



29 March, 2023

Radiative corrections for precise low- and high-energy (anti)neutrino flux constraints



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LA-UR-23-22298

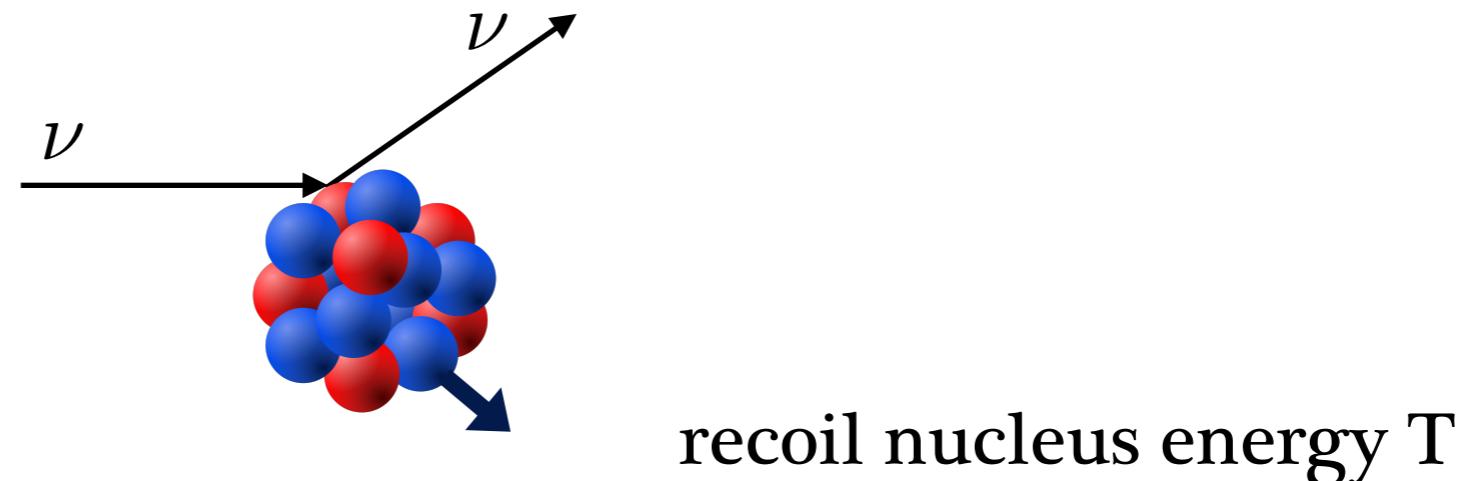
Outline

- 1) (Anti)neutrino energy spectra from muon,
pion, and kaon decays

- 2) Radiative corrections to inverse muon decay

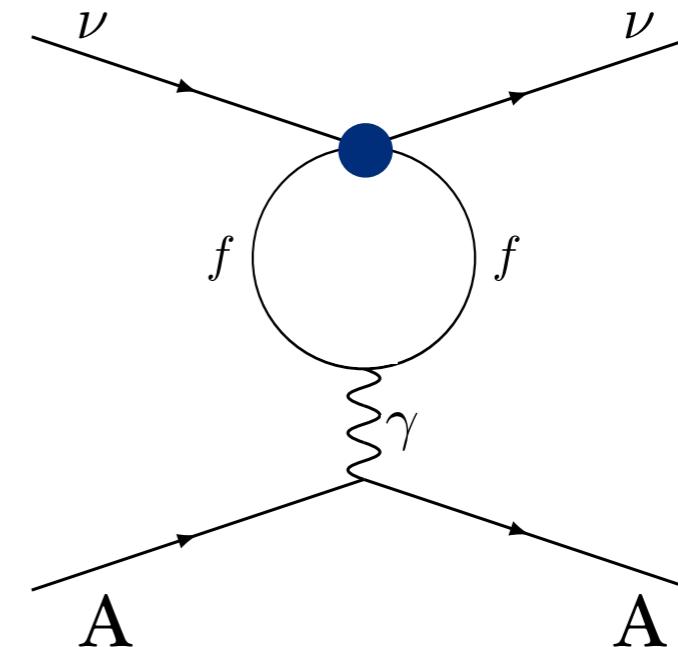
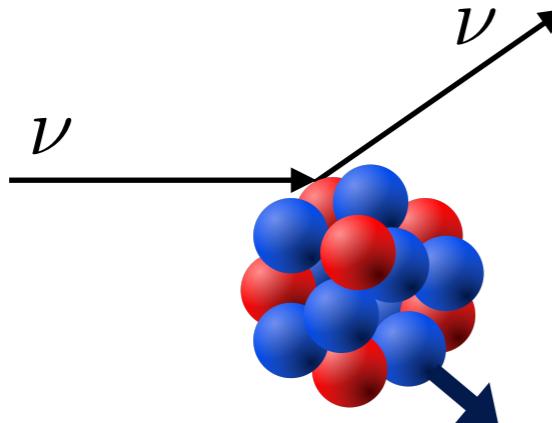
Coherent elastic neutrino-nucleus scattering

- at low neutrino energies (<50 MeV) nuclear state is unchanged
nucleus recoils as a whole
Stodolsky (1966), Freedman (1974), Kopeliovich and Frankfurt (1974)



- large cross section scales as squared number of neutrons N^2
$$\frac{d\sigma}{dT} \approx \frac{G_F^2 M_A}{4\pi} \left(1 - \frac{M_A T}{2E_\nu^2}\right) \left(N - (1 - 4\sin^2\theta_W) Z\right)^2$$
- first detection in 2017 at SNS, measured on CsI and Ar
COHERENT, Science 357 (2017) 6356, 1123-1126
- rapidly developing field nowadays

- CEvNS enters precision era with π DAR sources

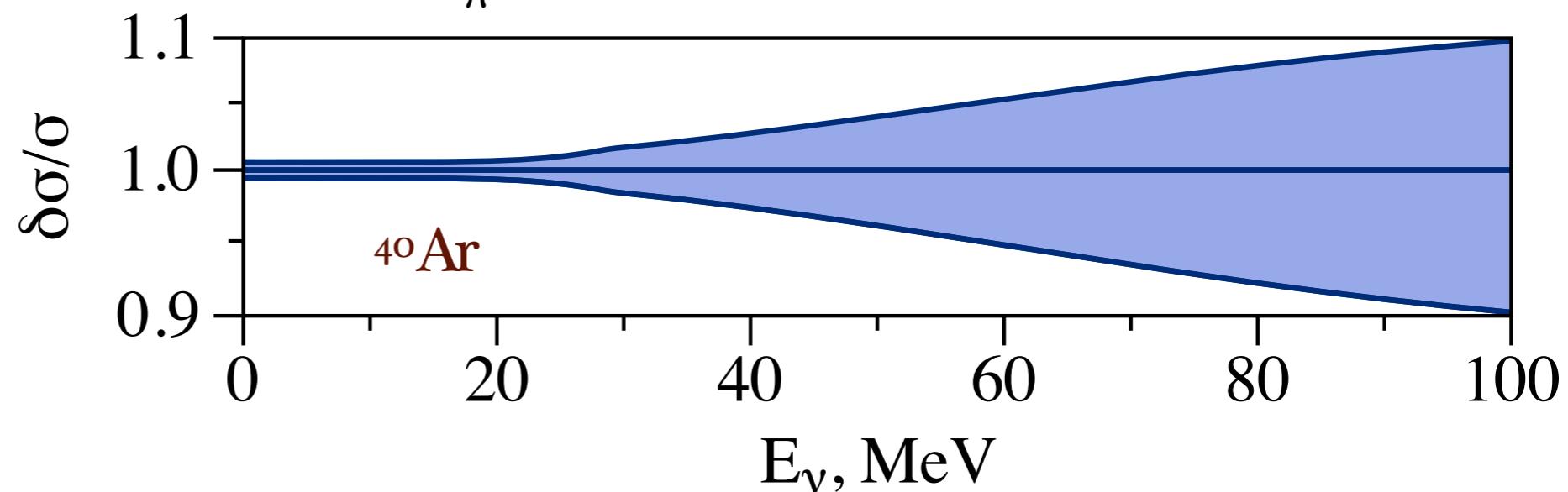


Coherent elastic neutrino-nucleus scattering

O.T., Pedro Machado, Vishvas Pandey and Ryan Plestid, JHEP 2102, 097 (2021)

$$F_W(Q^2) \rightarrow F_W(Q^2) + \frac{\alpha}{\pi} [\delta^{\nu_\ell} + \delta^{\text{QCD}}] F_{\text{ch}}(Q^2)$$

flavor-dependent
at percent level
for Coherent and CCM



Artificial neutrinos: accelerator

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$K^+ \rightarrow \mu^+ \nu_\mu$$

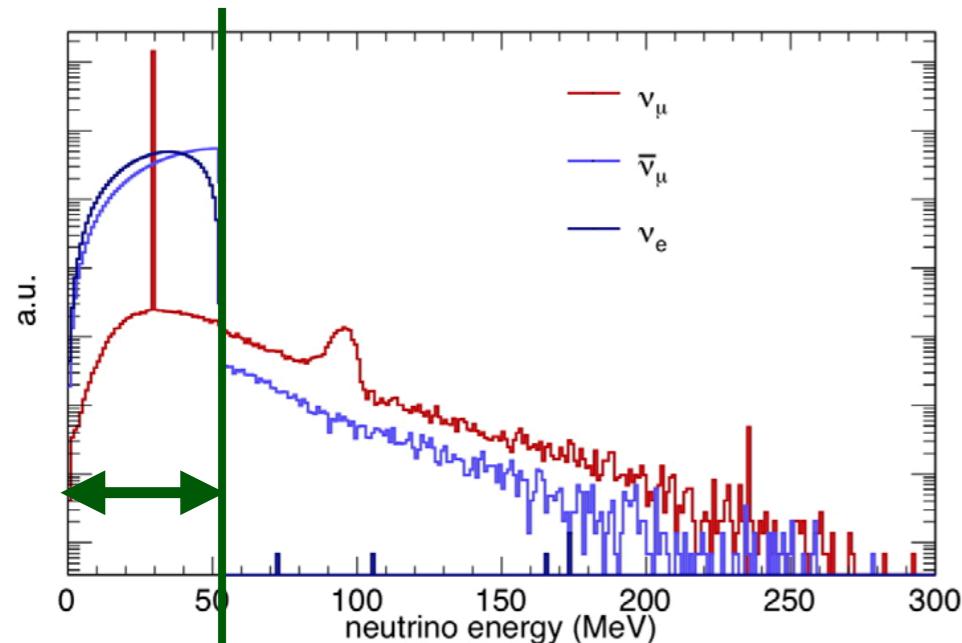
$$K^+ \rightarrow \pi^0 e^+ \nu_e$$

$$K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$$

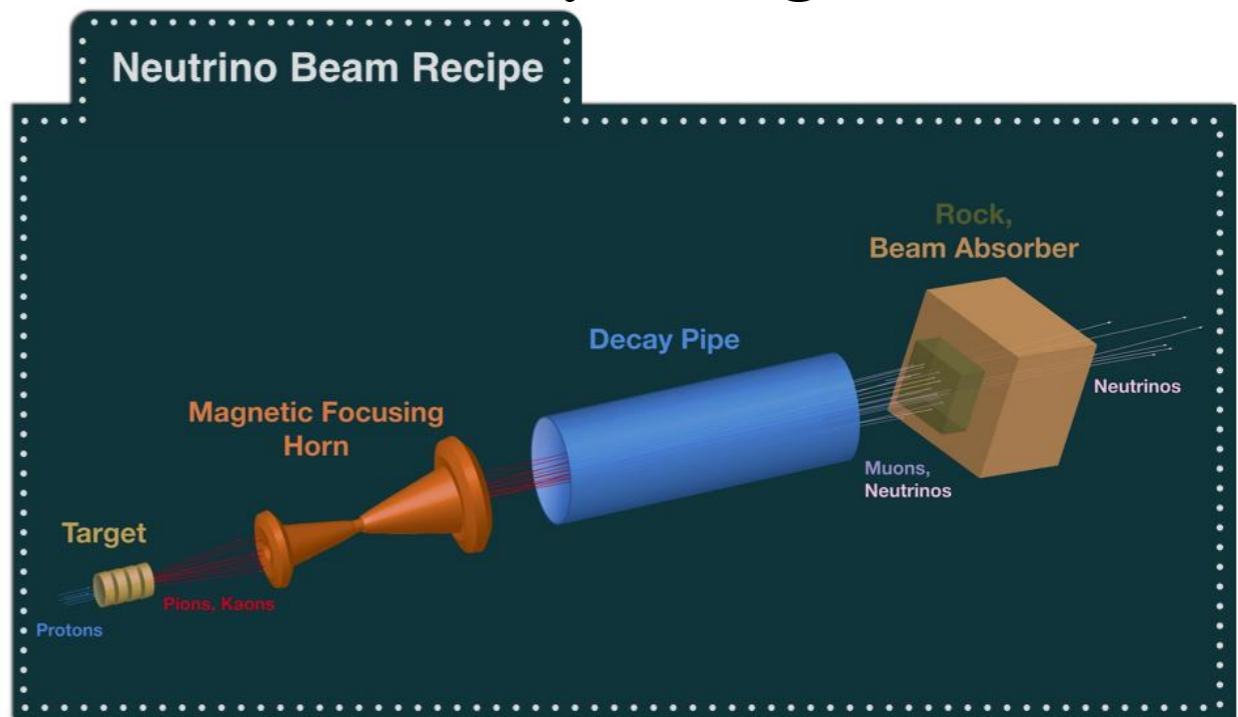
$$K_L^0 \rightarrow \pi^\pm e^\mp \nu_e$$

