University of Texas at Arlington

Improving Neutrino Physics with Hadron Production Data

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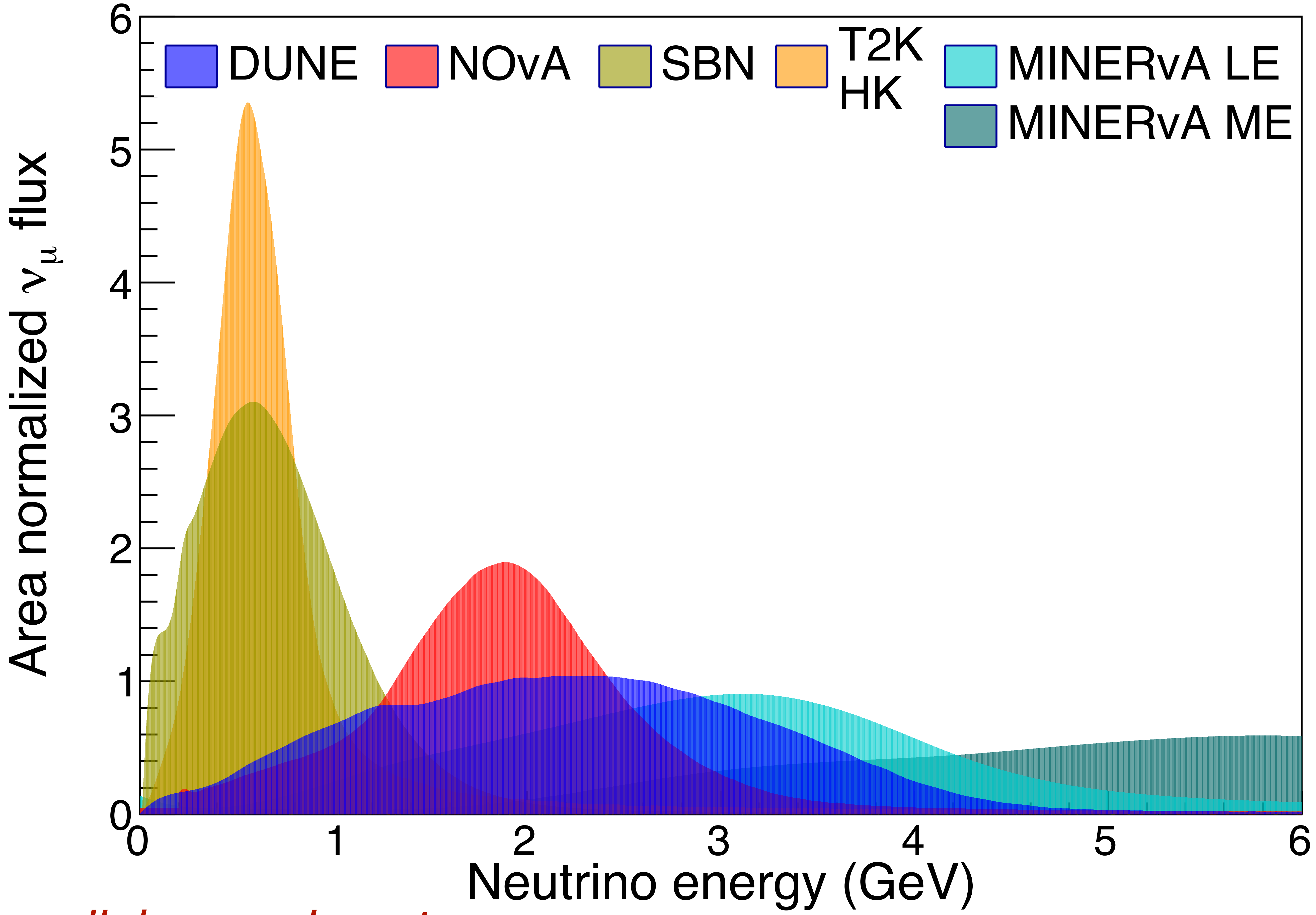
Introduction

Flux uncertainties in accelerator neutrino experiments are still large

- Impacts baseline predictions for near and far detectors, single-detector measururements and neutrino background in BSM searches

- Dominant uncertainties come from interactions in materials (target, horn, etc) or energies or phase spaces that have never been measured

We need more data with higher precision to improve our knowledge of the hadron production and improve the flux prediction



In this talk I will be focused on the neutrino flux at Fermilab experiments

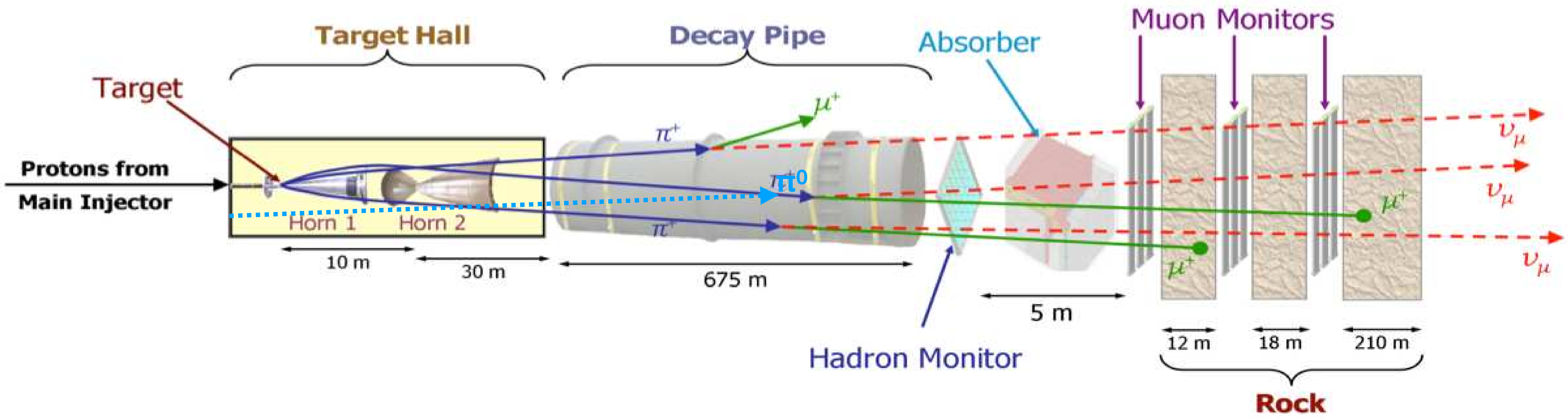
Outline

In this talk I will be focused on the neutrino flux at Fermilab experiments

1. Status of the use hadron production measurements in neutrino experiments for the neutrino flux uncertainties

2. Prospect of the new hadron production measurements in neutrino experiments to improve neutrino flux uncertainties

Neutrinos at Main Injector



- 120 GeV protons from Main Injector
- Graphite target: 0.95 cm (LE) and 1.2 m (ME)
- 2 Magnetic Horns
- Decay Pipe: 675 m filled with He
- 5m steel absorber

~1Km from target: NOvA ND, MINOS ND, MINERvA, ArgoNeuT and 2x2

NOvA	ν oscillations	Analysis / Running	14 mrad off-axis
MINERvA	ν-A cross sections	Analysis	On-axis
ArgoNeuT	ν-Ar interactions	Analysis	On-axis
MINOS	ν oscillations	Legacy	On-axis
2x2	ν-Ar interactions	Commissioning	On-axis

Also MicroBooNE and ICARUS at large off-axis angles

Commissioning | Legacy | Running | Analysis

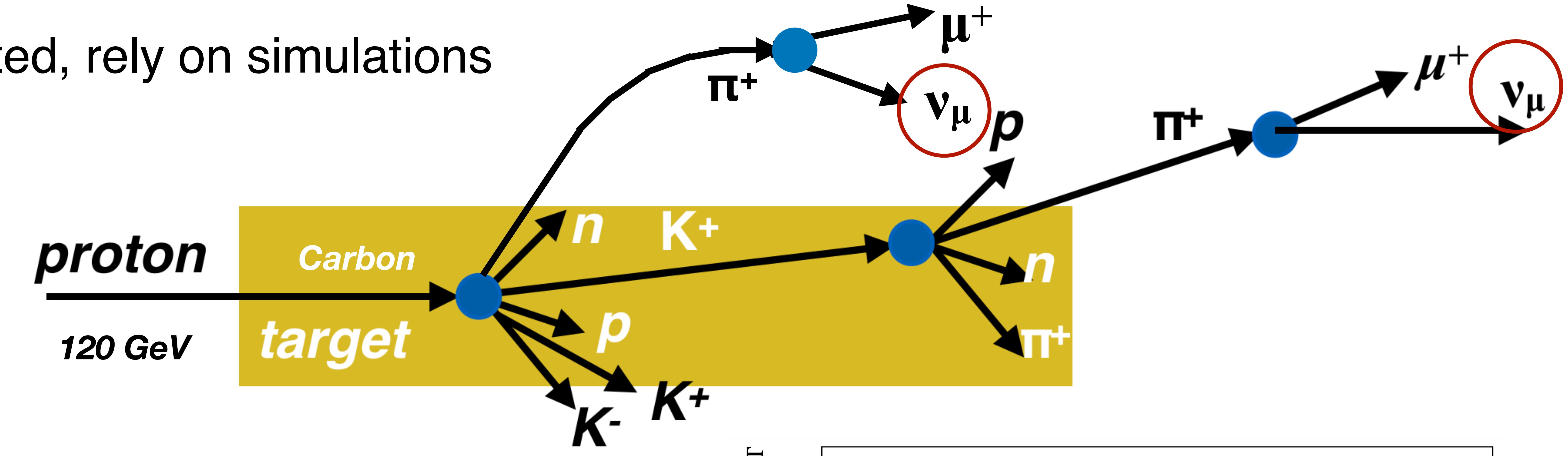
Characterizing the neutrino flux

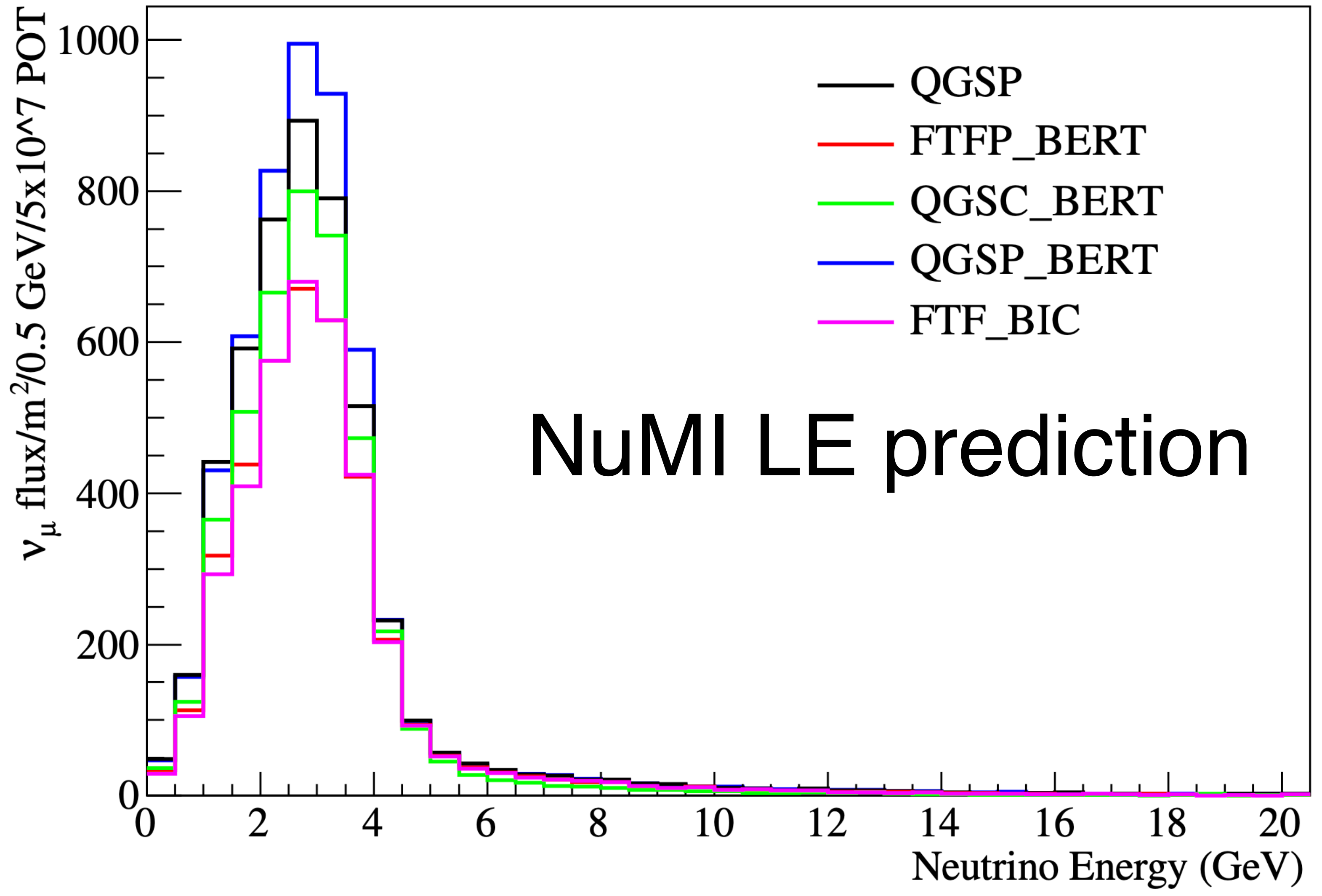
Predicting the neutrino flux is complicated, rely on simulations (model)

The hadron production models have large disagreements

Each interaction mismodel contributes to a mismodel of the neutrino yield and adds uncertainty

Experiments use external data (when possible) to correct the hadron production model





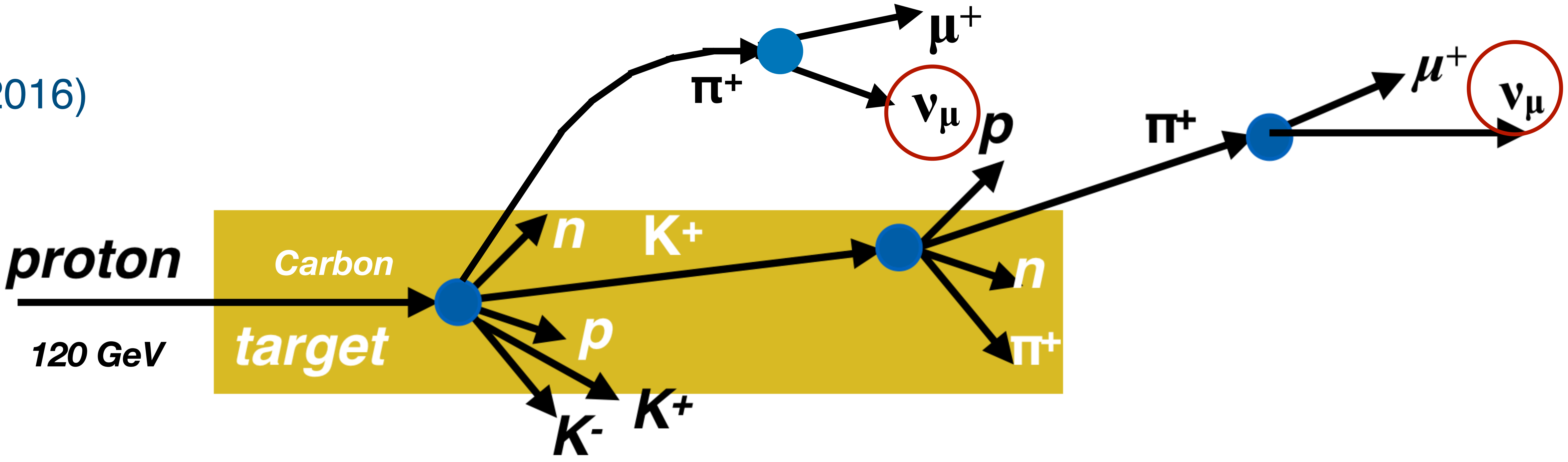
Package to Predict the Flux (PPFX)

