MINERvA Overview
NEUTRINOS22

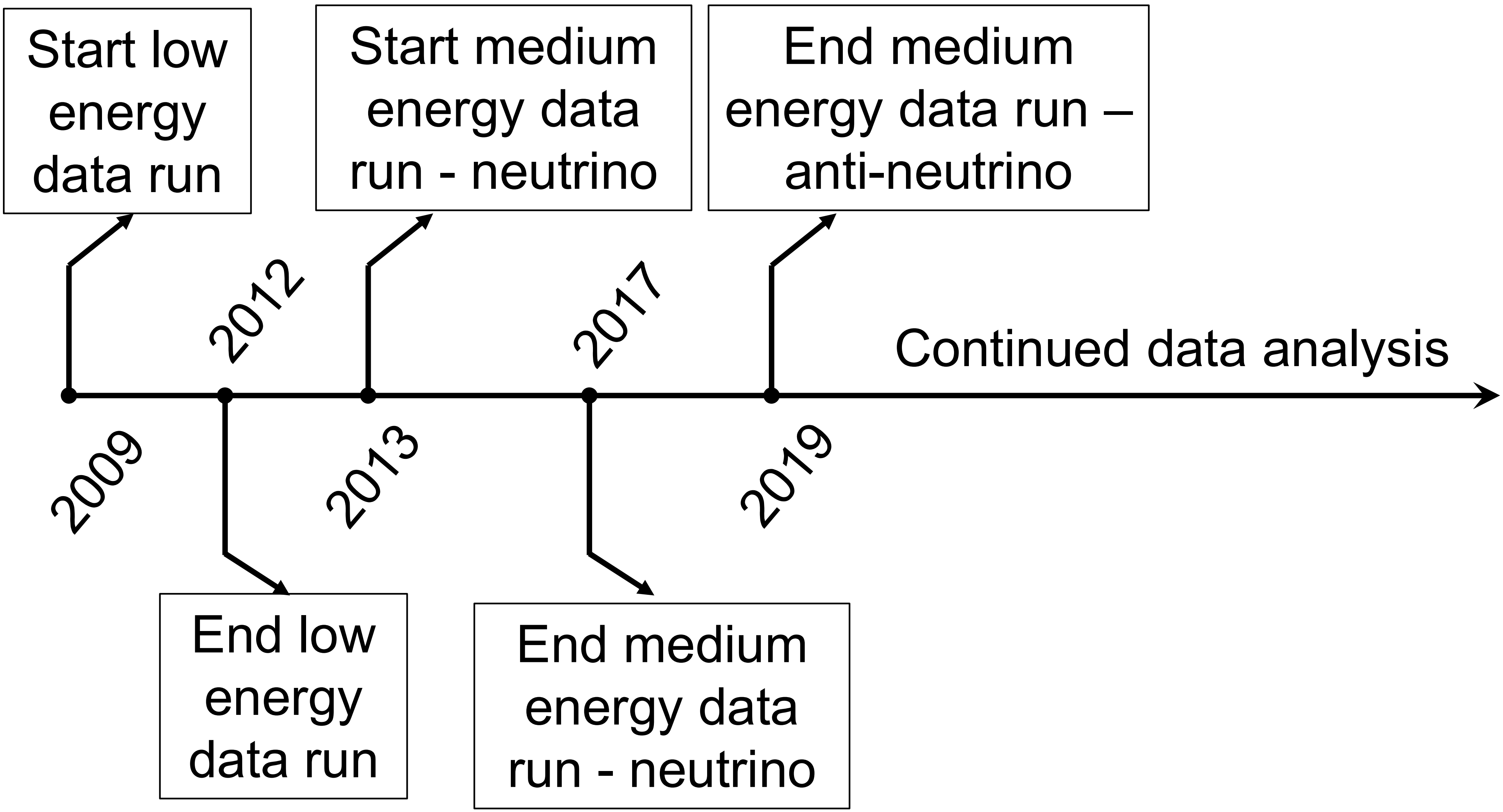
Daniel Ruterbories
On behalf of the MINERvA collaboration

February 23rd, 2022

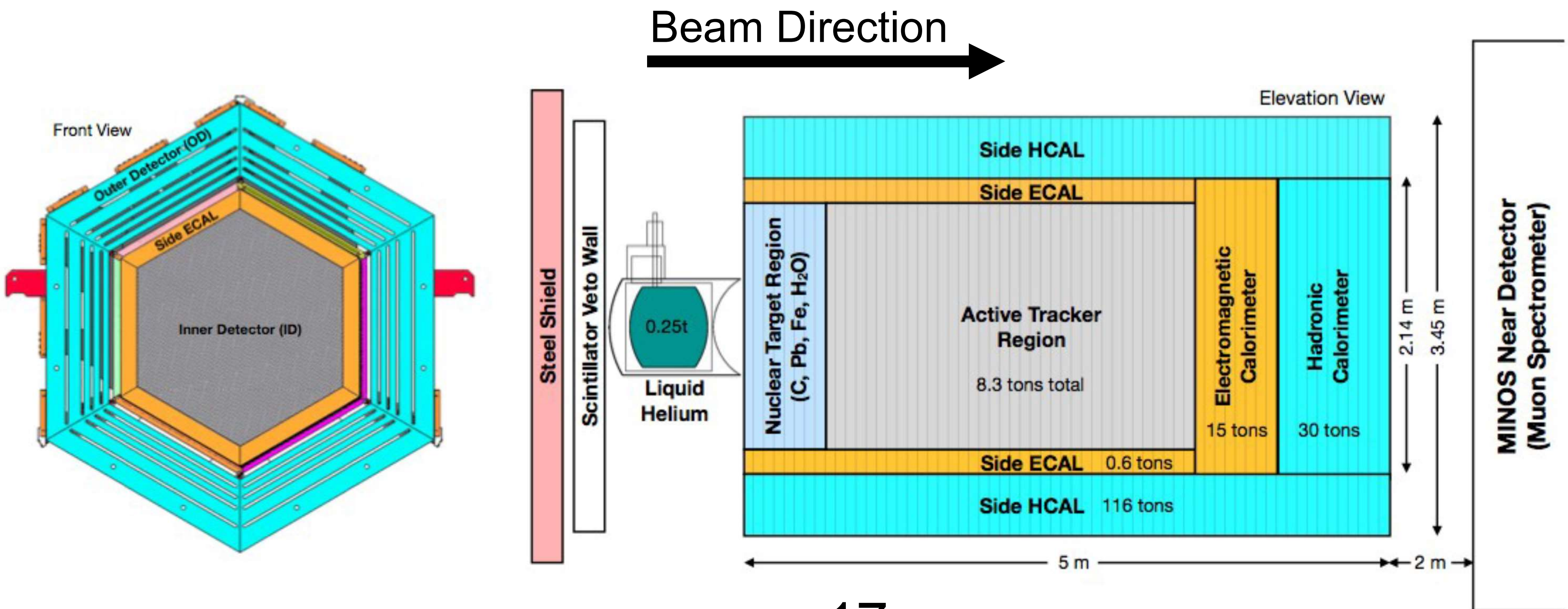
The MINERvA Experiment

- Study neutrino-nucleus scattering at a few GeV
  - Measure the effects of the nuclear environment on neutrino scattering
  - Improve understanding of neutrino-nucleus cross section model by working with generators
  - Benefits current and future neutrino oscillation experiments

