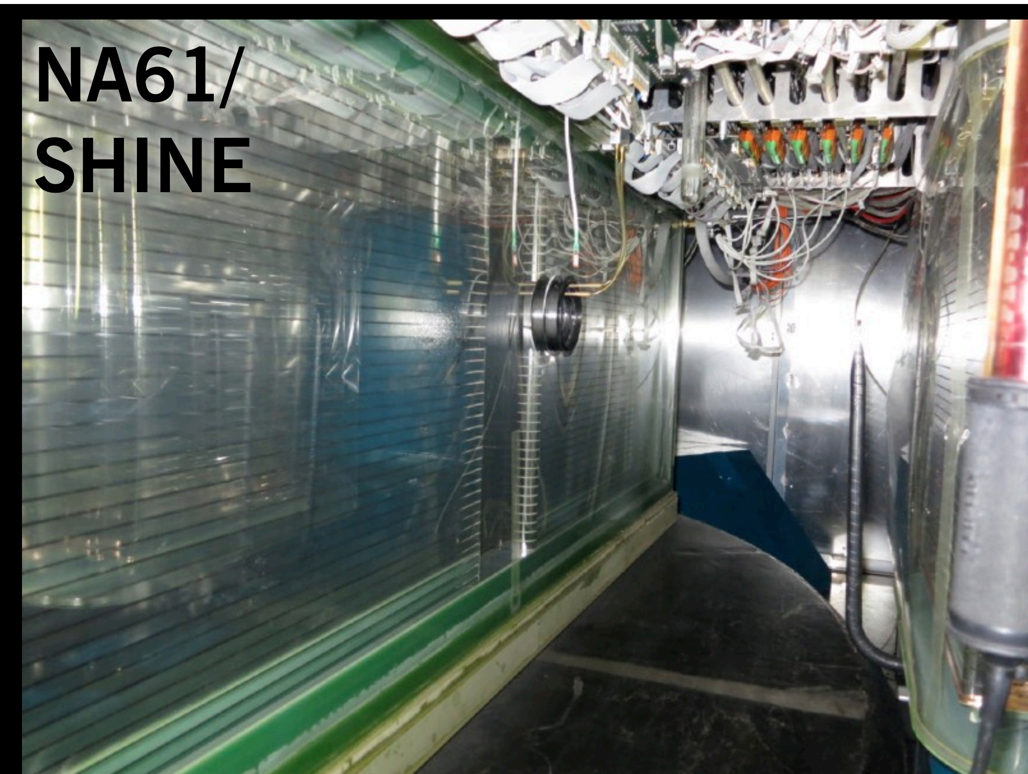


Dedicated experiments



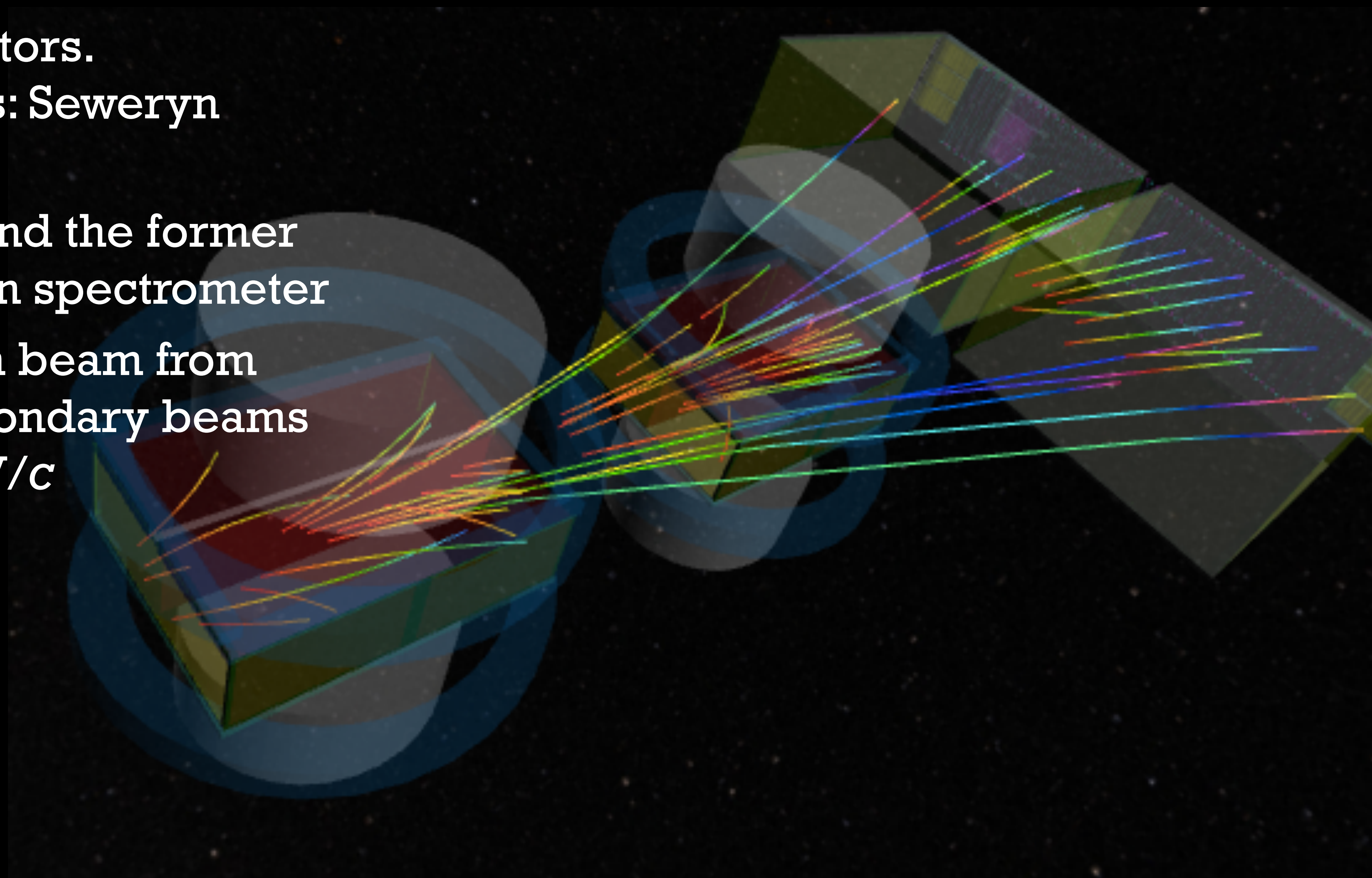


- In recent years, a loose program of hadron production measurements specifically for neutrino experiments has been underway
- HARP (CERN PS)
- EMPHATIC (FNAL MI)
- NA61/SHINE (CERN SPS)



NA61: The SPS Heavy Ion and Neutrino Experiment

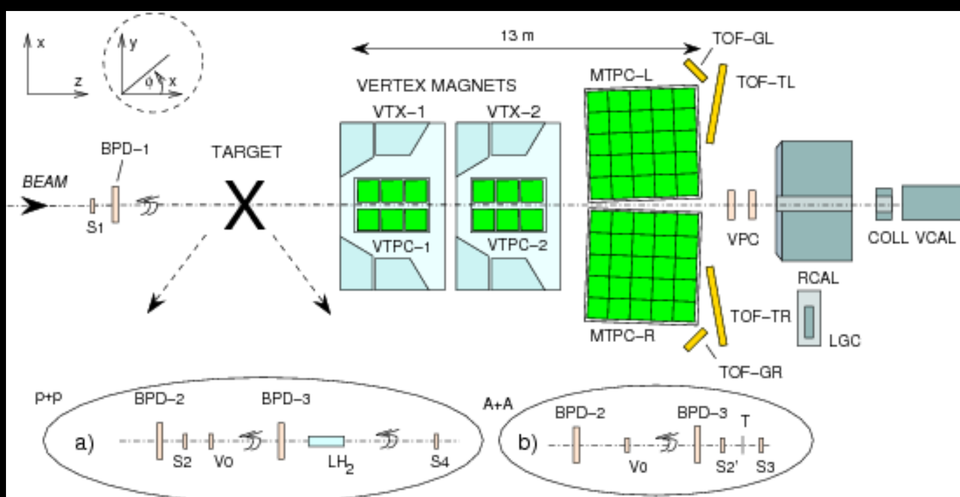
- Fixed-target experiment using H2 beam at CERN SPS
- ~150 collaborators. Spokespersons: Seweryn Kowalski, EDZ
- Designed around the former NA49 heavy-ion spectrometer
- Primary proton beam from CERN SPS, Secondary beams ~13 to 350 GeV/*c*



NA61: The SPS Heavy Ion and Neutrino Experiment

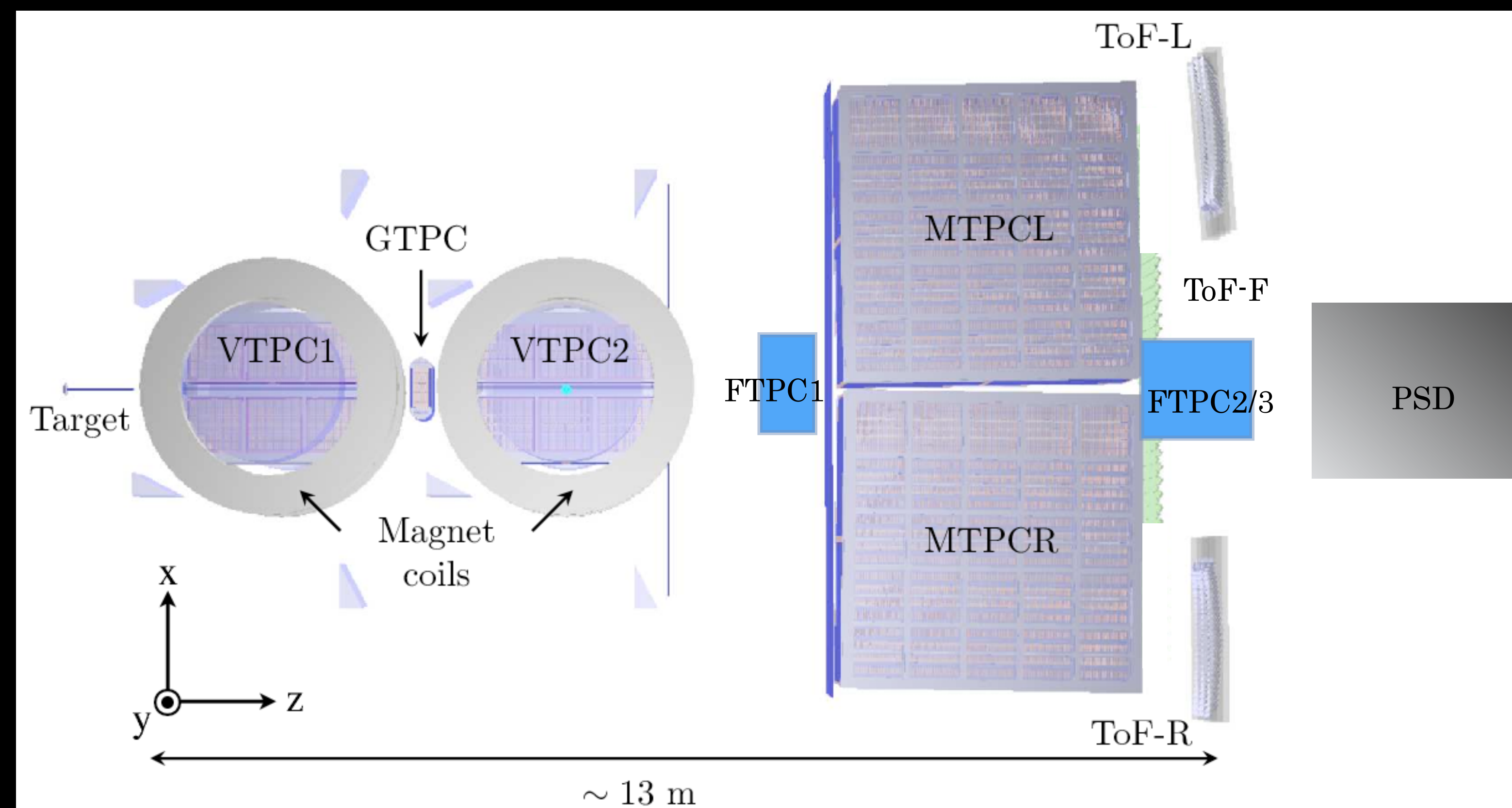
- Diverse physics program includes
  - Strong interactions/heavy ion physics
    - Onset of QCD deconfinement
    - Search for critical point
    - Open-charm production
  - Cosmic ray interaction studies
    - Hadron production for air-shower model predictions
    - $d/\bar{d}$ production for AMS experiment
    - Nuclear fragmentation cross-sections
  - Hadron production for neutrino beams

NA61 detector system



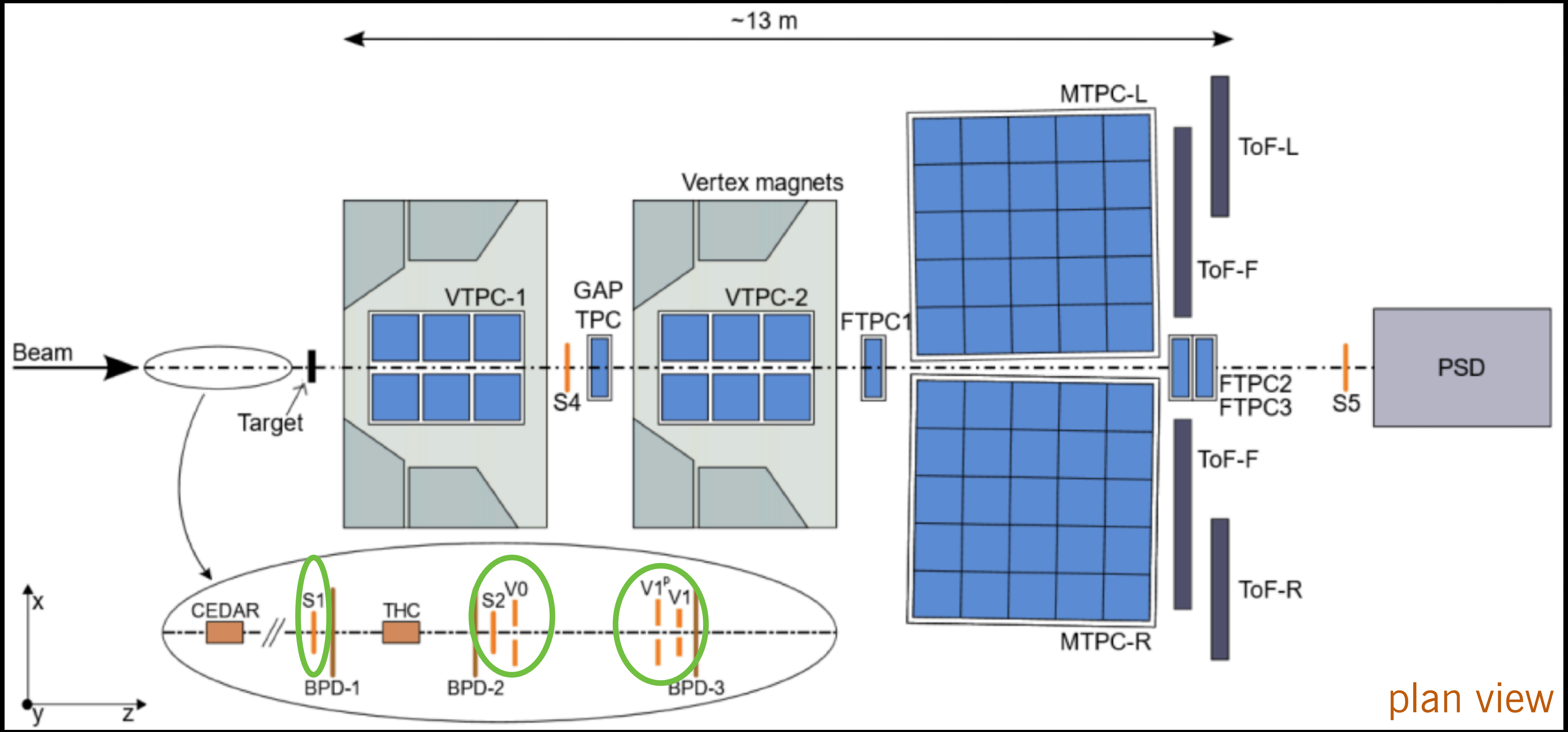
NA49

NA61



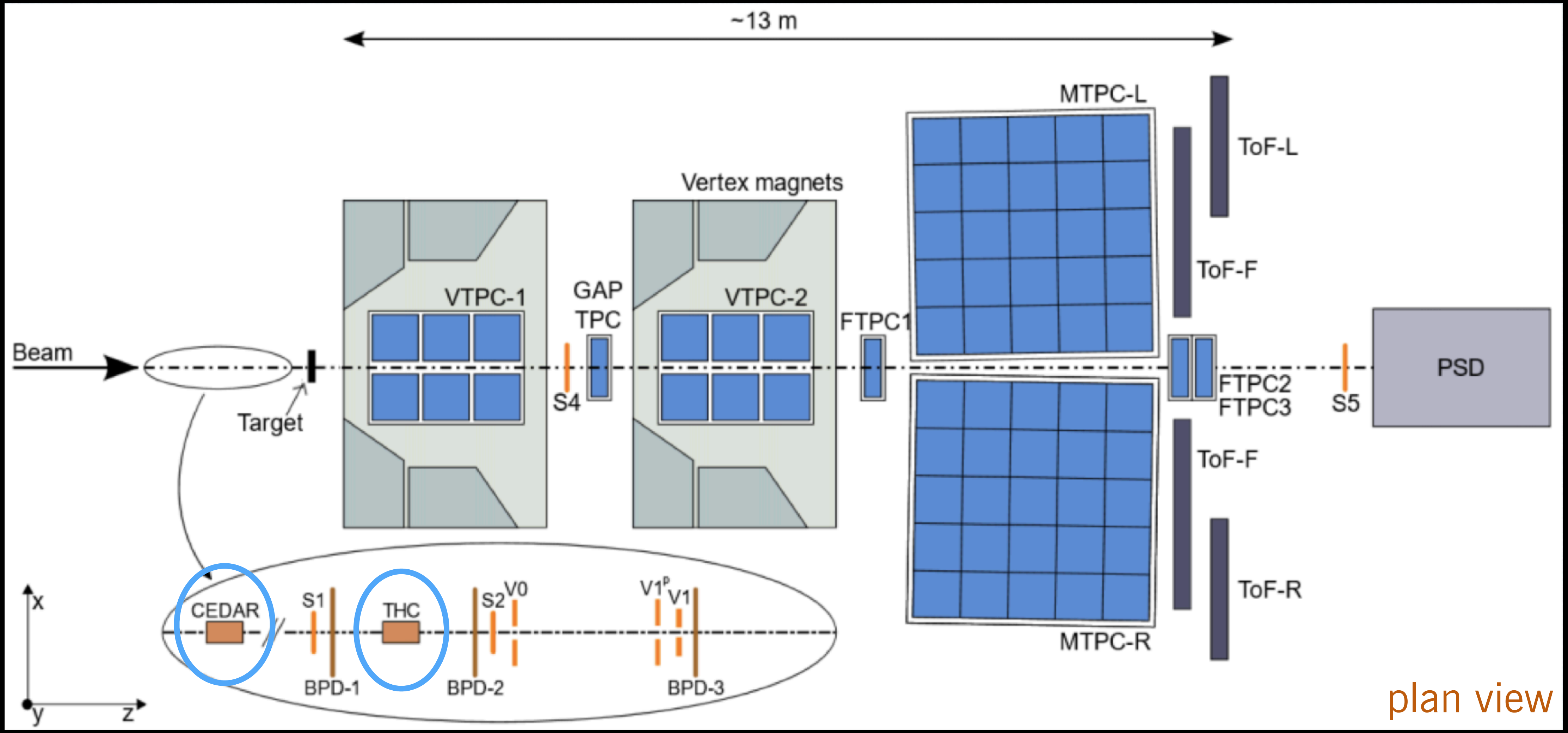
- Detailed beam instrumentation including PID and tracking before the target
- Several large-acceptance TPCs, two superconducting analysis magnets
- Scintillator-based time-of-flight detectors
- Projectile Spectator Detector: forward hadron calorimeter

