First Direct Measurement of Nuclear Dependence of Coherent Pion Production

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INTERSECTIONS @ Lake Buena Vista, FL

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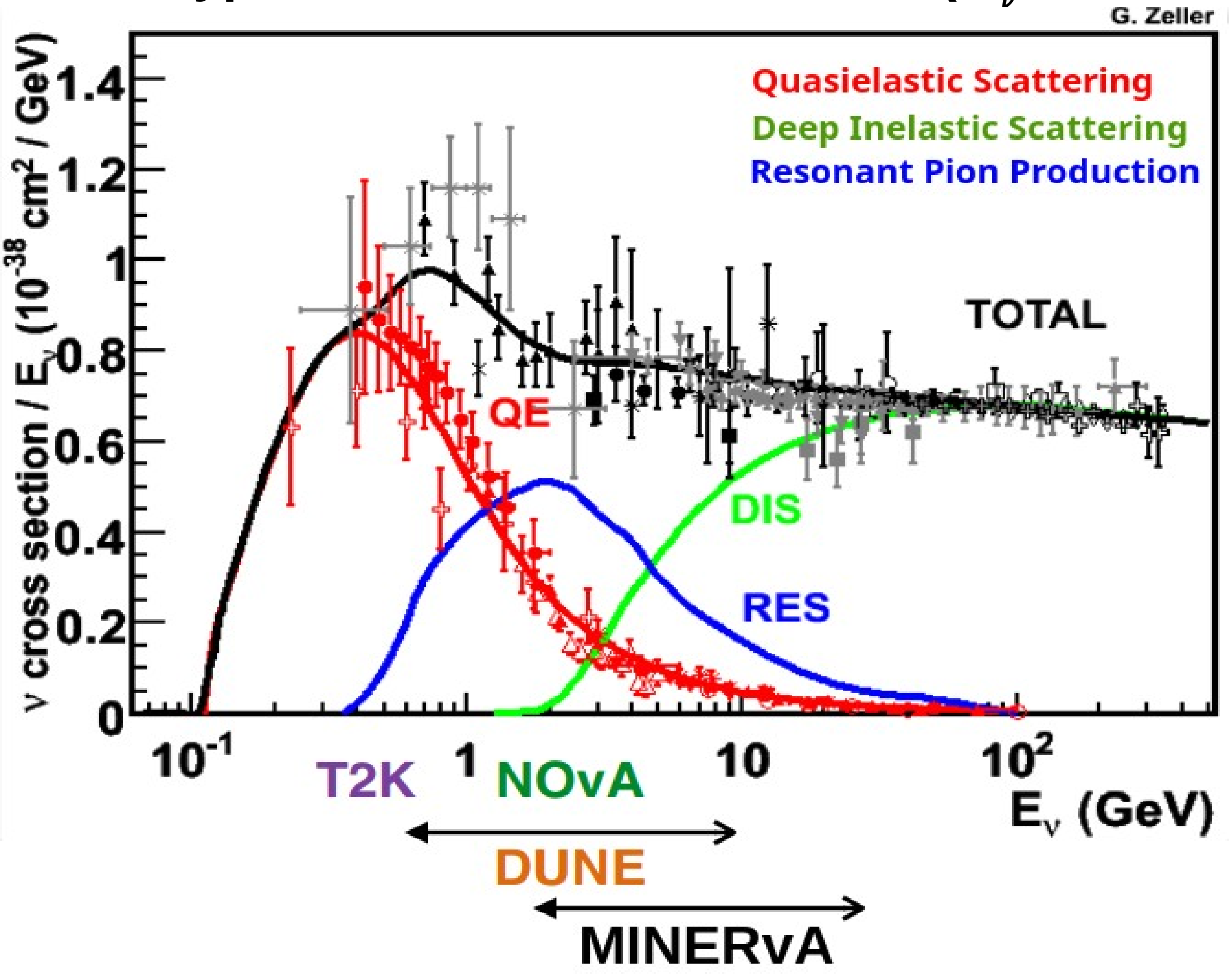
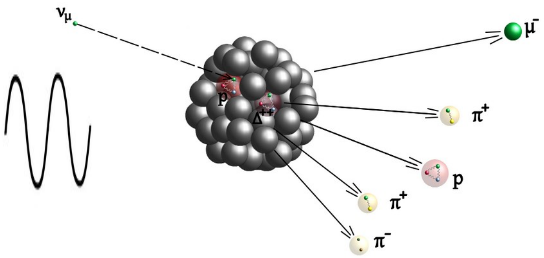
Content

1 – Neutrino Interactions (Briefly)

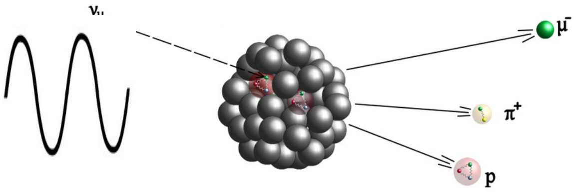
Types of Neutrino Interactions (E_ν ~ 0.1-20 GeV)



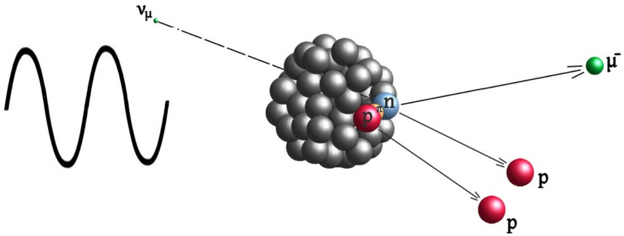
J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)



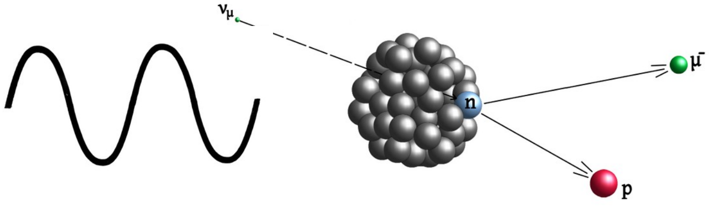
Deep Inelastic Scattering



Resonant Pion Production



2p2h Scattering

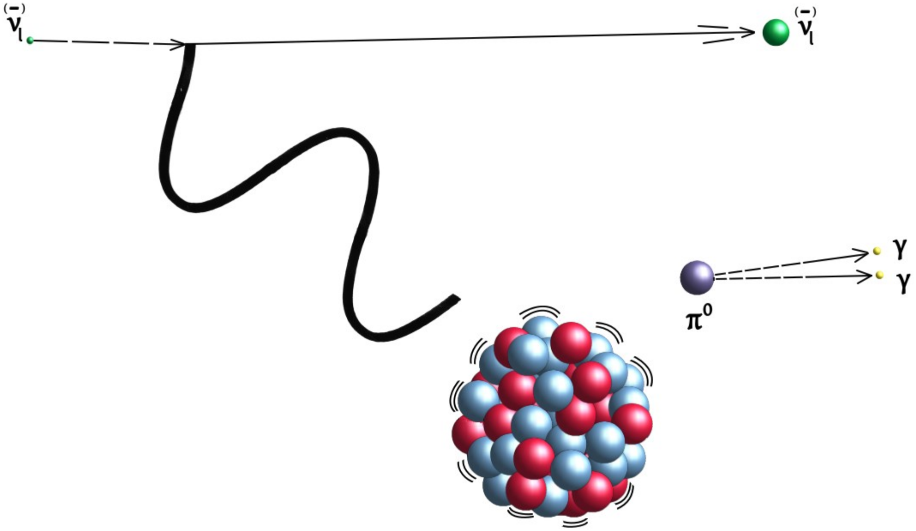


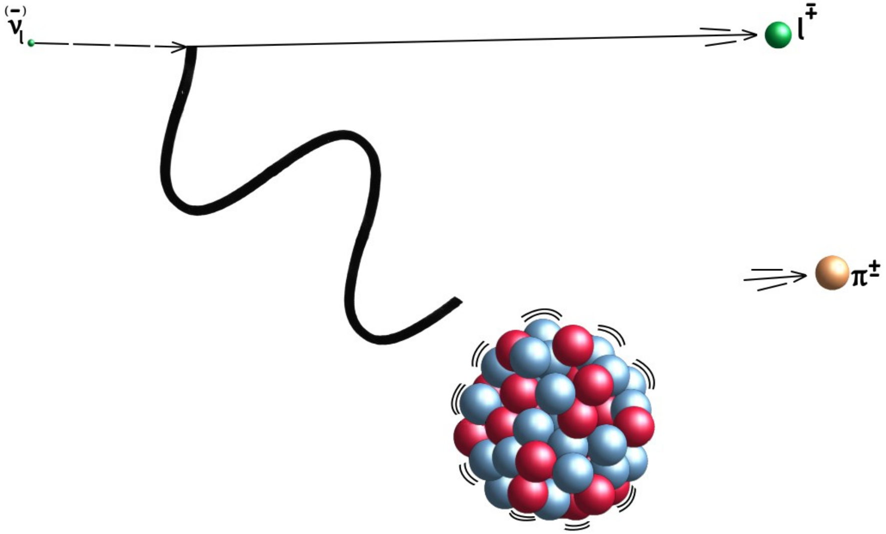
Quasielastic Scattering

2 – What Is Coherent Pion Production?

Features

- Neutrino-nucleus interaction.
- All nucleons react in phase (coherently).
- Nucleus left in its initial state (no breakup).
- Nucleus recoils undetected, O (~ keV).
- Forward lepton and forward pion created.
- Pion scatters coherently off the nucleus.
- Occurs in both c**harged (CC)** and **neutral (NC)** channels.
- It can be induced by a neutrino or anti neutrino of any flavor.





What Is Coherent Pion Production?

Features

- Coherence depends on the magnitude of the four-momentum transfer to the nucleus, **|t|**

$$|t| = \left|(p_\nu - p_l - p_\pi)^2\right|$$

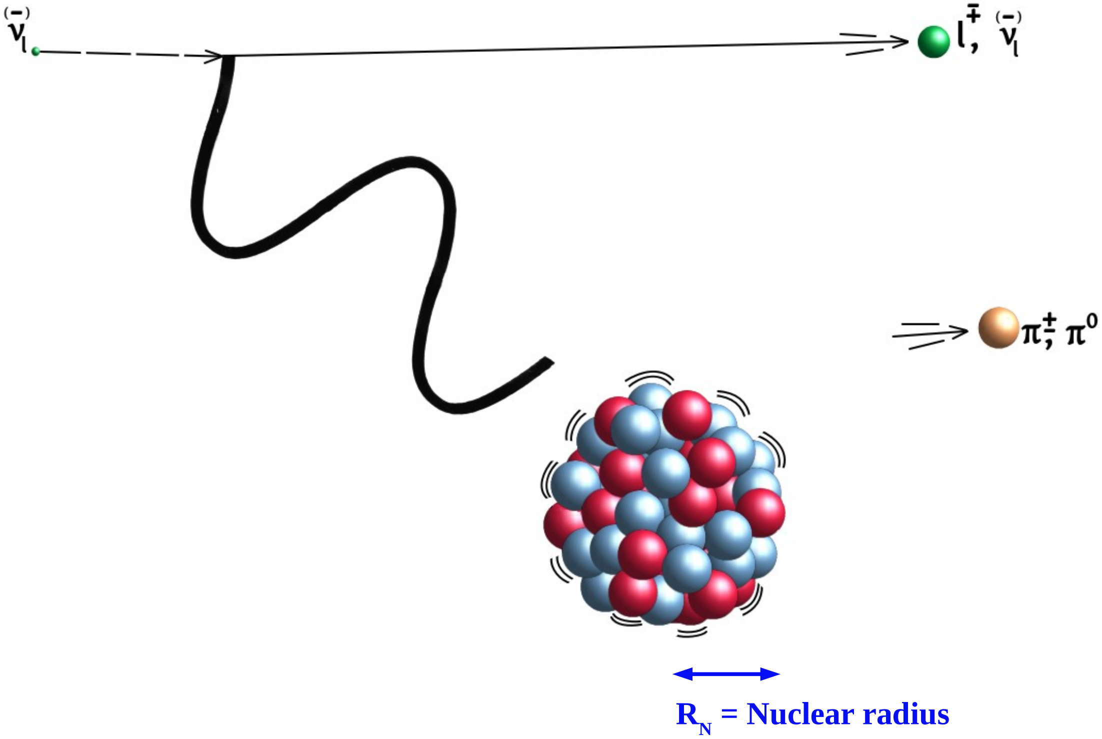
- There is a threshold **|t$_{min}$|**

$$|t_{min}| \simeq \left(\frac{Q^2 + m_\pi^2}{2E_\pi}\right)^2$$

- and a maximum **|t$_{max}$|**

$$|t_{max}| \simeq 1/R_N^2$$

within which the interaction takes place.



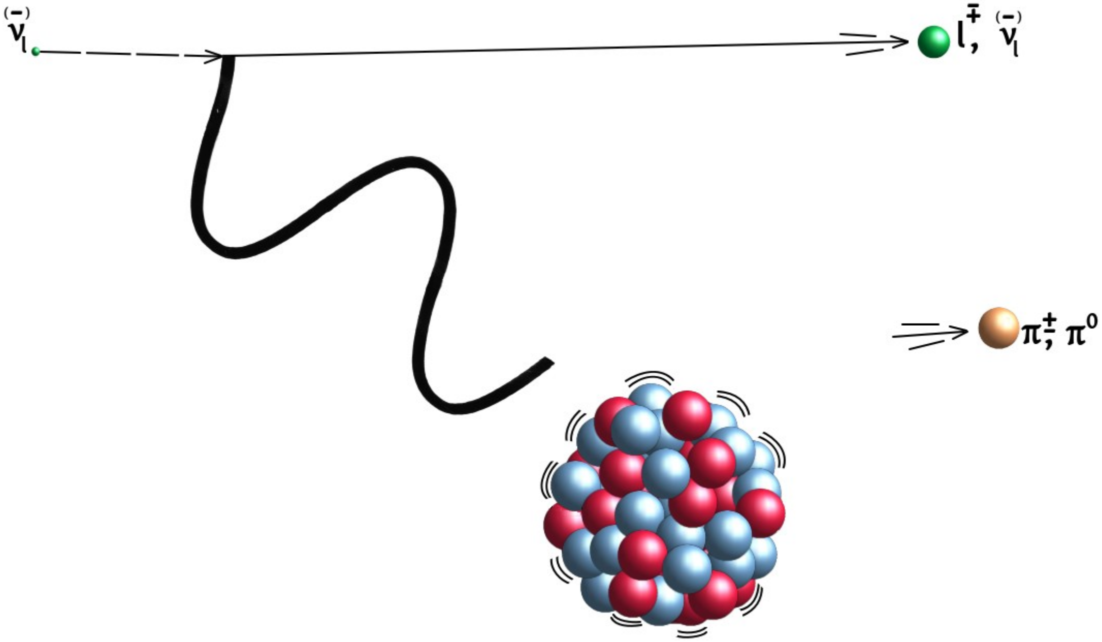
What Is Coherent Pion Production?

Phenomenology

Underlying details of the interaction **not truly understood.**

- **Partially Conserved Axial Current (PCAC) hypothesis**:
  A neutrino exchanges a W or Z boson in the presence of a nucleus. The boson then fluctuates to a π meson.

- **Microscopic Interpretation**:
  Coherent addition of all neutrino-nucleon interactions in the nucleus. Δ resonance production is the main process contributing to the final state.



What Is Coherent Pion Production?

The Rein-Sehgal Model

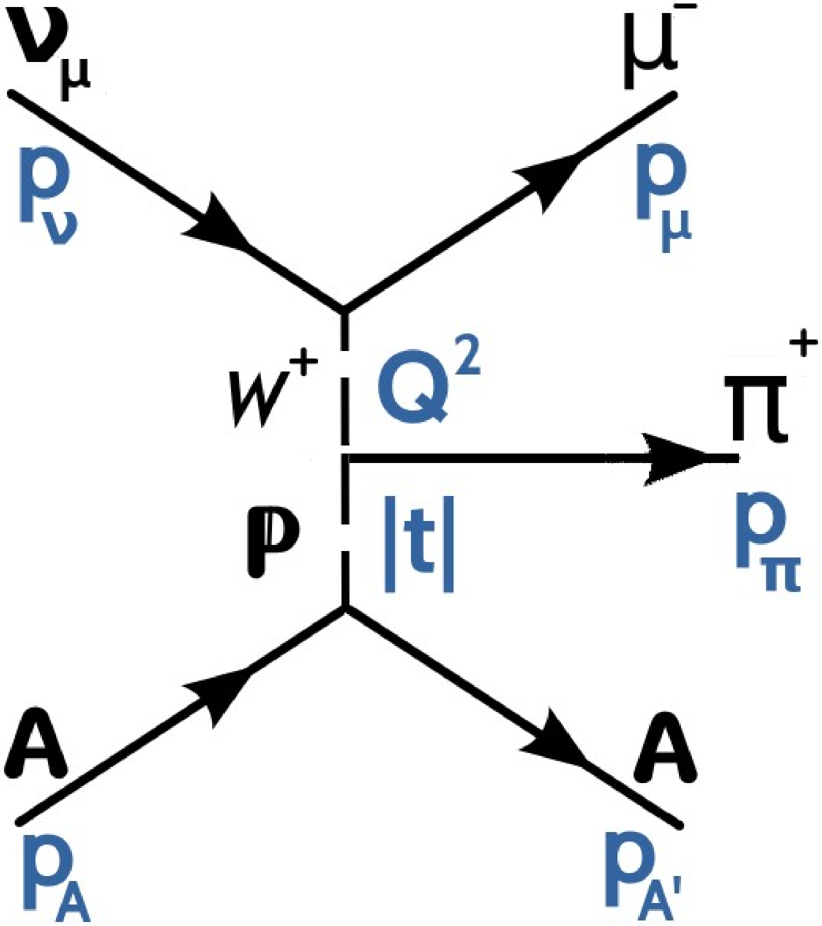
- Uses **Adler's theorem** to relate the inelastic process

$$\nu + A \rightarrow l + \pi + A$$

to the elastic process

$$\pi + A \rightarrow \pi + A$$

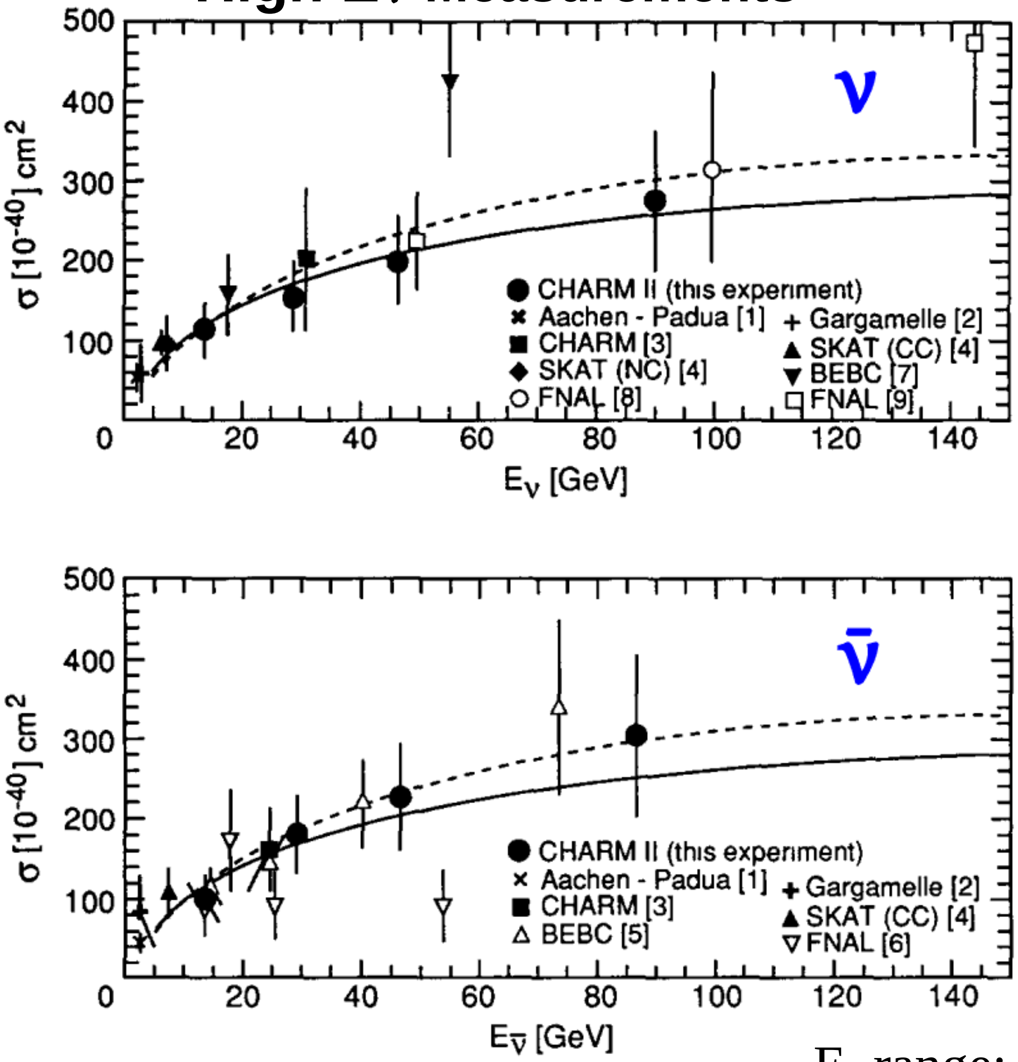
- It assumes the incoming neutrino and the outgoing lepton are parallel (**when $Q^2 = 0$**), and neglects the lepton mass.



3 – Previous Measurements

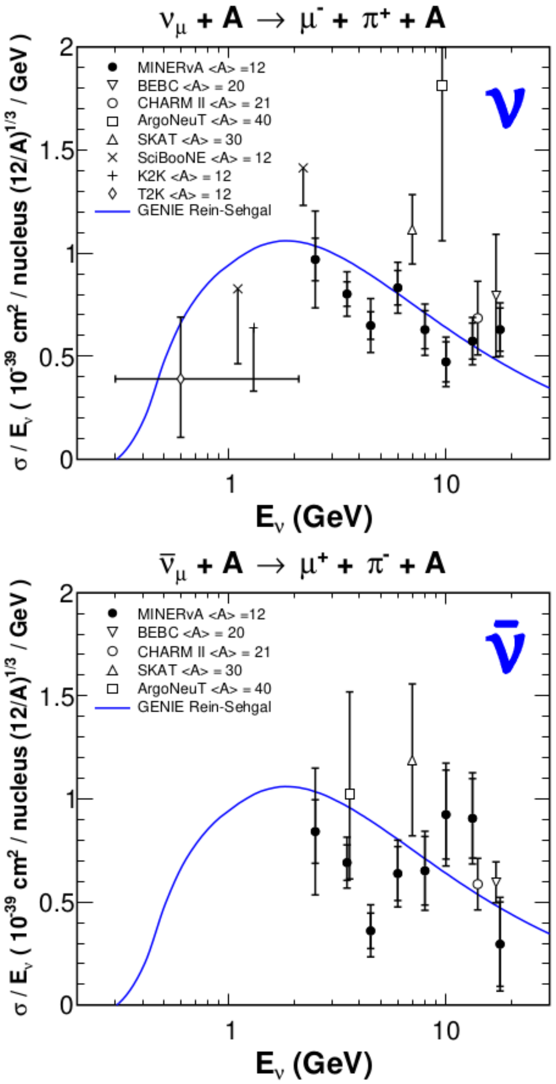
[Phys.Lett.B 313 (1993) 267-275]

High Eν Measurements



[Phys.Rev.D 97 (2018) 3, 032014]

Low Eν Measurements



- E_ν range: **~2 to ~300 GeV**
- *A* (nuclear mass) range: **^{12}C to ^{80}Br**
- Neutrino and anti-neutrino modes
- Cross sections scaled as ***$A^{1/3}$***

4 – *A*-Dependence of Coherent Pion Production

What Else? ⇒ ***A*-Scaling Measurements!**

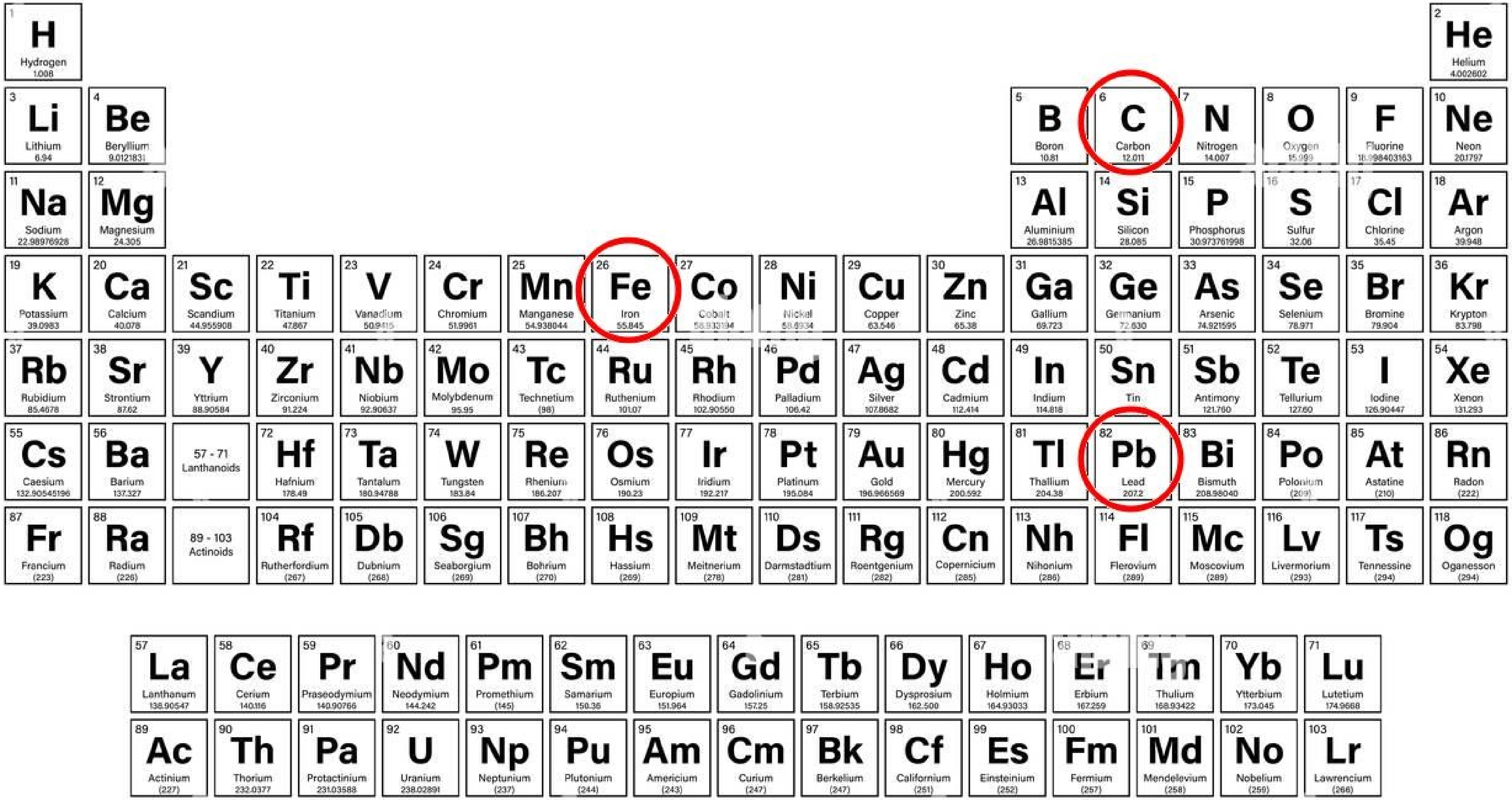
- So far, **NO** measurements for **nuclei beyond *A*** = **80**. ***A***-scaling of the cross section requires measurements in nuclei of very different mass.

- Different models predict different scaling of the coherent cross section with regards to the mass number ***A****:*
    - A set of models, like the **Rein-Sehgal** model, predict an ***A***-scaling as $A^{1/3}$.
    - Other models, like the **Berger-Sehgal** model, predict a ***A***-scaling as $A^{2/3}$.
    - The **Belkov-Kopeliovich** model predicts an “energy-dependent” ***A***-scaling. Scaling as $A^{1/3}$ at **low E_ν** and as $A^{2/3}$ at **high E_ν**.

4 – *A*-Dependence of Coherent Pion Production

What Else? → ***A*-Scaling Measurements!**

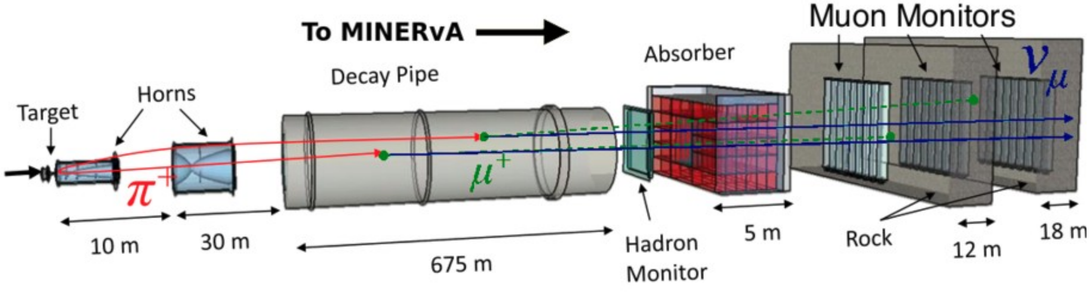
A = 12, 56, 207

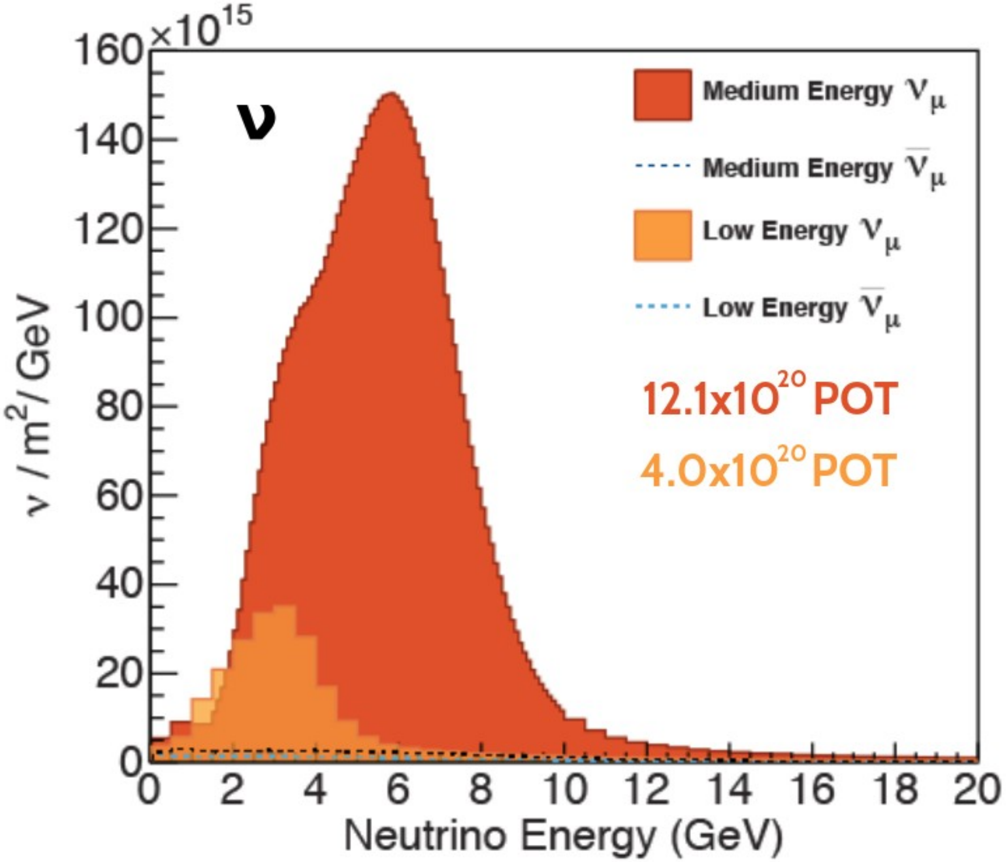


A-Dependence of Coherent Pion Production

Beamline and Fluxes

Beamline





Flux used in previous MINERvA measurement

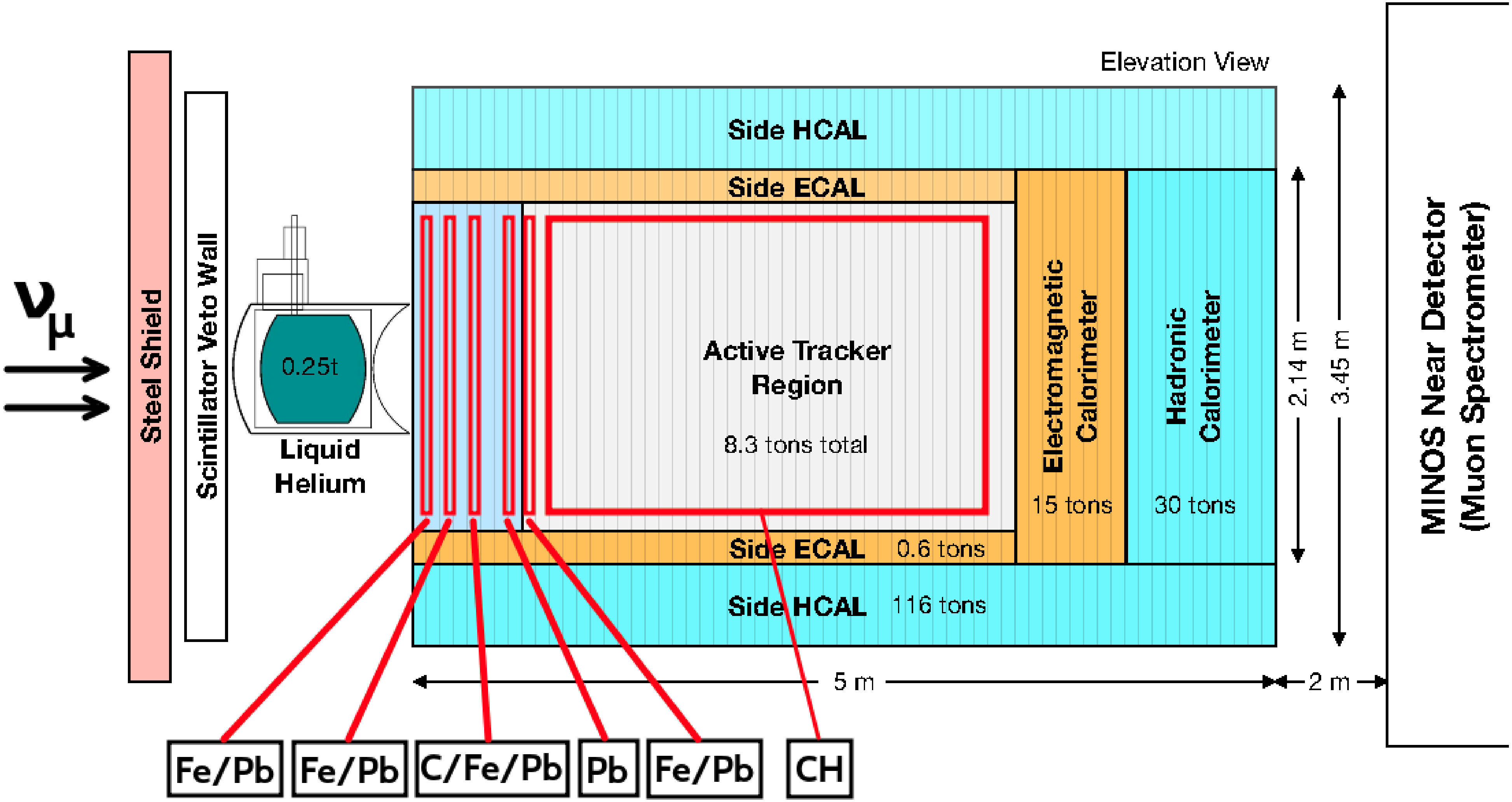
$\langle E_\nu \rangle \sim 3.5$ GeV

Flux used in this measurement

$\langle E_\nu \rangle \sim 6$ GeV

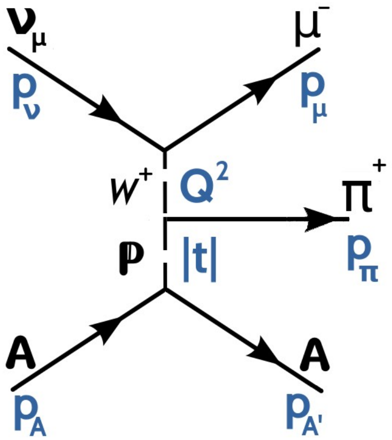
A-Dependence of Coherent Pion Production

