Medium-Energy era results from MINERνA

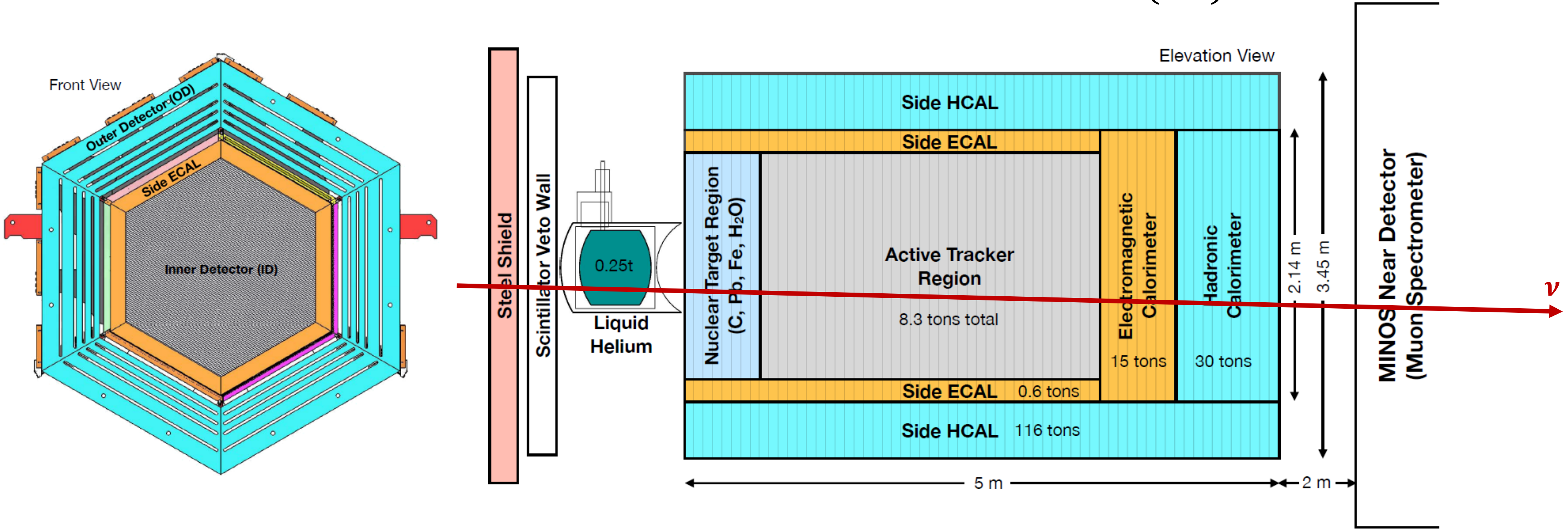
Lake Louise Winter Institute
John Plows, University of Oxford
On behalf of the MINERνA collaboration

23 / Feb / 2022

UNIVERSITY OF OXFORD

The MINERνA experiment @ FNAL

- Neutrino-nuclear (ν-A) interaction measurements
- Located on-axis in NuMI beamline
- Low-energy run 2009-2012
- Medium-energy 2013-2019
- Plastic scintillator (CH) tracker + nuclear targets



Adapted from *NIM A 743* (2014) 130

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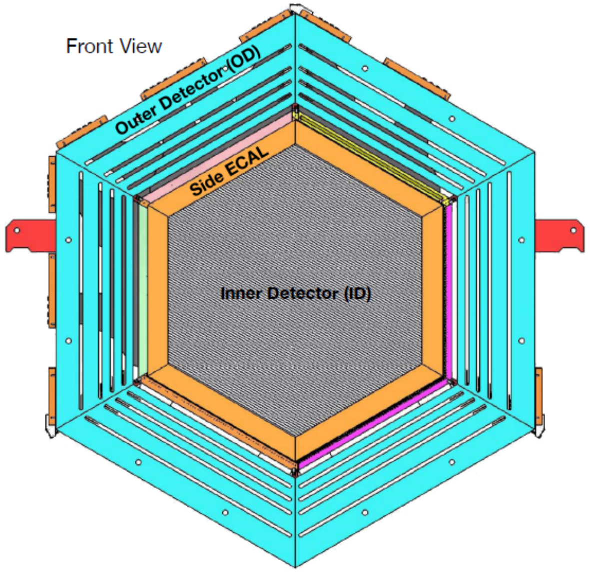
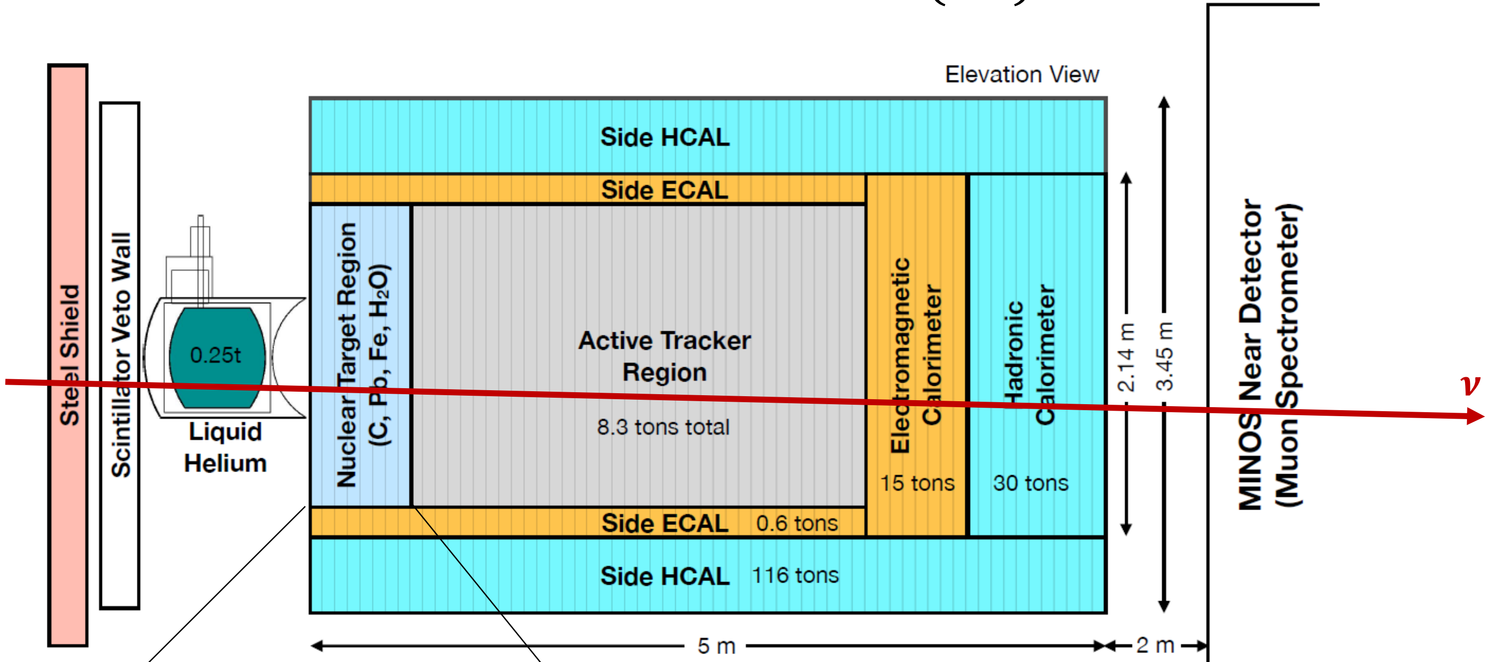
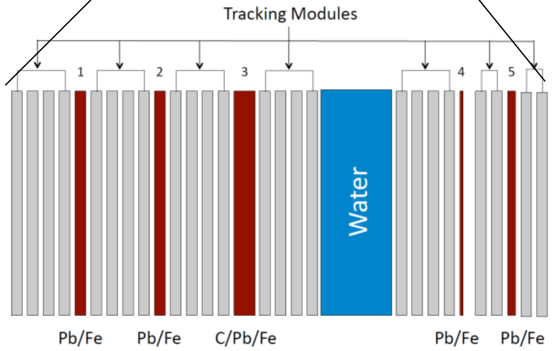
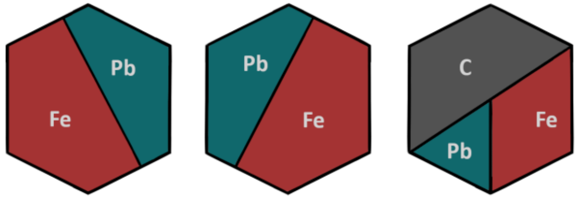


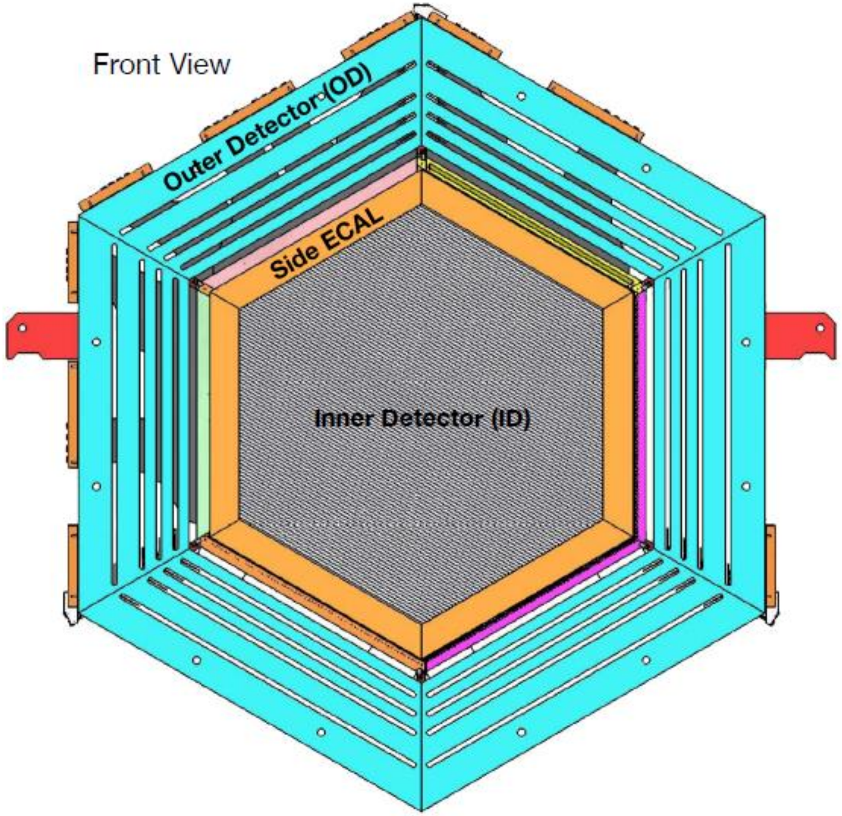


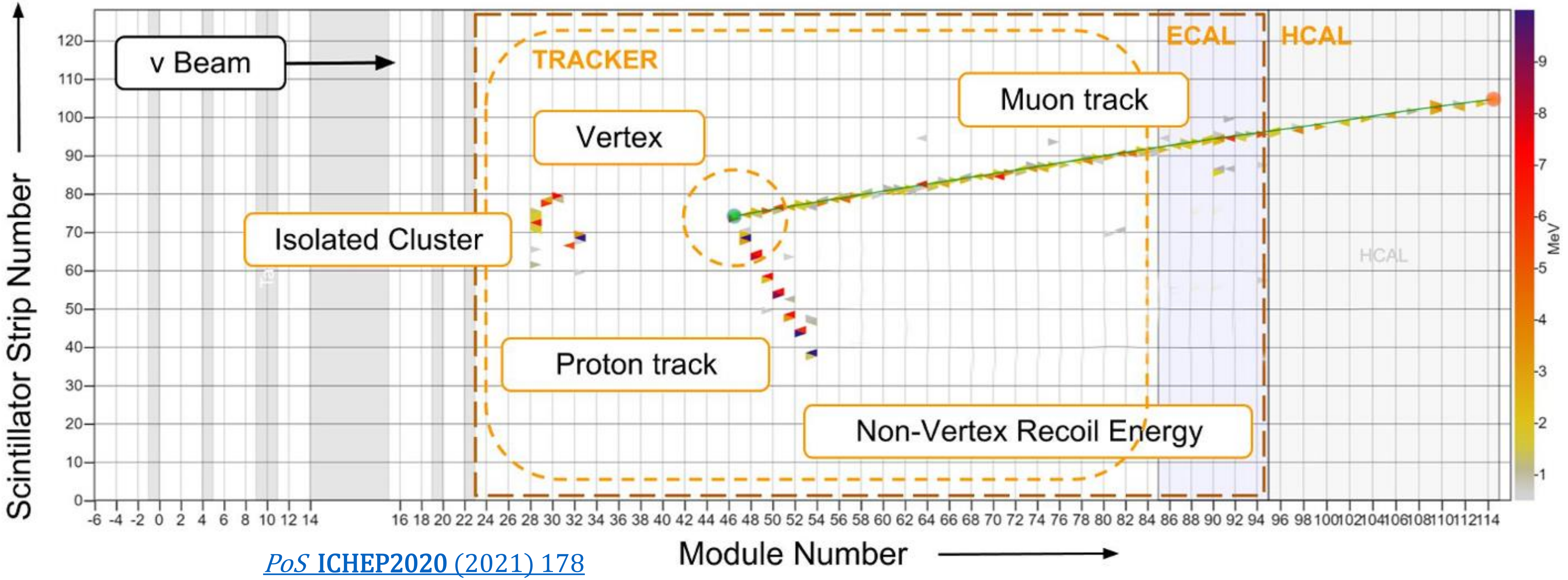




Adapted from *NIM A 743* (2014) 130


The
End


Front View
Outer Detector (OD)
Side ECAL
Inner Detector (ID)



[*PoS* **ICHEP2020** (2021) 178]

For a summary discussion of LE MINERνA results, and ME results up to ~ mid-2021, see this review article:
[*EPJ Special Topics* (2021)]

What’s a cross section?

$$\sigma_i = \beta \frac{\sum_j U_{ij} \left(N_j^{DATA} - N_j^{BKGD}\right)}{\epsilon_i \phi_i T}$$

- Total Cross Section: σ_i
- Material Correction Factor: β
- Unfolding Matrix: U_{ij}
- Number of Data Events: N_j^{DATA}
- Number of Background Predicted Events: N_j^{BKGD}
- Efficiency: ϵ_i
- Flux Per Bin: ϕ_i
- Number of Nucleons: T

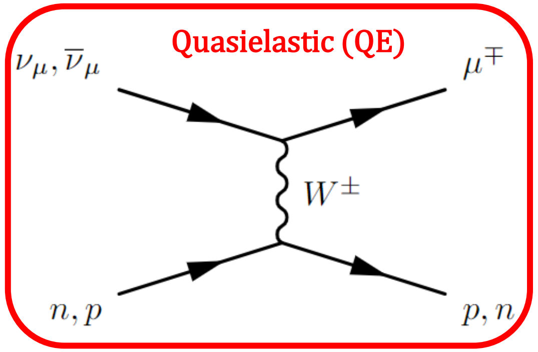
i (j) = true (reco) bin

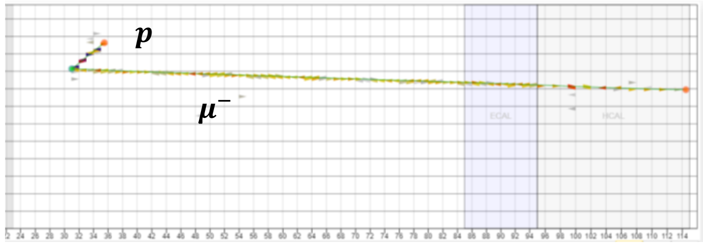
From Alex Ramírez

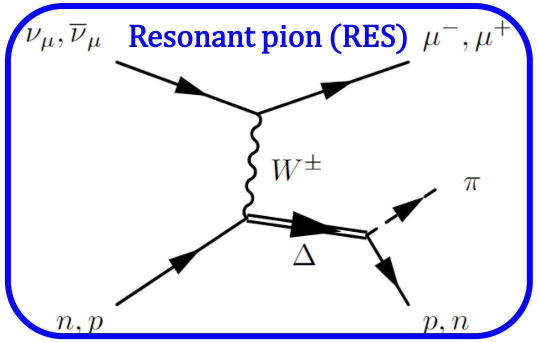
What MINERνA explores…

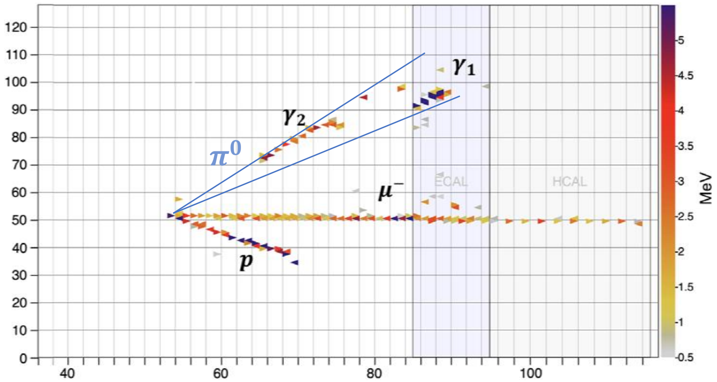
“Inside” the interaction point…

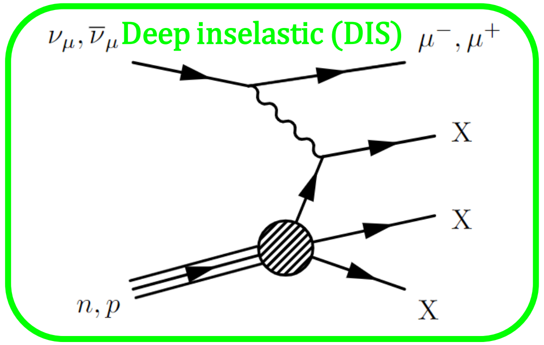
Probes interaction modes!