NA61/SHINE: a large-acceptance multiparticle spectrometer



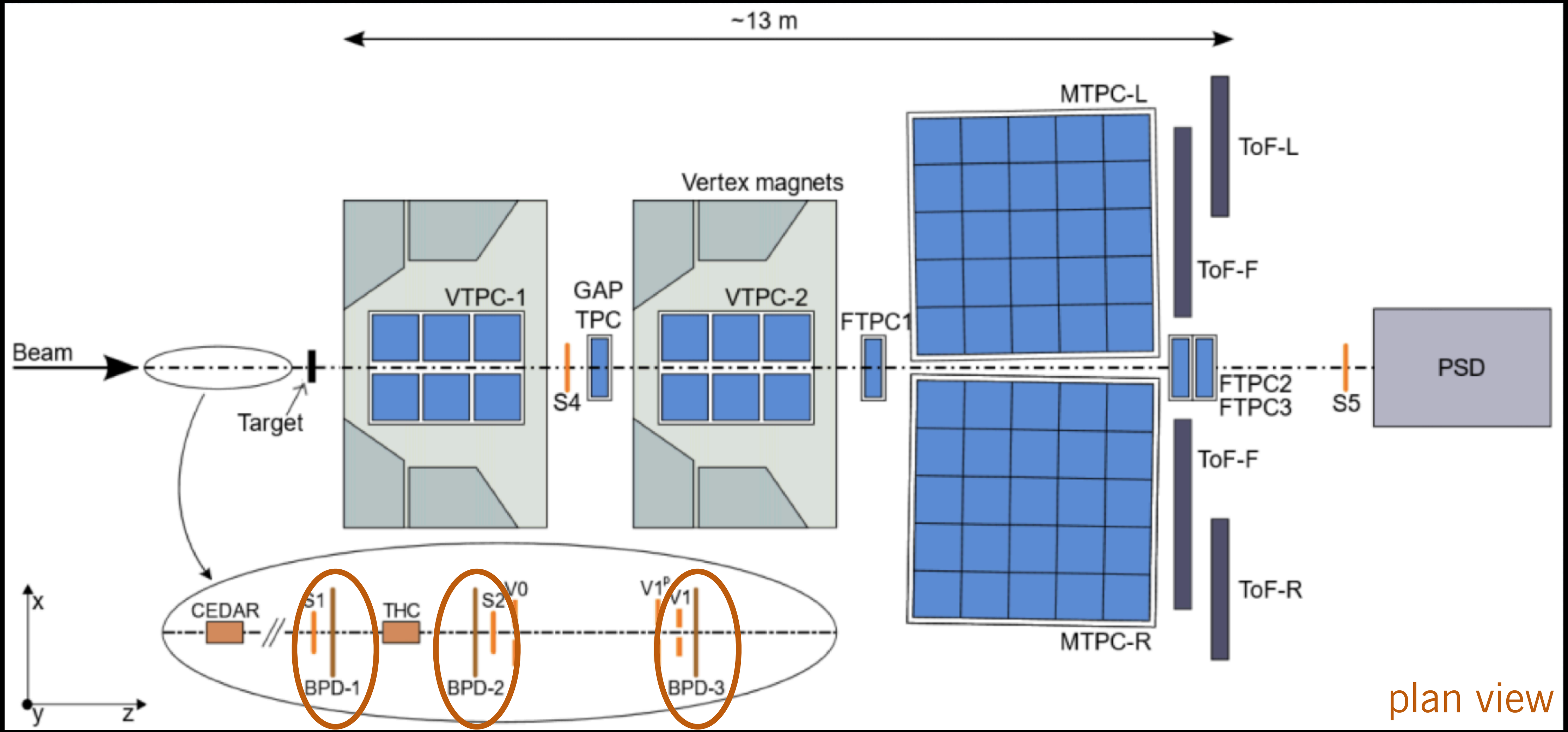
- Beam instrumentation:
  - Scintillators serve as initial trigger and detector timing signal, veto halo particles

NA61/SHINE: a large-acceptance multiparticle spectrometer



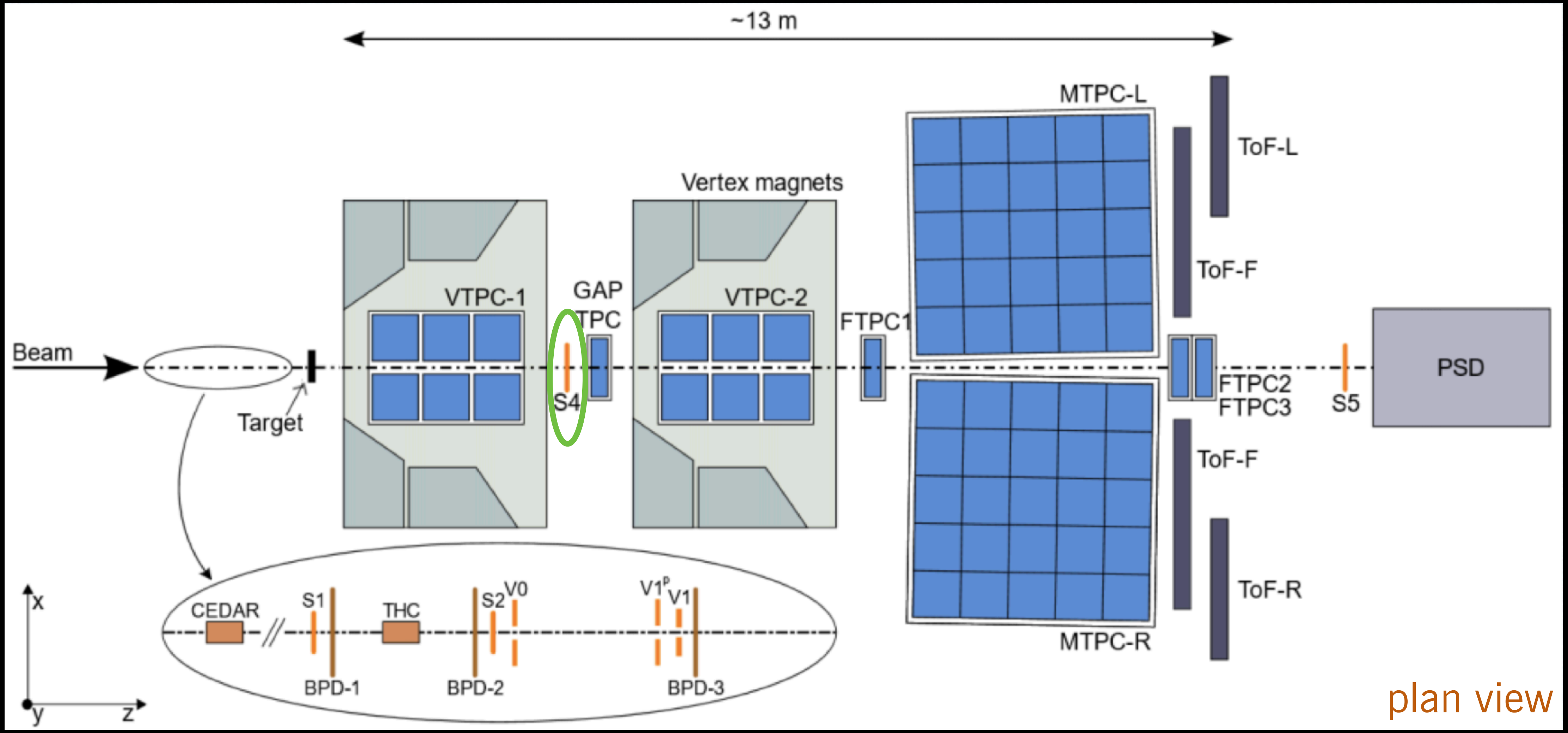
- Beam instrumentation:
  - CEDAR, THC (Threshold Cherenkov) identify beam particles with high accuracy

NA61/SHINE: a large-acceptance multiparticle spectrometer



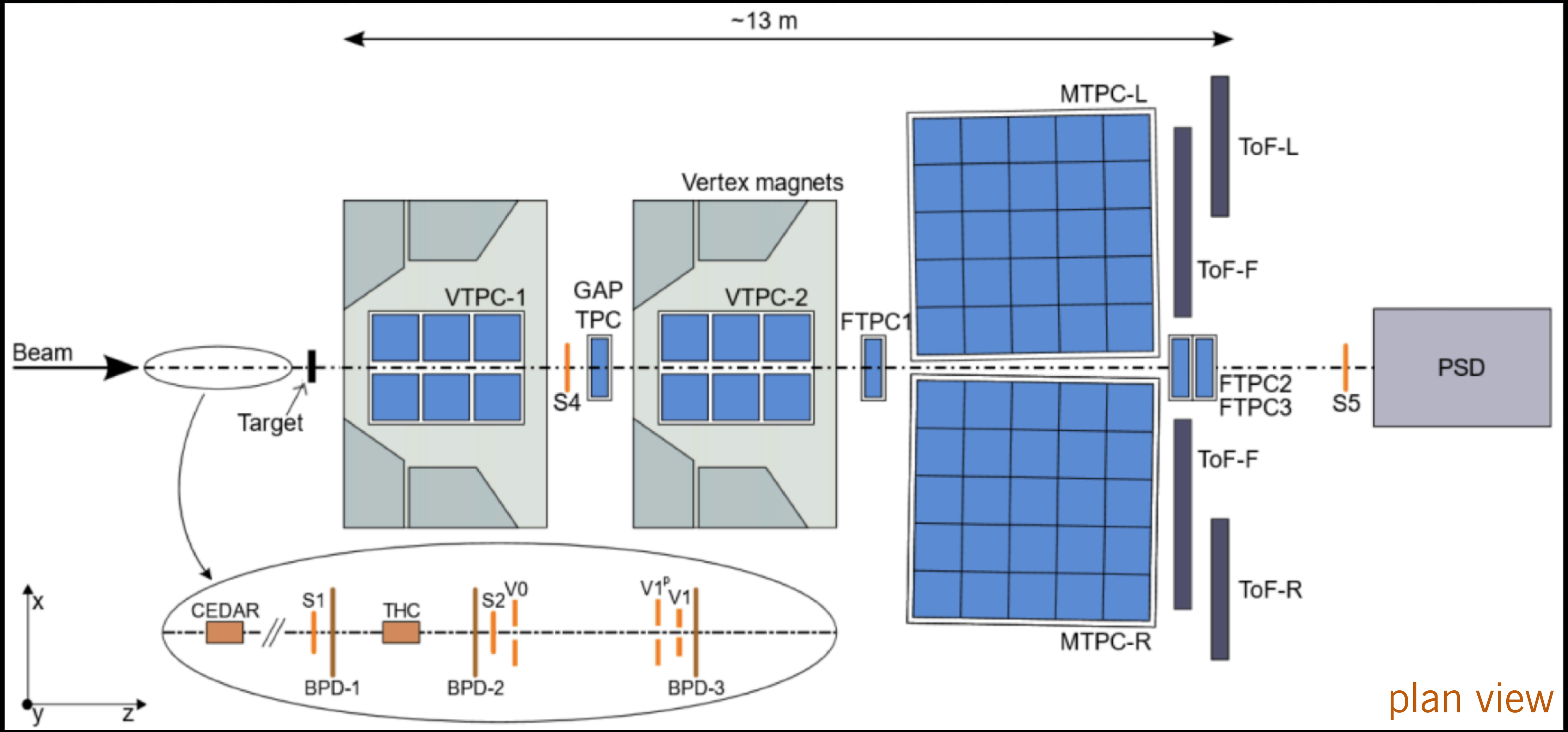
- Beam instrumentation:
  - Beam Position Detectors (BPDs) are tracking detectors that measure transverse position of each beam particle

NA61/SHINE: a large-acceptance multiparticle spectrometer



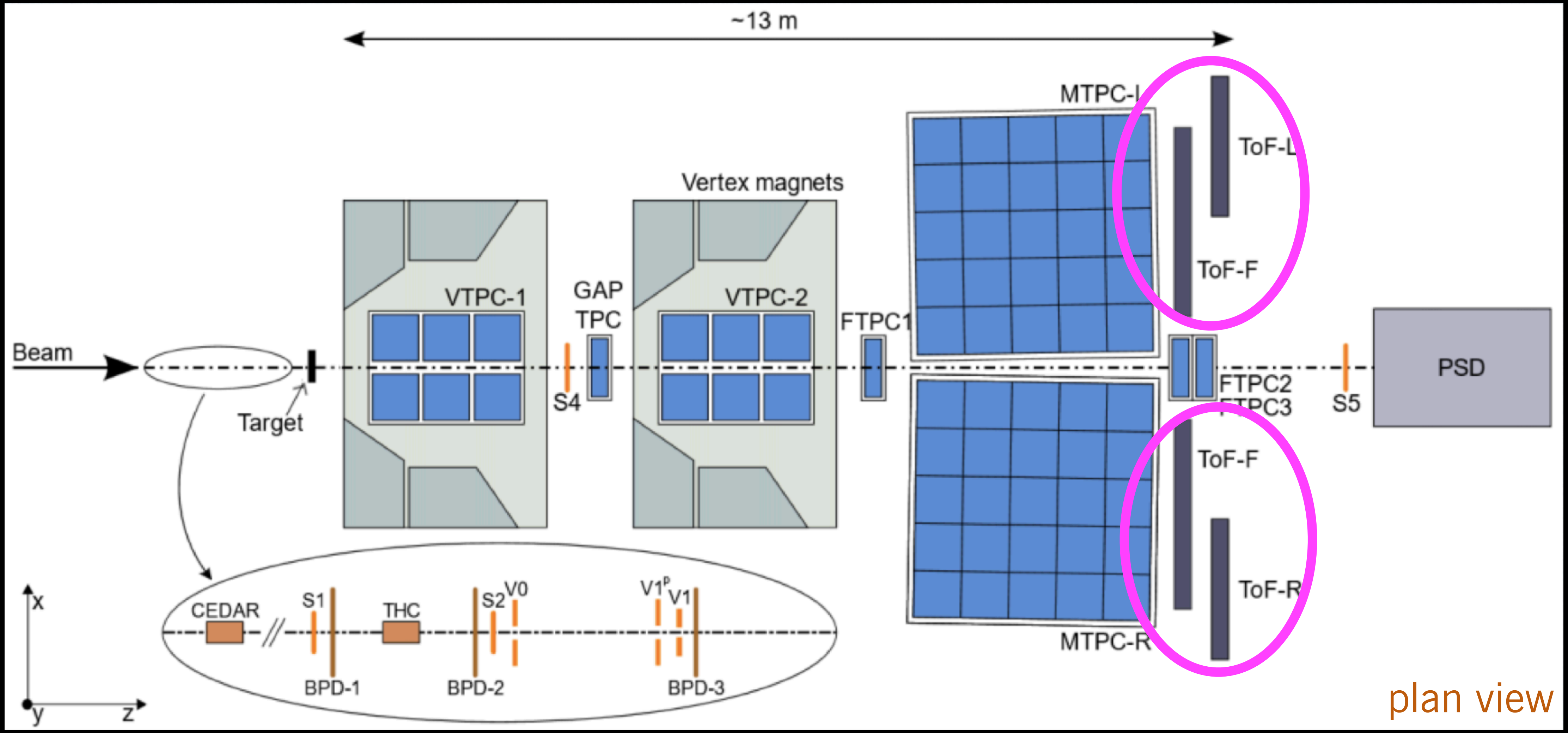
- Beam instrumentation:
  - Additional scintillator S4 in magnetic field can veto beam-momentum forward particles (non-interaction events)

NA61/SHINE: a large-acceptance multiparticle spectrometer



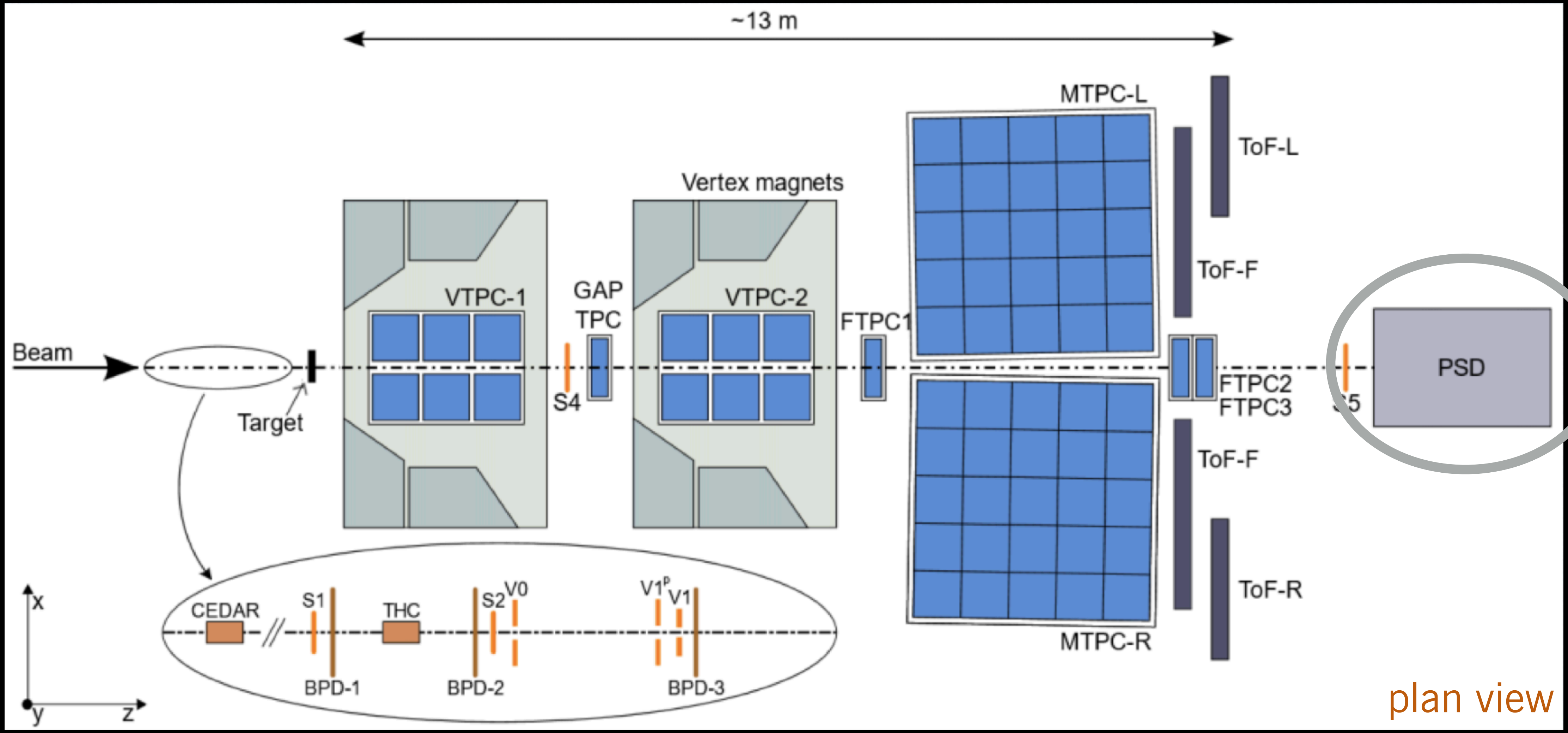
- Several large-acceptance TPCs provide charged-particle tracking and measure dE/dx.
- VTPC-1 and VTPC-2 sit inside superconducting analysis magnets for momentum measurement

NA61/SHINE: a large-acceptance multiparticle spectrometer



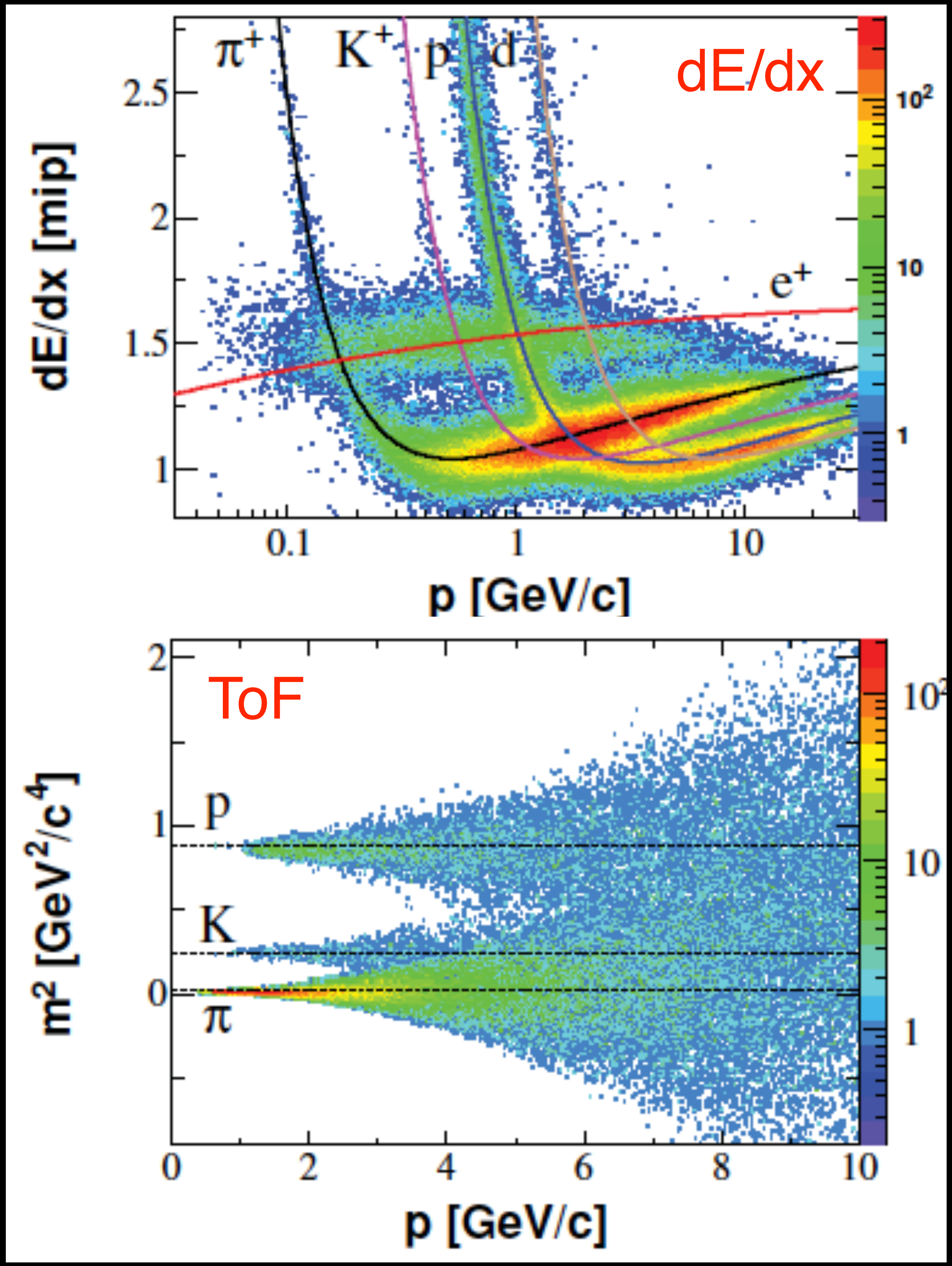
- Scintillator and multilayer resistive plate chamber (MRPC) time-of-flight detectors

