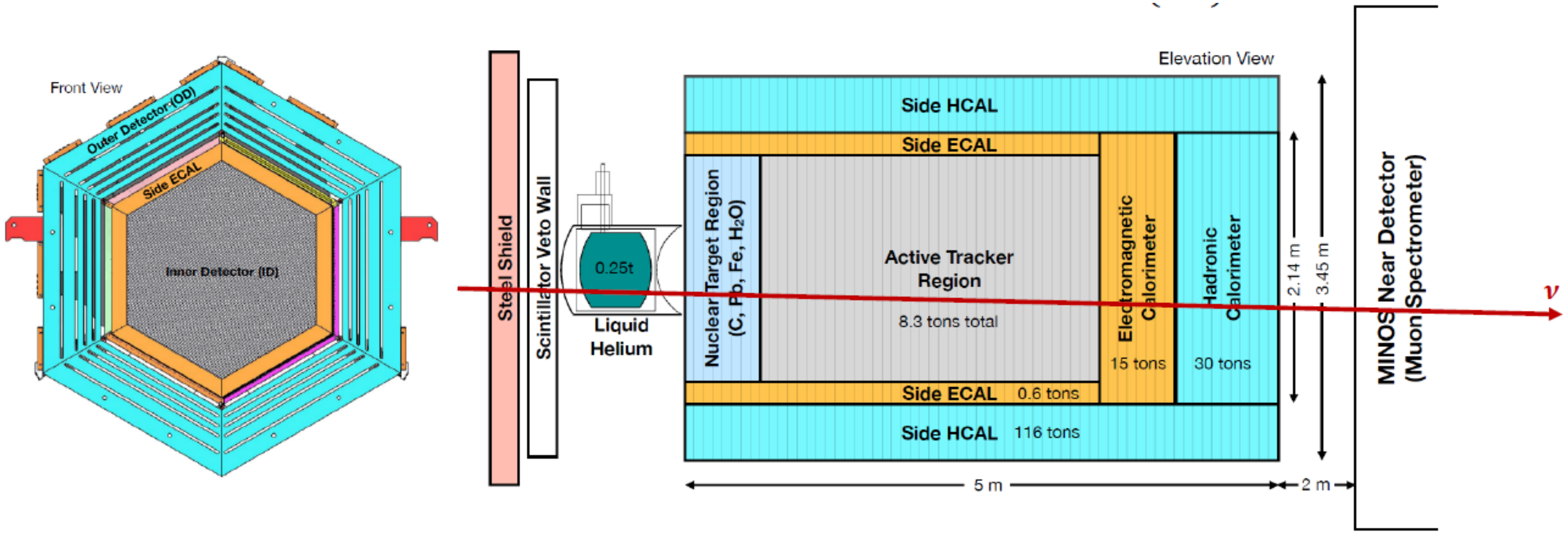
MINERνA Medium-Energy physics results

John Plows

On behalf of the MINERνA collaboration

ICHEP 2022, 07/July/2022

The **M**ain **IN**jector **E**xpe**R**iment for **ν-A** interactions



On-axis, NuMI beamline

Low-E : $\langle E_\nu \rangle = 3.5$ GeV ('10-'12)

Med-E : $\langle E_\nu \rangle = 6$ GeV ('13-'19)

Measures cross sections

1.2×10^{21} POT ν-mode and $\bar{\nu}$-mode

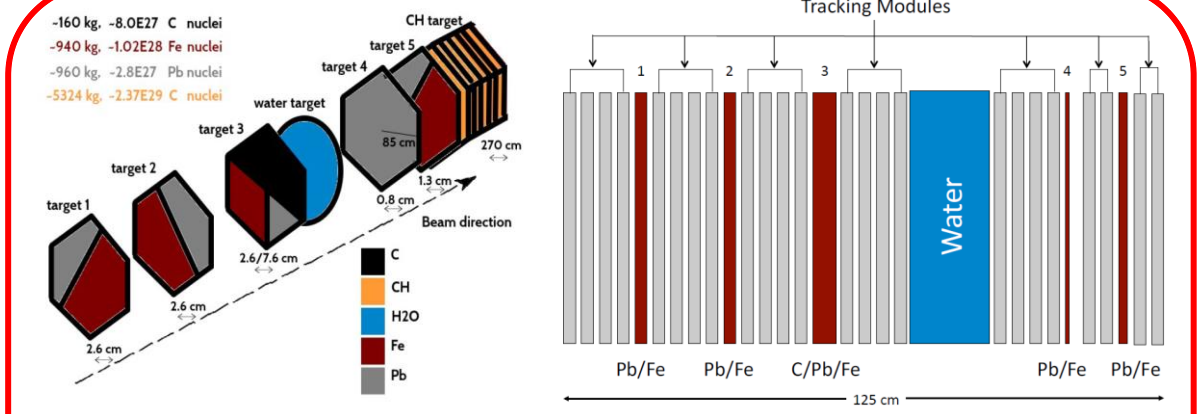
Active plastic tracker (strips) with PMTs for spatial + time info

Passive nuclear targets vary A

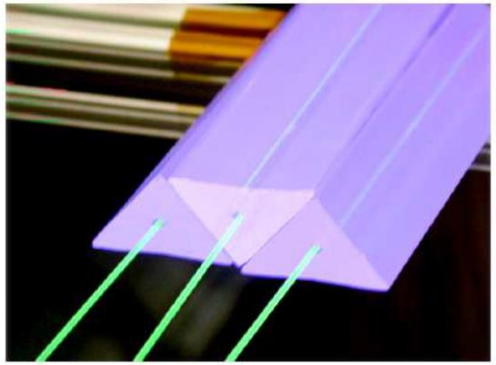
MINOS ND : μ charge + momentum

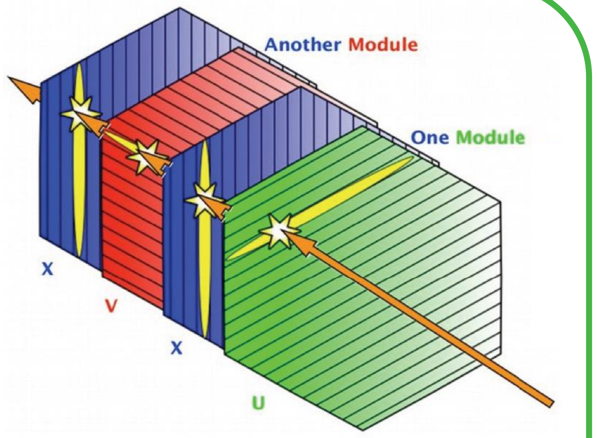
Details: *NIM A* **743** (2014) 130 (detector)

EPJ Special Topics **230** (2021) 4243 (review of LE physics)

