First Direct Measurement of Nuclear Dependence of Coherent Pion Production

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Joint Experimental-Theoretical Physics Seminar

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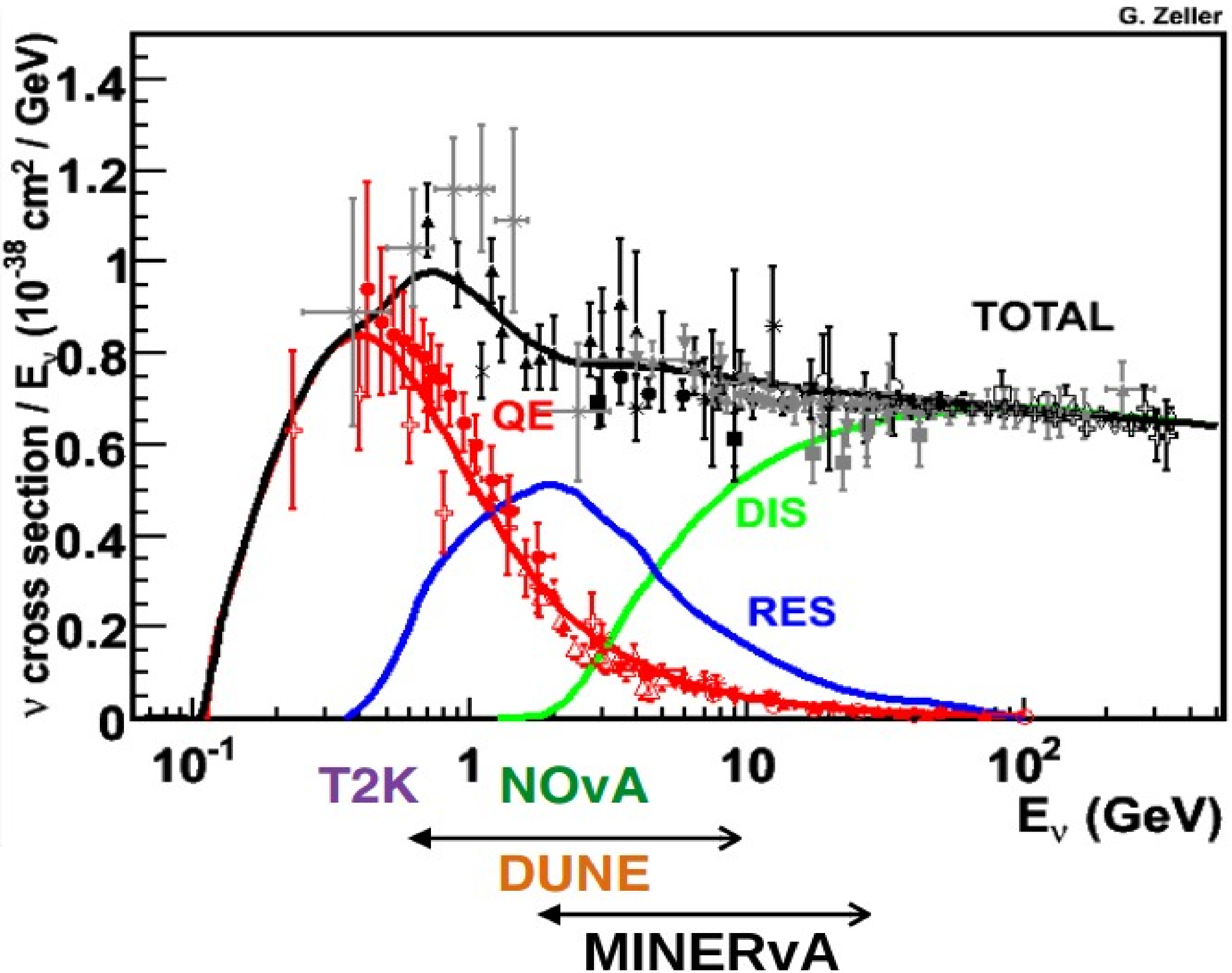
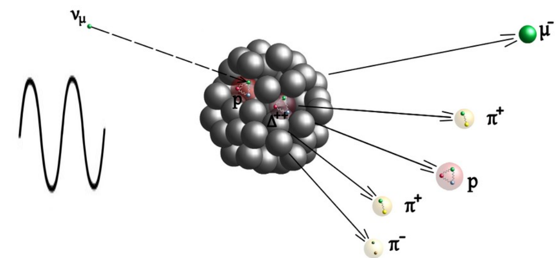
1 – Neutrino Interactions (Briefly)

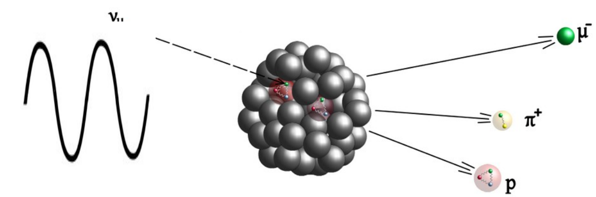
Types of Neutrino Interactions



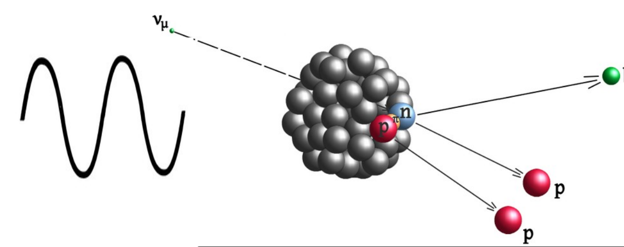
J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)



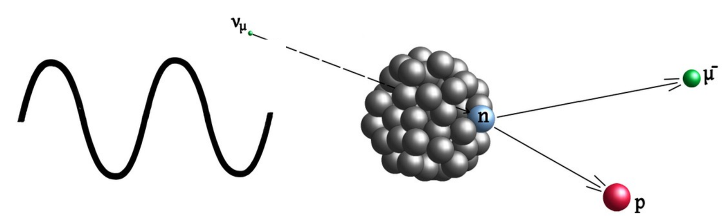
Deep Inelastic Scattering



Resonant Pion Production



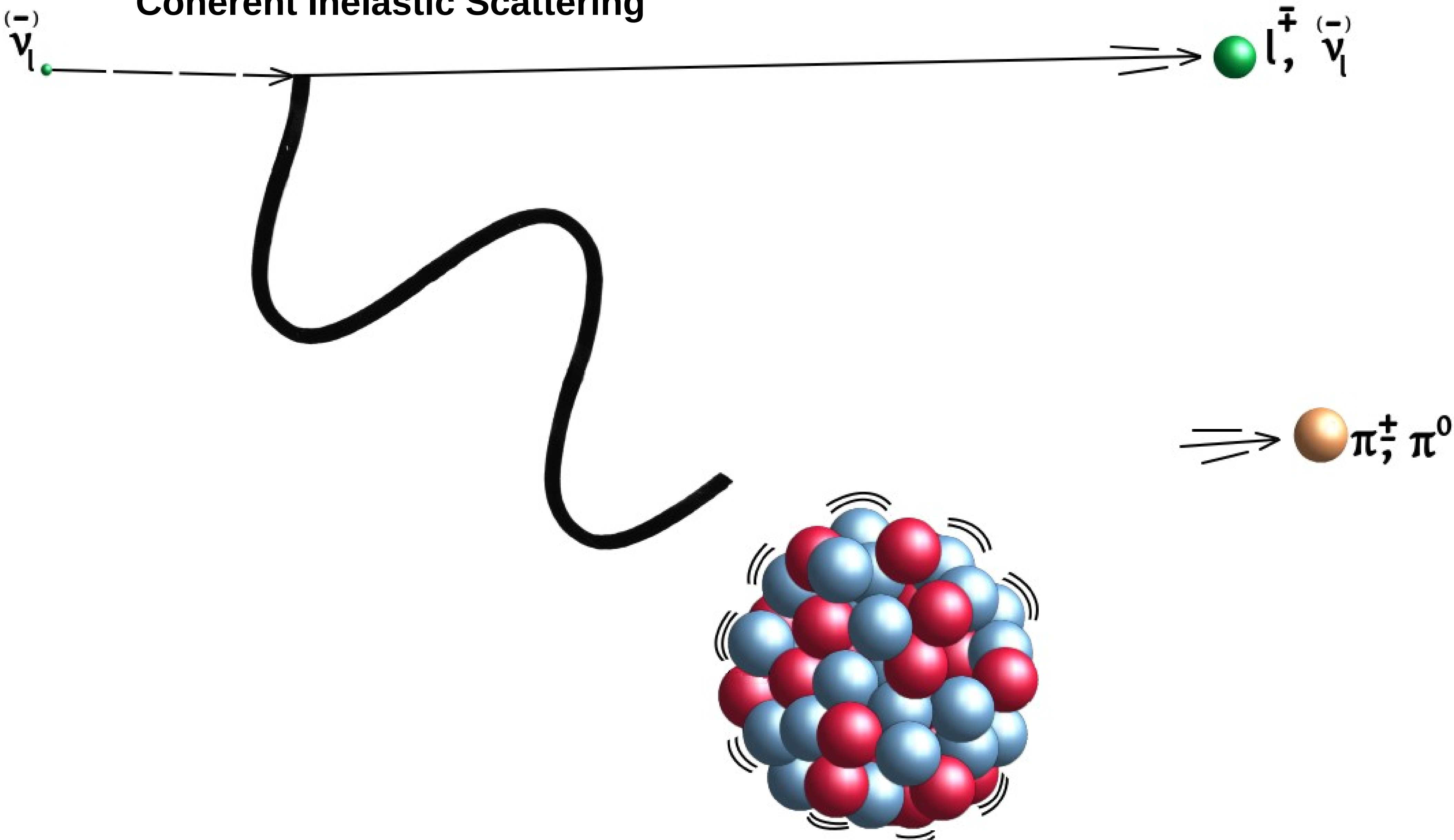
2p2h Scattering



Quasielastic Scattering

Neutrino Interactions (Briefly)

Coherent Inelastic Scattering

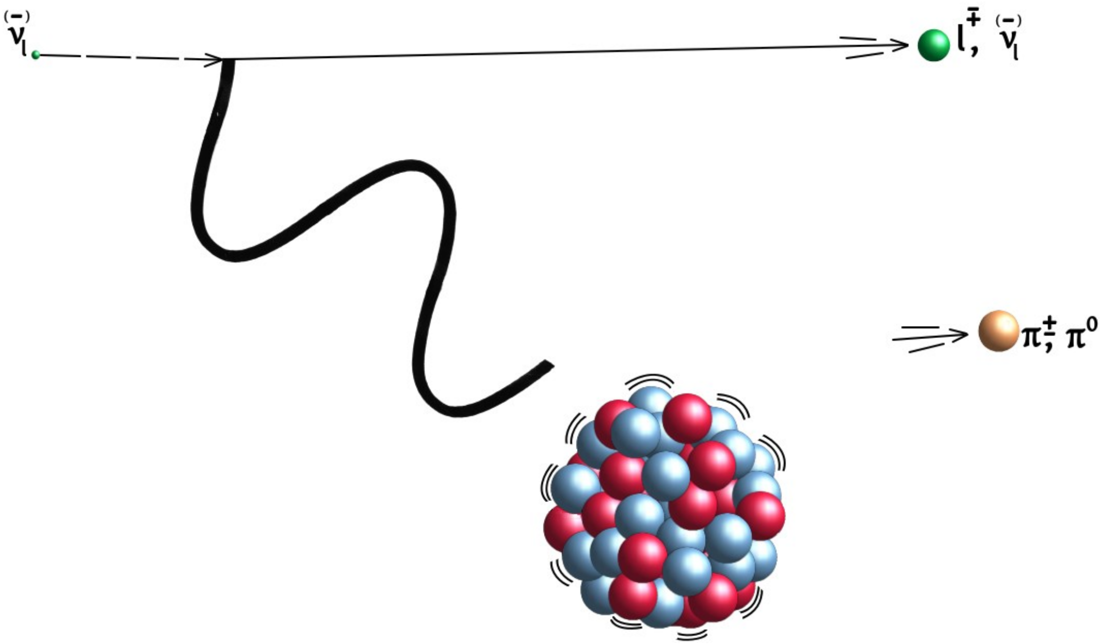


If wavelength (momentum) is long (small) enough...

2 - What Is Coherent Pion Production?

Features

- 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**|

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

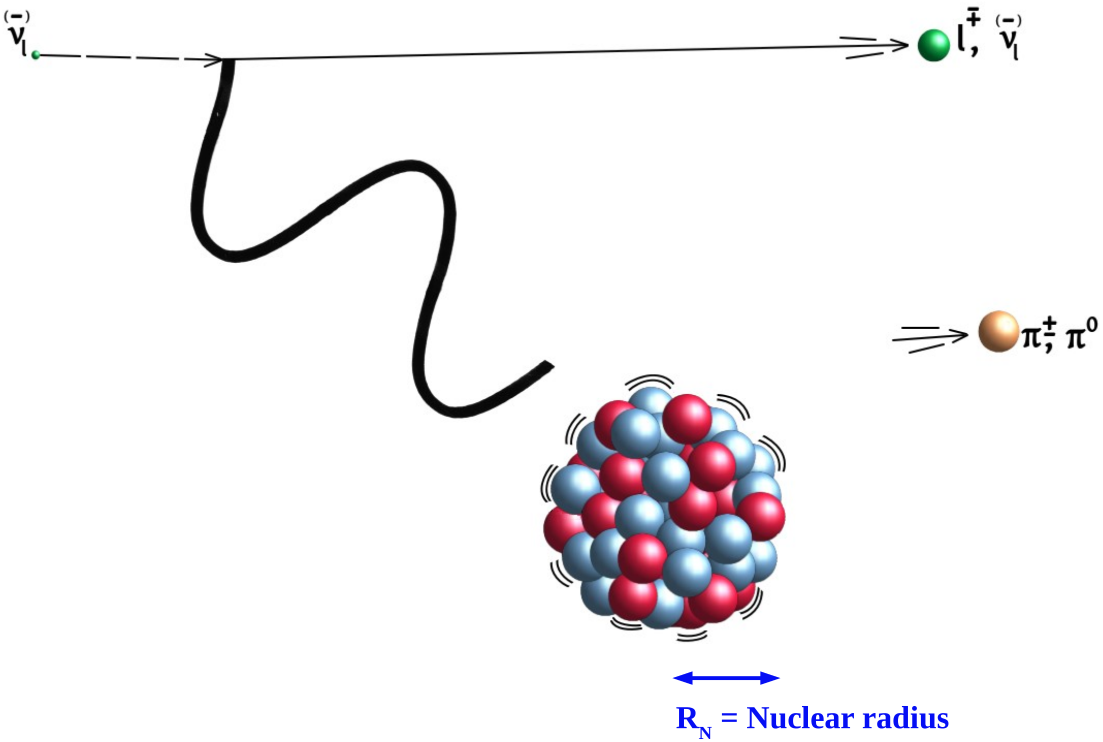
- There is a threshold $|\mathbf{t}_{\mathbf{min}}|$

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

- and a maximum $|\mathbf{t}_{\mathbf{max}}|$

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

within which the interaction takes place.



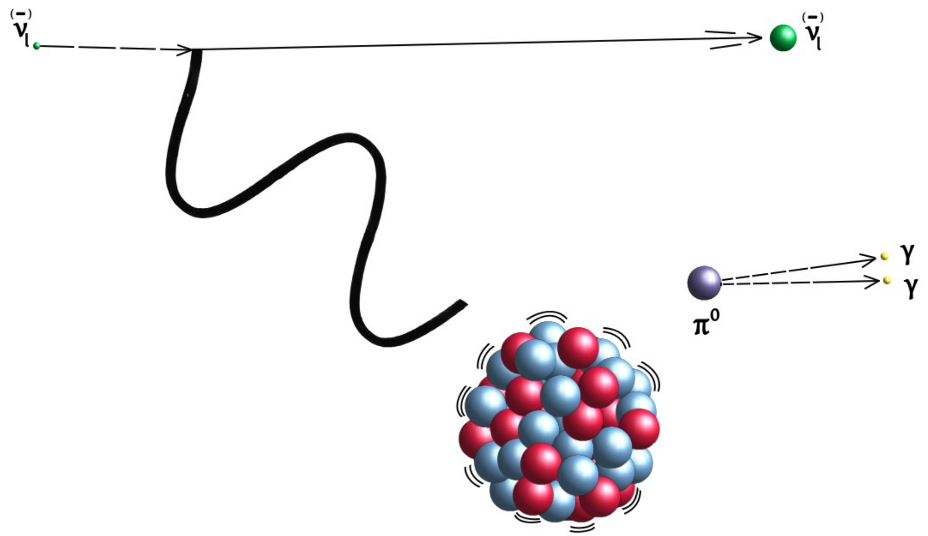
What Is Coherent Pion Production?

Topologies

NC Channel

$$\overset{(-)}{\nu}_l + A \rightarrow \overset{(-)}{\nu}_l + \pi^0 + A$$

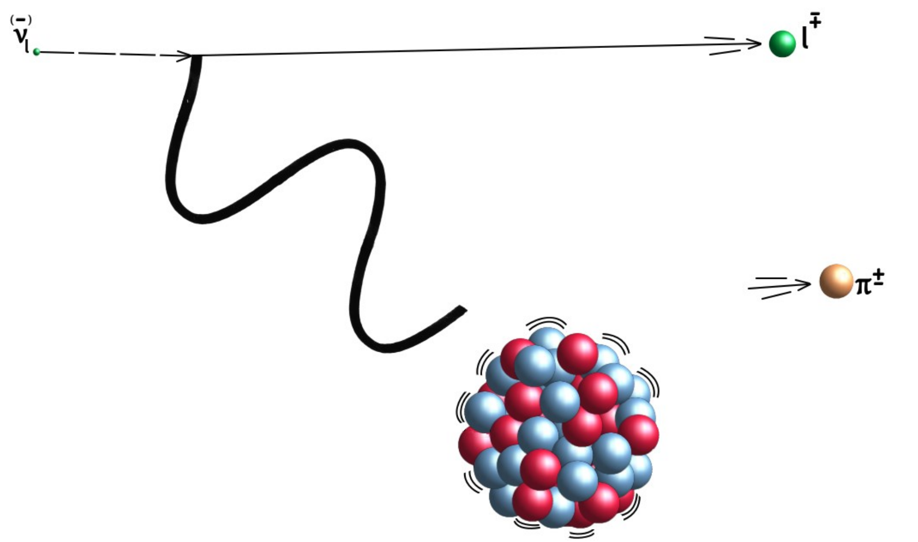
- Two forward gammas from the prompt decay of the neutral pi.



CC Channel

$$\overset{(-)}{\nu}_l + A \rightarrow l^{\mp} + \pi^{\pm} + A$$

- A forward charged lepton and a forward charged pi from the interaction vertex.

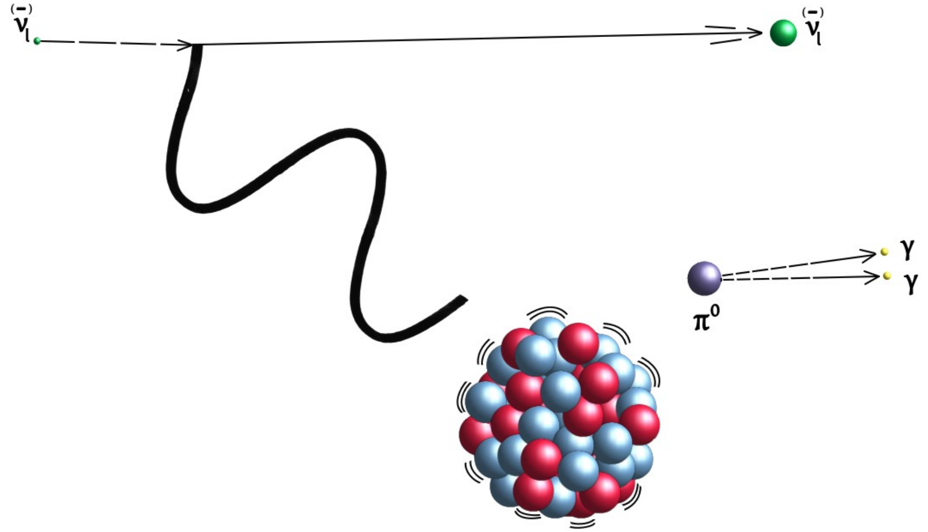


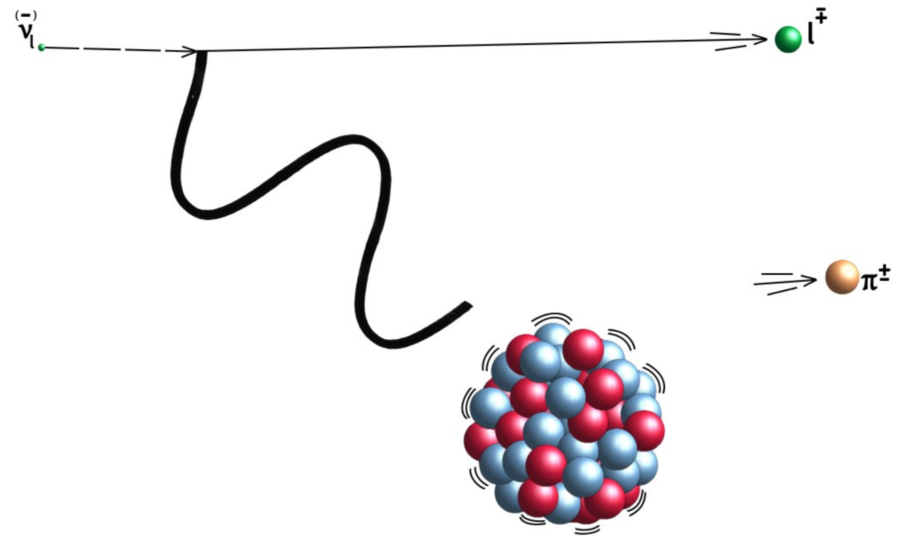
What Is Coherent Pion Production?

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

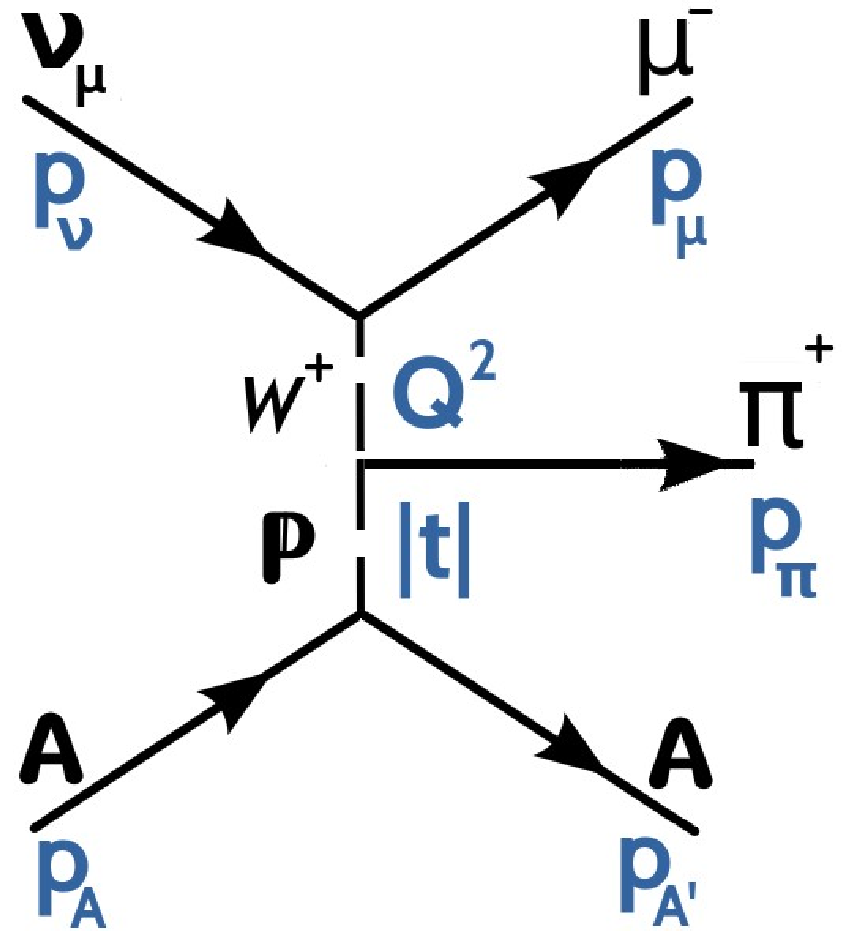
- Uses **Adler's theorem** to relate the inelastic process

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

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.



What Is Coherent Pion Production?

The Rein-Sehgal Model

- It extrapolates the CC cross section

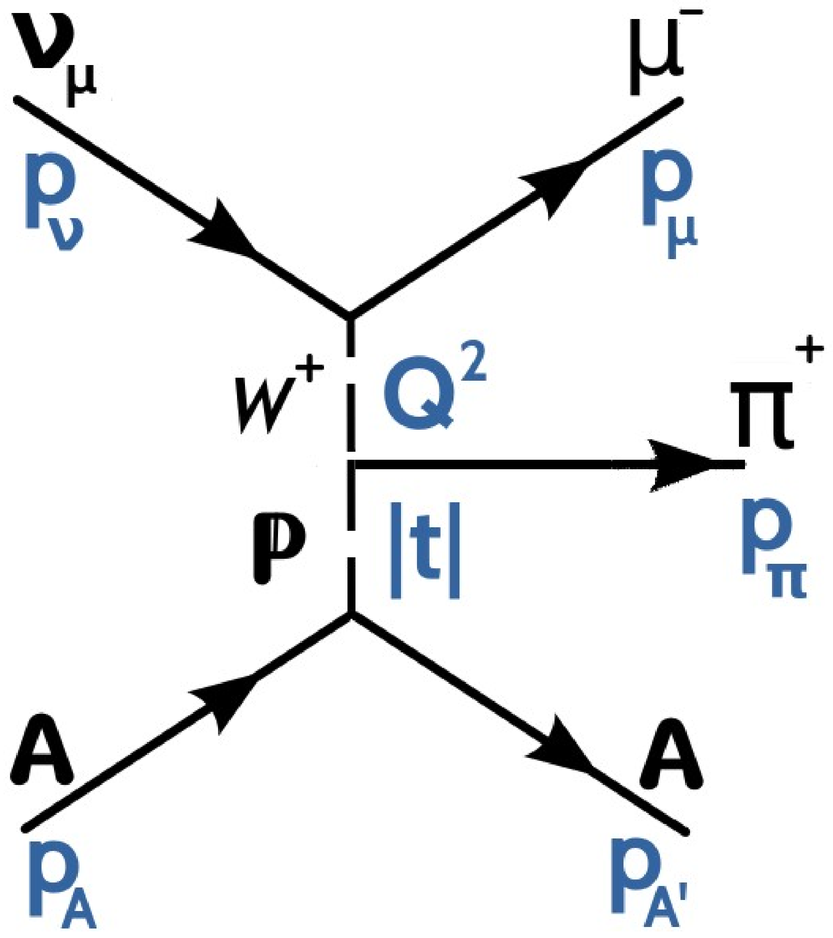
$$\left.\frac{d^3\sigma^{CC}_{coh}}{dQ^2 dy d|t|}\right|_{Q^2=0} = \frac{G_F^2 f_\pi^2}{2\pi^2}\frac{1-y}{y}\frac{d\sigma^{\pi^\pm A}}{d|t|}$$

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.



What Is Coherent Pion Production?

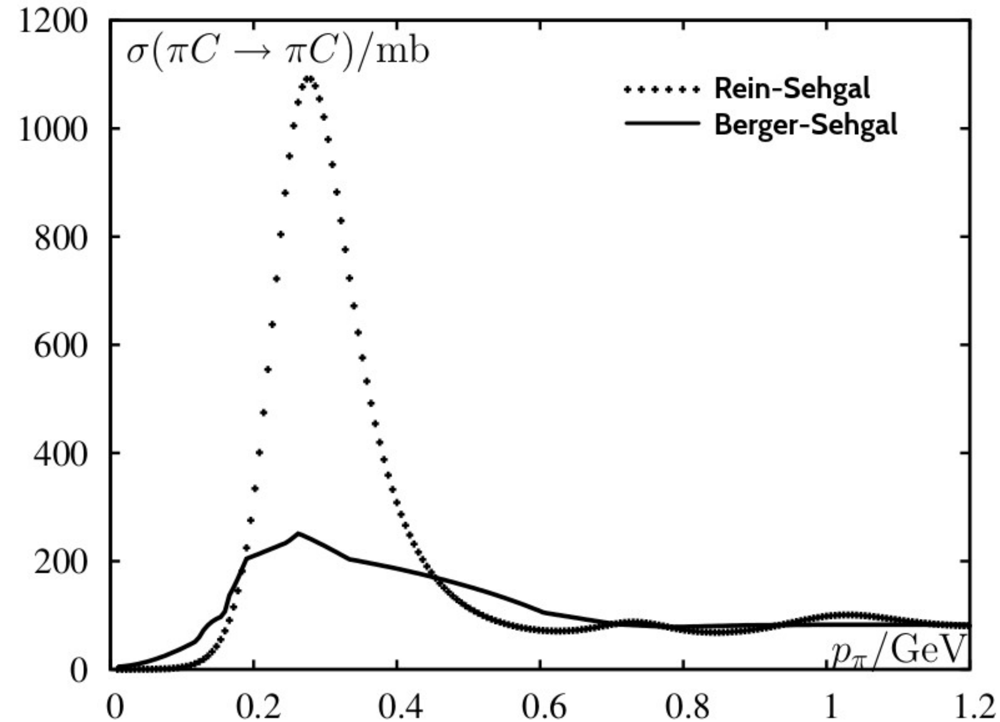
Other Models

Berger-Sehgal (B-S) **[Phys.Rev. D79, 053003 (2009)]**
- It uses π-carbon data for the π+A → π+A scattering.
- Includes lepton mass

Belkov-Kopeliovich (B-K) **[Sov.J.Nucl.Phys. 46 (1987) 499]**
- Predicts energy-dependent A-scaling of the cross section.

Paschos-Schalla (P-S) **[Phys.Rev. D80, 033005 (2009)]**
- Focuses on $Q^2 < 0.1\ \mathrm{GeV}^2$ region, also including the lepton mass.

Microscopic Models (M-M) **[Phys.Rev. C75, 055501 (2007)]**
- π production obtained through baryon Δ resonances.
- Valid for Eν < 2 GeV.



