
The T2K Flux and Hadron Production Data

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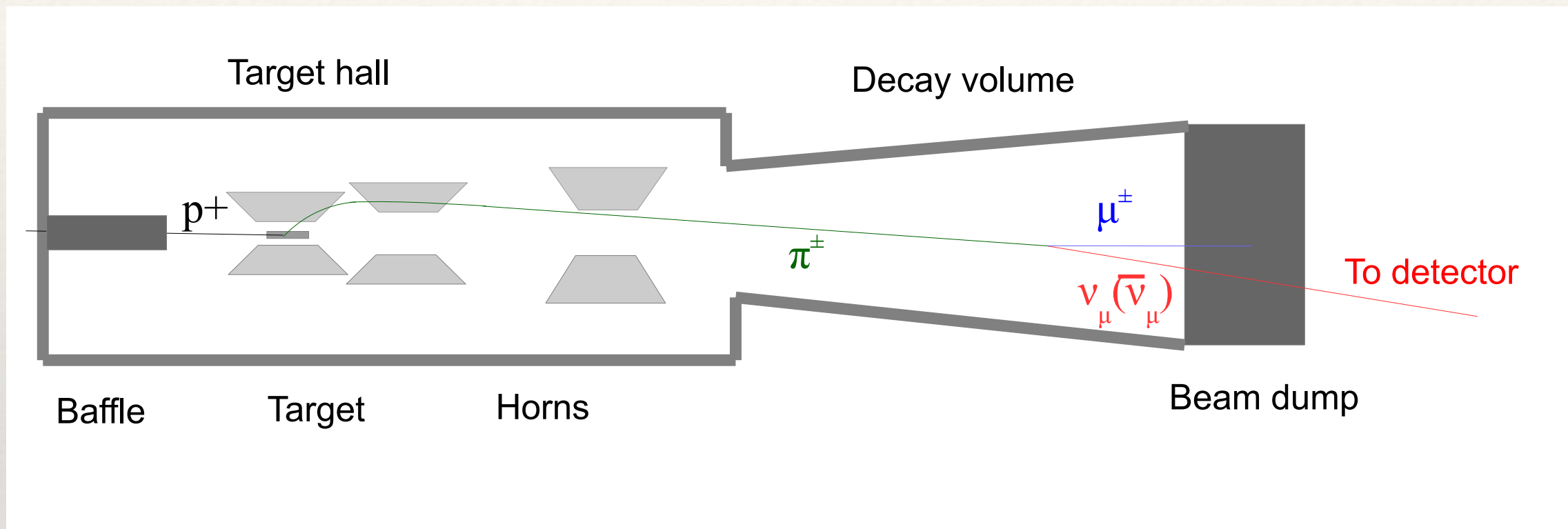
*9th International Workshop on Neutrino Beams and Instrumentation ,
Fermilab, Sept. 26, 2014*

Outline

- ❖ Description of the T2K flux simulation
- ❖ NA61 / SHINE data used to tune the T2K flux
- ❖ Other hadron production data
- ❖ The flux prediction and uncertainties
- ❖ New studies with replica target data

The Flux Prediction

- ❖ The flux prediction comes from a data-driven simulation of the secondary beam-line.



- ❖ Simulation starts with the proton beam upstream of the collimator at the entrance to the target hall.
- ❖ Includes interactions in the target, propagation through horn material and fields, interactions in the walls and beam dump, decays that produce neutrinos

The Flux Prediction Flow

Proton beam monitor
measurements

Proton beam profile and
emittance upstream of the baffle

FLUKA simulation of
baffle and target

Particles exiting the target

Alignment measurements
of beam line elements ,
horn field and current
measurements, CAD
descriptions

Position and geometry of
beam line elements,
magnetic field model

GEANT3 simulation of
the target hall and
decay volume

Neutrinos produced and
full ancestor history

NA61 / SHINE and other
hadron interaction data

Hadron interaction
lengths and production
multiplicities

Tuning with hadron
interaction data using
reweighting

Flux Prediction

Comments/Details of Simulation

- ❖ Since FLUKA tends to reproduce data well, we use it to simulate interactions in the baffle and target.
 - ❖ FLUKA 2008 for old flux predictions, FLUKA 2011 for new flux predictions
- ❖ GCALOR is used to simulate hadronic interactions in the GEANT3 simulation of the rest of the beam line.
- ❖ Custom decay code is used to point all neutrinos at each detector and weight events by the appropriate factor.
- ❖ Low energy neutrinos are rejected with some probability and weighted to give more statistics at high energy for a given number of stored triggers.
- ❖ See M. Friends talk from Monday for details of the hadron interaction reweighting (<https://indico.fnal.gov/getFile.py/access?contribId=3&sessionId=0&resId=0&materialId=slides&confId=8863>)

Hadron Interaction Reweighting

- ❖ Based on two types of measurements:
 - ❖ Double differential pion and kaon multiplicities for proton interactions on nuclei:

$$\frac{d^2 n}{dp d\theta} = \frac{1}{\sigma_{\text{prod}}} * \frac{d^2 \sigma}{dp d\theta}$$

$$W = \frac{\left[\frac{d^2 n}{dp d\theta} \right]_{\text{data}}}{\left[\frac{d^2 n}{dp d\theta} \right]_{\text{MC}}}$$

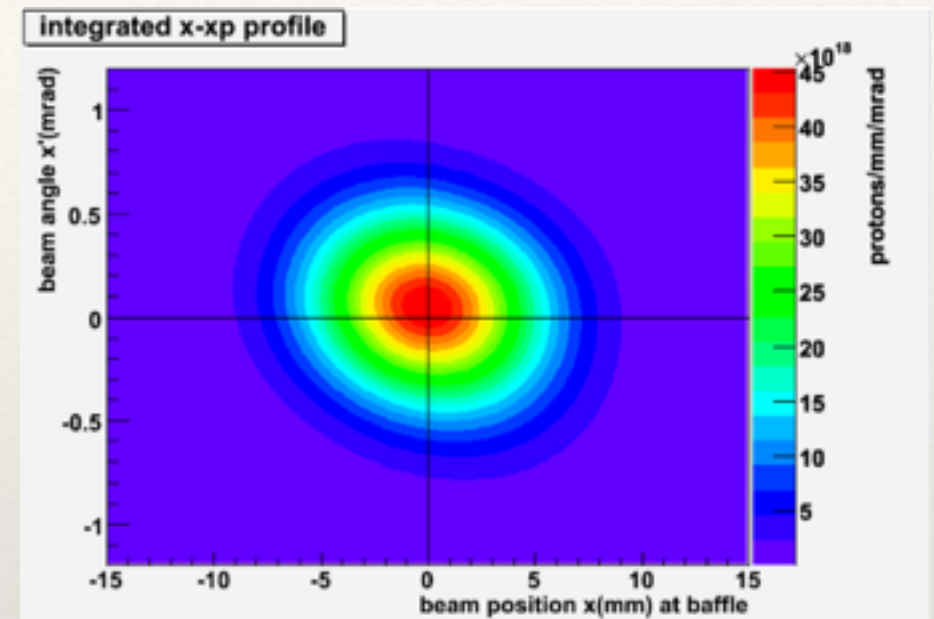
- ❖ Proton, pion and kaon interaction rates (production cross section) on nuclei:

$$\sigma_{\text{prod}} = \sigma_{\text{inel}} - \sigma_{\text{qe}}$$

$$W = \frac{\sigma_{\text{data}}}{\sigma_{\text{MC}}} * e^{-\rho d [\sigma_{\text{data}} - \sigma_{\text{MC}}]}$$

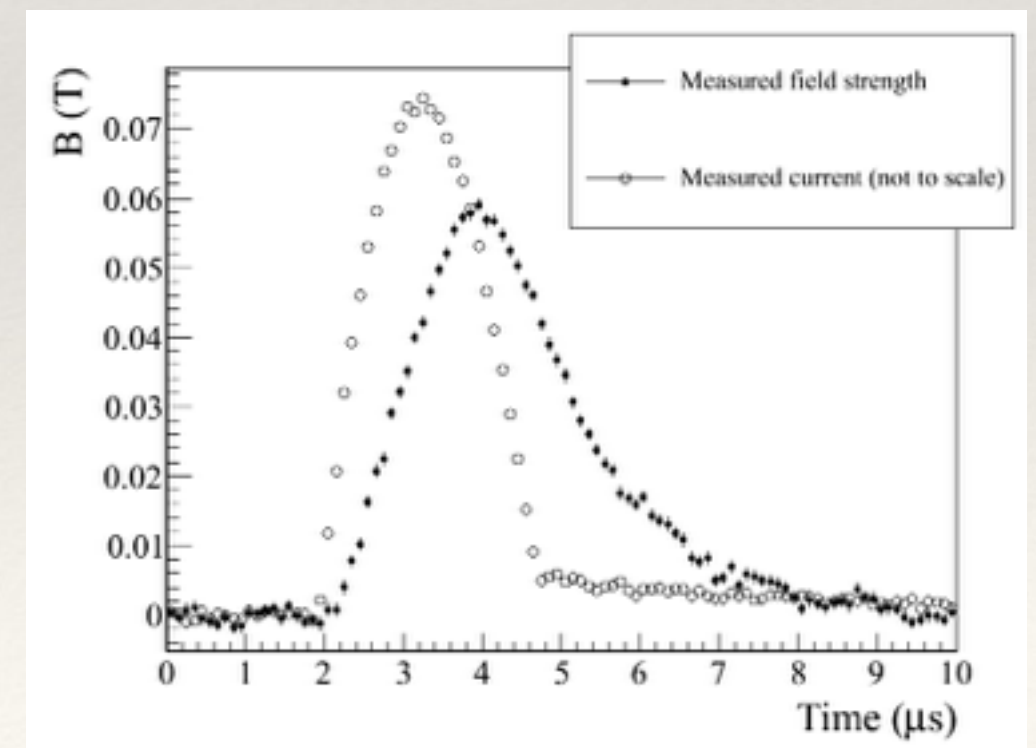
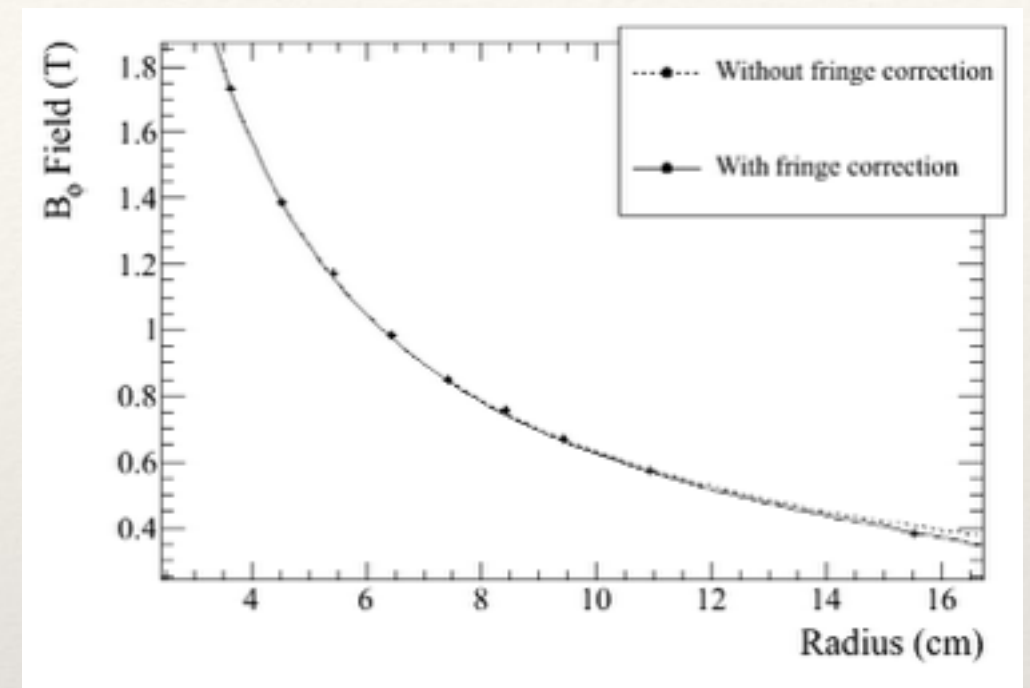
Proton Beam Inputs

- ❖ The proton beam monitors provide the beam current, profile and divergence at the input to the simulation.
- ❖ Fits to SSEM, ESM and OTR monitors give the profile of the beam upstream of the baffle.
- ❖ Dominant uncertainty for flux prediction is 0.6 mm Y position at target -> uncertainty on off-axis angle (~ 0.3 mrad).
- ❖ The uncertainty on the beam current measurement by the CT is 2.6%.
 - ❖ 2% calibration uncertainty
 - ❖ 1.7% monitor data analysis uncertainty
 - ❖ See M. Friends talk from Wednesday morning for CT calibration work.



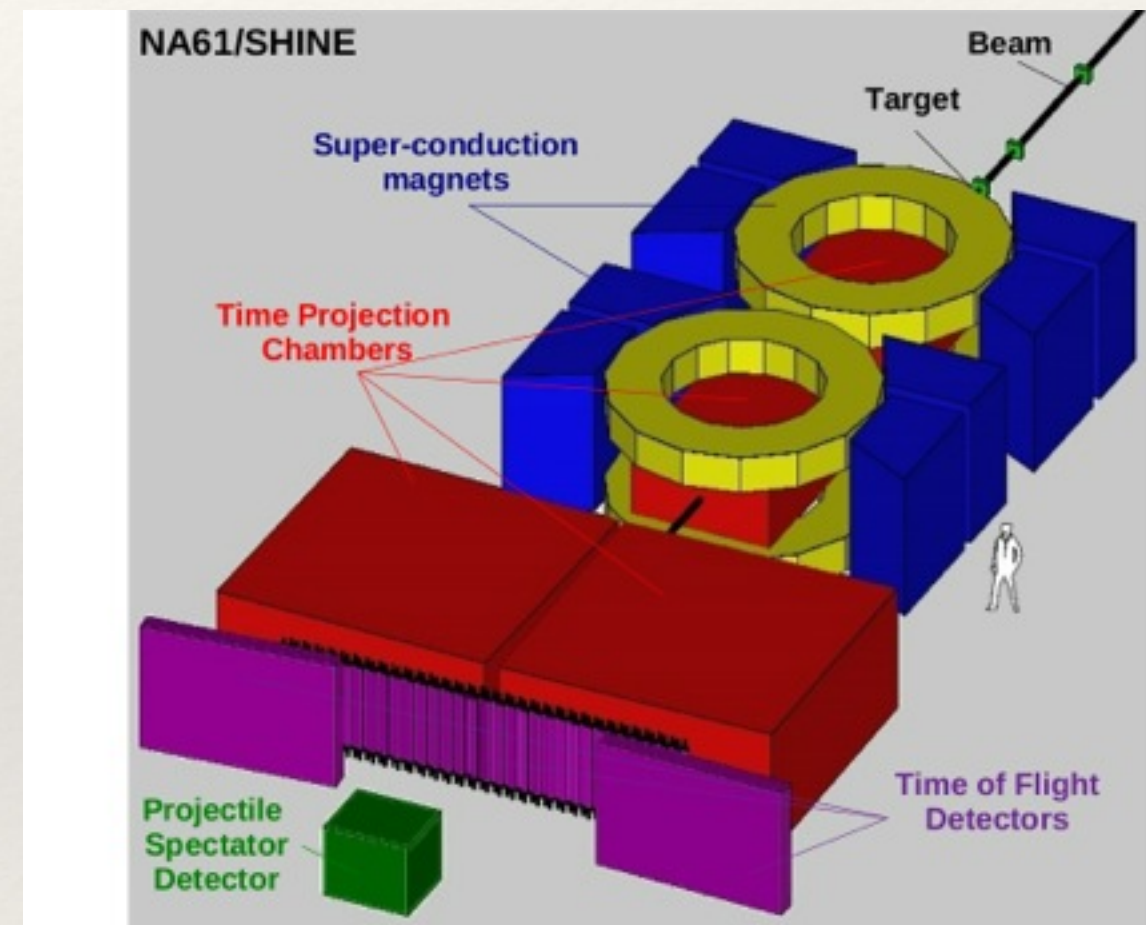
Horn Field Measurements

- ❖ The horns have ports through which the magnetic field is measured.
- ❖ The measured field is in good agreement with the expected field.
- ❖ The field is also measured inside of the inner conductor for each horn.
- ❖ An anomalous field of 600 G is observed.
- ❖ The field time dependence is delayed relative to the current.
- ❖ This field is not yet understood, but we model it and include a systematic uncertainty to cover its effect (<1% near the flux peak).



NA61/SHINE Hadron Data

- ❖ Main hadron interaction data are from the NA61/SHINE experiment.
- ❖ 30 GeV protons on thin and T2K replica targets
- ❖ Thin target data -> double differential particle multiplicities and proton interaction length
 - ❖ 2007: 0.7 M protons
 - ❖ 2009: 5.4 M protons
- ❖ Replica target data -> particle multiplicities binned in momentum angle and Z position along target
 - ❖ 2007: 0.2 M protons
 - ❖ 2009: 2.8 M protons
 - ❖ 2010: 10 M protons

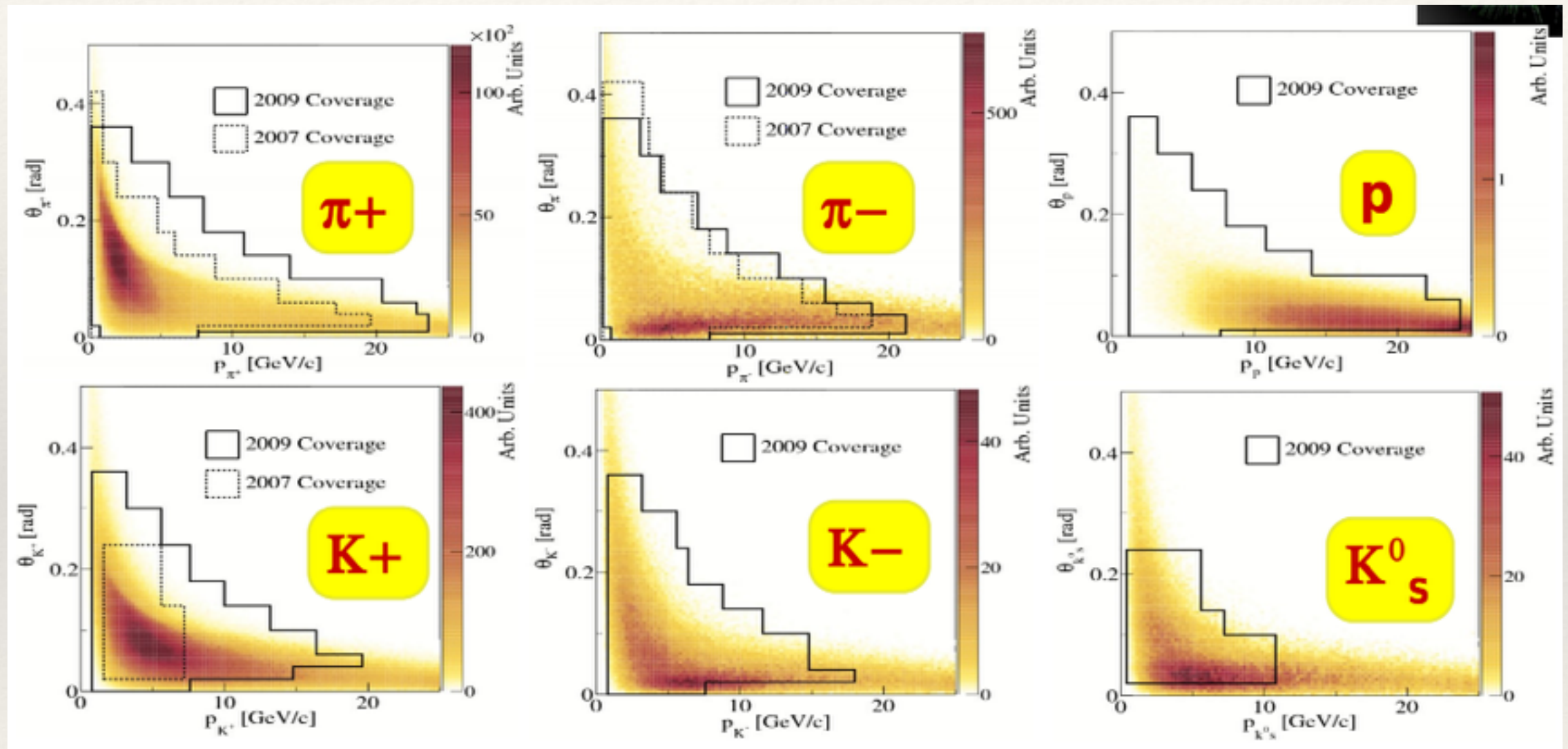


NA61/SHINE Data

- ❖ 2007 thin target data:
 - ❖ Pion multiplicities and p+C cross section: [Phys. Rev. C84 \(2011\) 034604](#)
 - ❖ K+ multiplicities: [Phys. Rev. C85 \(2012\) 035210](#)
 - ❖ Used in flux prediction for most recent T2K oscillation results
- ❖ 2007 replica target data: pion multiplicities and study comparing replica and thin target tuning for the T2K flux: [NIM A701 \(2013\) 99](#)
- ❖ 2009 thin target data:
 - ❖ Preliminary results with pion, charged and neutral kaon and proton multiplicities and update p+C cross section
 - ❖ Now working to update the T2K flux prediction with this data
- ❖ 2009 replica target data: preliminary pion multiplicities and comparisons with thin target data

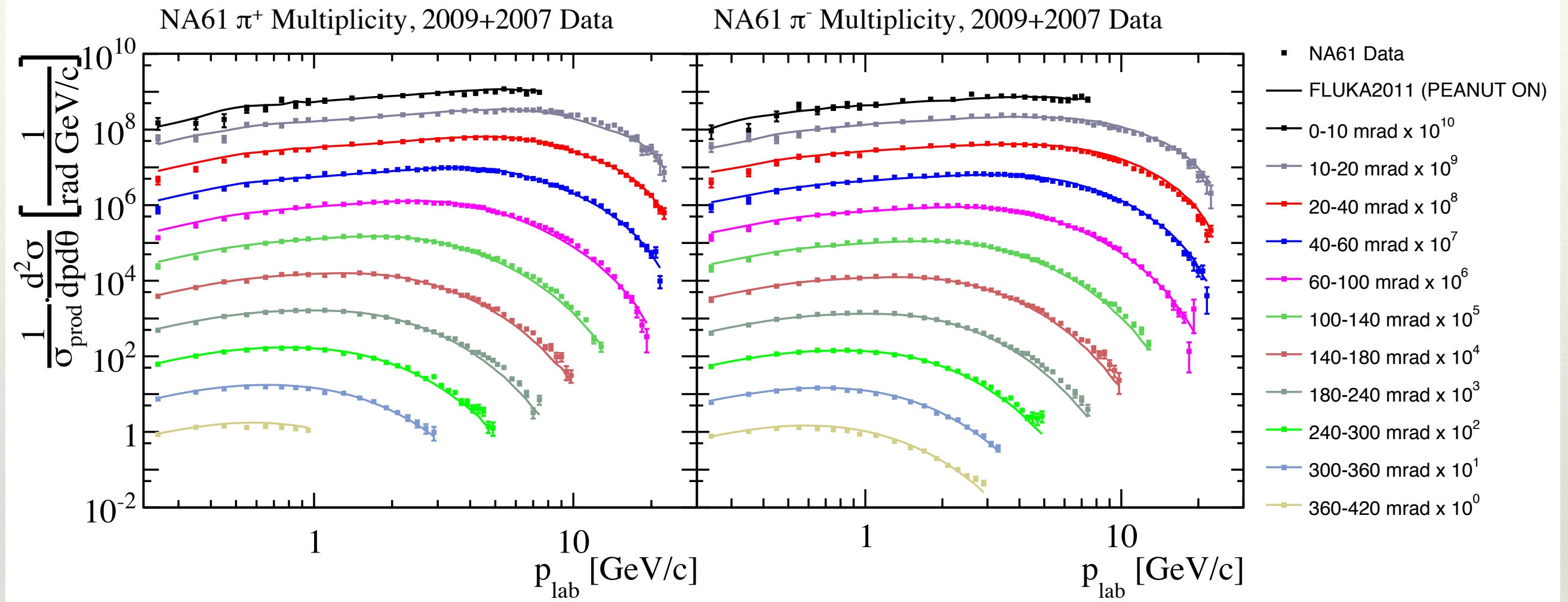
2007 vs 2009 Data Coverage

- ❖ Plots show the NA61 data coverage over the phase space contributing to the SK flux when positively charged particles are focused.



