First Look at HARP-Based K2K Flux Predictions

M. Sorel, P. Novella, J. J. Gomez-Cadenas

Valencia University

Outline

- HARP central values for near, far, and far/near flux predictions
- Flux uncertainties and energy bin-to-bin correlations from π^+ production uncertainties
- Comparison with current K2K predictions
- Validity of π^+ production uncertainty assumptions
- Model dependence of π^+ production parametrization
- Possible plot for summer conferences
- Pending issues, and open discussion on prioritization

Sanford-Wang Parametrization

- HARP data on inclusive π^+ production fitted to Sanford-Wang parametrization:

$$\frac{d^2\sigma(\text{p+A} \to \pi^+ + X)}{dp d\Omega}(p,\theta) = c_1 p^{c_2}(1 - \frac{p}{p_{\text{beam}}}) \exp[-c_3 \frac{p^{c_4}}{p_{\text{beam}}^{c_5}} - c_6 \vartheta (p - c_7 p_{\text{beam}} \cos^{c_8} \vartheta)]$$

where:

- X: any other particle in the final state
- p_{beam}: proton beam momentum in GeV/c
- p and θ: π^+ momentum and angle in units of GeV/c and radians, respectively
- $d^2\sigma/(dp d\Omega)$ units: mb/(GeV/c sr), where $d\Omega \equiv 2\pi\ d(\cos\theta)$
- $c_1, \ldots, c_8$: empirical fit parameters
- $c_3 \equiv 1$ and $c_5 \equiv 0$ are fixed in the χ^2 minimization procedure

HARP Sanford-Wang Parameters and Errors

- Fit to S-W parametrization not good: $\chi^2/\text{dof} = 210/42$
- Best-fit parameters and errors (errors at 68.27% CL for 6 dof $\Rightarrow$ $\Delta\chi^2 = 7.04$):

Parameter	Value
c_1	$(8.93 \pm 1.80)10^2$
c_2	1.19 ± 0.30
c_3	1.00
c_4	$(4.68 \pm 1.25)10^{-1}$
c_5	0
c_6	(5.51 ± 0.47)
c_7	$(1.72 \pm 0.33)10^{-1}$
c_8	$(5.22 \pm 1.02)10^1$

- S-W parameters correlation matrix:

Parameter	c_1	c_2	c_4	c_6	c_7	c_8
c_1	1.000					
c_2	-0.403	1.000				
c_4	-0.181	0.919	1.000			
c_6	-0.408	0.330	-0.010	1.000		
c_7	-0.659	-0.079	-0.150	0.096	1.000	
c_8	0.219	-0.338	-0.057	-0.705	0.365	1.000

π^+ Production $\rightarrow$ Flux Error Propagation

- Standard error matrix propagation, assuming linear approximation:

$$C^{\phi}_{ii'} = D_{ij} C^{\pi}_{jj'} (D_{i'j'})^T$$

where:

- i, i': index neutrino energy bins
- j, j': index S-W parameters
- $C^{\phi}_{ii'}$: near flux, far flux, or far/near flux ratio error matrix
- $C^{\pi}_{jj'}$: HARP S-W parameters error matrix
- D_{ij}: matrix of derivatives, defined as:

$$D_{ij} \equiv \frac{\phi_i(c_1, \ldots, c_j + \delta c_j, \ldots, c_8) - \phi_i(c_1, \ldots, c_j, \ldots, c_8)}{\delta c_j}$$

  where ϕ_i indicates the near flux, far flux, or far/near flux ratio
- Overall, 1+6=7 MC settings required to obtain these derivatives