MINERvA Detector

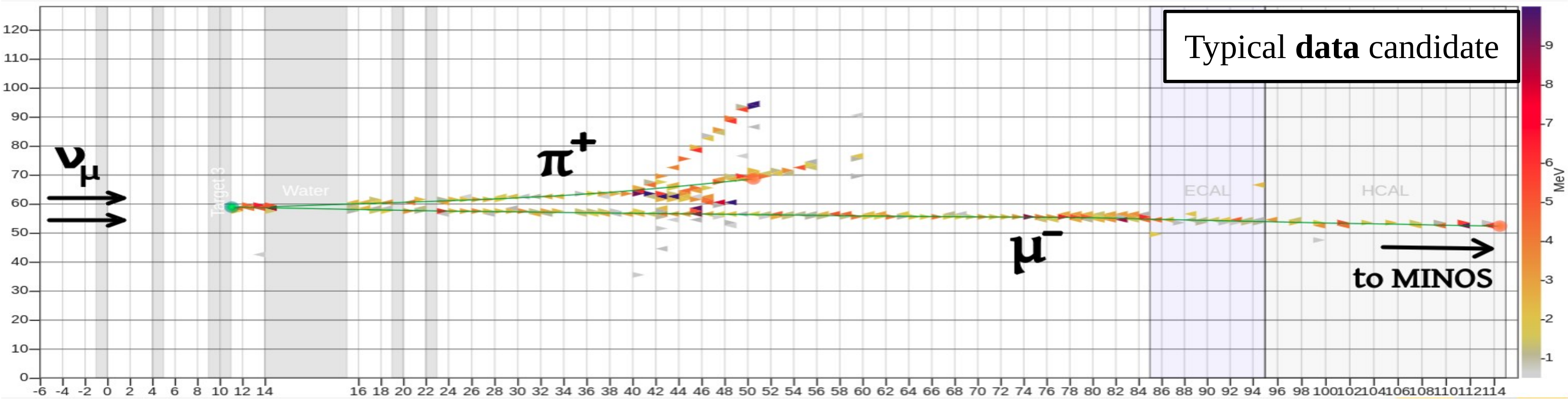


A-Dependence of Coherent Pion Production

Signal Definition



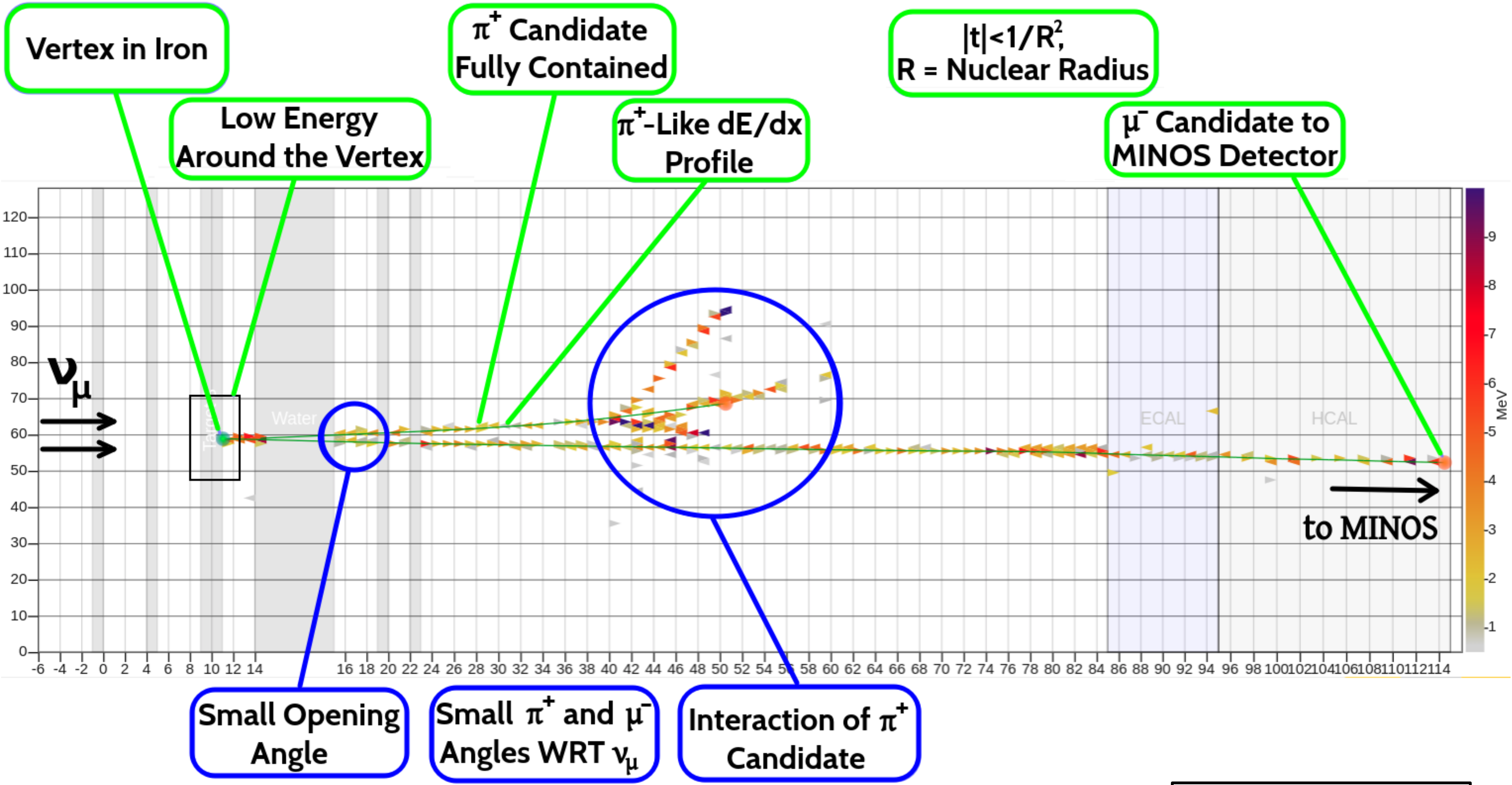
- ν_μ-induced CC coherent π^+ events in **C**, **Fe** and **Pb**.
- Multiplicity == 2 → μ^- and π^+ candidate tracks.
- Muon vertex inside the material under study.
- $2 < E_\nu < 20$ GeV to remove events with mis-reconstructed muon energy.
- Pions with angles larger than 70 degrees have zero efficiency due to the impossibility to reconstruct the track.
- Muons with angles grater than 13 degrees have zero acceptance in MINOS.


Typical **data** candidate

A-Dependence of Coherent Pion Production

Event Selection

CUTS APPLIED



Vertex in Iron

Low Energy Around the Vertex

π^+ Candidate Fully Contained

π^+-Like dE/dx Profile

$|t|<1/R^2$, R = Nuclear Radius

μ^- Candidate to MINOS Detector

Small Opening Angle

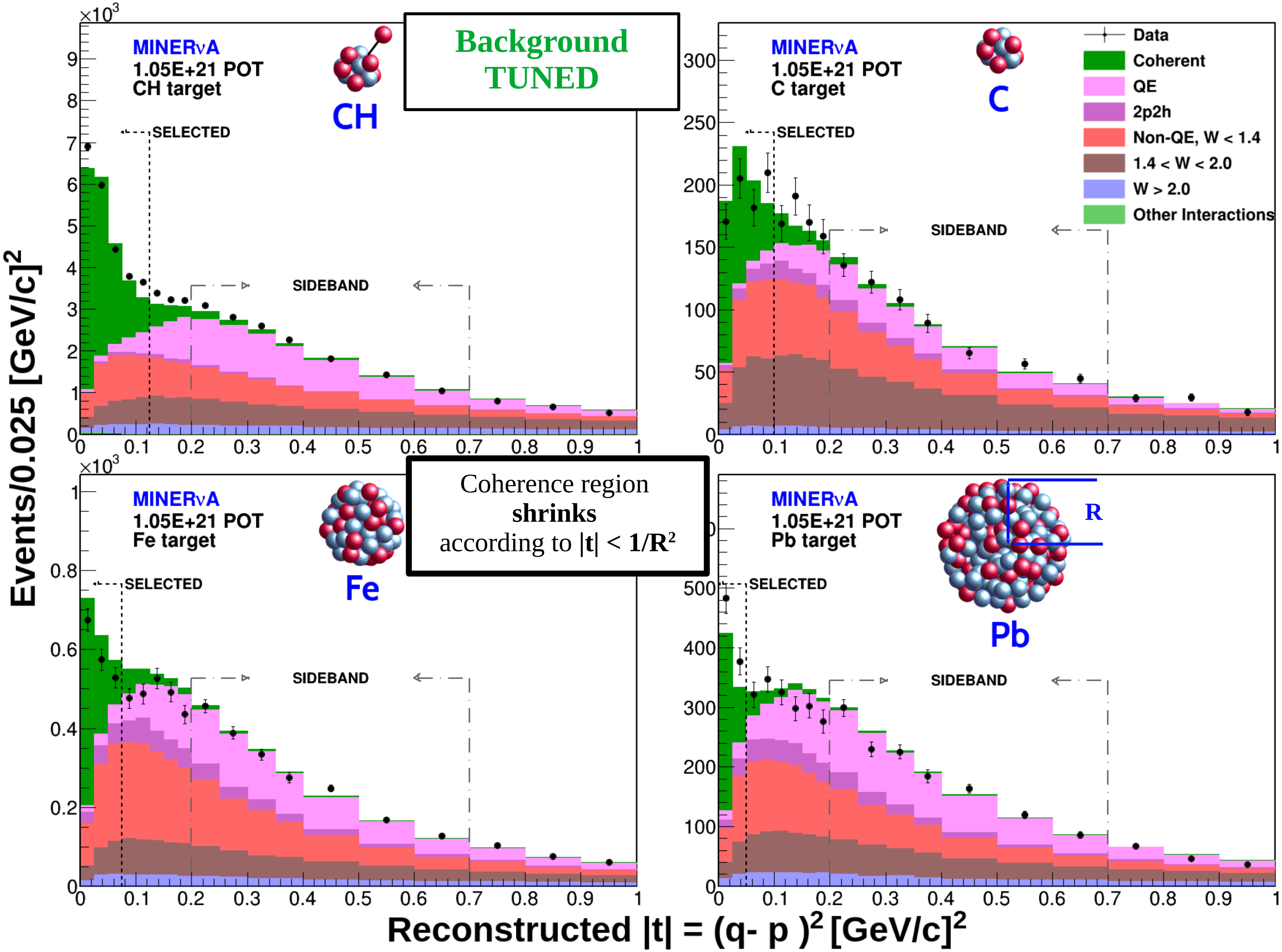
Small π^+ and μ^- Angles WRT ν_μ

Interaction of π^+ Candidate

OBSERVABLES

A-Dependence of Coherent Pion Production

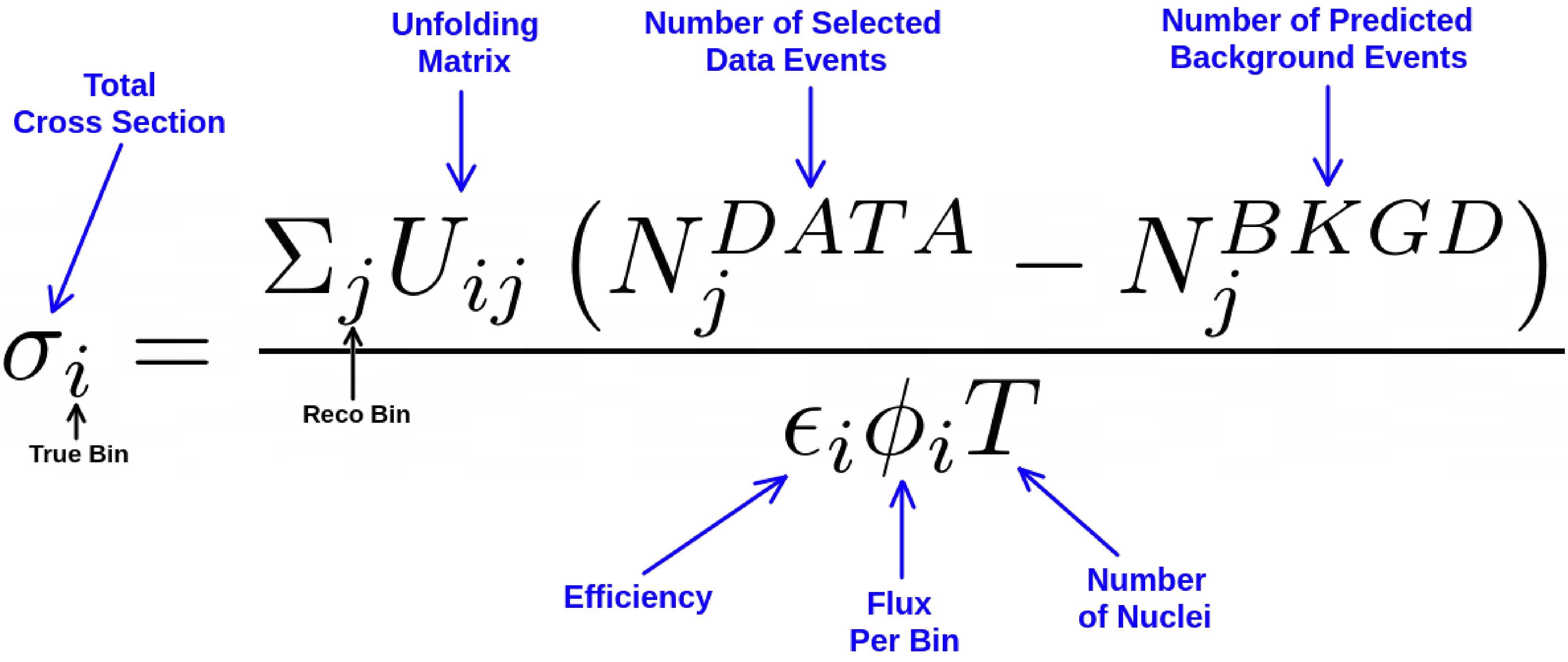
Tuned |t| Distributions



Background
TUNED

Coherence region
shrinks
according to |**t**| < **1/R**²

Cross Section Extraction



Total Cross Section

Unfolding Matrix

Number of Selected Data Events

Number of Predicted Background Events

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

True Bin

Reco Bin

Efficiency

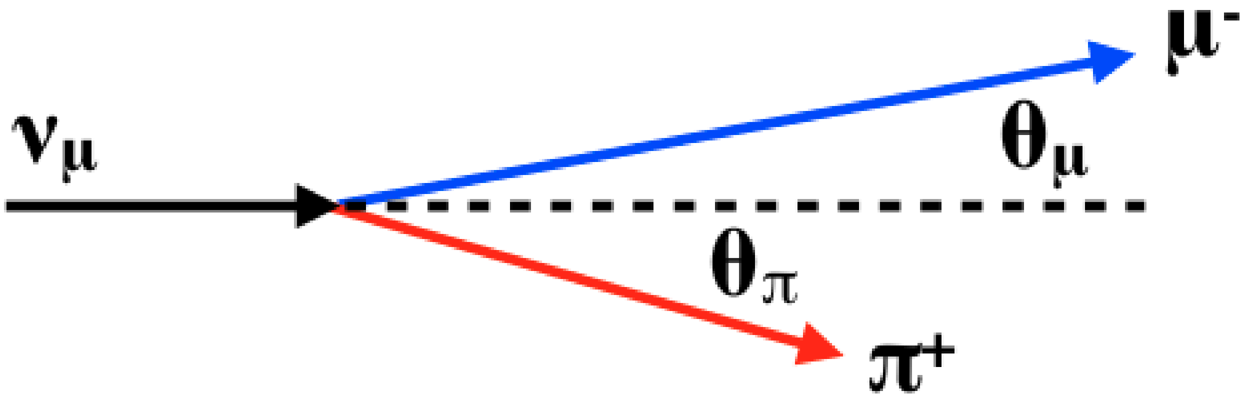
Flux Per Bin

Number of Nuclei

A-Dependence of Coherent Pion Production

Cross Sections

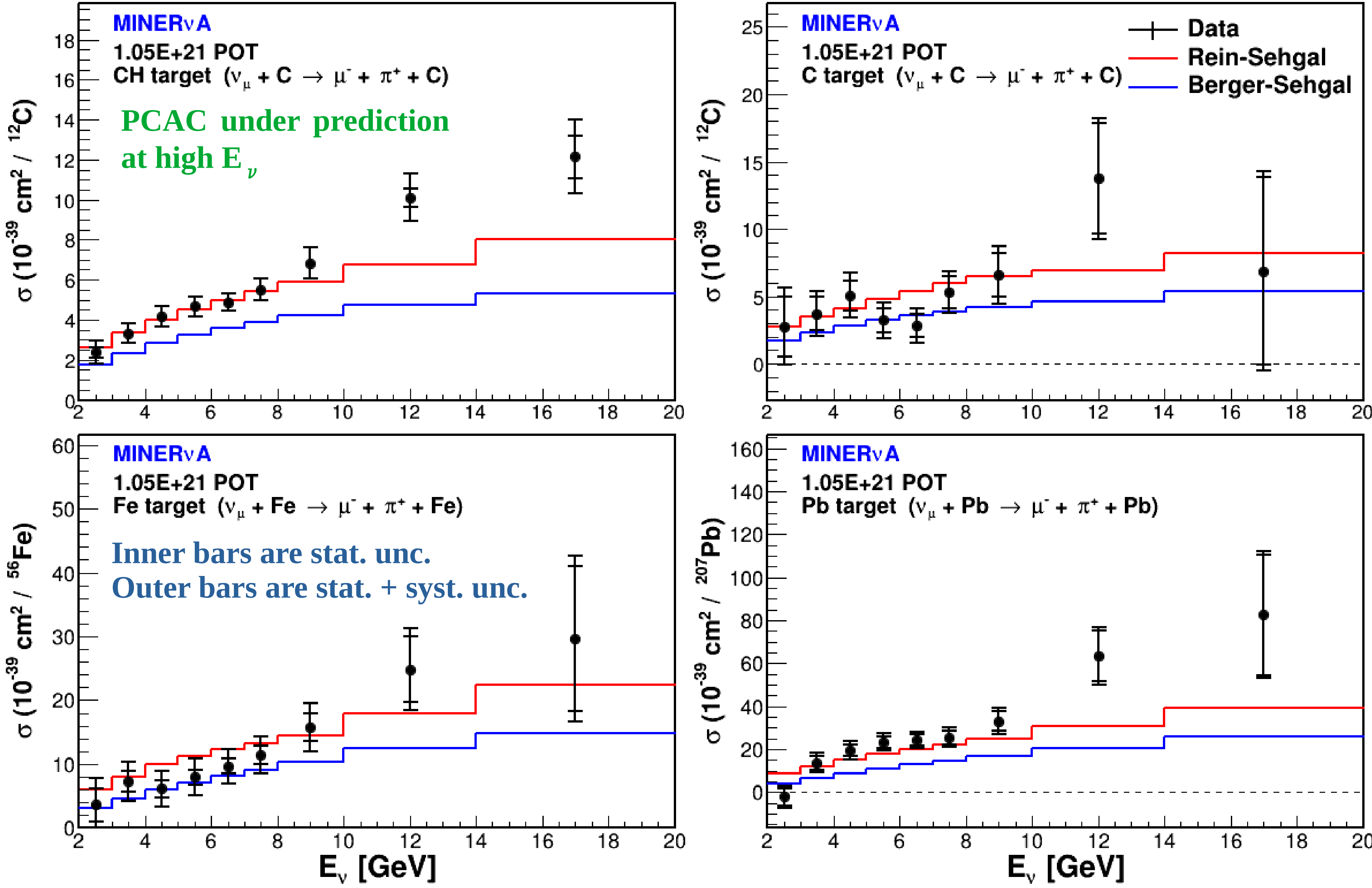
In 6 variables: $E_\nu,\ E_\pi,\ Q^2,\ \theta_\pi,\ \theta_\mu,\ E_\mu$



- $E_\nu \approx E_\mu + E_\pi$
- E_π from calorimetry in MINERvA
- E_μ from range in MINERvA + range/curvature in MINOS
- $Q^2 = -\left(p_\nu - p_\mu\right)^2 \approx 2E_\nu\left(E_\mu - P_\mu \cos\theta_\mu\right) - m_\mu^2$
- θ_π and θ_μ from reconstructed tracks in MINERvA

5 – Results: Cross Sections

σ_{E_ν}



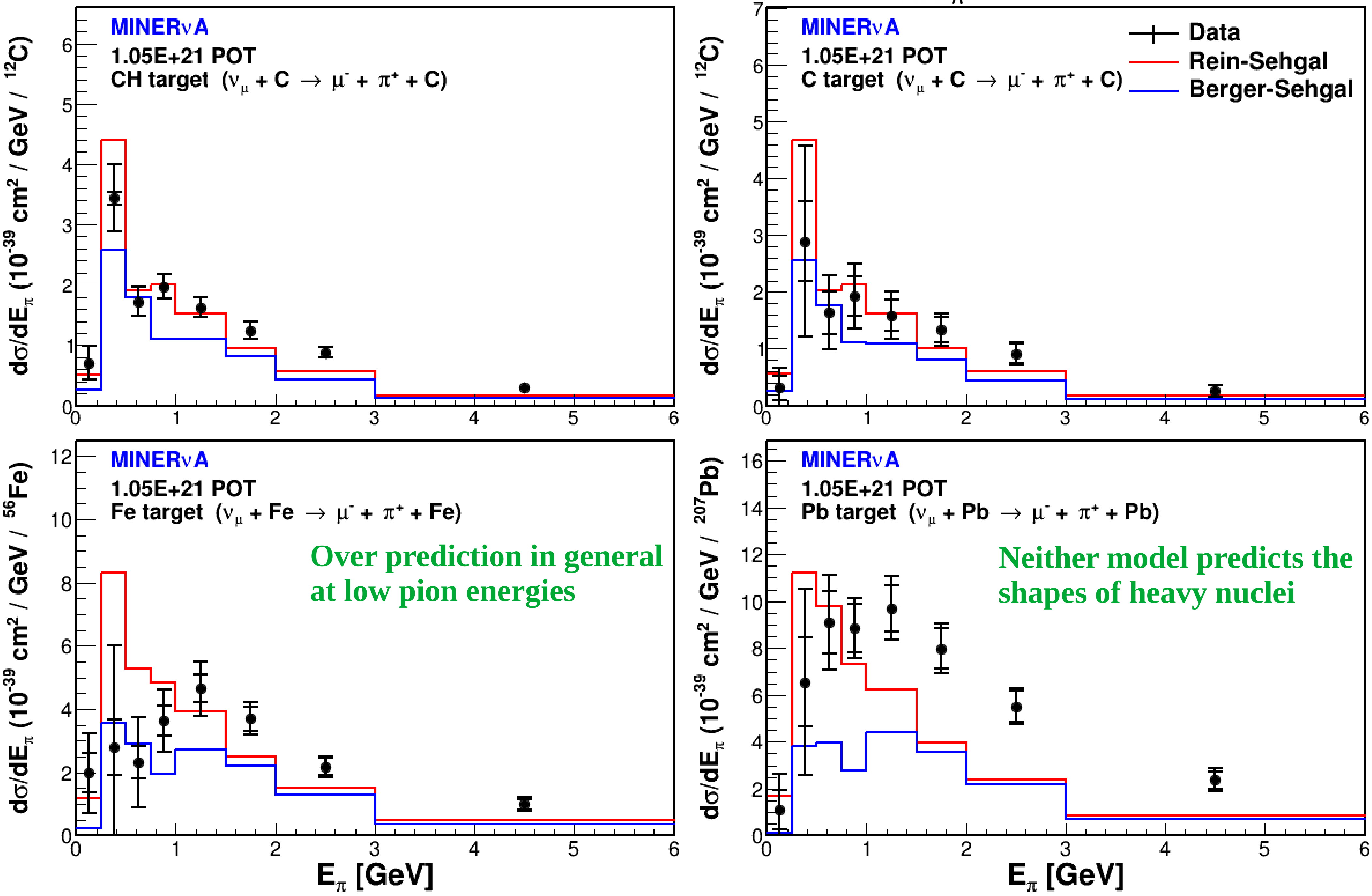
PCAC under prediction at high E_ν

Inner bars are stat. unc.

Outer bars are stat. + syst. unc.

Results: Cross Sections

$$\frac{d\sigma}{dE_\pi}$$

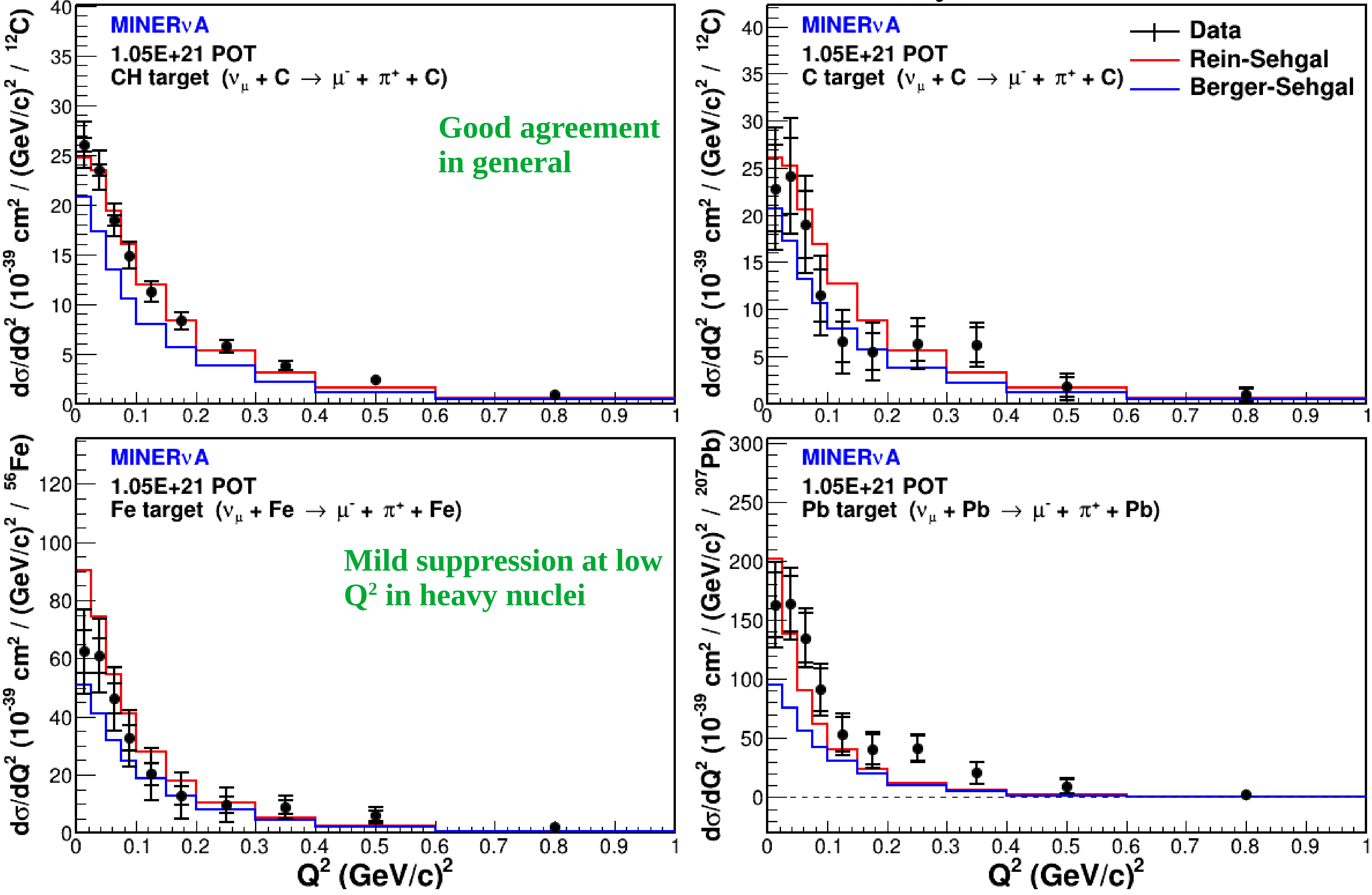


Over prediction in general at low pion energies

Neither model predicts the shapes of heavy nuclei

Results: Cross Sections

$$\frac{d\sigma}{dQ^2}$$

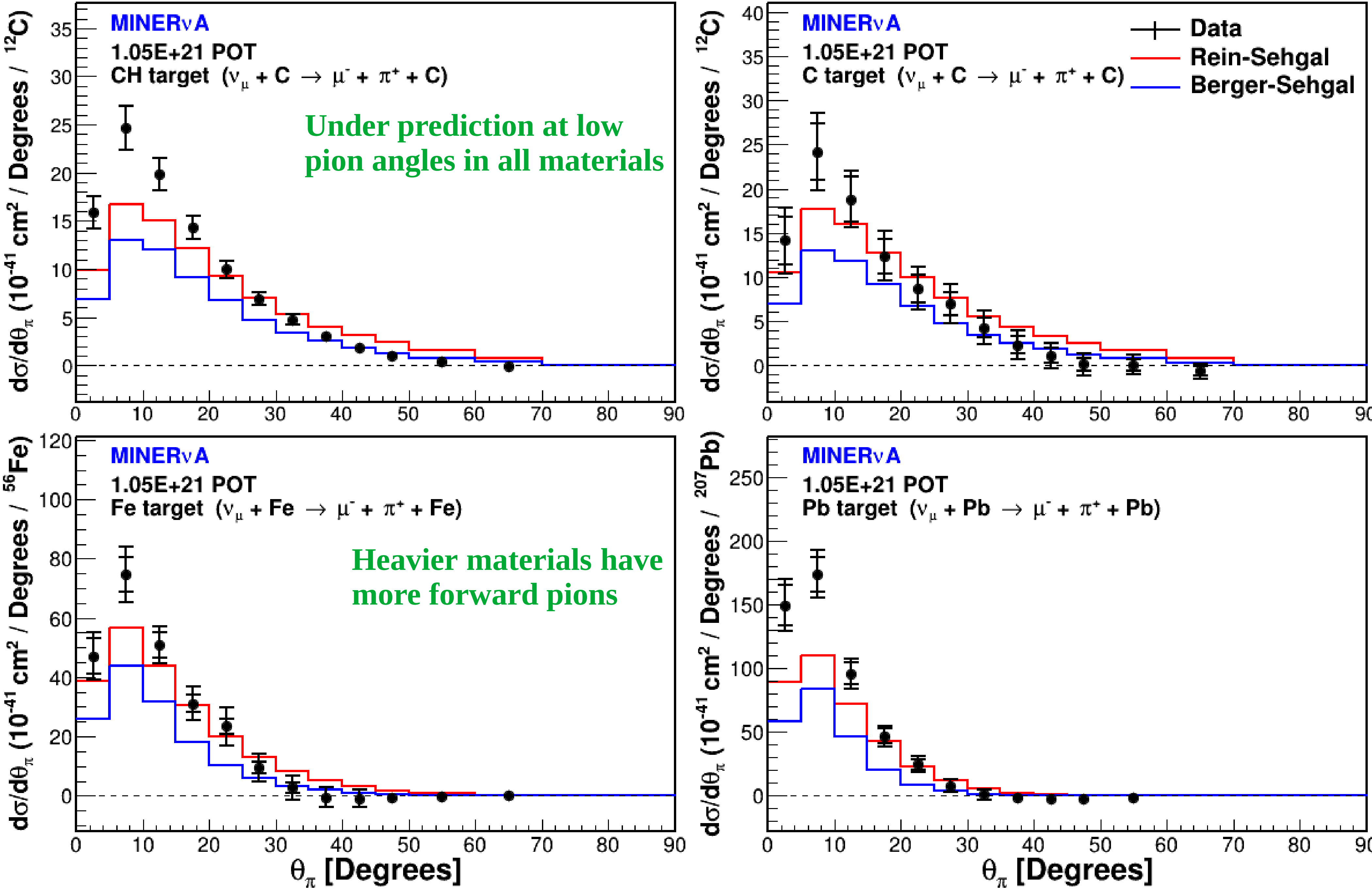


Good agreement in general

Mild suppression at low Q^2 in heavy nuclei

Results: Cross Sections

$$\frac{d\sigma}{d\theta_\pi}$$

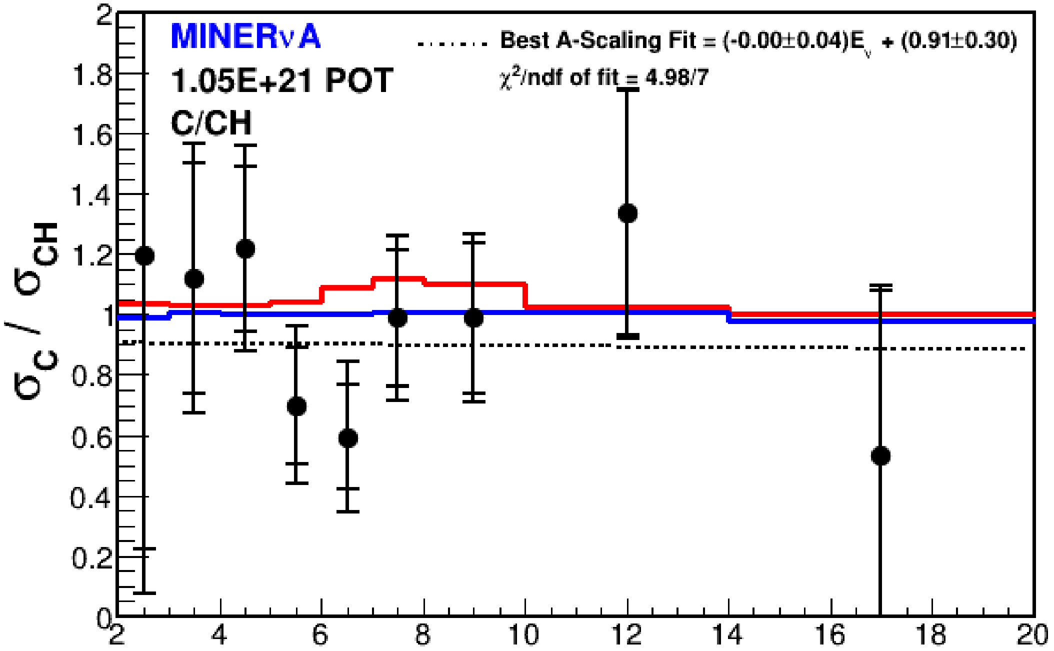


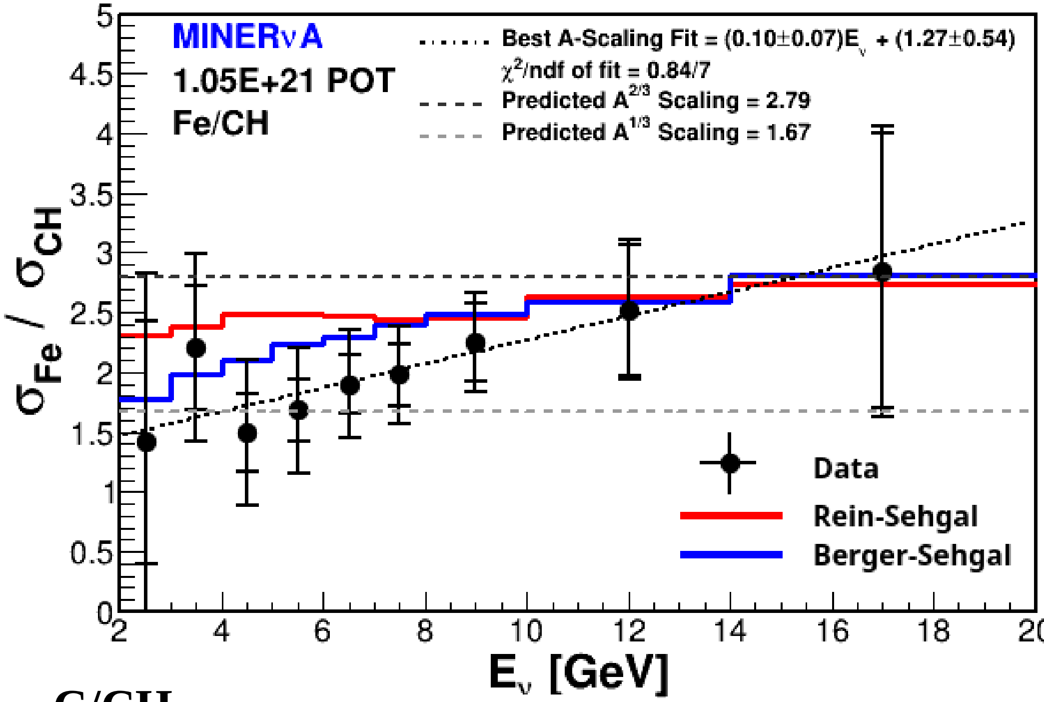
Under prediction at low pion angles in all materials

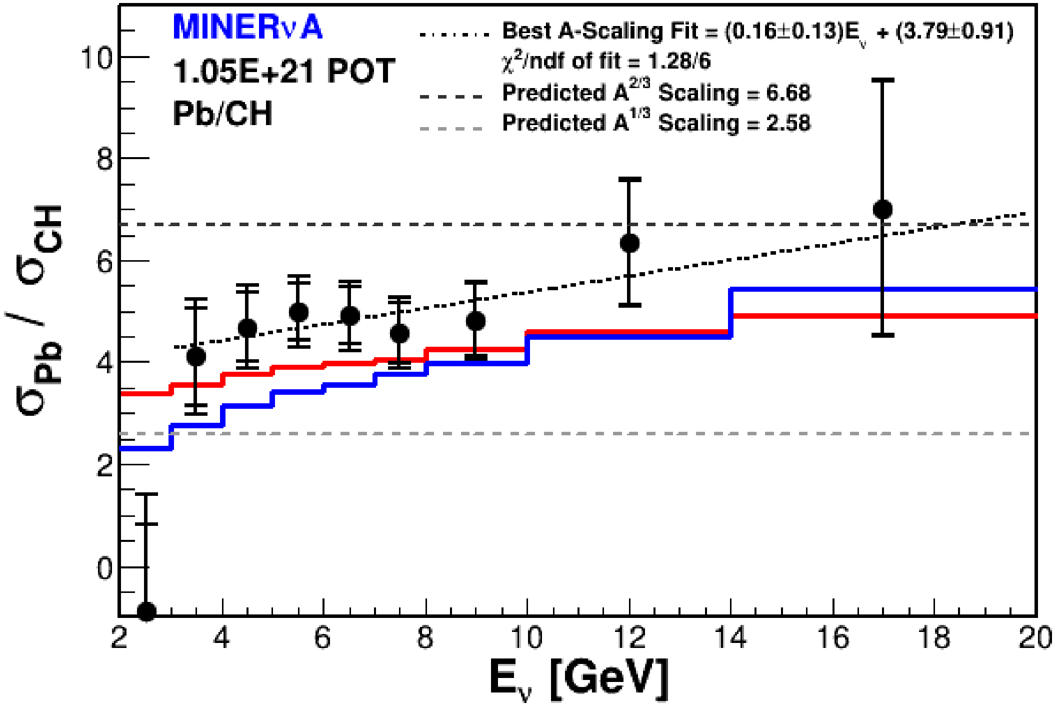
Heavier materials have more forward pions

Results: Cross Section Ratios

σE_ν







A-Scaling linear fit

C/CH

- consistent with unity.