*For NuMI, we implement this procedure in the code called **P**ackage to **P**redict the **F**lu**X** (PPFX)*

MINERvA, Phys. Rev. D 94, 092005 (2016)

$$w(p_{prod}, \theta_{prod}, E_{inc}, A) = \frac{[\frac{dn}{dp}]data}{[\frac{dn}{dp}]MC}$$

Correction per interacting particle, material and outgoing hadron



- It was developed in the context of the MINERvA experiment. It is used by MINOS, NOvA, MicroBooNE, ArgoNeuT, and ICARUS to predict the NuMI flux for various physics measurements

- DUNE also utilizes PPFX for its physics sensitivity projections and to calculate the expected flux systematic uncertainties

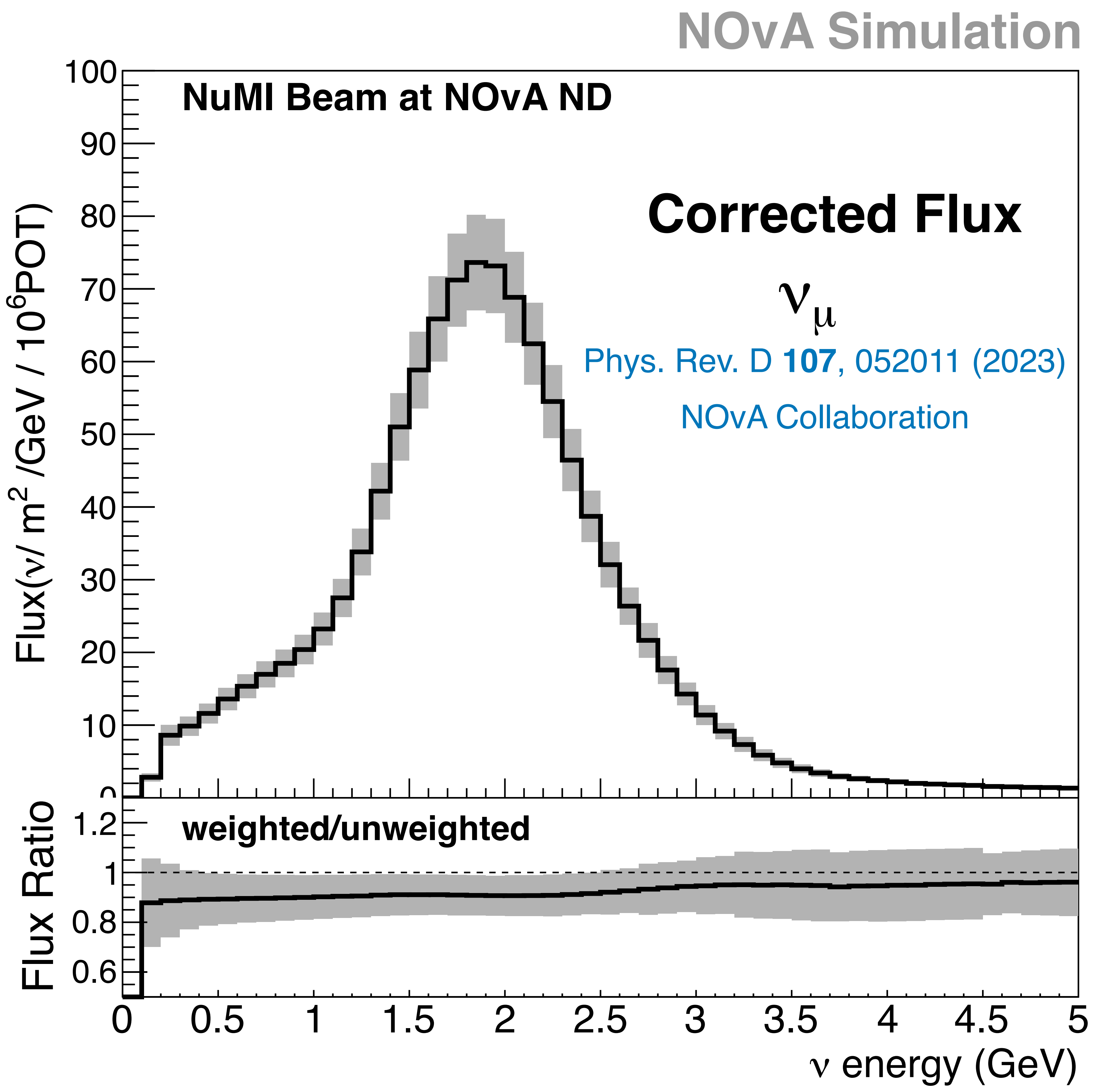
Neutrino flux uncertainties

I will be focused on NuMI (NOvA). Similar conclusions can be made for DUNE

PPFX, developped in the context of the MINERvA experiment incorporate HP data and calculate the flux prediction and uncertainties.

A quick summary of the procedure:

- NA49 p-C at 158 GeV/c using xF-scaling to 12-120 GeV/c
- A-depending scaling uncertainty to extend carbon data
- A large 40% when there is not direct or indirect data.

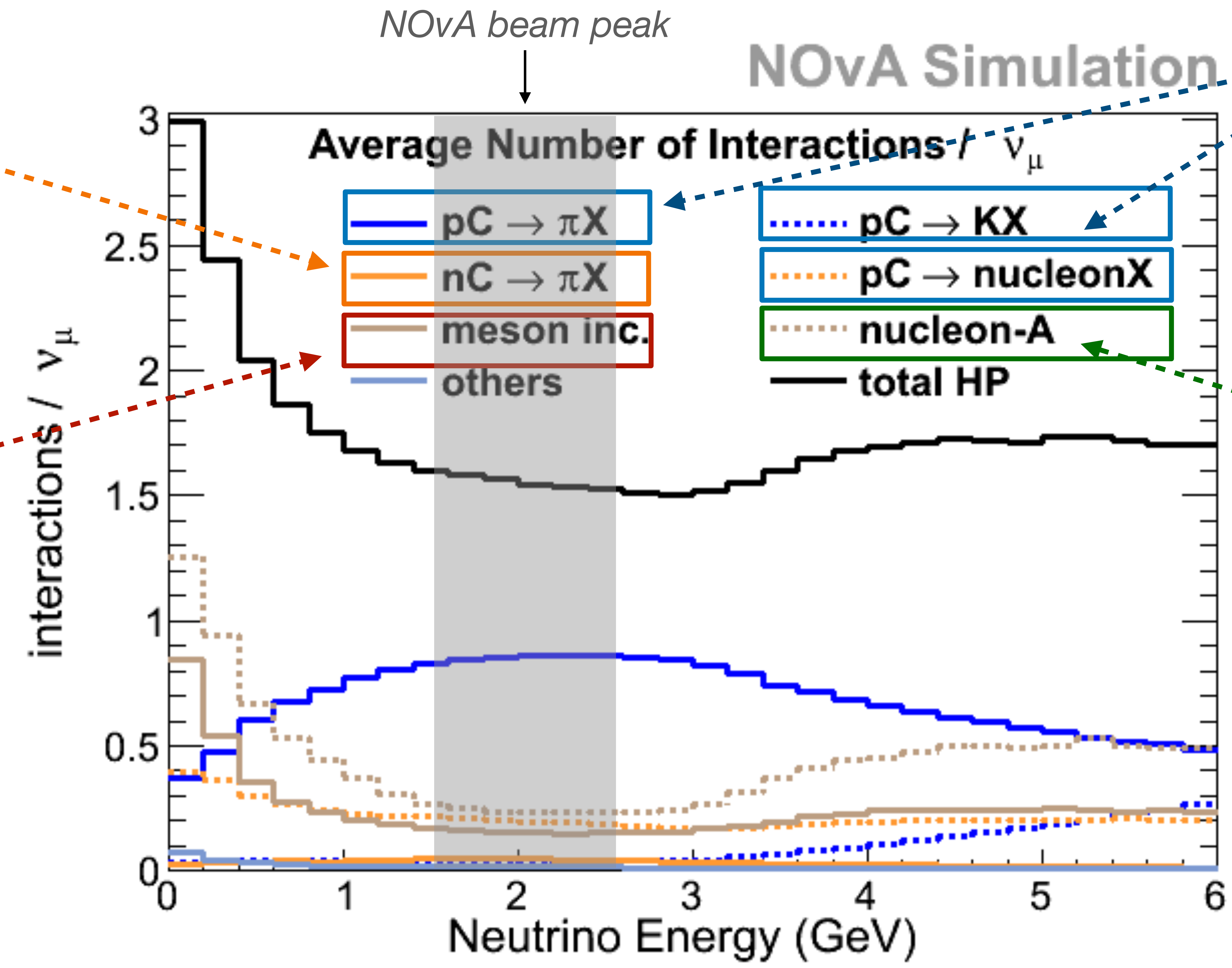


The beamline simulation G4NuMI: the full neutrino flux hadronic ancestry is stored. PPFX uses this information to calculate a correction to the simulation and the uncertainty

Hadronic Interactions

Extended based isospin symmetry

We assume large uncertainties for meson incident: 40%



Based directly on data (mostly NA49)

Quasi-elastics, extension p-C to p-A (A!=C), and interactions outside data coverage

Applying NA49 data

NA49 measured charged-pions, charged-kaons, protons and neutrons production of protons on carbon interactions @ 158 GeV

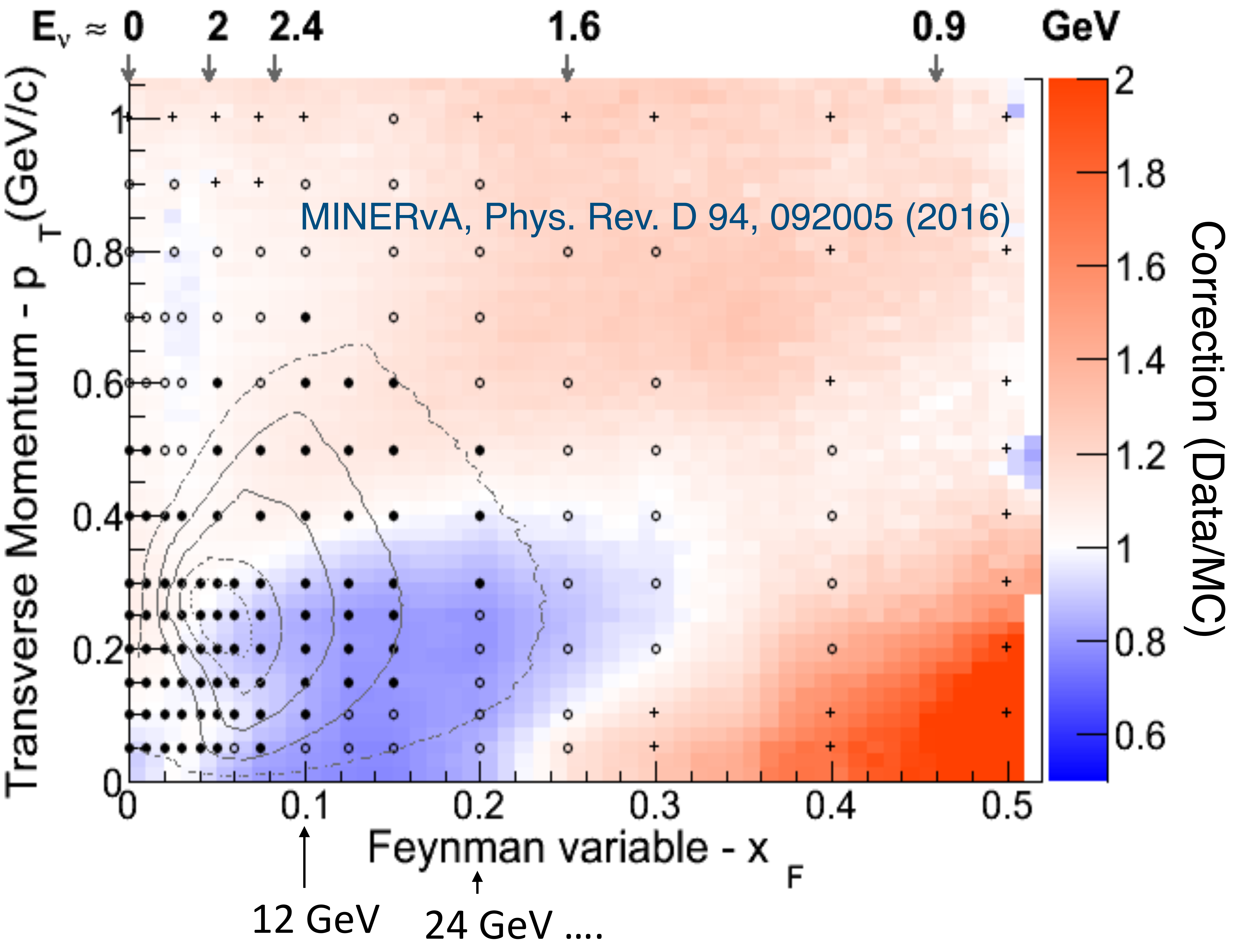
We use the Feynman scaling to apply data at 158 GeV to any proton in 12-120 GeV

$$x_F = \frac{p_L}{\sqrt{s}/2}$$

x_F: fraction of the longitudinal momentum in the nucleon-nucleon center of momentum

(solid circles are stat. uncer. < 2.5 %, empty circles < 5% and crosses > 5%)

Syst. uncertainty is 3.8%



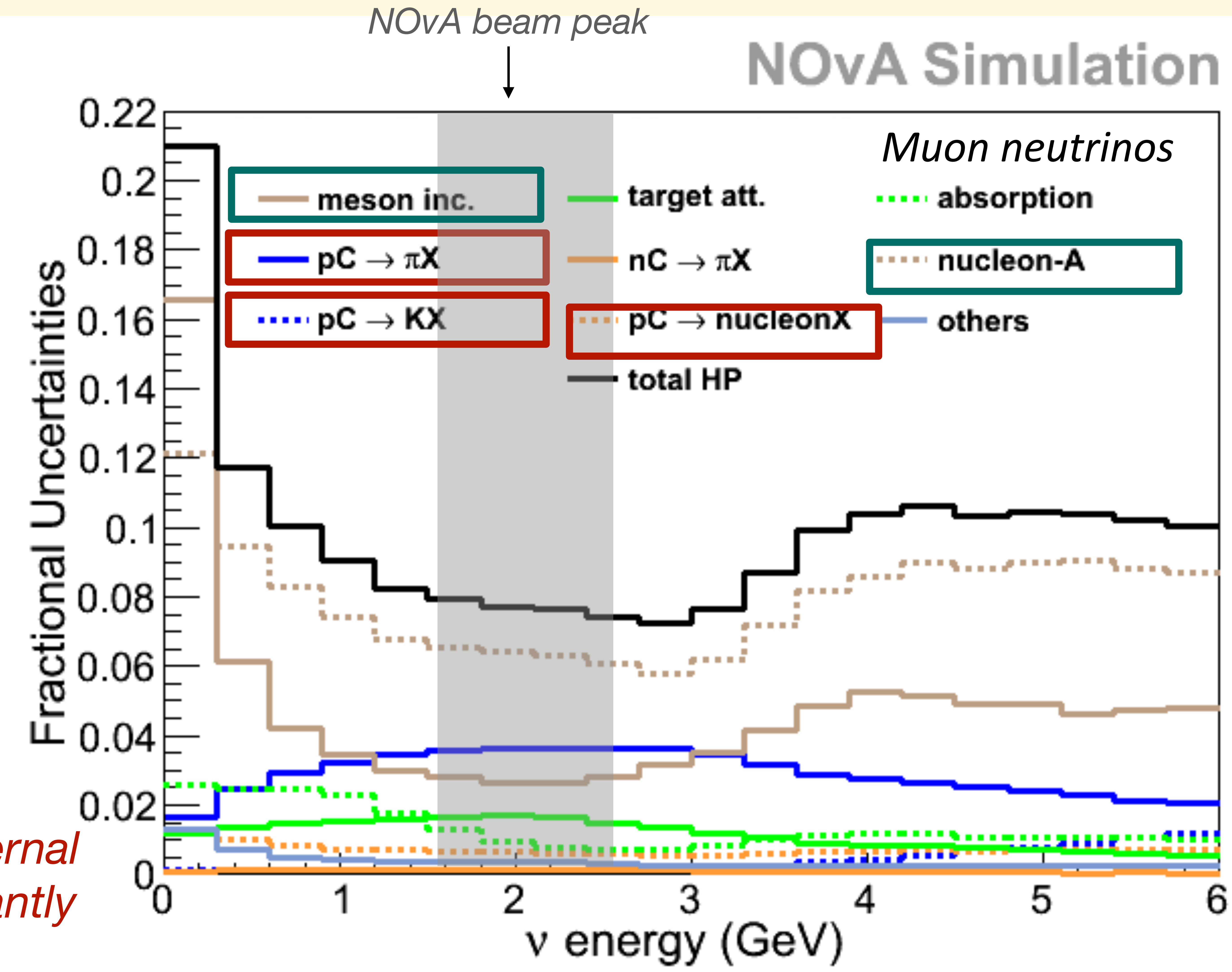
Flux uncertainties at NOvA

~ 8-9% uncertainties on the flux

At the flux peak, there is an average of 1.6 hadronic interactions per neutrino at NOvA