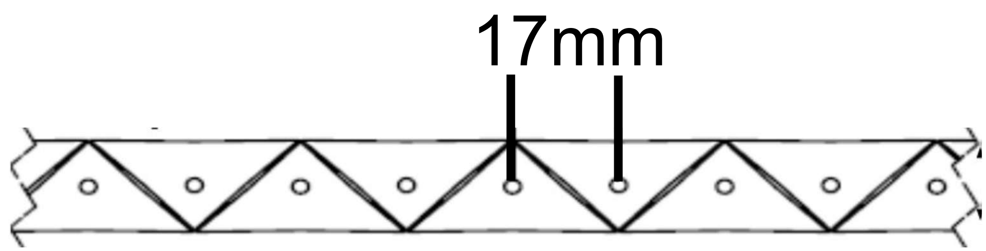
Experiment Timeline



Experimental Apparatus



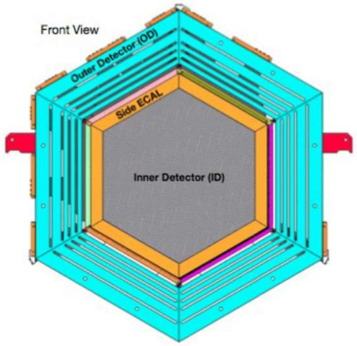
Three views:
X: Vertical
U,V: ±60

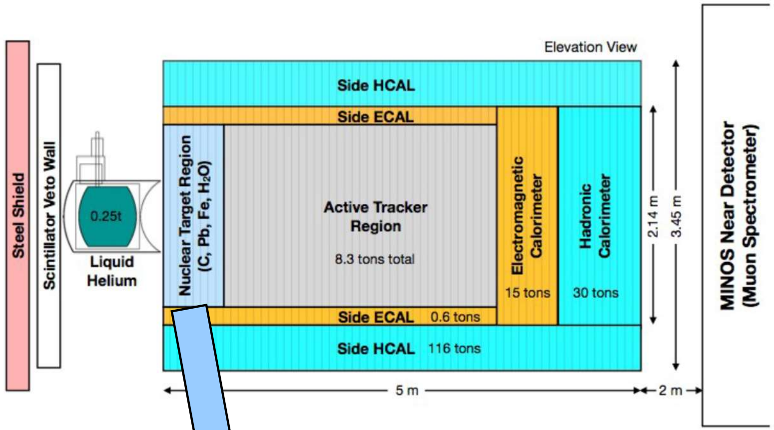


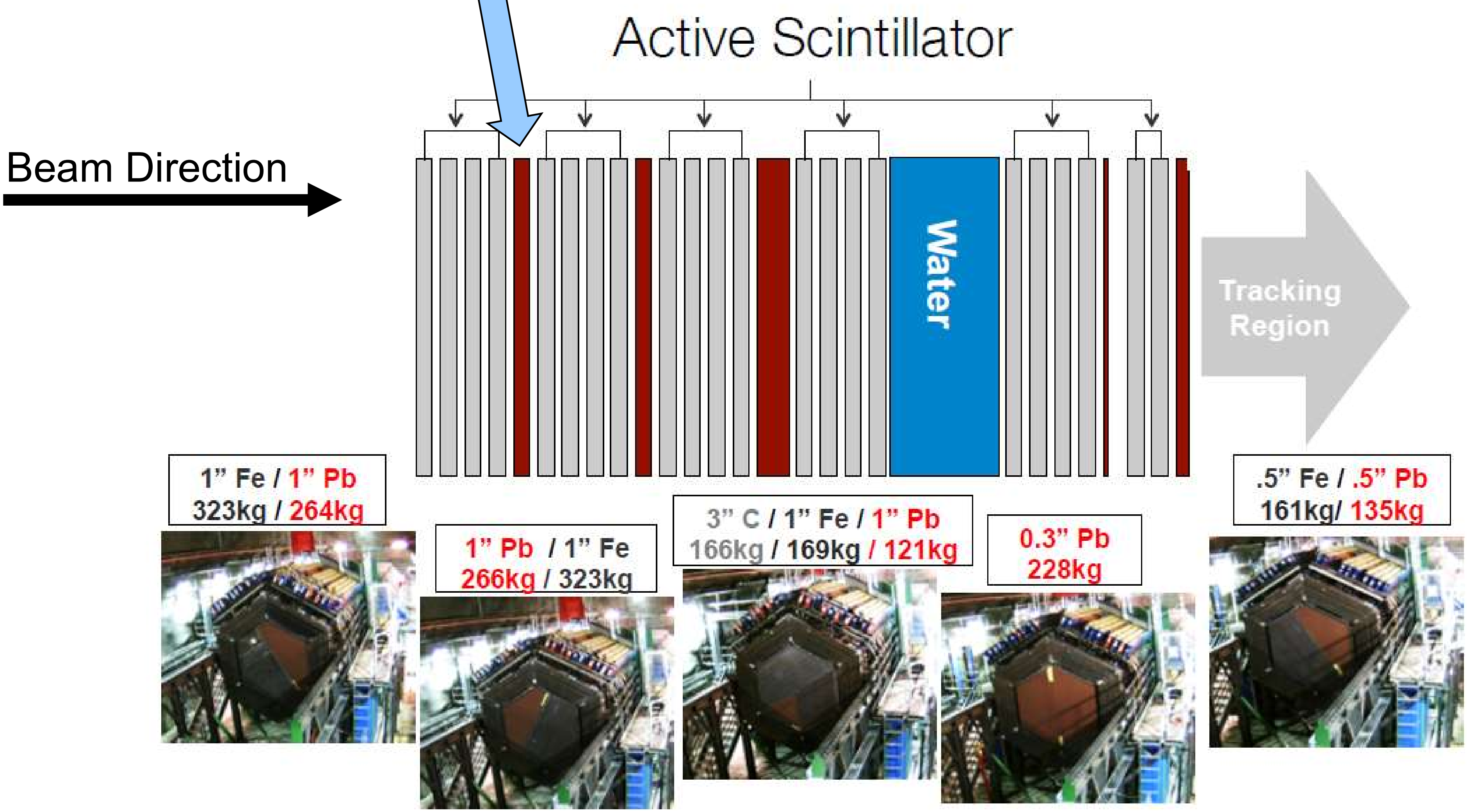
Spatial resolution ~3mm
Timing resolution ~3ns