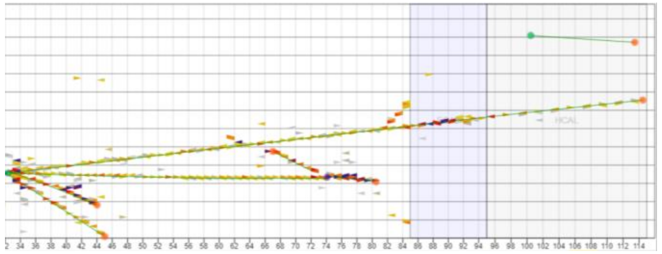






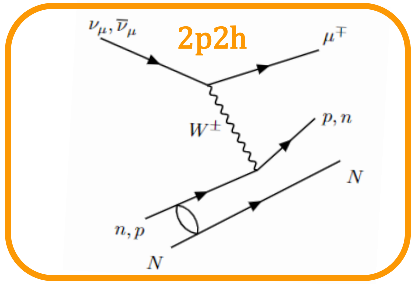


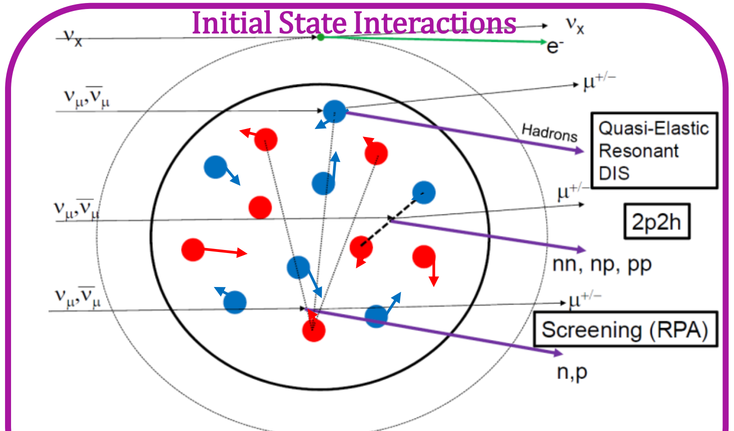




“Outside” the interaction point…

Probes nuclear effects!





Adapted from figure by Dan Ruterbories

+ Fermi motion

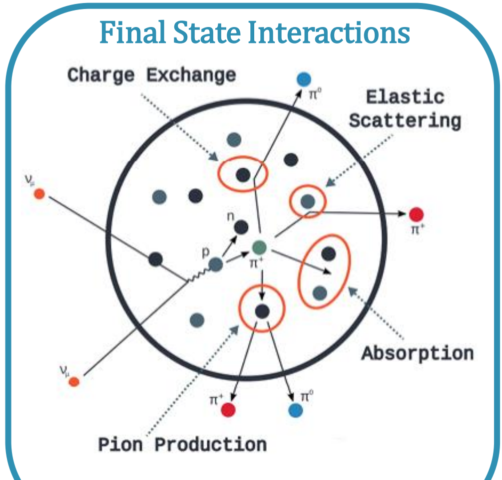
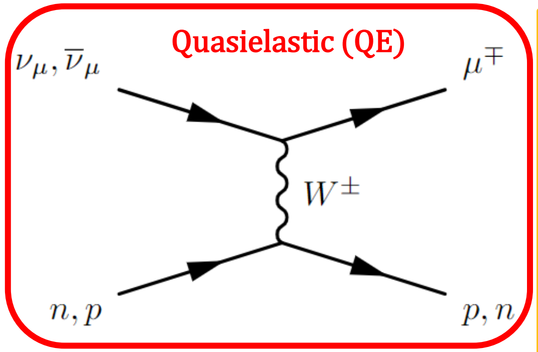


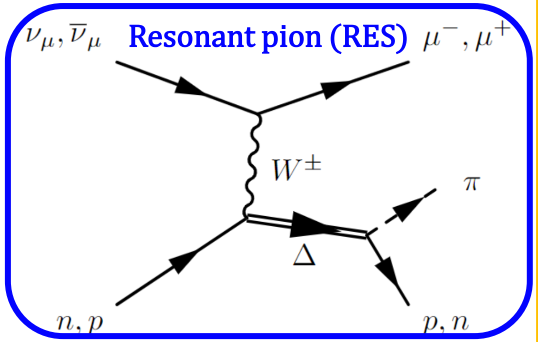
Figure by Tomasz Golan

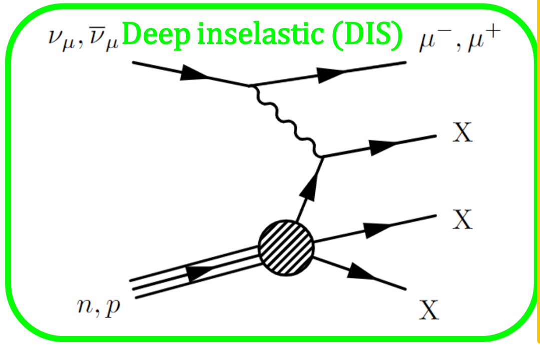
What MINERvA explores…

"Inside" the interaction point…

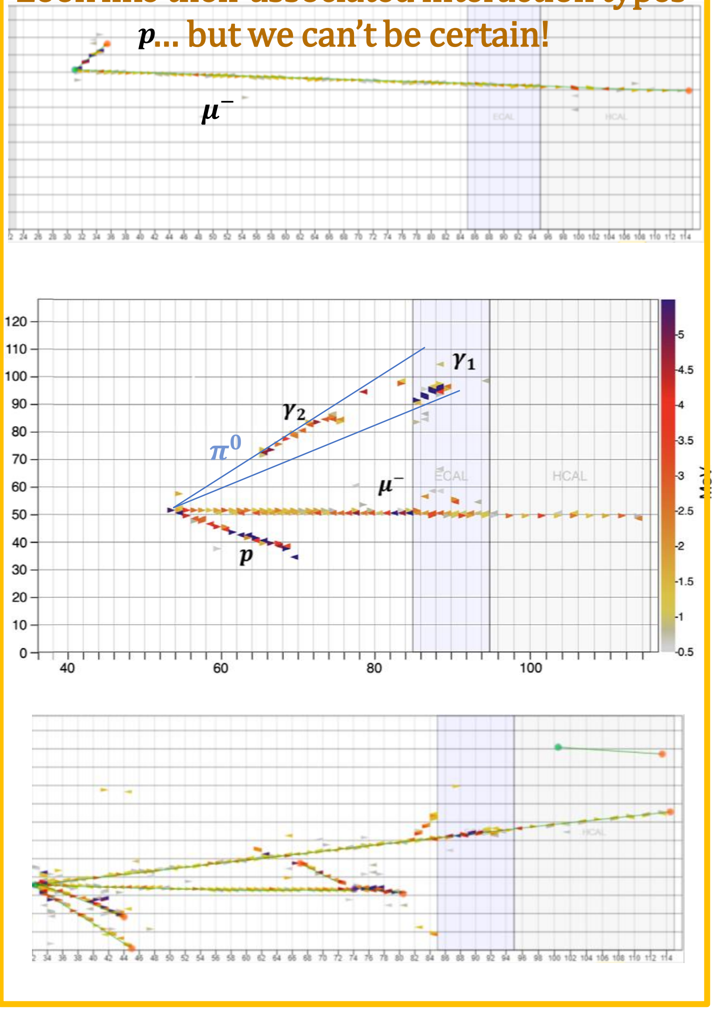
Probes interaction modes!







Look like their associated interaction types



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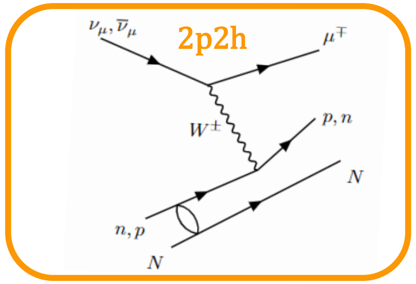
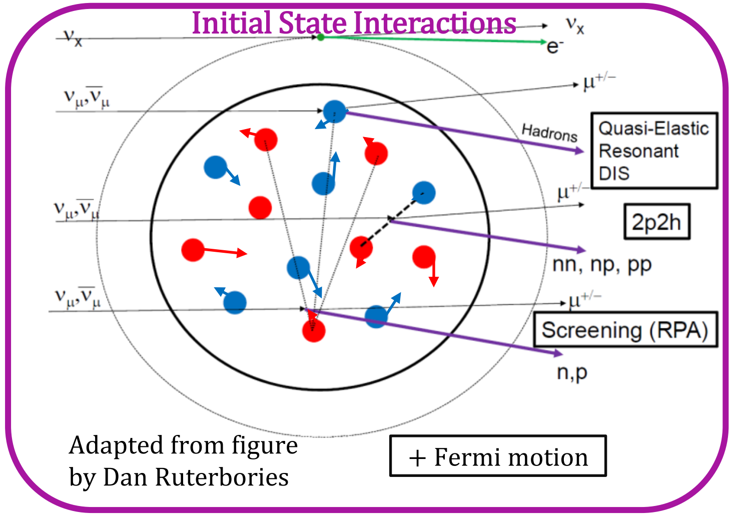
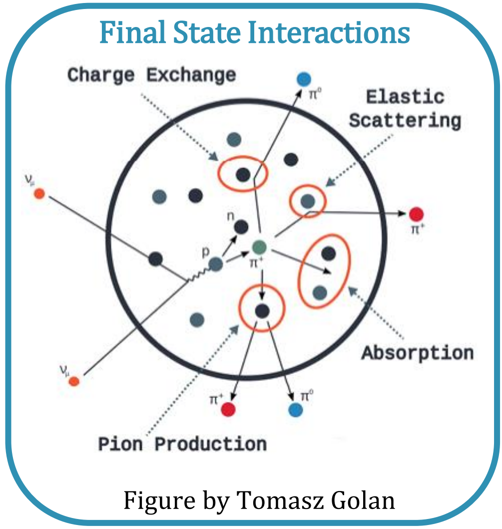
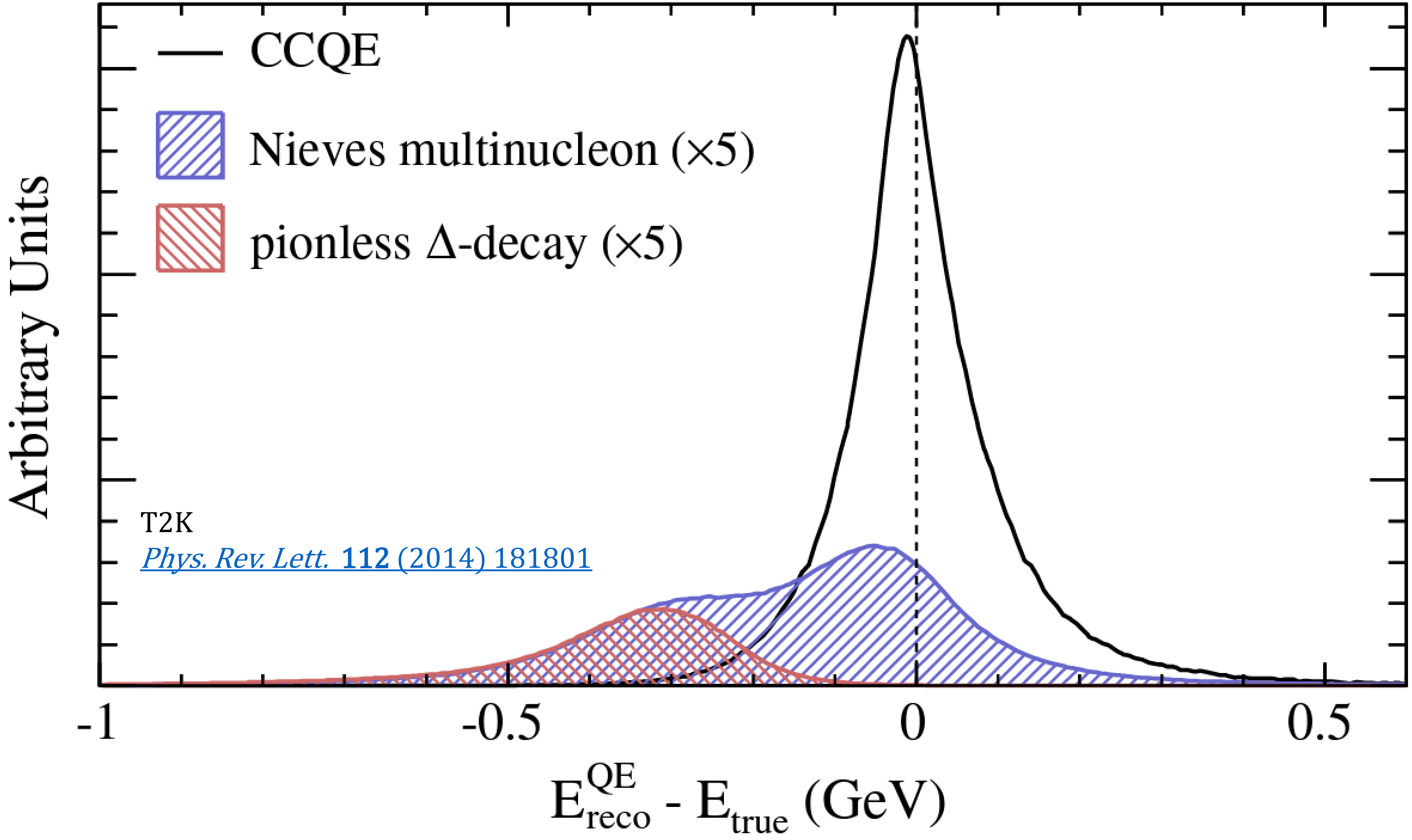
Probes nuclear effects!









