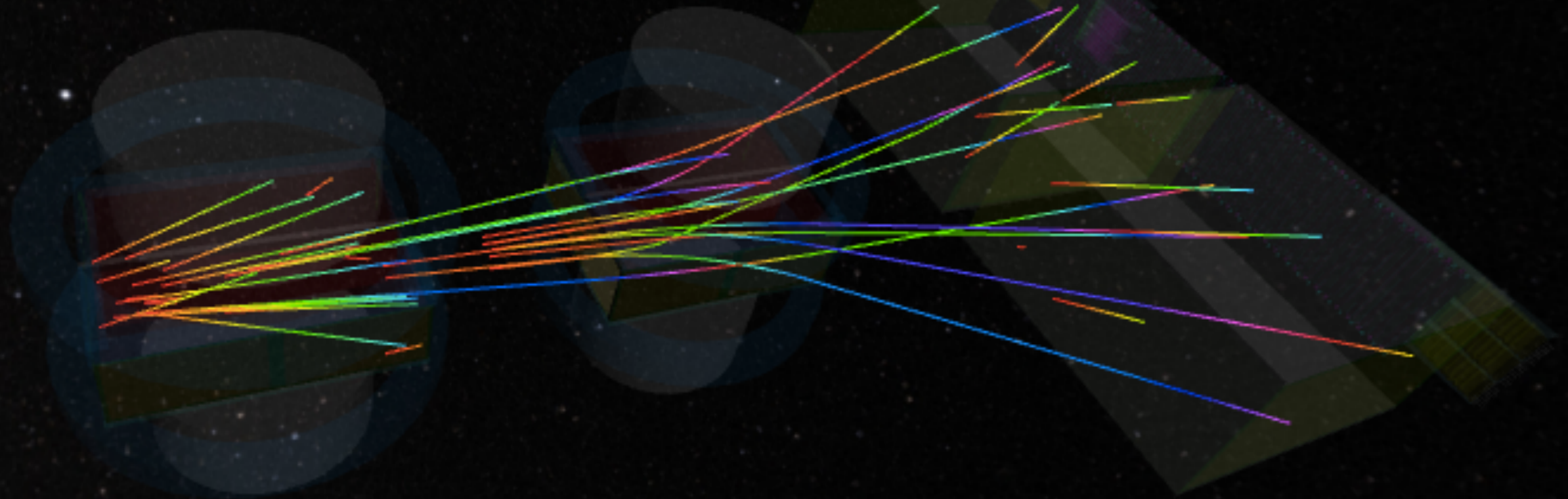# OVERVIEW OF HADRON PRODUCTION MEASUREMENTS FOR NEUTRINO EXPERIMENTS

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NA61/SHINE Beyond 2020 Workshop
University of Geneva
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OUTLINE

➤ Why hadron production measurements?

➤ In Situ Flux Measurement Strategies

➤ Overview of external data in various momentum ranges

   ➤ Data below 18 GeV/c

   ➤ Around 31 GeV/c

   ➤ Around 60-160 GeV/c

➤ What more is needed?

# WHY DO WE NEED HADRON PRODUCTION MEASUREMENTS?

➤ Important to **understand neutrino source** when making measurements using neutrinos for measurements of **flavor oscillation** and **neutrino interaction physics**

➤ For **atmospheric neutrinos** and **accelerator-based neutrino sources** the processes leading to neutrino production are complex and often not very well-modeled by MC
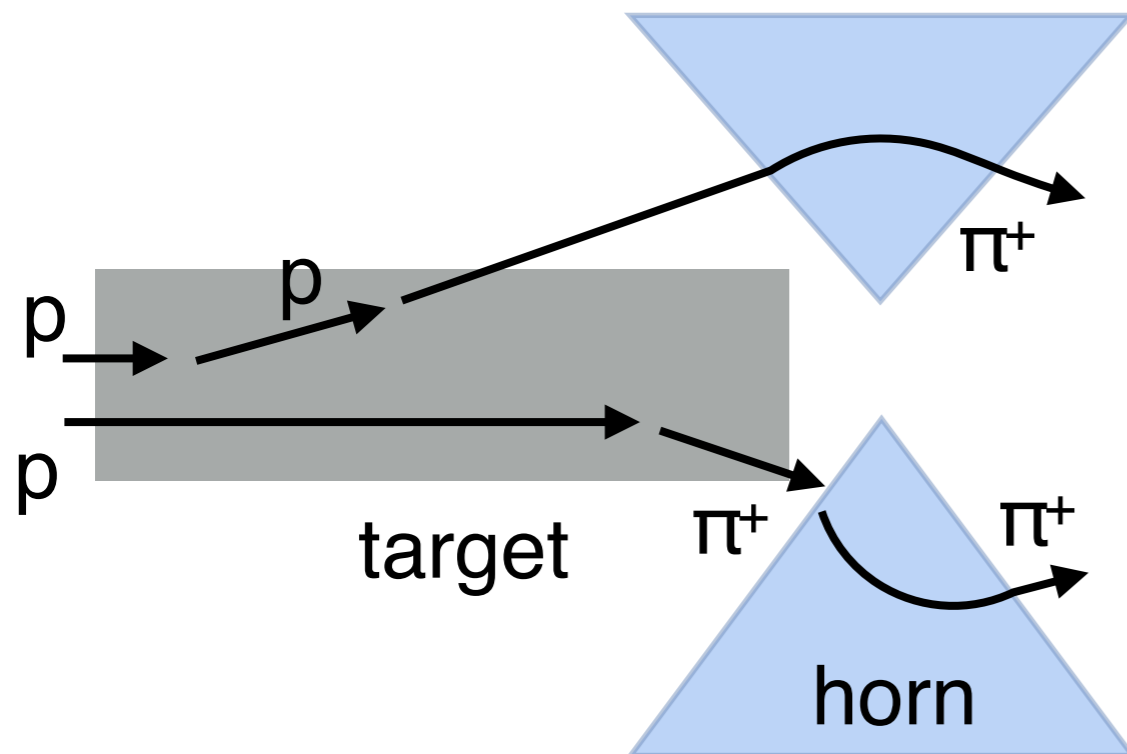

NA61 π^+ Weights/MC
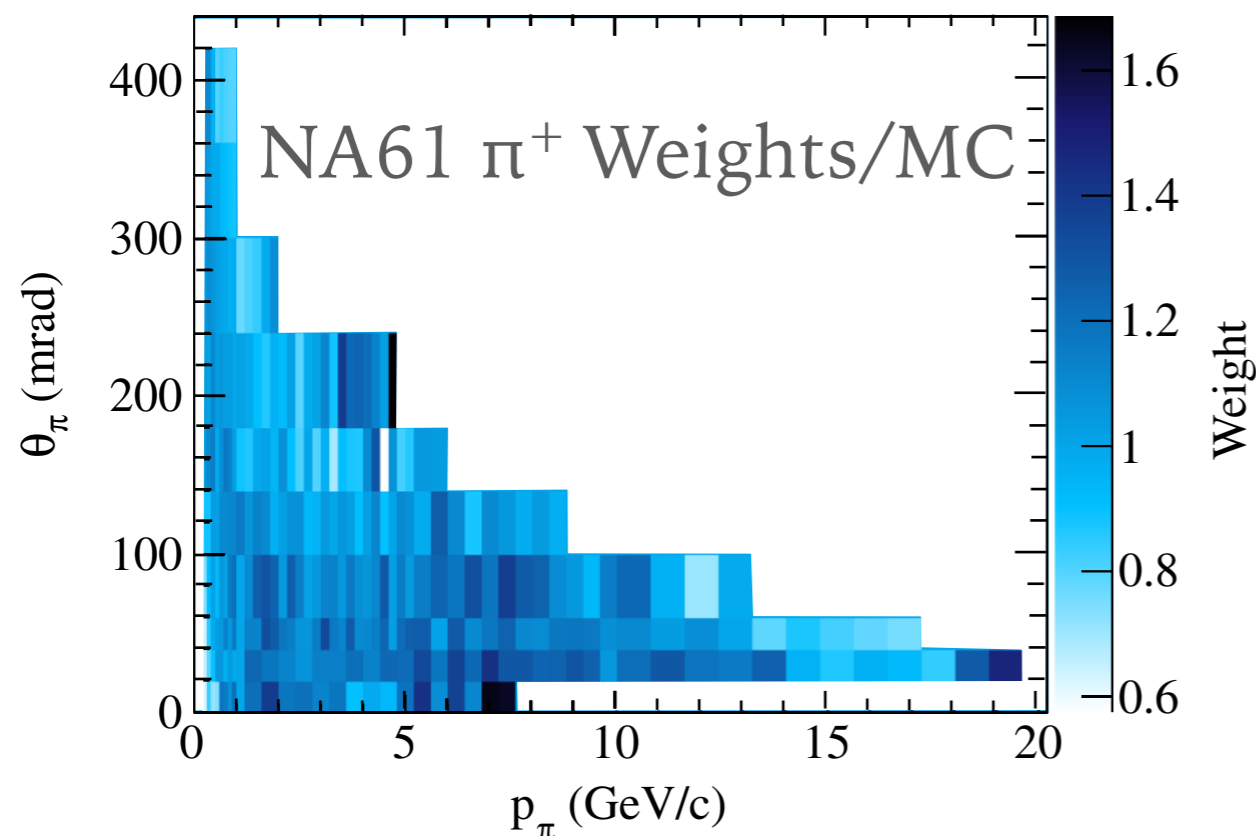
An example of hadron production predictions for T2K at left. Data disagrees with MC by 30% or more in some regions.