Interaction	External	Contribution
pC->π+- X	NA49	53.1%
pC->(p,n) X	NA49	12.5%
Sec. interacting protons	No data	14.4%
Interacting mesons	No data	9.4%
All others		10.6%

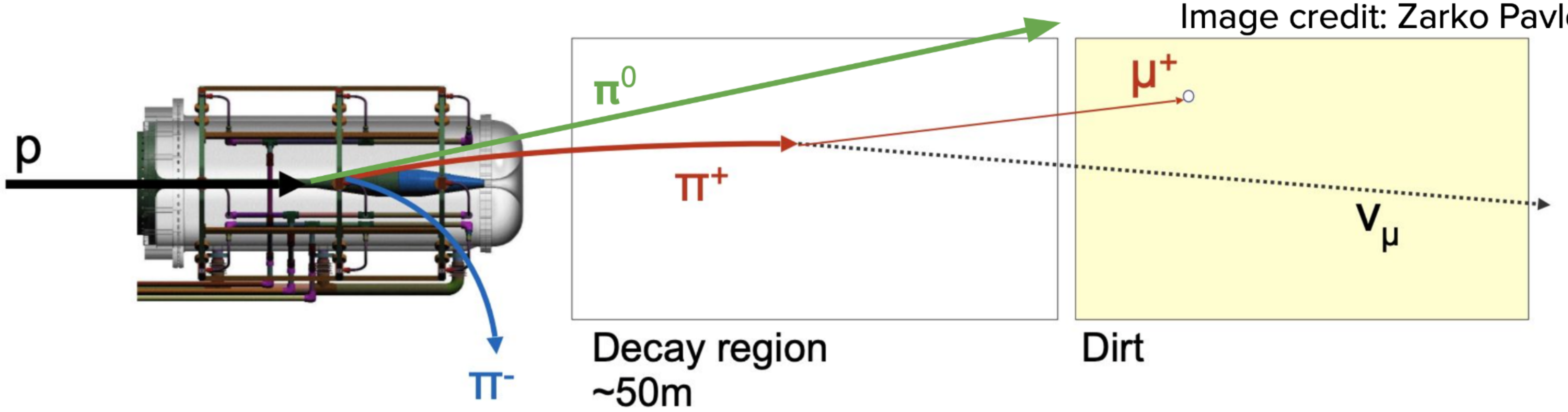
When we include constraints based on external data, the uncertainties are reduced significantly

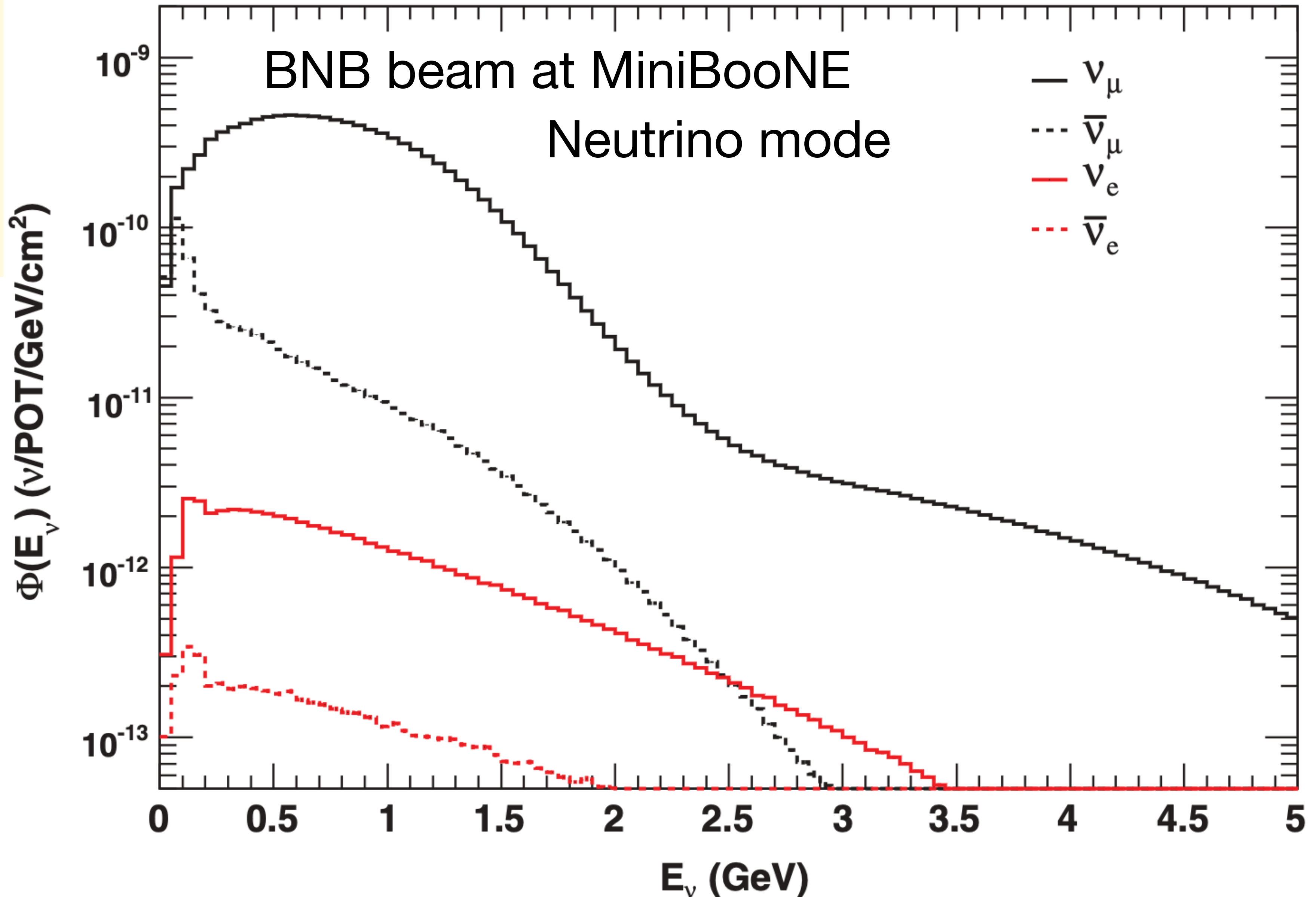


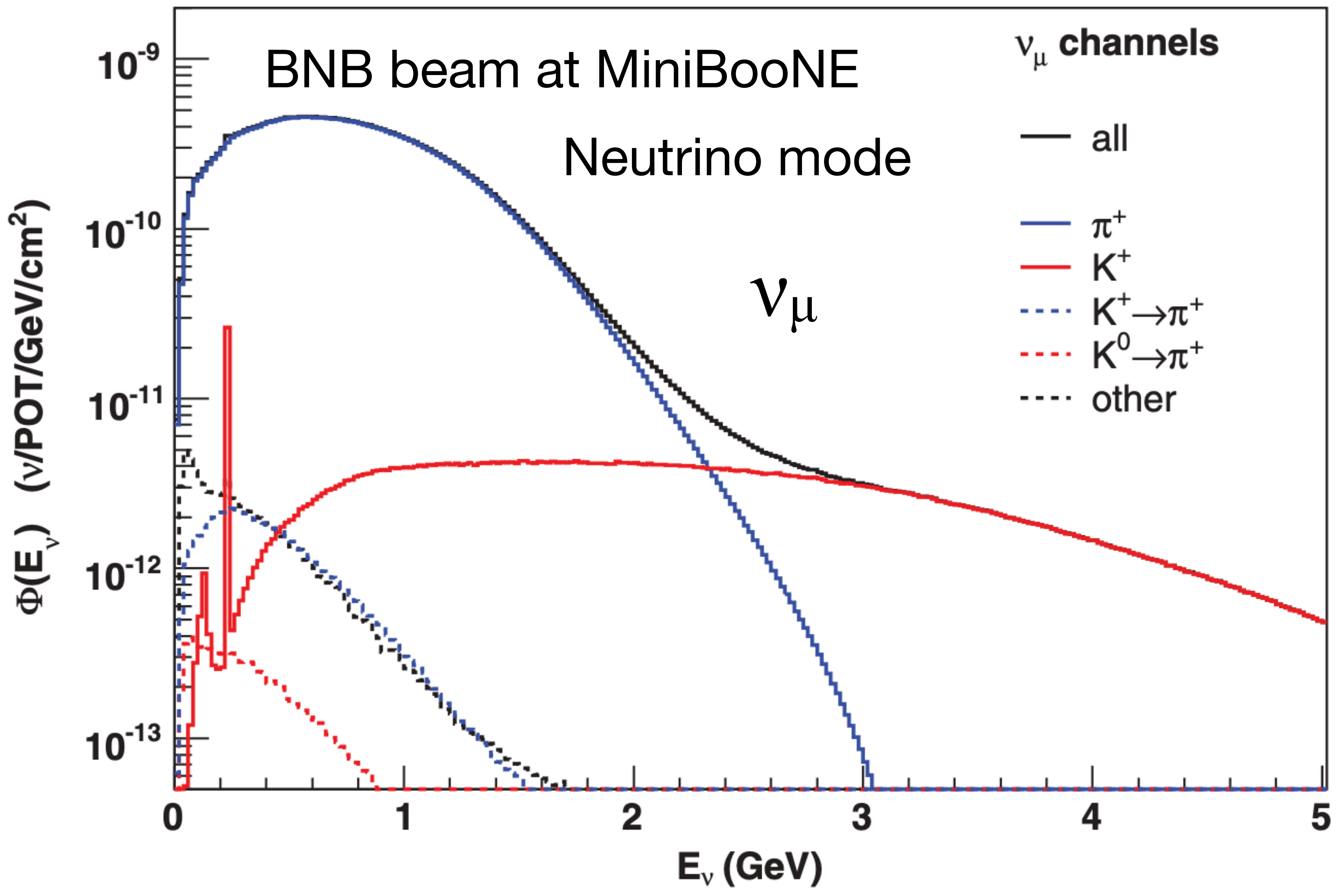
The BNB Beamline

- 8 GeV protons from the Booster
- 70 cm beryllium target
- 1 magnetic horn made of aluminum
- A collimator made of concrete, located between the Horn and the Decay Pipe
- 50 m Decay Pipe filled with Air. The Decay Pipe Wall made of concrete and steel
- 25m steel Absorber

Image credit: Zarko Pavlovic



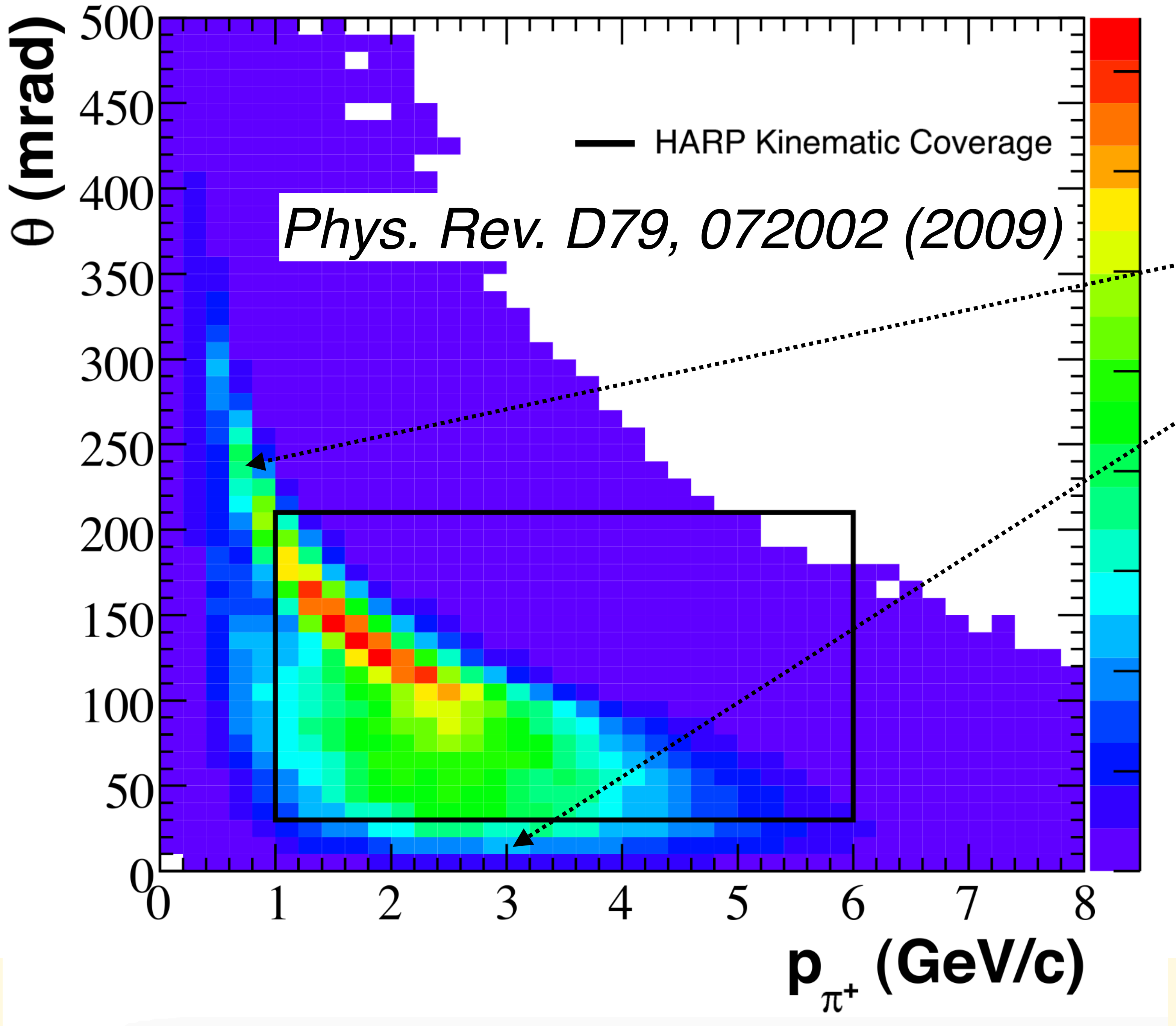




Phys. Rev. D79, 072002 (2009)