T2K
Phys. Rev. Lett. **112** (2014) 181801

WARNING:
Misunderstanding FSI causes
E_ν reconstruction bias

Reconstructing neutrino energy is hard
⇒ need to make assumption about interaction
⇒ must understand nuclear effects on topology (FSI) to reduce reco bias from incorrect assumptions!

Today's topics

"Inside" the interaction point…

Probes interaction modes!

1. Inverse Muon Decay

PHYSICAL REVIEW D **104**, 092010 (2021)

Constraining the NuMI neutrino flux using inverse muon decay reactions in MINERvA

D. Ruterbories,[1] Z. Ahmad Dar,[2,3] F. Akbar,[3] M. V. Ascencio,[4] A. Bashyal,[5] A. Bercellie,[1] M. Betancourt,[6] A. Bodek,[1] J. L. Bonilla,[7] A. Bravar,[8] H. Budd,[1] G. Caceres,[9] T. Cai,[1] M. F. Carneiro,[5,9,*] G. A. Díaz,[1] H. da Motta,[9] J. Felix,[7] L. Fields,[10] A. Filkins,[2] R. Fine,[1,†] A. M. Gago,[4] H. Gallagher,[11] A. Ghosh,[12,9] R. Gran,[13] D. A. Harris,[14,6] S. Henry,[1] D. Jena,[6] S. Jena,[15] J. Kleykamp,[1] M. Kordosky,[2] D. Last,[16] T. Le,[11,17] A. Lozano,[9] X.-G. Lu,[18] E. Maher,[19] S. Manly,[1] W. A. Mann,[11] C. Mauger,[16] K. S. McFarland,[1] A. M. McGowan,[1] B. Messerly,[20,‡] J. Miller,[12] J. G. Morfín,[6] D. Naples,[20] J. K. Nelson,[2] C. Nguyen,[20] A. Norrick,[2] A. Olivier,[1] V. Paolone,[20] G. N. Perdue,[6,1] K.-J. Plows,[18] M. A. Ramírez,[16,7] H. Ray,[21] H. Schellman,[5] C. J. Solano Salinas,[22] H. Su,[20] M. Sultana,[1] V. S. Syrotenko,[10] E. Valencia,[2,7] N. H. Vaughan,[5] A. V. Waldron,[23] B. Yaeggy,[12] K. Yang,[18] and L. Zazueta[2]

(The MINERνA Collaboration)

"Outside" the interaction point…

Probes nuclear effects!

2. Inclusive CC ν_μ in CH

PHYSICAL REVIEW D **104**, 092007 (2021)

Measurement of inclusive charged-current ν_μ cross sections as a function of muon kinematics at $\langle E_\nu \rangle \sim 6$ GeV on hydrocarbon

D. Ruterbories,[1,*] A. Filkins,[2] Z. Ahmad Dar,[2,3] F. Akbar,[3] D. A. Andrade,[4] M. V. Ascencio,[5] A. Bashyal,[6] L. Bellantoni,[7] A. Bercellie,[1] M. Betancourt,[7] A. Bodek,[1] J. L. Bonilla,[4] A. Bravar,[8] H. Budd,[1] G. Caceres,[9] T. Cai,[1] M. F. Carneiro,[6,9,†] G. A. Díaz,[1] H. da Motta,[9] S. A. Dytman,[10] J. Felix,[4] L. Fields,[7,11] R. Fine,[1] A. M. Gago,[5] H. Gallagher,[12] R. Gran,[13] D. A. Harris,[14,7] S. Henry,[1] D. Jena,[7] S. Jena,[15] J. Kleykamp,[1] M. Kordosky,[2] D. Last,[16] T. Le,[12,17] A. Lozano,[9] X.-G. Lu,[18] E. Maher,[19] S. Manly,[1] W. A. Mann,[12] C. Mauger,[16] K. S. McFarland,[1] B. Messerly,[10,‡] J. Miller,[20] J. G. Morfín,[7] D. Naples,[10] J. K. Nelson,[2] C. Nguyen,[21] A. Norrick,[2] A. Olivier,[1] G. N. Perdue,[7,1] M. A. Ramírez,[16,4] H. Ray,[21] H. Schellman,[6] G. Silva,[9] C. J. Solano Salinas,[22] H. Su,[10] M. Sultana,[1] V. S. Syrotenko,[12] E. Valencia,[2,4] A. V. Waldron,[23] C. Wret,[1] B. Yaeggy,[20] K. Yang,[18] and L. Zazueta[2]

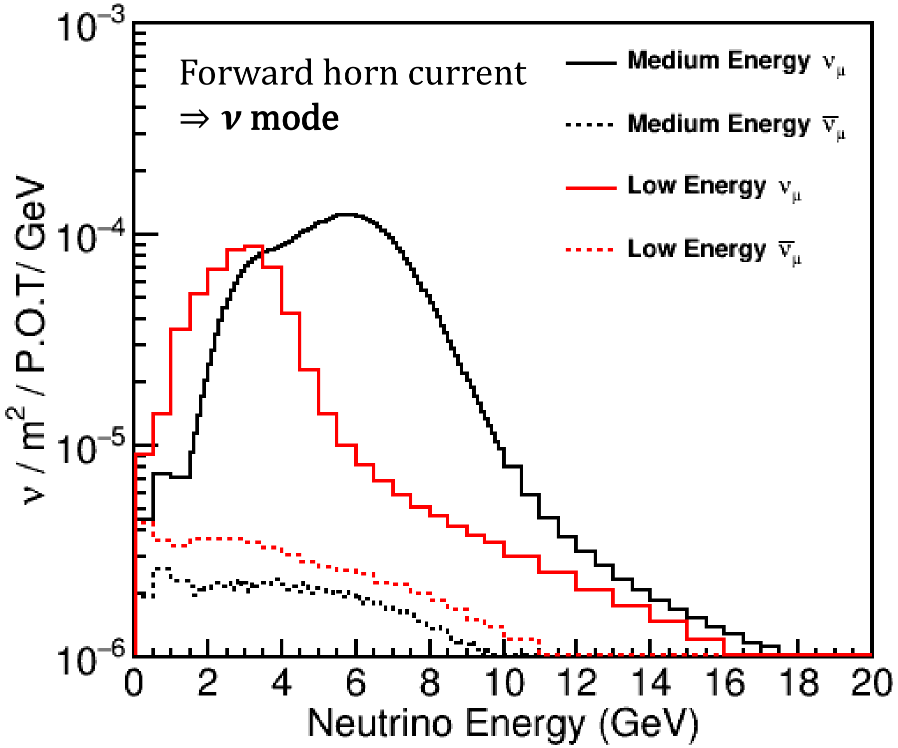
3. Low-recoil inclusive CC ν_μ in CH

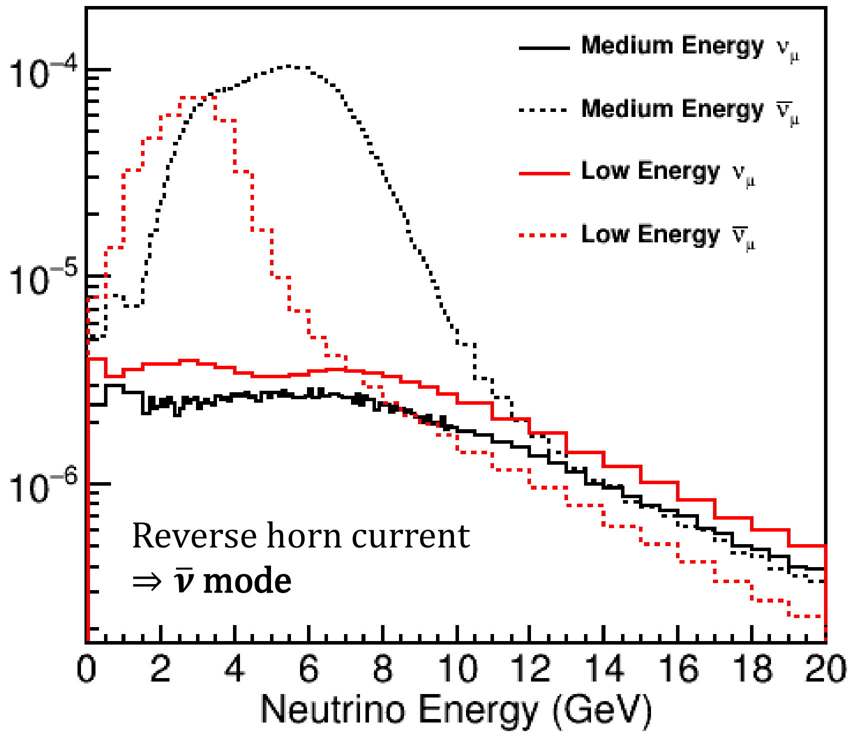
High Energy Physics - Experiment

[Submitted on 26 Oct 2021]

Measurement of inclusive charged-current $v_{\numu}$ scattering on hydrocarbon at {<Enu>} 6 GeV with low three-momentum transfer

M. V. Ascencio, D.A. Andrade, I. Mahbub, Z. Ahmad Dar, F. Akbar, A. Bashyal, S. Bender, A. Bercellie, M. Betancourt, A. Bodek, J. L. Bonilla, K. Bonin, H. Budd, T. Cai, M.F. Carneiro, G.A. Diaz, H. da Motta, J. Felix, L. Fields, A. Filkins, R. Fine, N. Fuad, A.M. Gago, H. Gallagher, A. Ghosh, R. Gran, T. Haluptzok, D. A. Harris, S. Henry, S. Jena, D. Jena, J. Kleykamp, A. Klustova, M. Kordosky, D. Last, A. Lozano, X.-G. Lu, E. Maher, S. Manly, W. A. Mann, C. Mauger, K. S. McFarland, J. Miller, J. G. Morfin, J. K. Nelson, 4C. Nguyen, A. Olivier, V. Paolone, G. N. Perdue, K.-J. Plows, M.A. Ramirez, H. Ray, B.J. Reed, P.A. Rodrigues, D. Ruterbories, H. Schellman, C. J. Solano Salinas, H. Su, M. Sultana, E. Valencia, N.H. Vaughan, A.V. Waldron, C. Wret, B. Yaeggy, K. Yang, L. Zazueta

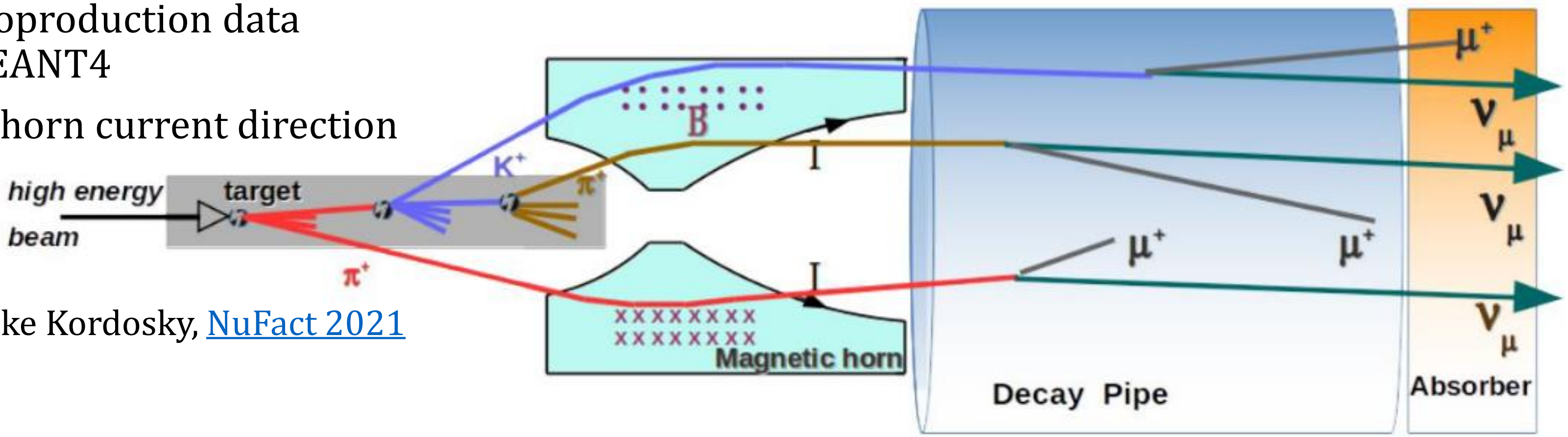




Flux produced by 120 GeV p + C

Using external hadroproduction data (mainly NA49) + GEANT4

Charge selection by horn current direction

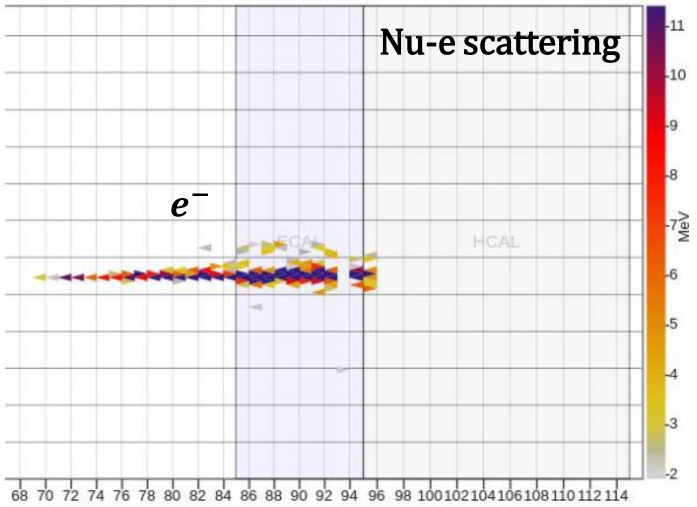


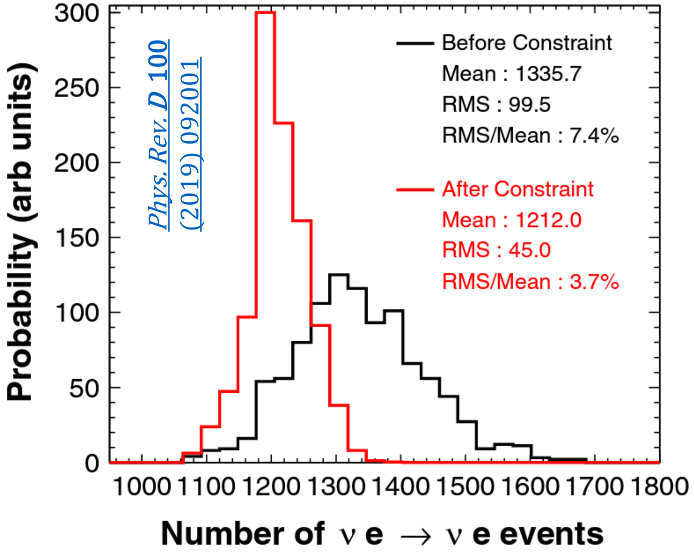
From Mike Kordosky, NuFact 2021

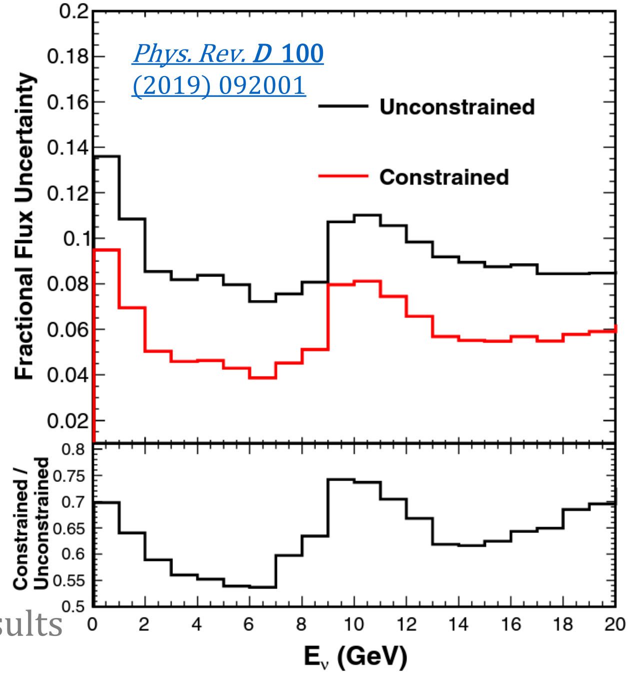
Prelude - non-nuclear interactions

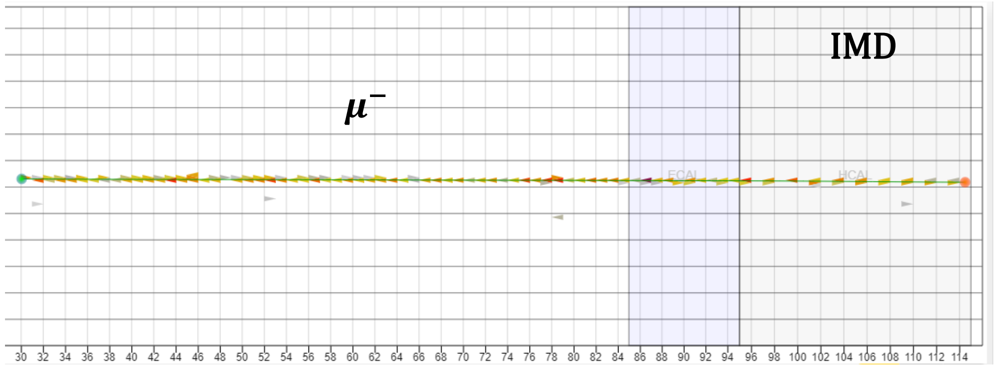
- Crucial to constrain our flux prediction
  - Needed for accurate cross-section measurement!
  - We make nominal flux prediction - some, not total, syst control!

