Measurement of A-scaling of nuclear effects in quasielastic-like cross sections at MINERvA as a function of muon and proton kinematics at E_ν=6GeV

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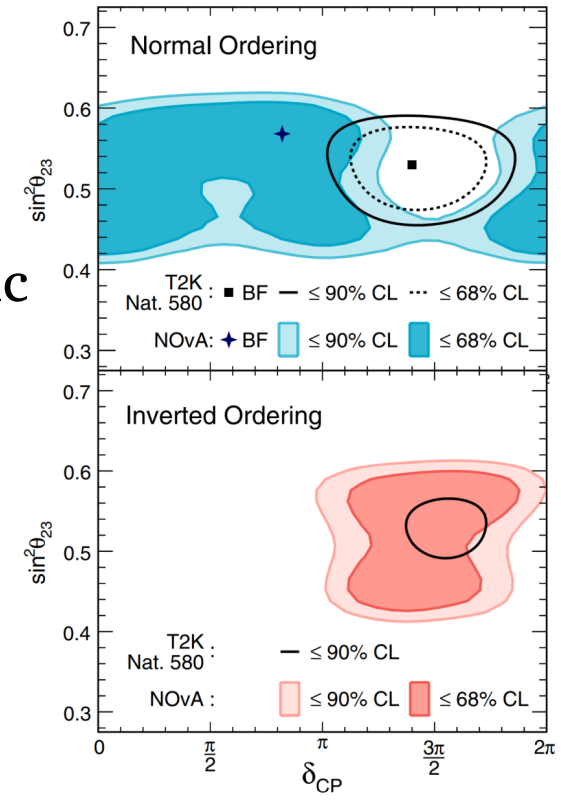
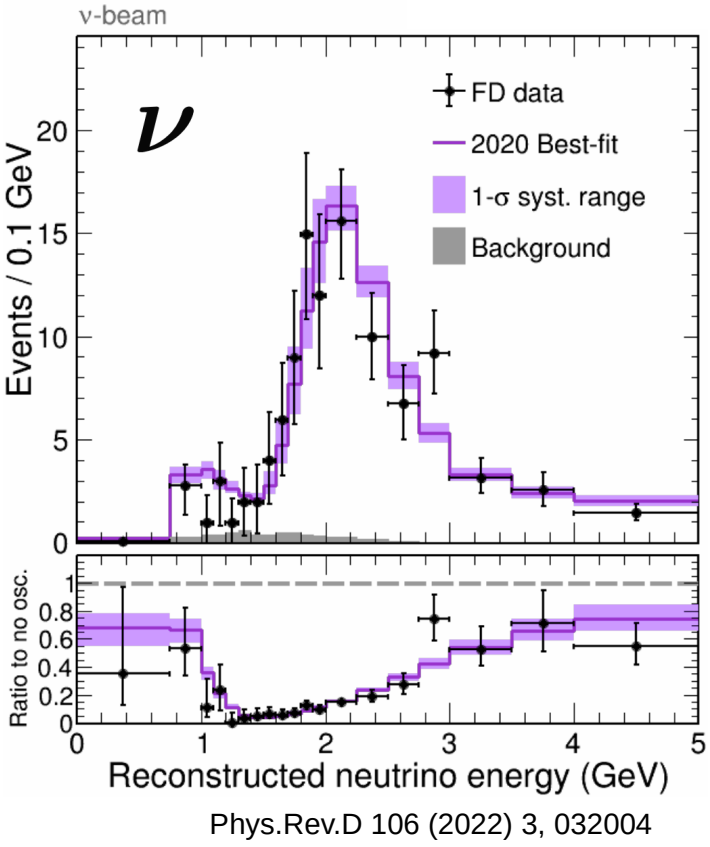
Neutrino Oscillation & Cross Sections