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.

Summary

1) **MINERvA** has performed the **first simultaneous measurement** in (four) different materials, of the **neutrino-induced coherent production of** π^+.

2) **First evidence** of the interaction in iron and lead nuclei **(^{56}Fe** and **^{207}Pb).** Lead being the **largest nucleus probed** so far.

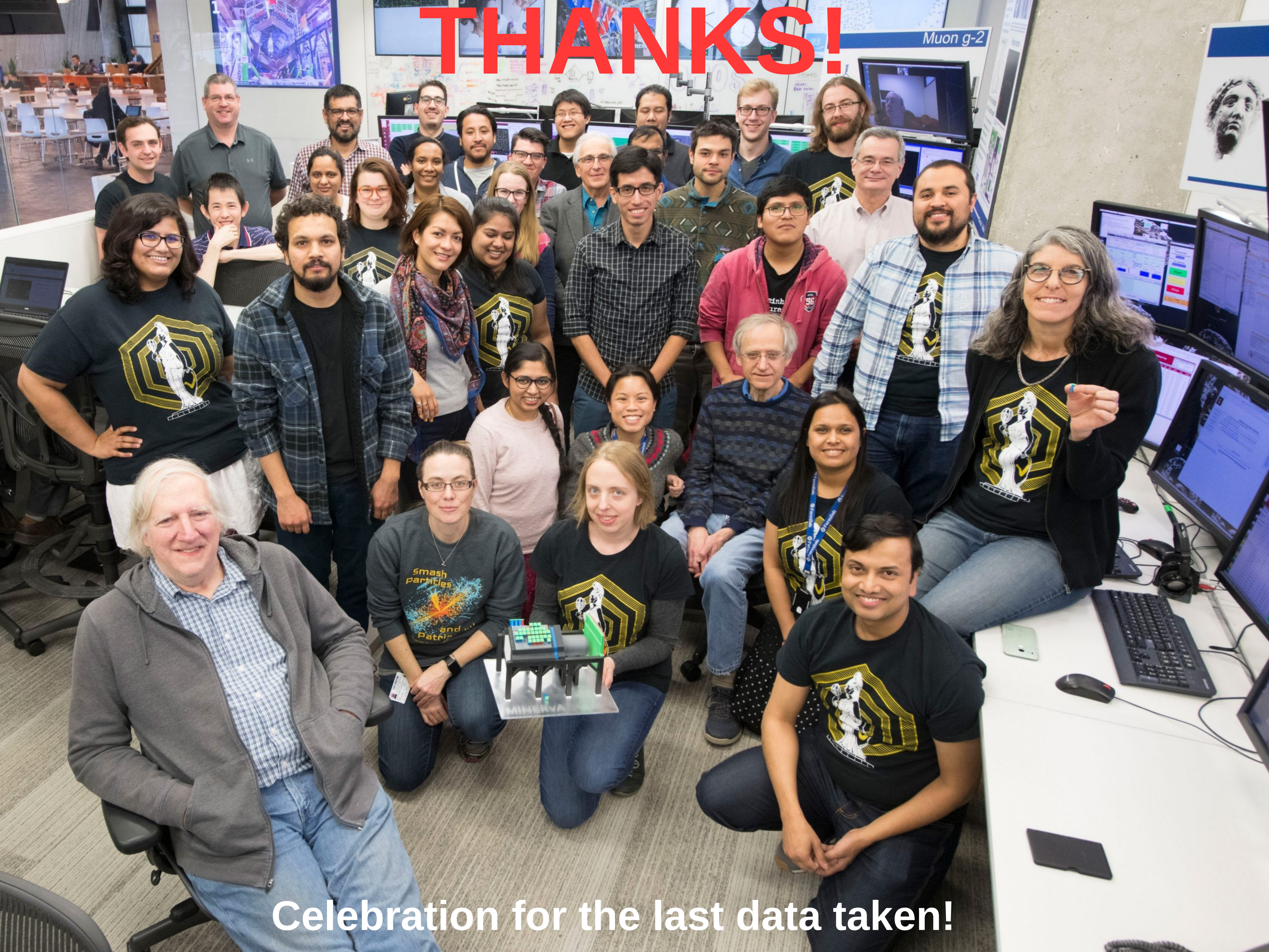
3) **First measurement** in a **pure carbon** target.

4) **World's largest ^{12}C, ^{56}Fe** and **^{82}Pb samples: ~15 k, ~0.7 k** and **~0.5 k events** and **most precise measurement** (using the CH target).

5) **First cross section ratios** of the interaction: σ_C/σ_{CH}, σ_{Fe}/σ_{CH} and σ_{Pb}/σ_{CH}.

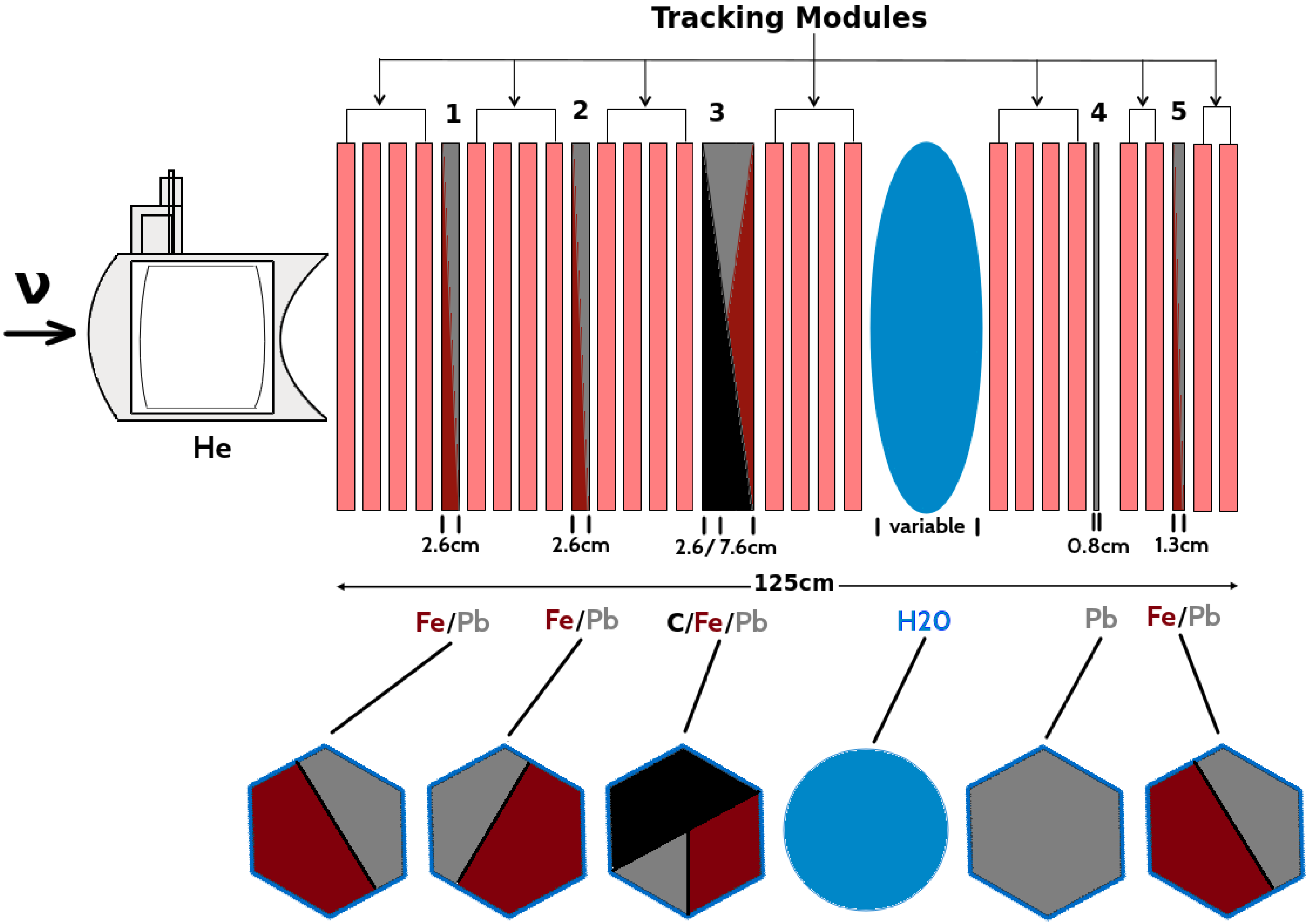
6) **Apparent energy-dependence** of the ***A*-Scaling** of the $\sigma(E_\nu)$ cross section with an apparent E_π**-dependence** origin.

THANKS!



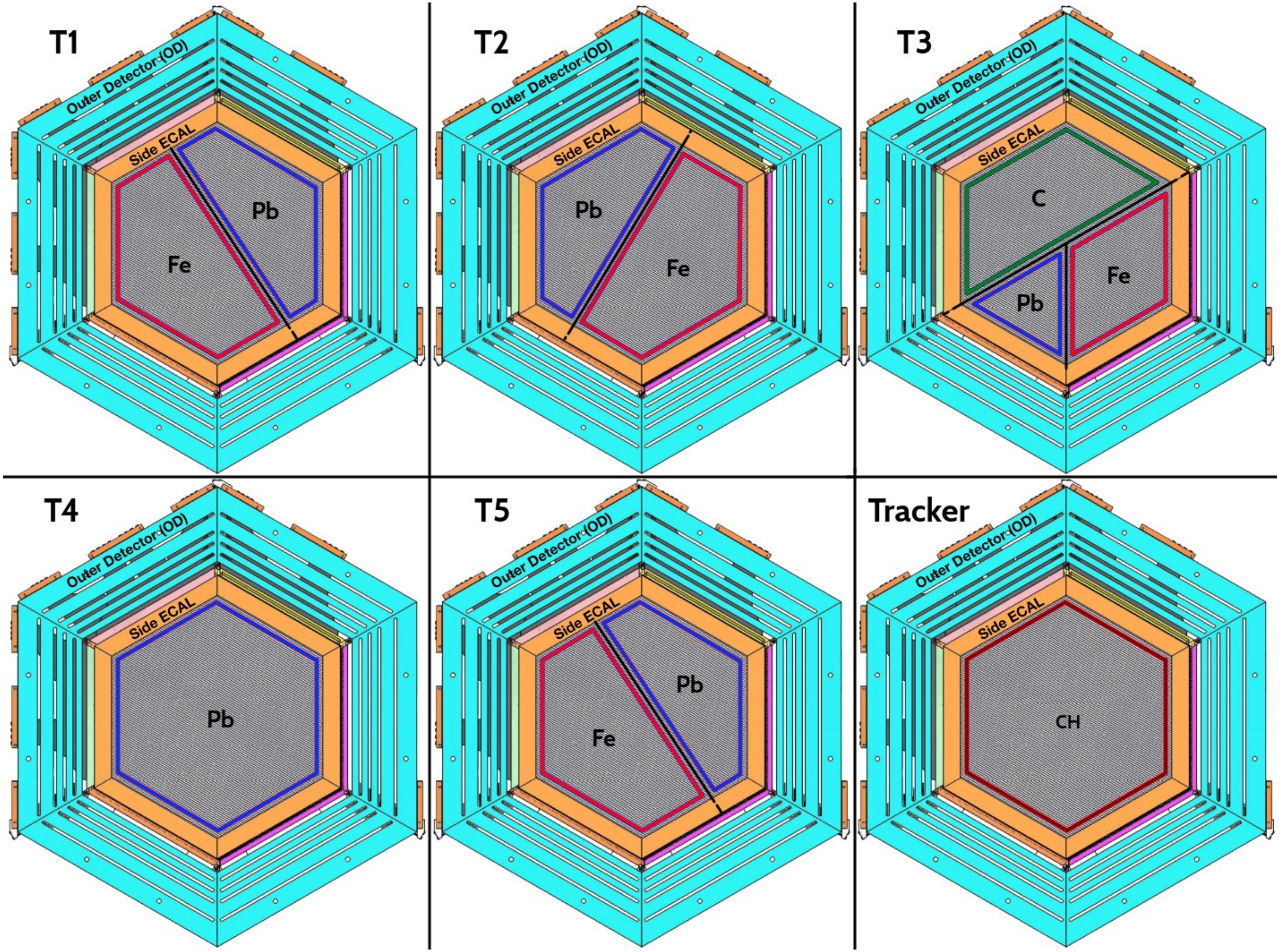
Celebration for the last data taken!

Side View of the Passive Target Region



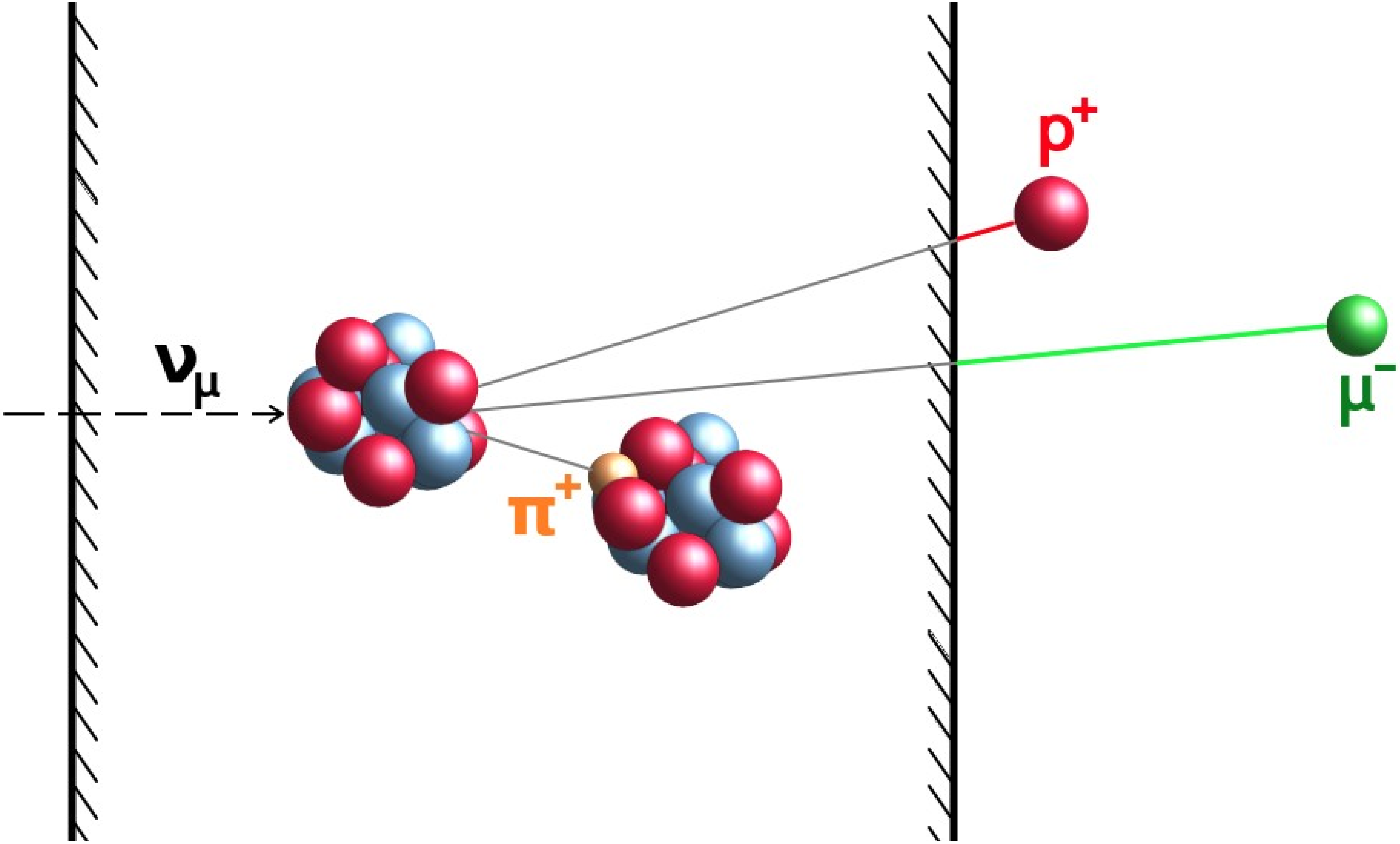
Backup – Detectors

Target Segments (Beam goes out of the page)



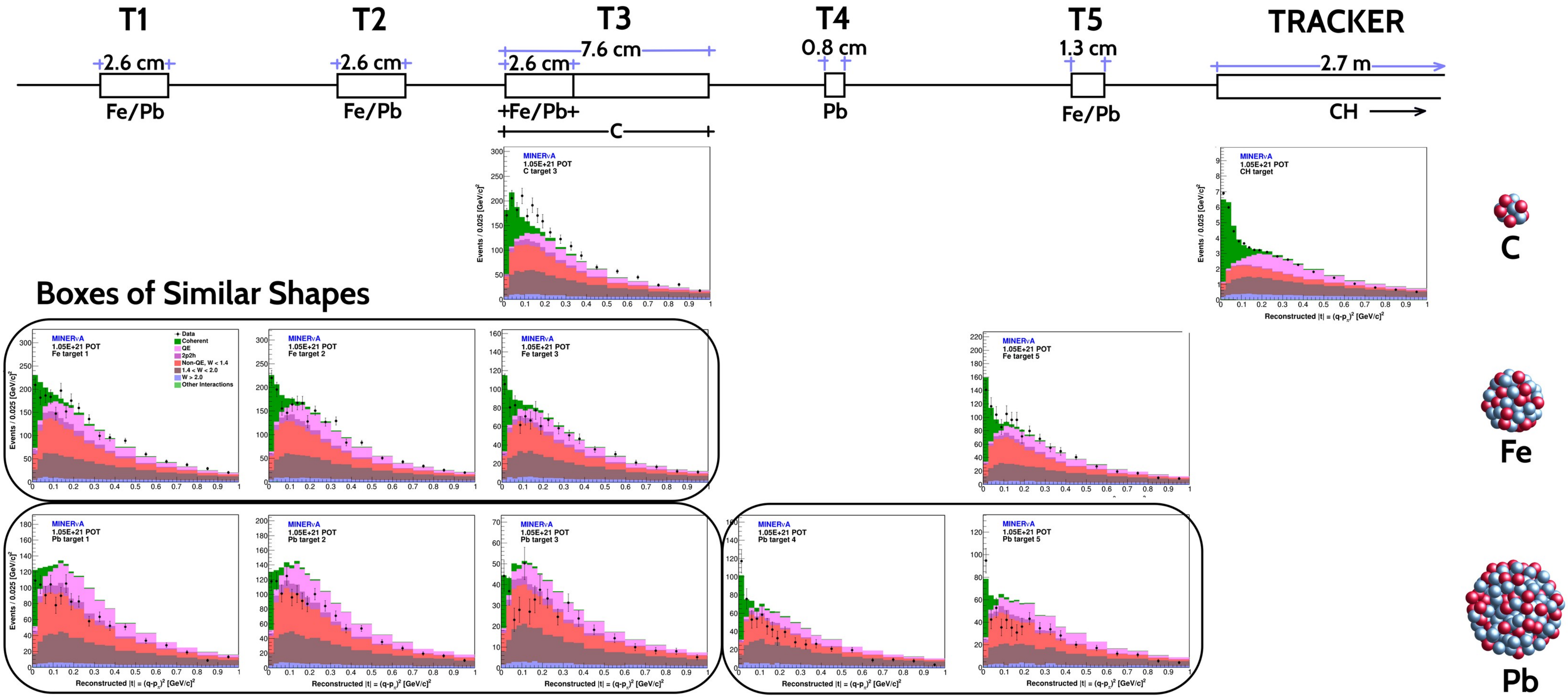
Backup – Detectors

Effect of Target Thickness – C and CH |t| Shapes Are Different



Backup – Detectors

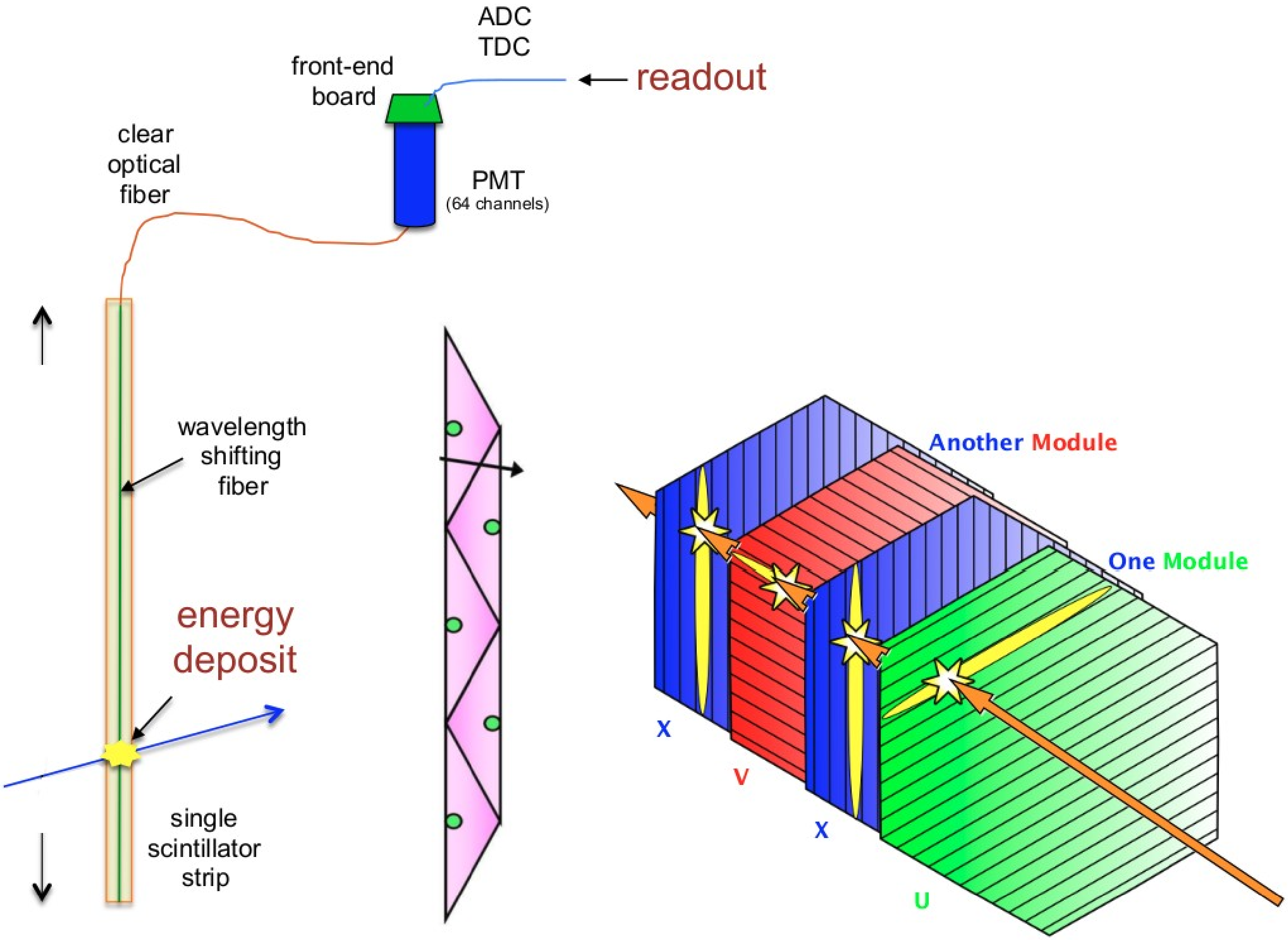
Effect of Target Thickness - |t| Shapes Depend on Thickness



