OVERVIEW OF HADRON PRODUCTION MEASUREMENTS

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NuINT 2017, Toronto

June 26, 2017

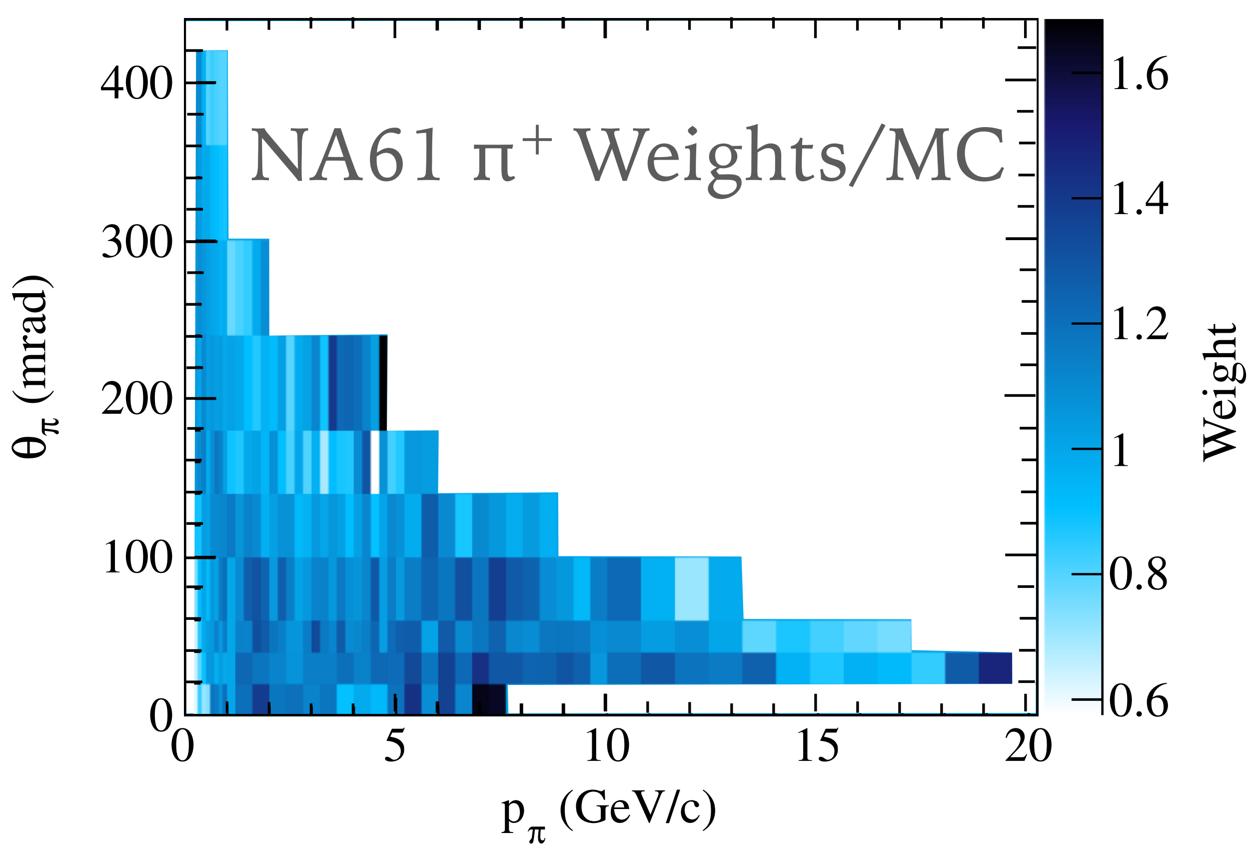
OUTLINE

- Why hadron production measurements?
- In Situ Flux Measurement Strategies
  - Hadron detectors
  - Muon monitors
- Overview of external data in various momentum ranges
  - Data below 18 GeV/c
  - Around 31 GeV/c
  - Around 60-160 GeV/c
  - 400-450 GeV/c
  - For future measurements See M. Hartz's and A. Longhin's talks

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



An example of hadron production predictions for T2K at left. Data disagrees with MC by 30% or more in some regions.

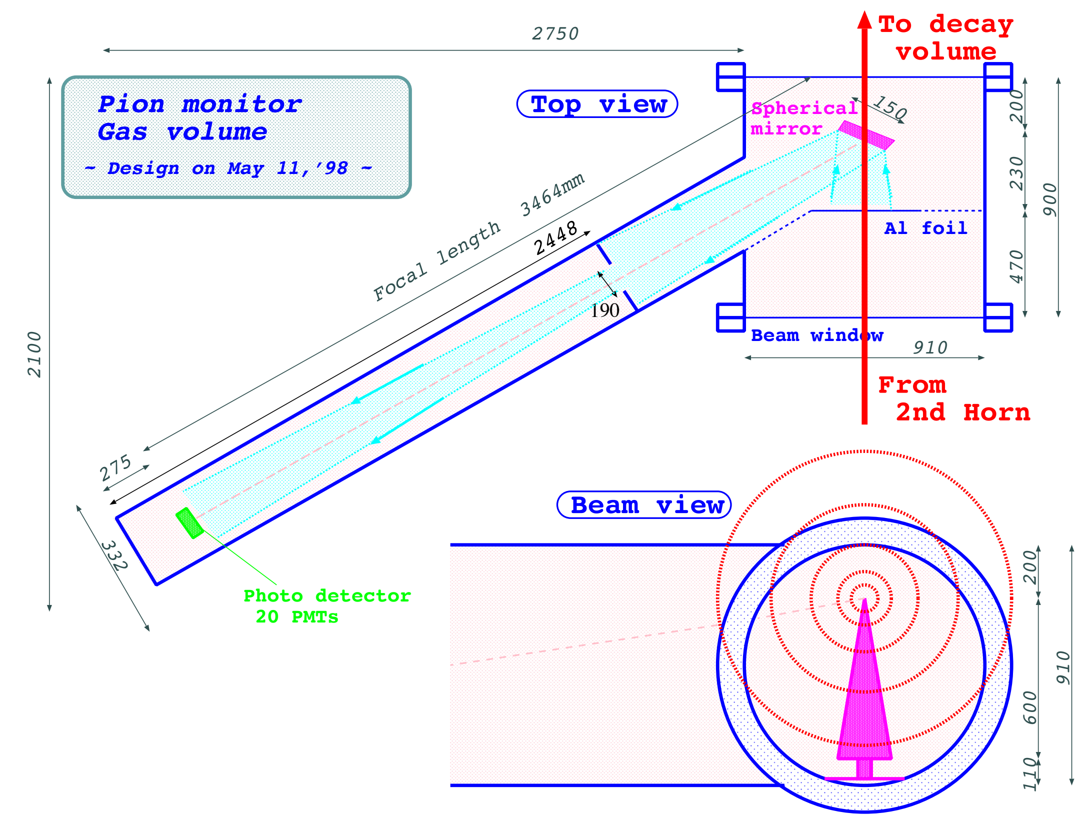
Phys Rev D ***87*** *012001 (2013)*

HADRON PRODUCTION MEASUREMENT STRATEGIES

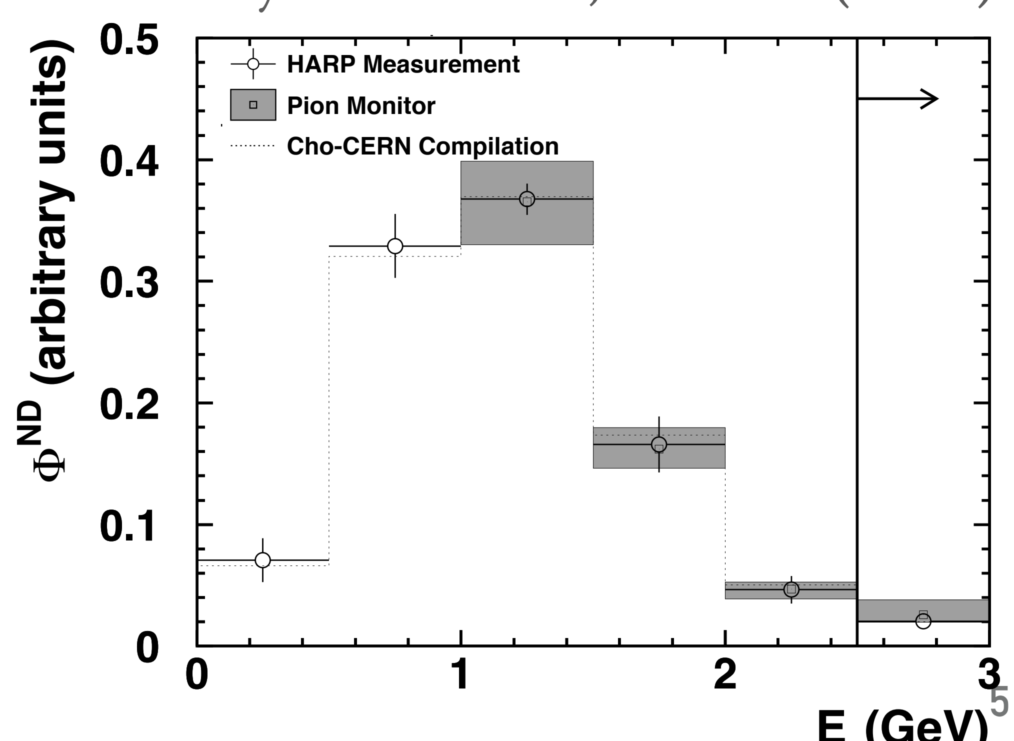
- **In Situ** measurements
  - Several strategies have been employed in accelerator-generated neutrino beams
  - Can involve very challenging detector environment!
- **External hadron production** measurements
  - Useful for both accelerator-generated neutrino beams and atmospheric neutrinos
  - Data 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)