Minimal Changes to K2K Beam MC

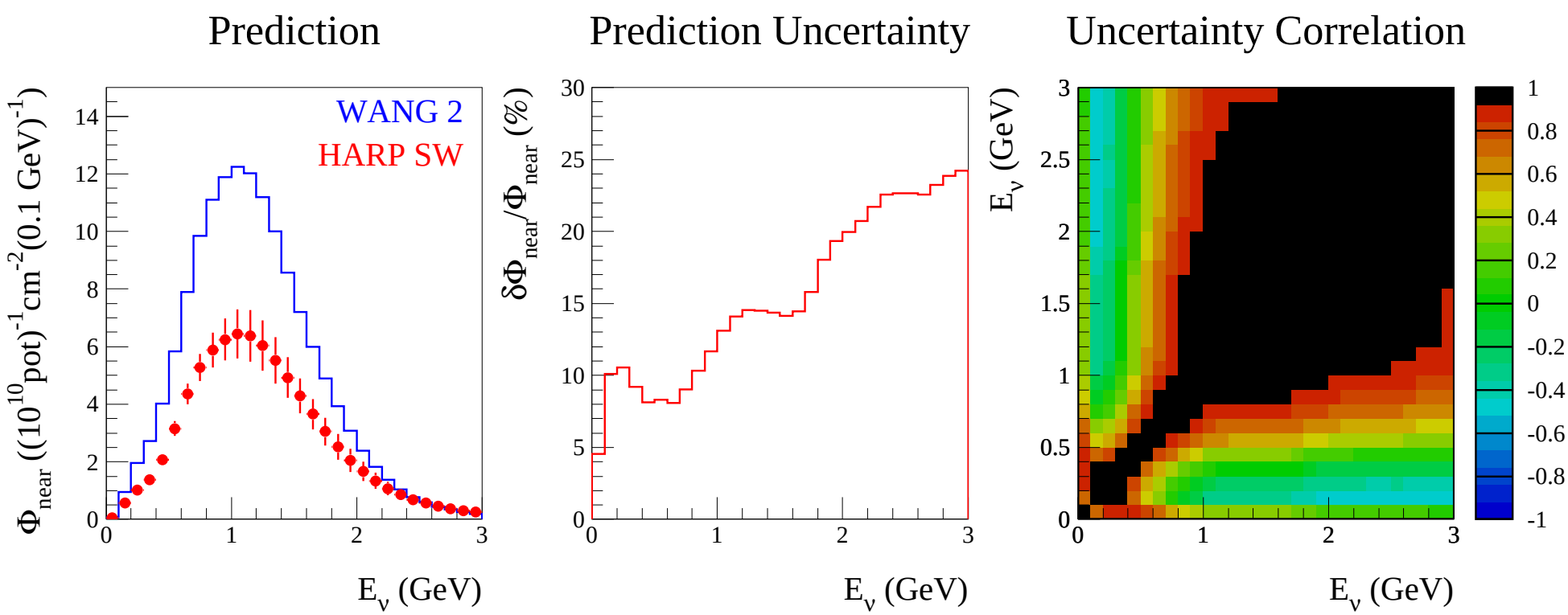
- Make S-W parameters for all secondaries in p+Al interactions user-selectable
  Before: hard-coded
- Make scaling between multiplicity per inelastic collision and cross-section user-selectable
  Before: hard-coded
- Allow to turn on/off Be→Al scaling for the π^+ production cross-section
  Before: always on, for HARP: off
- For secondaries other than π^+, use same settings as before

Results Presented in Next Three Slides

- Near flux defined as neutrinos crossing a on-axis disk at $z = 300$ m, of radius $r = 3$ m
- Far flux defined as neutrinos crossing a on-axis disk at $z = 250$ km, of radius $r = 40$ m
- HARP results based on $2 \cdot 10^{11}$ pot simulated, including a neutrino parent redecay factor of 1000; 10^{11} pot used for K2K default predictions