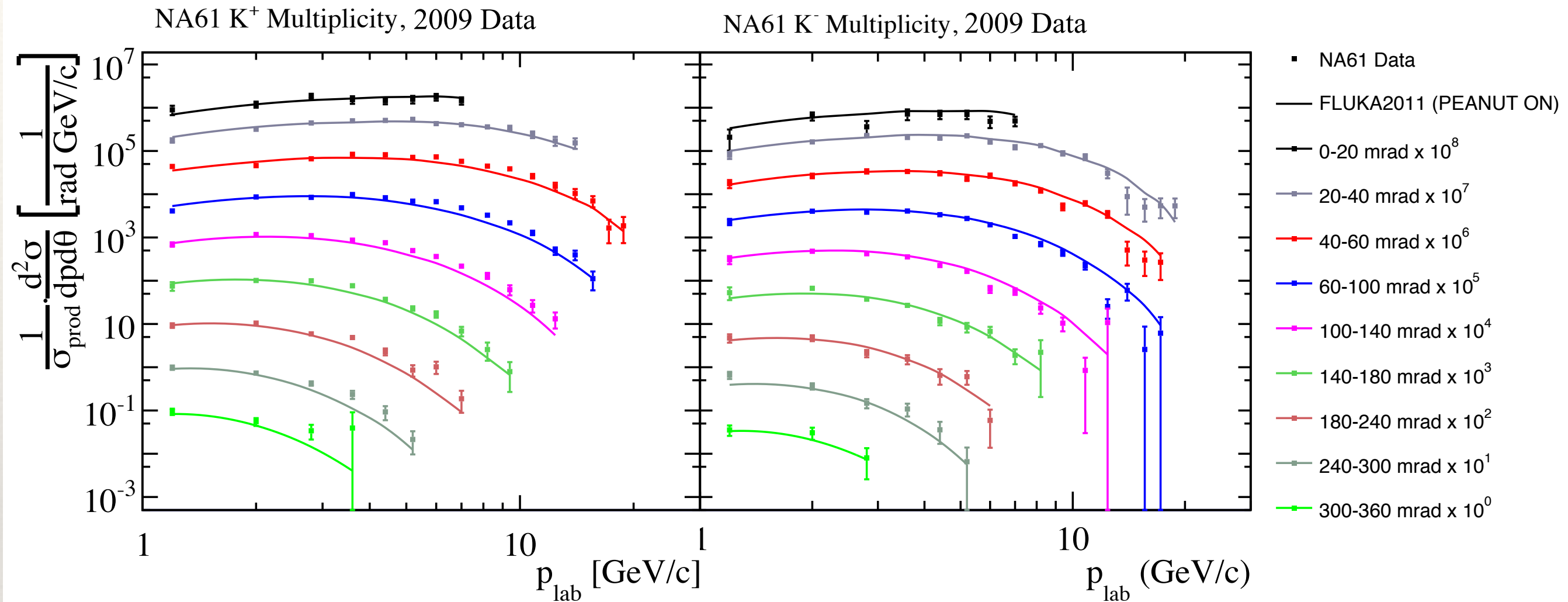
- ❖ The coverage of the hadron phase space relevant for the T2K flux, especially kaon production, is significantly improved with the 2009 thin target data.

NA61 2009 π^\pm Multiplicities



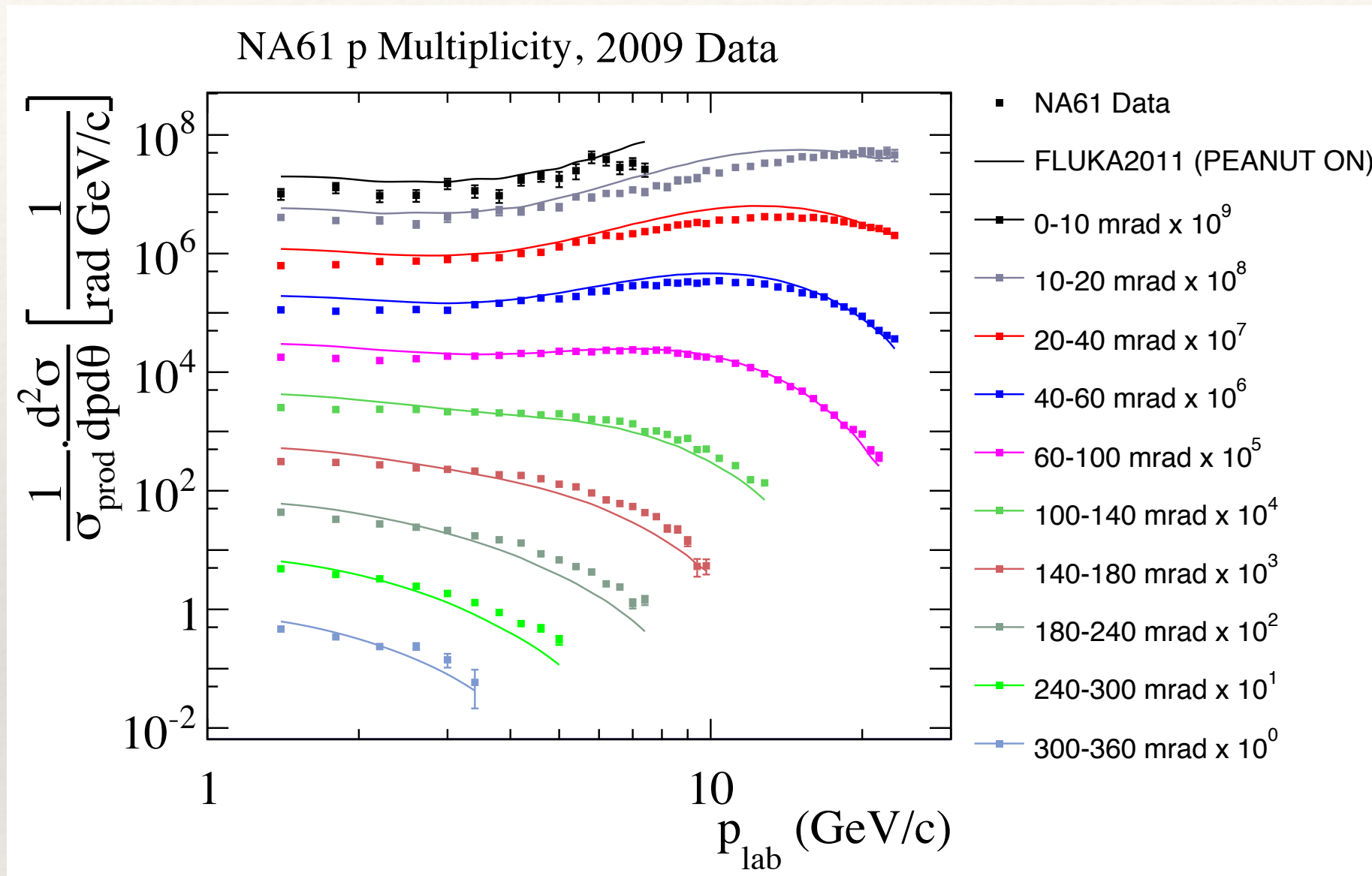
- ❖ In general there is good agreement between the NA61 data and FLUKA2011 with the PEANUT extended model turned on.
- ❖ May be the result of FLUKA tuning on NA61 2007 data.

NA61 2009 K^\pm Multiplicities



- ❖ Agreement for the K^- multiplicities is good.
- ❖ FLUKA systematically underestimates the K^+ production at higher momentum.

NA61 2009 Proton Multiplicities



- ❖ There are large discrepancies between NA61 data and the FLUKA prediction for secondary proton production.

Secondary and Out-of-Target Interactions

Some neutrinos come from interaction chains where there are secondary hadron interactions, sometimes out of the target.

Percent of the flux from different hadronic interaction chain configurations

	Number of Inelastic Hadronic Interactions in Chain Producing the Neutrino		
	1 Interaction	≥2 Interactions	≥1 Out of Target Interaction
N280 ν_μ flux	63.2%	36.8%	12.6%
N280 anti- ν_μ flux	39.5%	60.5%	49.8%
N280 ν_e flux	60.1%	39.9%	13.6%
N280 anti- ν_e flux	50.7%	49.3%	32.2%
SK ν_μ flux	63.2%	36.8%	12.4%
SK anti- ν_μ flux	41.5%	58.5%	45.1%
SK ν_e flux	61.7%	38.3%	12.7%
SK anti- ν_e flux	54.0%	46.0%	27.2%

Secondary and out-of-target interactions are a bigger contribution for the wrong sign flux.

Approach is to scale the NA61 data to different center of mass energy and target nuclei.

Parameterize and cross-check scaling methods with additional multiplicity data

Additional Multiplicity Data

- ❖ Single arm spectrometer measurements from Eichten et al. and Allaby et al. are used to:
 - ❖ Study the A scaling of the multiplicities
 - ❖ For K⁻ production and K⁺ production in the phase space not covered by NA61 (2007 based reweighting)
 - ❖ Study x scaling for kaon production
- ❖ BNL E910 data is used to study the x scaling for pion production.

Experiment	Beam Mom. (GeV/c)	Target	Particles
NA61/SHINE [11][12]	31	C	π^{\pm}, K^{+}
Eichten <i>et al.</i> [27]	24	Be, Al, ...	p, π^{\pm}, K^{\pm}
Allaby <i>et al.</i> [28]	19.2	Be, Al, ...	p, π^{\pm}, K^{\pm}
BNL-E910 [29]	6.4 – 17.5	Be	π^{\pm}

See the T2K flux paper for more details on the data: **Phys. Rev. D 87, 012001 (2013)**

Scaling Methods

- ❖ To do the scaling to different center of mass energies, we use the Feynman scaling to scale the NA61 / SHINE data.
- ❖ In the variables x_F and p_T , the invariant cross section is invariant for changes in the center of mass energy
- ❖ We crosscheck this approach with an independent approach of tuning with E910 data at 17.5 and 12.3 GeV / c proton momenta
- ❖ For the target nucleus scaling, we use the parametrization used in the BMPT paper:

$$E \frac{d^3 \sigma^{A_2}}{dp^3} = \left(\frac{A_2}{A_1} \right)^{\alpha(x_F, p_T)} E \frac{d^3 \sigma^{A_1}}{dp^3}$$

$$\alpha(x_F, p_T) = (a + bx_f + cx_F^2)(d + ep_T^2)$$

- ❖ The parameters come from a fit to the Allaby and Eichten data:

Table 43: Parameters for material scaling					
	a	b	c	d	e
nominal	0.74	-0.55	0.26	0.98	0.21
fitted π	0.75	-0.52	0.23	1.0 (fixed)	0.21
fitted K	0.77	-0.32	0.0	1.0 (fixed)	0.25

Production Cross Section Data

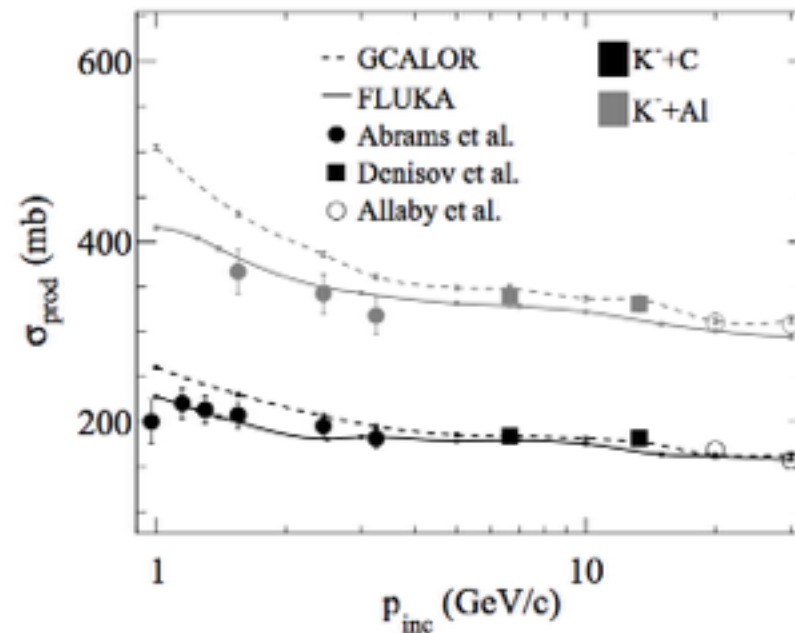
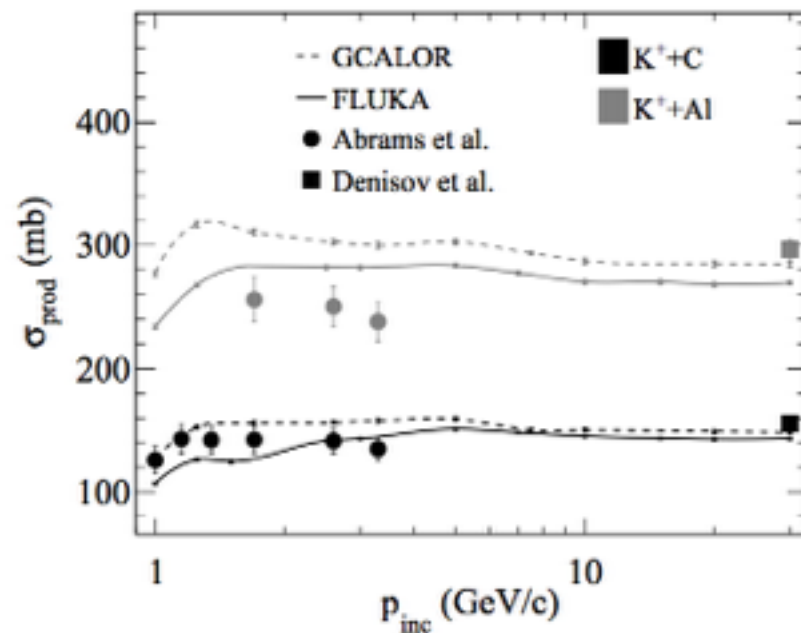
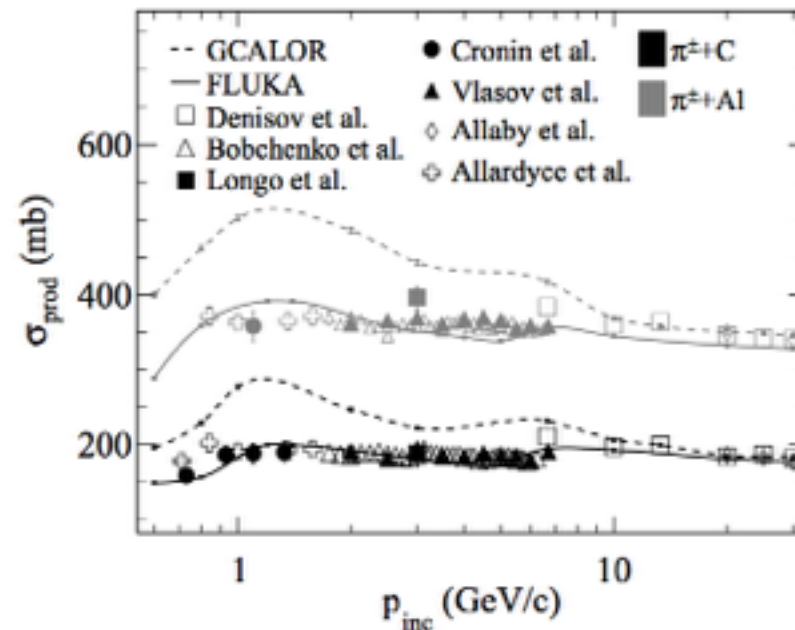
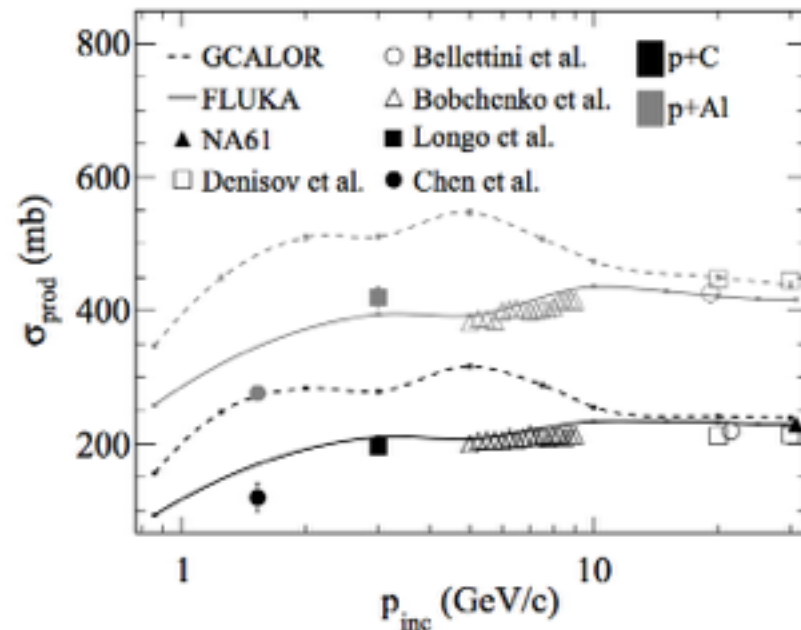
- ❖ Use various measurements of the inelastic cross sections:

Data	Beam	Target	Beam Momentum (GeV/c)	Measurement
Abrams <i>et al.</i> [30]	K^\pm	C, Cu	1 – 3.3	σ_{inel}
Allaby <i>et al.</i> [31][32]	π^-, K^-	C, Al, ...	20 – 65	σ_{inel}
Allardyce <i>et al.</i> [33]	π^\pm	C, Al, ...	0.71 – 2	σ_{inel}
Bellettini <i>et al.</i> [34]	p	C, Al, ...	19.3, 21.5	σ_{inel}
Bobchenko <i>et al.</i> [35]	π^-, p	C, Al, ...	1.75 – 9	σ_{inel}
Carroll <i>et al.</i> [36]	π^\pm, K^\pm, p	C, Al, ...	60 – 280	σ_{prod}
Cronin <i>et al.</i> [37]	π^-	C, Al	0.73 – 1.33	σ_{inel}
Chen <i>et al.</i> [38]	p	C, Al, ...	1.53	σ_{inel}
Denisov <i>et al.</i> [39]	π^\pm, K^\pm, p	C, Al, ...	6 – 60	σ_{inel}
Longo <i>et al.</i> [40]	π^+, p	C, Al	3	σ_{inel}
NA61/SHINE [11]	p	C	31	σ_{prod}
Vlasov <i>et al.</i> [41]	π^-	C, Al	2 – 6.7	σ_{inel}

- ❖ Most of these measurements include quasi-elastic scatters, so we subtract them off with the empirical formula for Bellettini et al.:

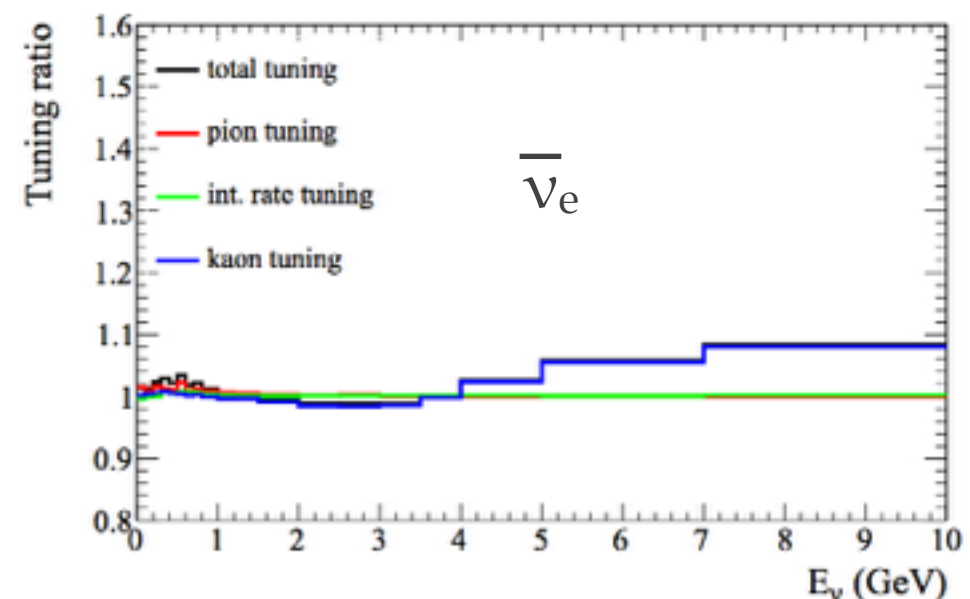
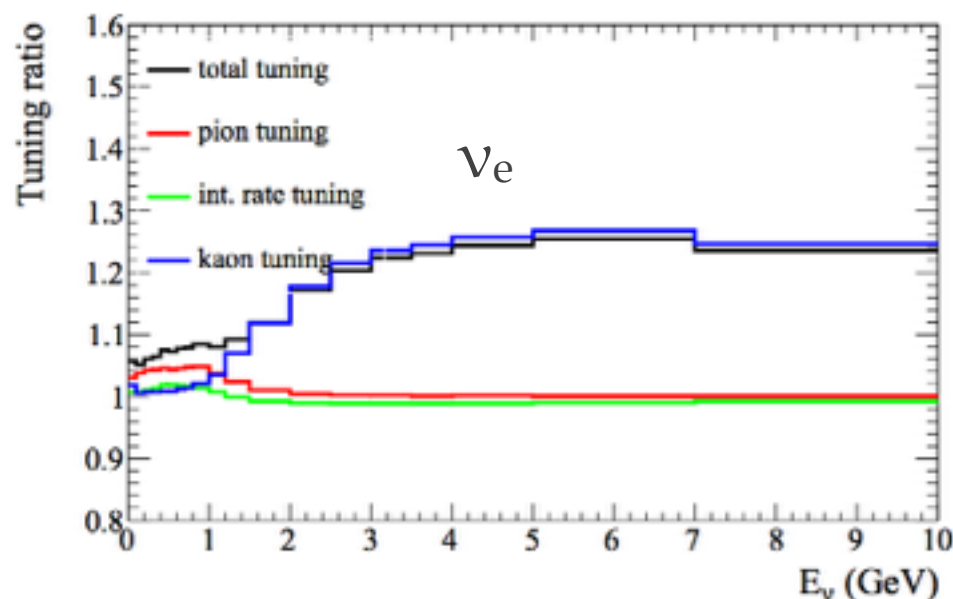
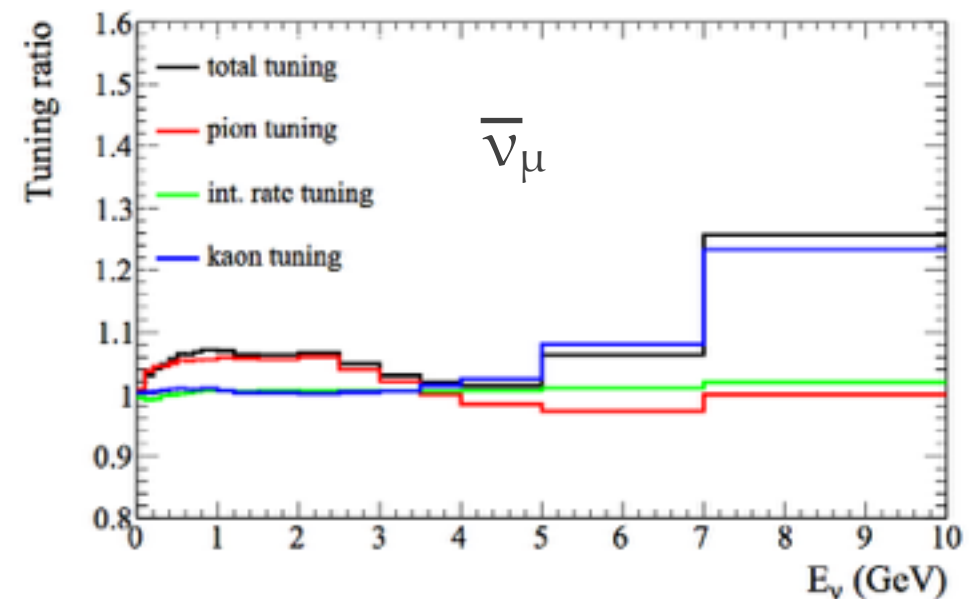
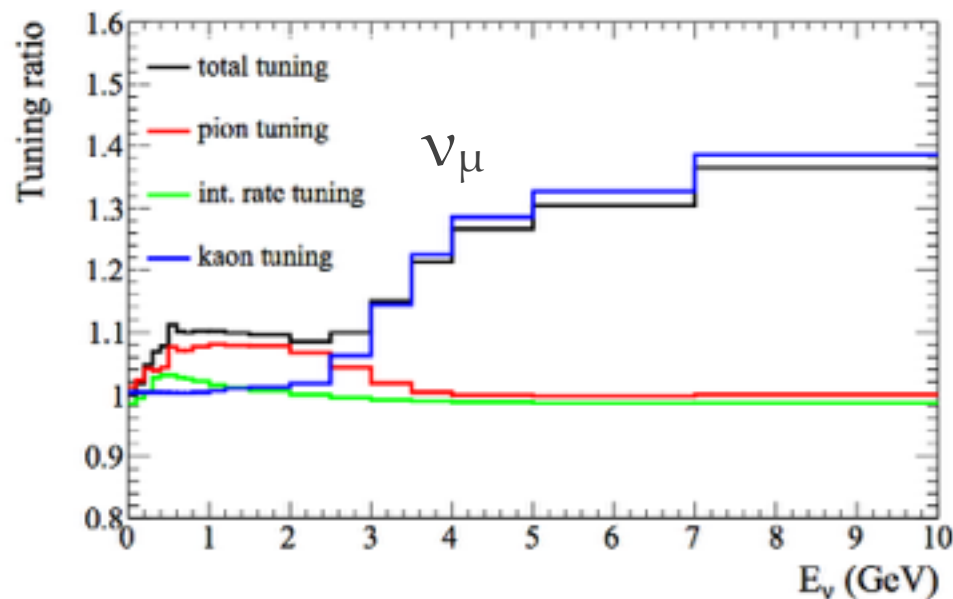
$$\sigma_{qe} = 0.8(\sigma_{hp}^{el} + \sigma_{hn}^{el})A^{1/3}$$