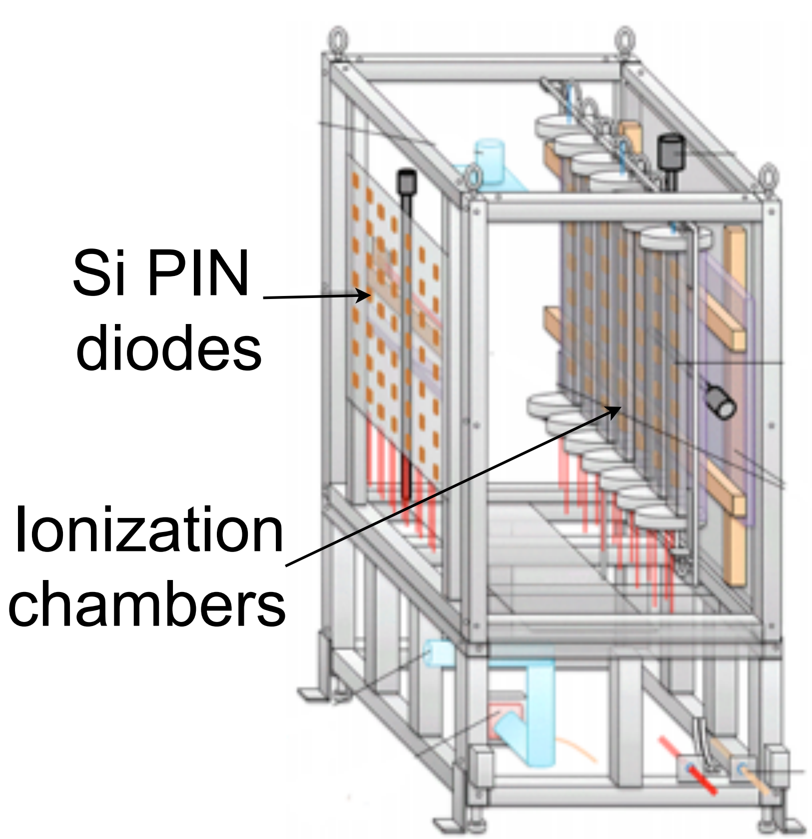
CHALLENGES OF IN SITU MEASUREMENTS

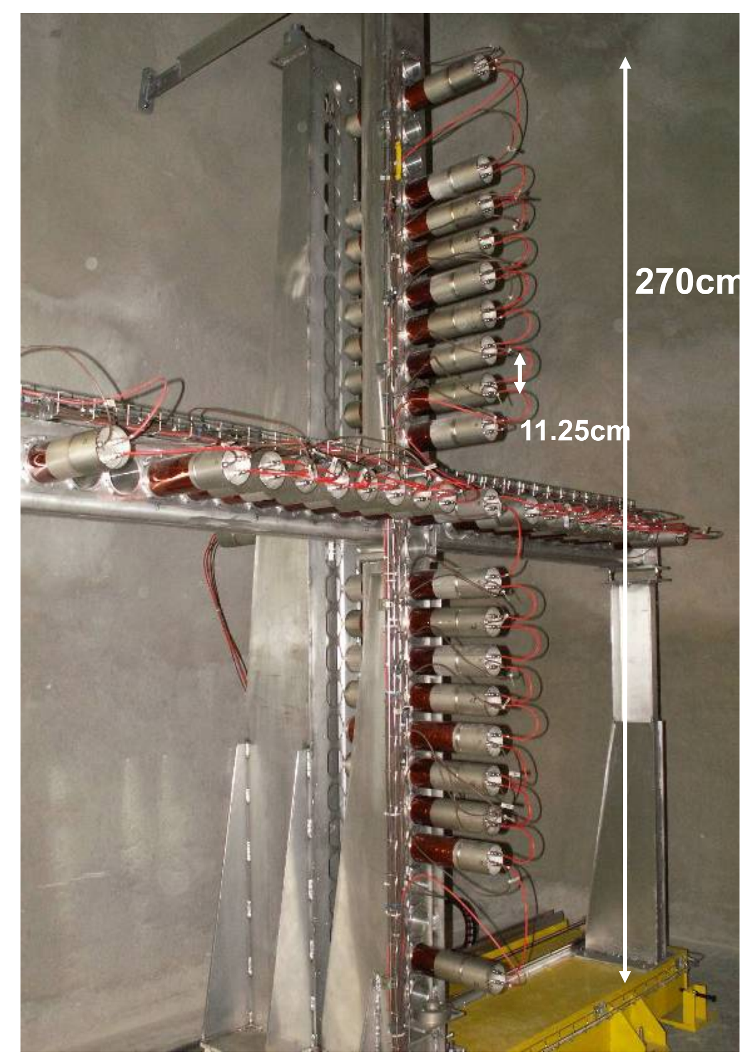
- In Situ measurements are the best option to reduce systematics associated with interactions outside the target, and to reduce uncertainties due to focusing and alignment
- But very high rates!
  - Ideally you'd like a few protons per spill, or perhaps up to one proton per RF bucket
  - Still at least 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

IN SITU MEASUREMENTS - MUON DETECTORS

- Can detect the muons that exit the absorber
- Muon spectrum correlated with higher energy pion spectrum in the decay pipe
- Typical designs have been gas or solid state ionization counters

T2K

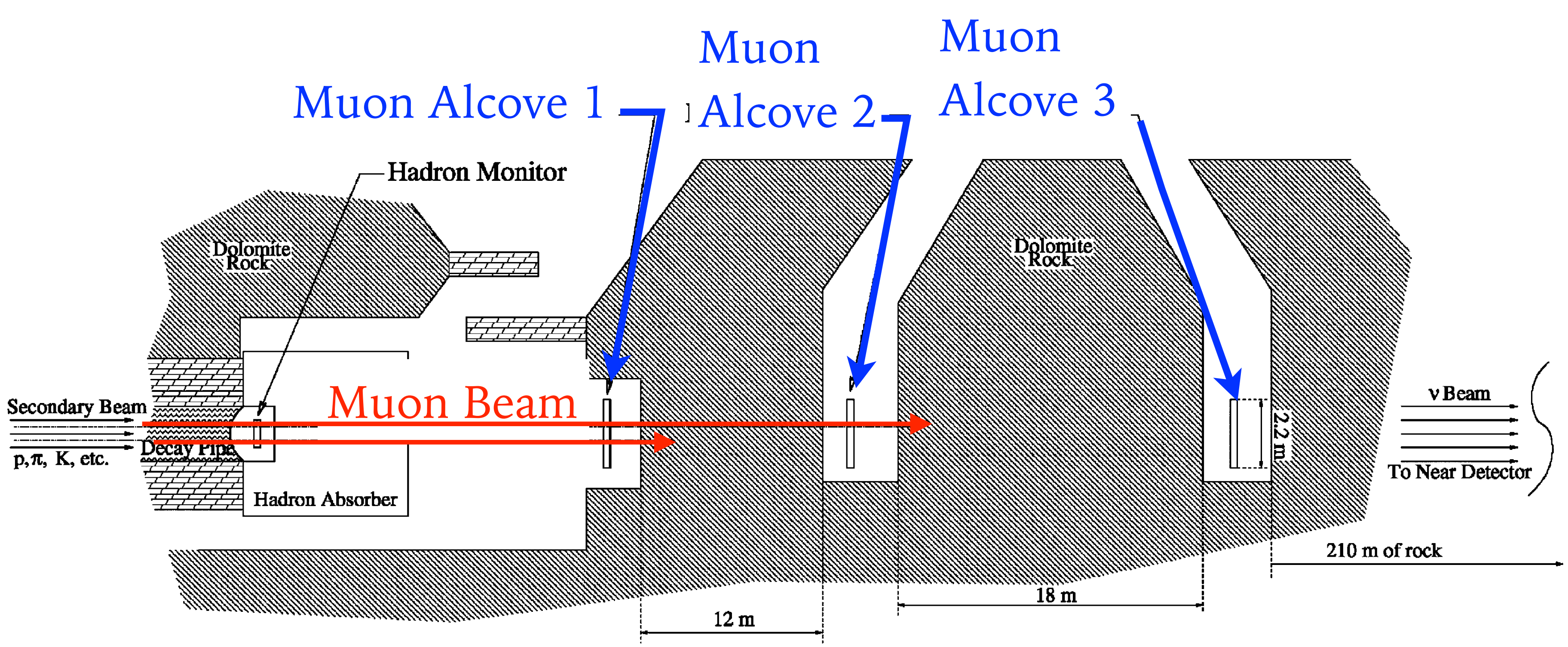




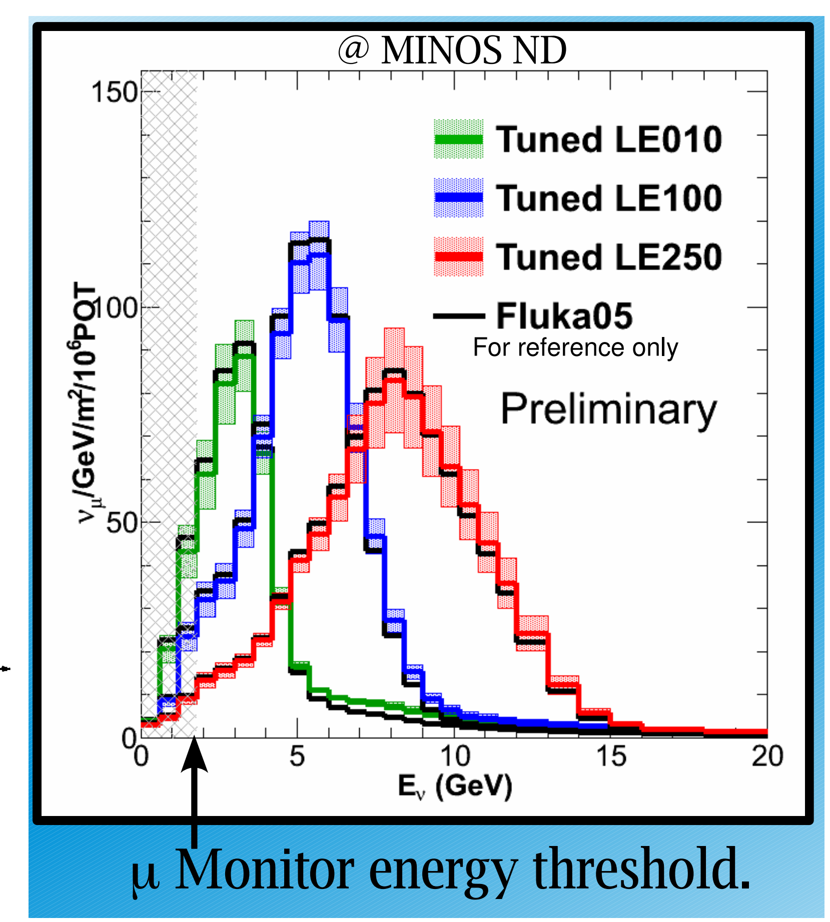
CNGS

NUMI MUON DETECTORS

- 3 (now 4) sets of ionization detectors, each alcove has different threshold
- Vary horn current and target z to vary p_t and p_z contribtions
- NuMI measurement error dominated by non-muon backgrounds and detector ionization scale