- Solution: use *in situ* measurements to control flux
  - Interactions with low theory uncertainties good probes
    - $\nu_x + e^- \rightarrow \nu_x + e^-$ (nu-e scattering)
    - $\nu_\mu + e^- \rightarrow \nu_e + \mu^-$ (Inverse Muon Decay, IMD)







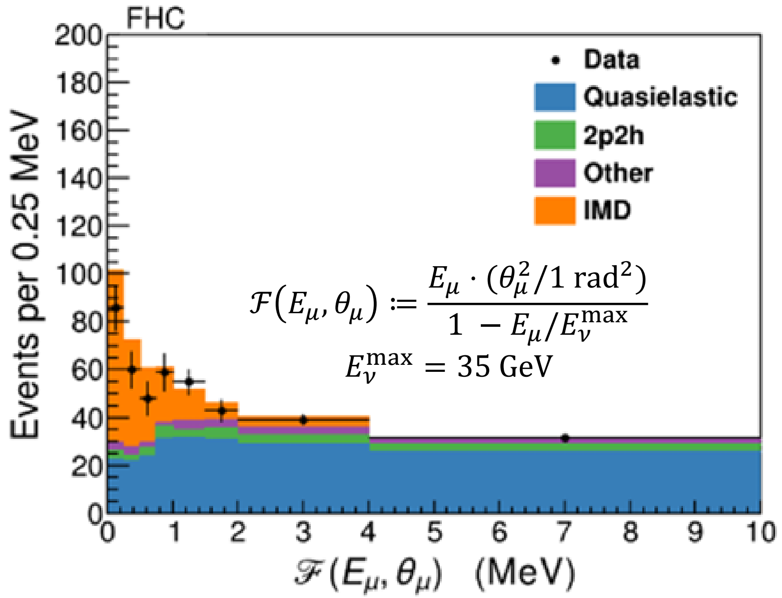


Reduce flux uncertainty ⇒ relevant for DUNE

Inverse Muon Decay

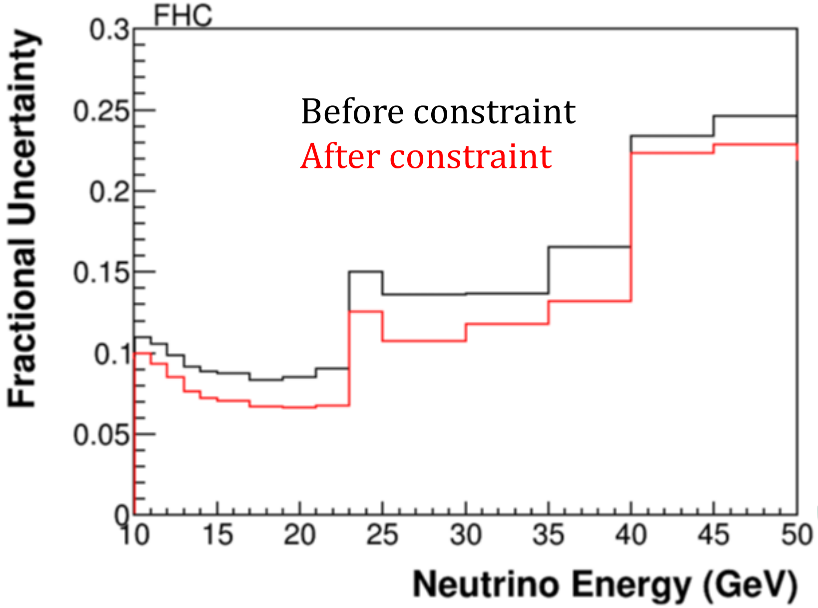
[*Phys. Rev. D* **104** (2021) 092010](#)

- Main idea: Constrain *a priori* flux prediction from g4numi using Bayes' theorem by measuring consistency of flux with N(expected events)



- IMD: $\boldsymbol{\nu_\mu + e^- \rightarrow \nu_e + \mu^-}$ **Signature**: 1 final-state, very energetic + forward muon
  (regular μ decay: $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$: crossing symmetry ⇒ same matrix element)
  - $\sqrt{s} \geq \frac{m_\mu^2 - m_e^2}{2m_e} \simeq 11$ GeV

- 127 cand. ν mode, 56 cand. $\bar{\nu}$ mode
  2 reasons for rarity - low cross-section
  AND much smaller flux
  (threshold @ 11 GeV ==> long, low flux tails)



Viable *in situ* measurement to reduce flux systematics!

Low-recoil + flux

cf. flux normalization with IMD

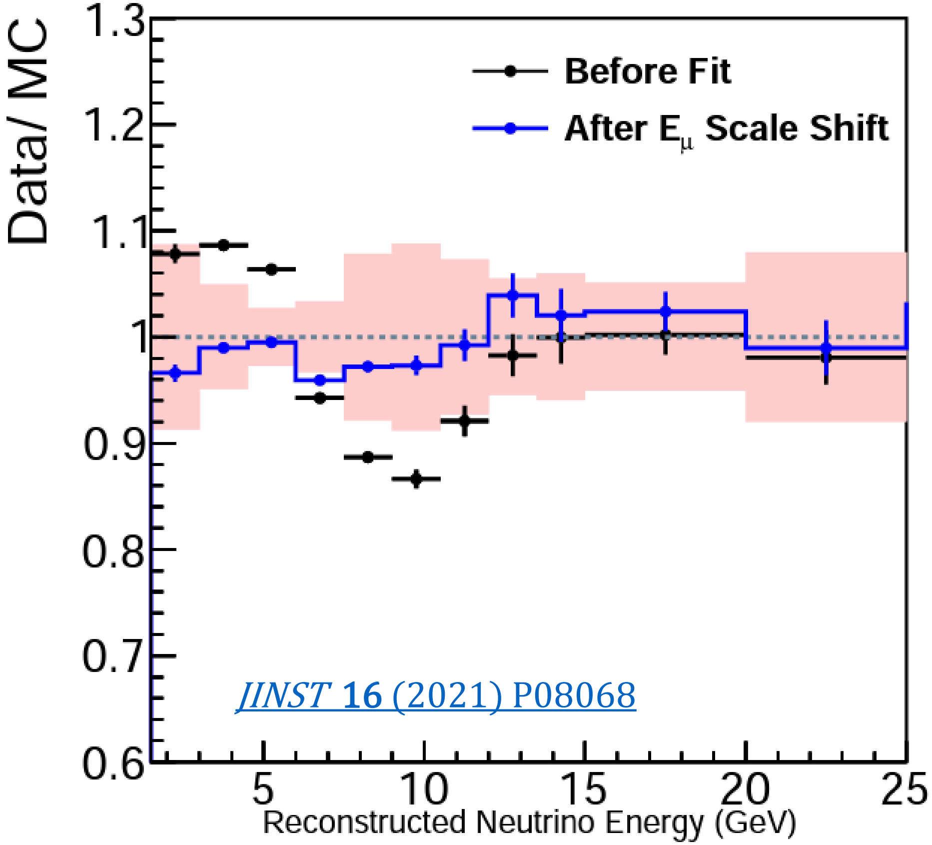
- MINERνA have also exploited low-recoil (ν) interactions to constrain flux shape

$$\frac{d\sigma}{d\nu} = \frac{G_F^2 M_{\text{nucleon}}}{\pi}\left(F_2\left(1 - \frac{\nu}{E_\nu}\right) + \frac{\nu}{E_\nu}\int_0^1 dx\,\left(xF_3 + \mathcal{O}(E_\nu^{-1})\right)\right) \simeq \frac{G_F^2 M_{\text{nucleon}}}{\pi} F_2$$

⇒ detected strange "wiggle" (black points) in flux shape!

⇒ either **1.8σ shift in E_μ scale (3.6%)** or ~10σ shift in target position
→ latter outside tolerance

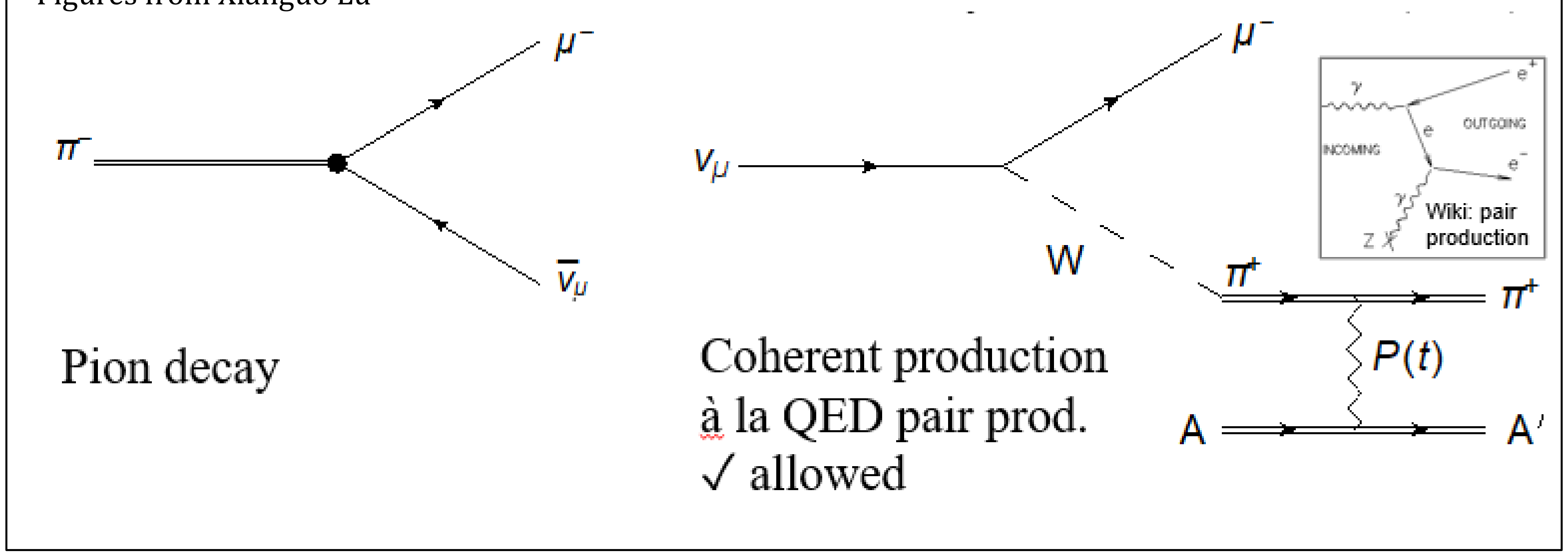
⇒ Shift in E_μ scale gives consistent result (blue)!



JINST **16** (2021) P08068

Another inverse decay?

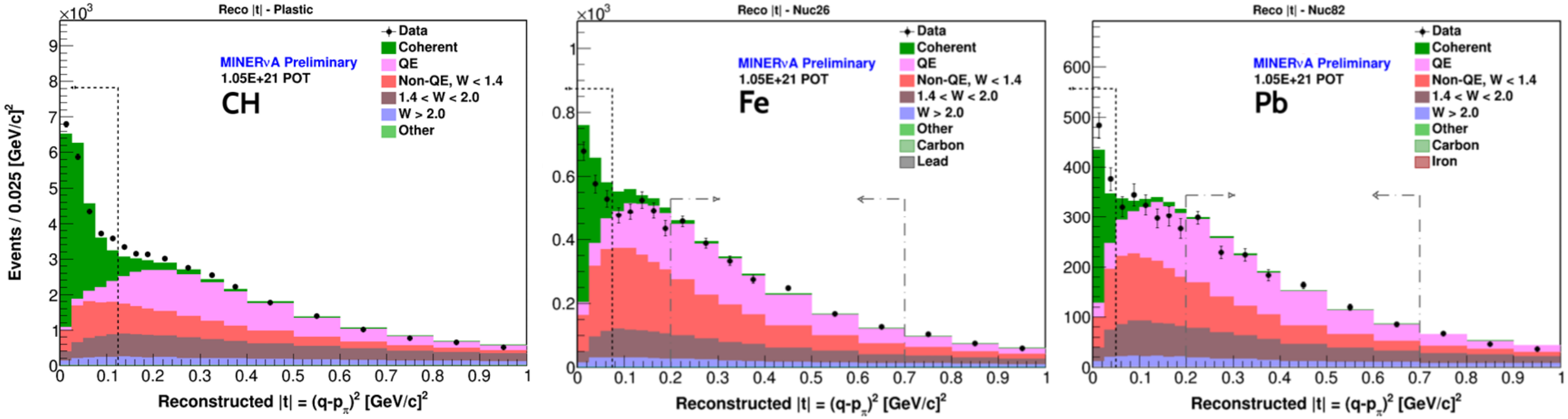
Figures from Xianguo Lu



Very rare interaction which <u>doesn't resolve nuclear structure</u>!
Vacuum-quantum-number (Pomeron) exchange with nucleus

Signature: 1 muon & 1 pion in the forward direction
(nucleus is **invisible** due to really low recoil)

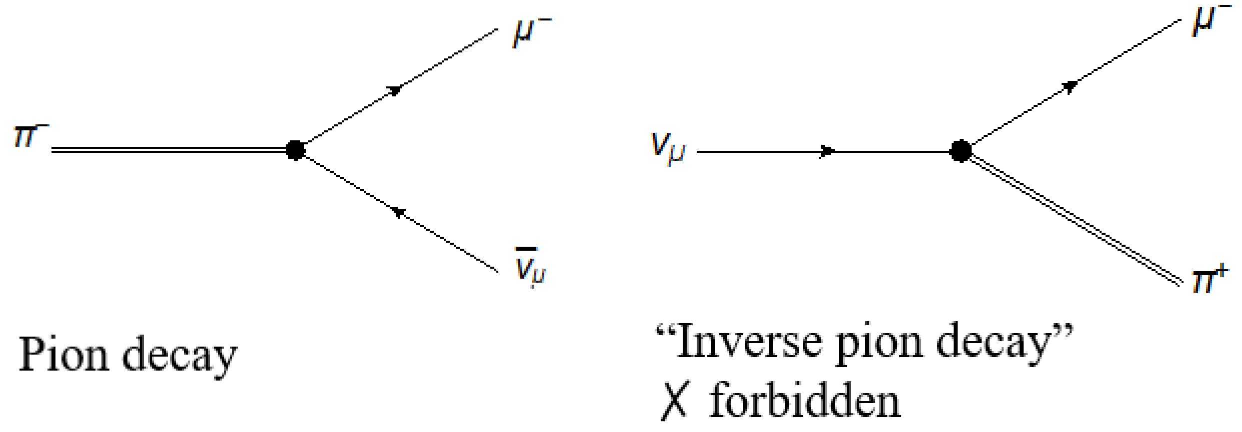
Figures from Alex Ramírez



MINERvA have published leading measurements in tracker CH before
Analysis of COH in nuclear targets upcoming - watch this space!

