Low-ν Flux

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Nov. 7th, 2017

Outline

- Reminder of low-ν method
- Flux uncertainty
  - Overview
  - Cross section model
  - FSI model
  - Energy scales
- Summary

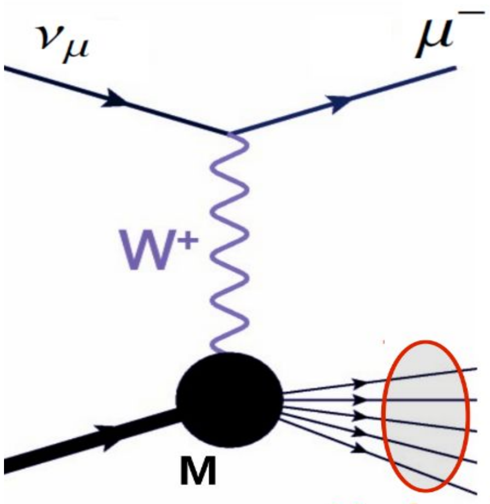
Sample

- Input flux (same as NDTF dst samples')
- Target: CH2
- Sample sizes: 500,000 charged-current events per sample
- MC model details
    - GENIE 2.12.6
    - Study uses Nieves model MEC (circa MINERvA 2017)
    - Comparing with MINERvA (GENIE 2.8.4 With RPA, Nieves MEC and CC1pi reweighted)

Reminder of Low-ν Method

- Relies on the information from hadron energy
  - $\nu = E_{Had} = E_\nu - E_\mu$
- $\frac{d\sigma^{\nu,\bar{\nu}}}{d\nu} = A(1 + \frac{B^{\nu,\bar{\nu}}}{A}\frac{\nu}{E} - \frac{C^{\nu,\bar{\nu}}}{A}\frac{\nu^2}{2E^2})$
- In the limit $\frac{\nu}{E} \to 0$
  - Cross sections are **constants** -- independent of neutrino energy
    - **Small ν/E dependent** correction

      $$S^{\nu(\bar{\nu})}(\nu_0, E) = \frac{\sigma^{\nu(\bar{\nu})}(\nu < \nu_0, E)}{\sigma^{\nu(\bar{\nu})}(\nu < \nu_0, E \to \infty)}$$
    - Flux normalized with external world data
      - cross section



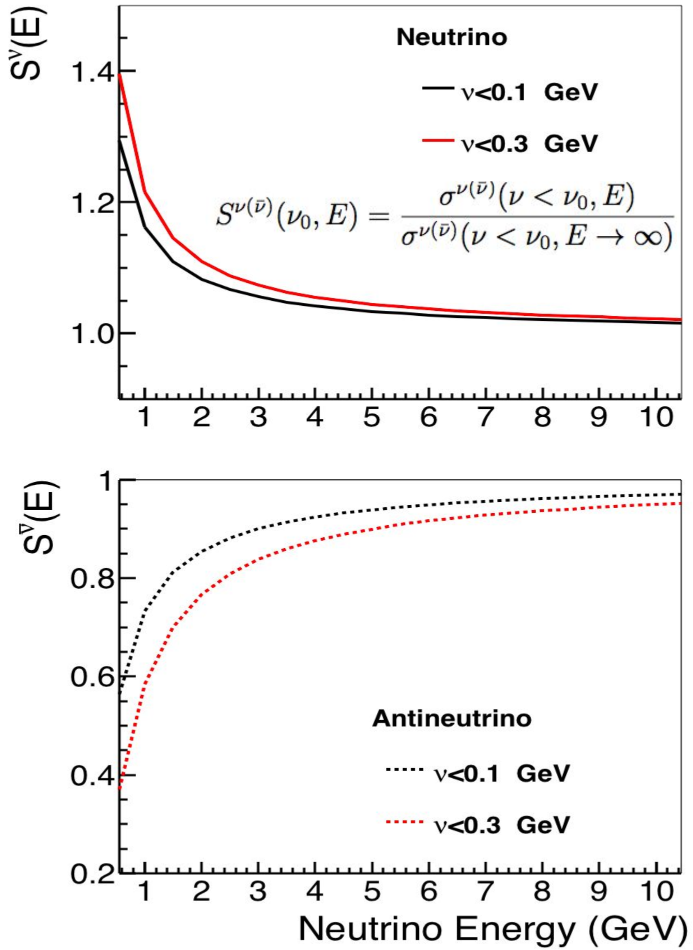
Hadronic system

Low-ν Flux

- Use truth information to extract low-ν flux
  - **Inclusive sample** $N^{\nu}(E_{\nu})$
    - CC events in neutrino energy range <10 GeV
  - **Flux sample** $F^{\nu}(E_{\nu})$
    - Inclusive sample with ν <0.1 GeV
  - **Model correction** $S^{\nu,\nu<\nu_0}(E_{\nu})$
  - **Normalization** H^{ν}
    - At Ev bin 9-10 GeV

$$\sigma^{\nu}(E_{\nu}) = \frac{N^{\nu}(E_{\nu})}{F^{\nu}(E_{\nu})} * \frac{S^{\nu,\nu<\nu_0}(E_{\nu})}{H^{\nu}}$$

$$\Phi^{\nu}(E_{\nu}) = \frac{F^{\nu}(E_{\nu}) * H^{\nu}}{S^{\nu,\nu<\nu_0}(E_{\nu})}$$



Flux Uncertainty Estimation Method

- Extract low-ν flux with single parameter shifted:

$$\Phi(E_\nu) = \frac{F(E_\nu) * H}{S^{\nu<\nu_0}(E_\nu)} \longrightarrow \Phi'(E'_\nu) = \frac{F'(E'_\nu) * H'}{S^{\nu<\nu_0}(E_\nu)}$$