σ_{prod} Data vs. MC



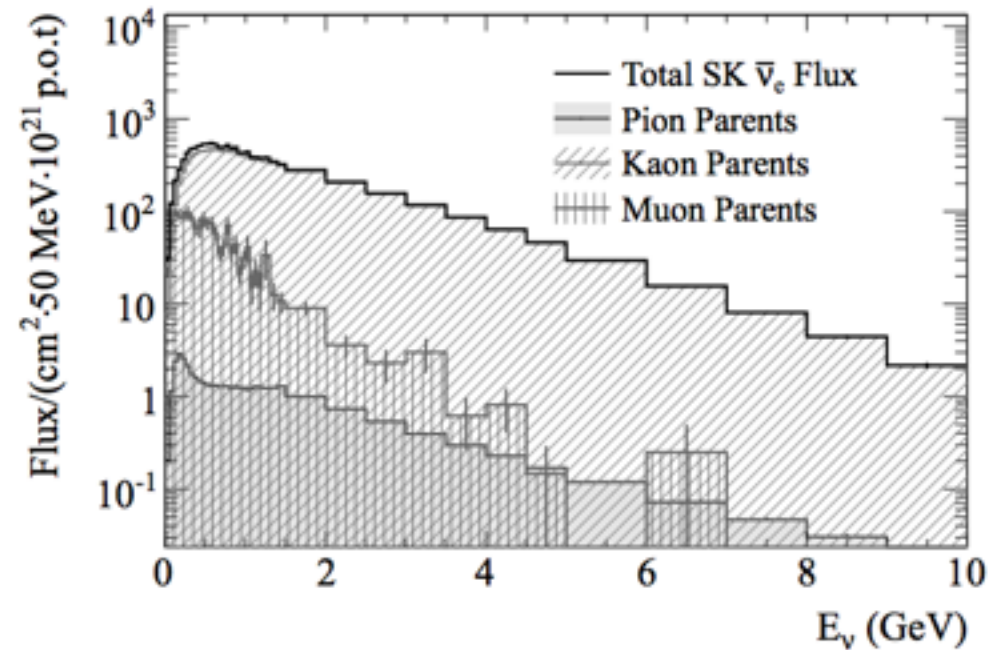
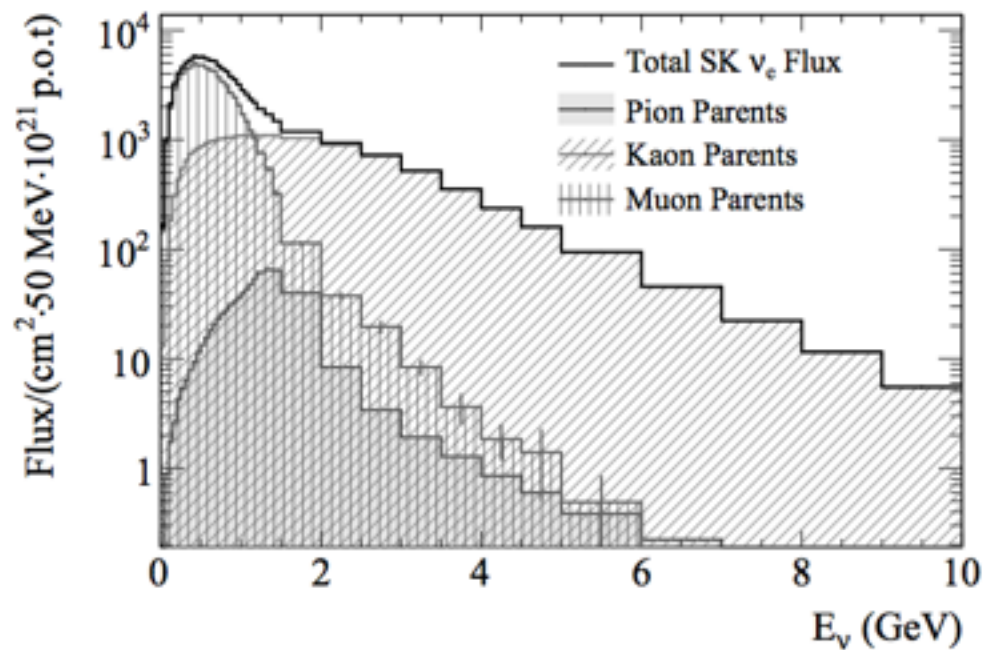
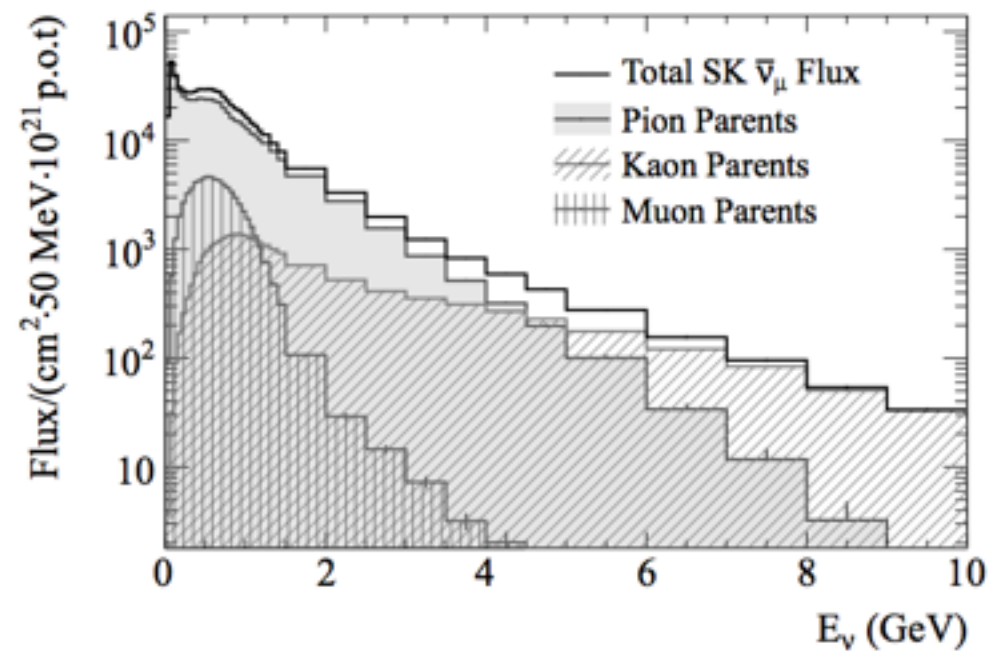
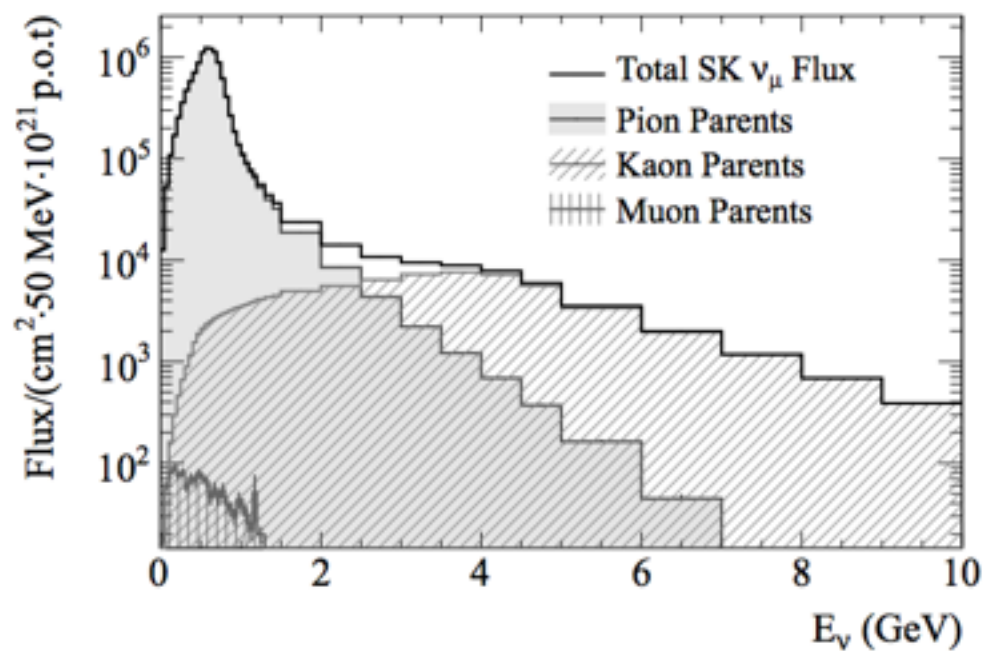
- ❖ We see good agreement between FLUKA and the data
- ❖ We only tune the out-of-target interactions modeled by GCALOR

Hadron Interaction Tuning Results



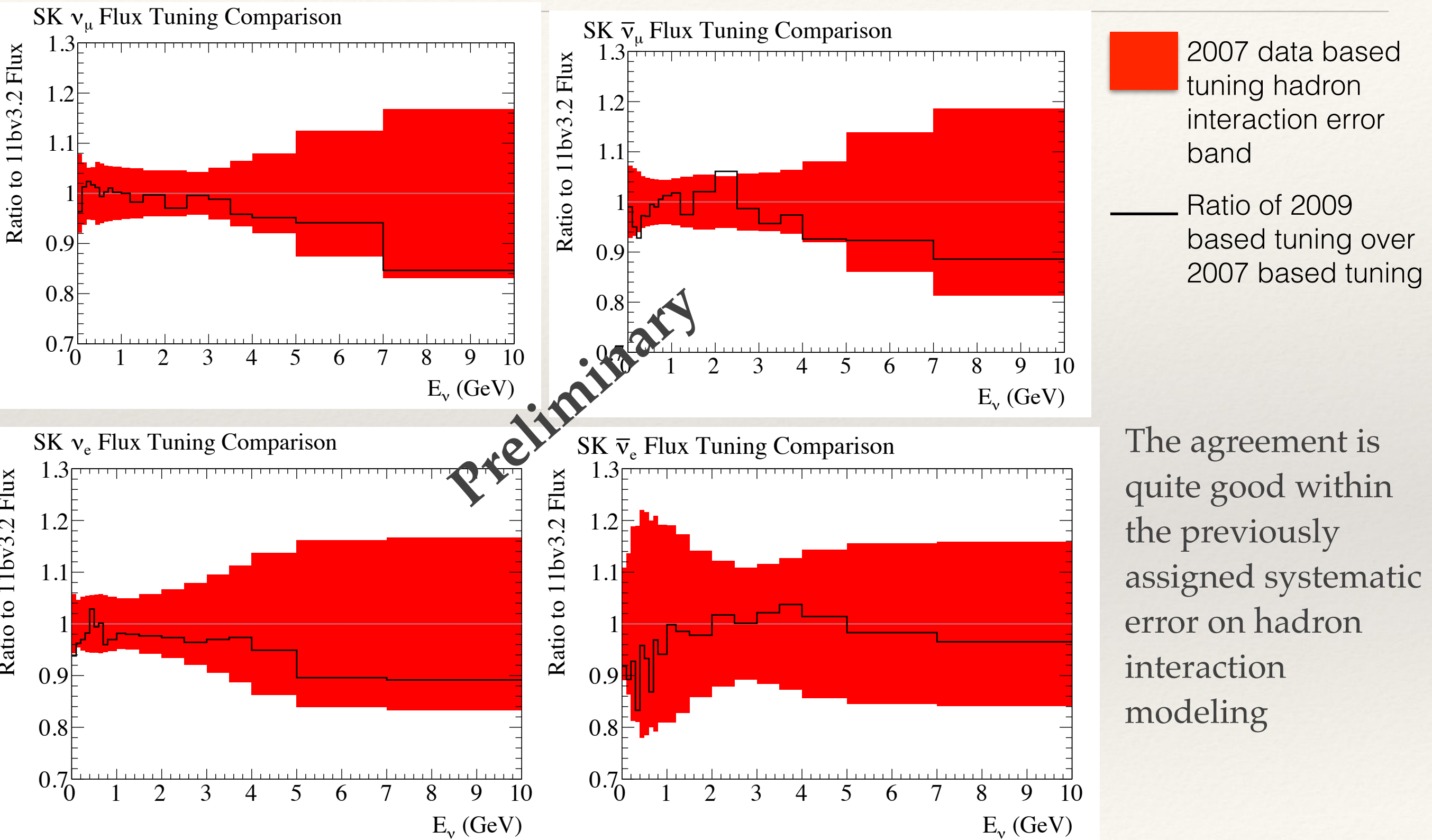
Ratios of the tuned flux over the pre-tuned flux for NA61 2007 data based tuning

The Flux Prediction



Based on the 2007 NA61 data:
Phys. Rev. D 87, 012001 (2013)

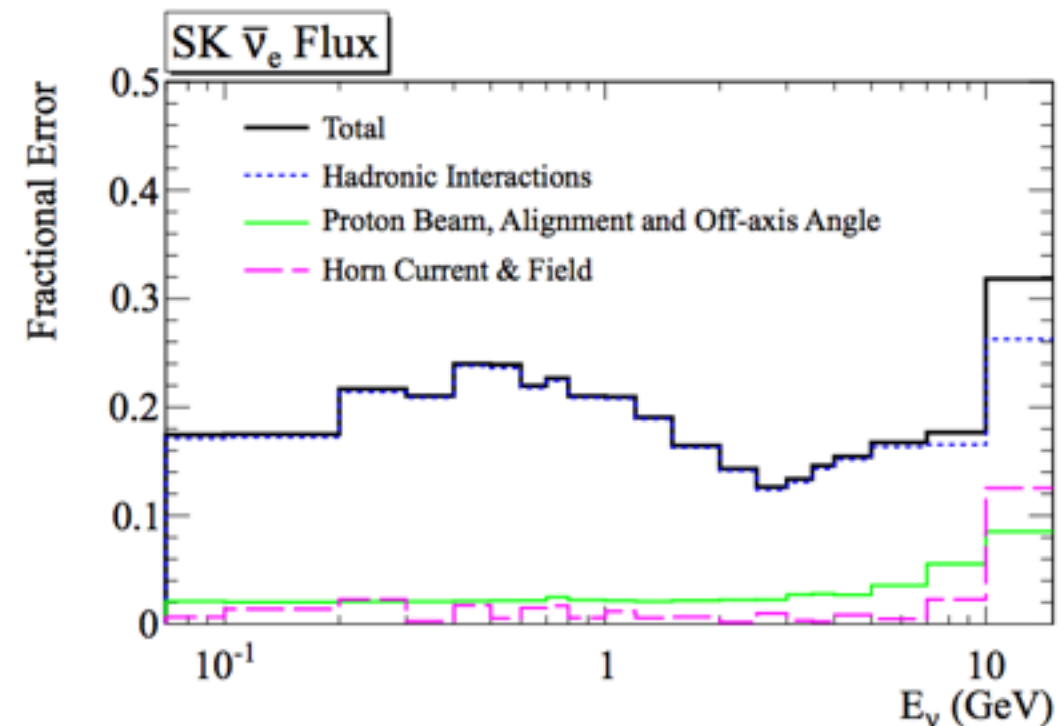
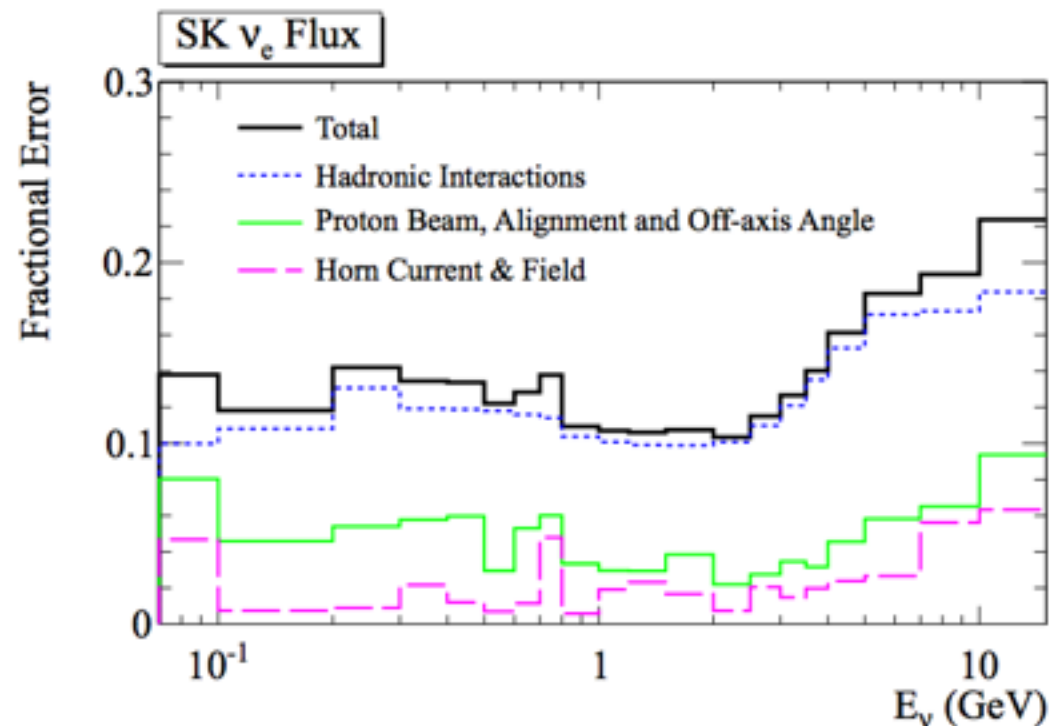
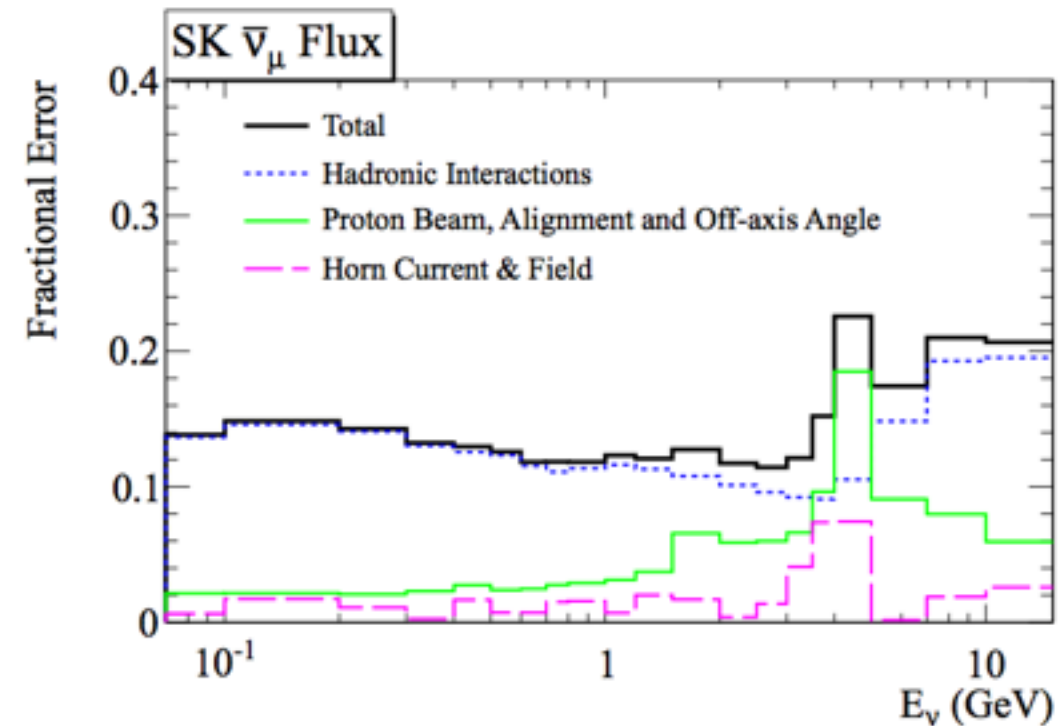
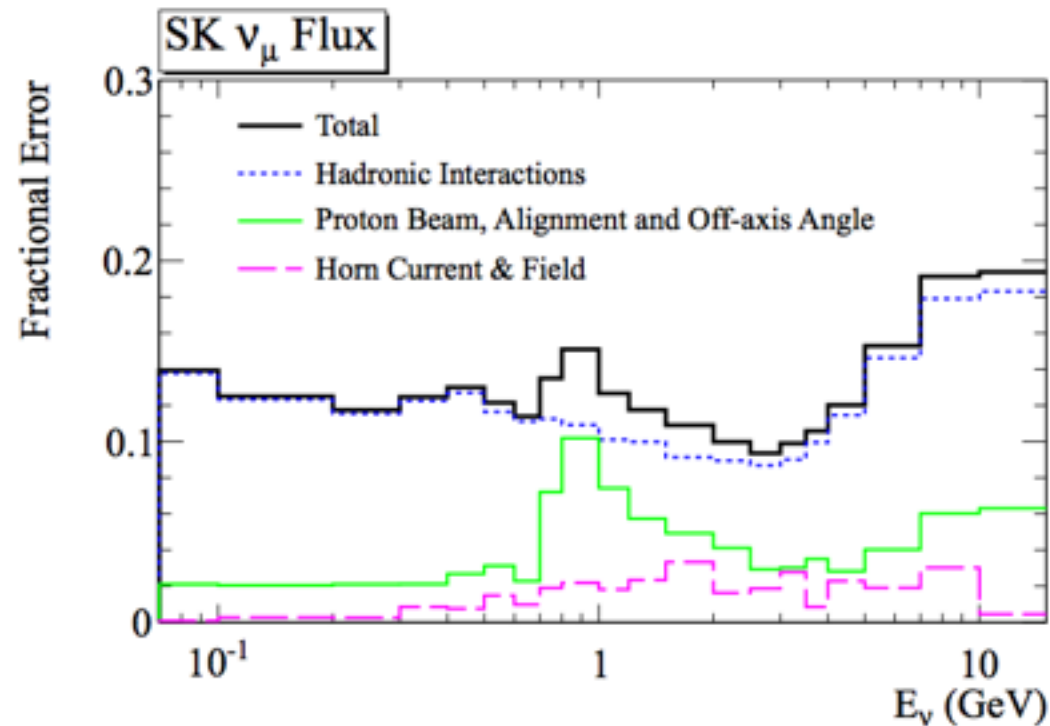
Comparison of 2009 and 2007 Tuning



