FPF White Paper: Neutrinos
Fluxes and Cross Sections

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Neutrino fluxes and cross sections

VII. Neutrino Physics
- A. Neutrino Fluxes
- B. Neutrino Cross Sections
- C. MC Tools for Neutrino Interactions
- D. BSM with Neutrinos

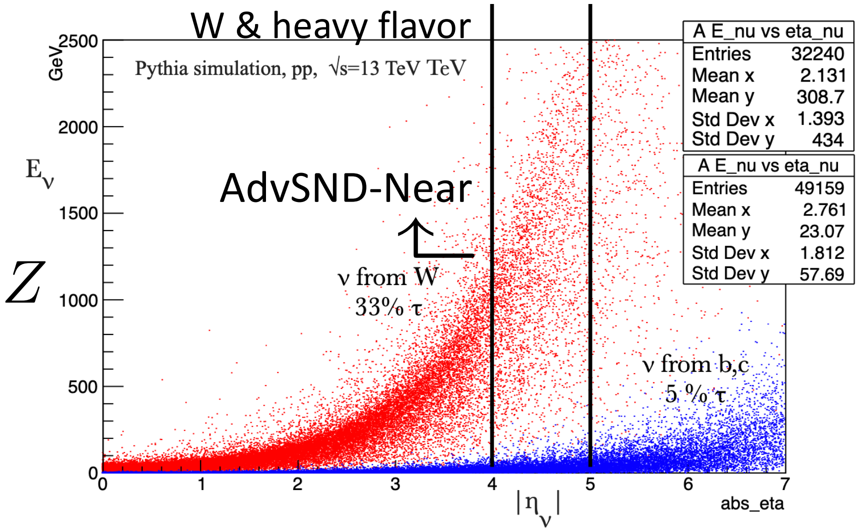
- *Neutrino fluxes* depend on perturbative QCD (e.g., heavy flavor) and more complex incorporation of QCD in light meson production.
- *Standard model neutrino and antineutrino cross sections* depend on detector target nucleon PDFs.
  - Monte Carlo modeling of neutrino interactions (Vishvas Pandey)
- Standard model results are the basis for Beyond the Standard Model searches/constraints.
  - BSM physics with neutrinos (Kevin Kelly)

Parallel Session Contributions:

- Y. Farzan
- T. Karkkainen
- Yong Du
- Weidong Bai
- A. Garcia
- Y. S. Jeong
- R. Plestid

Neutrino fluxes at the FPF

arXiv:1804.04413, Buontempo et al.