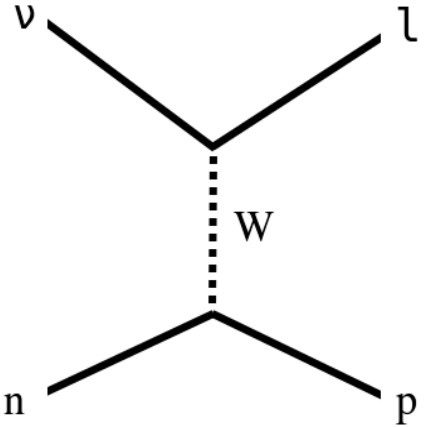
- Neutrino oscillation experiments measure parameters
- Uncertainty in cross section
  - increases neutrino oscillation systematic uncertainty
- Worldwide neutrino program uses many different nuclei



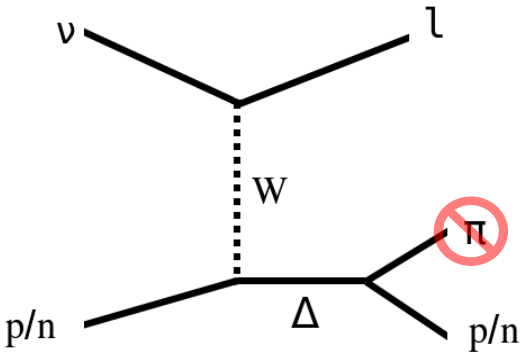


Phys.Rev.D 106 (2022) 3, 032004