Another inverse decay?

Figures from Xianguo Lu



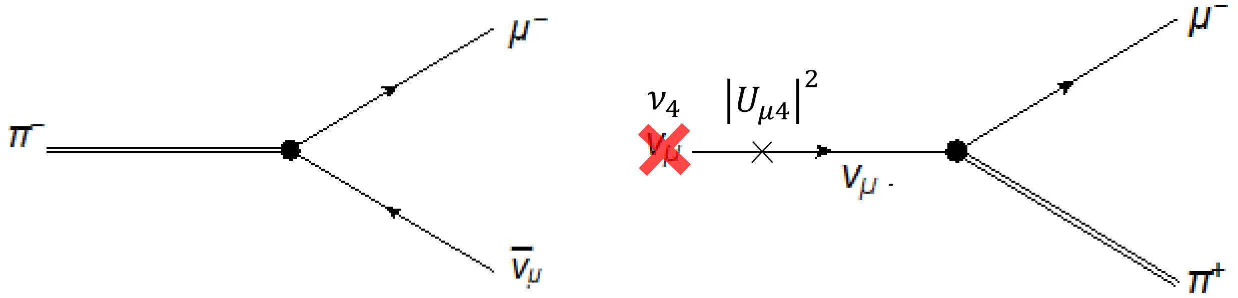
MINERνA analysis that is…
not an interaction at all!
Decay - HNL == BSM particle hypothesized as a consequence of neutrinos having mass

Signature: … also muon + pion in the forward direction (at least this particular decay mode - can be e.g. electron + pion if HNL heavy enough)
⇒ study COH as a SM background!

Another inverse decay?

BSM analysis!

Figures from Xianguo Lu



Pion decay

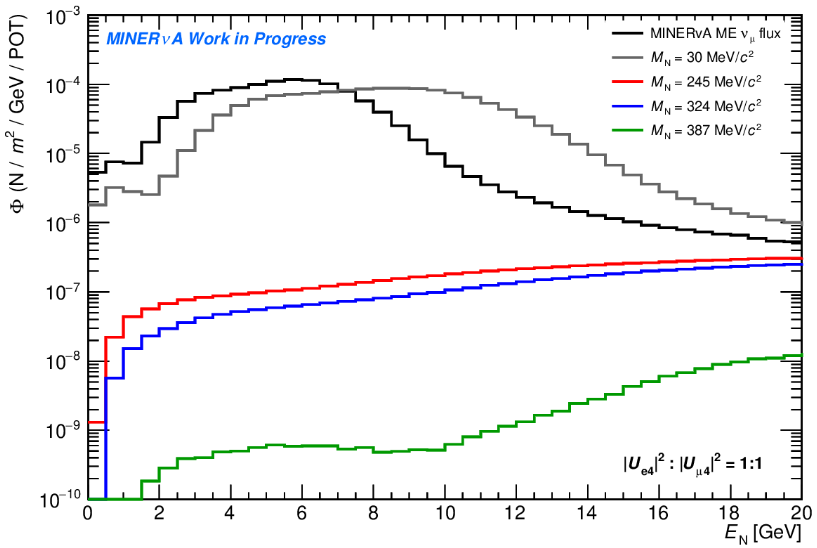
"Inverse pion decay"

✓ IF ν_μ is replaced by a heavy neutrino (heavy neutral lepton)

MINERvA analysis that is…
not an interaction at all!
Decay - HNL == BSM particle hypothesized as a consequence of neutrinos having mass

Signature: … also muon + pion in the forward direction (at least this particular decay mode - can be e.g. electron + pion if HNL heavy enough)
⇒ study COH as a SM background!

ME fluxes at tracker centre, FHC

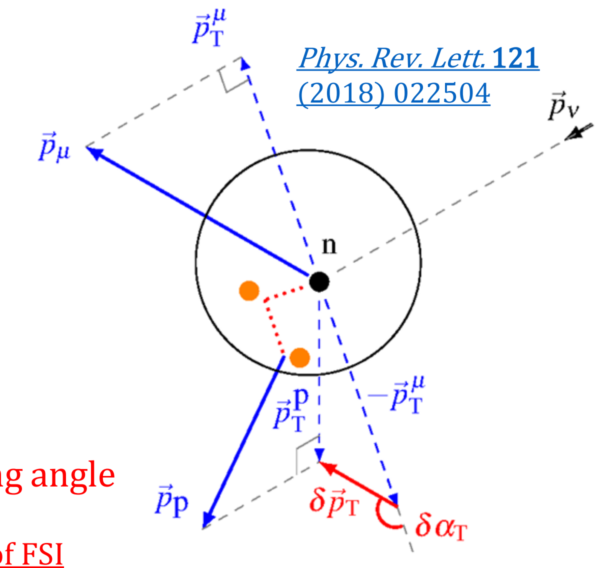


MINERvA has high-powered flux
+ large dataset
+ leading background reduction

⇒ good chance to detect HNL or
to provide leading constraints on HNL parameter space!

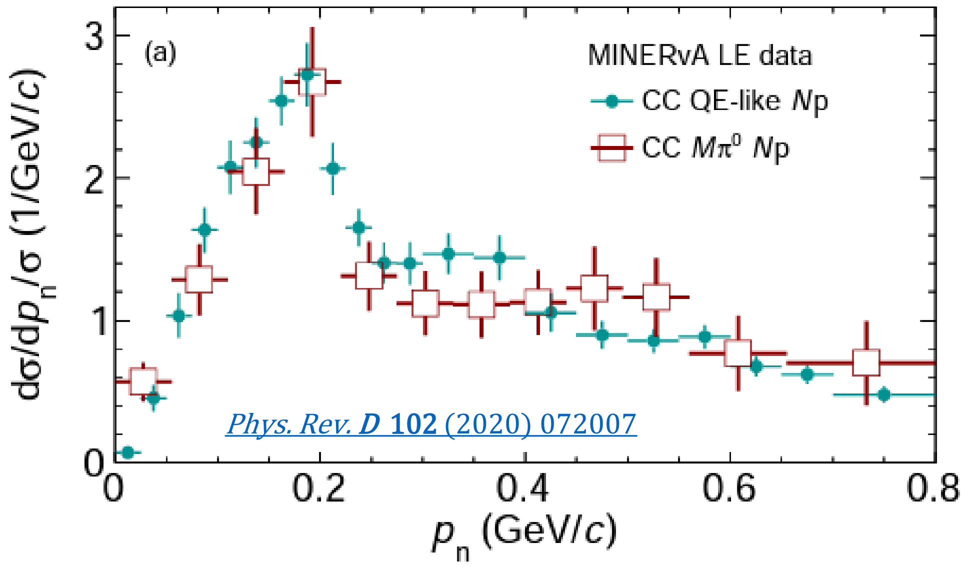
Nuclear effects @ MINERνA

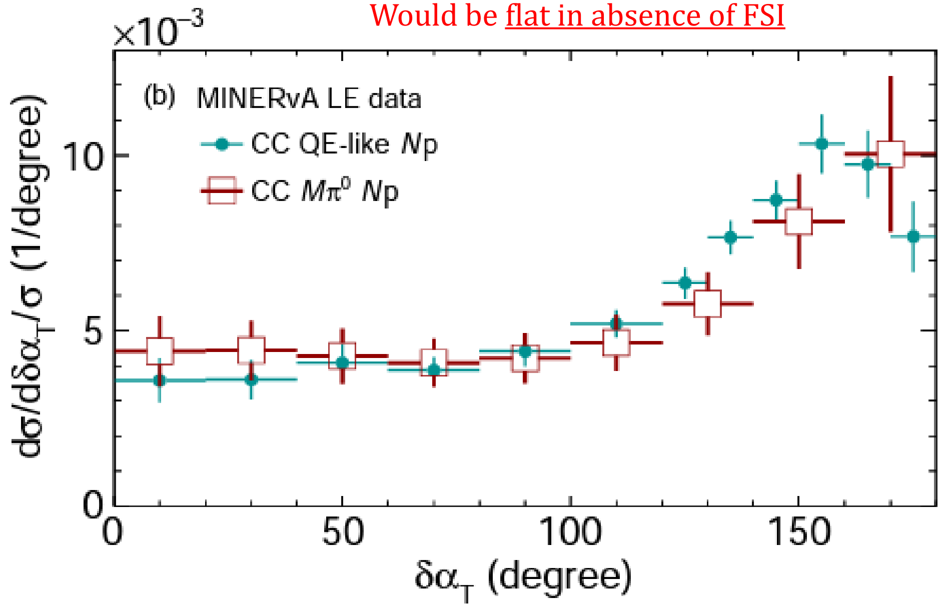
- Both ISI and FSI complicate cross- section measurements
  - ⇒ oscillation systematic errors!
- MINERνA pioneered Transverse Kinematic Imbalance (TKI)
  - Interactions with nucleus ⇒ apparent $\vec{p}_T$ in final state!



$\delta\alpha_T$ = transverse boosting angle
Most sensitive to FSI!
Would be flat in absence of FSI

p_n =emulated nucleon momentum
Probes Fermi motion in nucleus



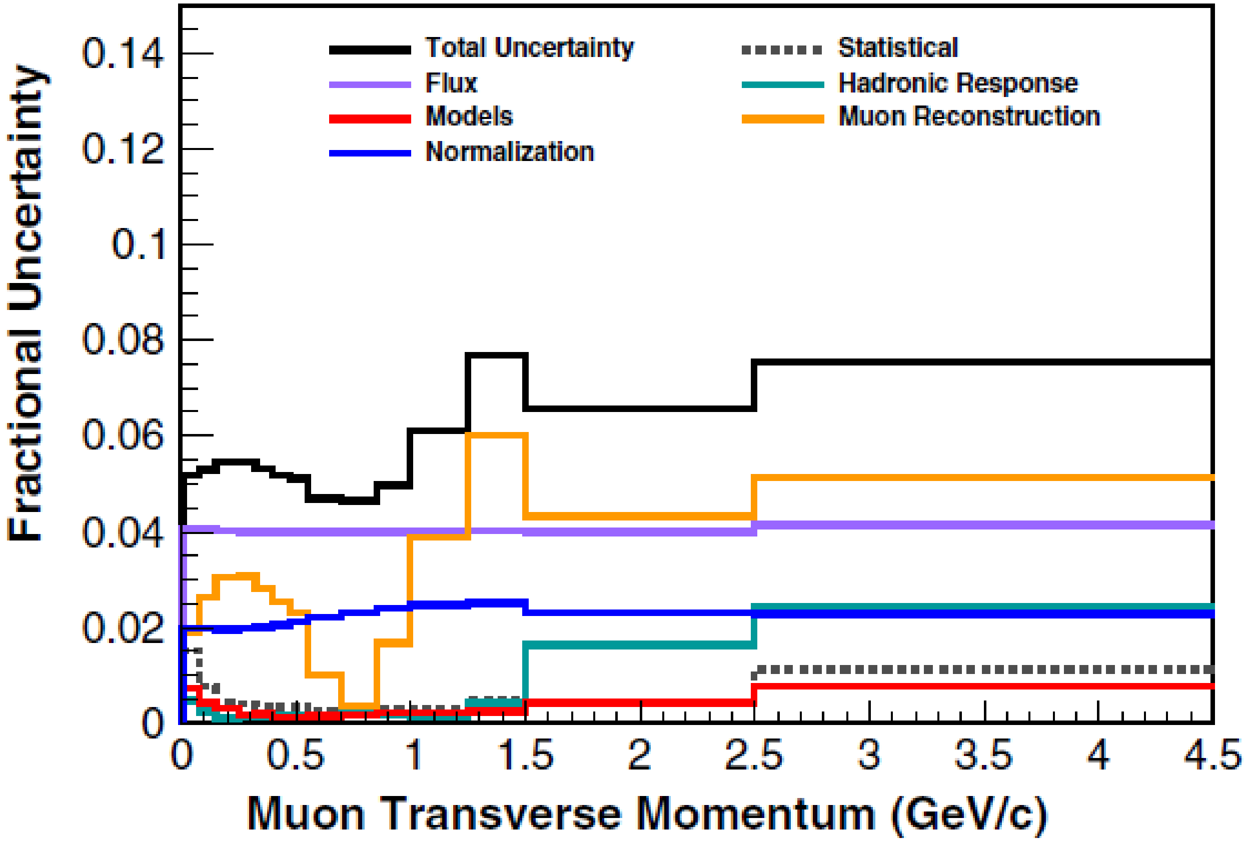


Nuclear effects @ MINERνA

- Both ISI and FSI complicate cross- section measurements
  - ⇒ oscillation systematic errors!

* Fractional uncertainties in each $p_{\parallel}$ bin can reach up to 20% (backup)

Inclusive muon analysis systematics - sub 10% fractional uncertainty! *



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

- We'll look at <u>inclusive probes</u>:
  - Compare measured rates to theory predictions
    ⇒ tune event generators
  - Muon kinematics
    - Precise measurement of σ
  - Low-recoil (= low q transfer)
    - Very sensitive to nuclear effects

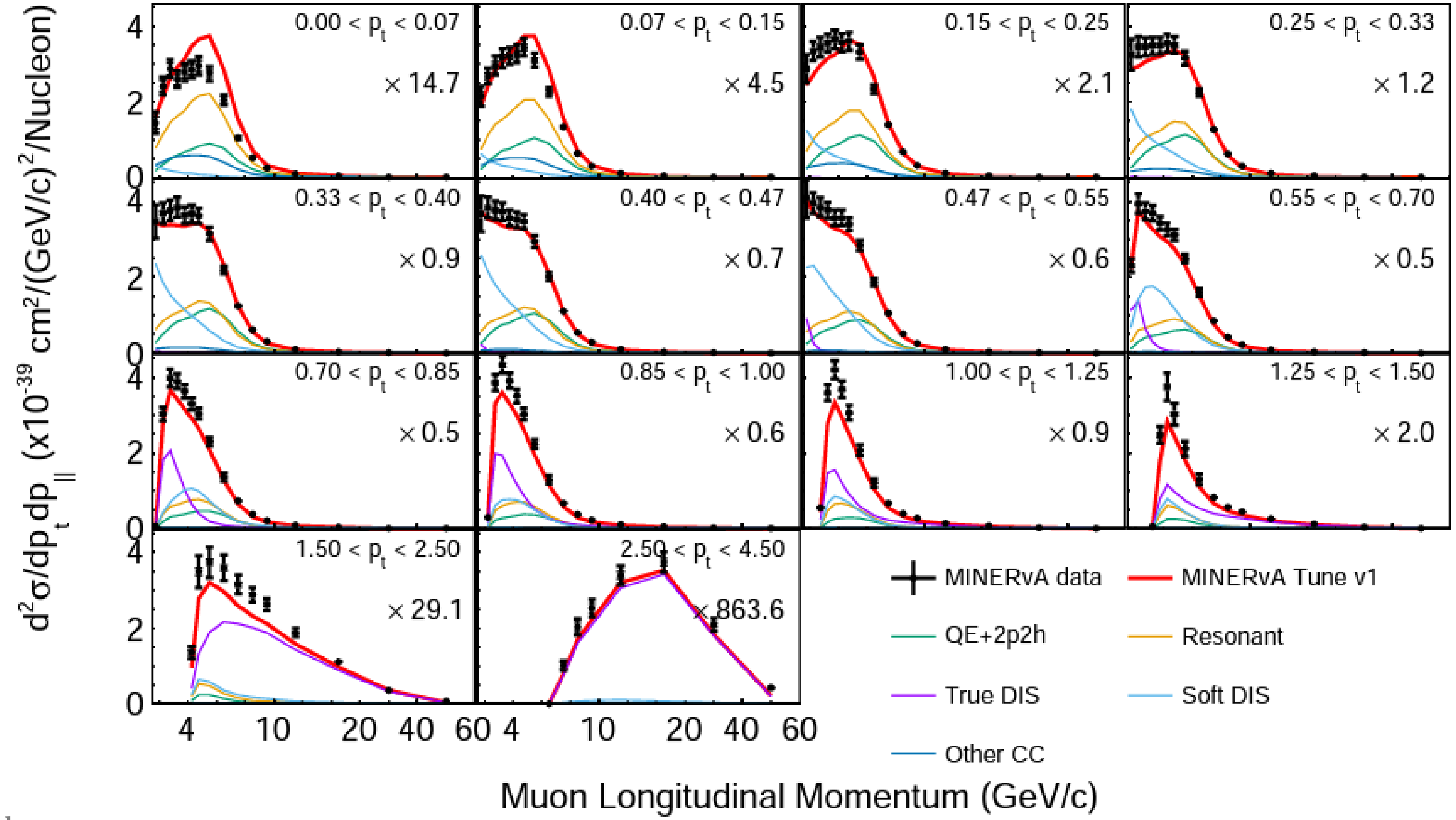
2D inclusive CH

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

- Allows for tuning of MINERνA's GENIE predictions
- + comparisons with other generators
  - Relevant for modelling of "soft DIS", FSI, 2p2h, nuclear models, …

"Soft DIS" refers to GENIE DIS events that are not "true DIS"
"True DIS" has 2 requirements:
1. Invariant mass of hadronic system:
$$W > 2\ \mathrm{GeV}/c^2$$
2. Four-momentum transfer from lepton vertex:
$$Q^2 > 1\ (\mathrm{GeV}/c)^2$$

Powerful probe to inform event generators!