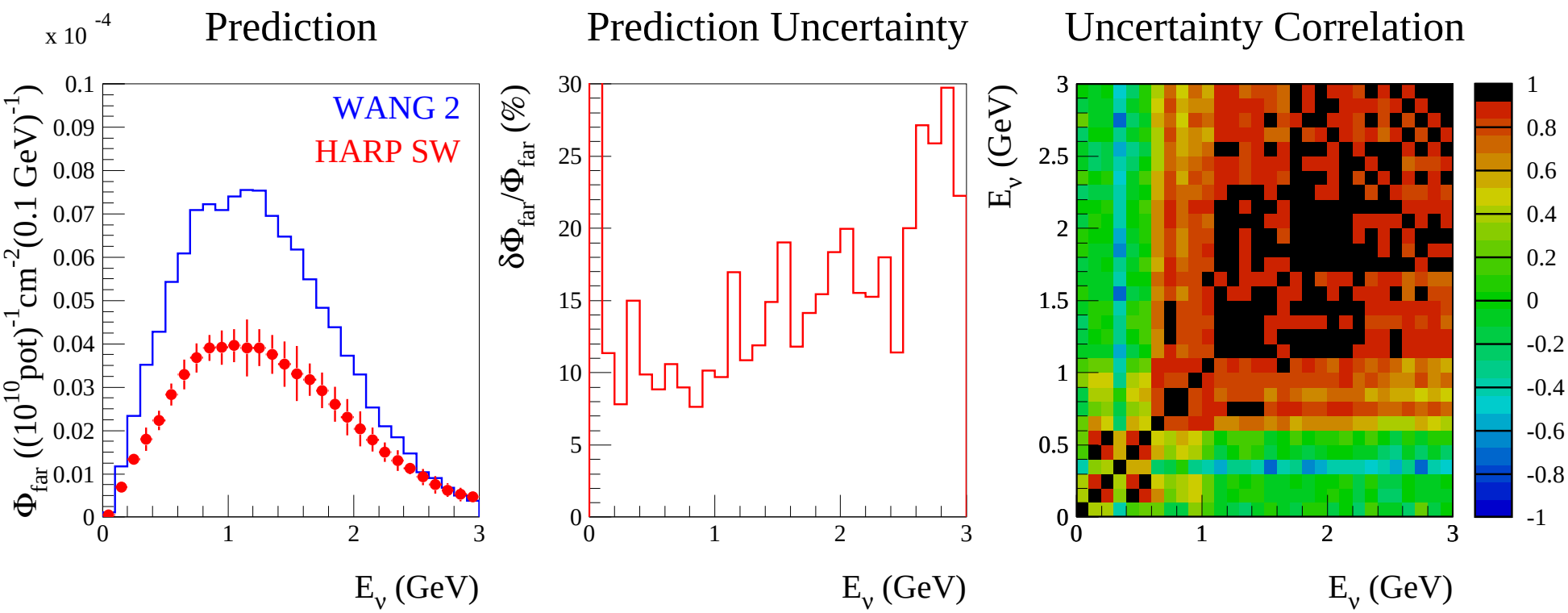
- Next three slides refer to muon neutrino near flux, far flux, and far/near flux ratio predictions, respectively
- Left panel will show HARP-based and K2K default flux predictions
- Middle panel will show HARP-based flux errors
- Right panel will show HARP-based flux correlations