  - Shape uncertainty from
    - Model correction S: when ν < 0.1 GeV, QEL and MEC contribute (small, MEC << QEL, ignore this for now)
    - Flux sample F(Ev)
  - Level uncertainty mainly from **inclusive sample**
    - Relative normalization (shape) to cross section at 9-10 GeV

$$H = \frac{N(10)}{F(10)} * \frac{S^{\nu<\nu_0}(10)}{\sigma(10)} \longrightarrow H' = \frac{N'(10)}{F'(10)} * \frac{S^{\nu<\nu_0}(10)}{\sigma(10)}$$

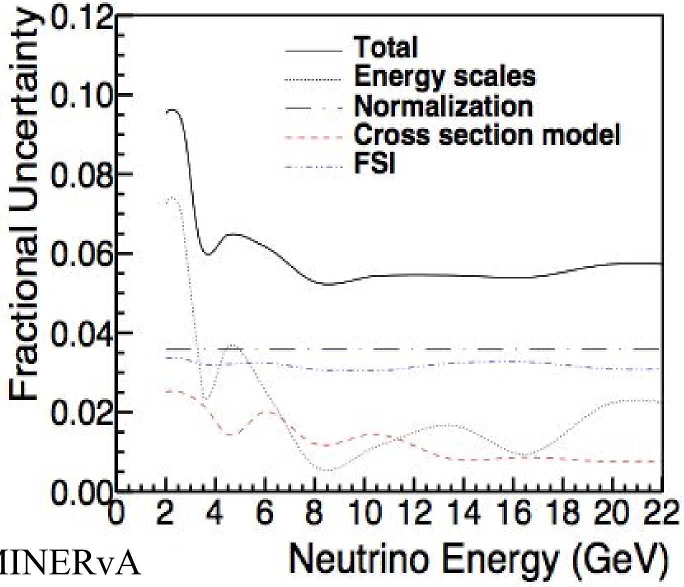
    - Depend on **N(10)** / **F(10)**

$$\sigma(10) = \frac{N(10)}{F(10)} * \frac{S^{\nu<\nu_0}(10)}{H}$$

$$\sigma(10) = \frac{N'(10)}{F'(10)} * \frac{S^{\nu<\nu_0}(10)}{H'}$$

Flux Uncertainty Estimation Method

L. Ren et al., Phys.Rev. D95 (2017) no.7, 072009



- Sources of uncertainty (separately evaluate pieces)
  - Cross section model
    - GENIE(CCQE, RES, DIS)
    - 2p2h
    - RPA
  - GENIE FSI model
  - Energy scales
  - Normalization (not included- shape only)
- Using truth information, does not include
  - Backgrounds
    - Negligible for neutrino, <1% for antineutrino flux in MINERvA
  - Smearing effect
- Comparing with MINERvA
  - MINERvA uses ν cut 0.3-2 GeV, here uses ν cut 0.1 GeV
  - MINERvA normalizes at 12-22 GeV, here normalizes at 9-10 GeV

Components of Flux Uncertainty

- Cross section model
  - GENIE(CCQE, RES, DIS)
  - 2p2h
  - RPA (recap)
- GENIE FSI model
- Energy scales (recap)
- Summary of flux uncertainties

Cross Section Model Uncertainties in GENIE

- Table from MINERvA
- Differences from MINERvA
  - Show MaCCQE uncertainty (+25% / -15%), which is removed by MINERvA
  - rvn1pi : 1 σ is +/-50% (GENIE recommended) instead of 15% in MINERvA
  - VeCFFCCQEshape not included due to technical problem (<0.6% in MINERvA)

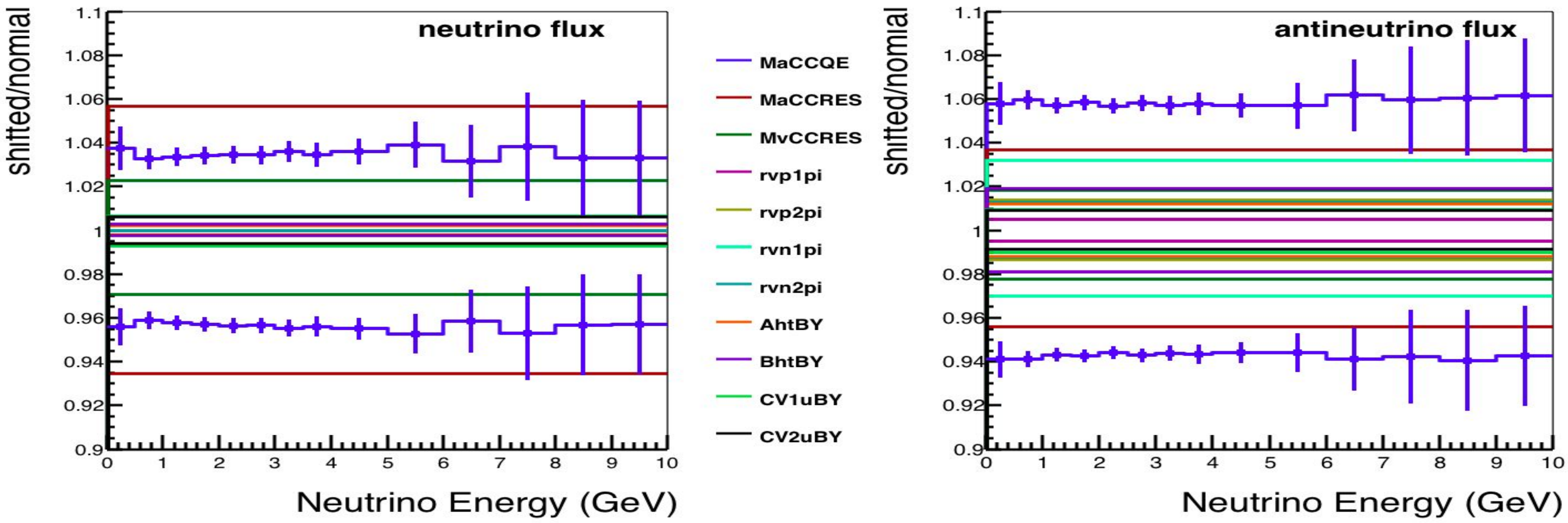
GENIE Knob name	Description	1 σ
MaRES	adjust M_A in Rein-Sehgal cross section	$\pm$20%
MvRES	adjust M_v in Rein-Sehgal cross section	$\pm$10%
Rvp1pi	1 pi production from νp non-resonant interactions	$\pm$50%
Rvn1pi	1 pi production from νn non-resonant interactions	$\pm$15%
Rvp2pi	2 pi production from νp non-resonant interactions	$\pm$50%
Rvn2pi	2 pi production from νn non-resonant interactions	$\pm$50%
VeCFFCCQEshape	Changes from BBBA to dipole	on or off
AhtBY	Bodek-Yang parameter A_{HT}	$\pm$25%
BhtBY	Bodek-Yang parameter B_{HT}	$\pm$25%
CV1uBY	Bodek-Yang parameter C_{V1u}	$\pm$30%
CV2uBY	Bodek-Yang parameter C_{V2u}	$\pm$40%