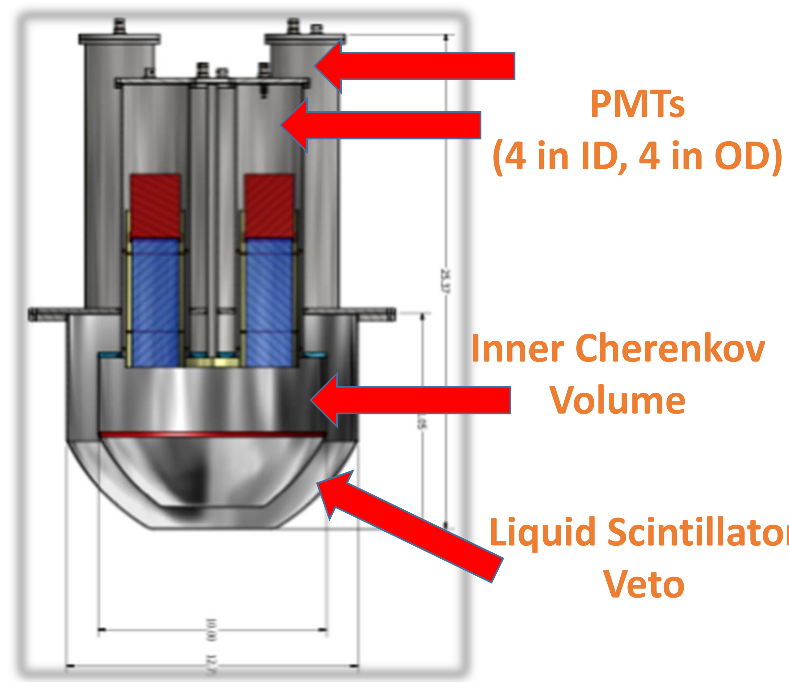
NIM A **568** (2006) 503



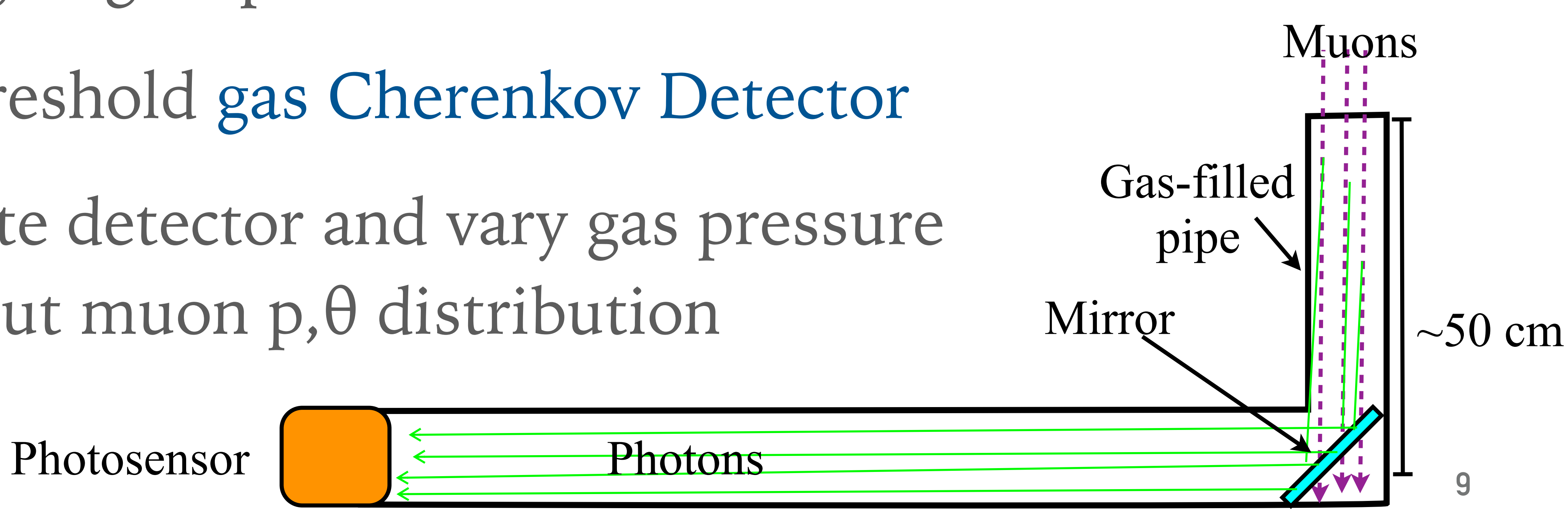
L. Loiacono, NBI, 2010

DUNE PROTOTYPE DETECTORS

- Considering solid state ionization detectors and two additional options
- Stopped Muon Counters
  - Look for Michel decays after main beam pulse
  - Placed behind different amounts of shielding to get spectrum info



- Variable threshold gas Cherenkov Detector
  - Can rotate detector and vary gas pressure to map out muon p,θ distribution

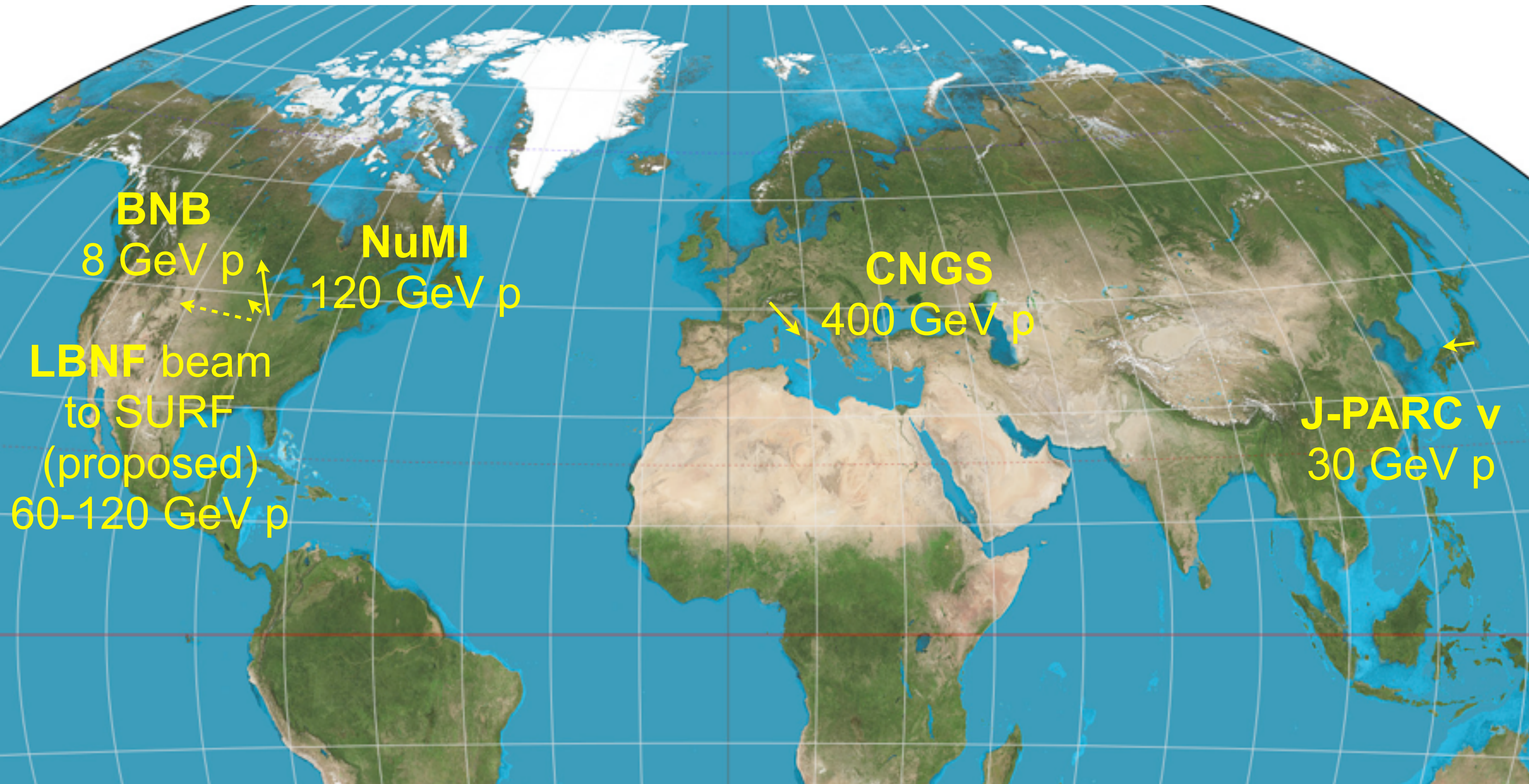


EXTERNAL MEASUREMENTS

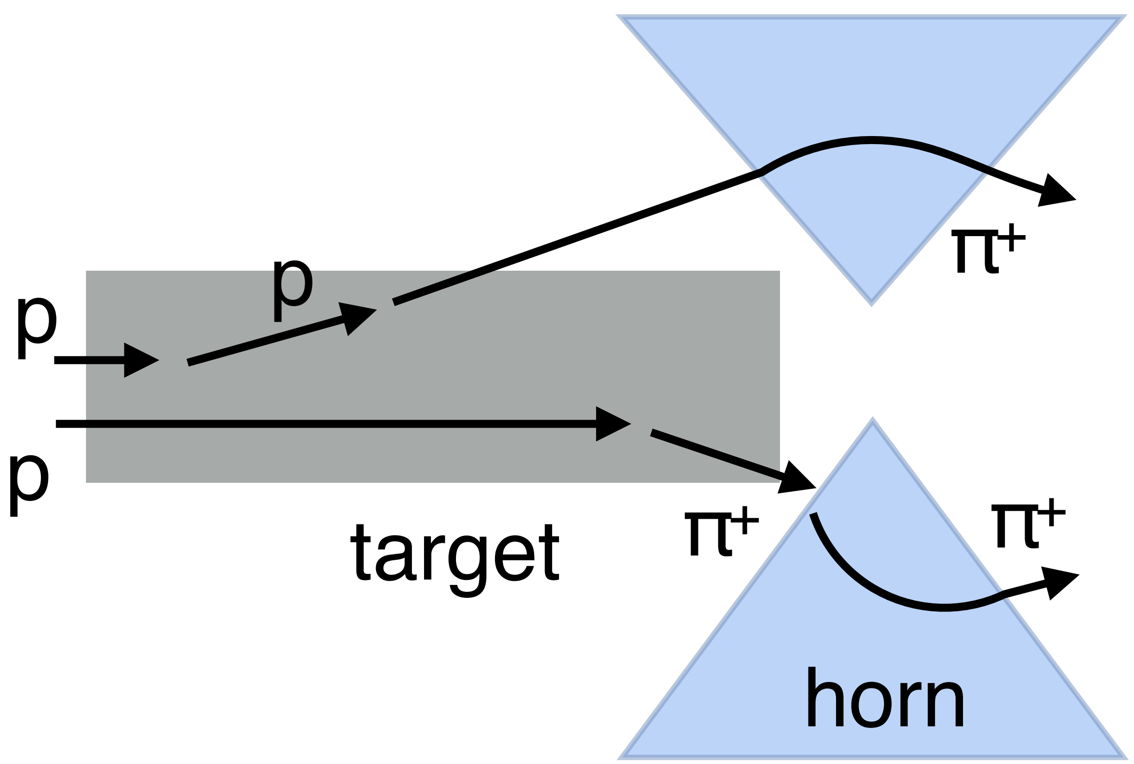
- Will summarize external data to predict fluxes in accelerator-generated neutrino beams and atmospheric neutrinos
- Existing data mostly has primary momenta in the range of 9 GeV/c to 450 GeV/c
- Will focus on the available external data here. Subsequent talks will provide examples of how experiments are utilizing this data to constrain flux uncertainties
  - **DUNE** Flux Prediction - See A. Bayshal's talk
  - **NuMI** Flux Prediction - See L. Aliaga's talk
  - **T2K** Flux Prediction - See K. Kowalik's talk and T. Vladisavljevic's poster