Muon Neutrino Near Flux



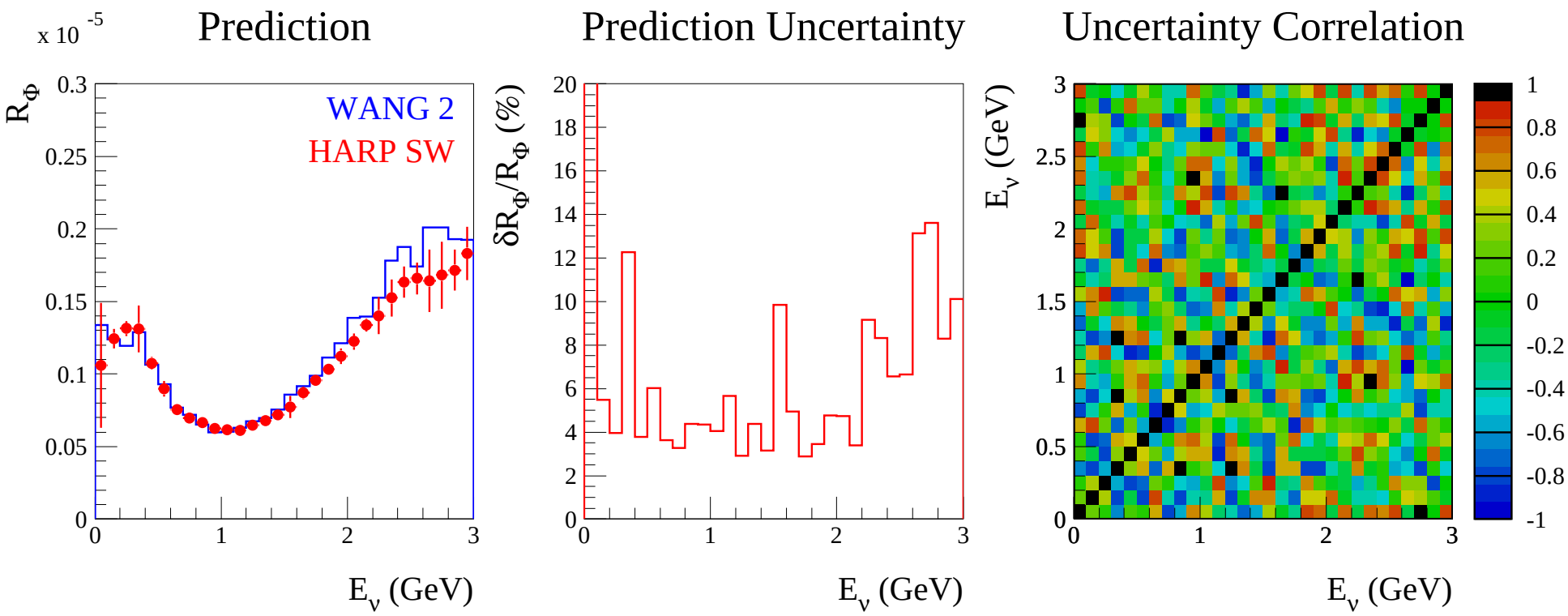
- HARP predicts significantly lower flux normalization than K2K default
- Similar energy shape. HARP has a slightly more significant high energy tail
- Error on near flux integrated between 0 and 3 GeV: 12.5%
- Typical near flux error in the 0.5-1 GeV region: about 10%