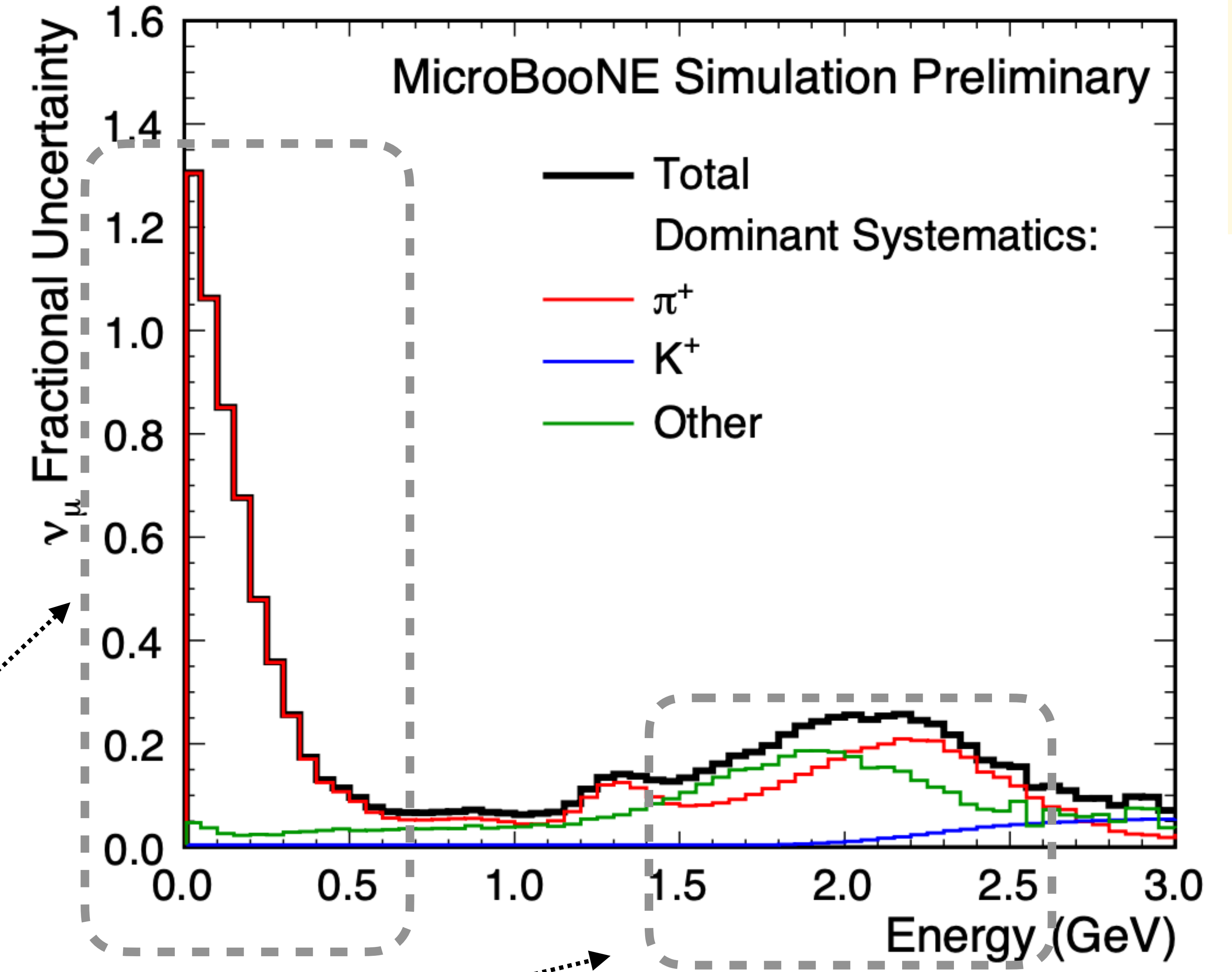
Current BNB Flux prediction

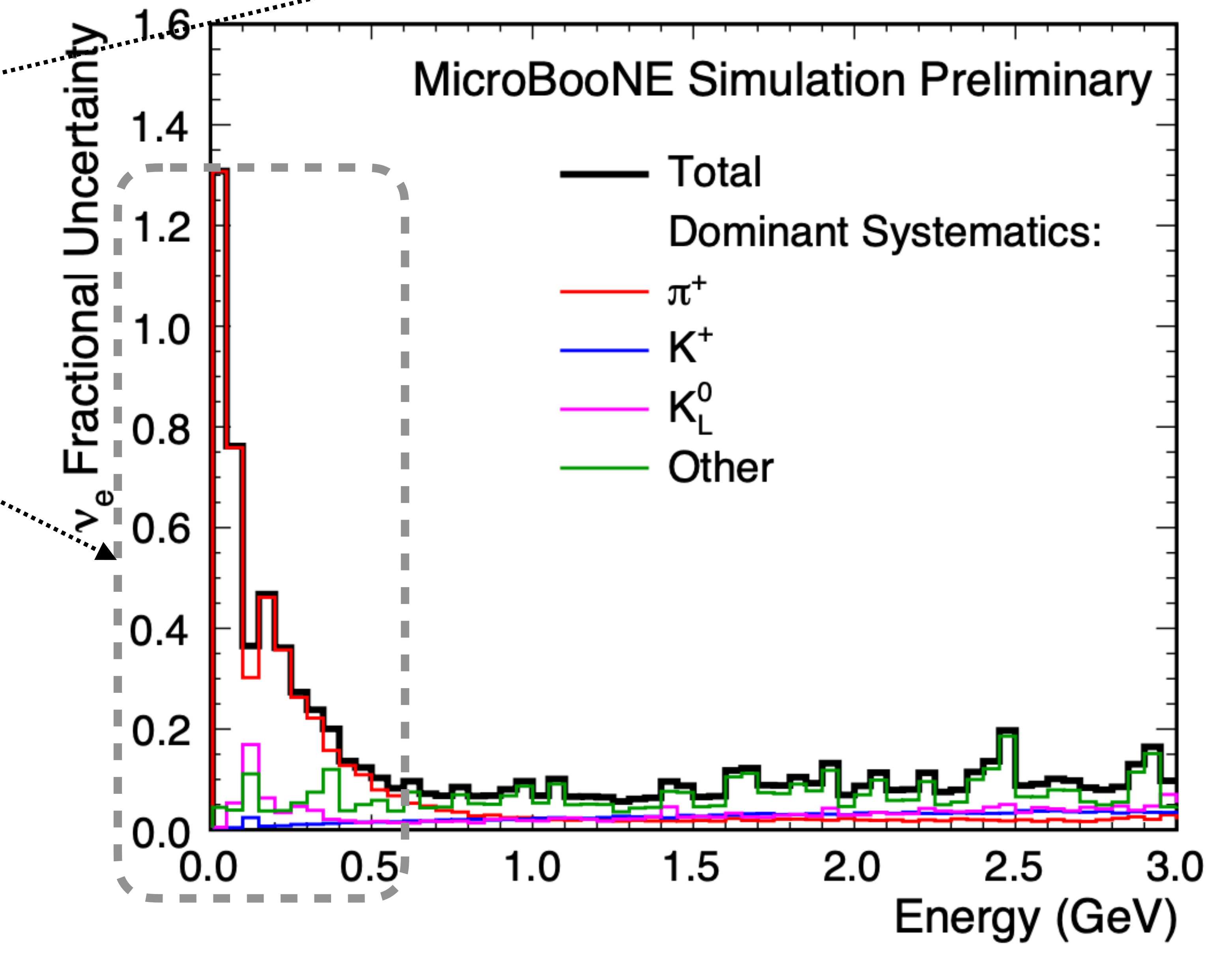
- Sanford-Wang (SW) fits to HARP and E910 to get the pBe -> π^{+-}
- Feynman-x scaling based on fit world for pBe -> K^+ and additional constraint from SciBooNE.
- SW fits to E910 and KEK to get the pBe -> K0L
- Large data on (σ_{inel},σ_{prod}) is available. σ_{qe} data is sparsed.



Large uncertainties come from out-of-the-coverage data

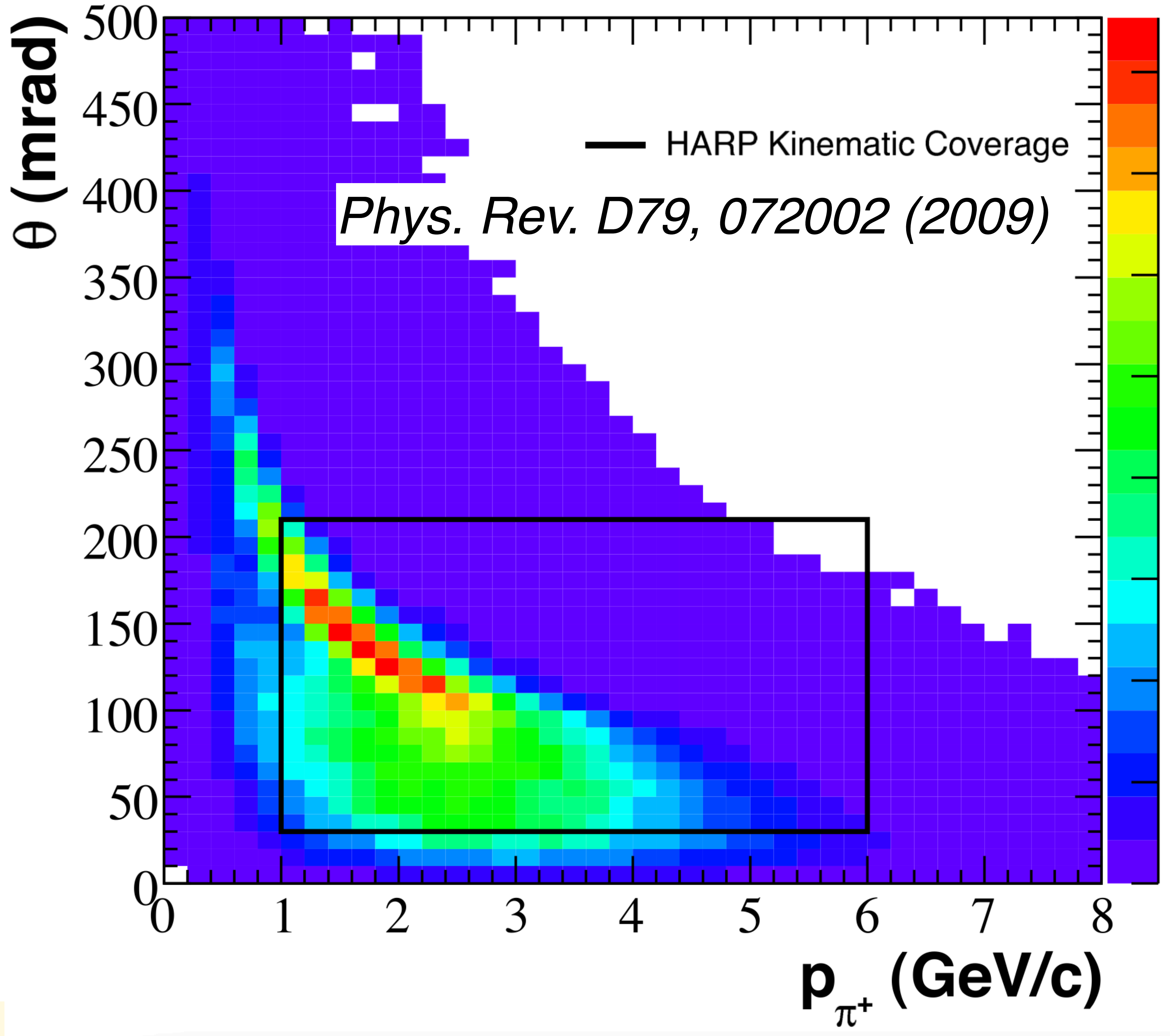
Small kaon uncertainty comes from neutrino data: reduced from 14% to 7%

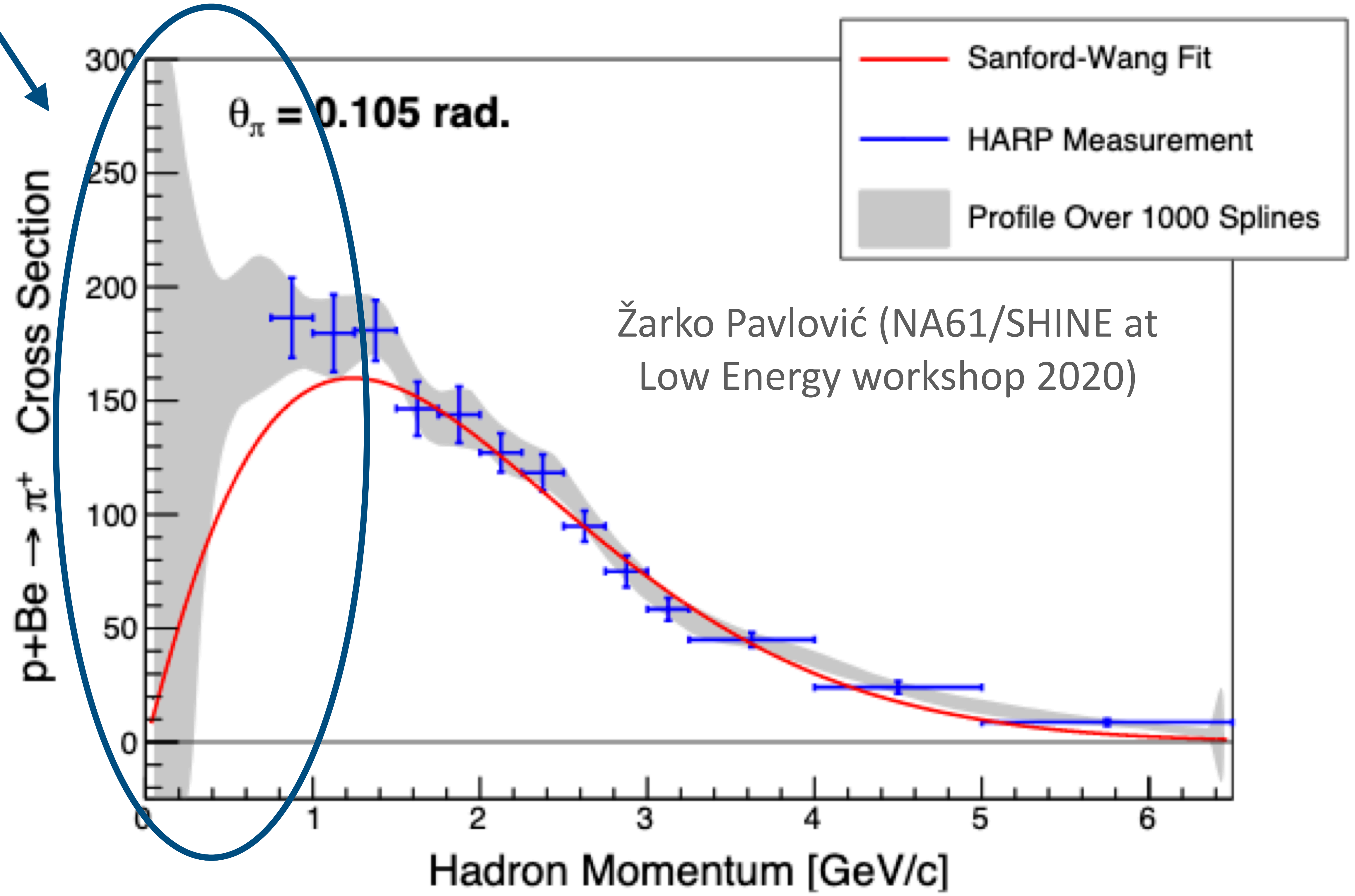




Use of HARP π^+ data

- For uncertainties, the interpolated HARP double differential cross sections using its covariance matrix, is compare to the Sanford-Wang (SW) prarametrization predition.
- The challenge is to model the region outsde the data coverage
- This can be improved using other datasets in conjuntion of Feyman-x and material scalings





Žarko Pavlović (NA61/SHINE at Low Energy workshop 2020)

Existing data to improve the flux calculation

- We have new hadron production datasets released in the last years coming from NA61/SHINE (CERN) and EMPHATIC that collaborators are working to implement in PPFX and be ready to use for NuMI experiments and DUNE
- There is an effort to improve the BNB flux prediction with existing data and new data for precise measurement.
    - SBN experiments are interested to use EMPHATIC and NA61/SHINE data
- Some assumptions due to the lack of direct data will be replaced by new data, such as
    - Test the limits of the Feynman-x energy scaling and material scaling
    - Extend the coverage of hadronic interactions with direct data