CURRENT AND FUTURE ACCELERATOR-GENERATED NEUTRINO BEAMS

➤ Initiated by protons with energies from 8 GeV to 120 GeV

➤ Previously CNGS beamline ran with 400 GeV protons
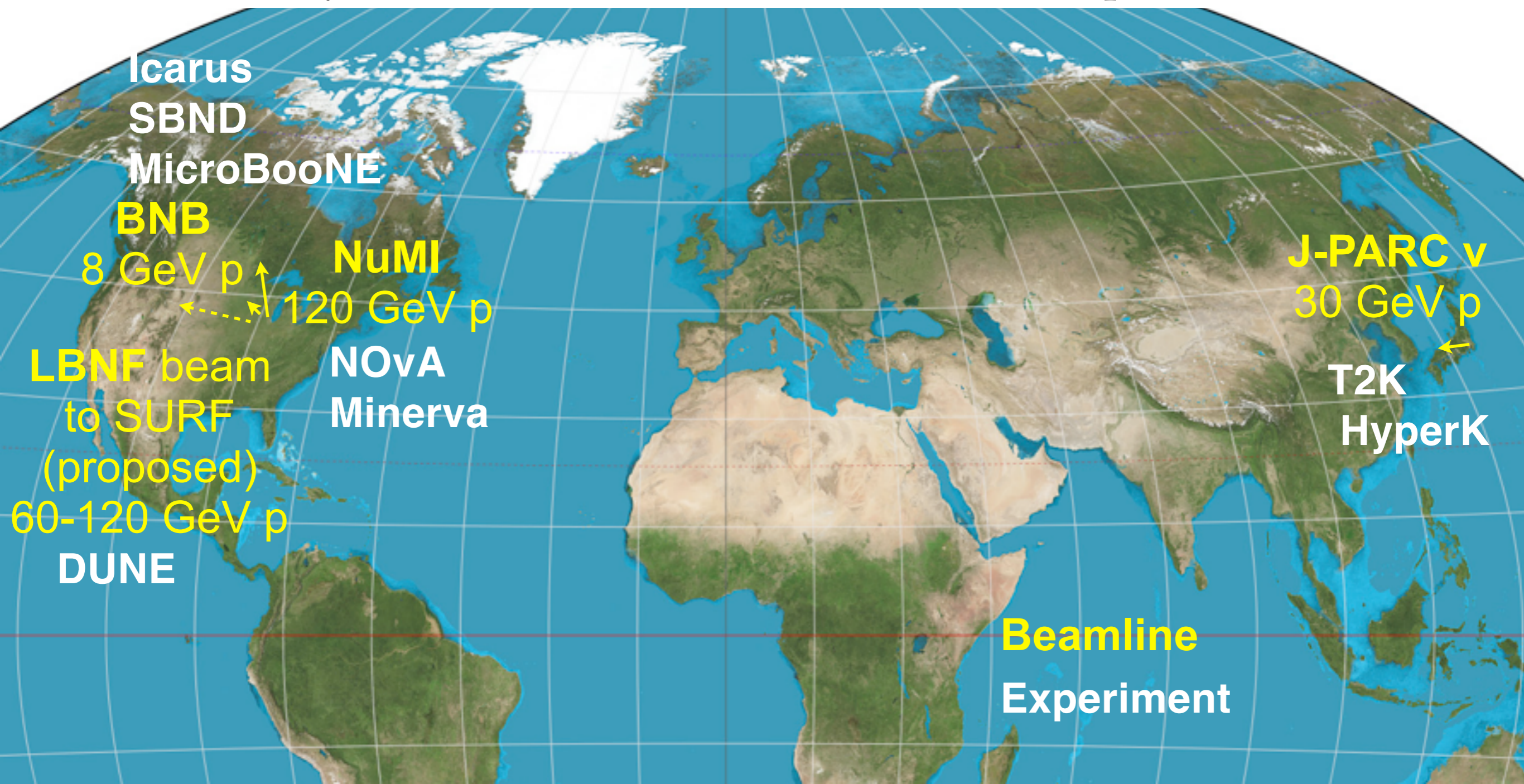
NEUTRINO PRODUCTION

Neutrino Parents in T2K

|	Flux percentage of each (all) flavor(s)			
Parent	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
Secondary				
$\pi^\pm$	60.0(55.6)%	41.8(2.5)%	31.9(0.4)%	2.8(0.0)%
$K^\pm$	4.0(3.7)%	4.3(0.3)%	26.9(0.3)%	11.3(0.0)%
K^0_L	0.1(0.1)%	0.9(0.1)%	7.6(0.1)%	49.0(0.1)%
Tertiary				
$\pi^\pm$	34.4(31.9)%	50.0(3.0)%	20.4(0.2)%	6.6(0.0)%
$K^\pm$	1.4(1.3)%	2.6(0.2)%	10.0(0.1)%	8.8(0.0)%
K^0_L	0.0(0.0)%	0.4(0.1)%	3.2(0.0)%	21.3(0.0)%

Phys Rev D **87** 012001 (2013)

➤ Secondary and tertiary interactions are also often significant, so ideally want **not just primary proton** data, but also thick target data and lower energy hadron data to constrain reinteractions

HADRON PRODUCTION MEASUREMENT STRATEGIES

➤ **In Situ** measurements

  ➤ Several strategies have been employed in accelerator-generated neutrino beams

  ➤ Can involve very challenging detector environment!

➤ **External hadron production** measurements

  ➤ Useful for both accelerator-generated neutrino beams and atmospheric neutrinos

  ➤ Data on thin target and replica targets

IN SITU MEASUREMENTS – HADRON DETECTOR IN BEAMLINE

➤ Can be a very **high rate**, very **high radiation** environment

➤ Example: **PIMON in K2K**

  ➤ Cherenkov detector after horns

  ➤ Mom limited >2 GeV/c, since below this uninteracted primary protons are above Cherenkov threshold