Boxes of Similar Shapes

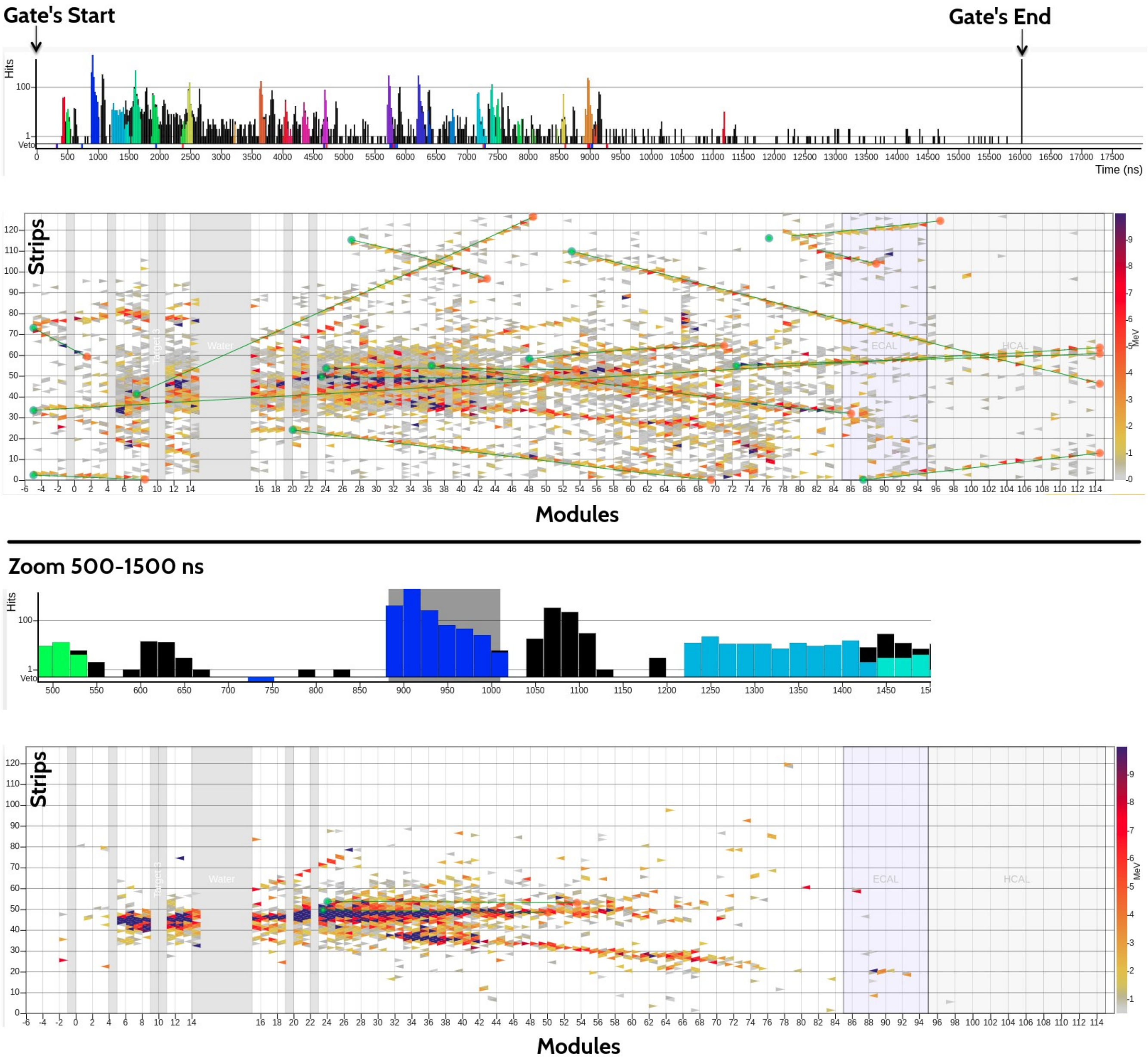
Backup – Detectors

Data Acquisition



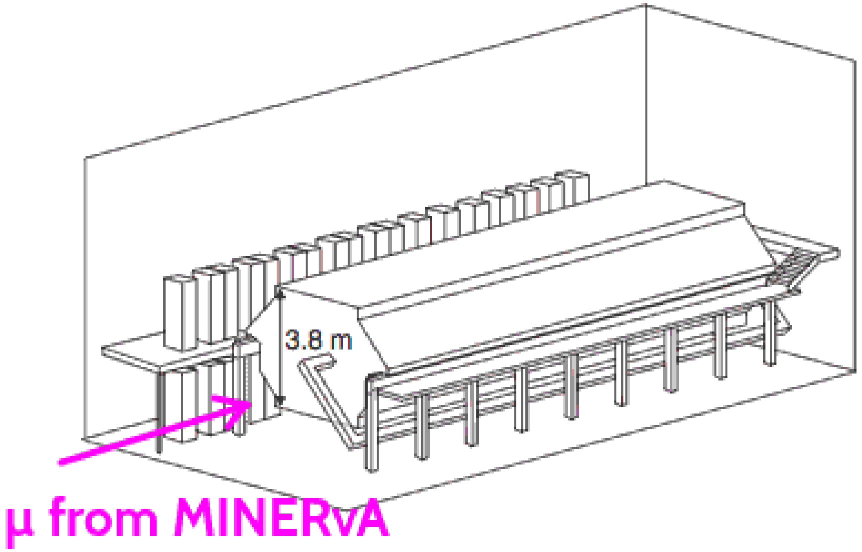
Backup – Detectors

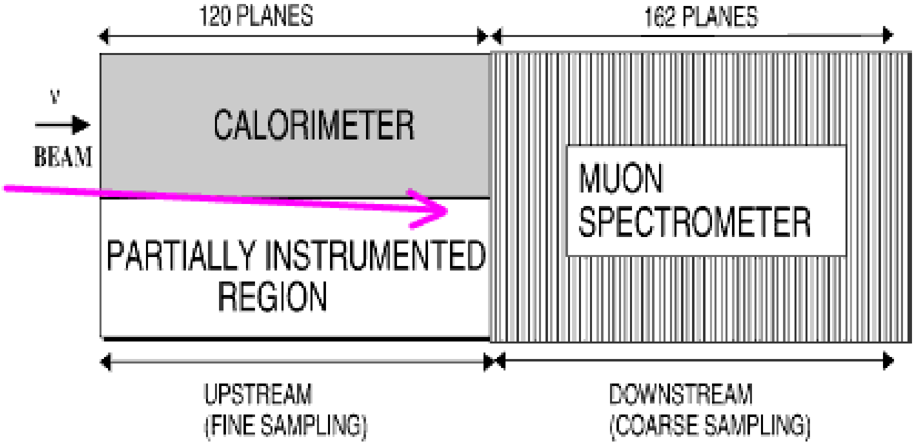
Data Acquisition

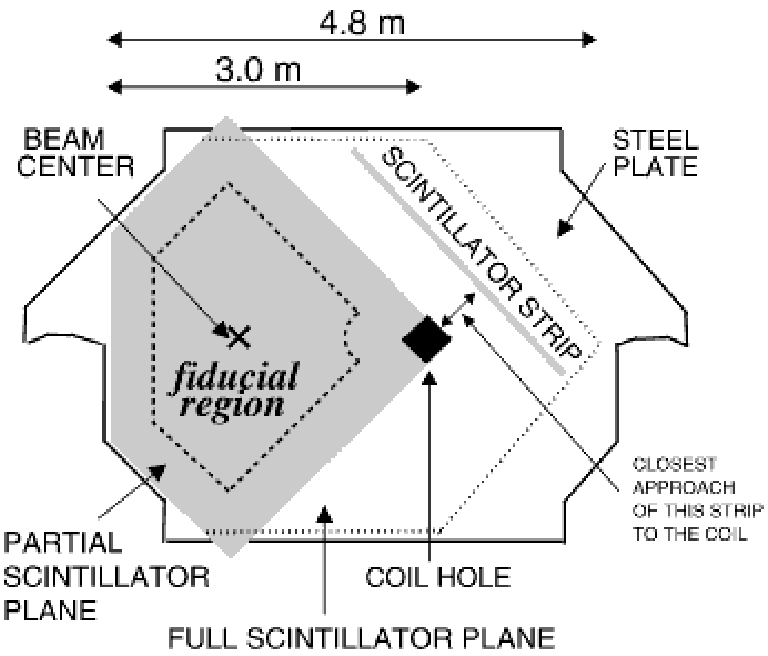


Backup – Detectors

The MINOS Detector



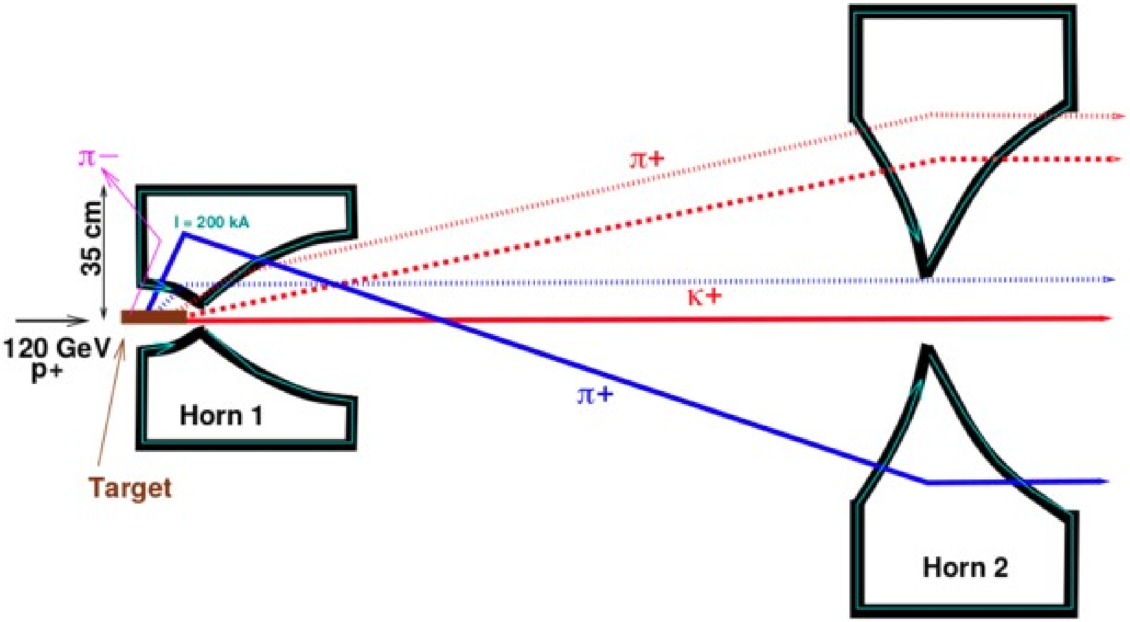




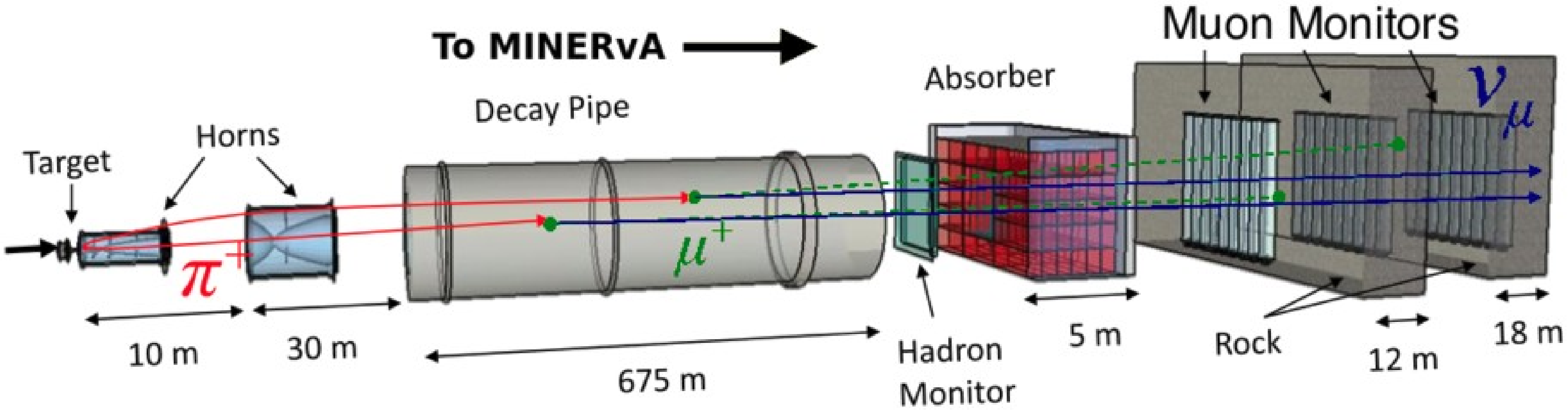
Backup – Beamline

The NuMI Beam at FNAL

Horns

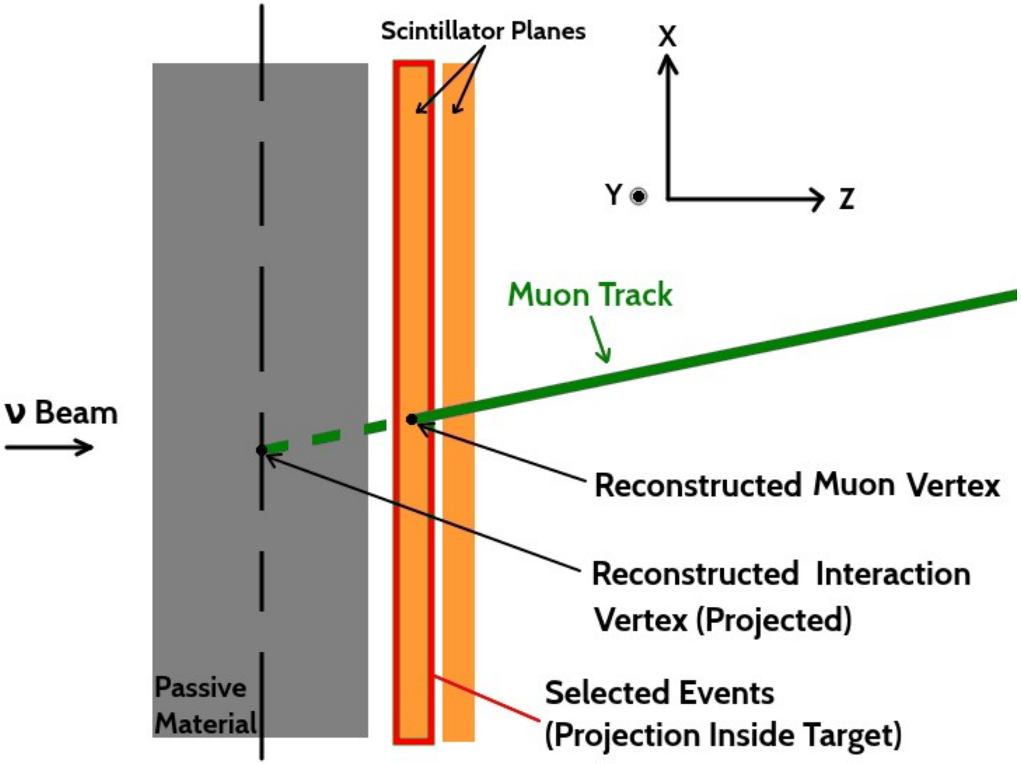


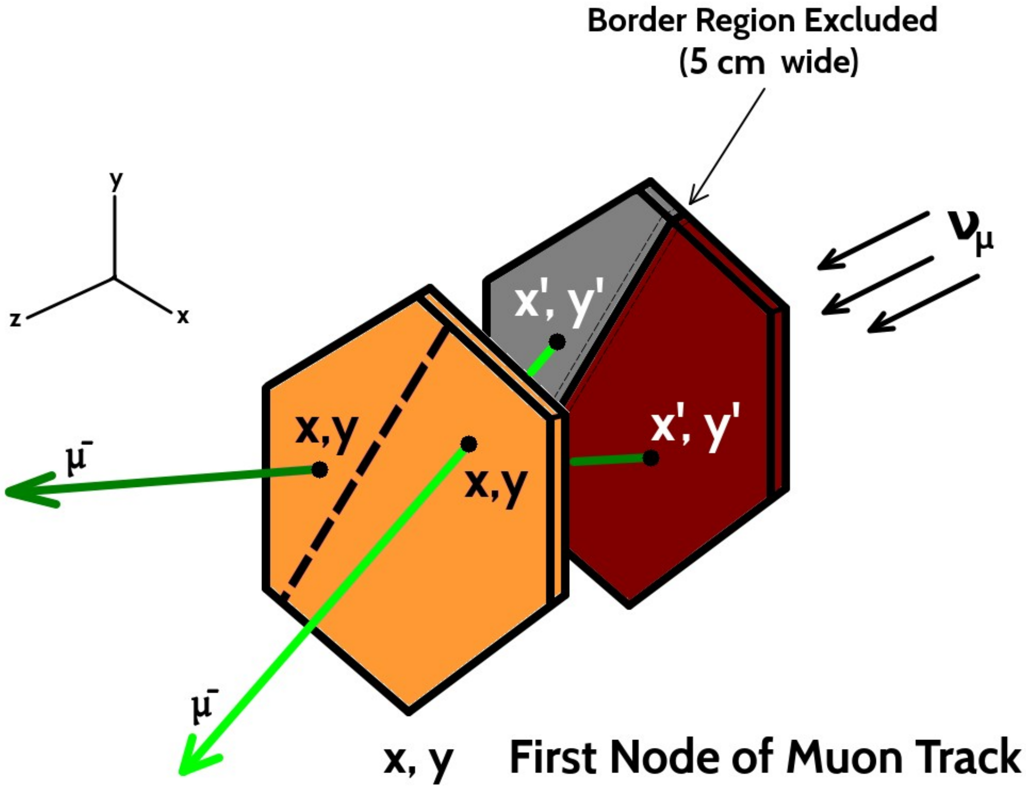
Beamline



Backup – Event Selection Cuts

Event Selection – Determining the Material



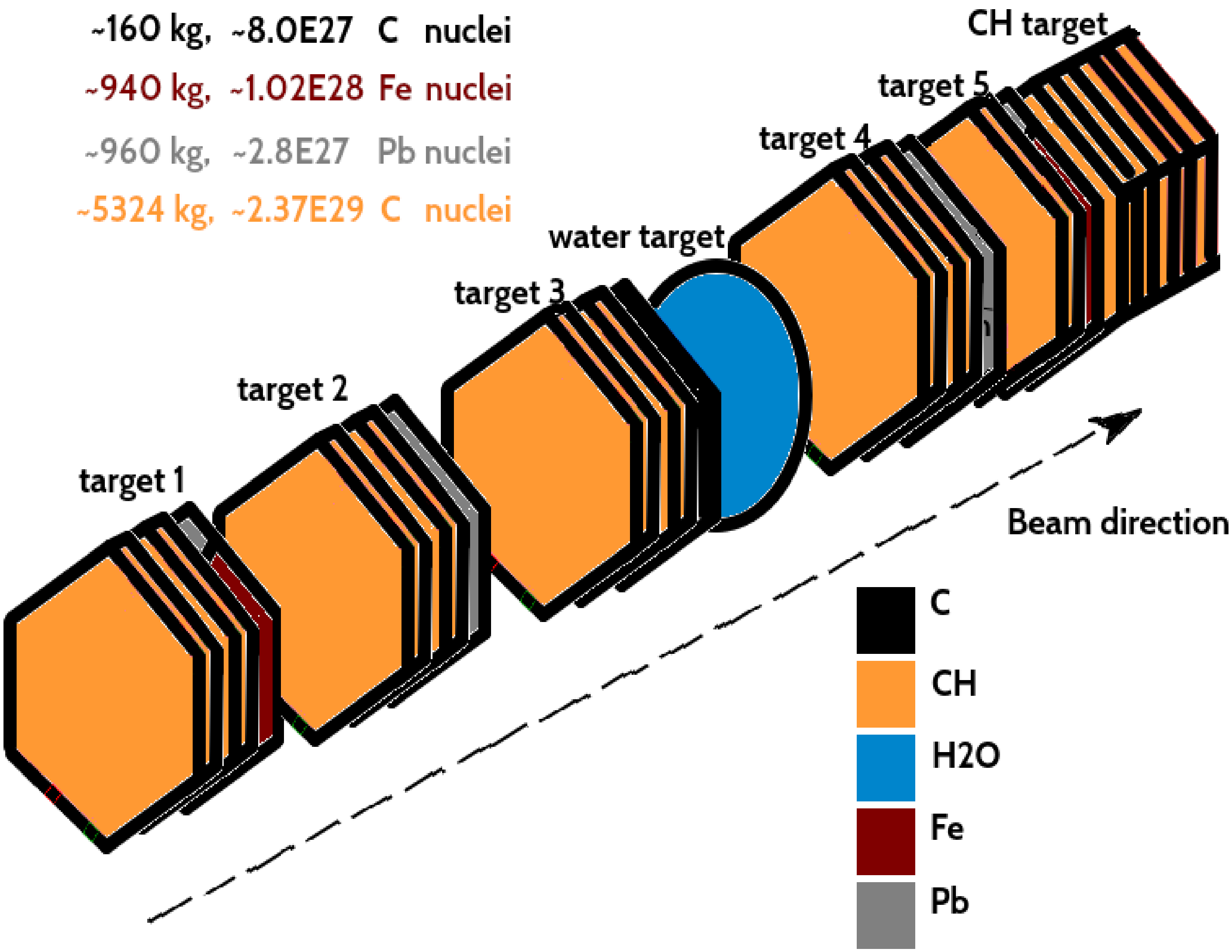


x, y First Node of Muon Track

x', y' Determines Material

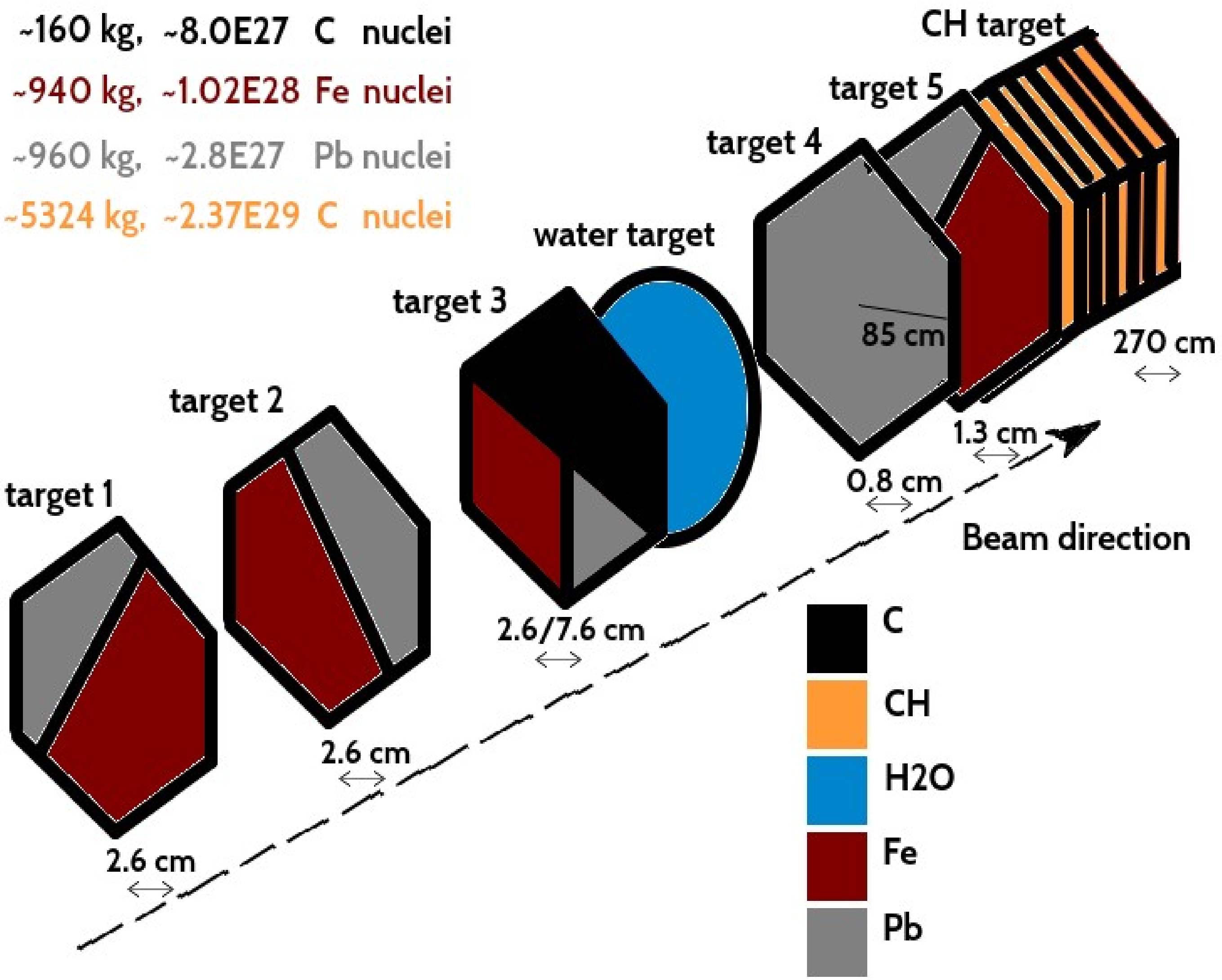
Backup – Nuclear Target Region

Passive Target Region



Backup – Nuclear Target Region

Passive Target Region – Enabled Due to High Statistics!



~160 kg, ~8.0E27 C nuclei

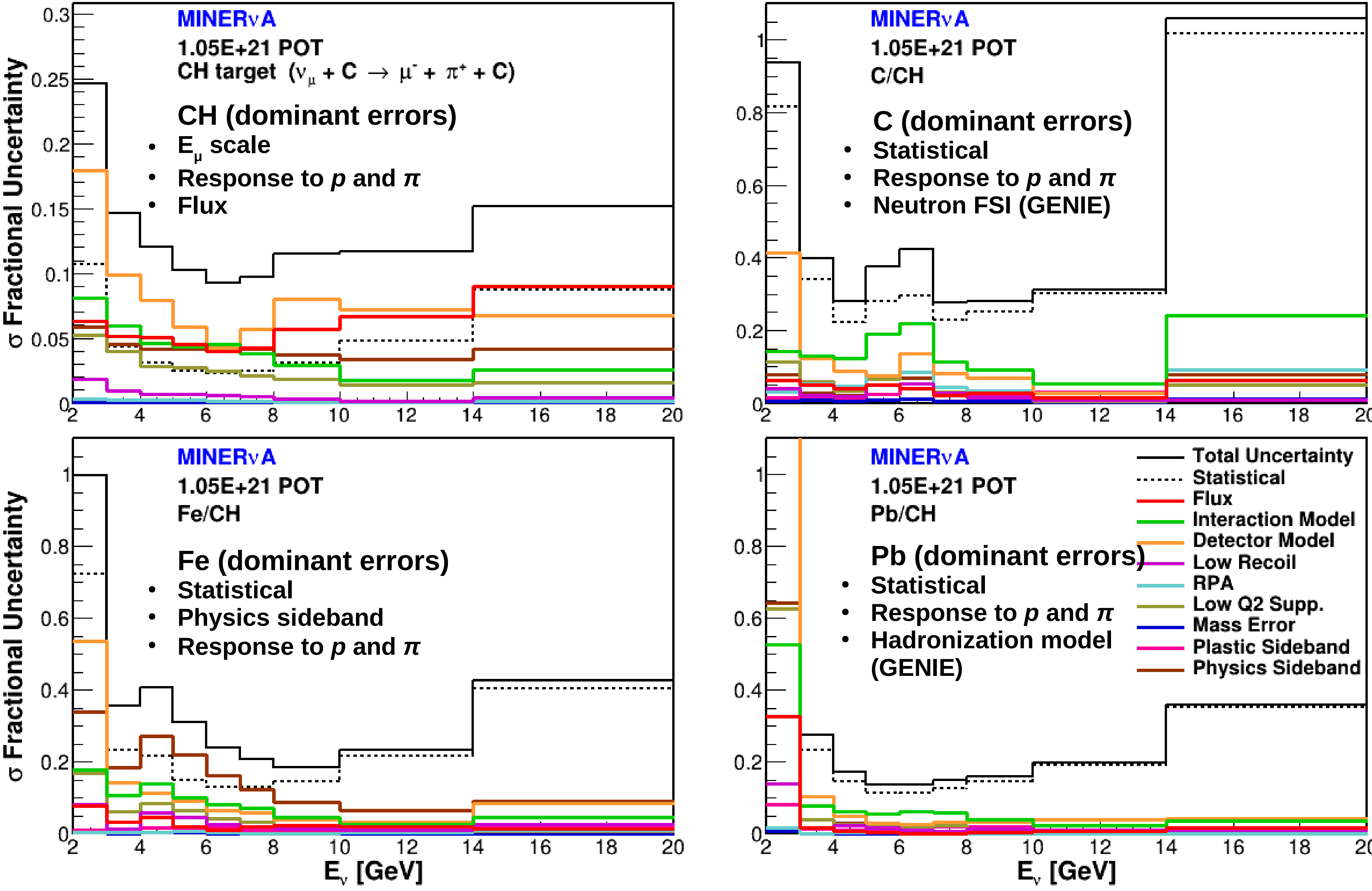
~940 kg, ~1.02E28 Fe nuclei

~960 kg, ~2.8E27 Pb nuclei

~5324 kg, ~2.37E29 C nuclei

Backup – Uncertainties

σ_{E_ν}



CH (dominant errors)

- E_μ scale
- Response to *p* and *π*
- Flux

C (dominant errors)

- Statistical
- Response to *p* and *π*
- Neutron FSI (GENIE)

Fe (dominant errors)

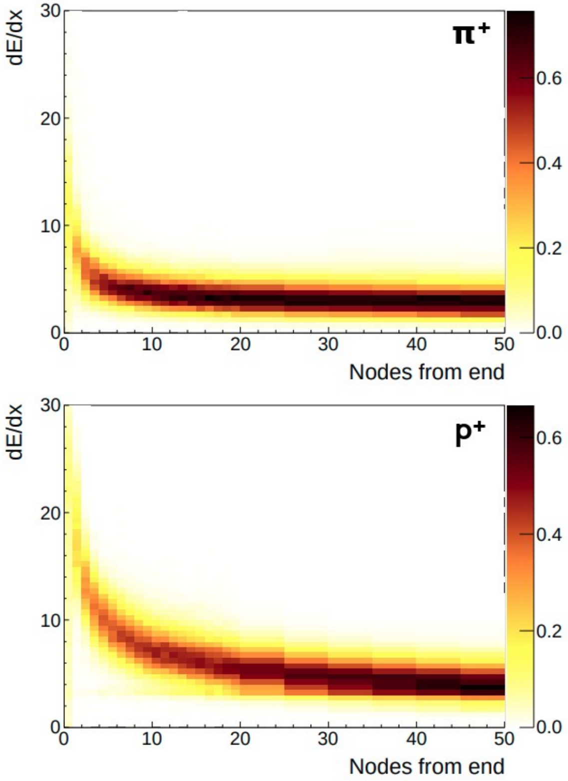
- Statistical
- Physics sideband
- Response to *p* and *π*

Pb (dominant errors)

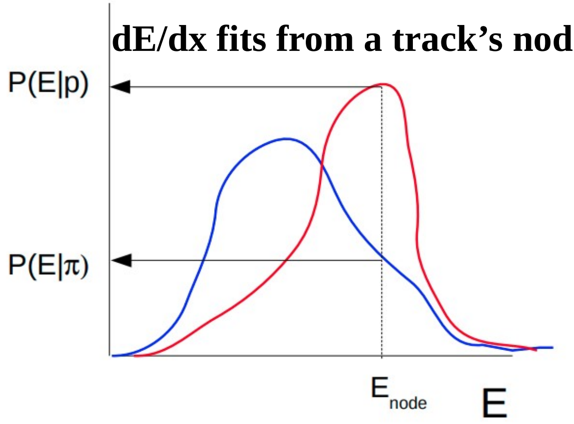
- Statistical
- Response to *p* and *π*
- Hadronization model (GENIE)

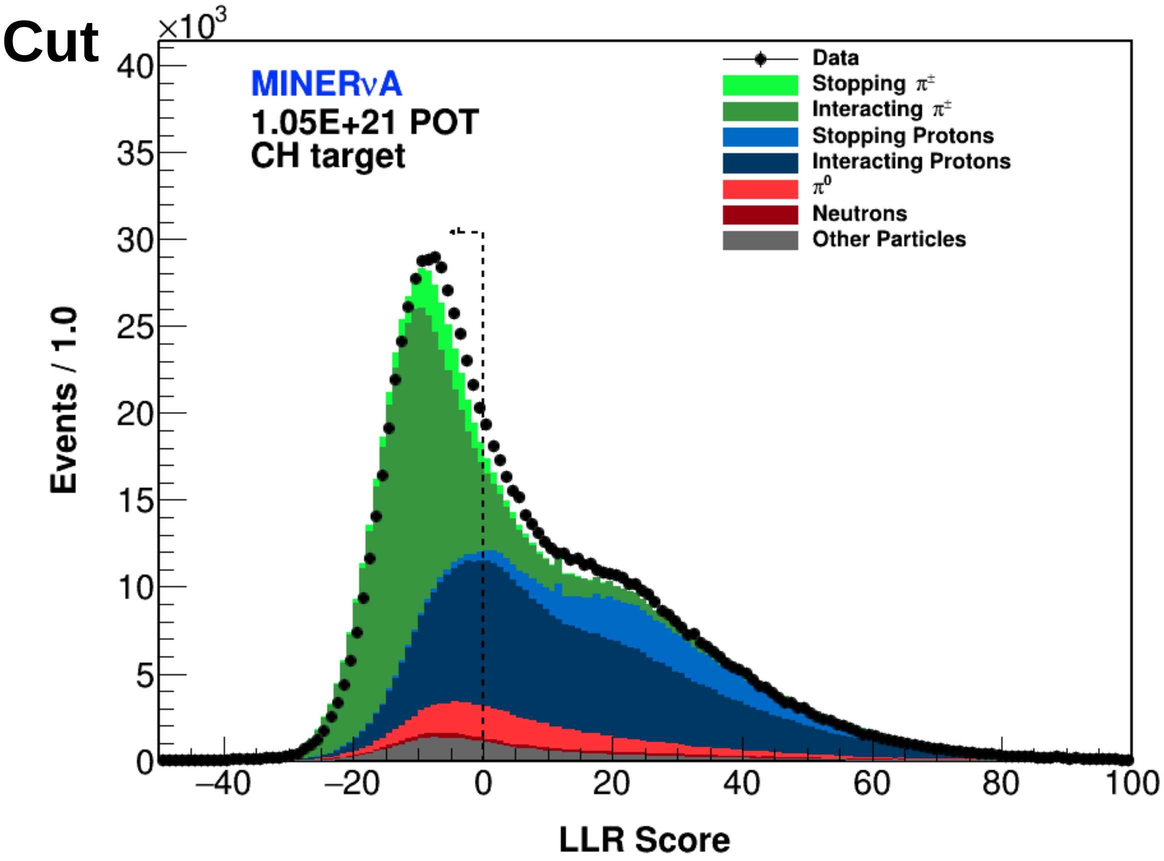
Backup – Event Selection Cuts

Event Selection – dE/dx Cut



dE/dx fits from a track's node

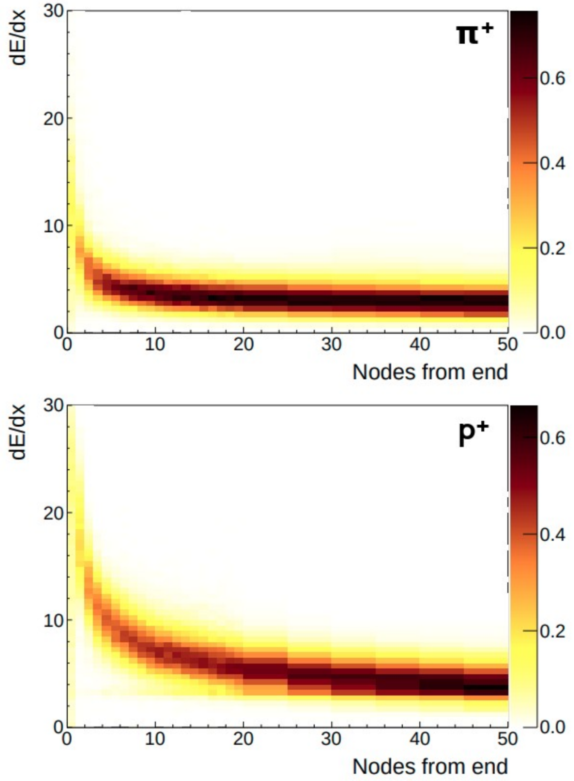


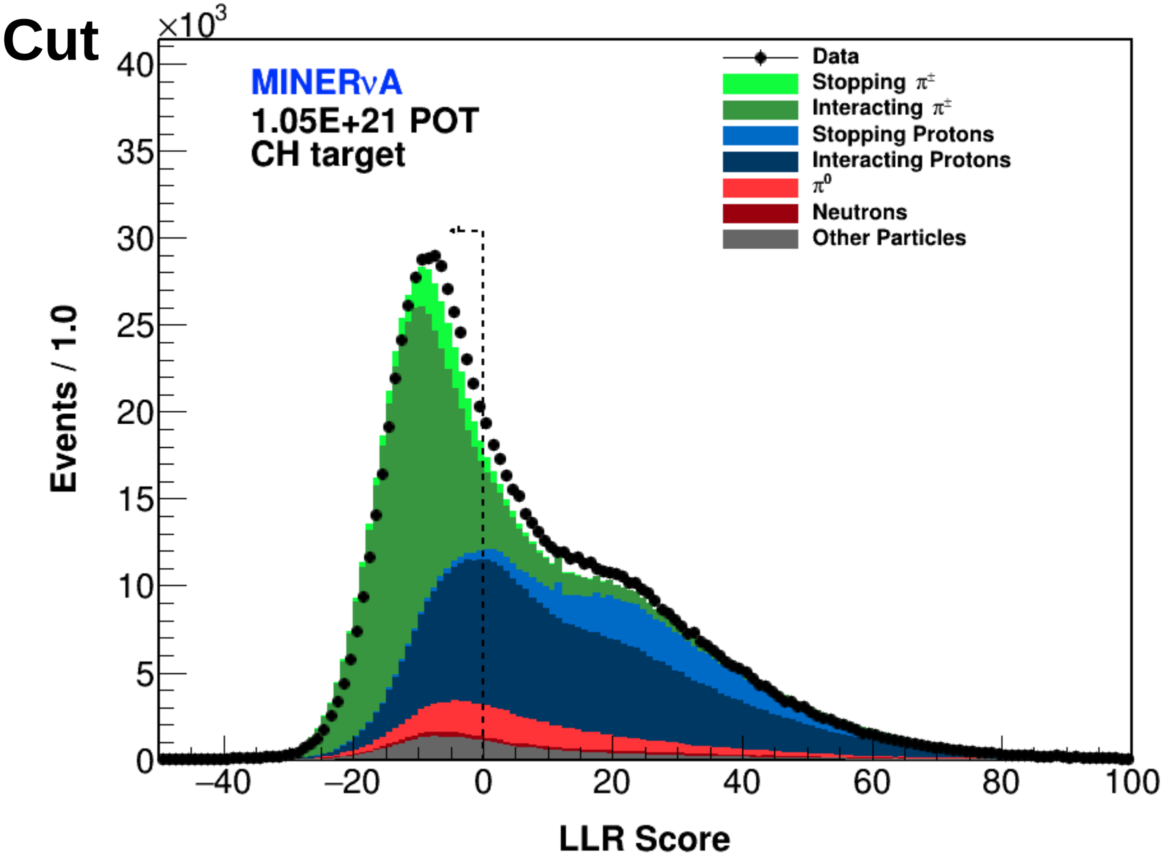


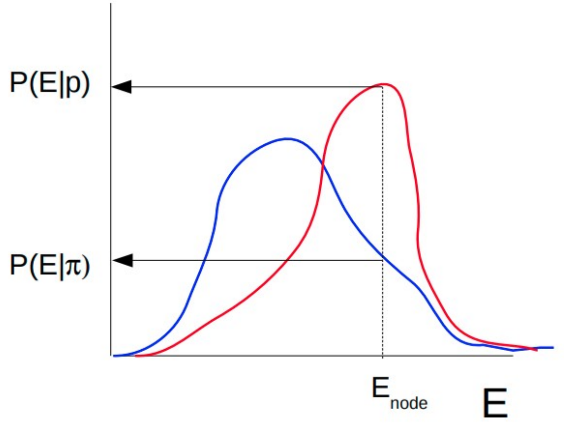
- Log Likelihood Ratio between proton and pion hypotheses.
- Contained track consistent with charged pion.
- Cut keeps ~70% of pions.
- And removes ~87% protons.

Backup – Reconstruction & Event Selection

Event Selection – dE/dx Cut







$$\mathcal{L}_{\pi^+,p} = \prod_{nodes} P\left(E_{node}|\pi^+,p\right)$$

← pion/proton hypotheses

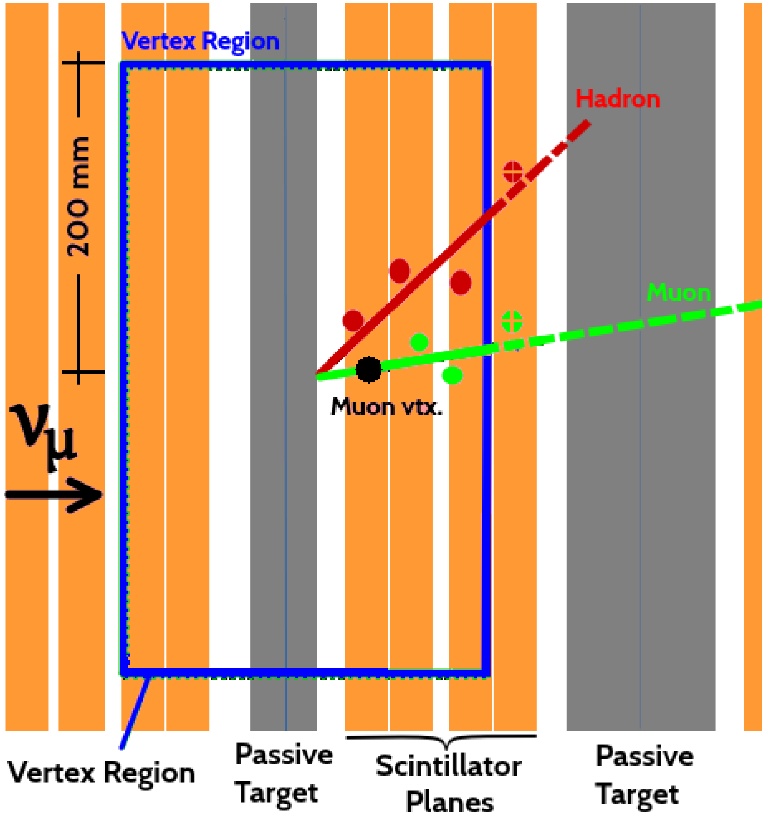
$$LR = \mathcal{L}_p/\mathcal{L}_{\pi+}$$

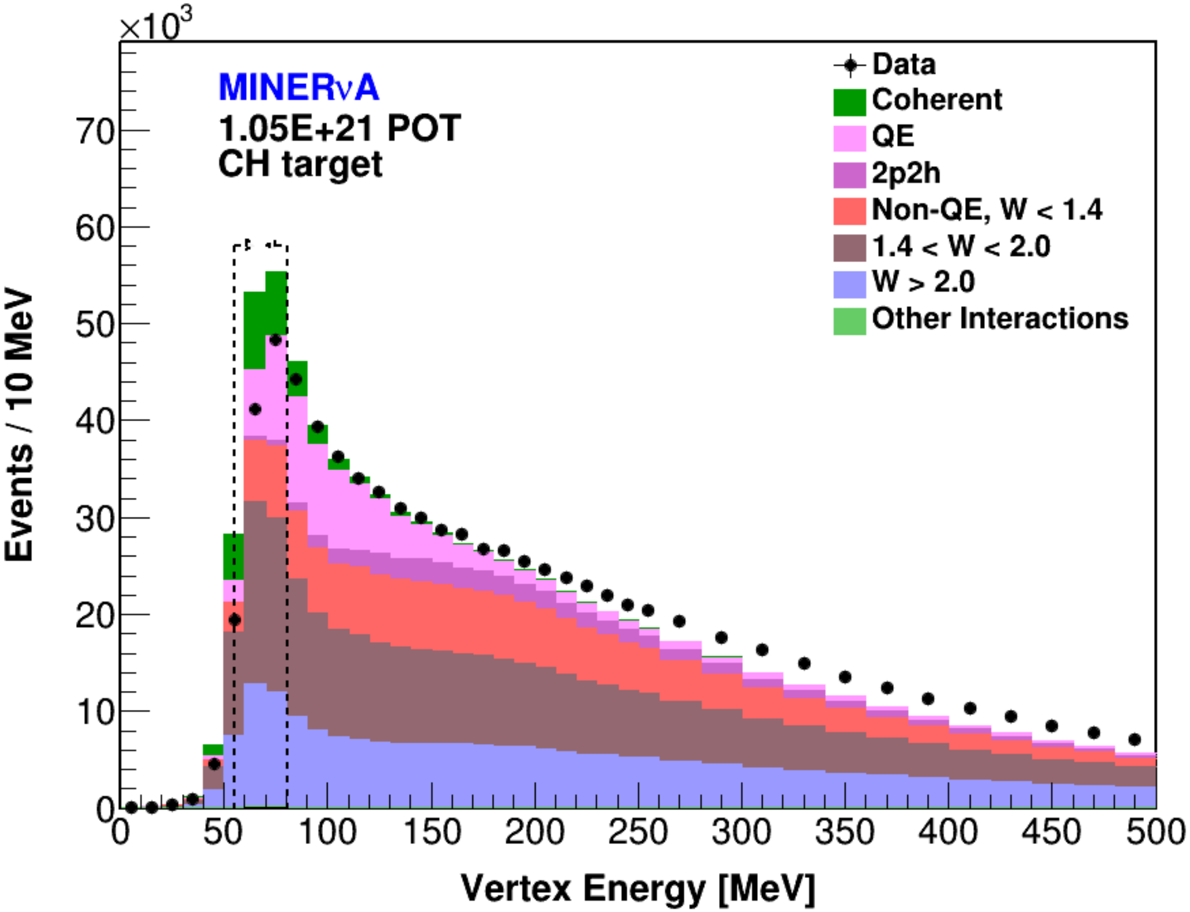
← Likelihood ratio

$$LLR = \sum_{nodes}\left[logP\left(E_{node}|p\right) - logP\left(E_{node}|\pi^+\right)\right]$$

Backup – Event Selection Cuts

Event Selection – Energy of Vertex Region





- Vertex energy consistent with 2 MIP ($\mu^- + \pi^+$).
- Cut keeps ~60% of signal.
- And removes ~86% background.