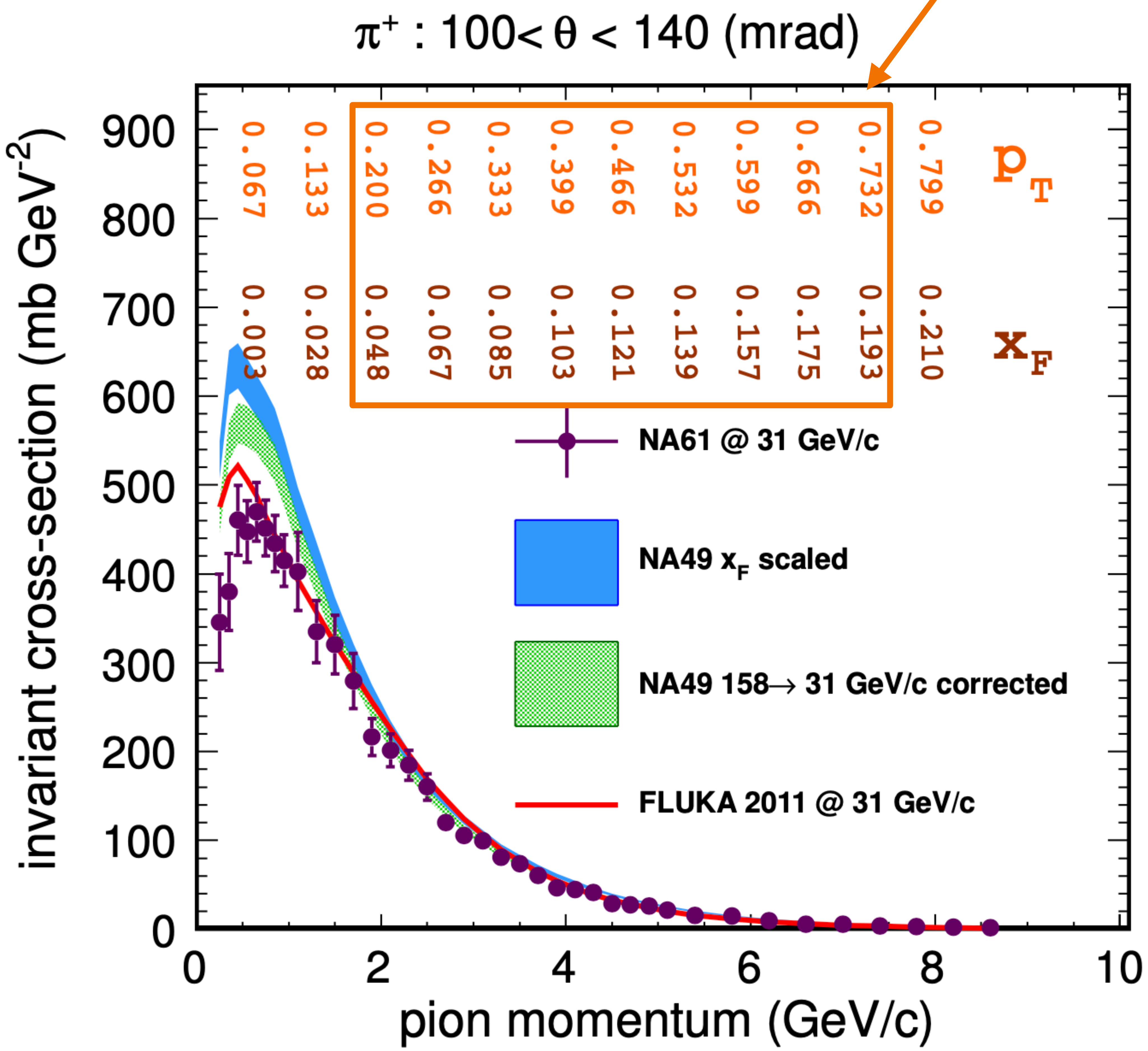
NA49 vs NA61 proton-carbon hadron production

- There is a general good agreement between **pion differential cross section in proton-carbon interactions**
- There is still a Feynman-x scaling violation at lower momentum that FLUKA did not capture completely.
- Other angles show similar pattern.

Datasets:

- **NA49**: Eur.Phys.J.C49:919-945,2007
- **NA61**: The European Physical Journal C, 76(2), 1-49 (2016)
- **NA61**: arXiv:2306.02961 [hep-ex]
- **HARP**: Phys. Rev. C 77, 055207 (2008)
- **Barton et al.**: Phys. Rev. D **27**, 2580 (1983)

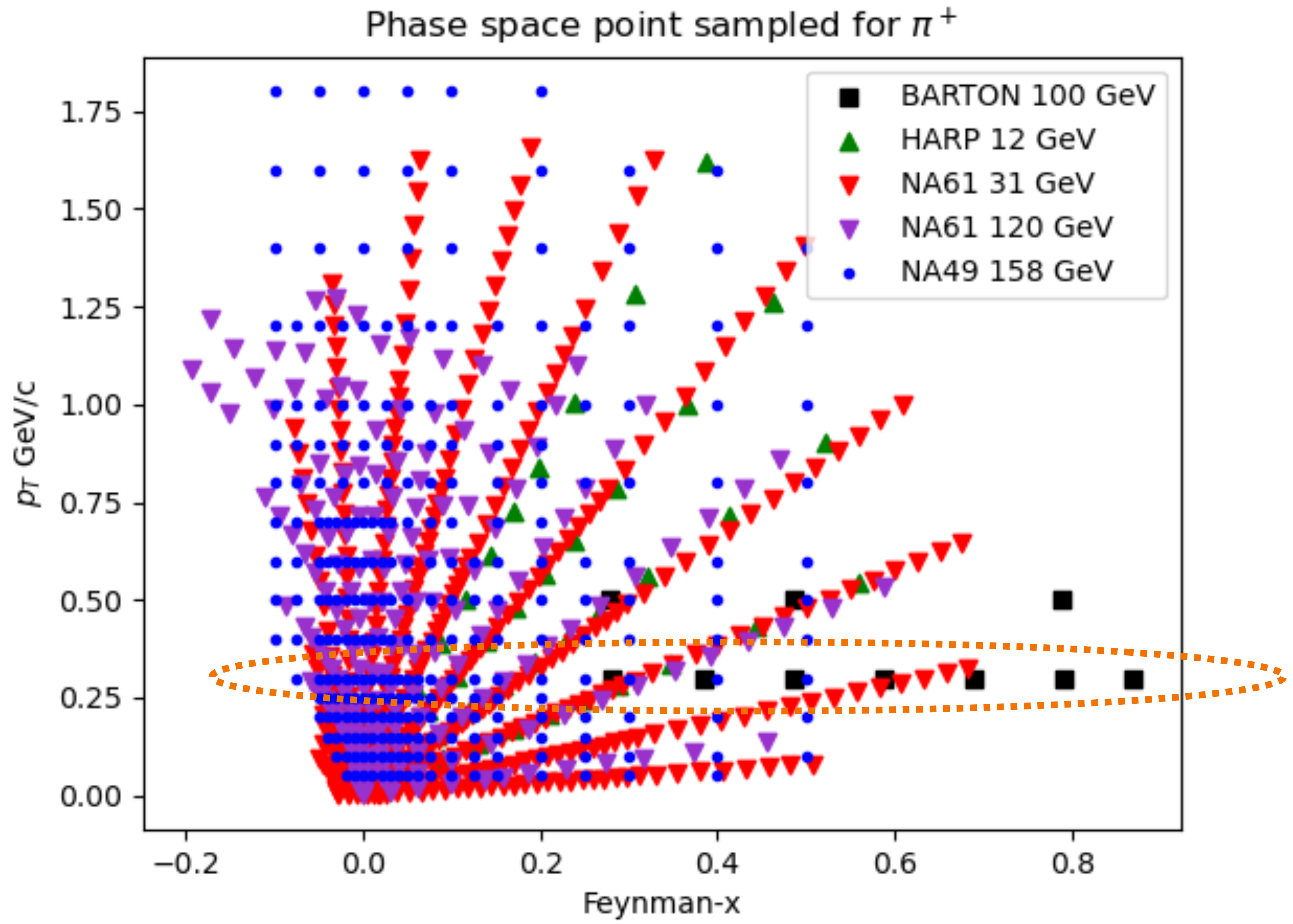
More relevant region for the neutrino peak at few-GeV

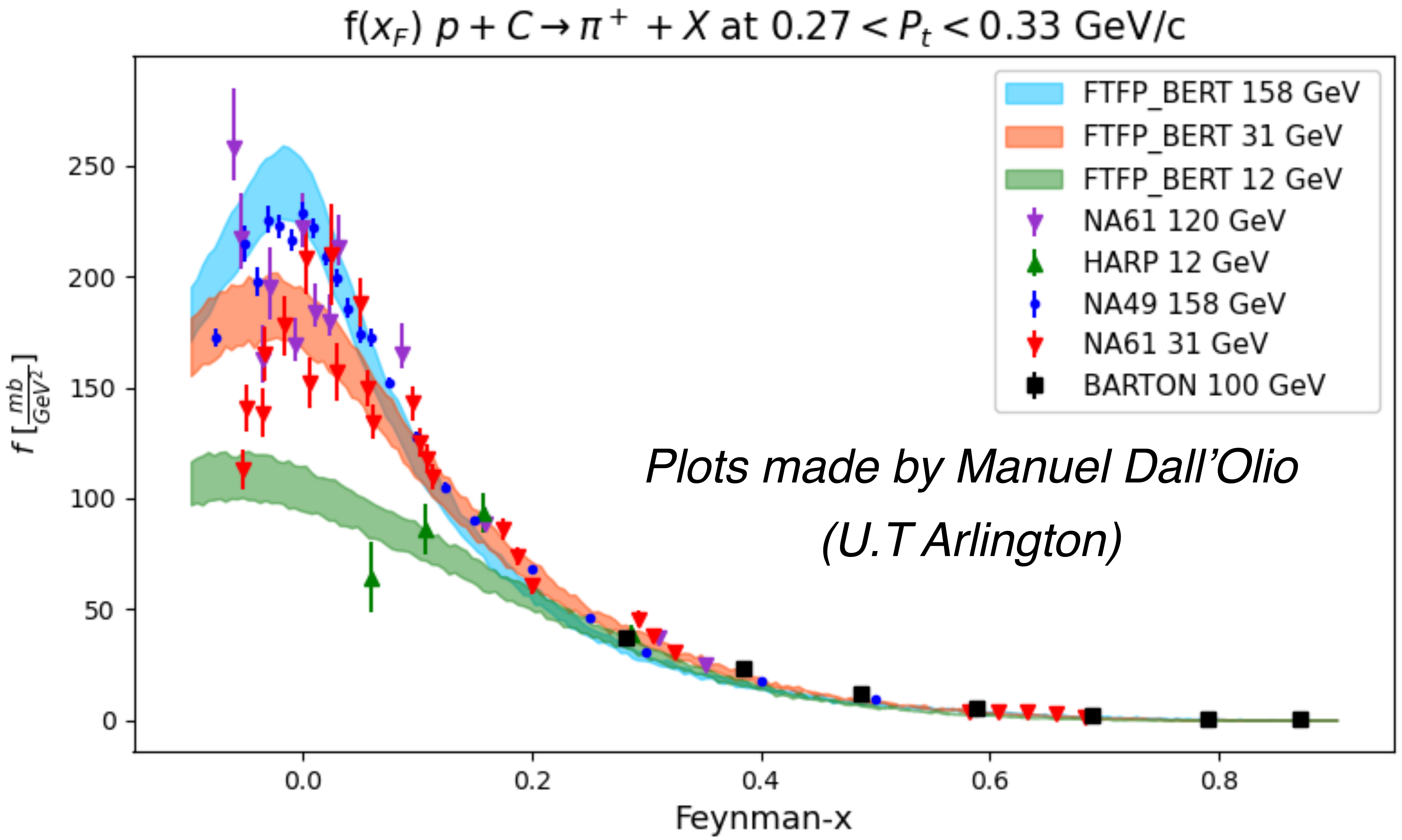


Proton-carbon hadron production

Pion differential cross section in proton-carbon interactions in comparison with Geant4 FTFP_BERT model

Procedure: convert datasets to invariant cross section and select values in a narrow transverse momentum region: **$0.27 < p_T < 0.33$ GeV/c**



