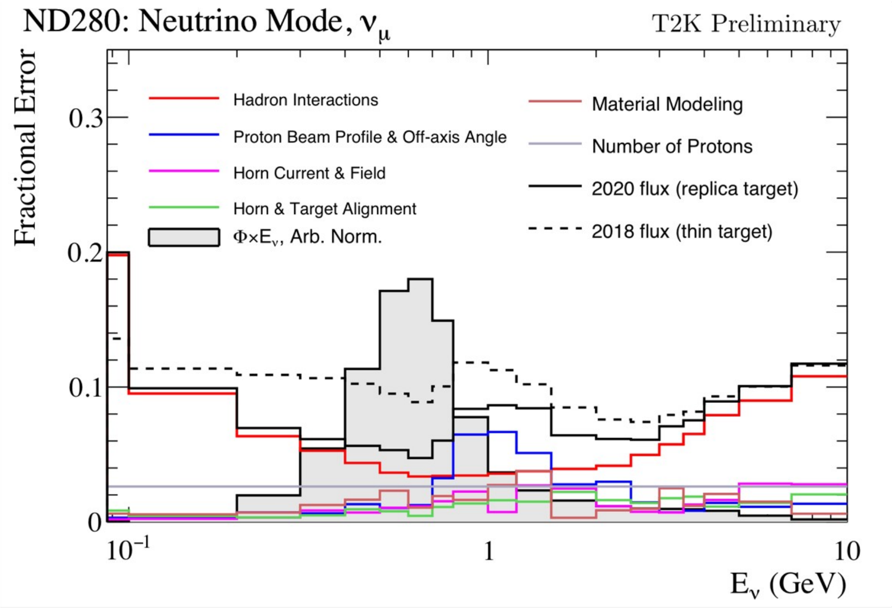
Physics at NuSTORM

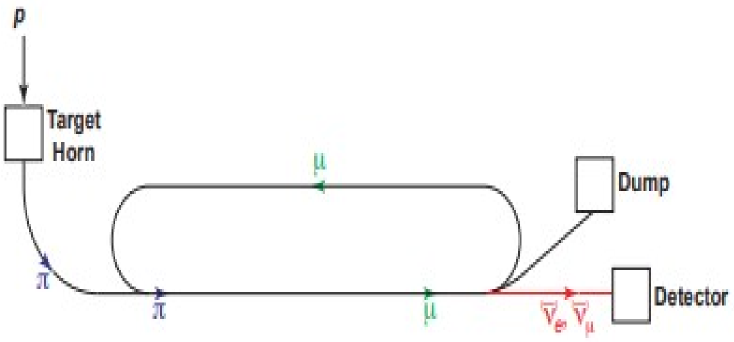
Steve Boyd / University of Warwick / 7 August 2020

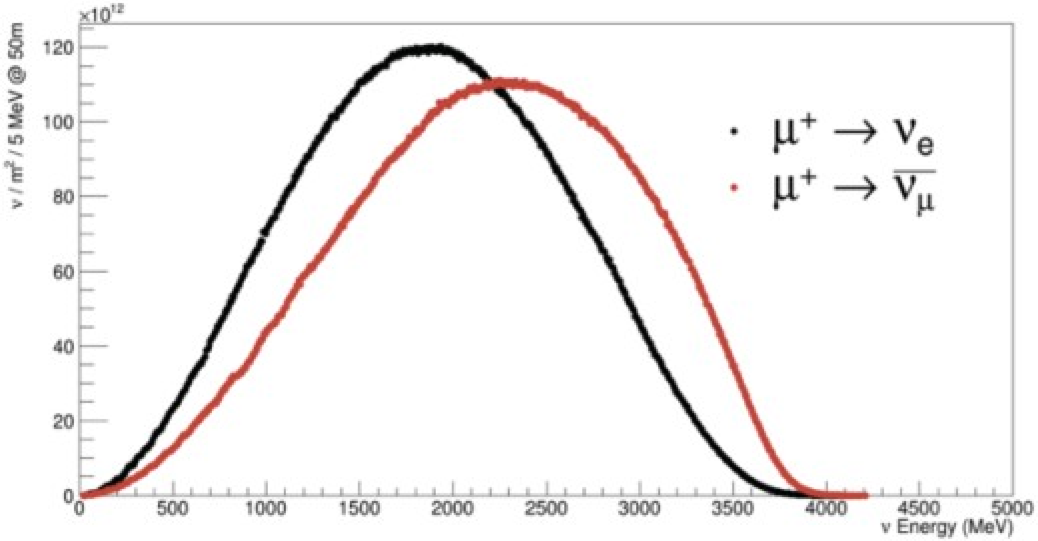
The problem with Neutrino Experiments

- Measurements at conventional neutrino experiments are hampered by
    - Lack of knowledge of absolute neutrino flux
    - Uncertainties in neutrino energy spectrum arising from hadronic physics in the primary proton-target interaction
    - Minimisation of non-ν_μ flavour components in the beam
- First two points mitigated by dedicated flux experiments (e.g. NA61/SHINE)



NuStorm





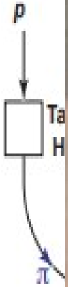
- Large neutrino flux in 0-6 GeV region
- Precisely known flux; both in absolute normalisation and energy spectrum
- Significant ν_μ/ν_e flavour composition with sign-tagging

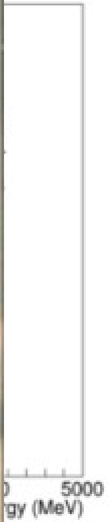
10^{21} POT on 100 ton LAr detector at 50 m

μ^+		μ^-	
Channel	N_{evts}	Channel	N_{evts}
$\bar{\nu}_\mu$ NC	1,174,710	$\bar{\nu}_e$ NC	1,002,240
ν_e NC	1,817,810	ν_μ NC	2,074,930
$\bar{\nu}_\mu$ CC	3,030,510	$\bar{\nu}_e$ CC	2,519,840
ν_e CC	5,188,050	ν_μ CC	6,060,580
π^+		π^-	
ν_μ NC	14,384,192	$\bar{\nu}_\mu$ NC	6,986,343
ν_μ CC	41,053,300	$\bar{\nu}_\mu$ CC	19,939,704

D. Adey, R. Bayes, A. Bross and P. Snopok, Ann.Rev.Nucl.Part.Sci 2015, 65:145-175

NuStorm





- La
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- Significant v_μ/v_e flavour composition with sign-tagging

n

			40
			30
			40
ν_e CC	5,188,050	ν_μ CC	6,060,580
π^+		π^-	
ν_μ NC	14,384,192	$\bar{\nu}_\mu$ NC	6,986,343
ν_μ CC	41,053,300	$\bar{\nu}_\mu$ CC	19,939,704