$$pp \to \pi, K, \text{hyperons}, \text{charm hadrons}, \text{b hadrons}, W, Z$$

$$\hookrightarrow \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$$

$\pi, K, \text{hyperons}$ shown from Monte Carlo generators

Focus on far forward region

$\text{charm hadrons}, \text{b hadrons}$ Monte Carlo generators

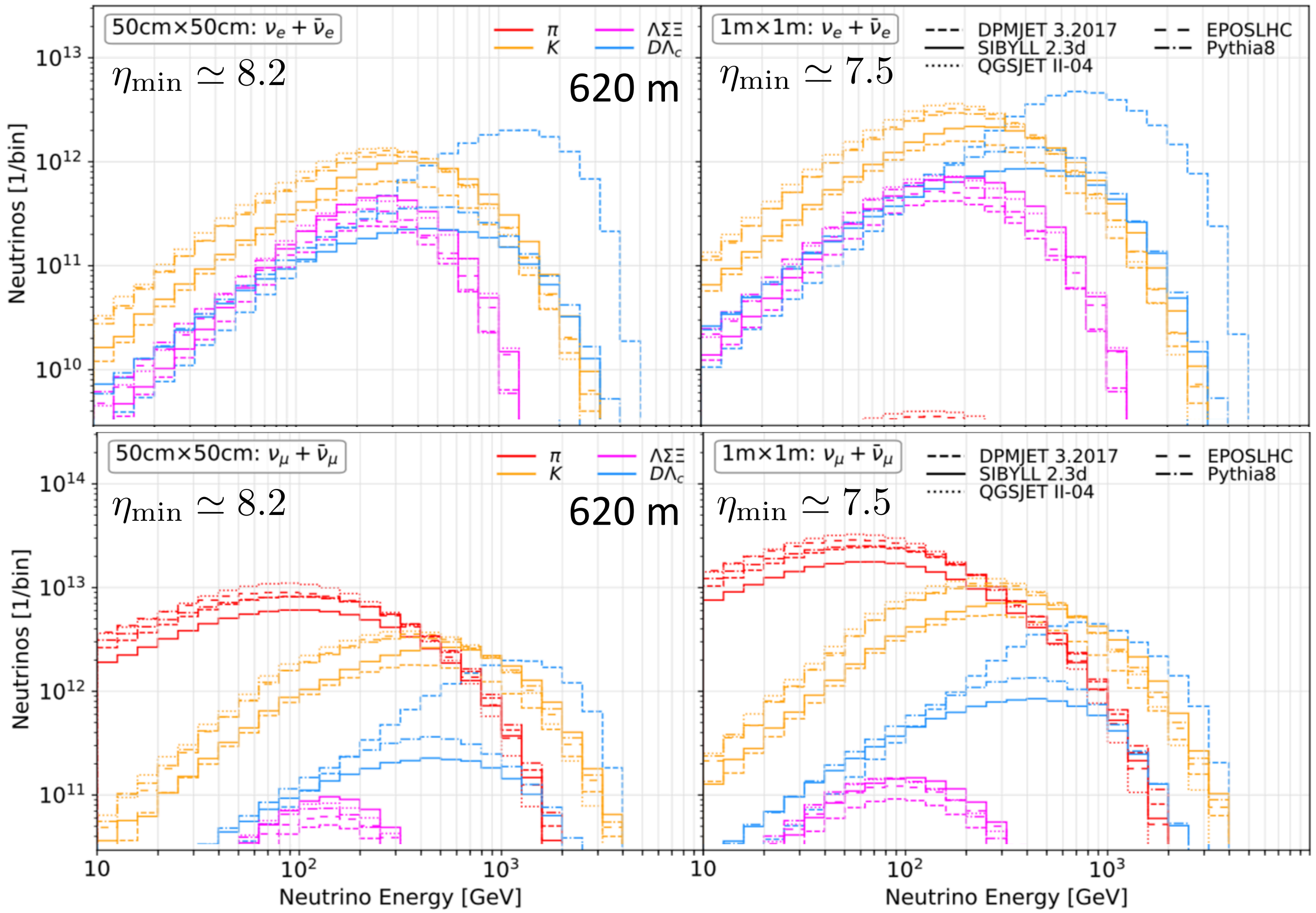
NLO QCD calculations ↰

- parton distribution functions (PDFs, intrinsic charm?)
- QCD renormalization/factorization scales
- transverse momentum? (kT, smearing)
- fragmentation

Monte Carlo results $\nu_e + \bar{\nu}_e\,, \nu_\mu + \bar{\nu}_\mu$

Kling & Nevay

$3000\ \mathrm{fb}^{-1}$



- Kaon, pion, charm: different energies and neutrino flavors.
- Especially for pions and kaons, need propagation through forward LHC infrastructure.
- Large uncertainties in charm contribution (LO in MC).
- More consistency in light hadron contributions.