NA61/SHINE: a large-acceptance multiparticle spectrometer

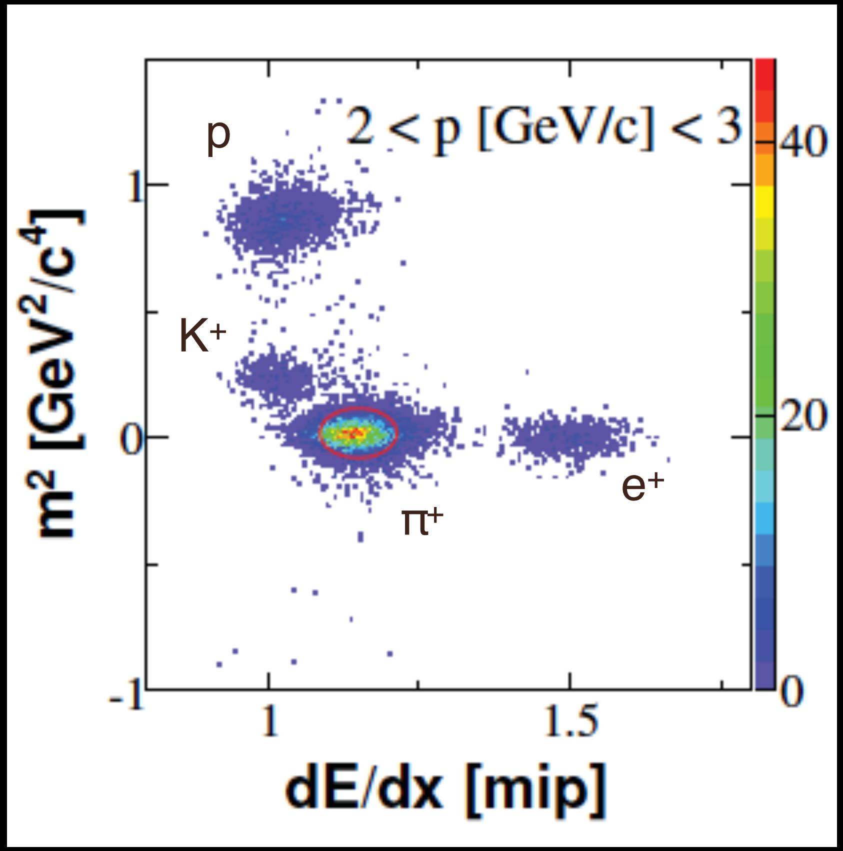


- Projectile Spectator Detector: forward hadron calorimeter (not used much for neutrino measurements)

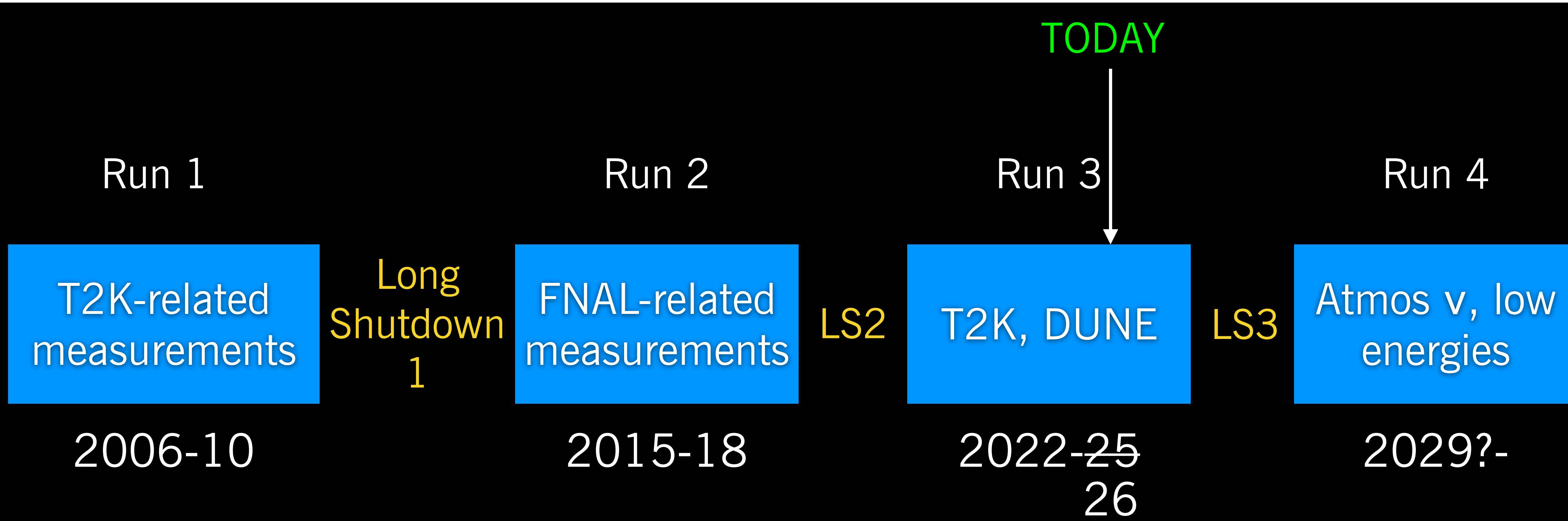
Particle identification



- Uses dE/dx in TPCs at higher momentum
- Transitions to TOF at lower p



NA61/SHINE 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

Twin approaches: thin- and replica-target measurements

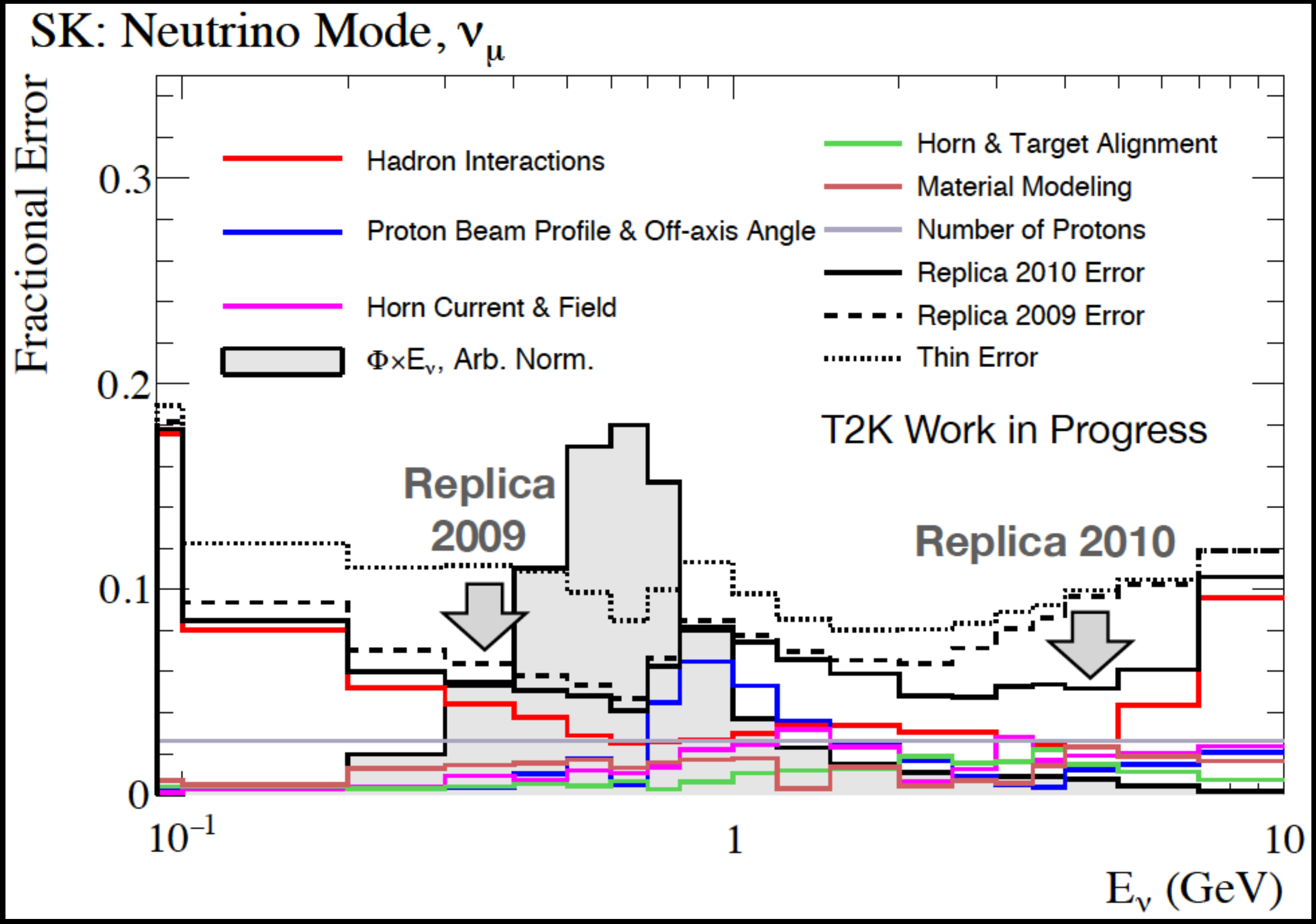
Graphite thin target (1.5 cm, 3.1% of λ_I)

- Need thin-target measurements to measure physics cross-sections (total inelastic and production cross-sections, and differential spectra), for inputs to generators
- Need measurements on replica (~meter-long) targets of same material and geometry as neutrino production targets.
  - Measure both beam survival probability and differential yields.
  - Make measurements specifically for each neutrino beam.
  - Usually use results to re-weight particles in beam MC at surface of target

REPLICA TARGETS

NA61/SHINE measurements for T2K

- Steady improvements to the T2K flux prediction (described in Phys.Rev. D87 (2013) no.1, 012001 and J.Phys.Conf.Ser. 888 (2017) no.1, 012064) as more NA61 data sets have been incorporated:
  - first thin-target
  - 2009 replica
  - 2010 replica data set (which added statistics and included kaon and proton yields)
- 20x more data collected in 2022 to improve high-energy end of flux (under analysis now)



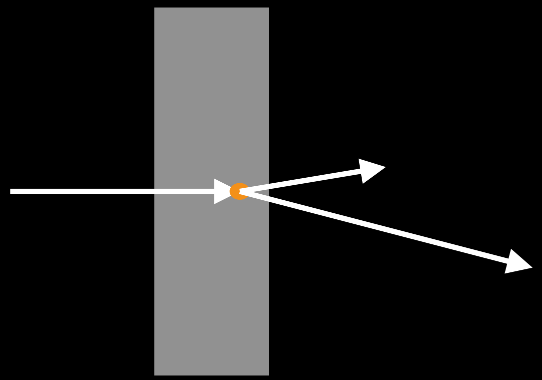
NA61/SHINE measurements for T2K

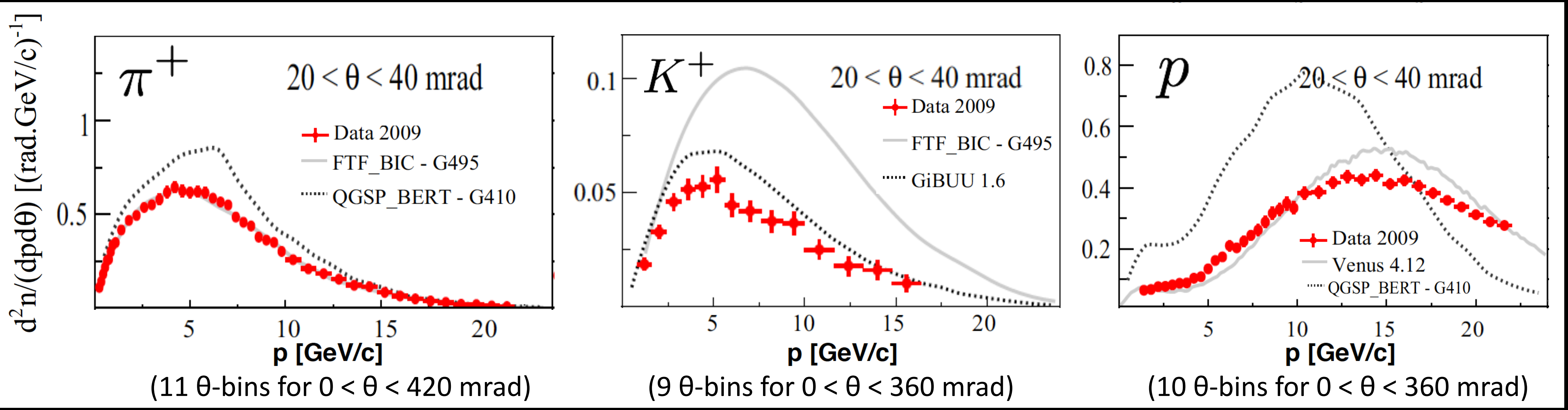
- Eight NA61/SHINE publications have come out of these data sets

THIN TARGET	
Total xsec, pion spectra	Phys. Rev. C84 034604 (2011)
K^+ spectra	Phys. Rev. C85 035210 (2012)
K^0_S and Λ^0 spectra	Phys. Rev. C89 025205 (2014)
$\pi^\pm$,$K^\pm$, p, K^0_S, Λ^0 spectra	Eur. Phys. J. C76 84 (2016)

T2K REPLICA TARGET	
methodology, $\pi^\pm$ yield	Nucl. Instrum. Meth. A701 99-114 (2013)
$\pi^\pm$ yield	Eur. Phys. J. C76 617 (2016)
$\pi^\pm$,$K^\pm$, p yield	Eur. Phys. J. C79 100 (2019)
p beam survival probability	Phys. Rev. D103 012006 (2021)

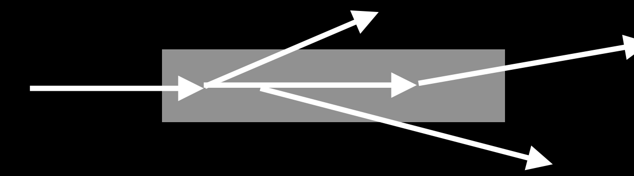
Thin-target results: p+C @ 30 GeV





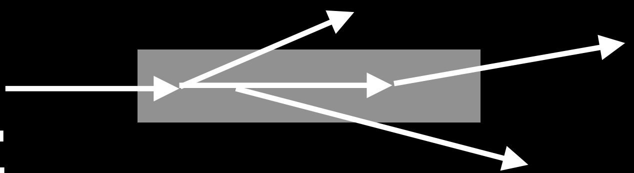
- One angle bin shown here for illustration
- MC generators fail badly for kaons and protons
- Published in Eur. Phys. J. **C76** 84 (2016): also contains yields of negative particles and neutral strange particles (V^0).

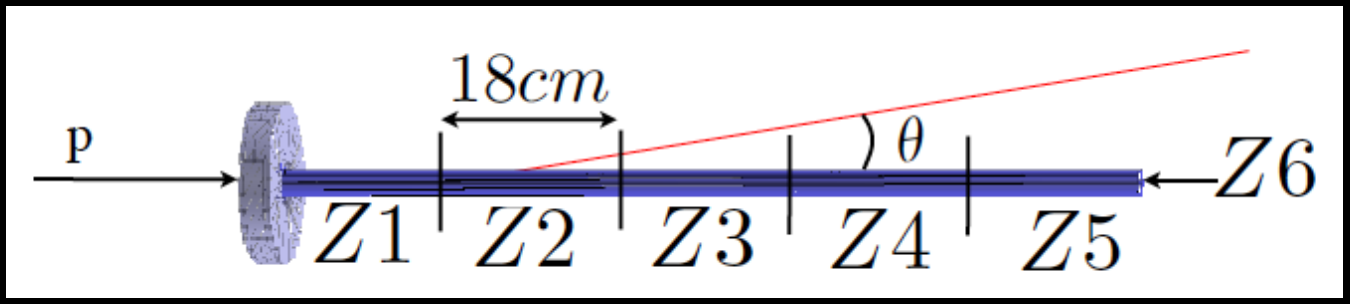
Replica-target measurements



- Exact target geometry of a particular neutrino beam (T2K: 90cm cylinder, NuMI/NOvA: 120cm of graphite fins)
- Most events have primary and secondary interactions in the target
- Measure particle yields vs not only p and θ, but also exit z along target (and possibly ϕ for targets like NuMI's that aren't cylindrically symmetric)
- Also measure beam particle survival as additional constraint on σ_{prod}
- In neutrino beam MC, apply weights to particles at surface of target in the simulation

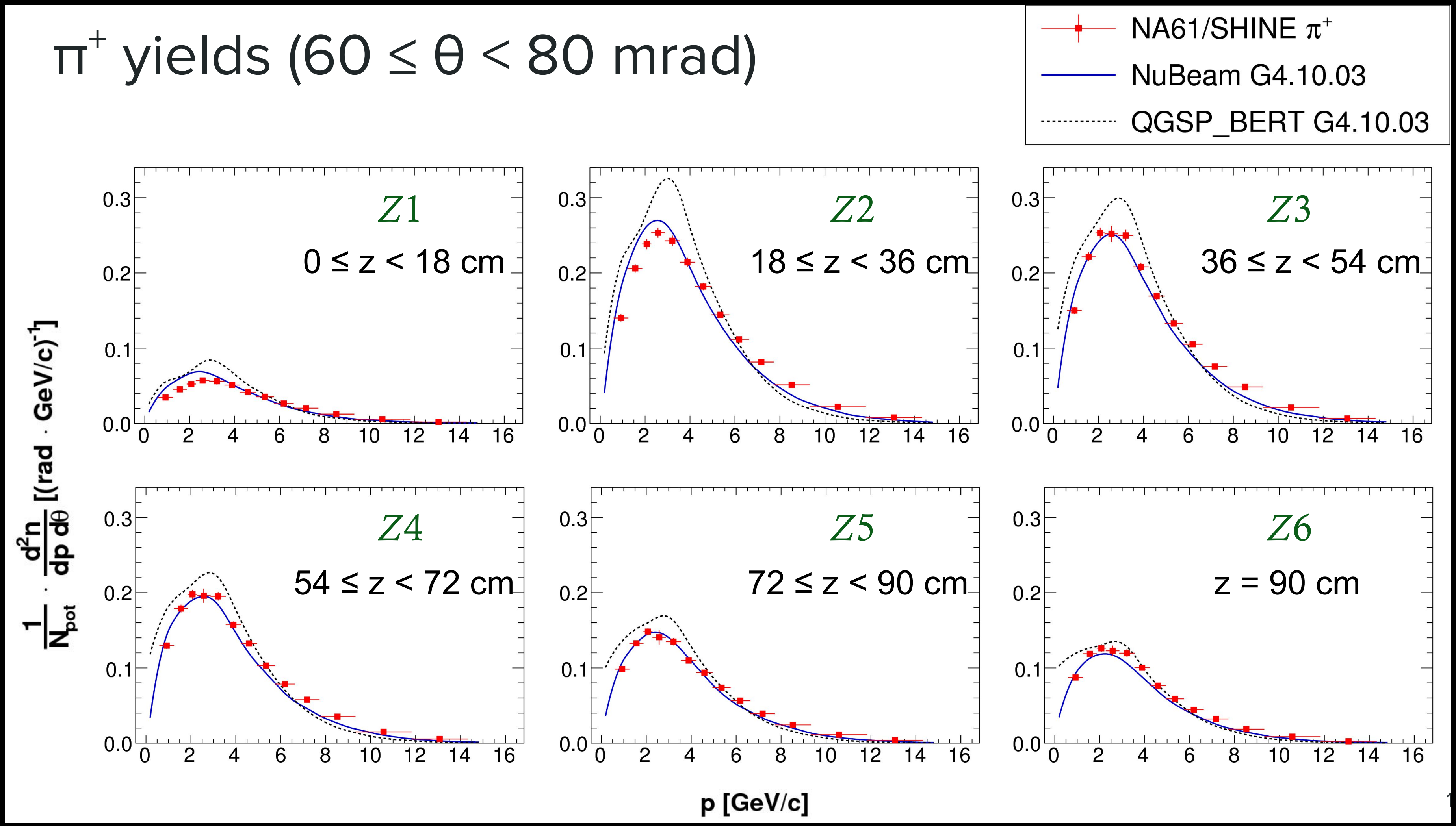
NA61 result: full differential yields from T2K replica target





- *Eur.Phys.J.* **C 79** 2, 100 (2019)
- Showing one angle bin of π^+ for illustration.