ACCELERATOR-GENERATED NEUTRINO BEAMS

➤ Initiated by protons with energies from 8 GeV to 400 GeV



NEUTRINO PRODUCTION



Neutrino Parents in T2K

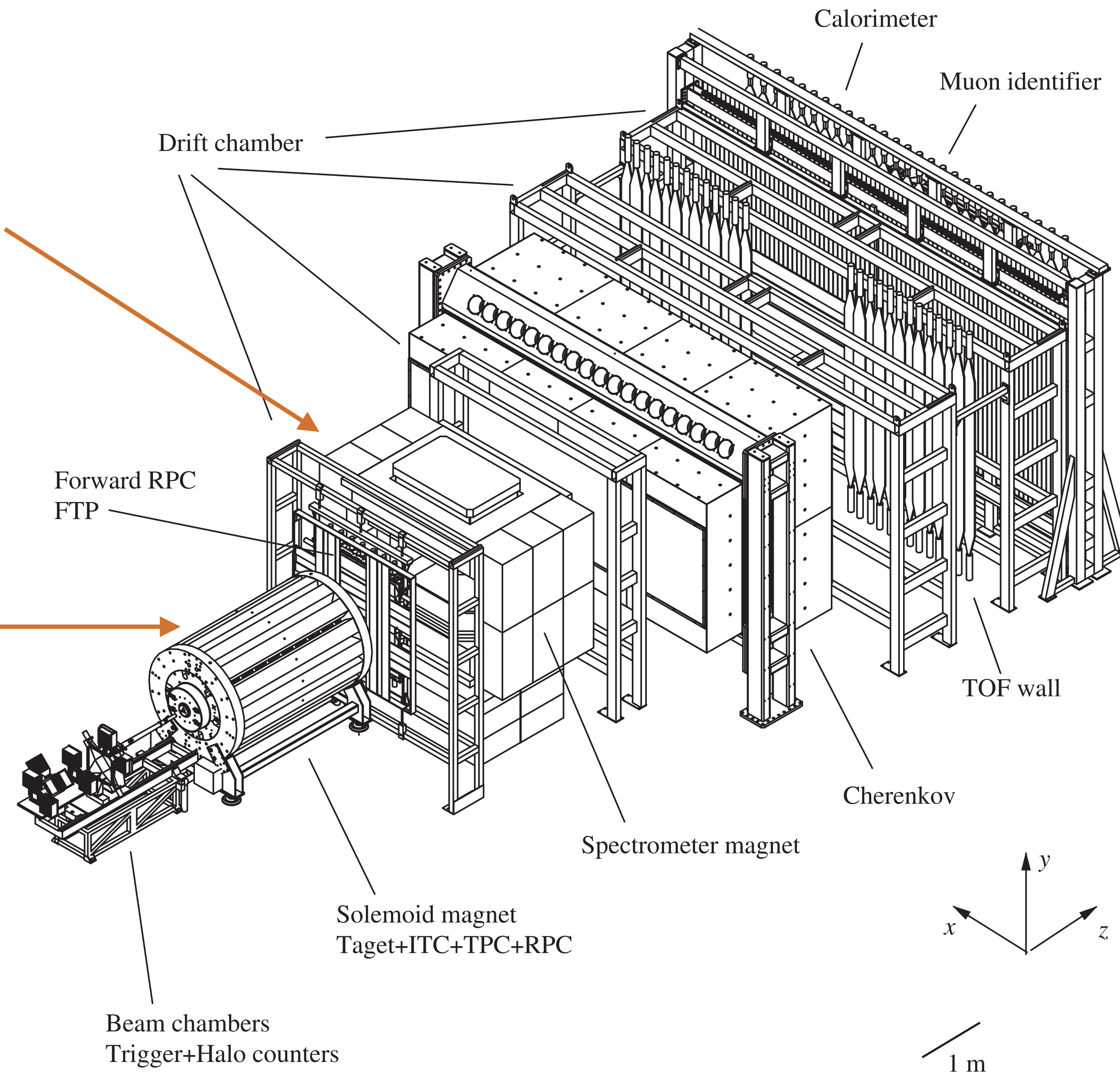
Parent	Flux percentage of each (all) flavor(s) ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
Secondary				
$\pi^\pm$	60.0(55.6)%	41.8(2.5)%	31.9(0.4)%	2.8(0.0)%
$K^\pm$	4.0(3.7)%	4.3(0.3)%	26.9(0.3)%	11.3(0.0)%
K_L^0	0.1(0.1)%	0.9(0.1)%	7.6(0.1)%	49.0(0.1)%
Tertiary				
$\pi^\pm$	34.4(31.9)%	50.0(3.0)%	20.4(0.2)%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

HARP EXPERIMENT

- Large-angle fixed target experiment at CERN PS
- Took data with p and $\pi^{\pm}$ 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



Nucl. Instr. Meth. A **571** (2007) 527

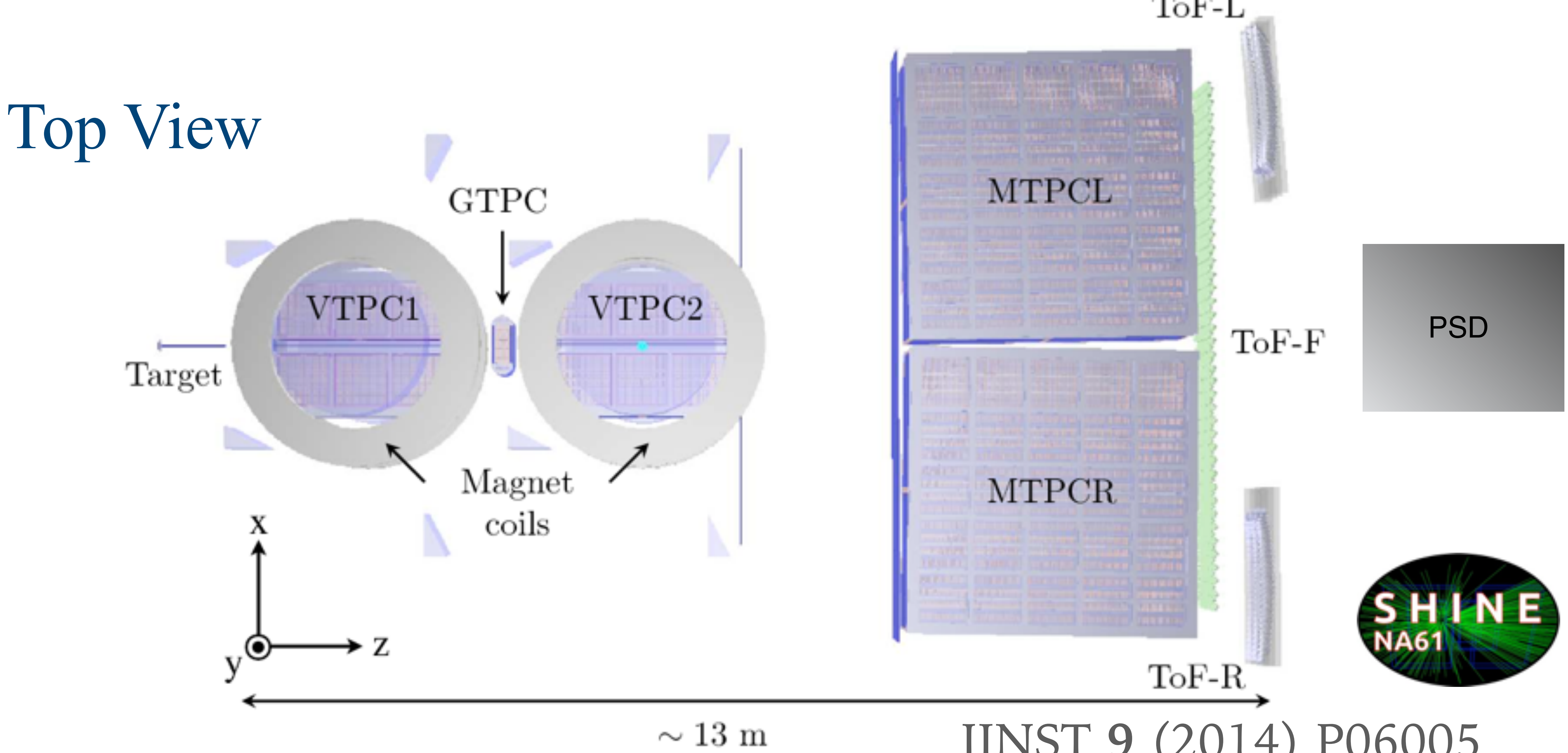
KEY THIN TARGET DATA BELOW 18 GEV/C

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 ~15% on total 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

- SPS Heavy Ion and Neutrino Experiment: Fixed target experiment using CERN SPS
- Primary 400 GeV/c p beam, Secondary beams ~26 to 160 GeV/c



JINST **9** (2014) P06005

- Comprises several large acceptance TPCs, Two inside magnets

THIN TARGET DATA AROUND 31 GEV/C

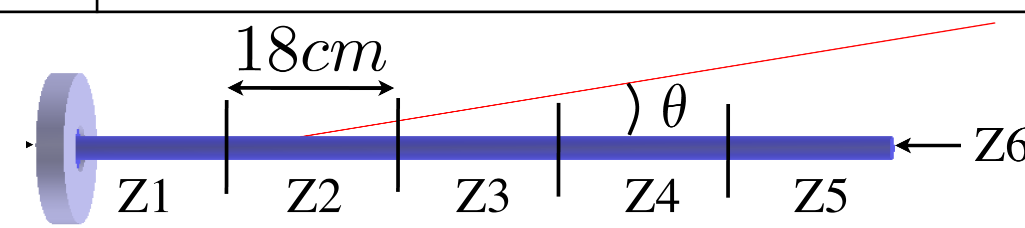
Data	Experiment	Hadron	Published
19.2 GeV/c p on p,Be, Al, Cu, Pb	Allaby et al	p,pbar, $\pi^{\pm}$, $K^{\pm}$	Tech. Rep. 70-12 (CERN, 1970)
24 GeV/c p on Be, Al, Cu, Pb	Eichten et al	p,pbar, $\pi^{\pm}$, $K^{\pm}$	Nucl. Phys. B**44**, 333 (1972)
31 GeV/c p + thin C target	NA61/SHINE	$\pi^{\pm}$	Phys. 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 ~5% for 20-140 mrad; K^{+} errors <~10% for p<12 GeV

THICK TARGET DATA AT 31 GEV/C

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

- Differential yields in (p,θ,z_{target})



- In upstream slices and high-angle downstream slices errors generally dominated by extrapolation of track back to target
- In middle slices, dominated by pion loss and feed-down corrections from the decays of strange particles and interactions outside of the target