Flux Uncertainties

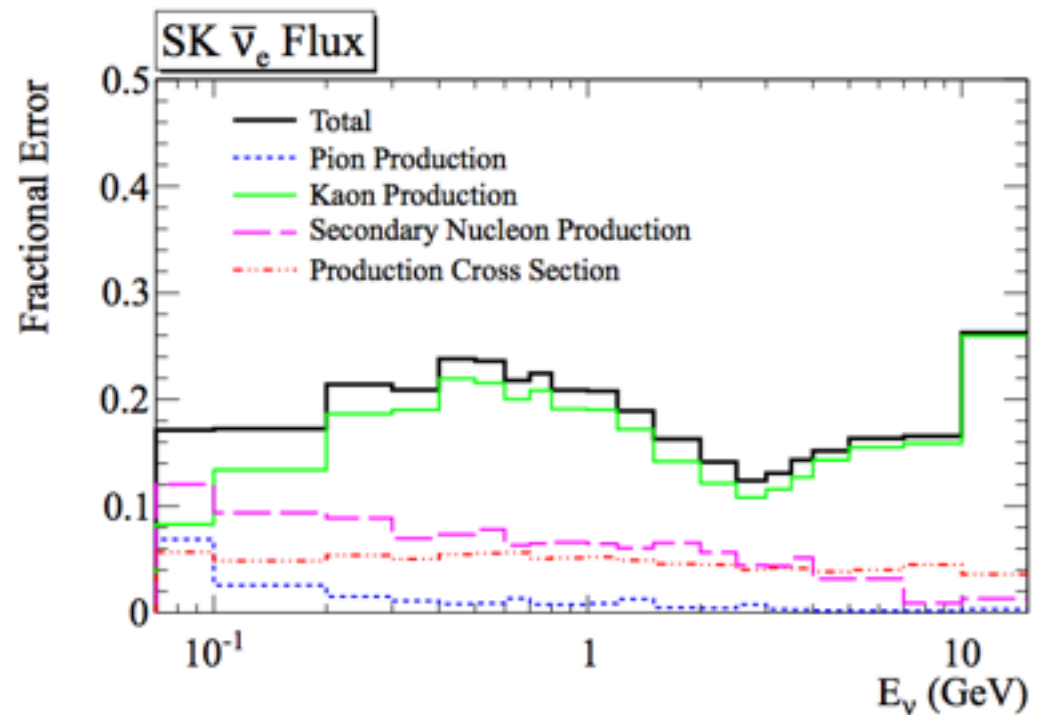
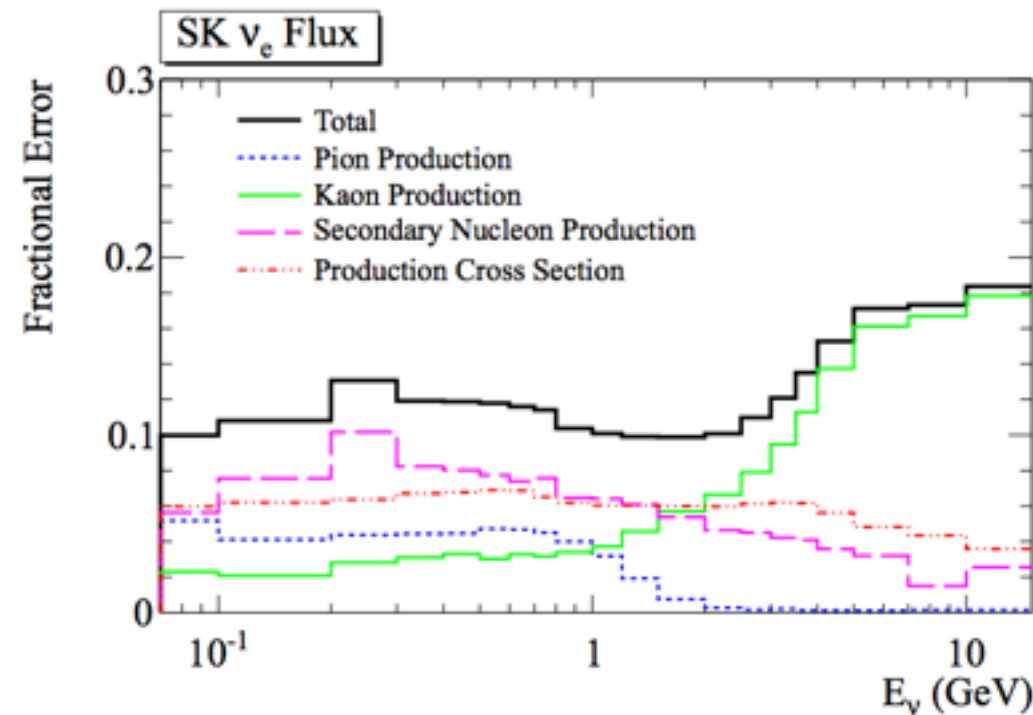
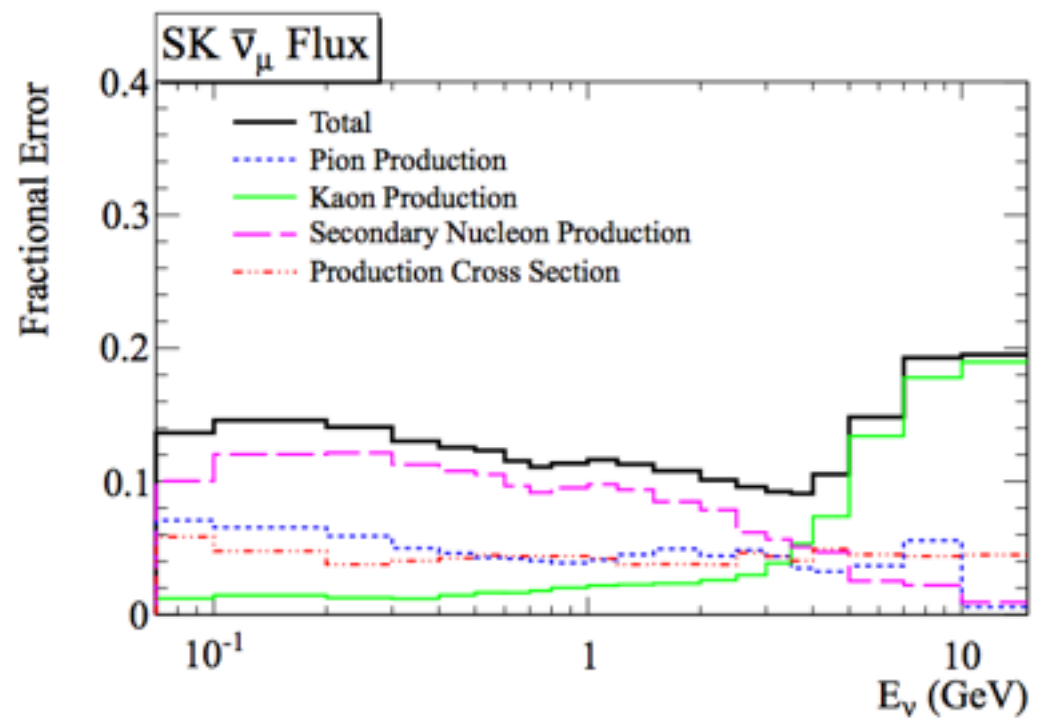
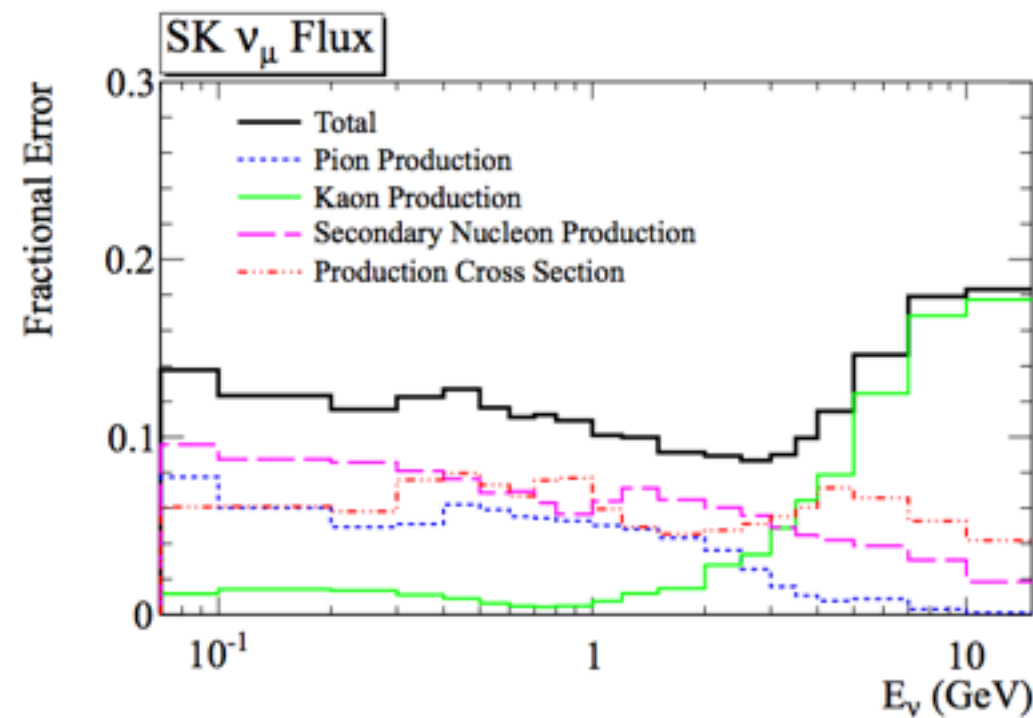
- ❖ We evaluate the uncertainty on the predicted flux before comparing predictions to neutrino data
- ❖ Propagate uncertainties from data: hadron interaction data, proton beam monitor measurements, horn field and current measurements and survey and alignment of beam line elements
- ❖ Also evaluate uncertainties associated with assumptions in hadron interaction tuning:
 - ❖ Assumption of Feynman scaling
 - ❖ Modeling of the quasi-elastic cross section subtracted from data measurements
- ❖ I show fractional errors here but we also calculate a full covariance matrix that includes correlations between different flux bins of energy, flavor, horn polarity and detector.

Evaluated Flux Uncertainties



Positive horn polarity

Hadron Interaction Uncertainties



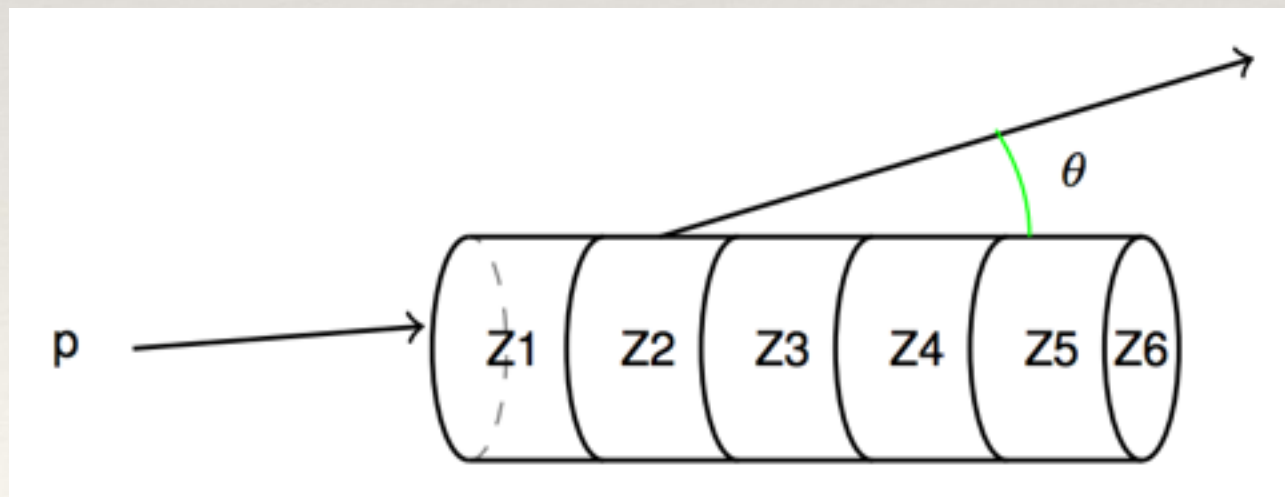
Positive horn polarity

Reducing Systematic Errors

- ❖ Near term:
 - ❖ NA61 2009 data will reduce the errors associated with the differential pion, kaon and proton production.
 - ❖ Improved secondary nucleon tuning that properly enforces baryon conservation will reduce the uncertainty associated with that part of the model.
- ❖ Longer term:
 - ❖ Replica target data will reduce uncertainties associated with particle re-interactions in the target.

NA61 Replica Target Data

- ❖ NA61 / SHINE has collected data with 30 GeV protons on a T2K replica target
- ❖ Preliminary investigation of T2K flux tuning with 2007 data (0.2M protons) have been published: **NIM A701(2013)99**
- ❖ Recently the 2009 data (2.8M protons) has been released (presented at Flavour Physics Conference in Vietnam)
- ❖ The thin target data are presented as particle multiplicities binned in the usual momentum and angle, but also z position along the target

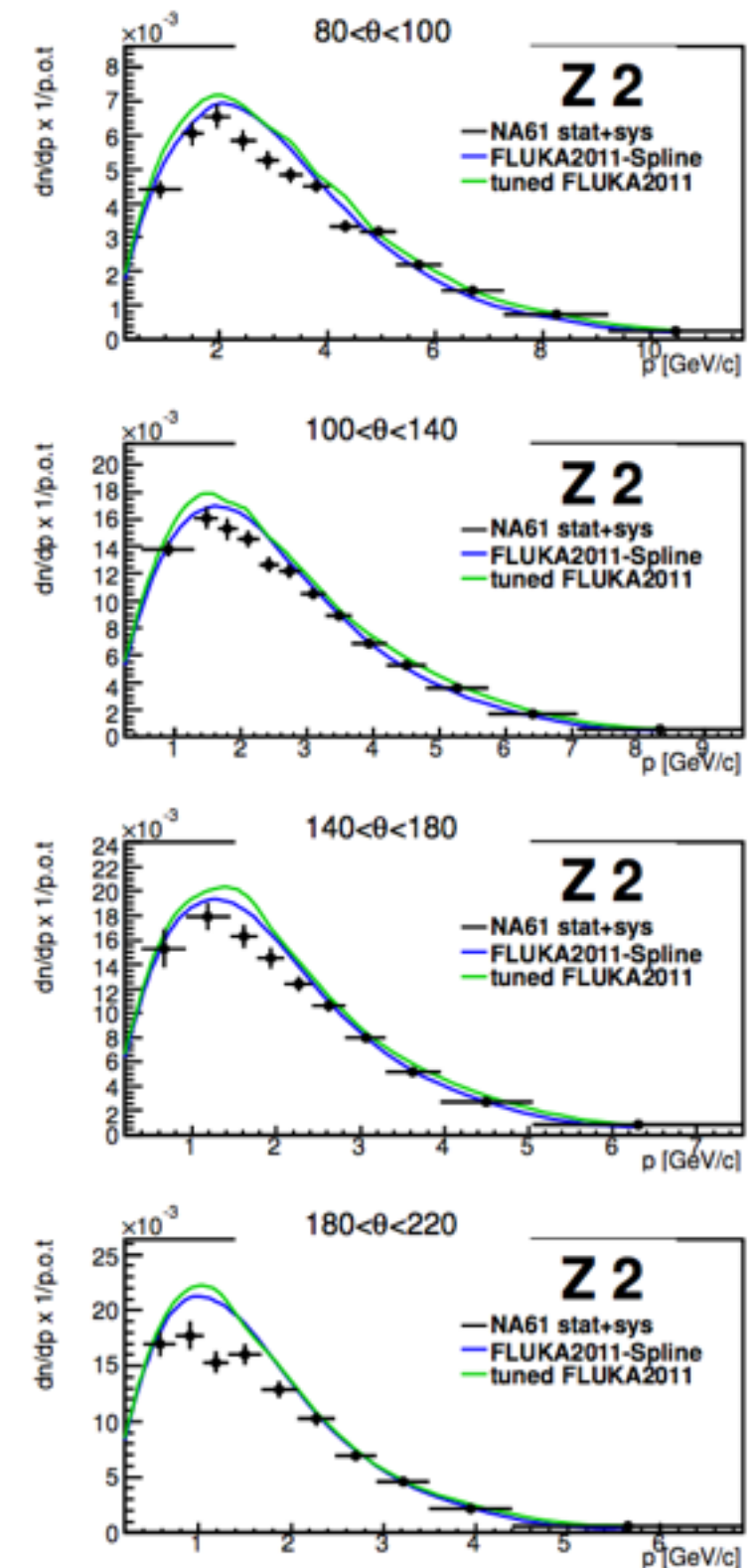


Using Replica Target Data

- ❖ Two potential ways to use the replica target data:
 - ❖ Use the measured multiplicities directly to predict the particle multiplicities exiting the T2K target.
 - ❖ Requires correcting for different proton beam conditions.
 - ❖ Coarse binning in Z may also require a correction or smooth parametrization of the data.
 - ❖ Adjust parameters in the thin target tuning to find agreement between the tuned simulation and replica target data.
 - ❖ There are many parameters in the thin target tuning that could be varied
 - ❖ Most straightforward candidates are the proton and pion interaction rates - **A. Haesler** has begun studying this approach (more on follow slides)

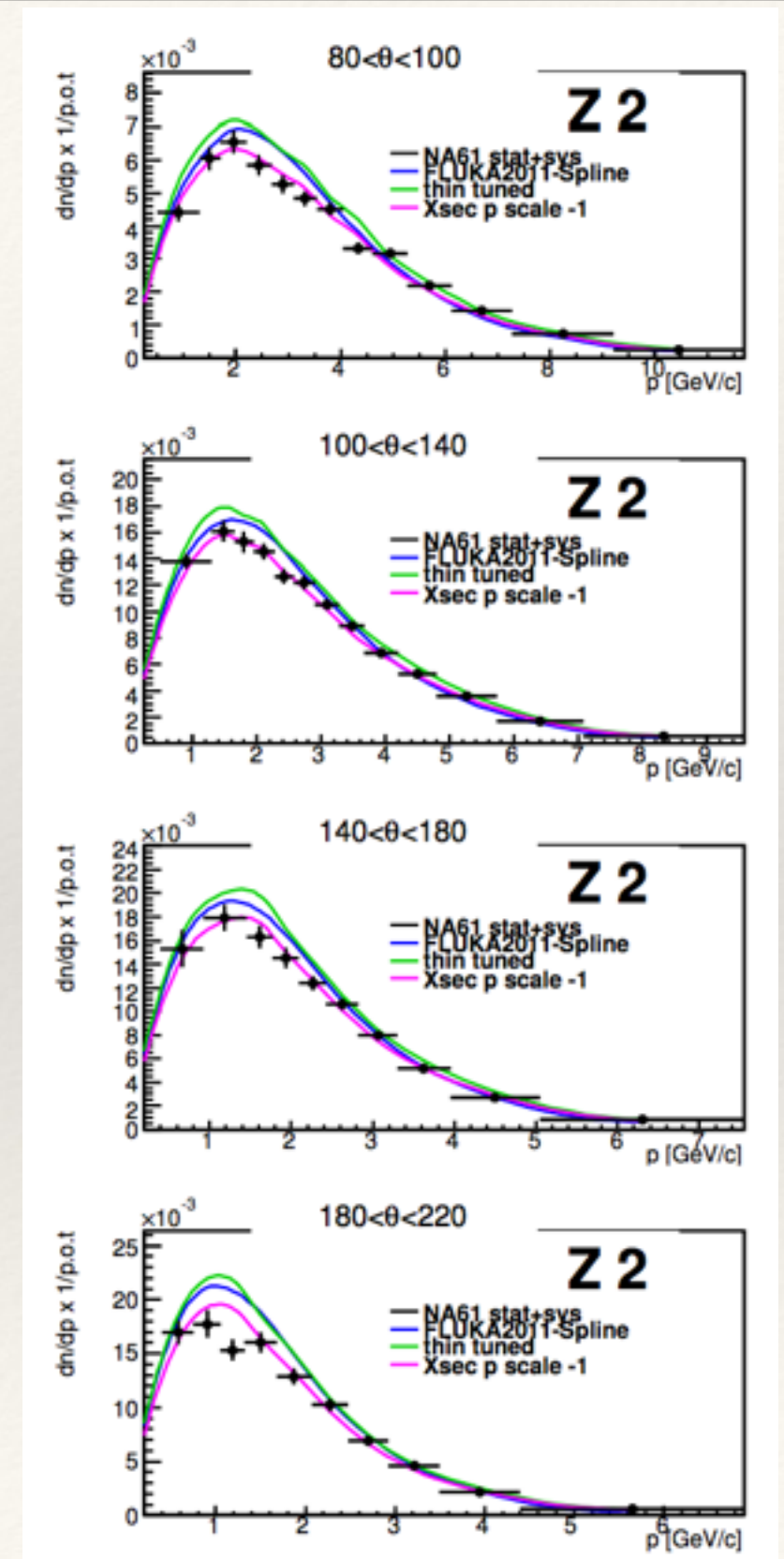
Thin Target Tuning & Replica Target Data

- ❖ Alexis produces a simulation of the T2K replica target where the hadronic interactions can be tuned in the same manner as the T2K flux.
- ❖ For some bins, the agreement isn't so great out of the box.
- ❖ He compares the simulation to the data and considers adjusting parameters from the thin target tuning within their systematic errors to find agreement.



Study of Production Cross Sections

- ❖ Alexis found that adjusting the interaction cross sections for protons or pions within the systematic errors applied by T2K can improve the agreement (magenta curve on right).
- ❖ These are preliminary results, but they indicate a useful way to use the replica target data.
- ❖ Apply the thin target tuning to the replica target simulation.
- ❖ Adjust the interaction probabilities within their systematic errors to find agreement between the data and simulation.