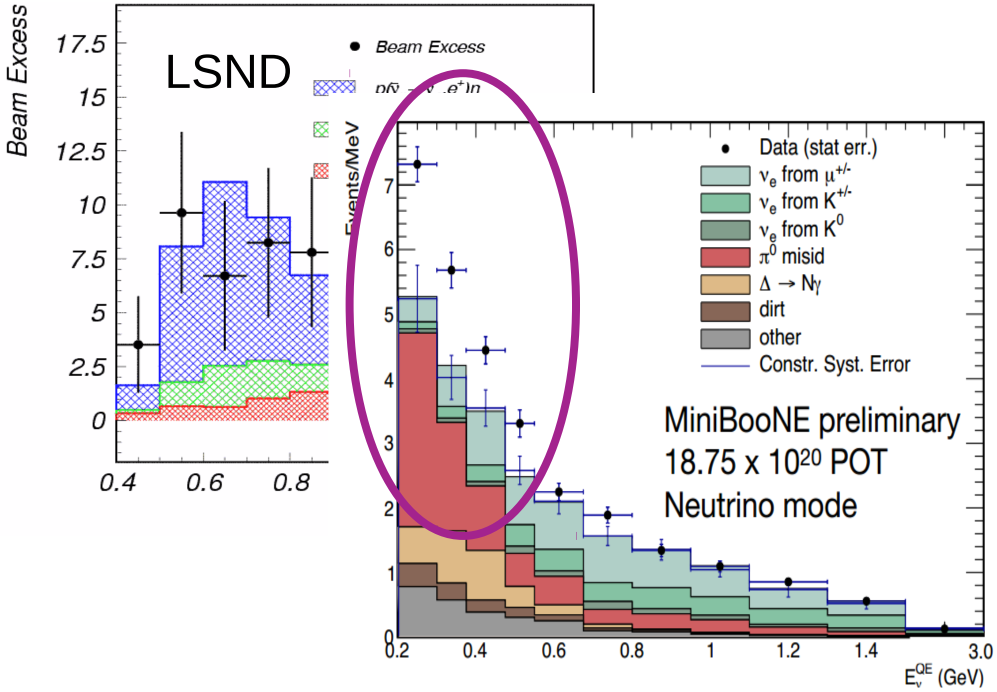
R. Bayes

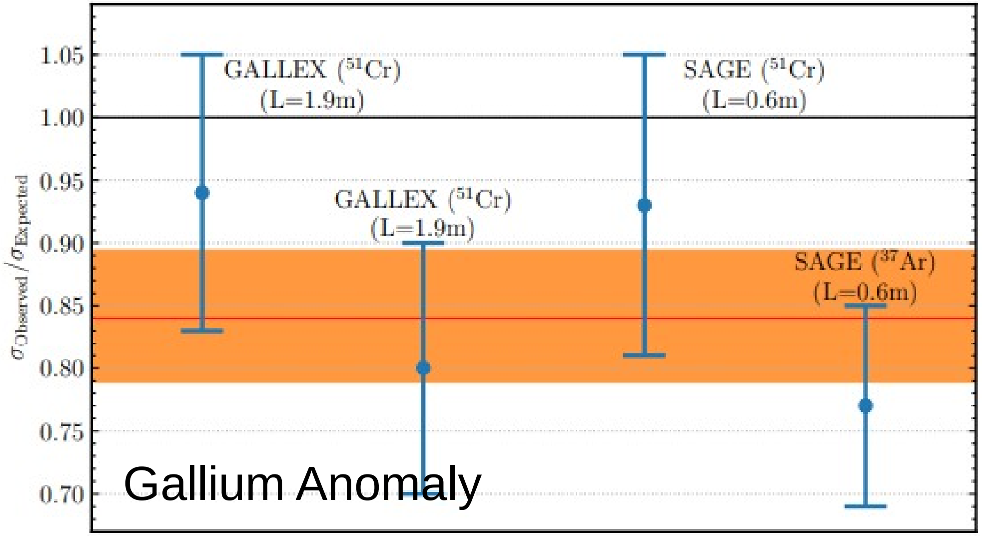
Physics Motivation

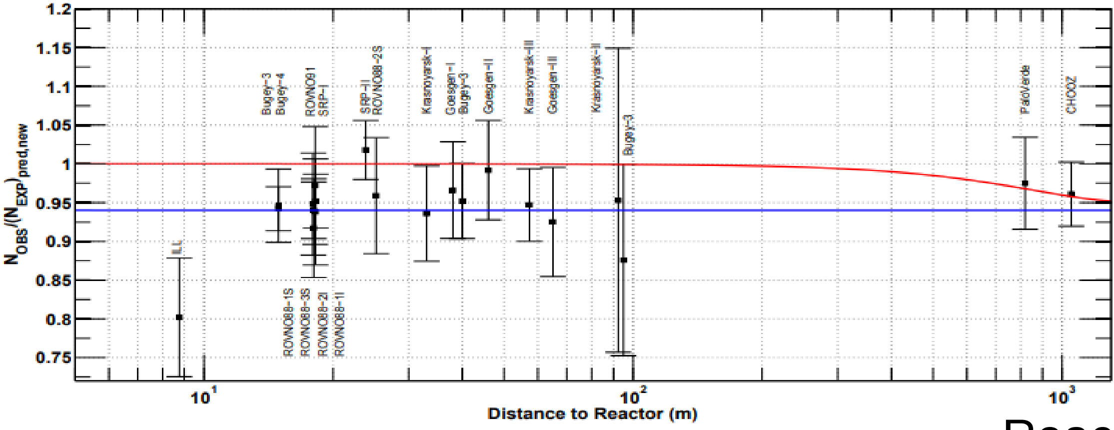
- Light sterile neutrino problem/opportunity
- BSM searches through flux distortion effects
- Neutrino cross sections in the 0 – 5 GeV regime
- Synergies with muon collider R&D program