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

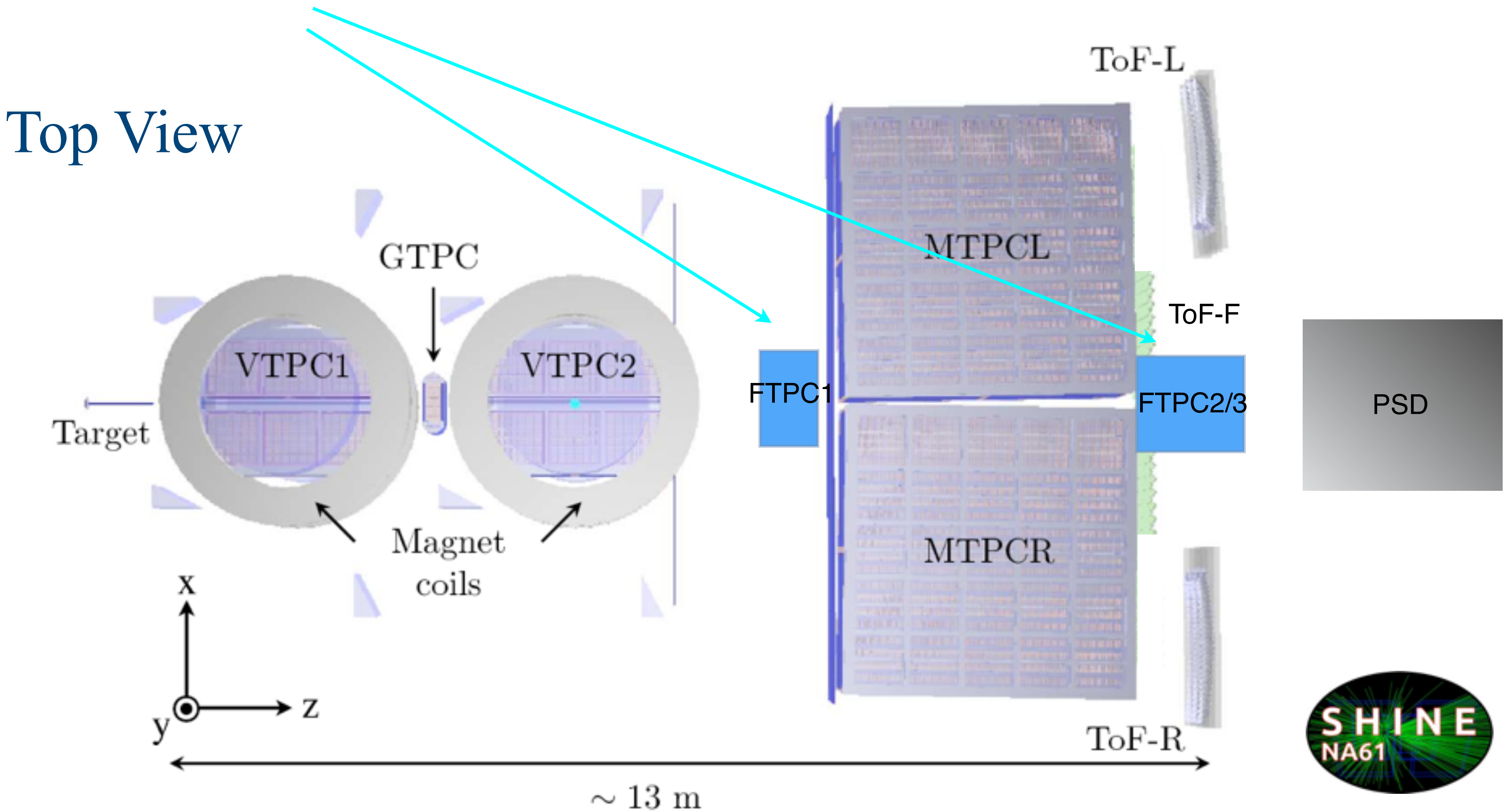
NA61/SHINE DATA FROM 60-120 GEV/C

- 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



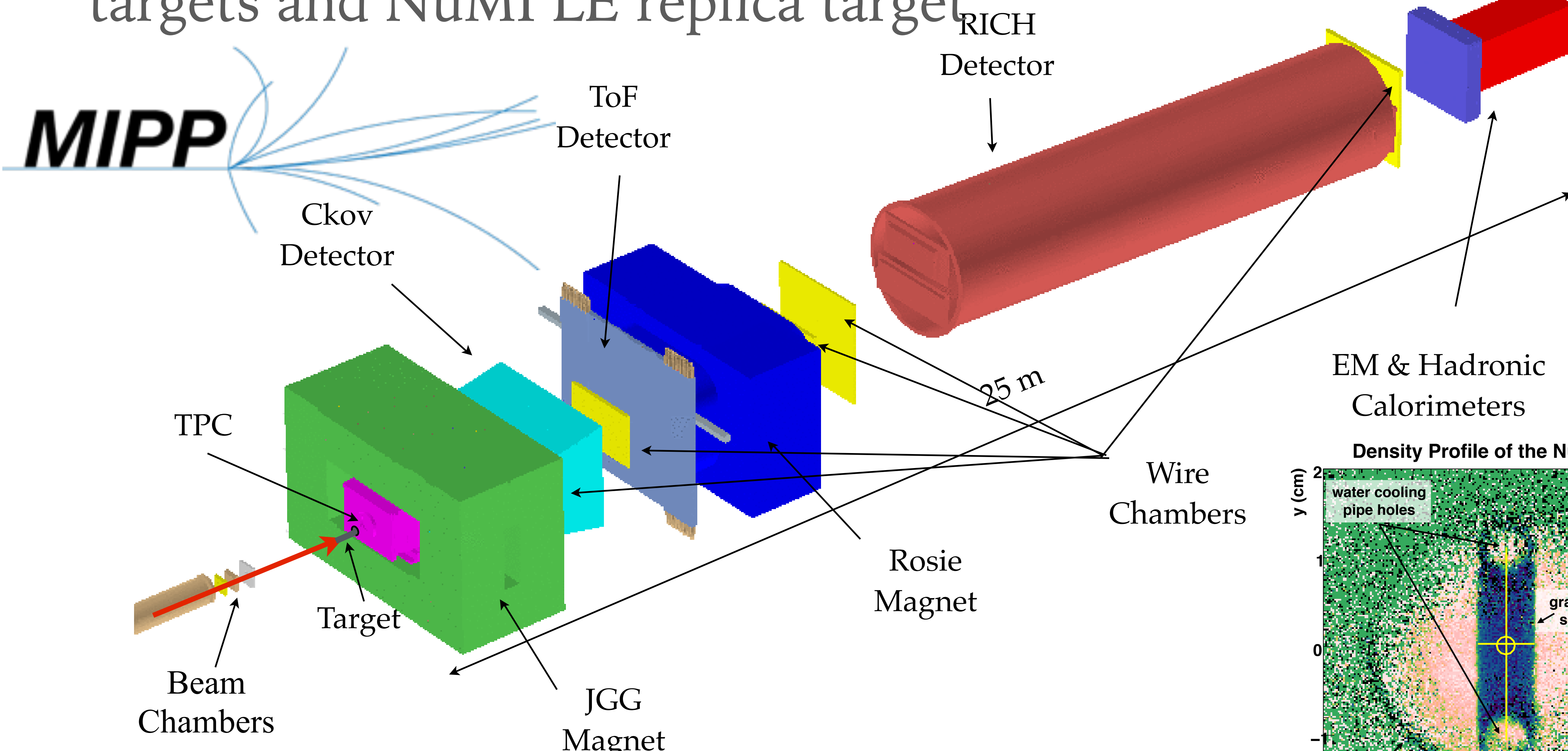
FUTURE NA61/SHINE PLANS

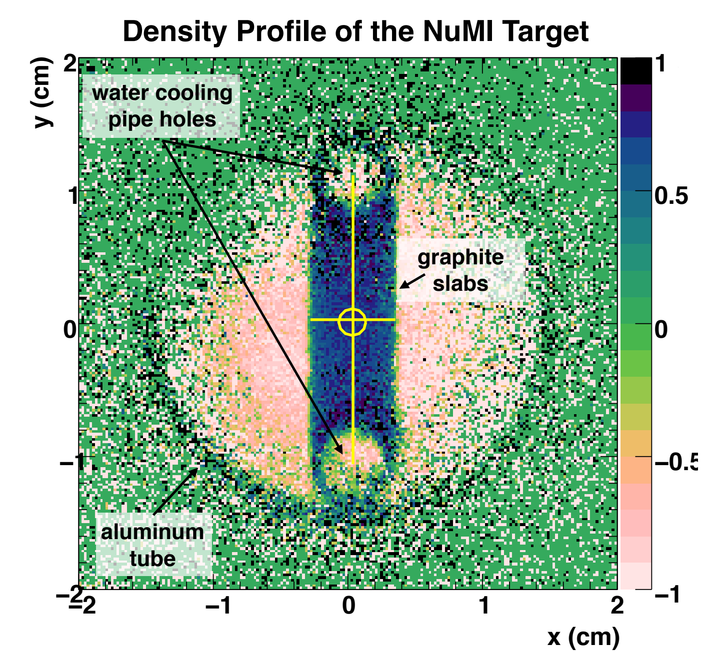
- Plan to collect **more neutrino-relevant data** over next 2 years possibly including the following
  - 120 GeV p+C and p+Be with new FTPCs
  - 90 GeV p+C
  - 60 GeV $\pi^+ + Al$
  - 30 GeV $\pi^+ + C$
  - 60 GeV $\pi^- + C$
  - NuMI ME replica target
- **Workshop** in Geneva **July 26-28** to discuss possibilities with NA61/SHINE after 2019-2020 shutdown
  - Replica targets for LBNF or Hyper-K?
  - Lower energy data for atmospheric neutrinos?


NA61 BEYOND 2020
Future Physics Opportunities with the NA61/SHINE Spectrometer
July 26-28, 2017
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Section de physique
SHINE
NA61
https://indico.cern.ch/event/629968/

MIPP EXPERIMENT

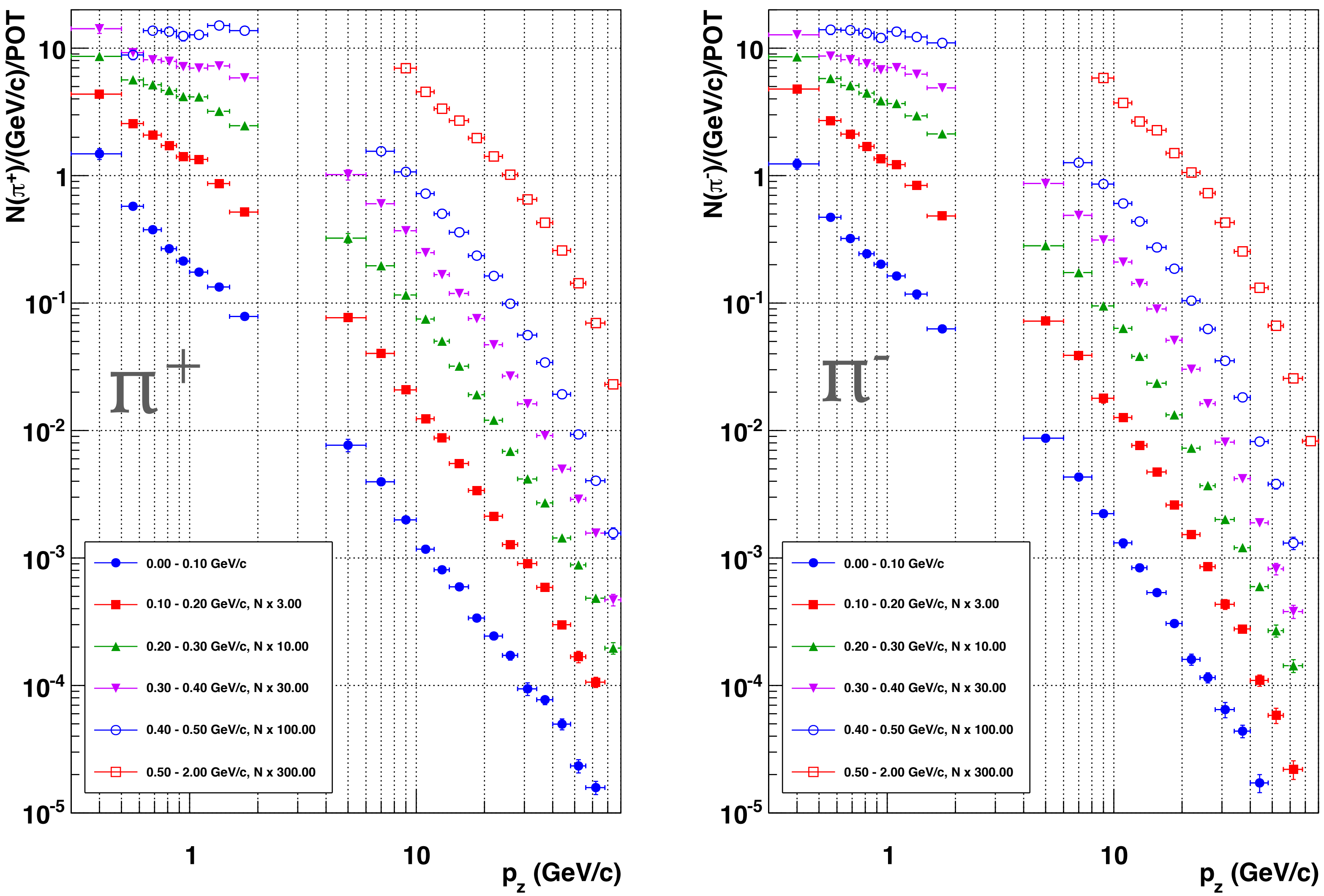
- Fermilab E907: Main Injector Particle Production
- p, π,K beams 5 GeV/c-120 GeV/c on thin LH_2,C, Be, Bi, U targets and NuMI LE replica target