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

3 – High Eν Measurements

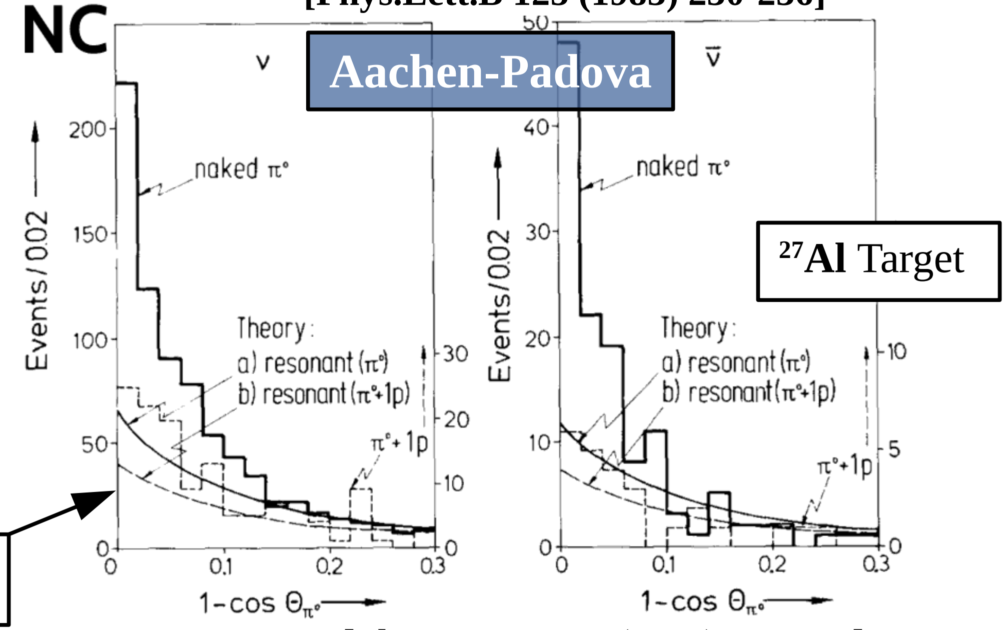
Purpose

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

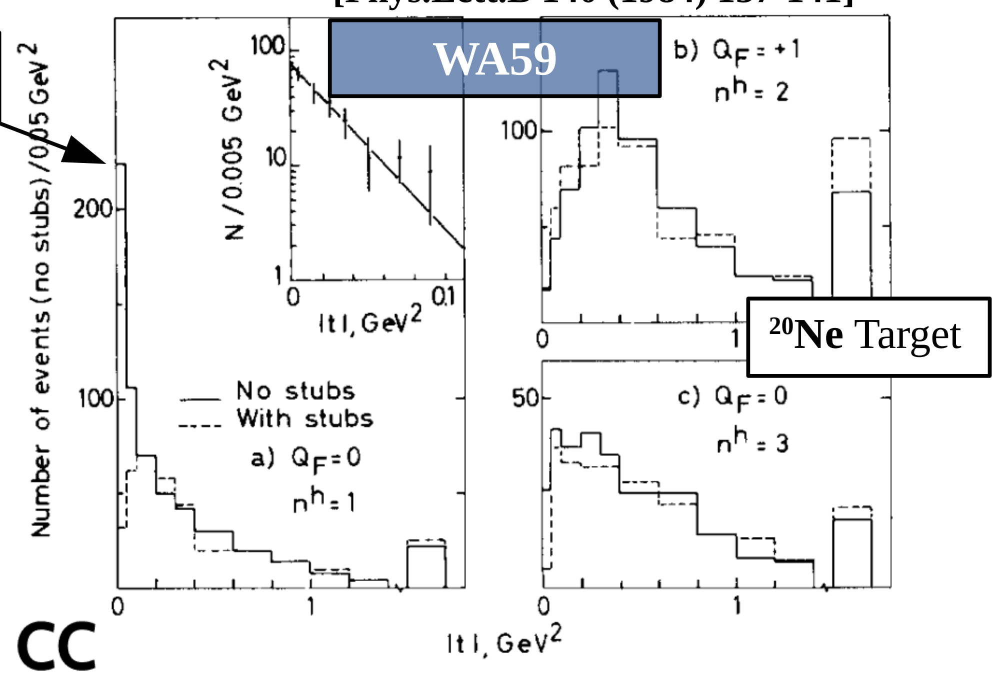
First NC Measurement

First CC Measurement

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



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



High Eν Measurements

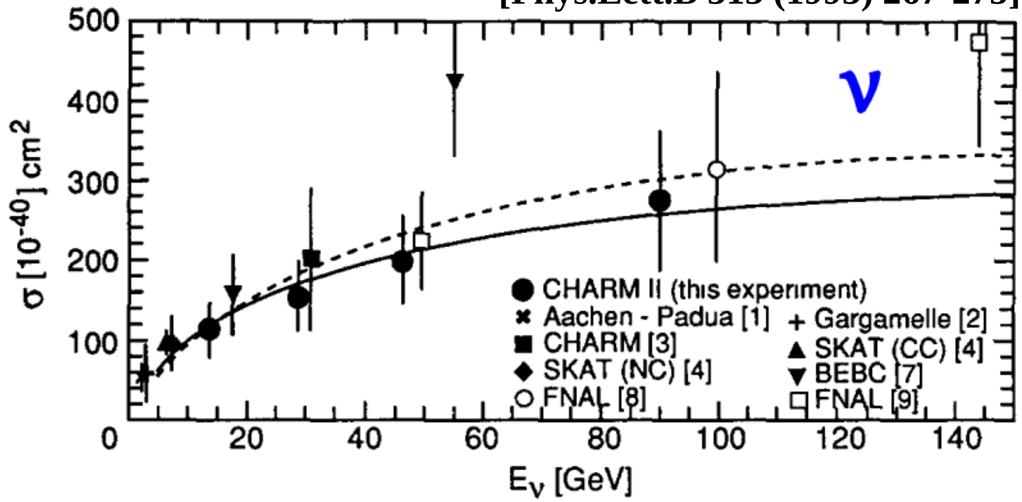
[Phys.Lett.B 313 (1993) 267-275]

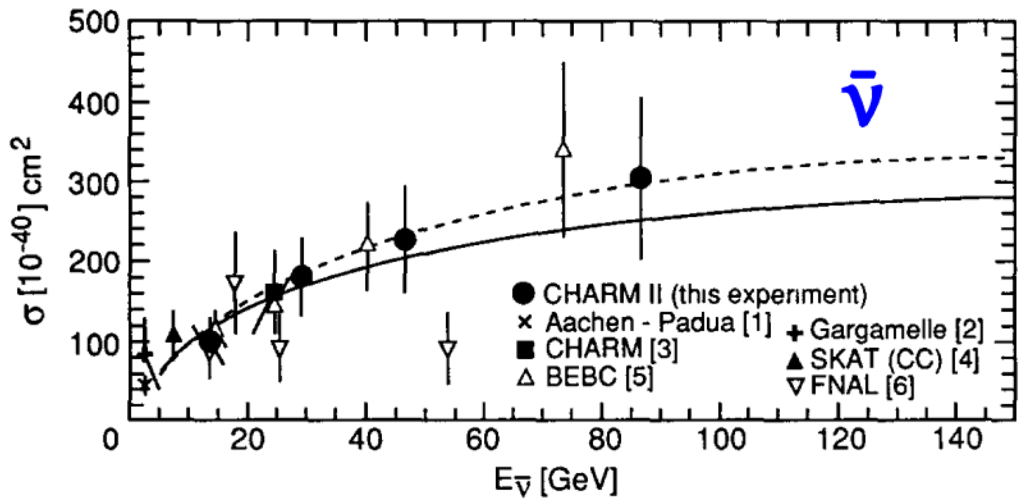
NC Measurements

- E_ν range: **~2 to ~300 GeV**
- *A* (nuclear mass) range: **^{12}C to ^{80}Br**
- ν modes: ν_μ and $\overline{\nu}_\mu$
- Signature of coherence: **1-Cos θ_π**

CC Measurements

- E_ν range: **~5 to ~300 GeV**
- *A* (nuclear mass) range: **^{12}C to ^{80}Br**
- ν modes: ν_μ and $\overline{\nu}_\mu$
- Signature of coherence: **|t|**





CC and NC Interactions:

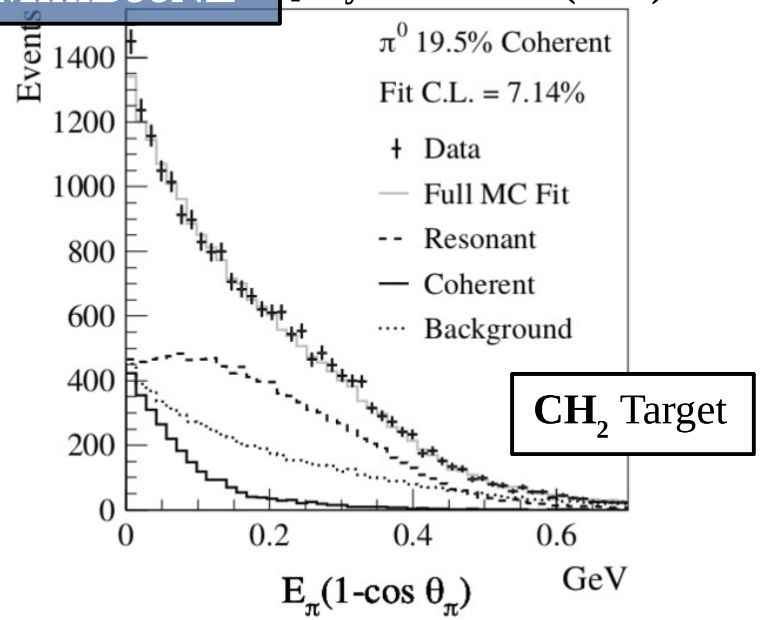
- Observed across different materials.
- In a wide range of neutrino energies.
- In both neutrino and anti-neutrino modes.

4 – Low Eν Measurements

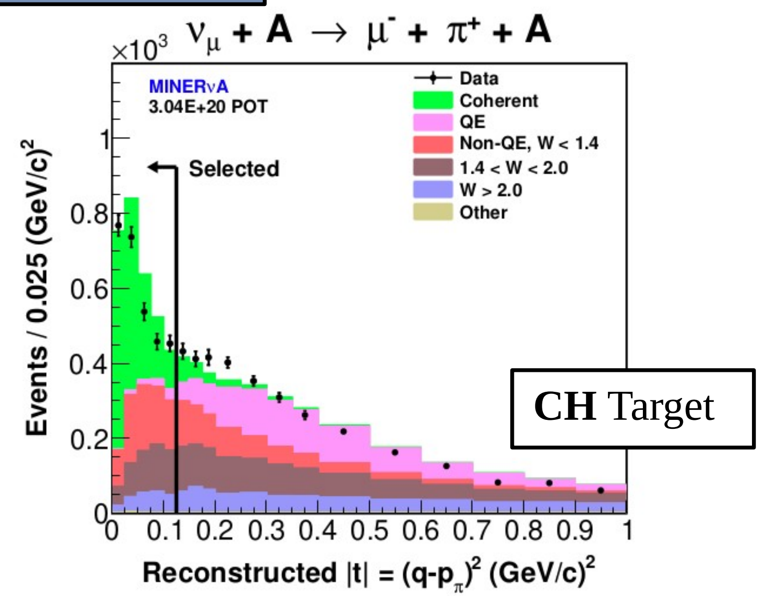
Purpose

- 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_ν < 2 GeV (NC).
- Proof of existence at E_ν < 5 GeV (CC).
- Most used model was also the one by Rein-Sehgal.

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



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



Low Eν Measurements

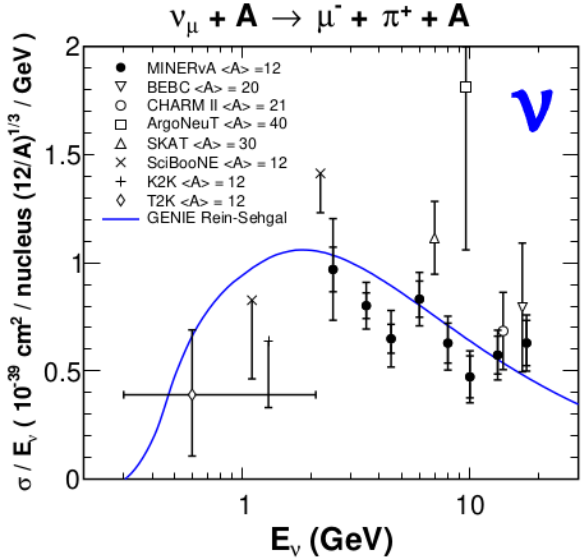
[Phys.Rev.D 97 (2018) 3, 032014]

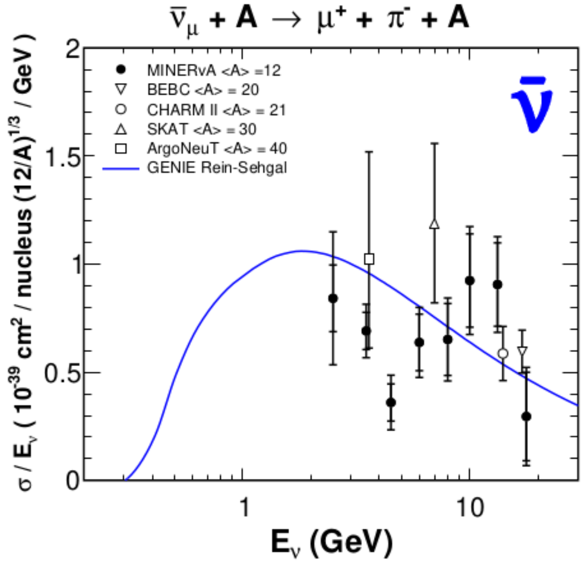
NC Measurements

- E_ν range: ~2 to ~300 GeV
- *A* (nuclear mass) range: **^{12}C only**.
- ν modes: ν_μ only
- Signature of coherence: **1-Cos θ_π**

CC Measurements

- E_ν range: ~1 to 9.6 GeV
- *A* range (nuclear mass) : **^{12}C to ^{40}Ar**
- ν modes: ν_μ and $\overline{\nu}_\mu$
- Signature of coherence: **|t|**





CC and NC Interactions:

- Observed across different materials.
- In a moderate range of neutrino energies.
- Anti-neutrino mode missing for NC channel.

5 – *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****:*

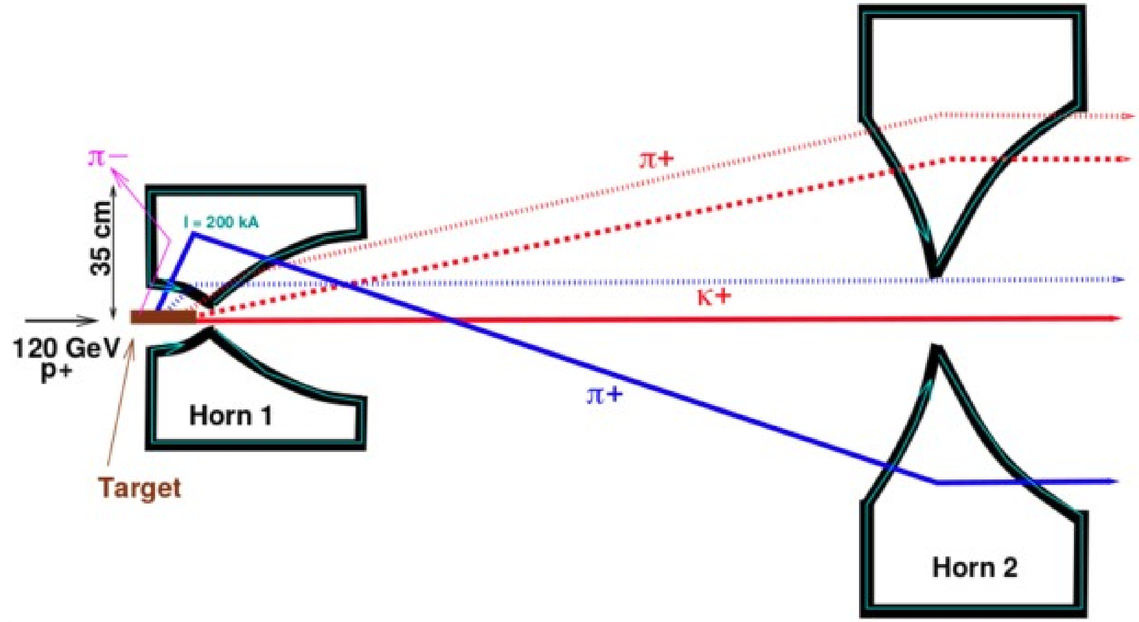
  - A set of models, like the **Rein-Sehgal** model, predict an ***A***-scaling as $A^{1/3}$.

  - Other models, like the **Berger-Sehgal** model, predict a ***A***-scaling as $A^{2/3}$.

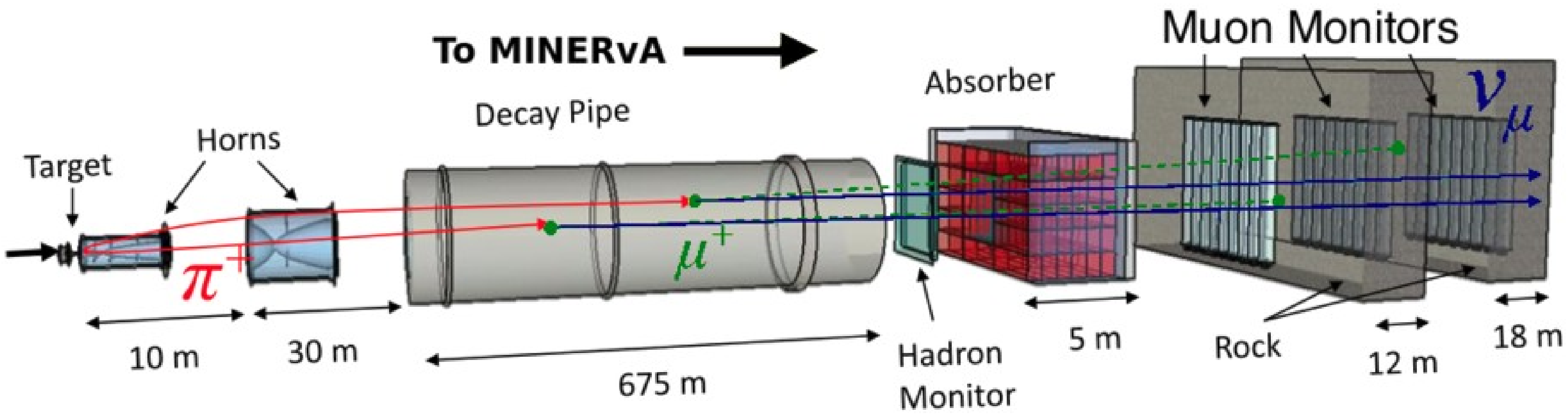
  - The **Belkov-Kopeliovich** model predicts an "energy-dependent" ***A***-scaling. Scaling as $A^{1/3}$ at **low E_ν** and as $A^{2/3}$ at **high E_ν**.

The NuMI Beam at FNAL

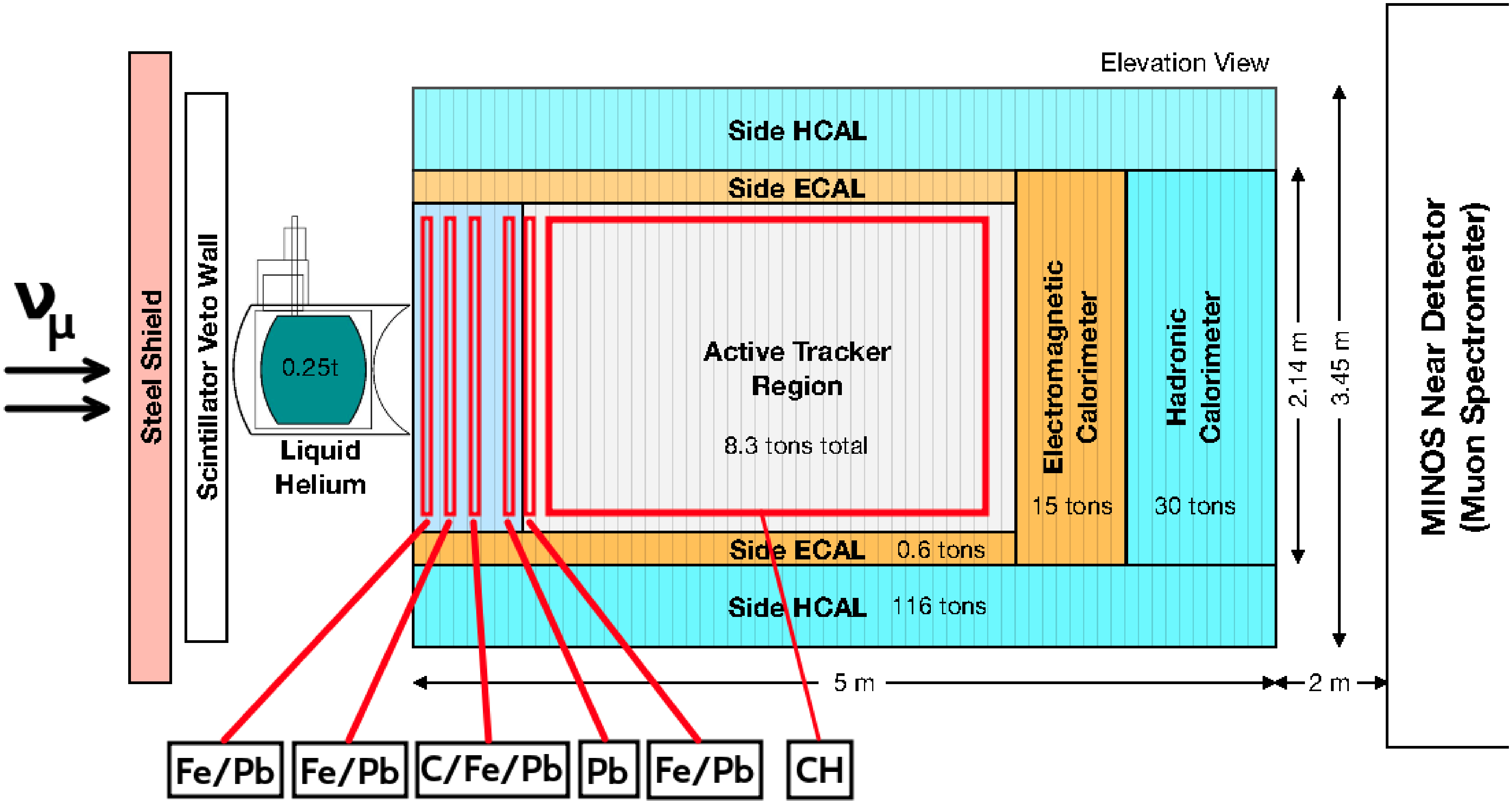
Horns



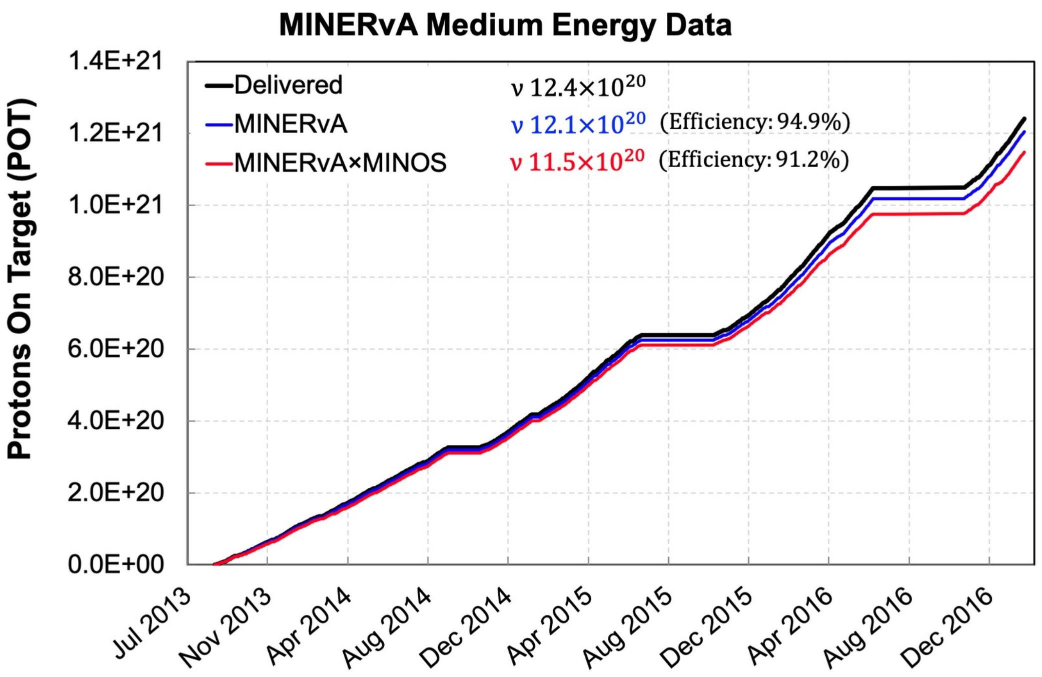
Beamline



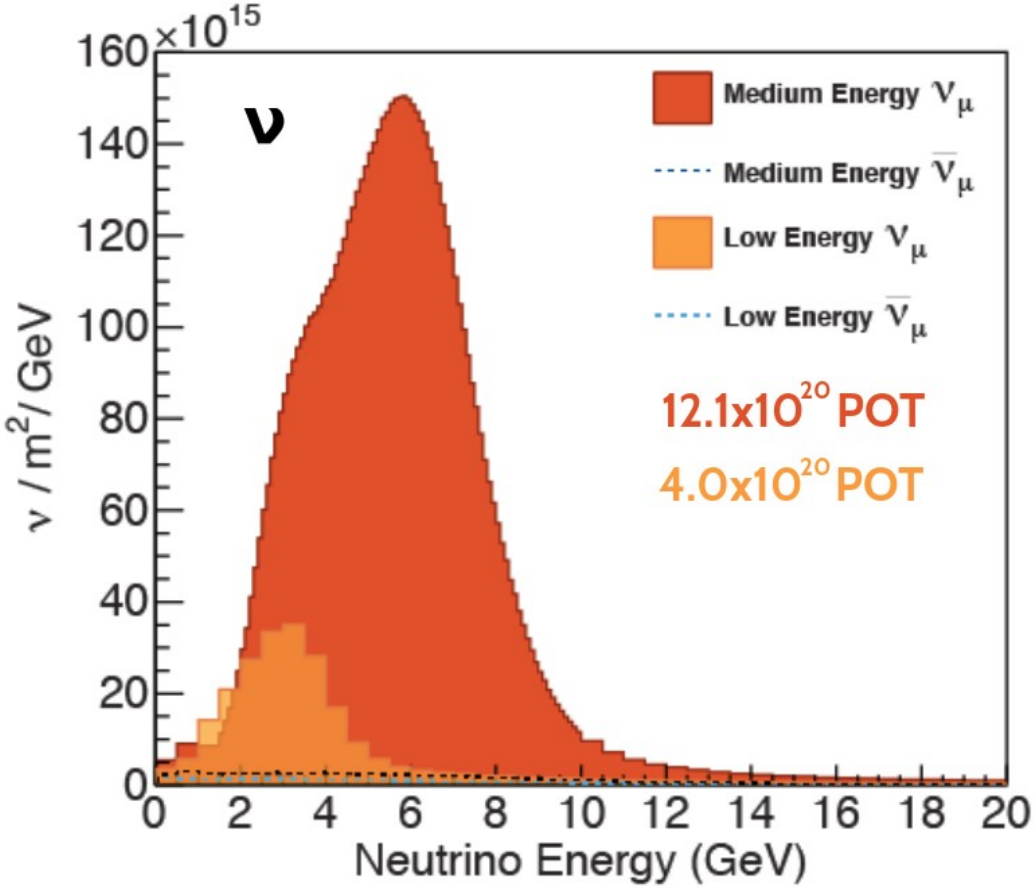
MINERvA Detector



ν_μ Data Set

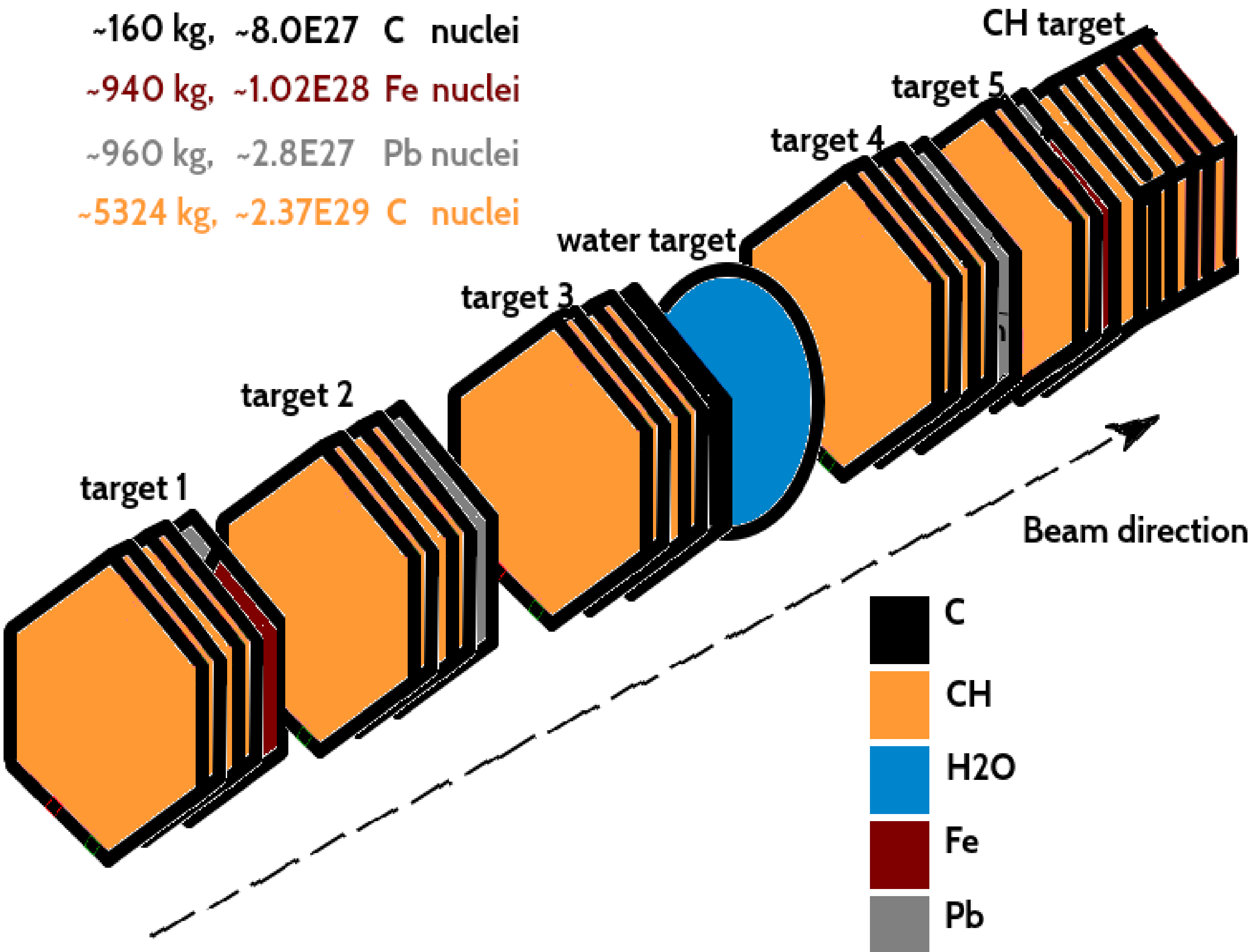


Thanks Accelerator Division for All the High Quality Beam!



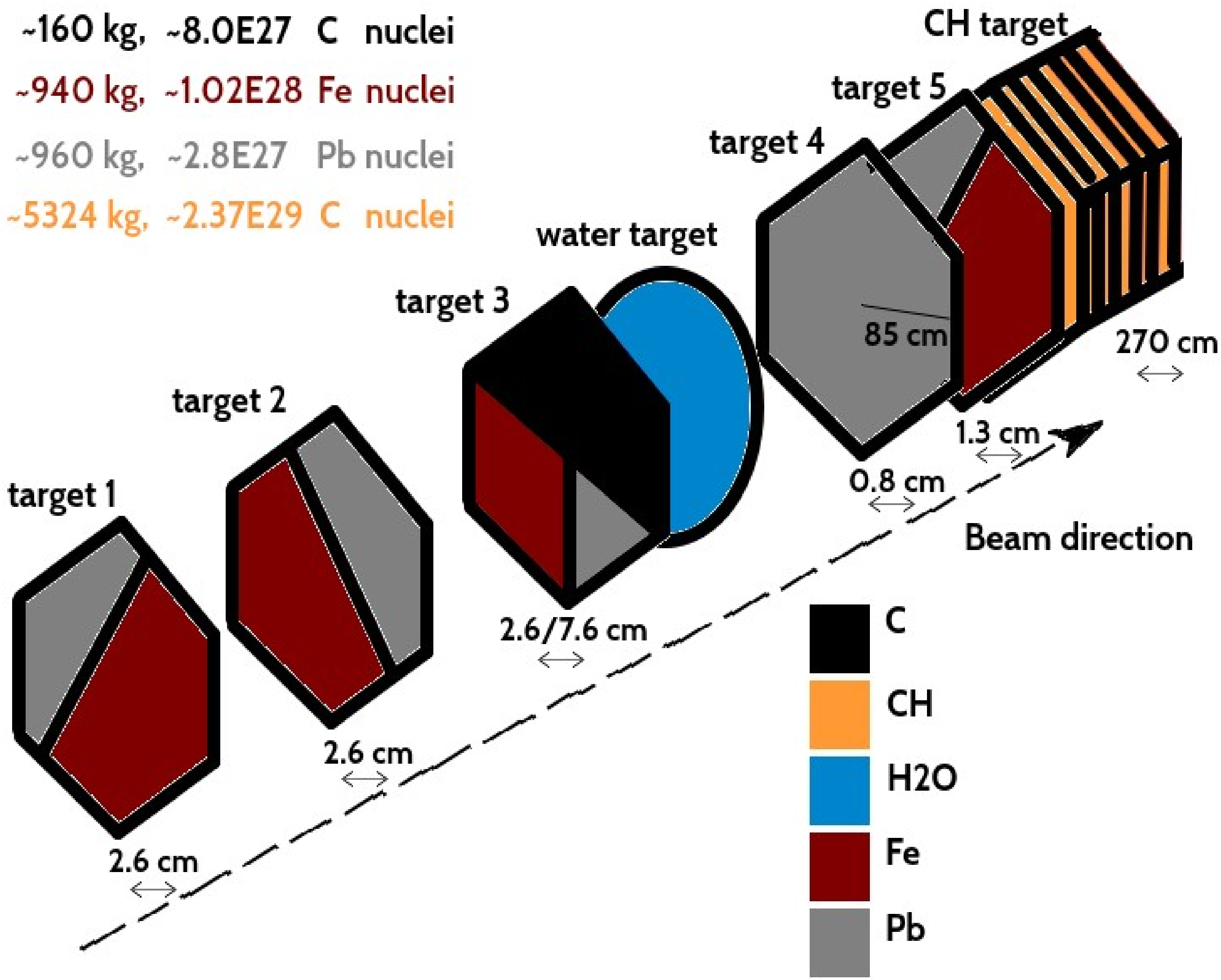
A-Dependence of Coherent Pion Production

Passive Target Region



A-Dependence of Coherent Pion Production

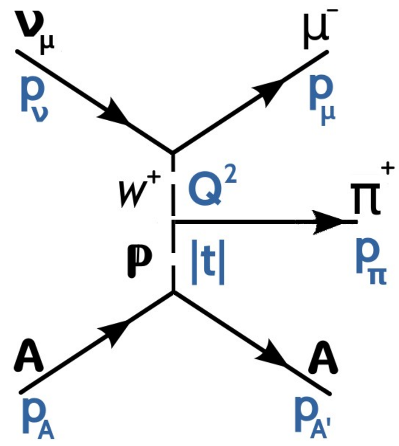
Passive Target Region – Enabled Due to High Statistics!

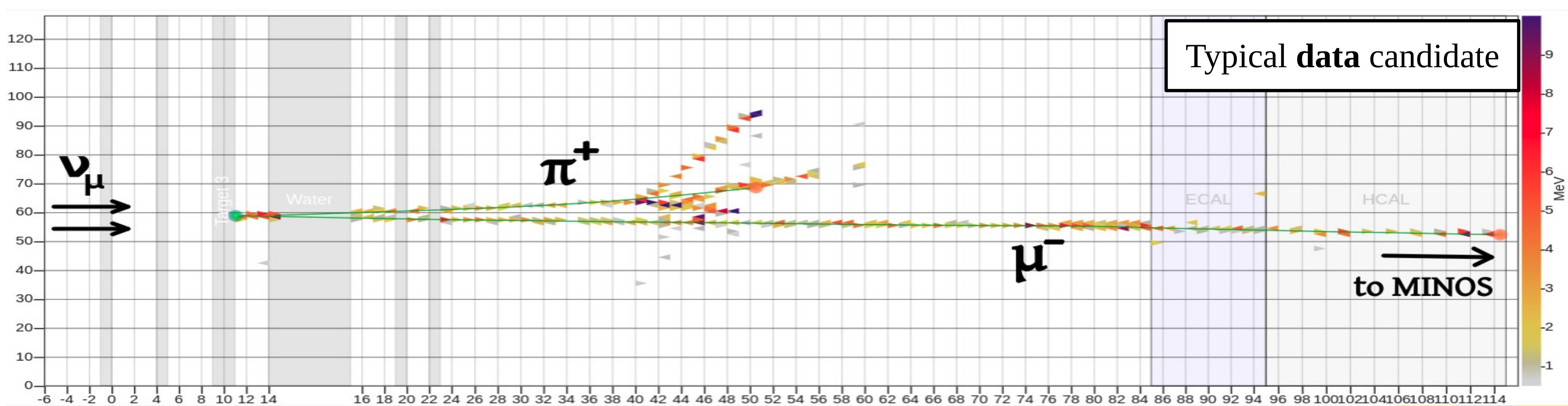


A-Dependence of Coherent Pion Production

Signal Definition

- ν_μ-induced CC coherent π^+ events in **C**, **Fe** and **Pb**.
- Multiplicity == 2 → $\boldsymbol{\mu^-}$ and $\boldsymbol{\pi^+}$ candidate tracks.
- Muon vertex inside the material under study.
- Muon reconstructed inside MINOS detector.
- 2 < E_ν < 20 GeV (muons unable to reach MINOS and high flux uncertainty, respectively).
- Coherent interactions in chemical elements other than **C**, **Fe** and **Pb**, but inside the fiducial volume, are considered signal (a correction due to this is applied to the cross section).