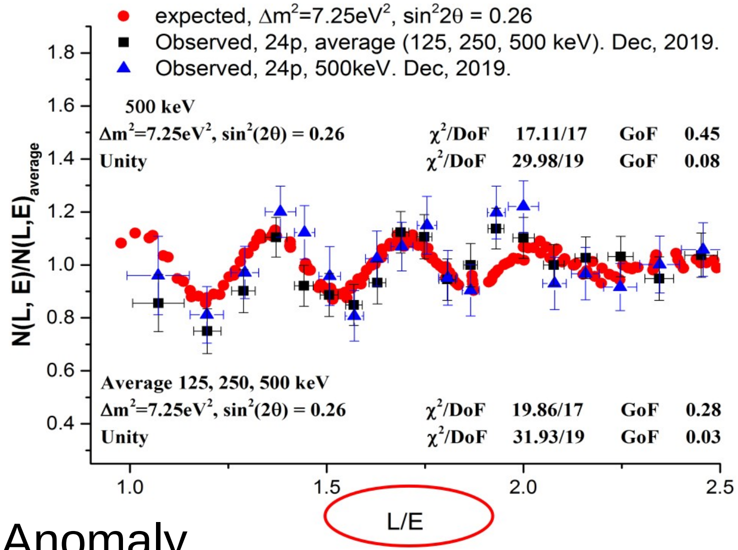
Light Sterile Neutrinos

Light Sterile Neutrinos









Reactor Anomaly

ν_μ disappearance

MiniBooNE, ICECUBE,SK
MINOS/MINOS+,NOVA

NO anomaly observed

ν_e disappearance

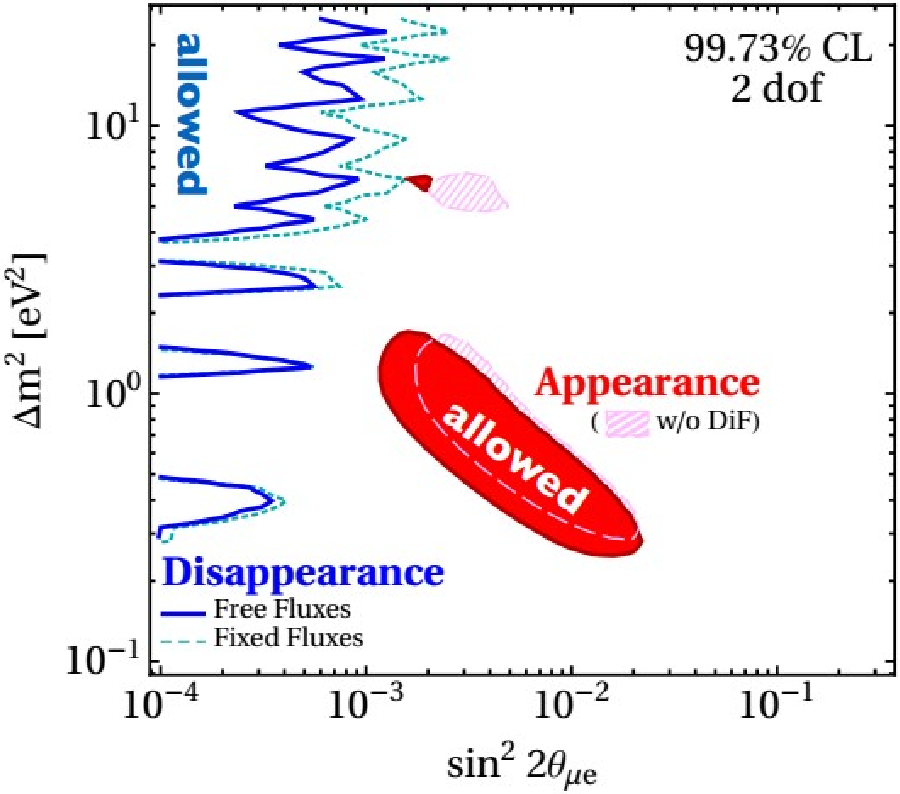
Reactor experiments,
Source experiments,
Solar and atmospheric experiments

3σ anomaly dominated by DANSS/NEO
BUT
Reactor best fit point is inconsistent
with global best fit point

$\nu_\mu - \nu_e$ appearance

LSND, MiniBooNE, NOMAD,
KARMEN, ICARUS, OPERA

5σ anomaly dominated by LSND

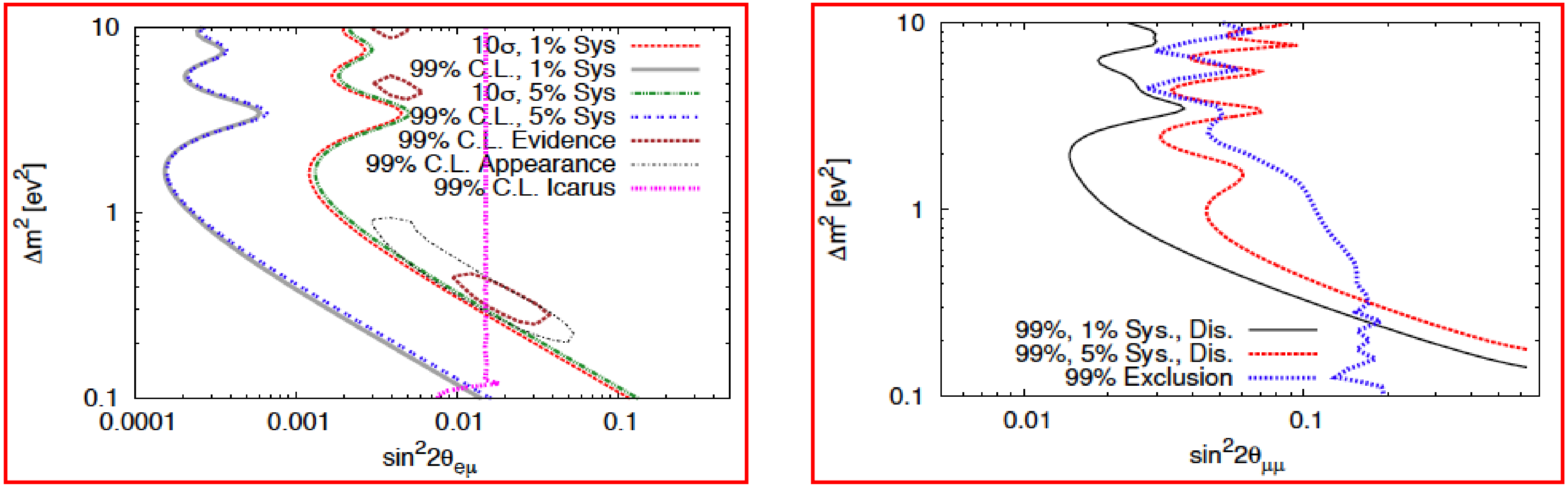


Significant tension between disappearance and appearance experiments (3+1 model)

In context

- Hints of new physics in the lepton sector from appearance and disappearance oscillation experiments – interpreted as eV-scale sterile neutrino signal
- Data does not fit into a simple 3+1 model.