$$K_L^0 \rightarrow \pi^\pm \mu^\mp \nu_\mu$$

decay at rest



decay in flight



Akimov et al., Science 357 6356, 1123-1126 (2017)

Coherent and CCM

meson decay: monochromatic line

www.fnal.gov

T2K, NOvA, MiniBooNE, MicroBooNE

MINERvA, MINOS, NuTeV

SBN, DUNE, HyperK, ESSnuSB

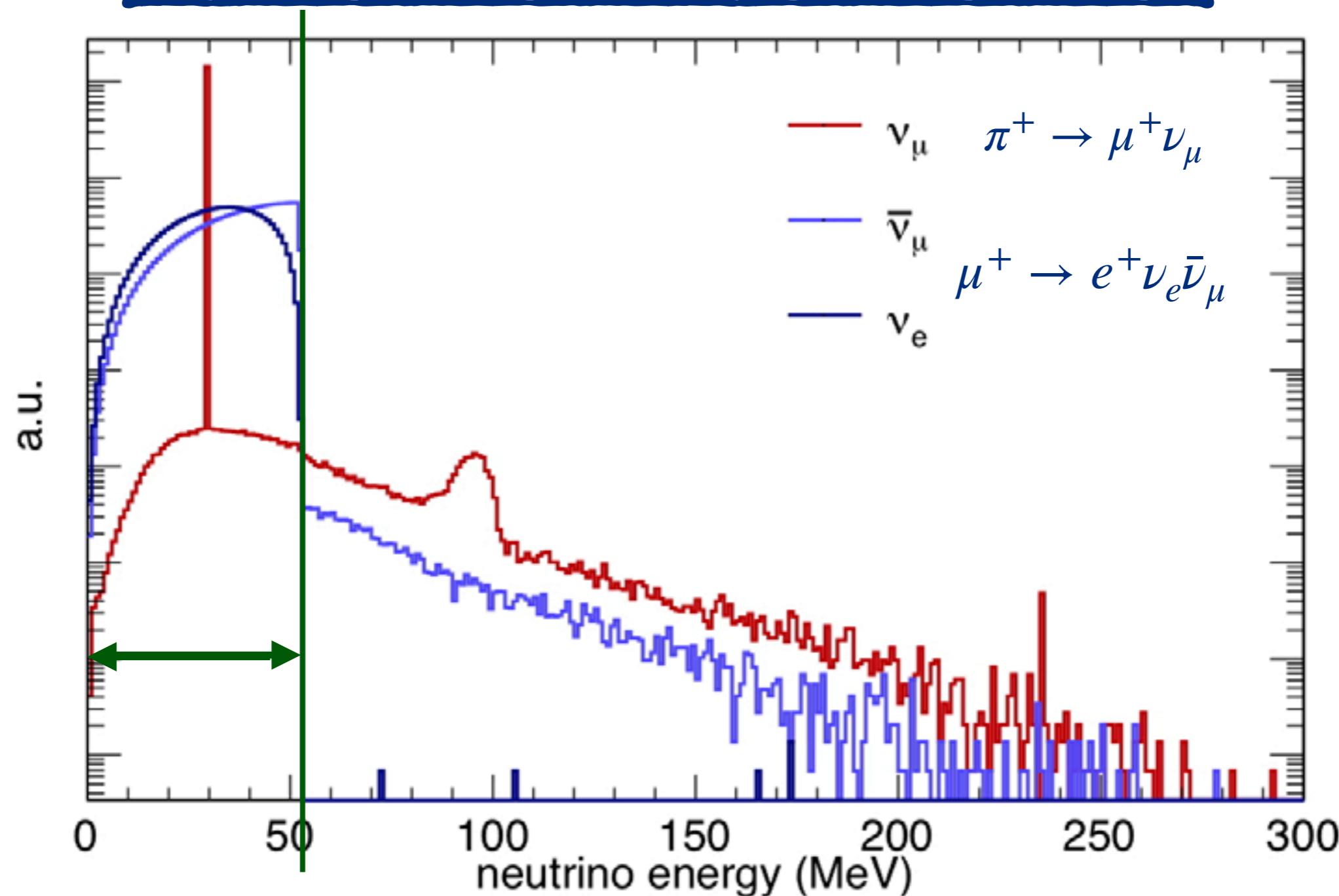
- ν s from decay of light mesons and muons; ν STORM and ENUBET



(Anti)neutrino energy spectra from muon, pion and kaon decays

O.T., Phys. Lett. B 829, 137108 (2022)

π DAR spectrum at tree level

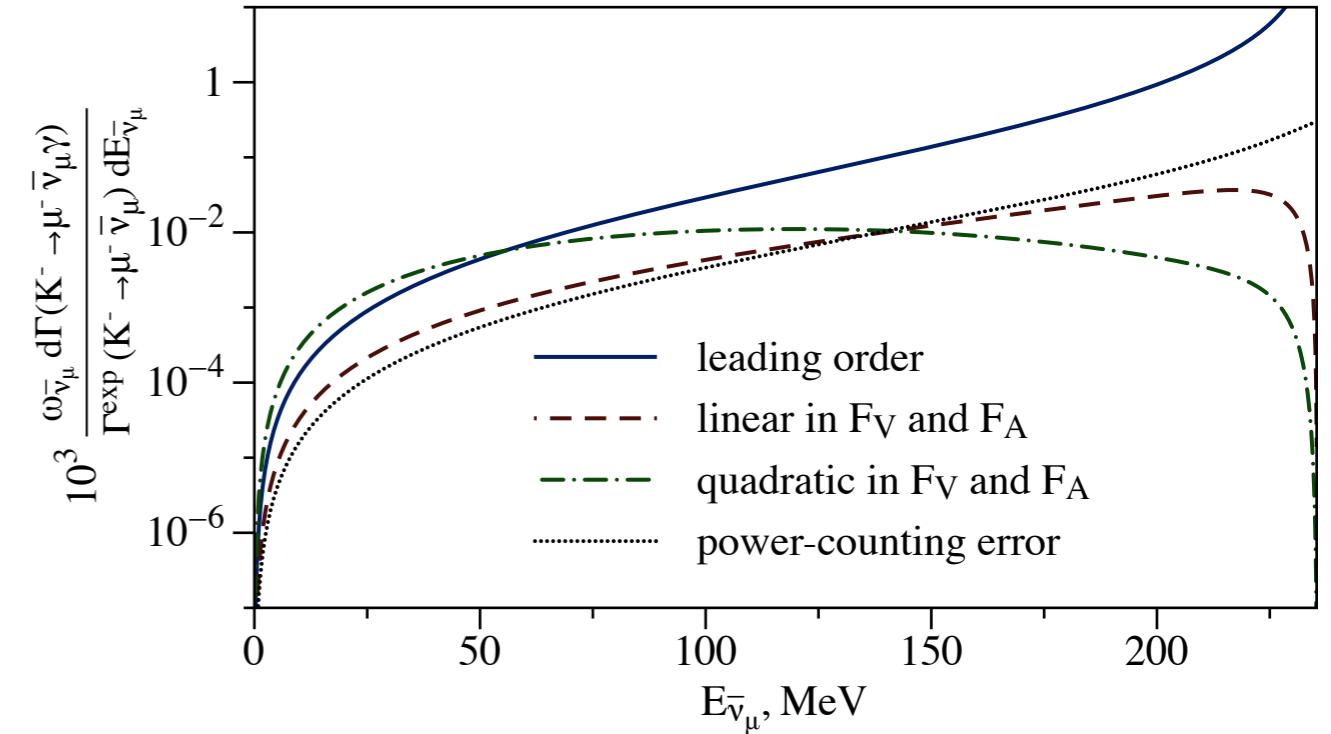
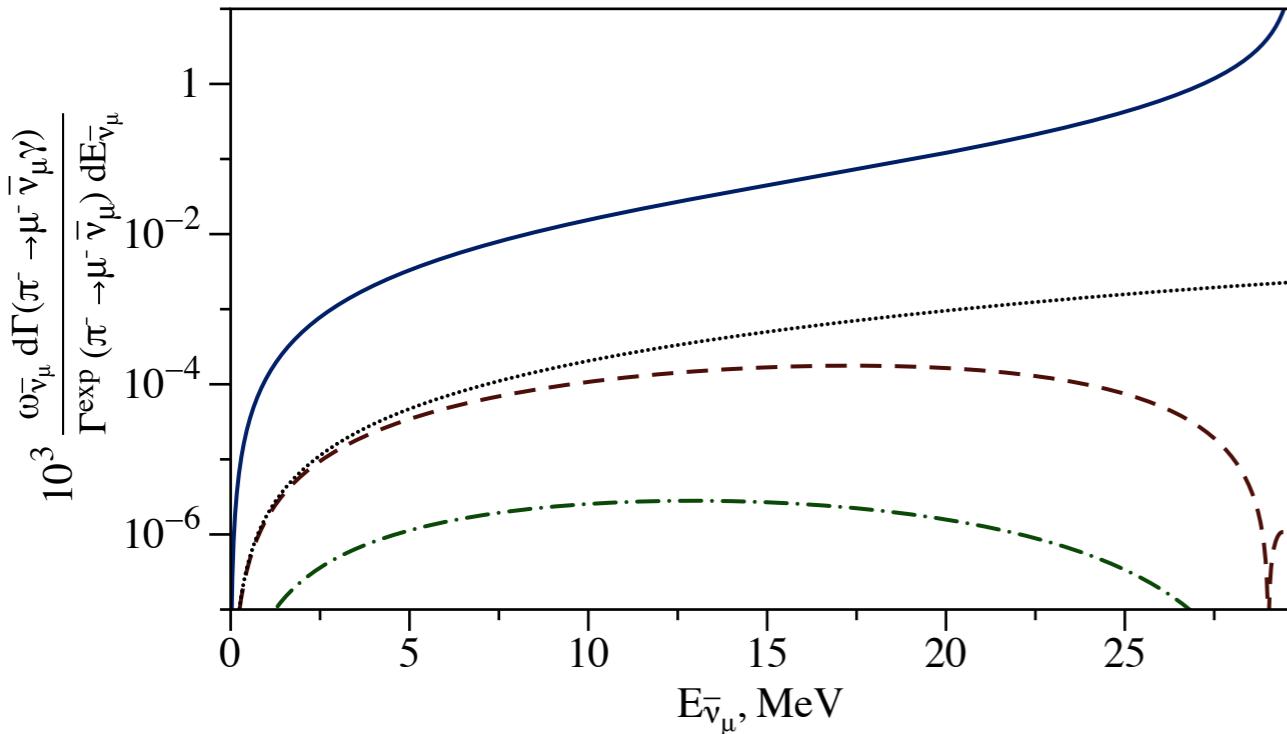