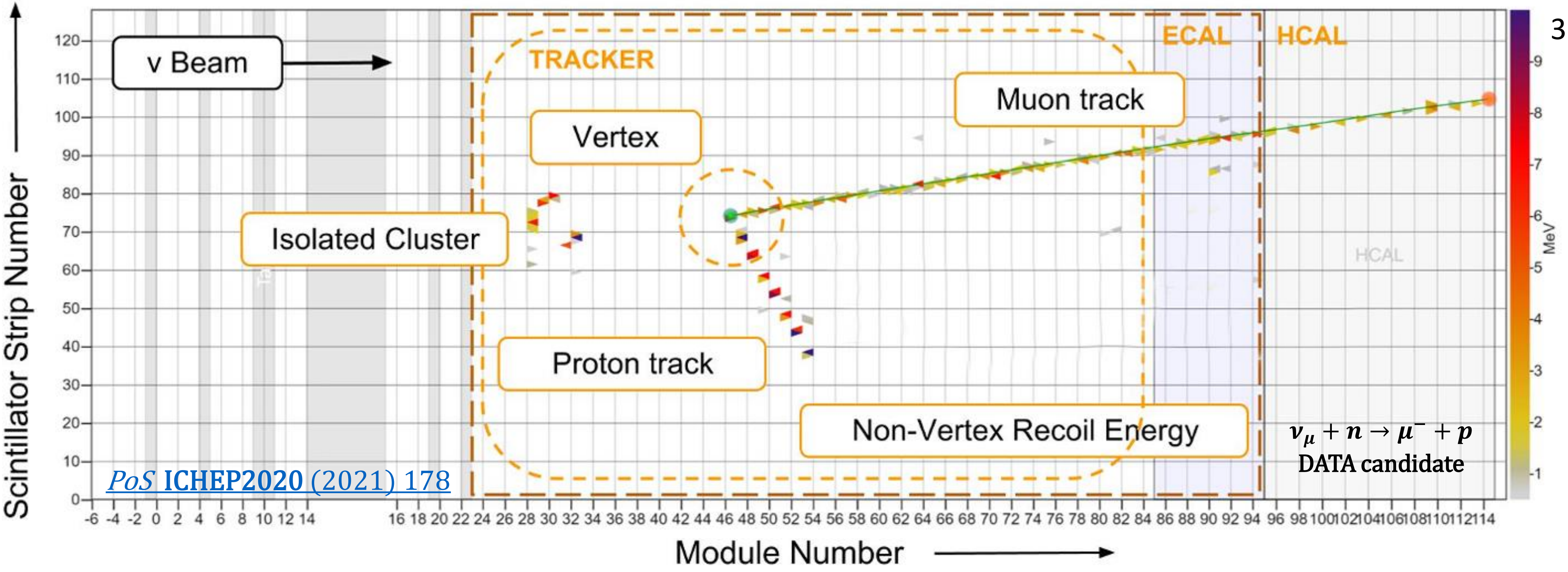


H_2O, He, C, Fe, Pb targets interspersed with scintillator



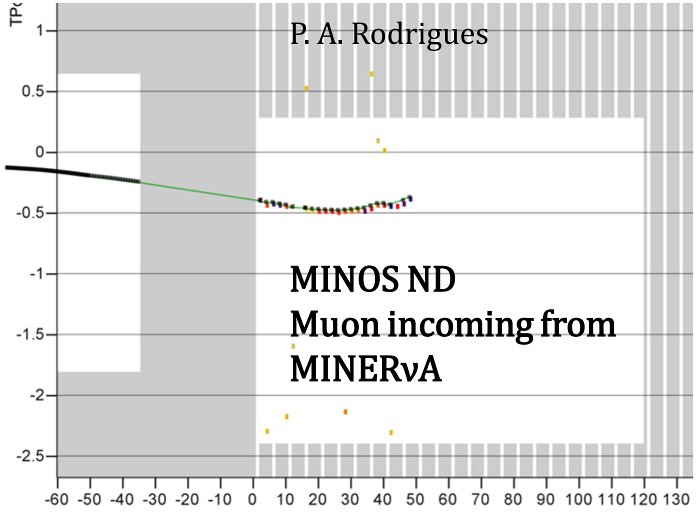


Polystyrene strips + fibres in XUXV config: 3d spatial info



PoS **ICHEP2020** (2021) 178

$\nu_\mu + n \rightarrow \mu^- + p$
DATA candidate



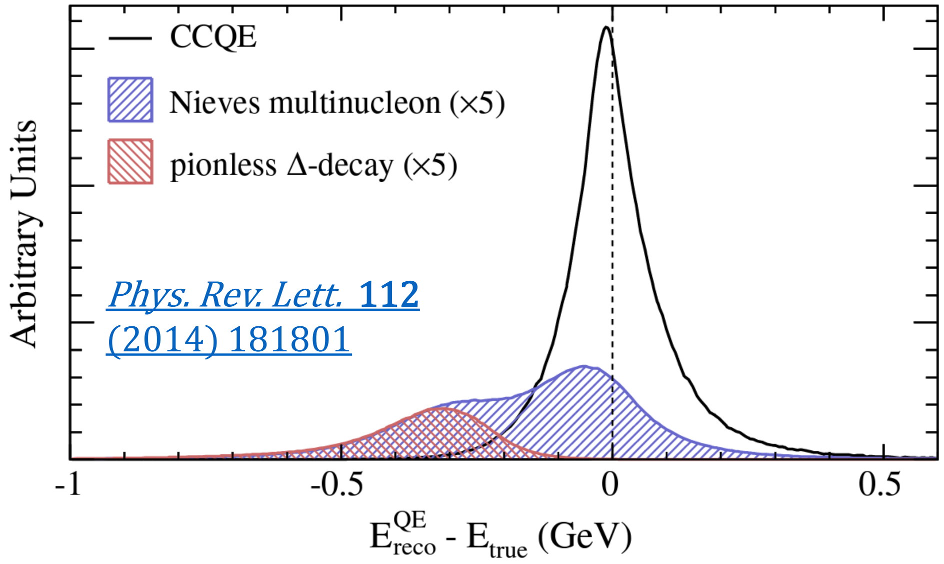
P. A. Rodrigues

MINOS ND
Muon incoming from MINERvA

MINERνA sees hits in tracker, ECAL, HCAL + OuterDetector
Profile particle candidates based on dE/dX
Match exiting muon track to MINOS

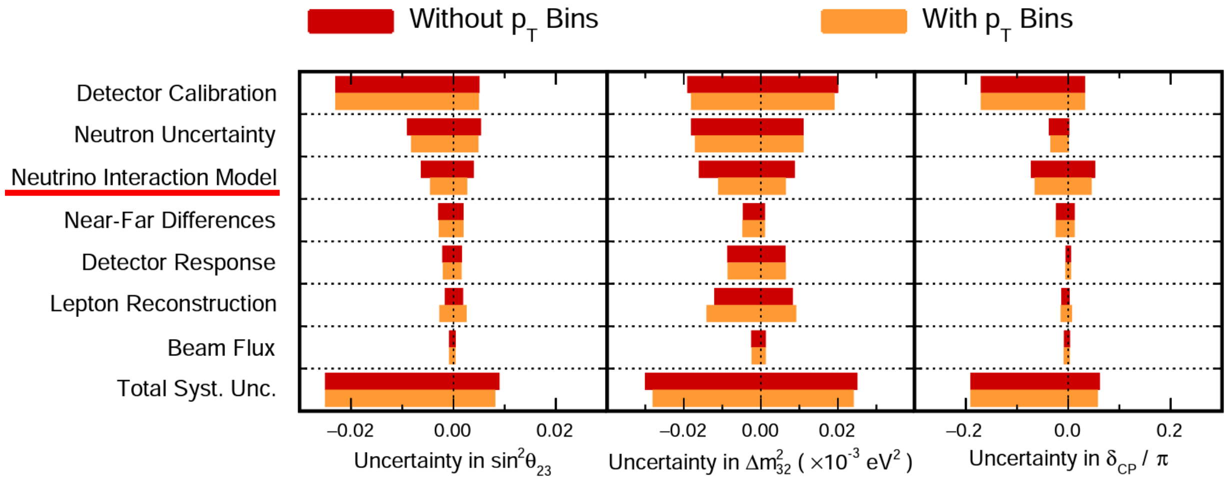
EM-coupled particles ($\pi^{\pm}, p, \gamma$ …) destroyed at ECAL
Hadronic particles (π^0, n …) destroyed at HCAL

Why measure cross sections?



Phys. Rev. Lett. **112** (2014) 181801

Bias on reconstructed E_ν - wrong interaction type
(T2K)



arXiv: 2108.08219 [hep-ex]

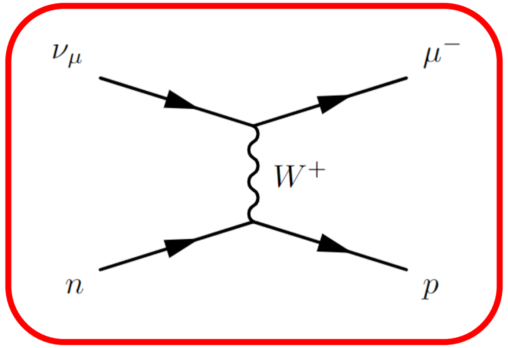
Systematic error sources for oscillation analysis
(NOνA)

- Oscillation analyses require precise reconstruction of neutrino energy
- $P(\nu_\alpha \rightarrow \nu_\beta) \propto \Delta m^2 \times \frac{L}{E_\nu}$
- E_ν is inferred by final-state particle energies ⇒ depends on interaction type!

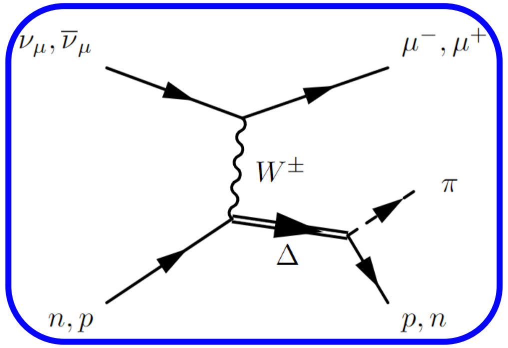
- Counting events requires knowledge of nuclear effects
  (Final State Interactions: particles exiting interaction vertex need to make it out of the nucleus)
- Lacking comprehensive theory of nuclear response ⇒ need measurements!

What does MINERνA probe?

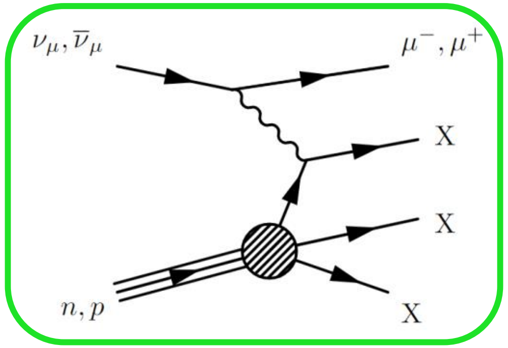
Intrinsic interaction types



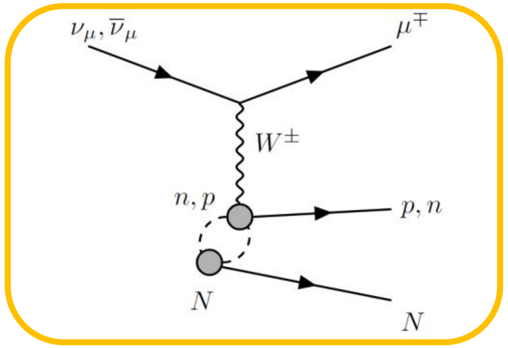
Quasielastic scattering (QE)



Resonant pion production (RES)

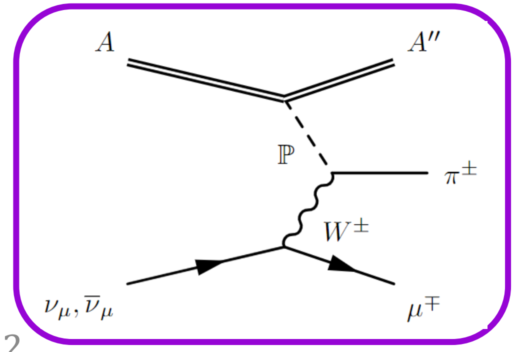


Deep inelastic scattering (DIS)



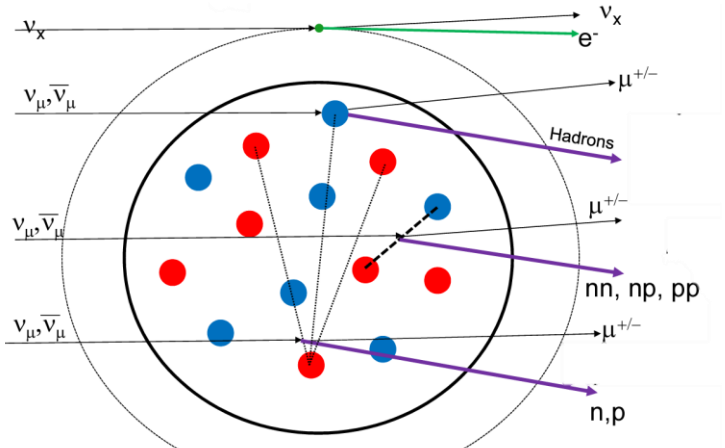
Multinucleon scattering (2p2h)

MINERνA is producing leading cross section measurements and tunes for Monte Carlo generators!