➤ For E_ν from 1-2.5 GeV, constrained near flux to ~12%, and F/N ratio to 7-10%
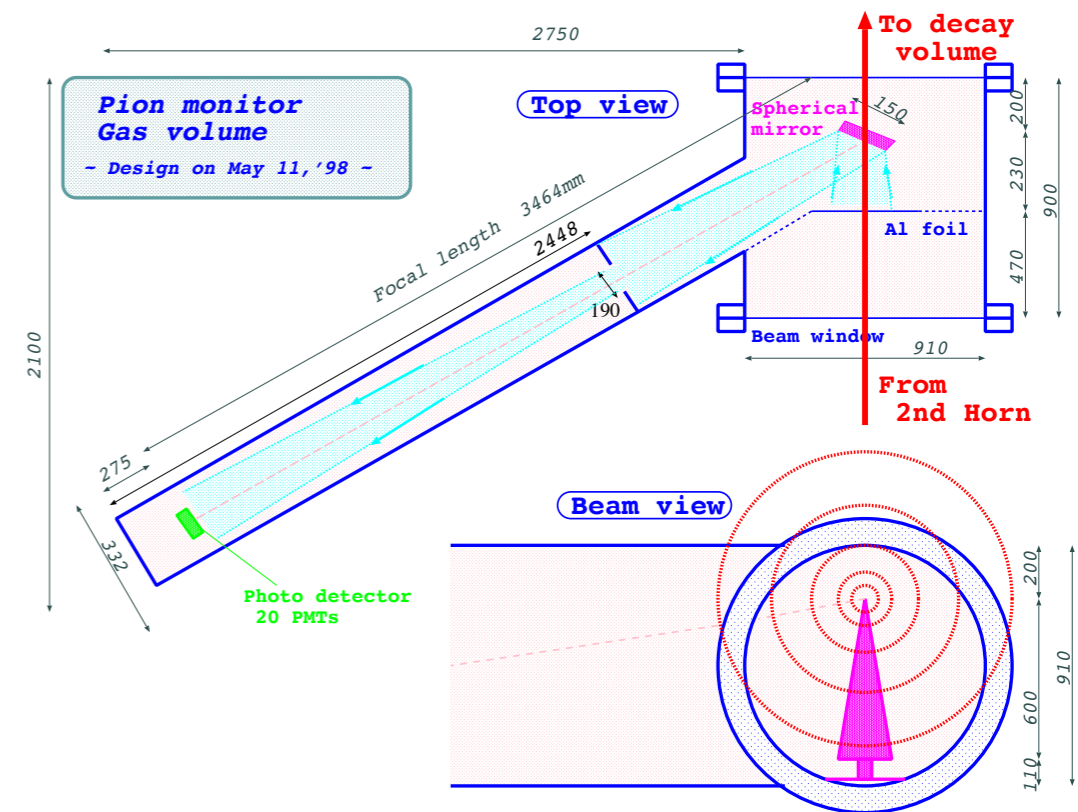
Phys. Rev. D 74, 072003 (2006)
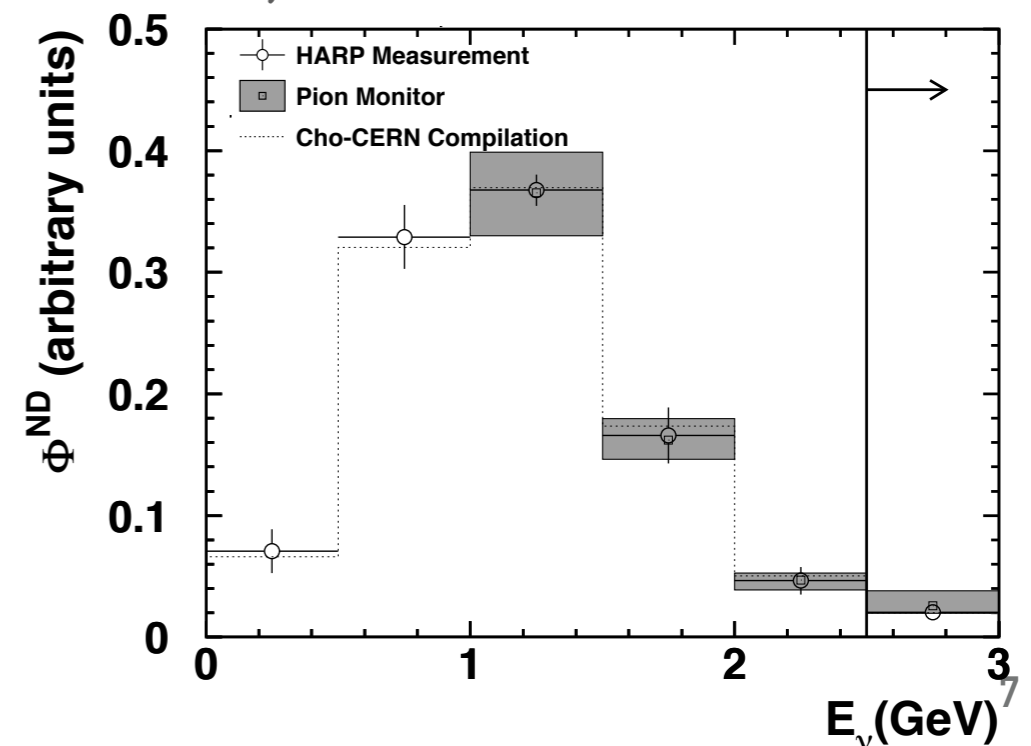
CHALLENGES OF IN SITU MEASUREMENTS

➤ In Situ measurements are the best option to reduce systematics associated with interactions outside the target, and to reduce uncertainties due to focusing and alignment

➤ But very high rates!

  ➤ Ideally you'd like a few protons per spill, or perhaps up to one proton per RF bucket

  ➤ Still at least 9 orders of magnitude below normal beam intensity

  ➤ Also very high radiation means that data must be taken at start of run and detectors will not likely survive for repeat measurements with replacement or upgraded targets and horns

EXTERNAL MEASUREMENTS

➤ Will summarize external data to predict fluxes in accelerator-generated neutrino beams and atmospheric neutrinos

➤ Existing data mostly has primary momenta in the range of 9 GeV/c to 450 GeV/c

➤ Will focus on the available external data here. Subsequent talks will provide examples of how this data is used and their needs

  ➤ **NuMI** Flux Prediction needs for NOvA and Minerva - See L. Aliaga's talks

  ➤ **T2K** and **HyperK** Fluxes - See talks from M. Wascko, F. Di Lodovico, M. Hartz, K. Sakashita, M. Friend, M. Pavin

  ➤ **DUNE** - See L. Fields' talk

SCALING OF HADRON PRODUCTION ABOVE ~30 GEV

➤ Feynman argued that invariant cross section $(E\frac{d^3\sigma}{d^3p})$ should be more or less constant with p_T and x_F, where $x_F = 2p_L^*/\sqrt{s}$

➤ Others have scaled by $x_R = E^*/E_{max}^*$
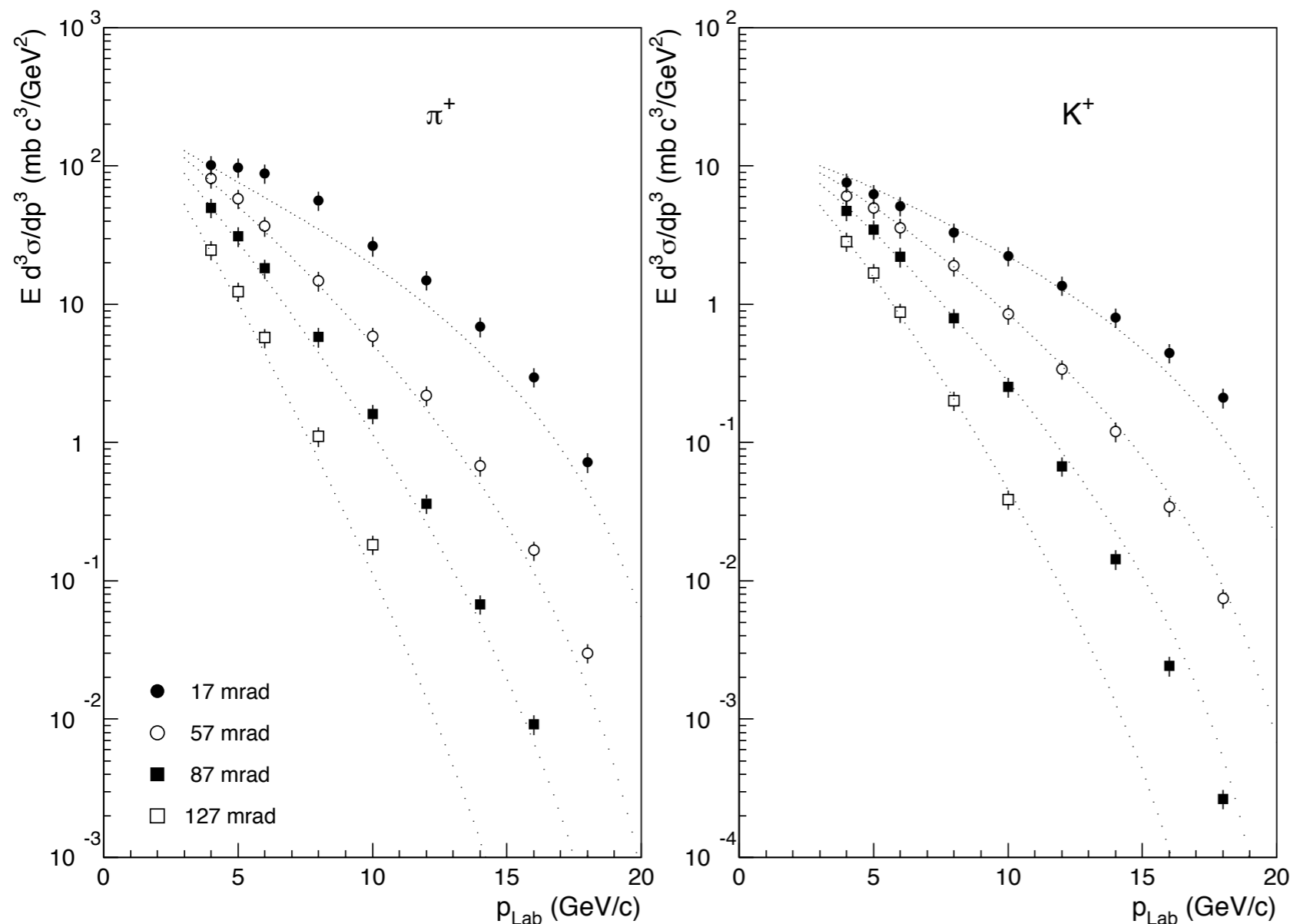
From Eur. Phys. J. C **20**, 13 (2001)