Nucl. Inst. and Meth. A743 (2014) 130
arXiv:1305.5199

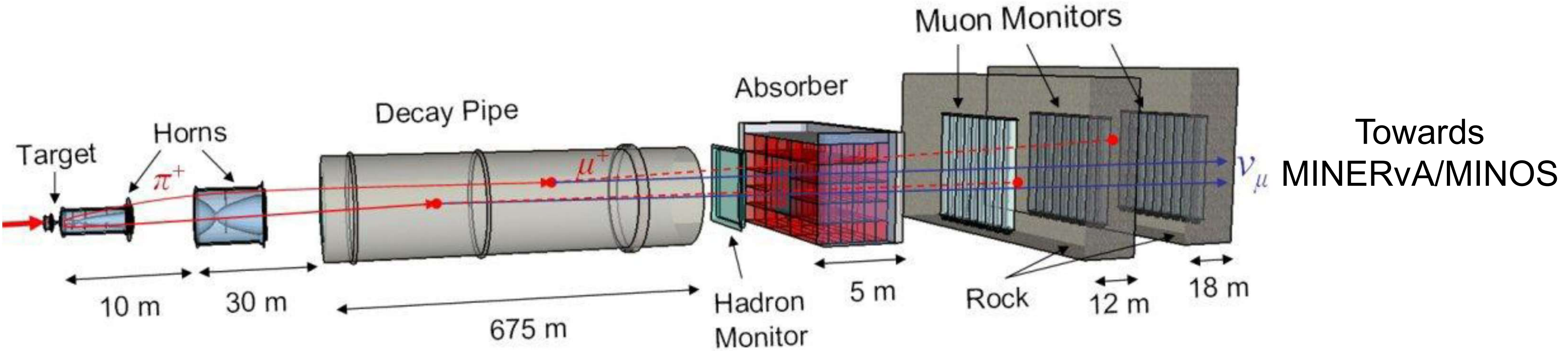
Experimental Apparatus



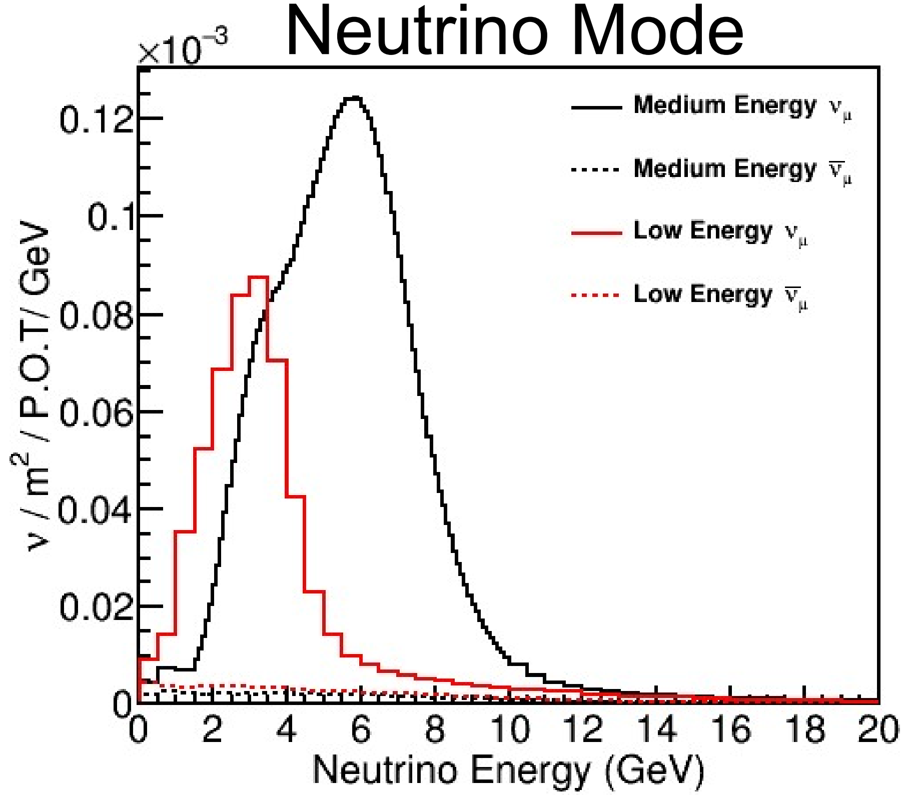




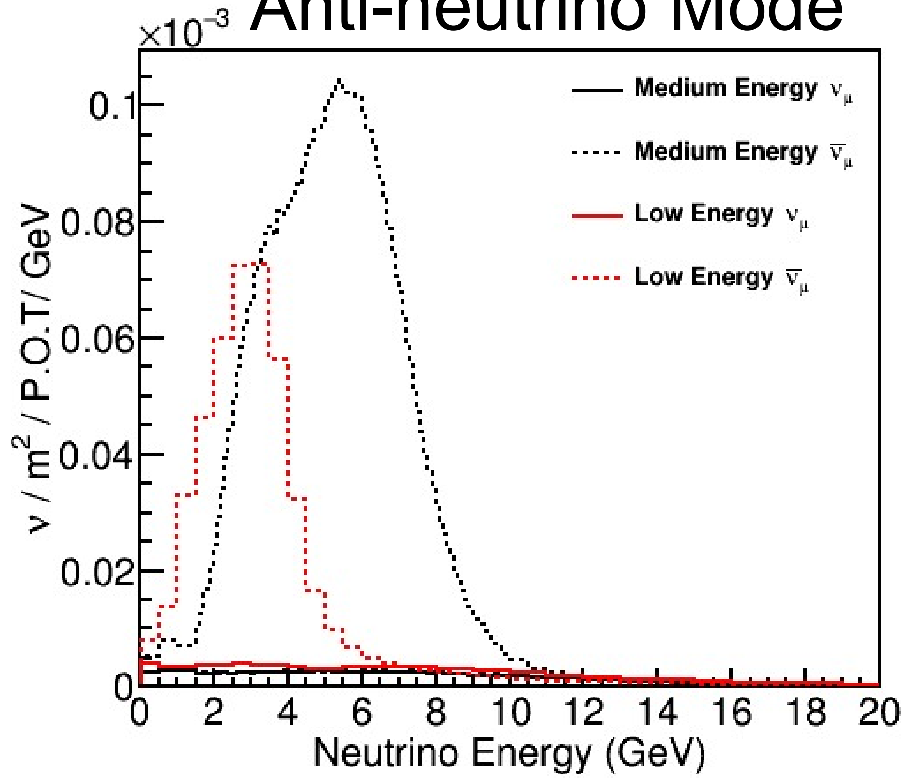
The NUMI beam



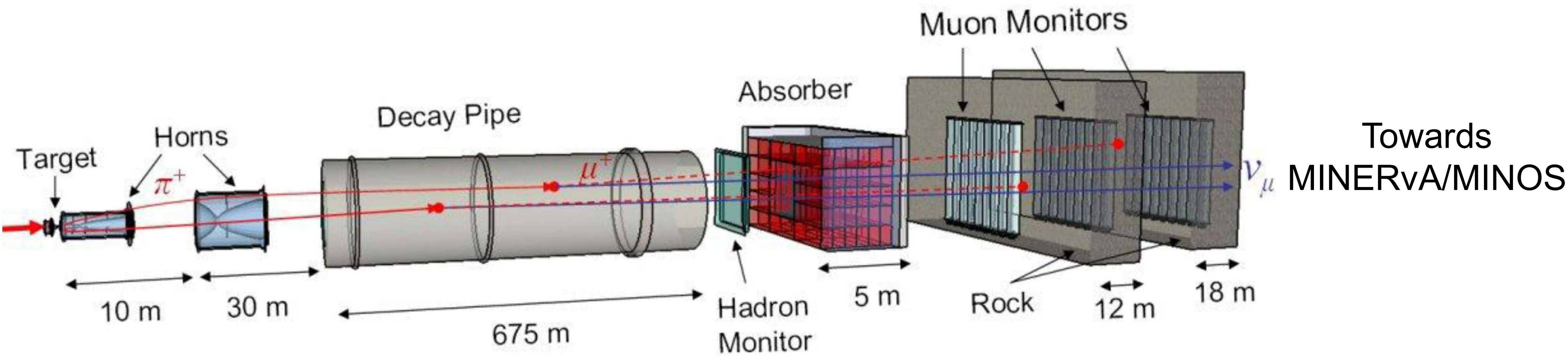
Neutrino Mode



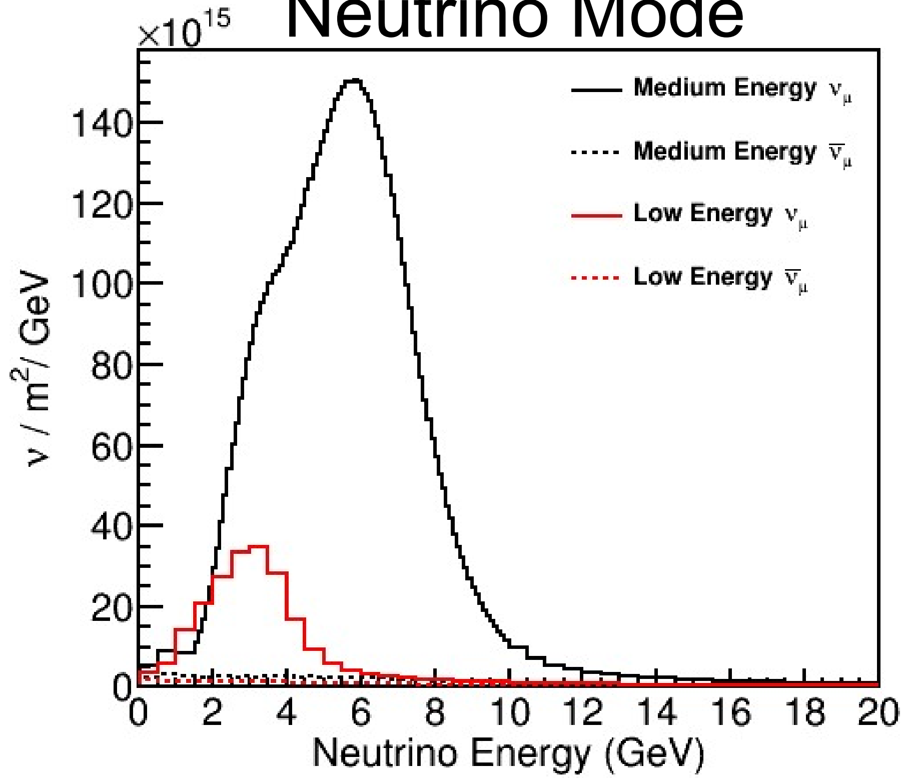
Anti-neutrino Mode



The NUMI beam



Neutrino Mode



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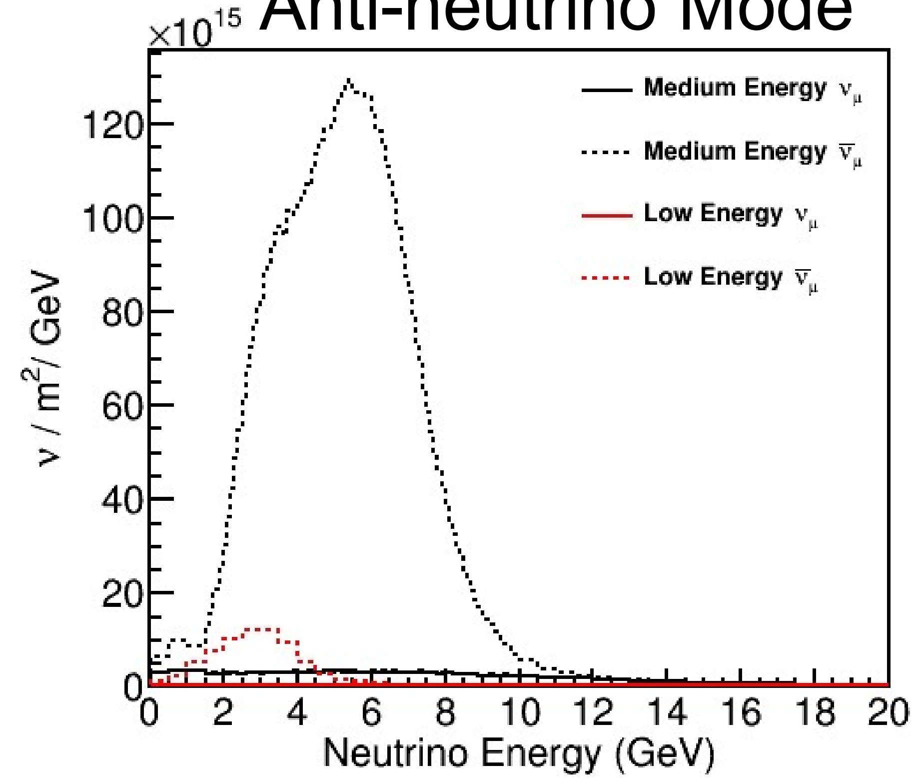
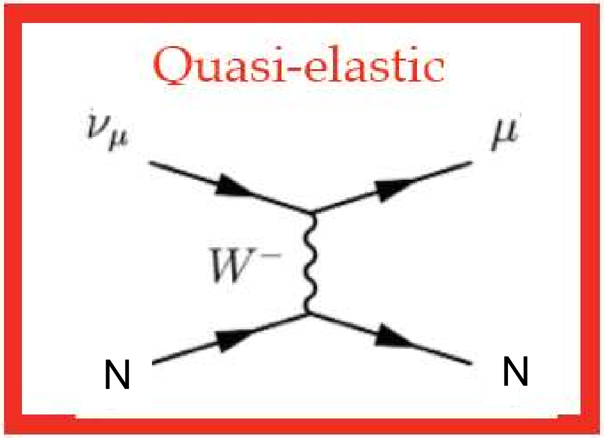
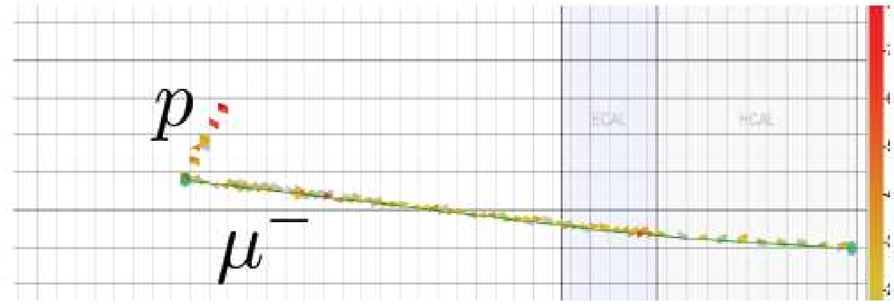
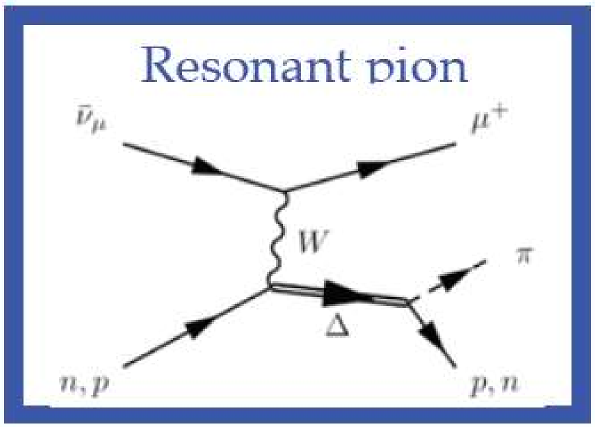