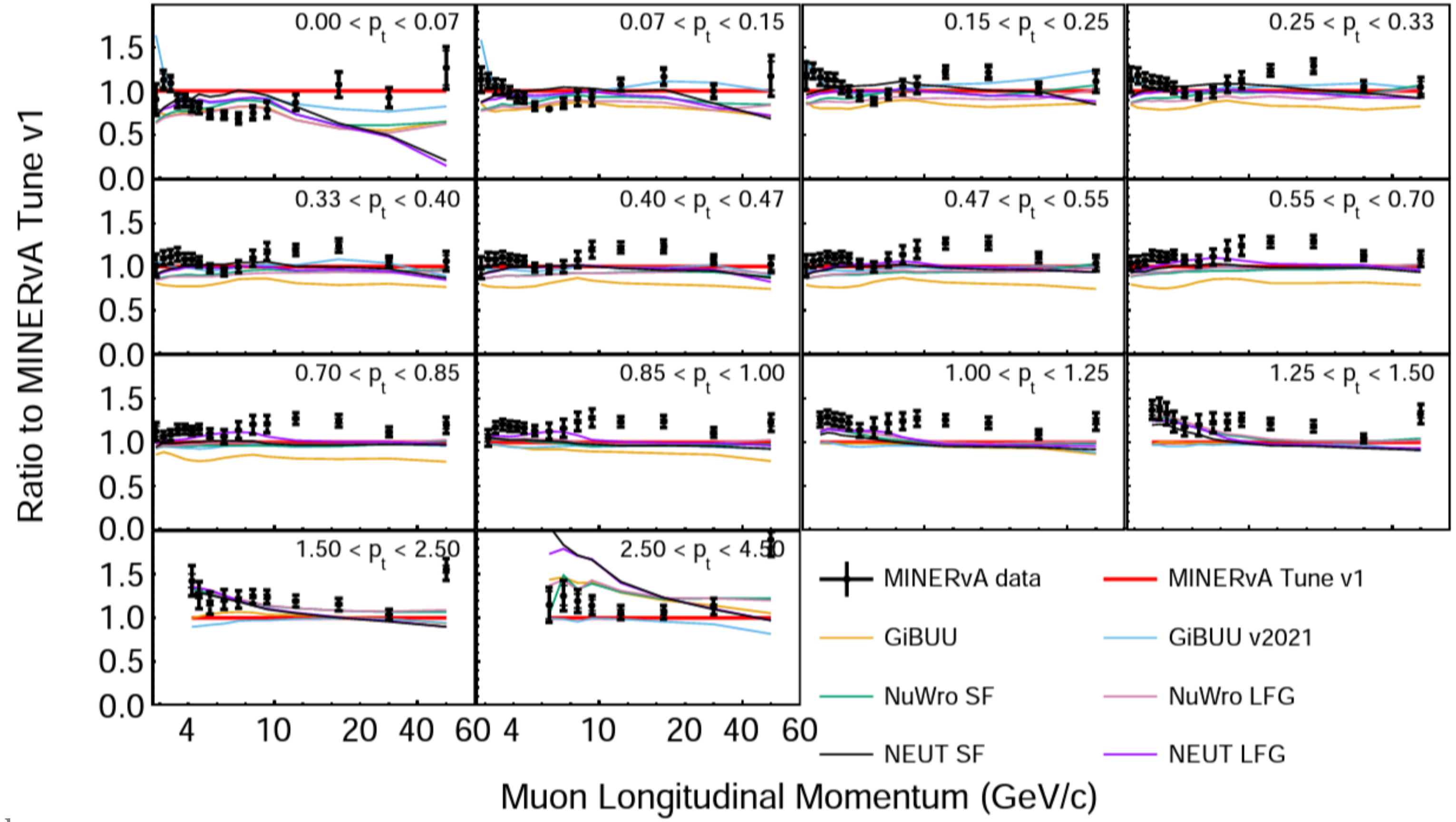


2D inclusive CH

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

- Poor χ^2 + different modelling between generators
  $\Rightarrow$ more $\mathrm{d}^2\sigma/\mathrm{d}v_1\mathrm{d}v_2$ for variables v_1, v_2 needed!

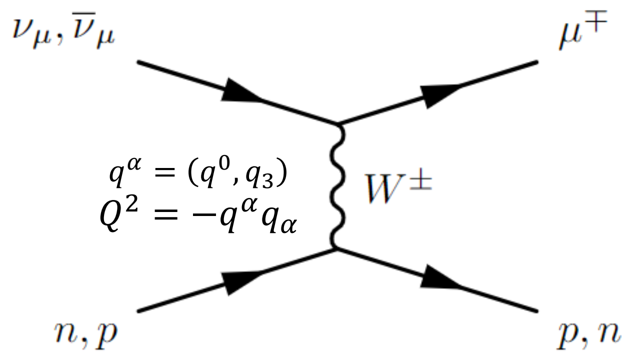
Different generators ⇒ different modelling of nuclear effects + interactions ⇒ different predictions!

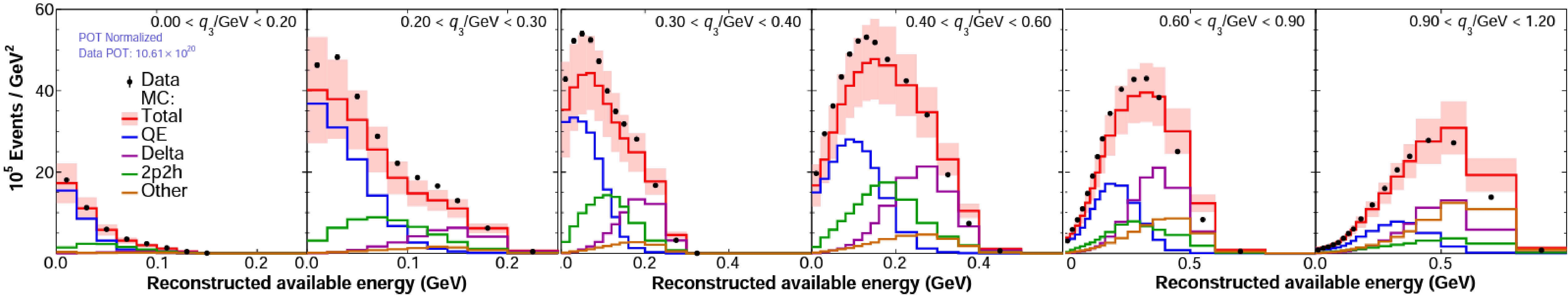


Powerful probe to inform event generators!

Low-recoil measurements [2110.13372 [hep-ex]]

- Call 4-momentum transfer q^α
- Low-q^0 processes are very sensitive to nuc. effects
- Use "available energy" $E_{avail} \coloneqq \sum T_p + \sum T_{\pi^\pm} + \sum E_{\text{other particles}}$ (neutrons not included!)
  - q^0 is a proxy for E_{avail}
  - $E_\nu = E_\mu + q^0 \Rightarrow q_3 = \sqrt{Q^2 + (q^0)^2}$
  - Nuclear physics inspired variable that helps us separate processes!
- Test MINERvA GENIE tunes (see backup for non-exhaustive list)





Build better tunes to our data!

Low-recoil measurements [2110.13372 [hep-ex]]

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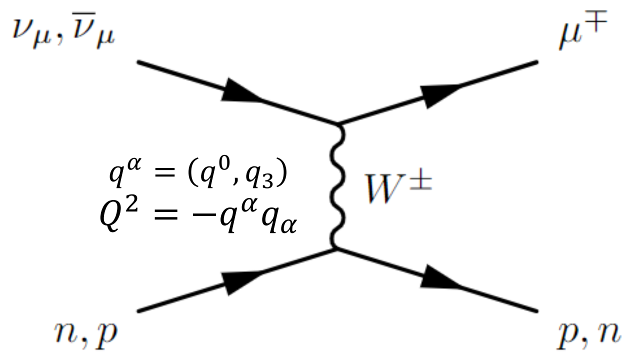
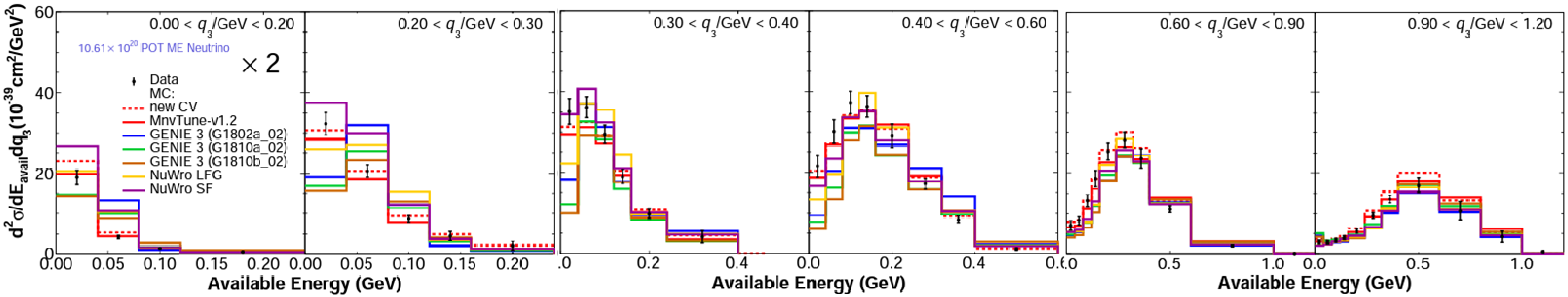


new CV == MINERvA Tune v3

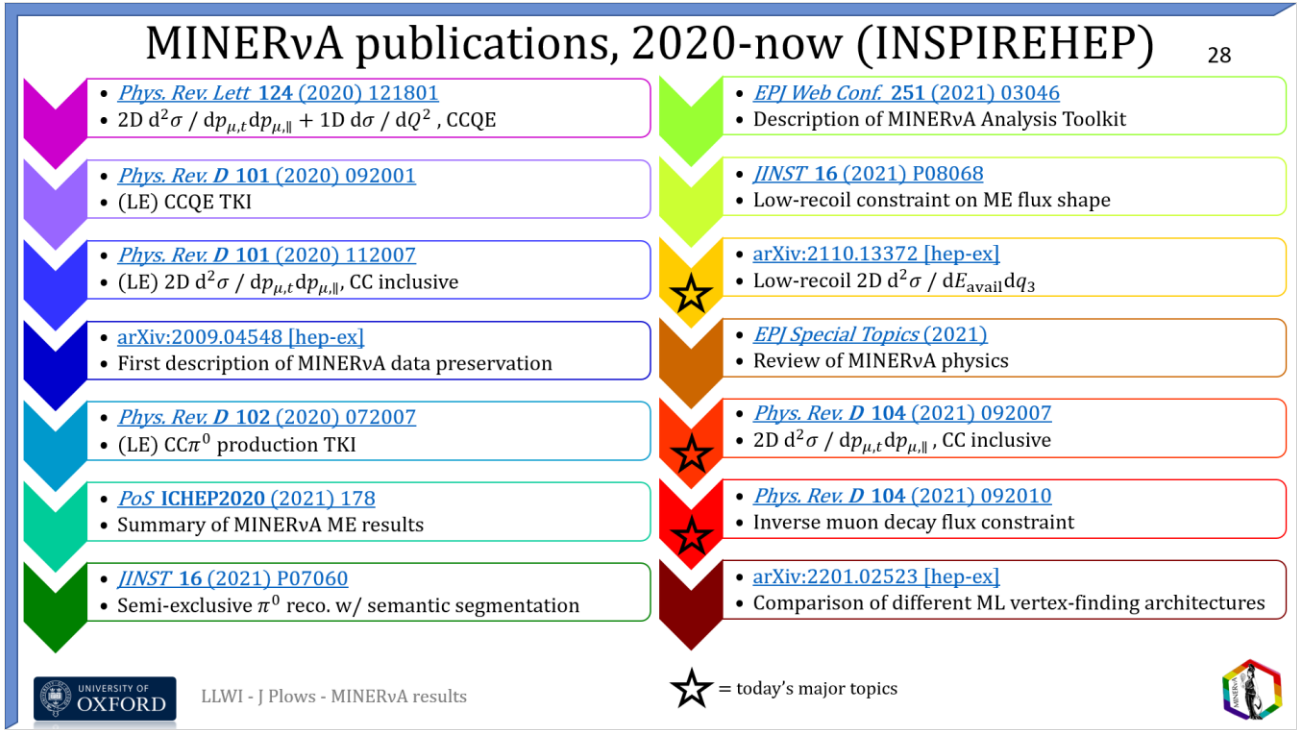


Build better tunes to our data!