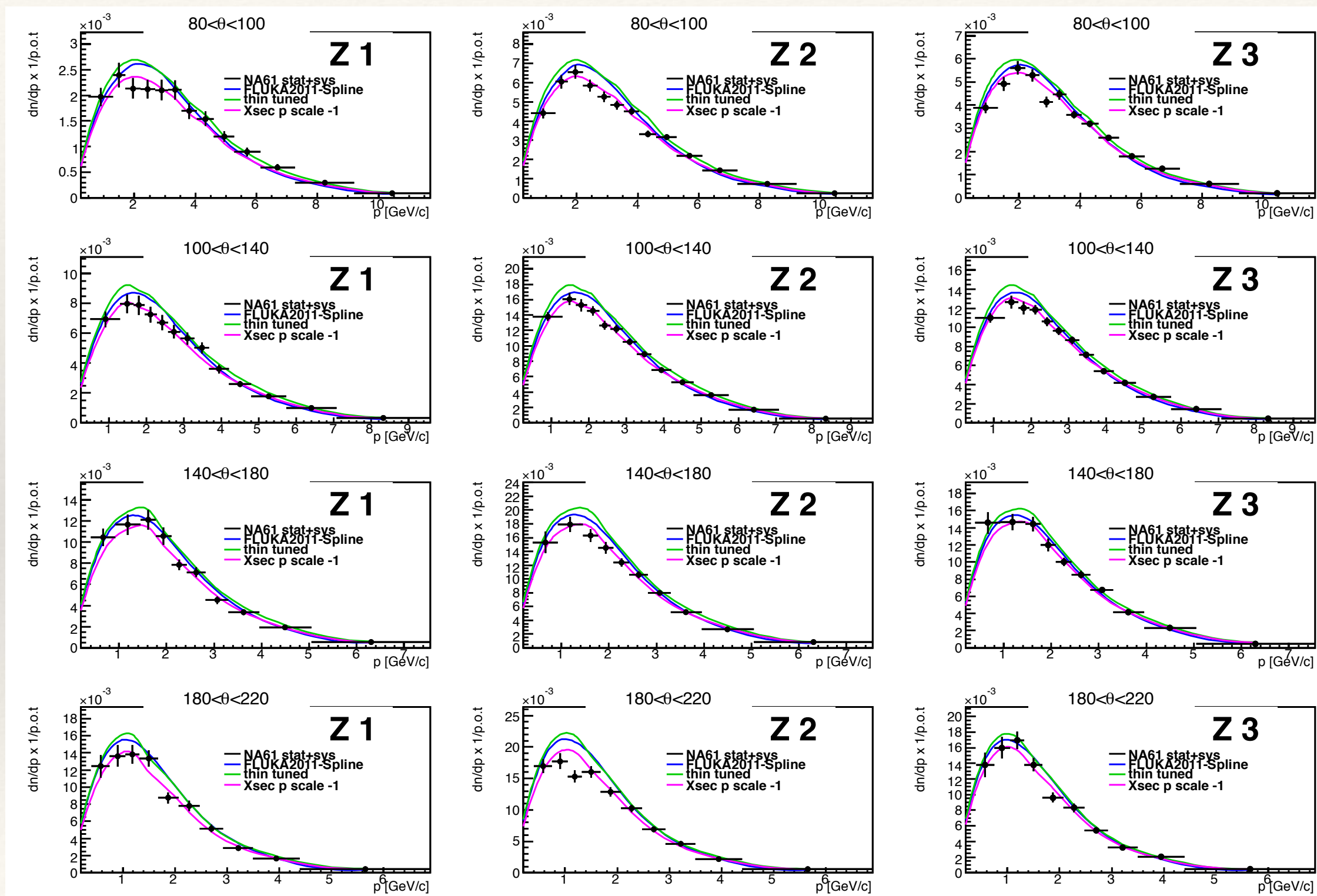


Conclusion

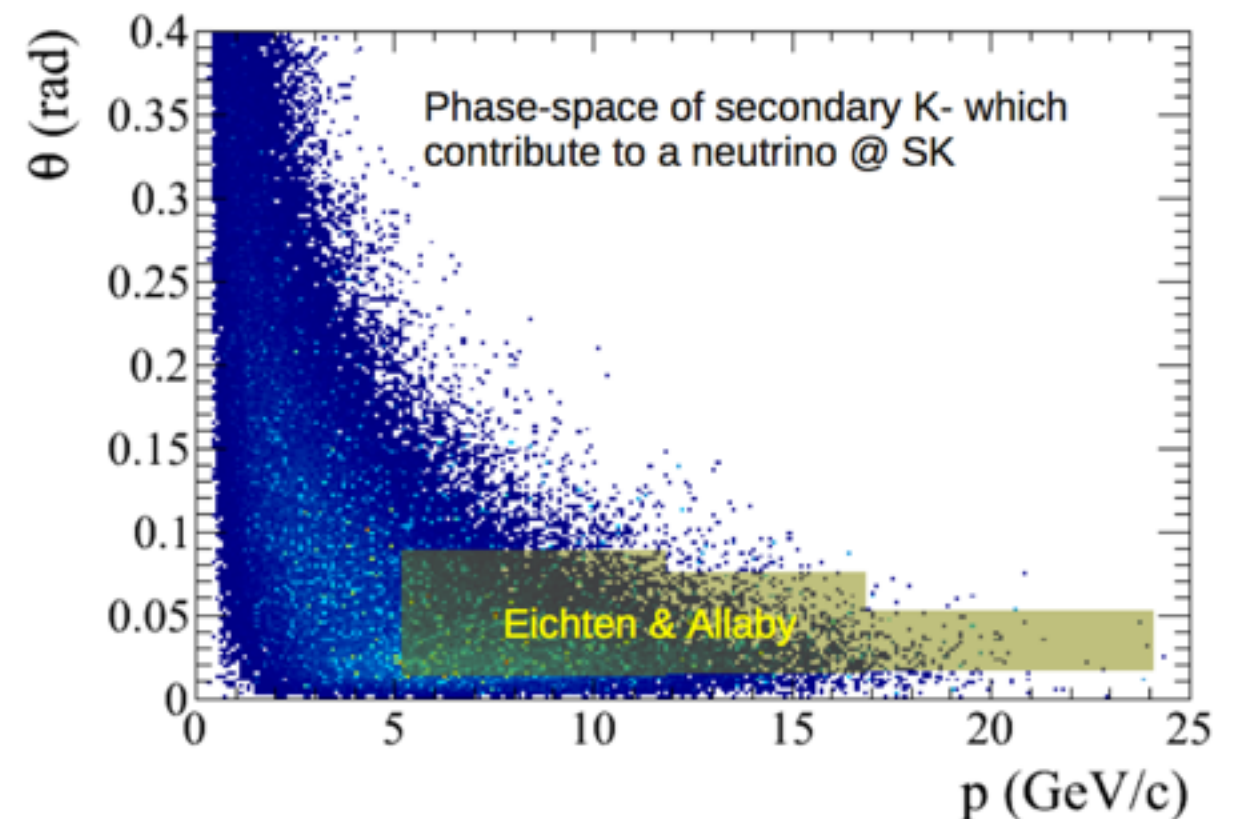
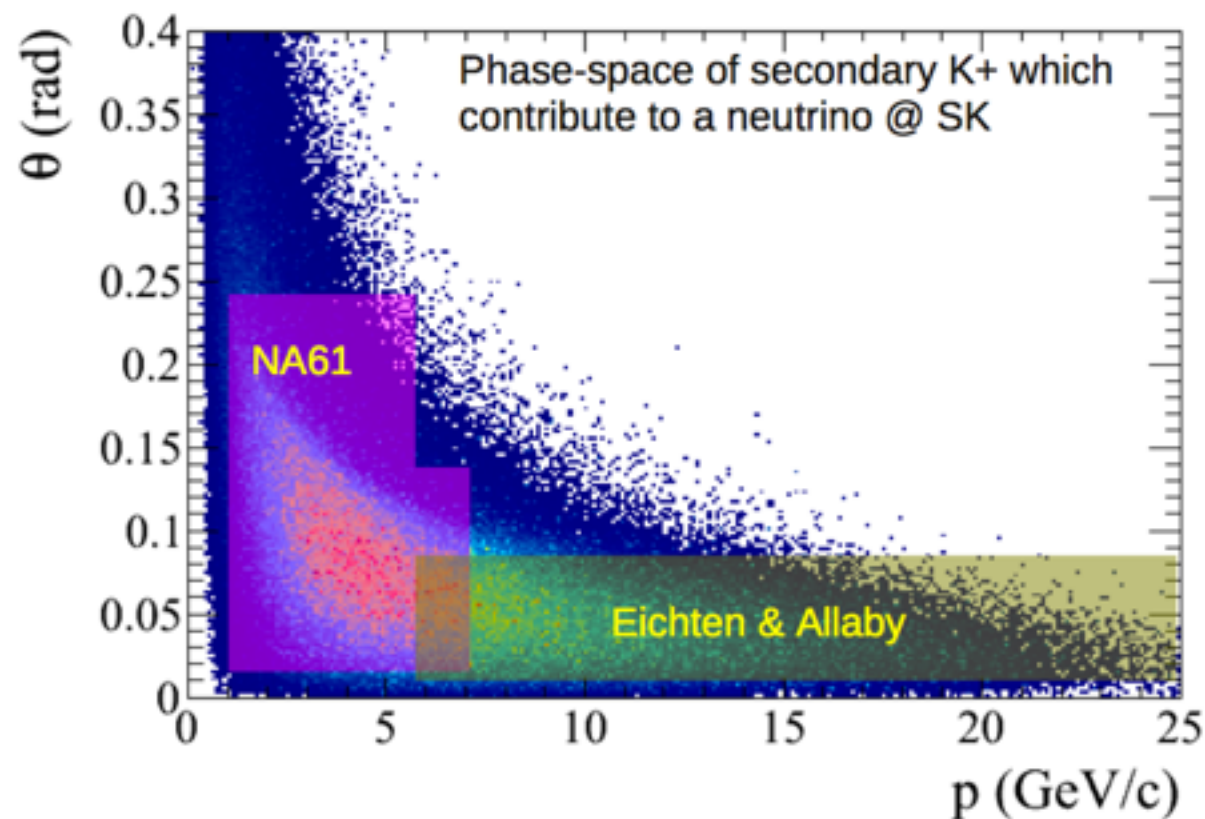
- ❖ The T2K flux prediction is tuned and constrained with beam monitor data, beam component alignment data, horn field data, hadron interaction data.
- ❖ NA61 / SHINE hadron interaction measurements of differential particle multiplicities and proton interaction length play a critical role in modeling hadron interactions in the T2K flux prediction.
 - ❖ The flux prediction is now being updated to include the NA61 2009 data.
 - ❖ Results are consistent with the previous flux prediction and we expect a reduction in systematic uncertainties.
- ❖ Preliminary NA61 2009 replica target data is released.
 - ❖ Studies of the consistency of replica and thin target data are underway.
 - ❖ Will eventually be included in the T2K flux prediction.

Extra Slides

Replica Target Data



Kaon Data



- ❖ Data from Eichten and Allaby are used to extend the coverage for K^+ and provide data for K^-
- ❖ Require scaling to higher center of mass energy and from Be to C

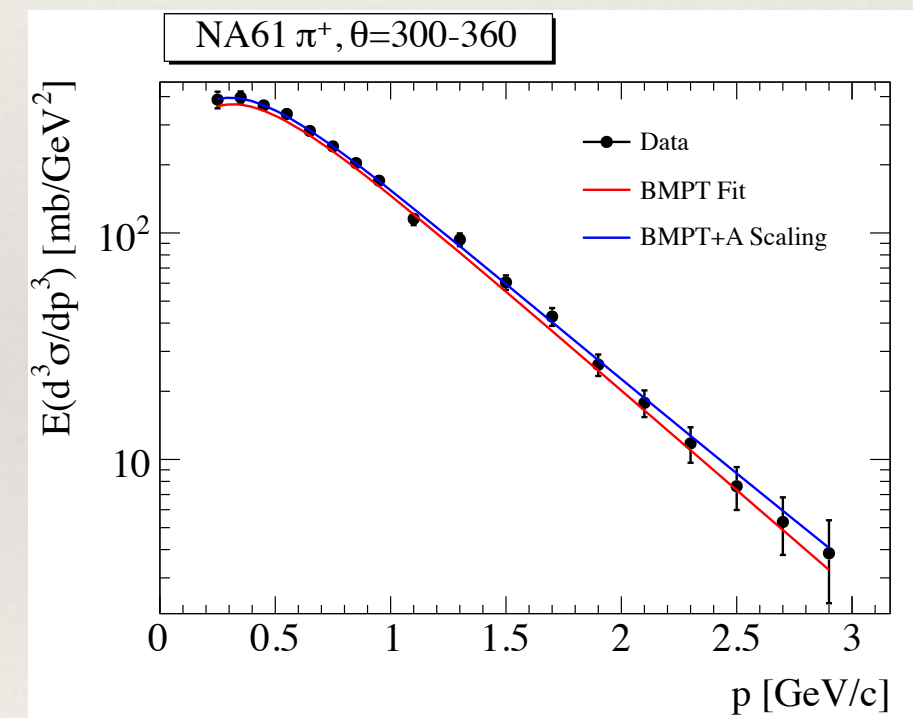
A Comment on Parameterizations of the Data

- ❖ In general we find that the BMPT parametrization does a better job of fitting data than Sanford-Wang
- ❖ However, there is a limitation:
 - ❖ BMPT is symmetric around $x_F=0$ so it does not work as well if some of the data is $x_F<0$.
 - ❖ This is true for part of the high angle / low momentum contribution to the T2K flux
- ❖ Found a simple solution that improves the situation a bit:
 - ❖ Assume the BMPT form for scattering on a deuteron
 - ❖ Apply the usual A scaling to the nuclear target for the data (can be fixed to the parametrization from the BMPT paper)

BMPT Fit Improvements

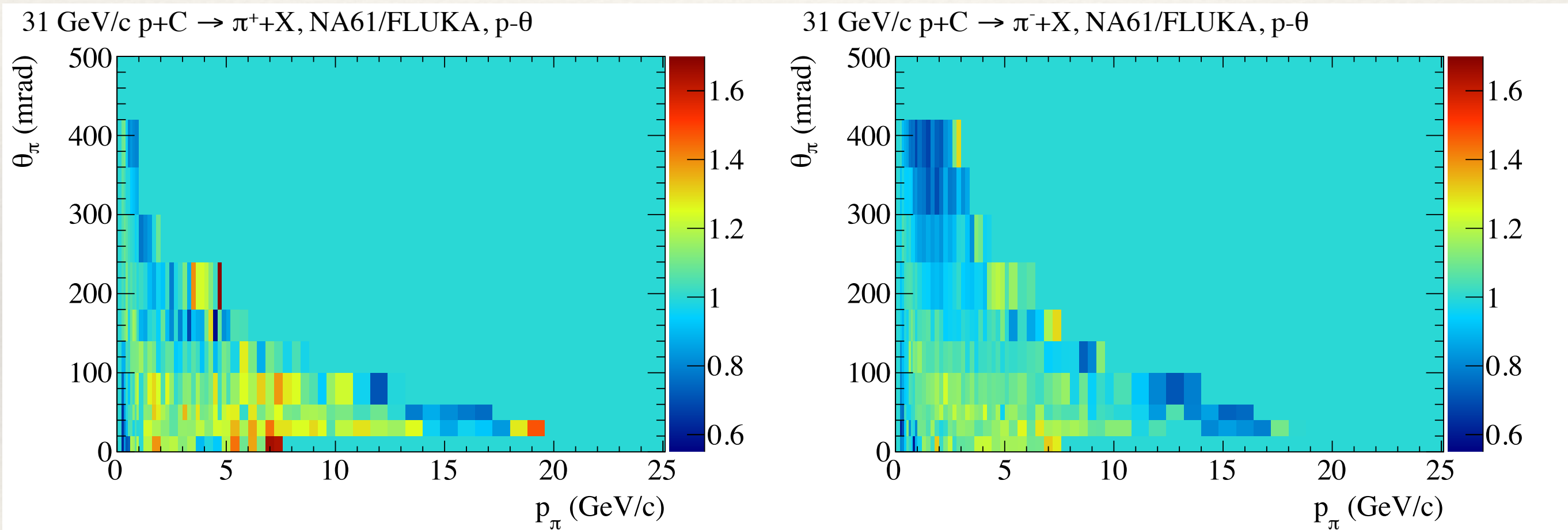
- ❖ NA61 2009 thin target data fit with original and modified BMPT parameterizations
- ❖ See improvement in the chi square for each particle type
- ❖ See improvement in the high angle bins

	π^+	π^-	K^+	K^-
d.o.f.	403	415	91	91
Original BMPT χ	529	475	81	137
Modified BMPT χ	465	370	75	124

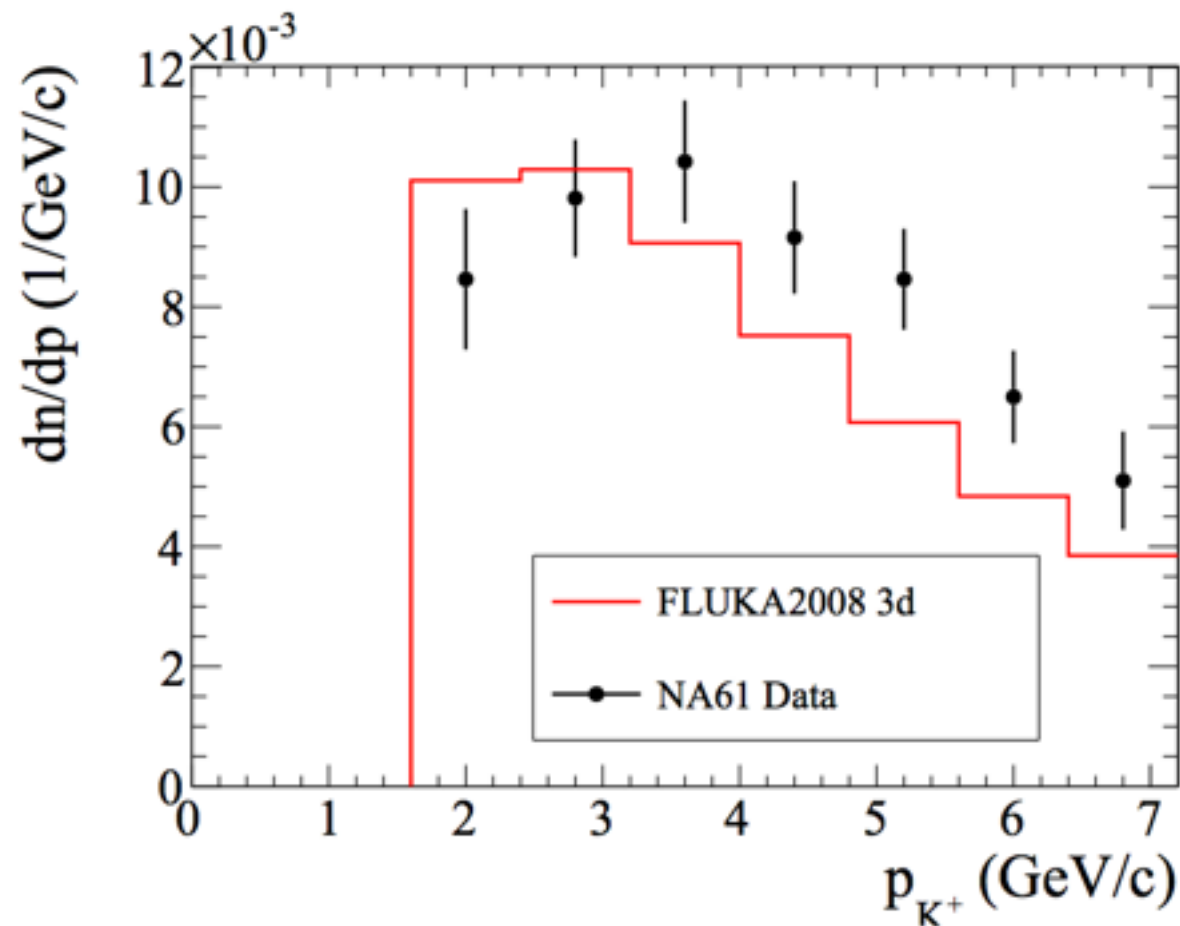


Weights From NA61 Pion Data

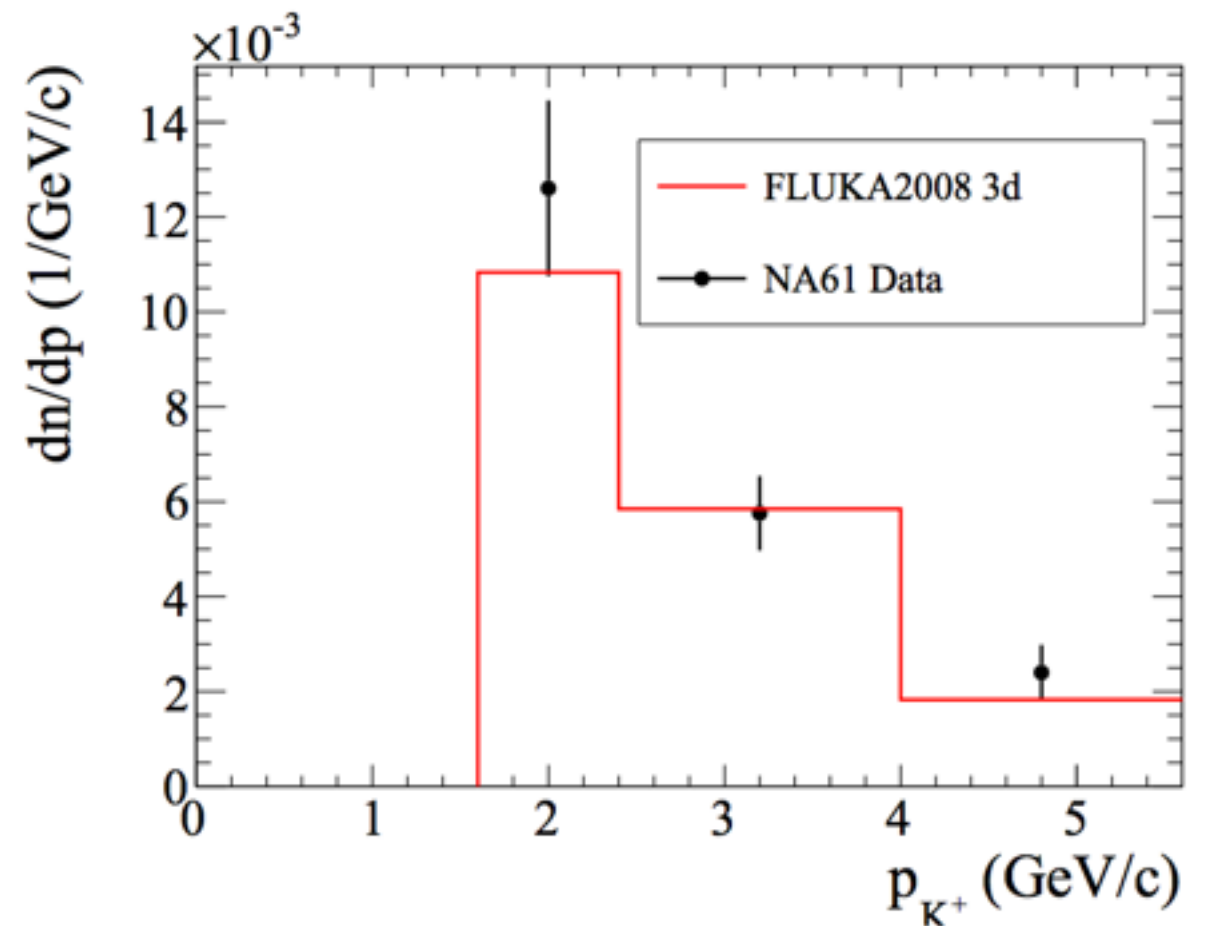
Weights are made by taking the ratio of the NA61 measured multiplicities to simulated multiplicities with FLUKA 2008 (used to simulate the target):



K⁺ Data and FLUKA 2008



(a) 20-140 mrad bin



(b) 140-240 mrad bin

FLUKA 2008 seems to underestimate the forward production at higher momenta

This is consistent with the comparisons to the Eichten and Allaby data.

Secondary and Out-of-Target Interactions

Some neutrinos come from interaction chains where there are secondary hadron interactions, sometimes out of the target

Percent of the flux from different hadronic interaction chain configurations

	Number of Inelastic Hadronic Interactions in Chain Producing the Neutrino		
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N280 ν_μ flux	63.2%	36.8%	12.6%
N280 anti- ν_μ flux	39.5%	60.5%	49.8%
N280 ν_e flux	60.1%	39.9%	13.6%
N280 anti- ν_e flux	50.7%	49.3%	32.2%
SK ν_μ flux	63.2%	36.8%	12.4%
SK anti- ν_μ flux	41.5%	58.5%	45.1%
SK ν_e flux	61.7%	38.3%	12.7%
SK anti- ν_e flux	54.0%	46.0%	27.2%

Secondary and out-of-target interactions are a bigger effect for the wrong sign flux

Approach is to scale the NA61 data to different center of mass energy and targets

Scaling Methods

- ❖ To do the scaling to different center of mass energies, we use the Feynman scaling to scale the NA61 / SHINE data
 - ❖ In the variables x_F and p_T , the invariant cross section is invariant for changes in the center of mass energy
 - ❖ We crosscheck this approach with an independent approach of tuning with E910 data at 17.5 and 12.3 GeV / c proton momenta
- ❖ For the target nucleus scaling, we use the parametrization used in the BMPT paper:

$$E \frac{d^3 \sigma^{A_2}}{dp^3} = \left(\frac{A_2}{A_1} \right)^{\alpha(x_F, p_T)} E \frac{d^3 \sigma^{A_1}}{dp^3}$$

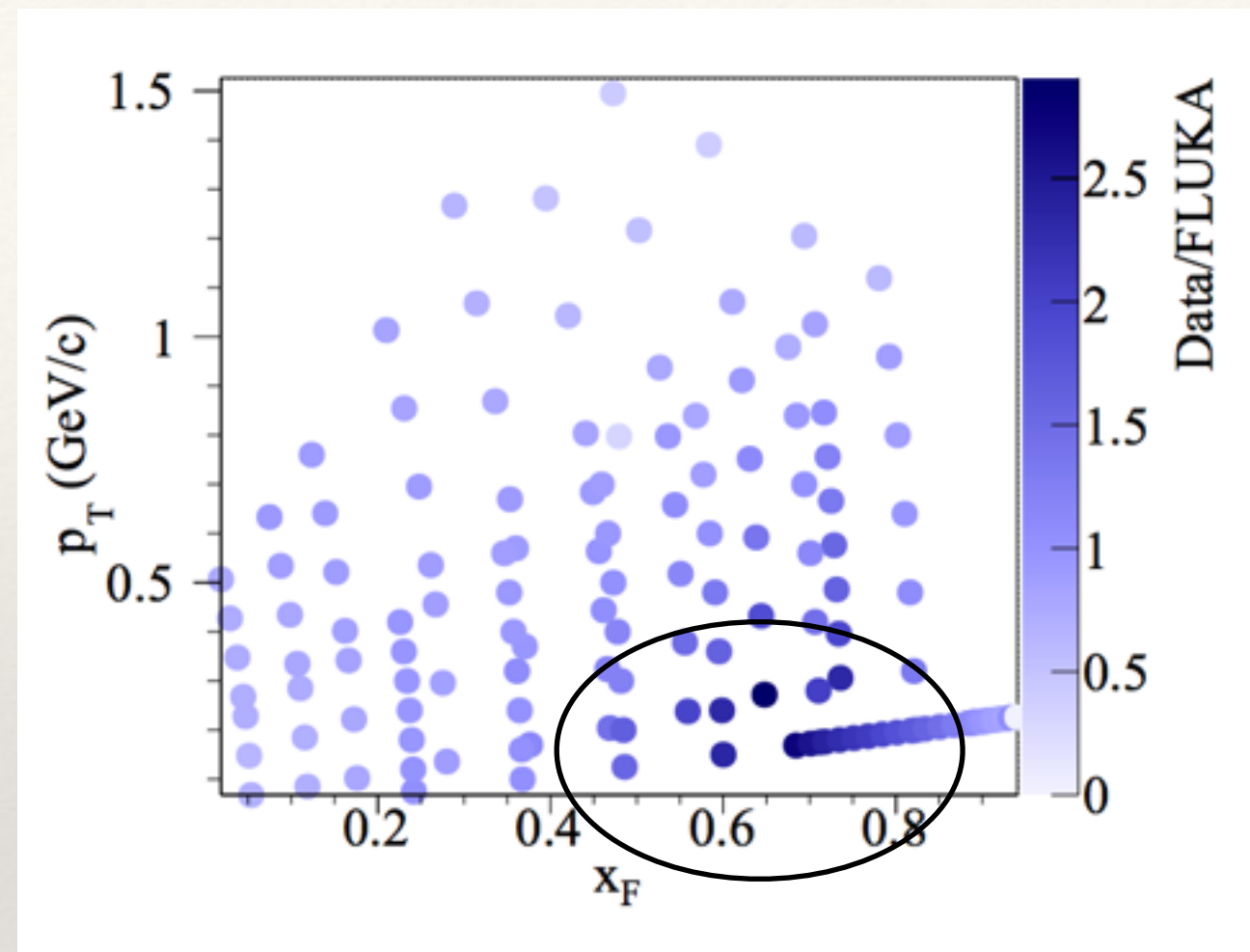
$$\alpha(x_F, p_T) = (a + bx_f + cx_F^2)(d + ep_T^2)$$

- ❖ The parameters come from a fit to the Allaby and Eichten data:

Table 43: Parameters for material scaling					
	a	b	c	d	e
nominal	0.74	-0.55	0.26	0.98	0.21
fitted π	0.75	-0.52	0.23	1.0 (fixed)	0.21
fitted K	0.77	-0.32	0.0	1.0 (fixed)	0.25