Coherent pion production (COH)

Nuclear effects



Daniel Ruterbories, FNAL JETP seminar, 25/Oct/19

Initial state:
- Fermi motion
- Nuclear model
- Binding energy
- Pauli blocking

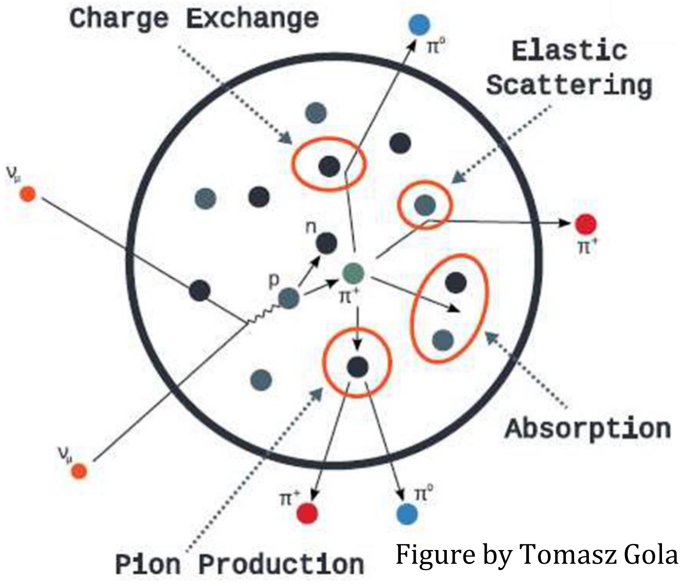


Figure by Tomasz Golan

Final state:
Reinteractions of final state products within nucleus lead to **different signatures in detector!**

Our newest results!

1. Flux constraint using Inverse Muon Decay (IMD)

   Adds to MINERνA's high-precision flux control!

2. High-statistics analyses
   1. 2D inclusive muon
   2. Low recoil
   3. 3D QE-like

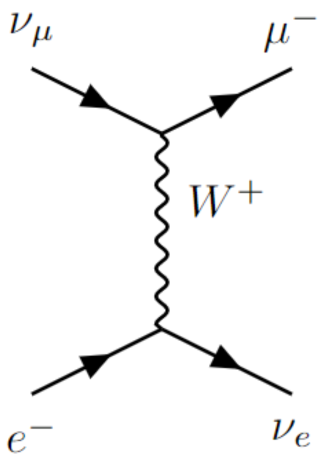
   Accurate tests for model predictions!

3. Upcoming: Coherent π^+ production from nuclear targets

Flux constraint with IMD

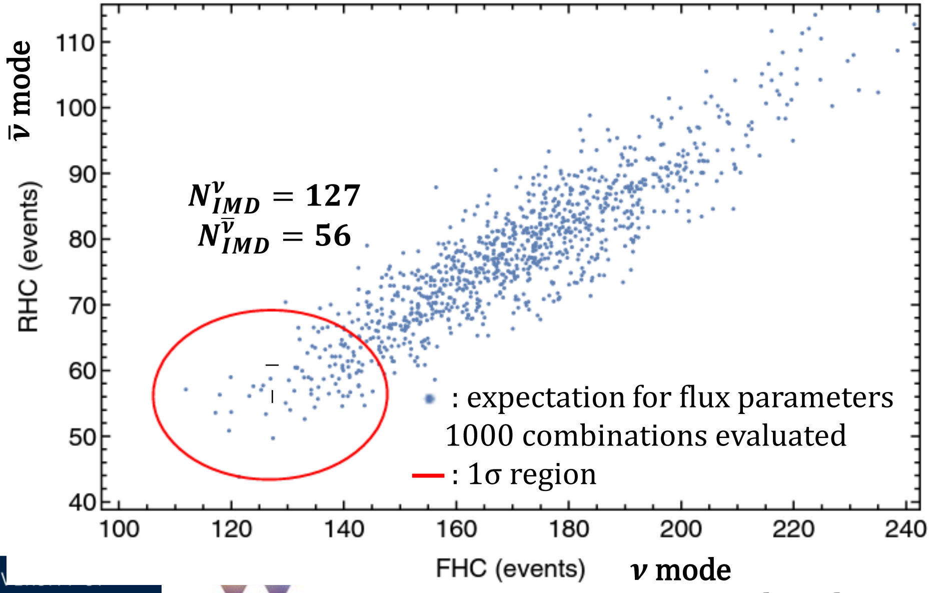
Phys. Rev. D **104** (2021) 092010

- Flux systematics often among most important source of systematic error
- Nominal flux prediction from beam simulation, some control over systematics
- *In situ* measurements to constrain flux prediction *a posteriori*
- Need well-understood cross-sections:
  - $\nu + e \rightarrow \nu + e$
  - $\boldsymbol{\nu_\mu + e \rightarrow \mu + \nu_e}$ **(IMD) - threshold at** $\boldsymbol{\frac{m_\mu^2 - m_e^2}{2m_e} \simeq 11\ \mathrm{GeV}}$



- Measure $N_{IMD}^{(\nu,\bar{\nu})}$ and compare with $N_{exp}^{(\nu,\bar{\nu})}$ (flux parameters)

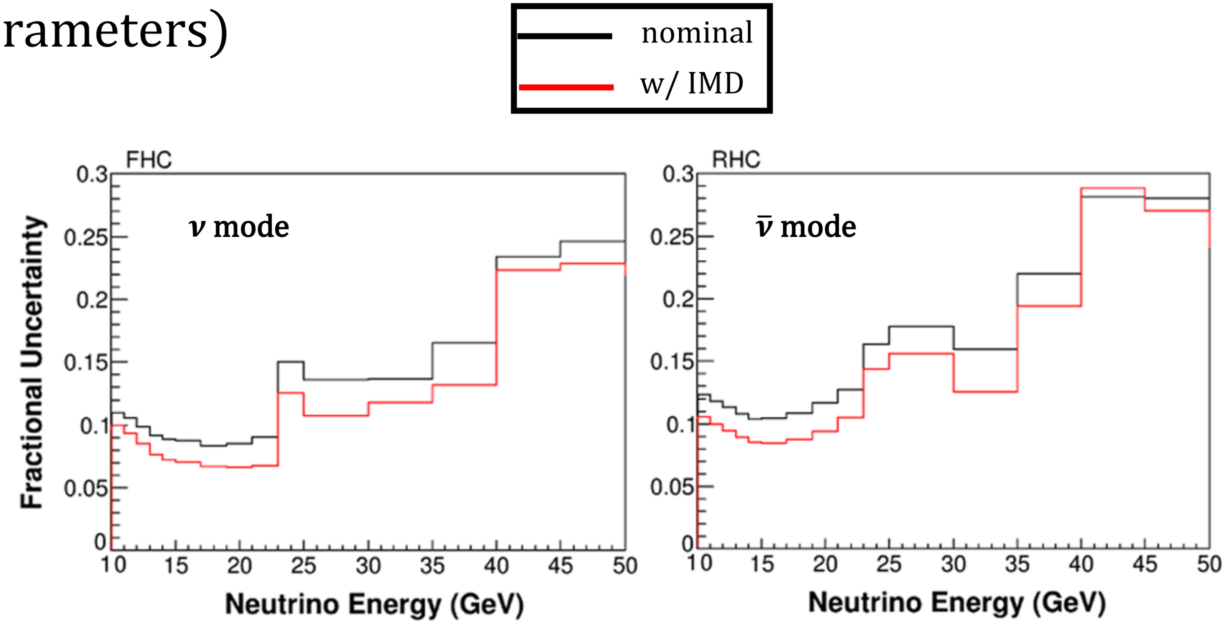
IMD Events by Flux Universe with $\Delta\chi^2$=1 Ellipse



$\boldsymbol{N_{IMD}^{\nu} = 127}$
$\boldsymbol{N_{IMD}^{\bar{\nu}} = 56}$

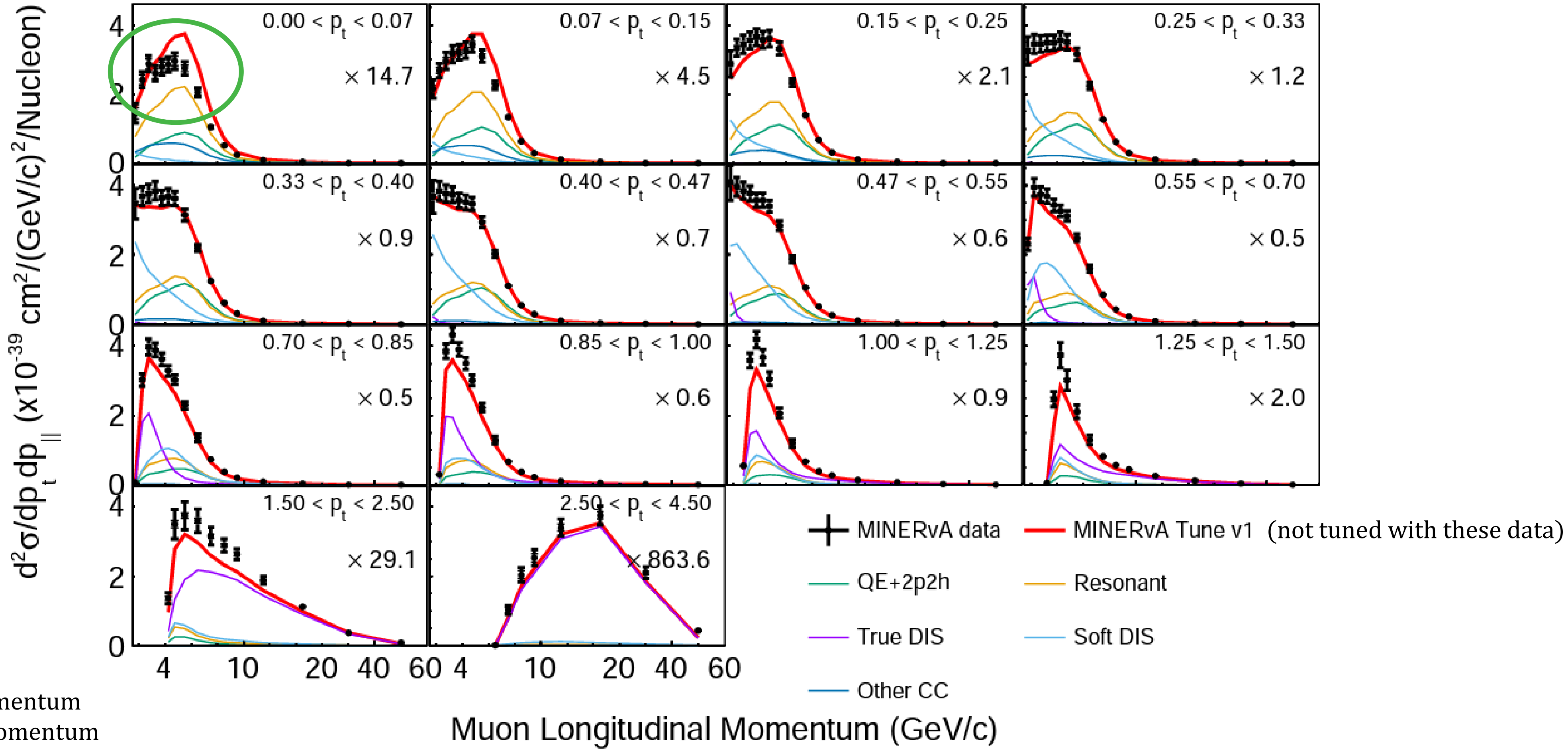
: expectation for flux parameters
1000 combinations evaluated

: 1σ region



2D: *Phys. Rev.* ***D*** **104** (2021) 092007

Inclusive muon analysis



(not tuned with these data)

p_t : μ transverse momentum
$p_{\parallel}$: μ longitudinal momentum

Favours low-p_t suppression of RES π production
Disfavours 2p2h enhancement

Cannot isolate specific source(s?) of mismodelling with one analysis alone!