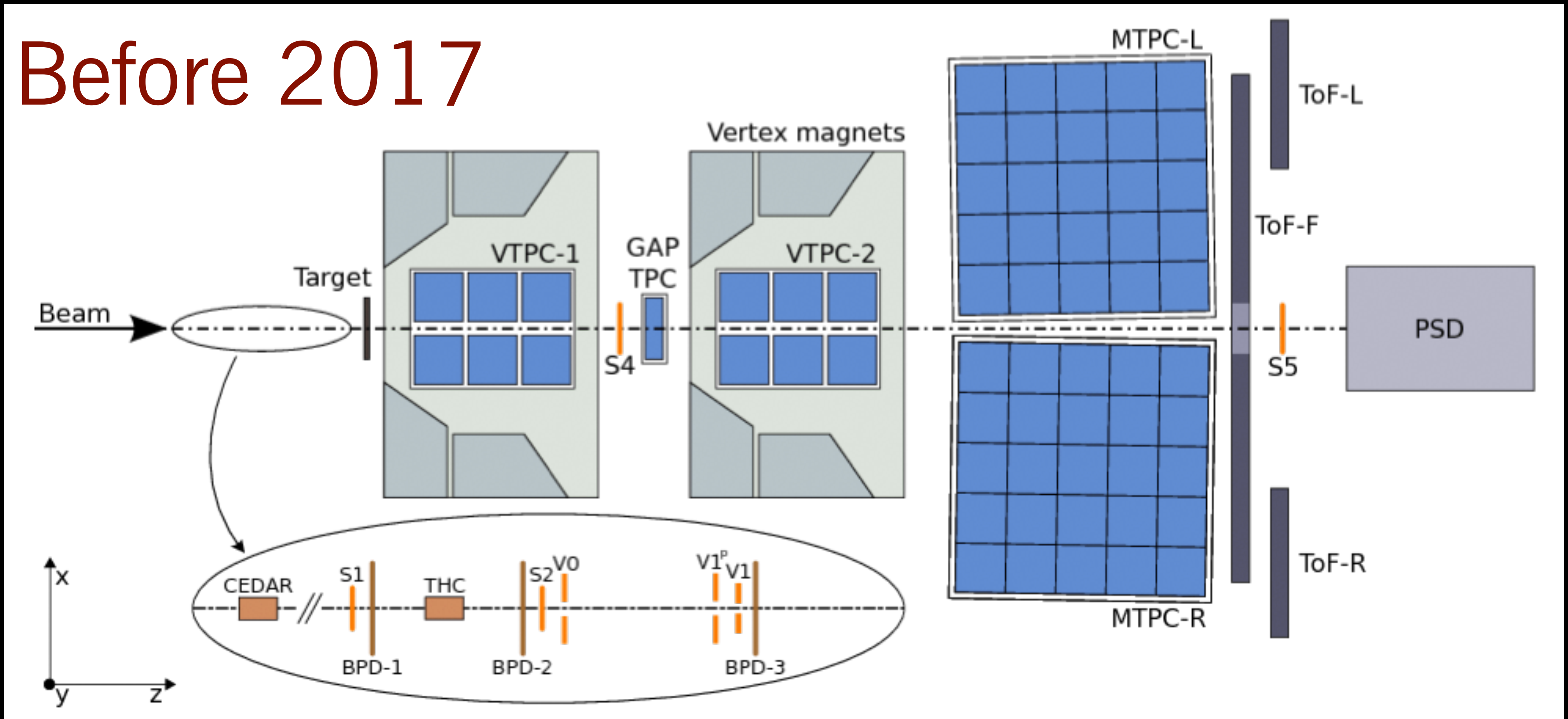
  Also have π^-, $K^\pm$, p yields



2015-18: A second phase of NA61 neutrino measurements

- Motivation: new coverage will be needed for DUNE, can help existing experiments as well in shorter term
- Project made specific upgrades:
  - Forward tracking system
    - New tandem TPC concept for rejecting out-of-time tracks
  - New readout electronics for time-of-flight detector
- Data collected in 2015-18 for this program

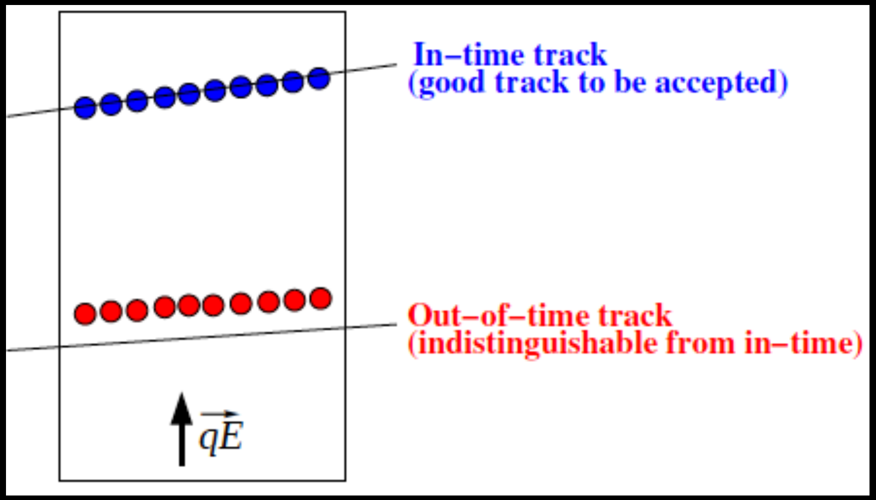
NA61 acceptance

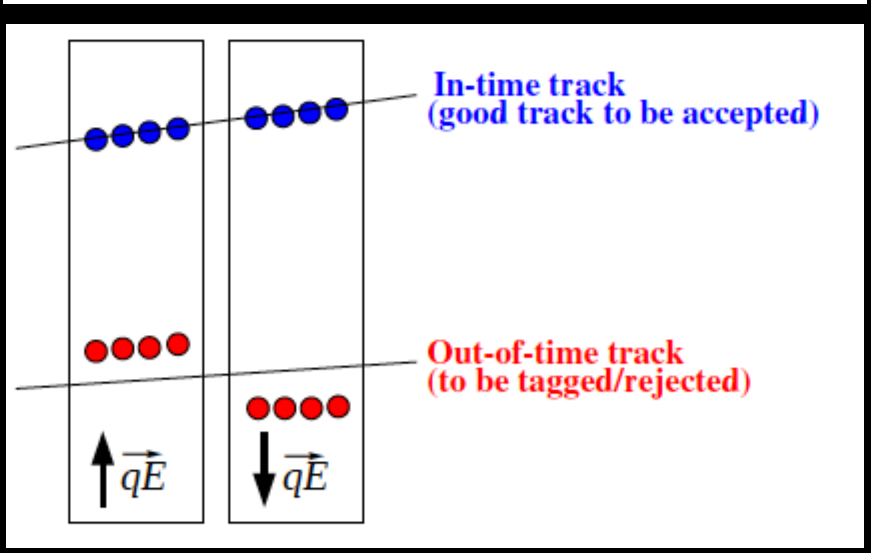


- NA61 setup before 2017 had a hole in the acceptance where the beam passes through
- Hole due to heavy ion needs: intense beam can't go through chambers
- Now, have full forward acceptance with Forward TPCs

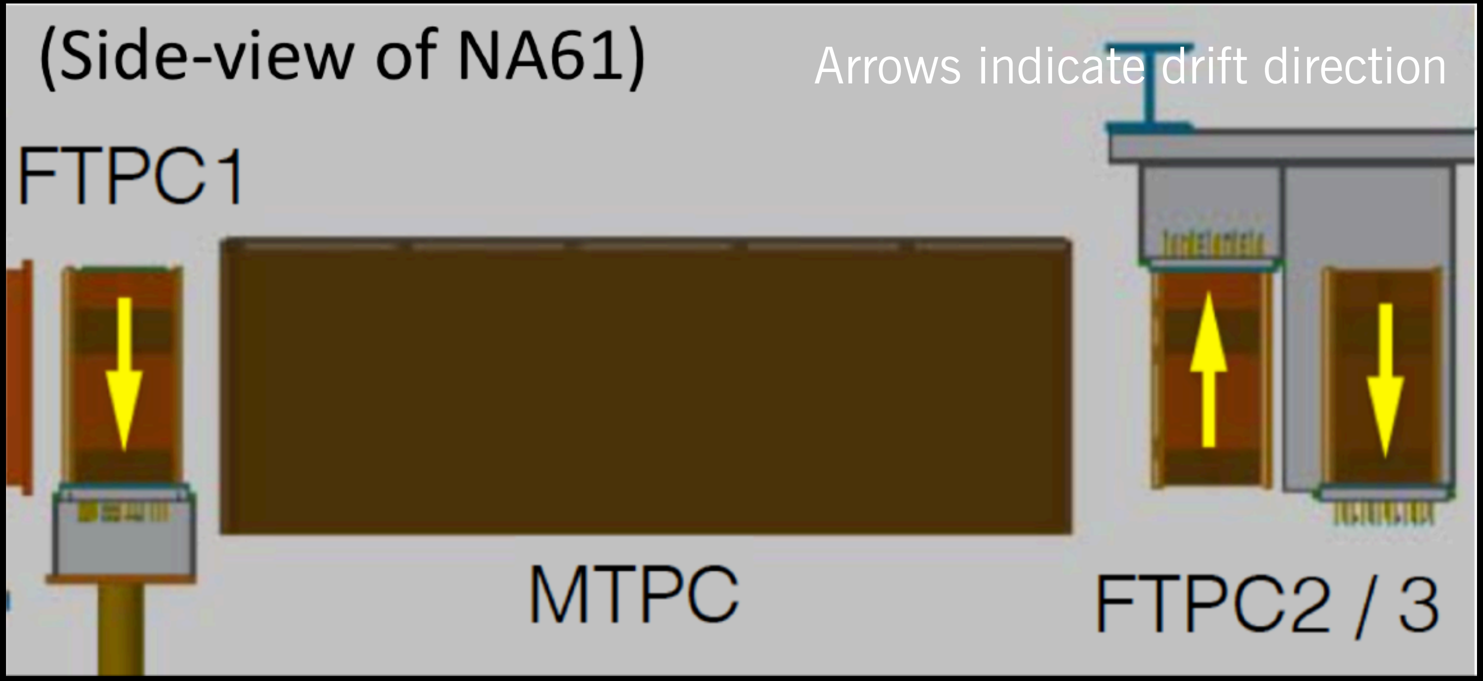
Forward TPCs

- New TPCs have been built for the neutrino program to fill the hole and complete the acceptance in the forward region
- Low-mass design with light plastic frame and thin printed Kapton field cage; FTPC1 removable for heavy-ion running
- Uses same electronics as other TPCs
- High rates in beam region drove development of new "Tandem TPC" concept. Paper published JINST 15 (07), P07013



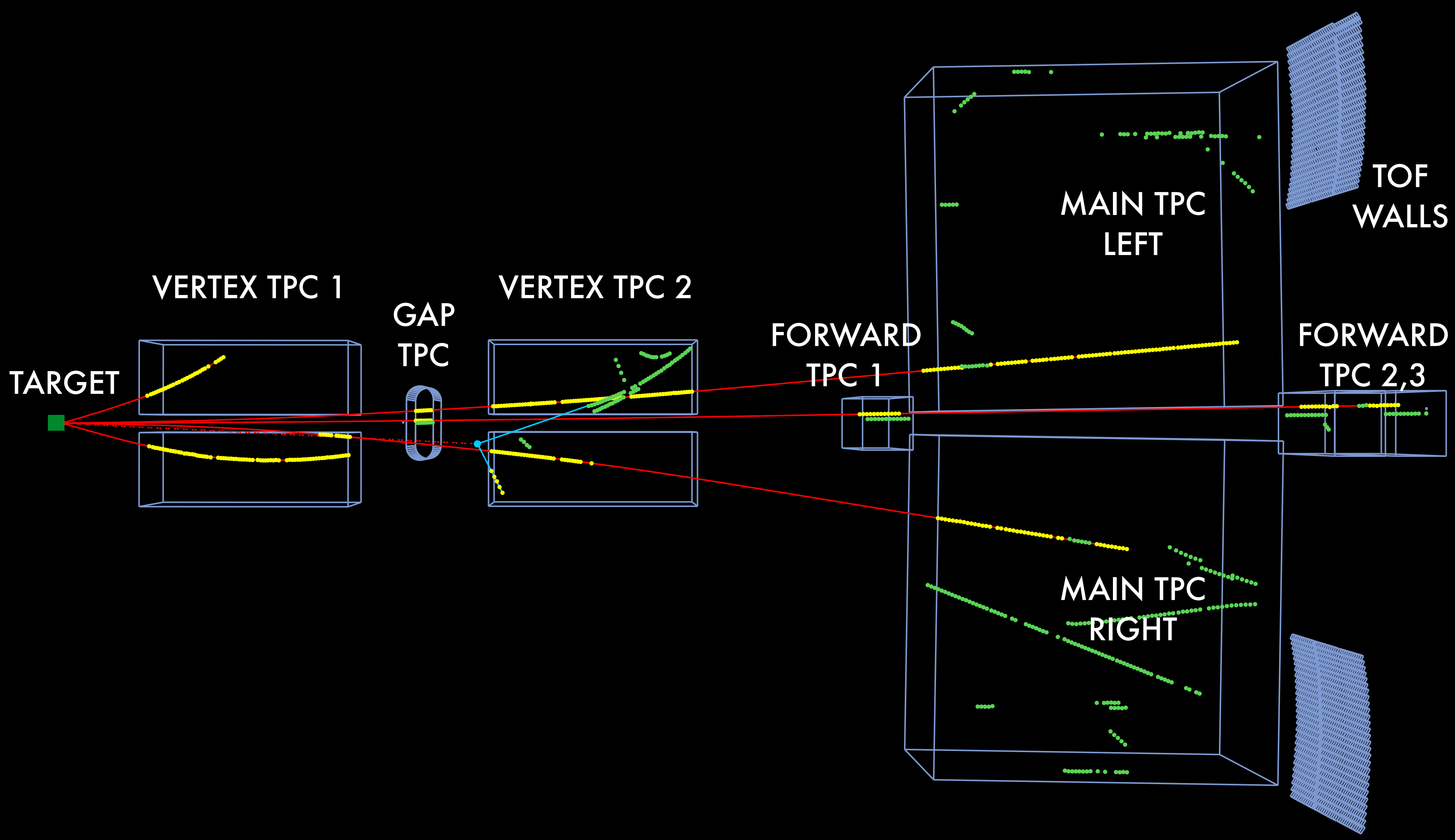


- Out-of-time tracks in a TPC are reconstructed as shifted in drift direction
- Successive field volumes have opposite drift direction: out-of-time tracks appear discontinuous and can be easily rejected



Event display

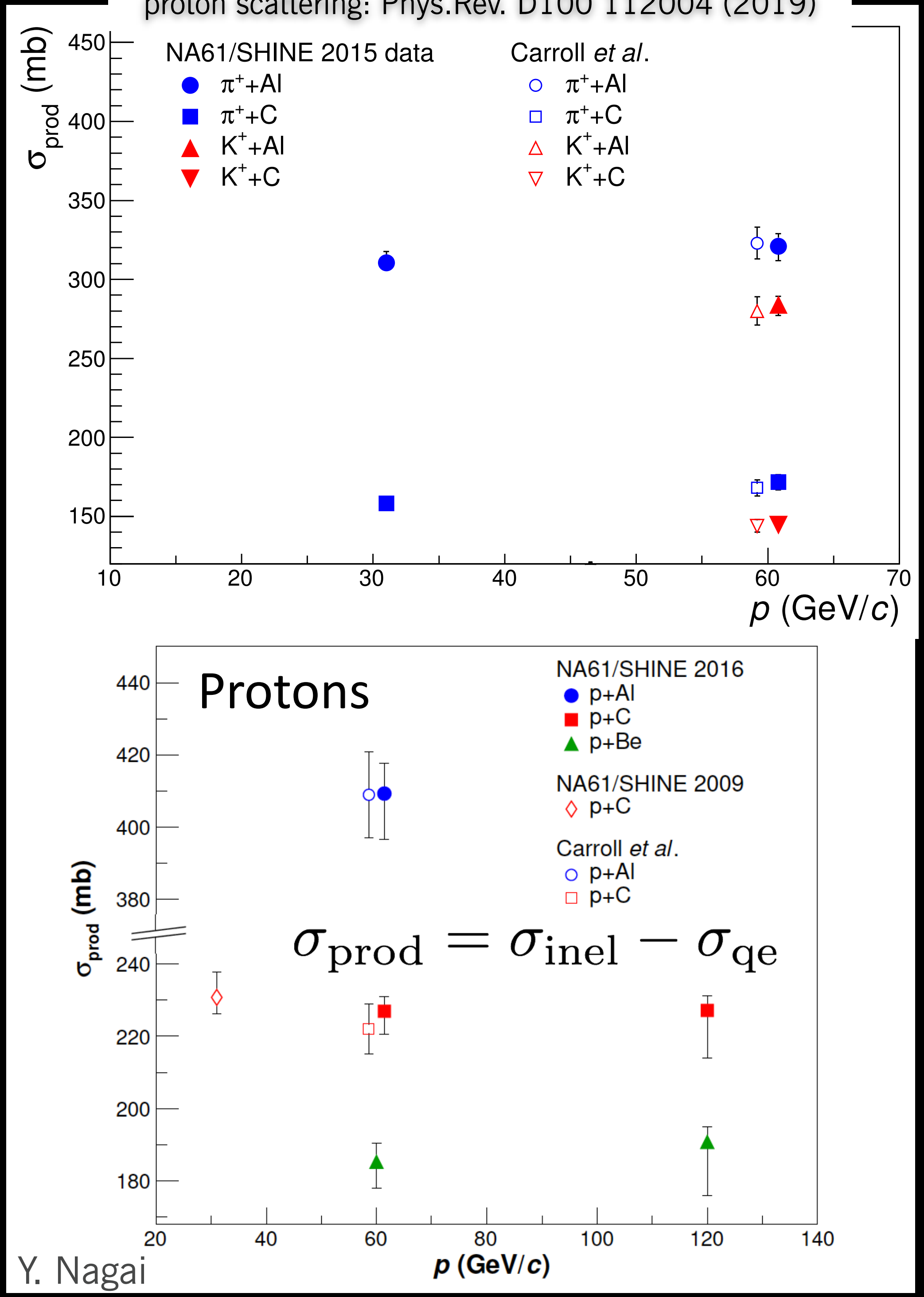
120 GeV p+C



NA61/SHINE results: total production cross-sections on nuclear targets

- Pion and kaon scattering on carbon and aluminum
- Published total production and total inelastic cross section measurements for data without magnetic field
- Definitions: (terminology not always used consistently in community or in hadronic event generators.)
    - $\sigma_{prod} = \sigma_{total} - \sigma_{el} - \sigma_{qe}$, requires new hadrons to be produced.
    - $\sigma_{inel} = \sigma_{total} - \sigma_{el}$.
- Before, NuMI had 5% error on pion interactions, 10-30% for kaons, and had to extrapolate from other energies for protons

pion/kaon scattering: Phys.Rev. D98 052001 (2018);
proton scattering: Phys.Rev. D100 112004 (2019)



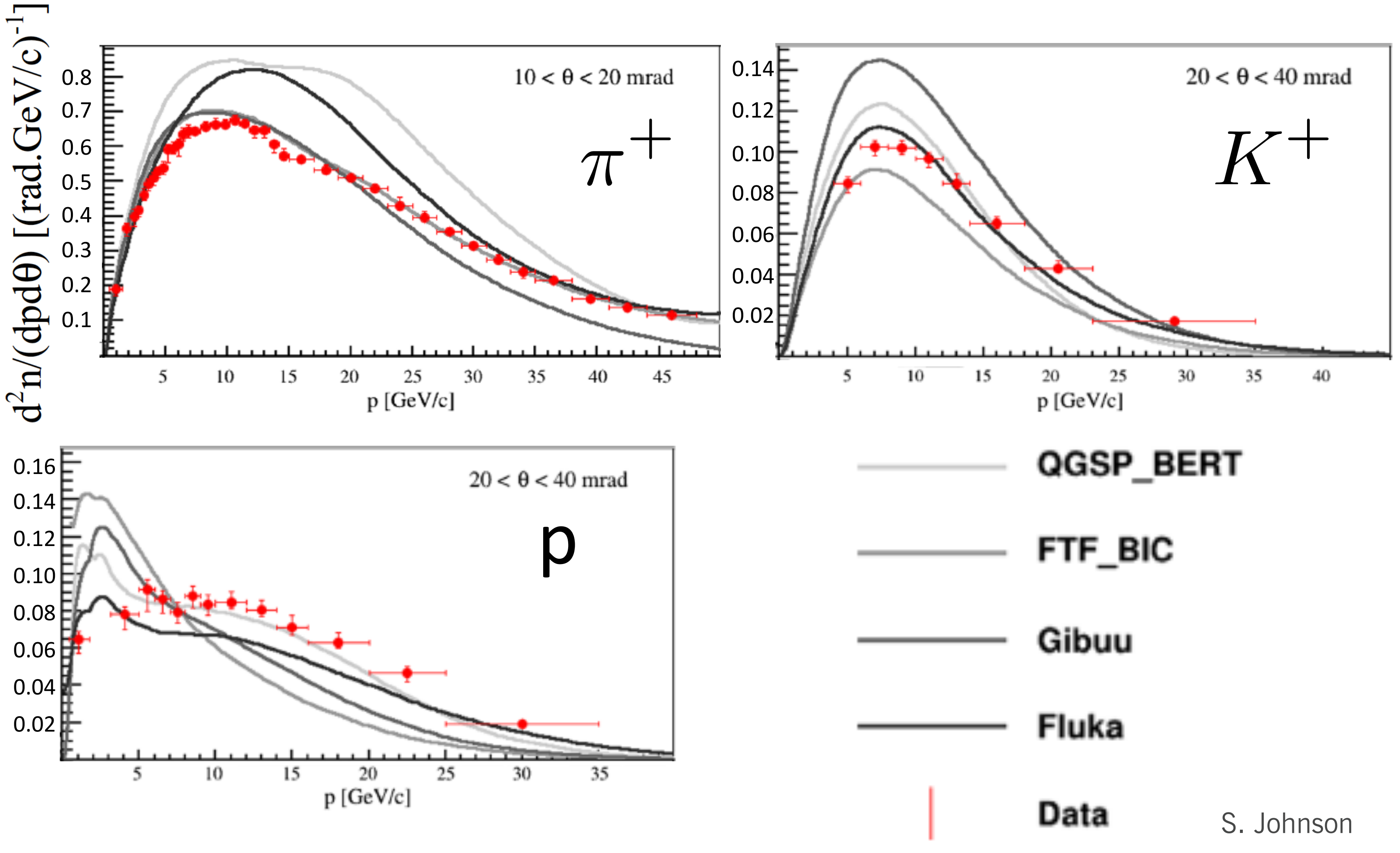
NA61 2016-17 neutrino data
Thin targets

2016	2017
p + C @ 120 GeV/c	π^+ + Al @ 60GeV/c
p + Be @ 120 GeV/c	π^+ + C @ 30 GeV/c
p + C @ 60 GeV/c	π^- + C @ 60 GeV/c
p + Al @ 60 GeV/c	p + C @ 120 GeV/c (w FTPCs)
p + Be @ 60 GeV/c	p + Be @ 120 GeV/c (w FTPCs)
π^+ + C @ 60GeV/c	p + C @ 90 GeV/c (w FTPCs)
π^+ + Be @ 60 GeV/c	