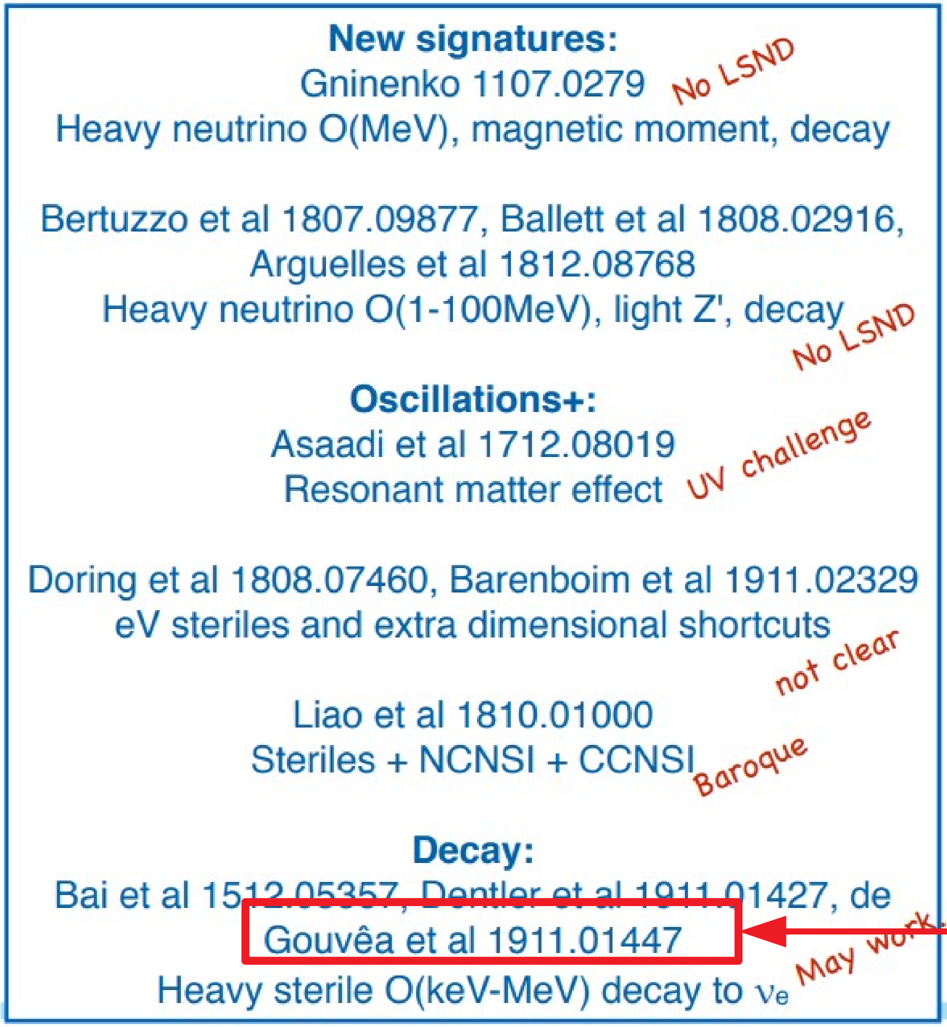
- Next data from the Fermilab Short Baseline Program



Adey et al., PRD 89 (2014) 07130

- NuStorm could provide precision measurements, or make the best limits, on light sterile neutrino production after SBND

Non-Standard Interactions



New signatures:
Gninenko 1107.0279
No LSND
Heavy neutrino O(MeV), magnetic moment, decay

Bertuzzo et al 1807.09877, Ballett et al 1808.02916,
Arguelles et al 1812.08768
Heavy neutrino O(1-100MeV), light Z', decay
No LSND

Oscillations+:
Asaadi et al 1712.08019
Resonant matter effect
UV challenge

Doring et al 1808.07460, Barenboim et al 1911.02329
eV steriles and extra dimensional shortcuts
not clear

Liao et al 1810.01000
Steriles + NCNSI + CCNSI
Baroque

Decay:
Bai et al 1512.05357, Dentler et al 1911.01427, de
Gouvêa et al 1911.01447
Heavy sterile O(keV-MeV) decay to ν_e
May work..

Pedro A. N. Machado, Neutrino 2020

- Other possibilities for the sterile "signal"
- Models present different modifications of the neutrino flux with L and/or E

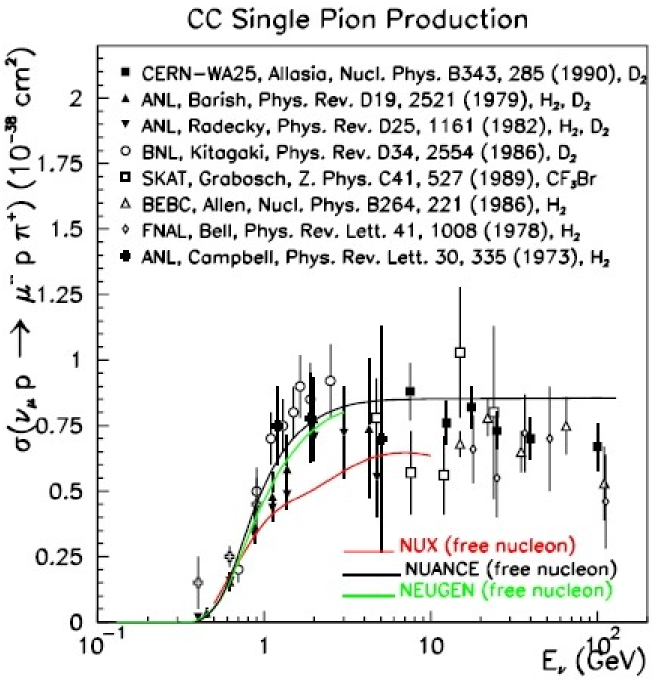
$$P_{\mu\mu} = (1 - U^2_{\mu 4})^2 + (U^2_{\mu 4})^2 e^{-\Gamma L}$$

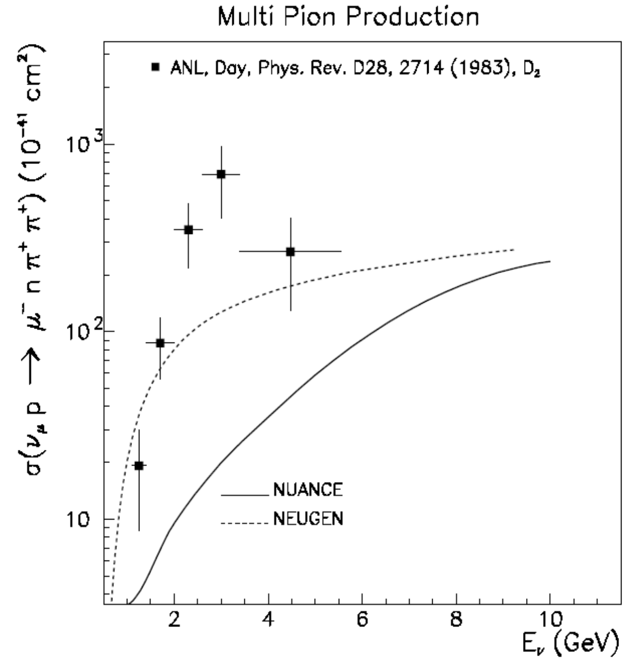
$$P_{\mu e} = (U^2_{\mu 4})(1 - e^{-\Gamma L})$$

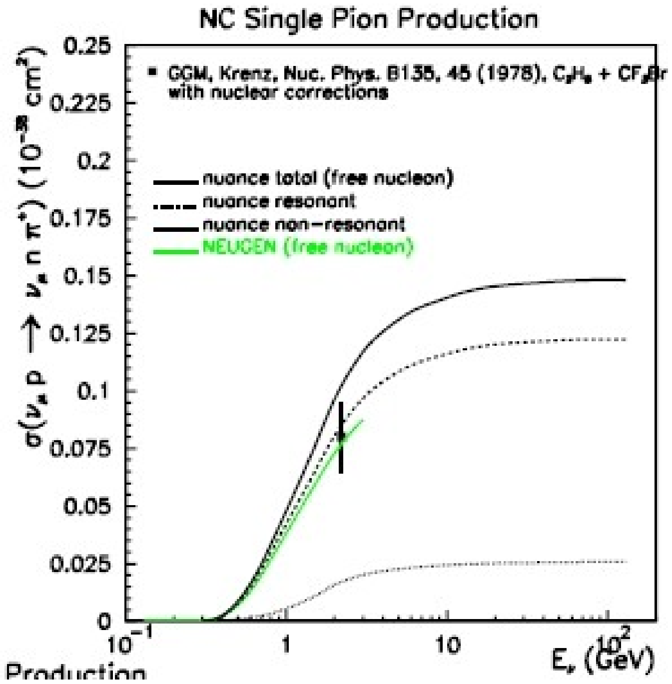
- Precision knowledge of the flux can help test all of these, or more generic, NSI models