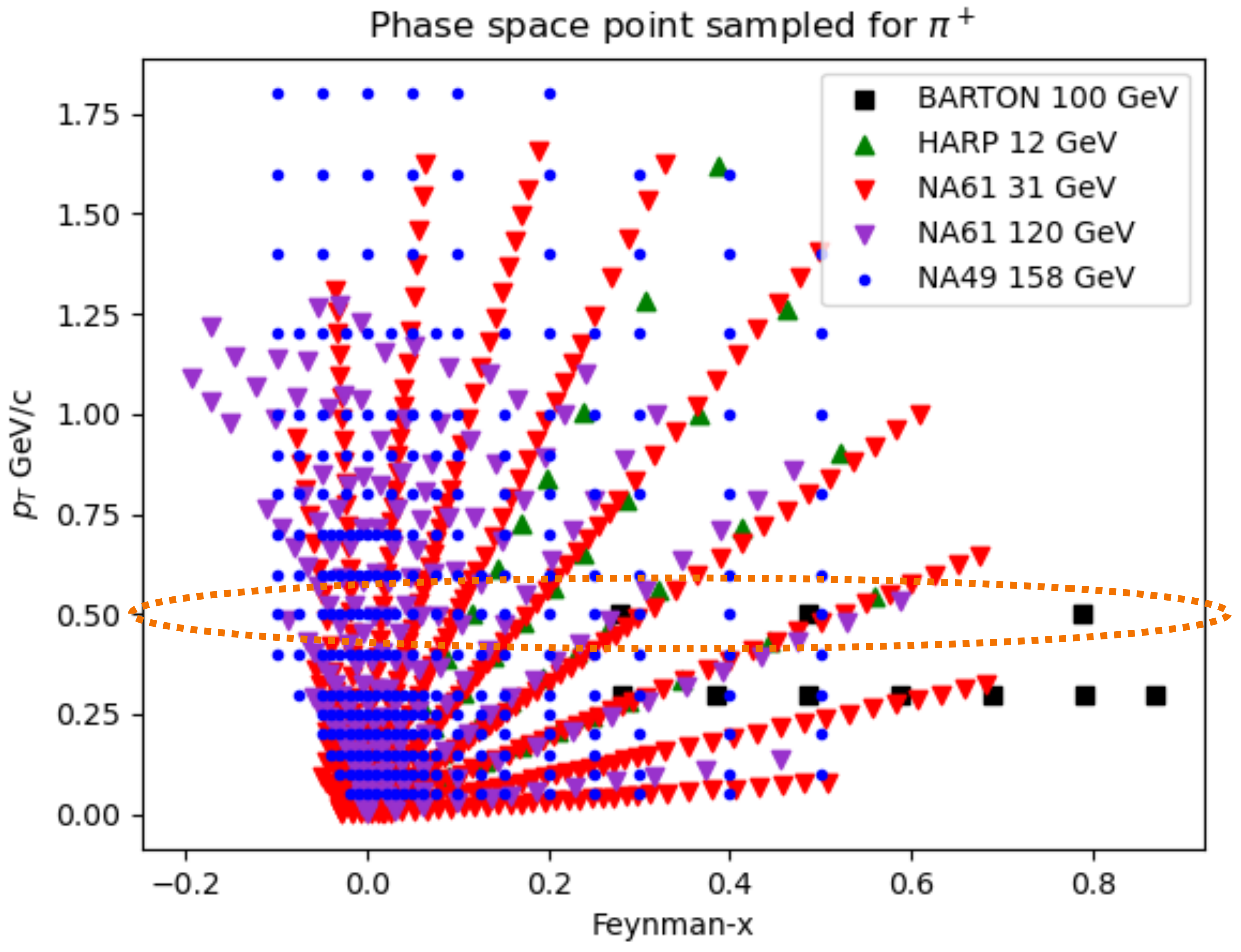


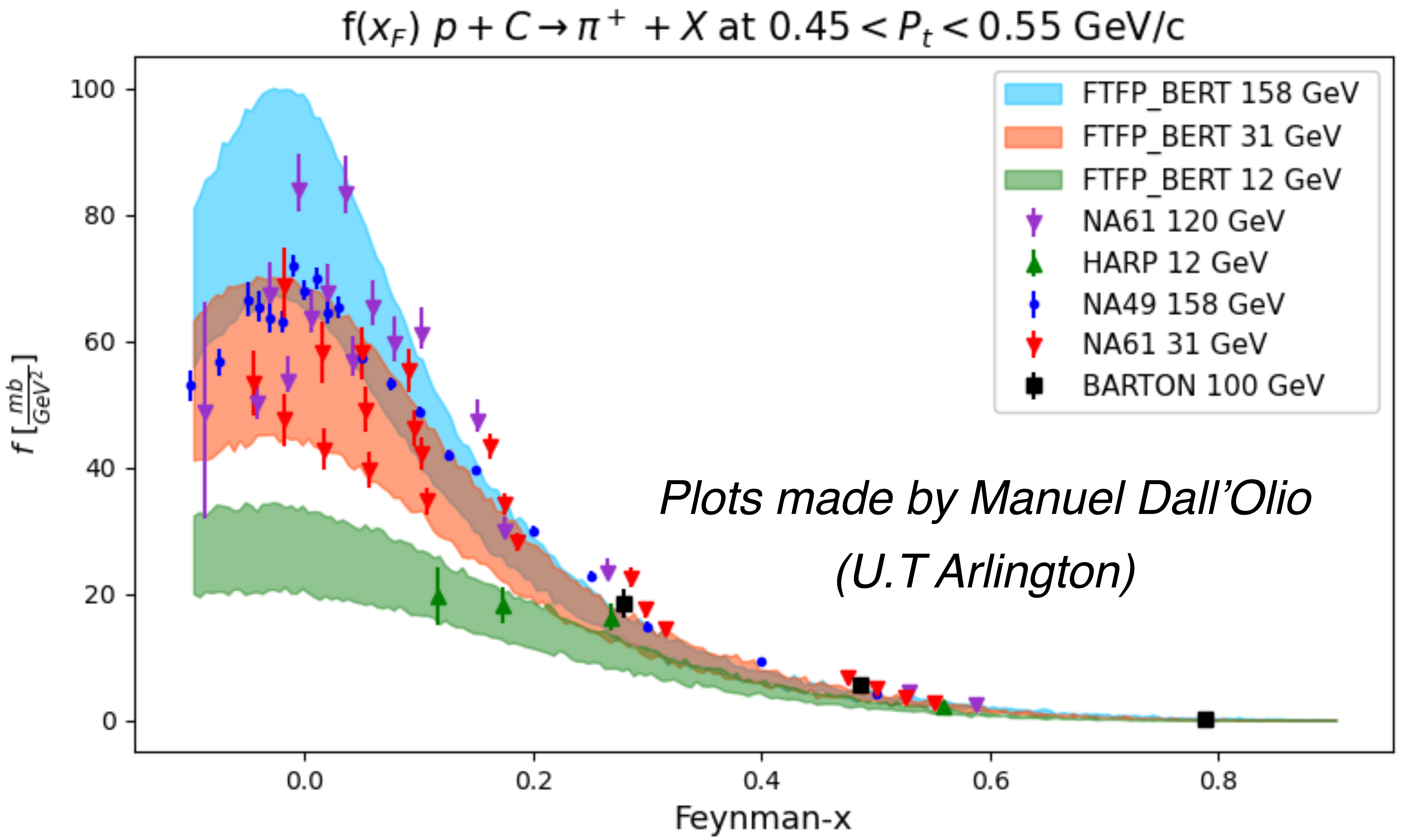
Plots made by Manuel Dall'Olio (U.T Arlington)

Proton-carbon hadron production

Pion differential cross section in proton-carbon interactions in comparison with Geant4 FTFP_BERT model

Procedure: convert datasets to invariant cross section and select values in a narrow transverse momentum region: **$0.45 < p_T < 0.55$ GeV/c**

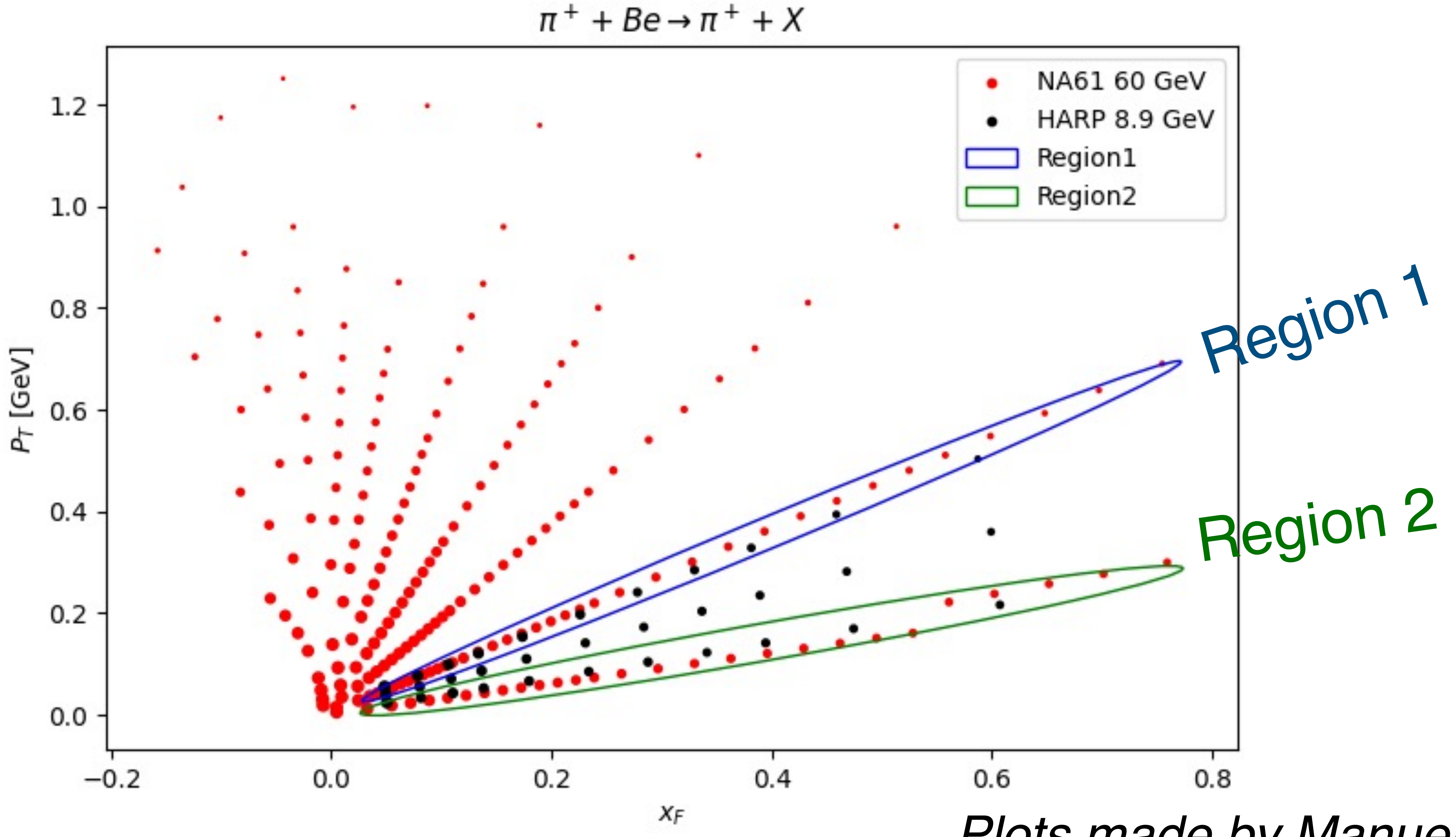


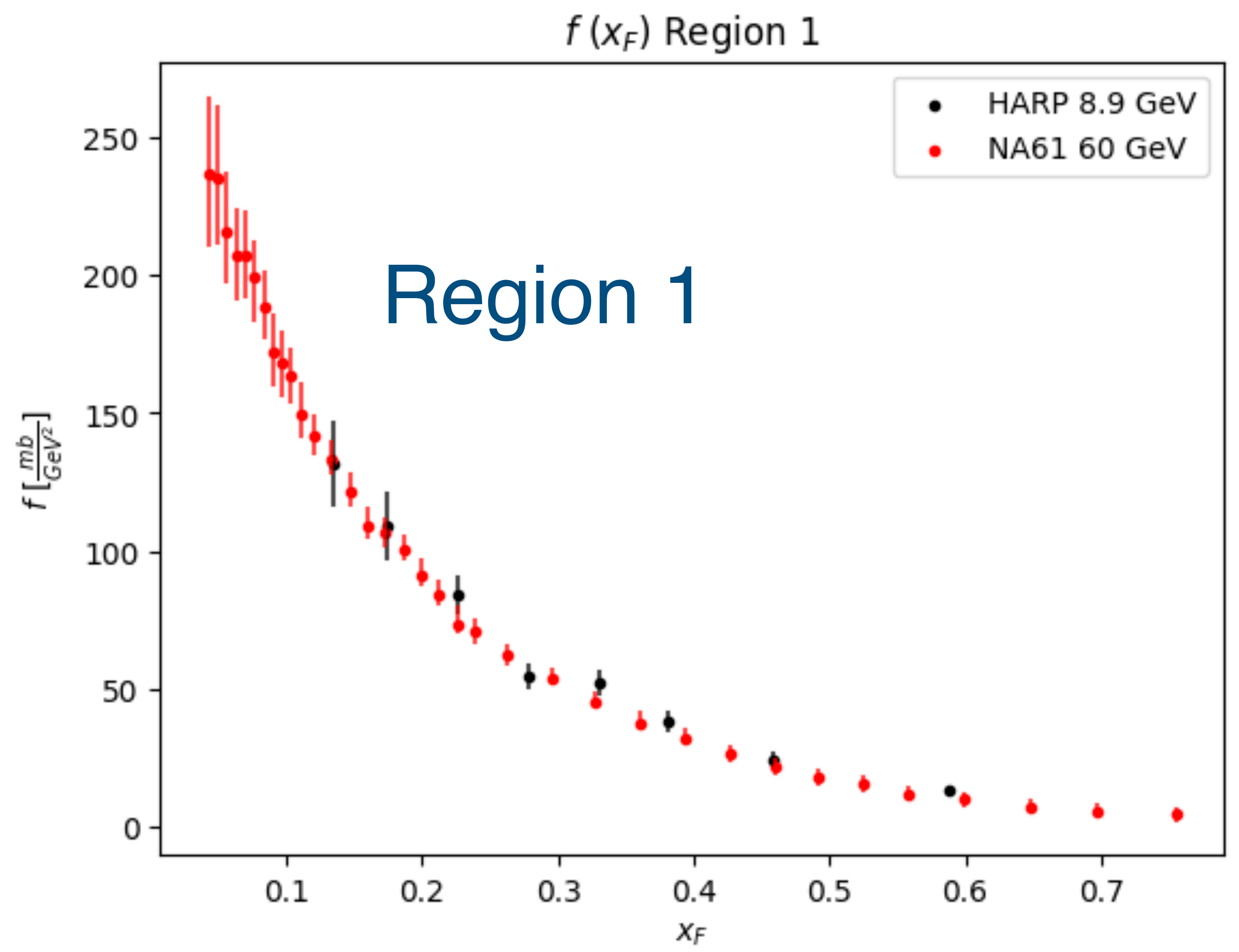


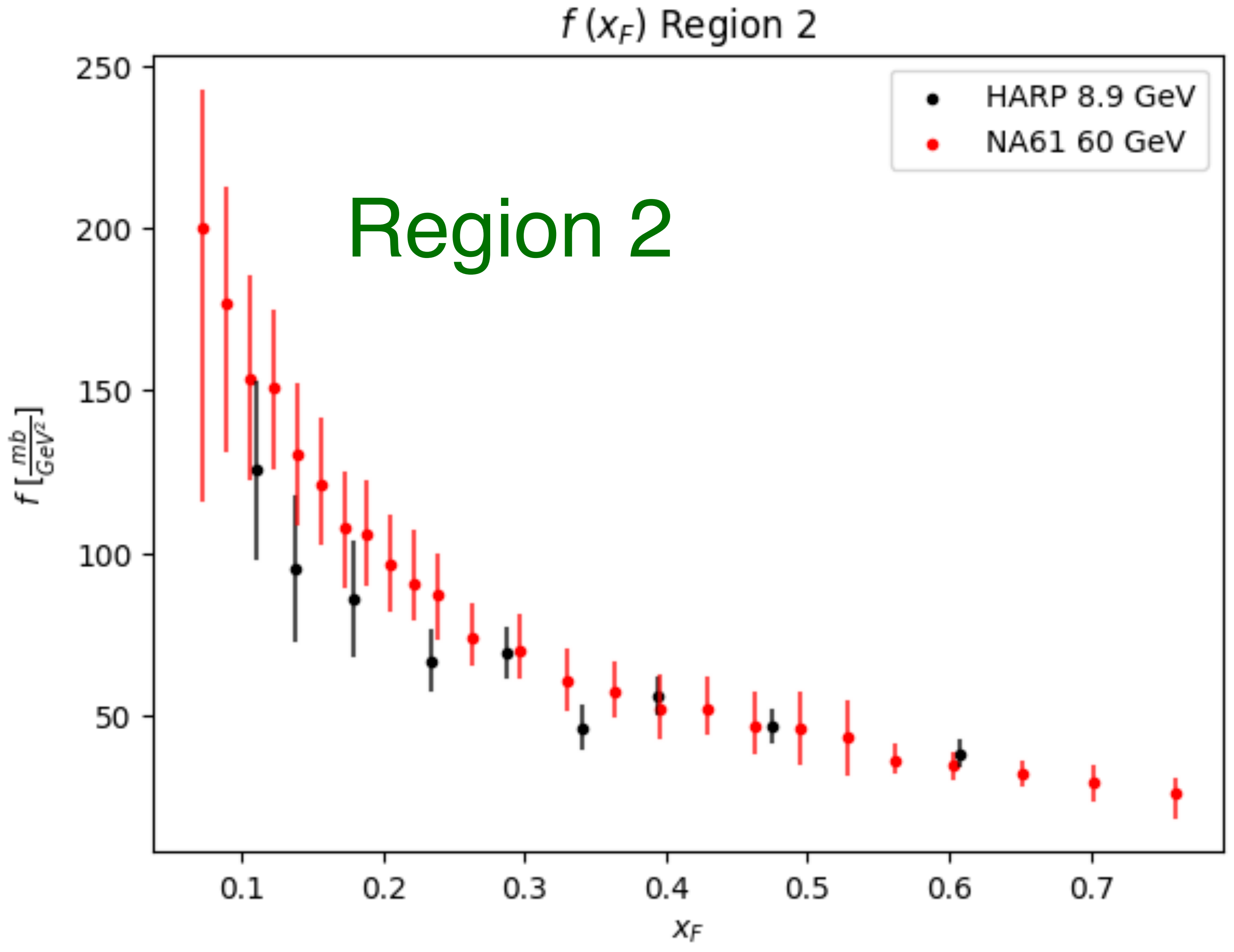
Plots made by Manuel Dall'Olio (U.T Arlington)

Pion-Beryllium hadron production

Simlar comparisons between pion production from incident pions at 60 GeV (NA61/SHINE) and HARP at 8.9 GeV/c