Cross Section Model Uncertainties in GENIE

- Dominated by MaRES, MaCCQE
  - MaCCQE not included in summary plots
- Most are level uncertainty propagated from the 9-10 GeV bin of inclusive sample.
- Only MaCCQE affect the shape of flux (ν < 0.1GeV)
  - Including smearing effect might introduce shift of shape from other systematics

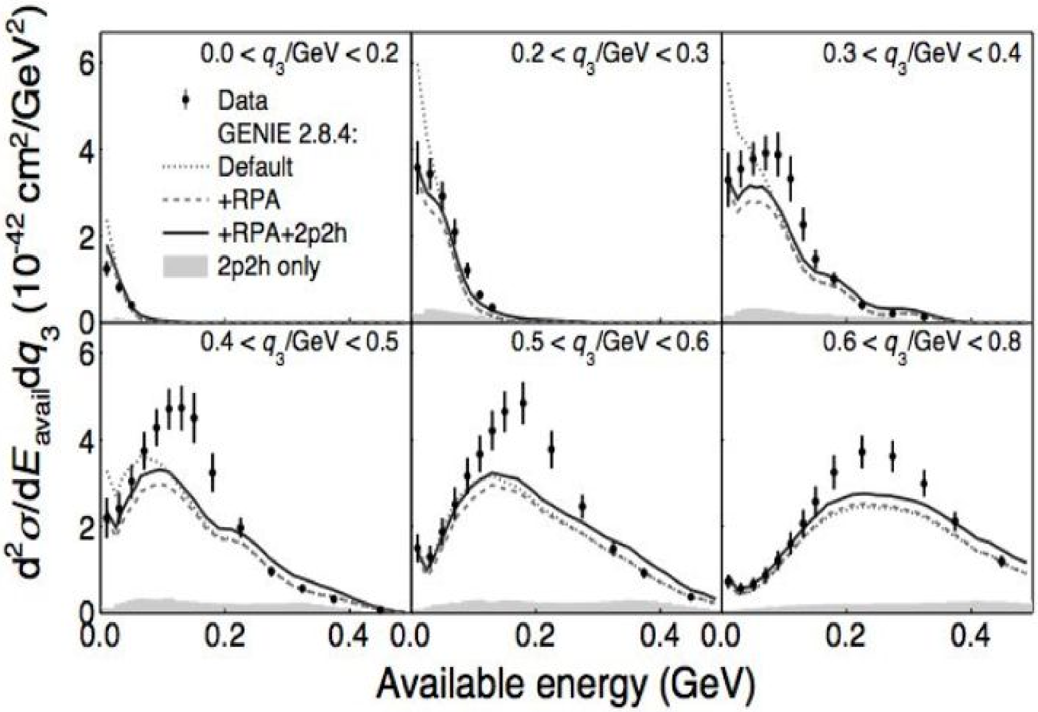
$$\Phi'(E'_\nu) = \frac{F'(E'_\nu) * H'}{S^{\nu<\nu_0}(E_\nu)}$$

$$H' = \frac{N'(10)}{F'(10)} * \frac{S^{\nu<\nu_0}(10)}{\sigma(10)}$$



MINERvA's 2p2h Uncertainty

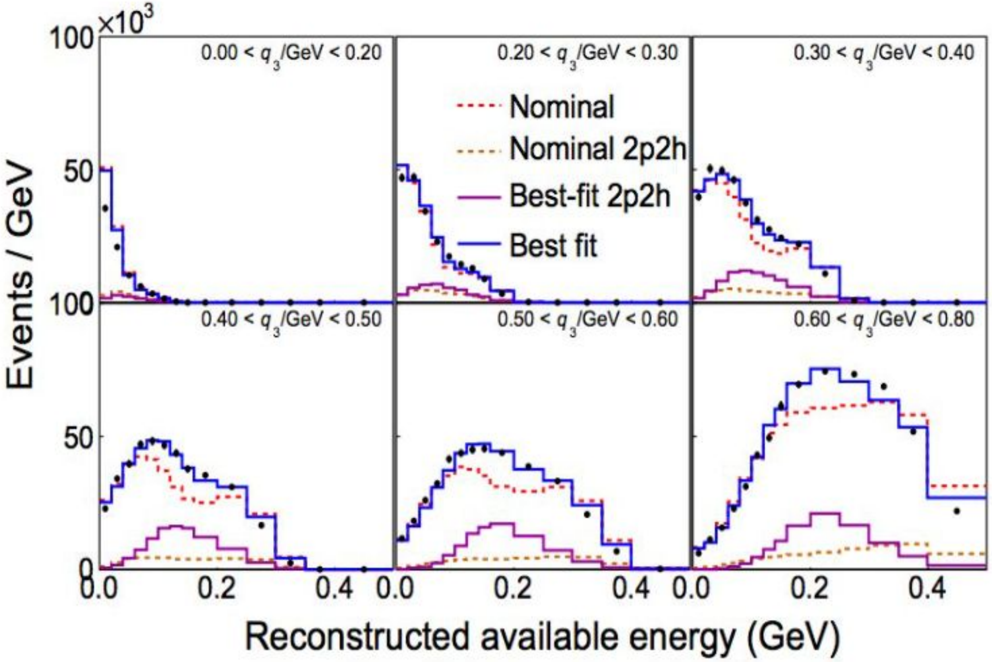
- MINERvA measured differential cross section at low 3-momentum transfer region for neutrino
- Available energy
  - ~Ehad (visible energy- not including neutron energy)
- Implementing Nieves 2p2h and RPA improves agreement with data
- 2p2h uncertainty
  - Remaining data MC difference