- Full particle yields and spectra from these data sets
- Goal with these measurements is to span the phase space of primary and secondary interactions in neutrino targets and surrounding materials
- Most data sets have published results; some analyses continuing
- Each measurement will be a point for interpolation in MC generators

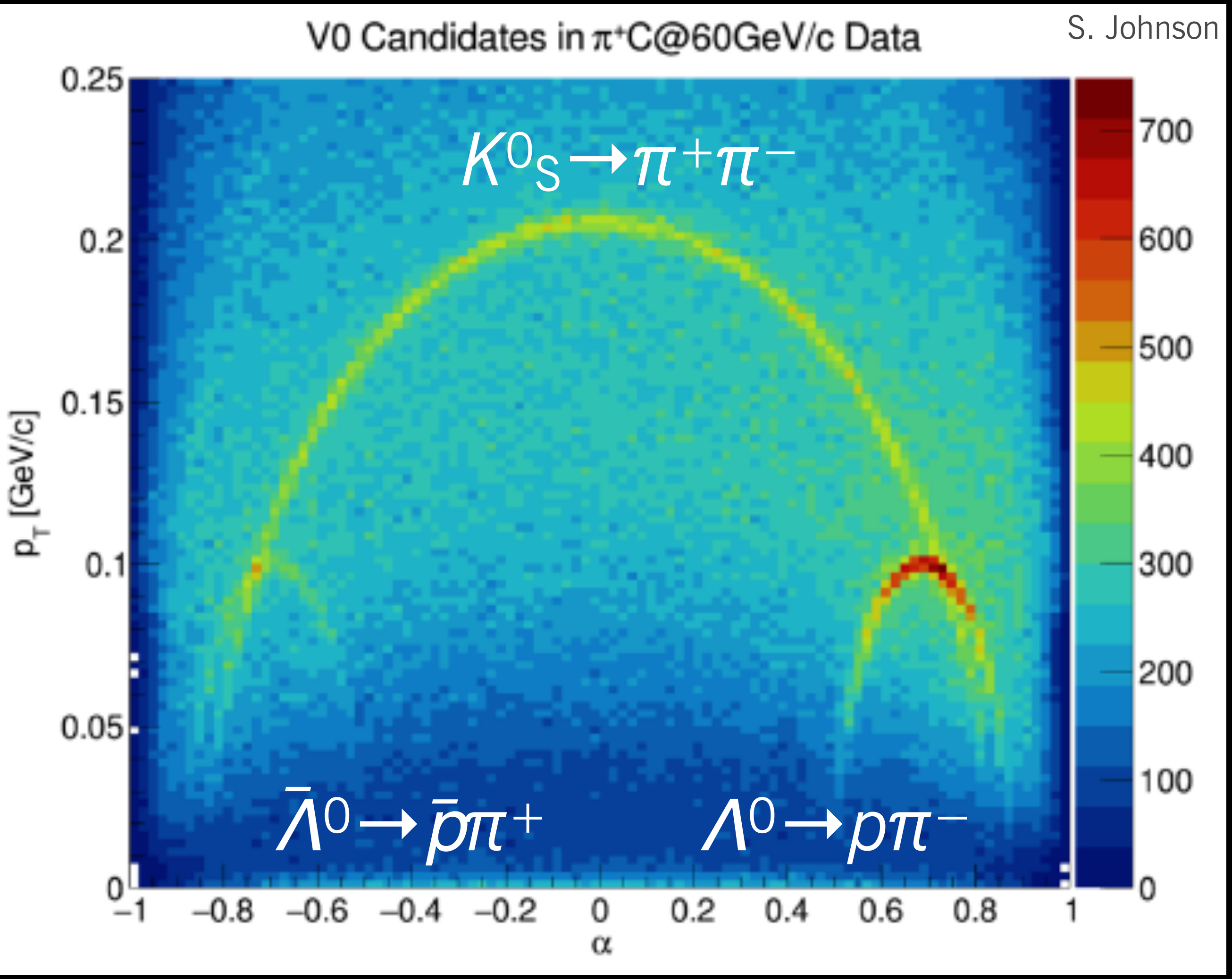
Thin-target charged hadron spectra

- Example: π^{+}+C @ 60 GeV (Phys.Rev. **D100** 112004 (2019))
- Measured differential production yields (positively-charged shown, also measured negatives)



Thin-target neutral hadron spectra

- Analysis of decays in flight using "V⁰" events: displaced vertex of two oppositely-charged particles.
- Visualize the events using Armenteros-Podolansky plots

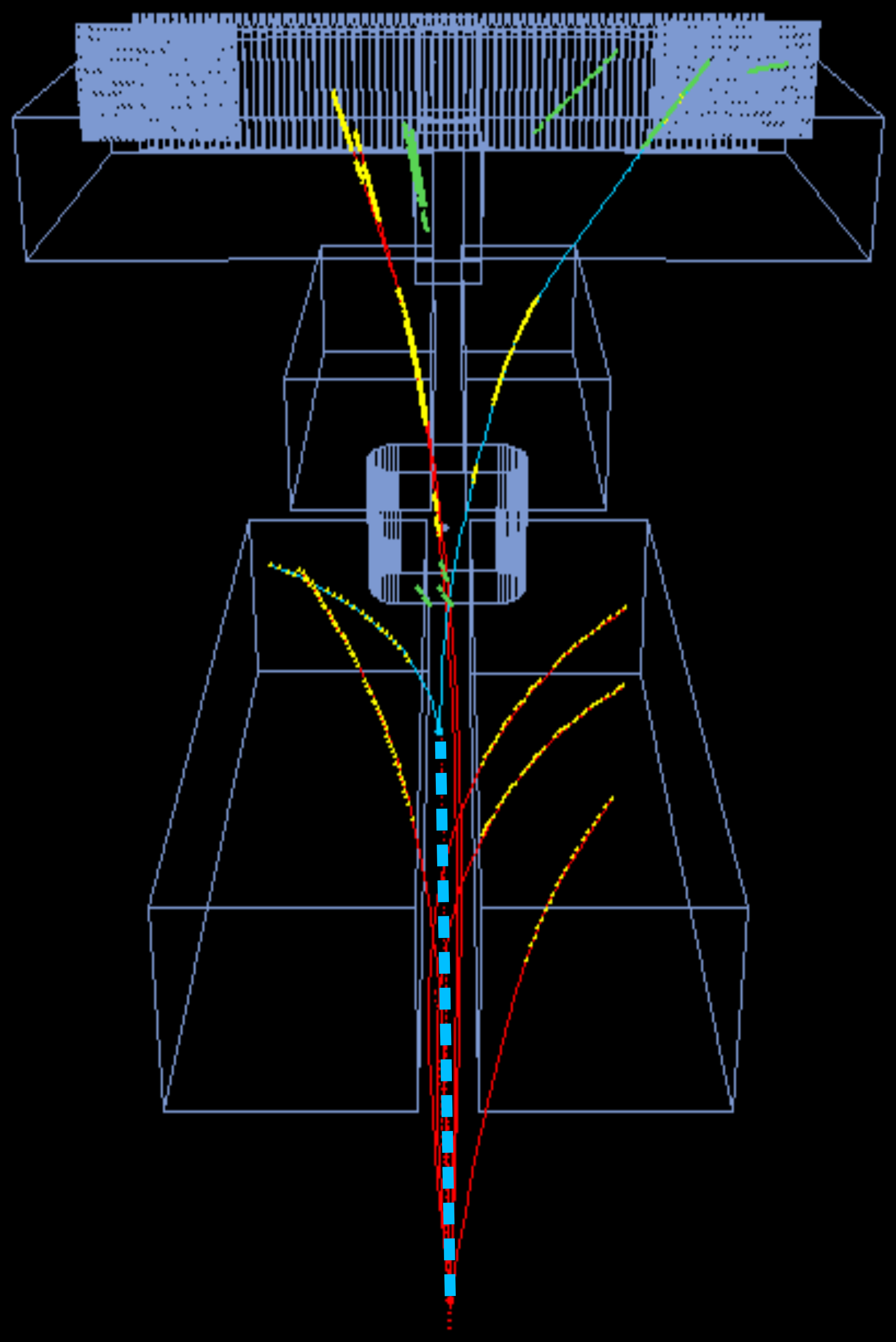


- Plot track p_T vs V trajectory against longitudinal momentum asymmetry of the tracks

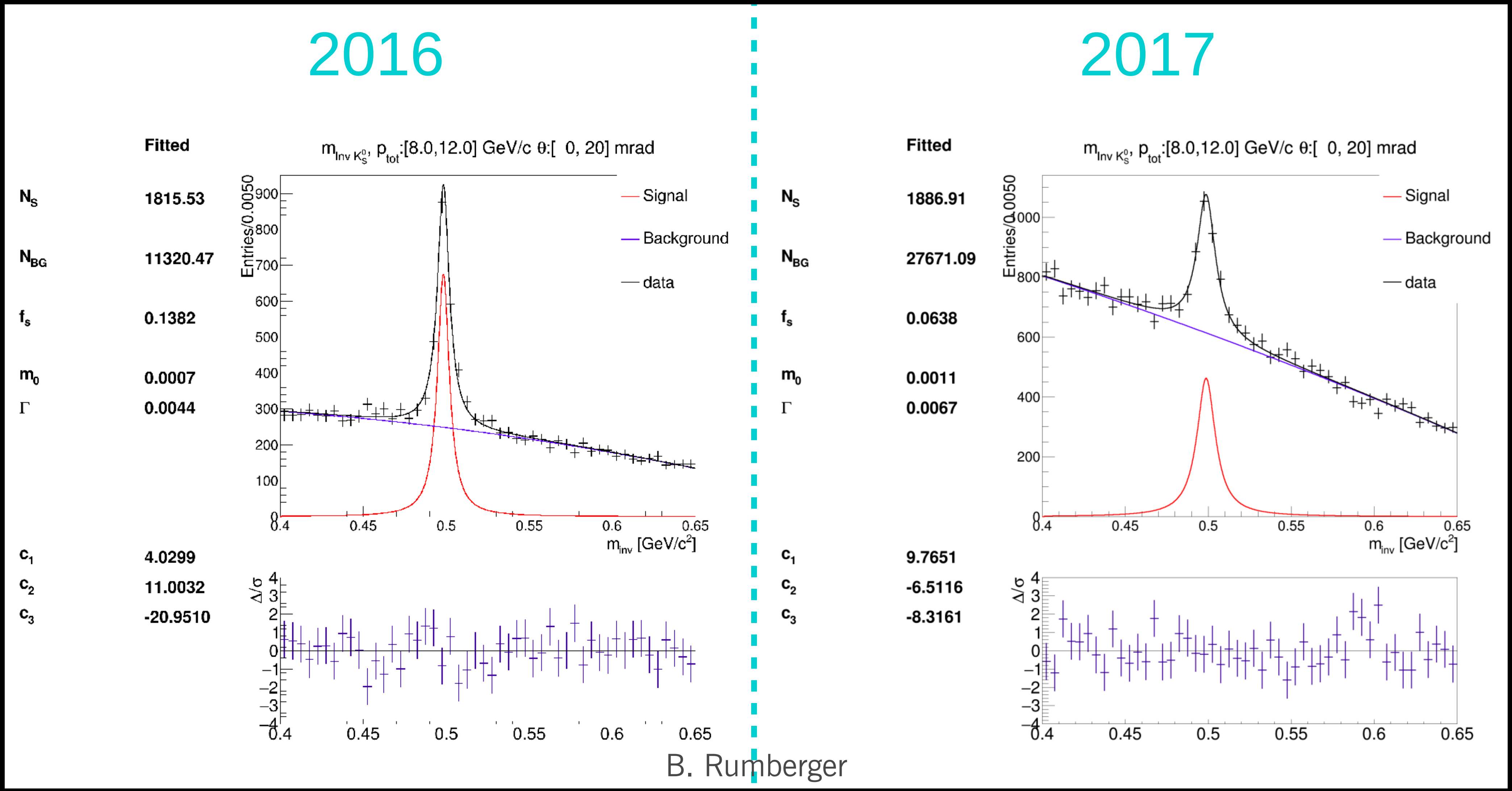
$$\alpha \equiv \frac{p_L^+ - p_L^-}{p_L^+ + p_L^-}$$

Results on spectra from thin-target p+C @ 120 GeV

- This data set is high priority: represents the primary proton interaction in NuMI/NOvA/MINERvA.
- Relies on new Forward TPCs to provide forward acceptance (magnet doesn't bend beam-energy protons into the older TPCs) to see elastic, quasi-elastic events
- New tracking algorithm is used for integrating the FTPCs into the analysis:
    - Cellular automaton-based local tracking with Kalman filter for global track fit
    - Superior identification of V^0 events
- Charged and neutral particle yields from ~3 million interactions



K^0_S invariant mass fits

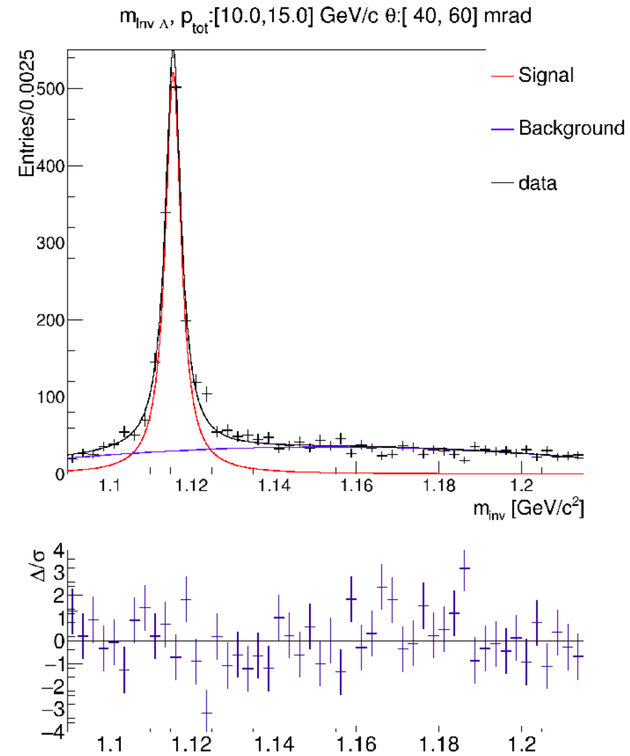


- Single kinematic bin shown
- 2016: Higher magnetic field, no forward TPCs
- 2017: Lower magnetic field, full forward TPC system

Λ^0

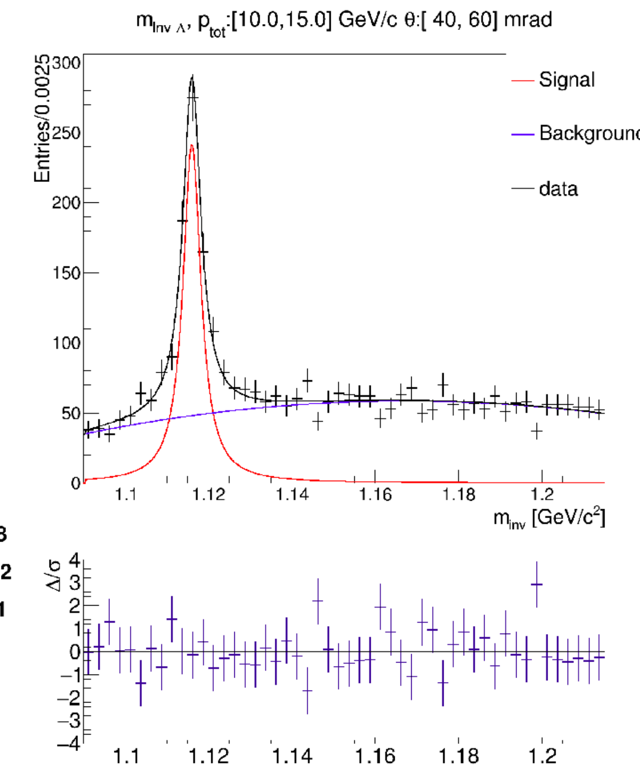
2016

Fitted	
N_S	1456.88
N_{BG}	1518.12
f_s	0.4897
m_0	0.0000
Γ	0.0023
c_1	-631.3202
c_2	1103.4291
c_3	-478.7071



2017

Fitted	
N_S	761.65
N_{BG}	2623.35
f_s	0.2250
m_0	0.0004
Γ	0.0026
c_1	-750.6588
c_2	1300.2512
c_3	-556.9631

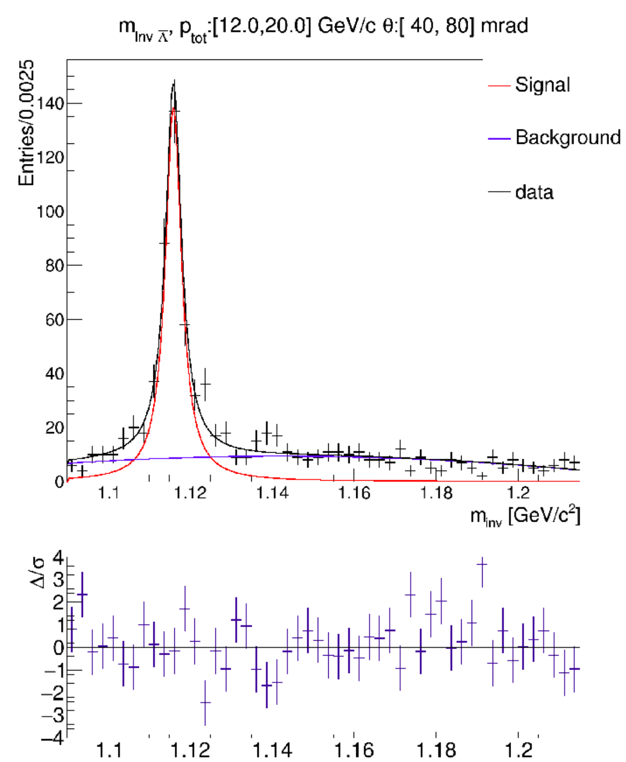


B. Rumberger

$\bar{\Lambda}^0$

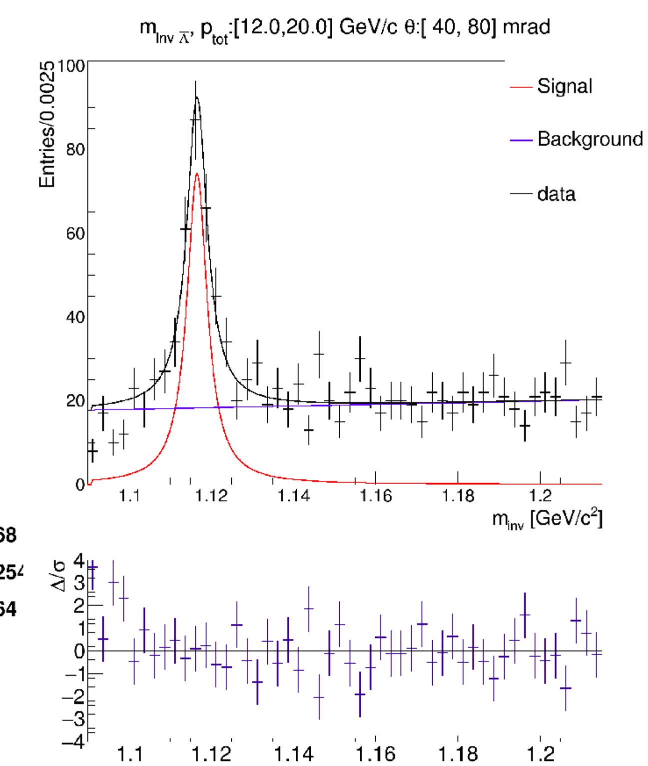
2016

Fitted	
N_S	401.00
N_{BG}	401.00
f_s	0.5000
m_0	0.0004
Γ	0.0024
c_1	-925.8070
c_2	1633.0437
c_3	-714.8490