Dashed = fit to 400 and 450 GeV p + Be data scaled in p_T and x_R

Points = data for 24 GeV p + Be interactions

A SCALING

➤ From BMPT:

$$E \frac{d^3 \sigma^{hA_1}}{dp^3} = \left(\frac{A_1}{A_2} \right)^{\alpha} \cdot E \frac{d^3 \sigma^{hA_2}}{dp^3} .$$

➤ Scales as a power law of degree α which depends on x_F, p_T

$$\alpha(x_F) = (0.74 - 0.55 \cdot x_F + 0.26 \cdot x_F^2) \cdot (0.98 + 0.21 \cdot p_T^2) \quad (10)$$
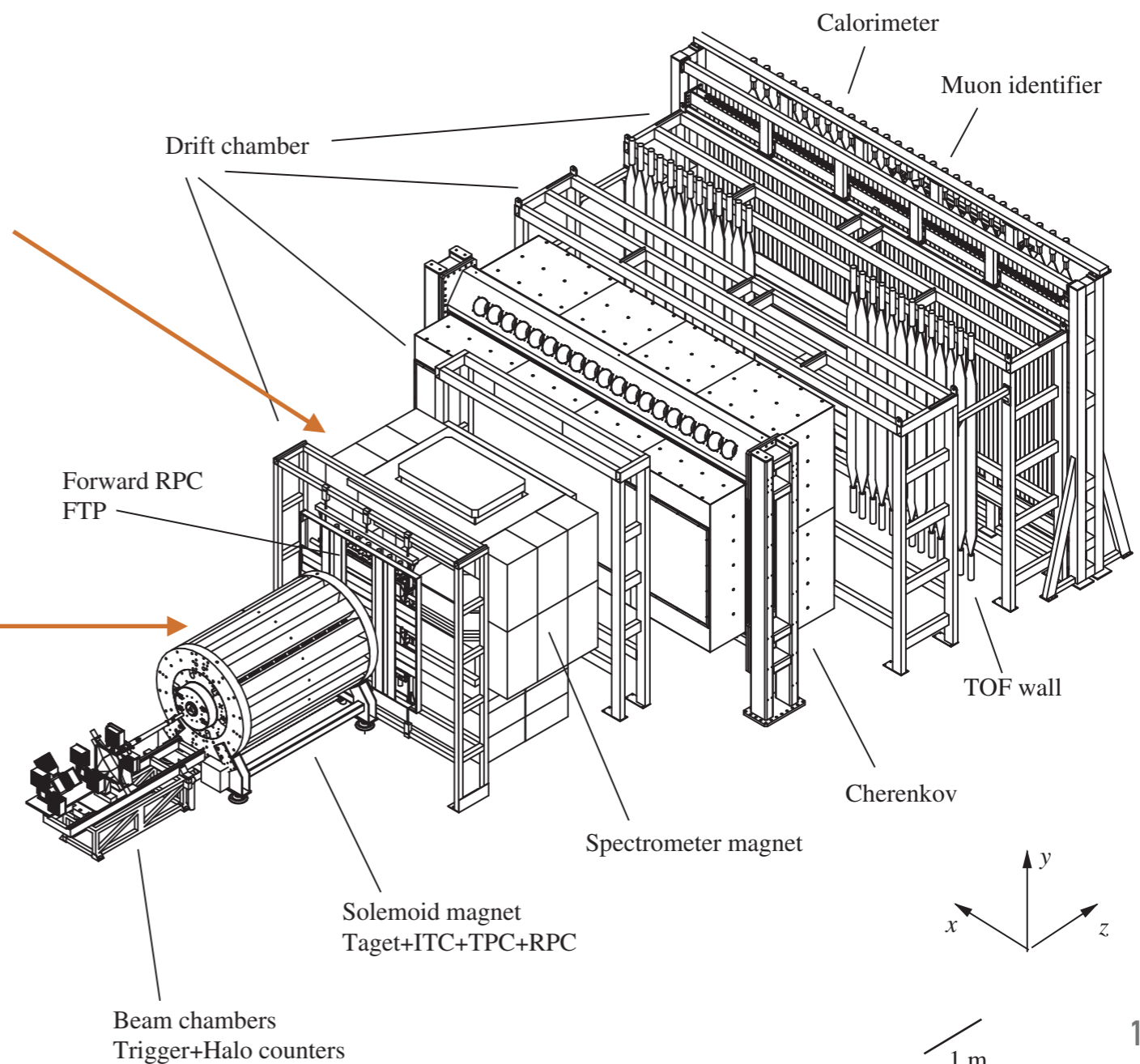
➤ At lower energies HARP data (Phys.Rev. C80 (2009) 035208) has shown that for the Sanford-Wang parameterization a correction of $corr = (A/A_{Be})^{\alpha}$ where

$$\alpha = \alpha_0 + \alpha_1 \times x_F + \alpha_2 \times x_F^2$$

	π^+	π^-
α_0	(0.69 ± 0.04)	(0.72 ± 0.04)
α_1	(-0.91 ± 0.21)	(-1.36 ± 0.20)
α_2	(0.34 ± 0.21)	(2.18 ± 0.21)

HARP EXPERIMENT

➤ Large-angle fixed target experiment at CERN PS

➤ Took data with p and π$^\pm$ beams from 1.5 to 15 GeV/c on a variety of targets

➤ Forward spectrometer could measure particles up to 250 mrad.

➤ Could also make high angle measurements up to 1050 mrad using TPC in solenoid

Calorimeter

Muon identifier

Drift chamber

Forward RPC
FTP

TOF wall

Cherenkov

Spectrometer magnet

Solenoid magnet
Taget+ITC+TPC+RPC

Beam chambers
Trigger+Halo counters

y

x z

1 m

KEY THIN TARGET DATA BELOW 18 GEV/C

Data	Experiment	Hadron	Published
8.9 GeV/c p + thin Be	HARP	π^+	Eur. Phys J C **52** (2007) 29
6.4, 12.3, and 17.5 GeV/c p + thin Be	BNL E910	$\pi^\pm$	Phys. Rev. C **77** (2008) 015209
12.9 GeV/c p + thin Al	HARP	π^+	Nucl. Phys. B **732** (2006) 1
12 GeV/c p and $\pi^\pm$ + C	HARP	$\pi^\pm$	Astr. Phys. **29** (2008) 257

➤ Additional HARP data on heavy targets, and at high angles

➤ Errors for 8.9 GeV/c data were ~9.8% on shape, 5% on normalization

➤ MiniBooNE flux predictions, hadrons give ~10% on ν_μ flux Phys Rev D 79 072002 (2009)

➤ MicroBooNE and SBL will build on 10 years of experience with Booster beam

NA61/SHINE EXPERIMENT

➤ <u>S</u>PS <u>H</u>eavy <u>I</u>on and <u>N</u>eutrino <u>E</u>xperiment: Fixed target experiment using CERN SPS