P. A. Rodrigues et al., Phys. Rev. Lett. 116, 071802 (2016)

MINERvA's 2p2h Uncertainty

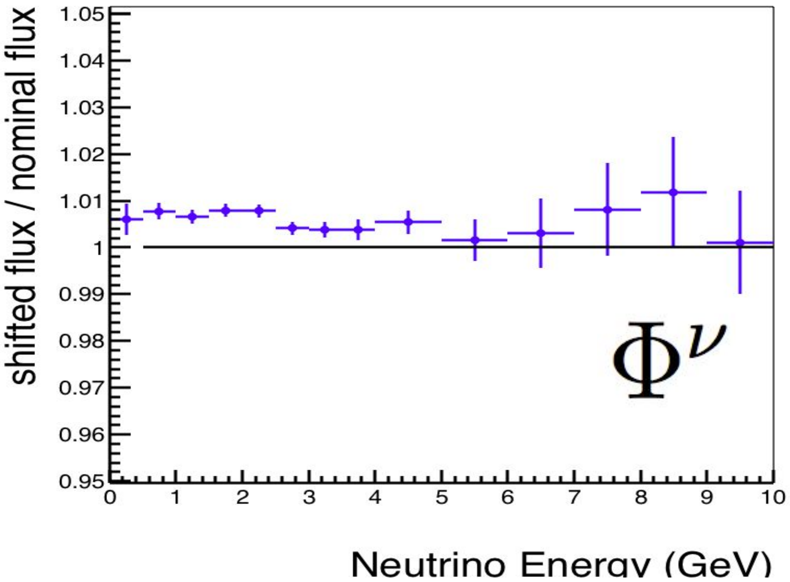
- MINERvA 2-step fit for low-ν flux:
  - (q3, Eavail) fit to data
    - Nominal vs best fit
  - Initial state reweighting
    - reweight nn/pp/np event to further improve the agreement with data
    - Small effect, not included in this study
- Apply in the region
  - q3 < 0.8 GeV
  - To both neutrino and antineutrino
    - MINERvA is working on antineutrino version

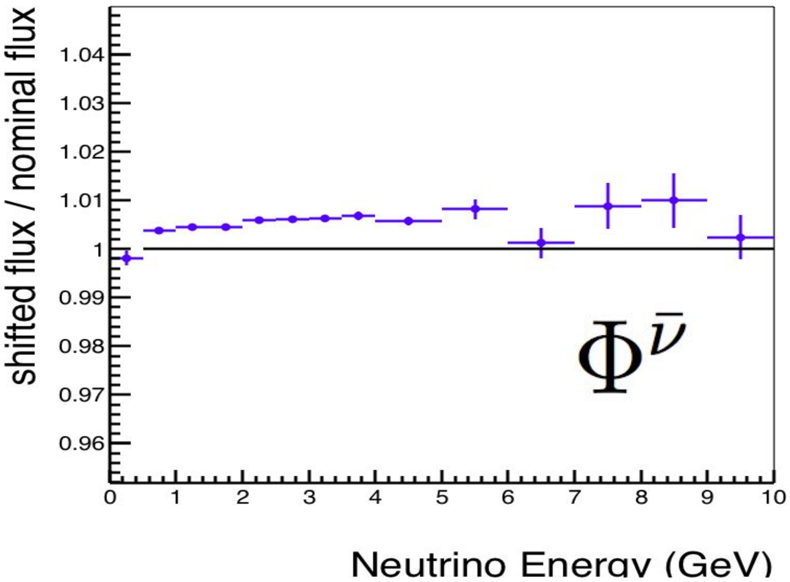


Ref: MINERvA internal document by P. A. Rodrigues

2p2h Model Uncertainty

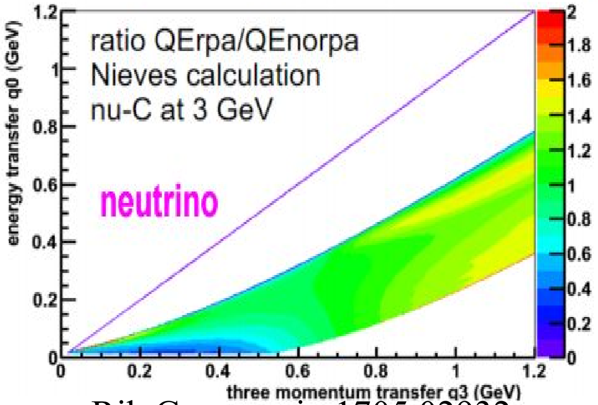
- MC sample size increased for this study
- <1% effect on flux
- Similar as MINERvA