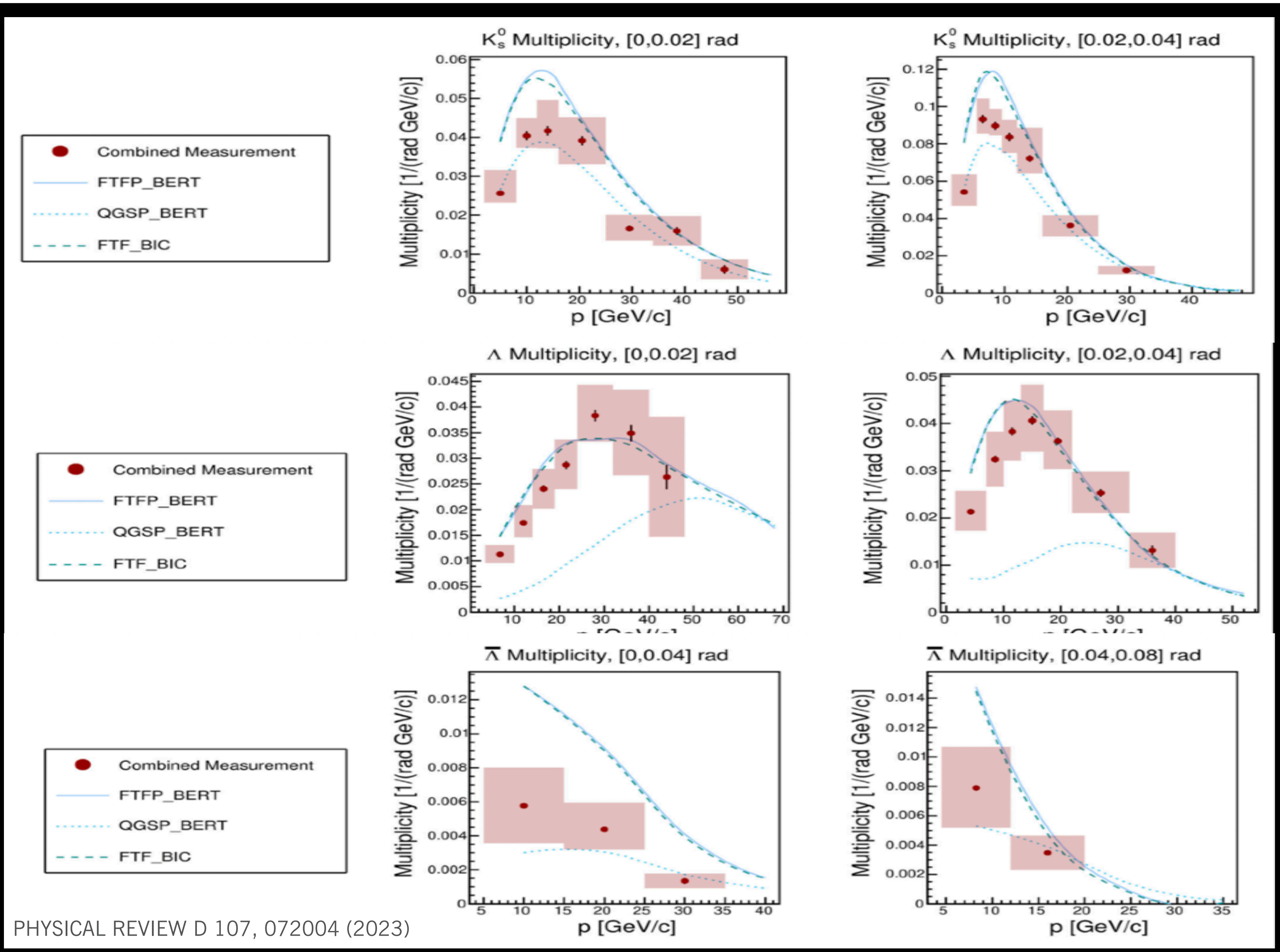
2017

Fitted	
N_S	268.42
N_{BG}	948.58
f_s	0.2206
m_0	0.0010
Γ	0.0030
c_1	6816.5868
c_2	11109.425
c_3	9598.0664



B. Rumberger

Multiplicity measurements published 2023

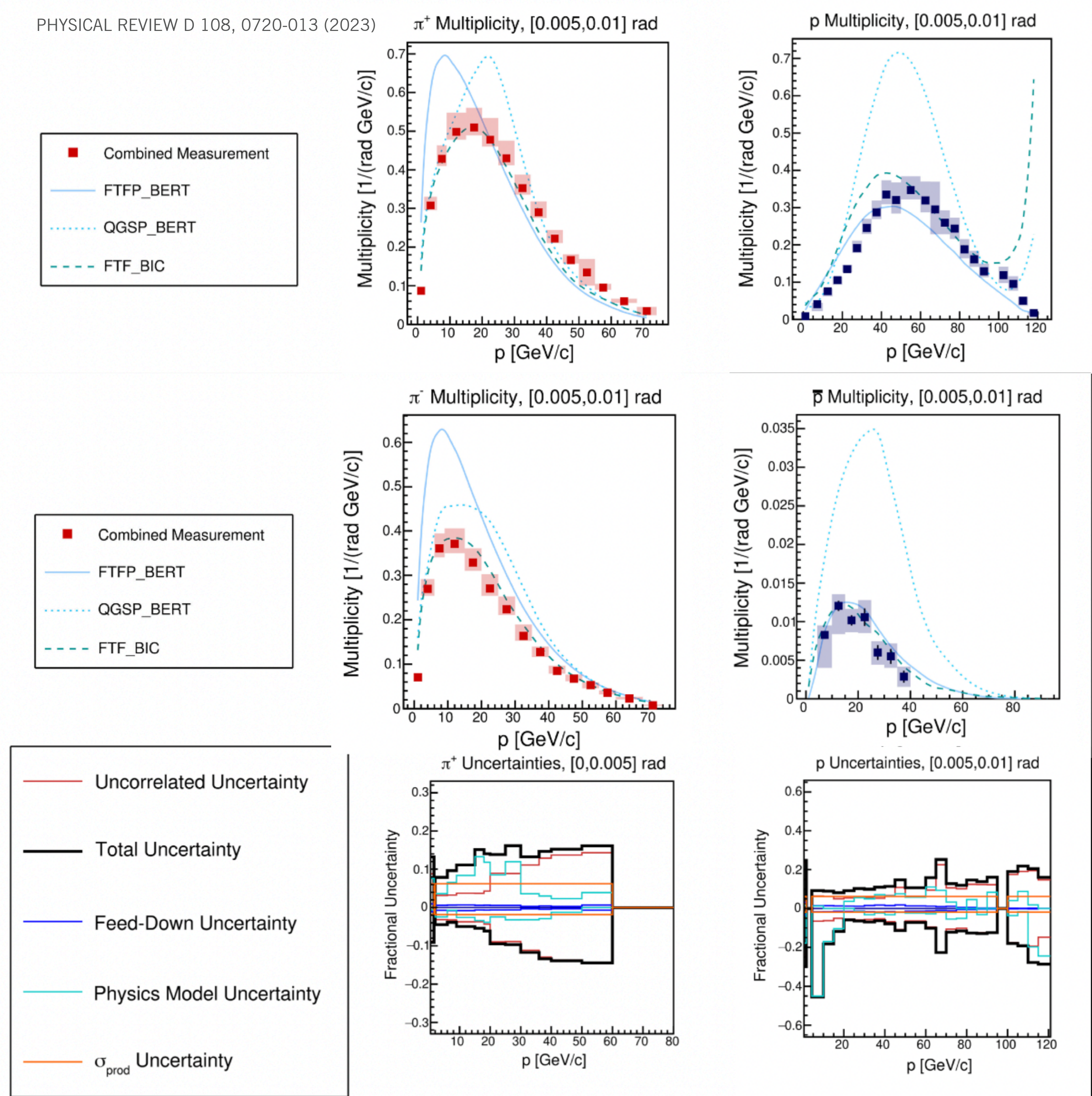


PHYSICAL REVIEW D 107, 072004 (2023)

- 2016 and 2017 combined to optimize resolution while increasing phase space coverage

p+C @ 120 GeV Charged hadron multiplicities: published 2023

- Measured multiplicities: π^+, π^-, p, $\bar{p}$, K^+, K^-
- Neutral hadron multiplicities used to estimate backgrounds from with weak neutral decay products
- Two complementary data sets again combined for final multiplicity result
- Results will soon be used to reduce DUNE beam flux uncertainties
- 2016, 2017 data sets combined



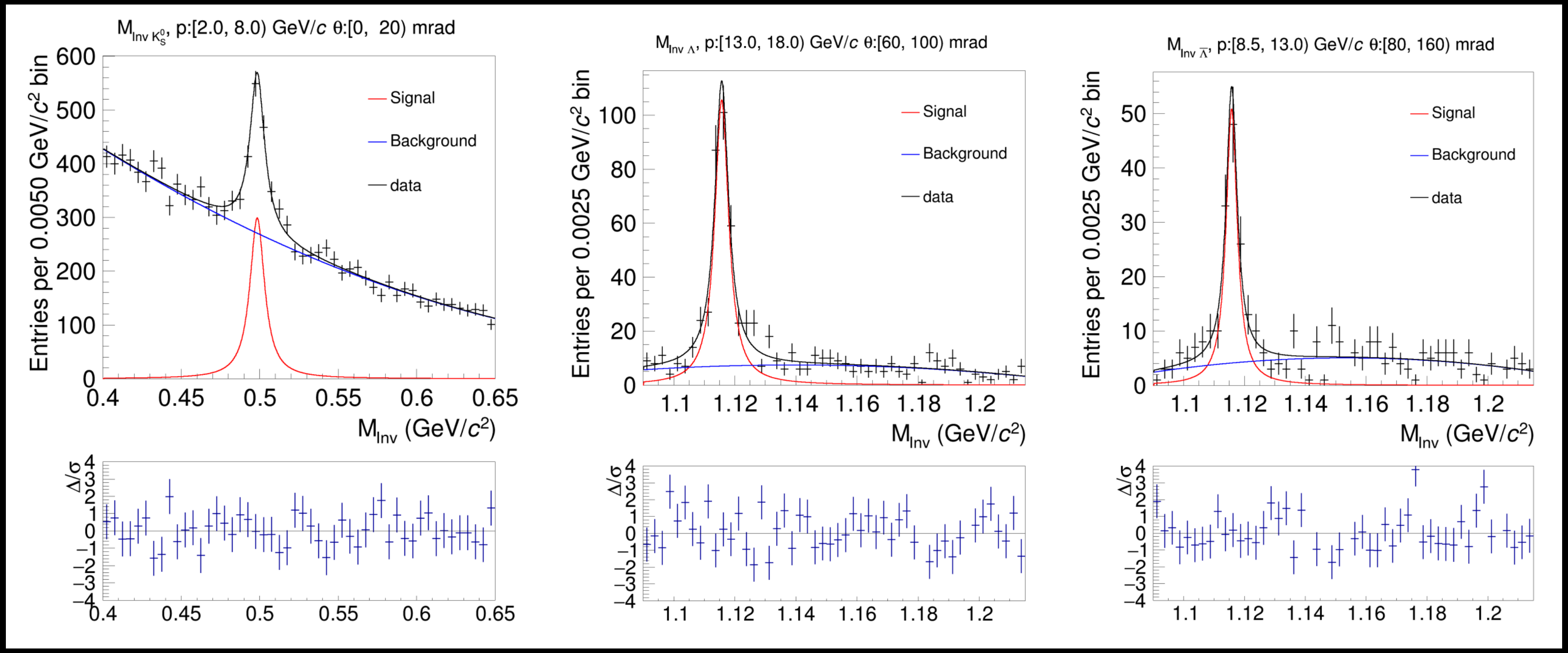
Intermediate energy interactions

- 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 published: *Phys.Rev.D* 112 012011 (2025)
- 60 GeV/*c* analysis is at an advanced stage, preliminary release of neutral yields; charged soon

p+C 90 GeV/c

- Newest NA61 neutrino publication: *Phys.Rev.D* 112 012011 (2025)
- Differential multiplicities for the charged and neutral analysis of the p+C 90 GeV/*c* dataset

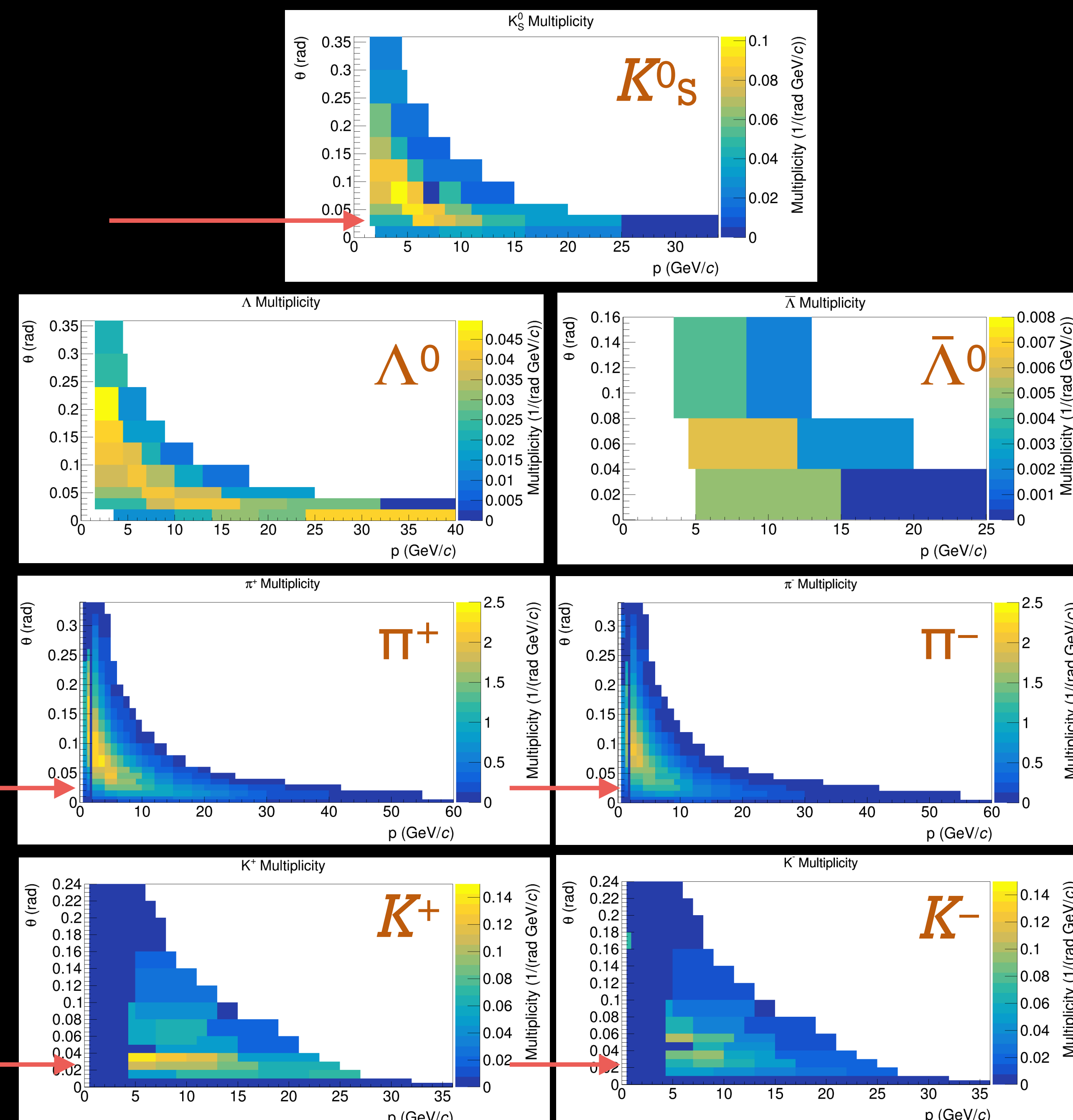
Invariant mass fits for reconstruction of K^0_S, Λ, $\bar{\Lambda}$



p+C 90 GeV/c

- Results on multiplicity of produced hadrons on thin carbon target

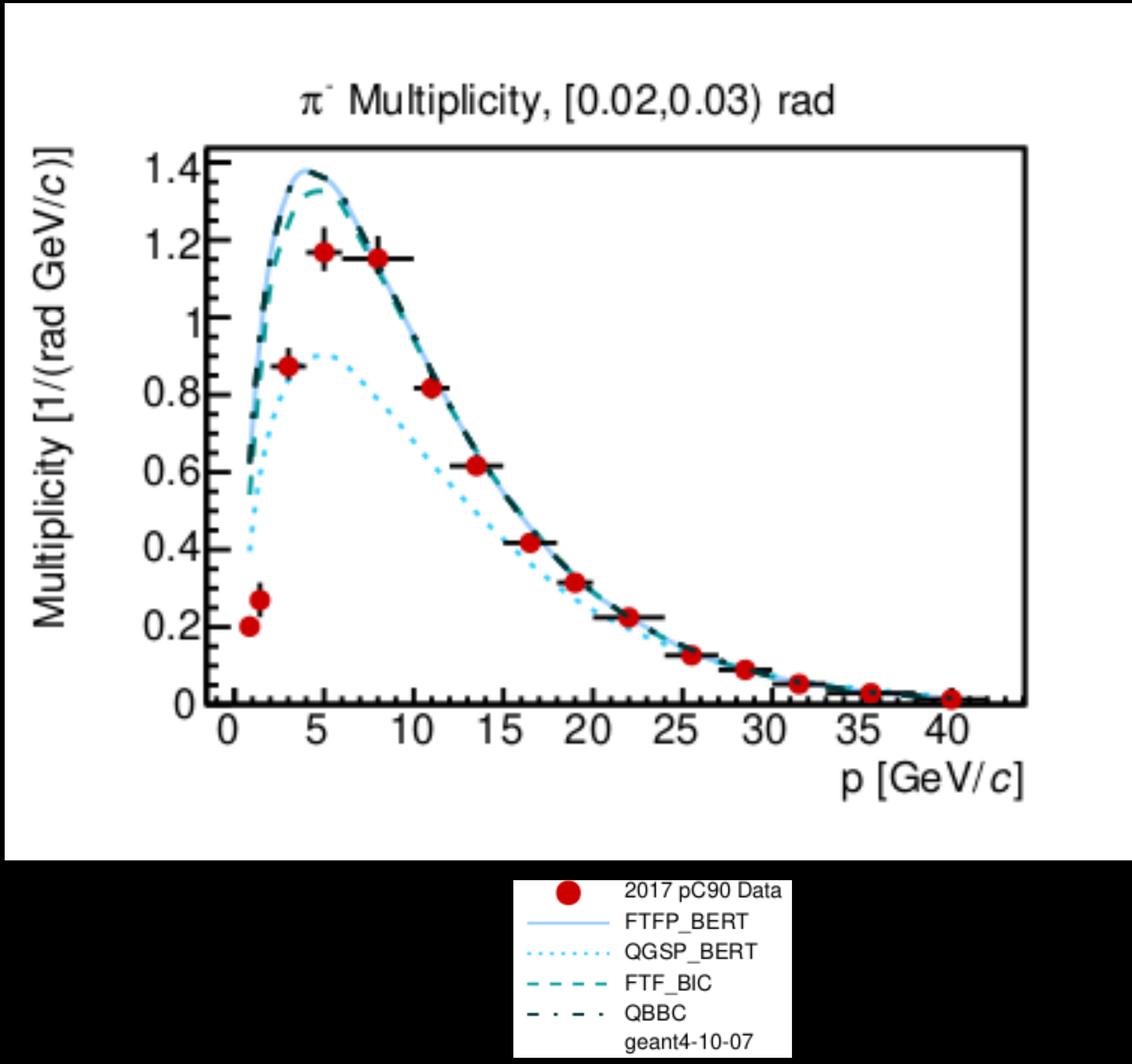
- Next: 1-D spectra with systematic errors for a specific angle bin



- *Phys.Rev.D* 112 012011 (2025)