What do events look like

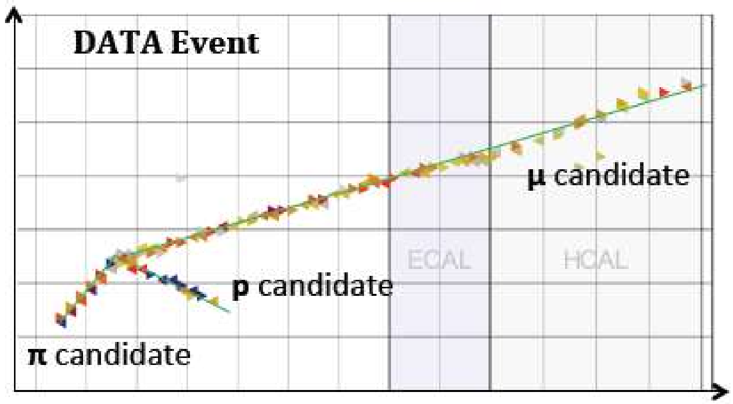


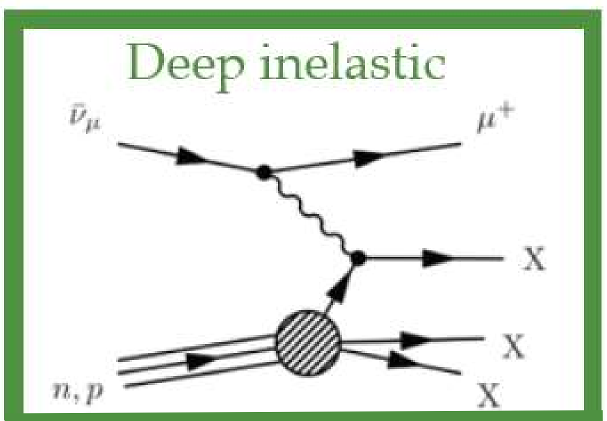
QE



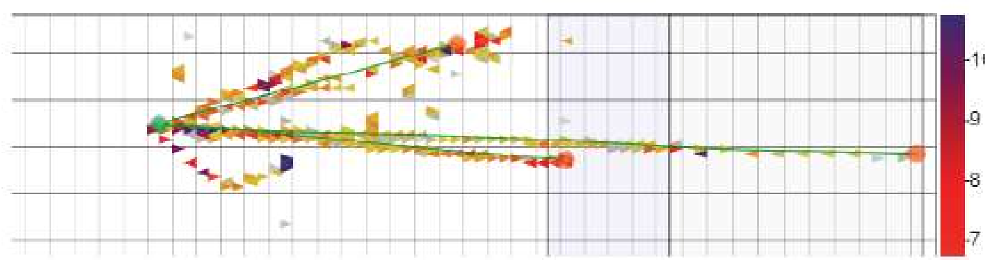


RES





DIS



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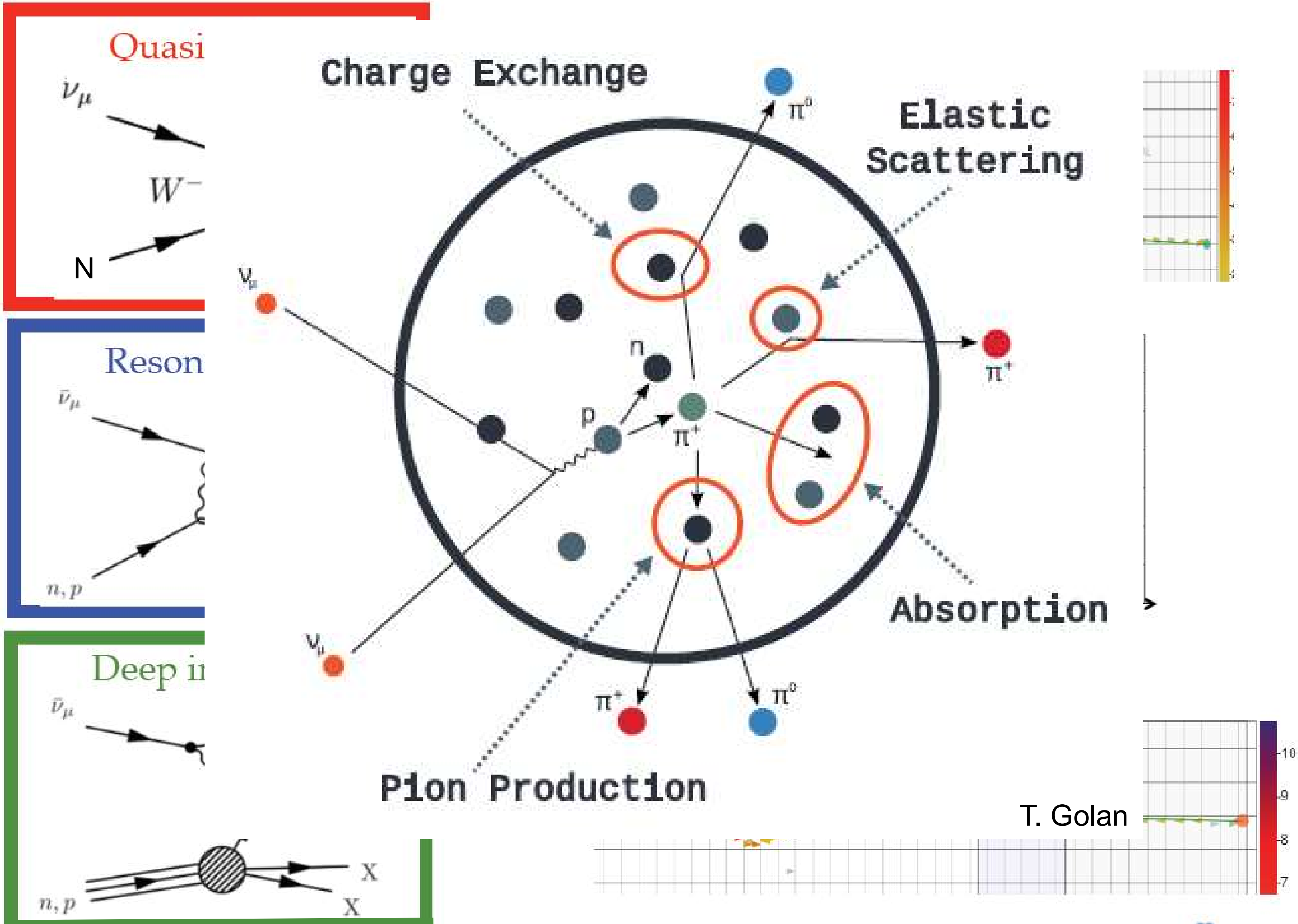
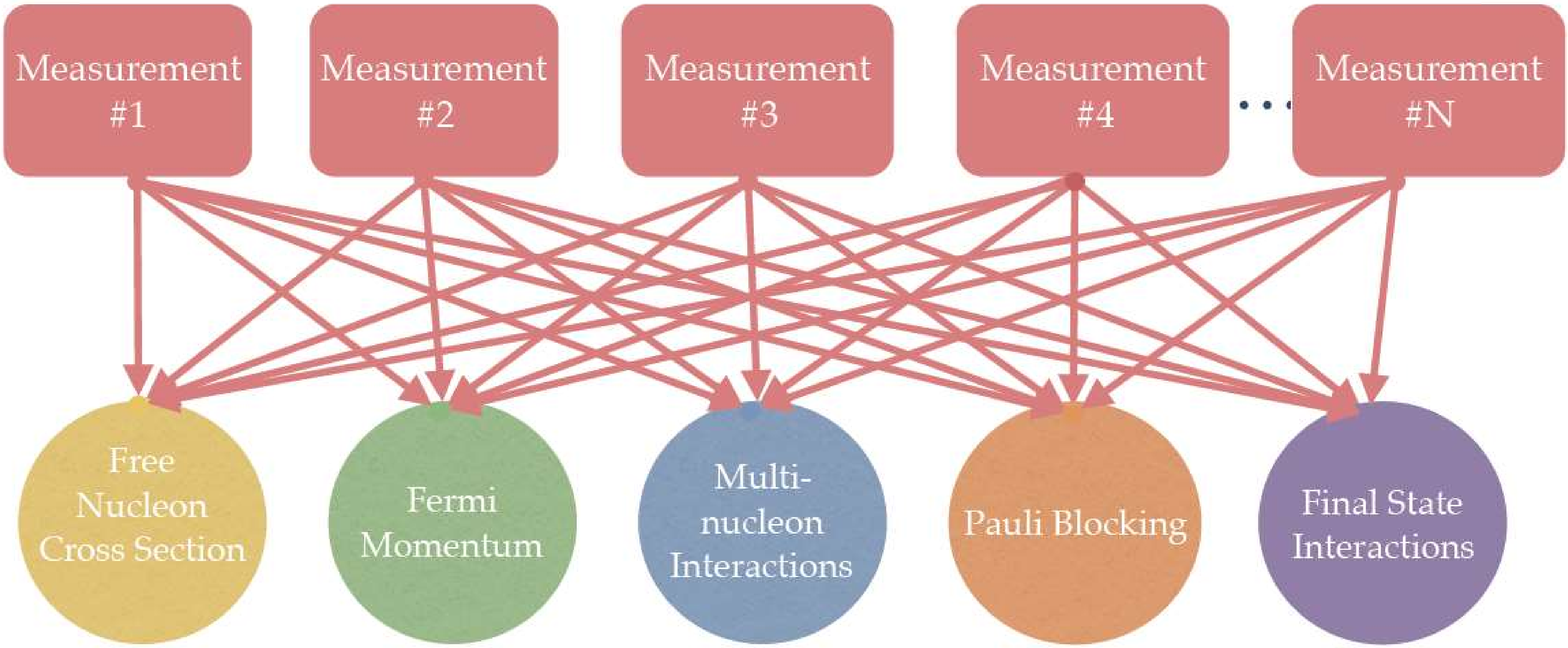