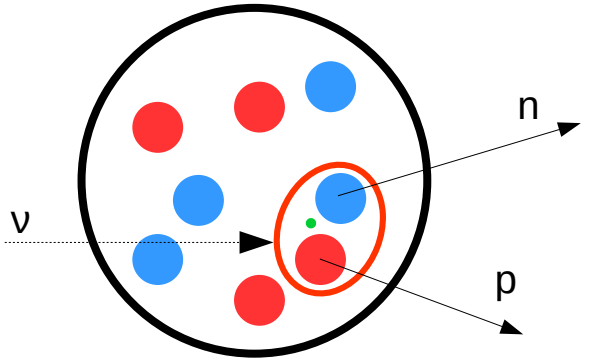
quasielastic-like cross section



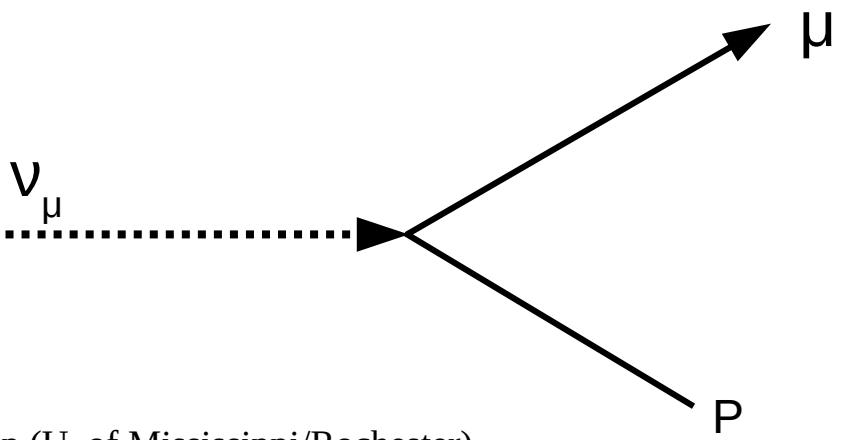
CCQE



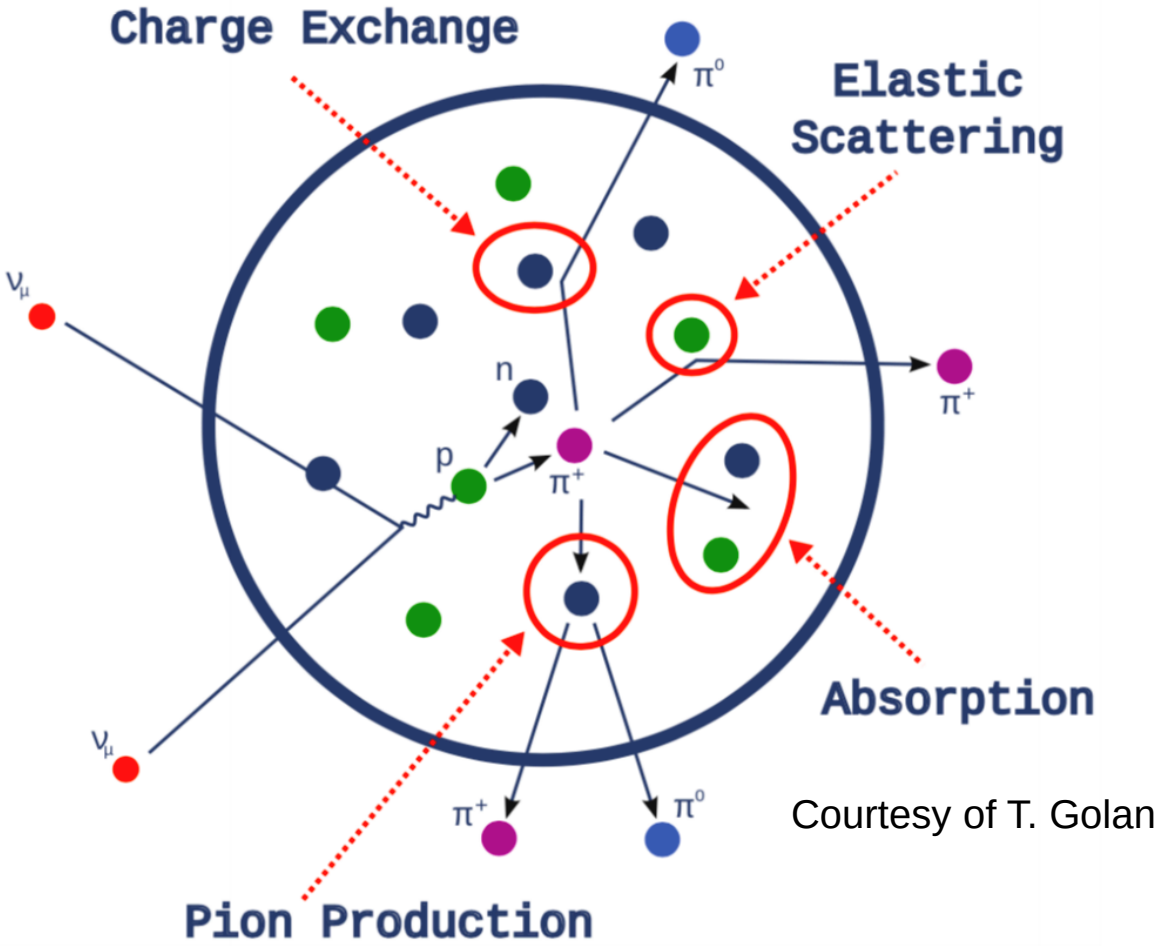
Resonant



2 particle, 2 hole



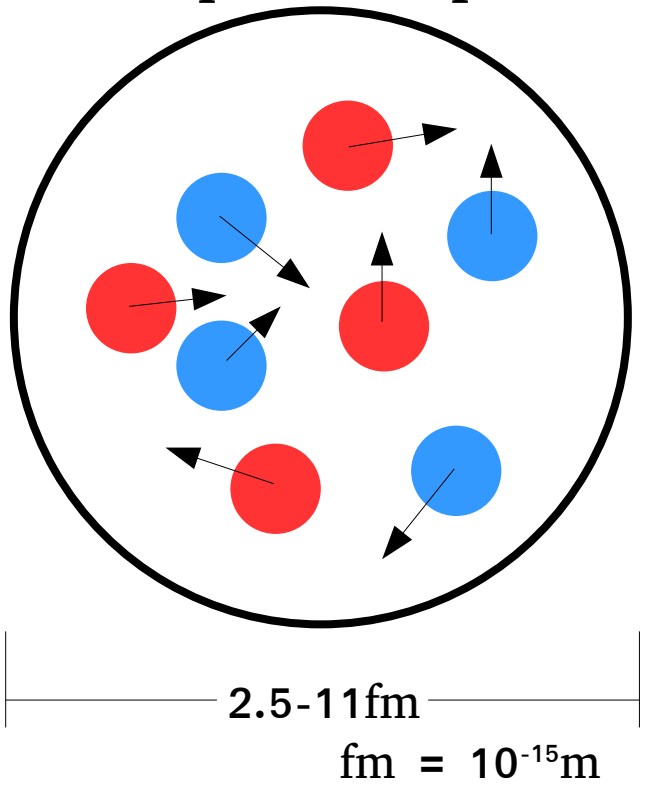
nuclear effects: Final State Interactions (FSI)