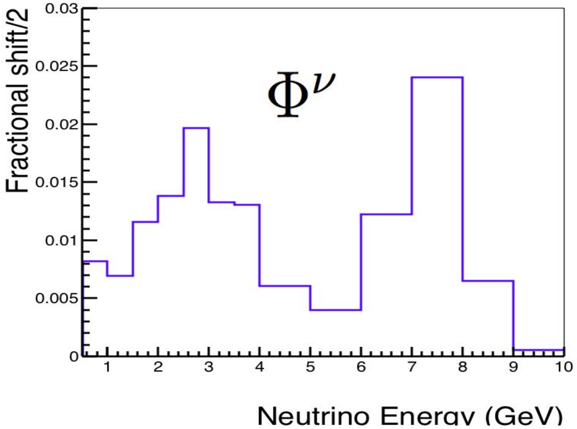


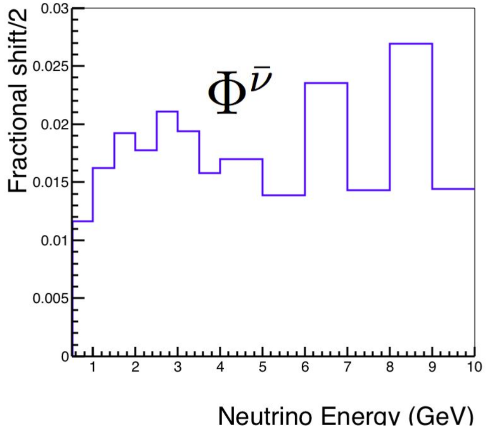
RPA (recap)

- Shown at collaboration meeting in August
  https://indico.fnal.gov/event/13293/session/7/contribution/83/material/slides/0.pdf
- MINERvA's prescription
  - Reweight QE events with 2D weight (q0 vs q3): QE RPA / QE no RPA
  - Extract low-ν flux with RPA weight, and take half of the change in flux as an uncertainty
  - Uncertainty of < 2.5% for neutrino and antineutrino flux (MINERvA: <1.5%)
    - Large statistical error above 6 GeV



Rik Gran, arxiv:1705.02932





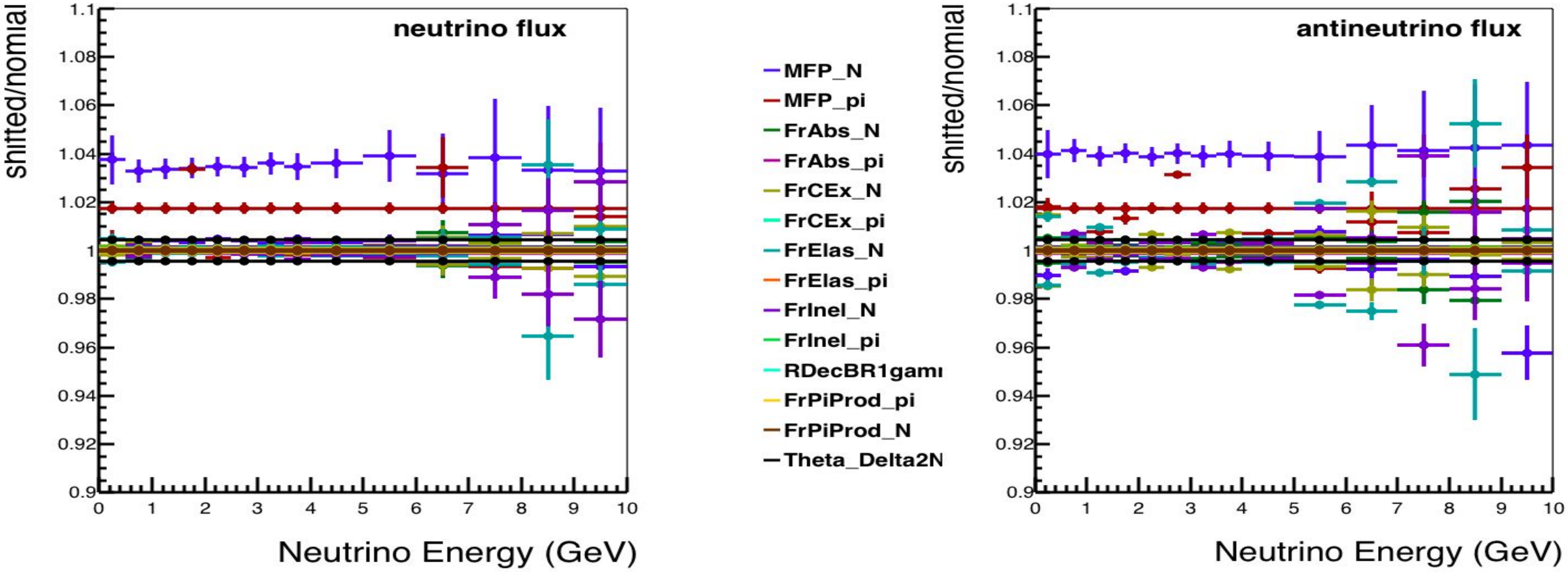
GENIE FSI Model Uncertainty

- MINERvA FSI uncertainties
- Differences from MINERvA
  - Bottom 3 uncertainties and AGKYxF1pi not included due to technical issue (<1% in MINERvA)

GENIE Knob name	Description	1 σ
MFP_N	mean free path for nucleons	$\pm 20\%$
FrCex_N	nucleon fates - charge exchange	$\pm 50\%$
FrElas_N	nucleon fates - elastic	$\pm 30\%$
FrInel_N	nucleon fates - inelastic	$\pm 40\%$
FrAbs_N	nucleon fates - absorption	$\pm 20\%$
FrPiProd_N	nucleon fates - pion production	$\pm 20\%$
MFP_pi	mean free path for pions	$\pm 20\%$
FrCEx_pi	pion fates - charge exchange	$\pm 50\%$
FrElas_pi	pion fates - elastic	$\pm 10\%$
FrInel_pi	pion fates - inelastic	$\pm 40\%$
FrAbs_pi	pion fates - absorption	$\pm 30\%$
FrPiProd_pi	pion fates - pion production	$\pm 20\%$
AGKYxF1pi	AGKY hadronization model x_F	$\pm 20\%$
Theta_Delta2Npi	Δ decay angular distribution	on/off
RDecBR1gamma	Res decay branching ratio to gamma	$\pm 50\%$
EFNUCR	Increase/decrease to nuclear size for low energy hadrons(± 0.6 fm).	
FZONE	Change formation time by 50%	
Hadronization_Alt1	Change AGKY model to do a simple phase space decay of hadrons.	