Low-recoil analysis

arXiv: 2110.13372 [hep-ex]

- Inclusive muon analysis
- Low-momentum transfer interactions very sensitive to nuclear effects

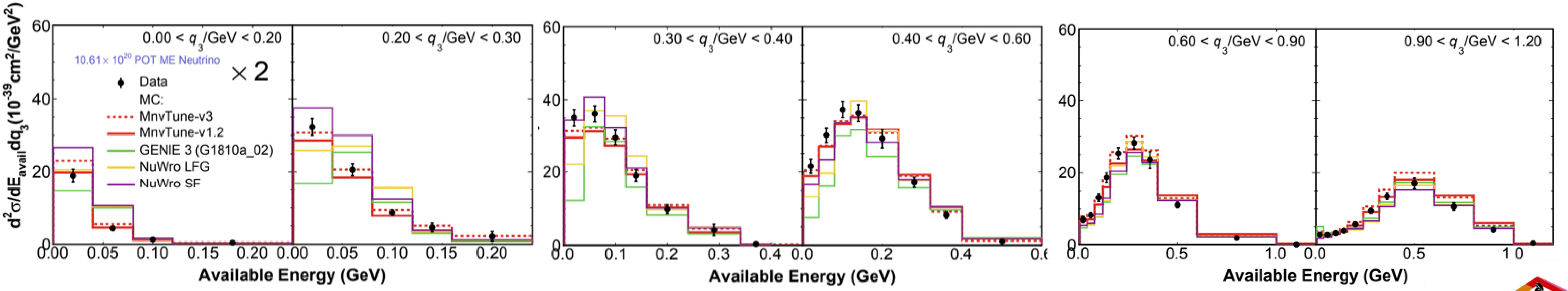
Improved visual agreement of MnvTunev3 BUT full covariance matrix means MnvTunev1.2 smaller χ^2

Progress made towards describing our data better! These results supersede the old LE result

MC/Generators	χ^2	χ^2/NDF
MnvTune-V3	1100.75	25.02
MnvTune-V1.2	963.154	21.89
NuWro SF	9981.78	226.86
NuWro LFG	16363.8	371.9
GENIE 3 (G1810a_02)	14148.9	321.57

SuSA 2p2h + enhanced Bodek-Ritchie tail + removal energy for RES

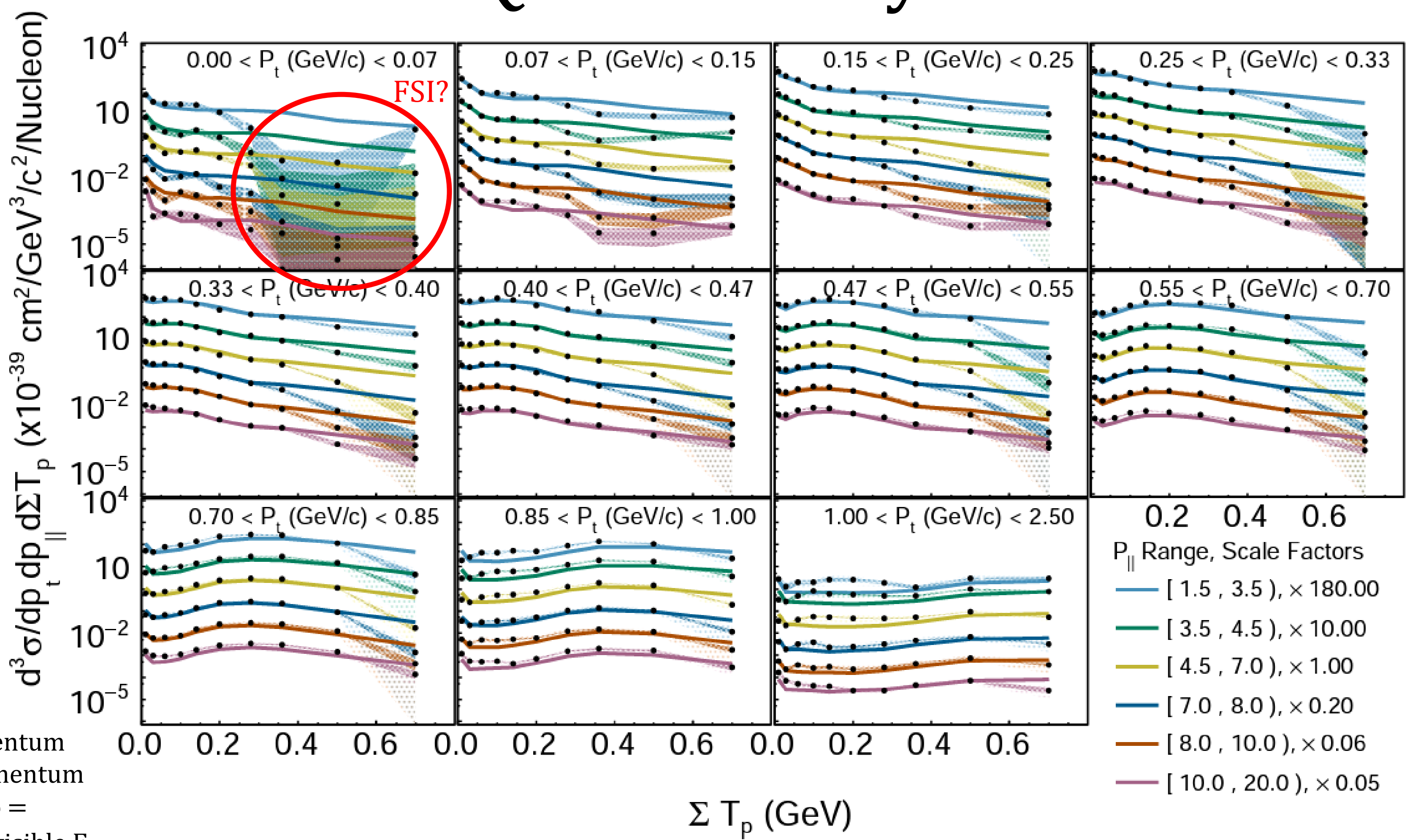
Valencia 2p2h + enhanced 2p2h + reweight non-RES π



3D: arXiv: 2203.08022 (PRL in press!)

QE-like analysis

Topology: $\nu_\mu + A \rightarrow \mu^- + \text{nucleons} + A$



Sensitive to nuclear effects

$\boldsymbol{p_t}$: μ transverse momentum

$\boldsymbol{p_\parallel}$: μ longitudinal momentum

$\boldsymbol{\Sigma T_p}$: sum of KE of all p = calorimetrically visible E

$\boldsymbol{q_0^{QE}}$: Energy component of 4-momentum transfer to nucleus

Important: Significant modelling shortfalls
Well-understood model necessary to make joint fits using multiple experiments!

More incoming!

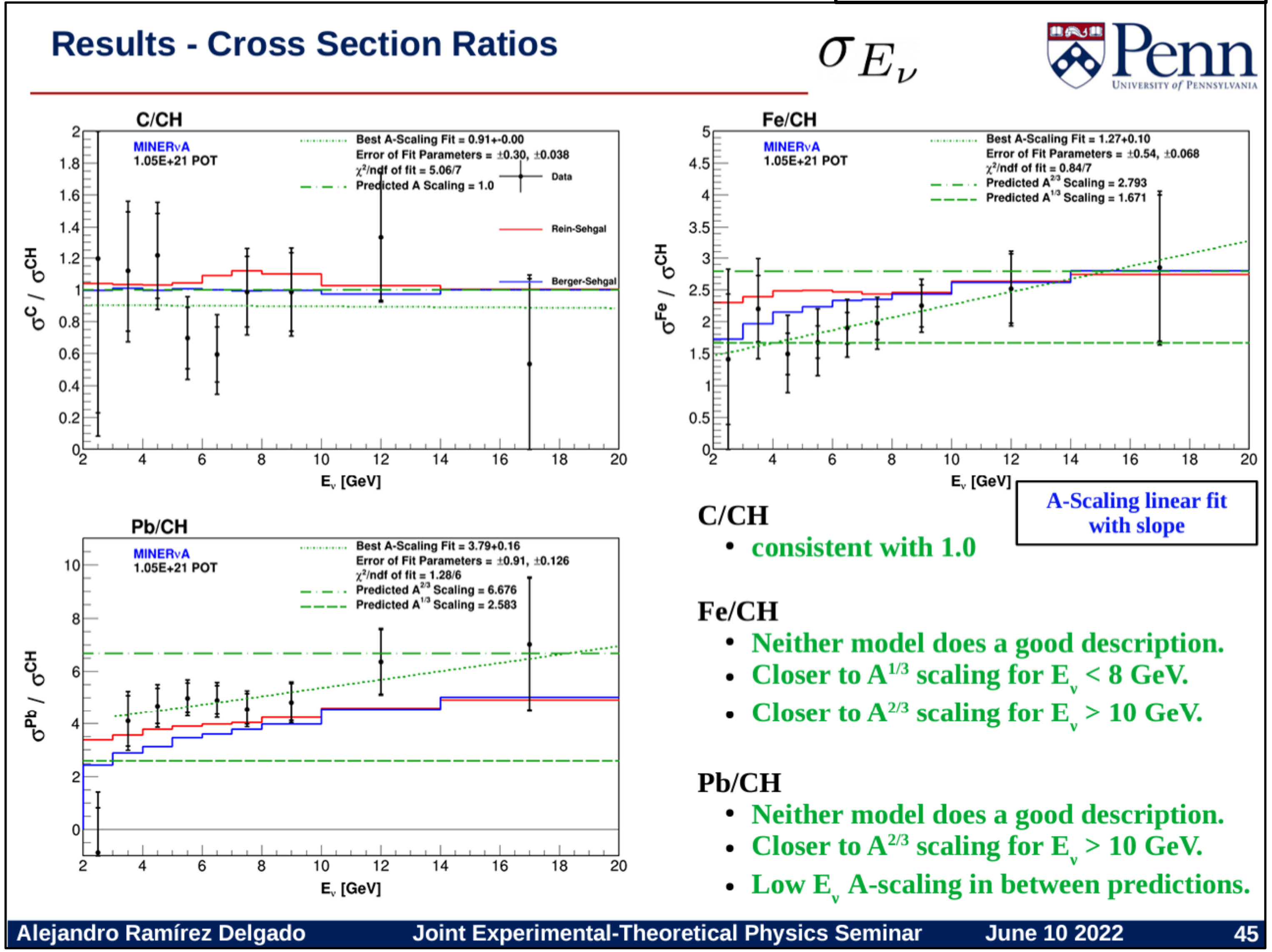
$\nu_\mu + A \rightarrow \mu^- + \pi^+ + A$, rare process (needs very low momentum transfer: very forward lepton + pion)
Nucleus interacts in phase:
no nuclear structure is resolved
(no nuclear effects seen!)