Neutrino cross-sections

ν_μ xsec circa-2007





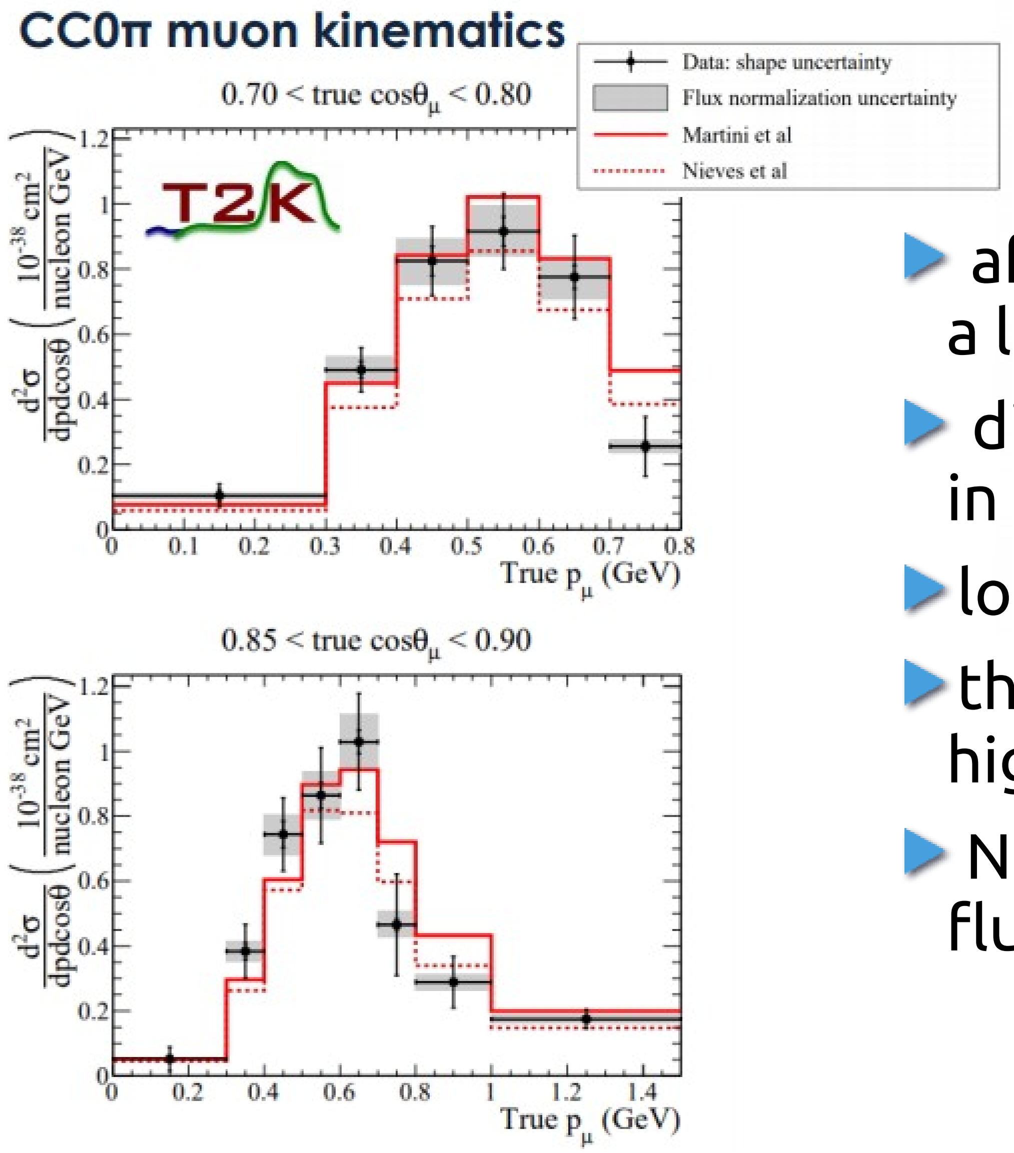


$$\nu_\mu p \rightarrow \mu^- p \pi^+ \qquad \nu_\mu p \rightarrow \mu^- n \pi^+ \pi^+ \qquad \nu_\mu p \rightarrow \nu_\mu n \pi^+$$