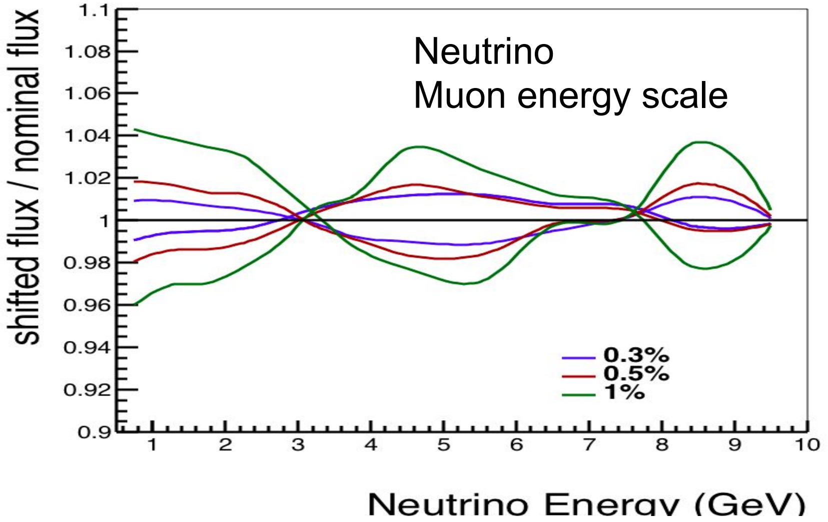
GENIE FSI Uncertainty

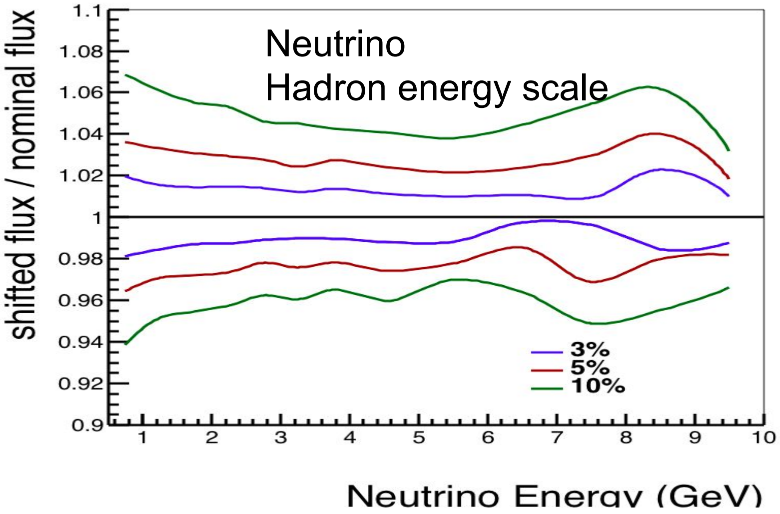
- Dominated by mean free path for nucleons
- Similar as MINERvA, ~1% larger



Energy scales (recap)

- Shown at collaboration meeting in August
  https://indico.fnal.gov/event/13293/session/7/contribution/83/material/slides/0.pdf
- Muon energy scale has larger effect than hadron energy scale
- Assume both are 1% in the following slides





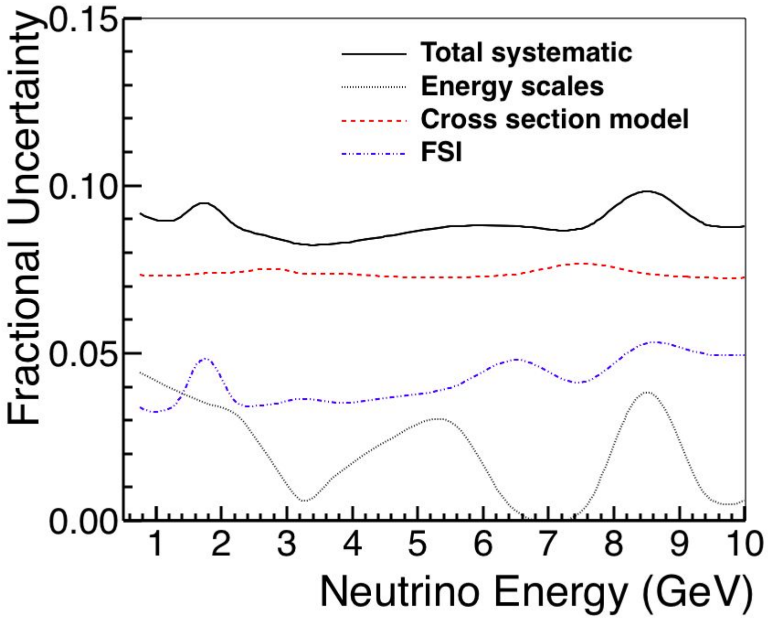
Summary of Flux Uncertainty for Neutrino

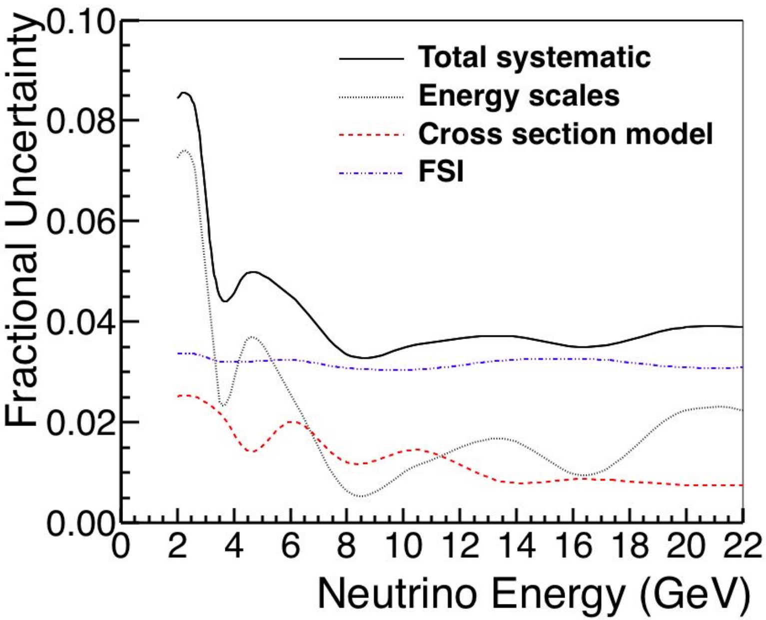
$$\Phi'(E'_\nu) = \frac{F'(E'_\nu) * H'}{S^{\nu<\nu_0}(E_\nu)}$$