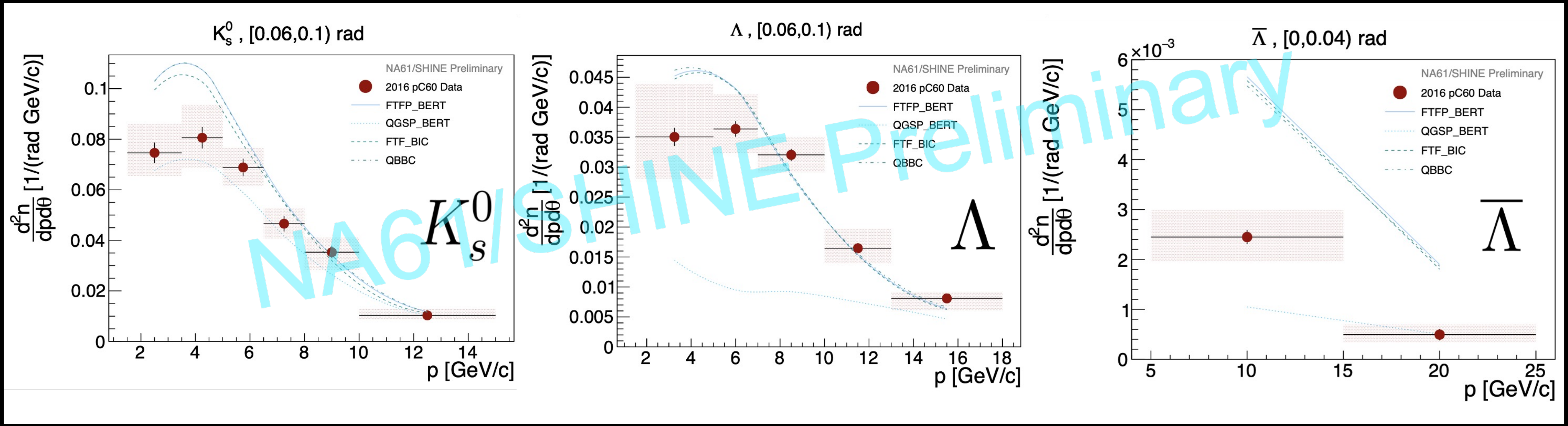
p+C 90 GeV/c

- 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, $\bar{\Lambda}$
- *Phys.Rev.D* 112 012011 (2025)



p+C 60 GeV/c

L. Ren, Lepton-Photon 2025



- New preliminary result on neutral hadron production
- Charged hadron production analysis underway

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
- Working on getting NA61/SHINE data into PPFX

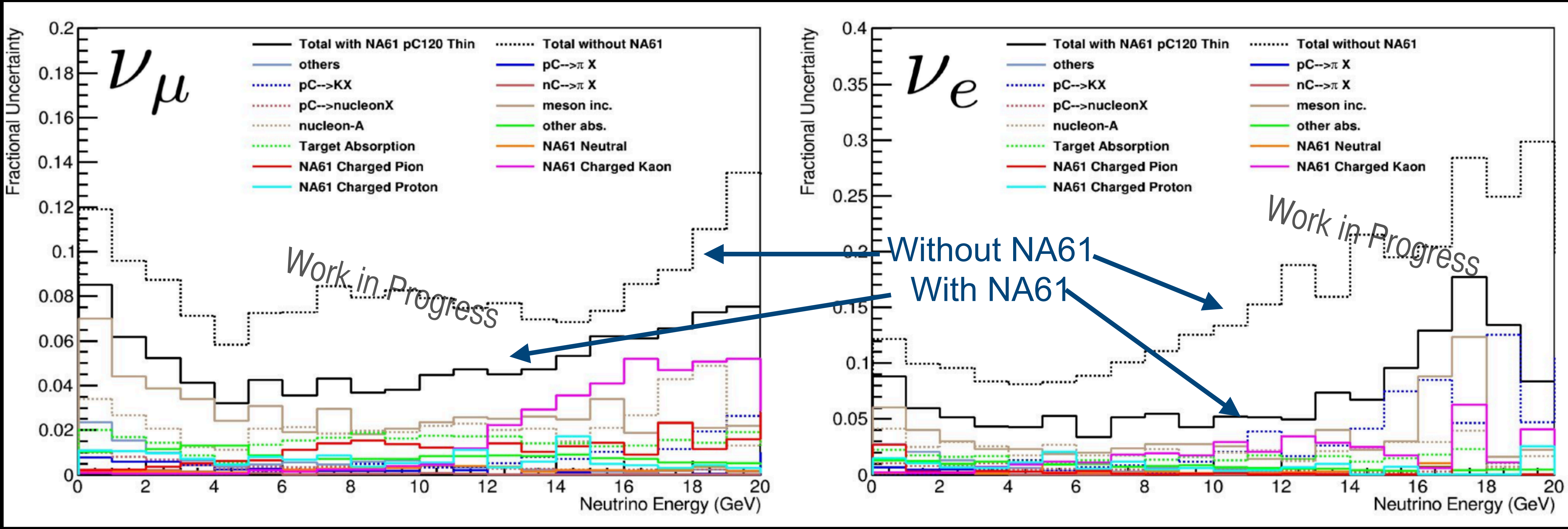
PPFX: Package to Predict FluX

L. Ren

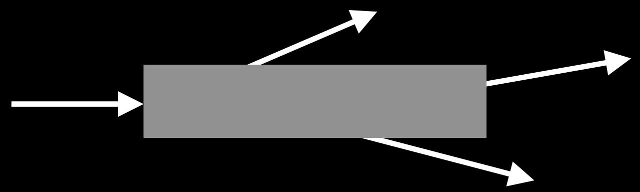
Total hadron production uncertainty includes:

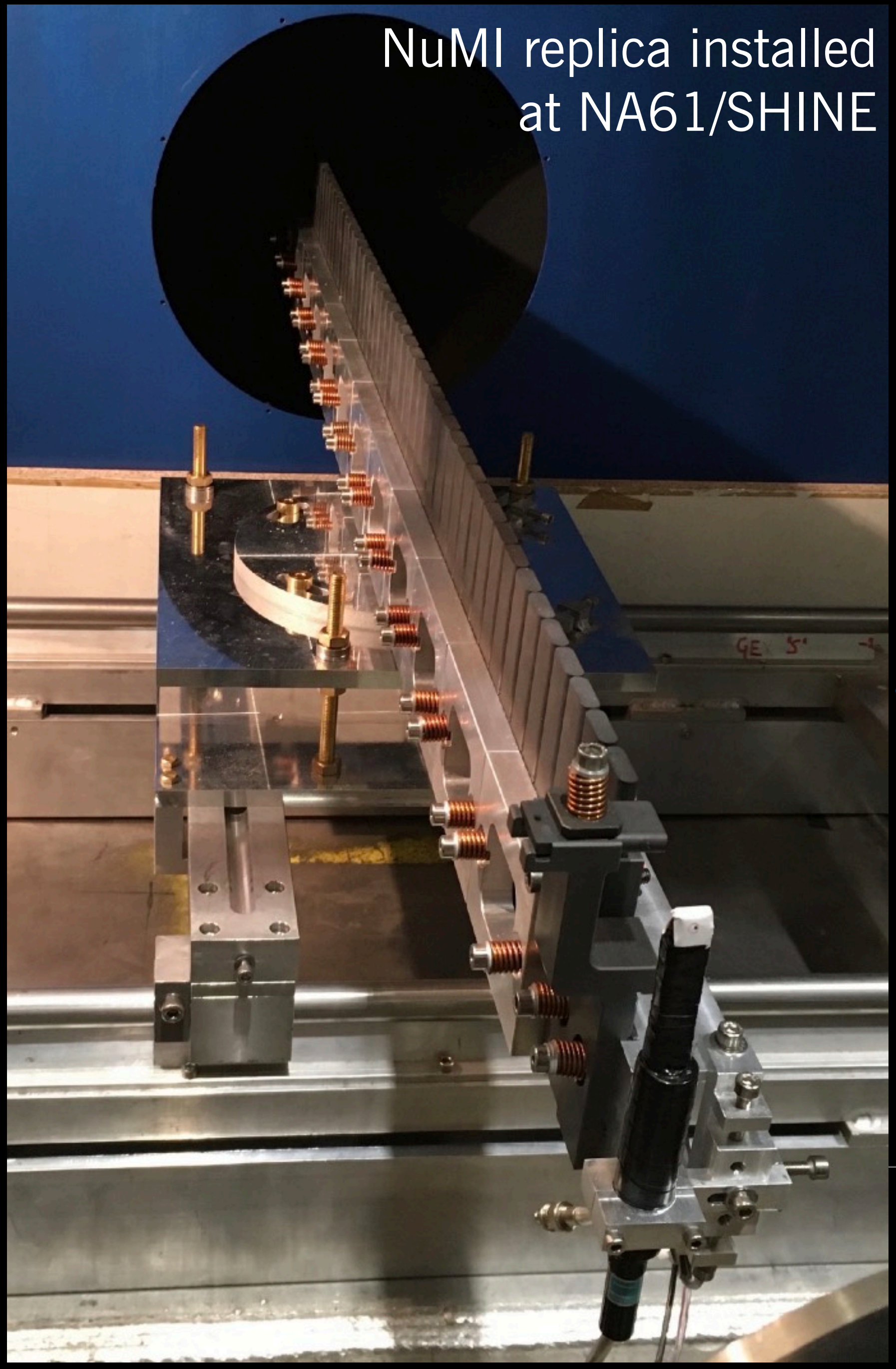
- Pion production (proton + carbon)
- Kaon production (proton + carbon)
- Pion production (neutron + carbon)
- Nucleon production (proton + carbon)
- Meson incident interactions
- Nucleon incident interactions
  - Absorption outside the target
  - Absorption inside the target
  - Others

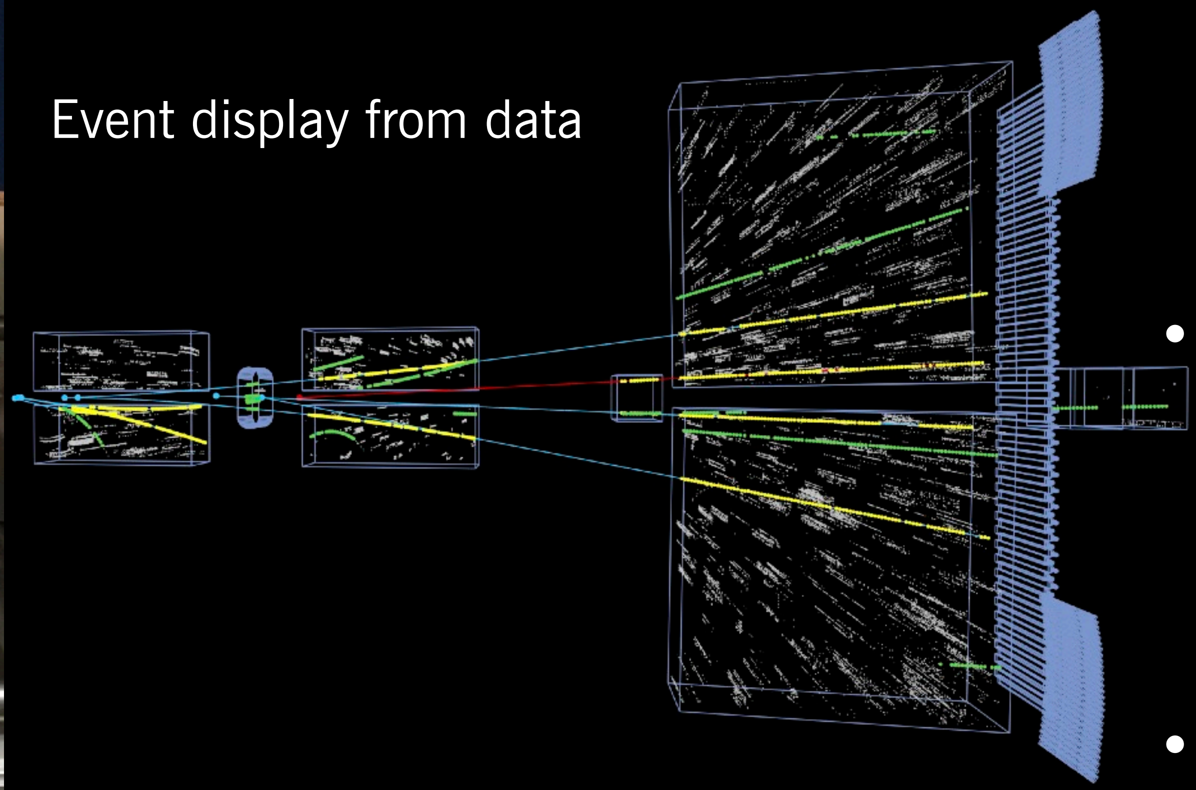
- NA61 p+C results can address the red items



Coming soon: measurements with NuMI replica target

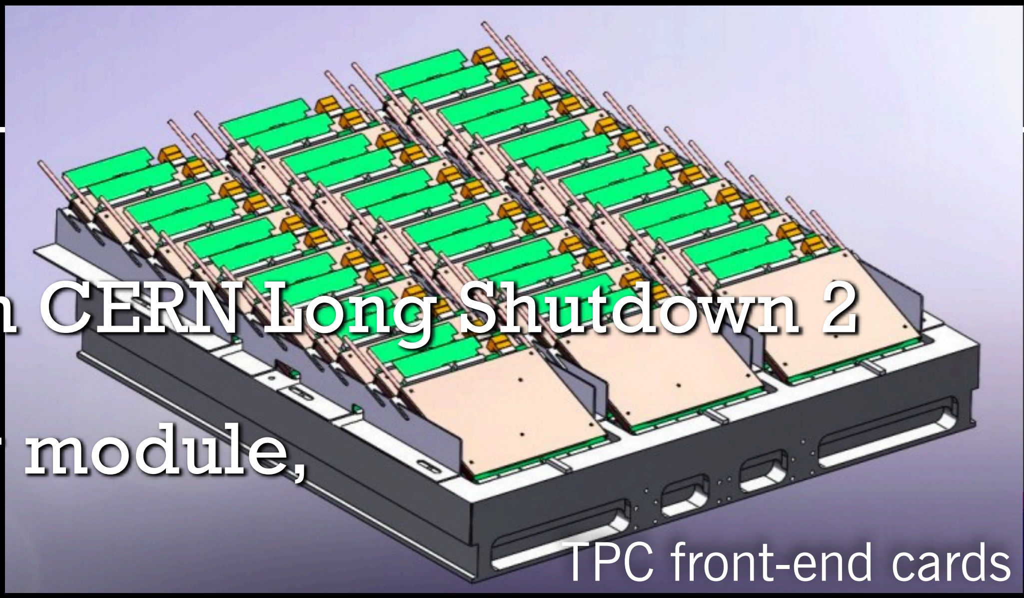






- Took high statistics (18M events) in 2018 with 120 GeV/c protons
- Analysis underway on hadron yields from this target
- Calibration in progress for this data set

Third phase: upgraded detector



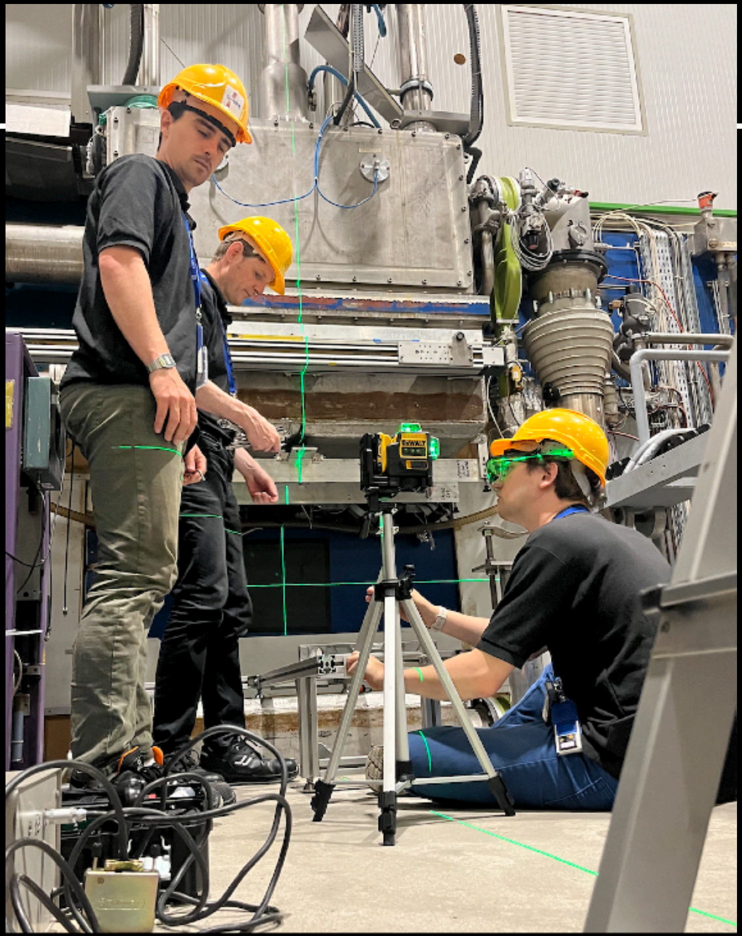
- Many major detector upgrades completed in CERN Long Shutdown 2
  - New forward Projectile Spectator Detector module, reconfiguration of existing detector
  - Replacement of old TPC electronics with system from ALICE
  - New silicon vertex detector for open charm studies
  - RPC-based replacement for TOF-L/R walls
  - New beam position detectors
  - New trigger/DAQ, combined with new electronics, will give a major upgrade in data collection rate (~100 Hz → ~1 kHz)

Data collection: Run 3

- 31 GeV/c protons on T2K replica-target: collected 180M events in 2022 (nearly 20x 2010 statistics) to measure high-momentum kaon yields
- Kaon scattering with thin targets for secondary interaction modeling. In 2023, took:
  - K+C @ 60GeV: 137.7 M
- Higher statistics at 120 GeV/c:
  - p + Ti @ 120 GeV: 111.7 M
  - p + C @ 120 GeV: 82.4 M

>20x the 2023 paper!

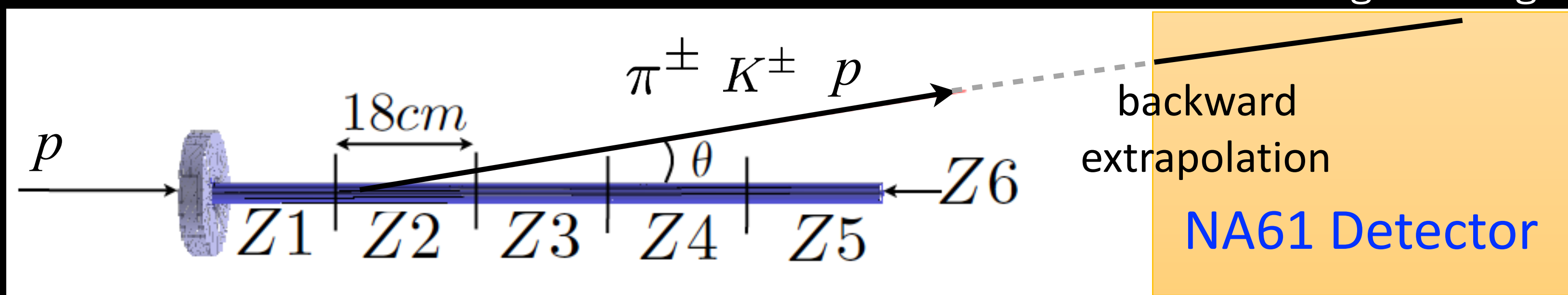
Data collection: Run 3



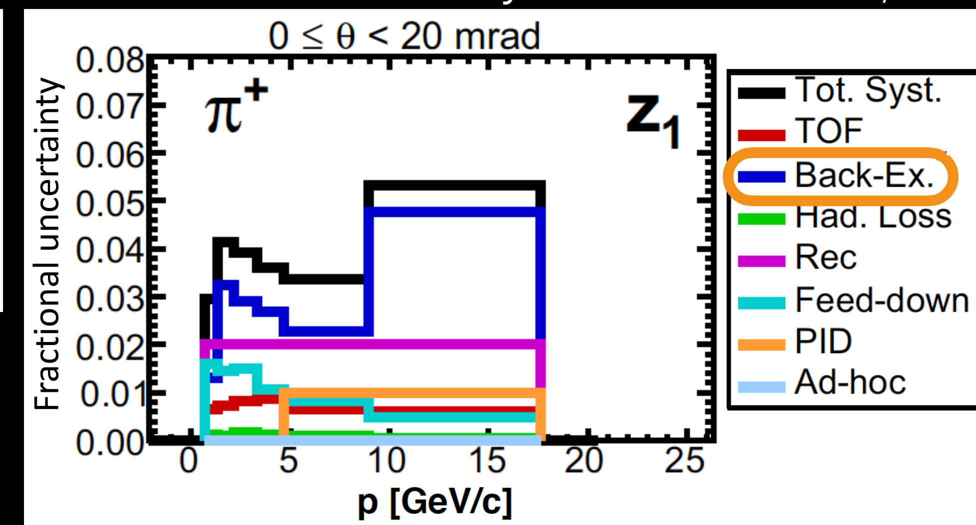
- LBNF/DUNE prototype target (2024-25)
- Target designed and built by RAL targetry group to expected dimensions of LBNF/DUNE target: 1.5 m long
- New TPC added to track particles exiting target
- Took 250M events summer 2024 with high-density IG510 graphite target
- Took 140M events summer 2025 with lower-density IG430 target