- Initial state effects
- Final state effects
- Secondary interactions

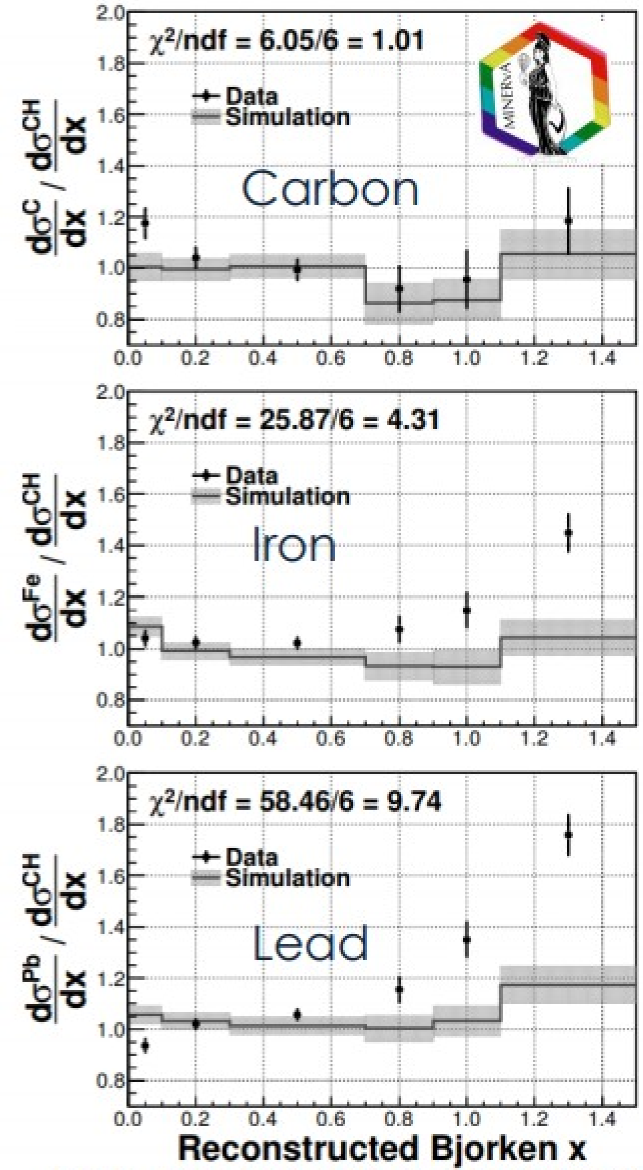
Also not understood

ν_μ xsec circa-now



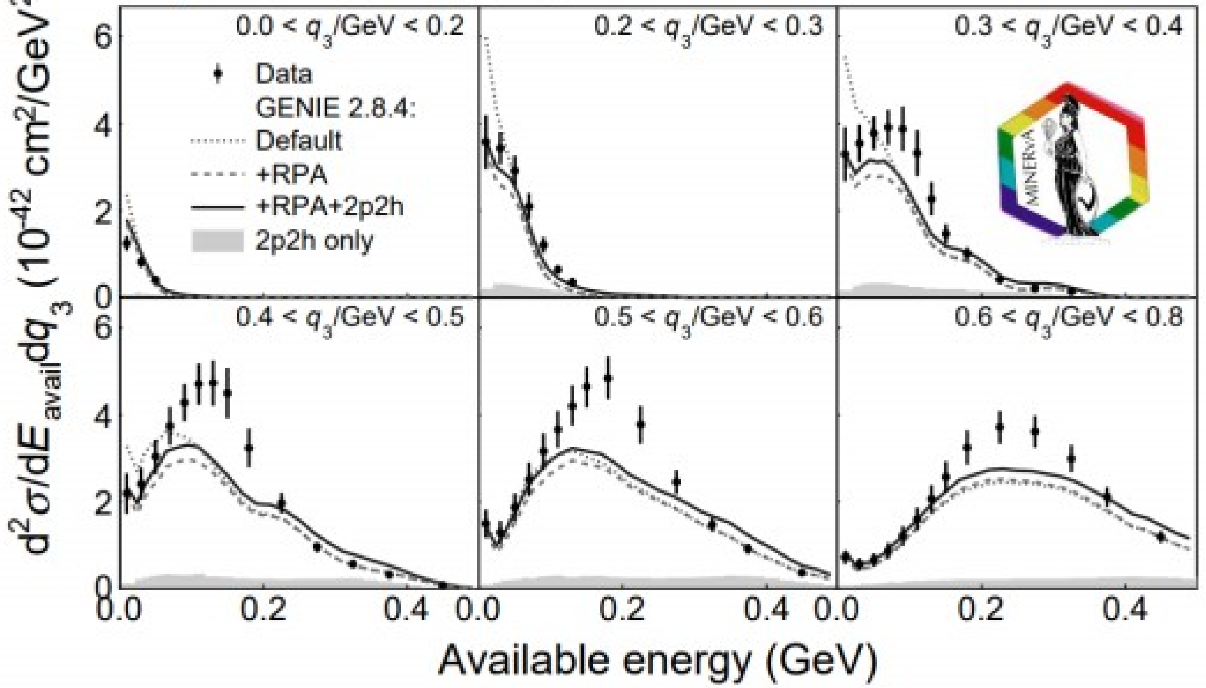
- after 10 years of work and a lot more data
- differential cross sections in primary lepton variables
- look sort of OK
- there are issues at both high and low q^2
- Note contribution of the flux uncertainty

ν_μ xsec circa-now



Phys. Rev. Lett. **112**, 231801 (2014)

Phys. Rev. Lett. **116**, 071802



- Hadronic kinematics are not well modelled
- Nuclear effects on heavy targets are not well modelled

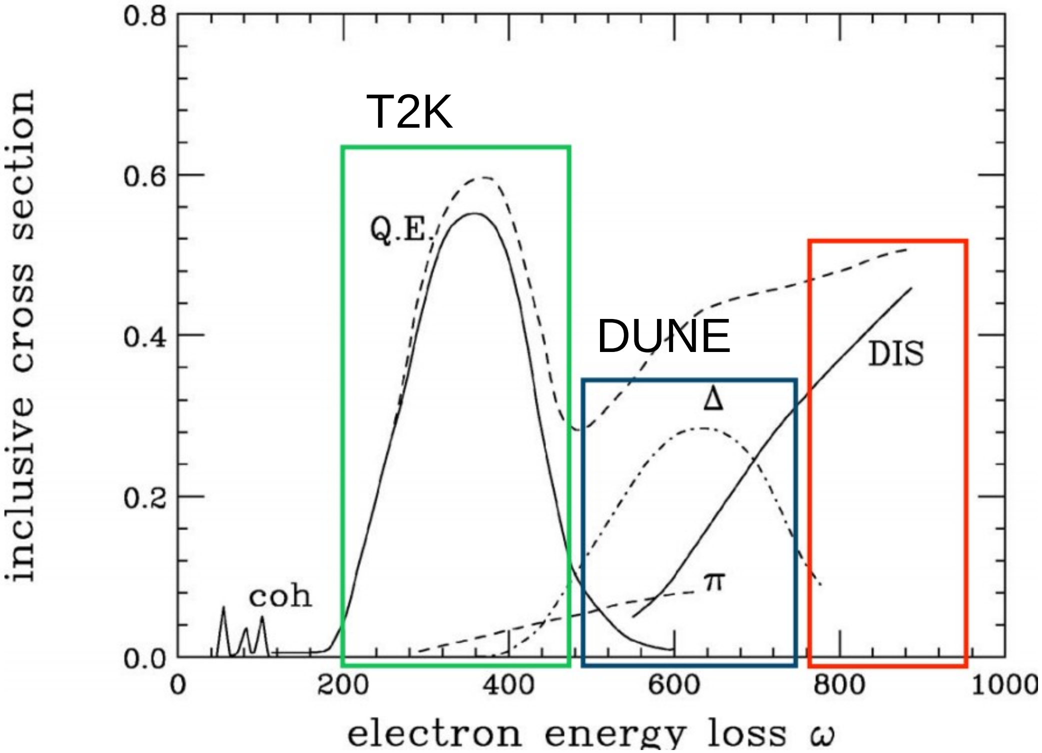
- We’re getting a better idea of what we don’t know

Nuclear physics

- Modelling of n-A interactions at a few GeV involves impulse approximation, but also multi-body physics:
    - short range correlations (SRC) (many-body correlations)
    - random phase approximation (RPA) effects (dressed propagator)
    - initial state models (FG vs RFG vs local RFG vs SF vs SUSAv2)
    - hadronisation and cascade models in the final state

- An opportunity if you are interested in understand nuclei

- Electron scattering experiments have been doing this for years : limited to vector current and scattering off the nuclear surface
- Neutrinos provide orthogonal information : scattering via the axial vector current and scattering within the nuclear volume
- Scope for engaging the nuclear and electron scattering community



Impact on oscillations

- Next generation oscillation experiments aim for a precision on oscillation parameters an order of magnitude lower than that achieved by current experiments