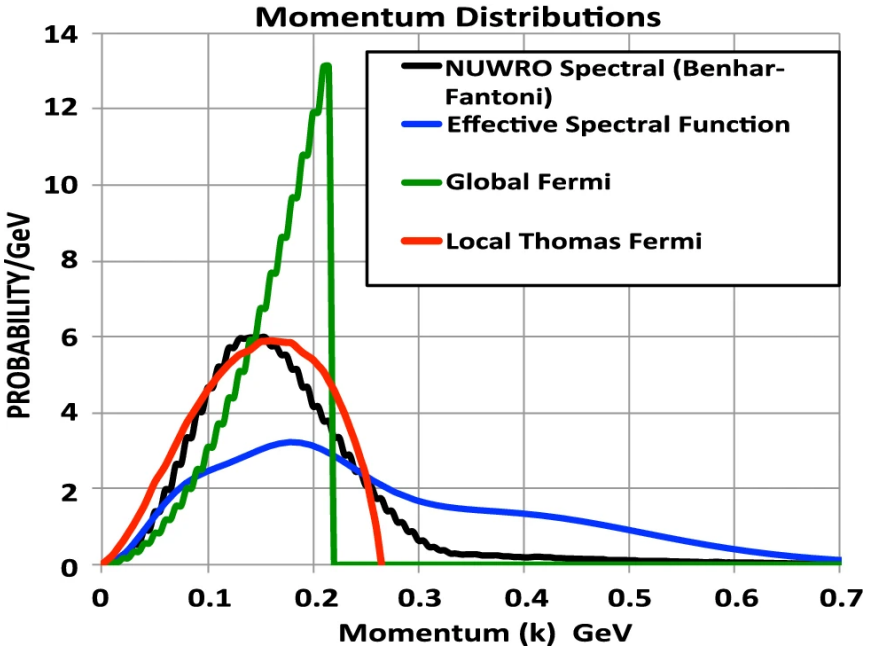


Courtesy of T. Golan

nuclear effects

Heisenberg Uncertainty Principle: $\Delta x \Delta p \geq \hbar/2$



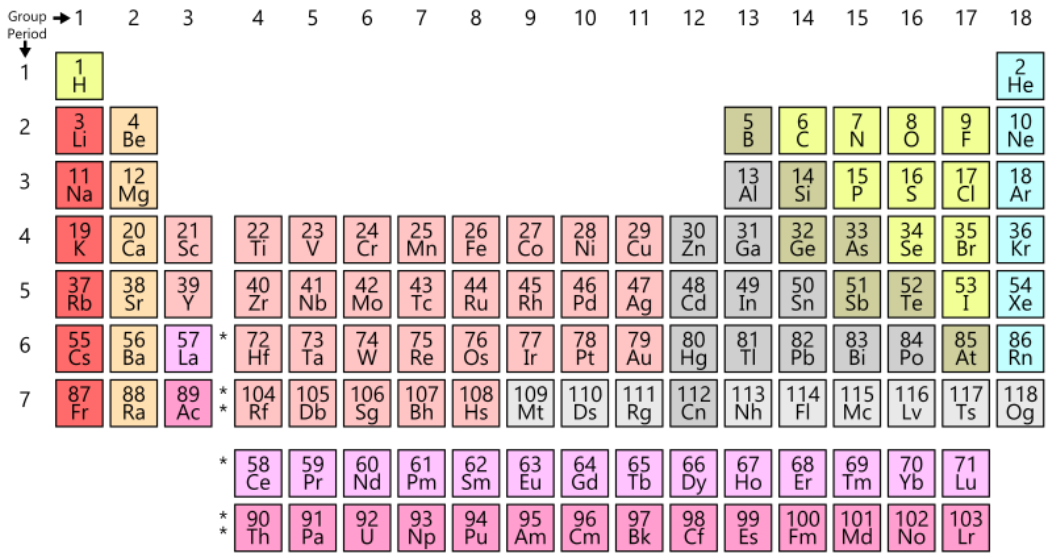