Muon Neutrino Far Flux



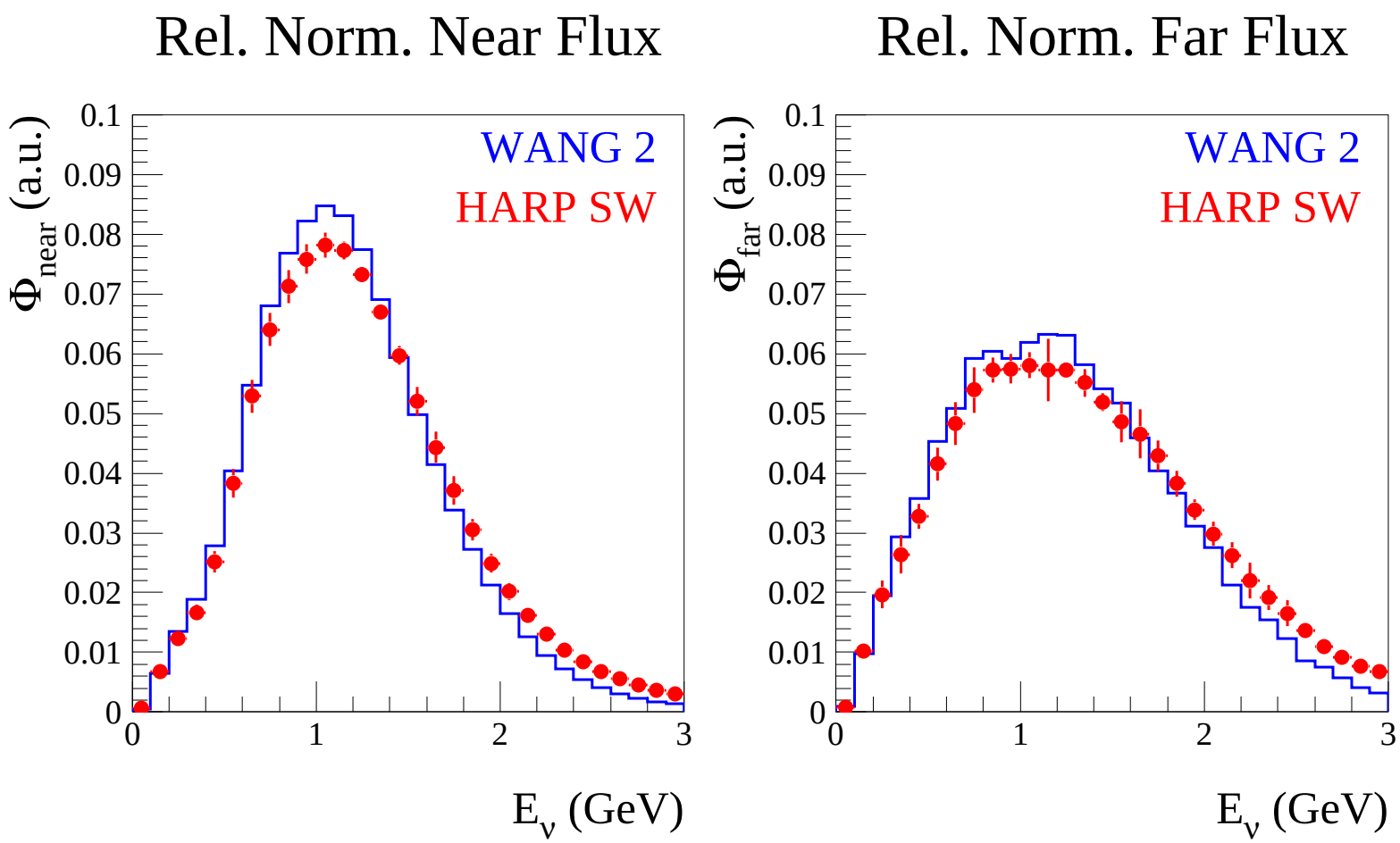
- Qualitatively, HARP / K2K default comparison is similar to the near flux one
- Error on far flux integrated between 0 and 3 GeV: 11.1%
- Typical far flux error in the 0.5-1 GeV region: about 10%
- Note: MC statistical error non-negligible ("true" error should decrease)

Muon Neutrino Far/Near Flux Ratio



- The far/near flux ratios predicted by the default K2K beam MC settings and HARP are very similar, generally consistent within HARP π^+ production errors
- HARP far/near flux ratio slightly lower at high energies
- Typical far/near flux ratio error in the 0.5-1 GeV region: about 4%
- Note: MC statistical error non-negligible ("true" error should decrease)

Relatively-Normalized Neutrino Fluxes



- As already mentioned, similar neutrino energy shapes arising from K2K default and HARP S-W π^+ production assumptions
- HARP errors shown refer to relatively-normalized flux distributions

Validity of Uncertainty Assumptions

- We have checked the validity of the error propagation:

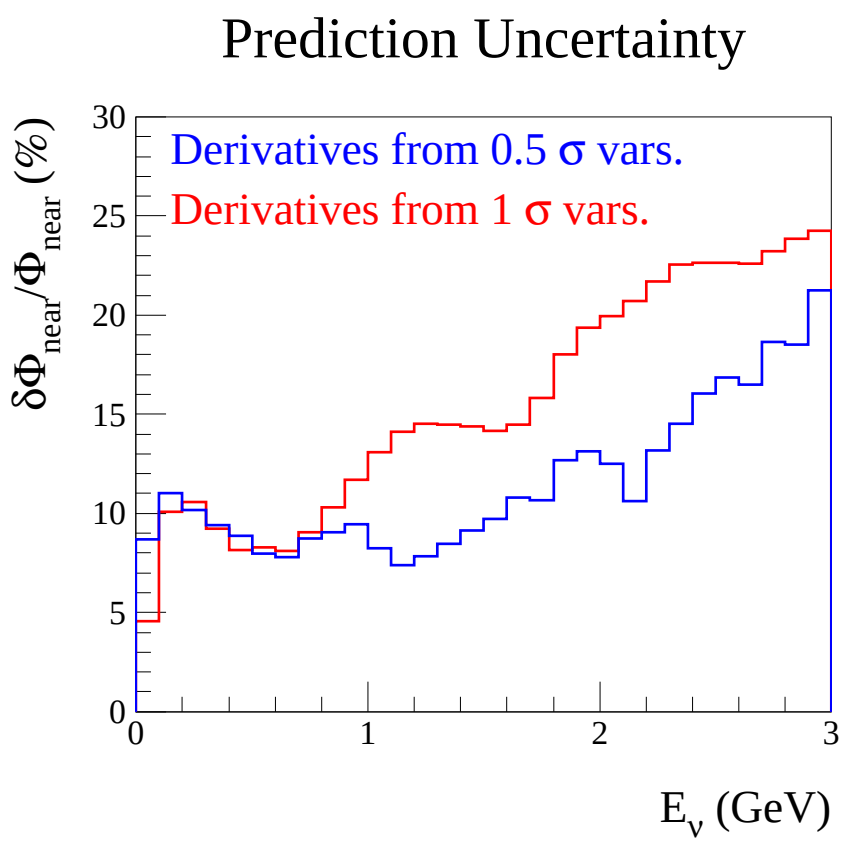
$$C^{\phi}_{ii'} = D_{ij} C^{\pi}_{jj'} (D_{i'j'})^T$$

where:

$$D_{ij} \equiv \frac{\phi_i(c_1, \ldots, c_j + \delta c_j, \ldots, c_8) - \phi_i(c_1, \ldots, c_j, \ldots, c_8)}{\delta c_j}$$

- Low statistics test: use $\delta c_j = 0.5\sigma(c_j)$ instead of default (somewhat arbitrary) choice $\delta c_j = \sigma(c_j)$, in computing the matrix of derivatives D_{ij}
- Methods should yield identical results if the neutrino flux is linear in all S-W parameters
- How good is this linear approximation?

Validity of Uncertainty Assumptions (2)