First measurement of COH π^+ production in C, Fe, and Pb

Crucial for testing model predictions: Rein-Sehgal, Berger-Sehgal, Belkov-Kopeliovich...

COH is also an intrinsic background to Heavy Neutral Leptons

Soon to be released on arXiv!



Results - Cross Section Ratios

A-Scaling linear fit with slope

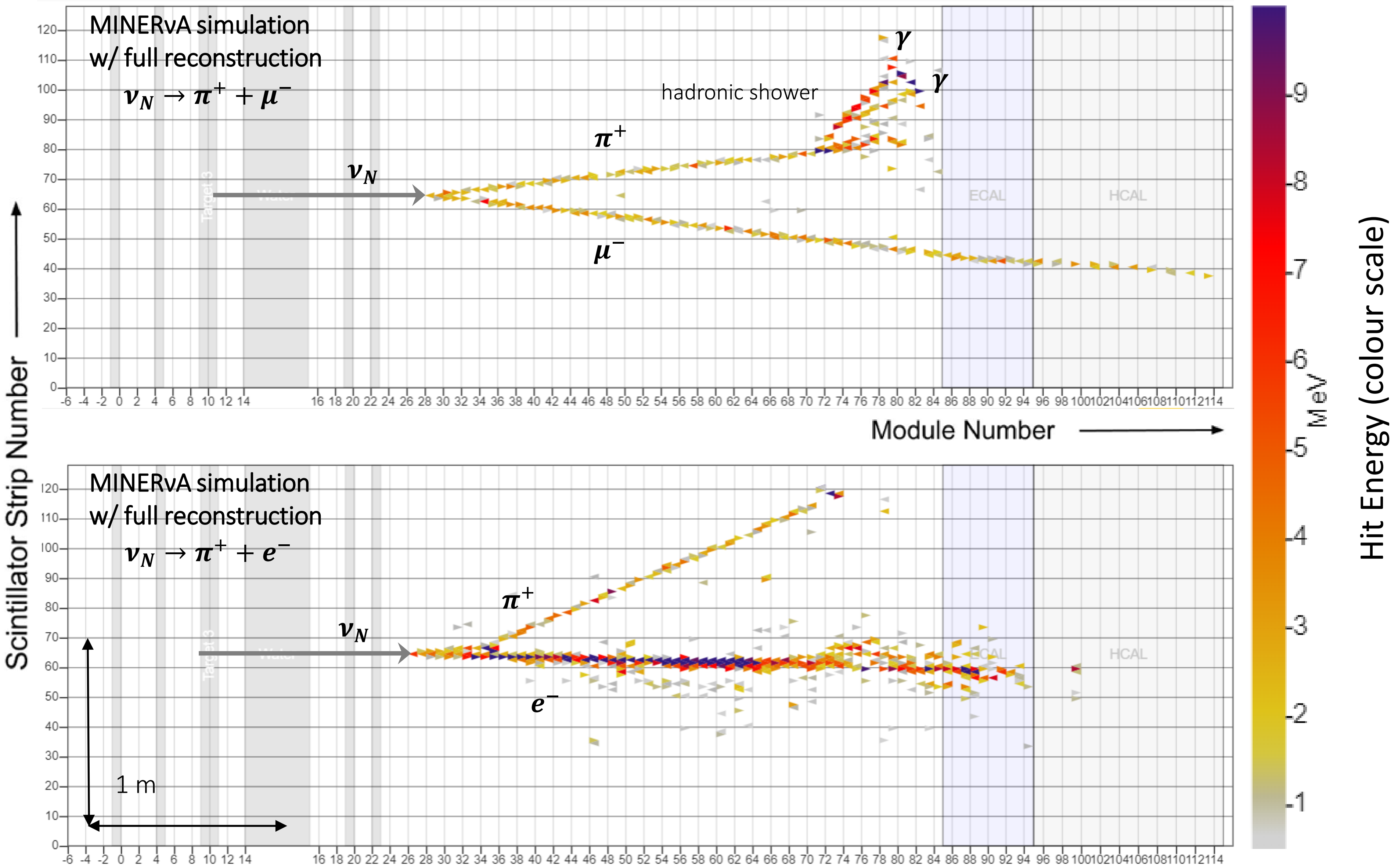
C/CH
- consistent with 1.0

Fe/CH
- Neither model does a good description.
- Closer to $A^{1/3}$ scaling for $E_\nu < 8$ GeV.
- Closer to $A^{2/3}$ scaling for $E_\nu > 10$ GeV.

Pb/CH
- Neither model does a good description.
- Closer to $A^{2/3}$ scaling for $E_\nu > 10$ GeV.
- Low E_ν A-scaling in between predictions.

Alejandro Ramírez Delgado Joint Experimental-Theoretical Physics Seminar June 10 2022 45

Heavy Neutral Leptons?



Outlook

- MINERνA is publishing leading cross section measurements relevant to precision oscillation experiments (present and future!)
- Large ME dataset + analyses now starting to come out
  - **Lots of exciting results incoming in the future!**
  - **What I've talked about + many, many more…**
- Looking forward: MINERνA Analysis Toolkit (MAT) to aid neutrino analyses
  - + data preservation effort: public release of MINERνA data

EPJ Web. Conf. **251** (2021) 03046
arXiv: 2009.04548 [hep-ex]

Try the MAT out!
(click below)

The future looks bright!