➤ Primary 400 GeV/c p beam, Secondary beams ~26 to 160 GeV/c

Top View
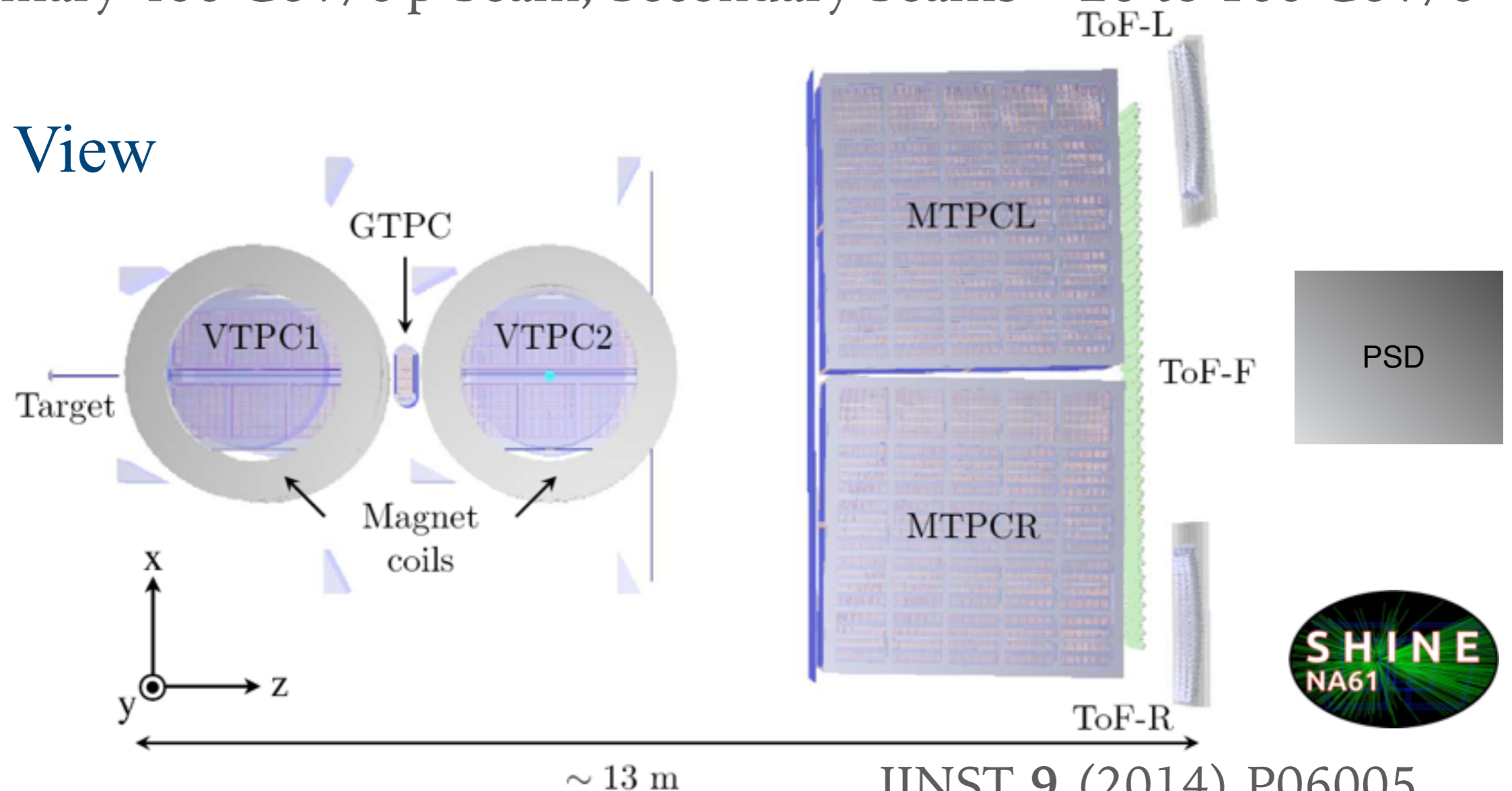
JINST **9** (2014) P06005

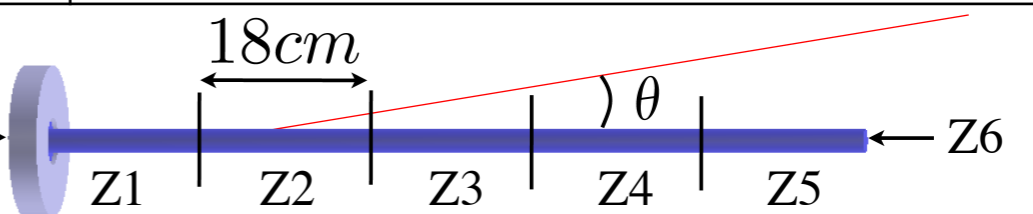➤ Comprises several large acceptance TPCs, Two inside magnets

THIN TARGET DATA AROUND 31 GEV/C

Data	Experiment	Hadron	Published
19.2 GeV/c p on p, Be, Al, Cu, Pb	Allaby et al	p, pbar, $\pi^{\pm}$, $K^{\pm}$	Tech. Rep. 70-12 (CERN, 1970)
24 GeV/c p on Be, Al, Cu, Pb	Eichten et al	p, pbar, $\pi^{\pm}$, $K^{\pm}$	Nucl. Phys. B**44**, 333 (1972)
31 GeV/c p + thin C target	NA61/SHINE	$\pi^{\pm}$	Phys. Rev. **C84** (2011) 034604
31 GeV/c p + thin C target	NA61/SHINE	K^+	Phys. Rev. **C85** (2012) 035210
31 GeV/c p + thin C target	NA61/SHINE	K_s^0, Λ	Phys.Rev. **C89** (2014) 025205
31 GeV/c p + thin C target	NA61/SHINE	$\pi^{\pm}$, $K^{\pm}$, K_s^0, Λ, p	Eur.Phys.J. **C76** (2016) 84

➤ Errors on π^+ production ~4-5% for 20-140 mrad; K^+ errors <~10% for p<12 GeV

Data	Experiment	Hadron	Published
31 GeV/c p + T2K replica target	NA61/SHINE	π^+	Nucl.Instrum.Meth. A701 (2013) 99-114
31 GeV/c p + T2K replica target	NA61/SHINE	$\pi^\pm$	Eur.Phys.J. C76 (2016) no.11, 617

ν_μ at SK (p250ka)

z_{target})

18cm

θ

Z1 Z2 Z3 Z4 Z5 Z6

gh-angle downstream slices errors

xtrapolation of track back to target

ed l

ys c

e ta

ν_μ energy spectrum at SK

NA61 LONG TARGET ERRORS   LOW ANGLE PI+
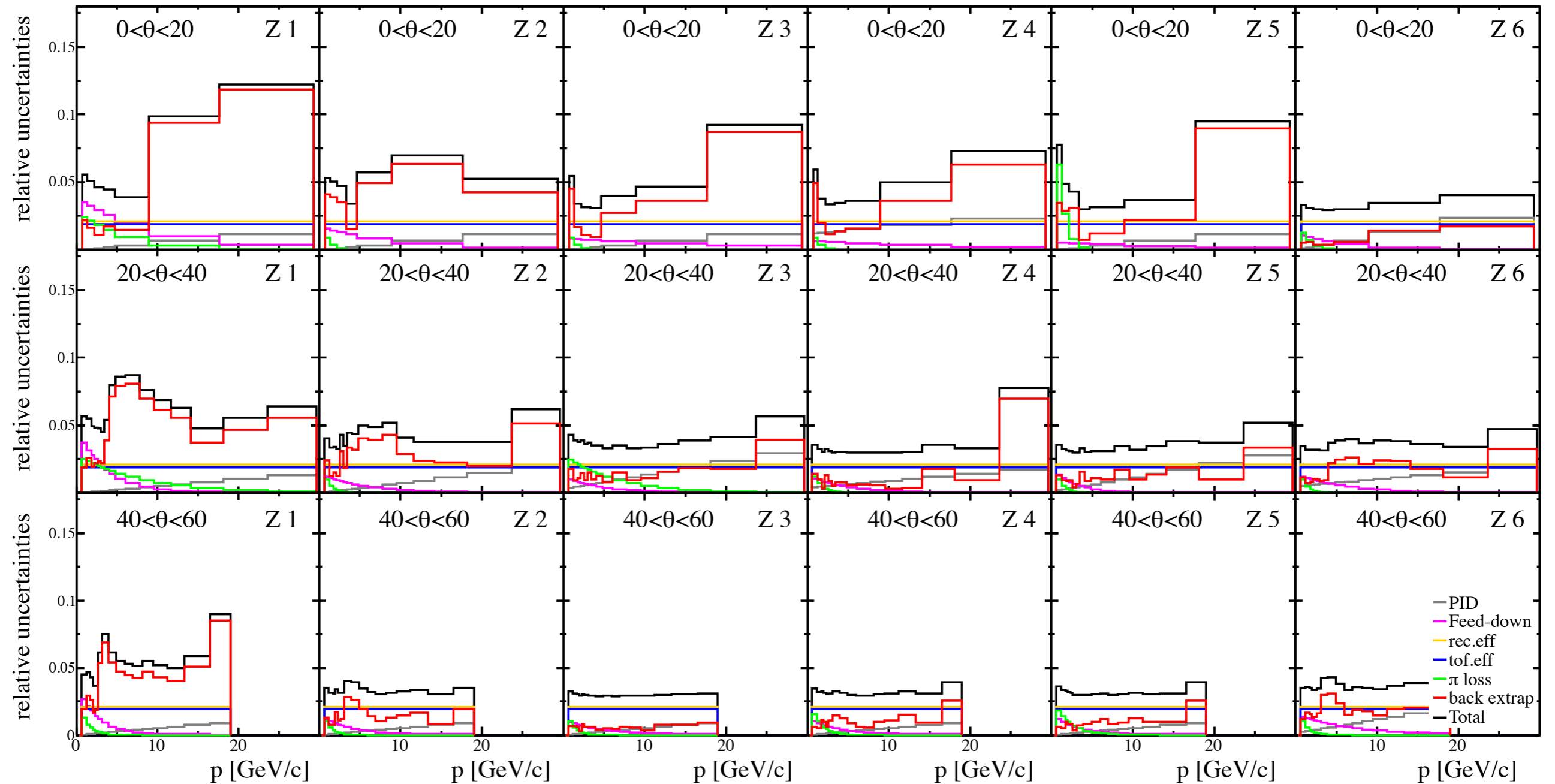
IMPROVEMENTS TO LONG TARGET MEASUREMENTS