Fast neutrino flux simulation

See also: Kling & Nevay, 2105.08270

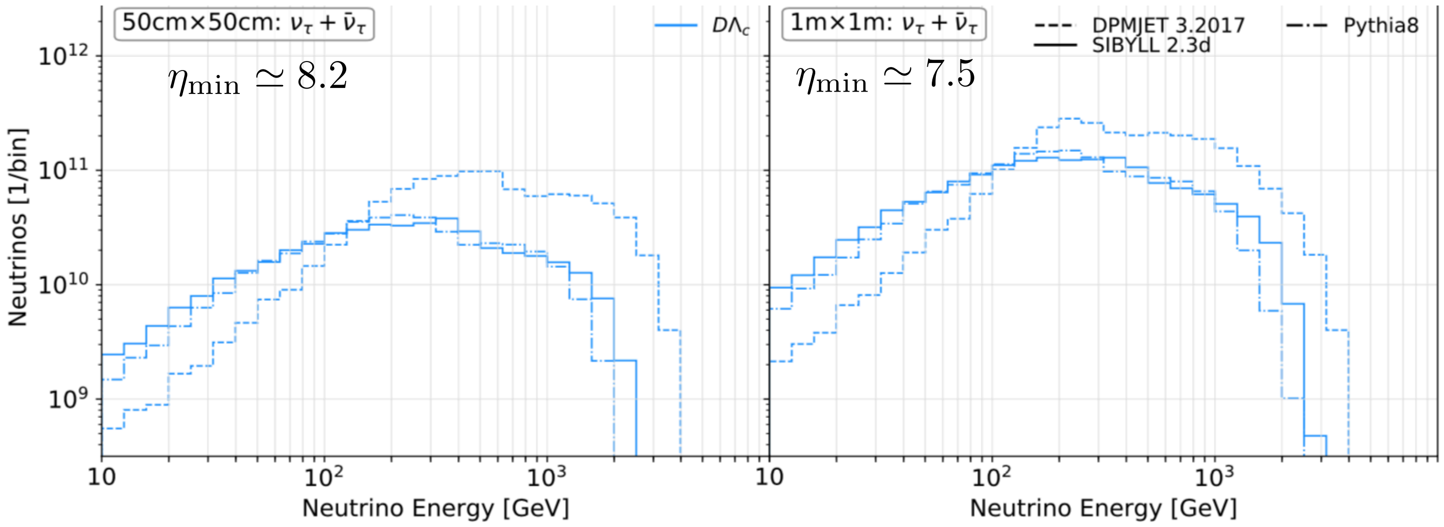
Note: different η_{min}

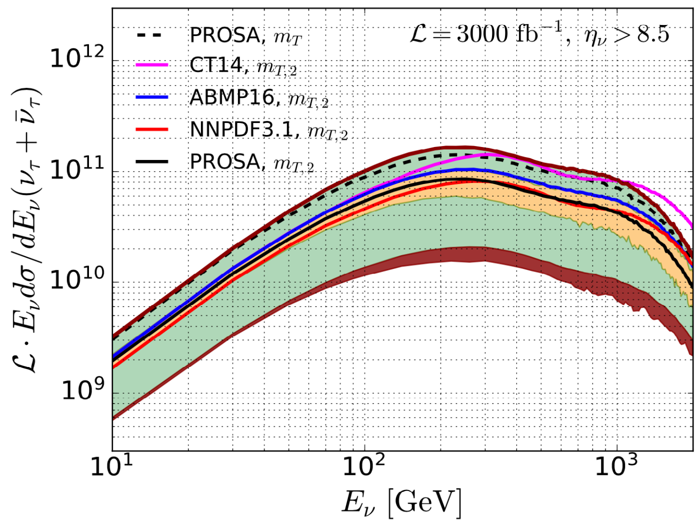
Monte Carlo and NLO results $\nu_\tau + \bar{\nu}_\tau$

Kling & Nevay

$3000\ \text{fb}^{-1}$

Bai et al.





LO MC

NLO QCD

- SIBYLL 2.3d tuned to charm production data, DPMJet & Pythia are not.
- NLO QCD can quantify errors: large scale dependence an indication of need for higher order terms (green), PDF uncertainty (PROSA, orange).

See also: Kling & Nevay, 2105.08270, Bai et al., 2112.11605

Numbers of CC events

Sibyll 2.3d/DPMJET 3.2017

Detector				Number of CC Interactions		
Name	Mass	Coverage	Luminosity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}	137 / 395	790 / 1.0k	7.6 / 18.6
FASERν2	20 tons	$\eta \gtrsim 8$	3 ab^{-1}	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}	36k / 113k	203k / 268k	1.5k / 4k
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}	6.5k / 20k	41k / 53k	190 / 754

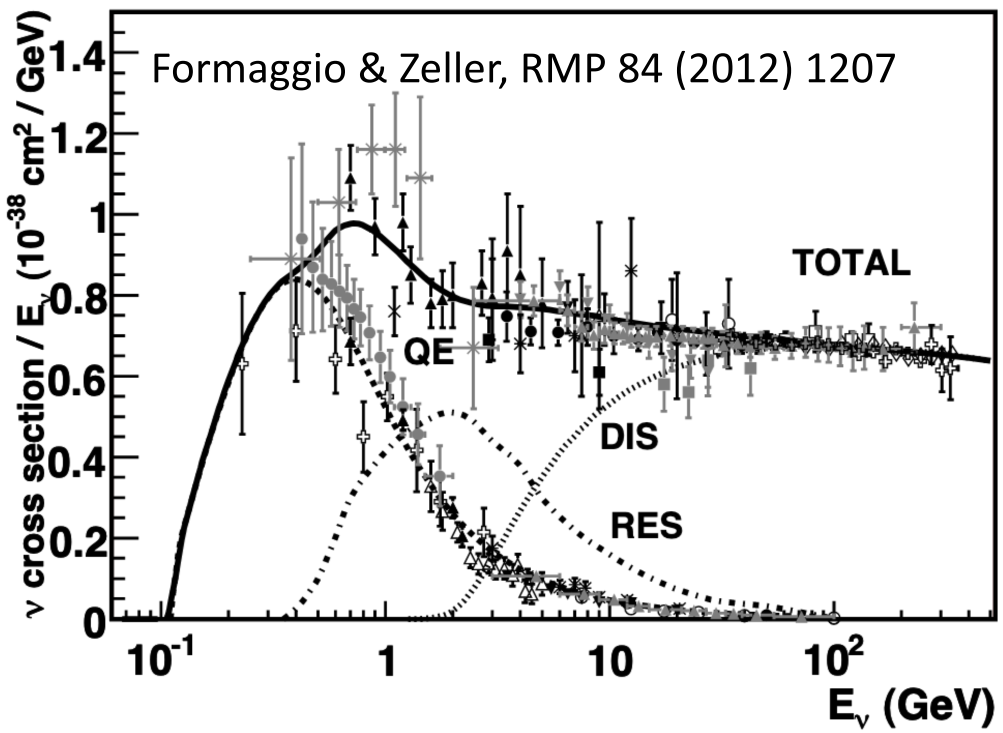
- Fast neutrino flux simulation tool useful for modeling.