- Assume both muon and hadron energy scales to be 1%
- Dominated by cross section model
  - GENIE (MaRES etc.) : level uncertainty propagate from inclusive sample (~7%)

$$H' = \frac{N'(10)}{F'(10)} * \frac{S^{\nu<\nu_0}(10)}{\sigma(10)}$$

MINERvA



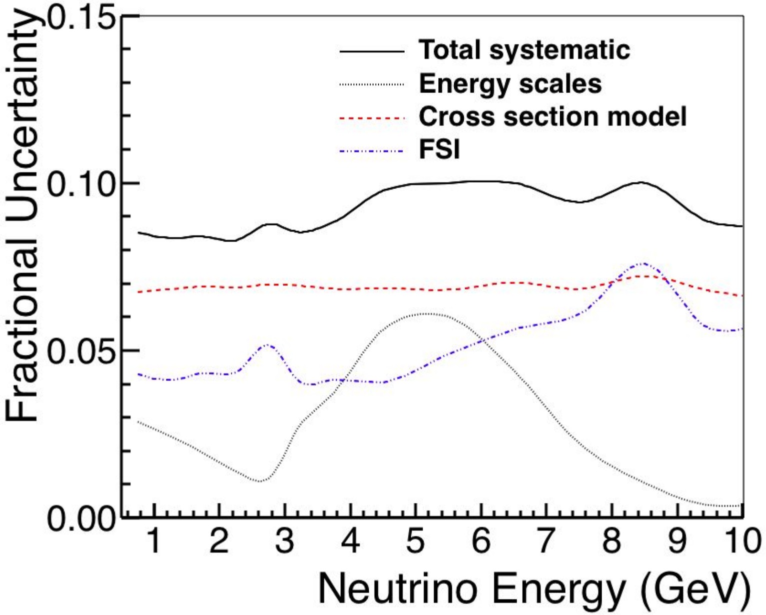


Summary of Flux Uncertainty for Antineutrino

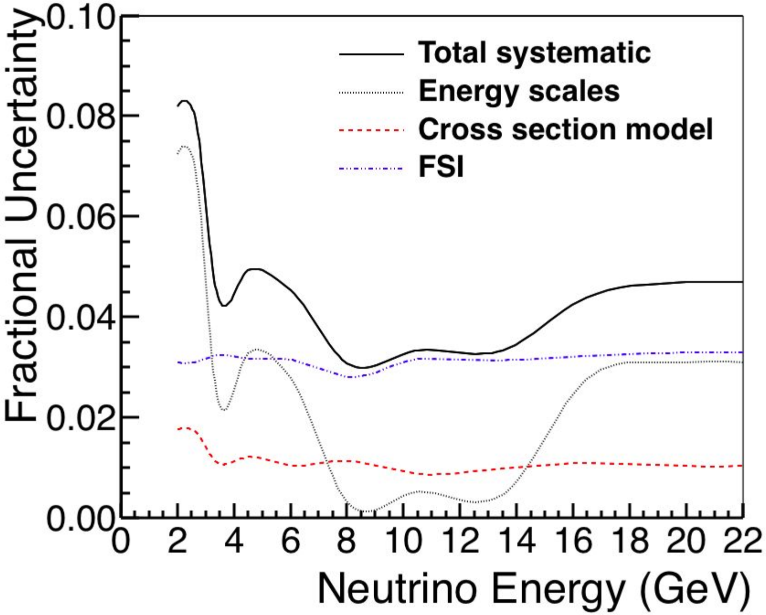
$$\Phi'(E'_\nu) = \frac{F'(E'_\nu) * H'}{S^{\nu<\nu_0}(E_\nu)}$$

$$H' = \frac{N'(10)}{F'(10)} * \frac{S^{\nu<\nu_0}(10)}{\sigma(10)}$$

- Assume both muon and hadron energy scales to be 1%
- Dominated by cross section model
    - GENIE (MaRES etc.) : level uncertainty propagate from inclusive sample (~7%)