➤ **Updated long target** results later this summer, including

  ➤ Increased data statistics

  ➤ $K^{\pm}$ and p yields

➤ Expected to reduce T2K flux uncertainties to 5% level

➤ Future analysis of data taken with higher magnetic field, which can **improve acceptance** for **forward particles** like protons

NA61/SHINE DATA FROM 60–120 GEV/C

➤ New effort in NA61 to collect data at energies and on targets of interest for Fermilab program, including NuMI and LBNF beamlines

➤ Analysis in progress of the following datasets collected in NA61/Shine in Fall 2016

Data Type	triggers
p + C @ 120 GeV/c	4.3 M
p + Be @ 120 GeV/c	2.2 M
p + C @ 60 GeV/c	2.9 M
p + Al @ 60 GeV/c	3.2 M
p + Be @ 60 GeV/c	2.1M
π^+ + C @ 60GeV/c	4.2 M
π^+ + Be @ 60 GeV/c	2.6 M

NA61/SHINE UPGRADES

➤ Upgrades to NA61/SHINE **electronics** underway

➤ 3 **new TPCs** added to improve forward coverage
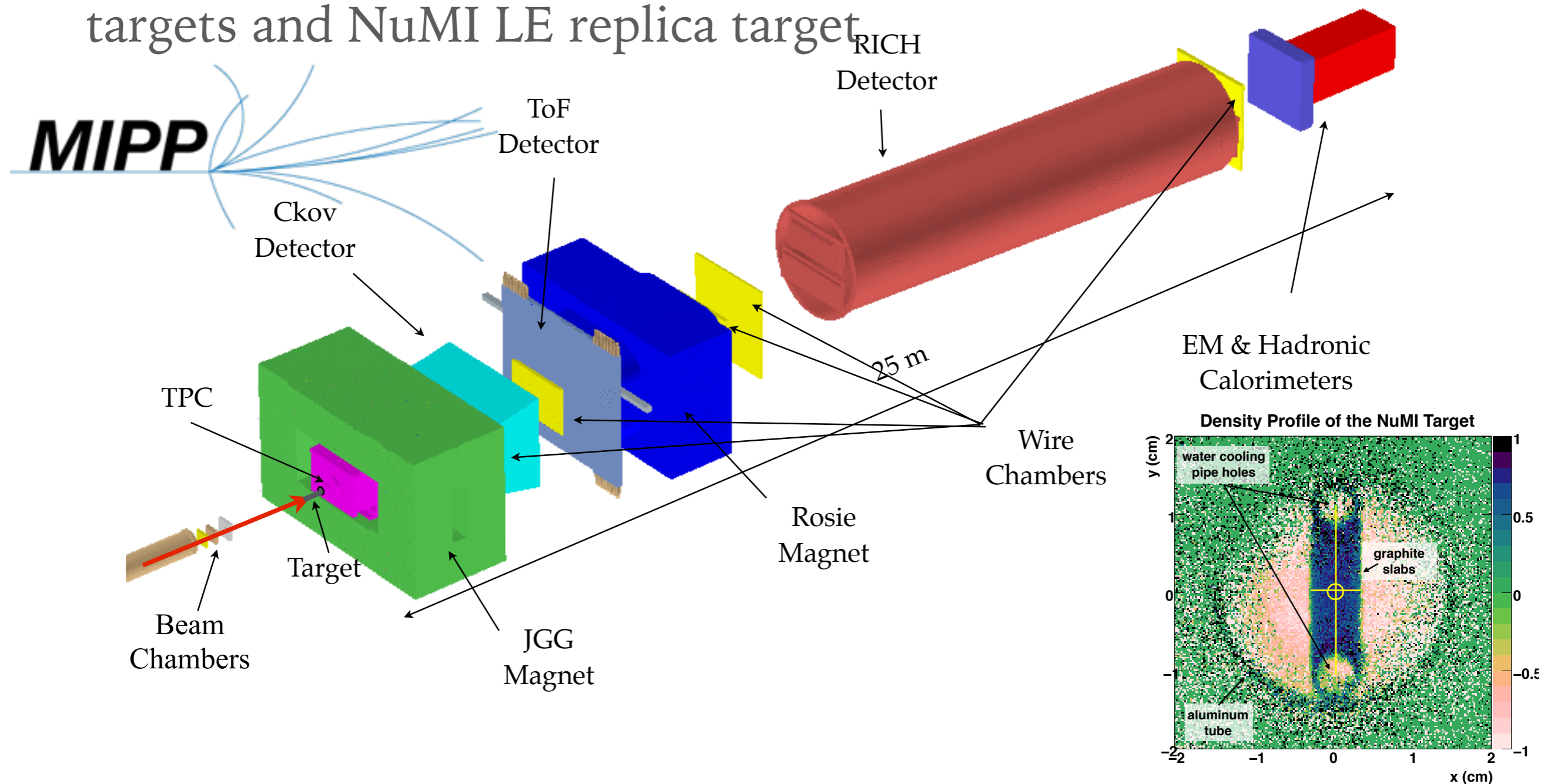