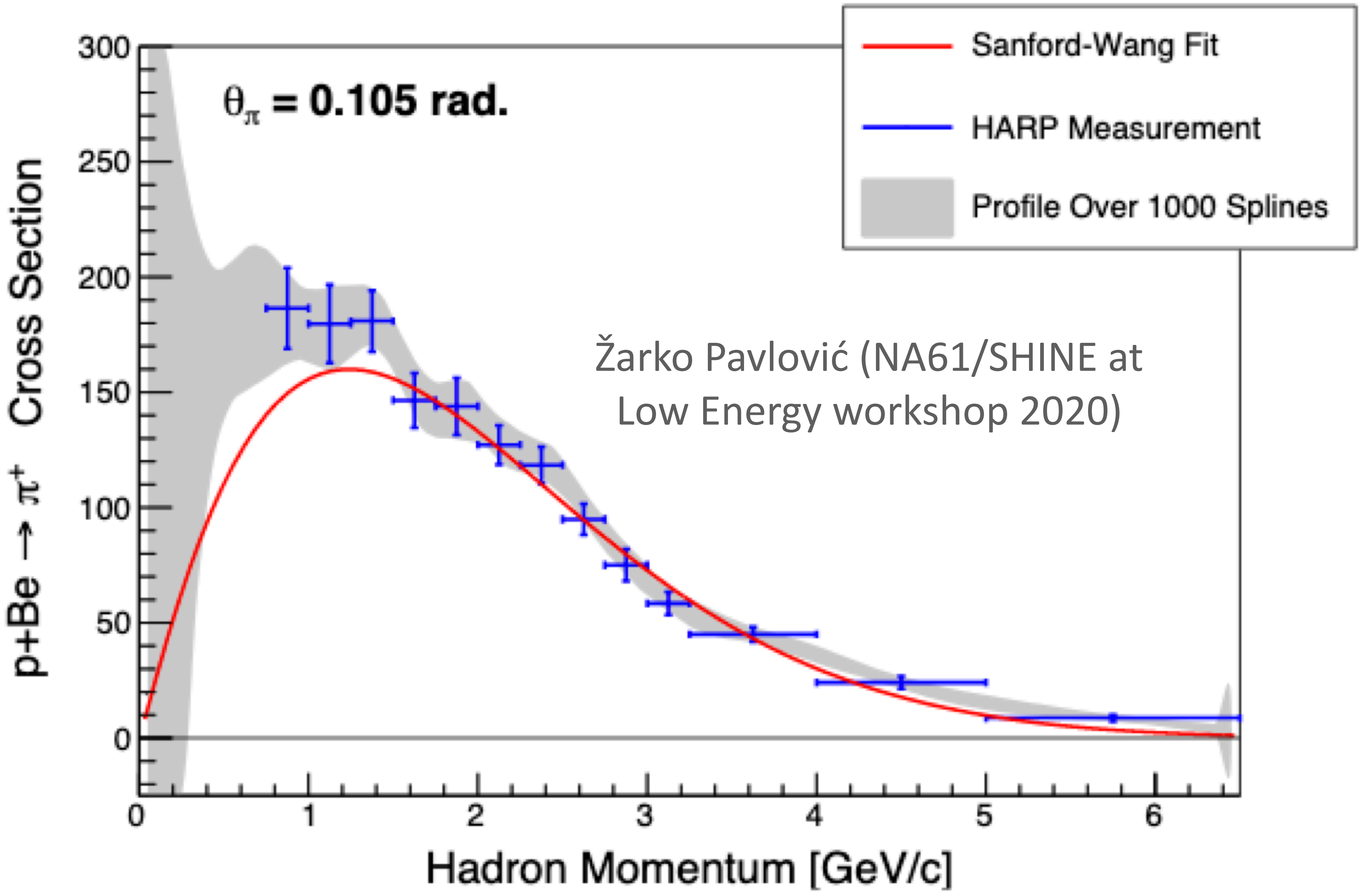
Plots made by Manuel Dall'Olio (U.T Arlington)

Datasets:

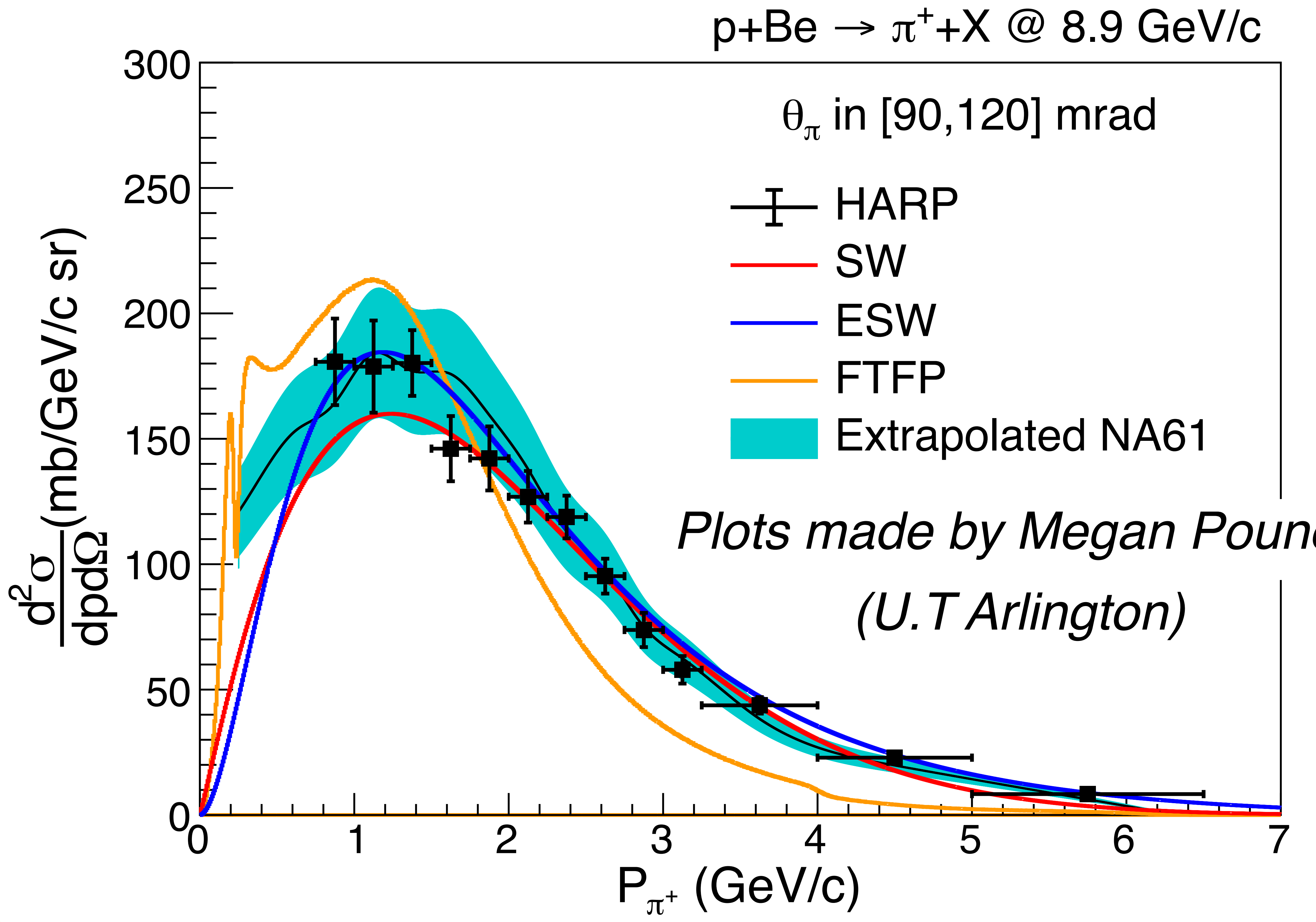
- **NA61**: *Phys.Rev.D* 100 (2019) 11, 112004
- **HARP**: Nuclear Physics A 821 (2009) 118–192

Low hadron prodcution momentum modeling

- Our objective is to apply NA61 data in carbon at 31 GeV to complement HARP data in berylium at 8 GeV at lower momentum (this idea is originally from Žarko Pavlović)
- Procedure:
  - Calculate the NA61 cross section as function of $f(x_F,p_t)$
  - Apply fit from HARP for pion production on several targets (Phys. Rev.C80, 035208, 2009)
  - Scale back to 8 GeV in the HARP kinematic variables



Žarko Pavlović (NA61/SHINE at Low Energy workshop 2020)



Plots made by Megan Pounds (U.T Arlington)

Summary

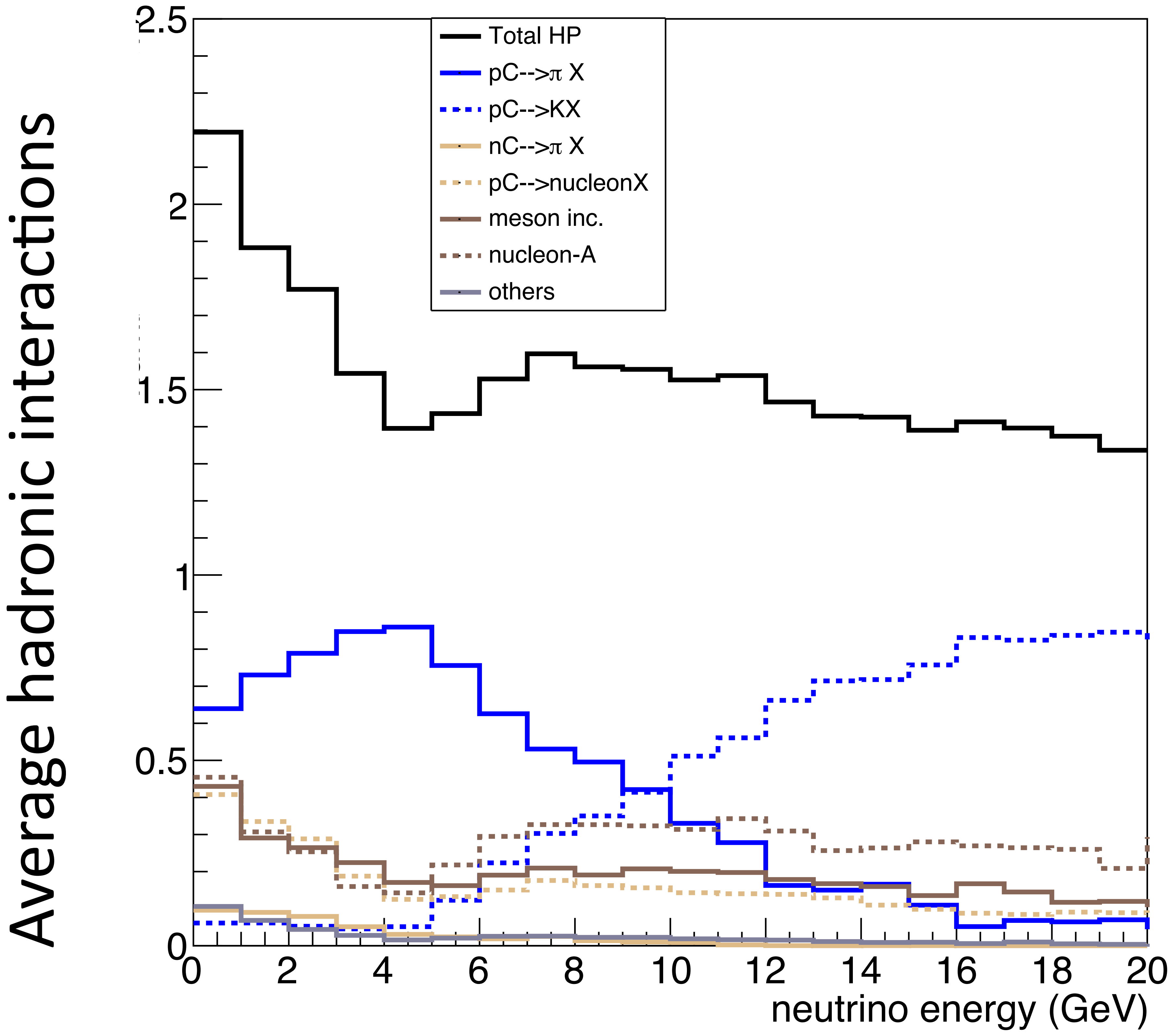
- Predicting the neutrino flux at both detectors in oscillation experiments, several single-detector measurements, and in the exploration of Beyond Standard Model (BSM) physics requires new HP data

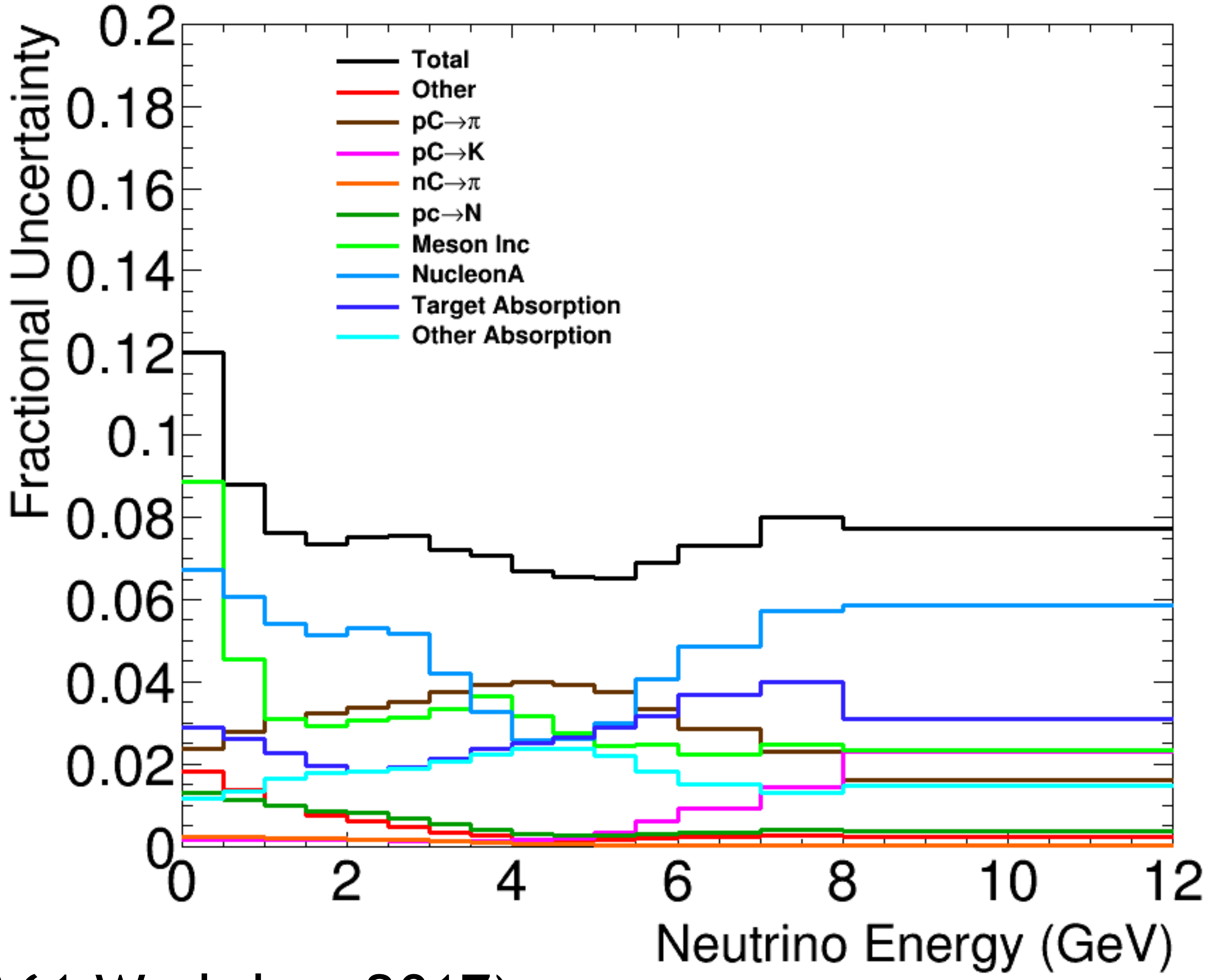
- Using HP data allows the neutrino experiments handle flux systematics in their physics program. The use of HP reduces the flux uncertainty significanly but it is still large for key measurements relevant for DUNE

- We will have the opportunity to make a complete map of hadronic interactions for relevant energies, materials and larger phase space coverage.