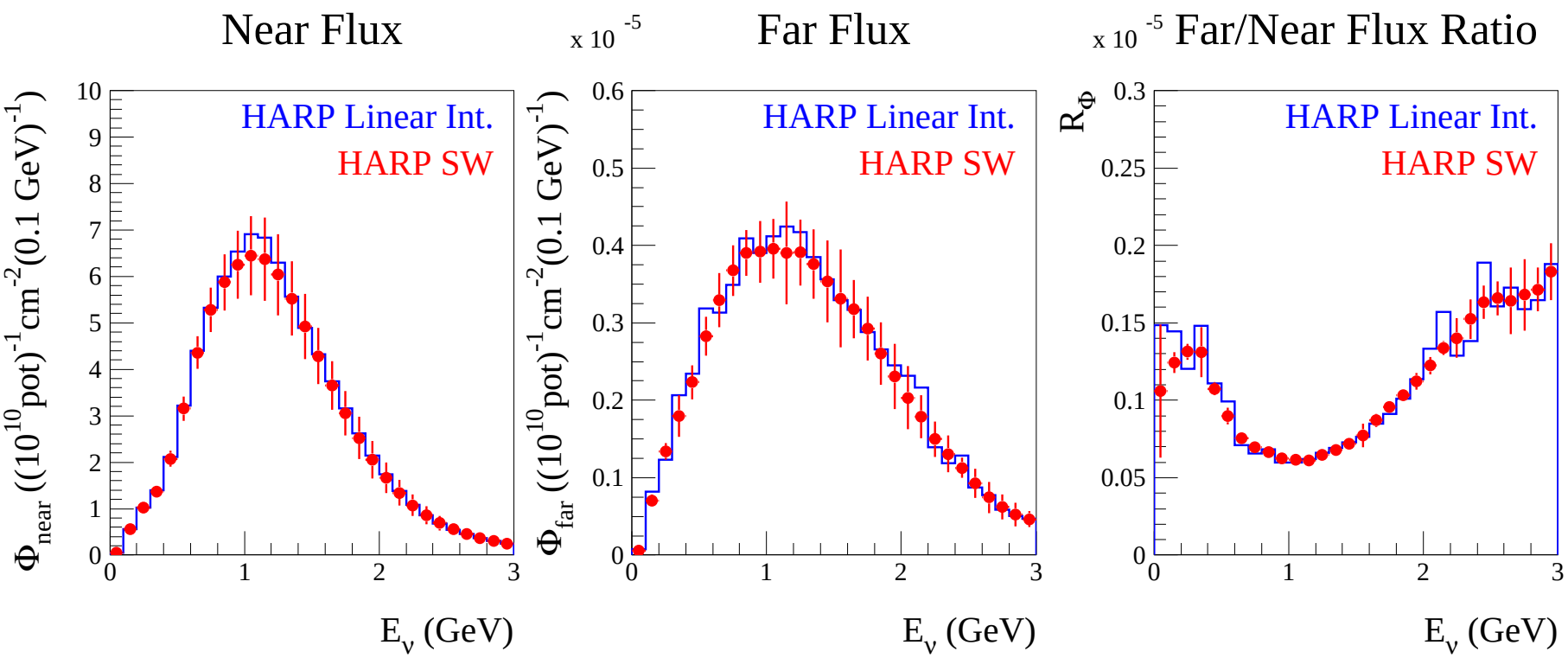


- Two choices yield similar results at low energies. At high energies, smaller errors from smaller steps in computing derivatives
- The choice $\delta c_j \equiv \sigma(c_j)$ might be more natural?
- Alternative error propagation methods being explored