Our Approach

L.Fields

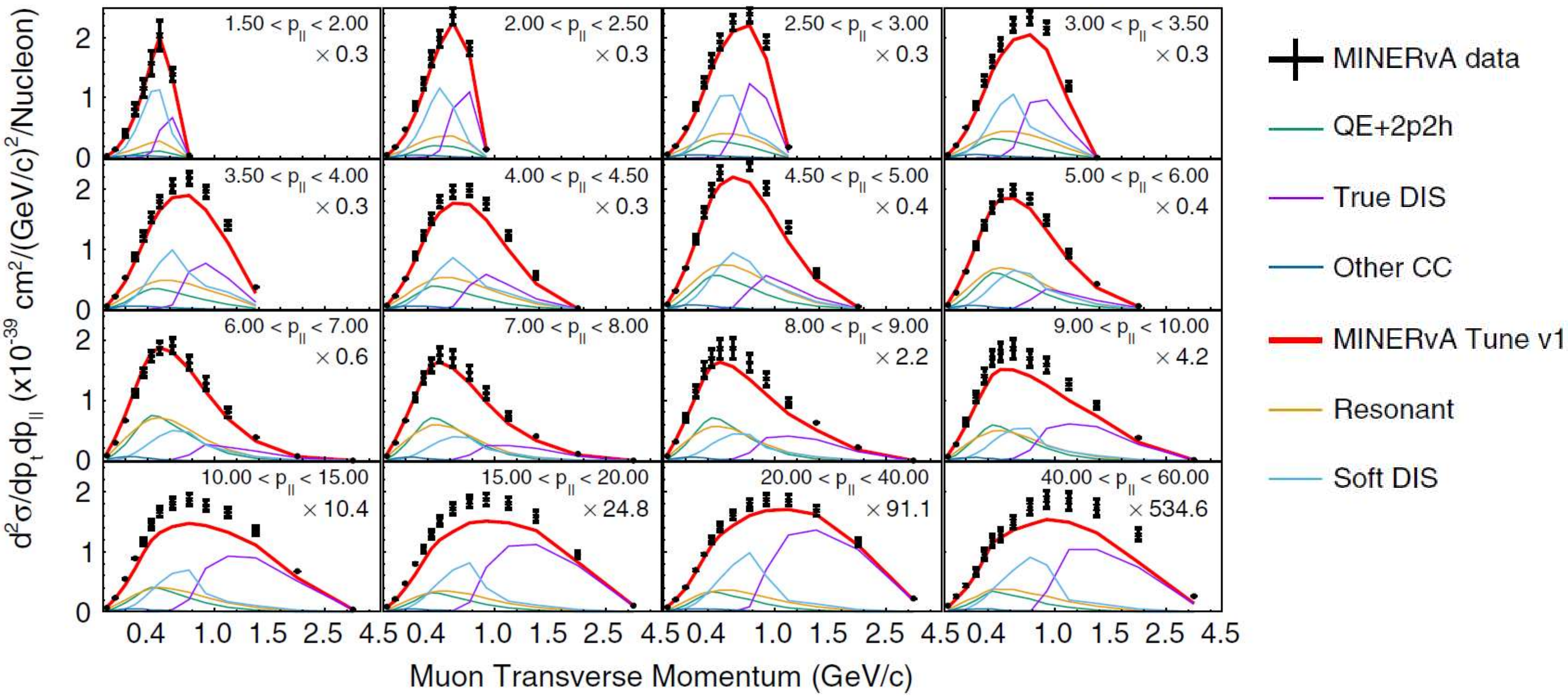


Recent Results

- Inclusive Cross Section
  - Phys.Rev.D 104 (2021) 9, 092007
- Constraining the flux – Inverse Muon Decay
  - Phys.Rev.D 104 (2021) 9, 092010
- Low Recoil Measurement
  - 2110.13372

Inclusive Measurement

- Provides a testbench with low uncertainties for model comparisons – does that model cocktail work?



Inclusive Measurement

205 degrees of freedom

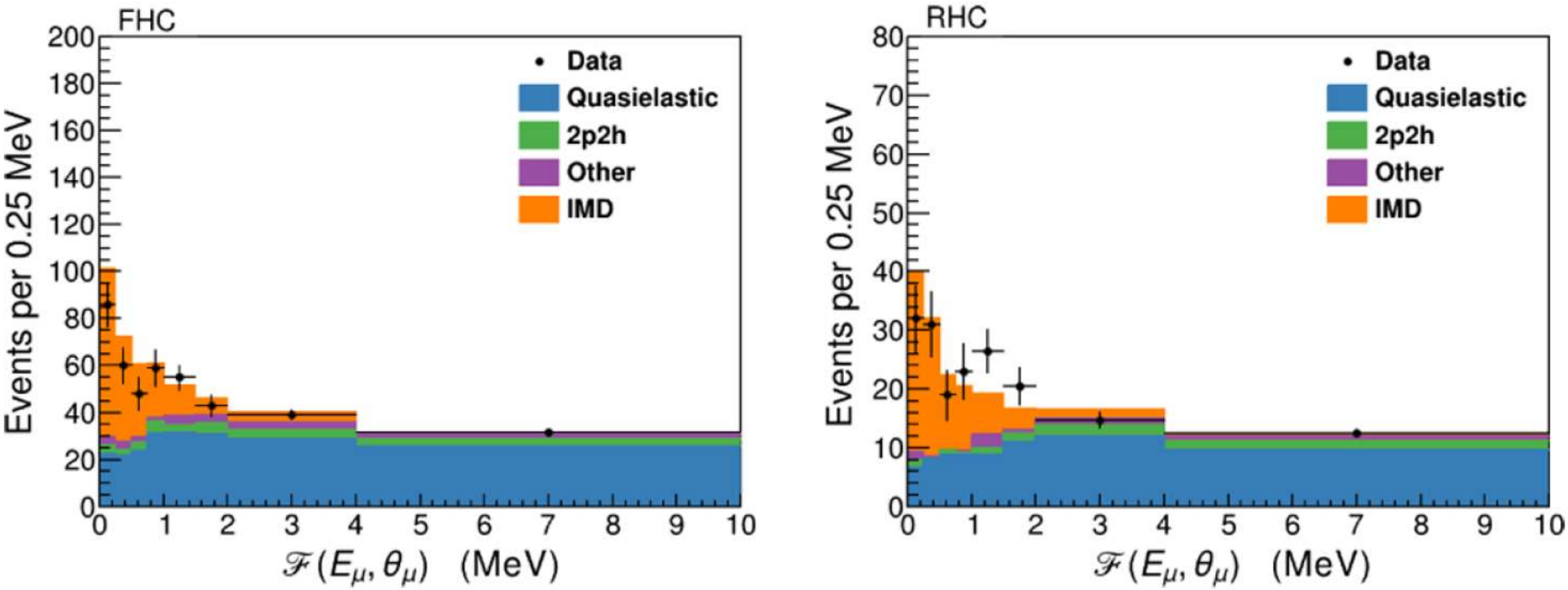
Process variant	Standard χ^2	Log-normal χ^2
MINERvA Tune v1	6786	7494
GENIE 2.12.6	8241	7892
GENIE 2.12.6 and NonResPionTune Only	9764	9910
GENIE 2.12.6 and QE RPA	5661	6544
GENIE 2.12.6 and Low Recoil Enhancement	12345	12074
MINERvA Tune v1 with nCTEQ15	6803	7530
MINERvA Tune v1 with nCTEQν	6954	7762
MINERvA Tune v1 with AMU	7652	8793
MINERvA Tune v1 using MK	6224	7049
MINERvA Tune v1 with Low Q^2 Pion—MINOS	4553	6388
MINERvA GENIE tune v2	5022	7833
GiBUU v2019	5800	9246
GiBUU v2021	5594	6779
NuWro with Spectral Function	5151	6394
NuWro with Local Fermi Gas	3789	4944
NEUT with Spectral Function	9151	10020
NEUT with Local Fermi Gas	6251	7452

- Model variations and generator predictions are universally disfavored
- Trends agree with the snapshot from model comparisons in the 3 GeV result

Inverse Muon Decay

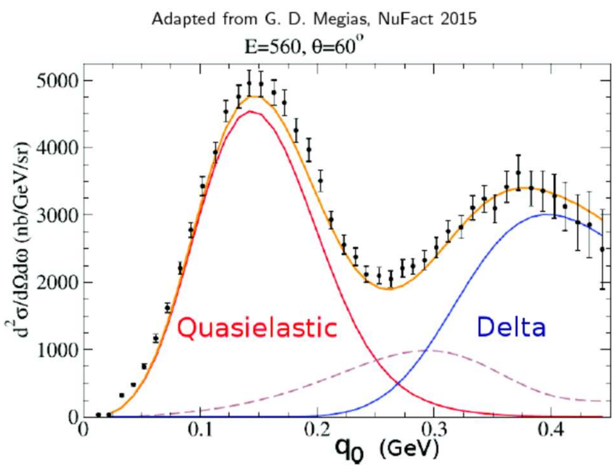
- $\nu_\mu + e \rightarrow \mu + \nu_e$: a standard candle!
  - Only problem is a kinematic threshold of 11 GeV
  - Useful for high energy flux tails
- A classic example of curiosity in a sea of events
- Realized in the midst of the inclusive measurement
  - How to extract 100s of events out of a pool of 4M
  - Signature: is a low angle, no recoil interaction