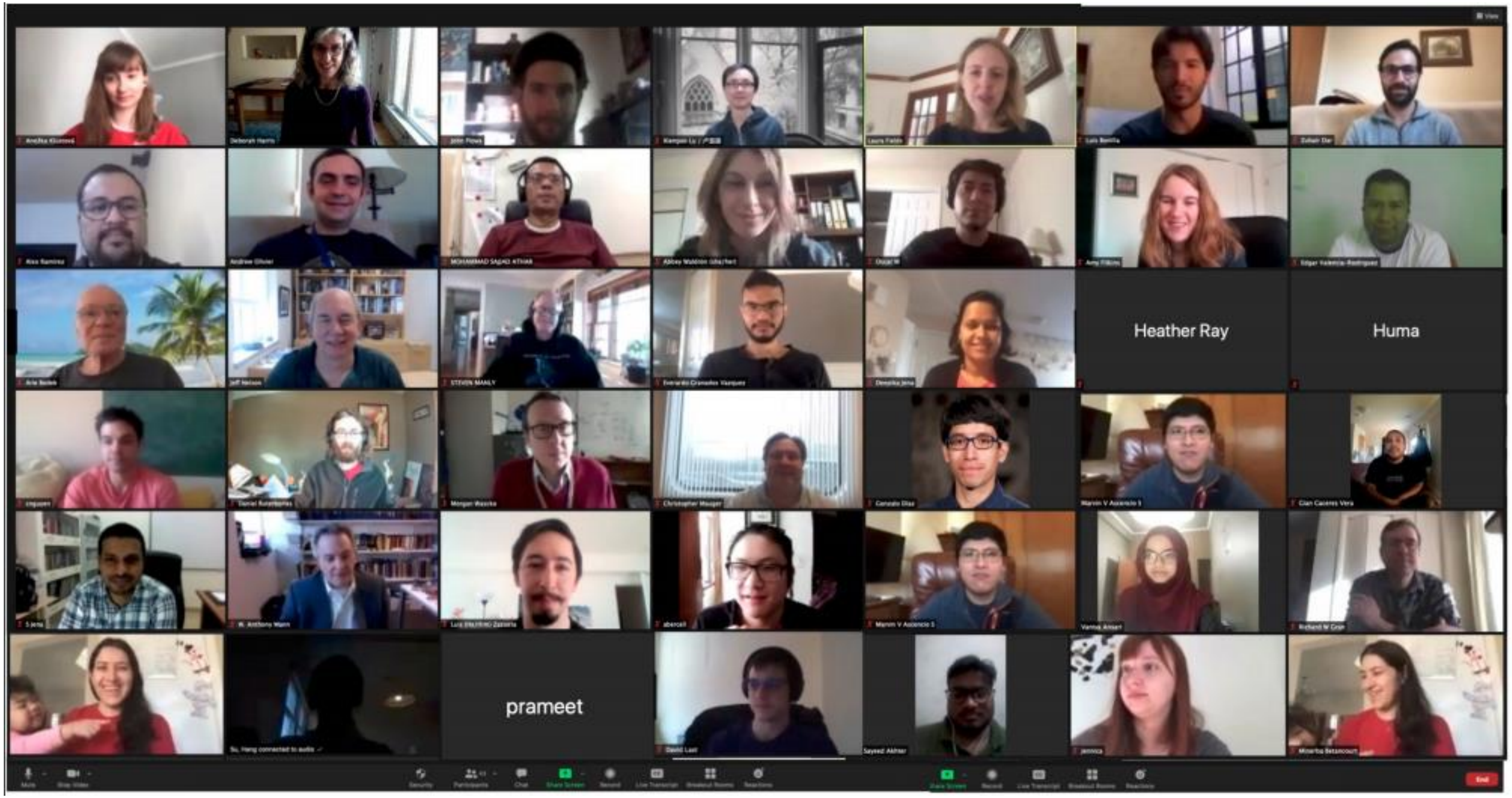
Summary

- MINERνA are producing leading analyses of rare interactions
- Leading *in situ* flux constraints relevant for e.g. DUNE
- Our data inform generator predictions

- There are still lots of analyses to cover + upcoming
- More results necessary + more on the way!



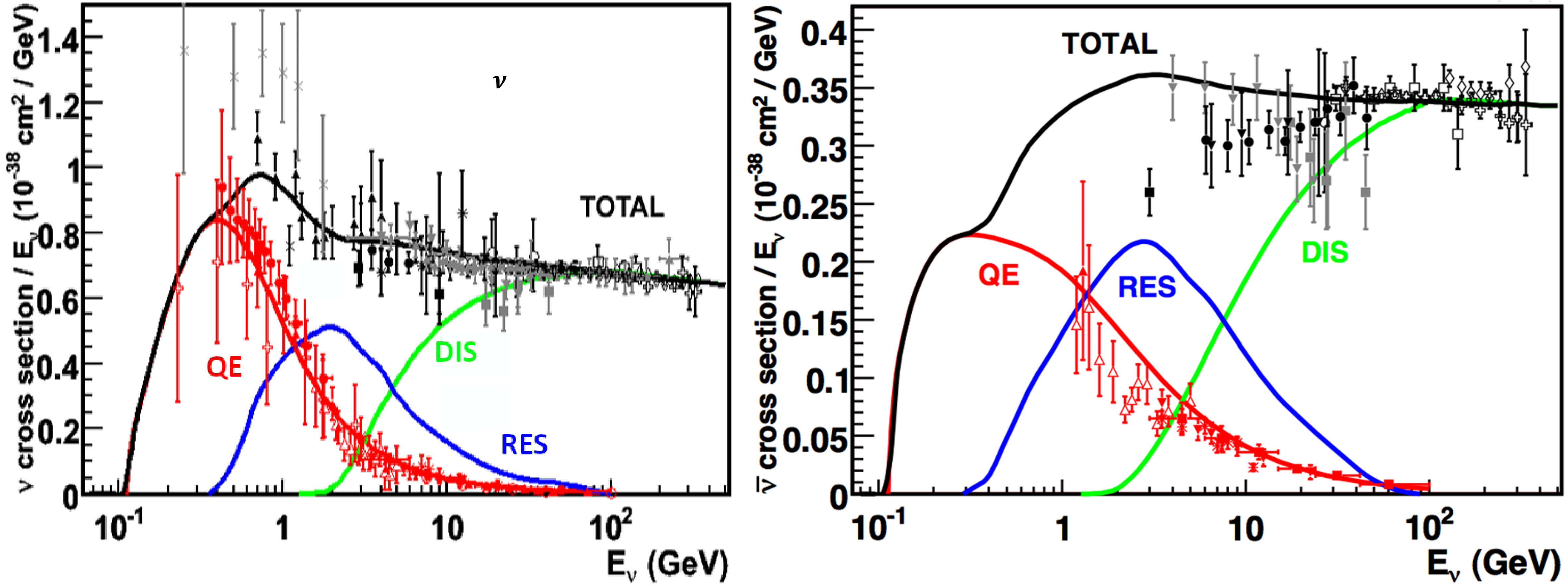
Our list of recent publications ☺
(see backup)



Thank you!

Backup

Neutrino interaction cross sections



Figures from 1205.2671 [hep-ex] using data from *Rev. Mod. Phys.* **84** (2012) 3

MINERνA publications, 2020-now (INSPIREHEP)

- *Phys. Rev. Lett* **124** (2020) 121801
- 2D $\mathrm{d}^2\sigma / \mathrm{d}p_{\mu,t}\mathrm{d}p_{\mu,\parallel}$ + 1D $\mathrm{d}\sigma / \mathrm{d}Q^2$, CCQE

- *Phys. Rev. D* **101** (2020) 092001
- (LE) CCQE TKI

- *Phys. Rev. D* **101** (2020) 112007
- (LE) 2D $\mathrm{d}^2\sigma / \mathrm{d}p_{\mu,t}\mathrm{d}p_{\mu,\parallel}$, CC inclusive

- arXiv:2009.04548 [hep-ex]
- First description of MINERνA data preservation

- *Phys. Rev. D* **102** (2020) 072007
- (LE) CCπ^0 production TKI

- *PoS* **ICHEP2020** (2021) 178
- Summary of MINERνA ME results

- *JINST* **16** (2021) P07060
- Semi-exclusive π^0 reco. w/ semantic segmentation

- *EPJ Web Conf.* **251** (2021) 03046
- Description of MINERνA Analysis Toolkit

- *JINST* **16** (2021) P08068
- Low-recoil constraint on ME flux shape

- ☆ arXiv:2110.13372 [hep-ex]
- Low-recoil 2D $\mathrm{d}^2\sigma / \mathrm{d}E_{\mathrm{avail}}\mathrm{d}q_3$

- *EPJ Special Topics* (2021)
- Review of MINERνA physics

- ☆ *Phys. Rev. D* **104** (2021) 092007
- 2D $\mathrm{d}^2\sigma / \mathrm{d}p_{\mu,t}\mathrm{d}p_{\mu,\parallel}$, CC inclusive

- ☆ *Phys. Rev. D* **104** (2021) 092010
- Inverse muon decay flux constraint

- arXiv:2201.02523 [hep-ex]
- Comparison of different ML vertex-finding architectures

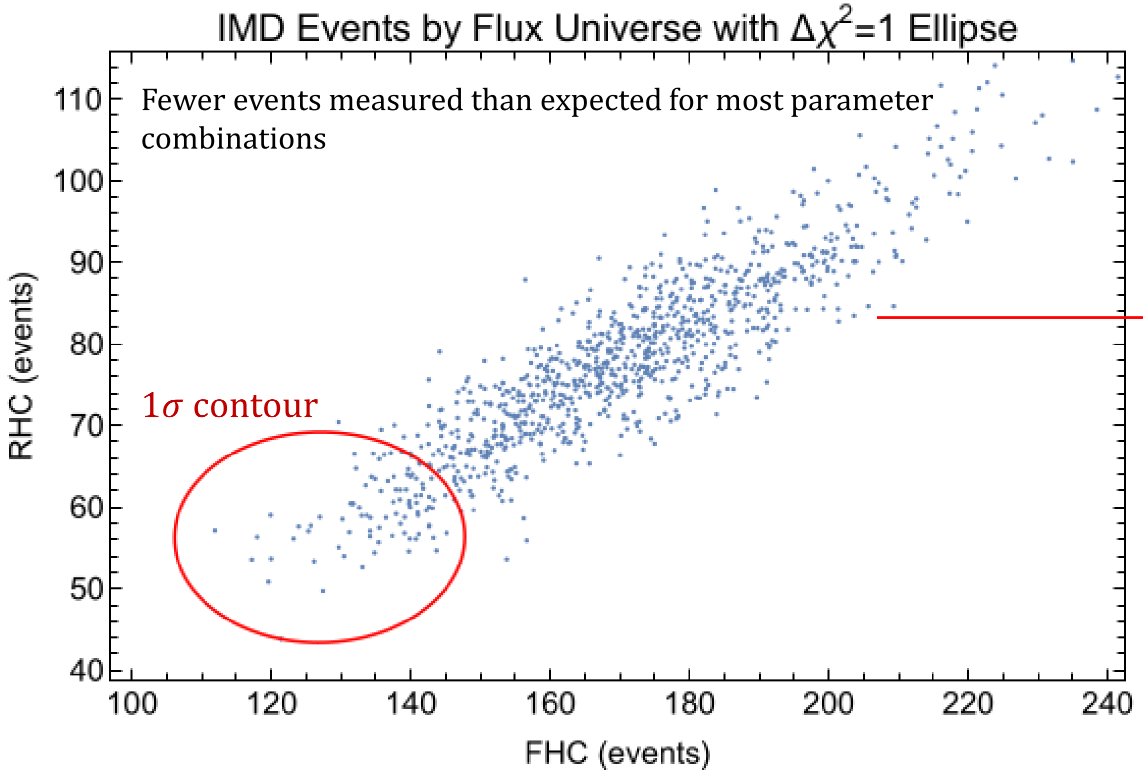
☆ = today's major topics

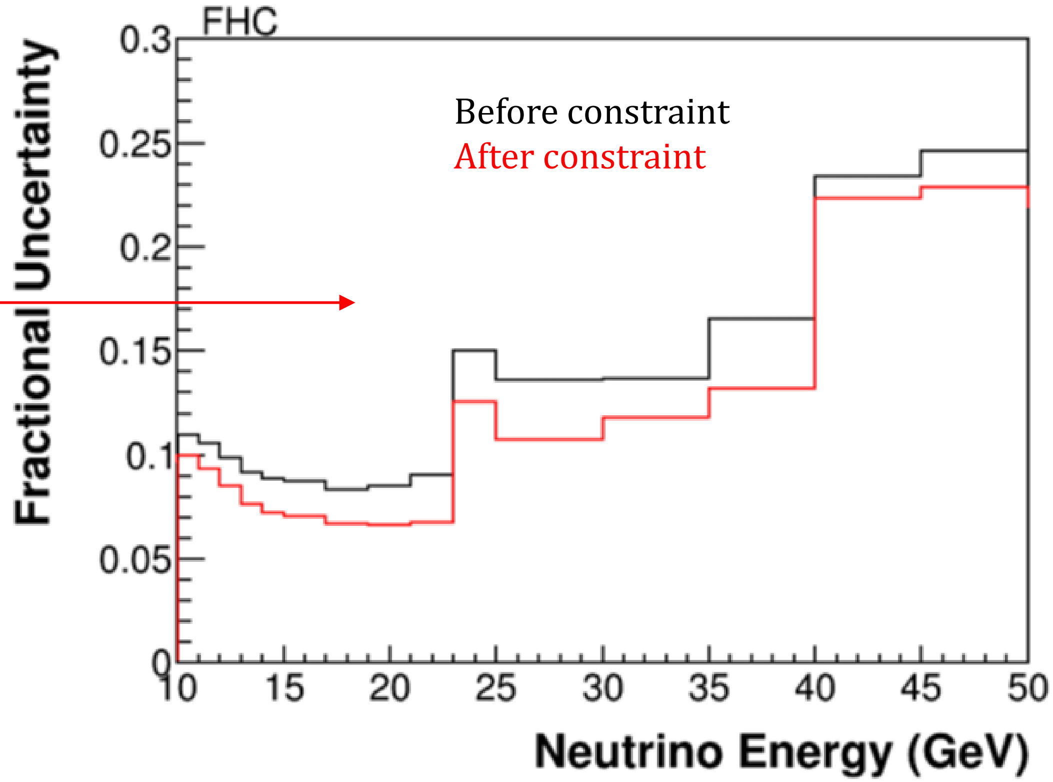
- Bayes' theorem : $P(N_{\text{IMD}} \mid \Phi) \cdot P(\Phi) = P(\Phi \mid N_{\text{IMD}}) \cdot P(N_{\text{IMD}})$

$$P\left(\{N_{\text{FHC}}, N_{\text{RHC}}\} \middle| \Phi_i^{\text{FHC,RHC}}\right) = \frac{1}{2\pi\sqrt{|V|}} \exp\left(-\frac{\Delta^T V^{-1} \Delta}{2}\right)$$

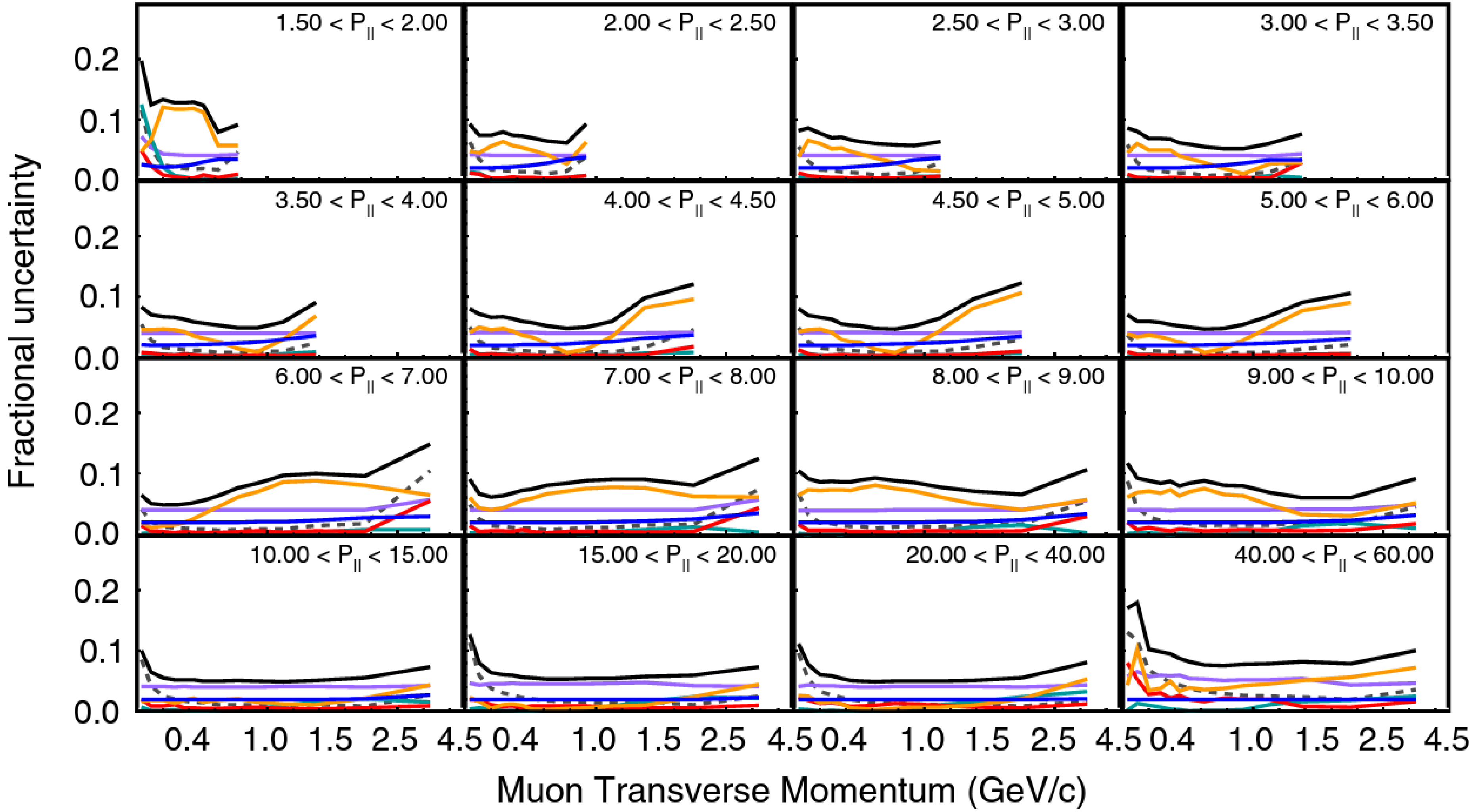
- Most flux parameters would lead to more events expected than predicted