- PDFs, including at large x, particularly important for HE neutrinos from charm.
- Plenty of room for improvements in MC modeling, beyond NLO QCD charm production.

NLO QCD

	ν_τ	$\bar{\nu}_\tau$	$\nu_\tau+\bar{\nu}_\tau$	$\nu_\tau+\bar{\nu}_\tau$		
$(\mu_R,\ \mu_F),\ \langle k_T\rangle$	(1, 1) $m_{T,2}$, 0.7 GeV					
				scale(u/l)	PDF(u/l)	σ_{int}
FASERν2 $\eta_\nu > 8.5$, 20 tons (W)	2296	1088	3384	+3144/-2519	+786/-1089	± 77
$\eta_\nu > 6.9$, 10 ton (Ar)	529	257	786	+692/-575	+152/-229	±11
$(\mu_R,\ \mu_F),\ \langle k_T\rangle$	(1, 2) m_T, 1.2 GeV			(1, 1) $m_{T,2}$, 0.7 GeV		
PDF	PROSA FFNS			NNPDF3.1	CT14	ABMP16
FASERν2 $\eta_\nu > 8.5$, 20 tons (W)	3808	1804	5612	3552	6492	4338
$\eta_\nu > 6.9$, 10 ton (Ar)	953	465	1418	748	1202	944