Akimov et al., Science 357 6356, 1123-1126 (2017)

- flavor-dependent spectrum at tree level with prompt ν_μ line

Radiative corrections to decay of mesons

- broadening of monochromatic line with elastic peak



- analytic spectra presented
- negligible change in flux-averaged cross sections due to distortion

$$\sigma_{\bar{\nu}_\mu}^{^{40}\text{Ar}} = (15.1867 \pm 0.25) \times 10^{-40} \text{ cm}^2$$

$$\sigma_{\bar{\nu}_\mu, \text{LO}}^{^{40}\text{Ar}} = (15.1875 \pm 0.25) \times 10^{-40} \text{ cm}^2$$

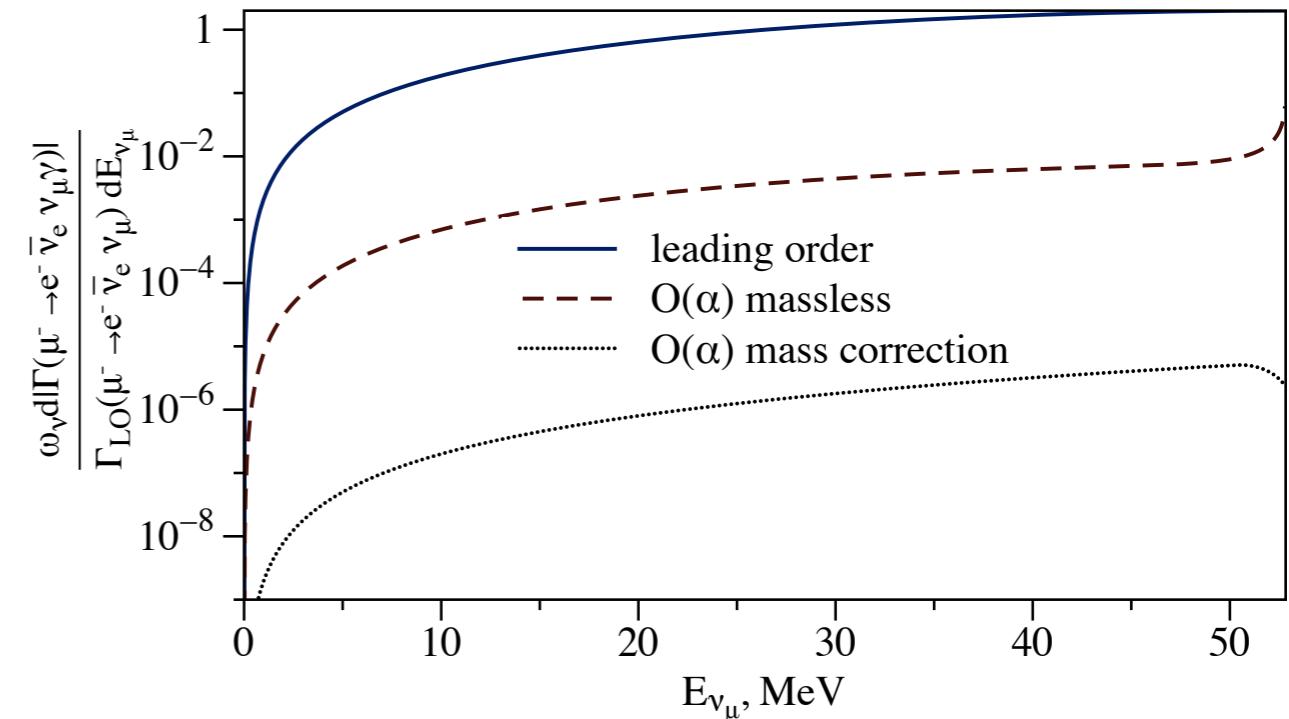
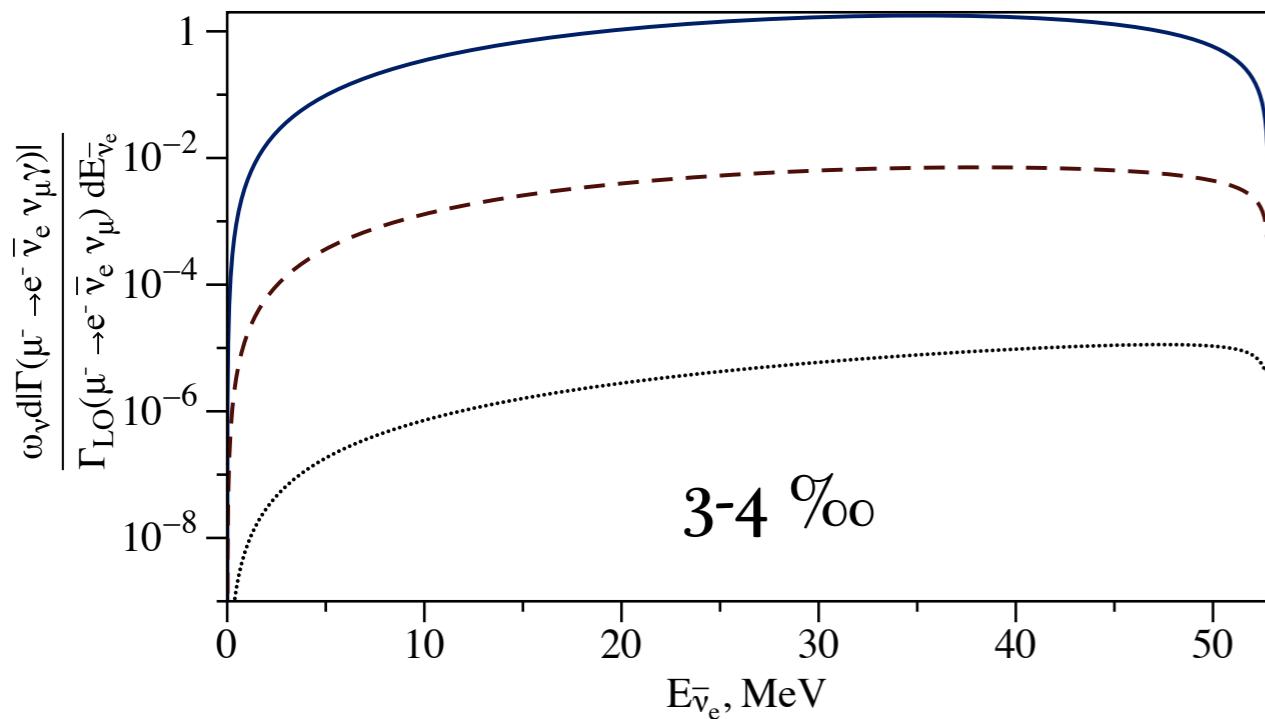
- $\lesssim 10^{-4}$ change in GeV (anti)neutrino fluxes

- negligible change when normalized to experimental lifetime

Radiative corrections to muon decay

- flavor-dependent distortions at permille level

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \gamma$$



- analytic spectra presented in agreement with b decays within QCD
M. Jezabek, J.H. Kuhn, Nucl. Phys. B 320, 20 (1989)
- permille change in flux-averaged cross sections due to distortion

$$\sigma_{\bar{\nu}_e}^{^{40}\text{Ar}} = (17.484 \pm 0.43) \times 10^{-40} \text{ cm}^2$$

$$\sigma_{\bar{\nu}_e, \text{LO}}^{^{40}\text{Ar}} = (17.490 \pm 0.43) \times 10^{-40} \text{ cm}^2$$

$$\sigma_{\nu_\mu}^{^{40}\text{Ar}} = (22.448 \pm 0.66) \times 10^{-40} \text{ cm}^2$$

$$\sigma_{\nu_\mu, \text{LO}}^{^{40}\text{Ar}} = (22.454 \pm 0.66) \times 10^{-40} \text{ cm}^2$$

- modern QED/EW form factors with different mass of leptons

- permille-level change in agreement with KLN theorem

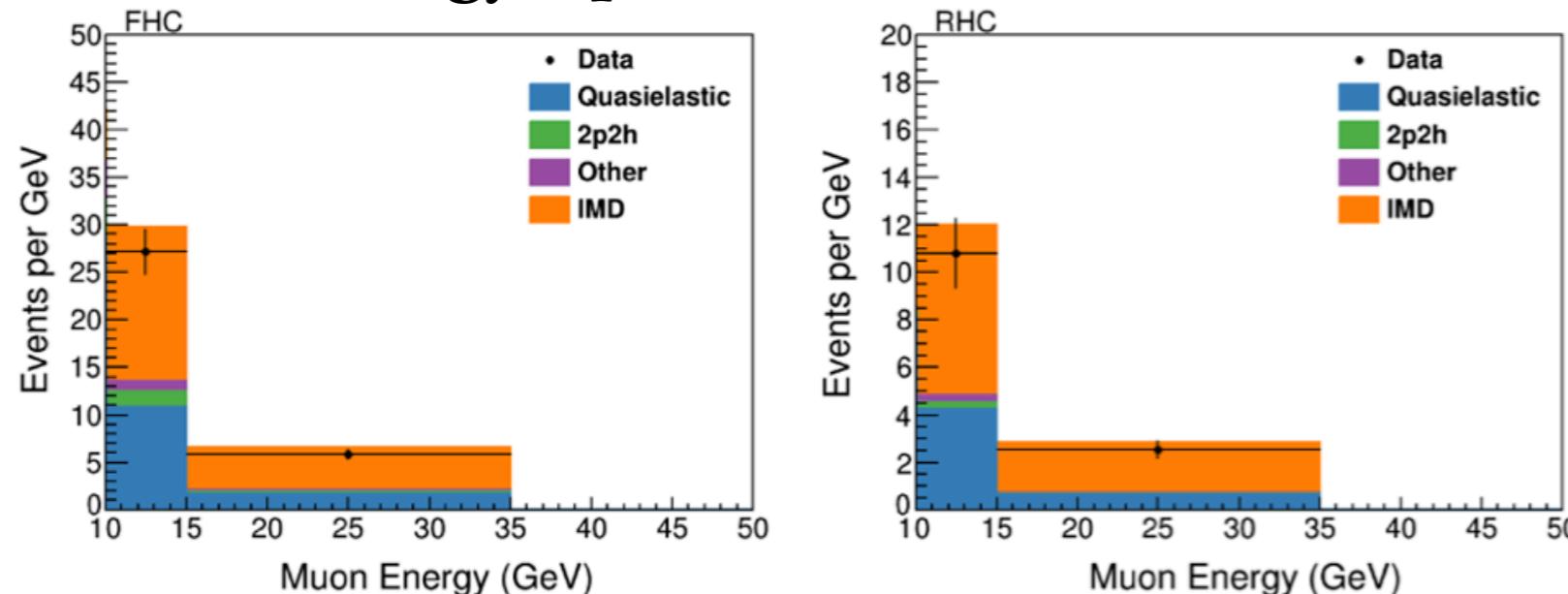


Radiative corrections to inverse muon decay for accelerator neutrinos

O.T., Kaushik Borah, Richard J. Hill,
Kevin S. McFarland, Daniel Ruterbories (2023)

MINERvA constraint by inverse muon decay

- muon energy spectrum:

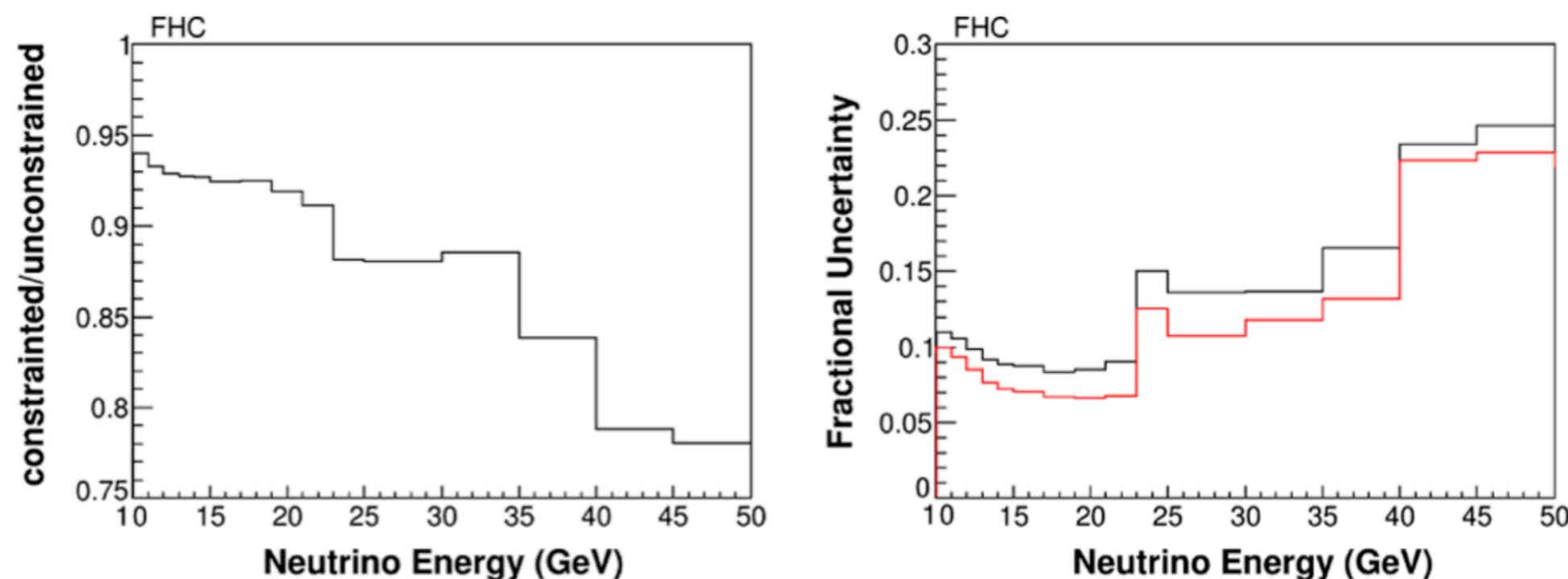


MINERvA, Phys.Rev.D 104, 092010 (2021)



$$E_\nu^{\text{thr}} \gtrsim 10.9 \text{ GeV}$$

- 10-20% correction on flux normalization, reduced error



- successful implementation by MINERvA collaboration

Inverse muon decay theory

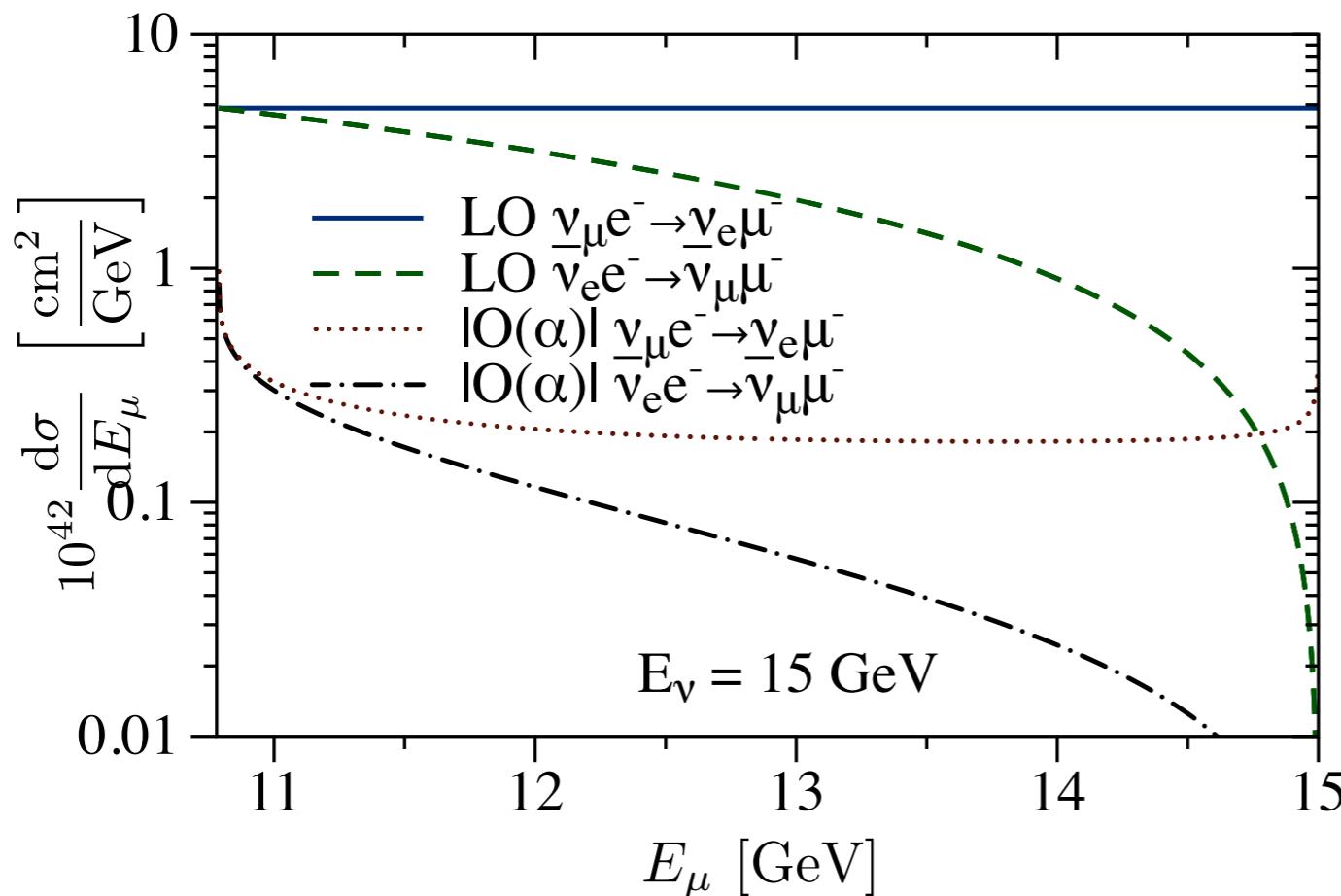
- precise Lagrangian with G_F from muon decay

$$\mathcal{L}_{\text{eff}} = -2\sqrt{2}G_F \bar{\nu}_e \gamma^\lambda P_L \nu_\mu \bar{\mu} \gamma_\lambda P_L e + \text{h.c.}$$

- 2.5 from 3 cross sections reproduced by alternative method

Bardin and Dokuchaeva (1987)

- new total cross sections, energy spectra, and 2D cross sections



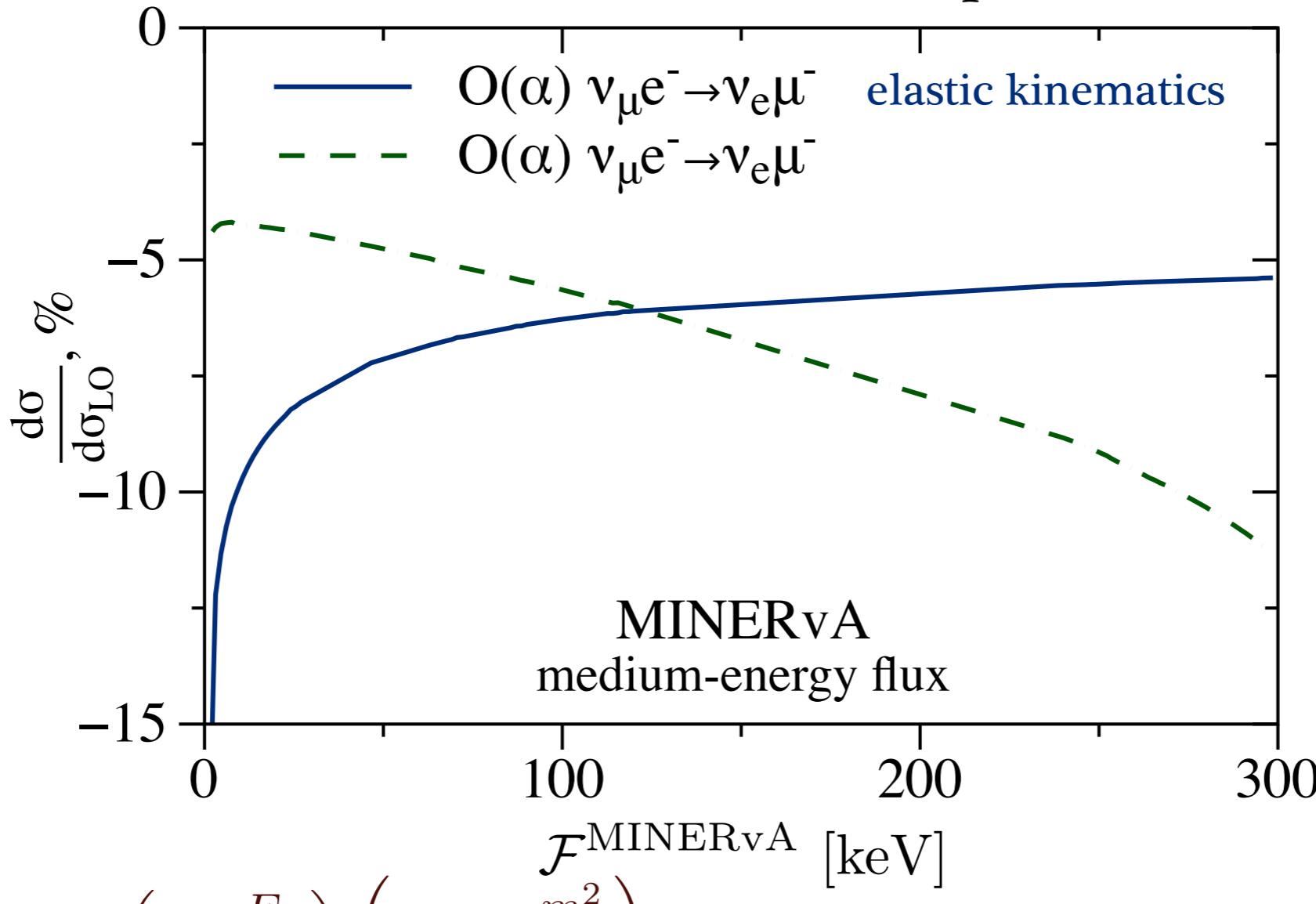
dominant neutrino component
has larger cross section

energy spectrum in
both channels

- muon energy spectrum verified $\nu_\mu e^- \rightarrow \nu_e \mu^-$, derived $\bar{\nu}_e e^- \rightarrow \bar{\nu}_\mu \mu^-$