Top View
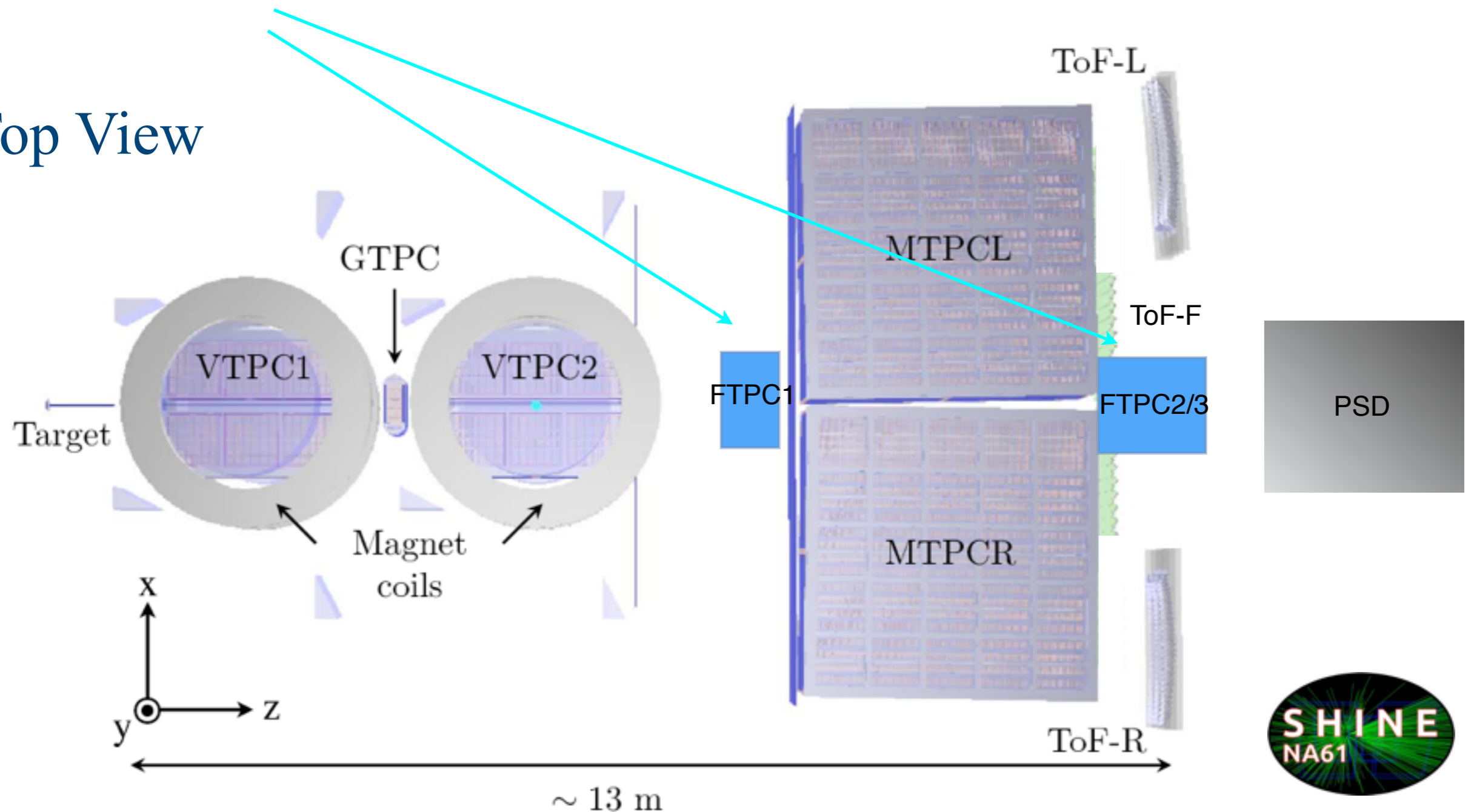
FUTURE NA61/SHINE PLANS

➤ Plan to collect **more neutrino-relevant data** over next 2 years possibly including the following

  ➤ 120 GeV p+C and p+Be with new FTPCs

  ➤ 90 GeV p+C

  ➤ 60 GeV π^+ + Al

 ➤ 30 GeV π^+ + C

  ➤ 60 GeV π^- + C

  ➤ NuMI ME replica target

MIPP EXPERIMENT

➤ Fermilab E907: **M**ain **I**njector **P**article **P**roduction

➤ p, π,K beams 5 GeV/c-120 GeV/c on thin LH_2,C, Be, Bi, U targets and NuMI LE replica target

RICH Detector

ToF Detector

Ckov Detector

25 m

TPC

EM & Hadronic Calorimeters

Wire Chambers

Target

Rosie Magnet

Beam Chambers

JGG Magnet

Density Profile of the NuMI Target

water cooling pipe holes

graphite slabs

aluminum tube

DATA AT 120 GEV/C

Data	Experiment	Hadron	Published
58, 84, 120 GeV/c p + various thin targets	MIPP	n	Phys.Rev. D**83** (2011) 012002
120 GeV/c p + NuMI replica target	MIPP	π±	Phys.Rev. D**90** (2014) 032001
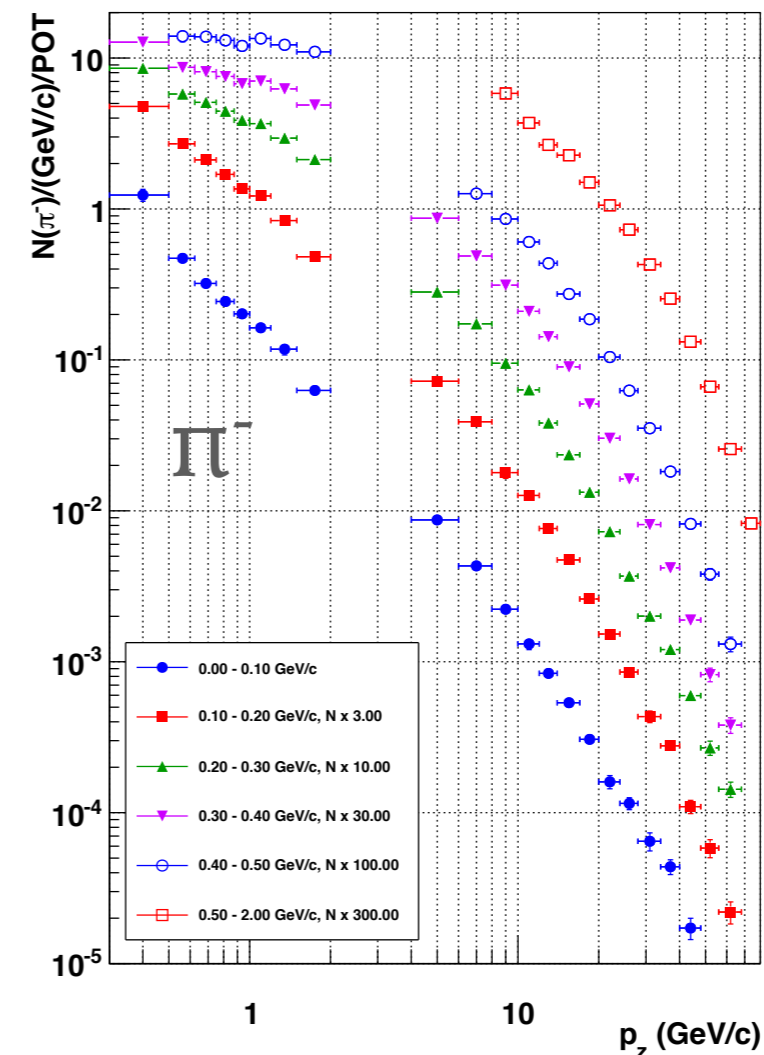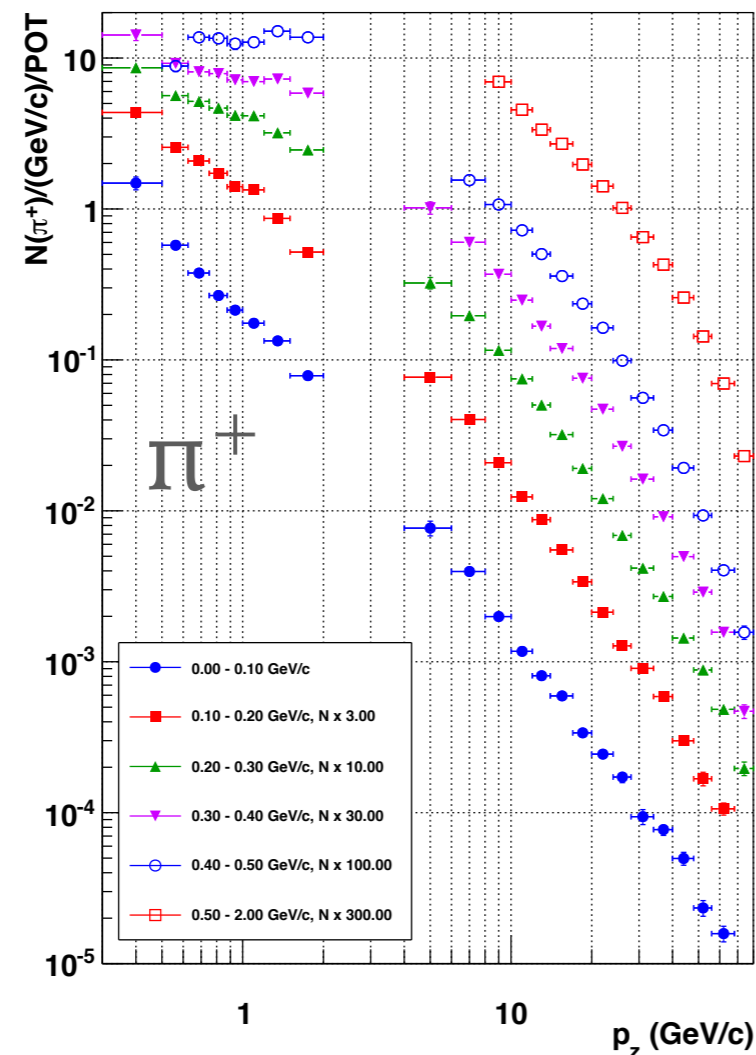
KEY THIN TARGET DATA AT 158 GEV/C