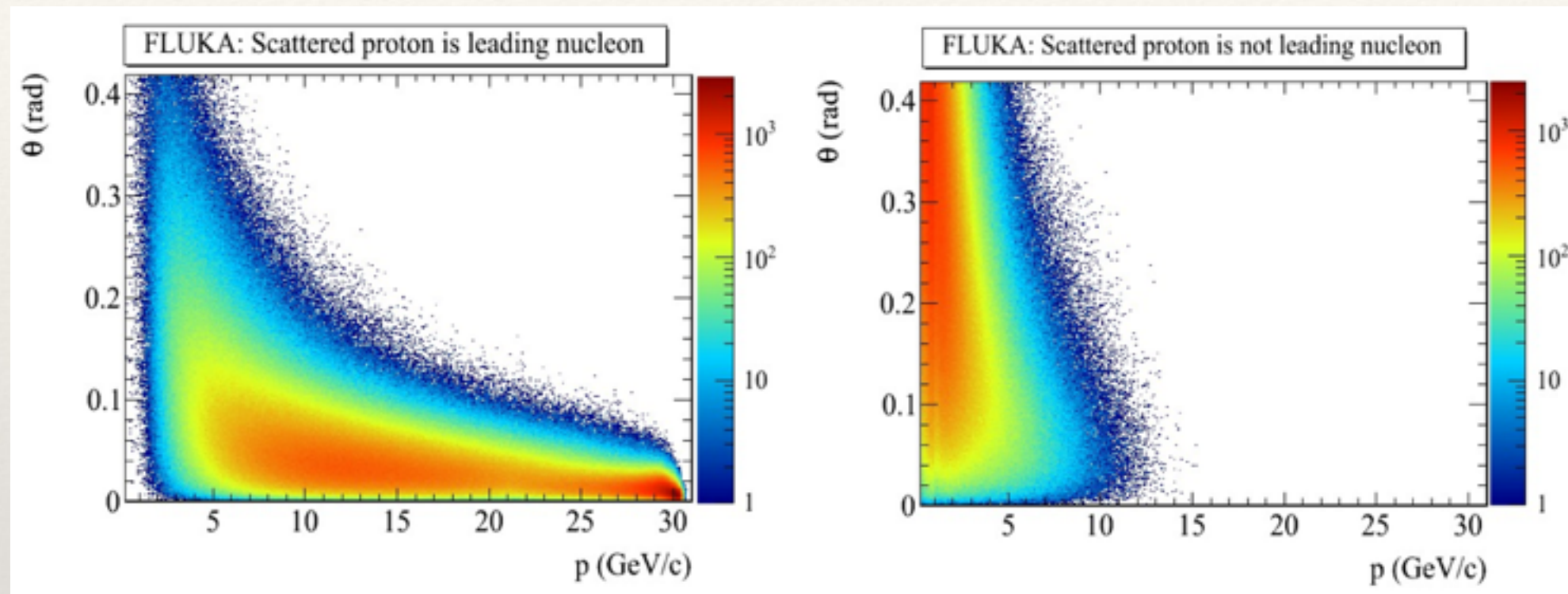
Secondary Nucleon Uncertainties

- ❖ The secondary nucleon production uncertainty is one of the dominant ones at low energy
- ❖ This is the uncertainty on the nucleons that are scattered into the final state in hadronic interactions that can then reinteract themselves
- ❖ With the NA61 2007, Eichten and Allaby data there were rather large discrepancies with FLUKA 2008
- ❖ We apply a large uncertainty that covers this discrepancy, but with a simplistic approach to reweighting the flux that does not fully account for baryon conservation



Baryon Conservation in Nucleon Reweighting

- ❖ We can break the nucleons contributing the flux into leading nucleons and nucleons produced in N/\bar{N} production or scattered out of the nucleus



- ❖ Any reweighting should enforce baryon number conservation for the leading nucleons
- ❖ S. Johnson at Univ. of Colorado is not implementing baryon number conserving reweighting that will be included in future T2K flux predictions
- ❖ Expect significant reduction in this uncertainty

Flux Covariance Matrix

- ❖ Uncertainties are evaluated in bins of flavor, energy and detector (ND280 or SK)
- ❖ To propagate these uncertainties into T2K analyses, we need to full covariance matrix including the ND280 and SK flux bins
- ❖ For each independent systematic error source we evaluate the covariance matrix (see next slide)
- ❖ Sum the covariance matrices for each error source to get the total covariance matrix

Evaluating the Covariance Matrix

- ❖ Some systematic effects, e.g. beam line component alignment, are evaluated with $(\pm)1\sigma$ variations

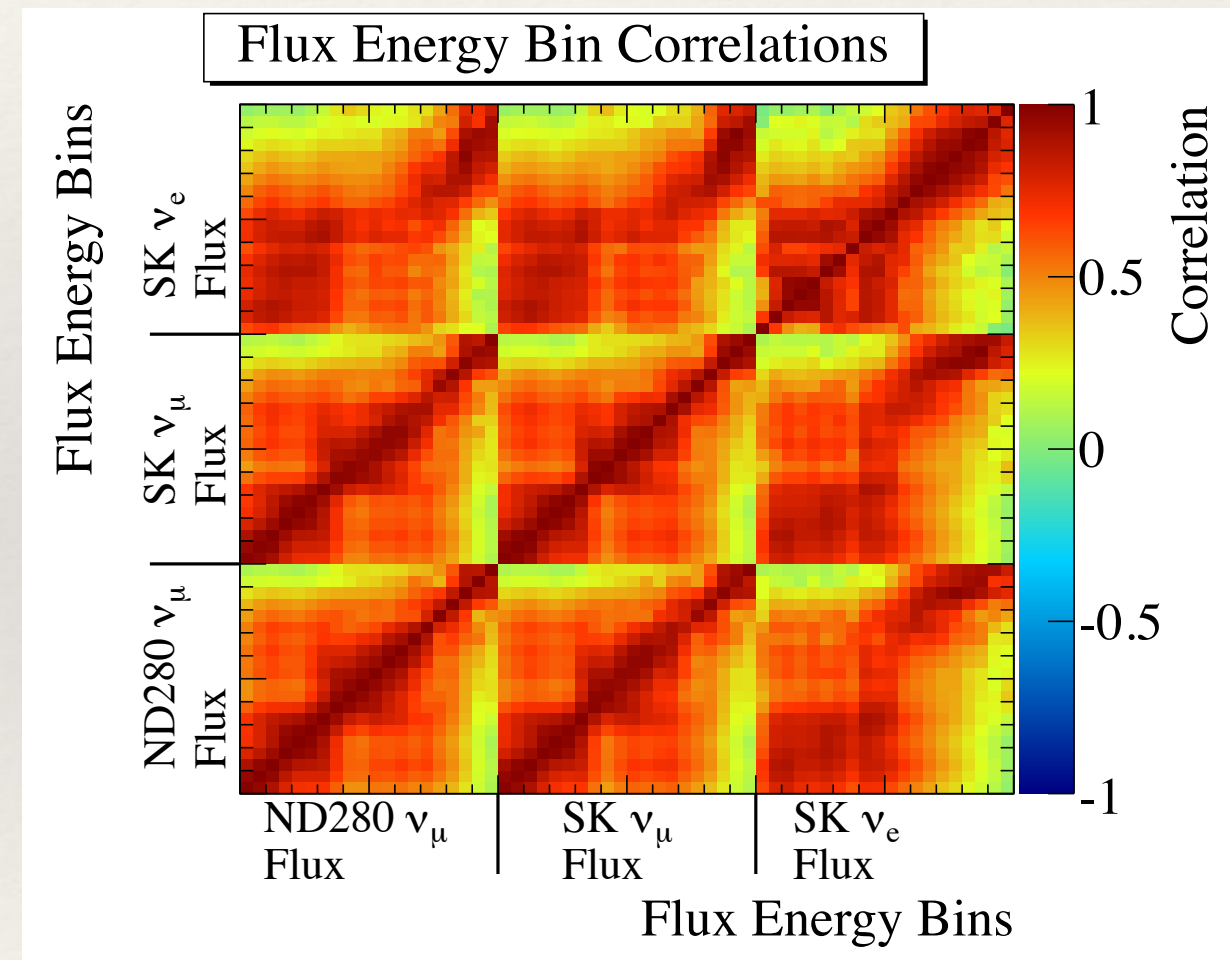
$$(V_b^\pm)_{i,j} = \frac{1}{2} \left[\frac{\Phi_i^+ - \Phi_i^{nom}}{\Phi_i^{nom}} * \frac{\Phi_j^+ - \Phi_j^{nom}}{\Phi_j^{nom}} + \frac{\Phi_i^- - \Phi_i^{nom}}{\Phi_i^{nom}} * \frac{\Phi_j^- - \Phi_j^{nom}}{\Phi_j^{nom}} \right]$$

- ❖ Others, such as NA61 data uncertainties are evaluated with many systematic throws

$$(V_b^{throw})_{i,j} = \frac{1}{N} \sum_{k=1}^{k=N} \left[\frac{\Phi_i^k - \Phi_i^{nom}}{\Phi_i^{nom}} * \frac{\Phi_j^k - \Phi_j^{nom}}{\Phi_j^{nom}} \right]$$

Flux Correlation Matrix

- ❖ We can take the covariance matrix and look at the correlation between ND280 ν_μ flux bins and SK ν_μ and ν_e flux bins
- ❖ There are significant correlations between ND280 ν_μ flux bins and SK ν_μ and ν_e flux bins
 - ❖ Correlations between the ν_μ and ν_e fluxes arise from their shared ancestor hadron phase space
- ❖ A constraint on the ND280 ν_μ flux also constrains the SK ν_μ and ν_e flux



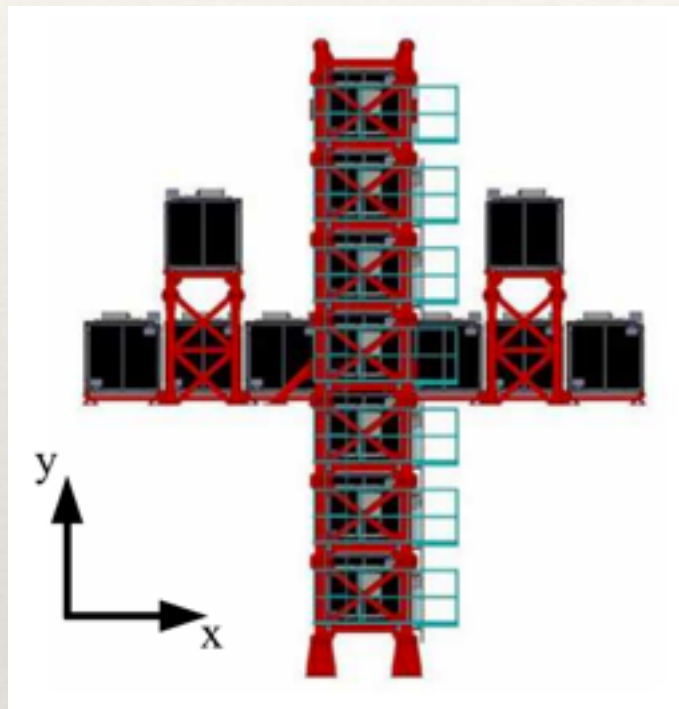
Using ND280 Data

- ❖ The first step was to predict the T2K flux using beam monitor, hadron interaction and alignment data
- ❖ Having evaluated the covariance matrix we now have a probability distribution function describing our knowledge of the T2K flux before looking at any neutrino data
- ❖ The next step is to use ND280 data to further constrain the flux model
 - ❖ For the interactions at T2K neutrino energies, there is no good method to measure the flux independently from the neutrino cross sections
 - ❖ A fit to ND280 data simultaneously constrains the flux and cross section models (I will mostly ignore the cross section model in this talk)

T2K Near Detectors

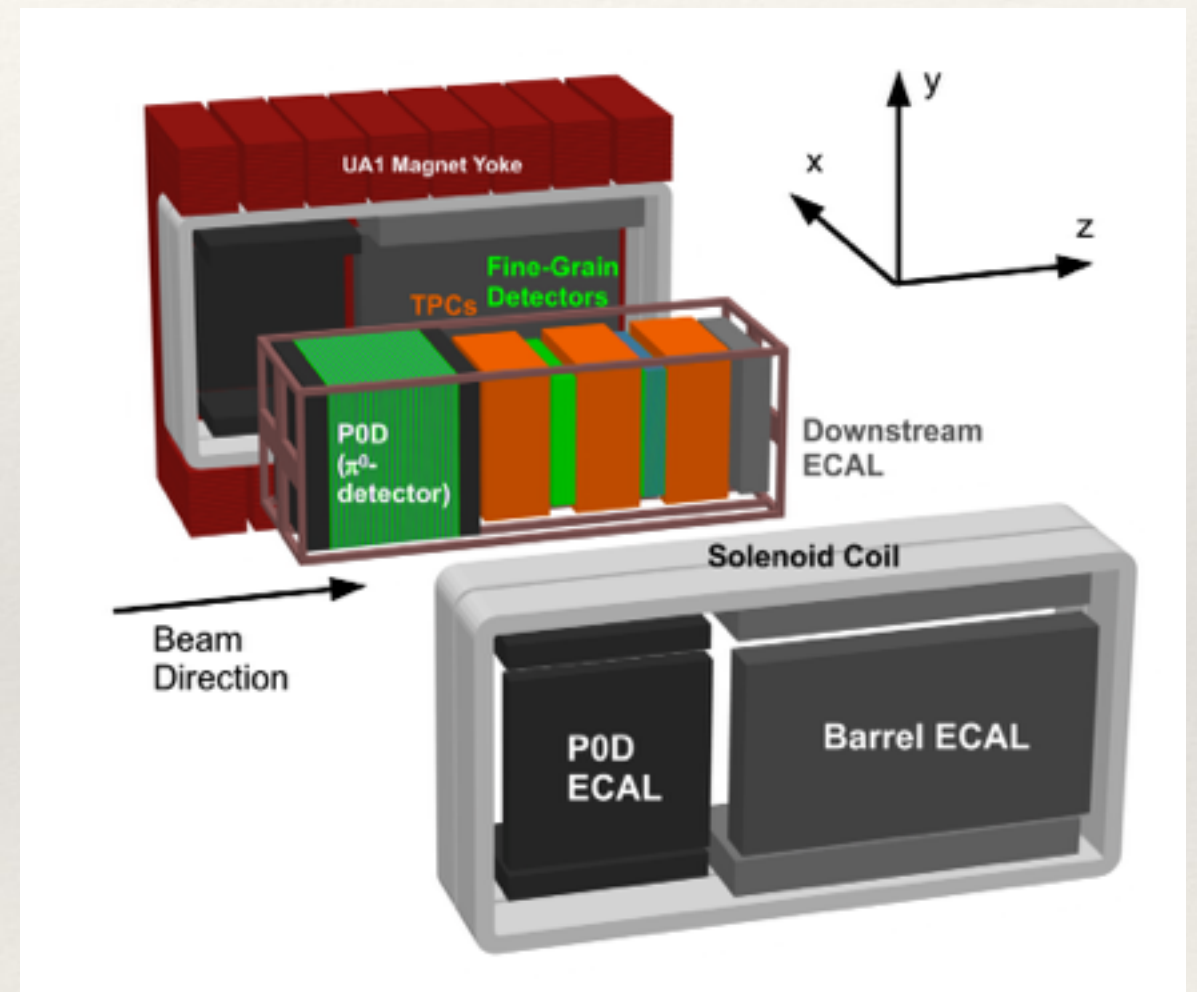
- ❖ T2K has two neutrino detectors at the 280 m near detector site:

INGRID



- Modules with iron and scintillator bar layers
- In cross configuration centered on beam axis
- Monitors the neutrino event rate and beam direction stability

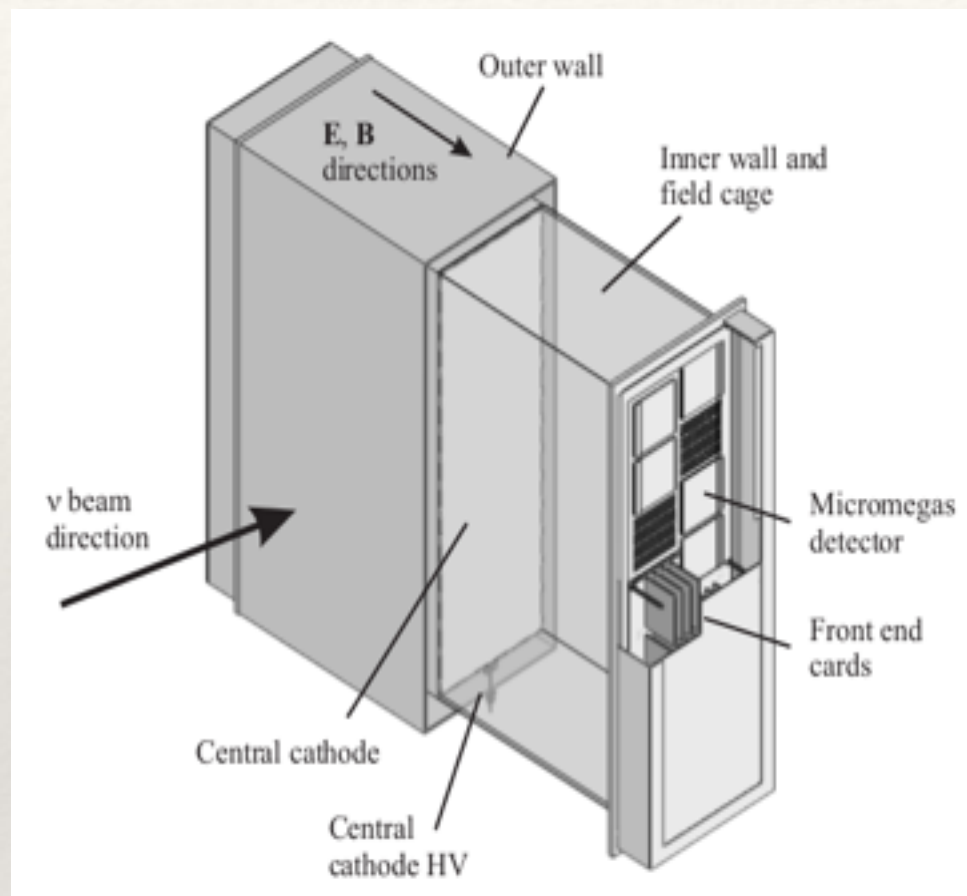
ND280



- Off-axis beam similar to SK
- Magnetized detector for charge separation and momentum measurements

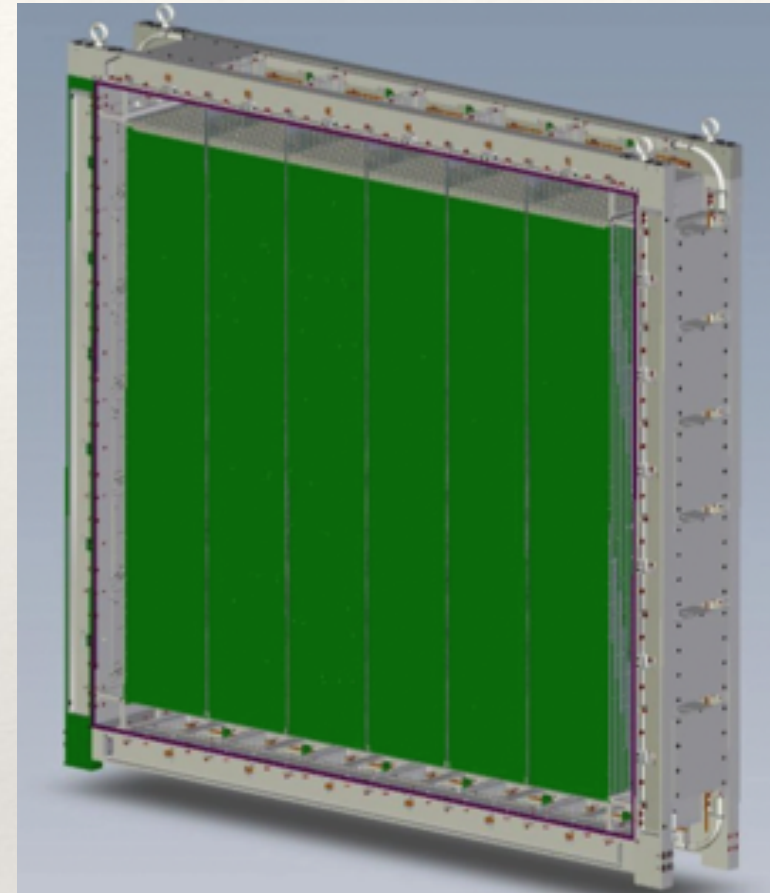
ND280 Tracker Sub-detectors

TPC



- Tracks charged particles in magnetic field
- 10% momentum resolution at 1 GeV/c

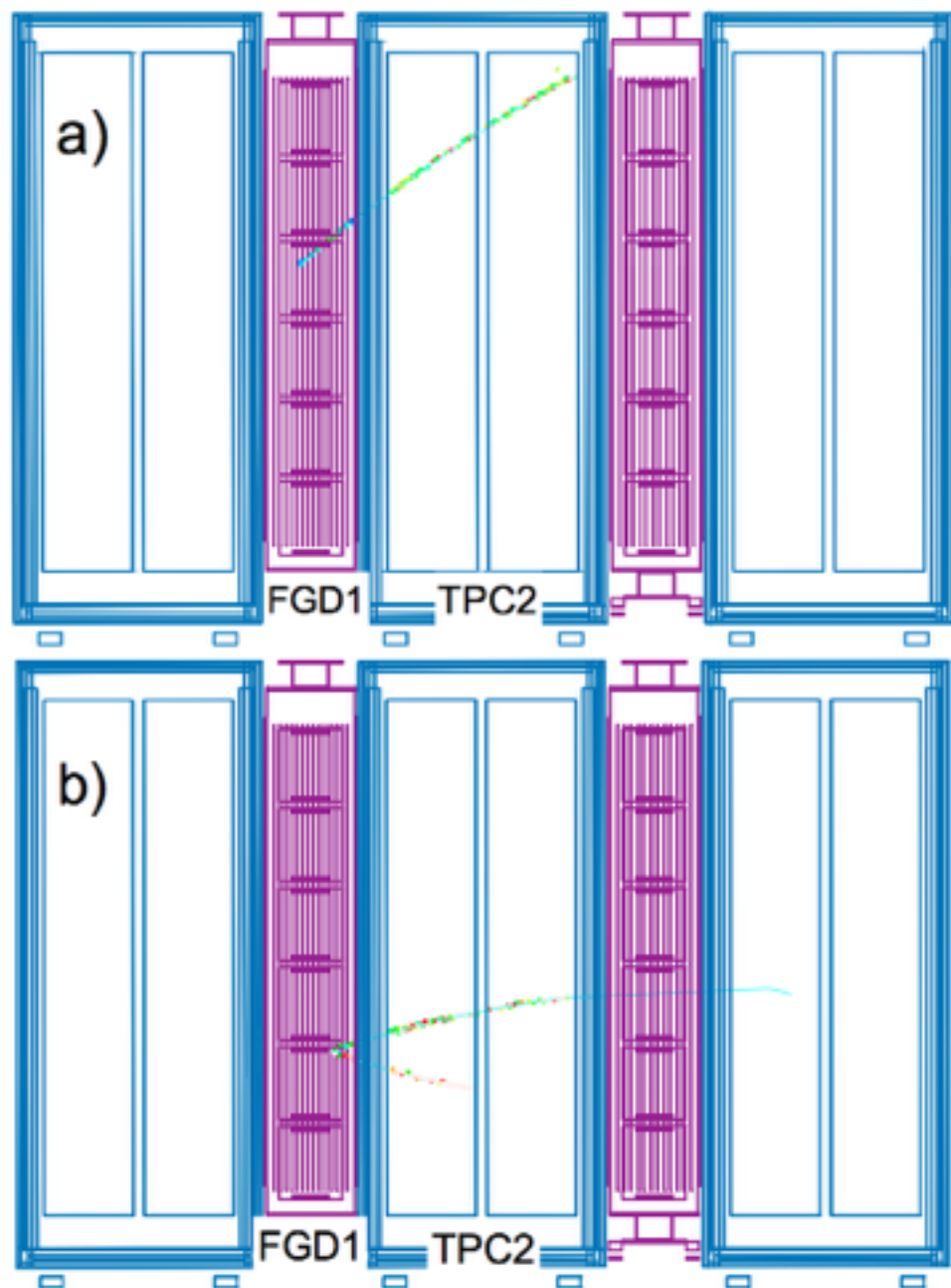
FGD



- Neutrino target: 2.2 tonnes of material
- FGD1 is plastic scintillator bars only
- FGD2 include water layers