Backup

LBNF Flux



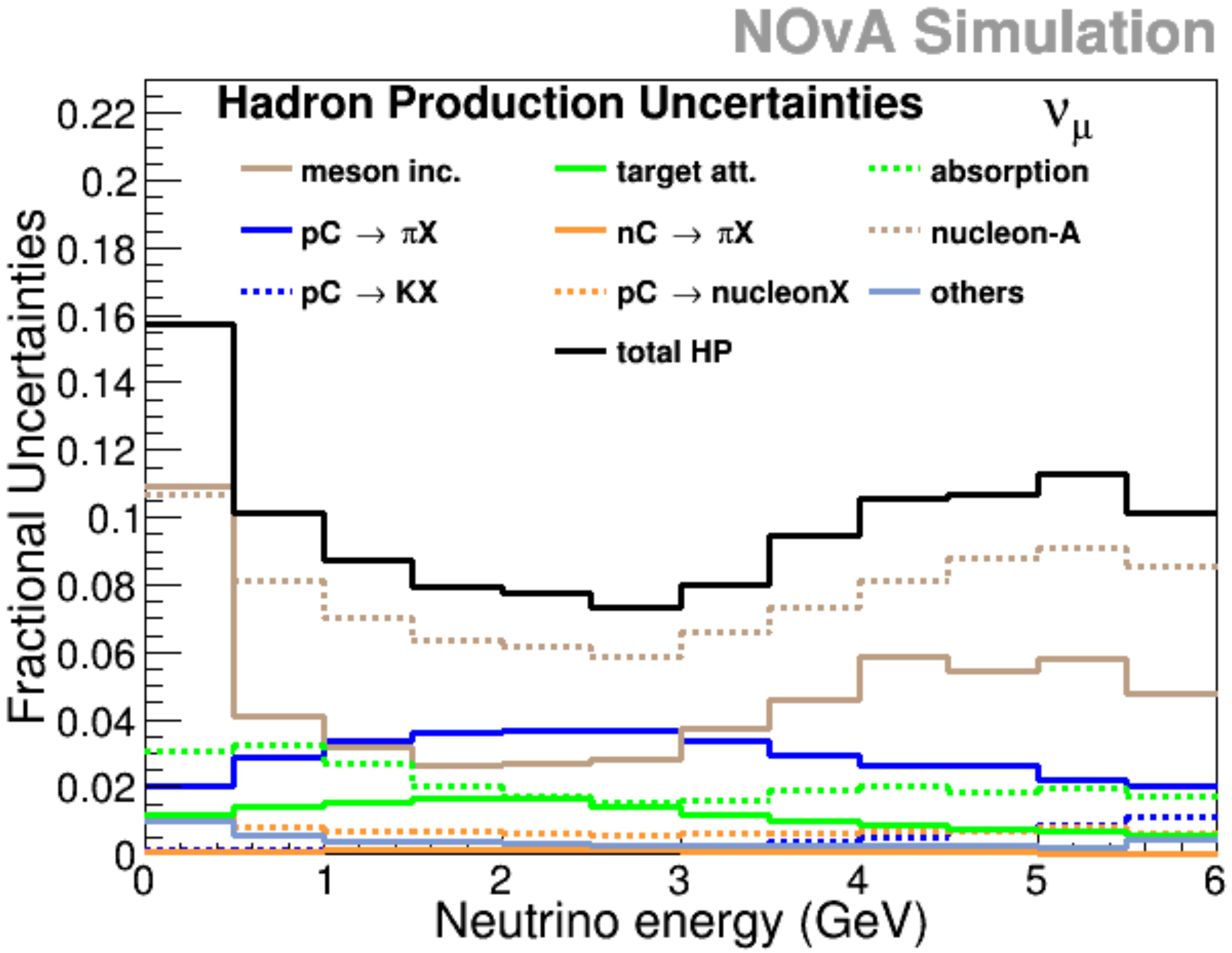


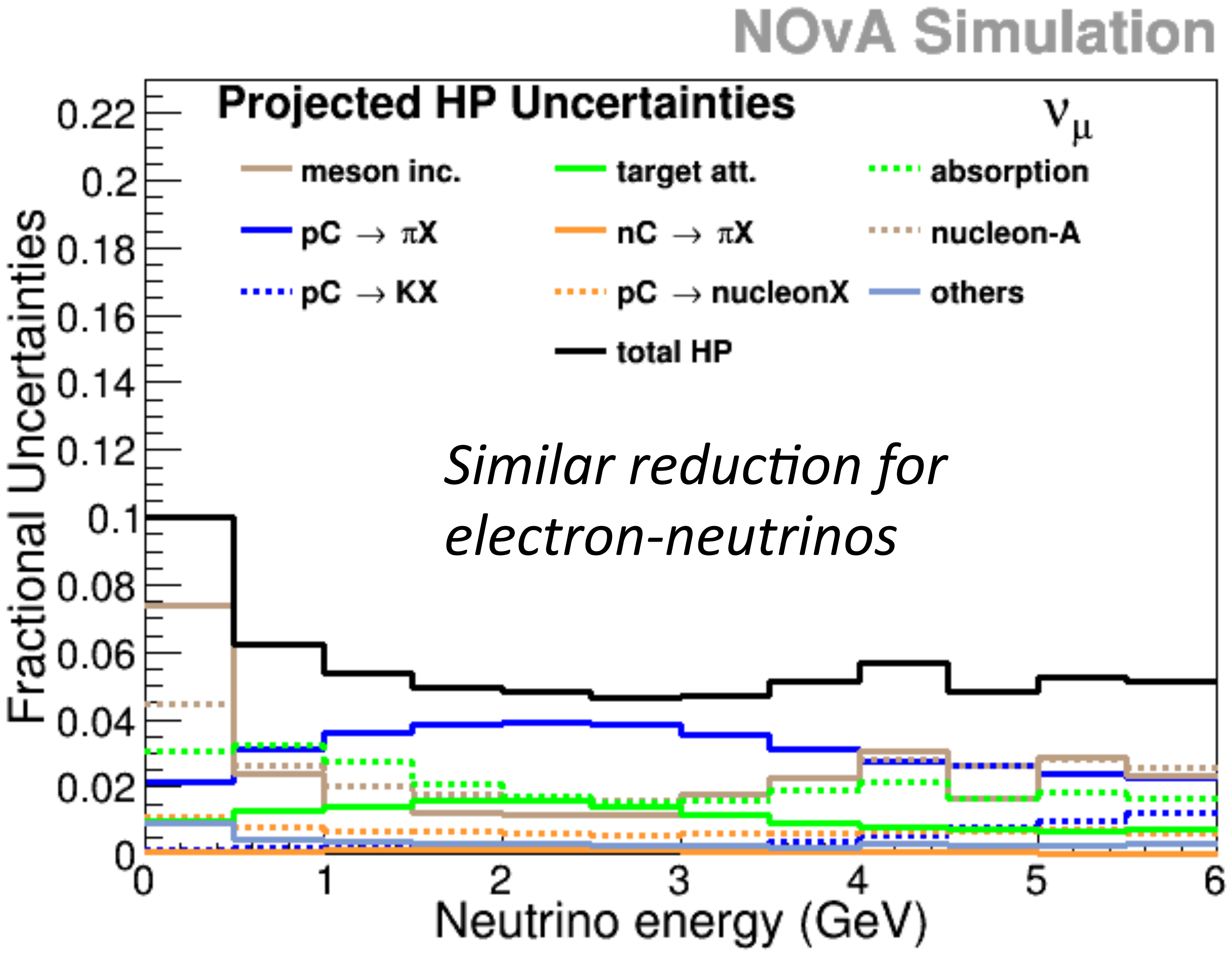
L. Fields (NA61 Workshop 2017)

Reasonably achievable gain from new data

With some conservative assumptions, we can expect a significant reduction in the uncertainty

- ***K absorption****: 60-90% -> 10%*
- ***QE interations****: 40 -> 10%*
- ***p,π,K + C[Fe,Al] -> p X****: 40 -> 10%*
- ***p,π,K + C[Fe,Al] -> K^{+-} X****: 40 -> 20%*



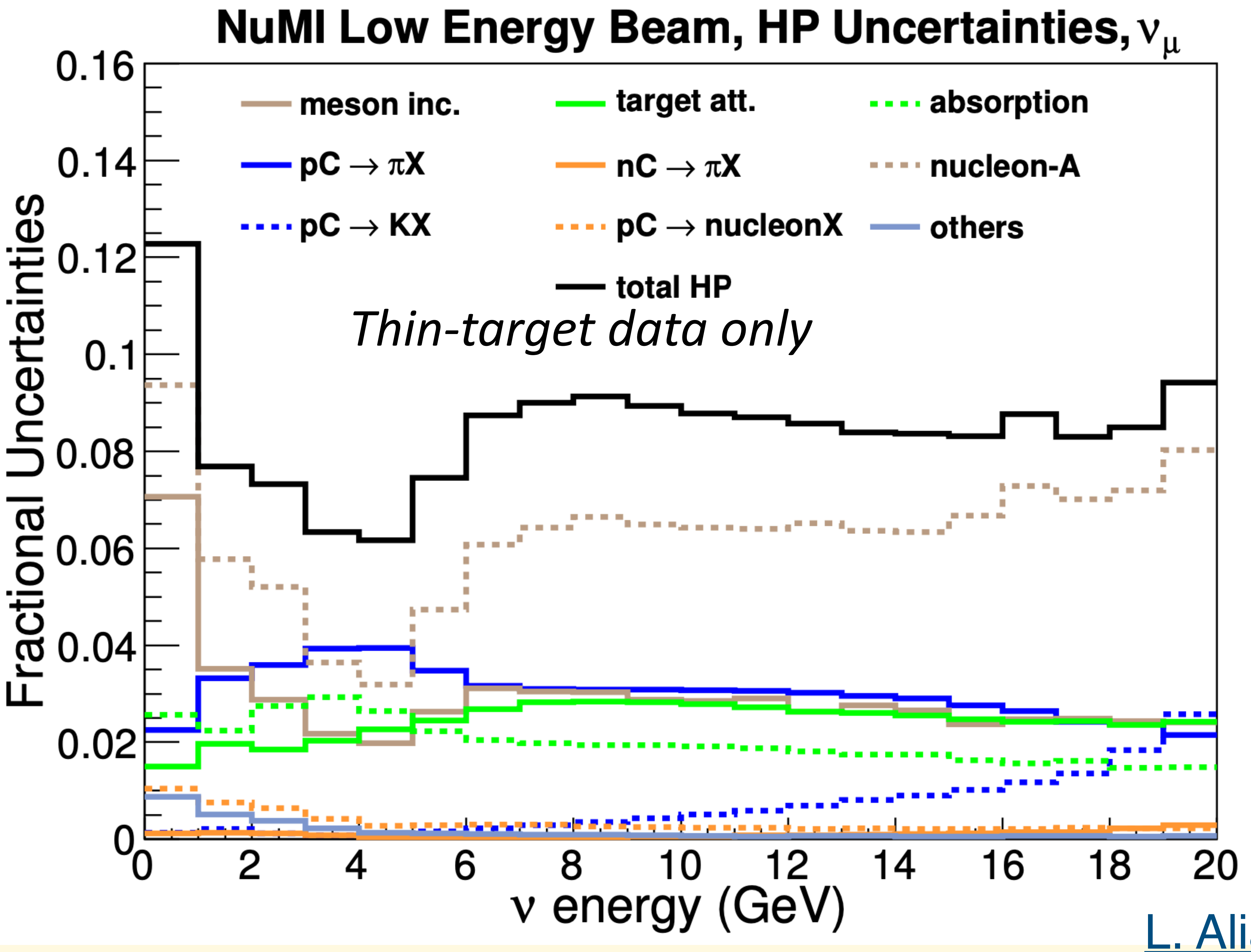


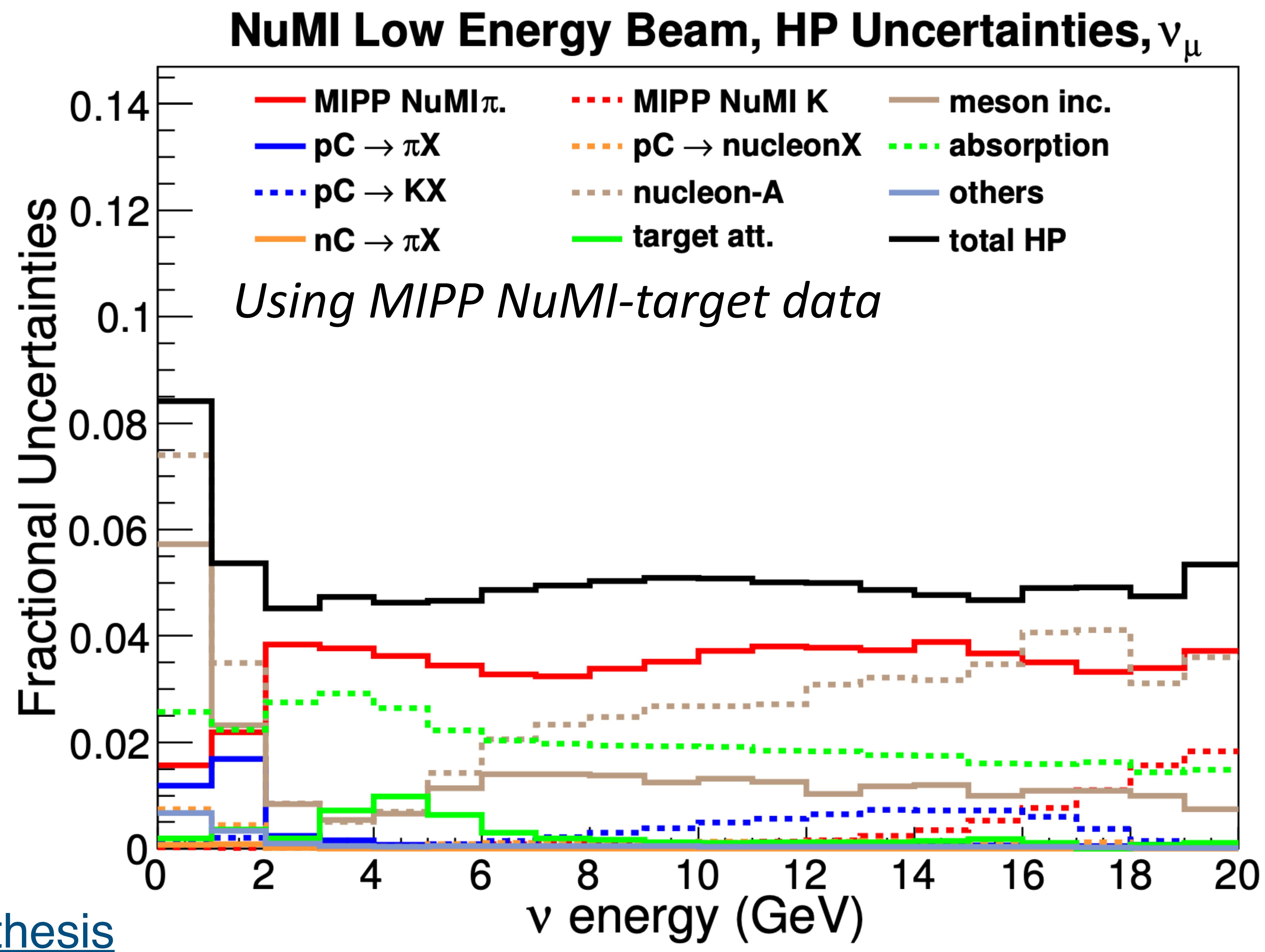
New data not only will reduce the uncertainty but will also enhance the robustness of our flux prediction

Hadron Production from the Target

Measurements by MIPP and NA61/SHINE of HP off real (or replica) targets significantly reduced the HP uncertainties when compared to thin target-based

MIPP: Phys. Rev. D 90, 032001 (2014)
NA61: Phys. Rev. D **103**, 012006 (2021)





L. Aliaga thesis