A-Dependence of Coherent Pion Production

Backgrounds From GENIE + Mnv Tune

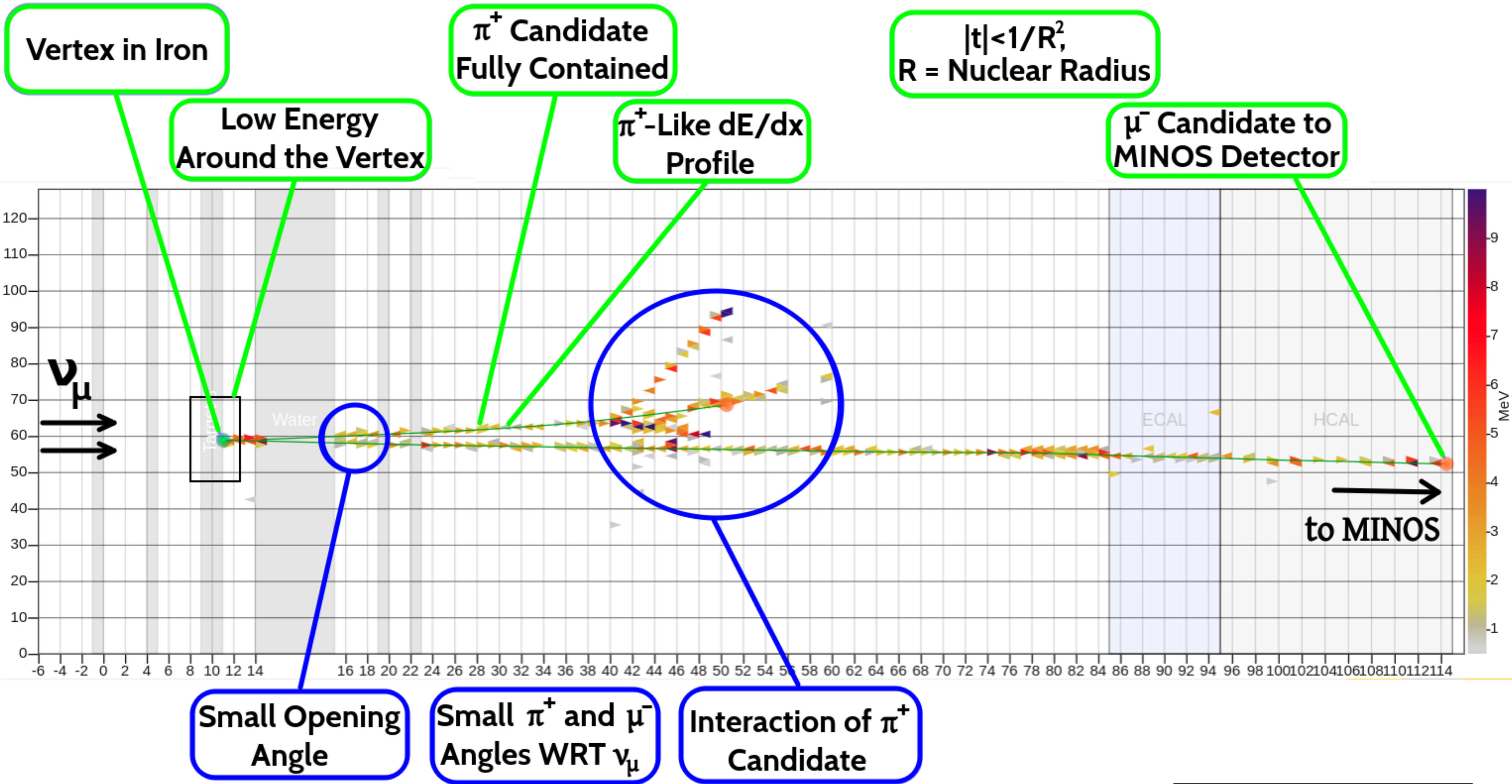
In terms of invariant hadron mass $W = \sqrt{(M^2 + 2M\nu - Q^2)}$

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

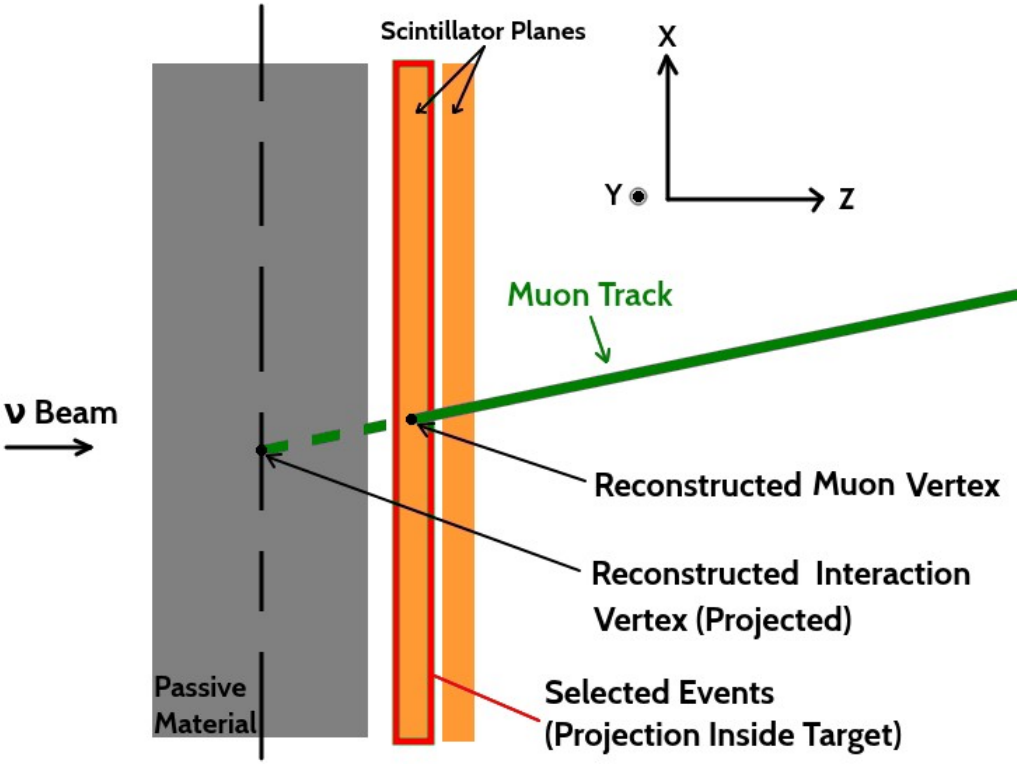
Event Selection

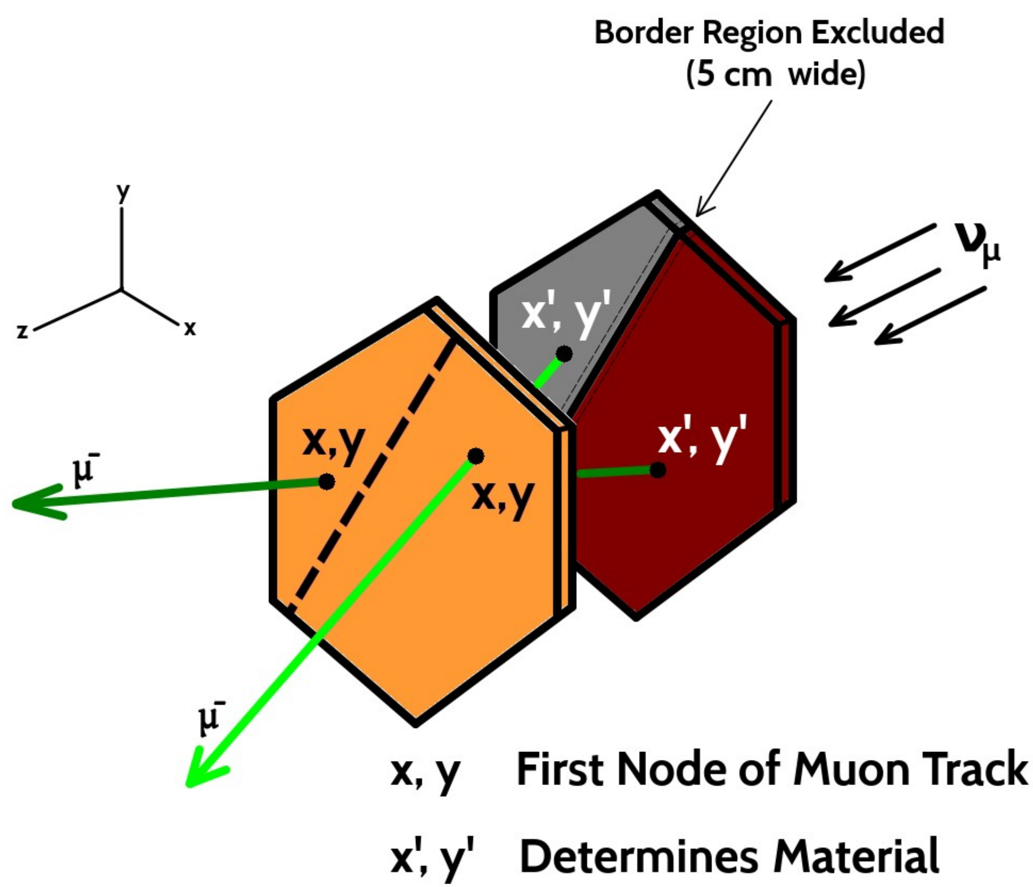
CUTS APPLIED



OBSERVABLES

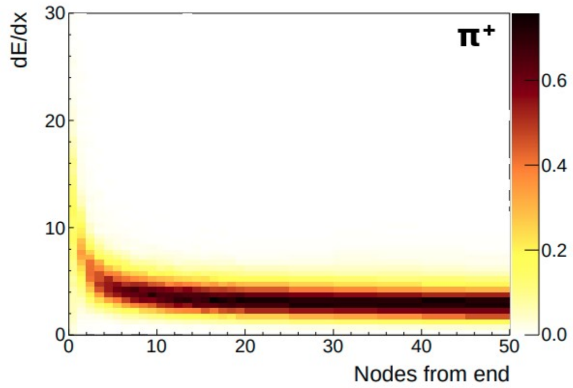
Event Selection – Determining the Material

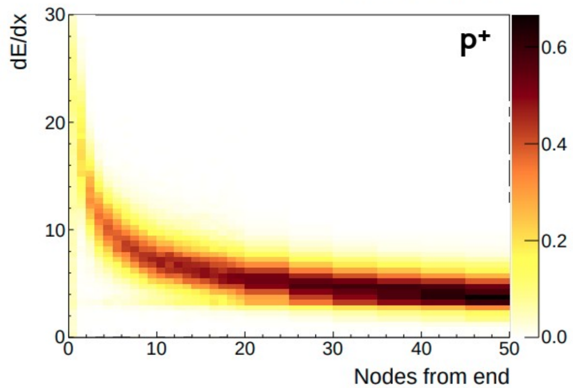


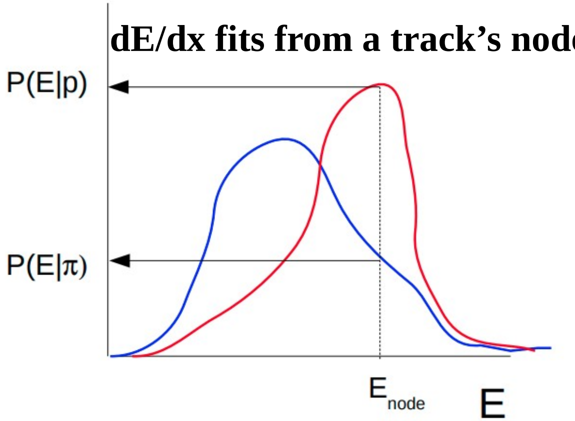


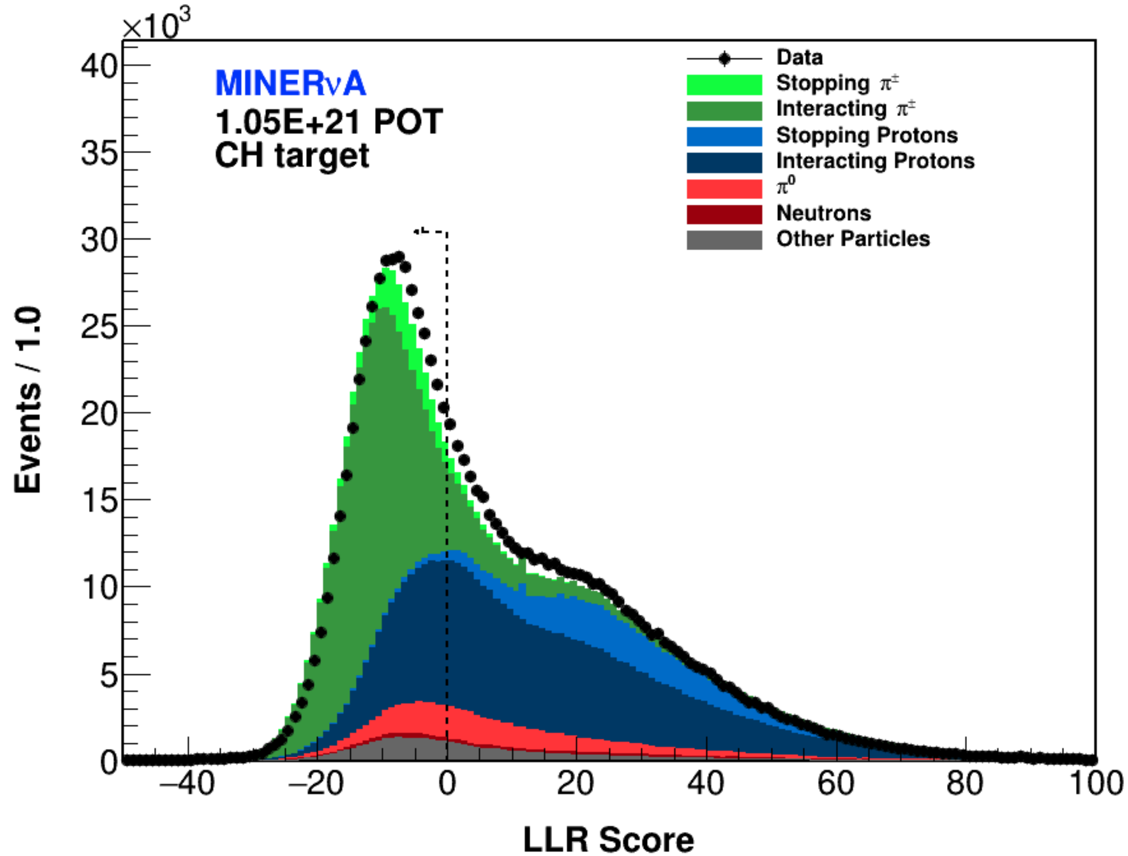
A-Dependence of Coherent Pion Production

Event Selection – dE/dx Cut





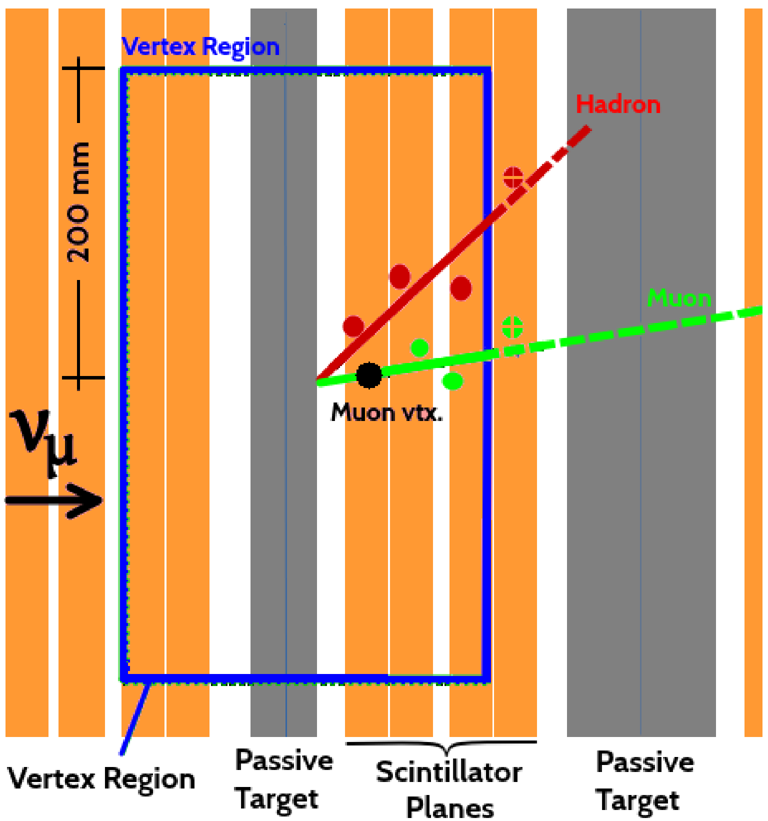


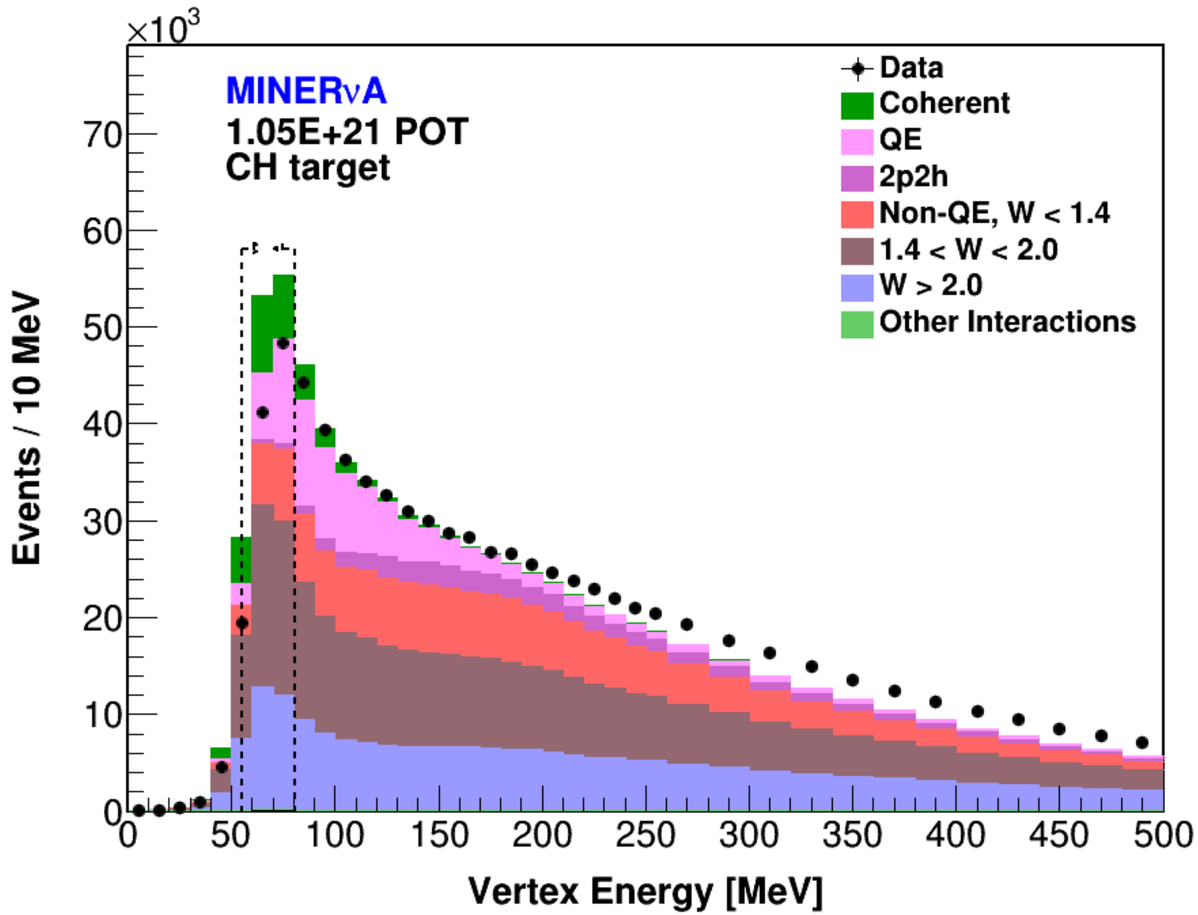


- Log Likelihood Ratio between proton and pion hypotheses.
- Contained track consistent with charged pion.
- Cut keeps ~70% of pions.
- And removes ~87% protons.

A-Dependence of Coherent Pion Production

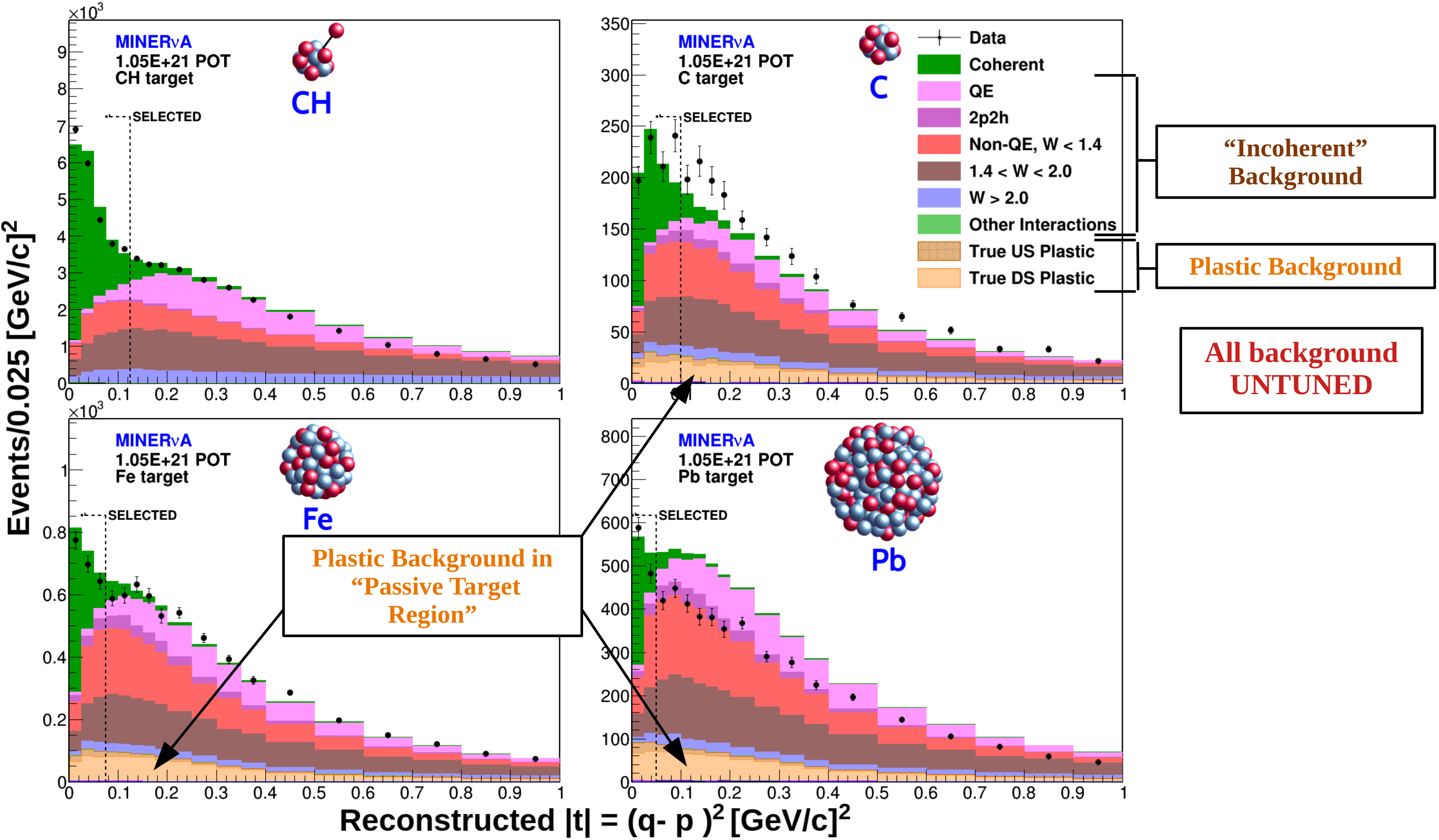
Event Selection – Energy of Vertex Region





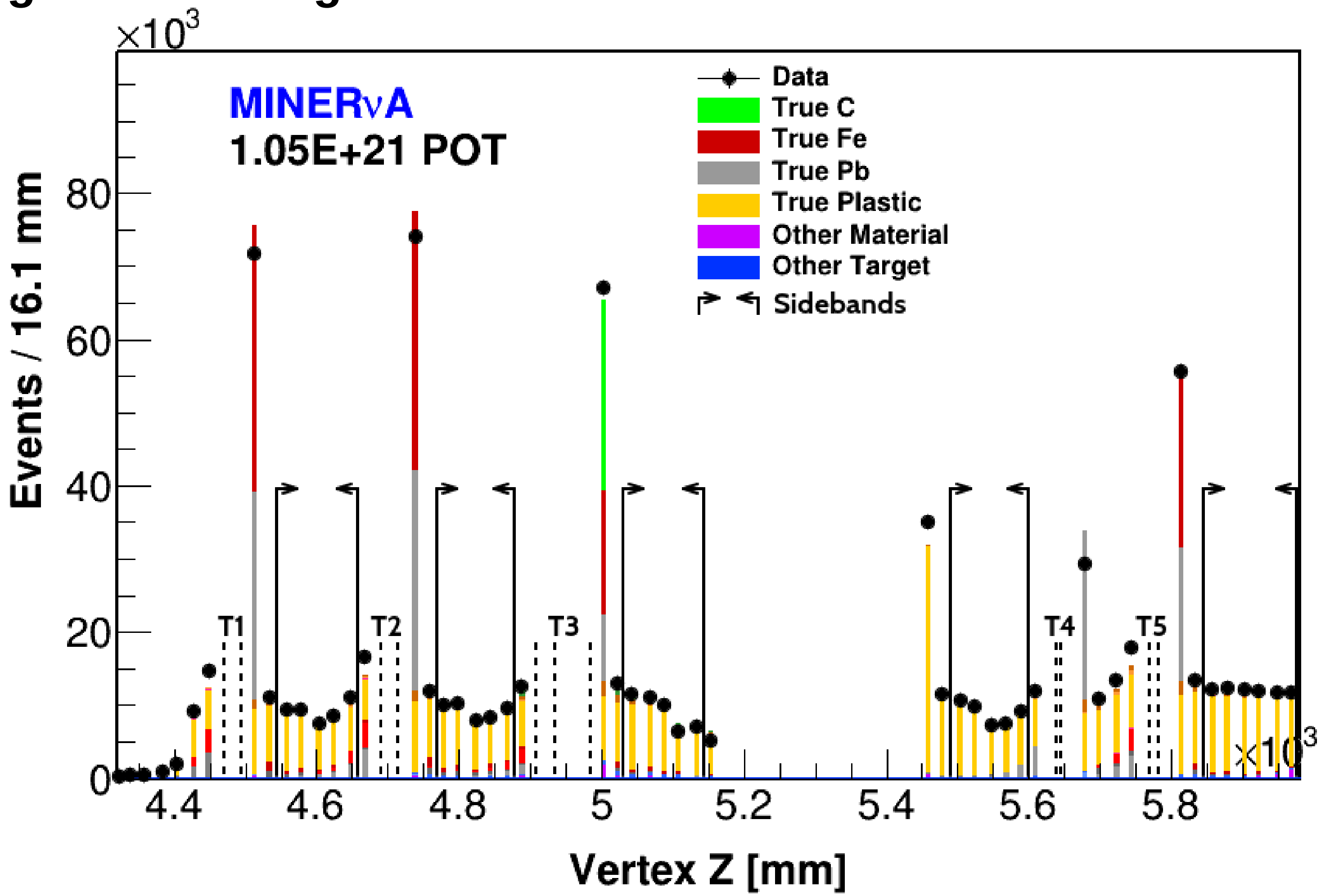
- Vertex energy consistent with 2 MIP ($\mu^- + \pi^+$).
- Cut keeps ~60% of signal.
- And removes ~86% background.

Event Selection – Momentum Transfer to the Nucleus |t|



A-Dependence of Coherent Pion Production

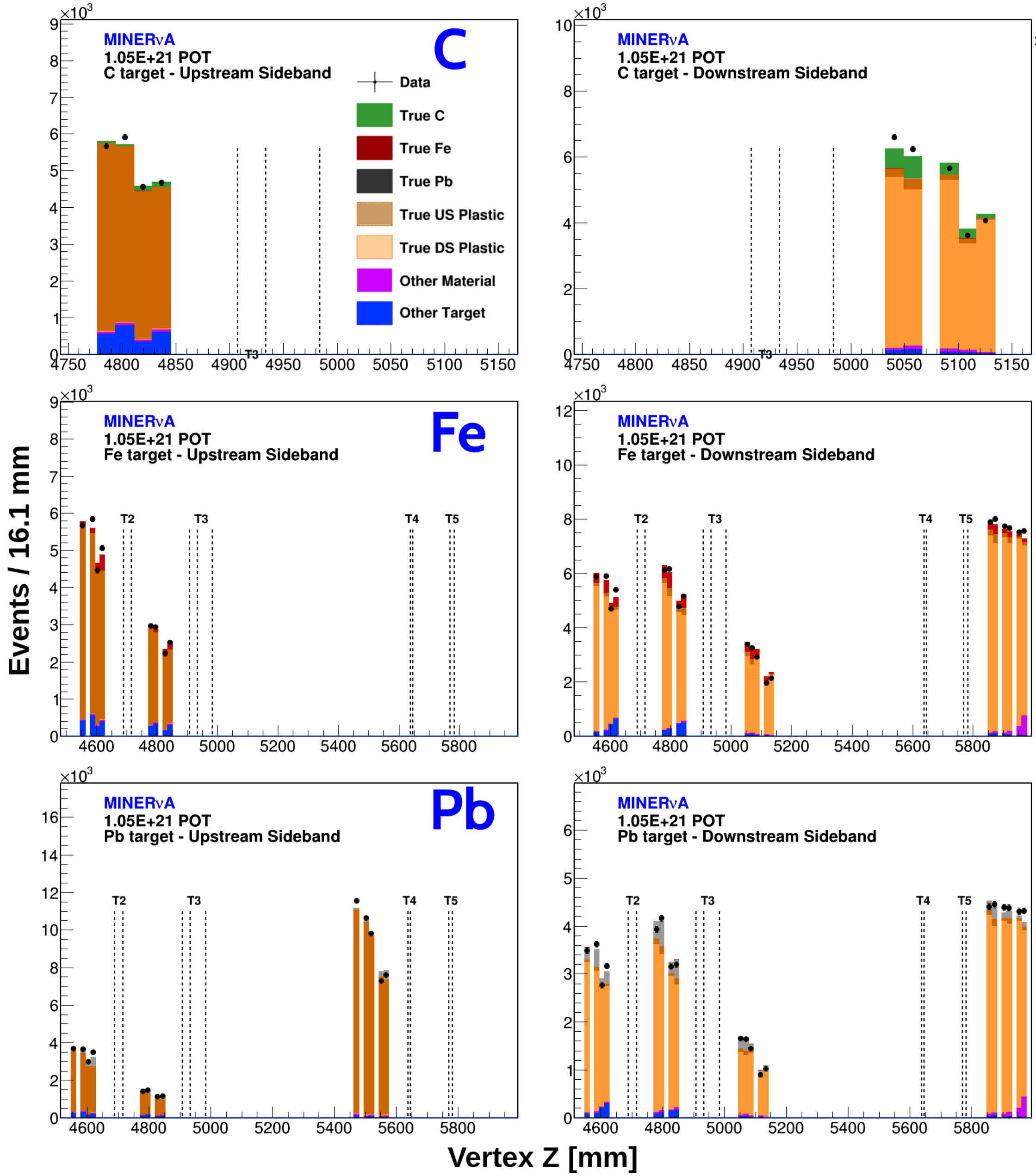
Background Tuning - Plastic Sidebands



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

A-Dependence of Coherent Pion Production

Background Tuning - Plastic Sideband



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

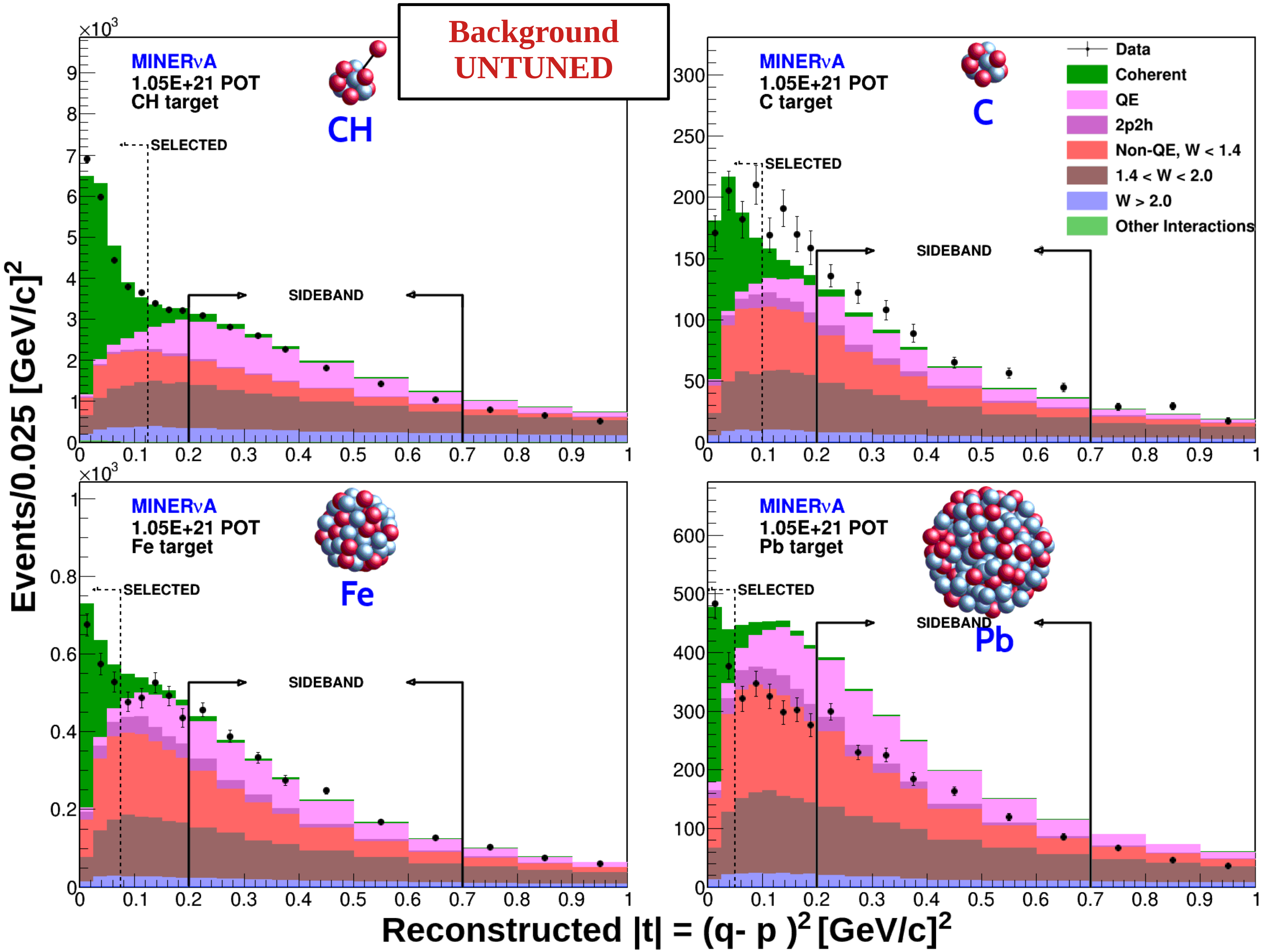
Plastic background TUNED

Tuned plastic background represents:

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

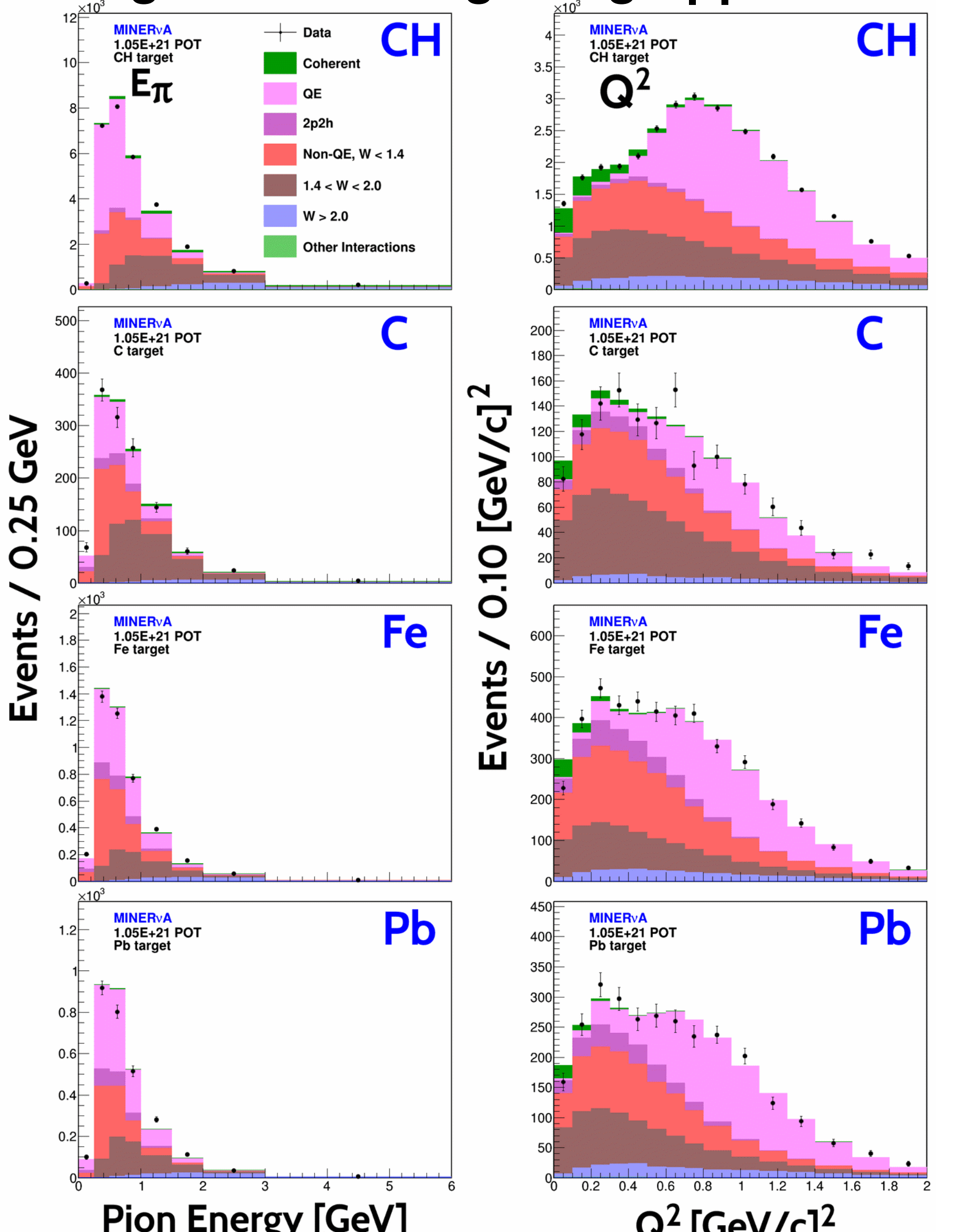
A-Dependence of Coherent Pion Production

Background Tuning – High |t| Sideband



A-Dependence of Coherent Pion Production

Background Tuning – High |t| Sideband



Scale Factors

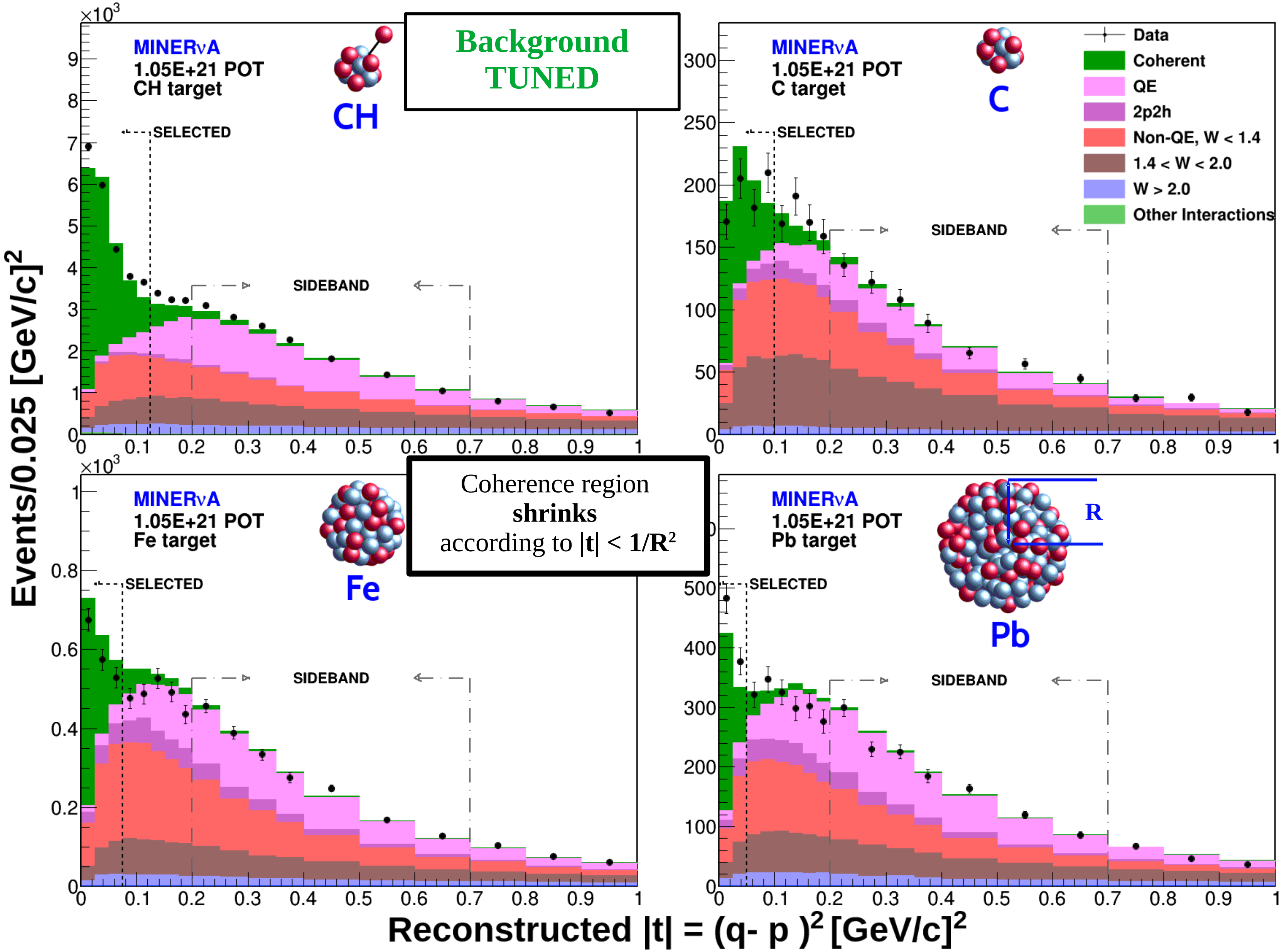
Material	CH	C	Fe	Pb
α_{QE}	1.22 ± 0.016	1.22 ± 0.016	1.40 ± 0.067	1.09 ± 0.054
α_{RES}	1.29 ± 0.040	1.17 ± 0.046	1.15 ± 0.088	0.66 ± 0.069
α_{INE}	0.60 ± 0.016	1.17 ± 0.046	0.58 ± 0.059	0.50 ± 0.053
α_{DIS}	0.65 ± 0.026	0.65 ± 0.026	1.08 ± 0.137	0.98 ± 0.144

Background TUNED

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**.

Tuned |t| Distributions



Cross Section Extraction

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

Total Cross Section

True Bin

Unfolding Matrix

Reco Bin

Number of Selected Data Events

Number of Predicted Background Events

Efficiency

Flux Per Bin

Number of Nuclei

A-Dependence of Coherent Pion Production

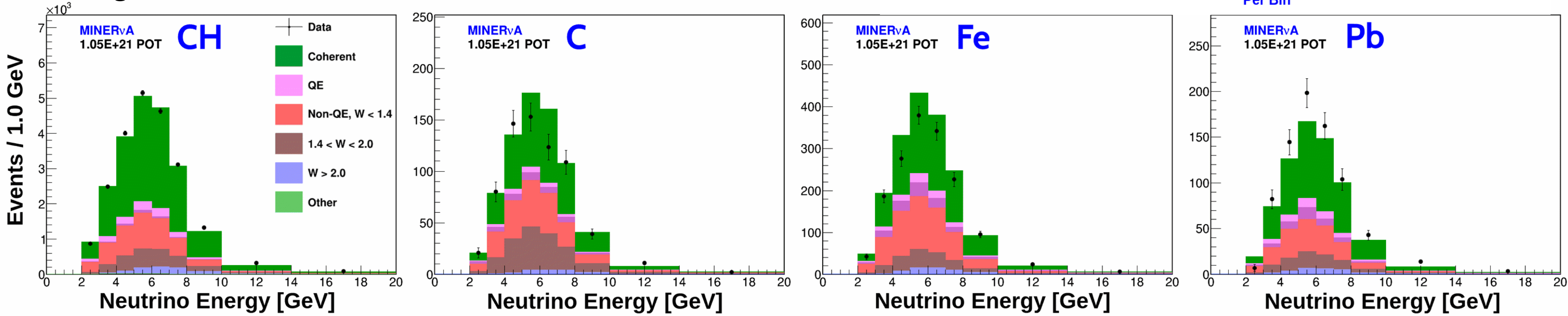
Cross Section Extraction

Selected Sample

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

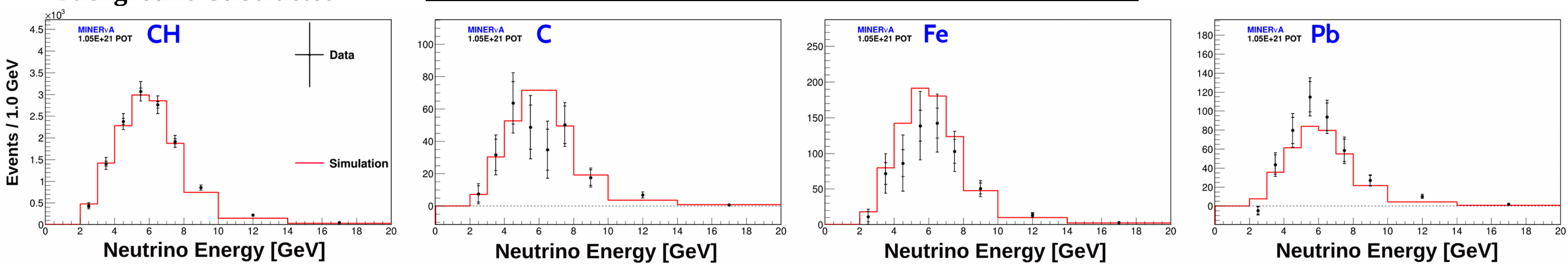
- σ_i: Total Cross Section (i: True Bin)
- U_{ij}: Unfolding Matrix (j: Reco Bin)
- N_j^{DATA}: Number of Selected Data Events
- N_j^{BKGD}: Number of Predicted Background Events
- ϵ_i: Efficiency
- ϕ_i: Flux Per Bin
- T: Number of Nuclei

Background Tuned



Material	CH	C	Fe	Pb
Candidate Events	14855	303	726	492

Background Subtracted



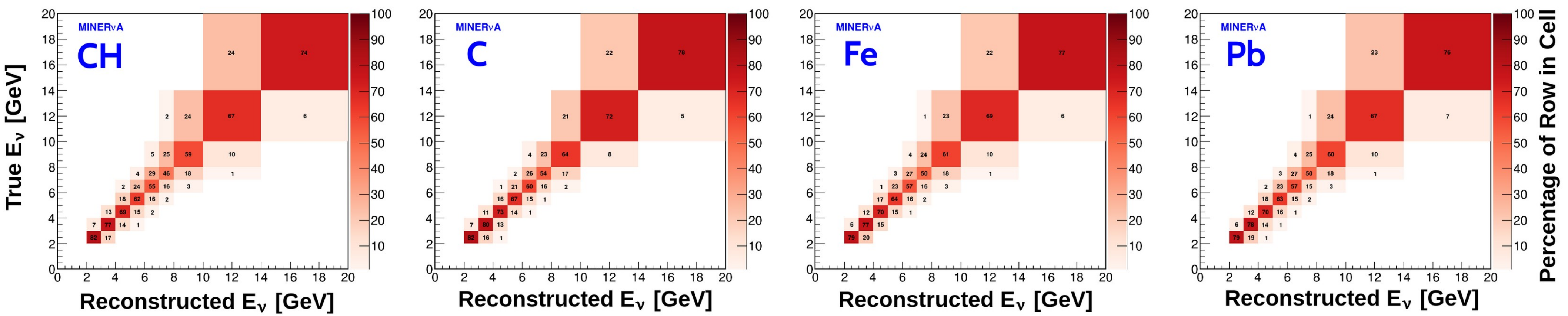
Cross Section Extraction

Unfolding

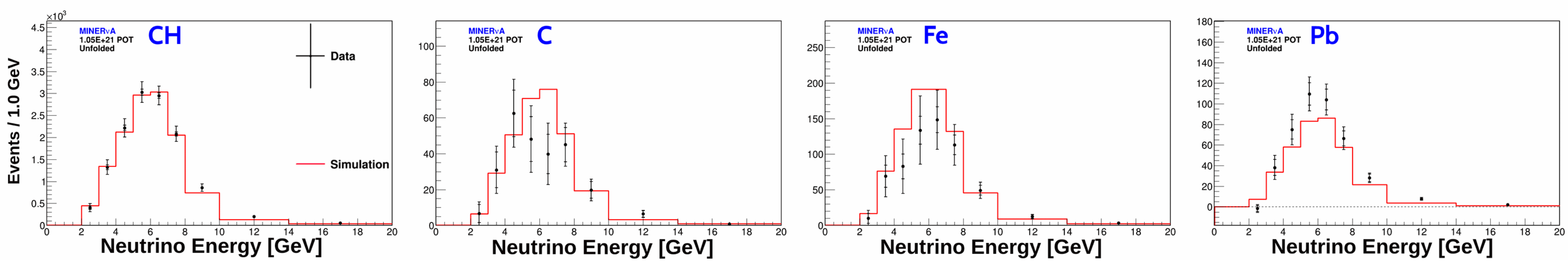
- **Bayesian Iterative Approach**
- **D'Agostini Method**

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

Migration Matrices



Unfolded Distributions



A-Dependence of Coherent Pion Production

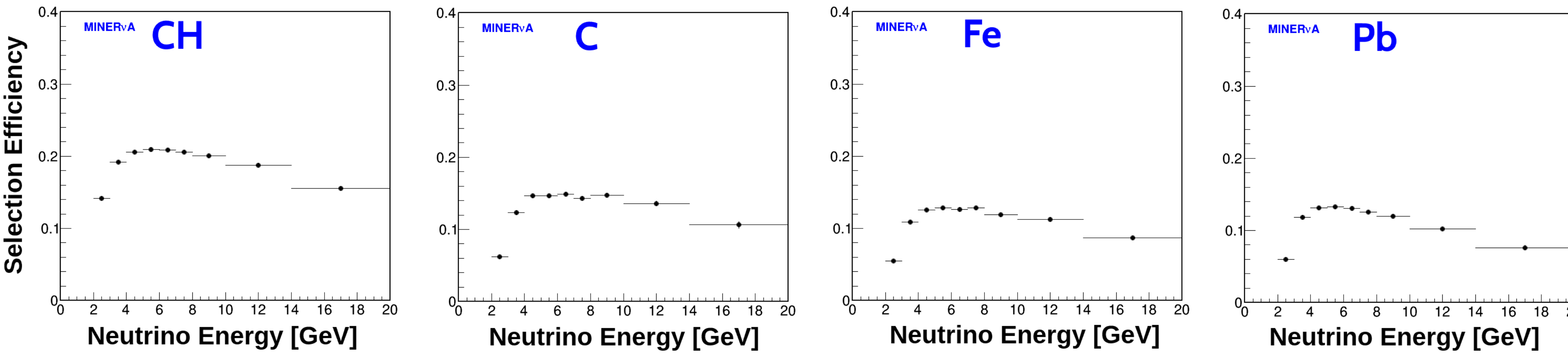
Cross Section Extraction

Efficiency Correction

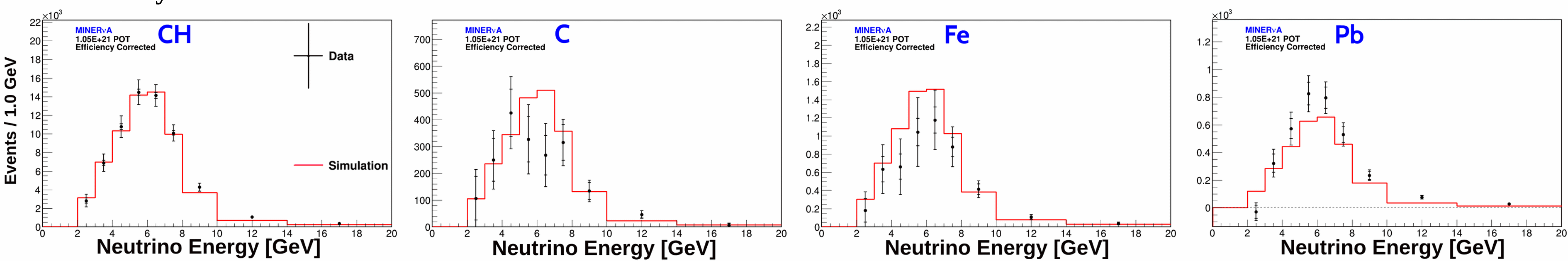
$$\sigma_i = \frac{\sum_j U_{ij}\left(N_j^{DATA} - N_j^{BKGD}\right)}{\epsilon_i \phi_i T}$$

Total Cross Section; True Bin; Unfolding Matrix; Reco Bin; Number of Selected Data Events; Number of Predicted Background Events; Efficiency; Flux Per Bin; Number of Nuclei

Selection Efficiency



Efficiency Corrected



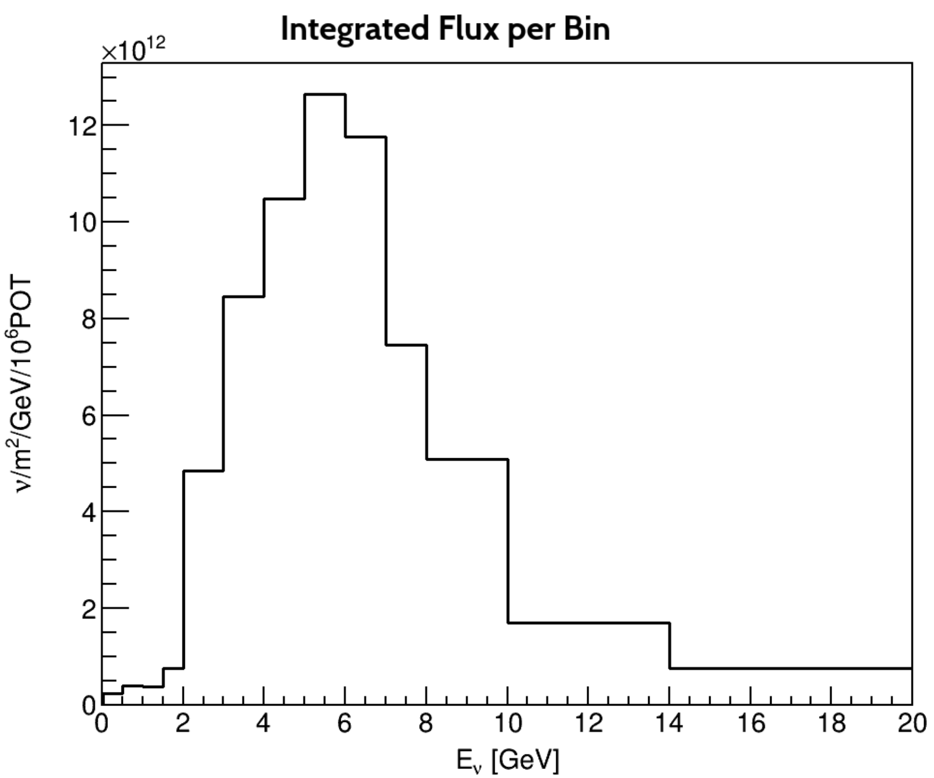
A-Dependence of Coherent Pion Production

Cross Section Extraction

Normalizations

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

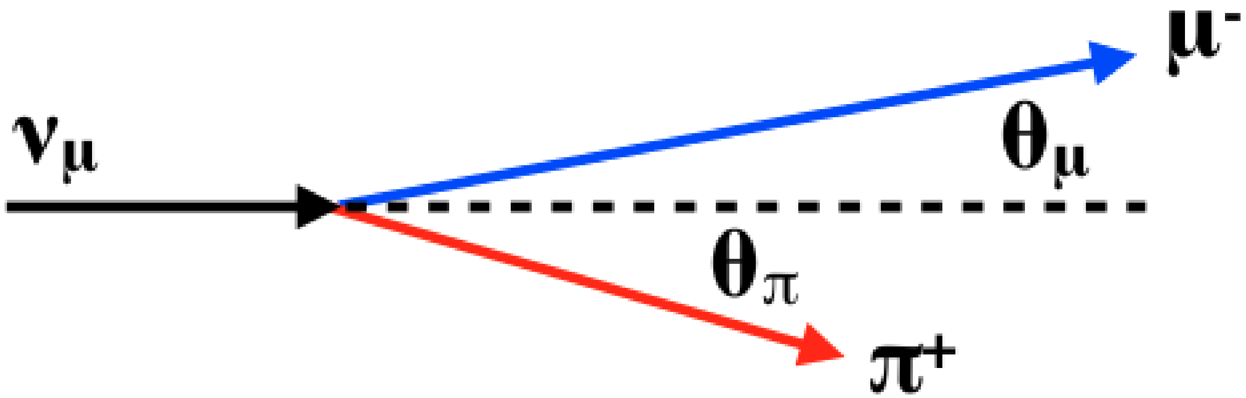
Total Cross Section (σ_i); True Bin (i); Reco Bin (j); Unfolding Matrix (U_{ij}); Number of Selected Data Events (N_j^{DATA}); Number of Predicted Background Events (N_j^{BKGD}); Efficiency (ϵ_i); Flux Per Bin (ϕ_i); Number of Nuclei (T)



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

Cross Sections

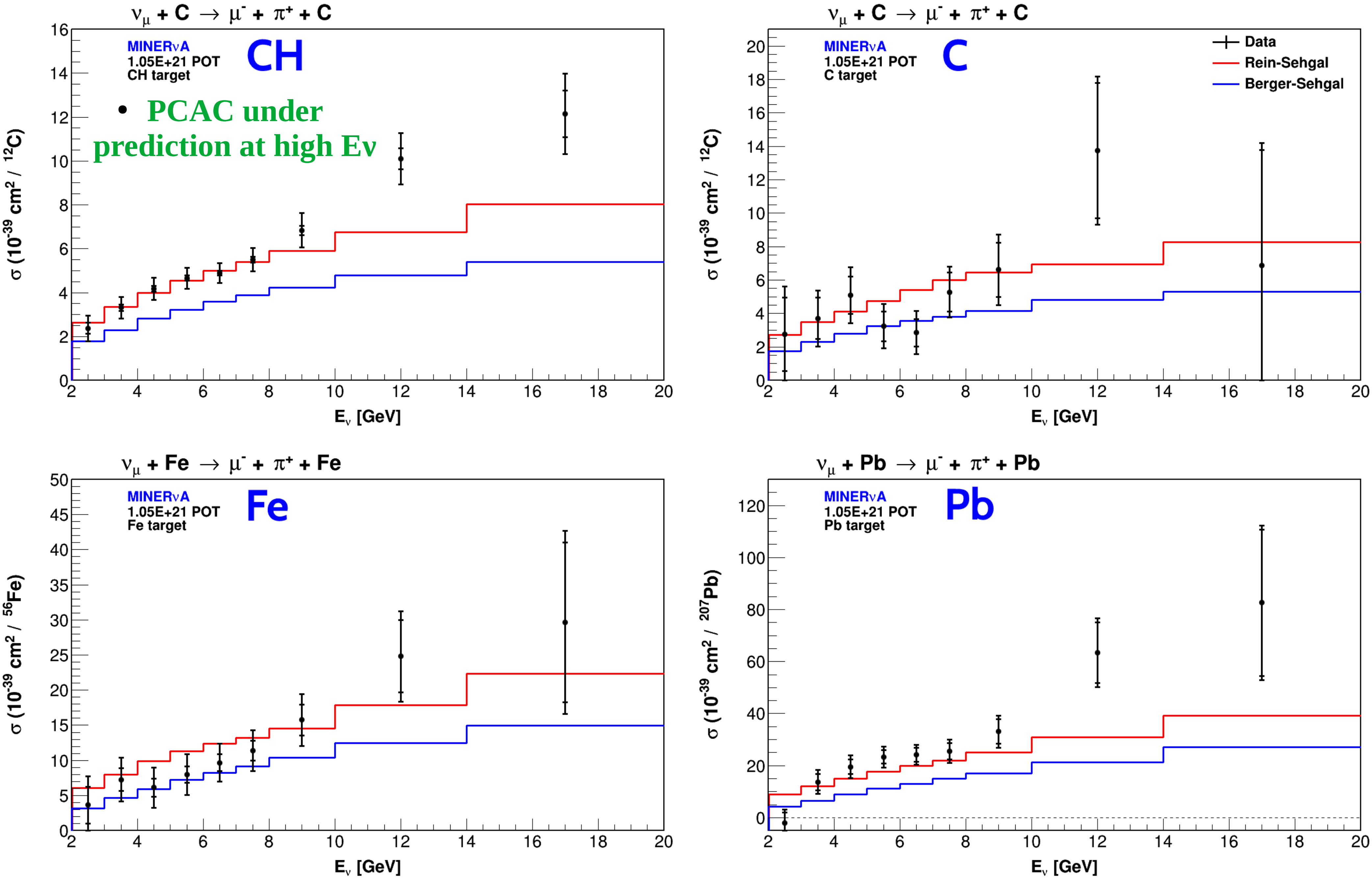
In 4 variables: $E_\nu,\ E_\pi,\ Q^2,\ \theta_\pi$