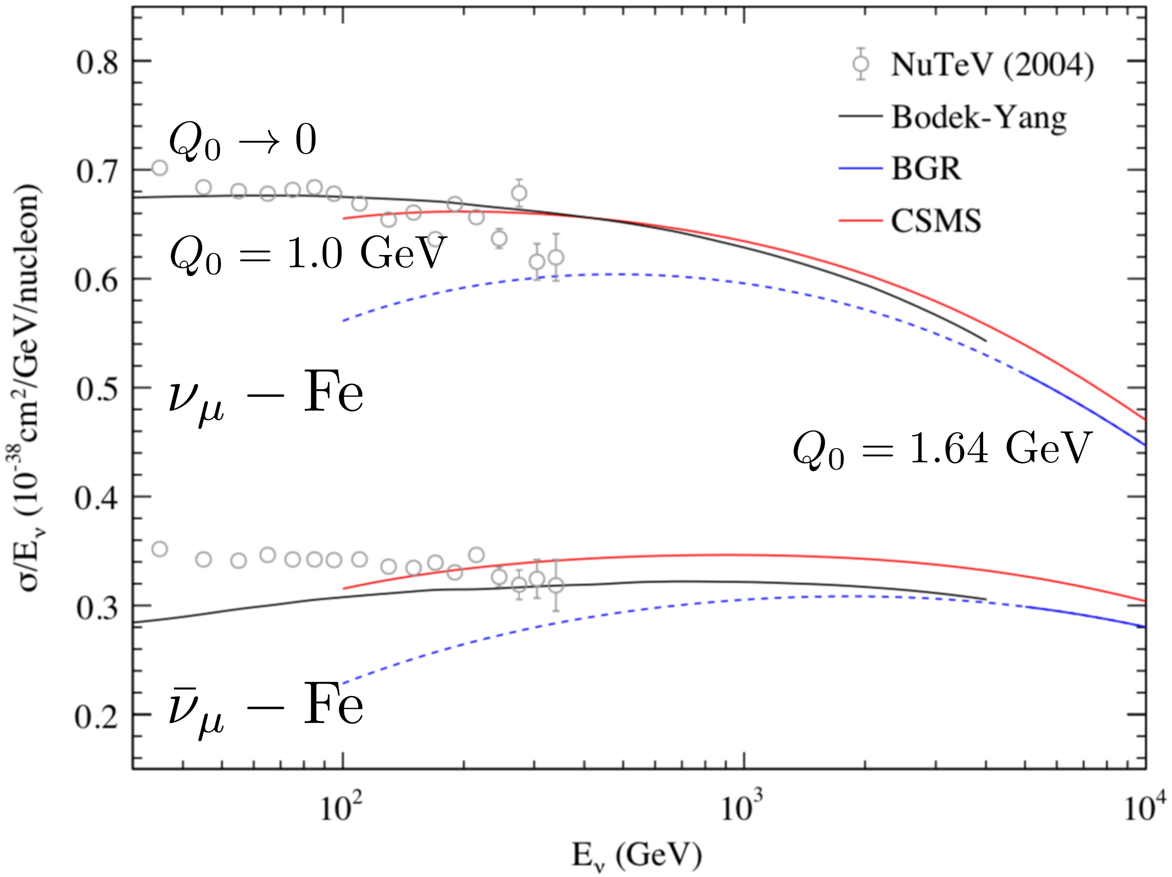
Neutrino cross sections



- Deep-inelastic scattering (DIS) at high energies: charged current (CC) and neutral current (NC)
- DIS at lower energies, impact of hadronic final state invariant mass *W* and momentum transfer *Q*
- Quasi-elastic (QE) and resonant (RES) scattering
- Scattering with electrons

Deep-inelastic scattering (DIS)

Garcia Soto



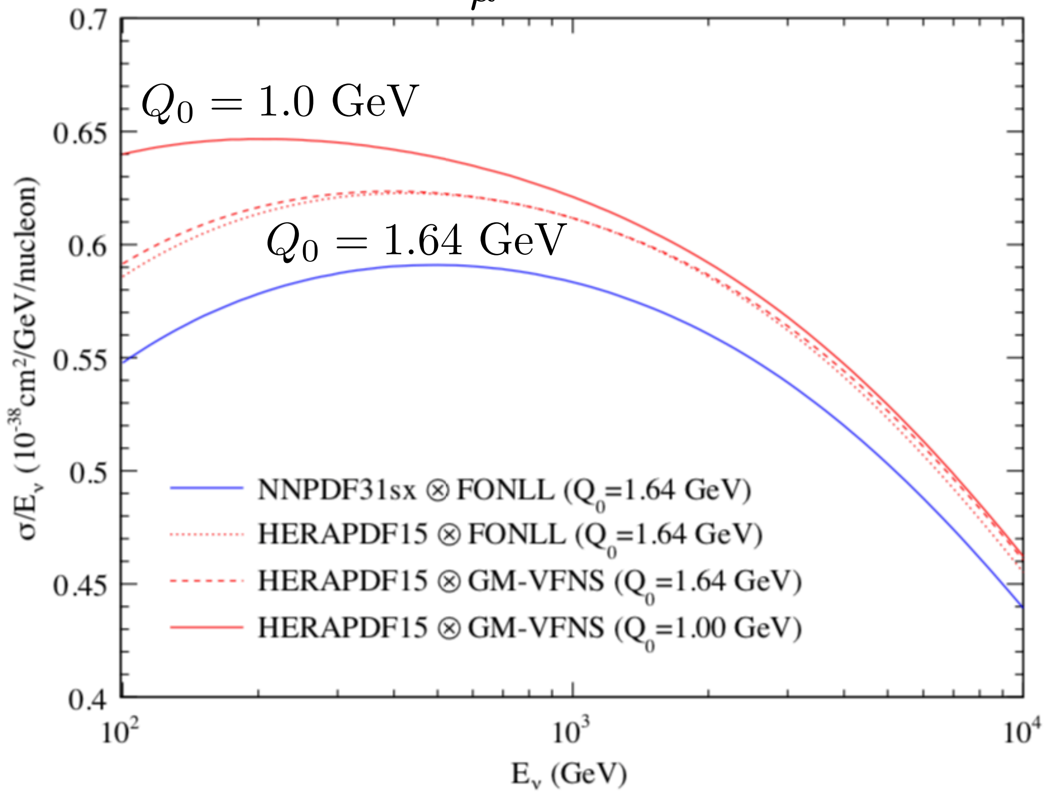
Differences in evaluations for E>300 GeV:

- Minimum Q_0 in structure functions
  - Bodek-Yang extrapolates to Q_0=0
- Treatment of heavy flavor (most relevant, neutrino production of charm)
- Parton distribution functions.

[large Q_0, blue dashed line, neutrino energy below limit of applicability]

Deep-inelastic scattering (DIS)

Garcia Soto $\nu_\mu - \mathrm{Fe}$



Conclusions:

- Agreement when minimum Q_0 is equal for same PDFs.
- Treatment of heavy flavor is not producing discrepancies (red dashed and dotted agree).
- Parton distribution functions are sufficiently different:
  - input PDFs, with disagreement $0.01<x<0.6$
  - (consequence, blue and red curves disagree).