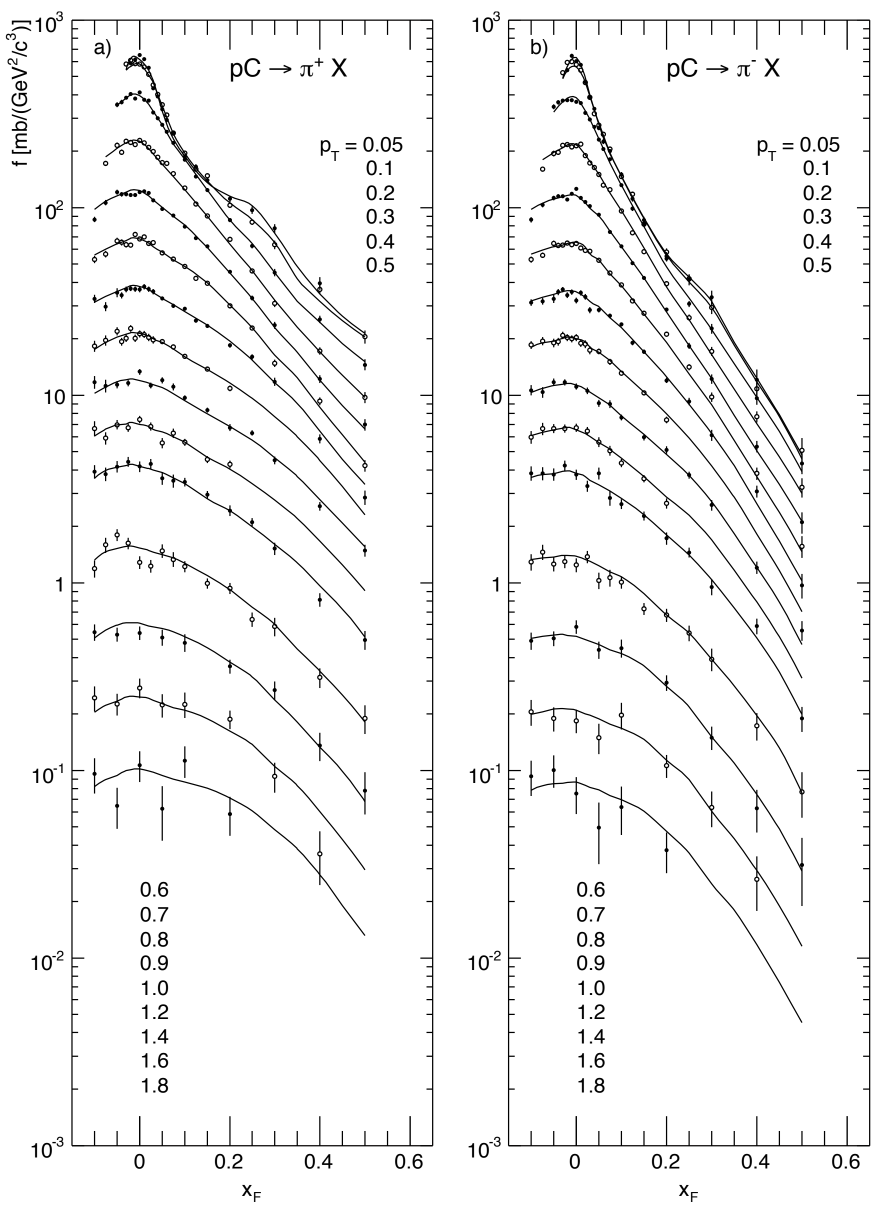
DATA AT 120 GEV/C

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	$\pi^{\pm}$	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. C**49** (2007) 897
158 GeV/c p +C	NA49	p, pbar, n, d, t	Eur.Phys.J. C**73** (2013) 2364



- ➤ For $\pi^{\pm}$ errors typically at the few % level

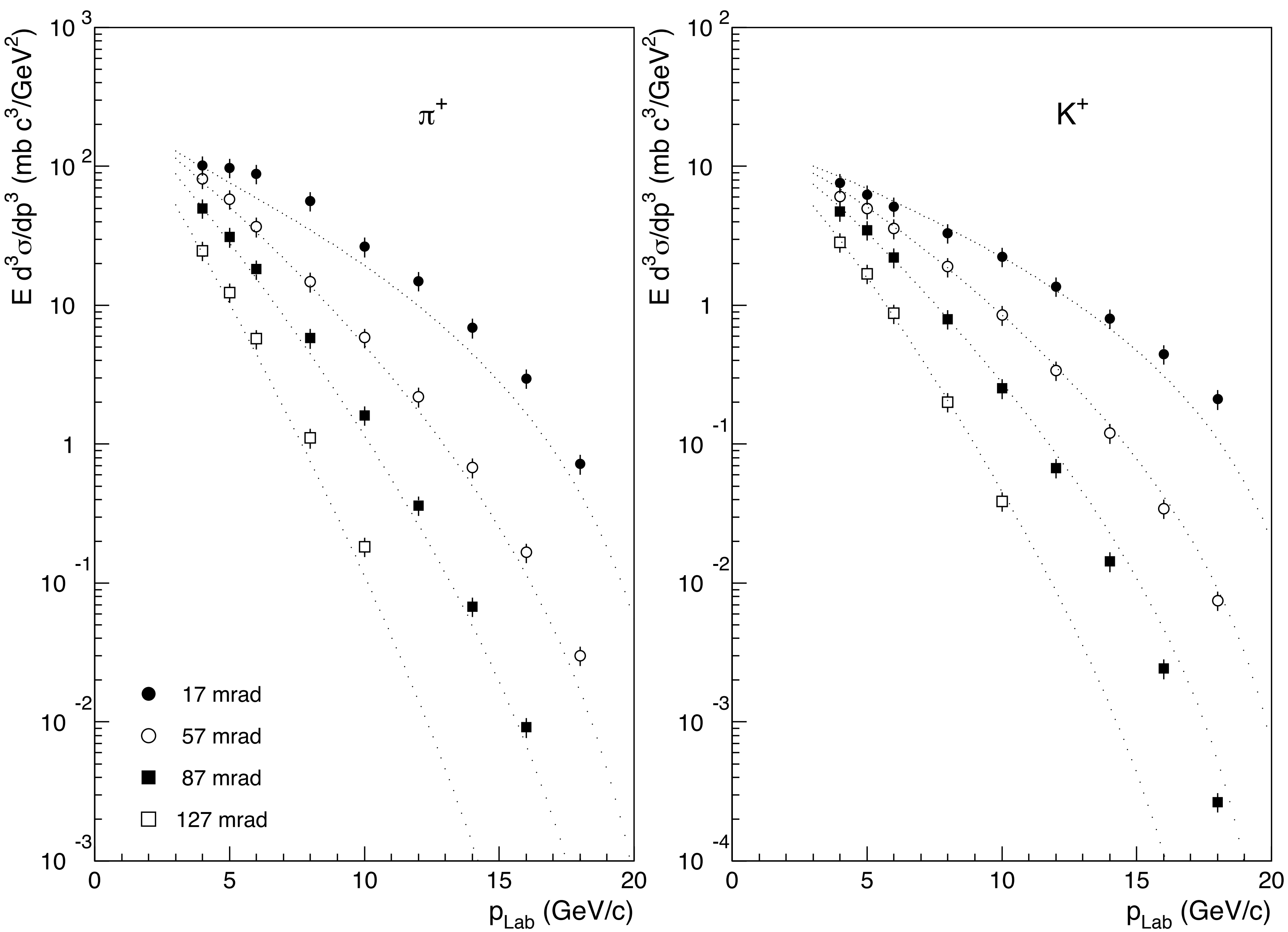
KEY DATA AT 400–450 GEV/C

Data	Experiment	Hadron	Published
400 GeV/c p + 10-50 cm Be target	NA20	$\pi^{\pm}$, $K^{\pm}$,p,pbar	CERN Tech. Rept. 80-70 (1980)
450 GeV/c p + 10 cm Be target	NA56/SPY	K/π ratio	Phys. Lett. B**420** (1998) 225
450 GeV/c p + 10 cm Be target	NA56/SPY	$\pi^{\pm}$	Phys. Lett. B**425** (1998) 208
450 GeV/c p + Be target	NA56/SPY	$\pi^{\pm}$, $K^{\pm}$,p,pbar	Eur. Jour. Phys. C**10** (1999) 605

- Accuracies in the 5-10% range
- Parameterized in Eur. Jour. Phys. C**20** (2001) 13

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)

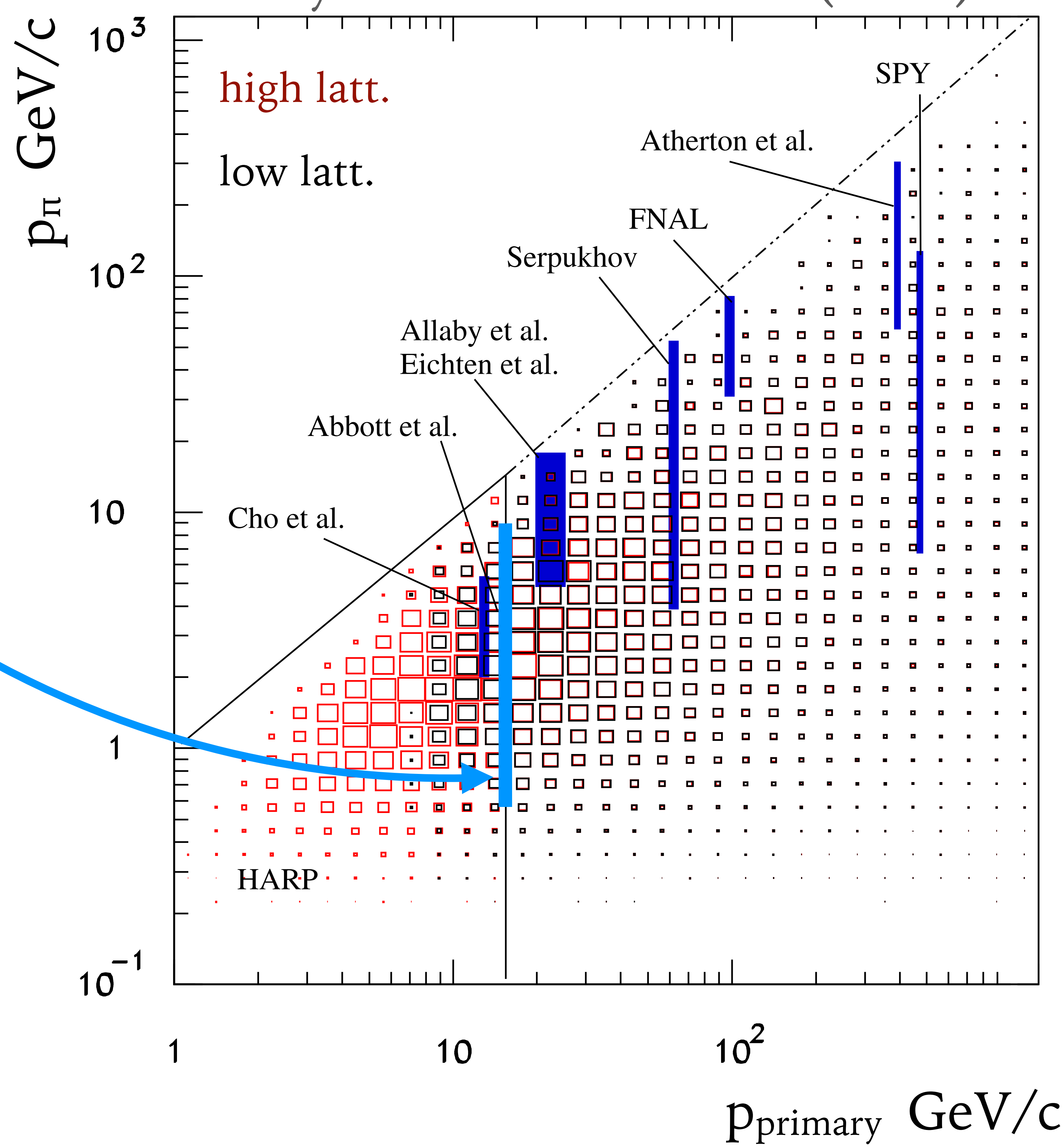
Dashed = fit to 400 and 450 GeV p + Be data scaled in p_T and x_R