Backup – Cross Section Extraction

Cross Section Extraction

Selected Sample

Total Cross Section

Unfolding Matrix

Number of Selected Data Events

Number of Predicted Background Events

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

True Bin

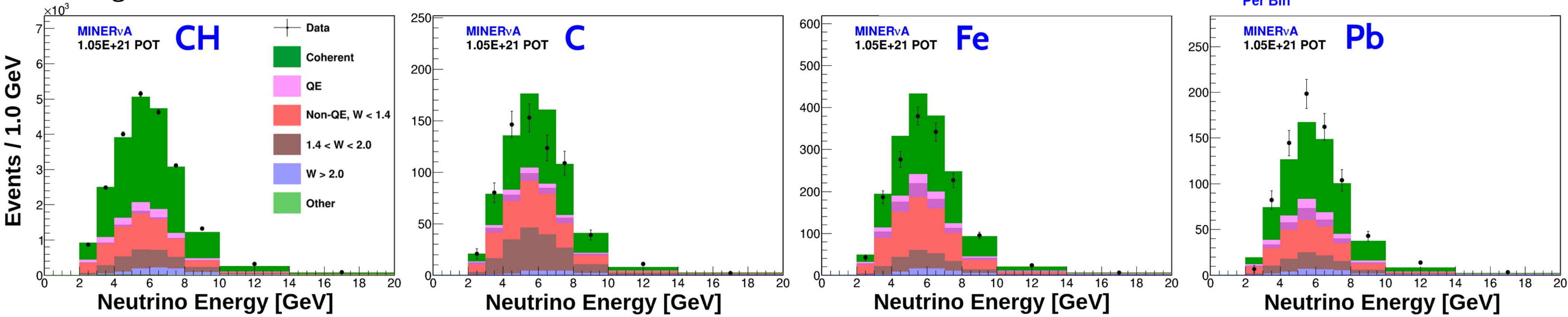
Reco Bin

Efficiency

Flux Per Bin

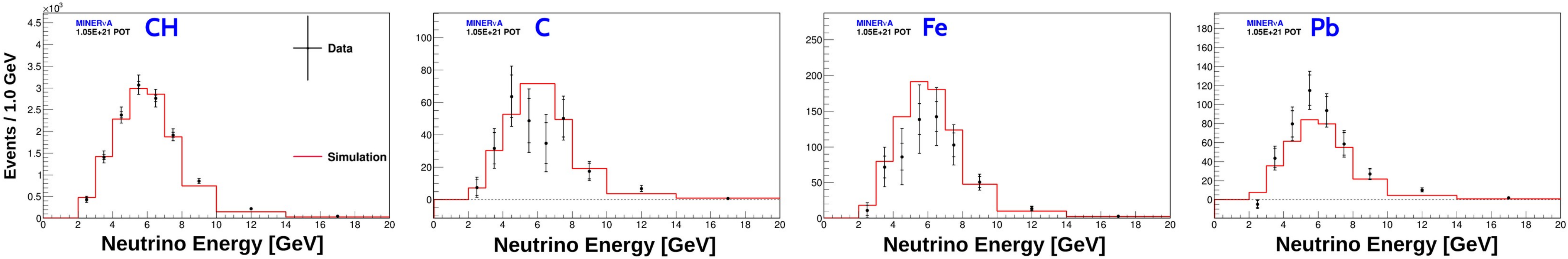
Number of Nuclei

Background Tuned



Material	CH	C	Fe	Pb
Candidate Events	14855	303	726	492

Background Subtracted

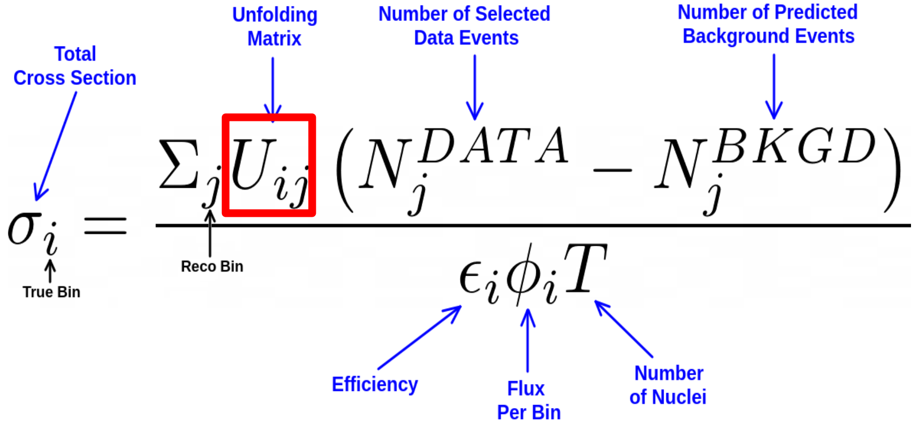


Backup – Cross Section Extraction

Cross Section Extraction

Unfolding

- **Iterative Approach**
- **D'Agostini Method**



Total Cross Section

Unfolding Matrix

Number of Selected Data Events

Number of Predicted Background Events

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

True Bin

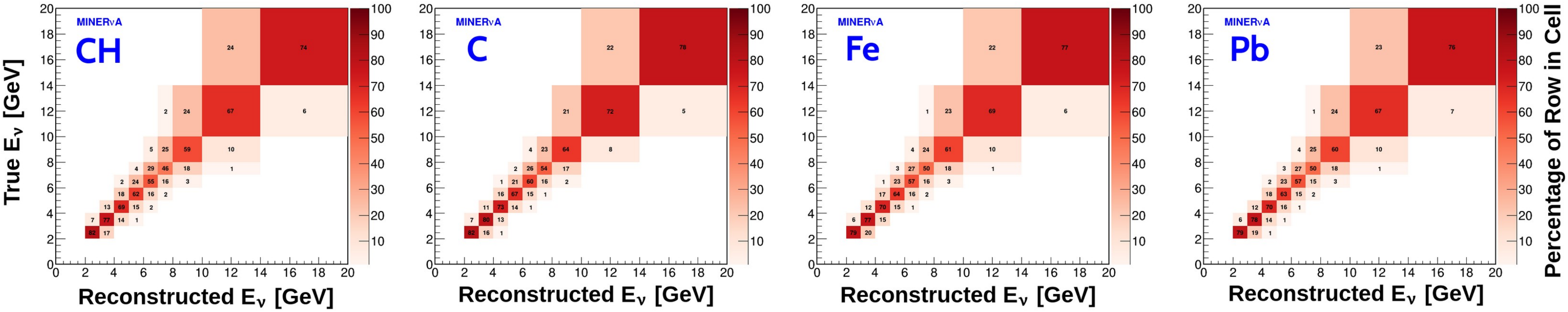
Reco Bin

Efficiency

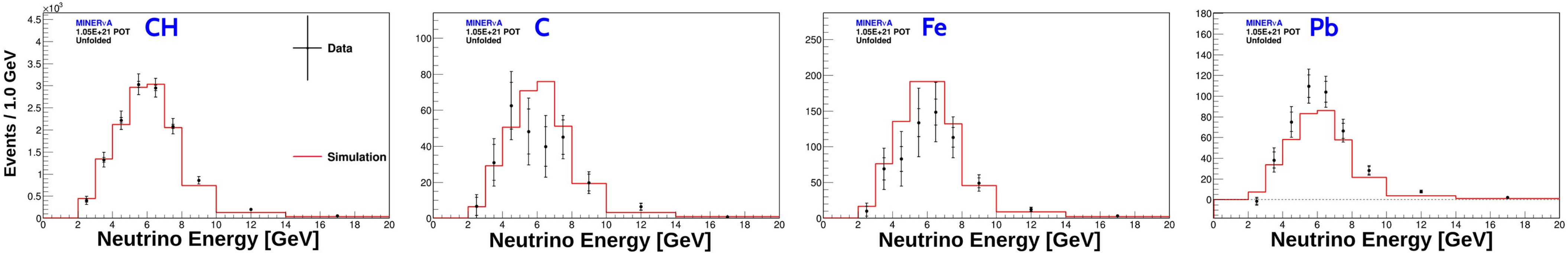
Flux Per Bin

Number of Nuclei

Migration Matrices



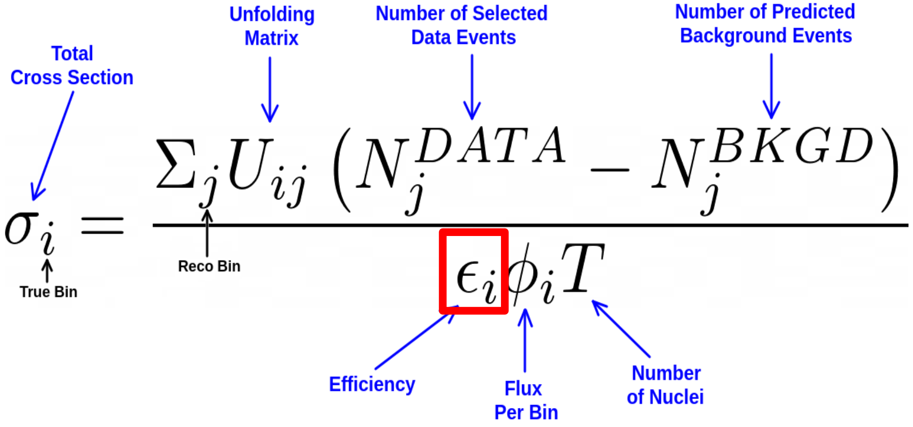
Unfolded Distributions



Backup – Cross Section Extraction

Cross Section Extraction

Efficiency Correction



Total Cross Section

Unfolding Matrix

Number of Selected Data Events

Number of Predicted Background Events

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

True Bin

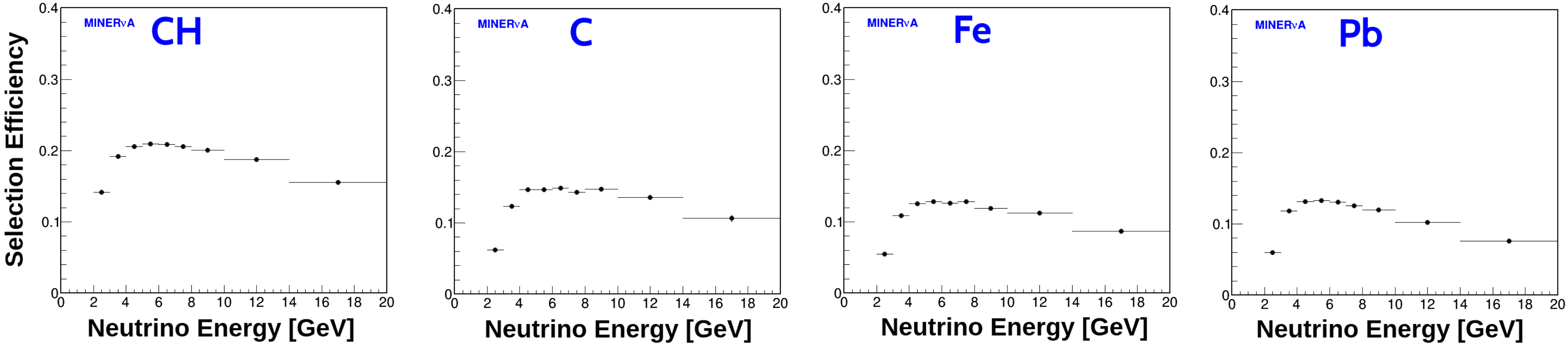
Reco Bin

Efficiency

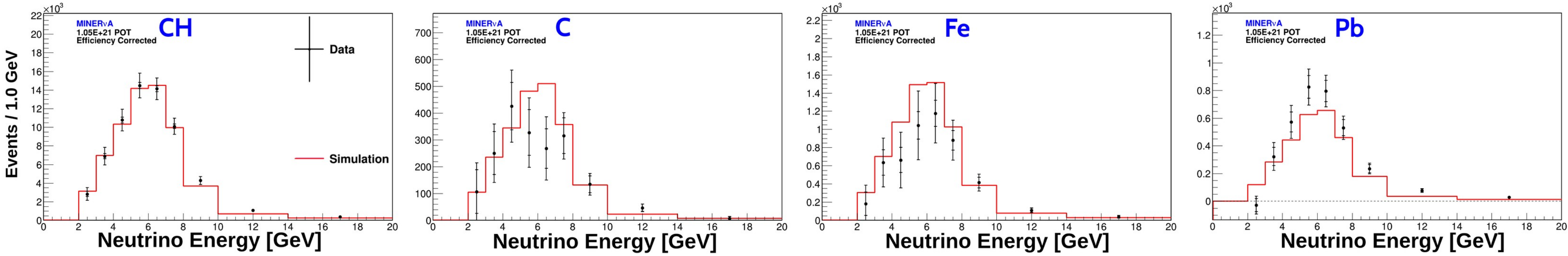
Flux Per Bin

Number of Nuclei

Selection Efficiency



Efficiency Corrected



Backup – Previous Measurements

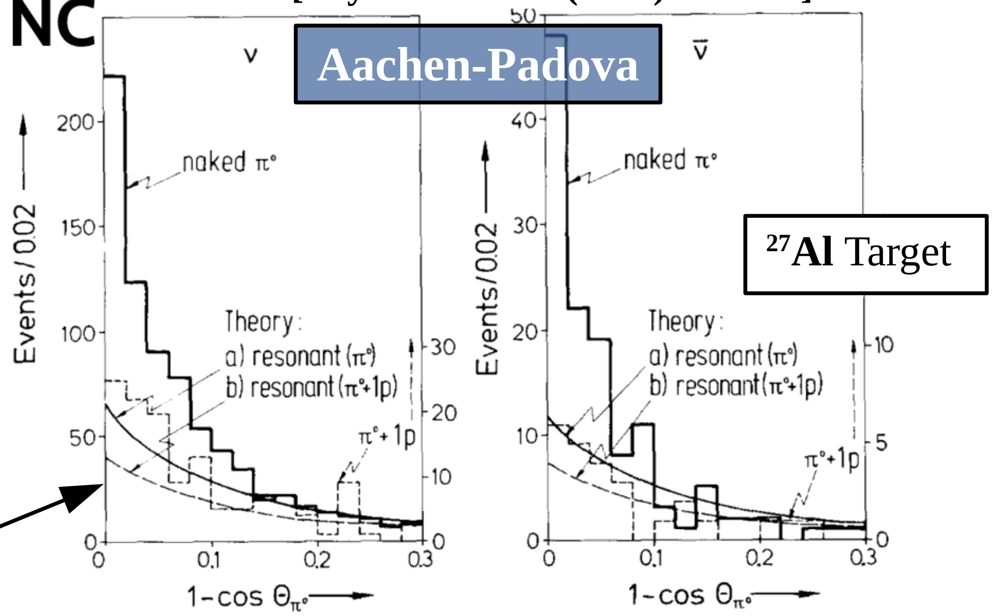
Purpose

- Meant to test **PCAC** hypothesis. Focused on understanding the nature of the weak currents.
- Mostly compared against the Rein-Sehgal and Belkov-Kopeliovich models

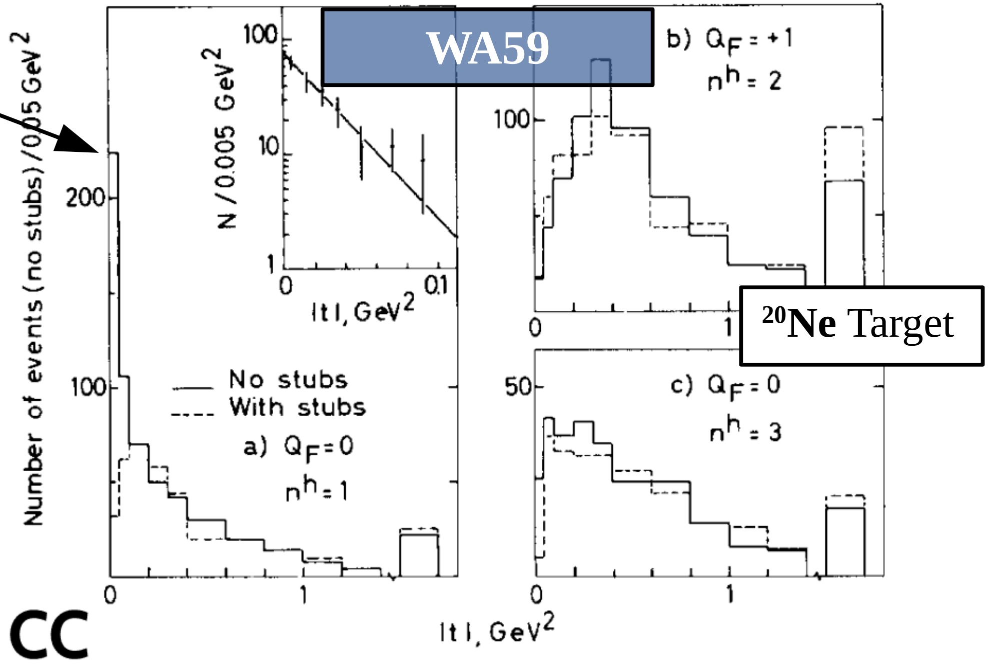
First NC Measurement

First CC Measurement

[Phys.Lett.B 125 (1983) 230-236]



[Phys.Lett.B 140 (1984) 137-141]

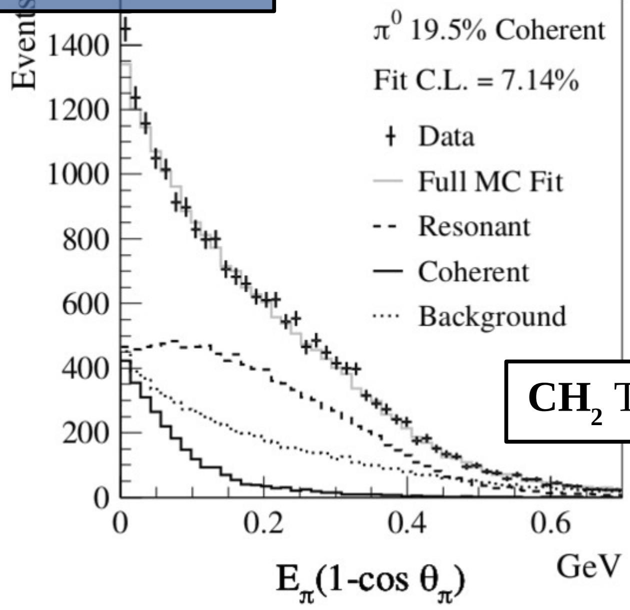


Backup – Previous Measurements

Purpose

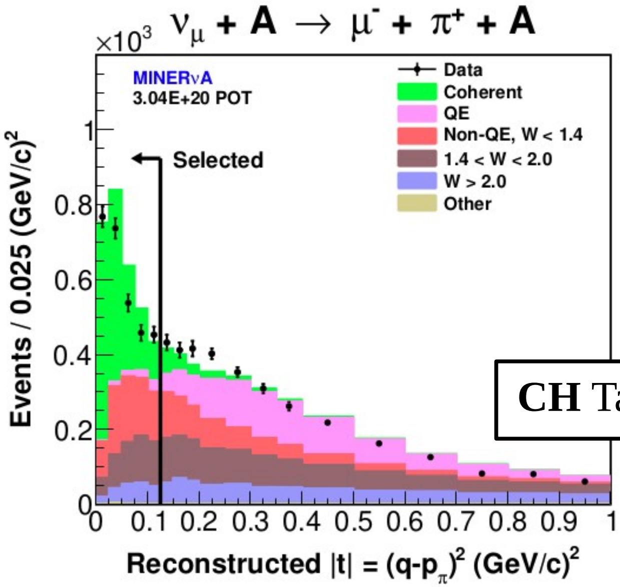
- Characterize it as **background for ν-oscillations.**
- **NC channel** can **mimic** the signal of **ν_e appearance** if one the photons goes undetected.
- **CC channel** can **mimic** the signal of **ν_μ disappearance** if the π^+ is misidentified as a proton, or if the π^- is not detected.
- Proof of existence at $E_\nu < 2$ GeV (NC).
- Proof of existence at $E_\nu < 5$ GeV (CC).
- Most used model was also the one by Rein-Sehgal.

MiniBooNE [Phys.Lett.B 664 (2008) 41-46]



CH_2 Target

MINERvA [Phys.Rev.Lett. 113 (2014) 26]



CH Target

Backup – Theory

|t| in Terms of the Muon and Pion Kinematics

- Considering the nucleus at rest and the energy transferred to it negligible, the neutrino energy can be expressed like:

$$E_\nu \approx E_\mu + E_\pi$$

- With that assumption, it follows

$$|t| = \left|(p_\nu - p_l - p_\pi)^2\right| \approx \left(\sum_{i=l,\pi} p_i^T\right)^2 + \left(\sum_{i=l,\pi} E_i - p_i^L\right)^2$$

- After deploying the algebra, is written like

$$\begin{aligned} |t| \quad &\simeq \quad |2\left(E_\mu + E_\pi\right)\left(E_\mu - p_\mu \cos\theta_{\nu\mu}\right) - m_\mu^2 \\ &-2 \quad \left(E_\pi^2 - \left(E_\mu + E_\pi\right) p_\pi \cos\theta_{\nu\pi} + p_\mu p_\pi \cos\theta_{\mu\pi}\right) + m_\pi^2| \end{aligned}$$

Backup – Theory

Diffractive Process

- Coherent inelastic pion production is also a diffractive process. This means that the momentum transfer to the target is “small”

$$\frac{d\sigma}{dt} \sim A\left(E_\pi\right) e^{-b|t|}$$

where $b\ [GeV/c]^{-2}$ ~ radius of the target:

- R_C ~ 2.77 fm, b ~ 40 $[GeV/c]^{-2}$
- R_{Fe} ~4.29 fm, b ~ 110 $[GeV/c]^{-2}$
- R_{Pb} ~7.16 fm, b ~ 270 $[GeV/c]^{-2}$

Backup – Diffractive Scattering Off Hydrogen

MINERvA’s LE Analysis [Phys.Rev.D 97 (2018) 3, 032014]

- The cross section is **$\nu + p \rightarrow \pi^+ + p$**
- $|t|_{\text{dif f}} = |(p_\nu - p_\mu - p_\pi)^2| = |(p_{p,f} - p_{p,i})^2| = 2m_p T_p$
- Because of the E_{Vtx} cut, the protons kinetic energy T_p is restricted to small values and therefore small |t|.
- The slope ***b*** in the cross section is only ~ 8 $[\text{GeV/c}]^{-2}$ compared to that of ***C*** ~ 40 $[\text{GeV/c}]^{-2}$

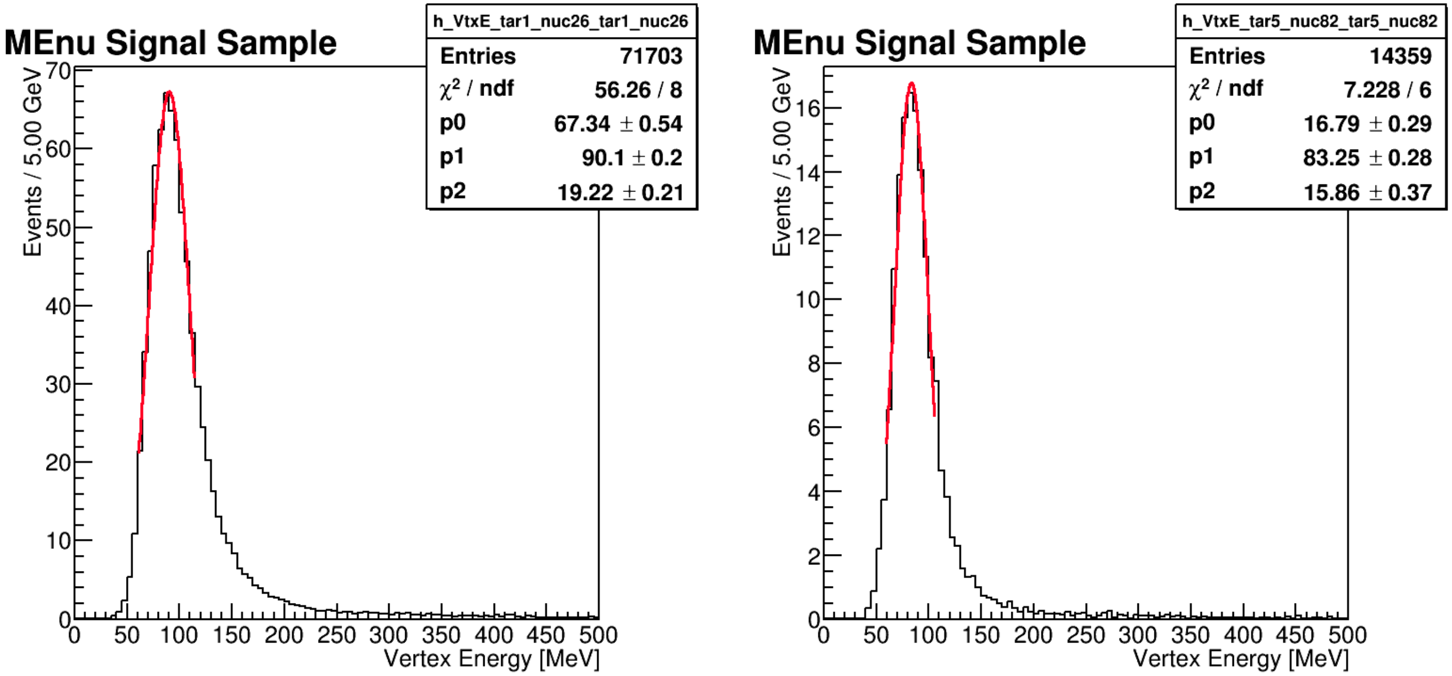
$$\frac{d\sigma}{dt} \sim A\left(E_\pi\right) e^{-b|t|}$$

- The small acceptance and the slow falling |t|-dependence of the cross section results in a small contribution to the coherent cross section.
- The LE MINERvA analysis showed that the measured diffractive cross section was consistent with zero!

Backup – Reconstruction & Event Selection

E_{Vtx} Fit

- Example of T1 Fe and T5 Pb distributions of the vertex energy using signal events only.
- The μ ± 1σ defines the E_{Vtx} cut.



Backup – Background Tuning

Backgrounds From GENIE + Mnv Tune

In terms of invariant hadron mass $W = \sqrt{(M^2 + 2M\nu - Q^2)}$

M = nucleon mass, ν = energy transfer from the neutrino.

- 🟪 **Quasielastic Scattering** (**QE**)
  - Random Phase Approximation (RPA) correction.
  - Z Expansion fit to deuterium data.
- 🟪 **Scattering off correlated nucleons** (**2p2h**)
  - Fit to MINERvA data.
- 🟥 **Resonant pion production** (**Non-QE, W < 1.4**)
  - 15% increment from re-analysis of deuterium data.
  - “Ad hoc” correction for $Q^2 < 0.7$ [GeV/c]^2 due to collective nuclear effects.
- 🟫 **“Inelastic Scattering”** (non-resonant pion production) (**1.4 < W < 2.0**)
  - 43% reduction of the non-resonant pion production, from re-analysis of deuterium data.
- 🟦 **Deep Inelastic Scattering** (**W > 2.0**)
- 🟩 **Other interactions**
  - ν_e-induced and NC-induced interactions

Backup – Plastic Background Tuning

χ^2 for Plastic Sidebands

- A χ^2 hypothesis is constructed for each material (C, Fe and **Pb**) and for each plastic region: upstream (US) and downstream (DS).
- The sidebands are the plastic planes in between targets, excluding the planes immediately next to the targets, and all the planes in between targets 4 and 5.

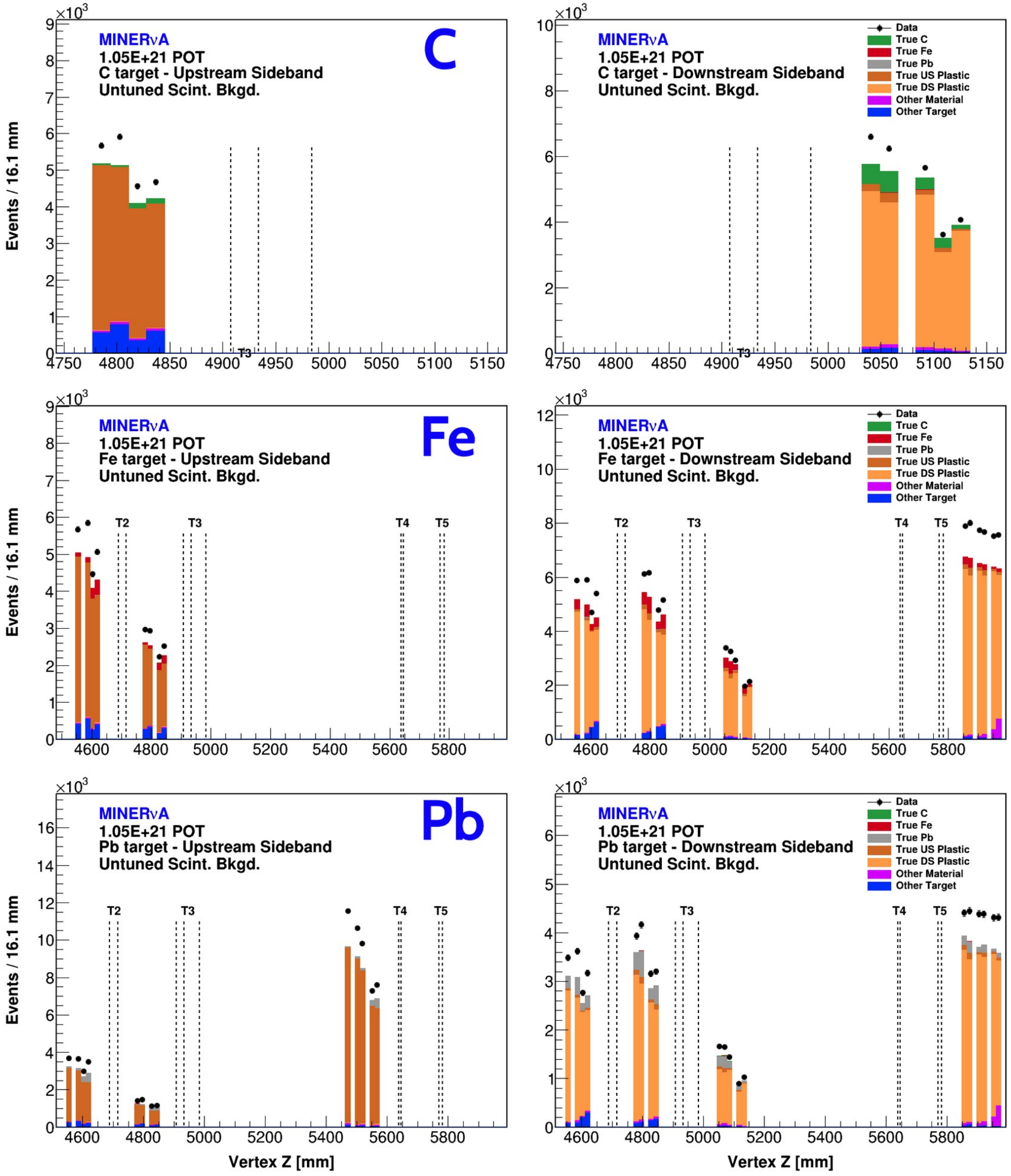
$$\chi^2 = \sum_i \left[\frac{MC^i_{signal} + MC^i_{other} + \alpha_{us} MC^i_{us} + \alpha_{ds} MC^i_{ds} - Data^i}{\sqrt{Data^i}} \right]^2$$

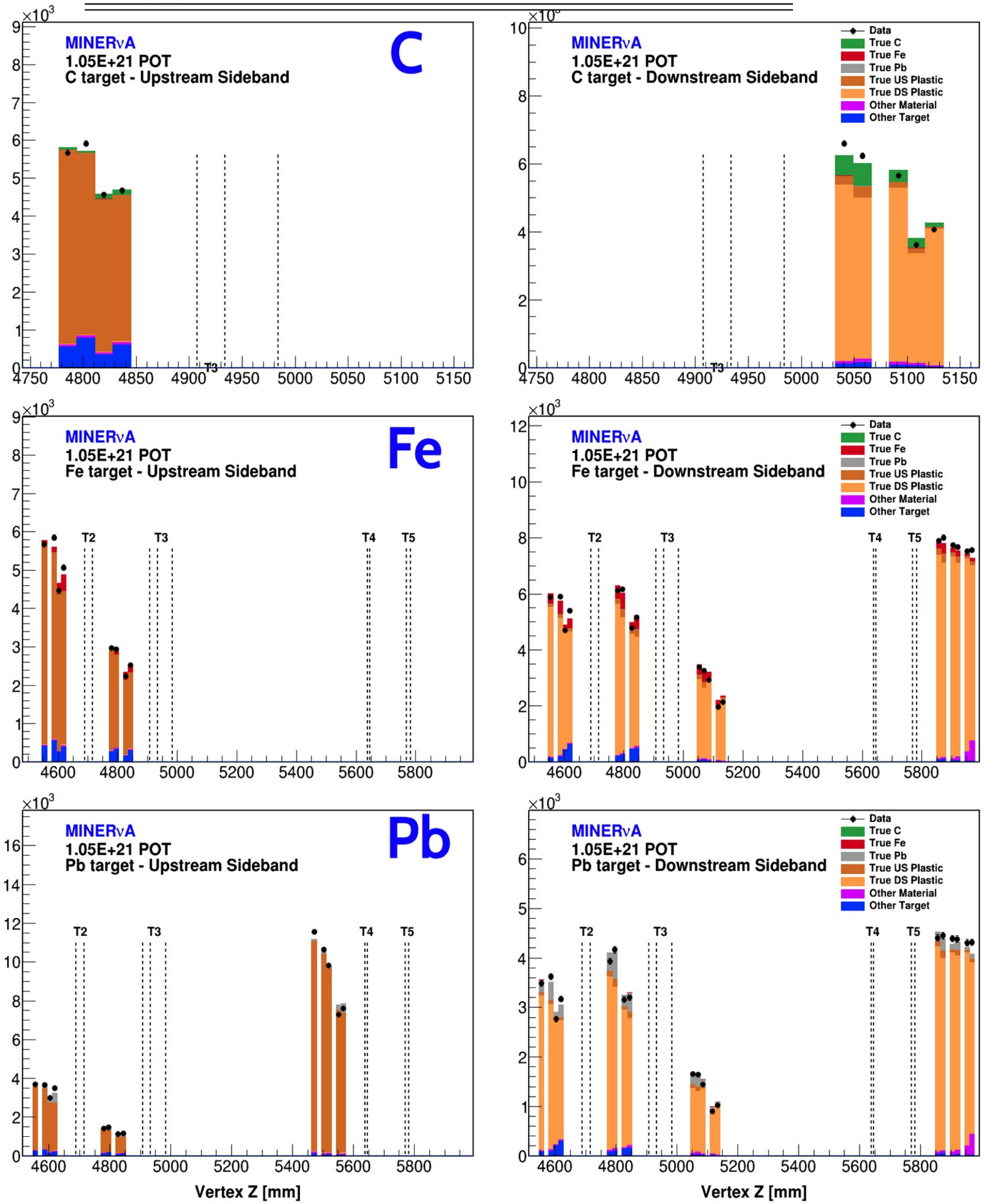
- **MC**$_{\textbf{signal}}$ = **C, Fe** or **Pb** MC contribution
- **MC**$_{\textbf{other}}$ = Other material and other target MC contribution
- **MC**$_{\textbf{us}}$ = Upstream plastic MC contribution
- **MC**$_{\textbf{ds}}$ = Downstream plastic MC contribution

Backup – Plastic Background Tuning

Untuned vs Tuned Sidebands

Material	C	Fe	Pb
α_{US}	1.15 ± 0.009	1.17 ± 0.004	1.16 ± 0.005
α_{DS}	1.11 ± 0.008	1.04 ± 0.005	1.17 ± 0.005