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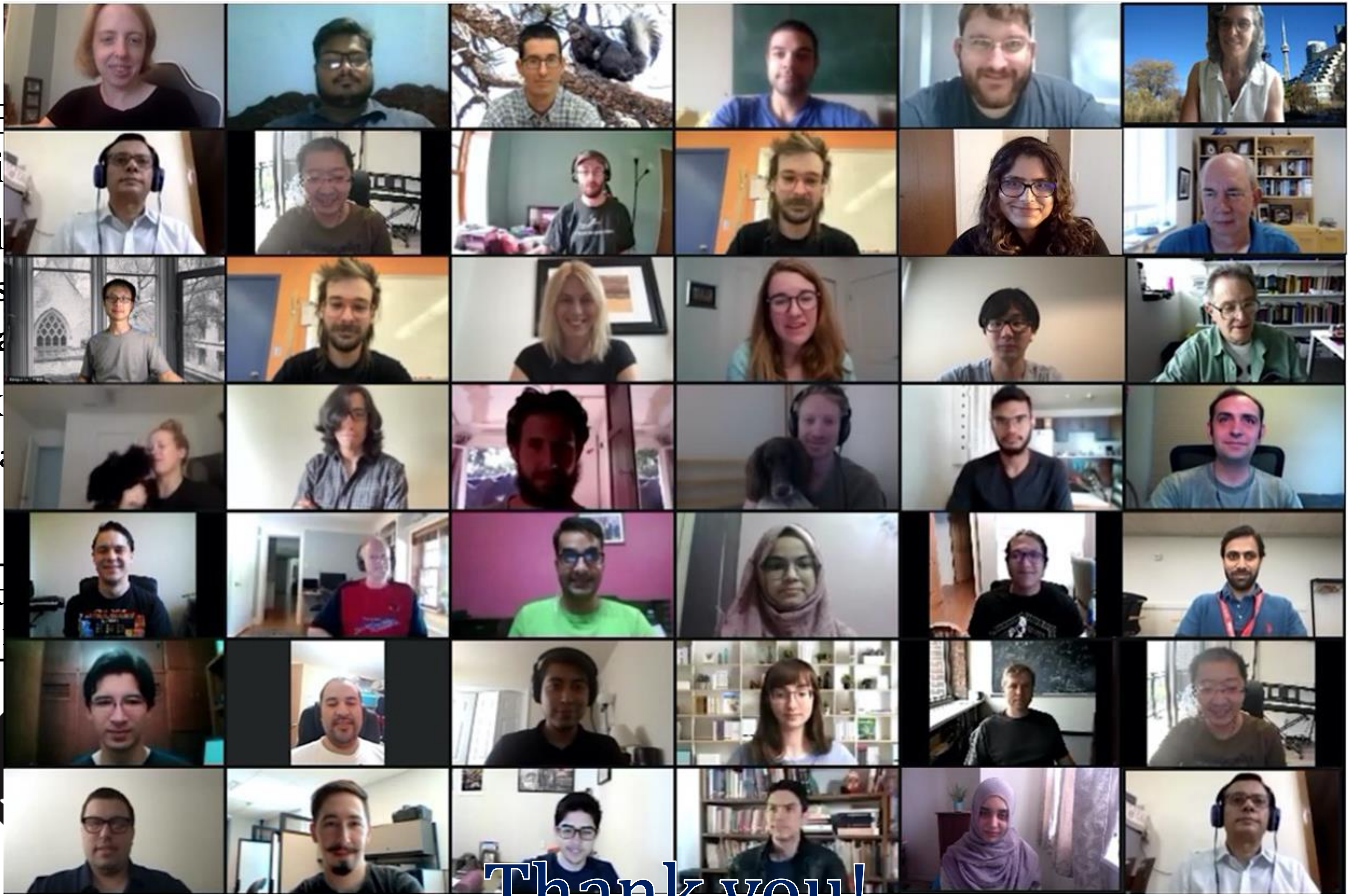
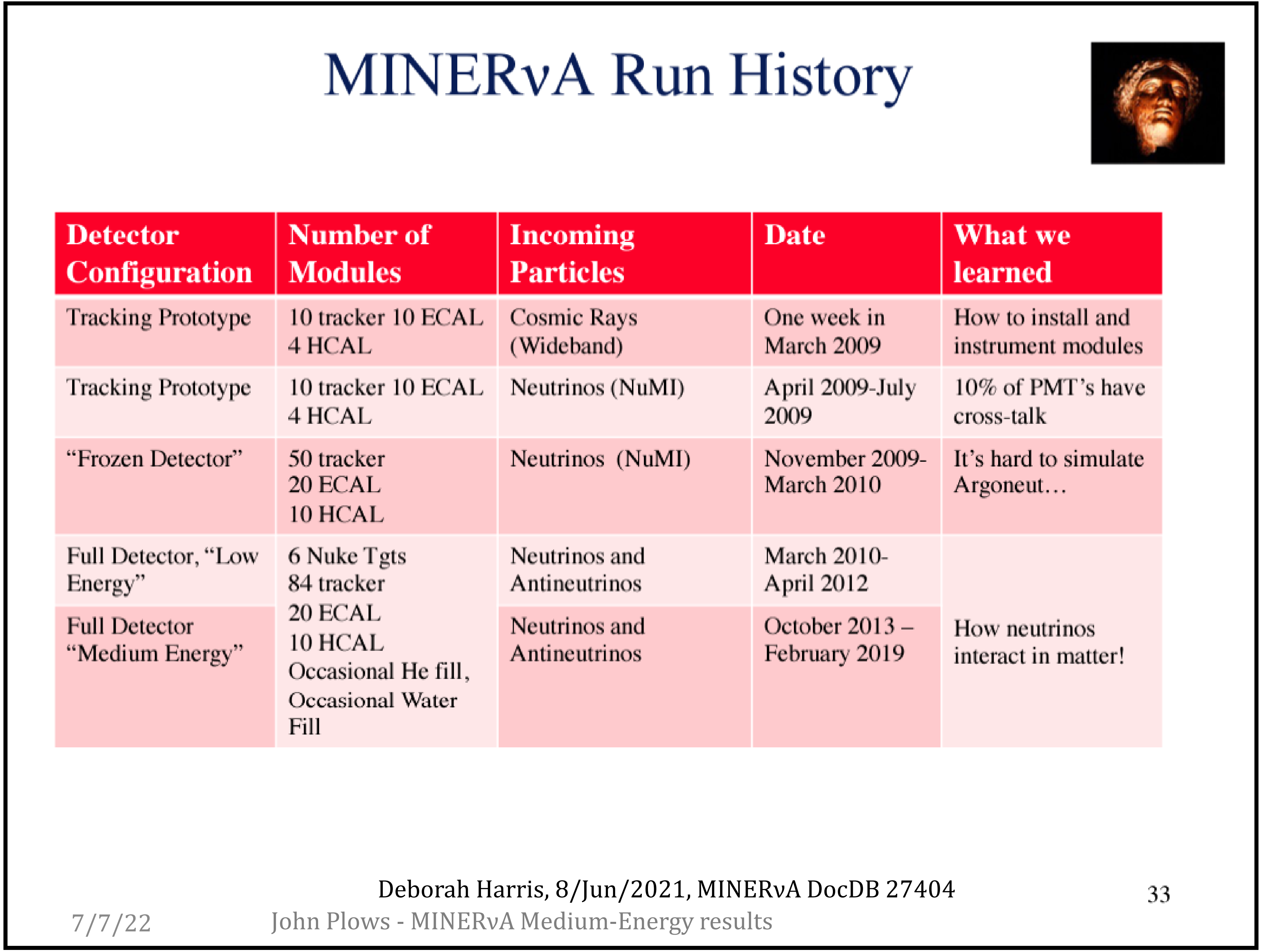


Thank you!

Backup



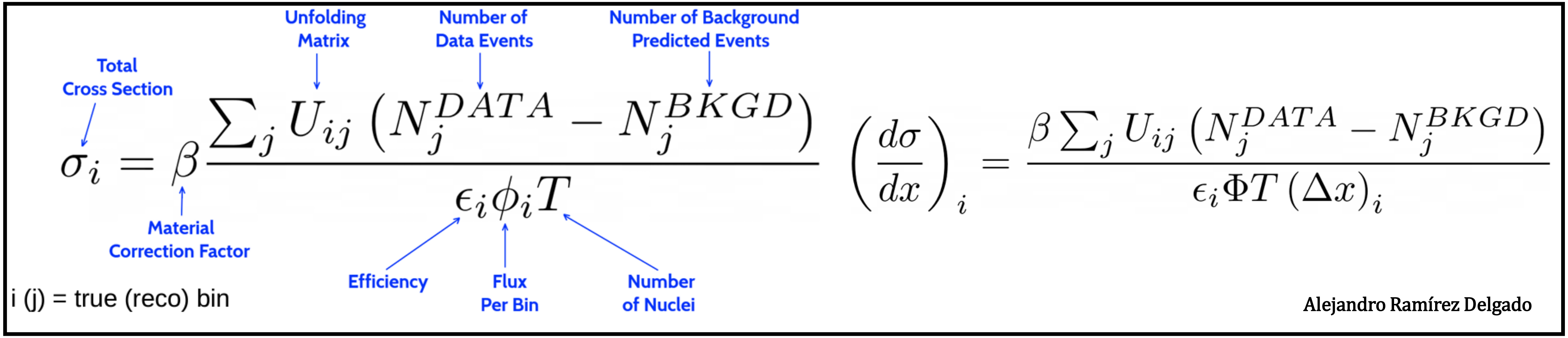
MINERνA Run History

Detector Configuration	Number of Modules	Incoming Particles	Date	What we learned
Tracking Prototype	10 tracker 10 ECAL 4 HCAL	Cosmic Rays (Wideband)	One week in March 2009	How to install and instrument modules
Tracking Prototype	10 tracker 10 ECAL 4 HCAL	Neutrinos (NuMI)	April 2009-July 2009	10% of PMT's have cross-talk
"Frozen Detector"	50 tracker 20 ECAL 10 HCAL	Neutrinos (NuMI)	November 2009-March 2010	It's hard to simulate Argoneut…
Full Detector, "Low Energy"	6 Nuke Tgts 84 tracker 20 ECAL 10 HCAL Occasional He fill, Occasional Water Fill	Neutrinos and Antineutrinos	March 2010-April 2012	How neutrinos interact in matter!
Full Detector "Medium Energy"		Neutrinos and Antineutrinos	October 2013 – February 2019	

Deborah Harris, 8/Jun/2021, MINERνA DocDB 27404

What is a cross section?

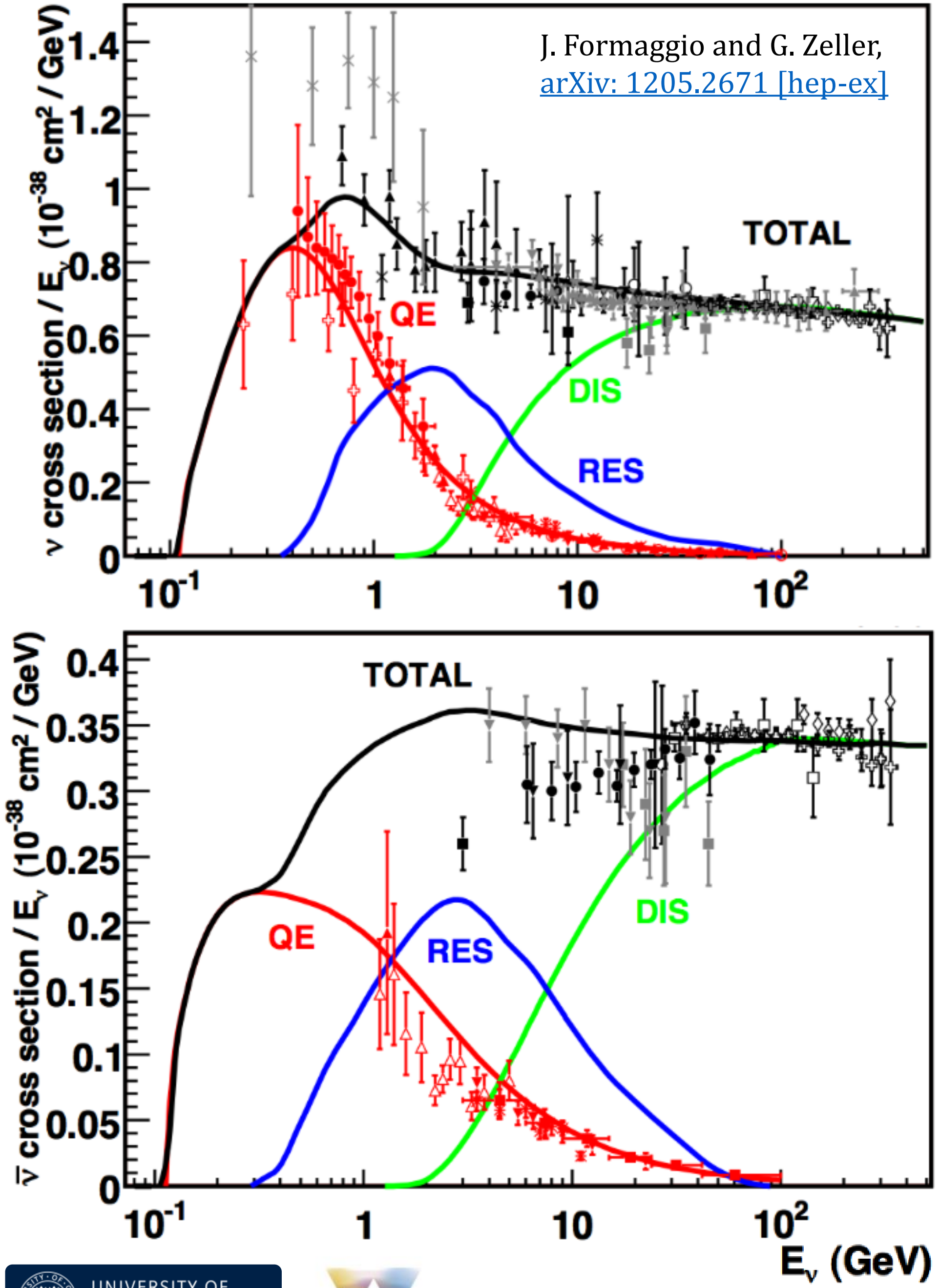
- "Intrinsic scattering probability" (Halzen & Martin, *Quarks and Leptons)*
- For reaction $A + B \rightarrow C + D$: given flux Φ_A $[\mathrm{L}^{-2}\mathrm{T}^{-1}]$ of species A, and number of species B in target $= n_B$, then we expect
$$N_{A+B\rightarrow C+D}[T^{-1}] = \sigma_{A+B\rightarrow C+D}[L^2] \times \Phi_A[L^{-2}T^{-1}] \times n_B$$
- Experimentally, need to relate reconstructed quantities to "true" ones (convolves detector response), detection efficiency, background subtraction…