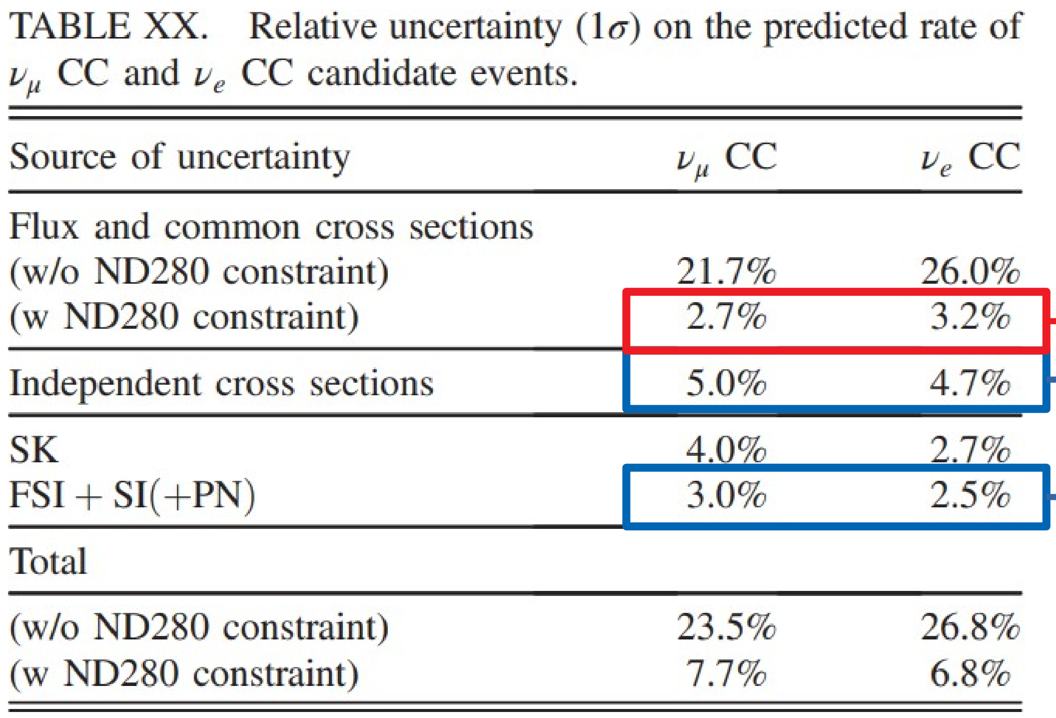


TABLE XX. Relative uncertainty (1σ) on the predicted rate of ν_μ CC and ν_e CC candidate events.

Source of uncertainty	ν_μ CC	ν_e CC
Flux and common cross sections		
(w/o ND280 constraint)	21.7%	26.0%
(w ND280 constraint)	2.7%	3.2%
Independent cross sections	5.0%	4.7%
SK	4.0%	2.7%
FSI + SI(+PN)	3.0%	2.5%
Total		
(w/o ND280 constraint)	23.5%	26.8%
(w ND280 constraint)	7.7%	6.8%

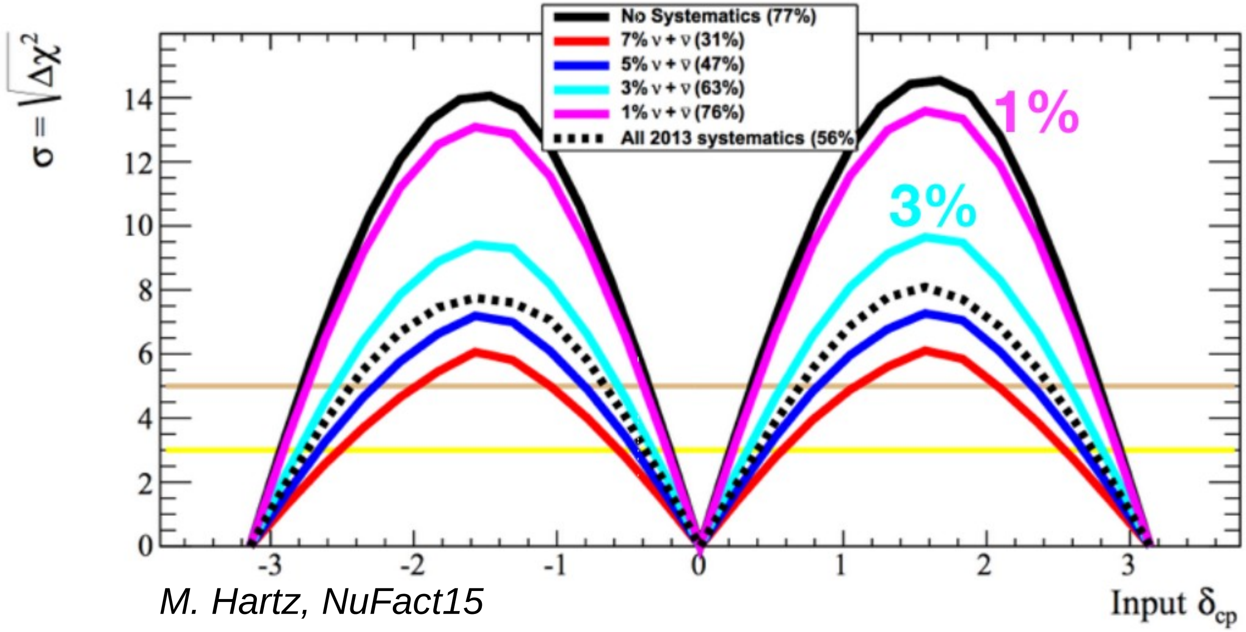
near detector constrained

Includes nuclear effects and FSI/SI and photonuclear uncertainties

Phys. Rev. D 91, 072010 (2015)

ν_e cross section

- There are very few measurements of any ν_e cross section at a few GeV
- Prediction of ν_e rate in oscillation experiments needs $\sigma(\nu_e)/\sigma(\nu_\mu)$



M. Hartz, NuFact15

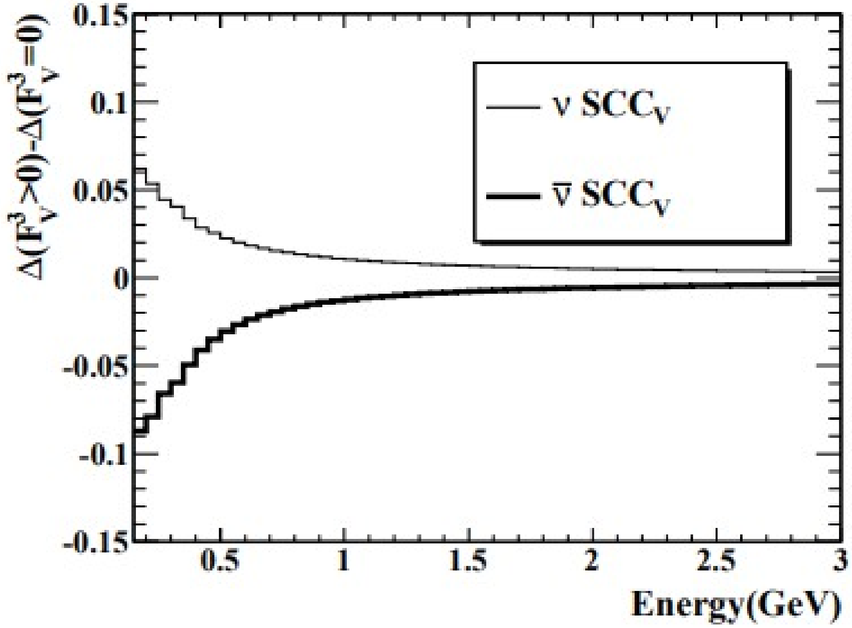
Effect of ν_e / anti-ν_e uncorrelated normalisation uncertainties

- Goal : Control ν_e systematic to 1% level

ν_e cross section

- There are very few measurements of any ν_e cross section at a few GeV
- Prediction of ν_e rate in oscillation experiments needs $\sigma(\nu_e)/\sigma(\nu_\mu)$
- CCQE : ν_e cross section can differ from ν_μ due to mass thresholds, phase space differences, unmeasured form factors, second class currents, radiative corrections,...
- RES : noone knows…..