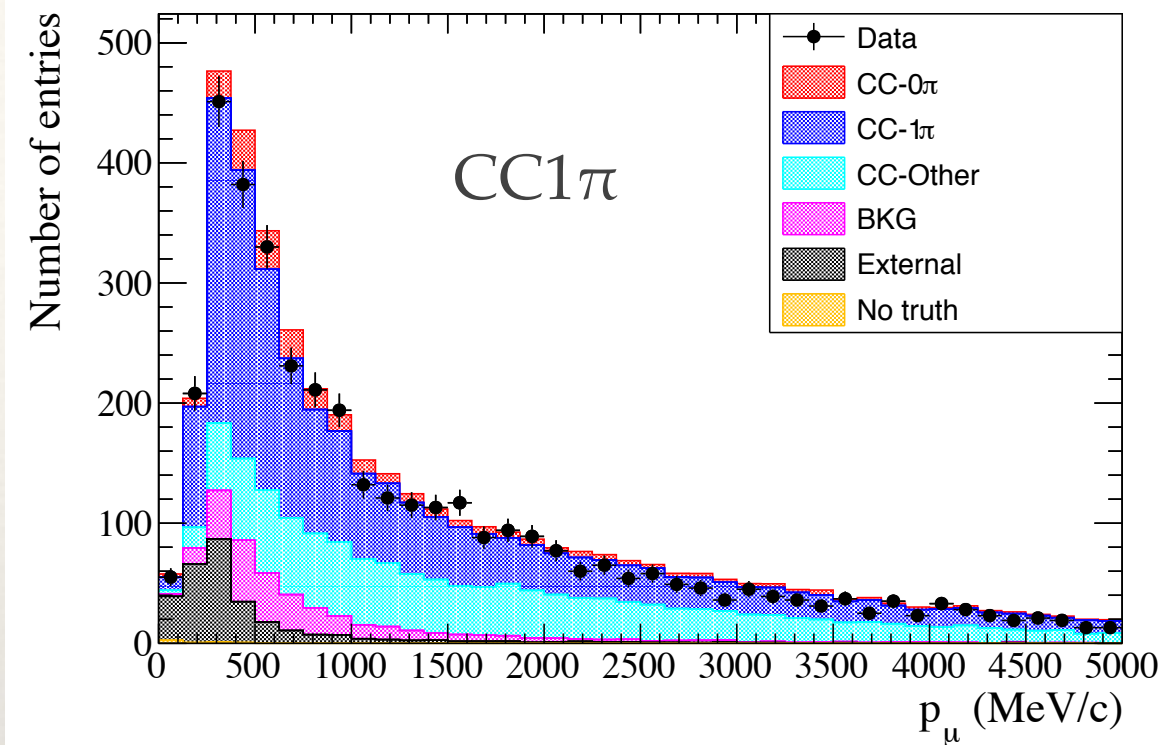
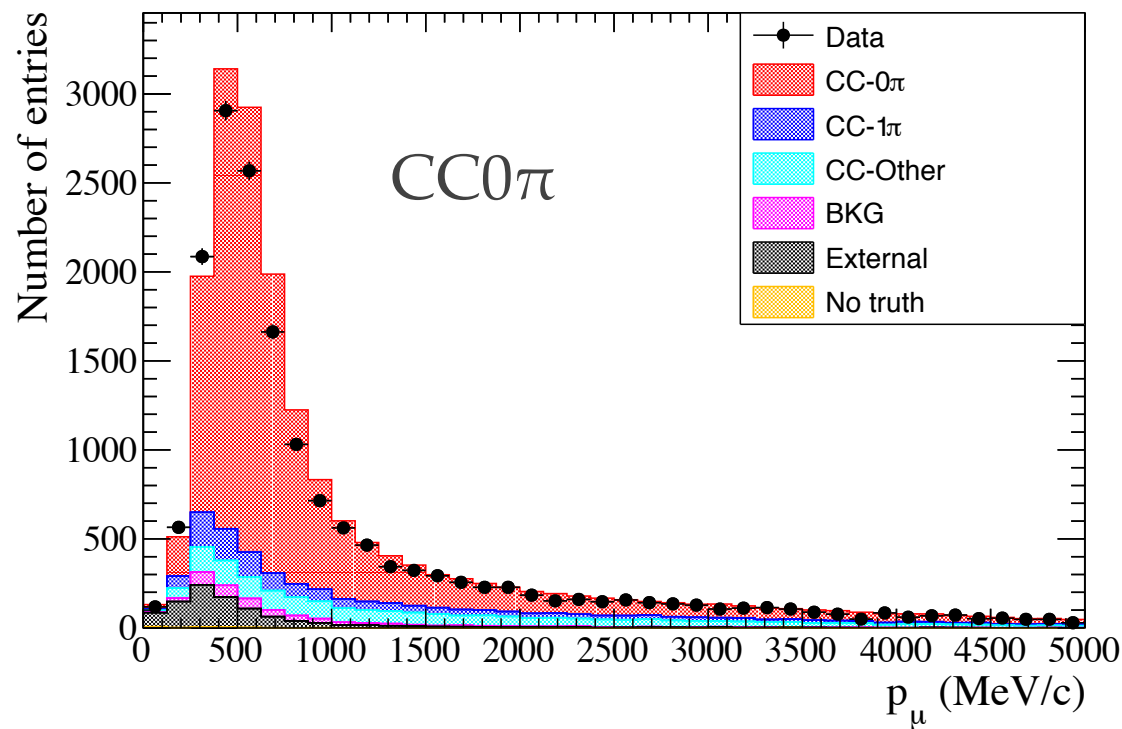
ND280 Data Samples

- ❖ Select a CC-inclusive sample with a μ^- originating in FGD1

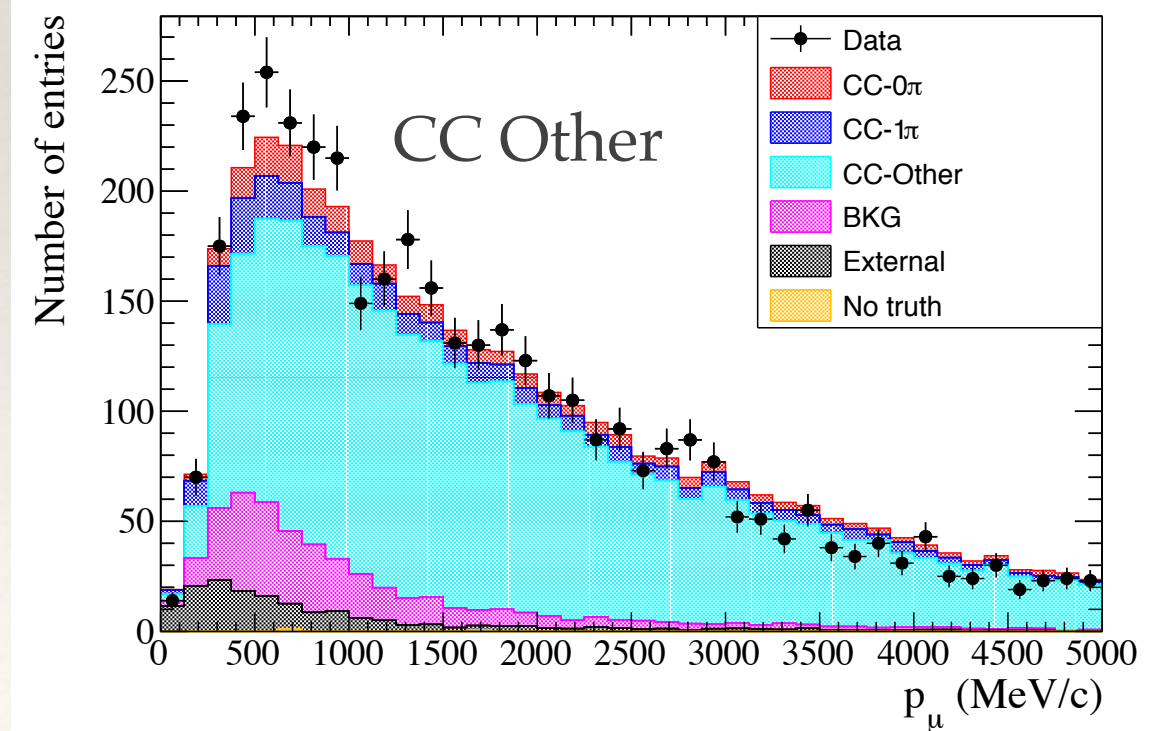


- ❖ Break the inclusive sample into three subsamples
 - ❖ $CC0\pi$ - no pion candidates in the event
 - ❖ $CC1\pi$ - 1 π^+ candidate and no other pion candidates
 - ❖ CC Other - all other CC inclusive candidates

CC Inclusive Samples



The three CC inclusive sub-samples and their agreement with the MC out of the box, before tuning the flux or cross section models.



Using ND280 Data

- ❖ The main constraint on the flux model from neutrino data comes from the ND280 data
- ❖ To constrain the flux model, we first define a set of flux parameters b_i that can vary the normalization of the flux in a given flavor, energy, detector bin:

$$\Phi'_i = b_i * \Phi_i$$

- ❖ The b_i all have a value of 1 prior to the ND280 data fit
- ❖ When we do a fit to ND280 CC-inclusive data, we want to allow the b_i to vary
- ❖ They are not free parameters. They have a prior constraint with an uncertainty evaluated by propagating errors through the flux simulation

Likelihood for ND280 Data Fit

- ❖ We construct a binned likelihood that depends on flux, cross section and detector modeling nuisance parameters:

$$\Delta\chi_{ND280}^2 = 2 \sum_i^{Nbins} N_i^p(\vec{b}, \vec{x}, \vec{d}) - N_i^d + N_i^d \ln[N_i^d / N_i^p(\vec{b}, \vec{x}, \vec{d})] +$$

$$\sum_i^{E_\nu \text{ bins}} \sum_j^{E_\nu \text{ bins}} \Delta b_i (V_b^{-1})_{i,j} \Delta b_j + \sum_i^{xsec \text{ pars}} \sum_j^{xsec \text{ pars}} \Delta x_i (V_x^{-1})_{i,j} \Delta x_j +$$

$$\sum_i^{Nbins} \sum_j^{Nbins} \Delta d_i (V_d(\vec{b}, \vec{x})^{-1})_{i,j} \Delta d_j + \ln\left(\frac{|V_d(\vec{b}, \vec{x})|}{|V_d^{nom}|}\right)$$

$$\Delta b_i = b_i - 1$$

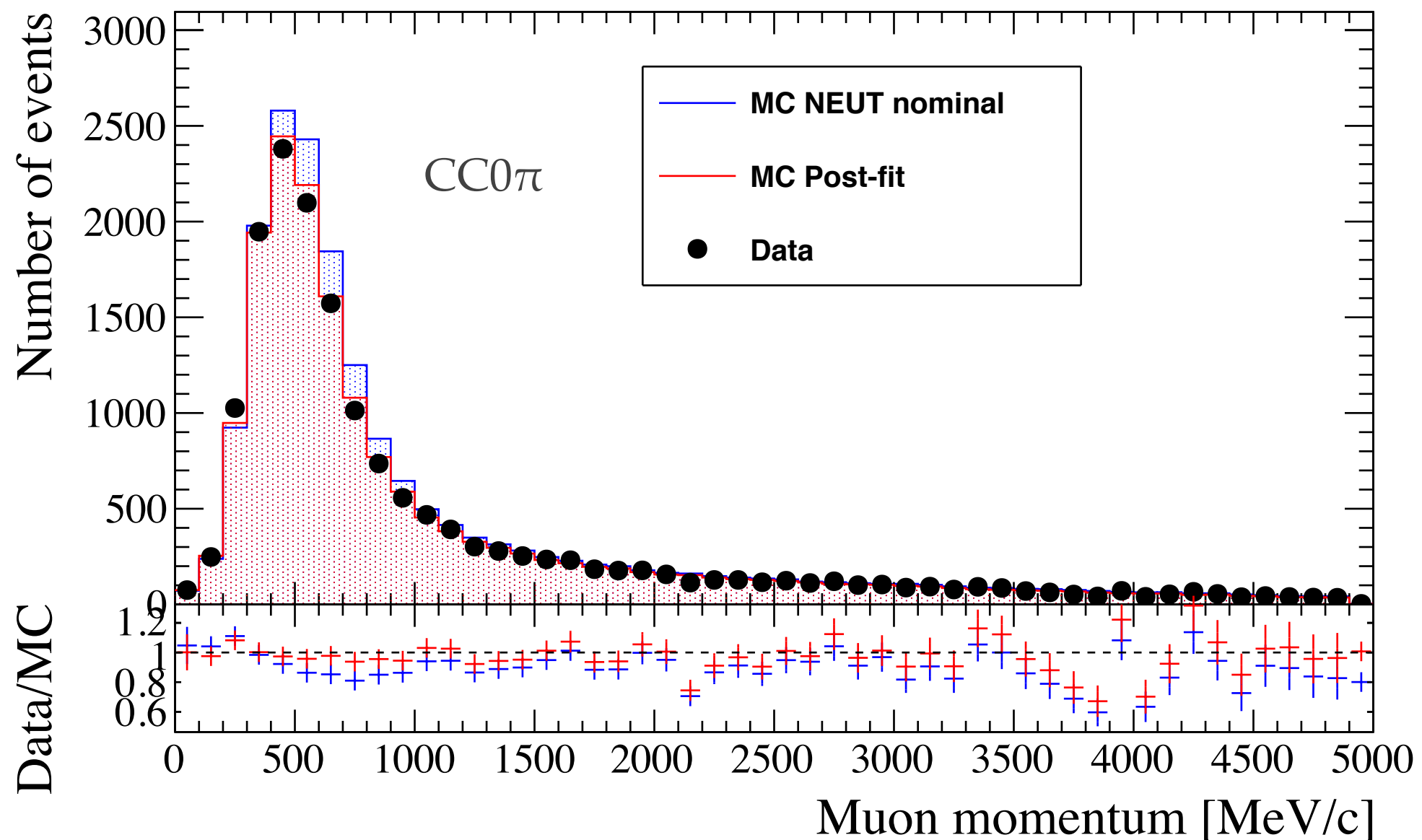
V_b^{-1} is the inverse of the covariance matrix describing the flux uncertainties

- ❖ The predicted number of events in a given bin depends on the nuisance parameters

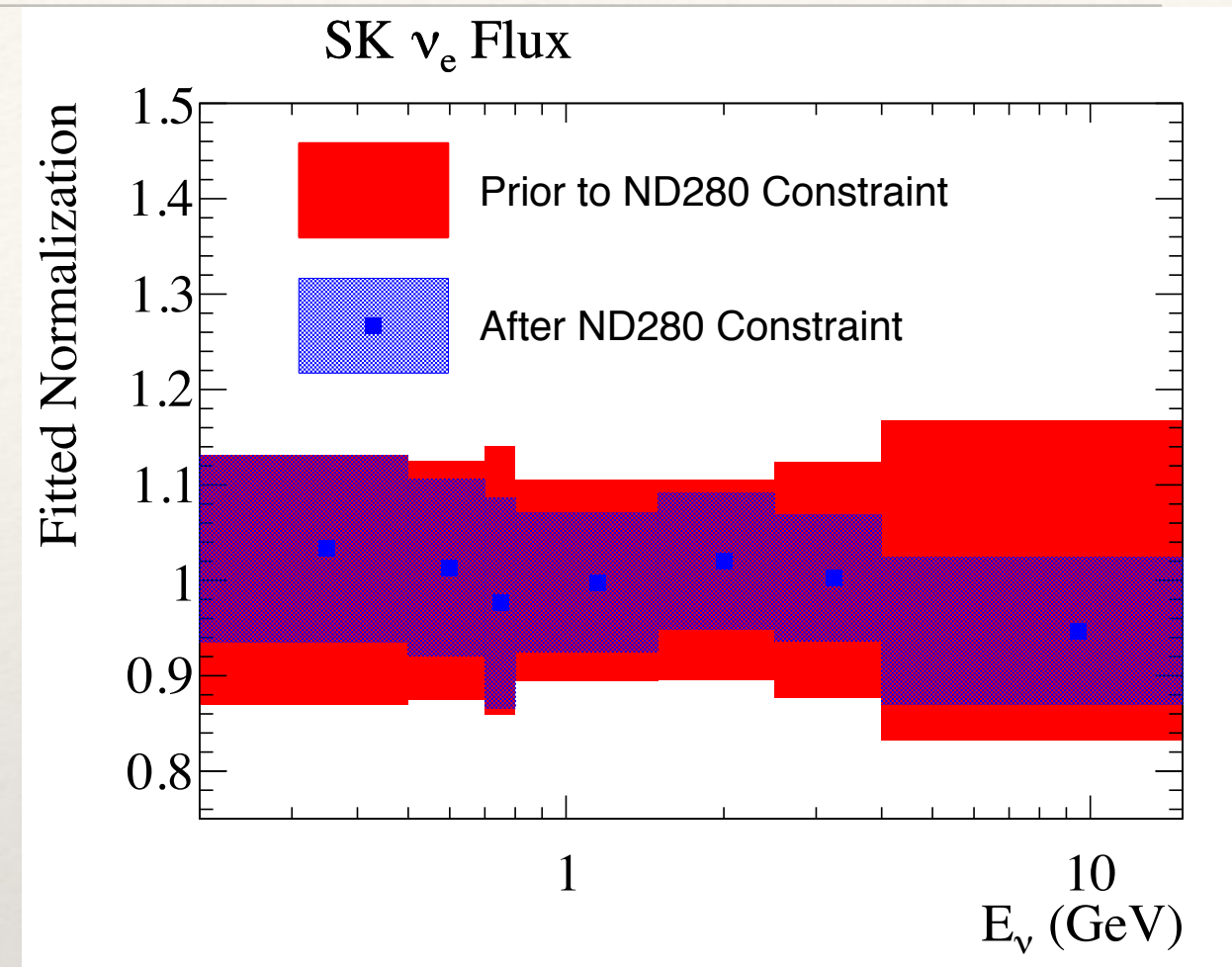
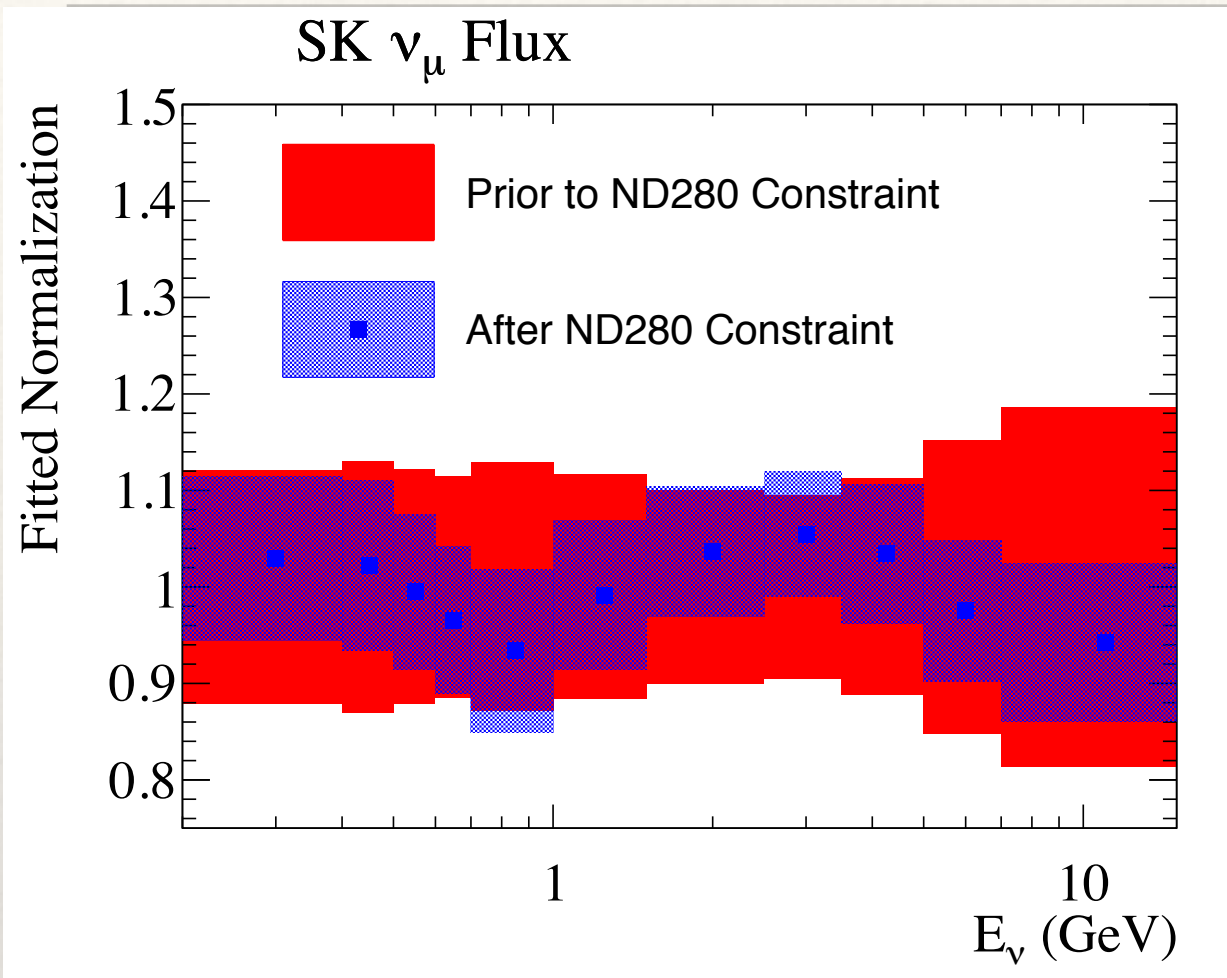
$$N_i^p = d_i \sum_j^{E_\nu \text{ bins}} \sum_k^{Int. \text{ modes}} b_j x_k^{norm}(E_j) w_{i,j,k}(\vec{x}) T_{i,j,k}^p$$

ND280 Fit Results

- ❖ After fitting the data while allowing the flux and cross section models to vary, good agreement is achieved between the data and MC



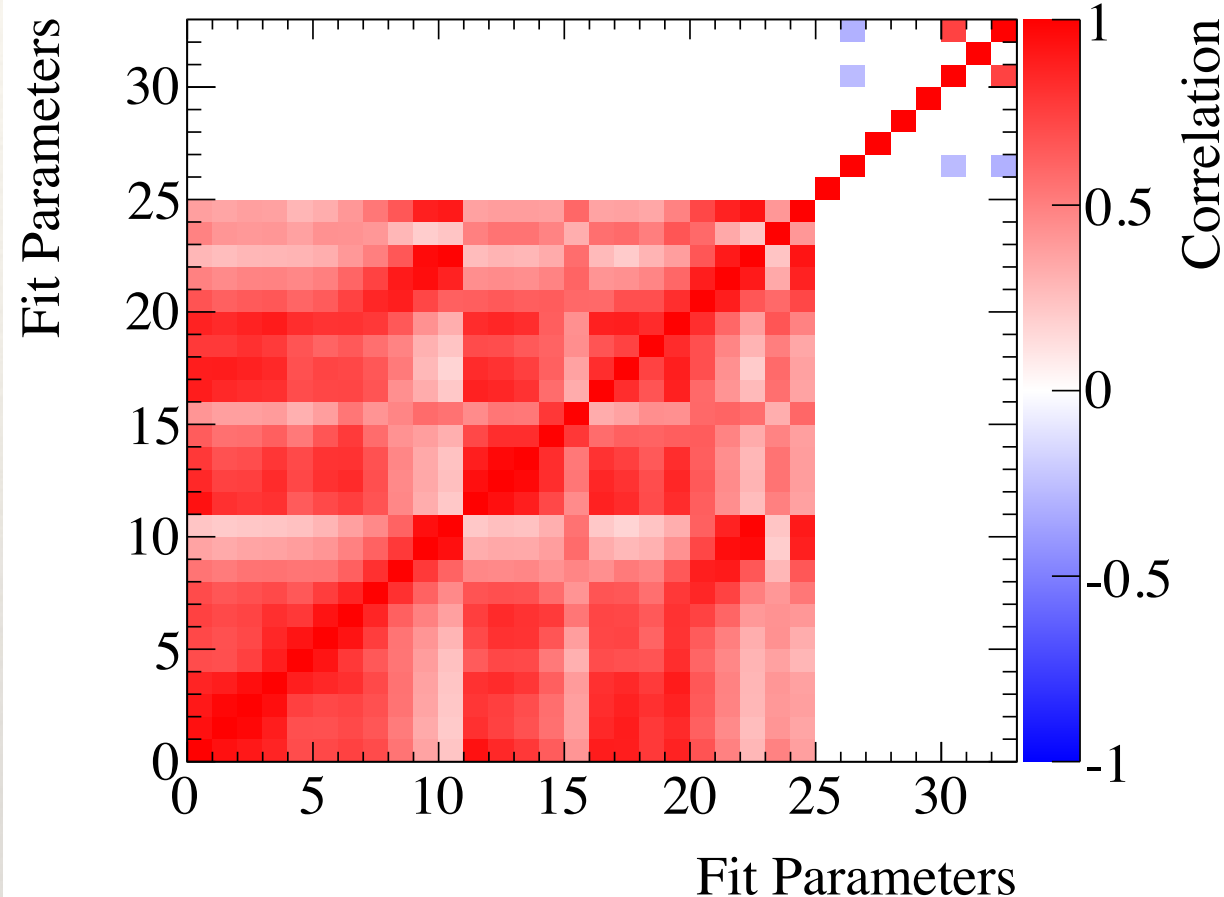
Fitted Flux Parameters



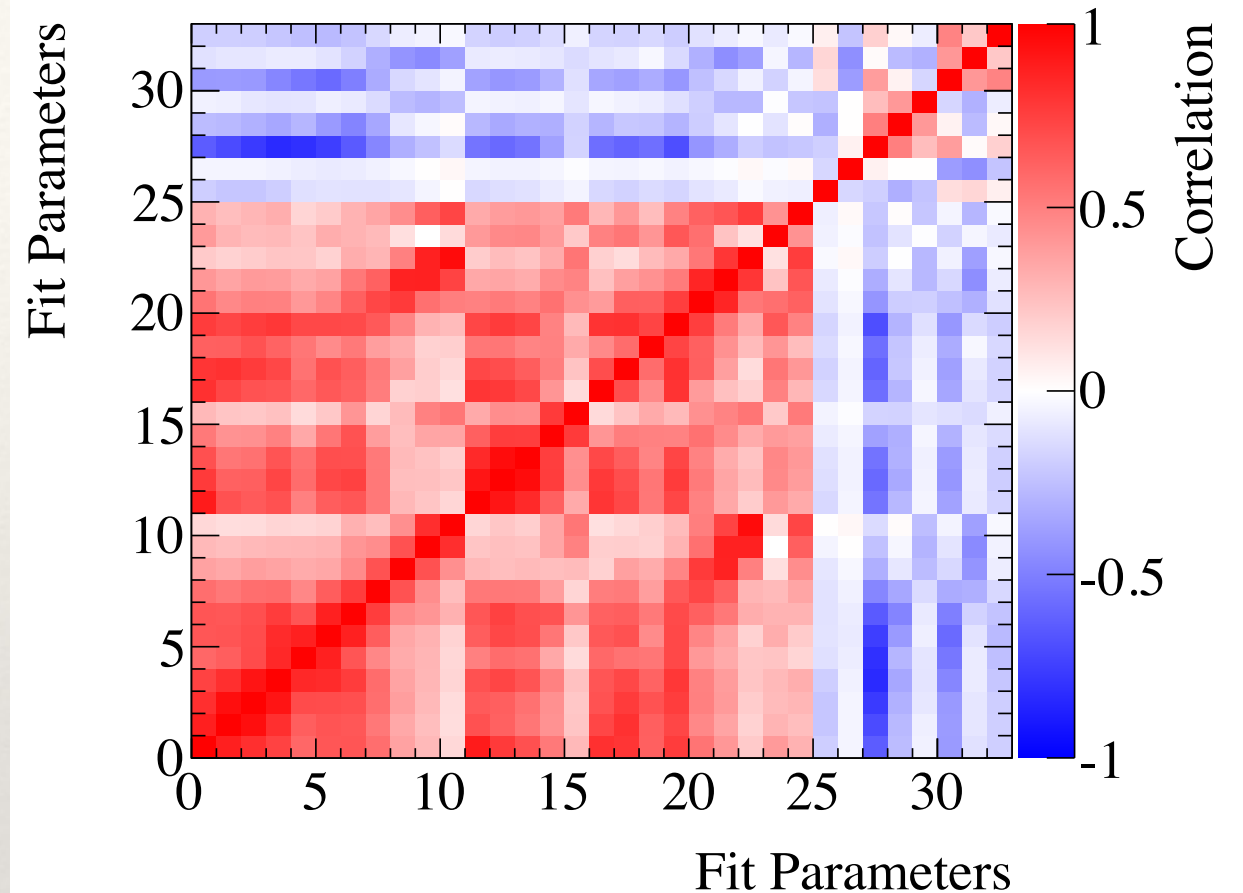
- ❖ The flux b_i parameters are adjusted by the fit and their errors are reduced
- ❖ Recall the correlations between ND280 ν_μ flux bins and SK ν_μ and ν_e flux bins
 - ❖ By fitting for the ND280 ν_μ flux we also constrain the SK ν_μ and ν_e flux through these correlations