Inverse muon decay theory

- radiative corrections to distribution of experimental discriminant

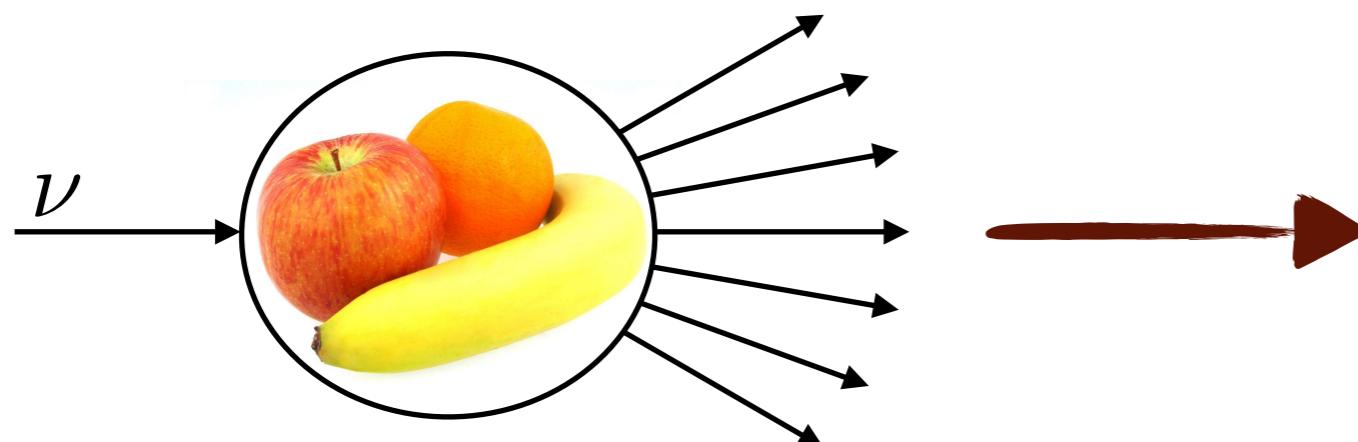


$$\mathcal{F} = E_\mu \theta_\mu^2 \approx \left(1 - \frac{E_\mu}{E_\nu}\right) \left(2m_e - \frac{m_\mu^2}{E_\mu}\right)$$
$$\mathcal{F}^{\text{MINERvA}} = \frac{E_\mu \theta_\mu^2}{1 - \frac{E_\mu}{35 \text{ GeV}}}$$

O.T., Kaushik Borah, Richard J. Hill, Kevin S. McFarland, Daniel Ruterbories (2023)

- double-differential distributions and corrections to \mathcal{F} distribution

Conclusions

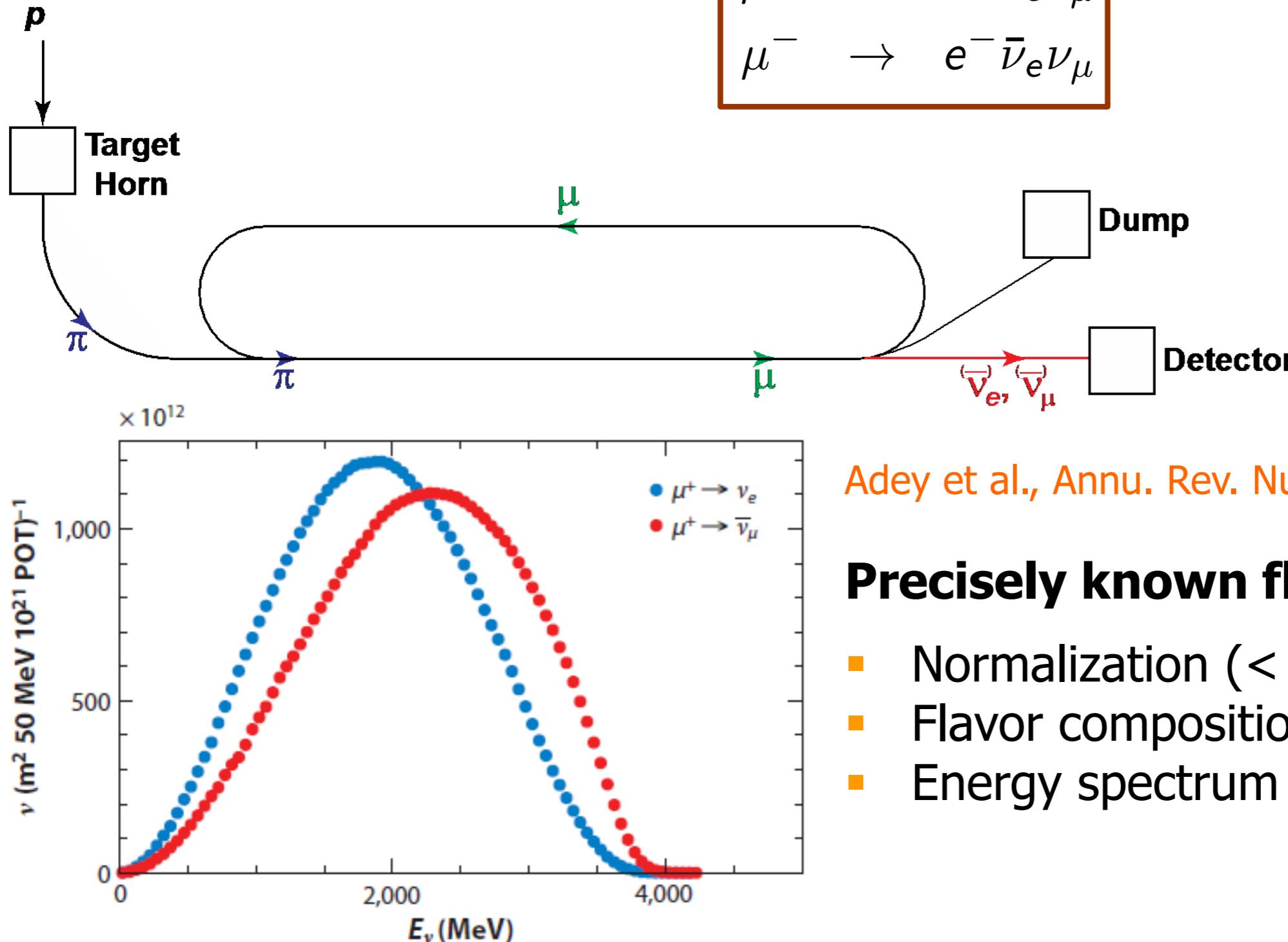


- first (anti)neutrino energy spectra from radiative meson decays
- QED/EW form factors with different mass of leptons
- precise neutrino spectra from muon decays
- common framework for muon and inverse muon decay
- radiative corrections to inverse muon decay observables

Thanks for your attention !!!

ν STORM

■ Neutrinos from Stored Muons



Adey et al., Annu. Rev. Nucl. Part. Sci. 2015.65

Precisely known flux:

- Normalization (< 1%)
- Flavor composition
- Energy spectrum

■ Feasibility at CERN: Ahdida et al., CERN-PBC-REPORT-2019-003

Enhanced NeUtrino BEams from kaon Tagging ERC-CoG-2015, G.A.

681647, PI A. Longhin, Padova University, INFN

- **CERN Neutrino Platform: NP06**
- **Physics Beyond Colliders CERN study**



Aims at demonstrating the **feasibility** and **physics performance** of a neutrino beam where **lepton production is monitored at single particle level**

- **Instrumented decay region**

$$K^+ \rightarrow e^+ \nu_e \pi^0 \rightarrow (\text{large angle}) e^+$$

$$K^+ \rightarrow \mu^+ \nu_\mu \pi^0 \text{ or } \rightarrow \mu^+ \nu_\mu \rightarrow (\text{large angle}) \mu^+$$
- **ν_e and ν_μ flux prediction from e^+/μ^+ rates**

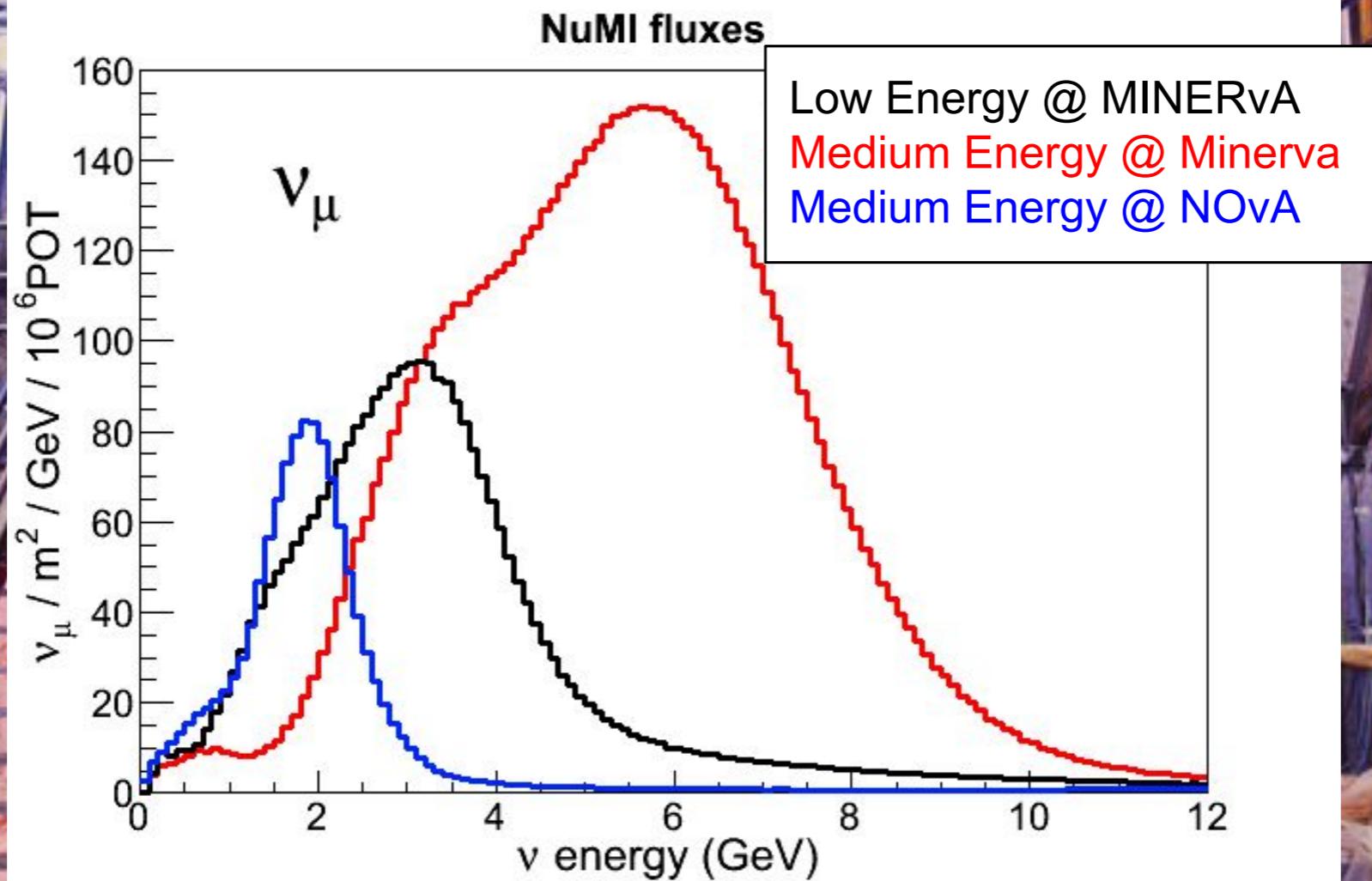
Requires a **collimated p-selected hadron beam**
 → **only decay products hit the tagger** → **manageable rates**
 Requires a “short”, 40 m, tunnel (~all ν_e from K , ~1% ν_e from μ)
 → **Bonus:** an “*a priori*” constraint on the ν energy by exploiting correlations between E_ν and the position of interactions in the detector (narrow band beams)

Uncertainty reduction for the tagged flux component

Constrain the flux model by exploiting correlations between the measured lepton distributions and the flux → Fit the model with data and get energy dependent corrections.