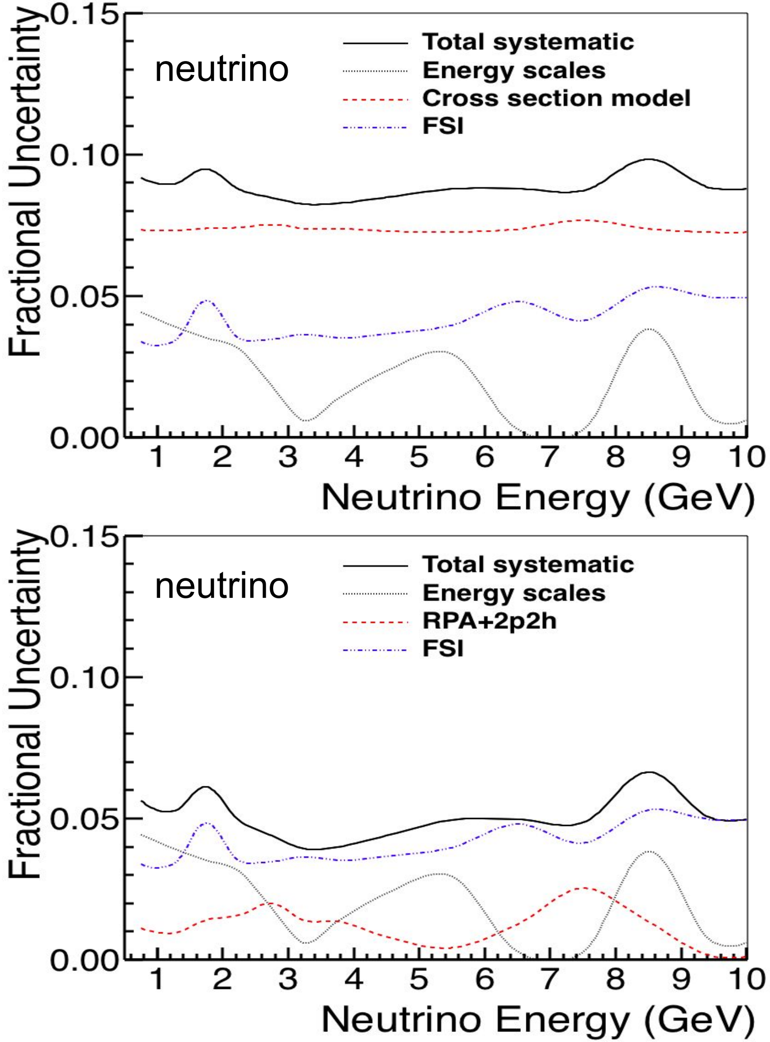


MINERvA



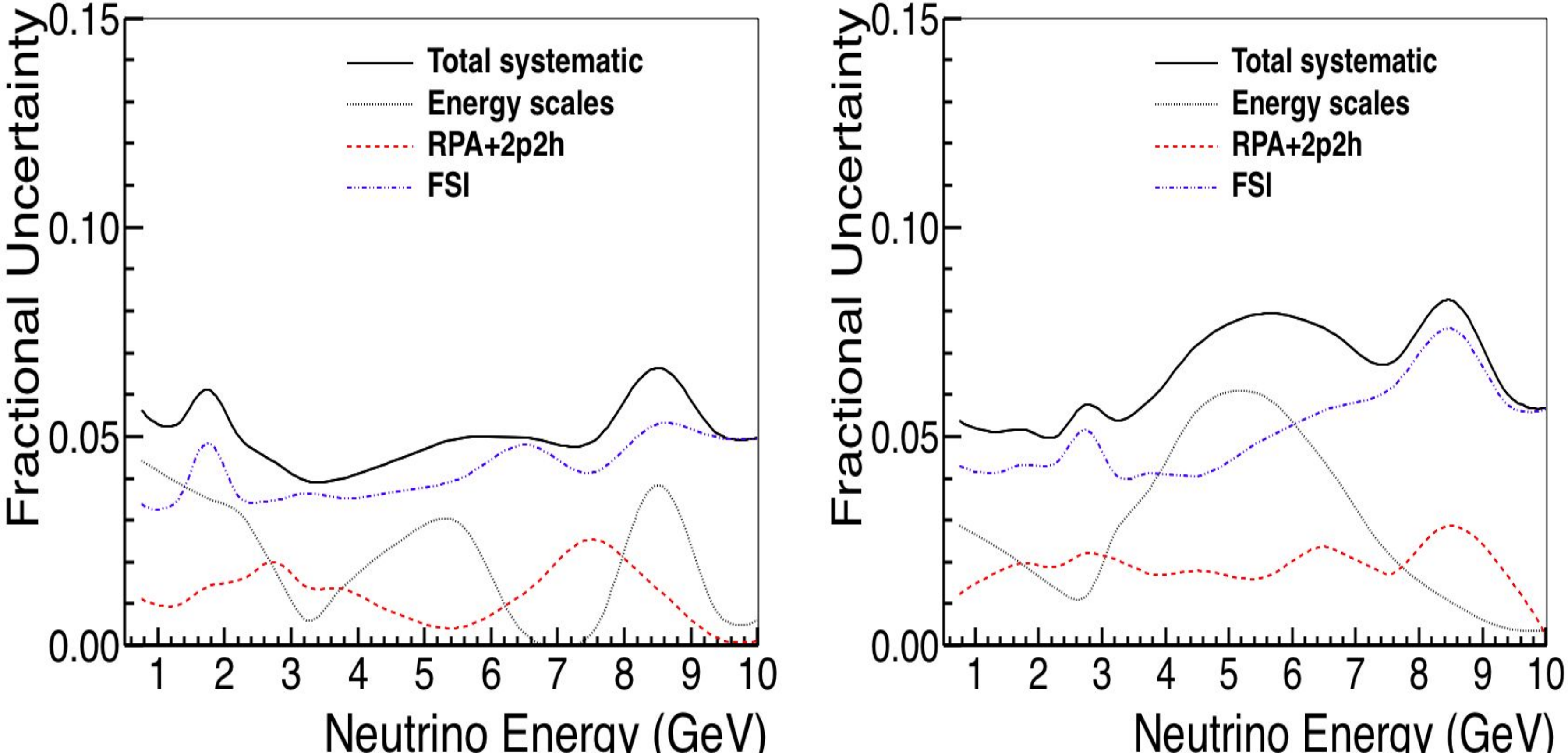
Conclusions

- Estimated low-ν flux uncertainty
  - Cross section model (GENIE, 2p2h, RPA)
  - GENIE FSI model
  - Energy scales
- Assume energy scales of 1% for both muon and hadron, we obtain total uncertainty of ~10% which is dominated by GENIE cross section model uncertainty (largest is MaRES)
- To improve
  - Change the way of external normalization to minimize or remove the level uncertainty coming from inclusive sample (GENIE model)
  - Better understanding of MaRES
  - Better understanding of GENIE FSI model



Backup

Remove GENIE Cross Section Model Uncertainty



Side Study: Effect of Neutron / FSI on Flux

- GENIE FSI model affect neutron number, which has large effect on flux shape
- Inclusive and flux samples w/ and /o FSI or Neutron K.E.
- With FSI, neutron makes ~40% flux shape difference (blue)
- Without FSI, much flat flux (green)