  ⇒ many parameter combinations weighted low



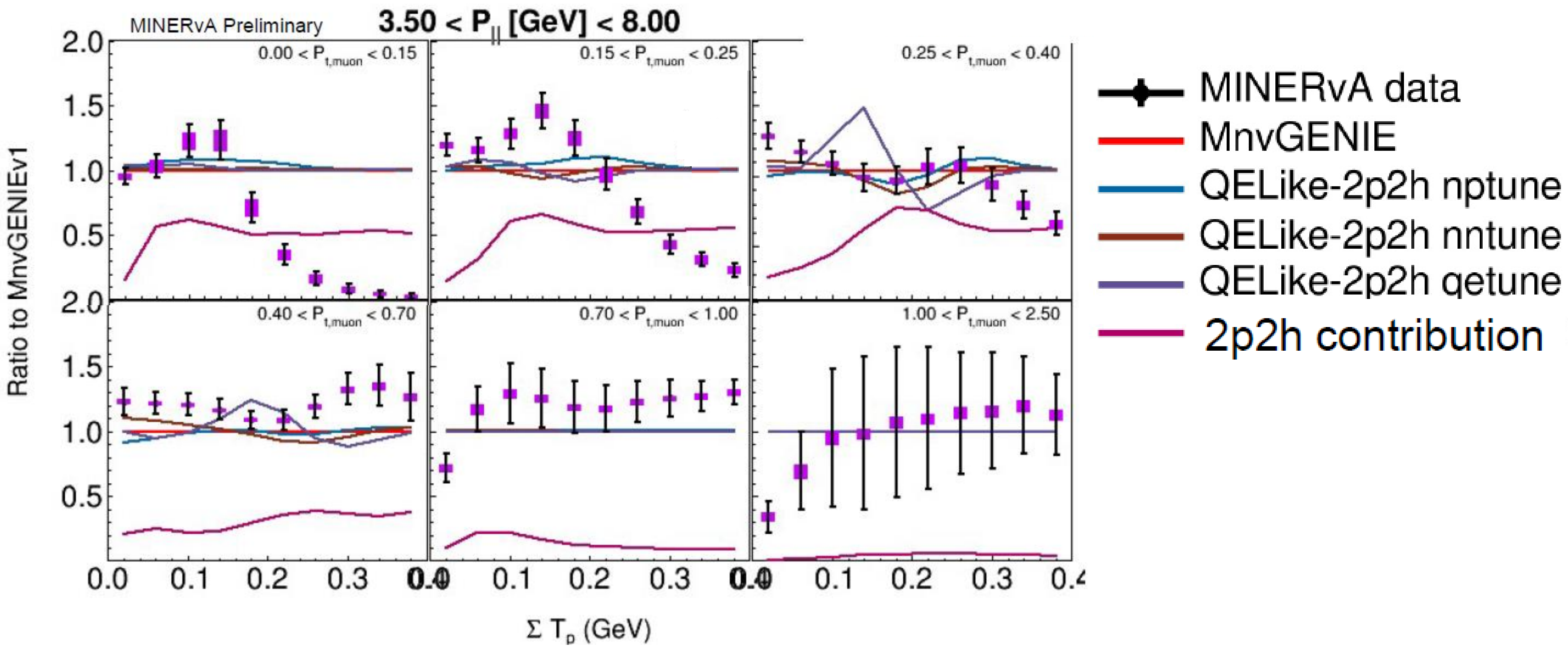


Fractional uncertainties in μ inclusive per $p_{||}$ bin



3D analysis (upcoming)

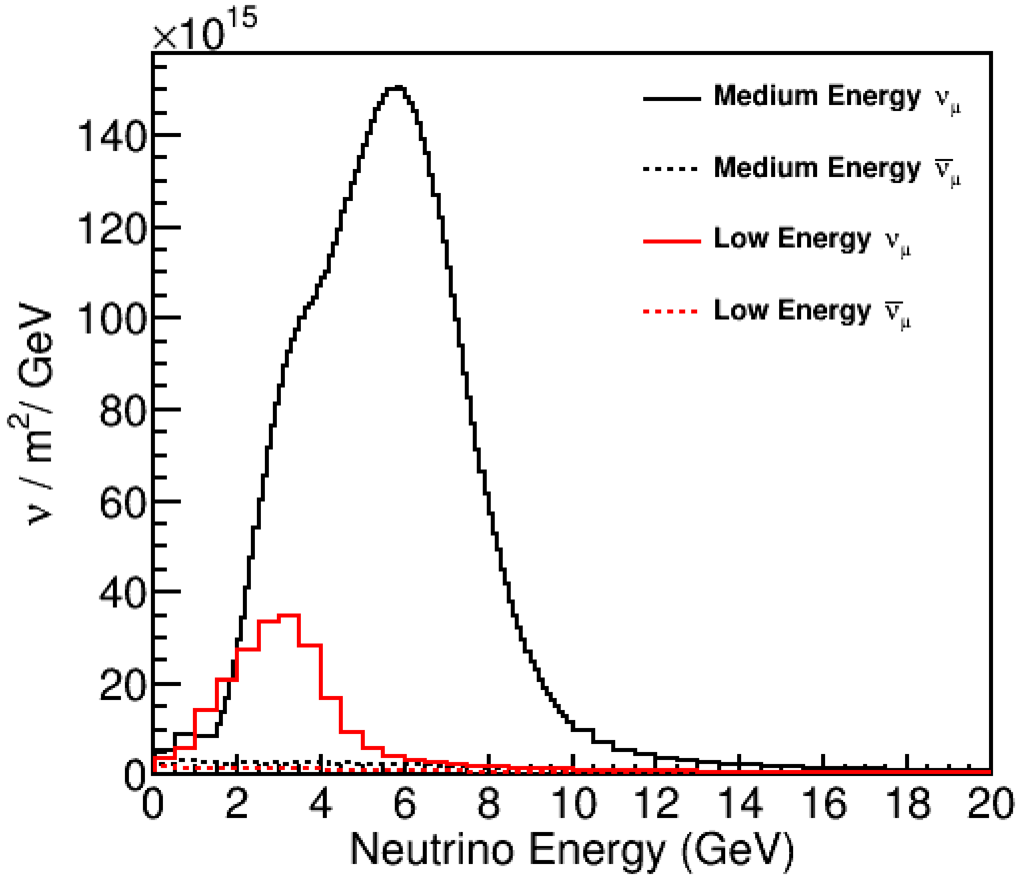
Dan Ruterbories, FNAL Joint Experimental and Theoretical Seminar, 25/Oct/2019



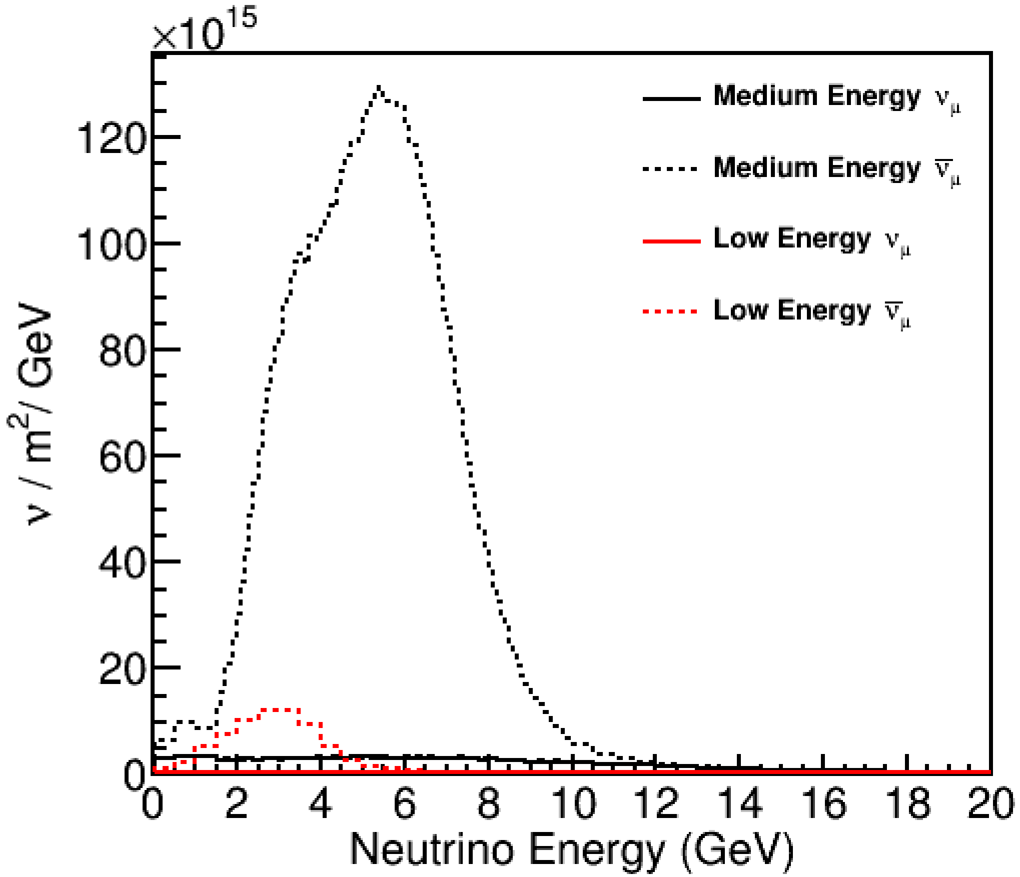
2p2h enhancement needed! Where?

Analysis in terms of muon $p_t, p_{\|}$ and hadronic visible energy, $\sum T_p$: e.g. at low $\sum T_p$ probes 2p2h enhancement and FSI for $p \rightarrow n$

FHC (ν)
1.21×10^{21} POT



RHC ($\bar{\nu}$)
1.24×10^{21} POT



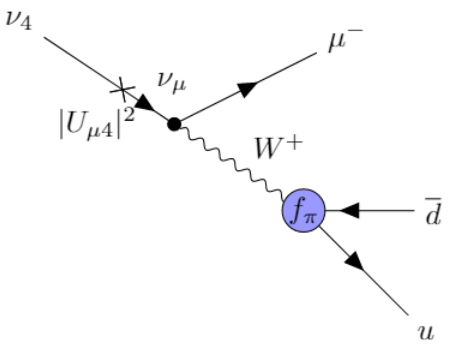
The MINERνA tunes (an incomplete list)

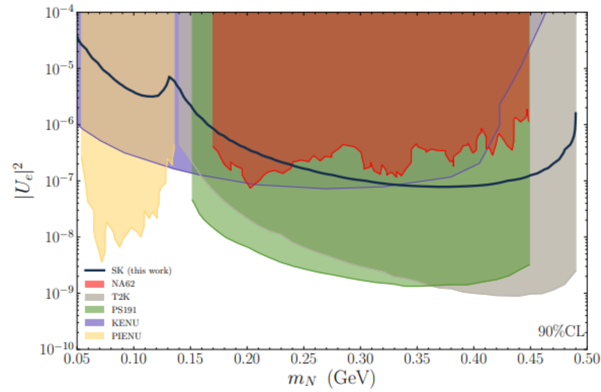
This science-related list is incomplete; you can help by adding missing items.

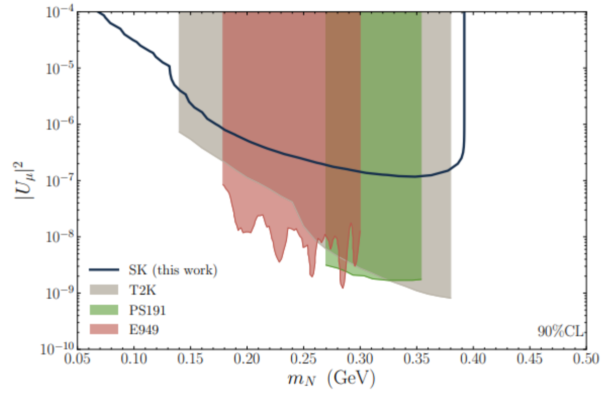
Tune	Non-resonant π reduction?	Low-Q^2 pion suppression?	COH pion prod reweight?	RES $E_{removal}$?	RPA for QE?	High-Q^2 Bodek-Ritchie enhancement?	2p2h model?	2p2h reweight?
GENIE v2.12.6	✗	✗	✗	✗	✗	✗	✗	✗
MnvTune v1	✓	✗	✗	✗	✓	✗	Valencia	✓
MnvTune v1.2	✓	✗	✓	✗	✓	✗	Valencia	✓
MnvTune v2	✓	✓	✗	✗	✓	✗	Valencia	✓
MnvTune v3	✓	✗	✗	✓	✓	✓	SuSA	✗

Heavy Neutral Leptons @ MINERνA

- HNL = heavy ($\mathcal{O}$(100 MeV – few TeV)) neutrinos
- Couple to SM through mixing: $\Gamma(N_\ell \to \{SM\}) \propto |U_{\ell 4}|^2$
- MINERνA is in good position to probe μ-like close to $m_K - m_\mu$ threshold due to:
  - High flux energy
  - Long exposure
  - Good $\mu^\mp\pi^\pm$ reconstruction
  - Leading COH measurements in CH
    - ⇒ good background reduction

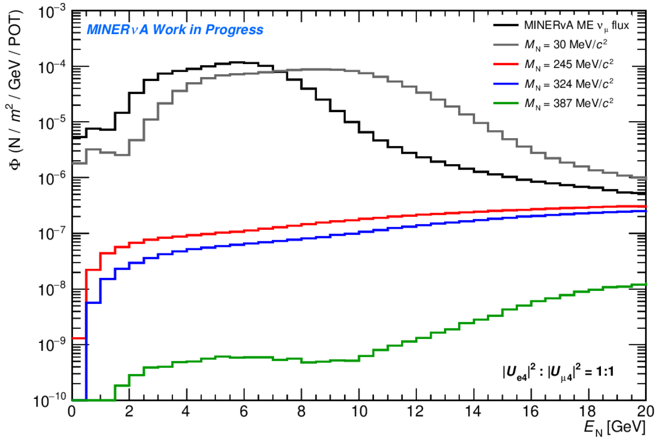






From *EPJ C* **80** (2020) 235

ME fluxes at tracker centre, FHC



ME fluxes at tracker centre, RHC