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

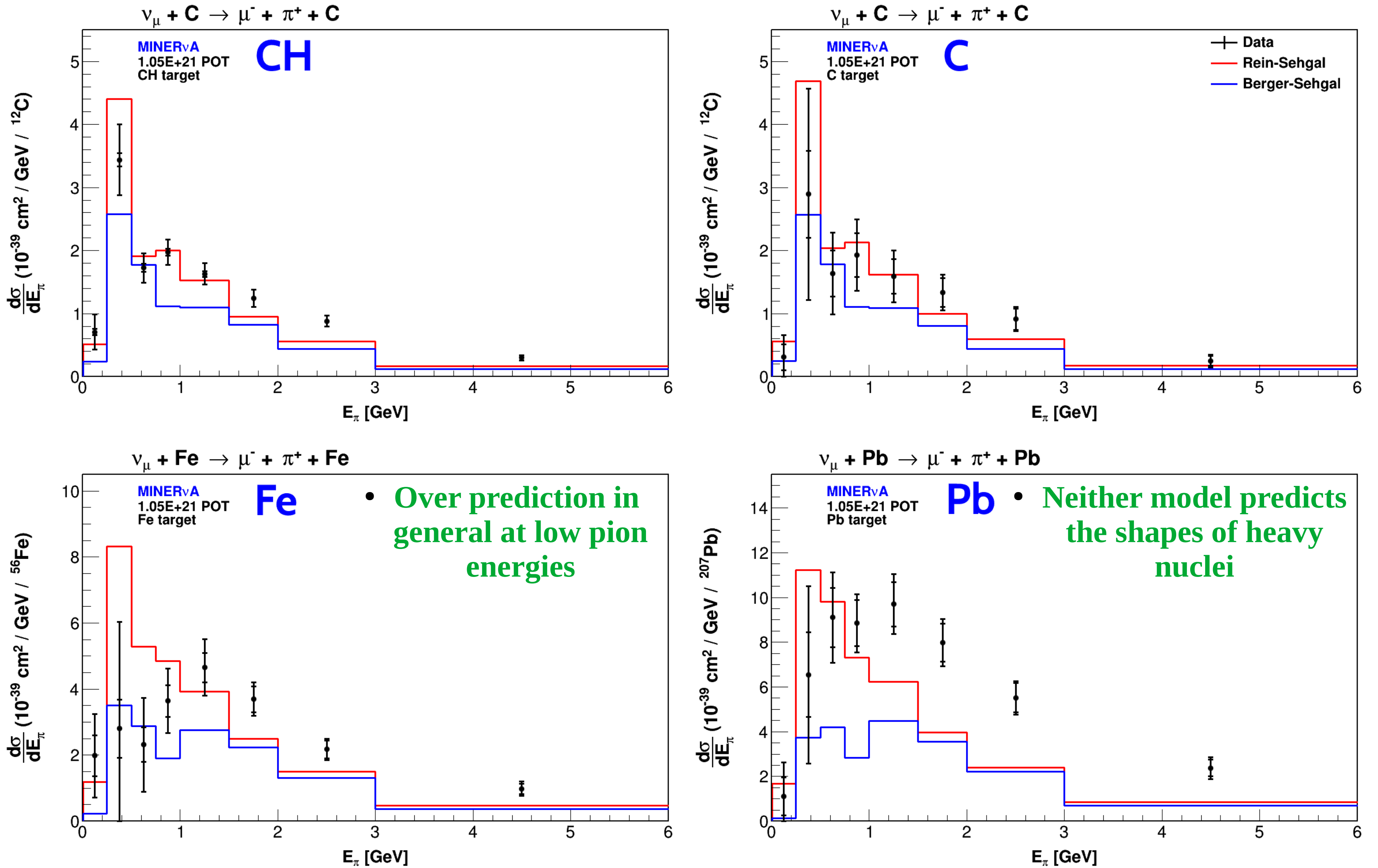
6 - Results – Total Cross Sections

σ_{E_ν}



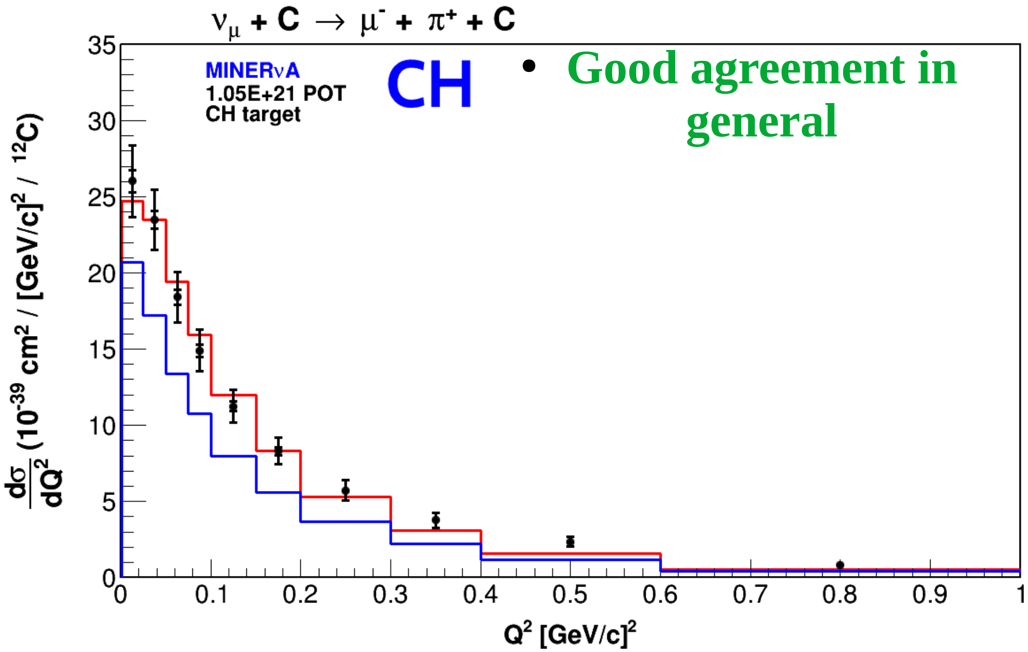
Results – Total Cross Sections

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

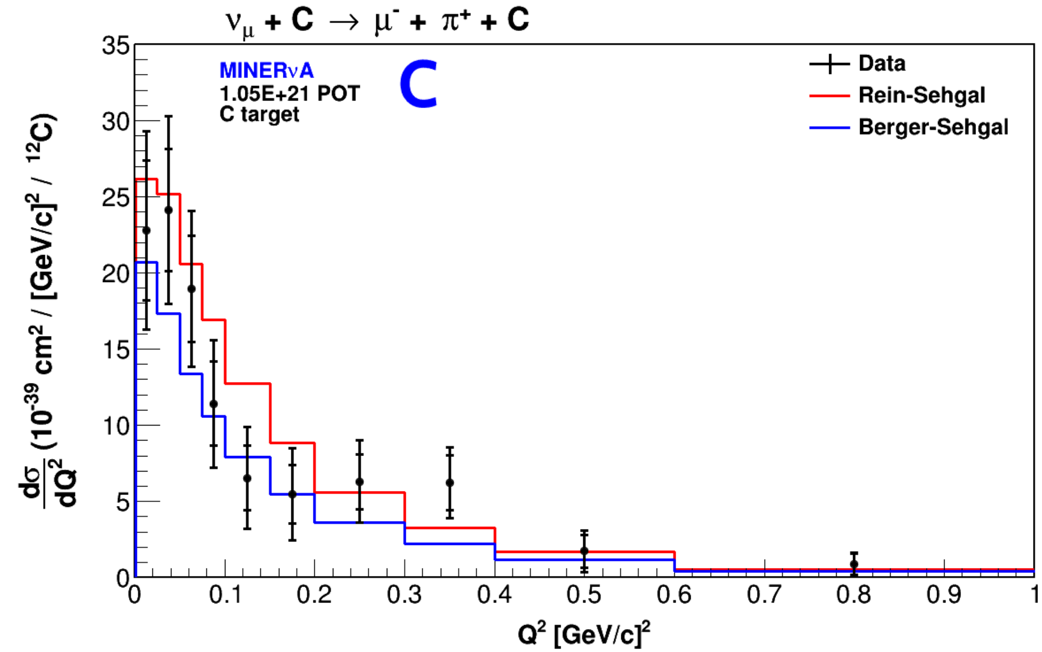


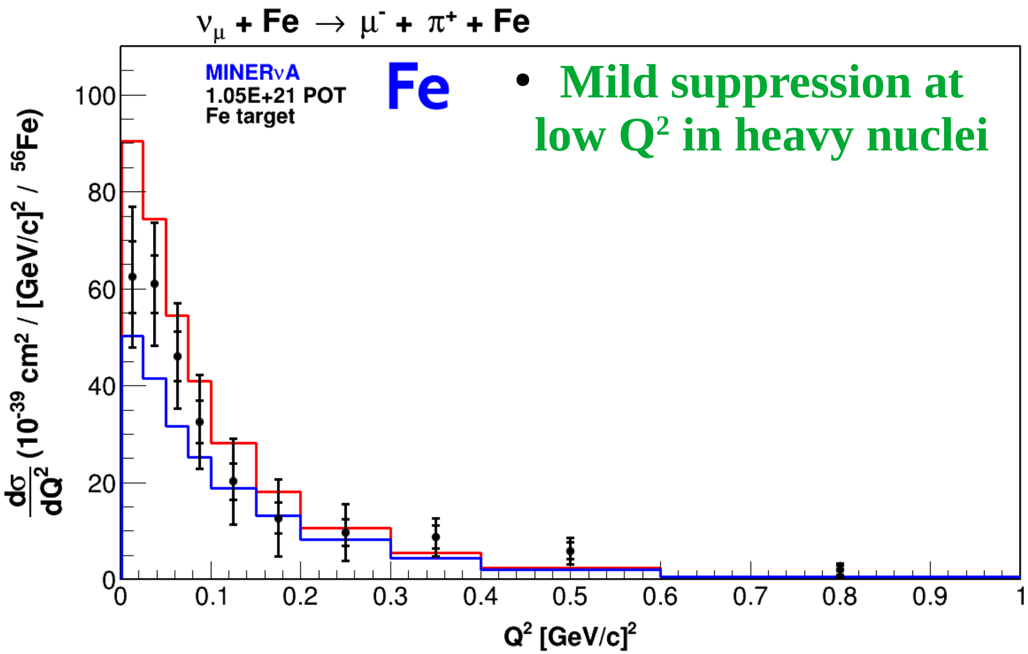
Results – Total Cross Sections

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

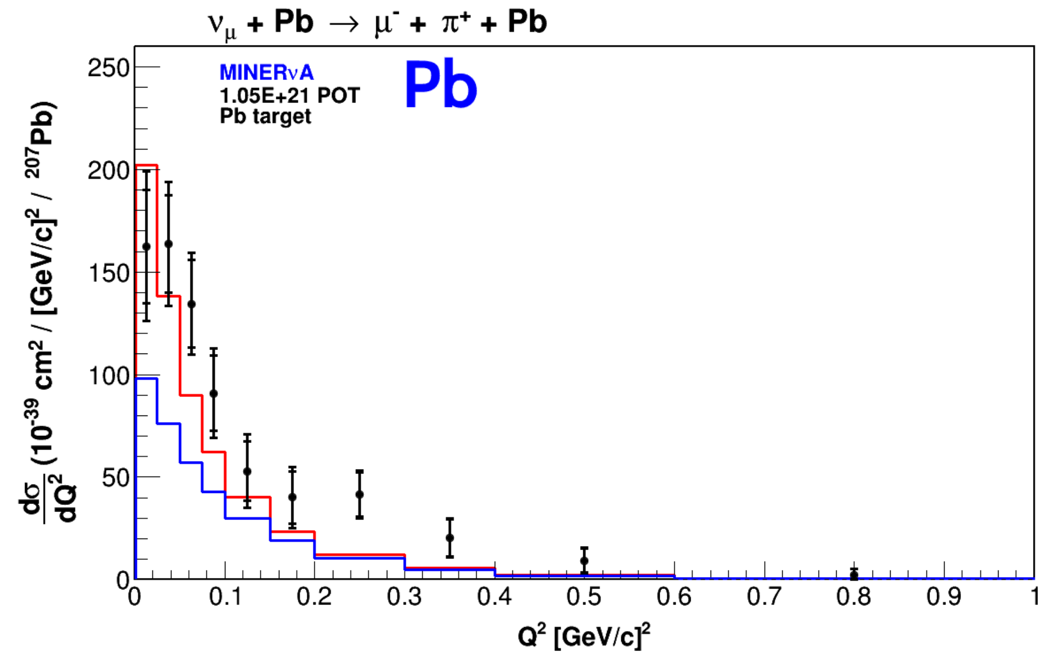


- Good agreement in general



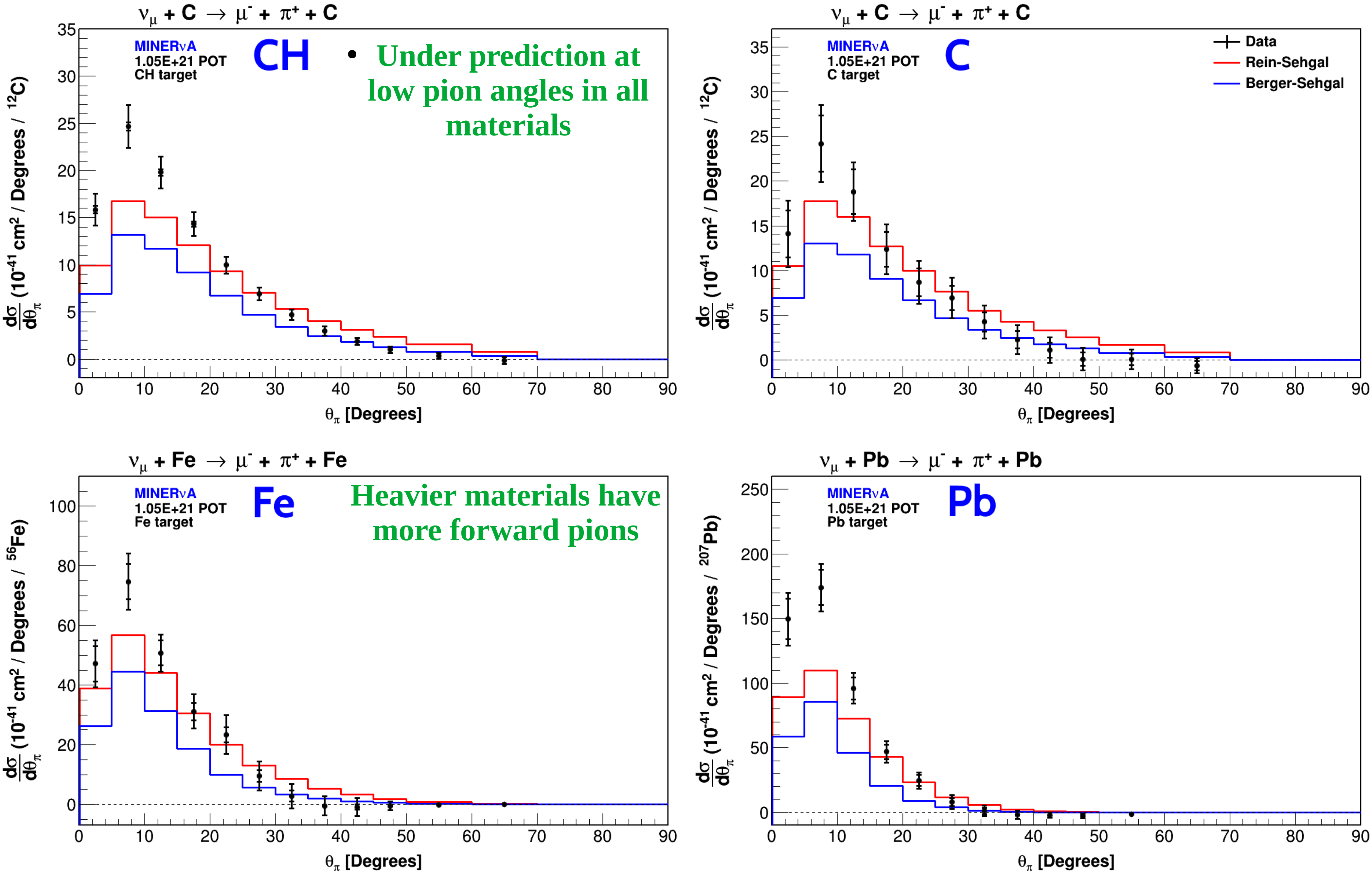


- Mild suppression at low Q^2 in heavy nuclei



Results – Total Cross Sections

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



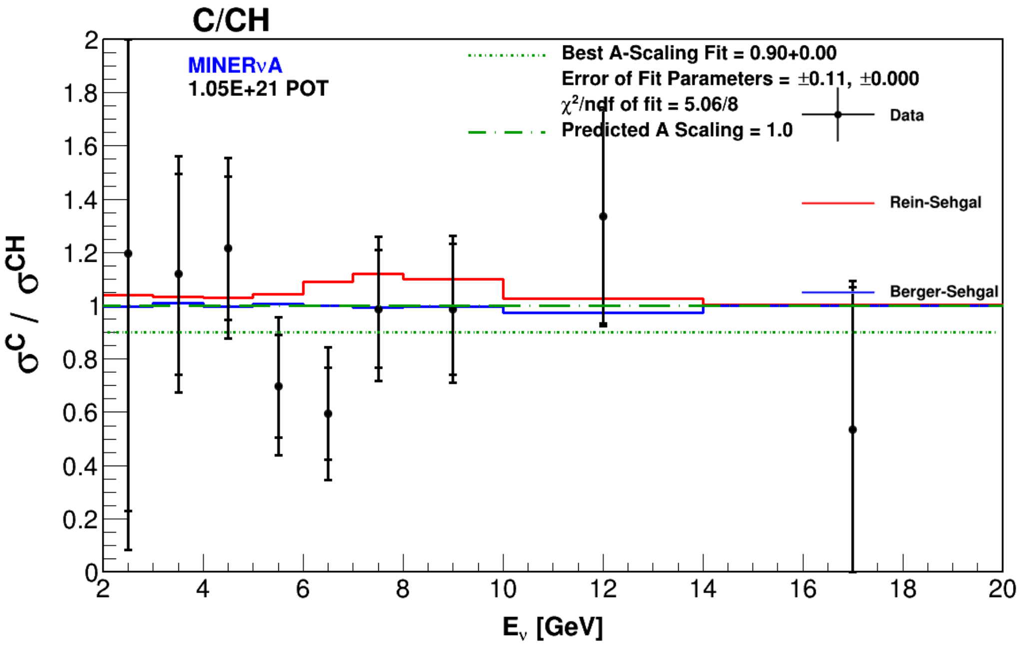
- Under prediction at low pion angles in all materials

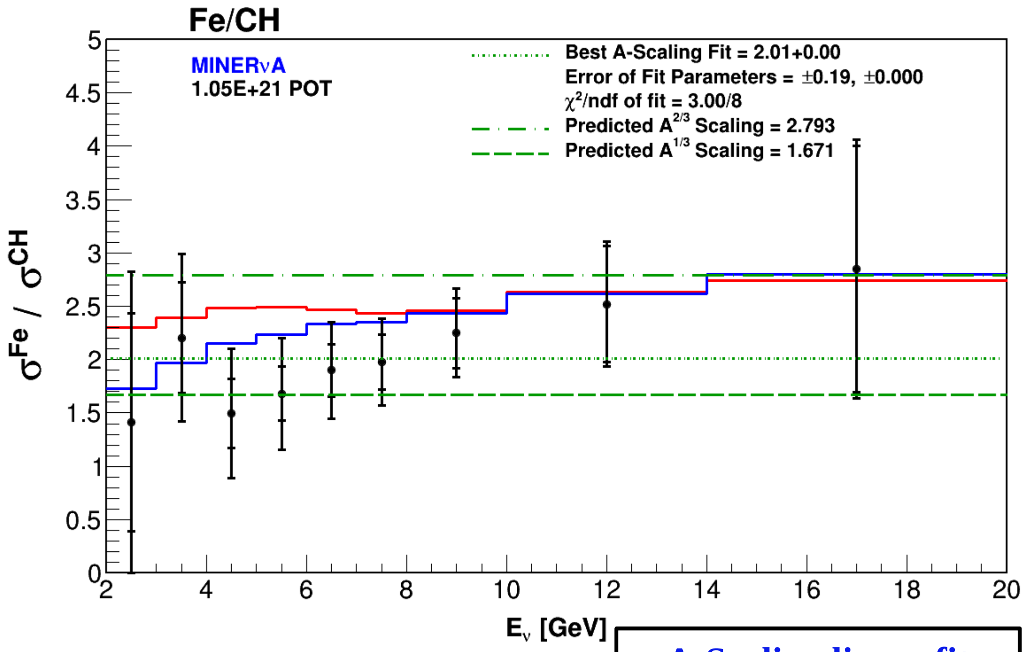
Heavier materials have more forward pions

Results - Cross Section Ratios

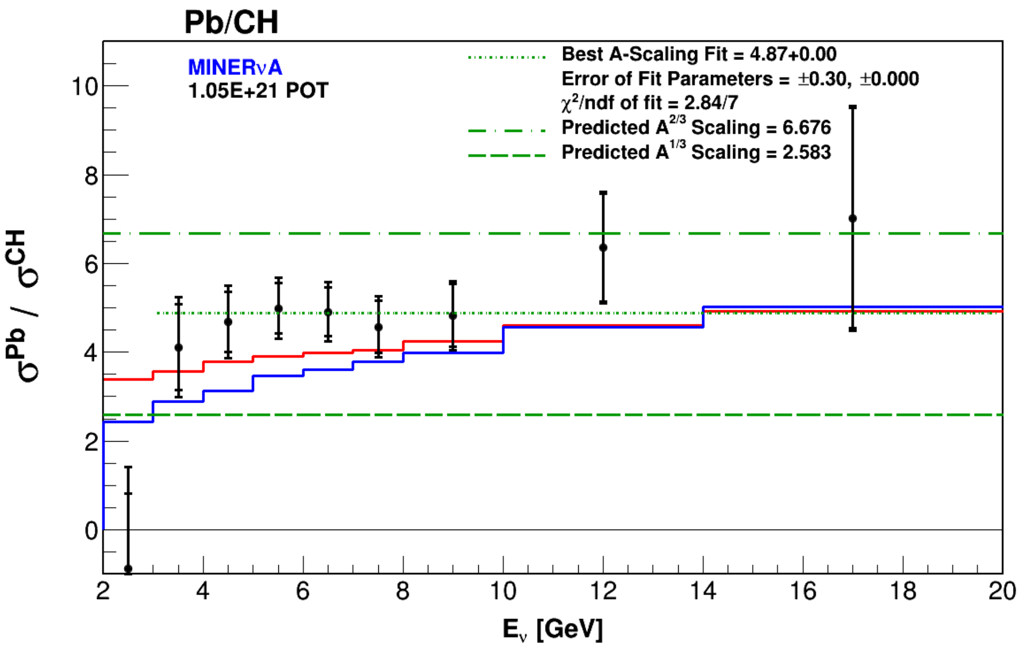
σ_{E_ν}

Penn
UNIVERSITY of PENNSYLVANIA





A-Scaling linear fit



C/CH

- consistent with 1.0

Fe/CH

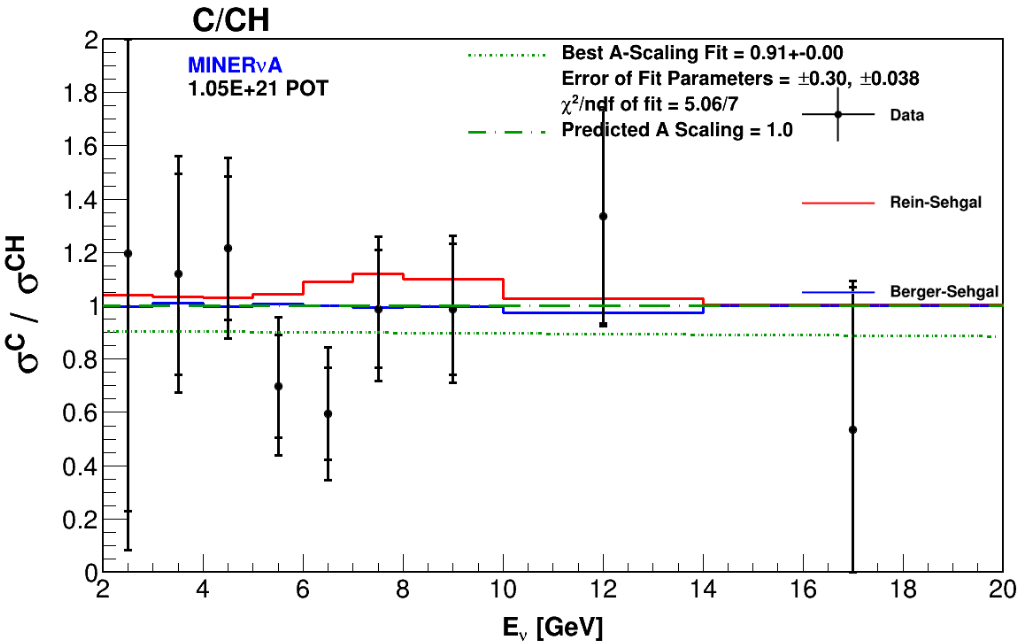
- Neither model does a good description.
- Closer to $A^{1/3}$ scaling for $E_\nu < 8$ GeV.
- Closer to $A^{2/3}$ scaling for $E_\nu > 10$ GeV.

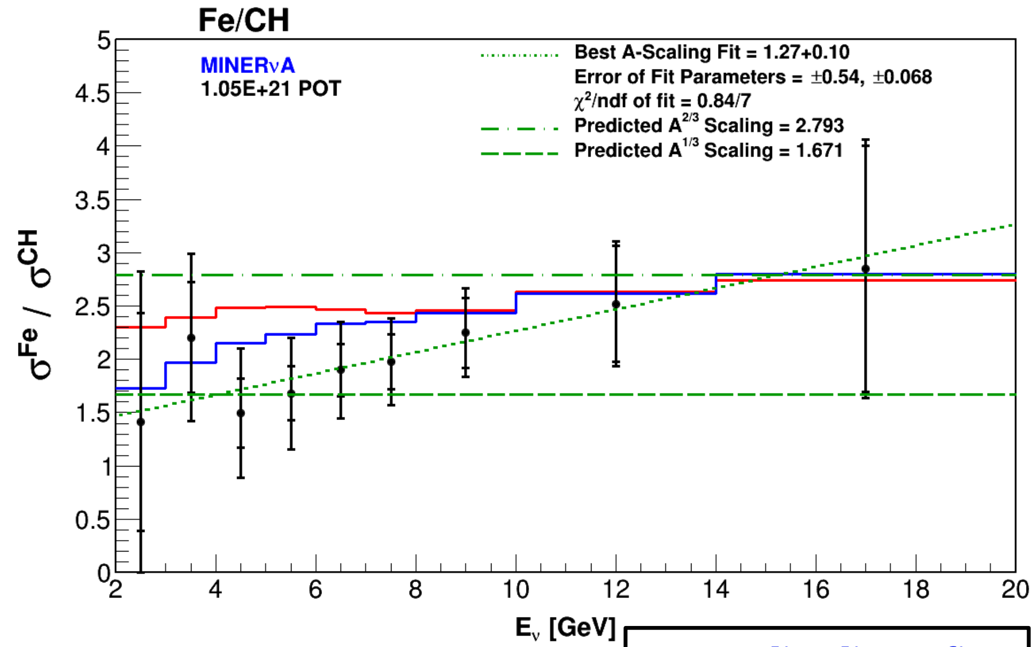
Pb/CH

- 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.

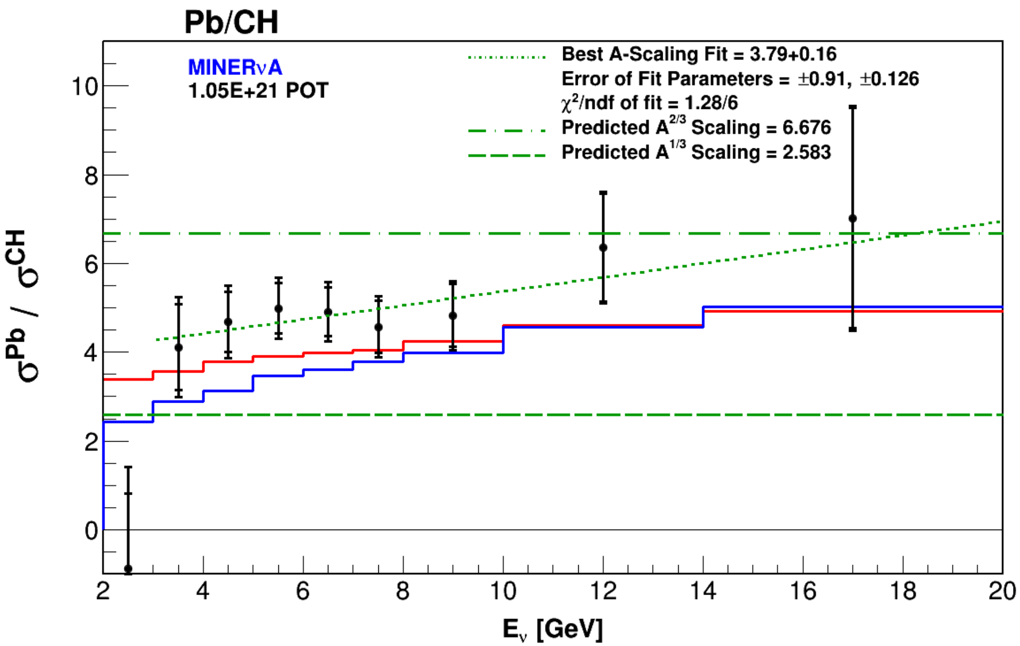
Results - Cross Section Ratios

σE_ν





A-Scaling linear fit with slope



C/CH

- consistent with 1.0

Fe/CH

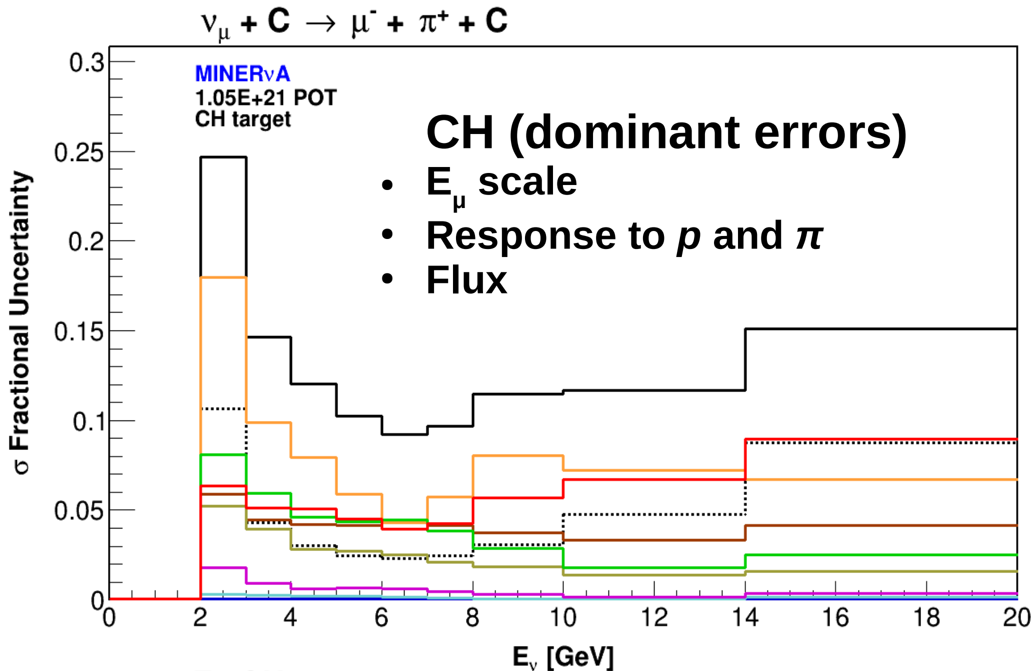
- Neither model does a good description.
- Closer to $A^{1/3}$ scaling for $E_\nu < 8$ GeV.
- Closer to $A^{2/3}$ scaling for $E_\nu > 10$ GeV.

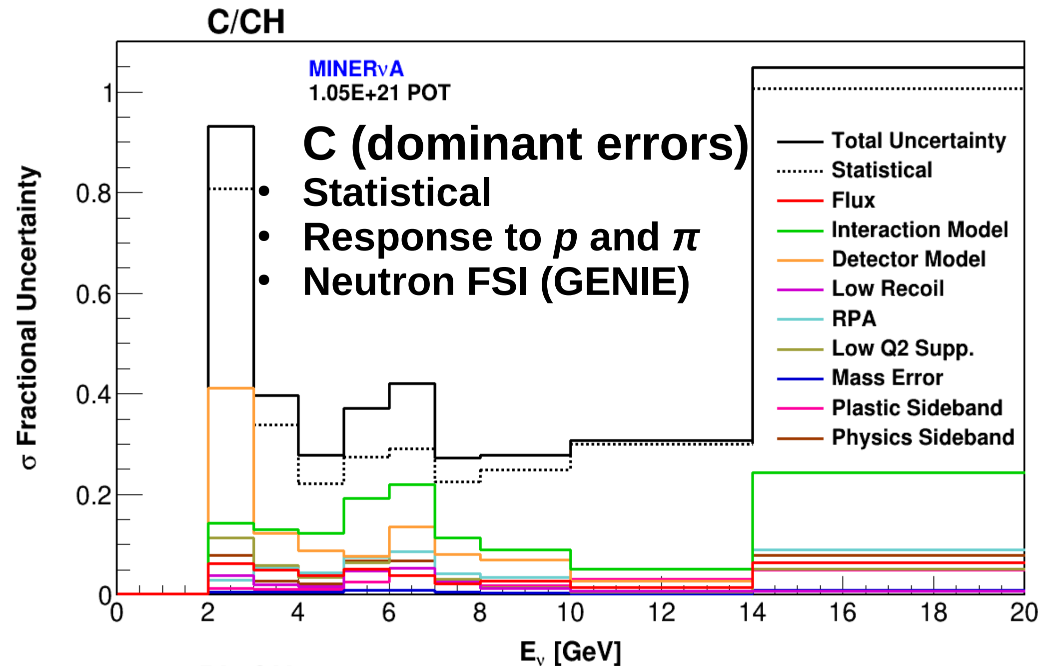
Pb/CH

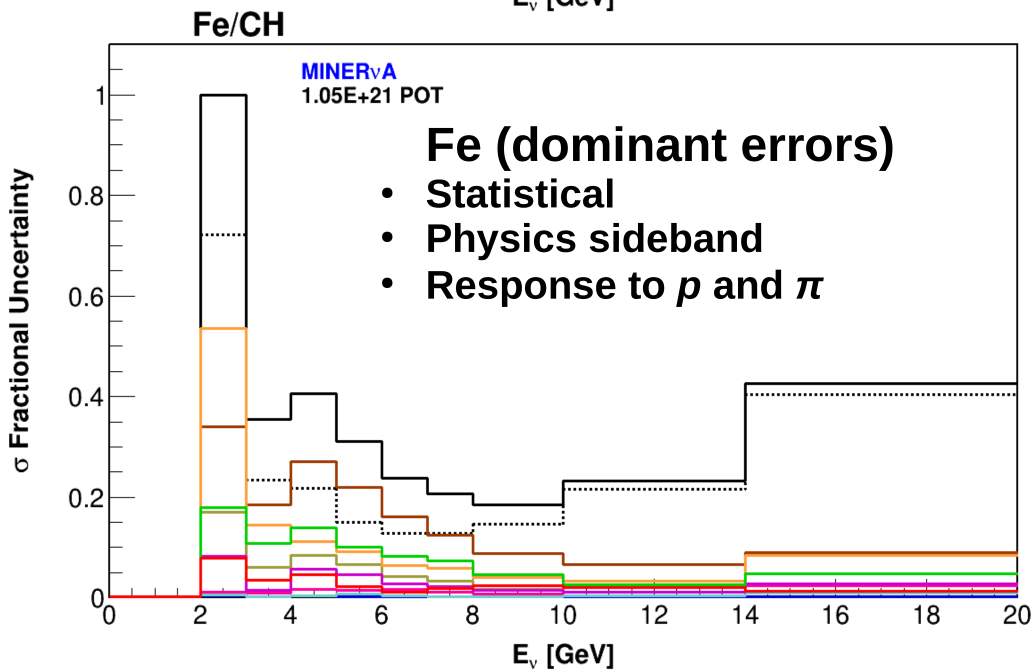
- Neither model does a good description.
- Closer to $A^{2/3}$ scaling for $E_\nu > 10$ GeV.
- Low E_ν A-scaling in between predictions.

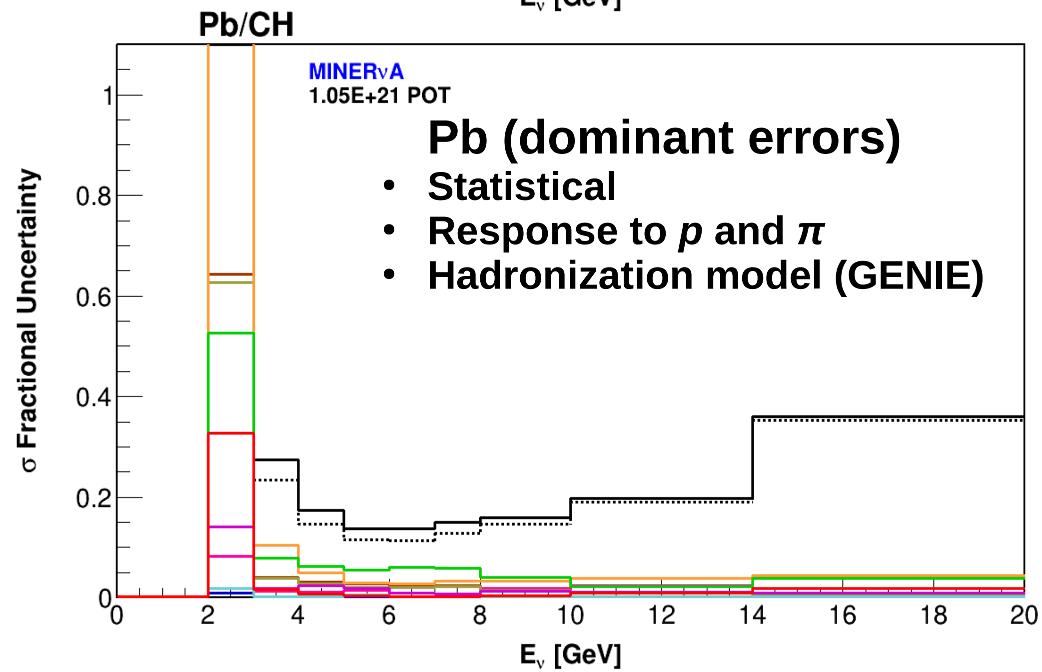
Results - Cross Section Error Summary

σ_{E_ν}









In 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 **(A_{Fe} = 56** and **A_{Pb} = 207).** Lead being the **largest nucleus probed** so far.

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

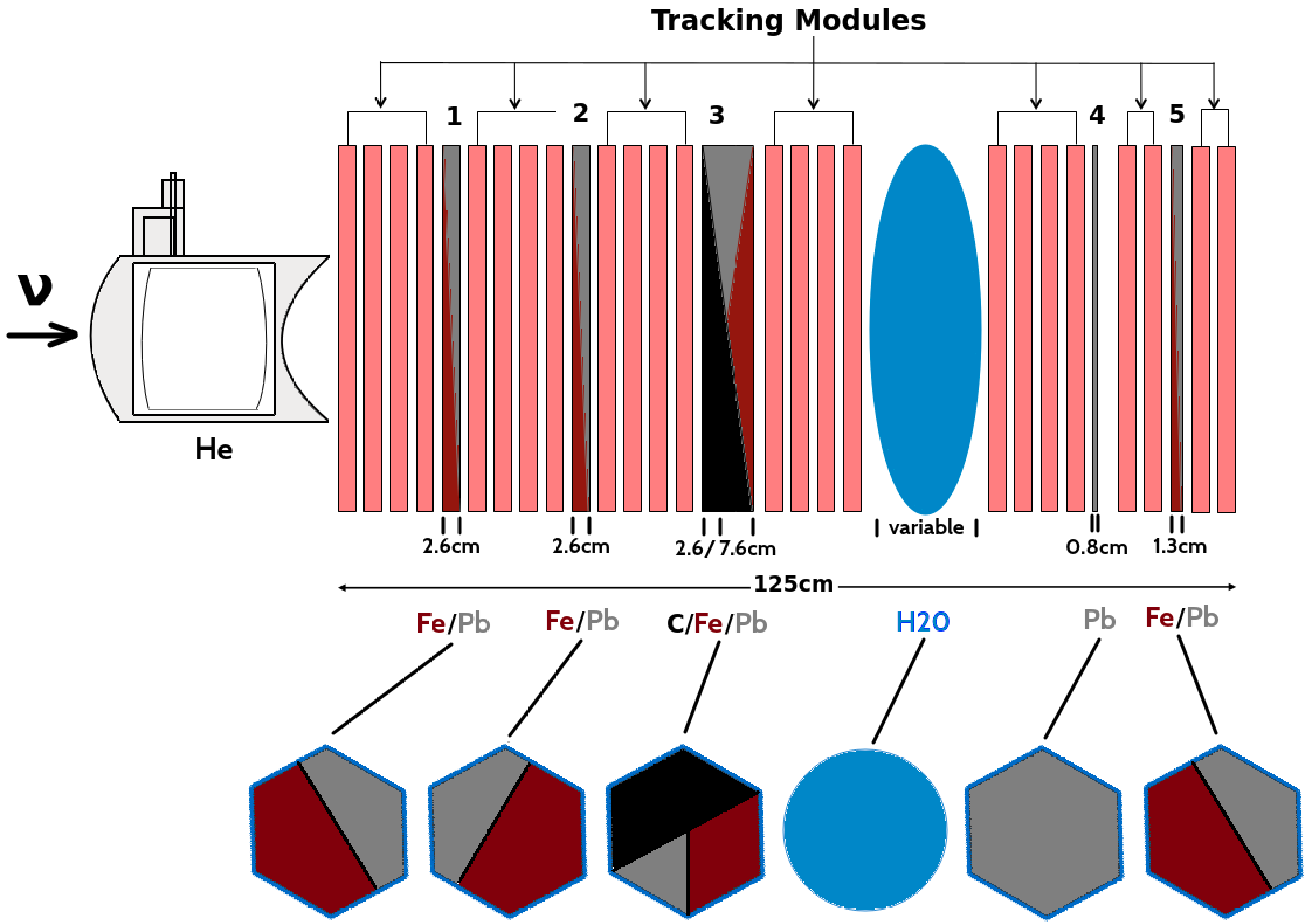
4) **World's largest statistical sample** and **most precise measurement** (using the *CH* target).

5) **First cross section ratios** of the interaction: **C/CH, Fe/CH** and **Pb/CH**.