The MINERvA Experiment

- Ran between 2009-12 in the NuMI low energy (LE) configuration: $E \approx 3.5$ GeV
- 2013-19 in the medium energy (ME) configuration: $E \approx 6$ GeV
- Huge dataset, especially in the ME configuration
 - Neutrino mode: $4.3 \times 10^6 \nu_\mu$ -CC interactions with MINOS acceptance.
 - Anti-neutrino mode 2.5×10^6 anti- ν_μ -CC interactions



Motivation for measuring flux and cross-sections: Oscillation Experiments

The event rate at a near detector is a convolution of three terms

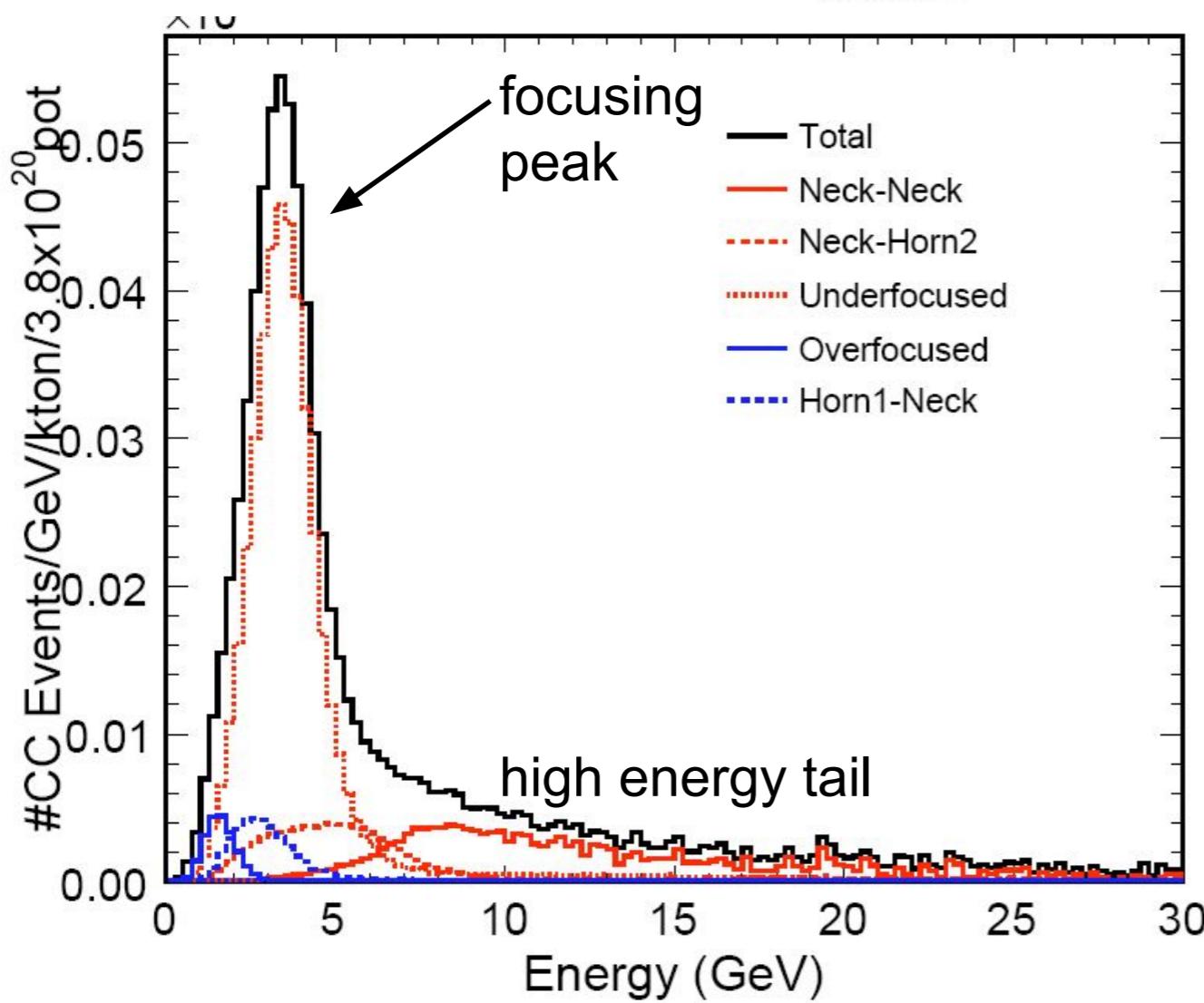
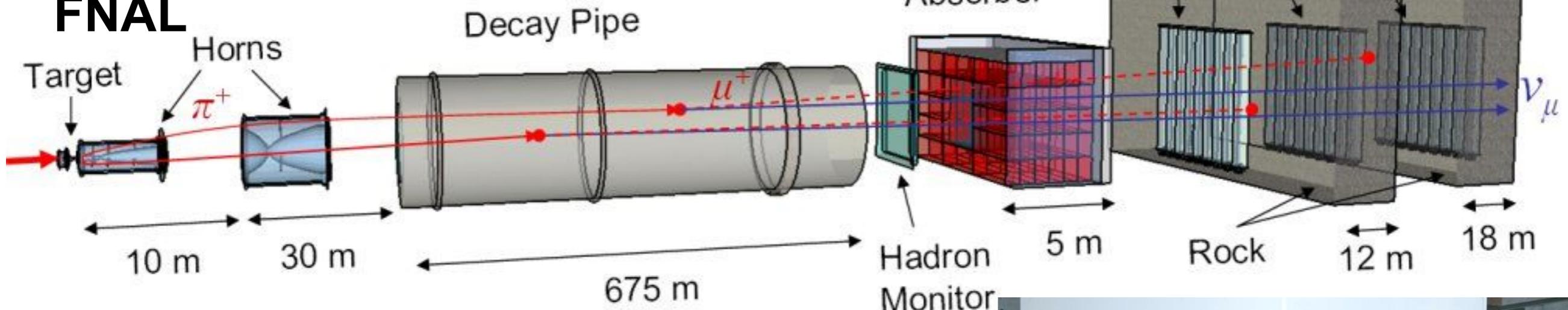
$$\Gamma_{\text{ND}}(E_{\text{reco}}) = \int \Phi_{\text{ND}}(E_{\text{true}}) \sigma_{\text{ND}}(E_{\text{true}}) R_{\text{ND}}(E_{\text{true}}, E_{\text{reco}}) dE_{\text{true}}$$

Neutrino
Flux

- Predicted, *a priori*, from a beam simulation (g4NuMI, g4LBNE)
- Hadron production data (NA49, NA61, MIPP, etc) used to improve the simulation. Incorporated via event by event reweighting.
- Uncertainties from the HP data, physics model, & beam optics propagated via many universes (a.k.a. multi-sim) approach.
- Some systematic control by changing horn currents, target position, or off axis position

The NuMI Beam

NuMI @
FNAL



in situ data: the low- ν technique

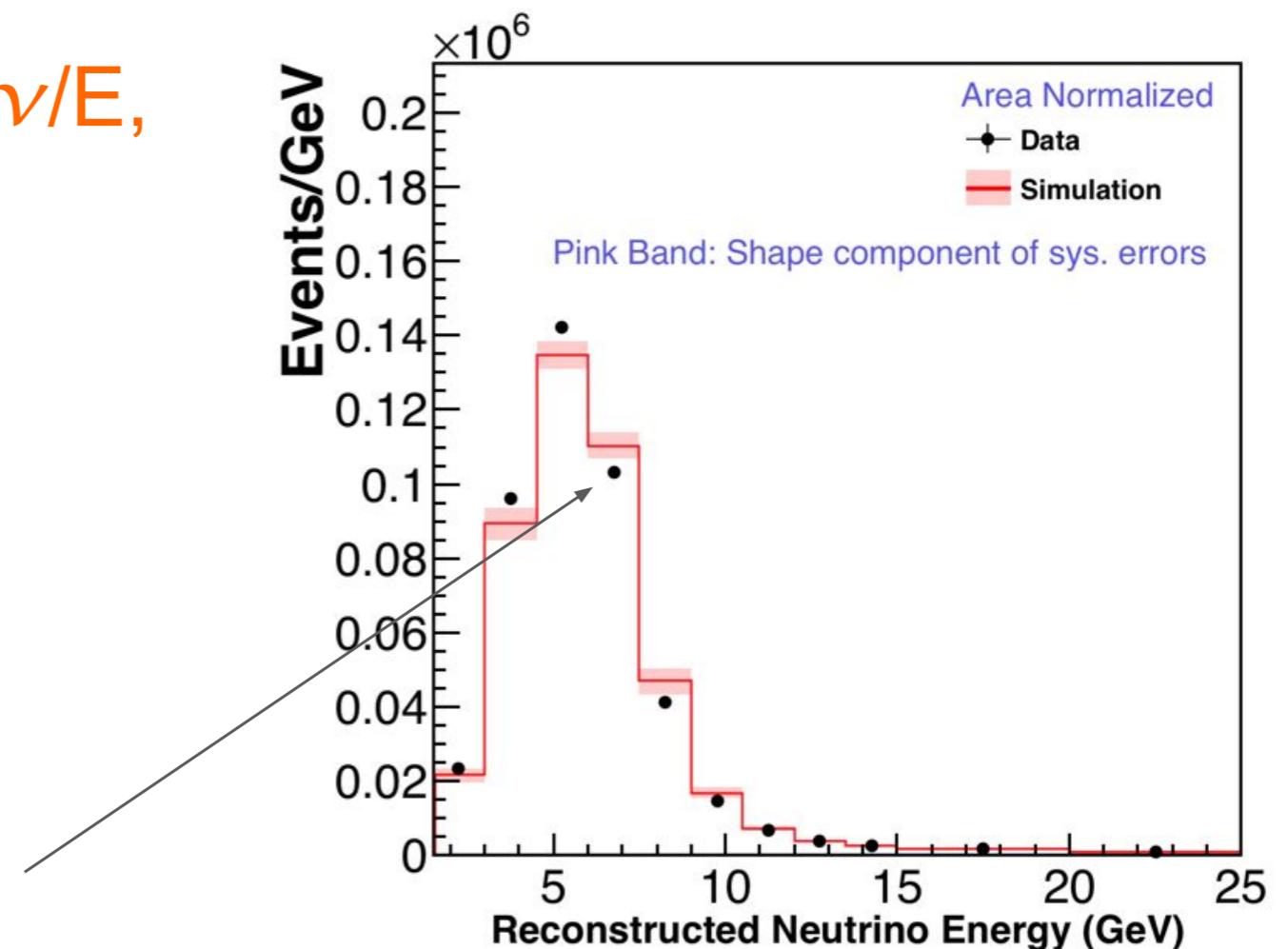
Cross-section as a function of the energy transfer ν

Becomes constant for small ν/E , resulting in a measurement of the flux shape.

Normalized to well measured high energy neutrino CC cross-section

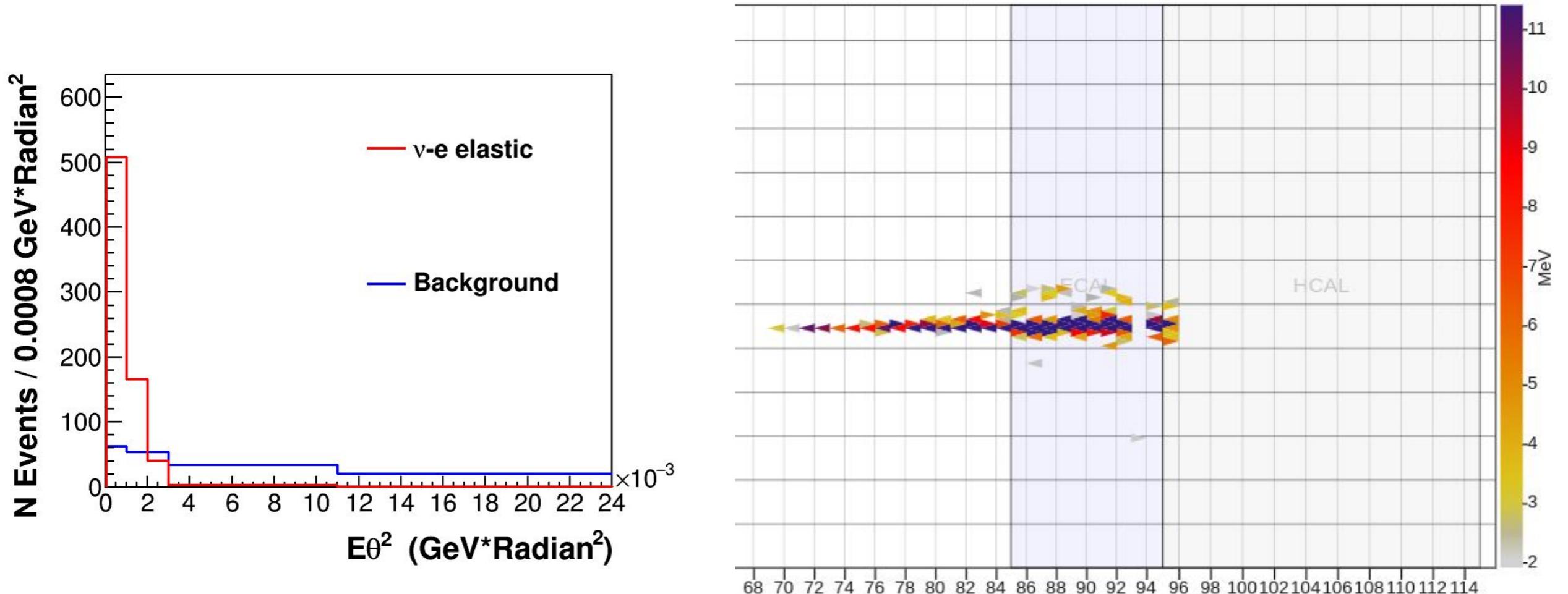
Data indicates a warping of the flux shape around the focusing peak. Best hypothesis is a 3.6% (1.8σ) shift in the muon energy scale .