Inverse Muon Decay

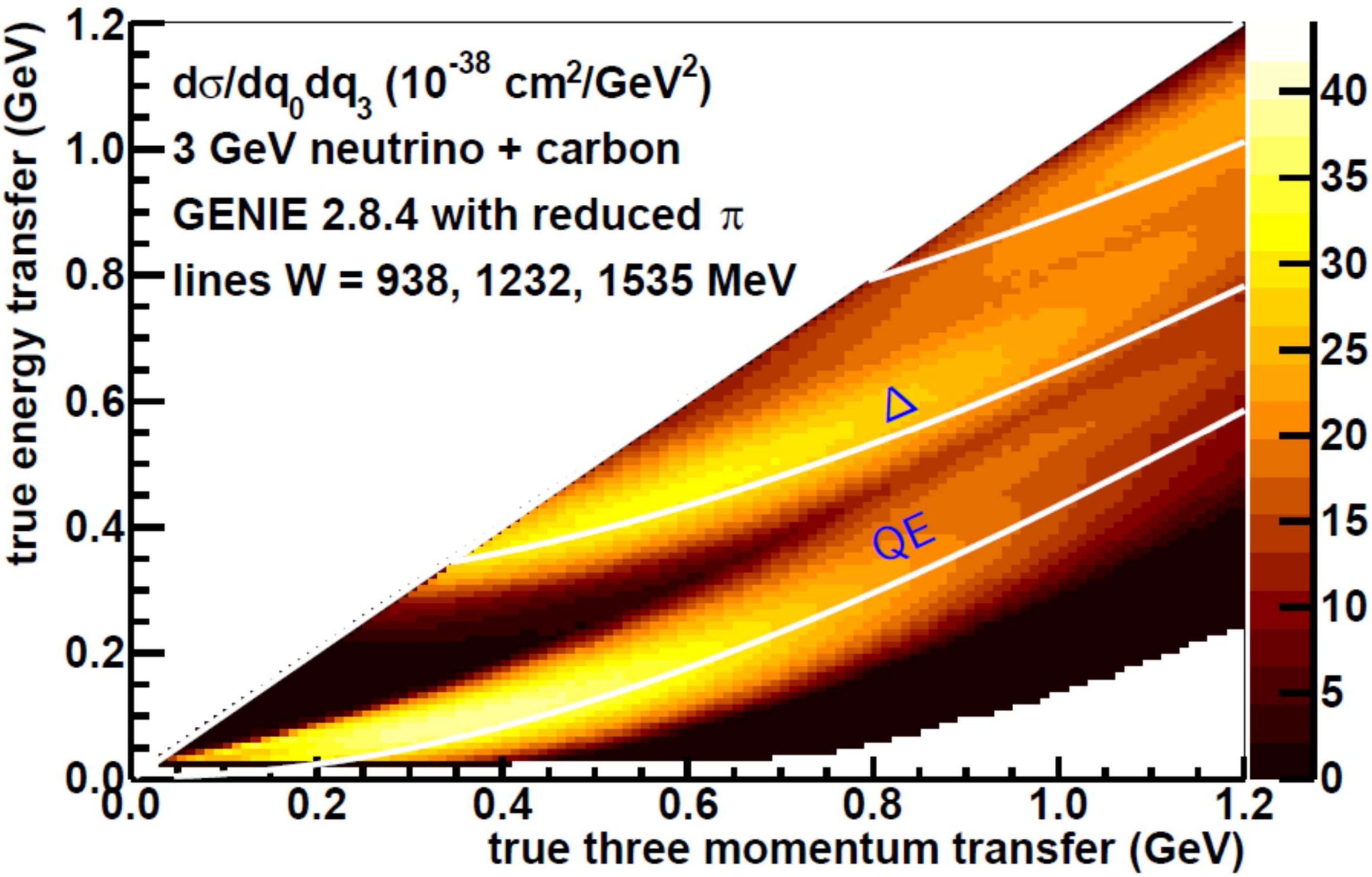


- Was able to select 127(56) in FHC(RHC)
- Statistical uncertainty dominated
- On its own can reduce the flux uncertainty from ~9-10% to 7-8%

Inclusive Charge Current cross section



$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - M_\mu^2$$
$$E_\nu = E_\mu + q_0$$
$$q_3 = \sqrt{Q^2 + q_0^2}$$



MINERvA makes similar measurements using the hadronic system and the outgoing lepton

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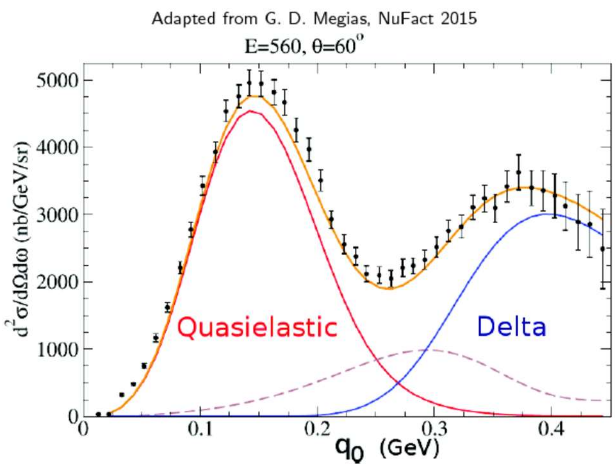

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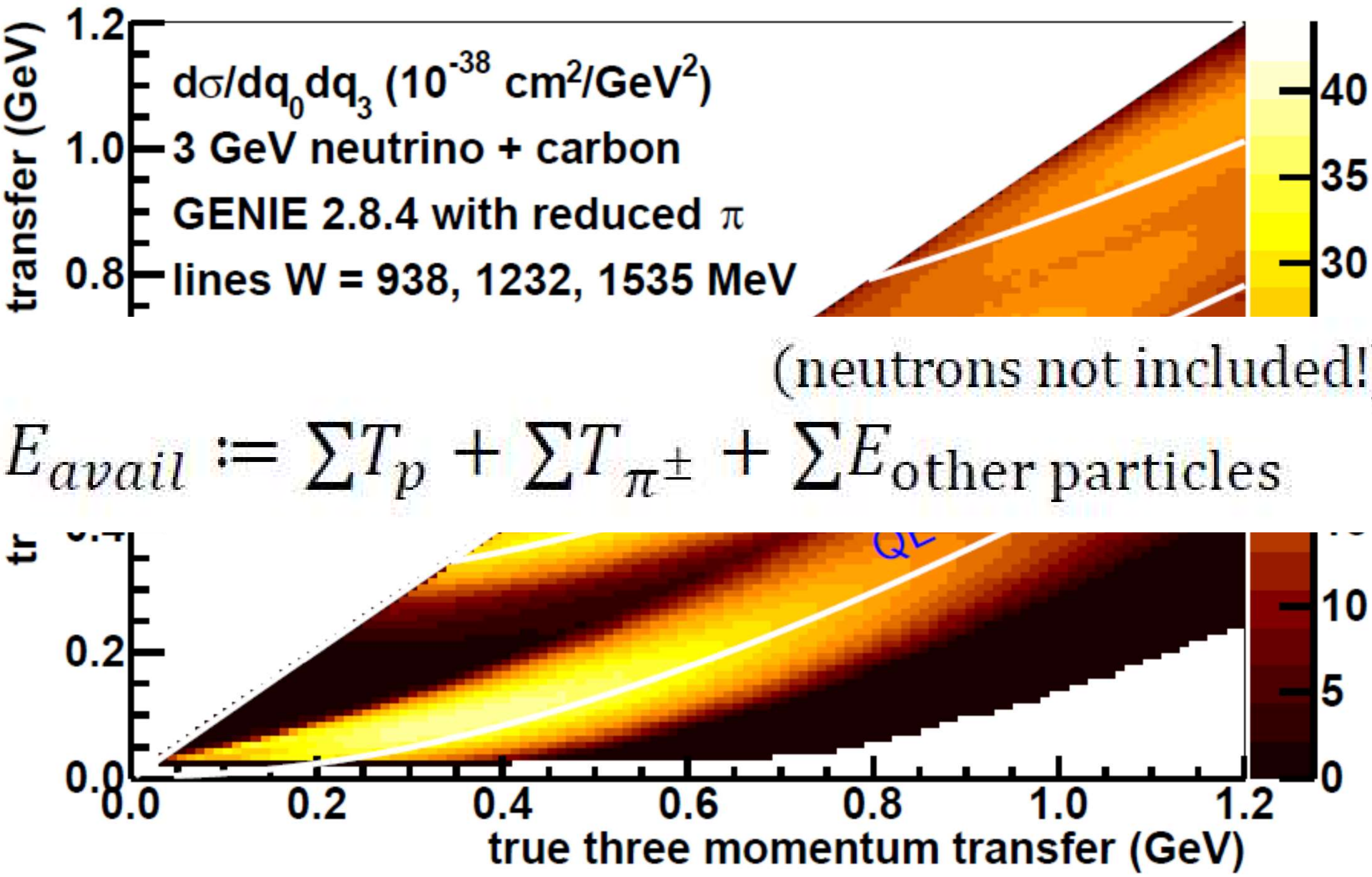


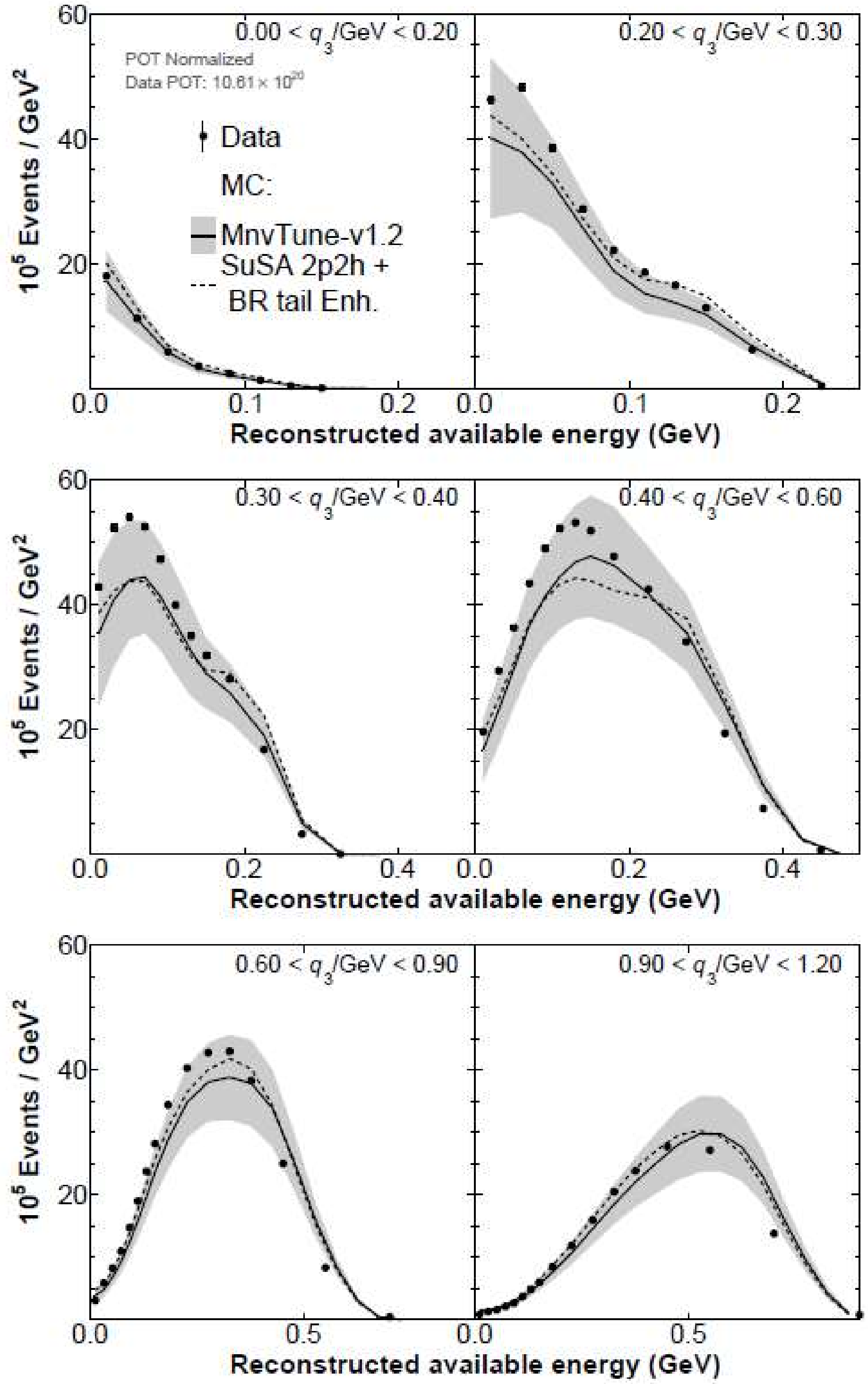
(neutrons not included!)