Model Dependence of π^+ Production Parametrization

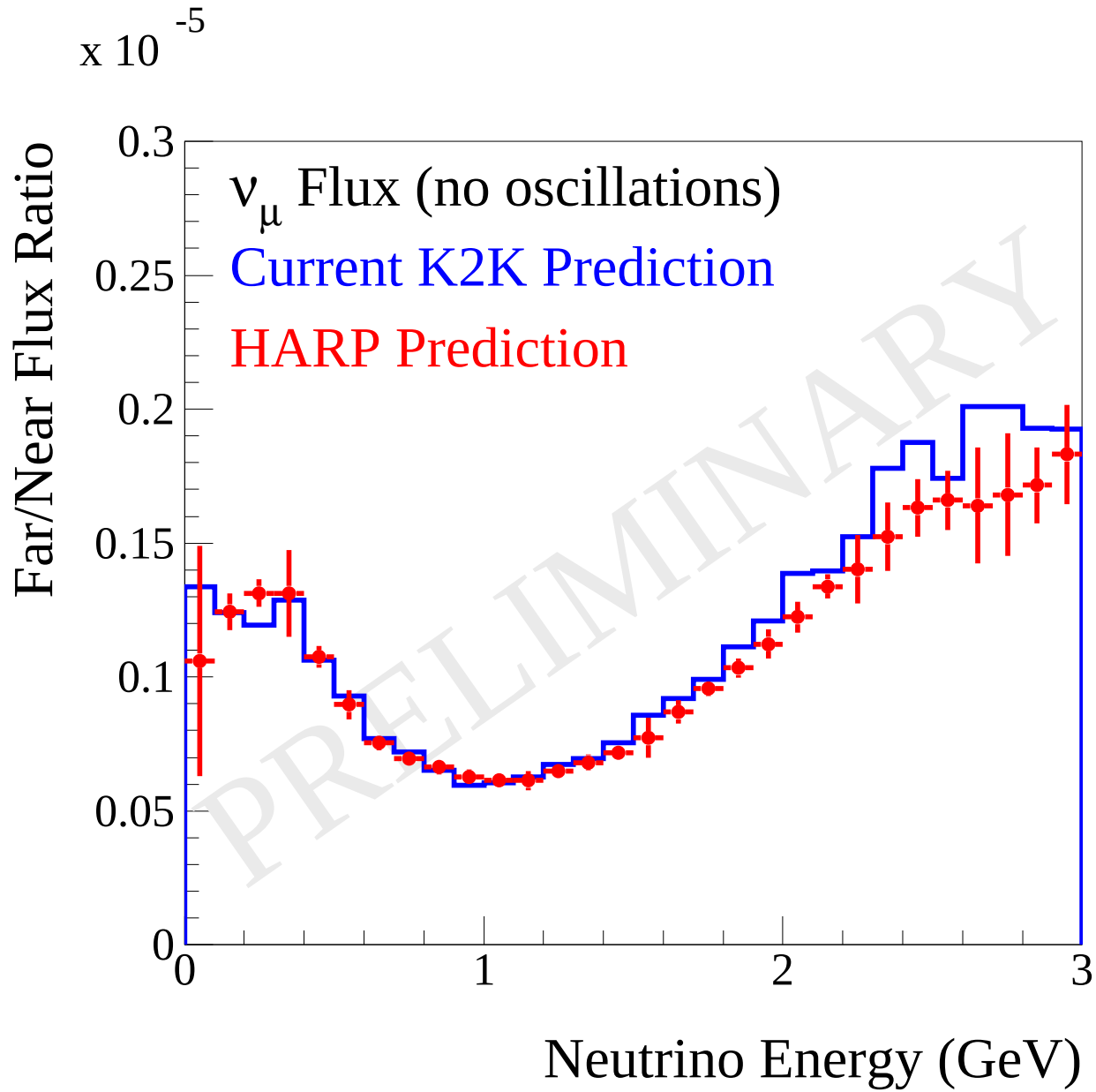
- Sanford-Wang fit to HARP data not particularly good: χ^2 / dof = 210 /42
- Two alternative approaches being explored:
  - Try to use more directly HARP data (but model-dependence is always present)
  - Try alternative parametrizations
- A "dumb", 2-dim linear interpolation of the HARP $d^2\sigma/(dpd\Omega)$ data points between $0.75 < p_\pi < 6.5$ GeV/c and $30 < \theta_\pi < 210$ mrad has been tried, to check robustness against parametrization choice. S-W parametrization still used in pion phase space requiring extrapolations
- Will also try spline and other, more sophisticated, parametrizations

Model Dependence of π^+ Production Parametrization



- Neutrino flux predictions are fairly insensitive even in the presence of "radical" changes in the parametrization of the HARP π^+ cross-section

Possible Plot for Conferences



Pending Issues and Discussion About Prioritization

- Increase MC statistics, and/or use more effective way of predicting fluxes, and/or combine energy bins, for K2K coll. mtg.
- Study flux homogeneity as a function of small "off-axis" angle, and neutrino energy .vs. off-axis angle, given beam pointing knowledge
- How to proceed, given bad Sanford-Wang fit to HARP data? Try parametrizations that are alternative to S-W?
- Add all relevant uncertainties, other than π^+ production, in the neutrino flux predictions!
- We are not going to be able to complete all aspects of the flux prediction analysis before the K2K collaboration meeting; what aspects (in addition to the ones described in this talk) should we focus on, in the near term?