- Important region of x-Q^2 space for DIS needs further study

DIS low-Q and low-W

$$W^2 = Q^2(1/x - 1) + m_N^2$$

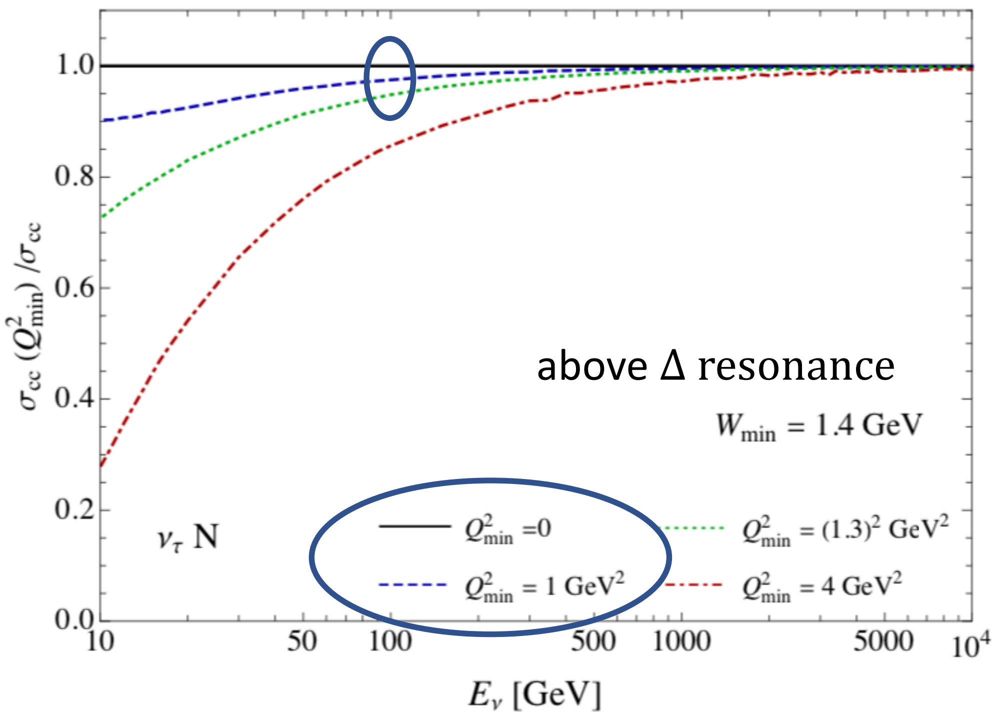
$$\Delta\ \text{res} : m_N + m_\pi < W \lesssim 1.4\ \text{GeV}$$

$$\text{more res} : 1.4\ \text{GeV} \lesssim W \lesssim 1.8 - 2\ \text{GeV}$$

Low Q extrapolations: Bodek-Yang

Capella et al. (CKMT)/Bertini et al.