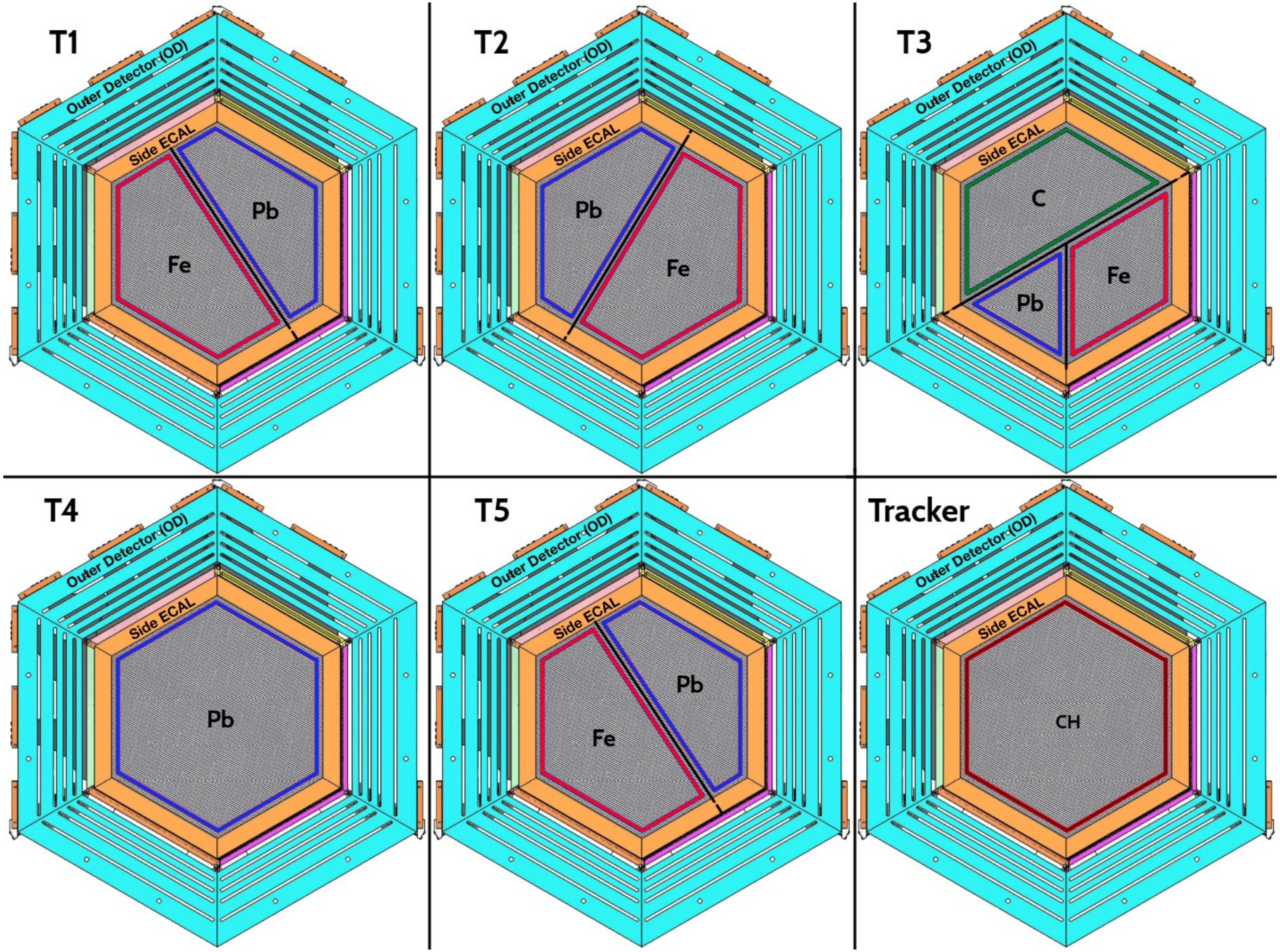
6) **Apparent energy-dependence** of the ***A*-Scaling** of the **σE_ν** cross section.


THANKS!
Muon g-2
Smash particles
MINERvA
Last Data Taken Celebration!

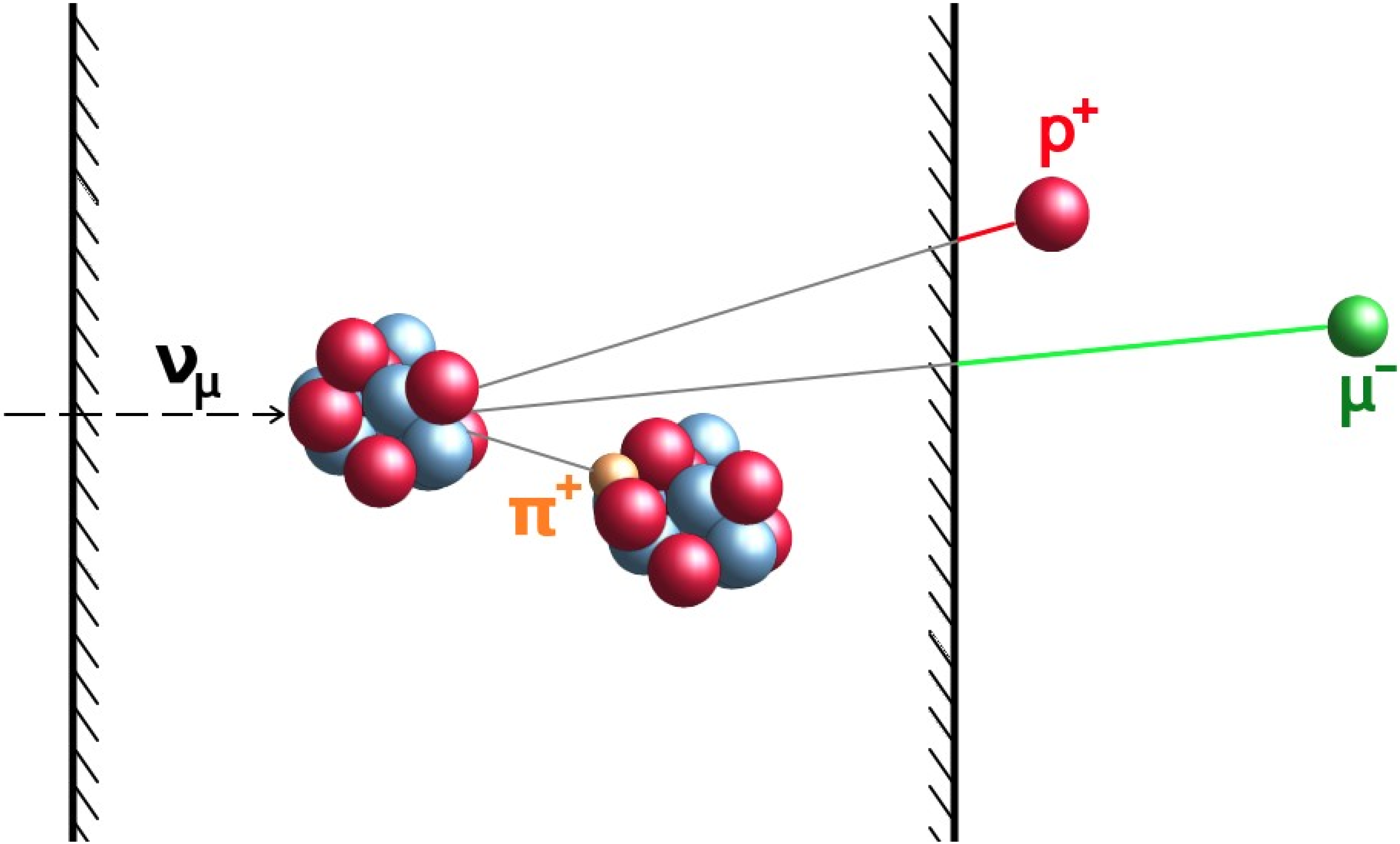
Side View of the Passive Target Region



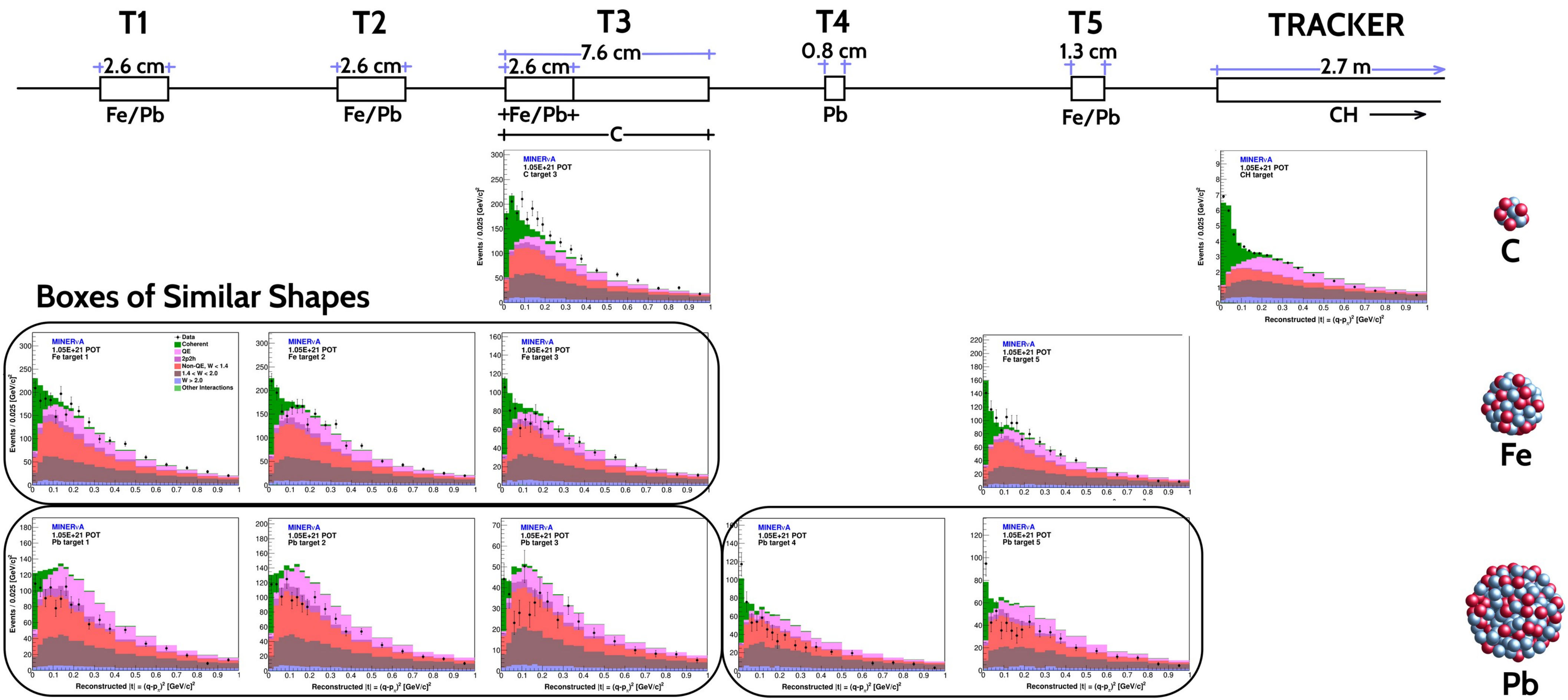
Target Segments (Beam goes out of the page)



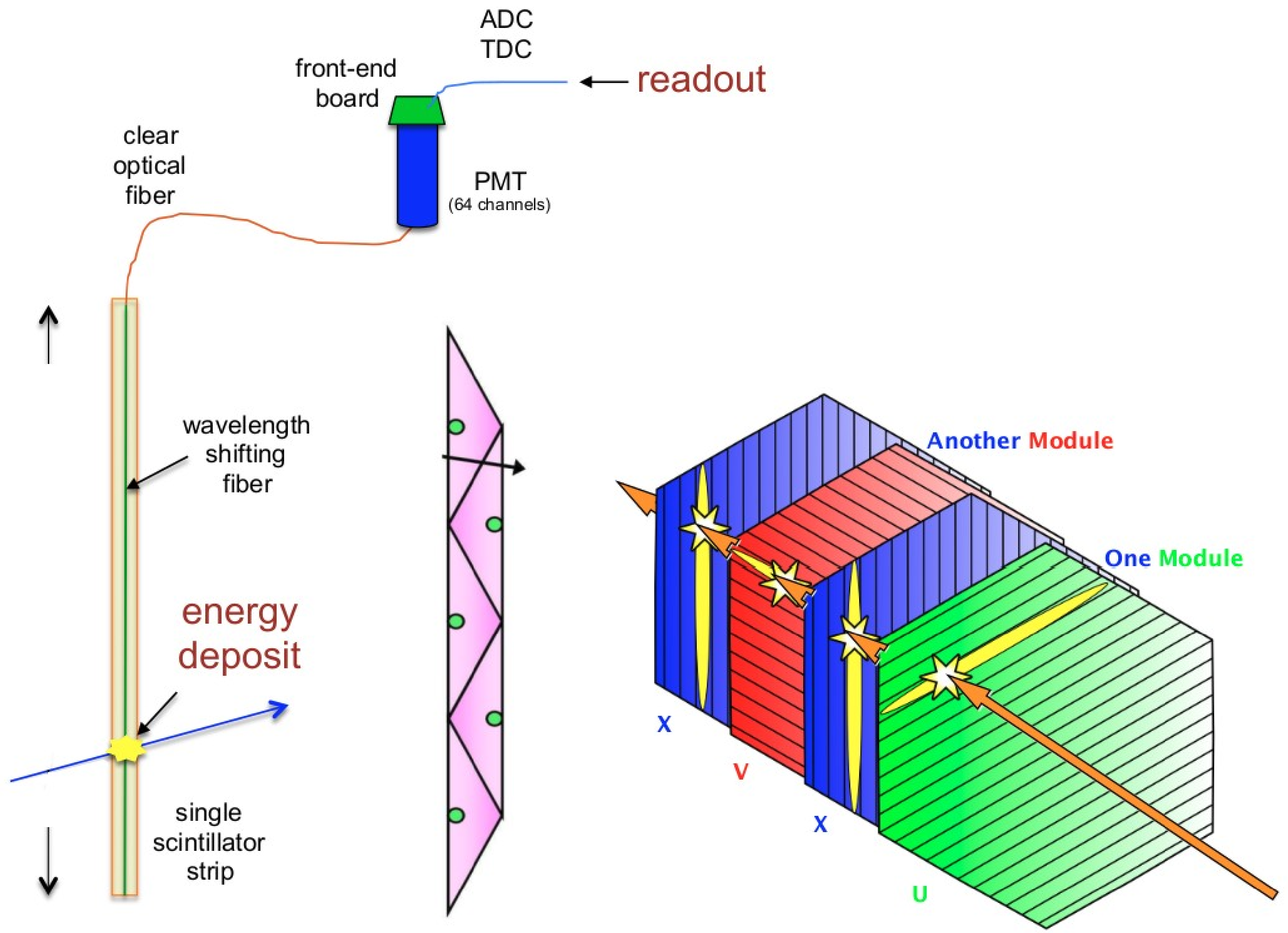
Effect of Target Thickness – Why Are C and CH |t| Shapes Different?



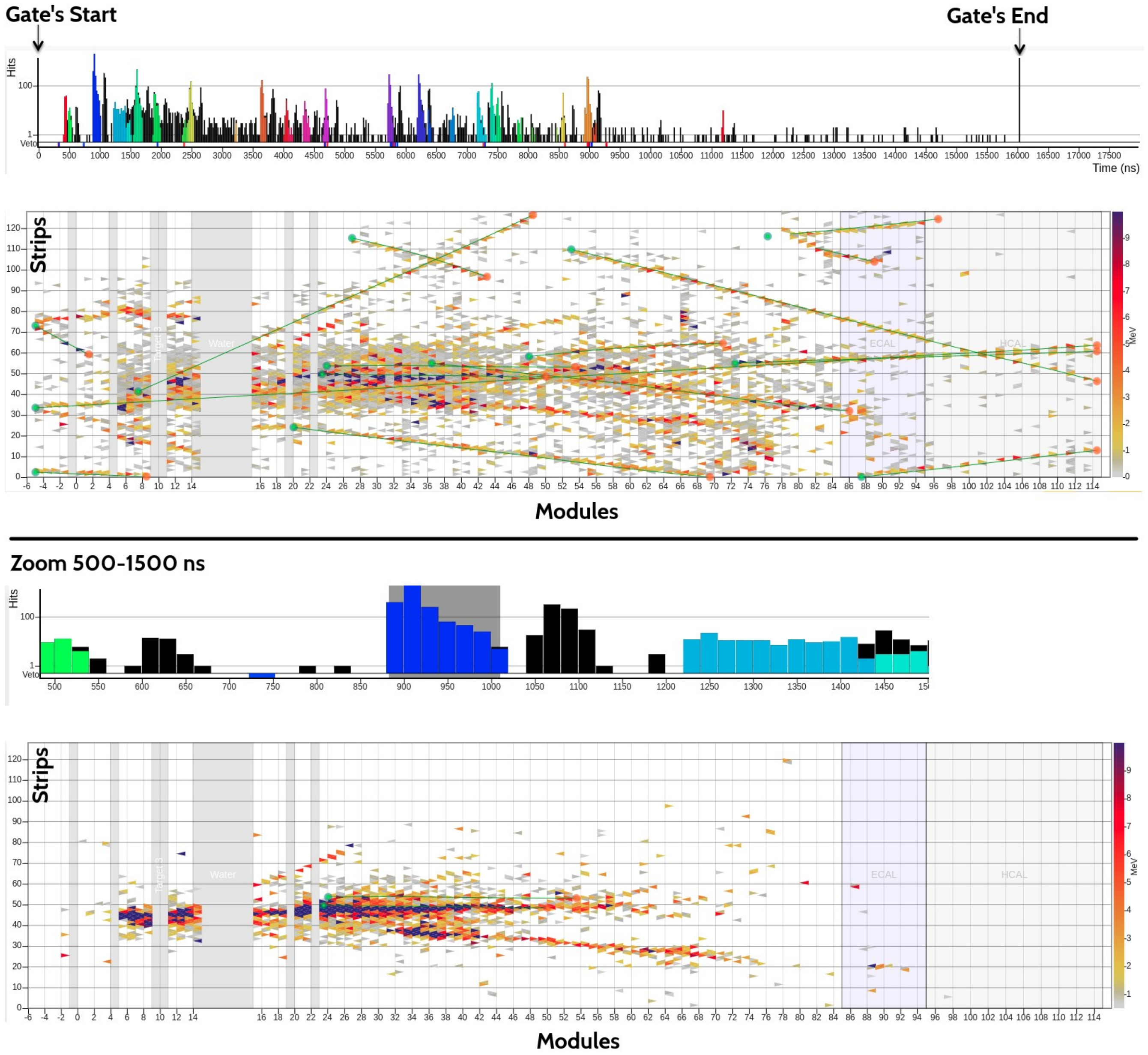
Effect of Target Thickness - |t| Shapes Depend on Thickness



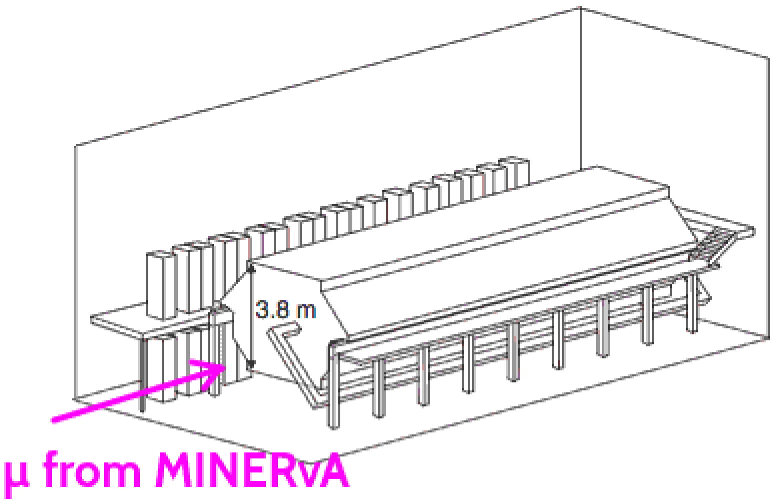
Data Acquisition

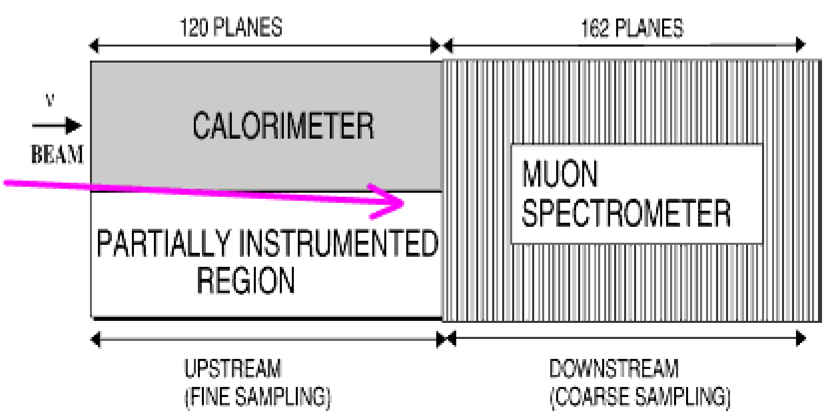


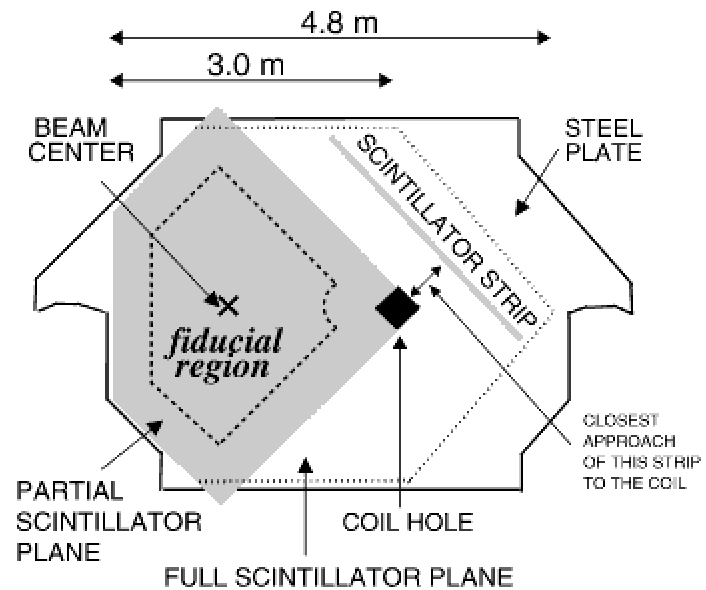
Data Acquisition



The MINOS Detector







|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

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

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:

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

Backup – Diffractive Scattering Off Hydrogen

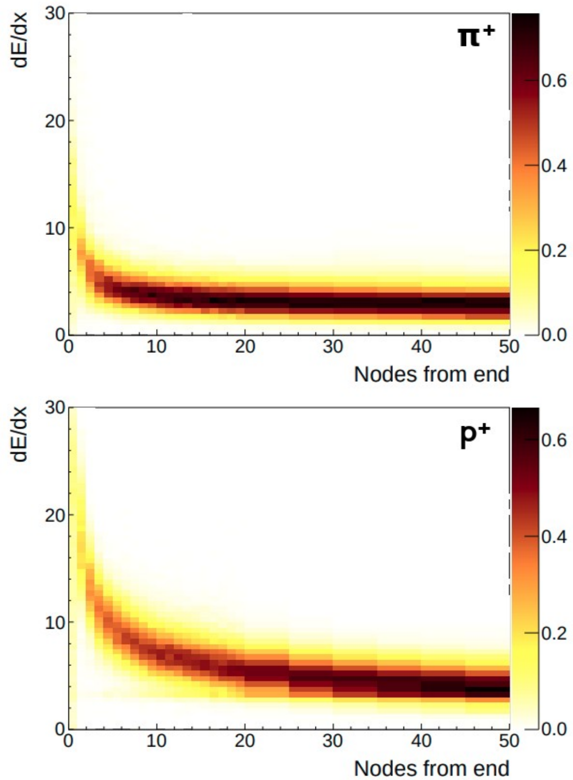
MINERvA's LE Analysis [Phys.Rev.D 97 (2018) 3, 032014]

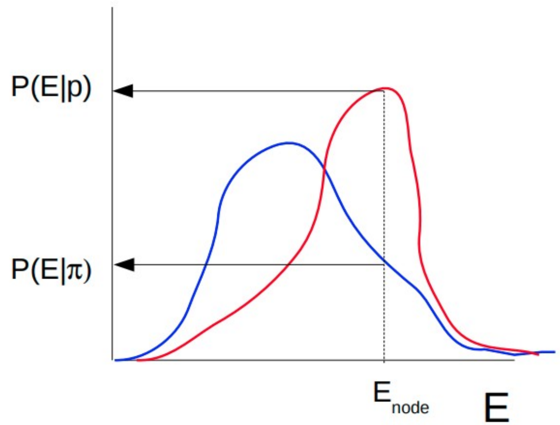
- The cross section is $\boldsymbol{\nu} + \mathbf{p} \rightarrow \boldsymbol{\pi}^+ + \mathbf{p}$
- $|t|_{dif\,f} = |(p_\nu - p_\mu - p_\pi)^2| = |(p_{p,f} - p_{p,i})^2| = 2m_p T_p$
- Because of the E_{Vtx} cut, the protons kinetic energy T_p is restricted to small values and therefore small |t|.
-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

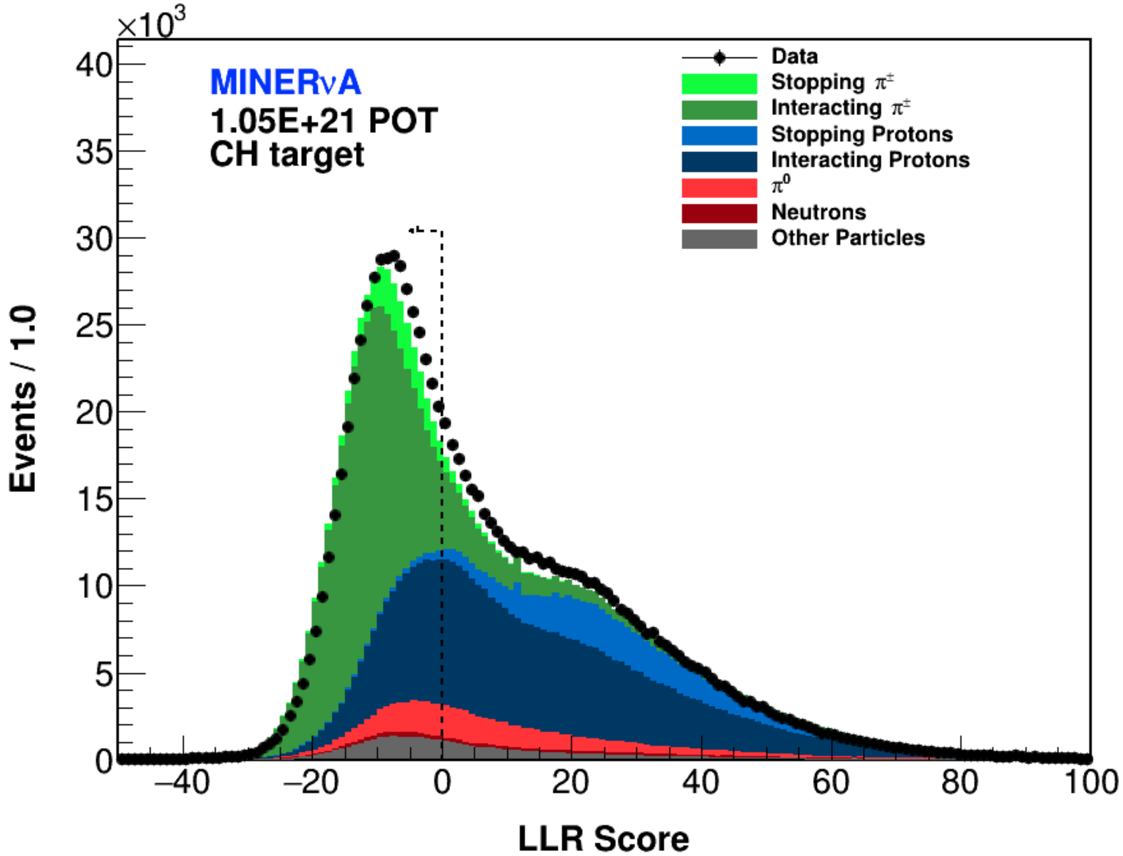
$$\frac{d\sigma}{dt} \sim A\left(E_\pi\right) e^{-b|t|}$$

- 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!

Event Selection - dE/dx Cut







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

pion/proton hypotheses

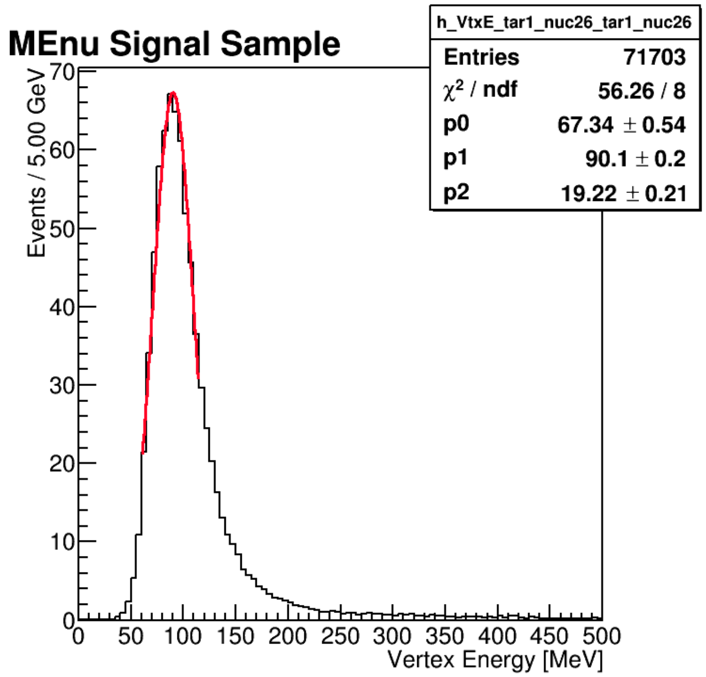
$$LR = \mathcal{L}_p / \mathcal{L}_{\pi^+}$$

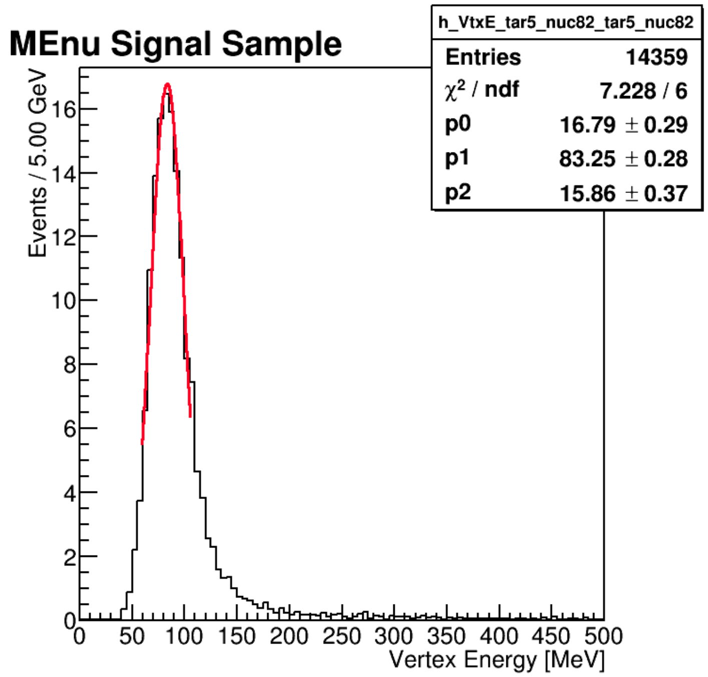
Likelihood ratio

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

E_{Vtx} Fit

- Example of T1 Fe and T5 Pb distributions of the vertex energy using signal events only.
- The $\mu \pm 1\sigma$ defines the E_{Vtx} cut.





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.