$$\frac{d\sigma}{d\nu} = A \left(1 + \frac{B}{A} \frac{\nu}{E_\nu} - \frac{C}{A} \frac{\nu^2}{E_\nu^2} \right)$$

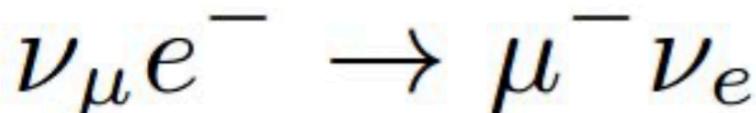


- “Use of Neutrino Scattering Events with Low Hadronic Recoil to Inform Neutrino Flux and Detector Energy Scale” A. Bashyal et al (MINERvA), 2021 JINST **16** P08068

Neutrino electron scattering

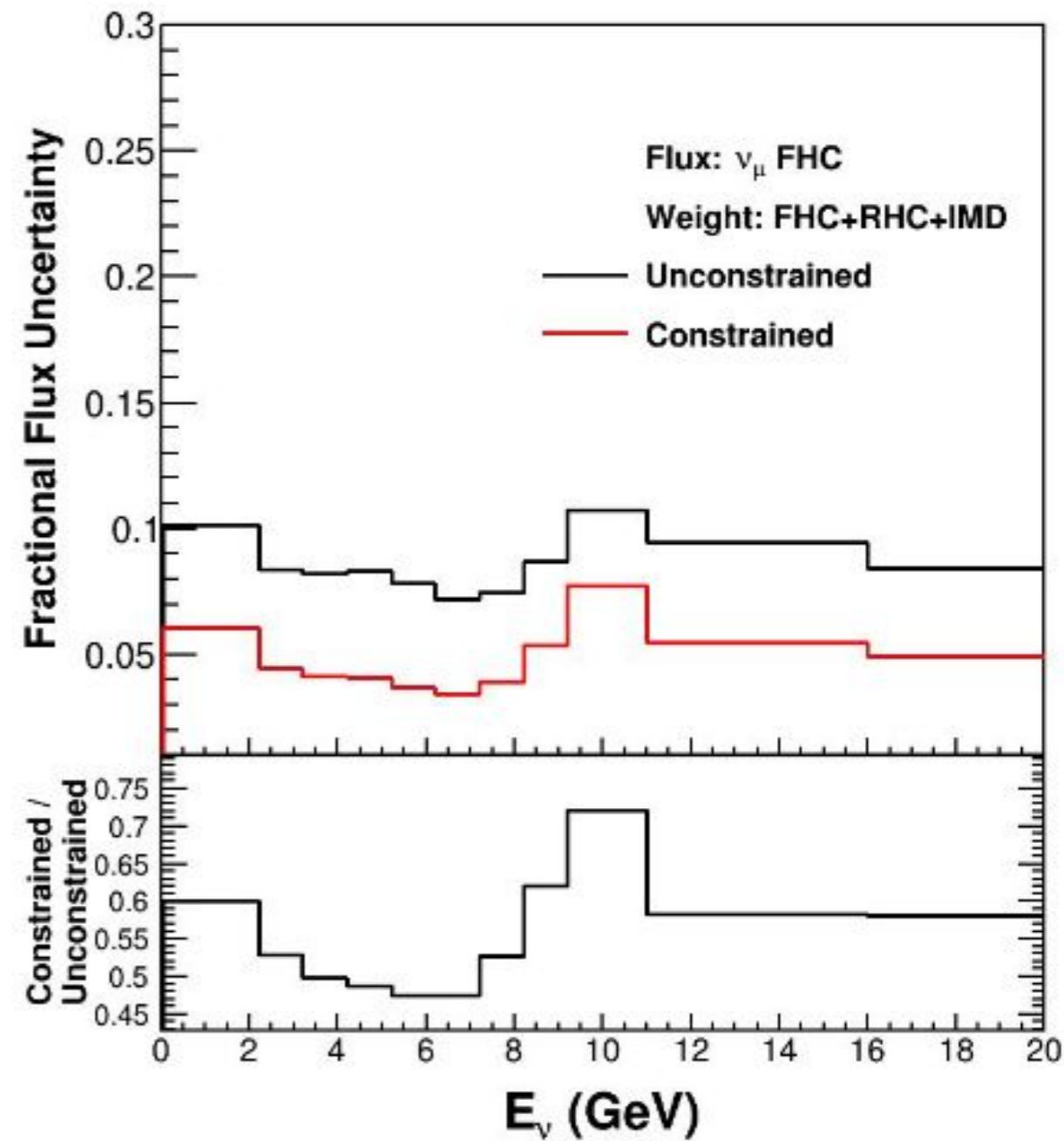
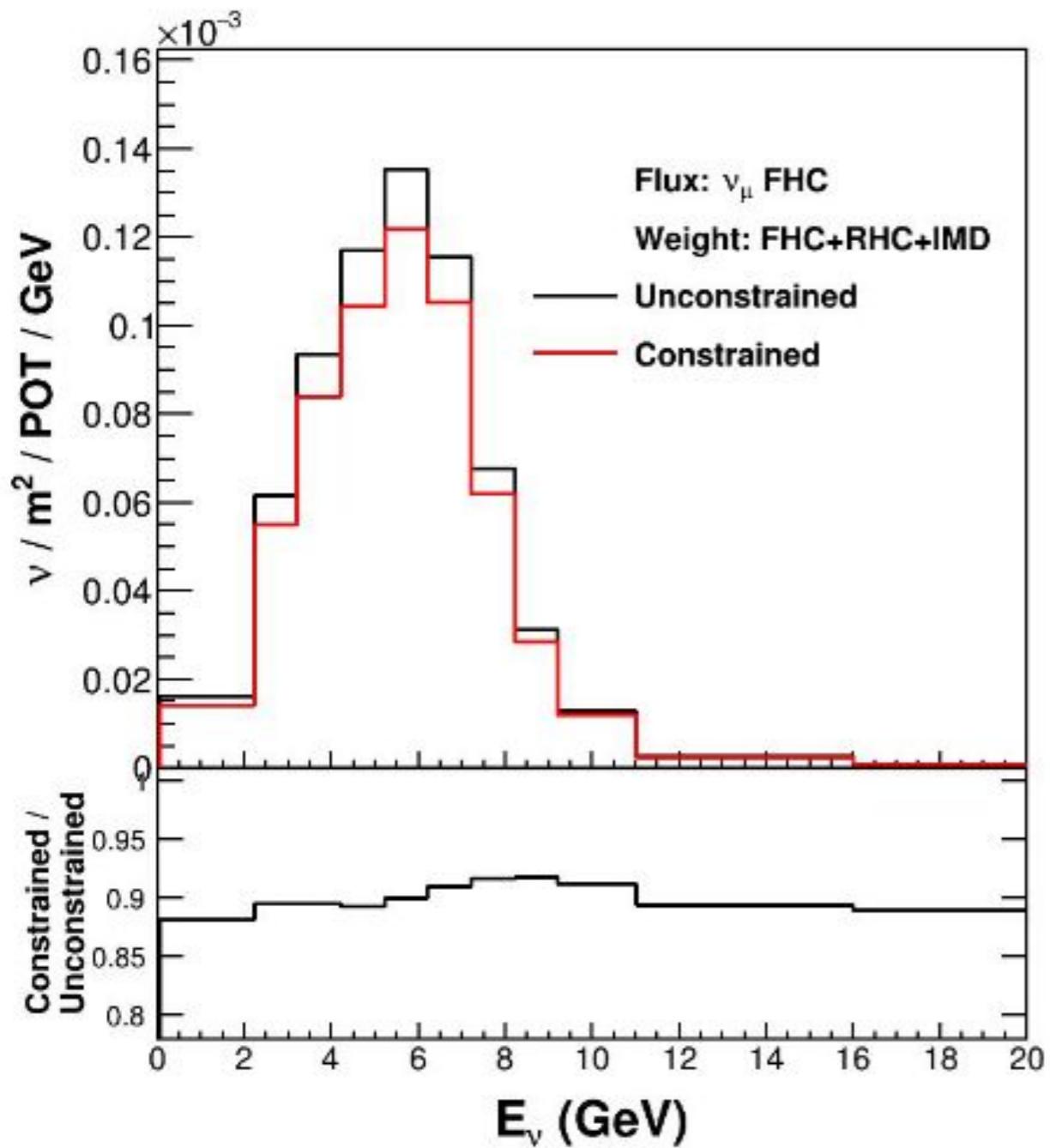


- Kinematics requires that $E_e \theta_e^2 < 2m_e$
- The signature is a very forward energetic electron with no hadronic recoil.
- Electron can radiate real photons. Important to include them in the cross-section.



- Similar to the neutrino electron elastic scattering, but with a very forward muon in the final state
- Threshold is ~11 GeV, so this process constrains the high energy component of the flux. Only sensitive to muon neutrinos.

Constrained flux

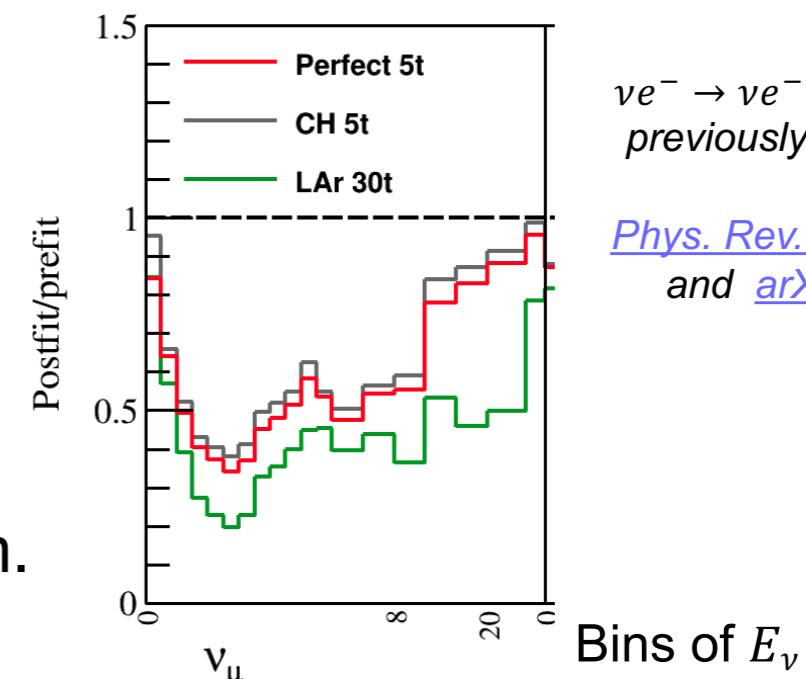


Neutrino Electron Scattering



- $\nu e^- \rightarrow \nu e^-$, cross-section uncertainties below 1% but reaction is only a few parts in 10^4 of total on nuclei.
- Events/year in ν beam
 - Rates sufficient in a LAr TPC (50 ton) for a measurement of total rate to better than 1% (stat).
- Simulated analysis, including leading interaction systematics on backgrounds, shows reduction in flux uncertainties.
 - 8% to 1-2% uncertainties at flux peak
 - Limited, but useful, capacity to probe spectrum.