Points = data for 24 GeV p + Be interactions

ATMOSPHERIC NEUTRINO FLUXES

- 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

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



SUMMARY

- 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
- Atmospheric fluxes could benefit from more low energy data

SANFORD–WANG PARAMETERIZATION

- J. R. Sanford and C. L. Wang, "Empirical formulas for particle production in p–Be collisions between 10 and 35 BeV/c", Brookhaven National Laboratory, AGS internal report, (1967), *unpublished*
- Depends on p_{beam}, p,θ of hadron
- 8 free parameters for π

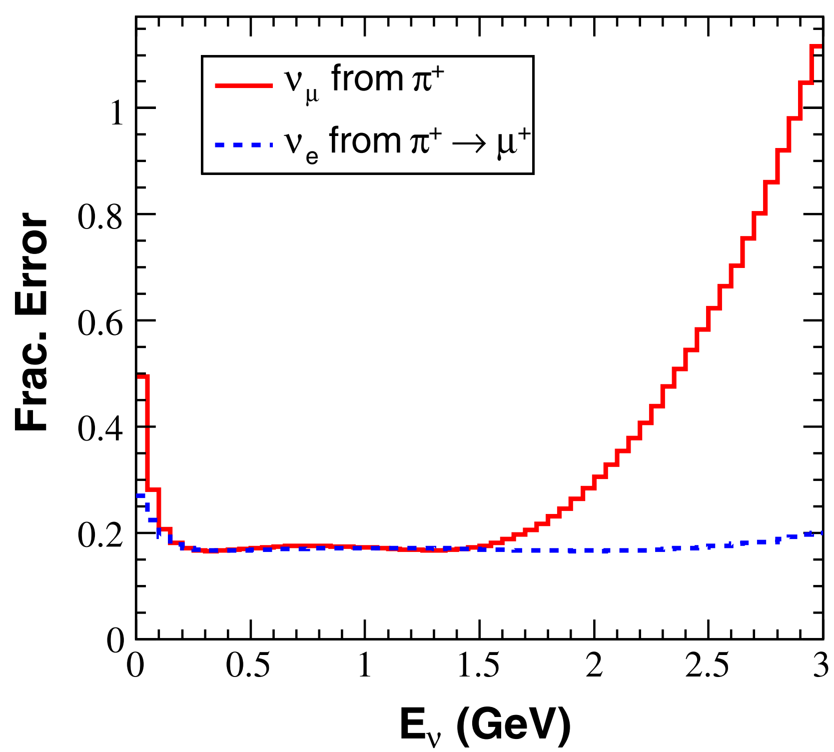
Reproduced from Phys.Rev. C80 (2009) 035208

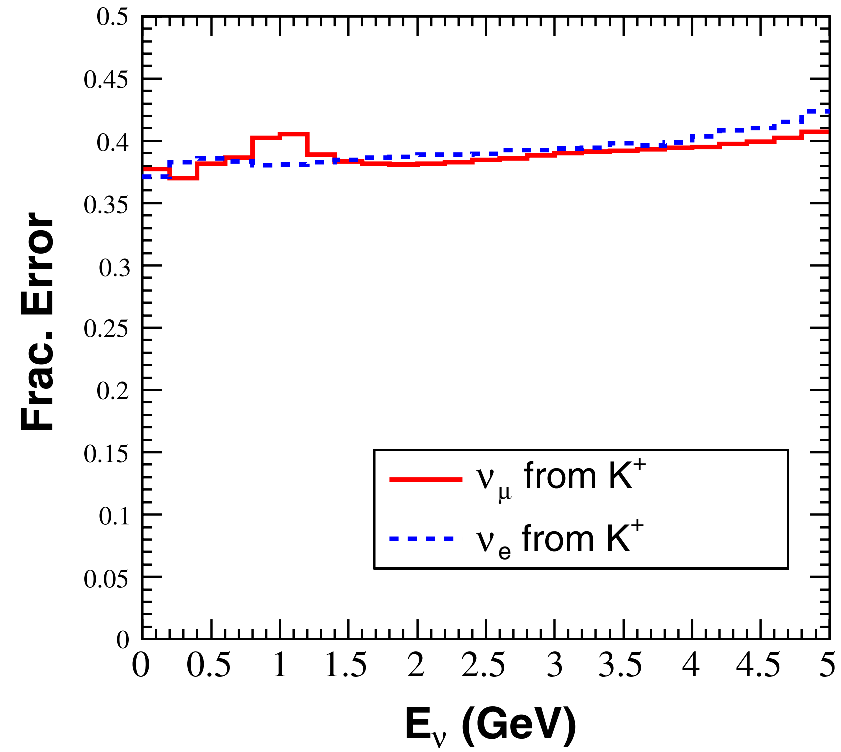
$$\frac{d^2\sigma(\mathrm{pA}\to\pi^\pm X)}{dpd\Omega} = c_1 \exp[B] p^{c_2} (1 - \frac{p}{p_{\mathrm{beam}}})$$

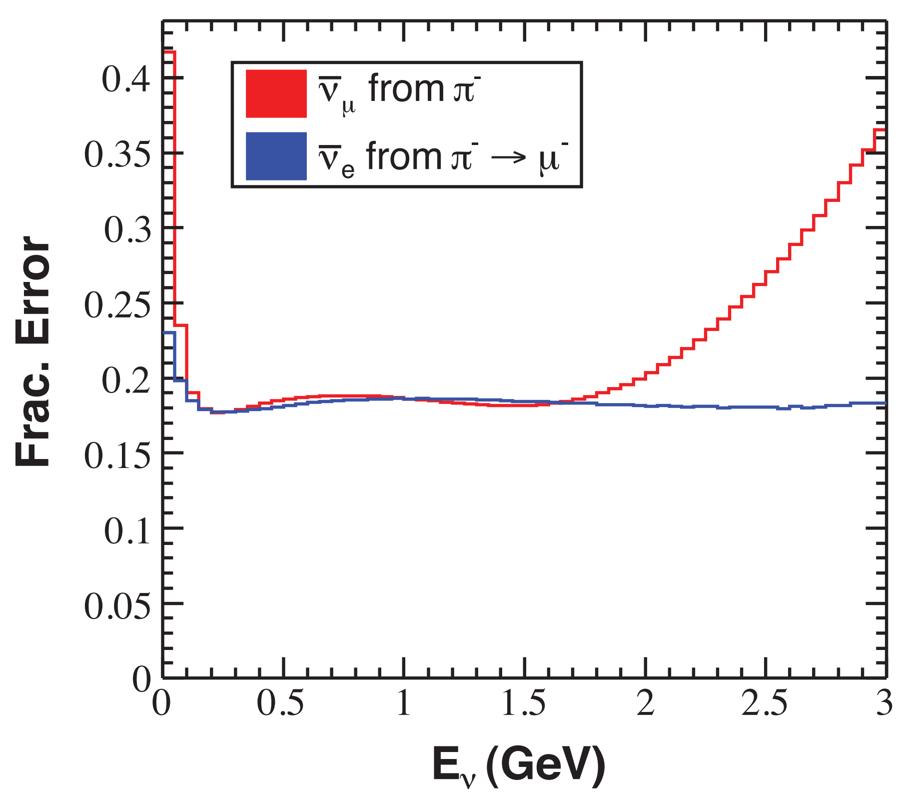
where:

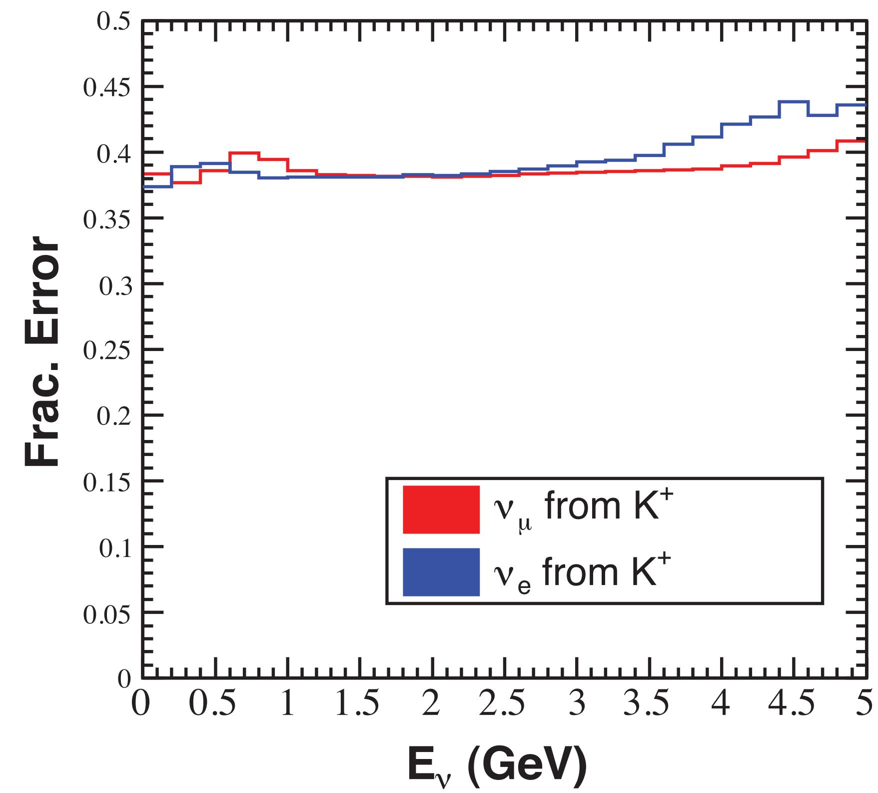
$$B = -c_3 \frac{p^{c_4}}{p_{\mathrm{beam}}^{c_5}} - c_6\theta(p - c_7 p_{\mathrm{beam}} \cos^{c_8}\theta)$$