Backup – Plastic Background Tuning

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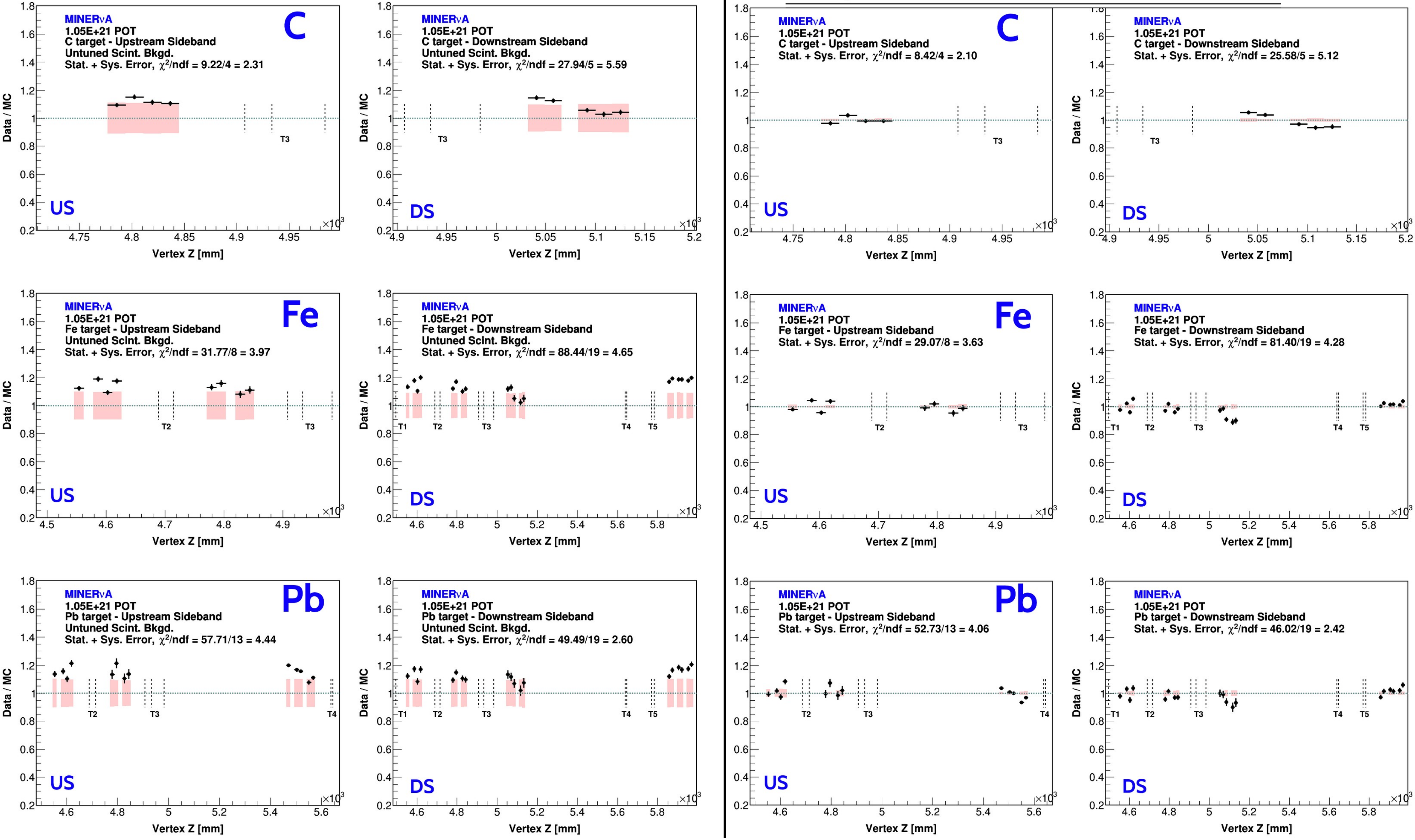
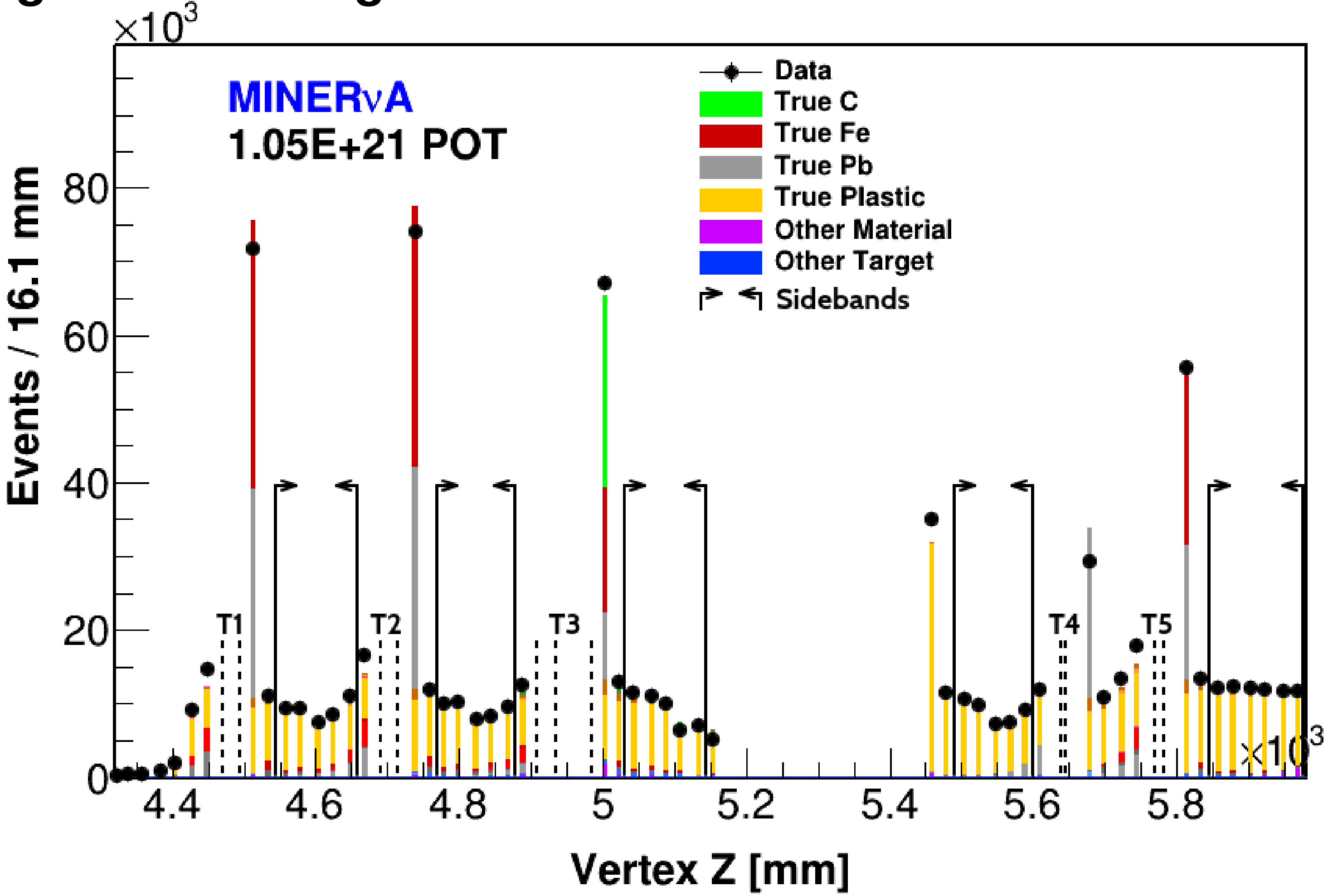
Untuned vs Tuned Sidebands



Backup – Plastic Background Tuning

Background Tuning - Plastic Sidebands



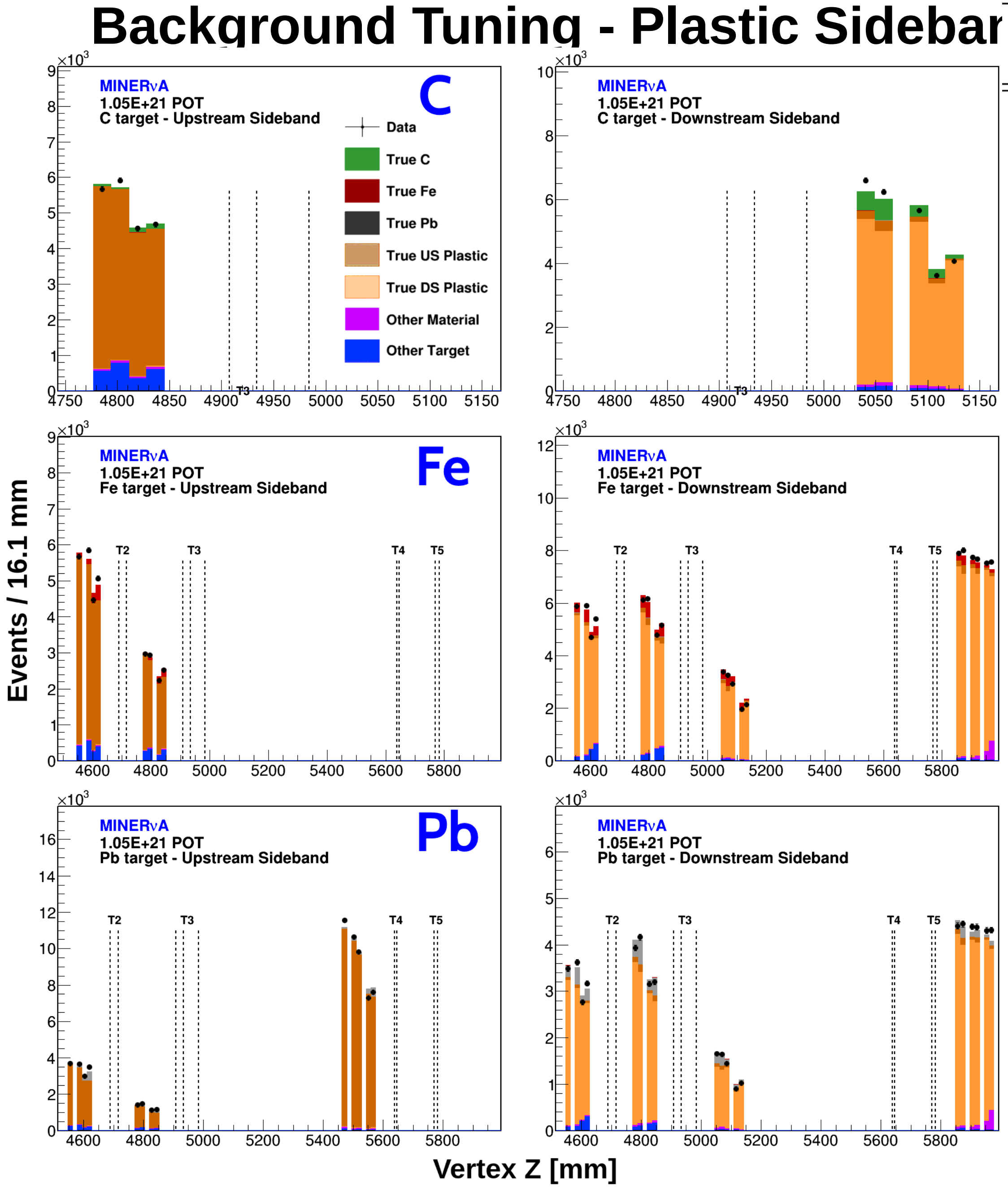
- Plastic regions between targets used as sidebands
- **Upstream** and **Downstream** plastic tuned separate
- Different sidebands for each material (**C**, **Fe** and **Pb**)

Backup – Plastic Background Tuning

Scale Factors

Material	C	Fe	Pb
α_{US}	1.15 ± 0.009	1.17 ± 0.004	1.16 ± 0.005
α_{DS}	1.11 ± 0.008	1.04 ± 0.005	1.17 ± 0.005

Plastic background TUNED



Tuned plastic background represents:

- **~14%** of the selected **C** and **Fe** samples
- **~20%** of the selected **Pb** sample

Backup – Incoherent Background Tuning

χ^2 for High |t| Sideband

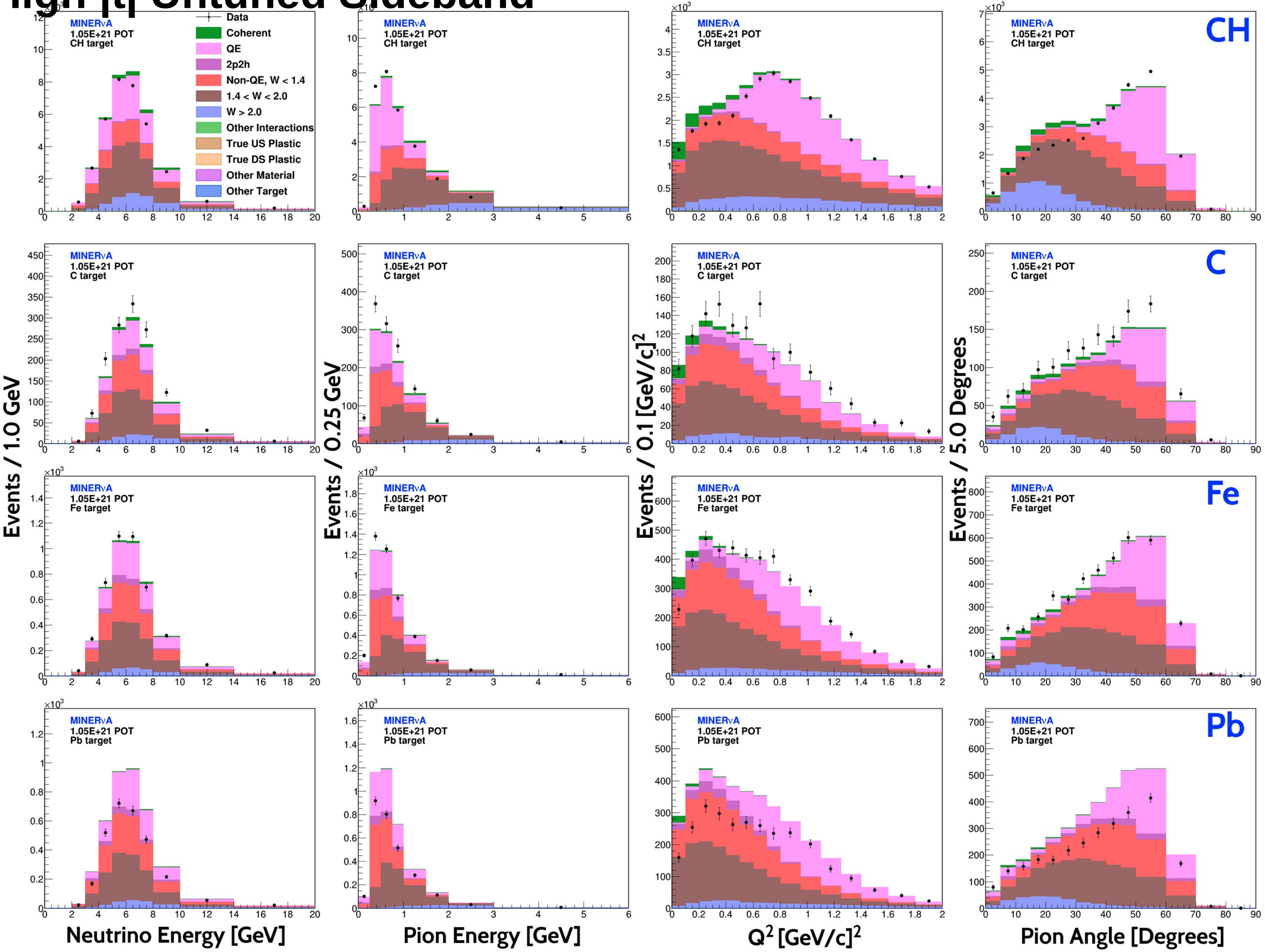
- The tuning is performed simultaneously in $\mathbf{E_\pi}$ and $\mathbf{Q^2}$ variables, after the $\mathbf{E_{vtx}}$ cut, inside the $0.2 < |t| < 0.7$ [GeV/c]^2 sideband.

$$\chi^2 = \sum_i \sum_j \frac{\left[N_{ij}^{Data} - \sum_k \alpha_k N_{ijk}^{MC}\right]^2}{\sum_k \alpha_k N_{ijk}^{MC}}$$

- $\mathbf{N^{Data}}$ = Number of data events in the *ij* bin.
- $\mathbf{N^{MC}}$ = Number of MC events from the *k* background, in the *ij* bin.
- $\boldsymbol{\alpha_k}$ = Scale factor for each background.

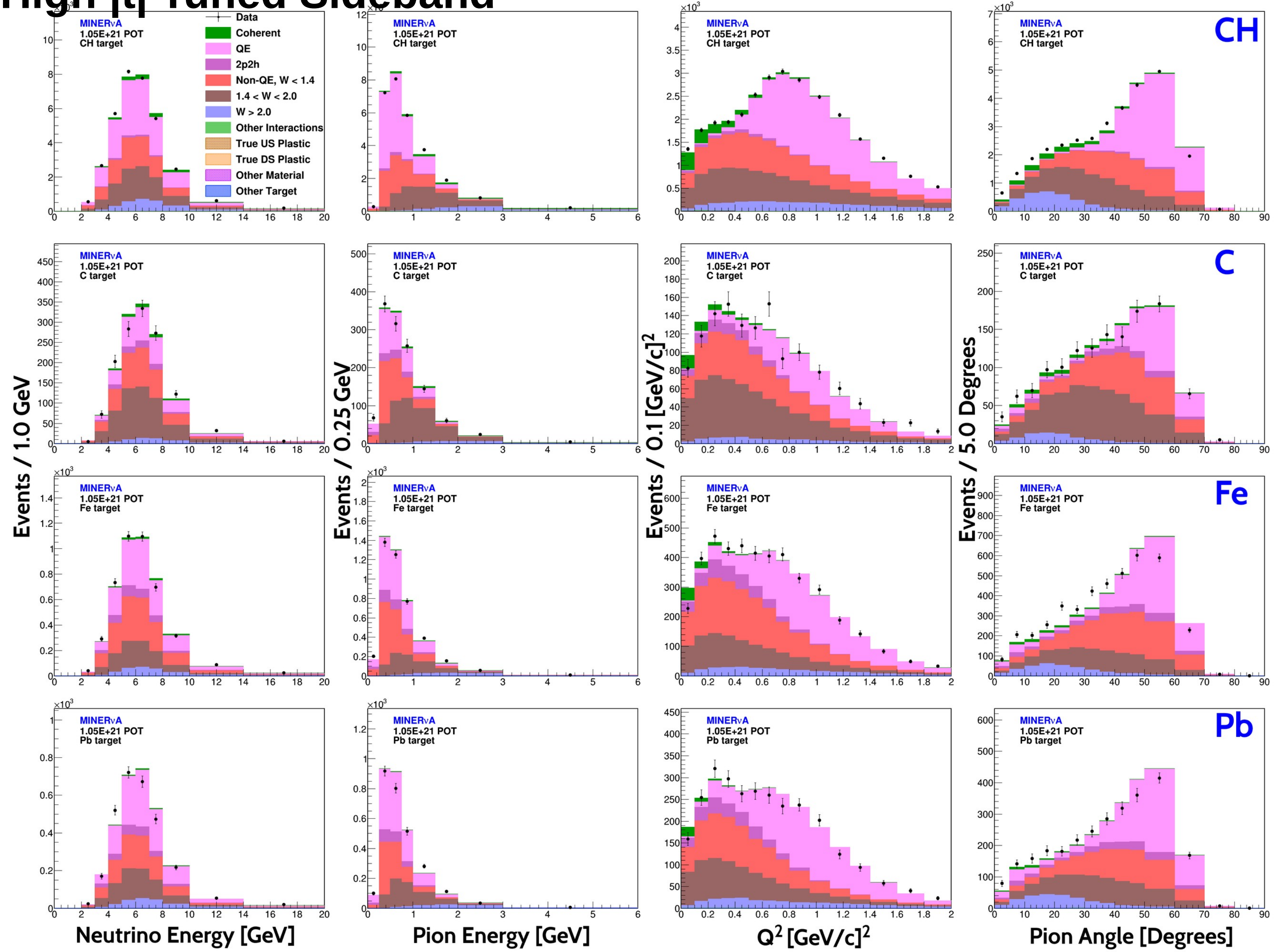
Backup – Incoherent Background Tuning

High |t| Untuned Sideband



Backup – Incoherent Background Tuning

High |t| Tuned Sideband



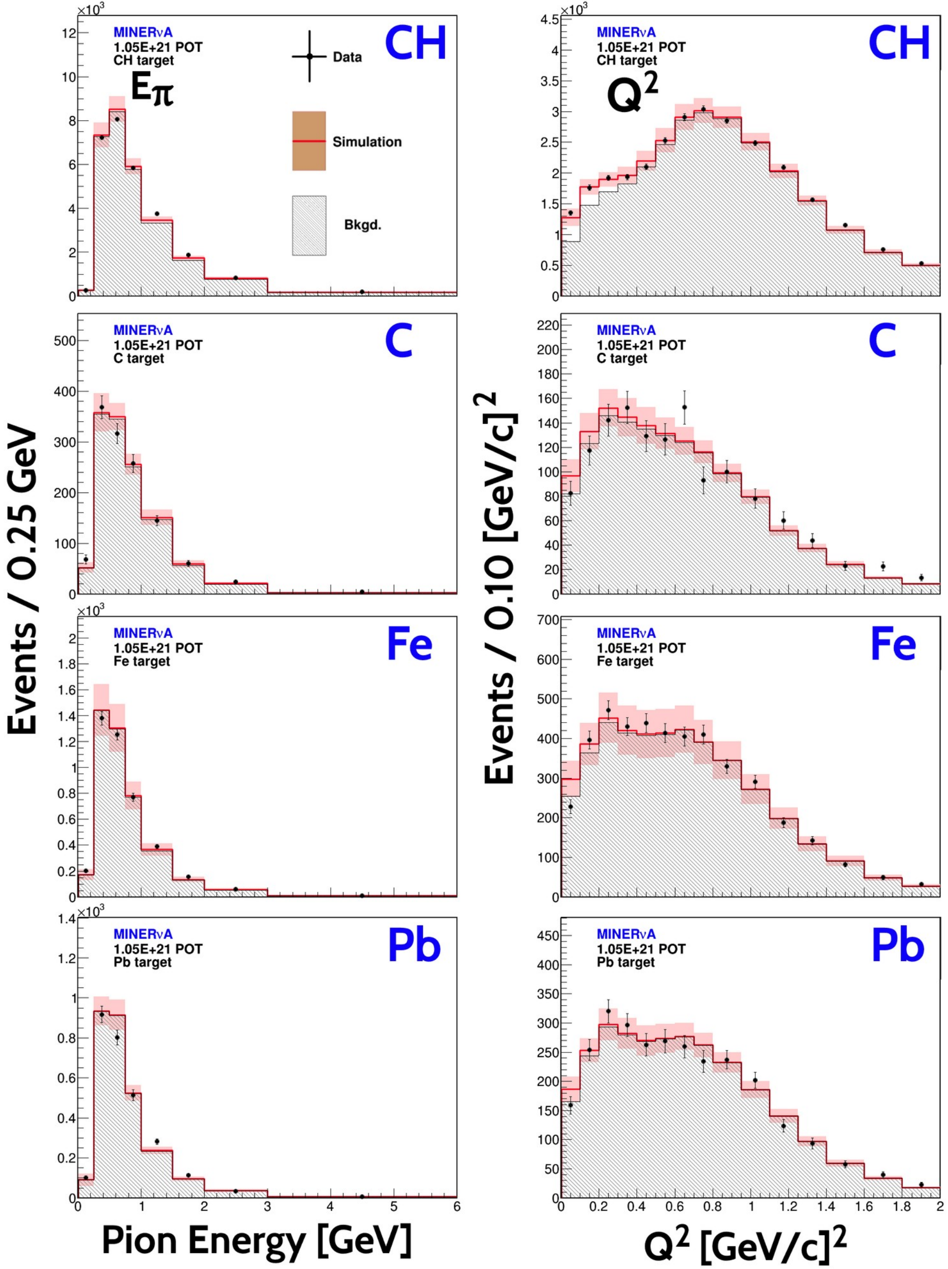
Backup – Incoherent Background Tuning

Scale Factors

Material	CH	C	Fe	Pb
α_{QE}	1.22 ± 0.016	1.22 ± 0.016	1.40 ± 0.067	1.09 ± 0.054
α_{RES}	1.29 ± 0.040	1.17 ± 0.046	1.15 ± 0.088	0.66 ± 0.069
α_{INE}	0.60 ± 0.016	1.17 ± 0.046	0.58 ± 0.059	0.50 ± 0.053
α_{DIS}	0.65 ± 0.026	0.65 ± 0.026	1.08 ± 0.137	0.98 ± 0.144

Background TUNED

High |t| Sideband Tuned

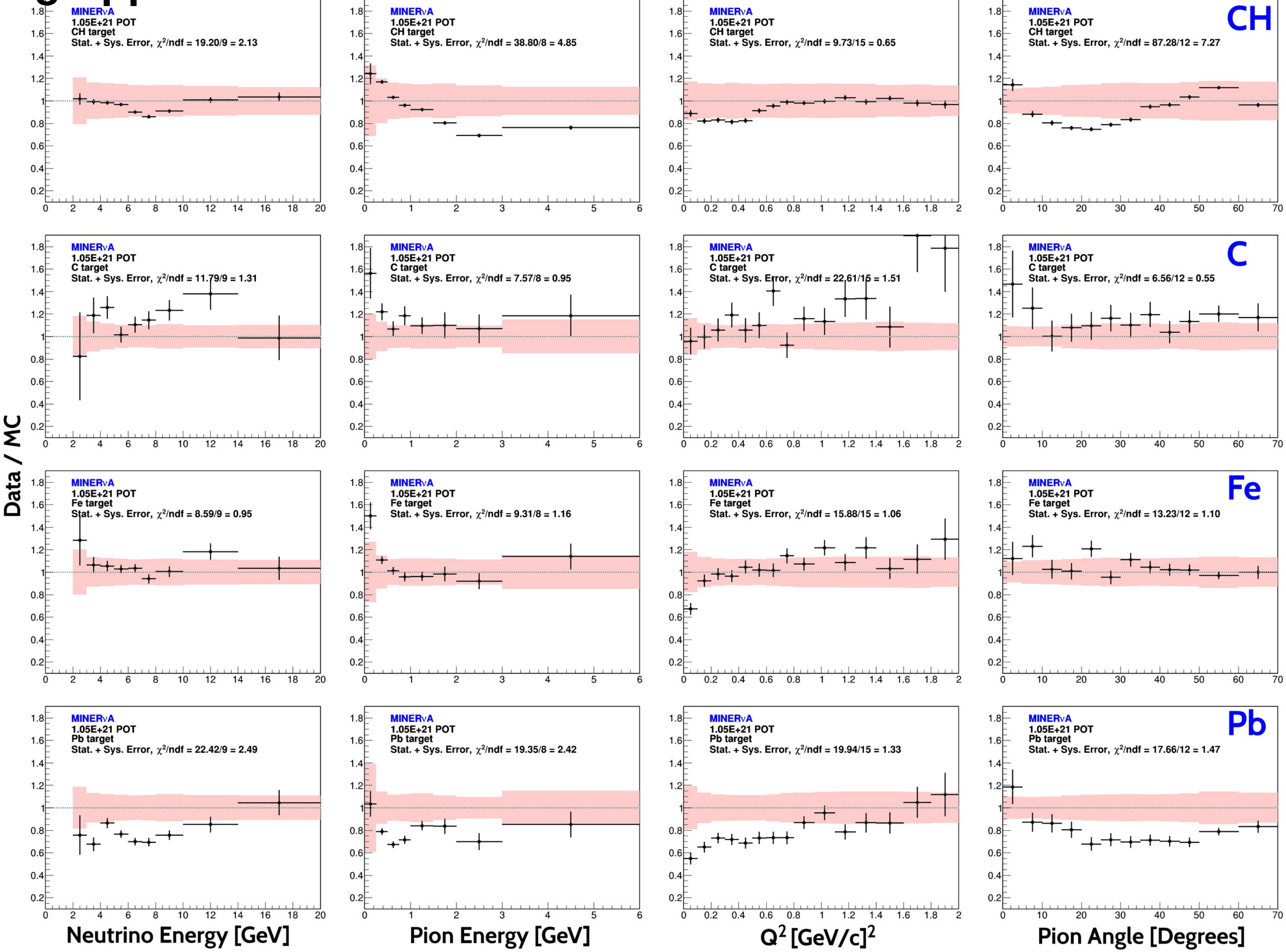


Distributions from high |t| sidebands

- Tuned in $\mathbf{E_\pi}$ and $\mathbf{Q^2}$ simultaneously.
- Samples from $\mathbf{0.3 < |t| < 0.7}$ [Gev/c]^2

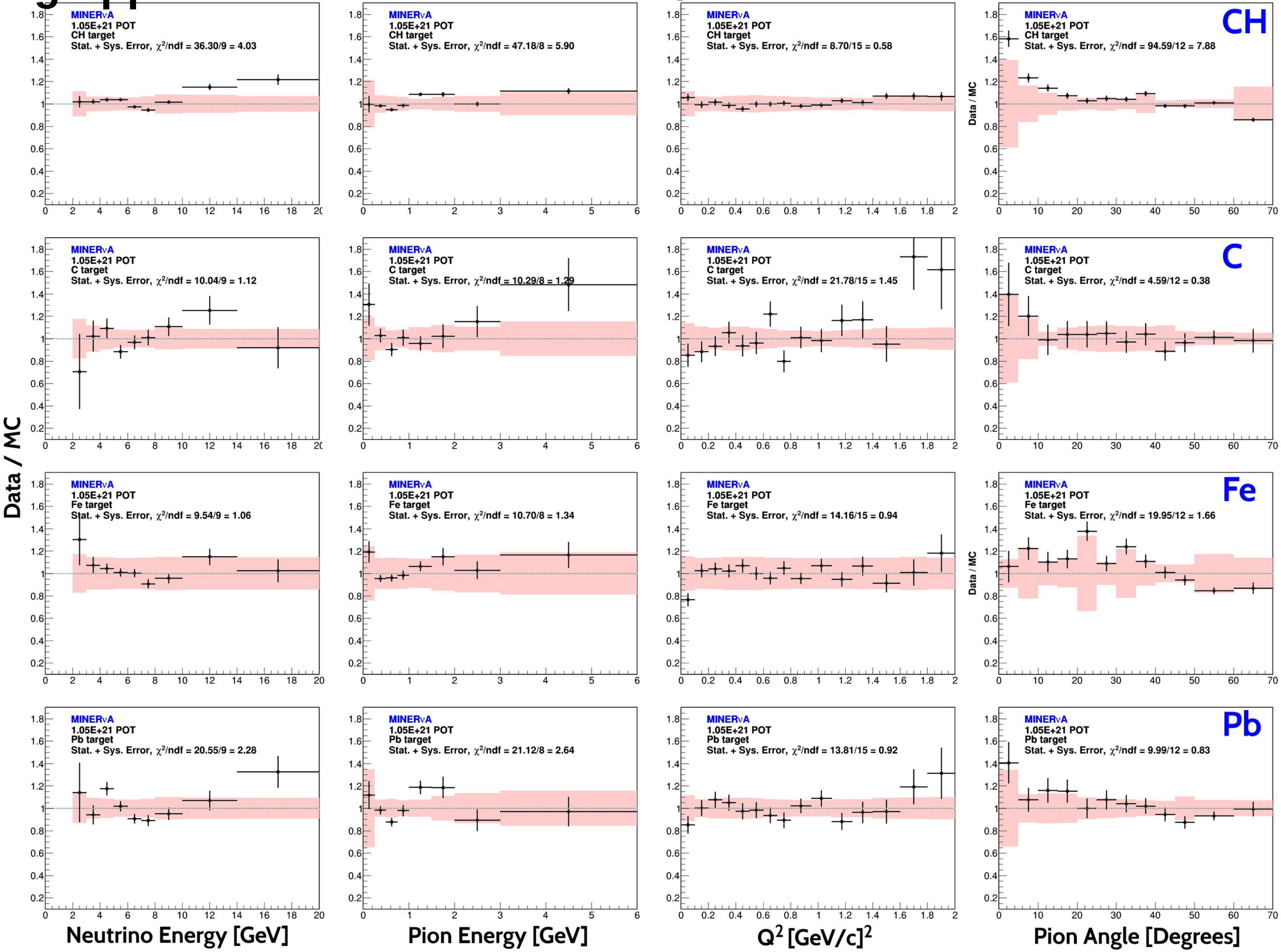
Backup – Incoherent Background Tuning

High |t| Untuned Sideband – Data/MC



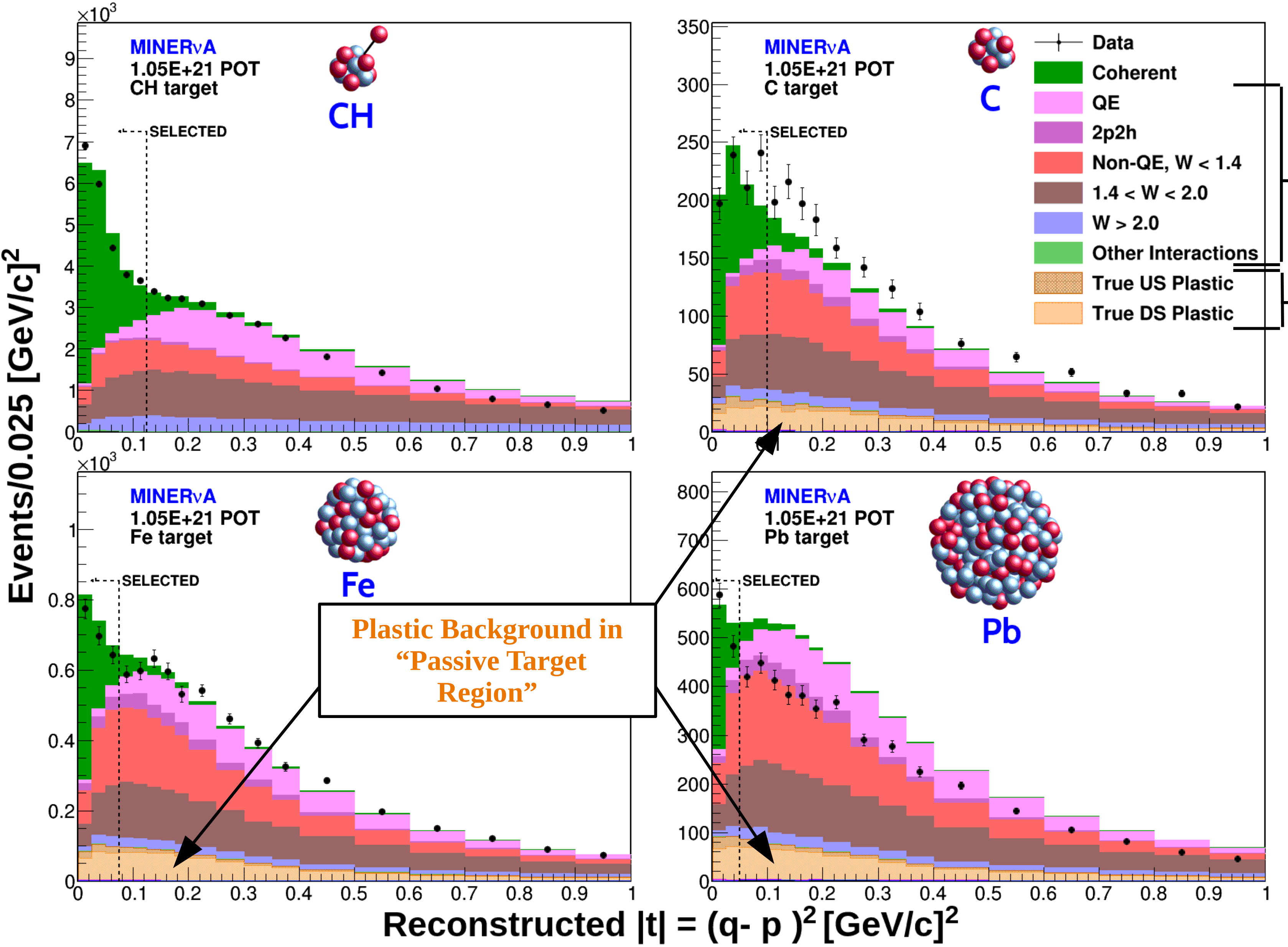
Backup – Incoherent Background Tuning

High |t| Untuned Sideband - Data/MC



Backup – Incoherent Background Tuning

Event Selection – Momentum Transfer to the Nucleus |t|



Plastic Background in "Passive Target Region"