Detector	LAr TPC	HPg Ar TPC	3D Scint Tracker
$\nu_\mu + e$ ($E_e > 500$ MeV)	6600	130	1100



$\nu e^- \rightarrow \nu e^-$ flux constraint previously demonstrated by MINERvA, [Phys. Rev. D 93, 112007](#), and [arXiv:1906.00111](#)

5 August 2019

Kevin McFarland: DUNE's Near Detector

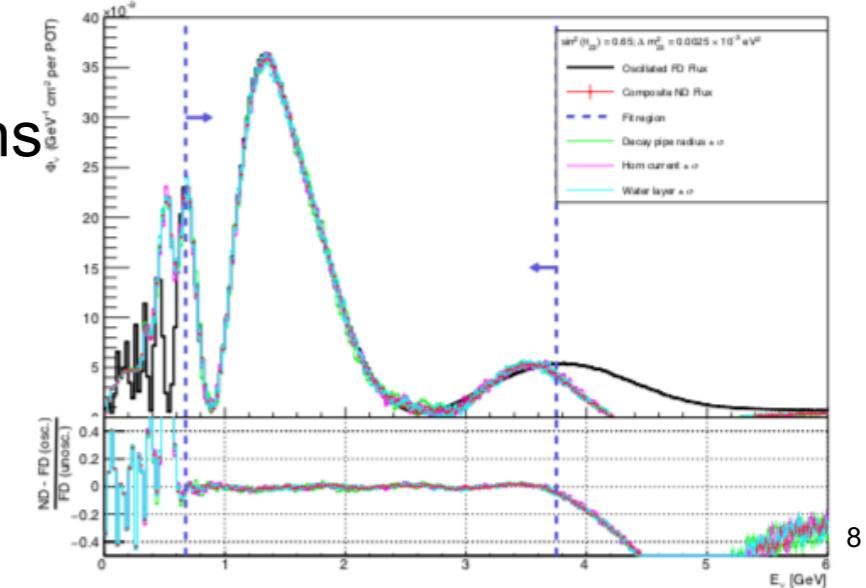
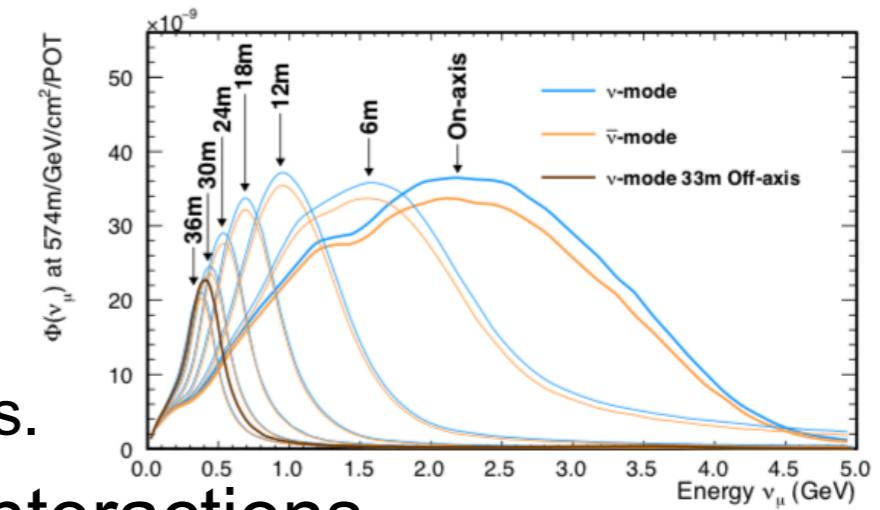
~ 6000 inverse muon decay (IMD) events in 5 years of data taking

arXiv: [1910.10996](#)

DUNE PRISM



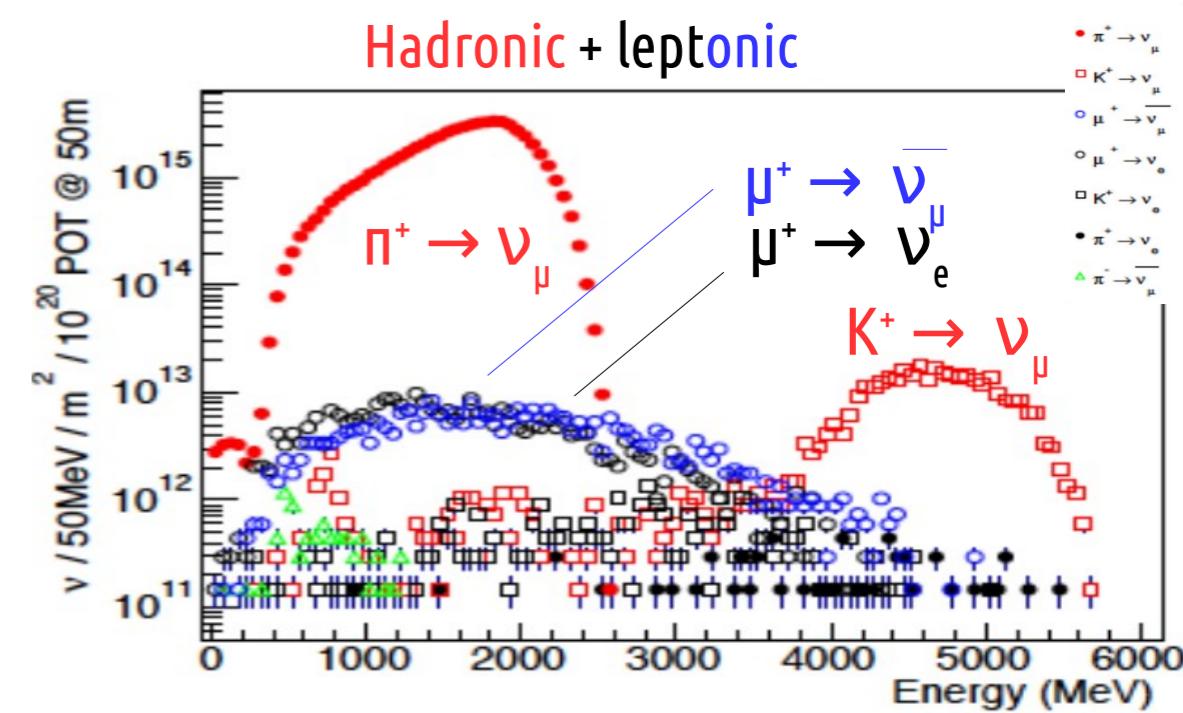
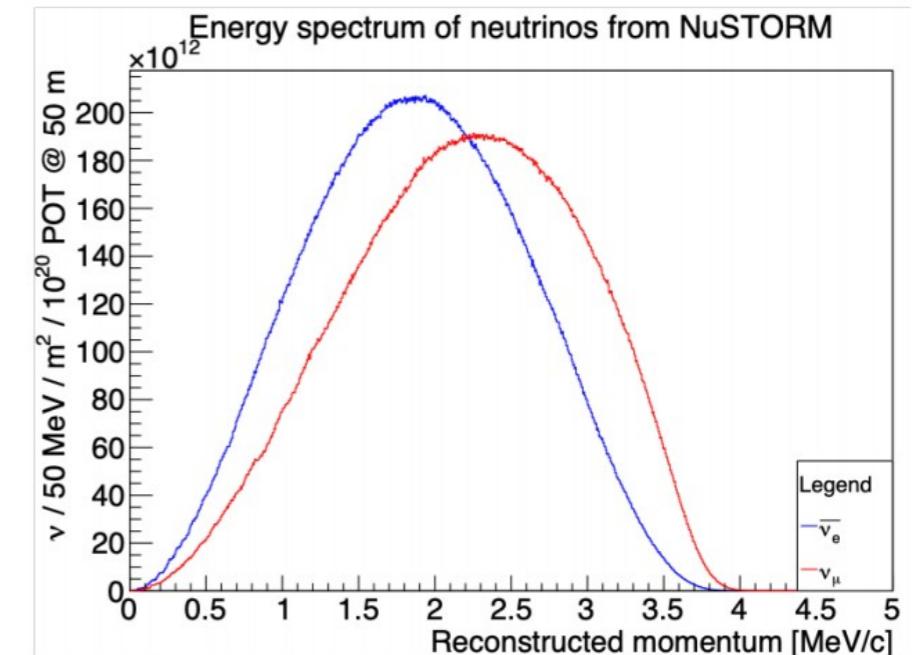
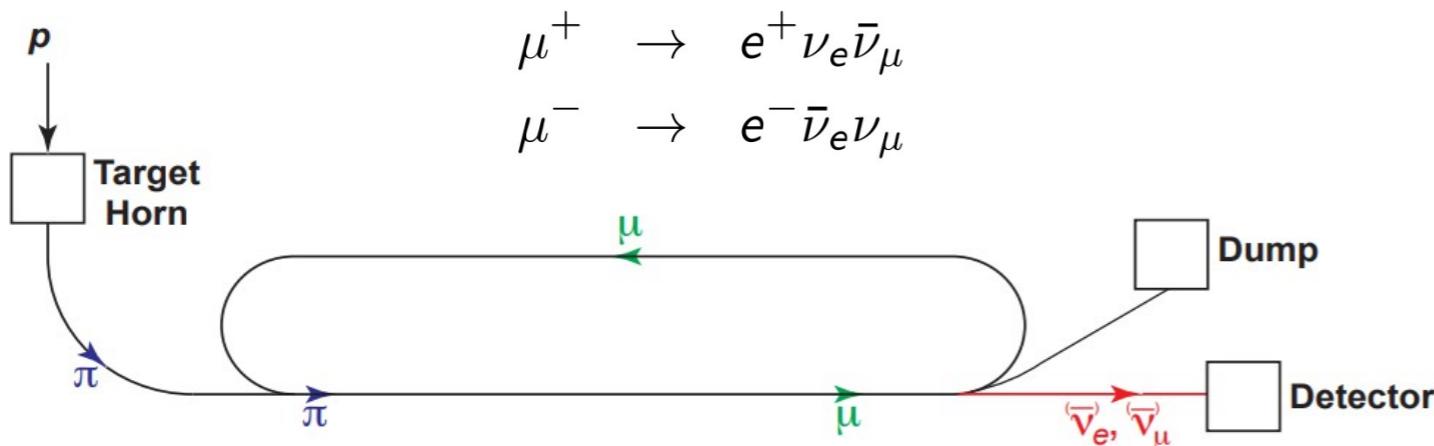
- If near detector is movable...
- Flux at near detector location varies with transverse position: range of “off axis” fluxes.
 - Exploit this to make a pseudo “monochromatic” beam by combinations of fluxes at different locations.
- Monochromatic beam can directly measure interactions vs. true E_ν to understand relationship to reconstructed E_ν^{reco} .
 - One analysis strategy: form directly the expected flux of muon neutrinos after oscillations that should be observed at the far detector.
 - Then measure the observed response and translate to far detector.
 - Interaction model independent, by construction.



Precise fluxes for cross-section program

nuSTORM implementation at the SPS

ν_e and ν_μ beams from decay of circulating low-E muons



Novel beams (meson based)

ENUBET

Talk by G. Brunetti

2) Conventional “meson based” beams brought to a new standard → use a narrow band beam and shift the monitoring at the level of decays by instrumenting the decay tunnel (tag high-angle leptons) → remove the main limit to cross section measurements by reducing the flux normalization uncertainty from O(5-10%) to ~O(1%).



Hadro-production (p-target) uncertainties → by-passed by lepton “counting”

An **ancillary facility** providing **physics input** to the long-baseline program: reduction of systematics thanks to unprecedented measurements of the ν_e (and ν_μ) cross sections