$$E_{avail} := \sum T_p + \sum T_{\pi^\pm} + \sum E_{\text{other particles}}$$

MINERvA makes similar measurements using the hadronic system and the outgoing lepton

Low Recoil Result

- Model Studies
  - QE+2p2h region
    - Replace Valencia 2p2h with SuSA 2p2h
    - Modify Bodek-Ritchie tail



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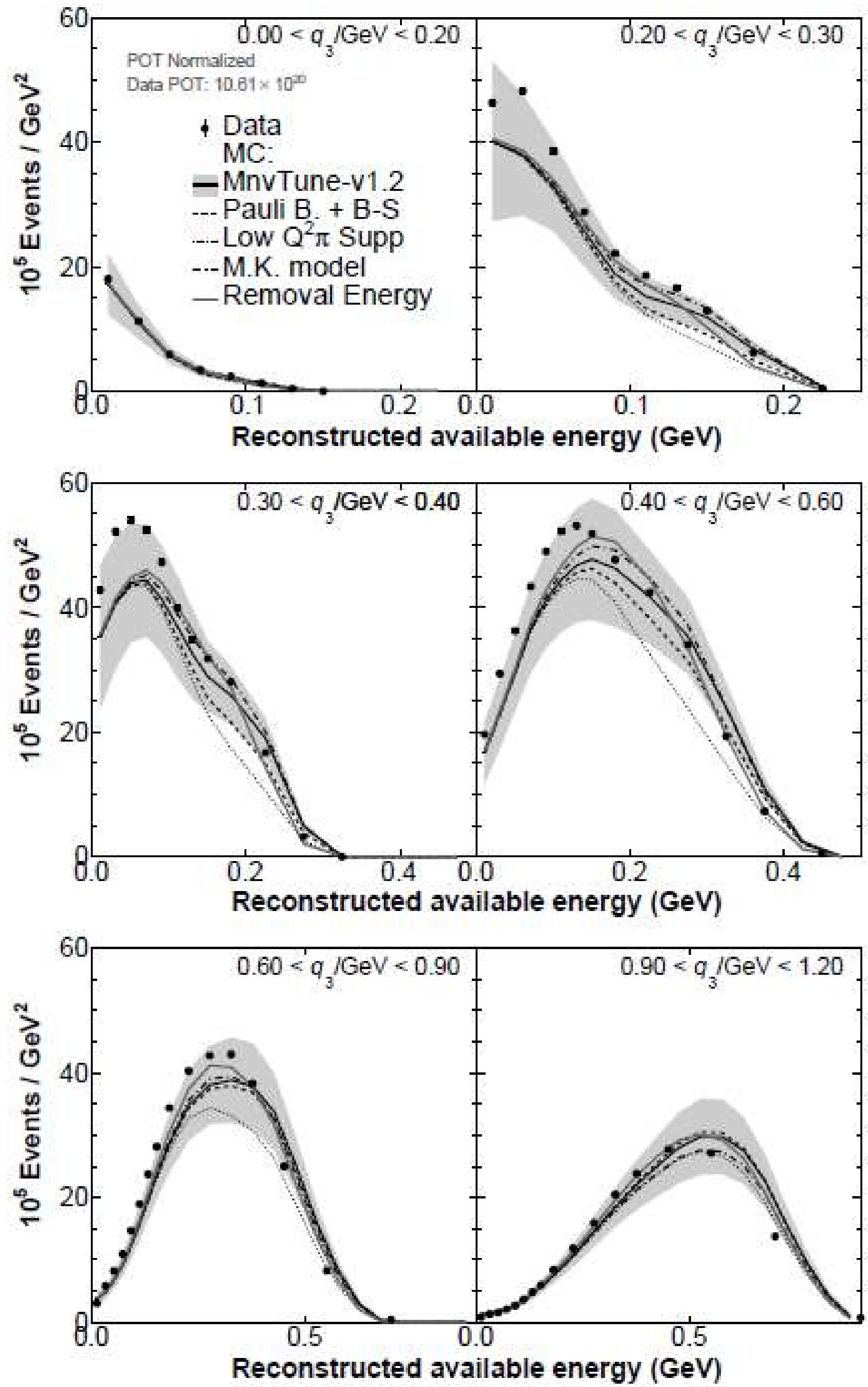
  - Resonant regions
    - Rein-Sehgal -> Berger-Sehgal
    - Rein-Sehgal->M. Kabirnezhad
    - Investigate removal energy
    - Low Q^2 suppression



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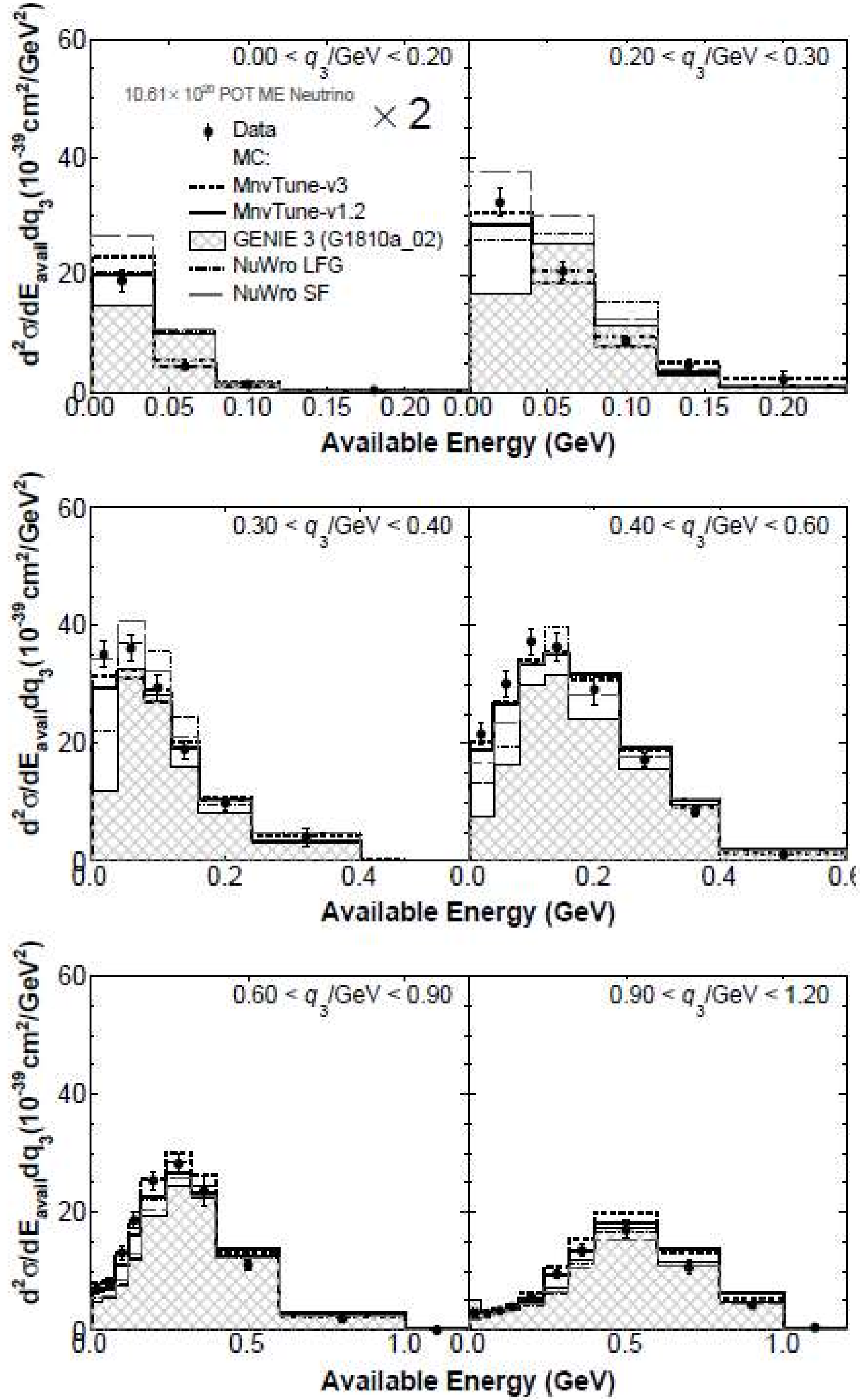