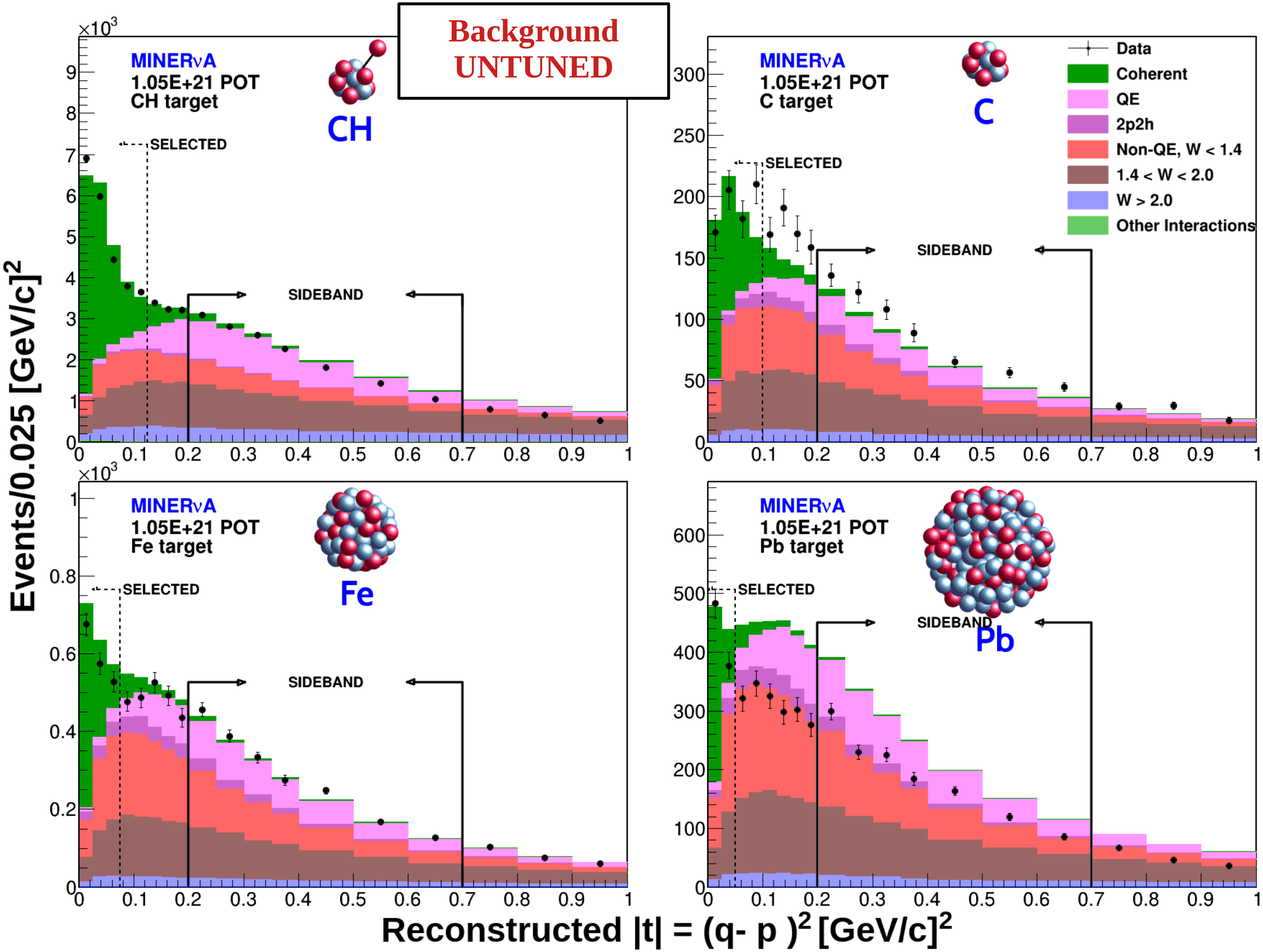
"Incoherent" Background

Plastic Background

All background UNTUNED

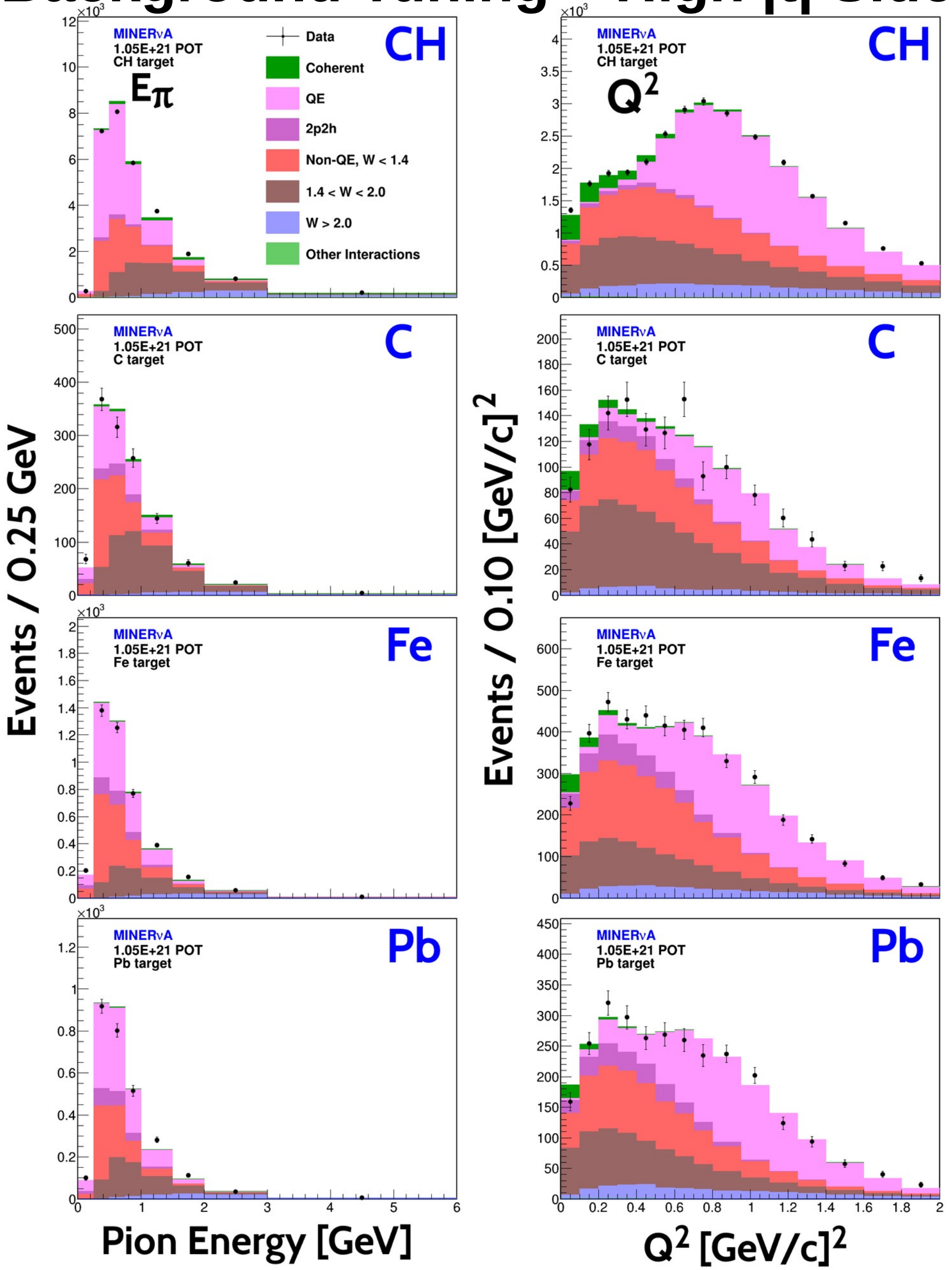
Background Tuning – High |t| Sideband

Background UNTUNED



Backup – Incoherent Background Tuning

Background Tuning – High |t| Sideba



Scale Factors

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α_{RES}	1.29 ± 0.040	1.17 ± 0.046	1.15 ± 0.088	0.66 ± 0.069
α_{INE}	0.60 ± 0.016	1.17 ± 0.046	0.58 ± 0.059	0.50 ± 0.053
α_{DIS}	0.65 ± 0.026	0.65 ± 0.026	1.08 ± 0.137	0.98 ± 0.144

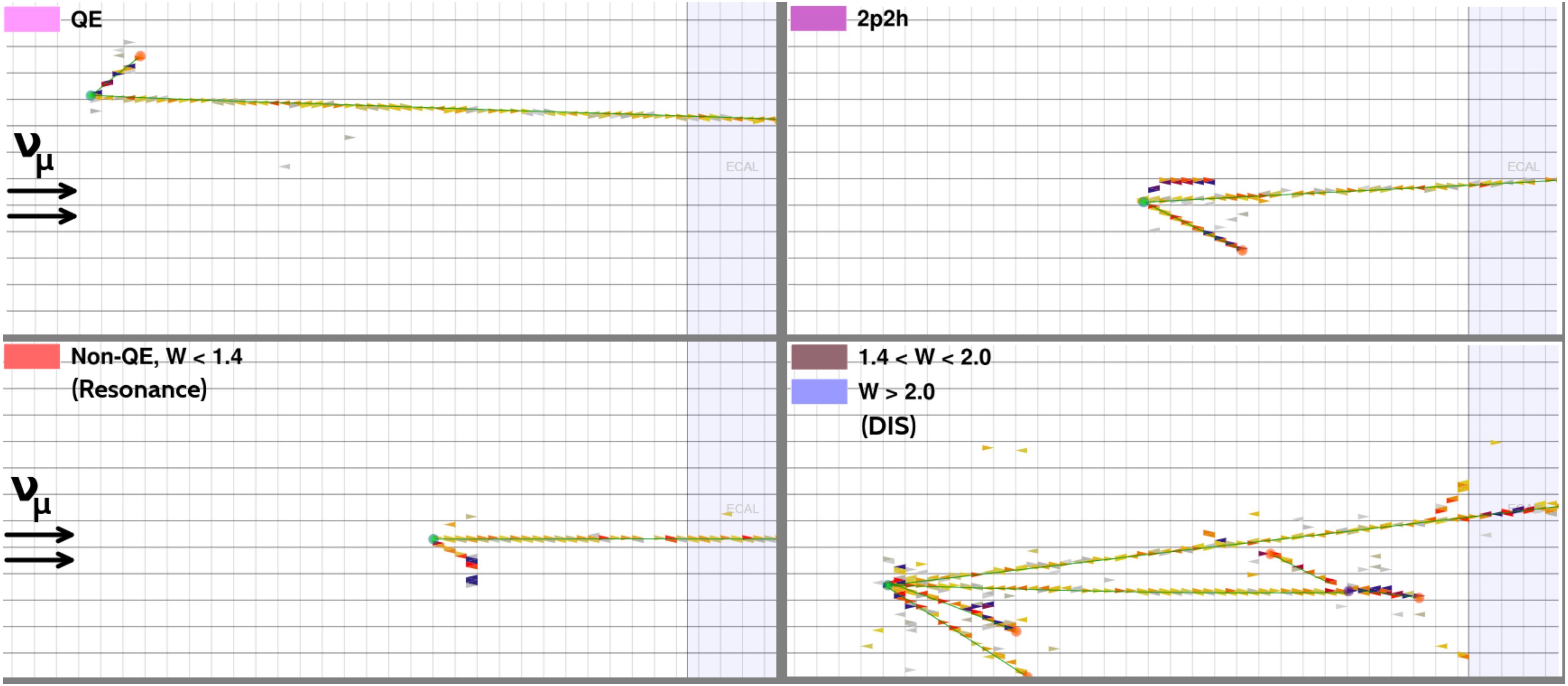
Background TUNED

Distributions from high |t| sidebands

- Tuned in $\mathbf{E_\pi}$ and $\mathbf{Q^2}$ simultaneously.
- Samples from **0.3** < |**t**| < **0.7** [Gev/c]^2.
- Backgrounds in terms of **W**.

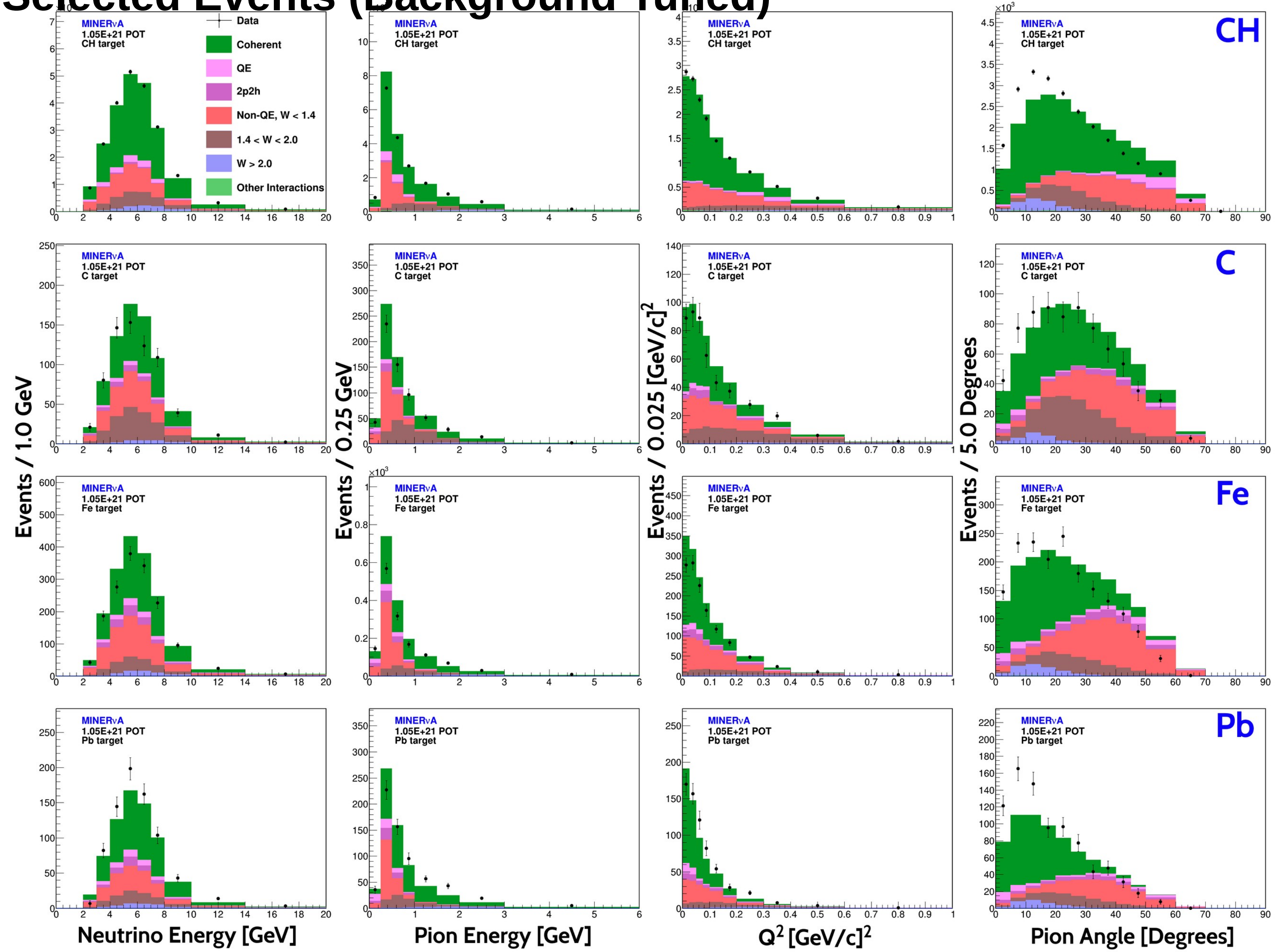
Backup – Cross Section Extraction

Backgrounds – In Terms of Invariant Mass (W)



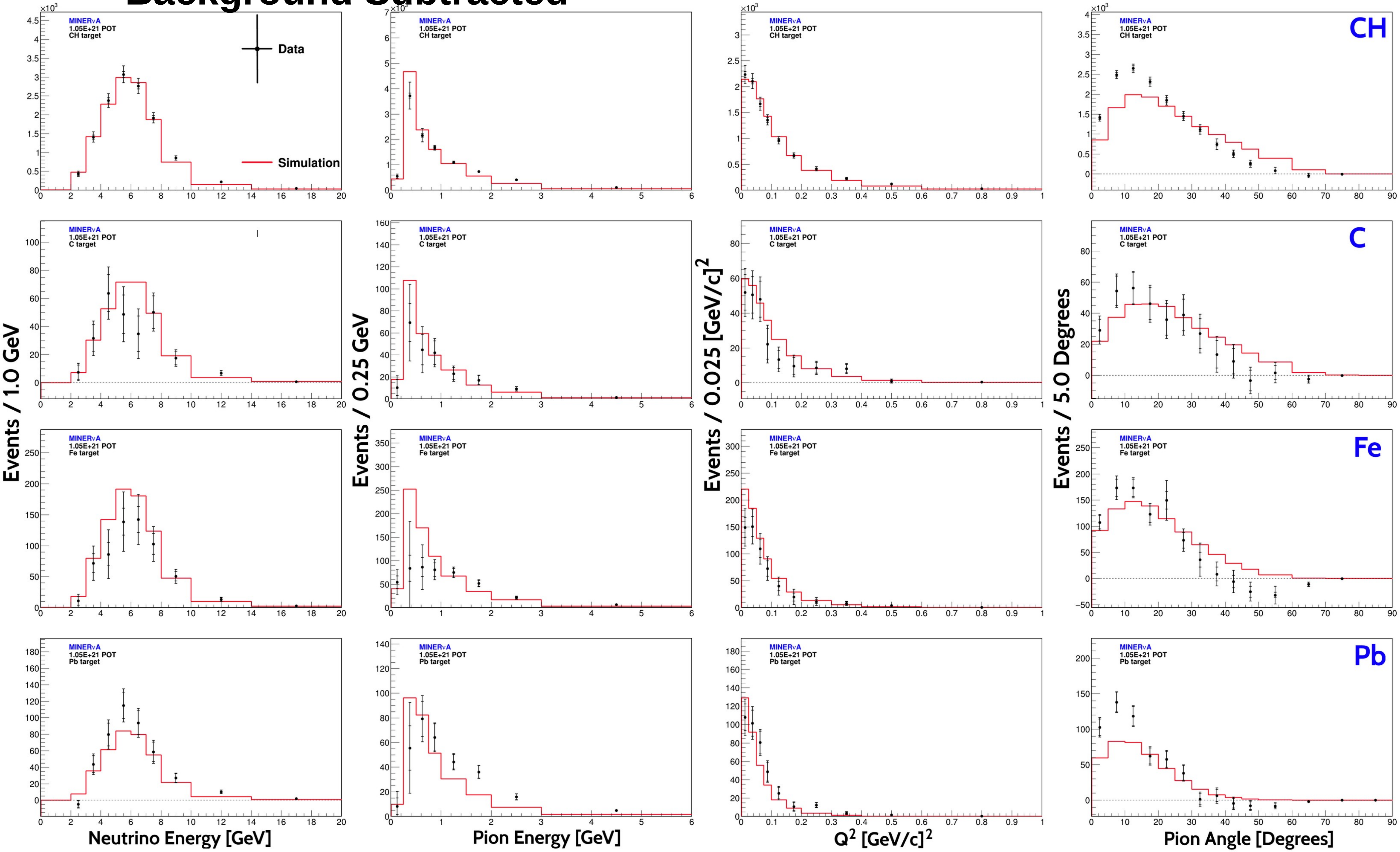
Backup – Cross Section Extraction

Selected Events (Background Tuned)



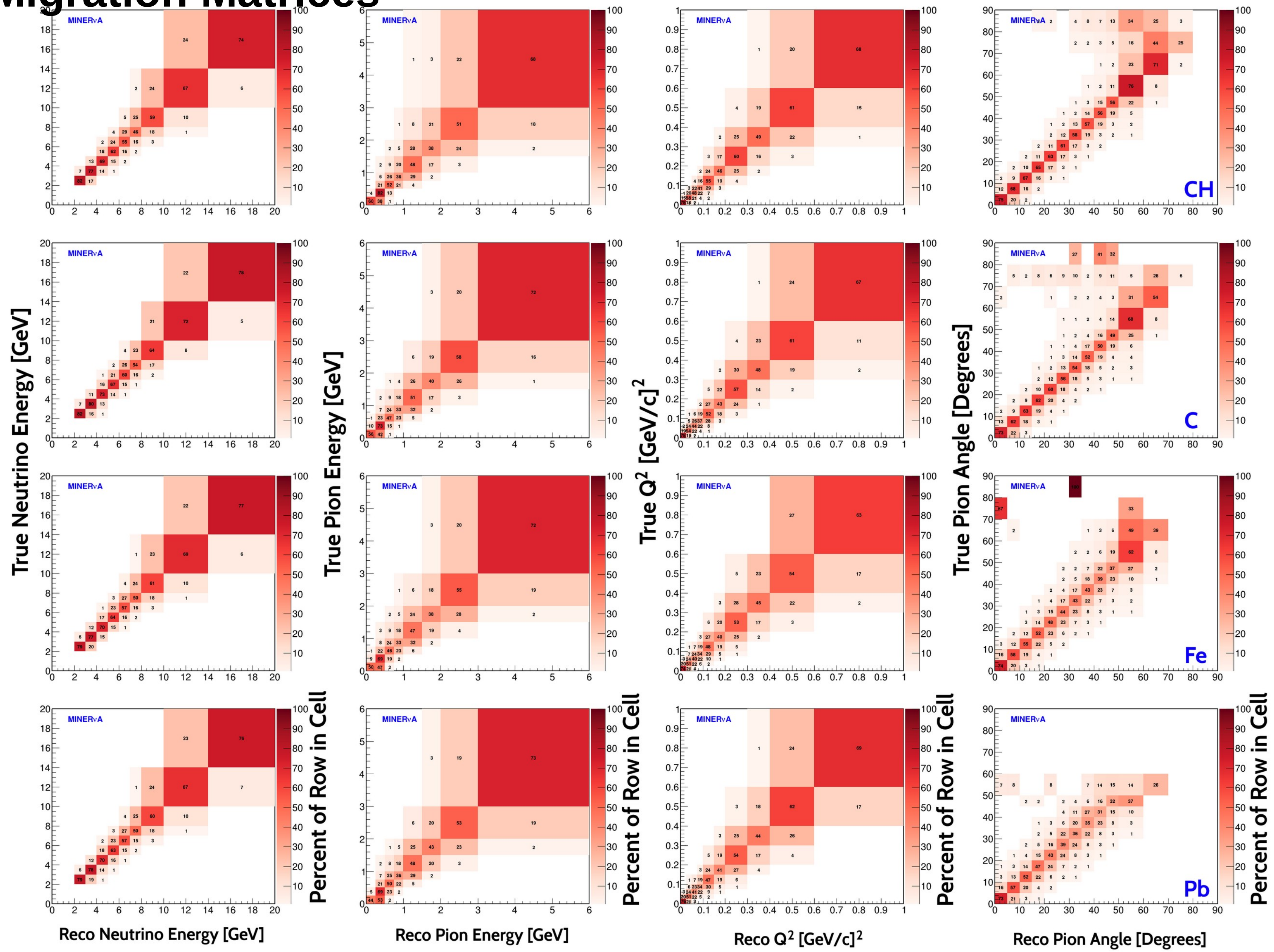
Backup – Cross Section Extraction

Background Subtracted



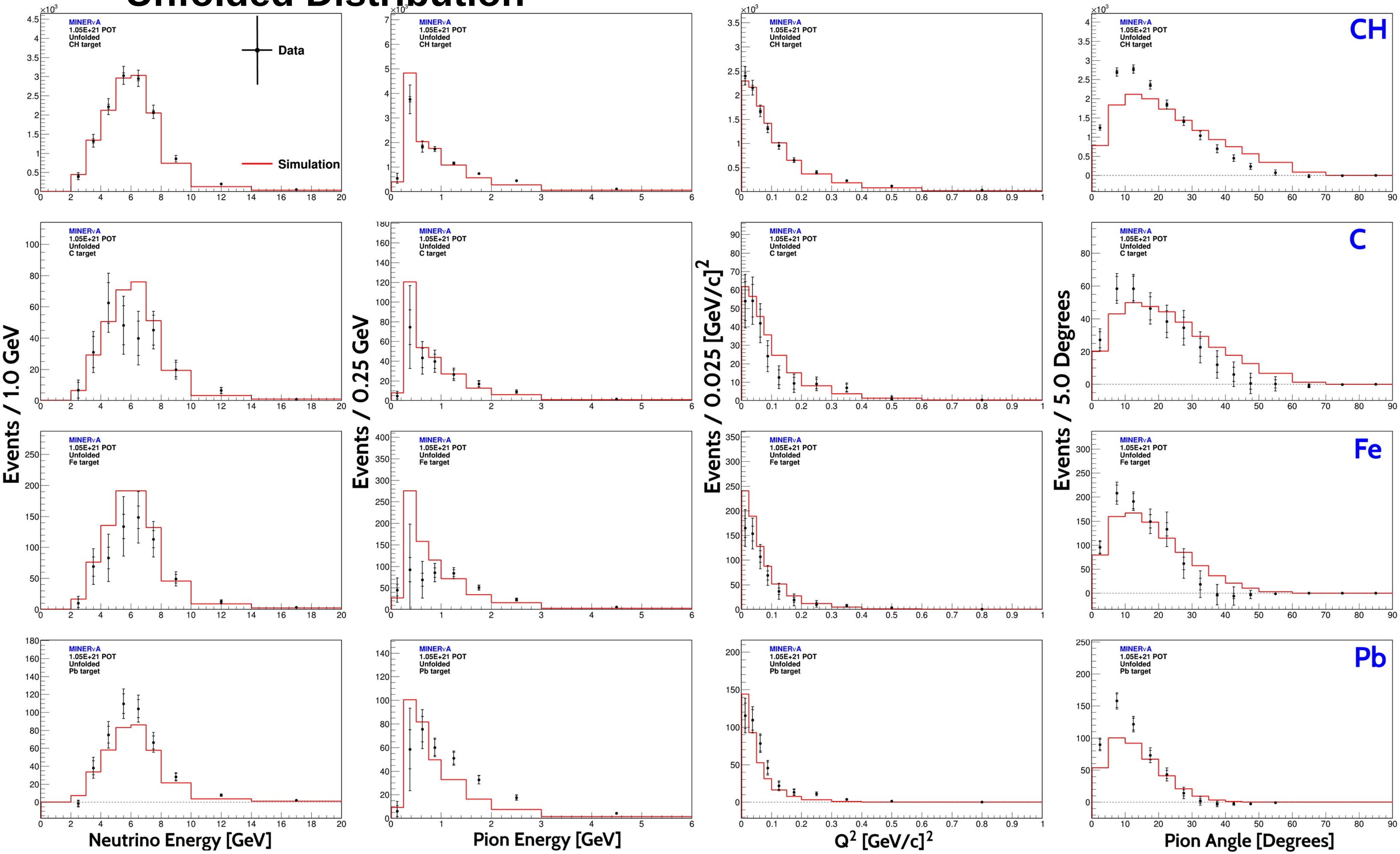
Backup – Cross Section Extraction

Migration Matrices



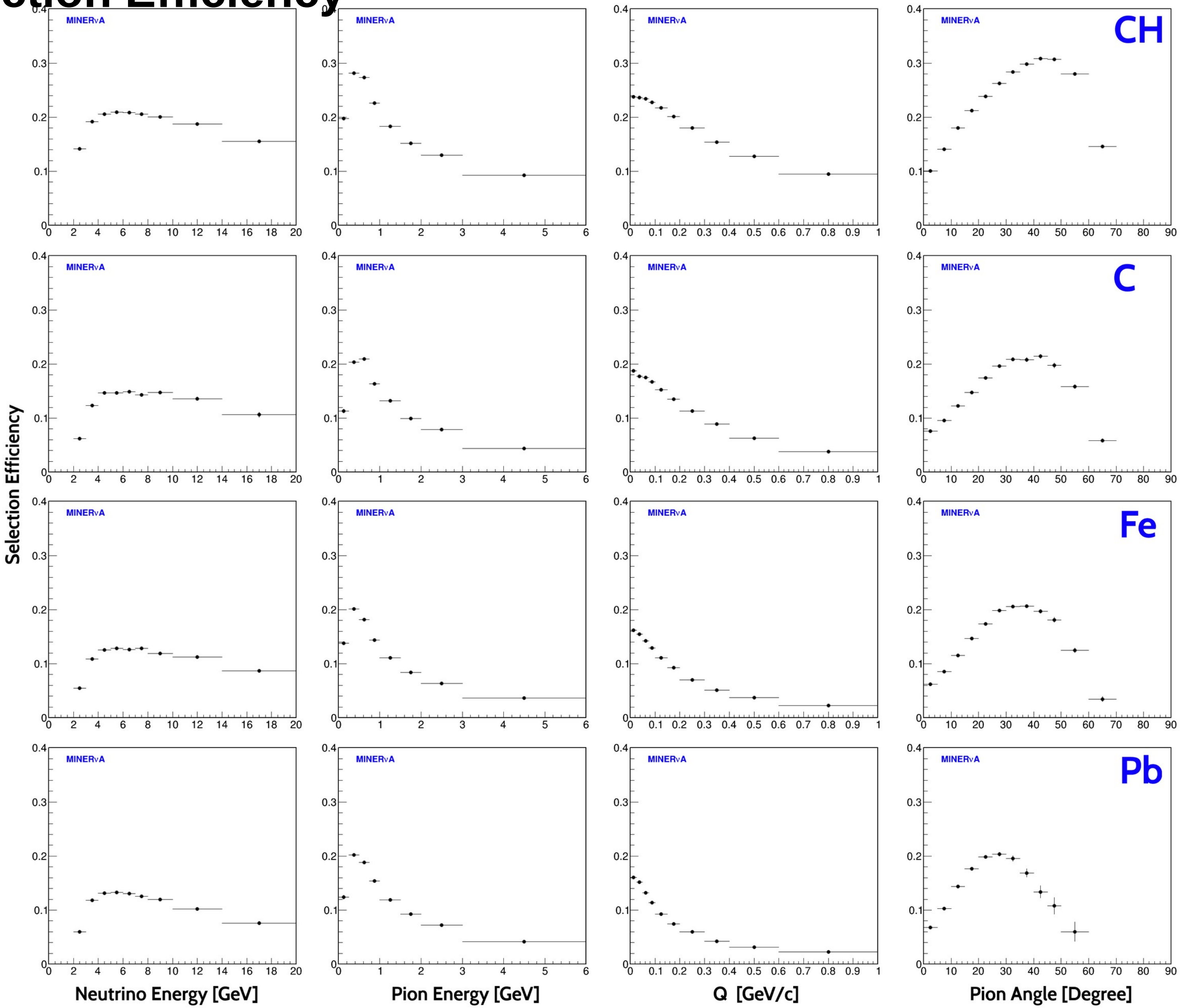
Backup – Cross Section Extraction

Unfolded Distribution



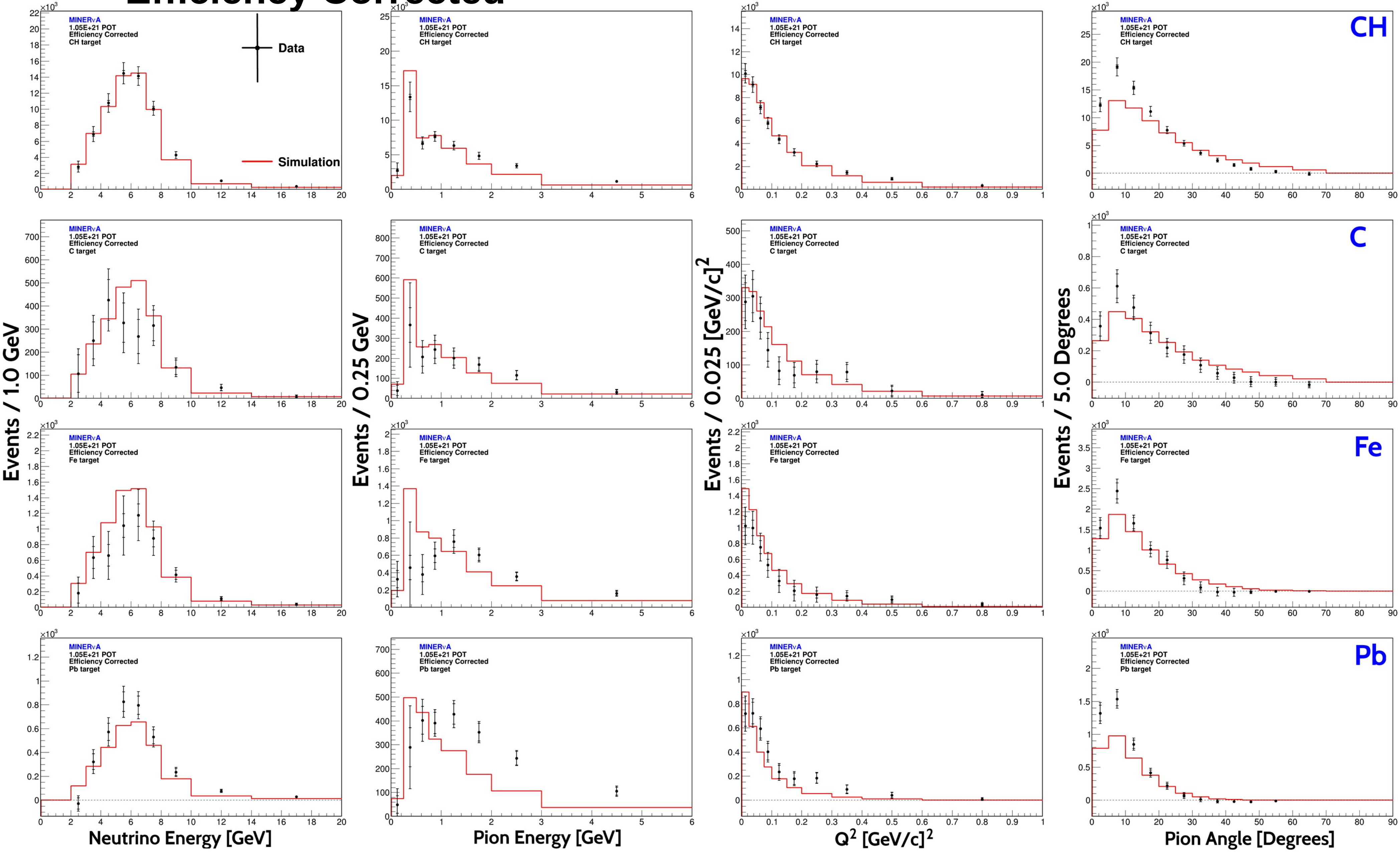
Backup – Cross Section Extraction

Selection Efficiency



Backup – Cross Section Extraction

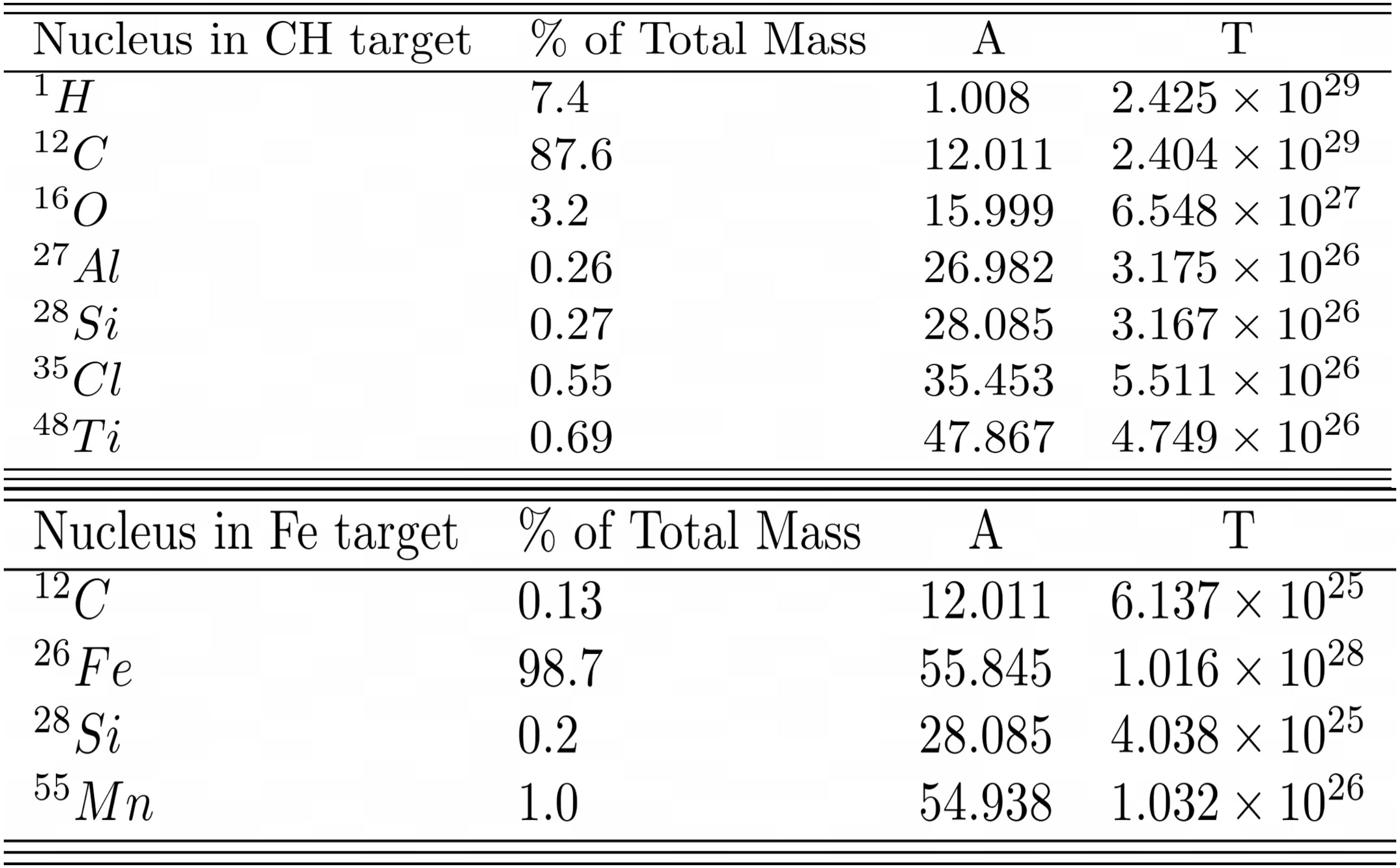
Efficiency Corrected



Backup – Cross Section Extraction

Correction Due To Other Materials in the Fiducial Volume

The ***C*** and ***Pb*** target have less than 1% contribution from other materials. The contribution from other materials to the ***CH*** and ***Fe*** targets is specified below



Nucleus in CH target	% of Total Mass	A	T
^{1}H	7.4	1.008	2.425×10^{29}
^{12}C	87.6	12.011	2.404×10^{29}
^{16}O	3.2	15.999	6.548×10^{27}
^{27}Al	0.26	26.982	3.175×10^{26}
^{28}Si	0.27	28.085	3.167×10^{26}
^{35}Cl	0.55	35.453	5.511×10^{26}
^{48}Ti	0.69	47.867	4.749×10^{26}

Nucleus in Fe target	% of Total Mass	A	T
^{12}C	0.13	12.011	6.137×10^{25}
^{26}Fe	98.7	55.845	1.016×10^{28}
^{28}Si	0.2	28.085	4.038×10^{25}
^{55}Mn	1.0	54.938	1.032×10^{26}

Mass fraction, mass number A, and number of nuclei from all materials present in the CH and Fe targets. Included for every material.