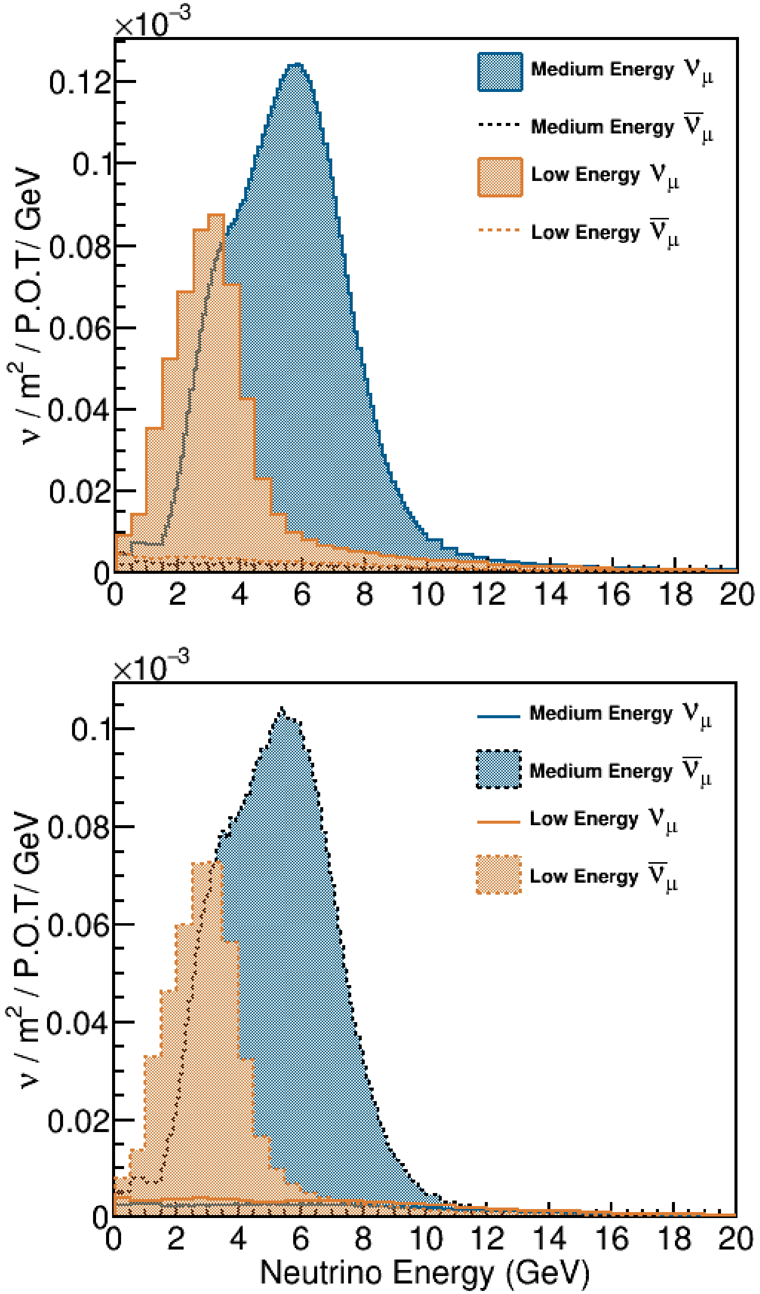


$$\sigma_i = \beta \frac{\sum_j U_{ij}\left(N_j^{DATA} - N_j^{BKGD}\right)}{\epsilon_i \phi_i T} \qquad \left(\frac{d\sigma}{dx}\right)_i = \frac{\beta \sum_j U_{ij}\left(N_j^{DATA} - N_j^{BKGD}\right)}{\epsilon_i \Phi T\,(\Delta x)_i}$$

i (j) = true (reco) bin

Alejandro Ramírez Delgado


J. Formaggio and G. Zeller, [arXiv: 1205.2671 [hep-ex]](https://arxiv.org/abs/1205.2671)



“FHC” (ν mode):

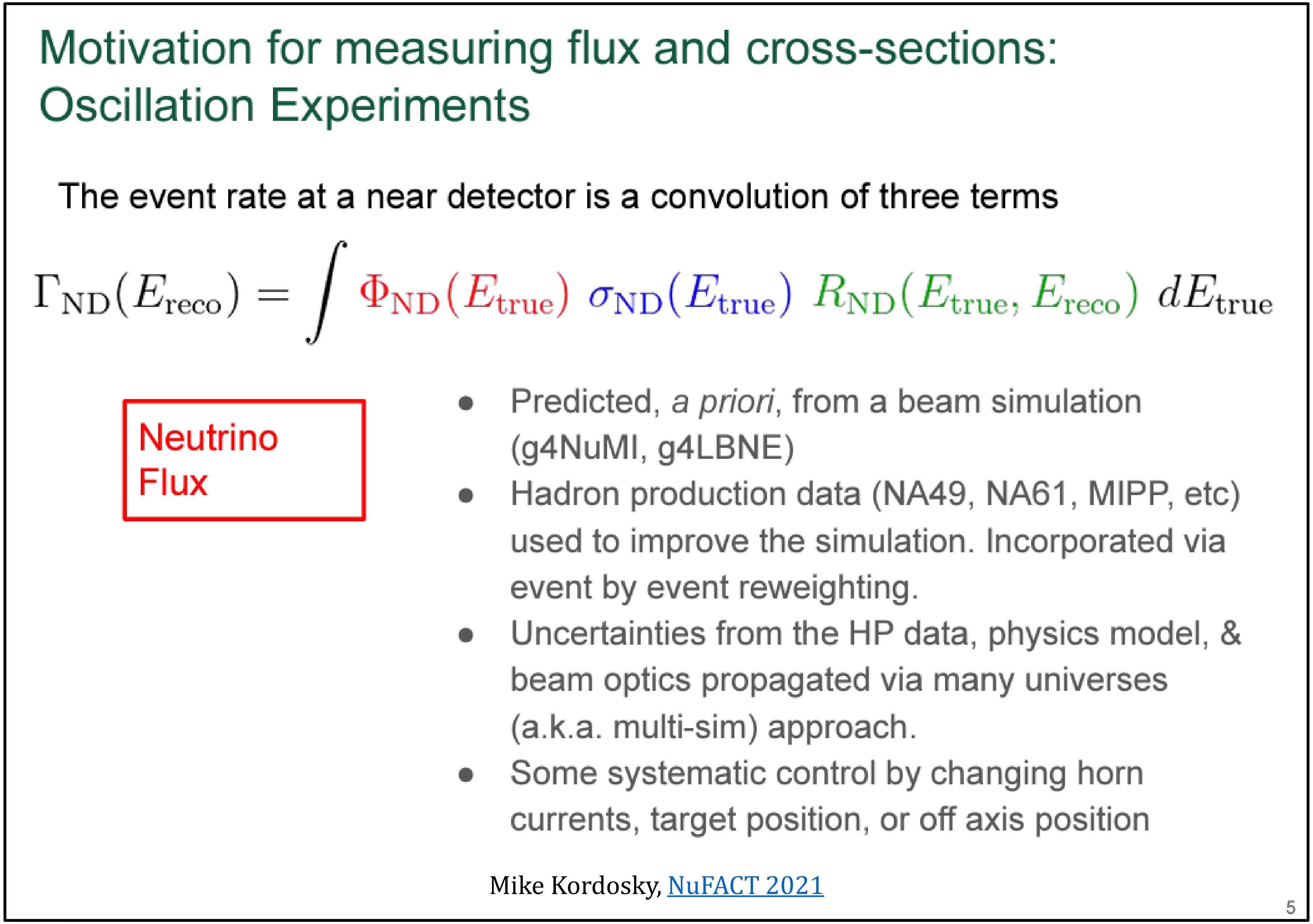
LE POT: 4×10^{20}

ME POT: 12.1×10^{20}

“RHC” ($\bar{\nu}$ mode):

LE POT: 1.7×10^{20}

ME POT: 12.4×10^{20}



Motivation for measuring flux and cross-sections: Oscillation Experiments

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

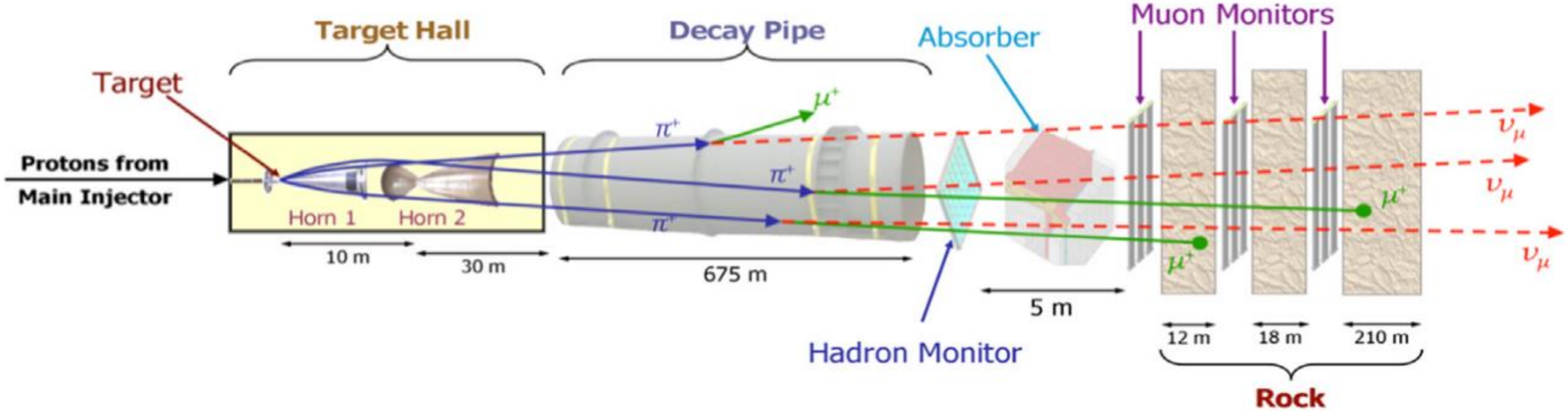
$$\Gamma_{\mathrm{ND}}(E_{\mathrm{reco}}) = \int \Phi_{\mathrm{ND}}(E_{\mathrm{true}})\ \sigma_{\mathrm{ND}}(E_{\mathrm{true}})\ R_{\mathrm{ND}}(E_{\mathrm{true}}, E_{\mathrm{reco}})\ dE_{\mathrm{true}}$$