Understanding pions

Channel	ν_μCC1$\pi^\pm$ [17]	ν_μCC$N\pi^\pm$ [18]	ν_μCC1π^0 [19]	$\bar{\nu}_\mu$CC1π^0 [18]
N_{bins} p_μ	8	9	8	9
N_{bins} θ_μ	9	9	9	9
N_{bins} T_π	7	7	7	7
N_{bins} θ_π	14	14	11	11
N_{bins} total	38	39	35	36
Signal definition	$1\pi^\pm, \geq 0\pi^0$ $1\mu^-$ $W_{\text{rec}} < 1.4$ GeV not applicable	$> 0\pi^\pm, \geq 0\pi^0$ $1\mu^-$ $W_{\text{rec}} < 1.8$ GeV not applicable	$1\pi^0, 0\pi^\pm$ $1\mu^-$ $W_{\text{rec}} < 1.8$ GeV $\theta_\mu < 25°$	$1\pi^0, 0\pi^\pm$ $1\mu^+$ $W_{\text{rec}} < 1.8$ GeV not applicable

- A series of fits were performed using our low energy dataset in Phys.Rev.D 100 (2019) 7, 072005

Methodology

- Compare fit results with a default GENIE, ANL/BNL fit, all 4 samples together, individually
  - Tensions between nucleon and nuclear data show up as large penalty terms
  - Two different additional knobs used – pion absorption and pion inelastic scattering

Take away #1,#2

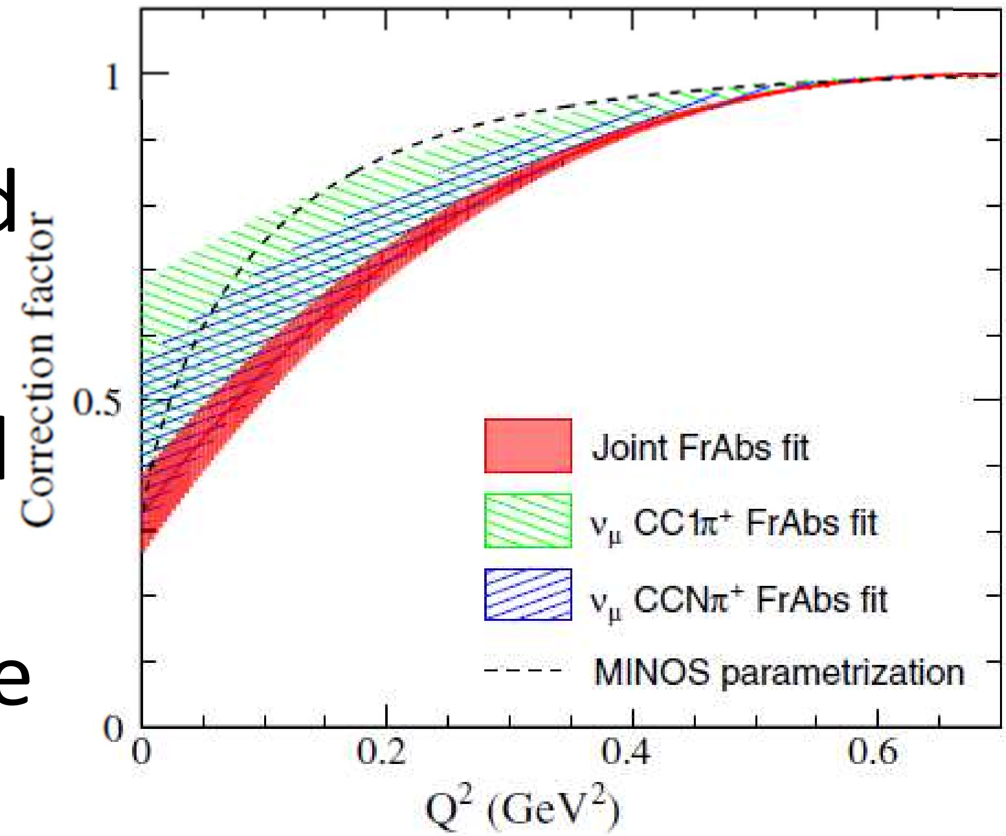
- Using either pion absorption or inelastic scattering results in similar results
- Application of the global tune to the individual channels results in various successes or failures

TABLE VII. Individual channel tuning results when the FrInel dial is treated as the free FSI parameter.

Parameter	ν_μCC1$\pi^\pm$	ν_μCC$N\pi^\pm$	ν_μCC1π^0	$\bar{\nu}_\mu$CC1π^0
M_A^{res} (GeV)	0.97 ± 0.05	0.97 ± 0.05	1.03 ± 0.05	0.96 ± 0.05
NormRes (%)	109 ± 7	108 ± 7	103 ± 7	112 ± 7
NonRes1π (%)	42 ± 4	42 ± 4	43 ± 4	43 ± 4
NonRes2π (%)	300 (limit)	110 ± 30	300 (limit)	300 (limit)
π-iso	1 = Iso (limit)	1 = Iso (limit)	1 = Iso (limit)	1 = Iso (limit)
FrInel (%)	117 ± 54	127 ± 33	0 (limit)	80 ± 59
MINERνA χ^2	37.1	63.4	86.9	34.9
χ^2_{pen}	0.7	1.3	3.4	0.2
Total χ^2	37.8	64.7	90.3	35.1
N_{DoF}	35	36	32	33

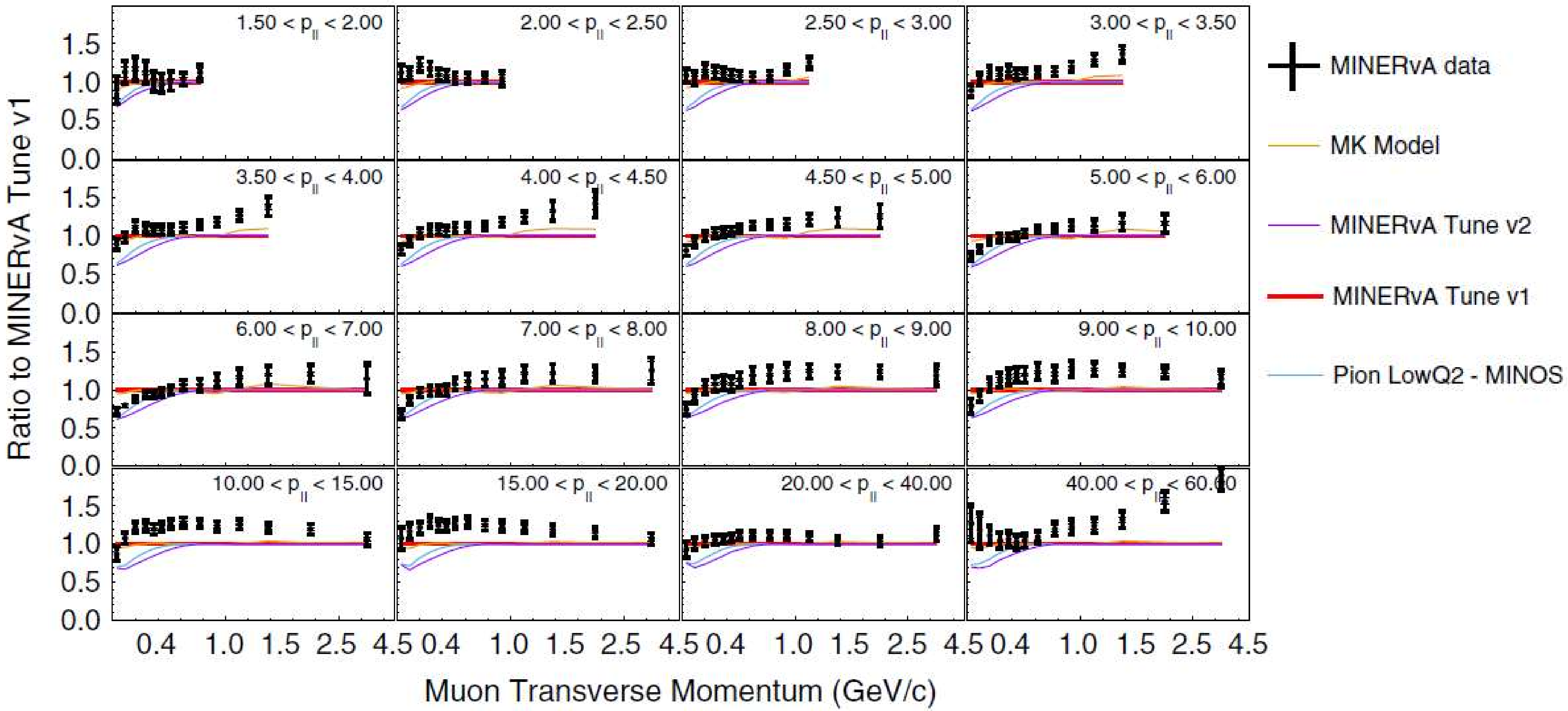
Necessary to add empirical description

- Alleviates a tension between nucleon and nuclear data
- But, now the charged pion data is less well described than before
  - Tension between charged and neutral processes?



Example of Low Q^2 suppression

- While beneficial, the pion fit does not capture the effect in the inclusive sample



Data Preservation

- MINERvA's data is valuable and relevant to the global neutrino effort
- To facilitate the future utility of the data we are working on preserving our data in a form that future analysis ideas can be explored
- If you have ideas of possibilities you should get in to contact with MINERvA.
- Many upcoming analyses from MINERvA use data preservation products

Looking Forward

- Pions – Pion – Pions!
  - Coherent pion production on carbon, iron, lead
  - Charged pion production on carbon, iron, lead
  - Neutral pion production on iron and lead
  - Charge pion production below tracking threshold
- Transition region (Shallow Inelastic Scattering)
- High Statistics DIS on carbon, iron, lead
- Improved flux constraint
- Quasielastic-like
  - Triple Differential
  - Anti-neutrino lepton kinematics
  - Transverse kinematic imbalance on carbon, iron, lead, water
  - Multi-variate transverse kinematic imbalance
- Don't forget about all our anti-neutrino data