Parameter Correlations

Parameter Correlation Matrix Prior to ND280 Constraint



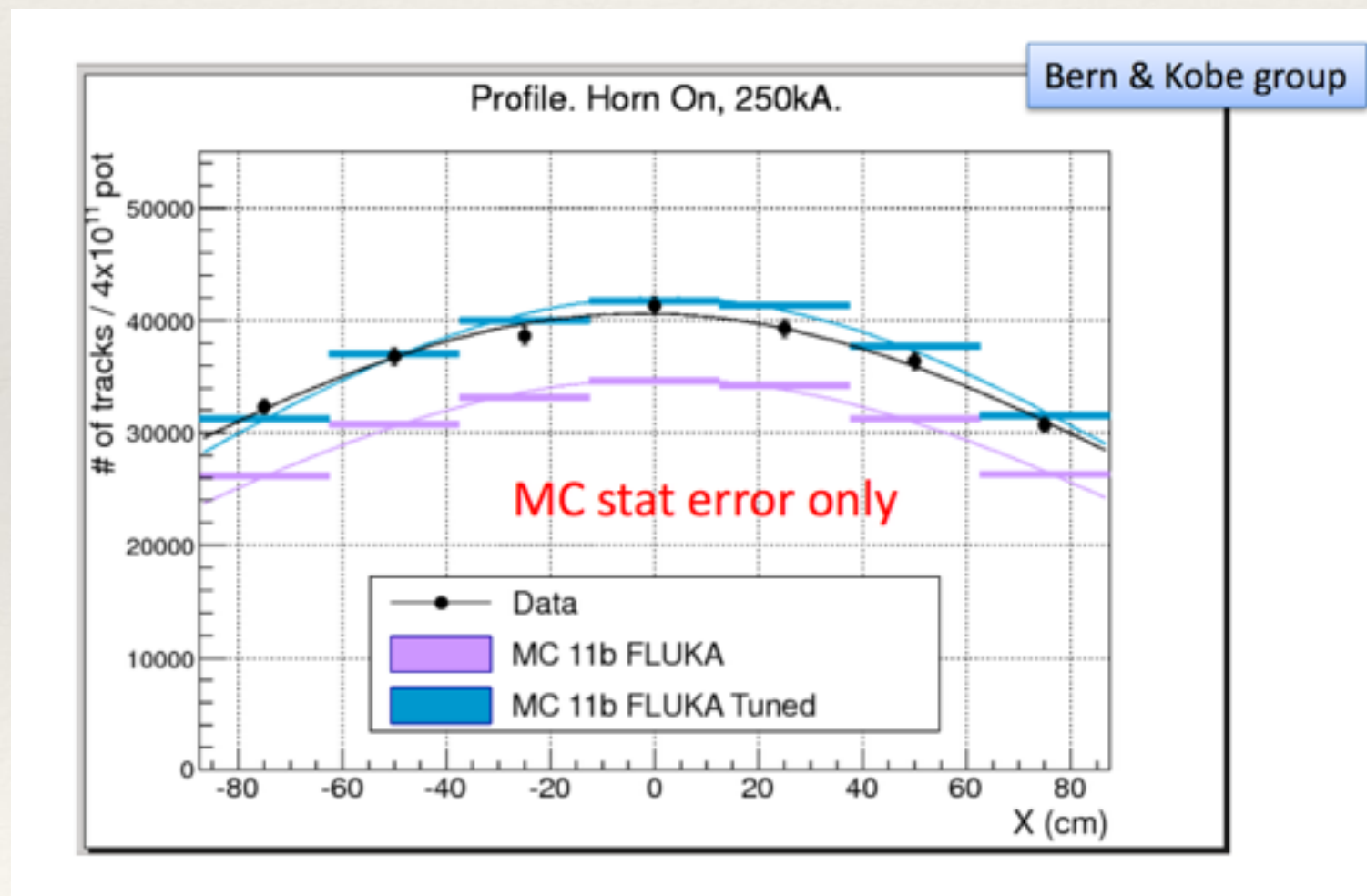
Parameter Correlation Matrix After ND280 Constraint



- ❖ Prior to the fit, there are no correlations between the b_i parameters (<25) and cross section model parameters (≥ 25)
- ❖ The fit introduces (anti)correlations, so we can only think of total uncertainties on SK predictions by including both flux and cross section parameter uncertainties

Muon Monitor Data

- ❖ The muon monitor is used to tune the beam direction
- ❖ Not directly used to constrain the neutrino flux
- ❖ However, we see better agreement with MUMON and emulsion data with the hadron interaction tuning applied:

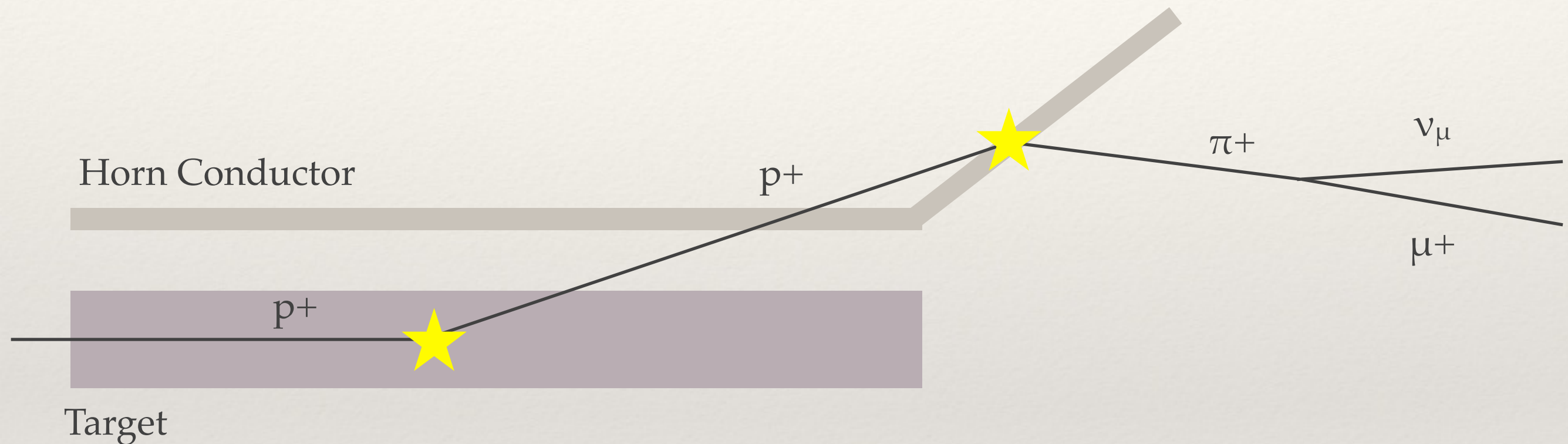


Flux Prediction

- ❖ T2K uses a **data-driven** simulation to prediction the neutrino flux
 - ❖ GEANT3 description of the secondary beam line geometry
 - ❖ Incident proton beam phase space modeled using **measurements from proton beam monitors**
 - ❖ Interactions in baffle / target are simulated with FLUKA, outside of baffle / target with GEANT3 / GCALOR
 - ❖ Hadronic interactions inside and outside of the target are tuned based on **hadronic interaction data including NA61**
- ❖ Systematic errors are evaluated based on uncertainties on the simulation input data and modeling methods
 - ❖ The prediction is tuned using a fit to near detector (ND280) data

Hadron Interaction Tuning (1)

- ❖ For each neutrino produced, we save the information of its ancestor particles and their hadronic interactions

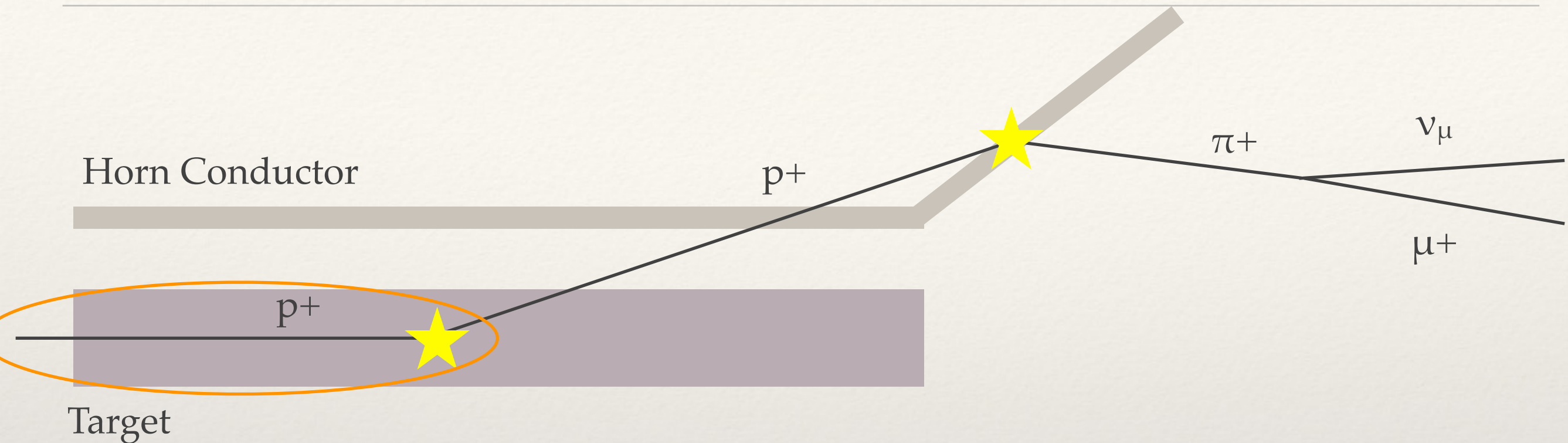


- ❖ 4 momentum of each ancestor particle is saved.
- ❖ Distance traveled through each material by each ancestor particle is saved
- ❖ Interaction type (elastic or inelastic) producing the particle is saved

Hadron Interaction Tuning (2)

- ❖ Tuning is done by reweighting the probability of:
 - ❖ The particle being produced - weighting the multiplicity distribution
- ❖ The particle surviving for the simulated distance and then reinteracting - weighting the interaction length (production cross section)

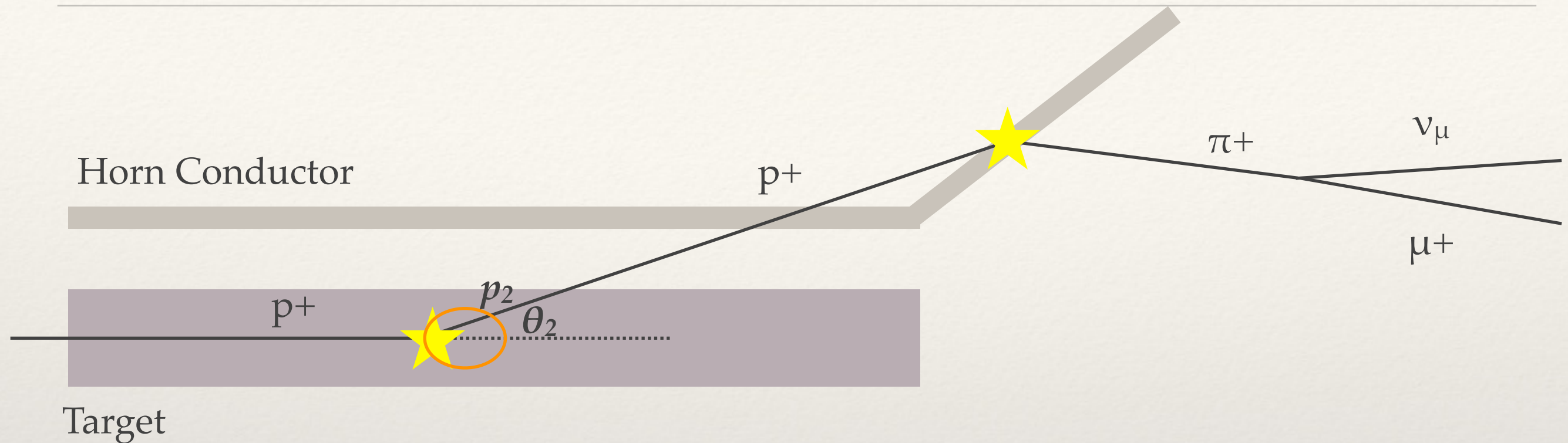
Tuning Example in Steps (1)



Reweight the probability that a proton with momentum p_1 travels a distance $d_{1,c}$ before interacting, assuming the production cross section is tuned from $\sigma_c(p_1)$ to $\sigma'_c(p_1)$

$$W = e^{-\rho_c[\sigma'_c(p_1) - \sigma_c(p_1)]d_{1,c}} * \frac{\sigma'_c(p_1)}{\sigma_c(p_1)}$$

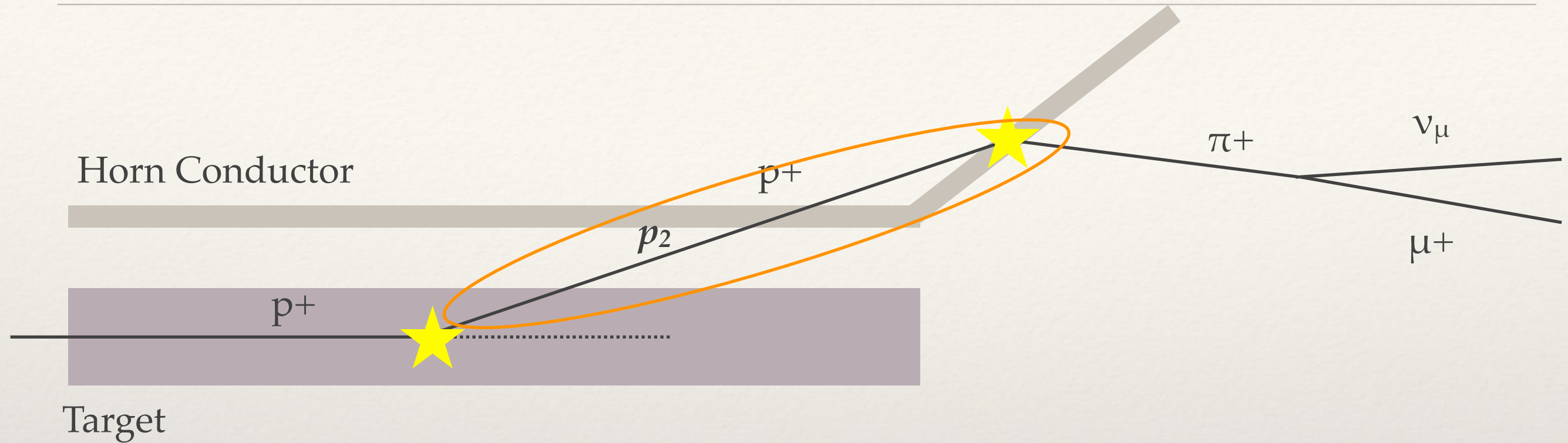
Tuning Example in Steps (2)



Reweight the probability to produce a secondary proton with momentum p_2 and scattering angle θ_2 based on the ratio of the multiplicity in data over MC

$$W = e^{-\rho_c[\sigma'_c(p_1) - \sigma_c(p_1)]d_{1,c}} * \frac{\sigma'_c(p_1)}{\sigma_c(p_1)} * \frac{\frac{dn'_c(p_2, \theta_2 | p_1)}{dp d\theta}}{\frac{dn_c(p_2, \theta_2 | p_1)}{dp d\theta}}$$

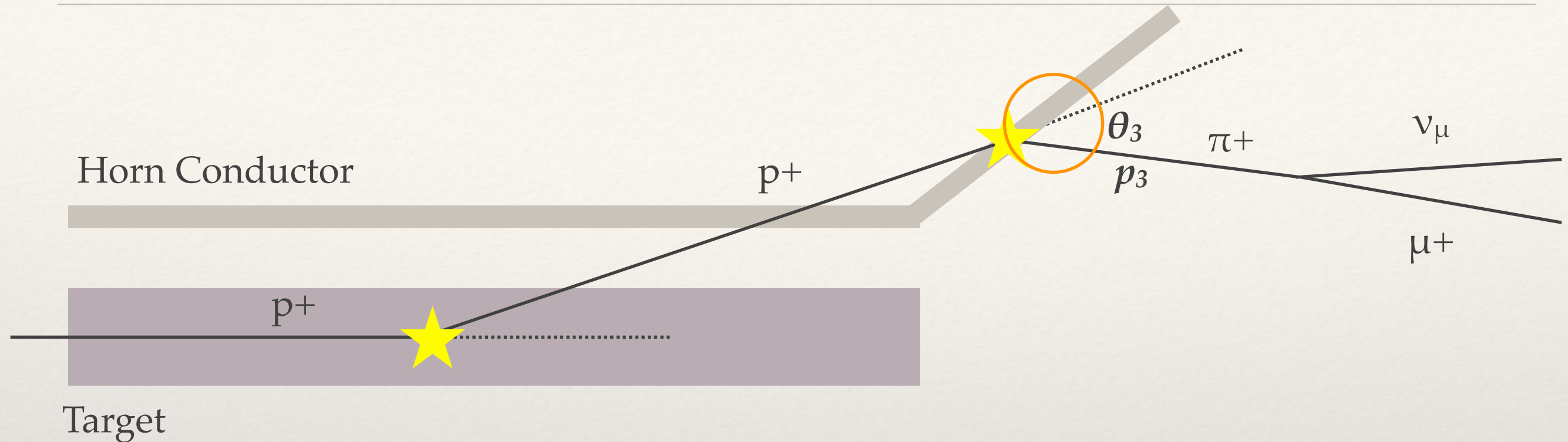
Tuning Example in Steps (3)



Reweight the probability that the secondary proton survives through the target and part of the horn before interacting

$$W = e^{-\rho_c[\sigma'_c(p_1) - \sigma_c(p_1)]d_{1,c}} * \frac{\sigma'_c(p_1)}{\sigma_c(p_1)} * \frac{\frac{dn'_c(p_2, \theta_2 | p_1)}{dpd\theta}}{\frac{dn_c(p_2, \theta_2 | p_1)}{dpd\theta}} * e^{-\rho_c[\sigma'_c(p_2) - \sigma_c(p_2)]d_{2,c}} * e^{-\rho_{Al}[\sigma'_{Al}(p_2) - \sigma_{Al}(p_2)]d_{2,Al}} * \frac{\sigma'_{Al}(p_2)}{\sigma_{Al}(p_2)}$$

Tuning Example in Steps (4)



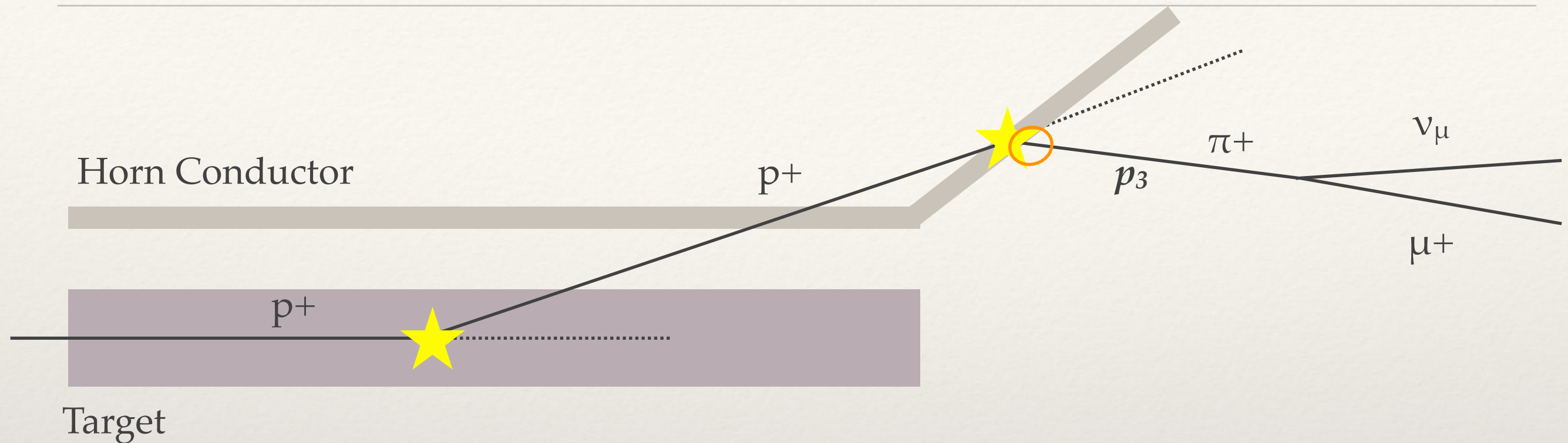
Reweight the probability to produce a tertiary pion with momentum p_3 and scattering angle θ_3 based on the ratio of the multiplicity in data over MC

$$W = e^{-\rho_C[\sigma'_C(p_1) - \sigma_C(p_1)]d_{1,C}} * \frac{\sigma'_C(p_1)}{\sigma_C(p_1)} * \frac{\frac{dn'_C(p_2, \theta_2 | p_1)}{dpd\theta}}{\frac{dn_C(p_2, \theta_2 | p_1)}{dpd\theta}} * e^{-\rho_C[\sigma'_C(p_2) - \sigma_C(p_2)]d_{2,C}} * e^{-\rho_{Al}[\sigma'_{Al}(p_2) - \sigma_{Al}(p_2)]d_{2,Al}} * \frac{\sigma'_{Al}(p_2)}{\sigma_{Al}(p_2)}$$

$$* \frac{\frac{dn'_{Al}(p_3, \theta_3 | p_2)}{dpd\theta}}{\frac{dn_{Al}(p_3, \theta_3 | p_2)}{dpd\theta}}$$

Data

Tuning Example in Steps (5)



Reweight the probability that the pion with momentum p_3 survives traversing the horn Al without interacting

$$W = e^{-\rho_c[\sigma'_c(p_1) - \sigma_c(p_1)]d_{1,c}} * \frac{\sigma'_c(p_1)}{\sigma_c(p_1)} * \frac{\frac{dn'_c(p_2, \theta_2 | p_1)}{dpd\theta}}{\frac{dn_c(p_2, \theta_2 | p_1)}{dpd\theta}} * e^{-\rho_c[\sigma'_c(p_2) - \sigma_c(p_2)]d_{2,c}} * e^{-\rho_{Al}[\sigma'_{Al}(p_2) - \sigma_{Al}(p_2)]d_{2,Al}} * \frac{\sigma'_{Al}(p_2)}{\sigma_{Al}(p_2)}$$

$$* \frac{\frac{dn'_{Al}(p_3, \theta_3 | p_2)}{dpd\theta}}{\frac{dn_{Al}(p_3, \theta_3 | p_2)}{dpd\theta}} * e^{-\rho_{Al}[\sigma'_{Al}(p_3) - \sigma_{Al}(p_3)]d_{3,Al}}$$

Data