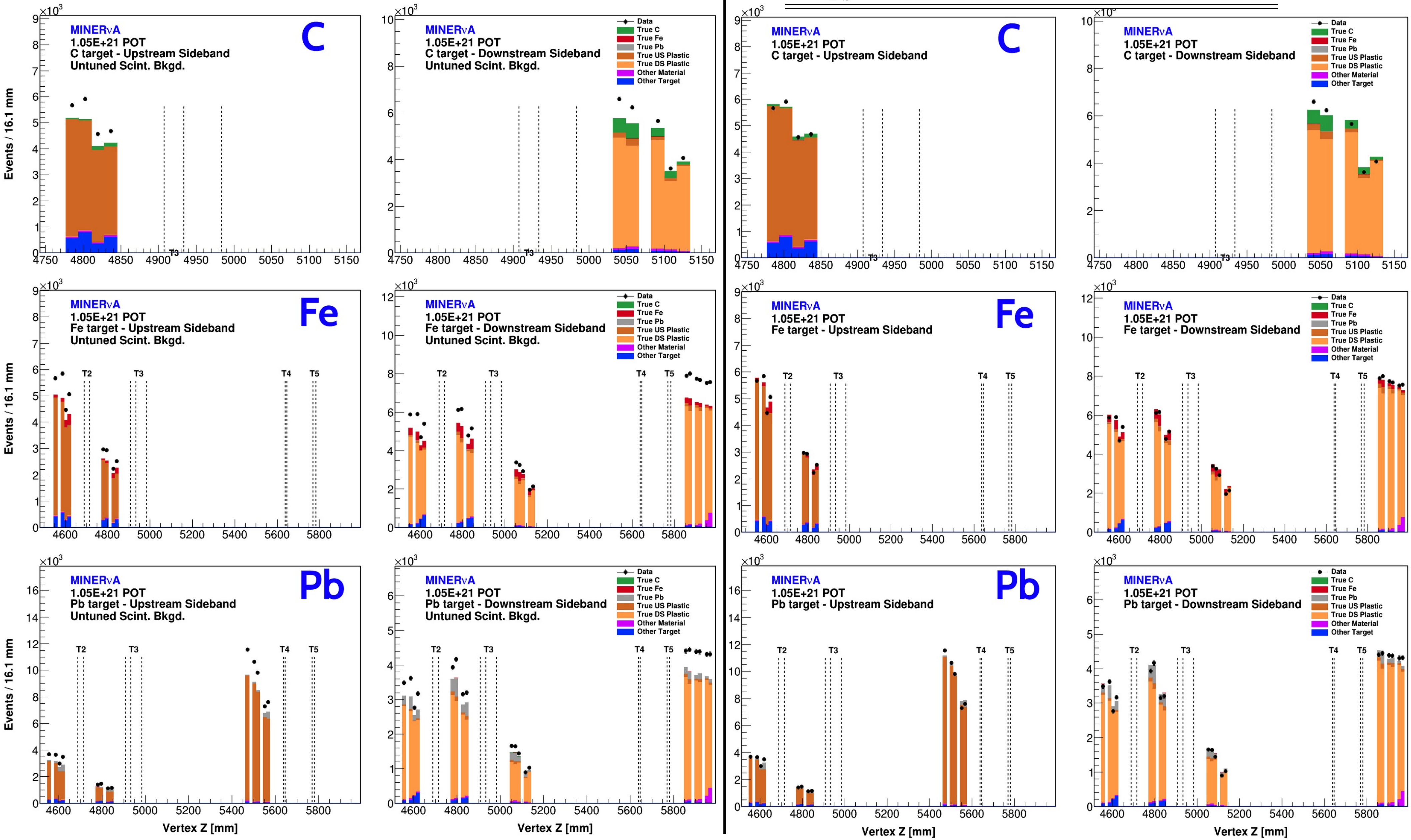
$$\chi^2 = \sum_i \left[\frac{MC^i_{signal} + MC^i_{other} + \alpha_{us} MC^i_{us} + \alpha_{ds} MC^i_{ds} - Data^i}{\sqrt{Data^i}} \right]^2$$

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

Backup – Plastic Background Tuning

Untuned vs Tuned Sidebands

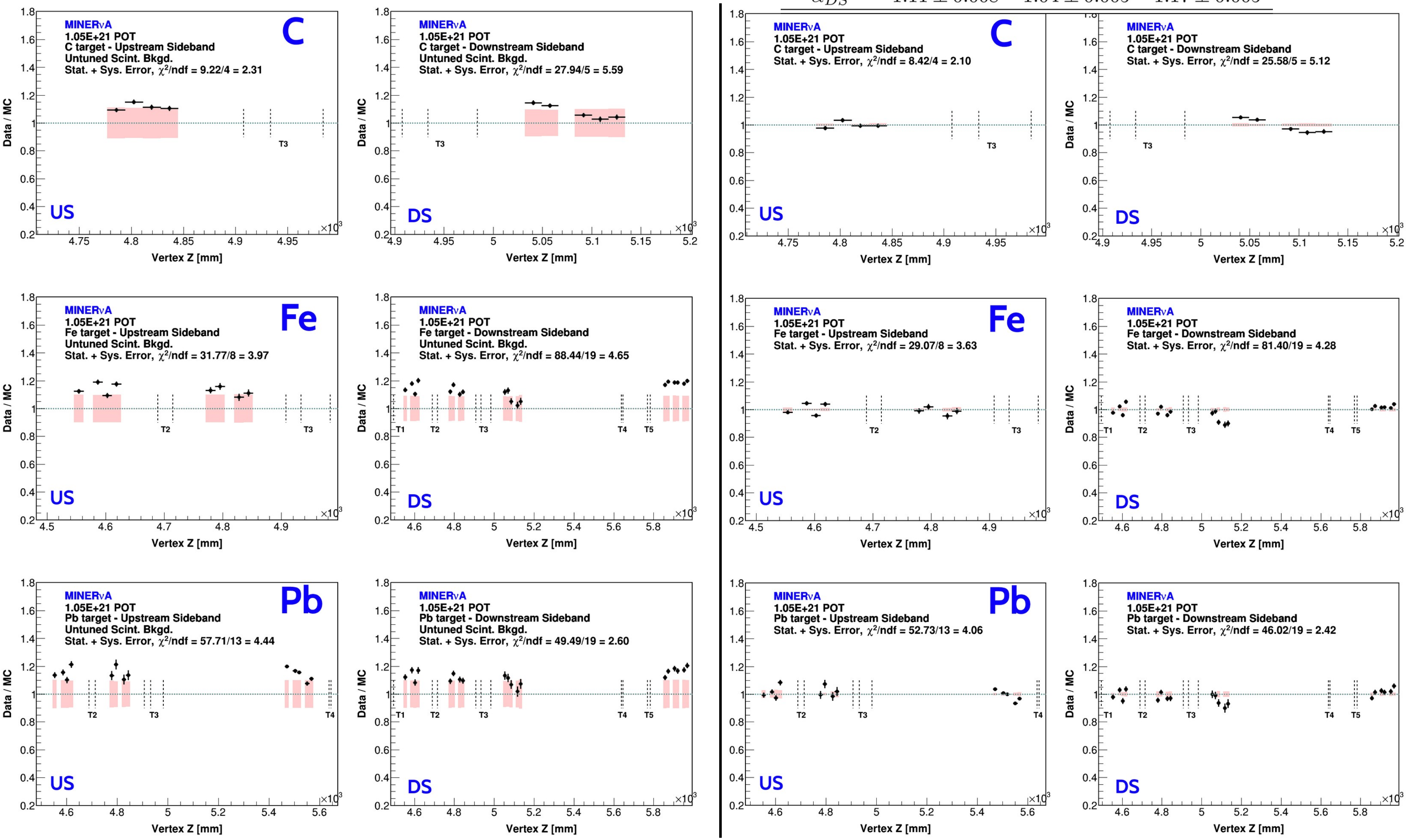
Material	C	Fe	Pb
α_{US}	1.15 ± 0.009	1.17 ± 0.004	1.16 ± 0.005
α_{DS}	1.11 ± 0.008	1.04 ± 0.005	1.17 ± 0.005



Backup – Plastic Background Tuning

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

Untuned vs Tuned Sidebands



Backup – Incoherent Background Tuning

χ^2 for High |t| Sideband

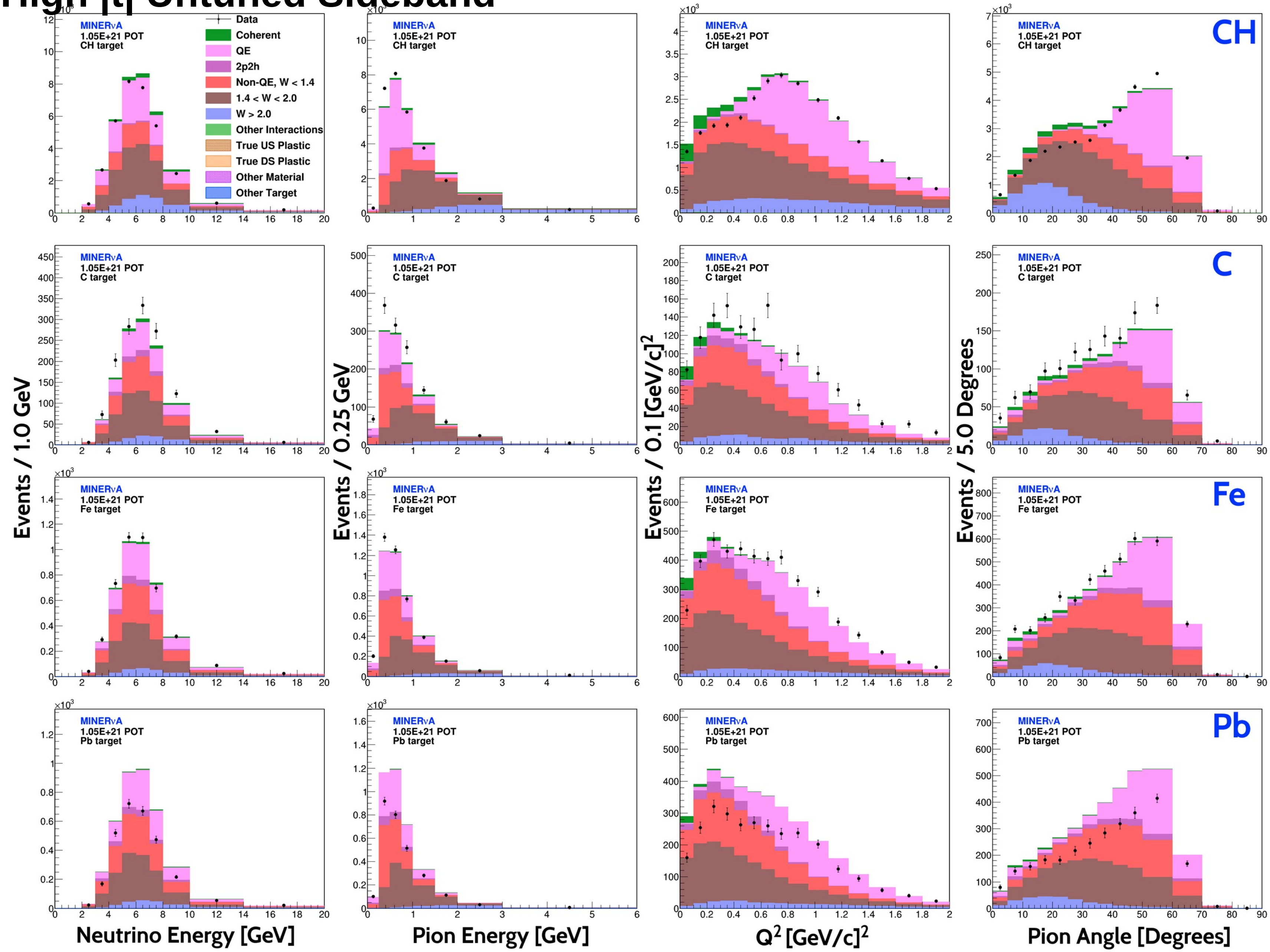
- The tuning is performed simultaneously in $\mathbf{E_\pi}$ and $\mathbf{Q^2}$ variables, after the $\mathbf{E_{vtx}}$ cut, inside the $0.2 < |t| < 0.7$ [GeV/c]^2 sideband.

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

- $\mathbf{N^{Data}}$ = 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.

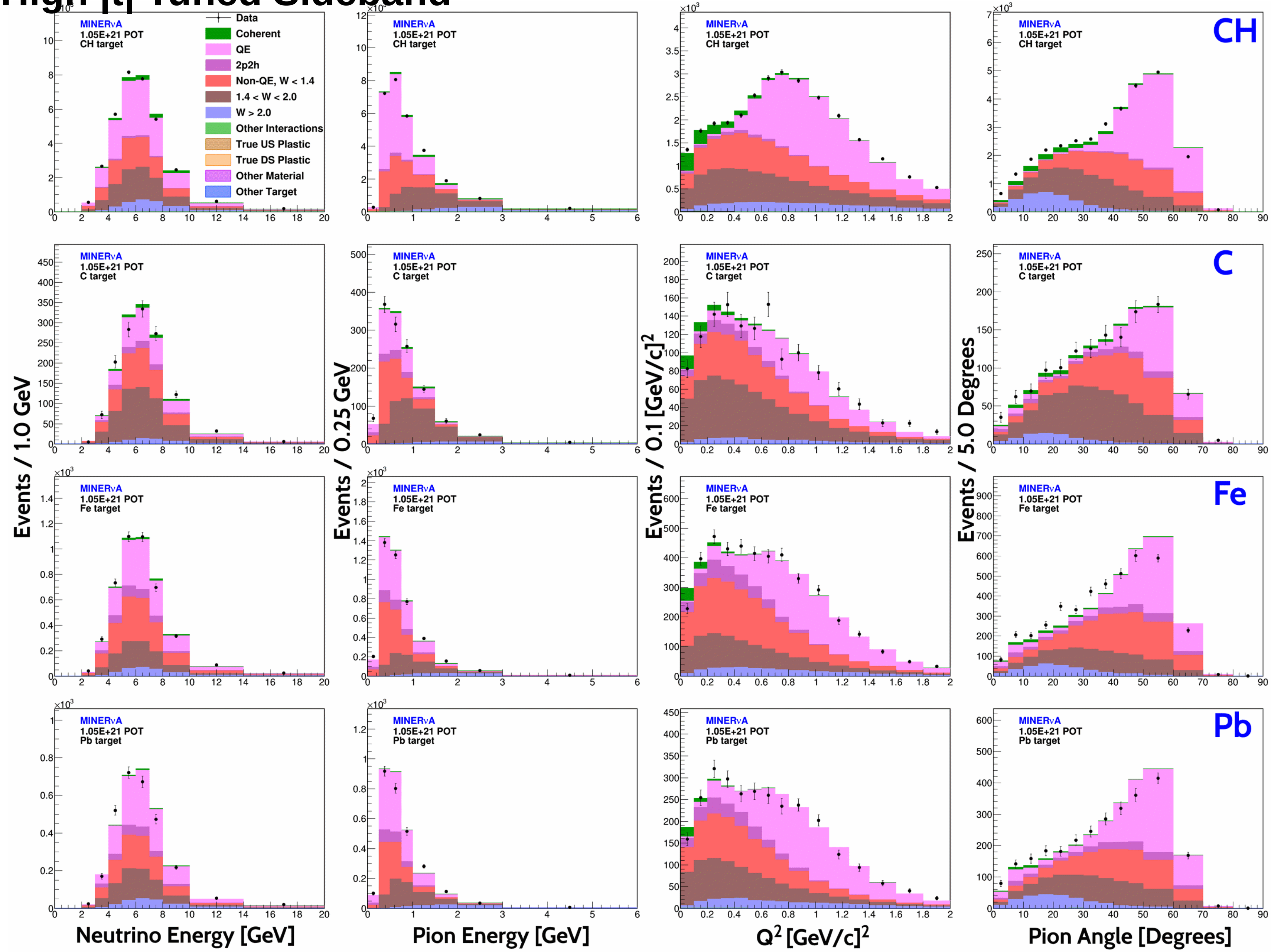
Backup – Incoherent Background Tuning

High |t| Untuned Sideband



Backup – Incoherent Background Tuning

High |t| Tuned Sideband



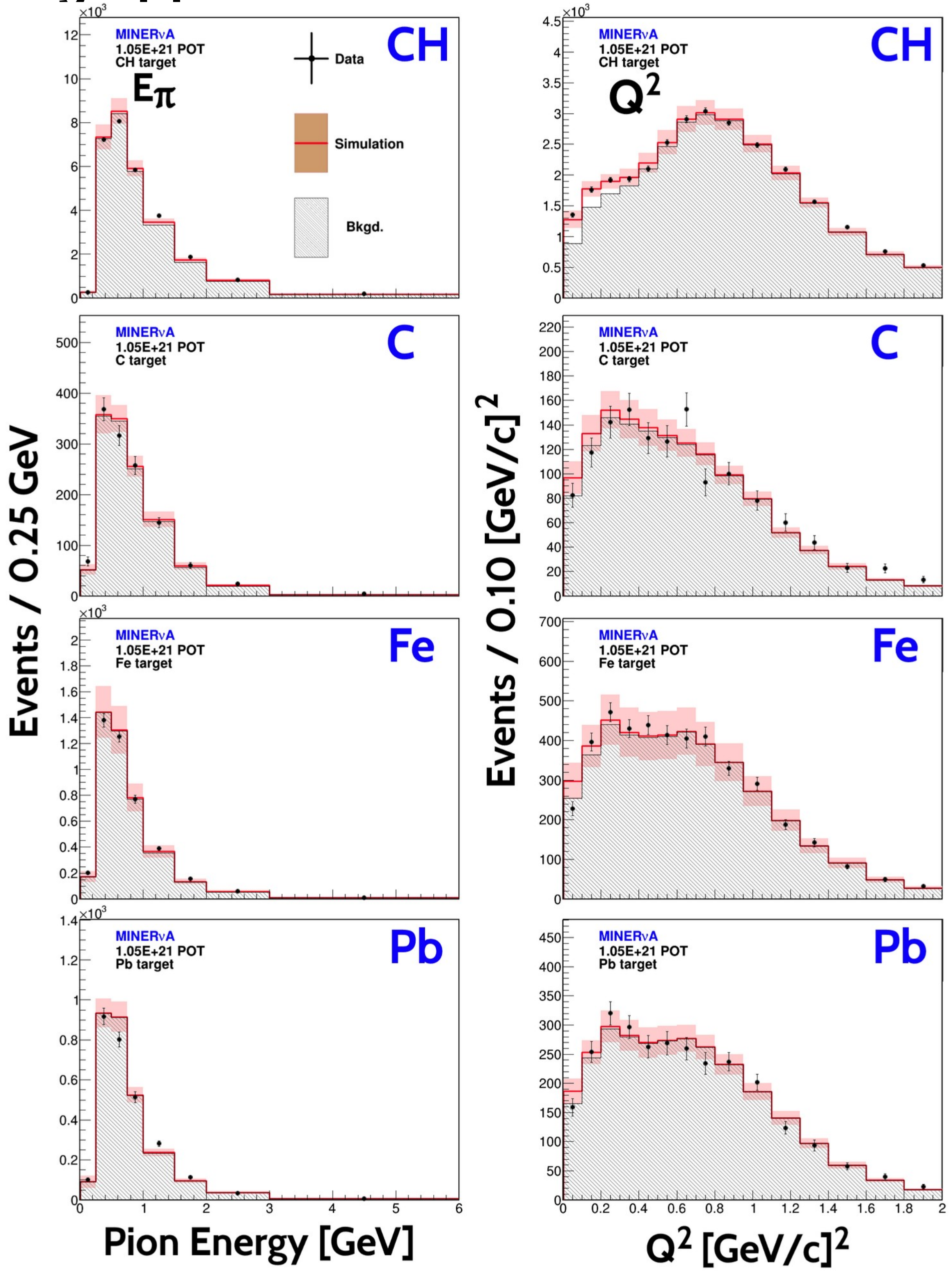
Backup – Incoherent Background Tuning

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

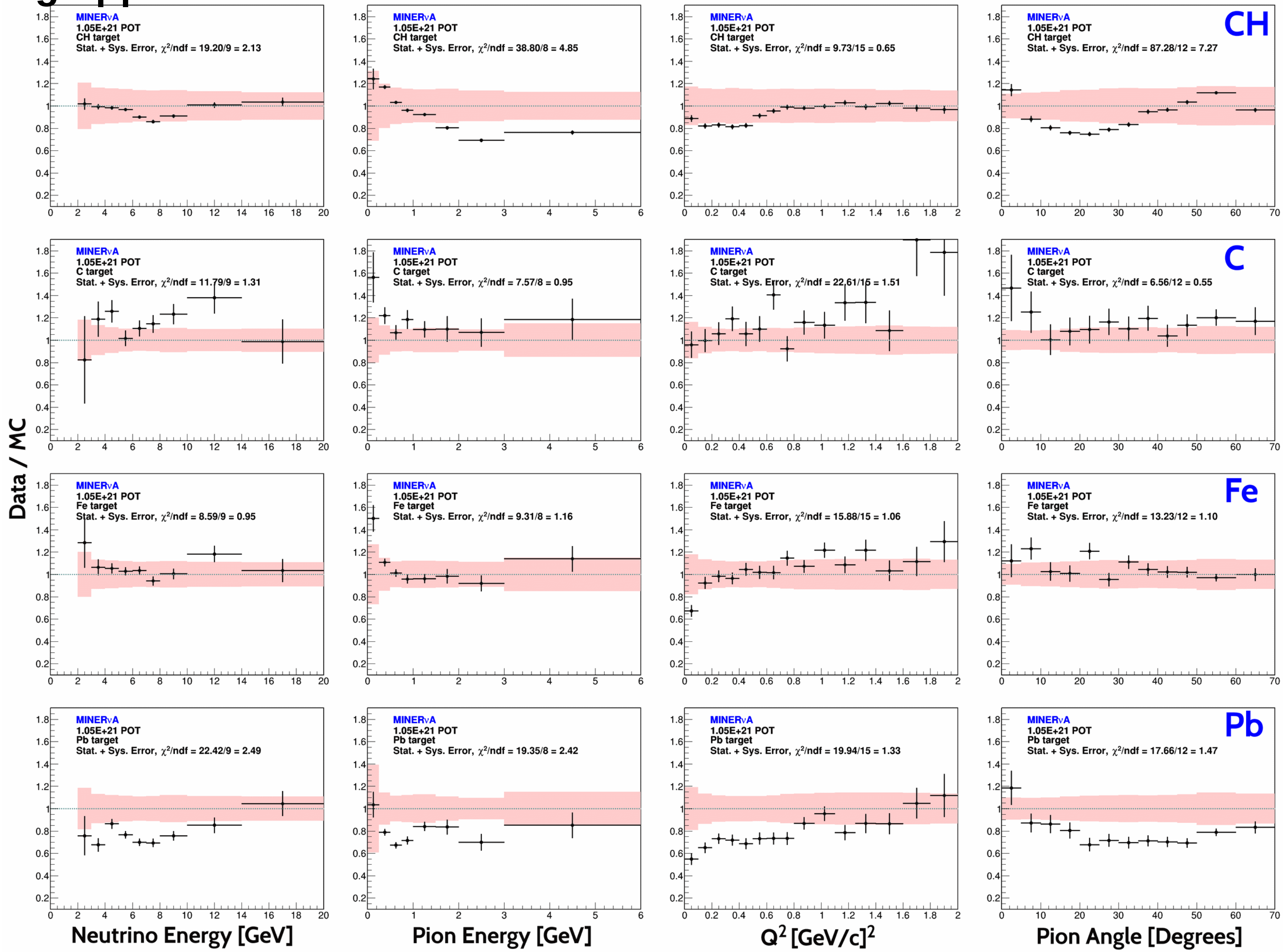


Distributions from high |t| sidebands

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

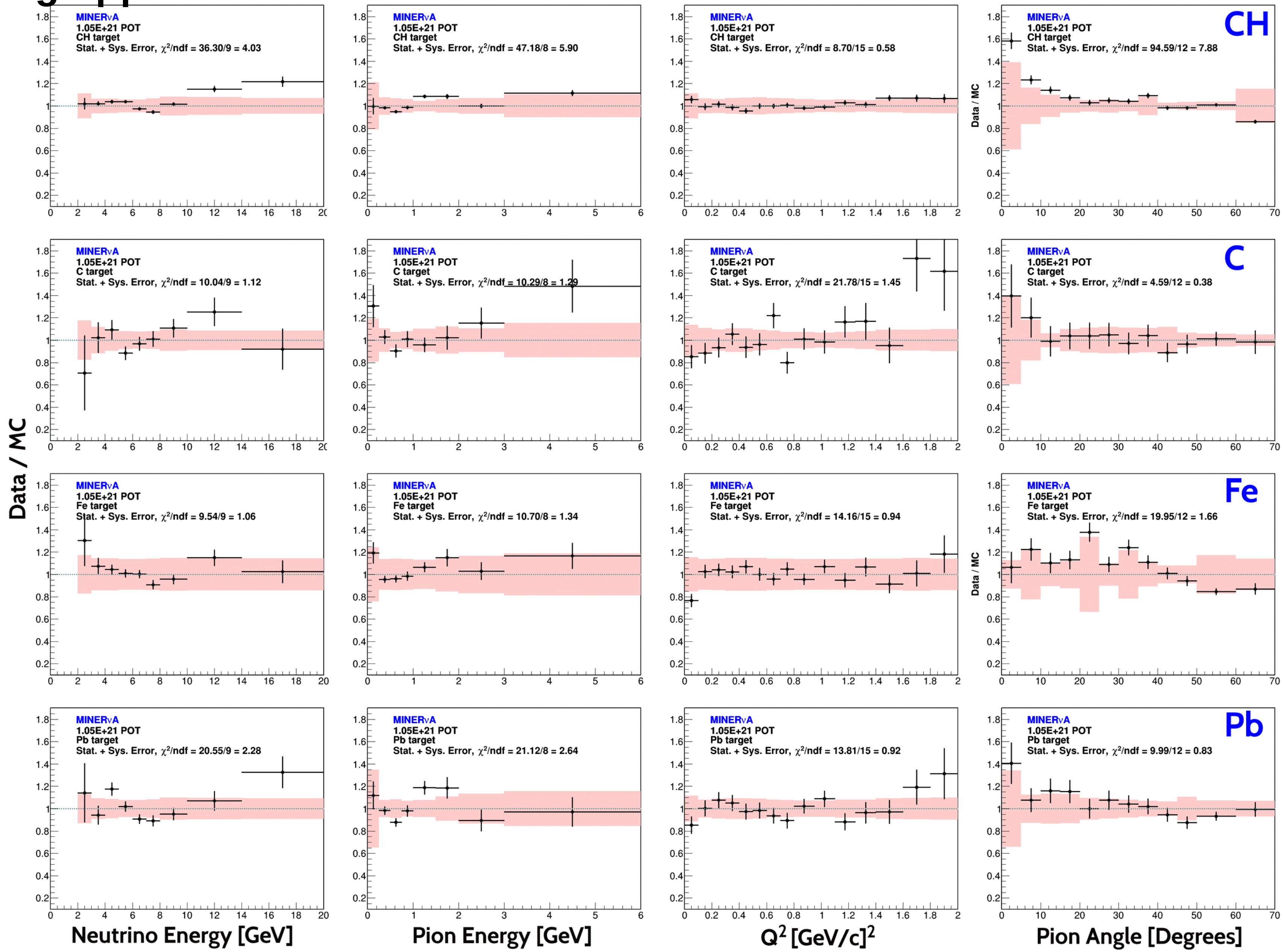
Backup – Incoherent Background Tuning

High |t| Untuned Sideband – Data/MC



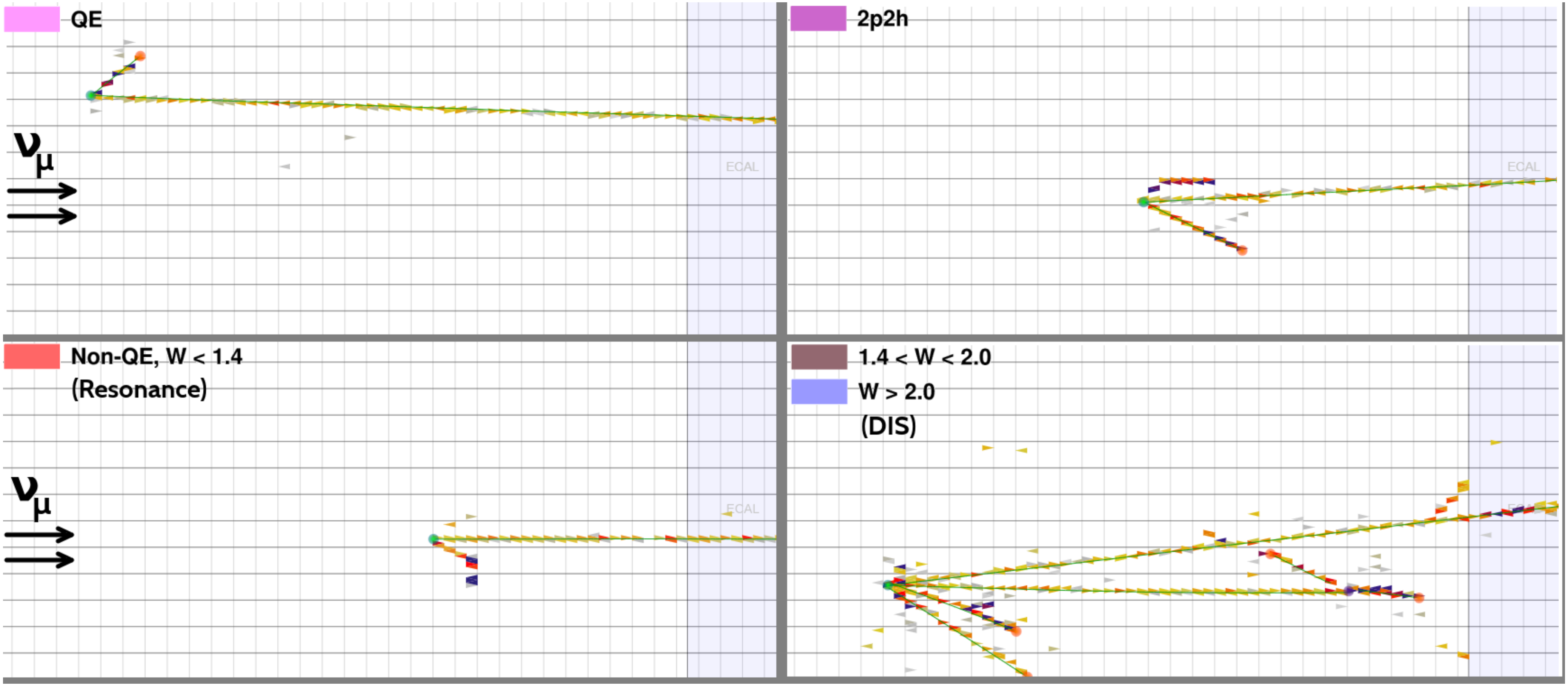
Backup – Incoherent Background Tuning

High |t| Untuned Sideband - Data/MC



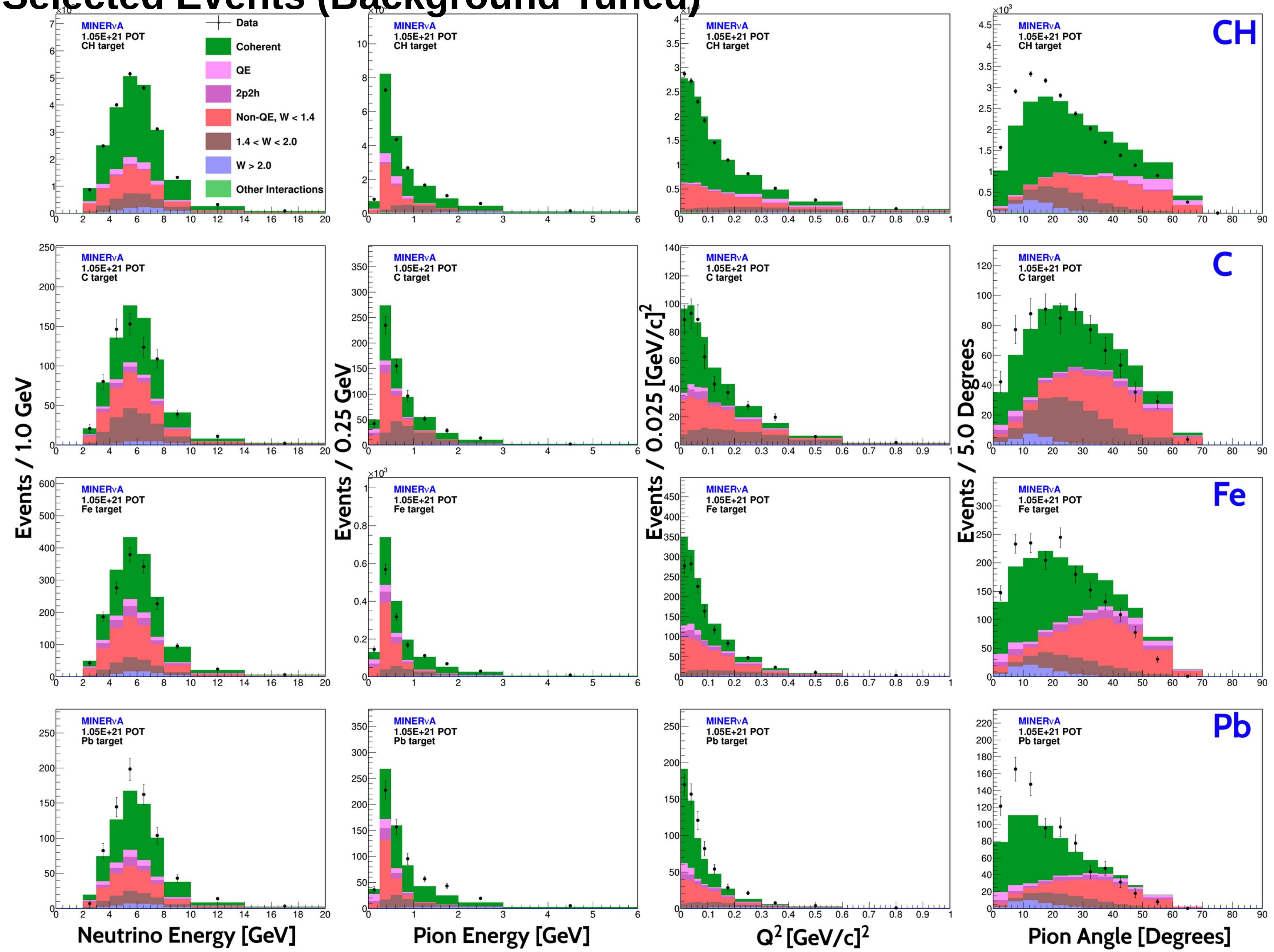
Backup – Cross Section Extraction

Backgrounds – In Terms of Invariant Mass (W)



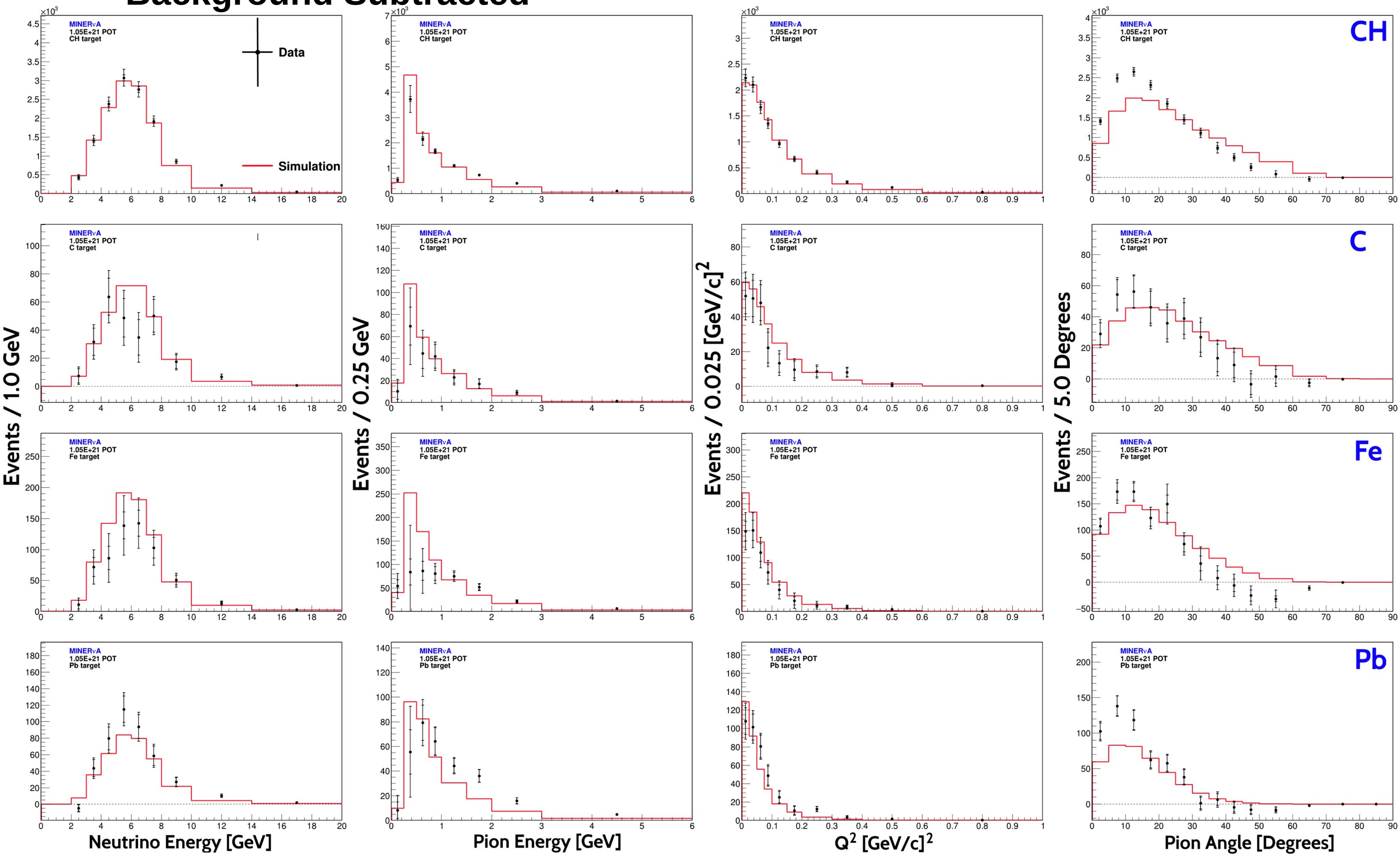
Backup – Cross Section Extraction

Selected Events (Background Tuned)