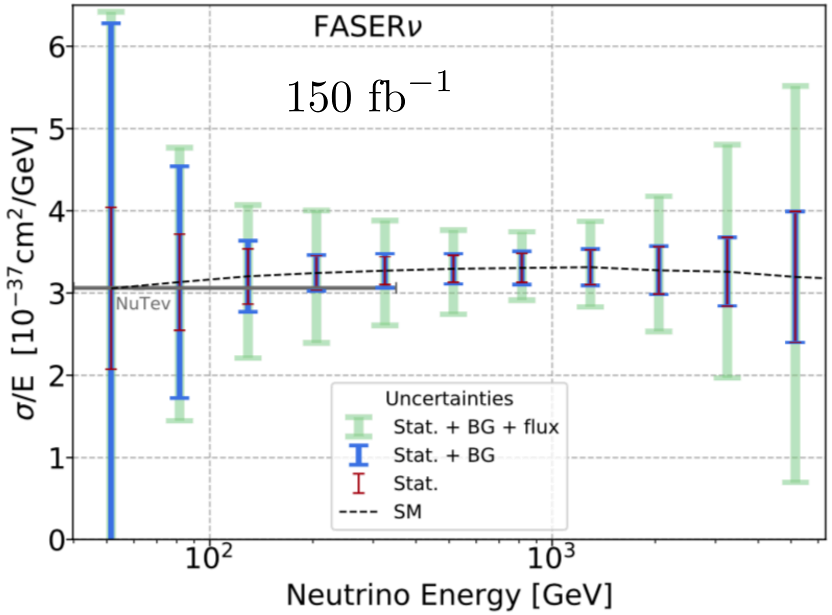
Jeong & Reno

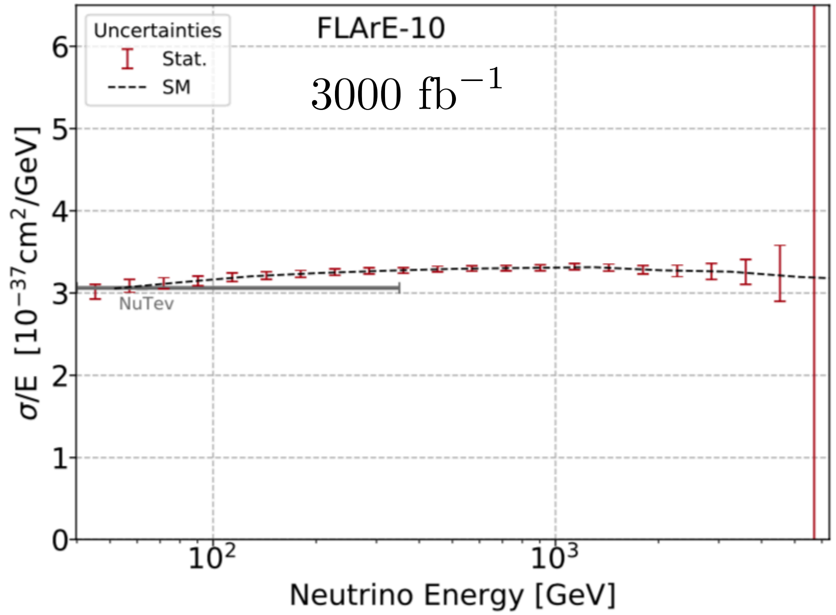


- For W_{min}=1.4 GeV, Q_0=Q_{min}<1 GeV give 3-5% of the cross section for E>100 GeV.
- W_{min}<1.4 GeV, with CKMT extrapolation, <1-2 % for E>100 GeV.
- Important region of x-Q^2 space needs further study

Neutral current scattering

Ismail, Mammen Abraham, Kling





- Neural network to separate neutrino NC events from neutral hadron background events.
- Sensitivity to neutrino flux uncertainty reduced in NC/CC ratio.

- Apply to constraints on BSM physics.

See also: Ismail, Mammen Abraham, Kling, 2012.10500

Neutrino elastic and resonant scattering

Trojanowski

Detector	CCQE ν_e	CCQE $\bar{\nu}_e$	CCQE ν_μ	CCQE $\bar{\nu}_\mu$	CCQE ν_τ	CCQE $\bar{\nu}_\tau$	CCRES ν_e	CCRES $\bar{\nu}_e$	CCRES ν_μ	CCRES $\bar{\nu}_\mu$	CCRES ν_τ	CCRES $\bar{\nu}_\tau$	NCEL all	NCRES all
FASERν2	57	50	570	355	1.9	1.6	170	183	1.6k	1.1k	5.4	5.1	170	1.3k
FLArE-10	43	40	425	260	2.0	1.6	120	140	1.2k	860	5.6	5.1	130	940
FLArE-100	325	290	3.3k	2k	20	15	930	980	9.2k	6.8k	54	50	980	6.5k

- CC quasi-elastic and CC resonant interactions
- NC elastic and NC resonant
- Cross sections do not increase with energy as DIS does, so overall small numbers