Neutrino Flux

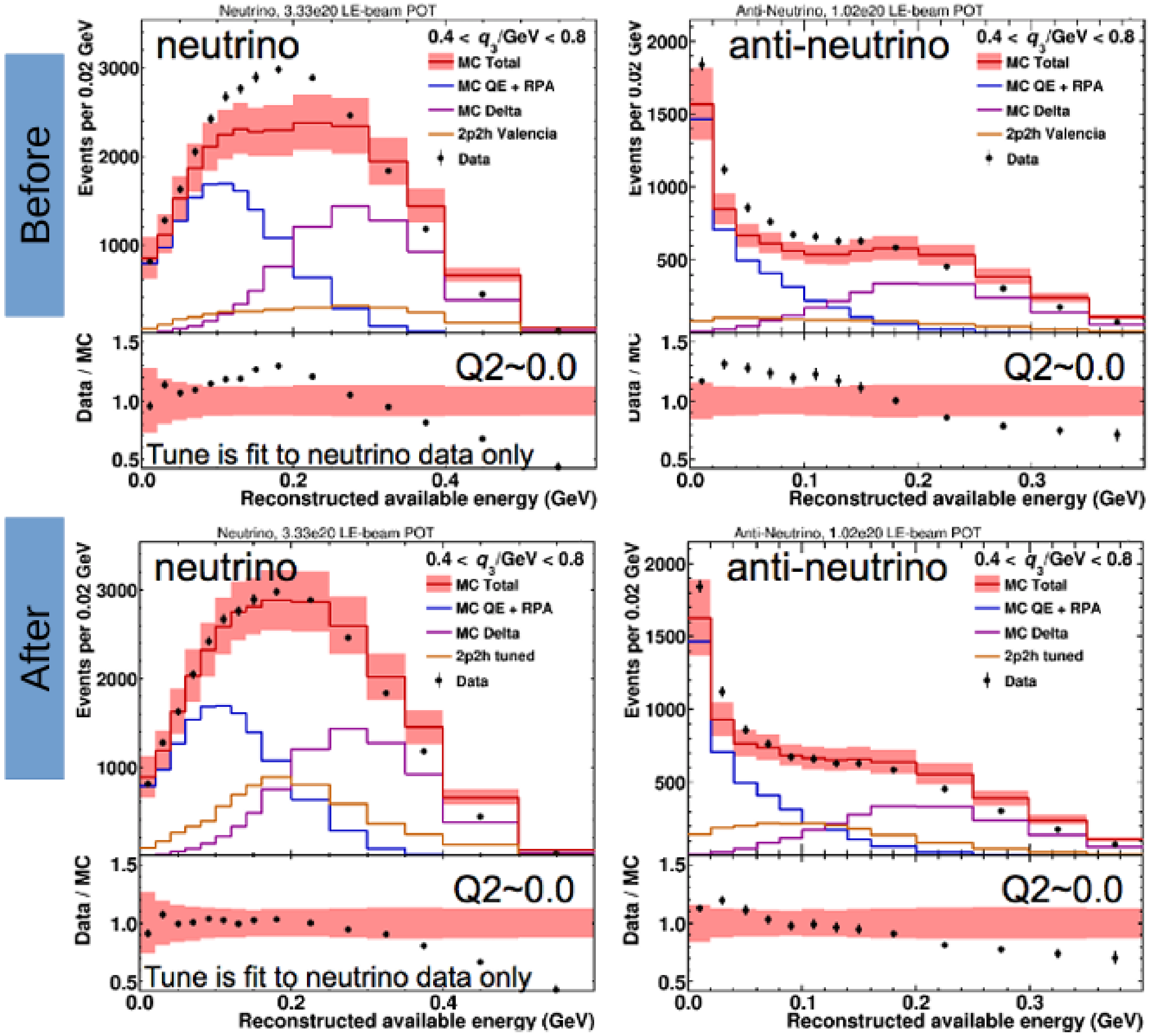
- Predicted, *a priori*, from a beam simulation (g4NuMI, g4LBNE)
- Hadron production data (NA49, NA61, MIPP, etc) used to improve the simulation. Incorporated via event by event reweighting.
- Uncertainties from the HP data, physics model, & beam optics propagated via many universes (a.k.a. multi-sim)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

Mike Kordosky, NuFACT 2021

NIM A **806** (2016) 279-306



“FHC”: $+I_{horn} \Rightarrow$ +’ve hadrons selected $\Rightarrow \nu$ beam
“RHC”: $-I_{horn} \Rightarrow$ -’ve hadrons selected $\Rightarrow \bar{\nu}$ beam



Phys. Rev. Lett. 116, 071802

Phys. Rev. Lett. 120, 221805 (2018)

MnvTune v1

From Low-recoil inclusive LE neutrino analysis

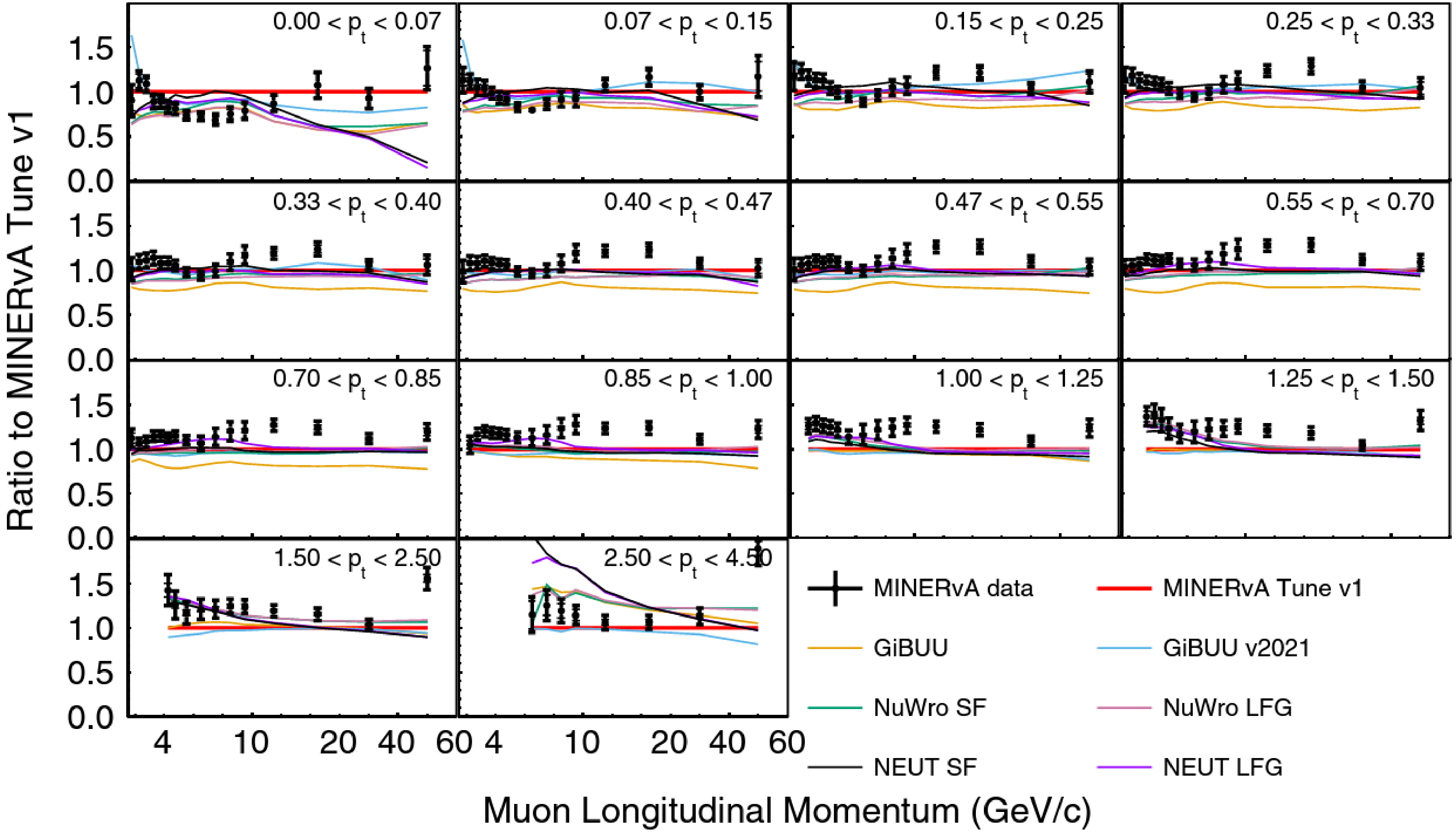
Data excess observed ⇒ tuned our baseline MC model

- Increased 2p2h rate
- Included Random Phase Approximation
- Suppressed non-resonant pion creation

Antineutrino low-recoil measurement was subsequently improved, too!

Andrew Olivier, Fermilab Users' Meeting, 16/Jun/22

2D: [*Phys. Rev. D* **104** (2021) 092007]



Heavy Neutral Leptons?

HNL: Heavy neutrino states that are <u>unstable</u>

Produced in NuMI beam

Decay in MINERνA to final states that mirror COH π production!

More details:

[*Phys. Rev. D* **100** (2019) 052006](https://doi.org/10.1103/PhysRevD.100.052006) (T2K search)

[arXiv:2203.08039 [hep-ph]](https://arxiv.org/abs/2203.08039) (Snowmass overview)