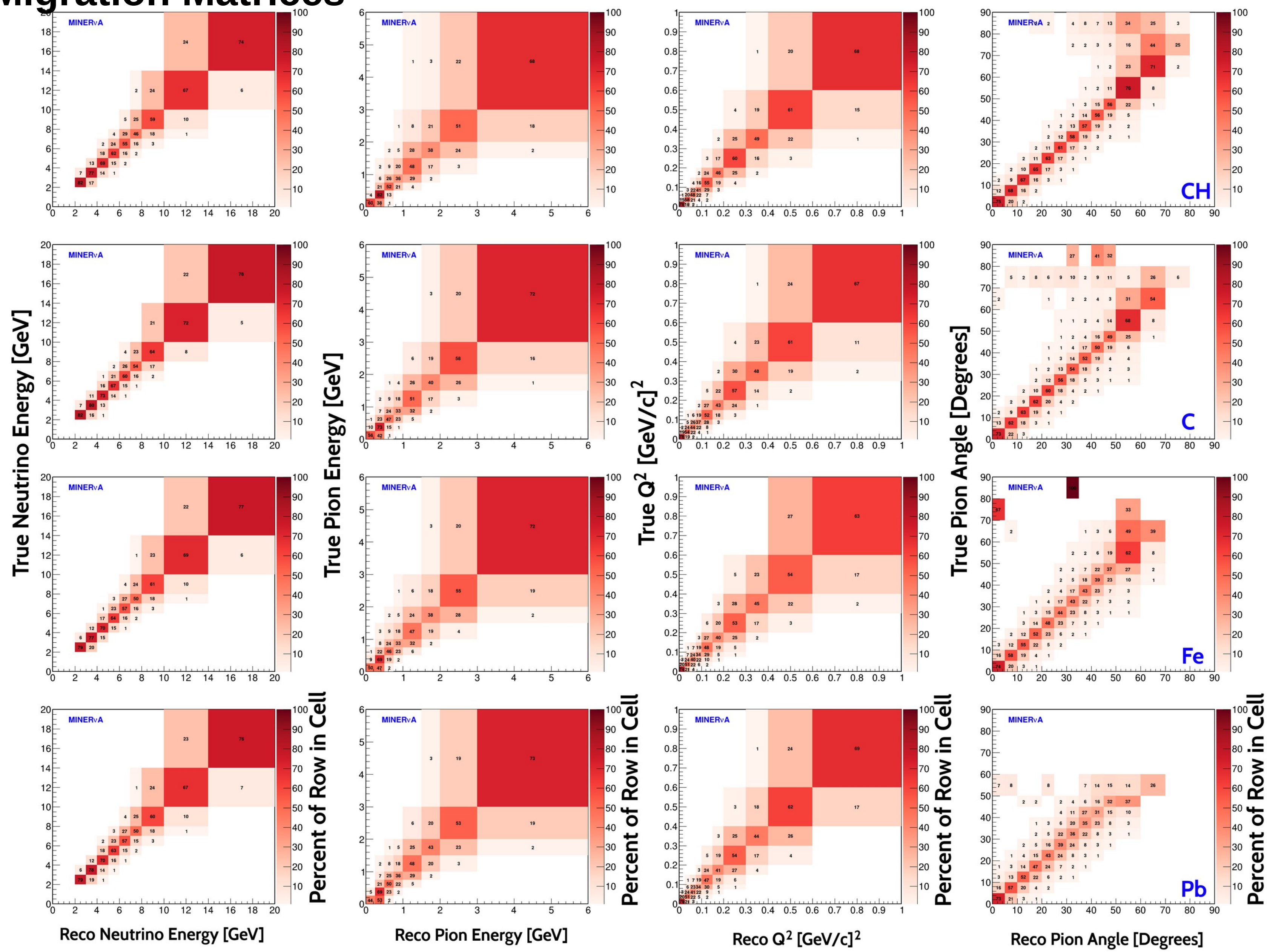


Backup – Cross Section Extraction

Background Subtracted

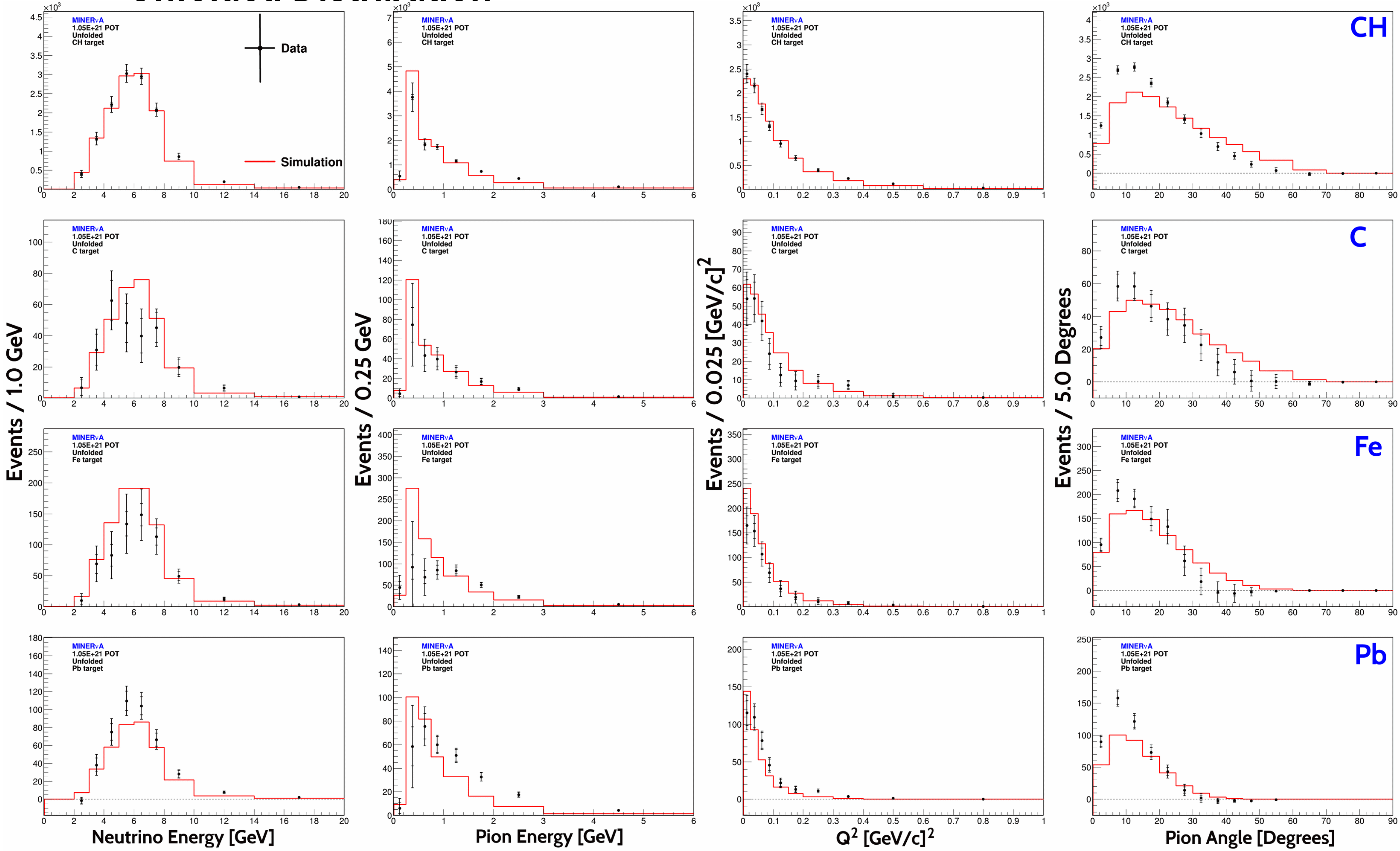


Migration Matrices



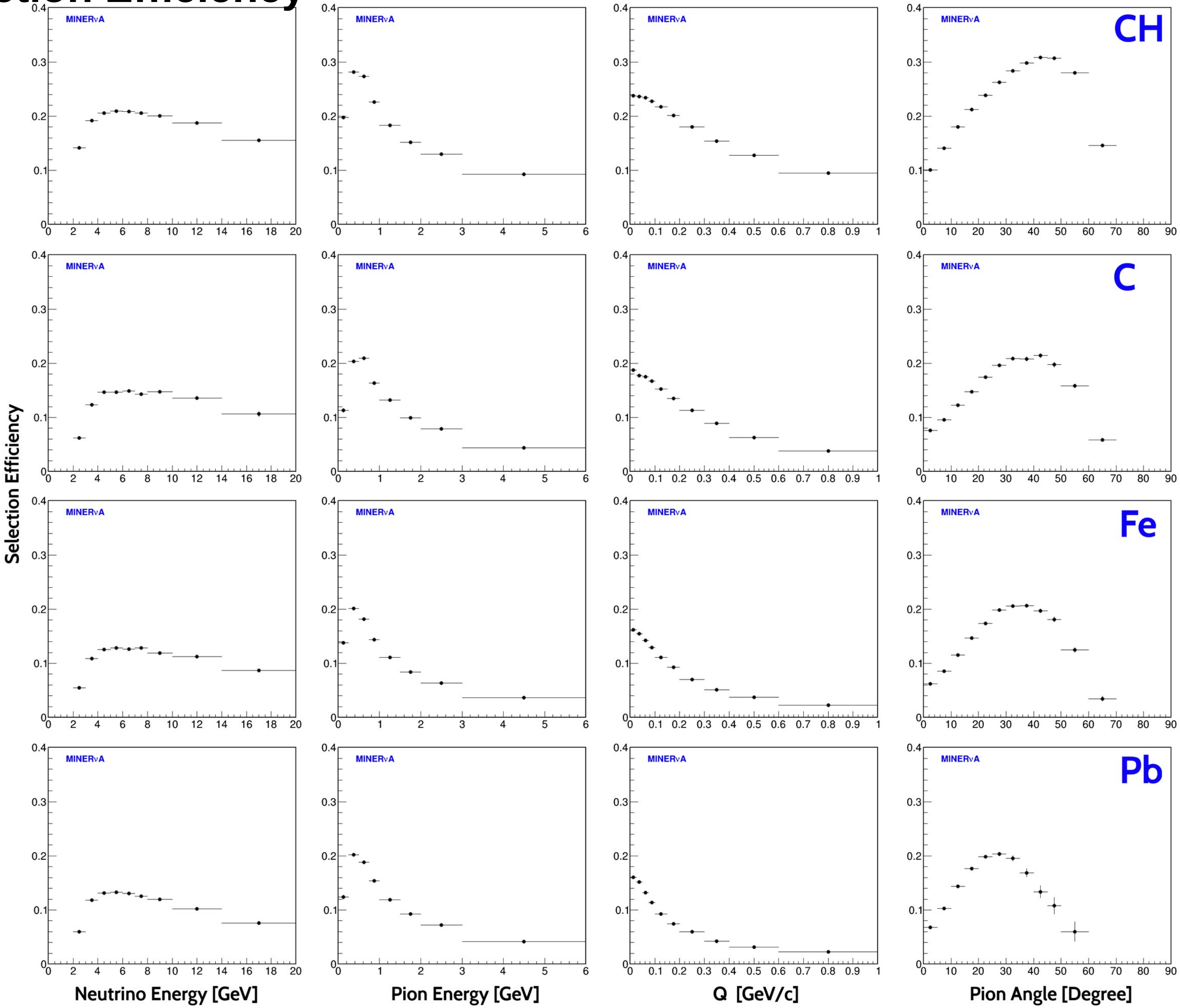
Backup – Cross Section Extraction

Unfolded Distribution



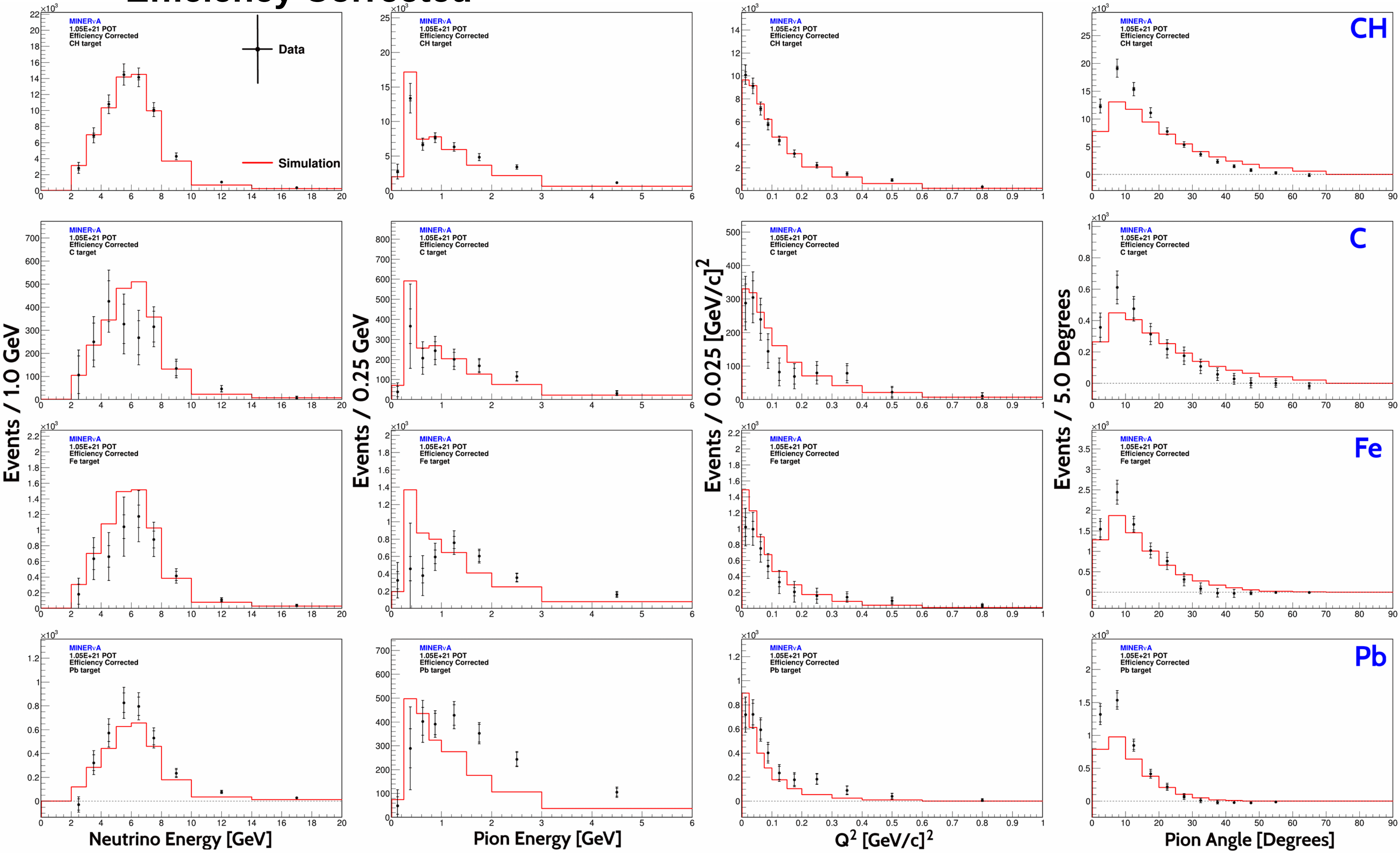
Backup – Cross Section Extraction

Selection Efficiency



Backup – Cross Section Extraction

Efficiency Corrected



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.

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 $A^{1/3}$ as in the Rein-Sehgal model. Using $A^{2/3}$ yields similar values

Penn University of Pennsylvania

Correction Due To Other Materials in the Fiducial Volume

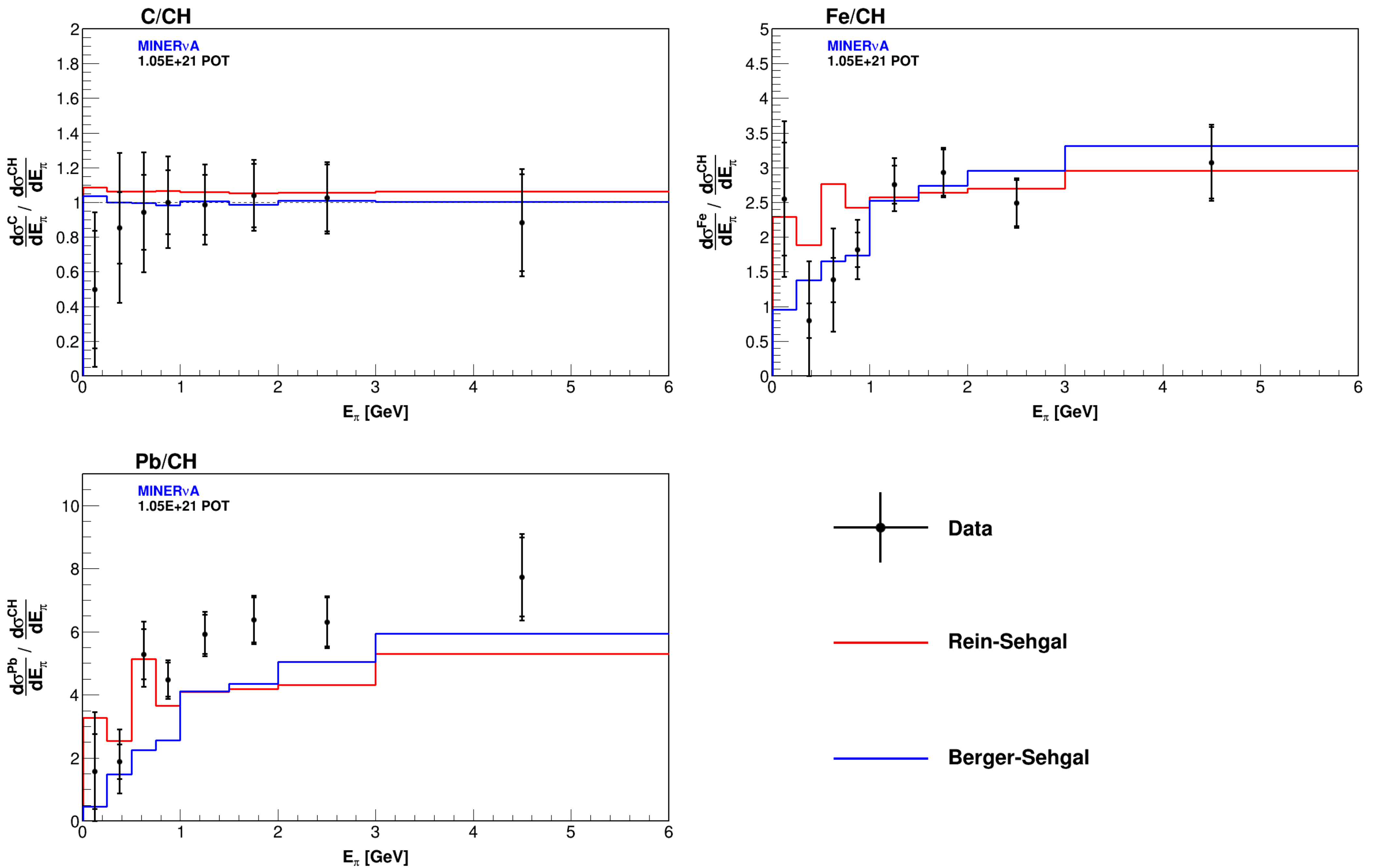
$$\sigma_i = \beta \frac{\sum_j U_{ij} \left(N_j^{DATA} - N_j^{BKGD}\right)}{\epsilon_i \phi_i T}$$

- 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 Nuclei: T

Material	β
CH	0.96
C	1.0
Fe	0.98
Pb	1.0

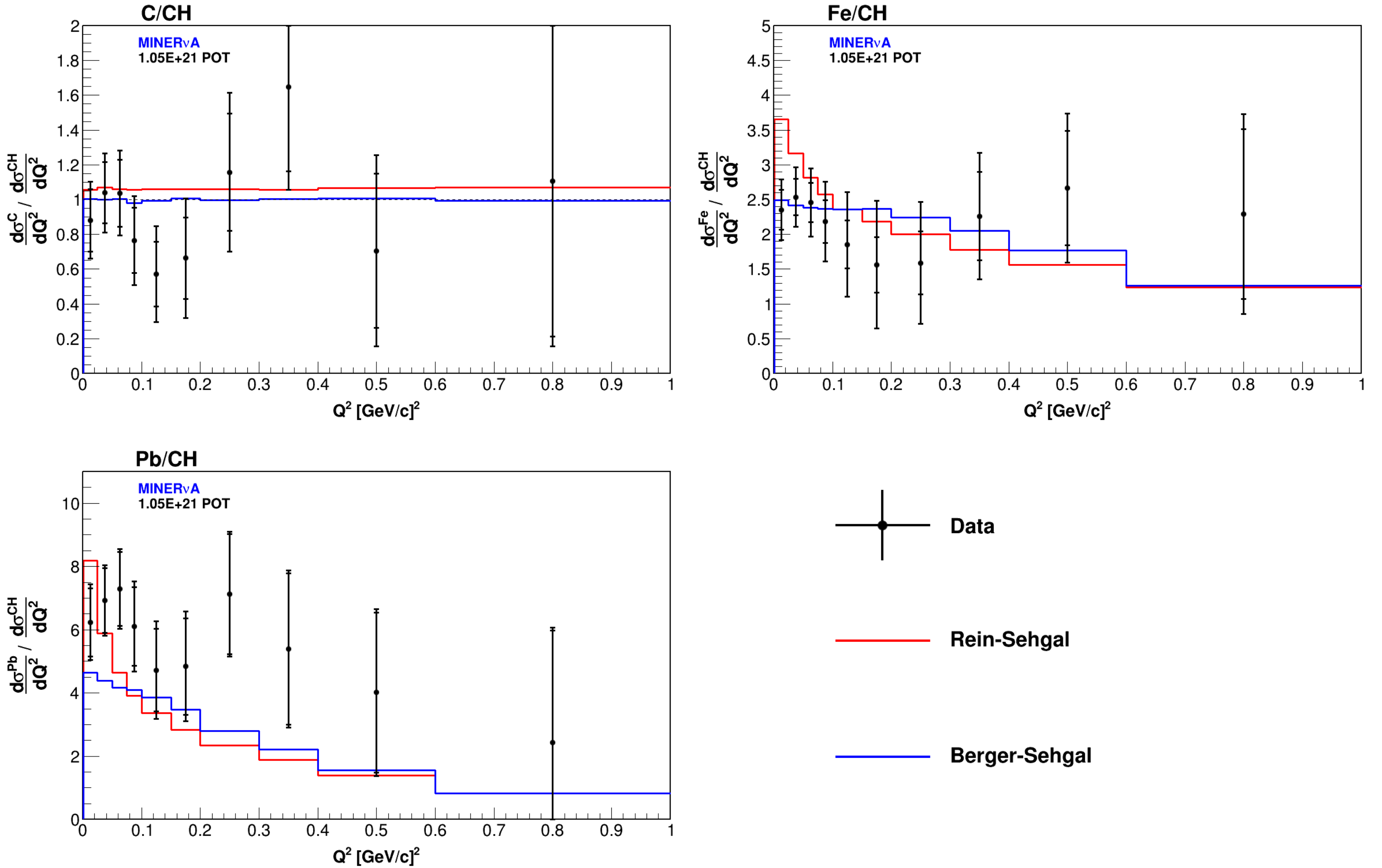
Backup – Results – Cross Section Ratios

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



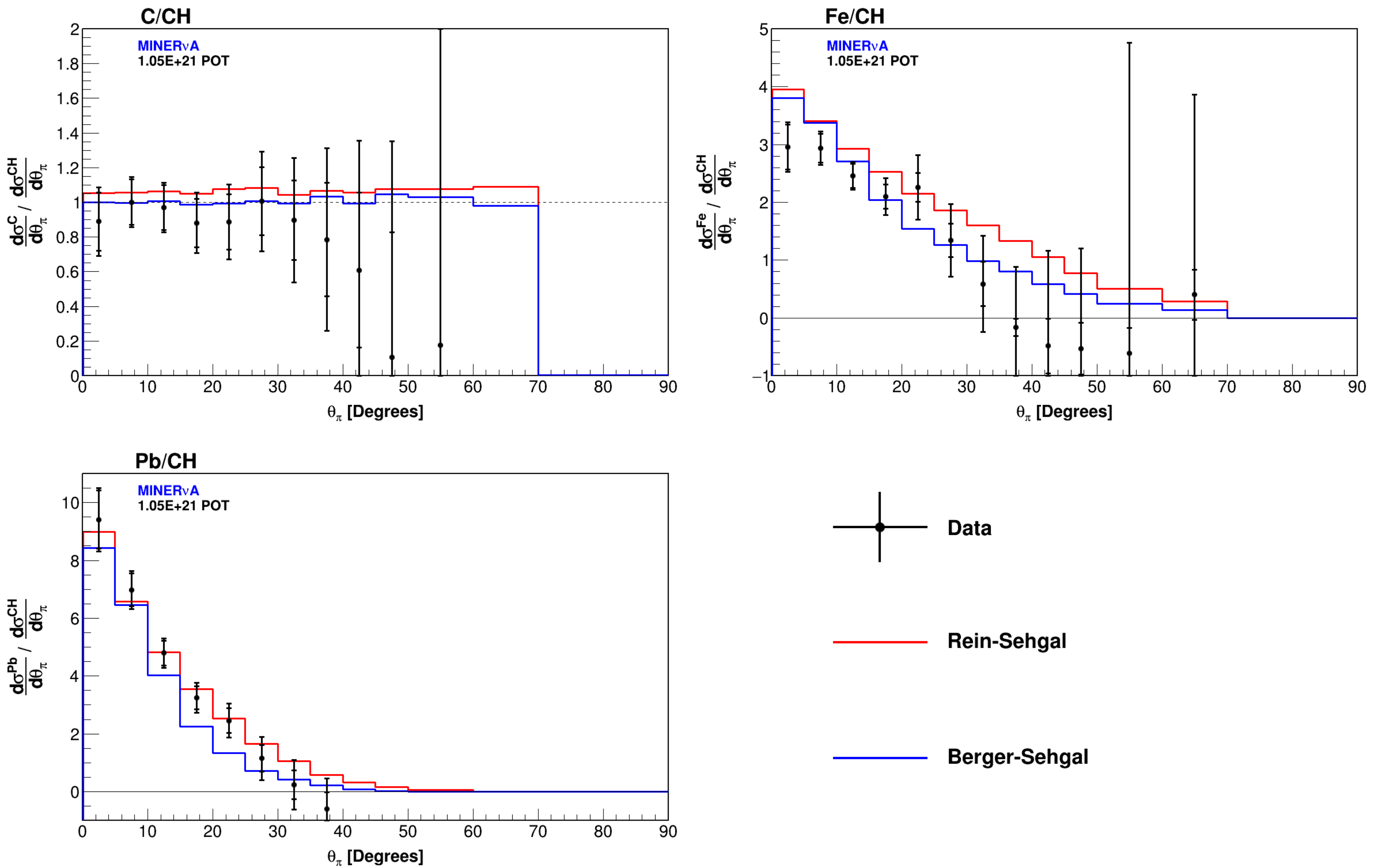
Backup – Results – Cross Section Ratios

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



Backup – Results – Cross Section Ratios

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



Backup – 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]**

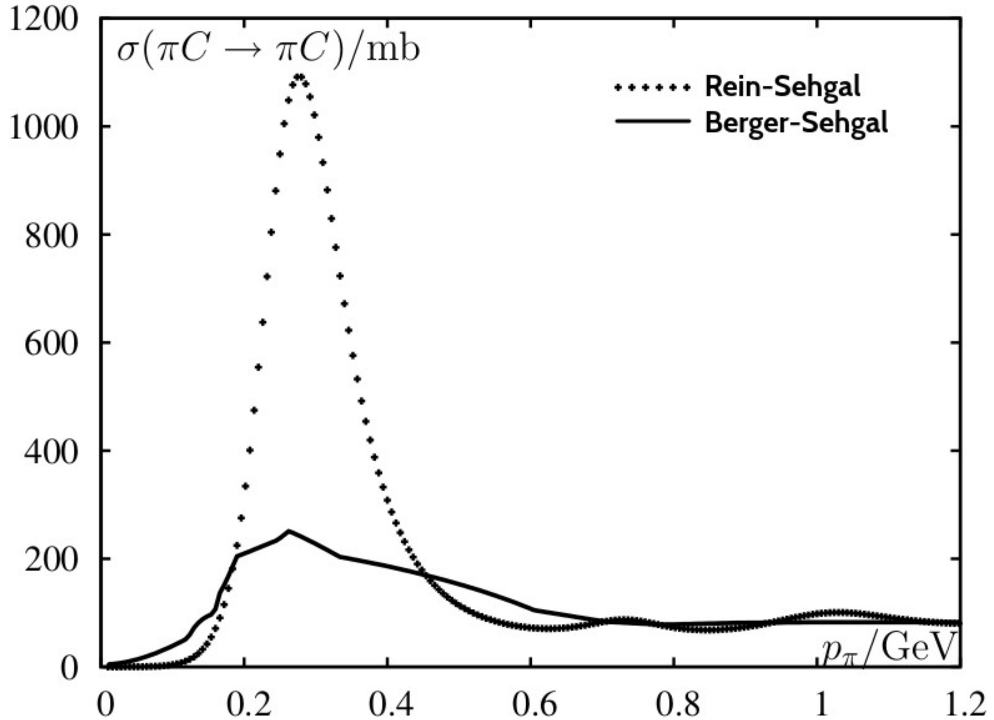
- Axial current dominated by heavy meson fluctuations, $\mathbf{a}_1$ or $\boldsymbol{\rho\pi}$ system.
- Predicts energy-dependent A-scaling of the cross section.

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)]**

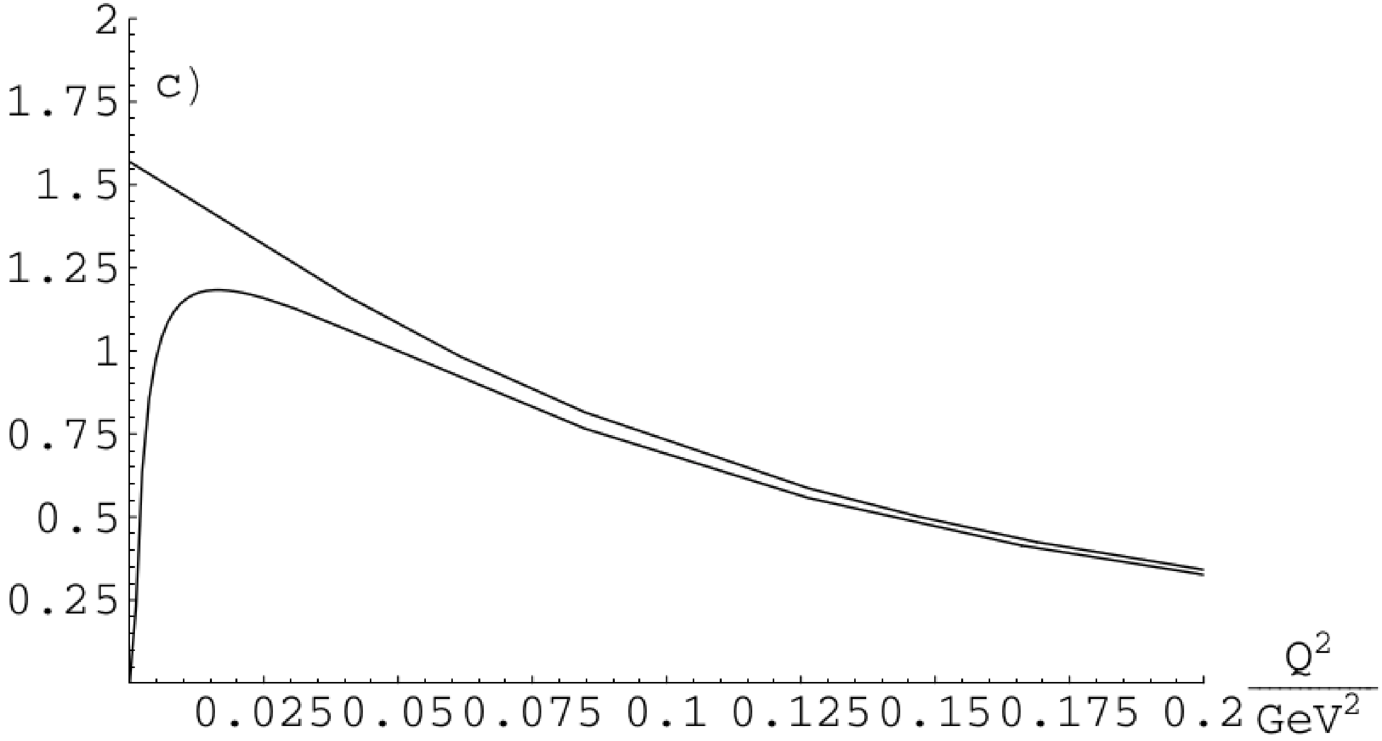
- Consider the individual contribution of nucleons to the cross section. π production obtained through baryon Δ resonances.
- Valid for Eν < 2 GeV.



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 $Q^2 < 0.1\ [\mathrm{GeV/c}]^2$ 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**	$< E_{\nu(\overline{\nu})} >$, **range** $[GeV]$	**MATERIAL**	$< A >$
NC					
Aachen-Padova	1983	$\nu/\overline{\nu}$	2	Al	27
Garmamelle	1984	$\nu/\overline{\nu}$	2	CF_3Br (Freon)	36
SKAT	1985	$\nu/\overline{\nu}$	7	CF_3Br (Freon)	36
CHARM	1985	$\nu/\overline{\nu}$	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**	$< E_{\nu(\overline{\nu})} >$, **range** $[GeV]$	**MATERIAL**	$< A >$
CC					
WA59	1984	$\overline{\nu}$	40	NeH_2	20
SKAT	1986	$\nu/\overline{\nu}$	7	CF_3Br (Freon)	36
BEBC WA59	1986	$\overline{\nu}$	5-150	Ne	20
E632	1989	$\nu/\overline{\nu}$	150 (110)	Ne	20
BEBC WA59	1989	ν	5-150	Ne	20
CHARM II	1993	$\nu/\overline{\nu}$	20	Glass	20.7
E632	1993	$\nu/\overline{\nu}$	80 (70)	Ne	20
K2K	2005	ν	1.3	C	12
SciBooNE	2009	ν	1.1	C	12
MINERvA (LE)	2014	$\nu/\overline{\nu}$	3.6	C	12
ArgoNeuT	2015	$\nu/\overline{\nu}$	9.6 (3.6)	Ar	40
T2K	2016	ν	< 1.5	C	12
MINERvA (ME)	2022	ν	6	C, **Fe**, **Pb**	12, **56**, **207**