Background to light DM scattering with protons, e.g.,

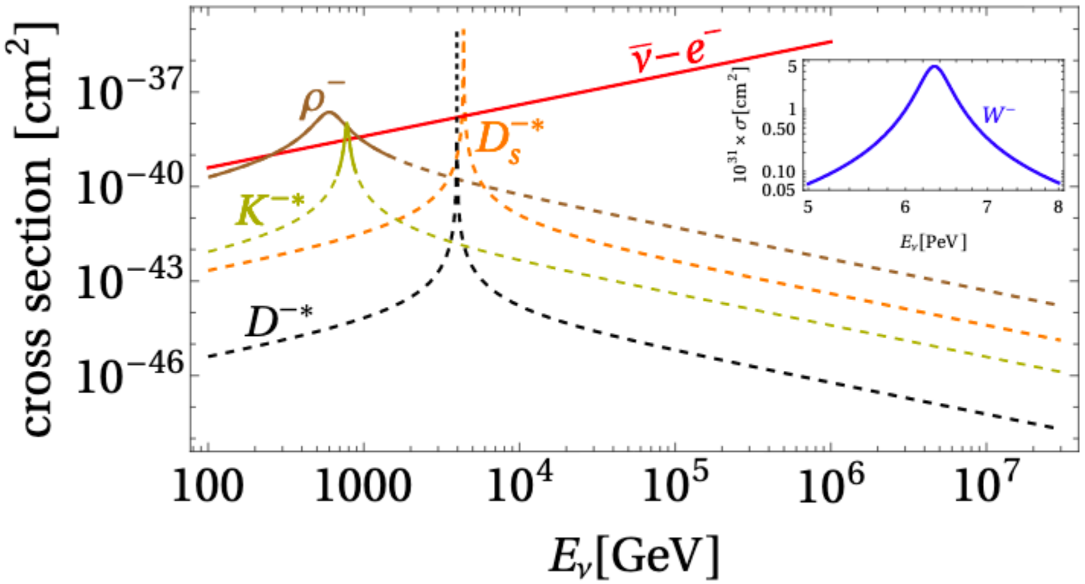
NC Elastic $\nu p \to \nu p$

NC Resonant $\nu p \to \Delta \to \nu \pi p,\ m_\Delta - m_p \sim 300\ \mathrm{GeV}$

See also, Batell et al., 2107.00666

$\bar{\nu}_e + e^-$ resonance scattering

Plestid and Brdar



Experiment	ρ^-, $\pm\Gamma/2$	ρ^-, $\pm2\Gamma$	K^{-*}, $\pm\Gamma/2$	K^{-*}, $\pm2\Gamma$
FASERν	0.3	0.5	–	–
FASERν2	23	37	0.7	3
FLArE-10	11	19	0.3	2
FLArE-100	63	103	2	8
DeepCore	3 (1)	5 (2)	–	–
IceCube	8 (40)	(17, 83)	–	–

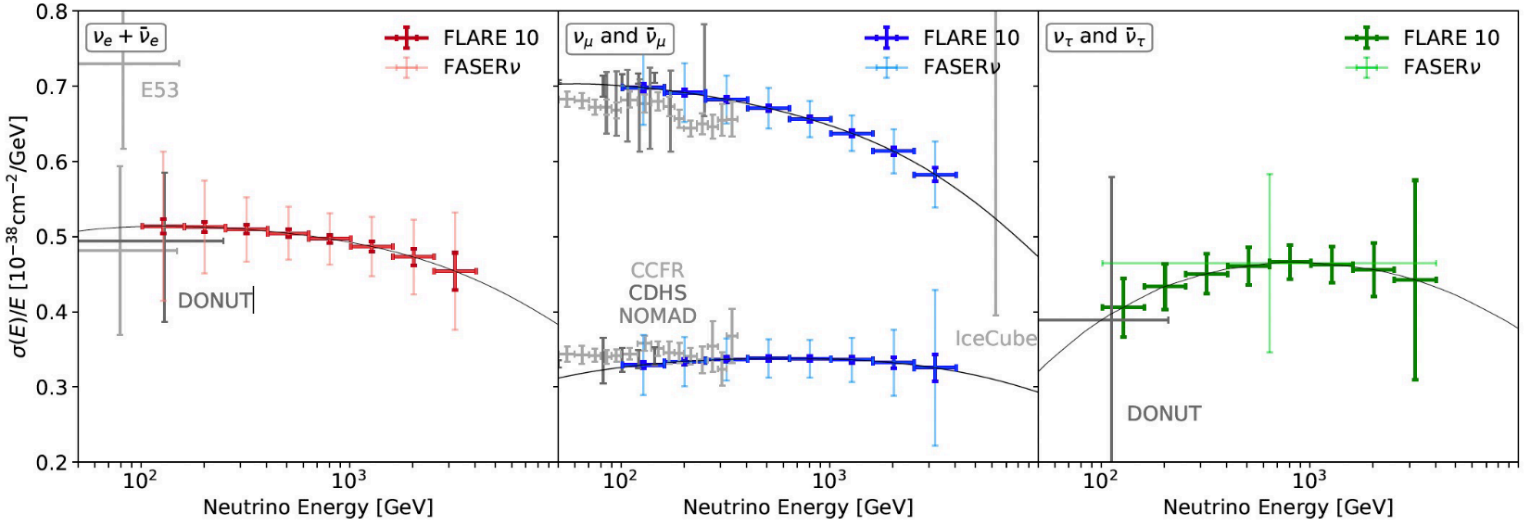
Rho at *E*=580 GeV $\rho^- \to \pi^-\pi^0$

- displaced vertices
- small pi-pi opening angle
- reconstruct invariant mass

See also: Brdar, de Gouvea, Machado & Plestid 2112.03283

Summary

- Flux predictions and corresponding uncertainties is an area of continued work.
- Neutrino cross section measurements are key physics goals, especially for tau neutrinos.
- Interesting standard model physics, backgrounds to BSM searches in subdominant processes.
- Strong ties to other topics discussed in this workshop.



Jianming Bian

Overleaf draft

As we have a complete draft:

Please add authorship with affiliation to the Neutrino Section.

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