Backup – Cross Section Extraction

Correction Due To Other Materials in the Fiducial Volume

The correction ***β*** is defined as the number of coherent interactions in the material under study in the fiducial volume of a given target, over the total number of coherent interactions in the same fiducial volume

$$\beta = \left(N_M^{coh}/N^{coh}\right) = \frac{\phi\epsilon_M\sigma_M T_M}{\sum_i \phi\epsilon_i\sigma_i T_i} \approx \frac{A_M^{1/3}T_M}{\sum_i A_i^{1/3}T_i}$$

- where φ, ϵ_M , σ_M and T_M are the flux, efficiency, cross section and number of nuclei in each material due to ***C*** in the CH target, and due to ***Fe*** in the Fe targets
- *M* is either ***C*** or ***Fe***.
- The same quantities with the *i* sub index, correspond to the remaining materials in the same target. The assumption of equal flux and efficiency in all materials has been made.
- The cross section has been supposed to scale as $\boldsymbol{A^{1/3}}$ as in the Rein-Sehgal model. Using $\boldsymbol{A^{2/3}}$ yields similar values

Backup – Cross Section Extraction

Correction Due To Other Materials in the Fiducial Volume

Unfolding Matrix

Number of Data Events

Number of Background Predicted Events

Total Cross Section

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

Material Correction Factor

Efficiency

Flux Per Bin

Number of Nuclei

Material	β
CH	0.96
C	1.0
Fe	0.98
Pb	1.0

Backup – Cross Section Normalizations

Cross Section Extraction

Flux and Number of Targets

Total Cross Section

Unfolding Matrix

Number of Selected Data Events

Number of Predicted Background Events

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

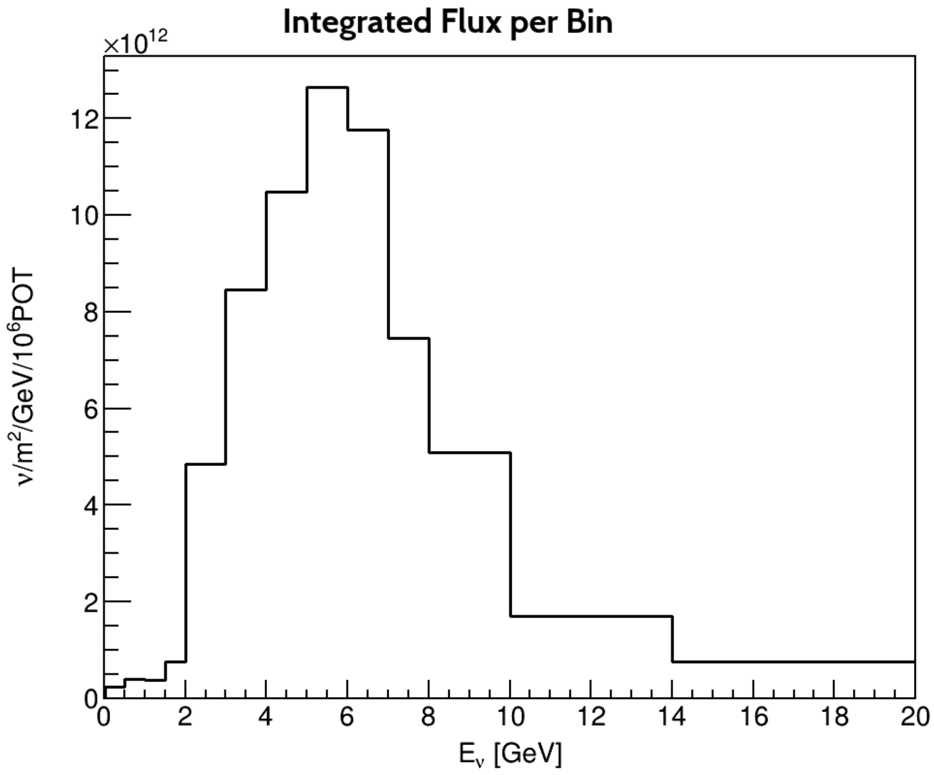
True Bin

Reco Bin

Efficiency

Flux Per Bin

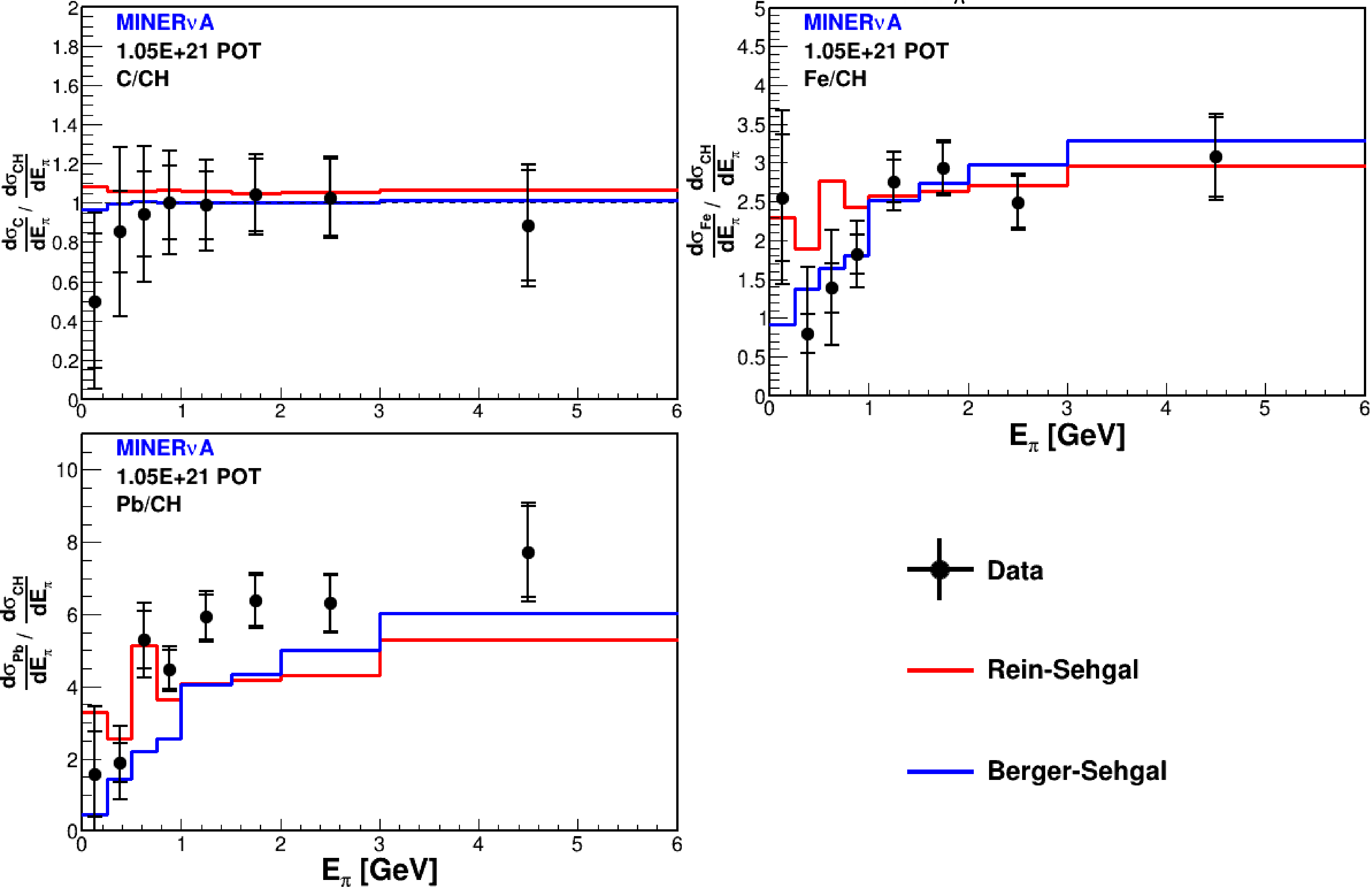
Number of Nuclei



Material	No. of Nuclei
CH	23.6E+28
C	0.79E+28
Fe	1.02E+28
Pb	0.28E+28

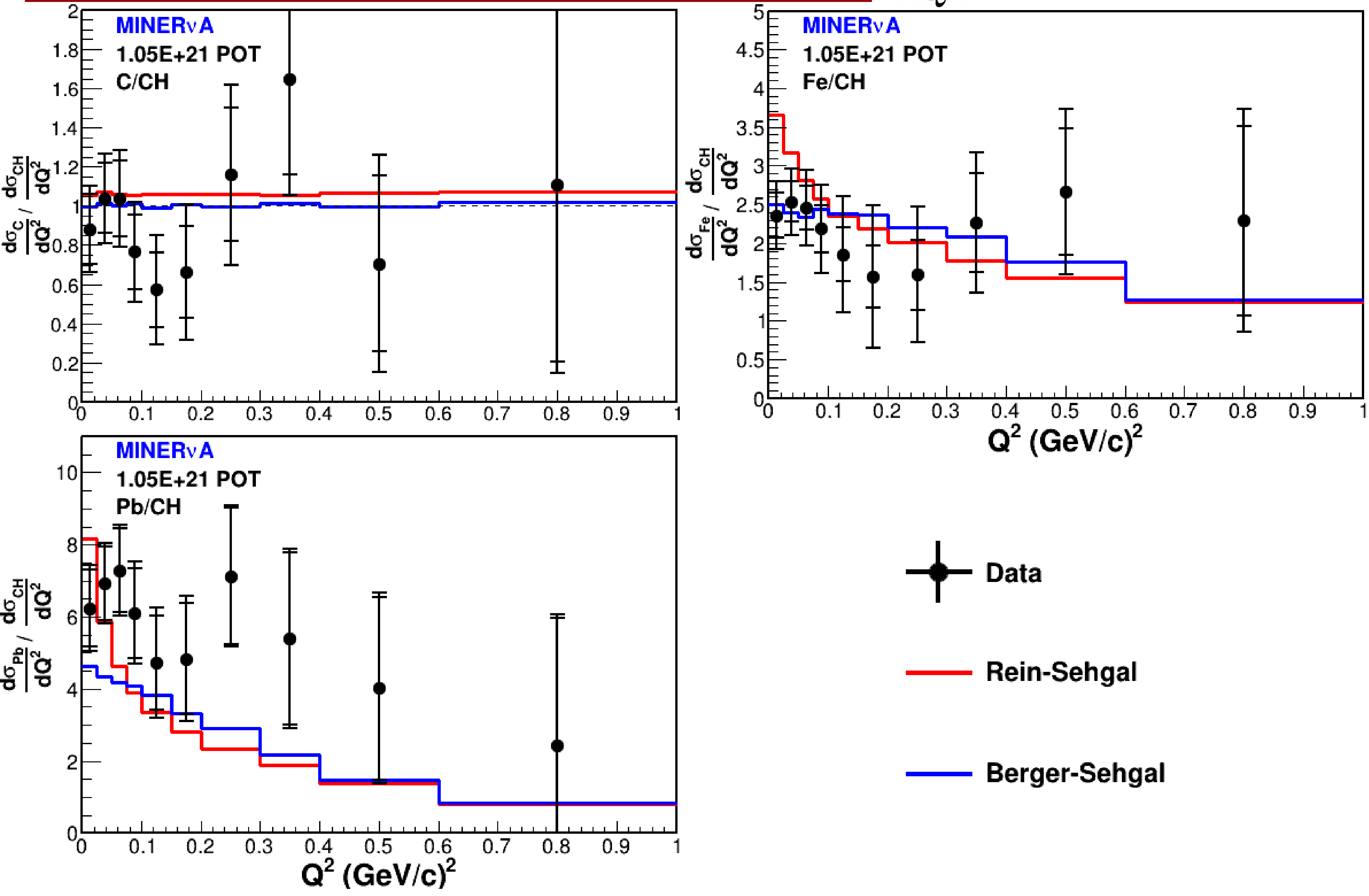
Backup – Results – Cross Section Ratios

$$\frac{d\sigma}{dE_\pi}$$



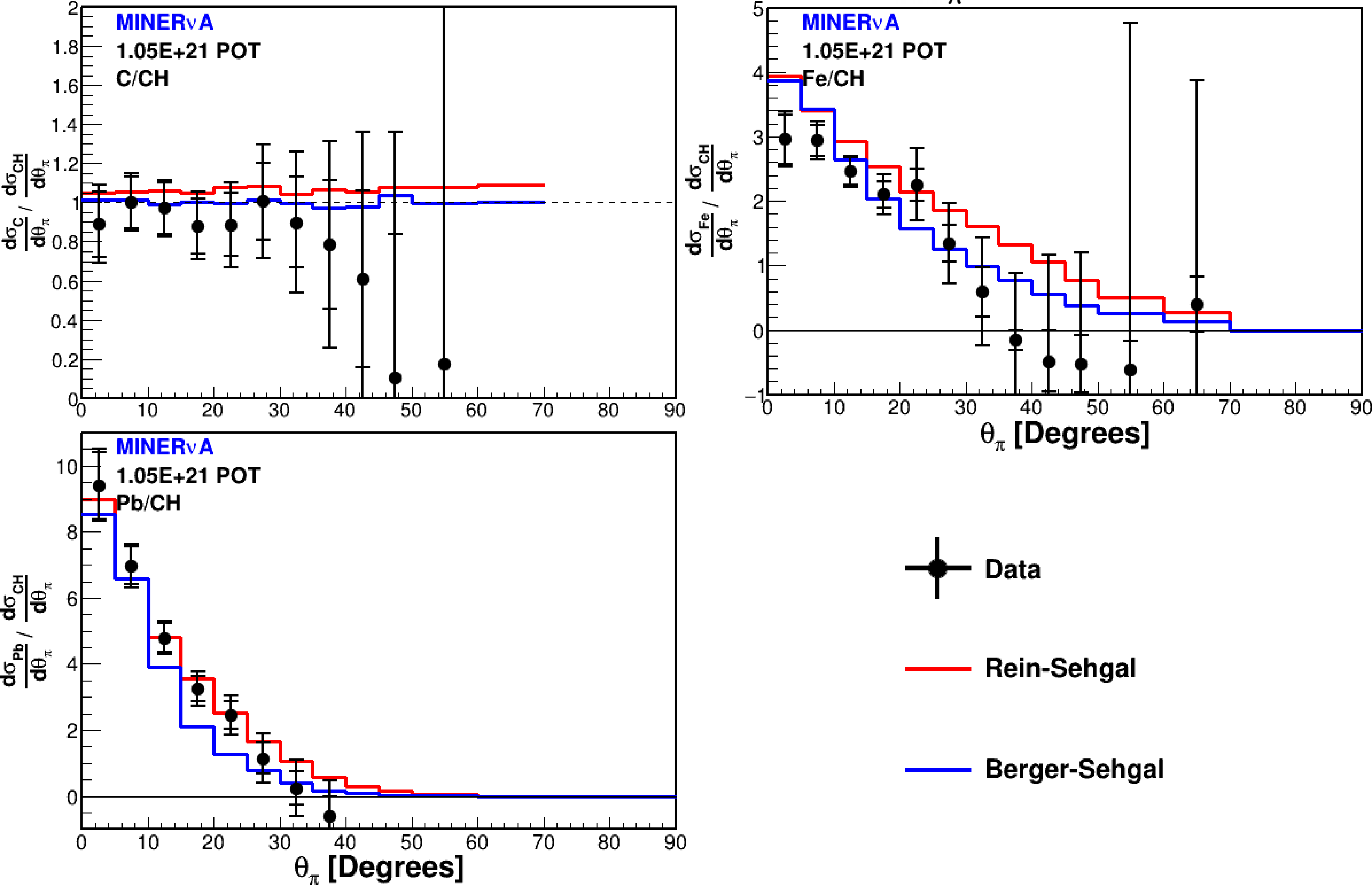
Backup – Results – Cross Section Ratios

$$\frac{d\sigma}{dQ^2}$$



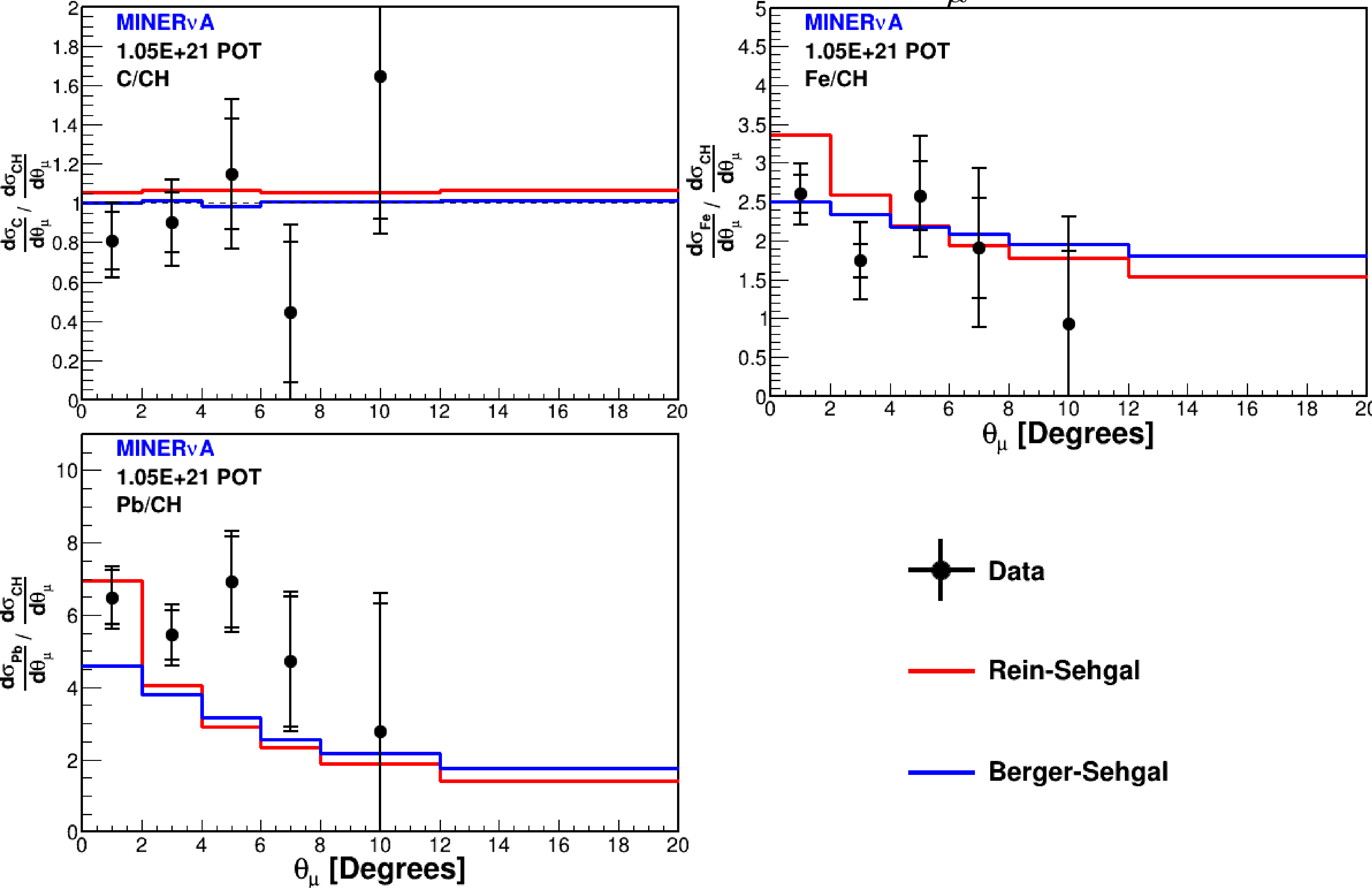
Backup – Results – Cross Section Ratios

$$\frac{d\sigma}{d\theta_\pi}$$



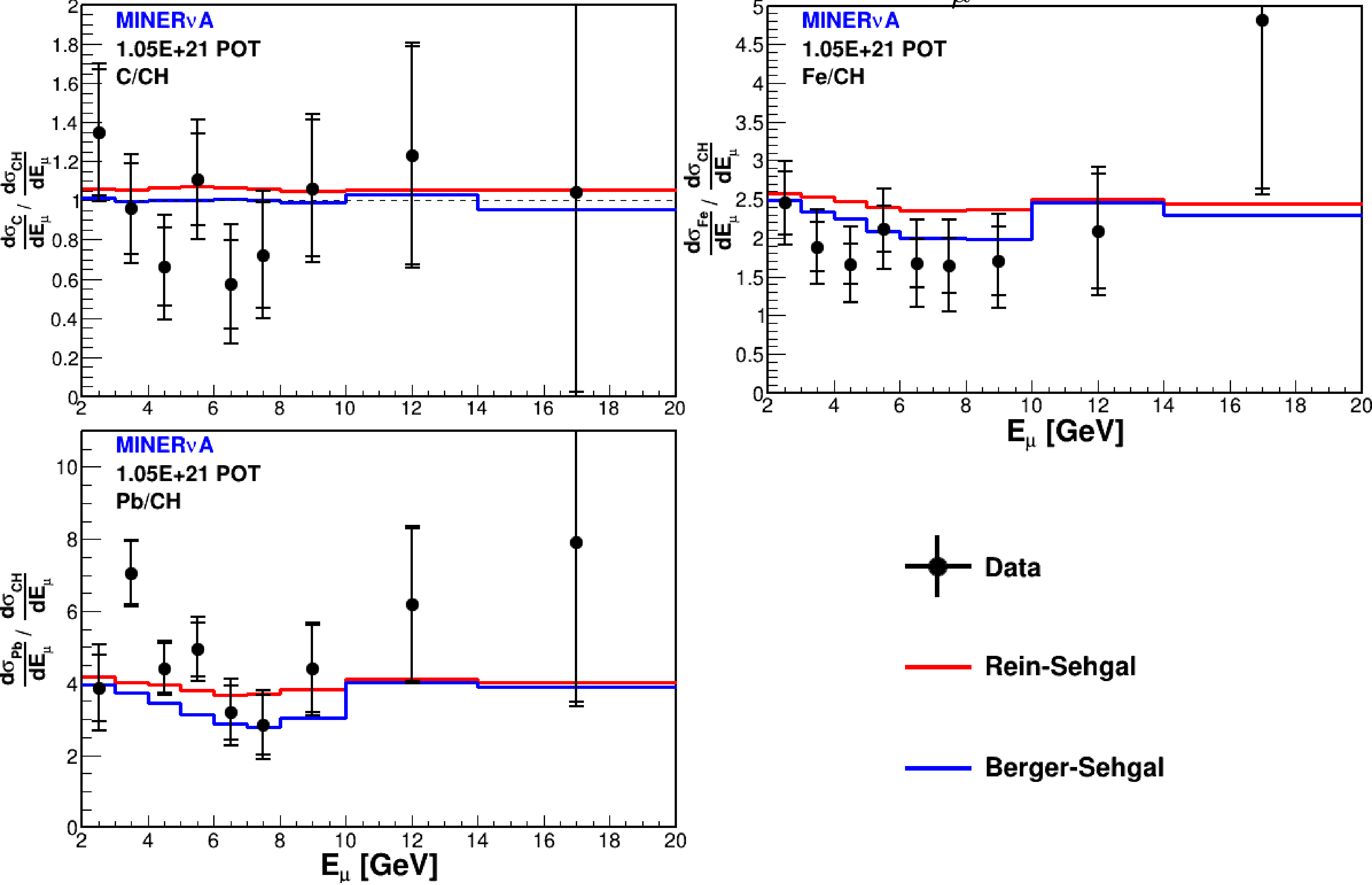
Backup – Results – Cross Section Ratios

$$\frac{d\sigma}{d\theta_\mu}$$



Backup – Results – Cross Section Ratios

$$\frac{d\sigma}{dE_\mu}$$



Backup – Coherent Models

The Rein-Sehgal Model

- It extrapolates the CC cross section

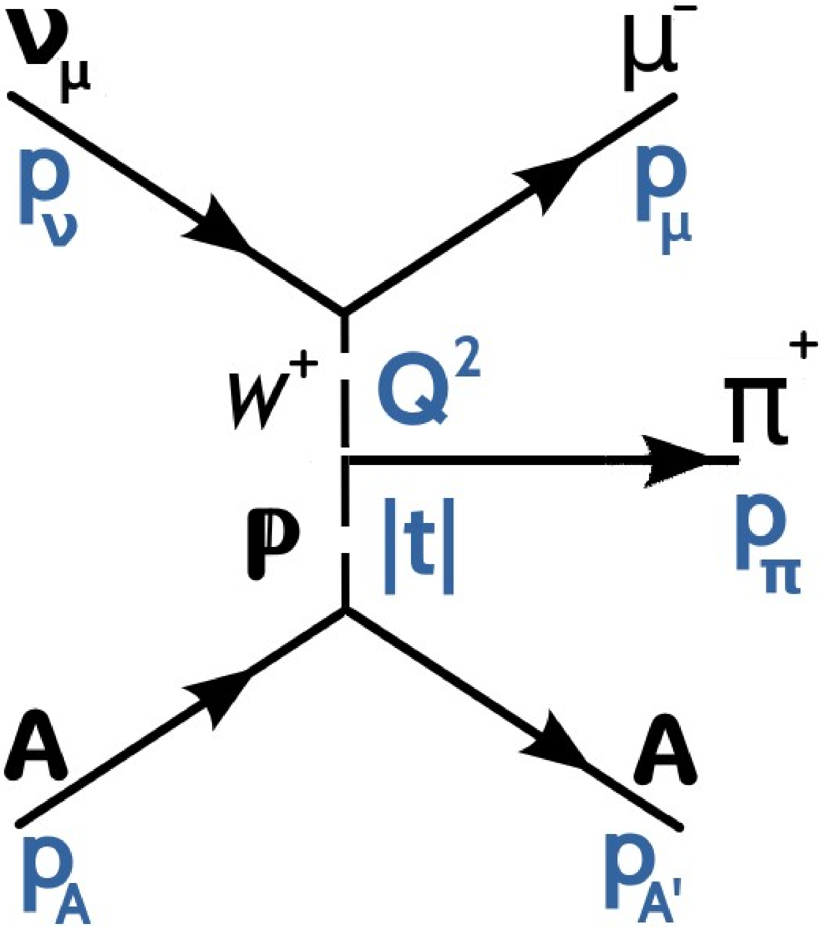
$$\left.\frac{d^3\sigma^{CC}_{coh}}{dQ^2dyd|t|}\right|_{Q^2=0} = \frac{G_F^2 f_\pi^2}{2\pi^2}\frac{1-y}{y}\frac{d\sigma^{\pi^\pm A}}{d|t|}$$

to **$Q^2 > 0$**

- Using a form factor

$$\left[m_A^2/\left(m_A^2+Q^2\right)\right]^2$$

- Pion-nucleus scattering is modeled using pion-nucleon data.



Backup – Coherent Models

Other Models

Berger-Sehgal (B-S) **[Phys.Rev. D79, 053003 (2009)]**

- It uses π-carbon data for the π+A → π+A scattering.
- It predicts lower cross section at low P_π (see figure).
- Includes lepton mass

Belkov-Kopeliovich (B-K) **[Sov.J.Nucl.Phys. 46 (1987) 499]**

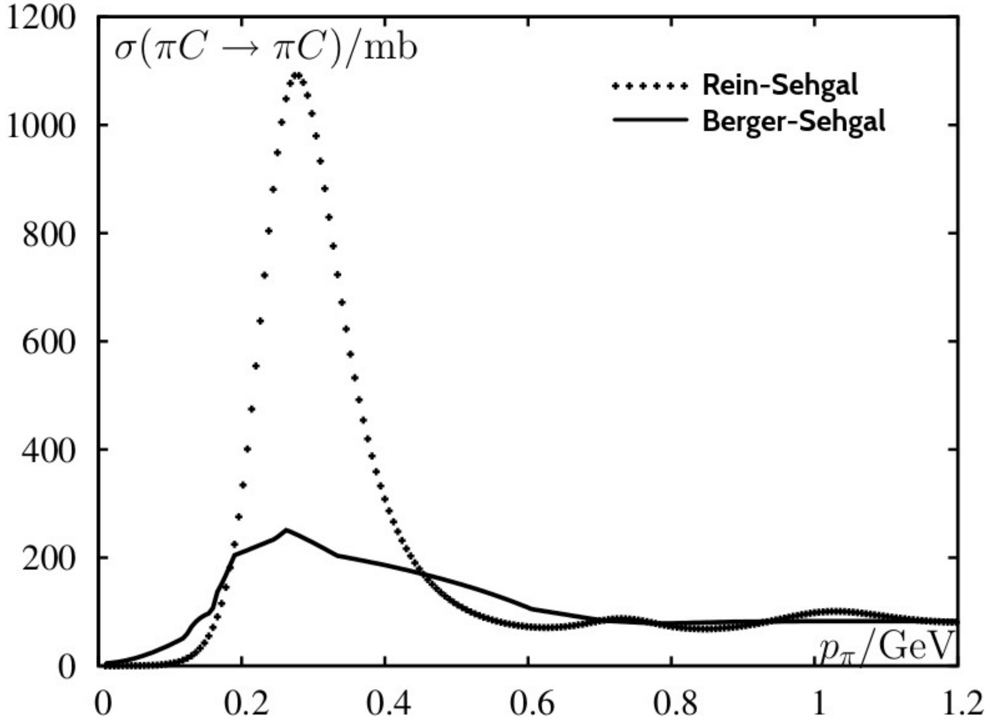
- Axial current dominated by heavy meson fluctuations, $\mathbf{a}_1$ or $\boldsymbol{\rho\pi}$ system.
- Predicts energy-dependent A-scaling of the cross section.

Paschos-Schalla (P-S) **[Phys.Rev. D80, 033005 (2009)]**

- Similar to B-S. It also uses π-carbon data for the π+A elastic scattering.
- Focuses on $Q^2 < 0.1$ GeV^2 region, also including the lepton mass.

Microscopic Models (M-M) **[Phys.Rev. C75, 055501 (2007)]**

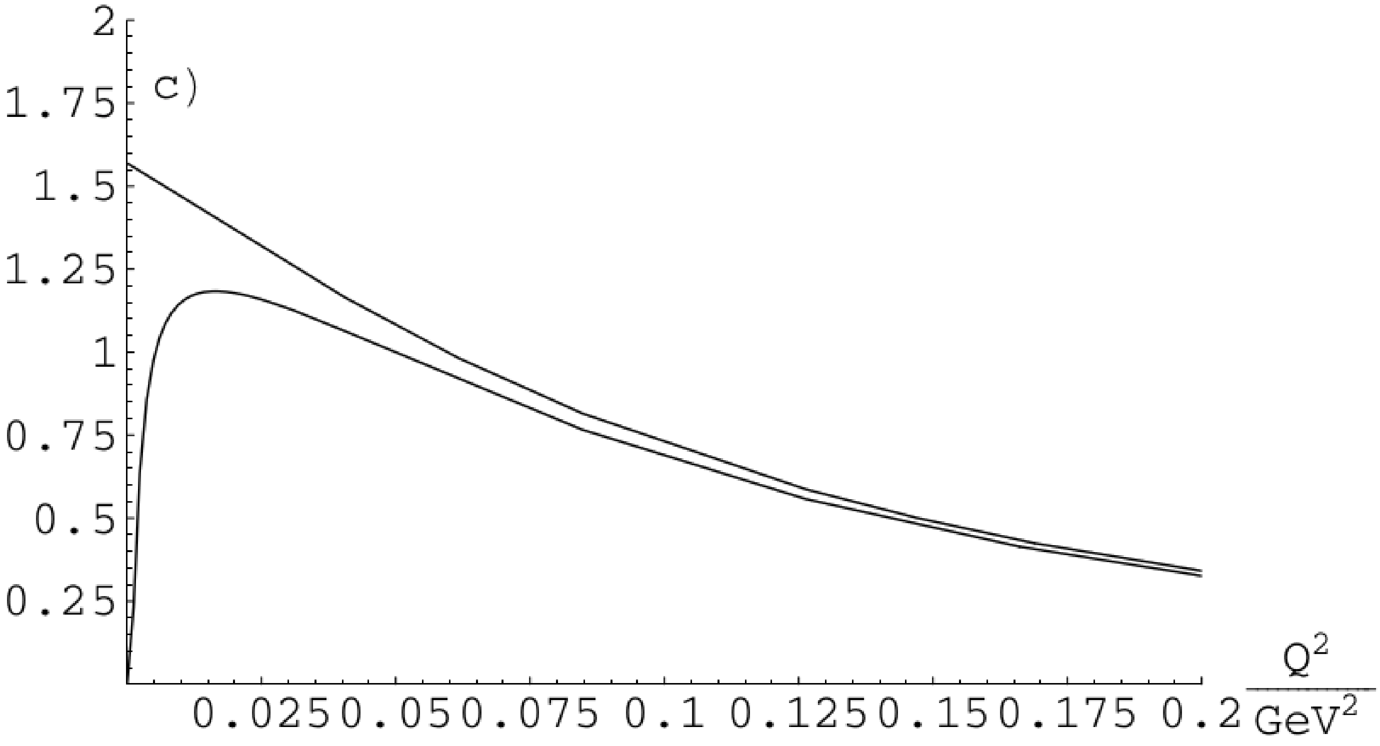
- Consider the individual contribution of nucleons to the cross section. π production obtained through baryon Δ resonances.
- Valid for Eν < 2 GeV.



Elastic pion-Carbon cross section.
Berger-Sehgal vs Rein-Sehgal predictions

Lepton Mass in the R-S Model

Suppression of the CC cross section on carbon for $Q^2 < 0.1$ [GeV/c]^2 and $E_\nu = 2.0$ GeV. The upper (lower) distribution corresponds to the cross section without (with) the lepton mass correction.



Backup – Summary of All NC and CC Coherent π^+

MINERvA will also be adding **Fe** and **Pb** to the literature!

EXPERIMENT	**YEAR**	**BEAM**	$< E_{\nu(\bar{\nu})} >$, **range** $[GeV]$	**MATERIAL**	$< A >$
NC					
Aachen-Padova	1983	$\nu/\bar{\nu}$	2	Al	27
Garmamelle	1984	$\nu/\bar{\nu}$	2	CF_3Br (Freon)	36
SKAT	1985	$\nu/\bar{\nu}$	7	CF_3Br (Freon)	36
CHARM	1985	$\nu/\bar{\nu}$	31 (24)	$CaCO_3$ (Marble)	20
15' BC	1986	ν	20	NeH_2	20
MiniBooNE	2008	ν	0.7	CH_2	12
NOMAD	2009	ν	24, 2.5-300	C	12.8
SciBooNE	2010	ν	0.8	C	12

EXPERIMENT	**YEAR**	**BEAM**	$< E_{\nu(\bar{\nu})} >$, **range** $[GeV]$	**MATERIAL**	$< A >$
CC					
WA59	1984	$\bar{\nu}$	40	NeH_2	20
SKAT	1986	$\nu/\bar{\nu}$	7	CF_3Br (Freon)	36
BEBC WA59	1986	$\bar{\nu}$	5-150	Ne	20
E632	1989	$\nu/\bar{\nu}$	150 (110)	Ne	20
BEBC WA59	1989	ν	5-150	Ne	20
CHARM II	1993	$\nu/\bar{\nu}$	20	Glass	20.7
E632	1993	$\nu/\bar{\nu}$	80 (70)	Ne	20
K2K	2005	ν	1.3	C	12
SciBooNE	2009	ν	1.1	C	12
MINERvA (LE)	2014	$\nu/\bar{\nu}$	3.6	C	12
ArgoNeuT	2015	$\nu/\bar{\nu}$	9.6 (3.6)	Ar	40
T2K	2016	ν	< 1.5	C	12
MINERvA (ME)	2022	ν	6	C, **Fe**, **Pb**	12, **56**, **207**