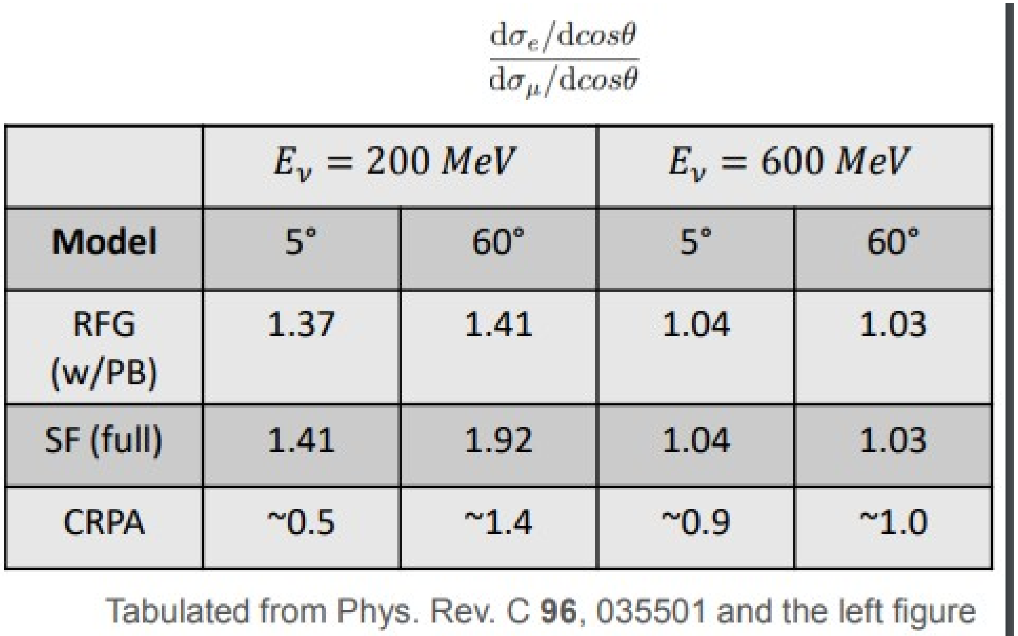
Day & McFarland, Phys Rev D86, 053003



1% - 5% effect on difference between muon and electron CCQE cross sections due to inclusion of second class currents

ν_e cross section

- There are very few measurements of any ν_e cross section at a few GeV
- Prediction of ν_e rate in oscillation experiments needs $\sigma(\nu_e)/\sigma(\nu_\mu)$
- Even the nuclear models make a difference.
- Different models predict different ratios at different points in phase space.



$$\frac{d\sigma_e/d\cos\theta}{d\sigma_\mu/d\cos\theta}$$

	$E_\nu = 200\ MeV$		$E_\nu = 600\ MeV$	
Model	5°	60°	5°	60°
RFG (w/PB)	1.37	1.41	1.04	1.03
SF (full)	1.41	1.92	1.04	1.03
CRPA	~0.5	~1.4	~0.9	~1.0

Tabulated from Phys. Rev. C **96**, 035501 and the left figure

NuSTORM is the only facility which can do the precision $\sigma(\nu_e)/\sigma(\nu_\mu)$ measurements needed for the next-gen (& next-next-gen?) long baseline experiments

ν_e cross section

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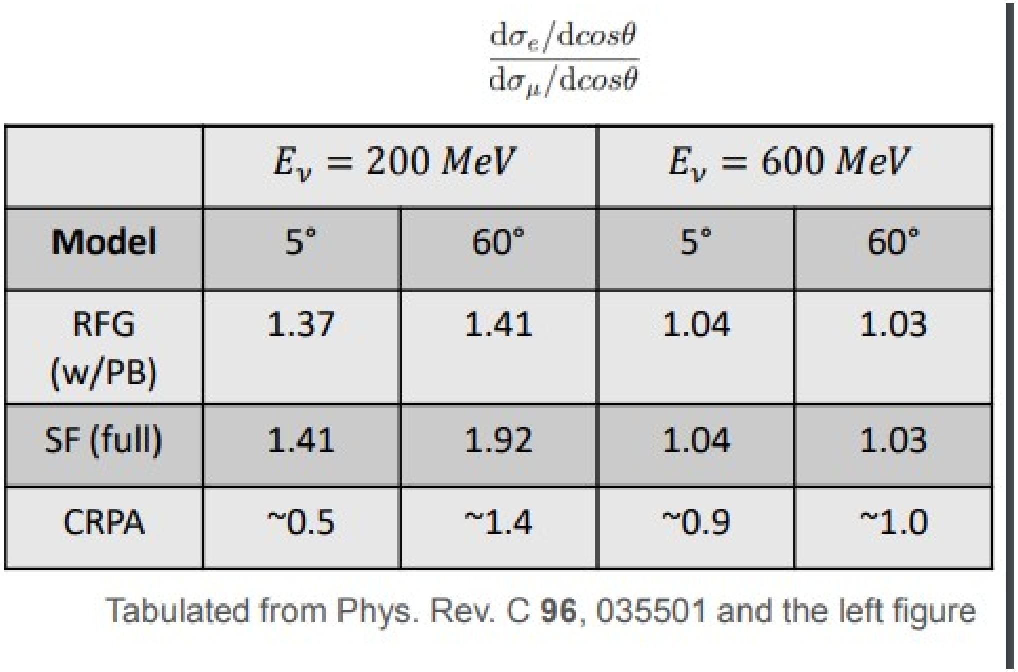

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Facility needs the right detector or detector complex for full exploitation – see Neil McCauley’s talk next!

Muon collider R&D

NuSTORM offers an R&D testbed for technologies needed for a muon collider including

- High power target and pion capture
- Large aperture ring
- Extending MICE 4D cooling demonstrator to 6D cooling
- Storage ring instrumentation

- See talks by Jaroslaw Pasternak, Jean-Baptiste Lagrange and Shinji Machida for information on the beam from people who actually know what they are talking about

Summary

- The unique precision of the neutrino flux, the flavour composition and the neutrino intensity make NuSTORM an exciting opportunity for neutrino physics
  - permits very sensitive sterile neutrino and BSM searches
  - percent level precision on muon and *electron* neutrino cross section measurements
- NuSTORM provides a muon accelerator technology testbed and proof-of-principle for the use of stored muons for particle physics