Data	Experiment	Hadron	Published
158 GeV/c p +C	NA49	$\pi^{\pm}$	Eur.Phys.J. **C49** (2007) 897
158 GeV/c p +C	NA49	p, pbar, n, d, t	Eur.Phys.J. **C73** (2013) 2364
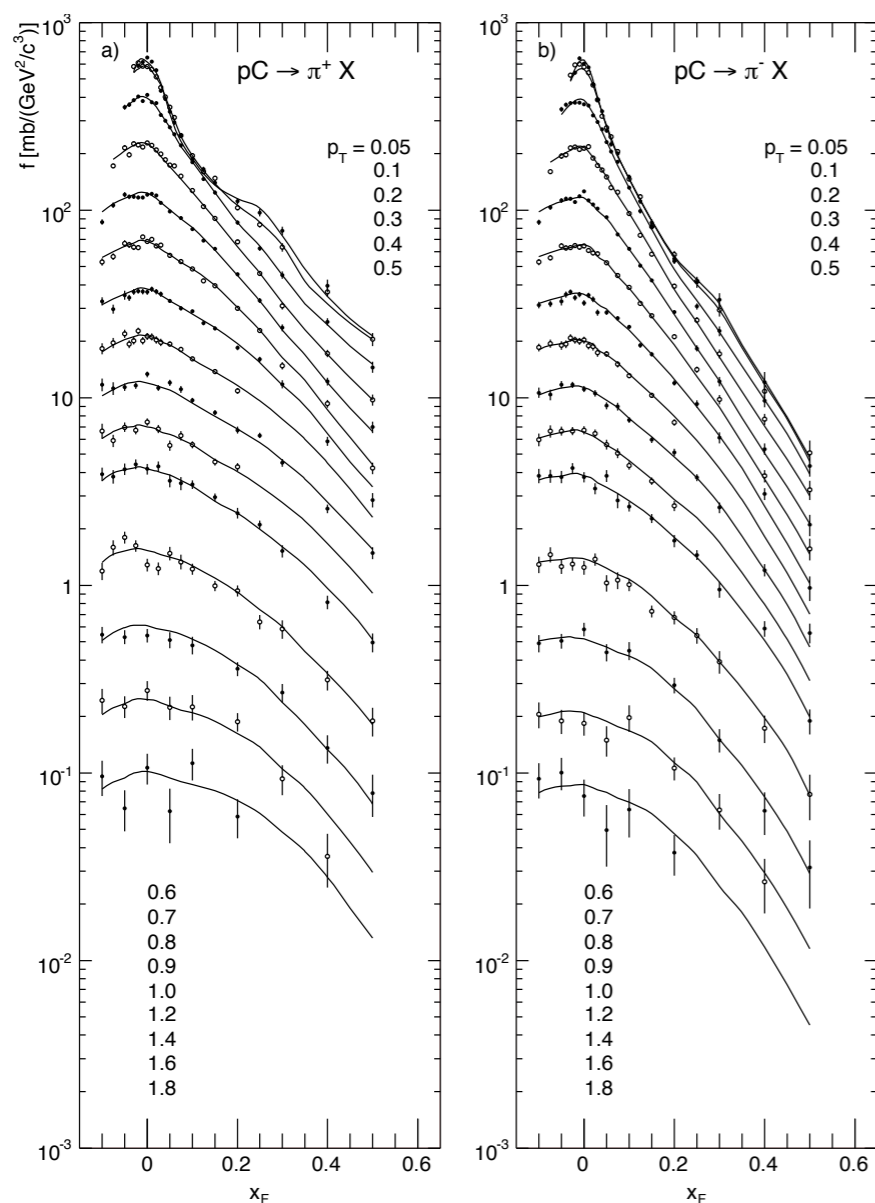
➤ For $\pi^{\pm}$ errors typically at the several % level

LONG TARGET DATA FOR DUNE?

➤ DUNE is likely to have a graphite or Be target.

  ➤ Current optimized design favors a 2 m long target.

  ➤ Extrapolation to determine where the particle exited the target could be a big issue

  ➤ Some ideas: (See also A. Blondel's talk on Friday)

    ➤ Place target (partially) inside first TPC?

    ➤ Additional tracking detectors around target?

ATMOSPHERIC NEUTRINO FLUXES

Phys Rev D **74** 094009 (2006)

➤ Flux errors ~15% in most important region for underground neutrinos

➤ Additional 12 GeV HARP data on N_2 and O_2 since then   Astr. Phys. 30 (2008) 1

➤ More data below 20 GeV would help
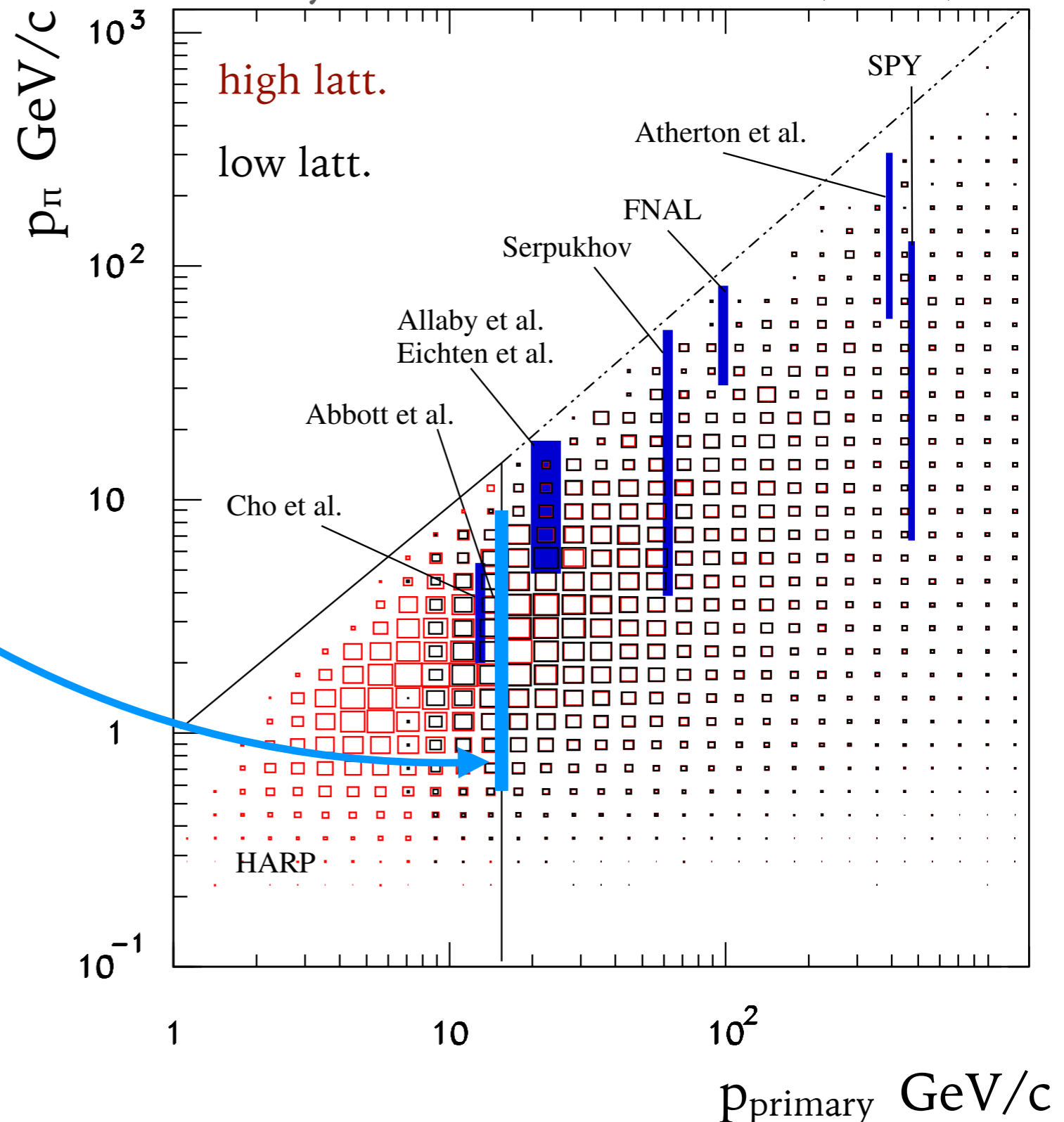
SUMMARY OF DATA SO FAR

➤ Lots of progress over the past 5 years in understanding hadron production uncertainties and their impact on neutrino flux uncertainties

  ➤ Increasingly measurements are available with uncertainties at the few % level

➤ More measurements that can have a major impact on the T2K and NuMI/LBNF fluxes expected over the next few years

FUTURE NEEDS AND IMPROVEMENTS

➤ While there is a lot of thin target data (and some of it has uncertainties of a few %), most of this data is focussed on interactions of **primary protons**

   ➤ Often large uncertainties on hadron production to reinteractions of hadrons elsewhere in target or beam

   ➤ Need more data with π^+, π^-, and K beams

➤ Long target measurements ideally include all of the reinteractions in the target, so these are always desirable when possible

➤ Not a lot of low energy data. More Pion interaction data below 30 GeV could benefit T2K/HyperK, and data around 9 GeV could benefit the short-baseline program at Fermilab and the predictions for atmospheric neutrino fluxes