Long-target tracker

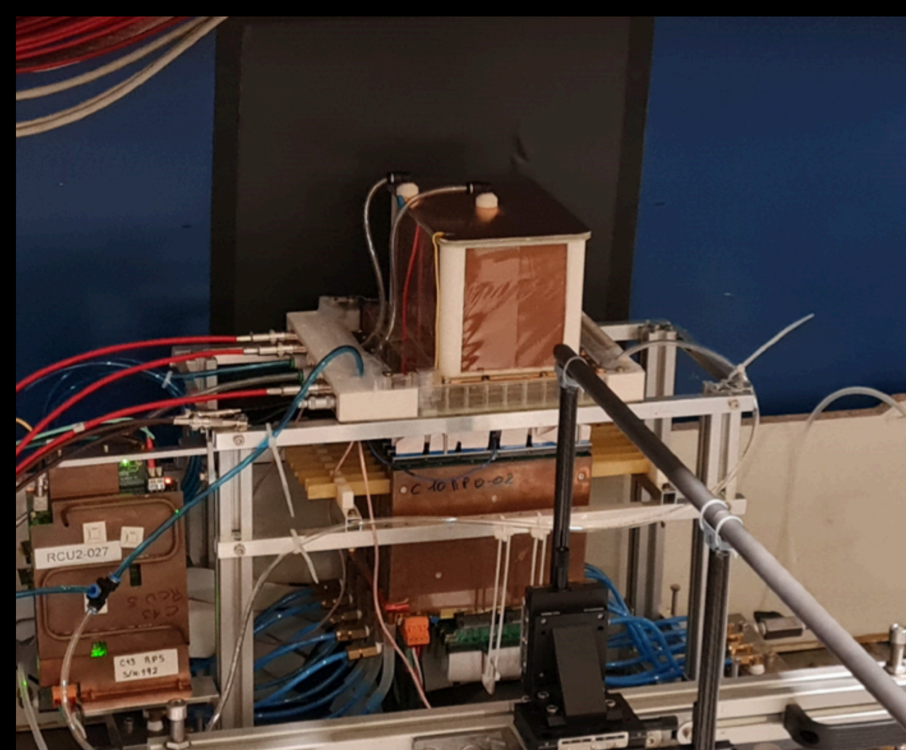
image: Y. Nagai

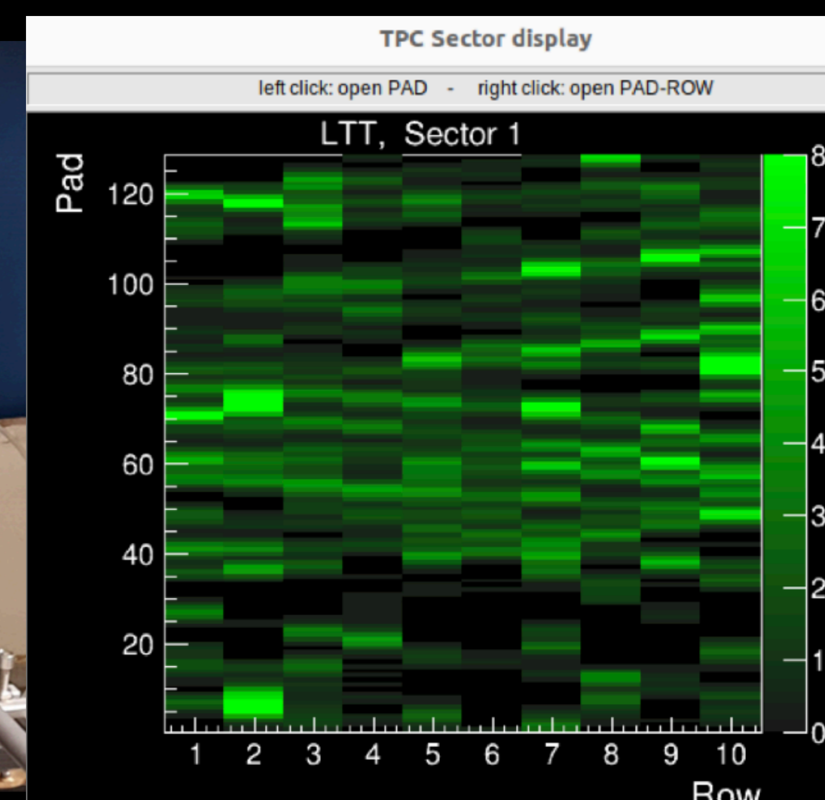


Eur.Phys.J.C 79 (2019) 2, 100



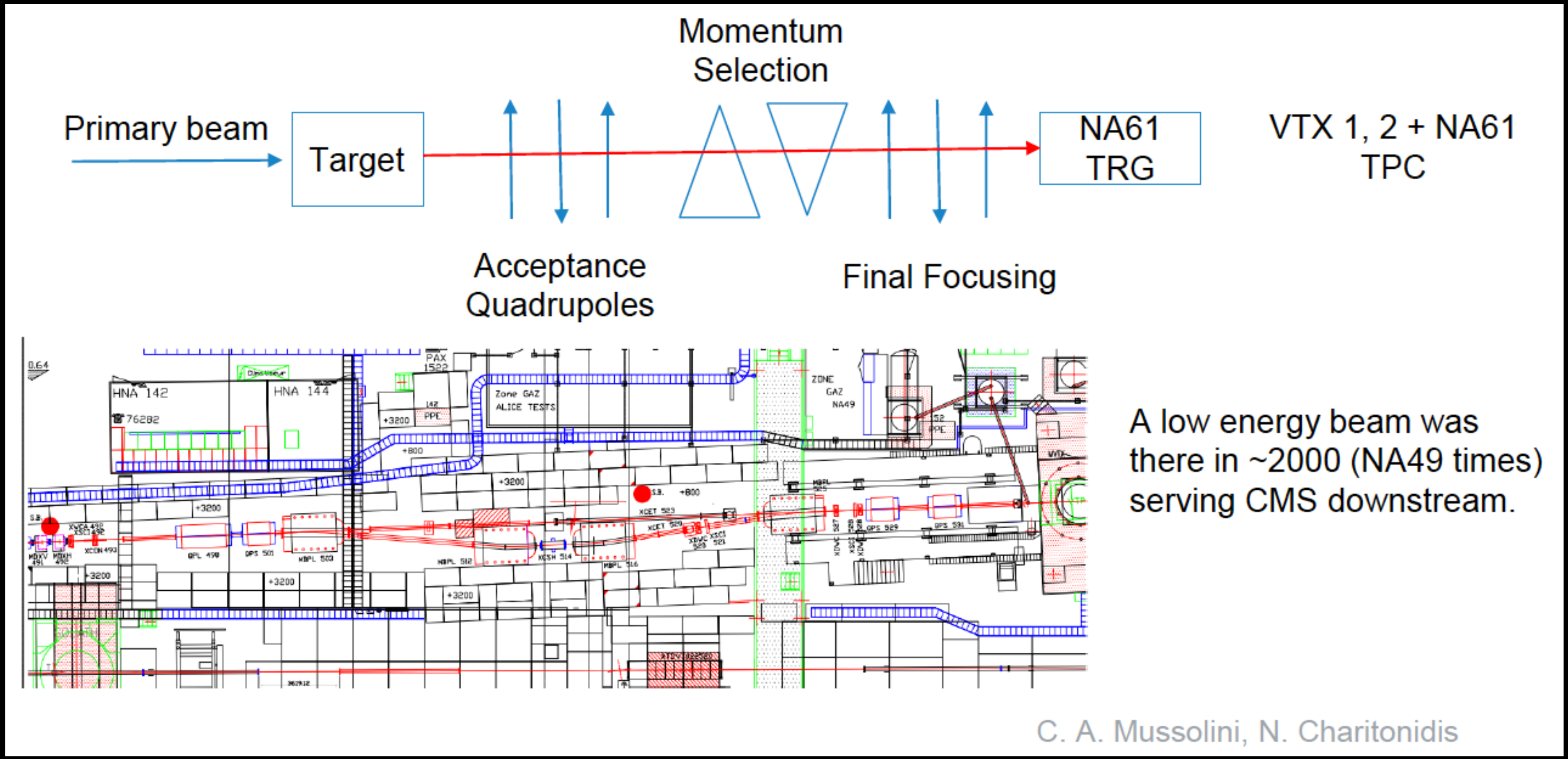
- A leading systematic error with the T2K replica target has been extrapolation of shallow-angle tracks backward to the target surface
- Additional small TPC built at KFKI/Wigner in Budapest
    - Sits at the end of the target to measure exit point of tracks more precisely





Future after Run 3: 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…



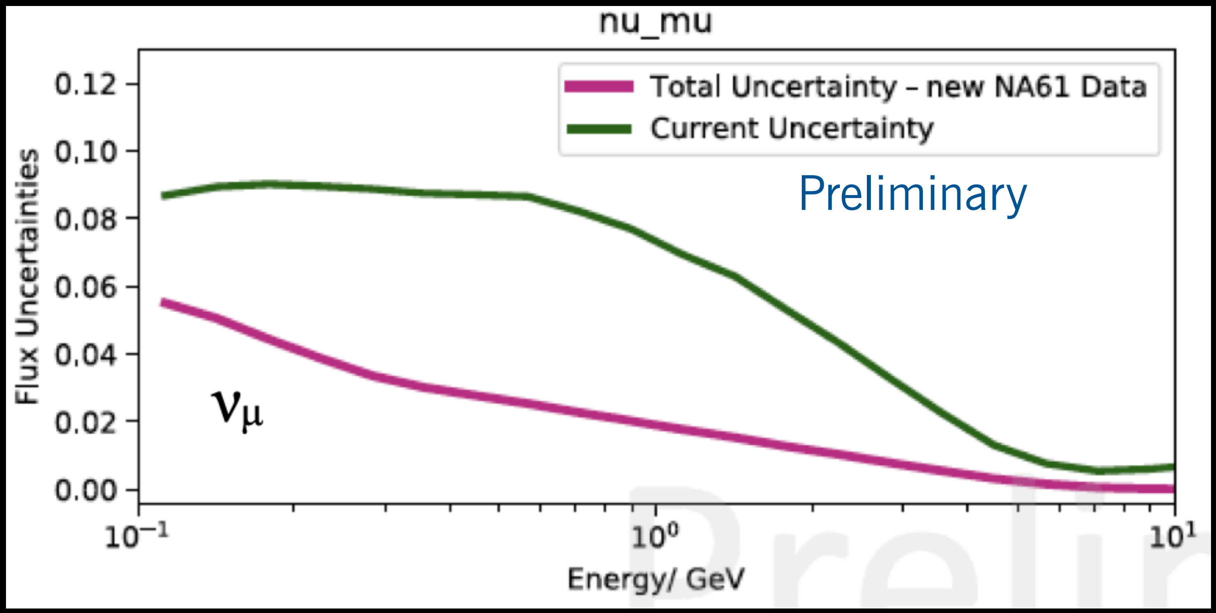
Design by C. Mussolini and N. Charitonidis

- New beam design by CERN beam group in collaboration with NA61/SHINE.
- Existing beam will remain available with easy changeover, so future replica-target and other high-energy measurement capability would be preserved

Physics cases for the low-energy beam

- Atmospheric neutrino flux uncertainties rather large at present in the energy range around 1 GeV
- Much of this is due to hadron cross-section uncertainties
- A program of precise measurements with 3-20 GeV/c beams on nitrogen could make major improvements in flux (factor of >2)
- Can not only improve oscillation measurements but also background estimates for exotic processes in DUNE, Hyper-K.

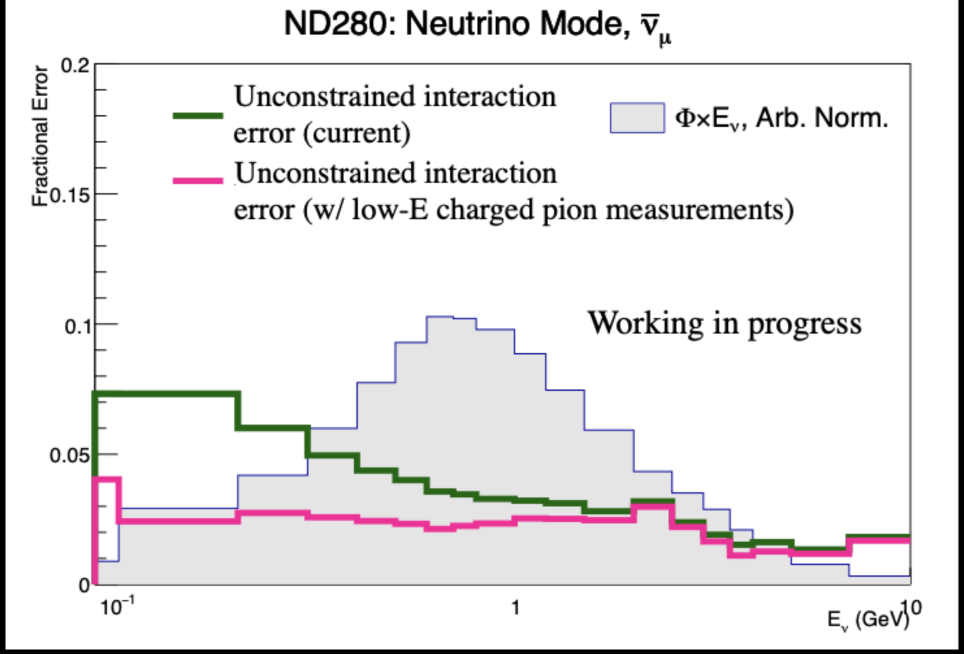
L. Cook (Bartol Group) atmospheric neutrino flux



Physics cases for the low-energy beam

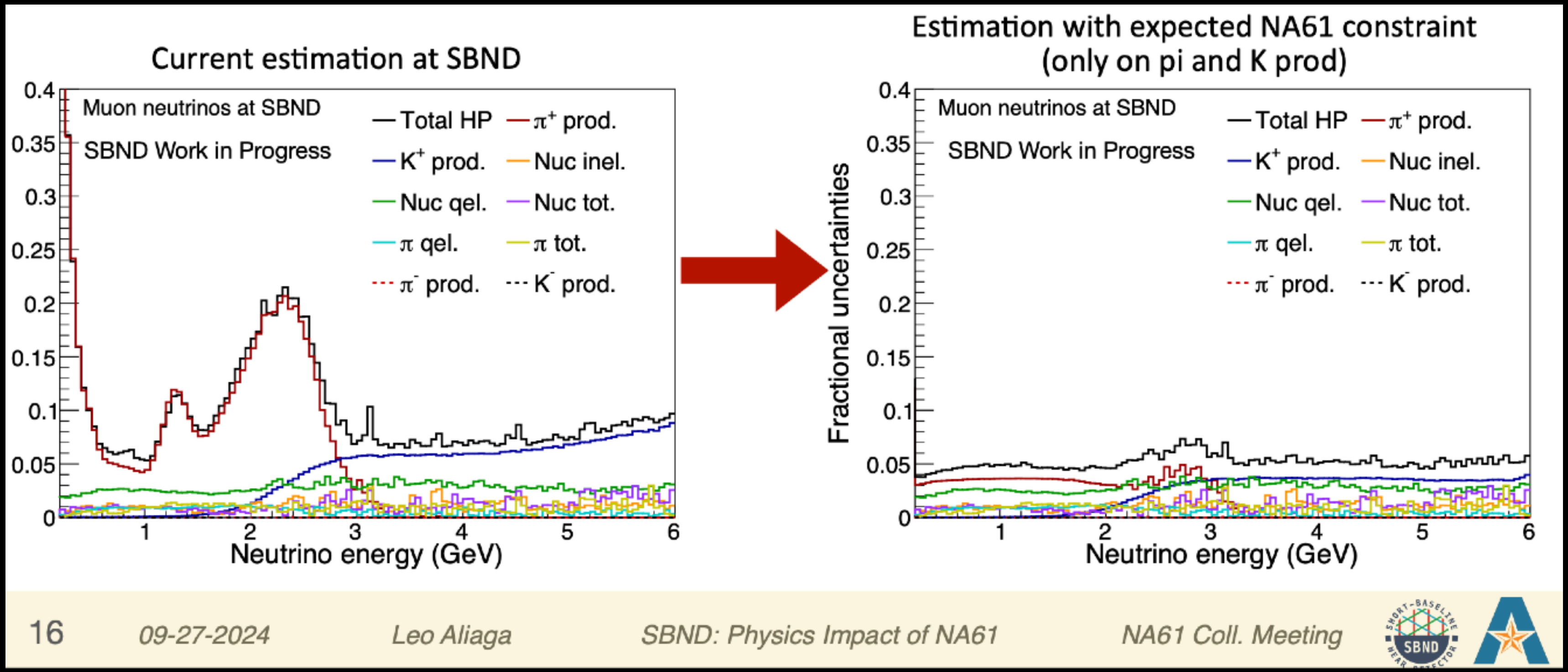
- T2K/HyperK secondary interactions
  - Wrong-sign neutrinos are a serious issue
  - Secondary interactions outside the target are responsible for much of this
  - These interactions can be studied with low-energy proton and pion beams
- DUNE low-energy secondary interactions can also benefit from these measurements

T2K/HyperK wrong-sign flux uncertainties



Physics cases for the low-energy beam

- Short-baseline neutrino beam at Fermilab uses 8.9 GeV/*c* protons on a beryllium target
- Still relies on HARP measurements which have significant errors
- Can be significantly improved with new measurements
- Direct improvement to cross-sections needed by DUNE

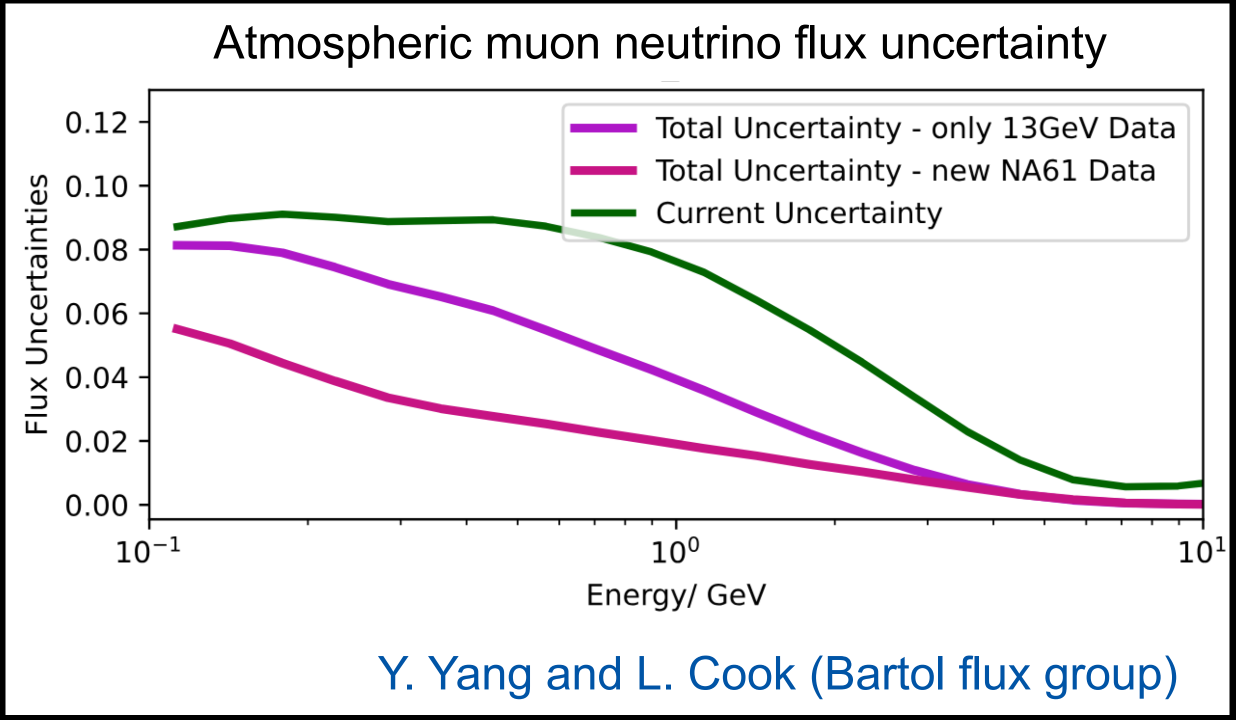


Status of the low-energy beam project

- Beam development approval/funding process is still underway
- Letter from 11 collaborations submitted to CERN in November 2024
- Strong support in European Strategy for Particle Physics process
- CERN management requested submissions to SPSC for additional physics review
- Hoping for approval in the next several months for construction during/just after coming Long Shutdown 3

New opportunity: intermediate energy program

- Low-energy beam operation can't begin until after Long Shutdown 3 (2029 at earliest)
- Current beam can go down to ~15 GeV with reasonable quality and usable proton yield
- Data will be collected at this lowest energy in 2026 as a first step toward low-energy program
- Major goal is improvement to the atmospheric flux in the 1 GeV region
- Liquid nitrogen target under construction in Japan for this measurement (and for Run 4)
- Potential for *p*+Be data for BNB flux (reduce momentum scaling need)



NA61/SHINE++ Opportunities beyond 2025

- Interested in **low-energy data** at NA61/SHINE?
  - Or in other possible new beam/target combinations? Current beam will still be available.
- Open workshop "NA61++/SHINE: Physics Opportunities from Ions to Pions" — we are still looking for new ideas and new people
- *INDICO: https://indico.cern.ch/event/1174830/*

- Atmospheric neutrino flux
- T2K/HK beam-related physics
- DUNE beam-related physics

- Booster Neutrino Beam
- New target materials
- COMET
- JSNS2

and much more!

Our critical need: people!

- None of these programs is possible without physicist effort!
- Already short of people to work on analysis of existing data sets since last upgrade greatly increased physics reach
- Anyone can join with full access to data, and physics analyses can be started right away. Many opportunities highly relevant for DUNE, T2K/HK
  - Enormous data sets on 120 GeV p+C p+Ti, or K^++C, replica target… are waiting for you!
  - New atmospheric neutrino data sets to be collected this year

Conclusions

- NA61/SHINE has provided unique and critical data to support the global neutrino program
- More data sets coming, including prototype LBNF/DUNE targets
- Low-energy beam and other future programs under study.
- Critical needs for the future program: new people/institutions to join the collaboration to work on these topics.

Thanks on behalf of the NA61/ SHINE Collaboration

Speaker supported by US Department of Energy