MINIBOONE FLUX ERRORS FROM HADRON PROD









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)

NA61 THIN VS THICK

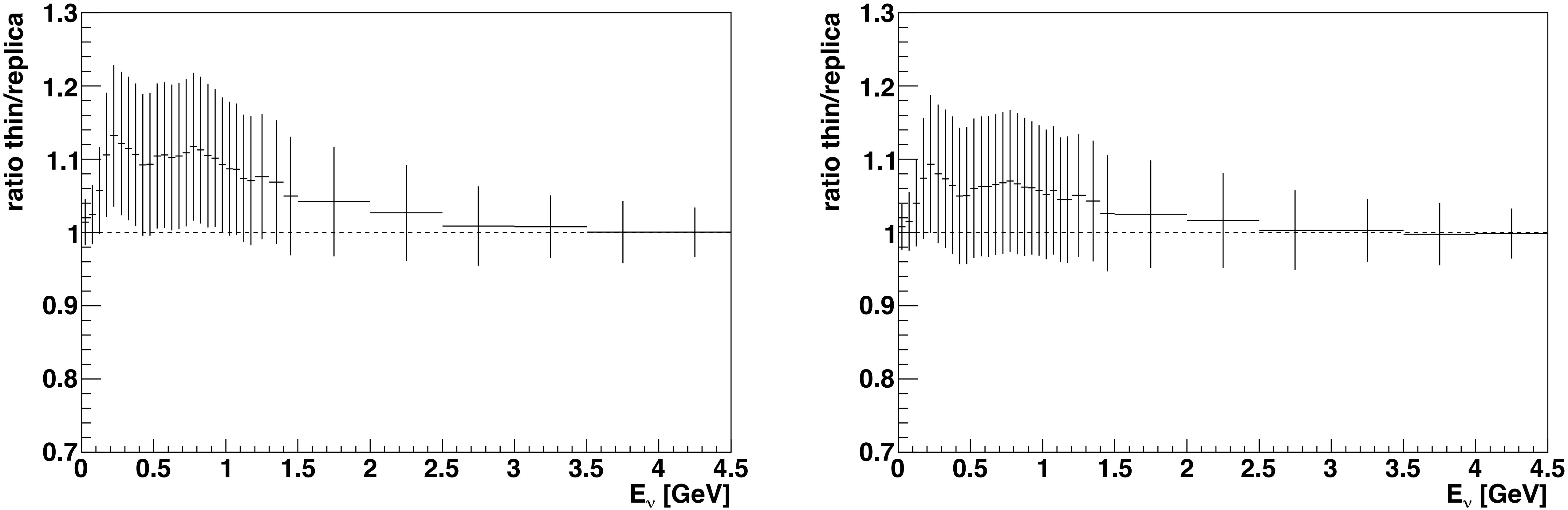
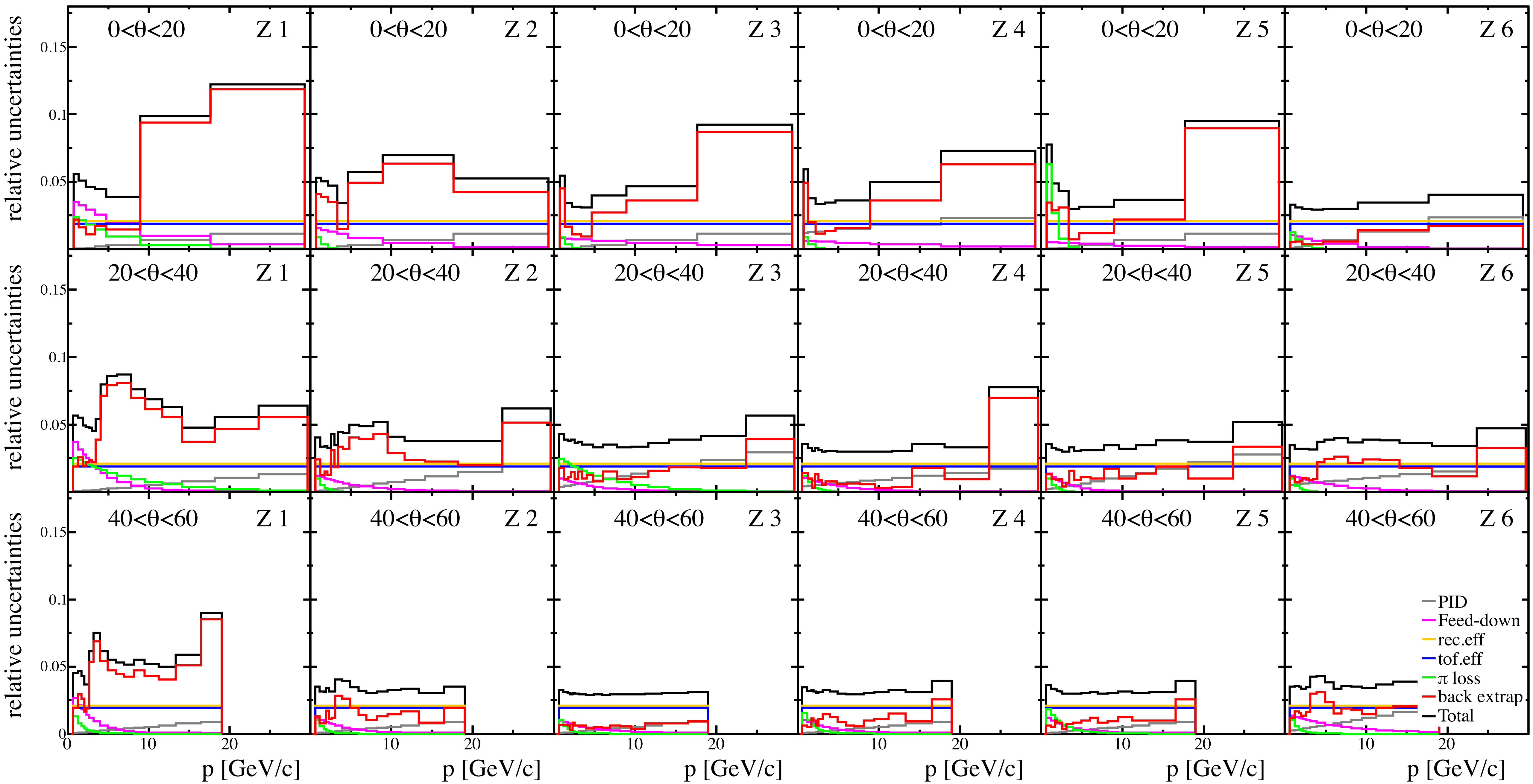


Fig. 28: Ratio of the ν_μ flux at SK re-weighted with the thin target procedure to the p+(T2K RT)@31 GeV/c flux. For the latter pion spectra presented in this paper have been used in the re-weighting. The dominant part of the ν_μ spectra at high E_ν comes from kaons and thus is not affected by the re-weighting of the pion spectra. The left plot shows the ratio calculated using the FLUKA production cross section, whereas the FLUKA cross section reduced by 20 mb was used to obtain the ratio presented in the right plot. Vertical error bars show the full uncertainties on the ratio which are dominated by systematical uncertainties.

NA61 LONG TARGET ERRORS -1   LOW ANGLE PIPLUS



➤ Backward extrapolation dominates at small angles and upstream bins

NA61 LONG TARGET ERRORS -2 MID ANGLE PIPLUS

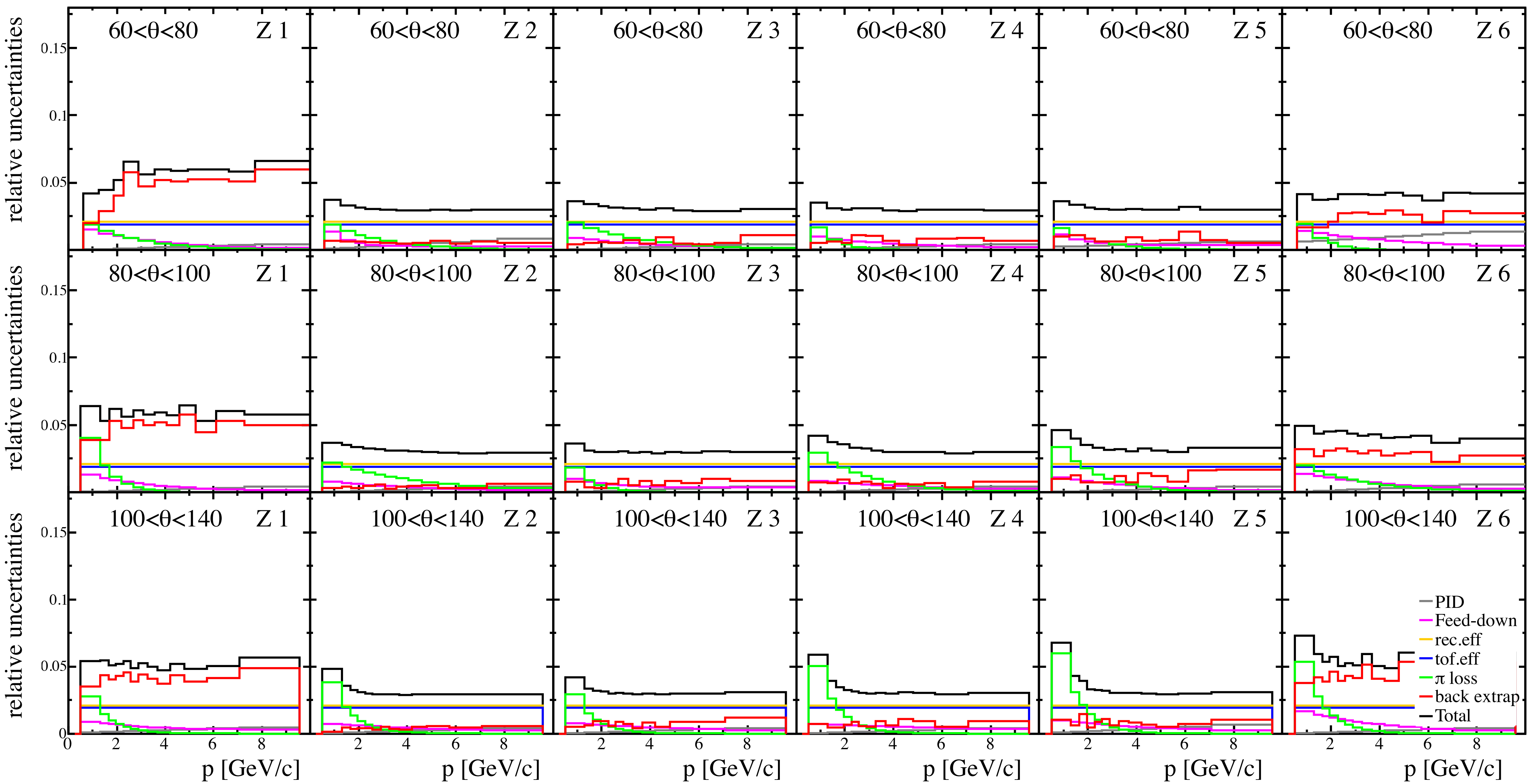


Fig. 14: Components of the systematic uncertainties for positively charged pion spectra, in the polar angle range from 0 to 140 mrad, and for the six longitudinal bins as a function of momentum.

NA61 DE/DX VS P