Also:

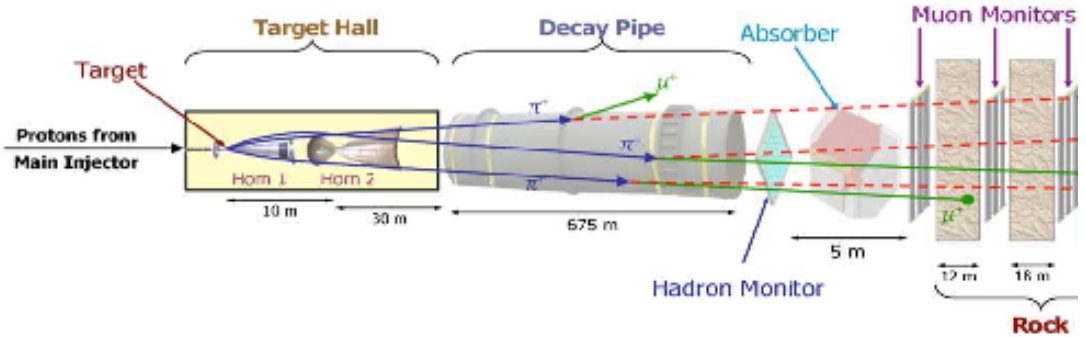
- Binding energy
- Nuclear structure
- 2p2h correlations

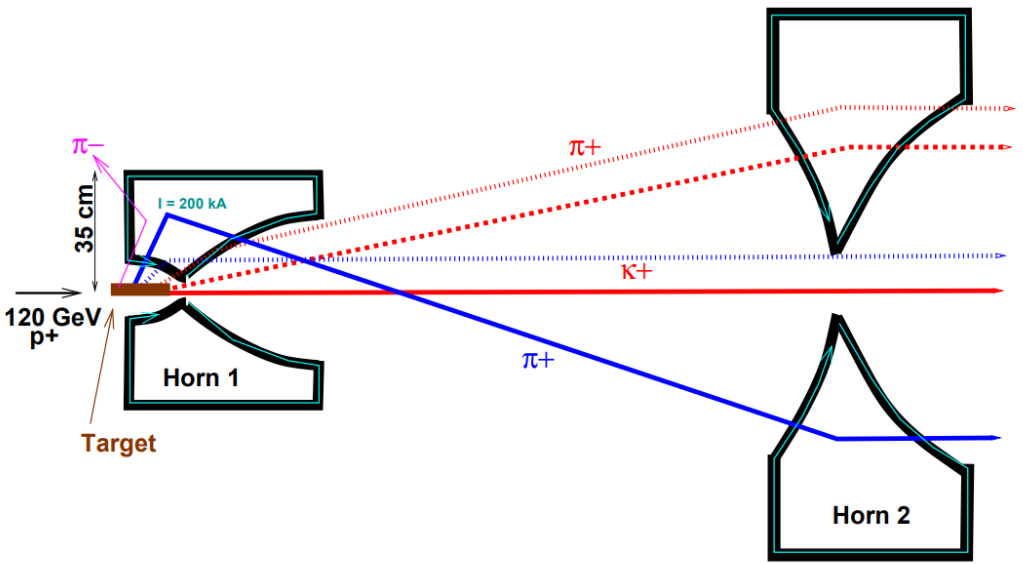
Nuclear effects change QE-like cross section

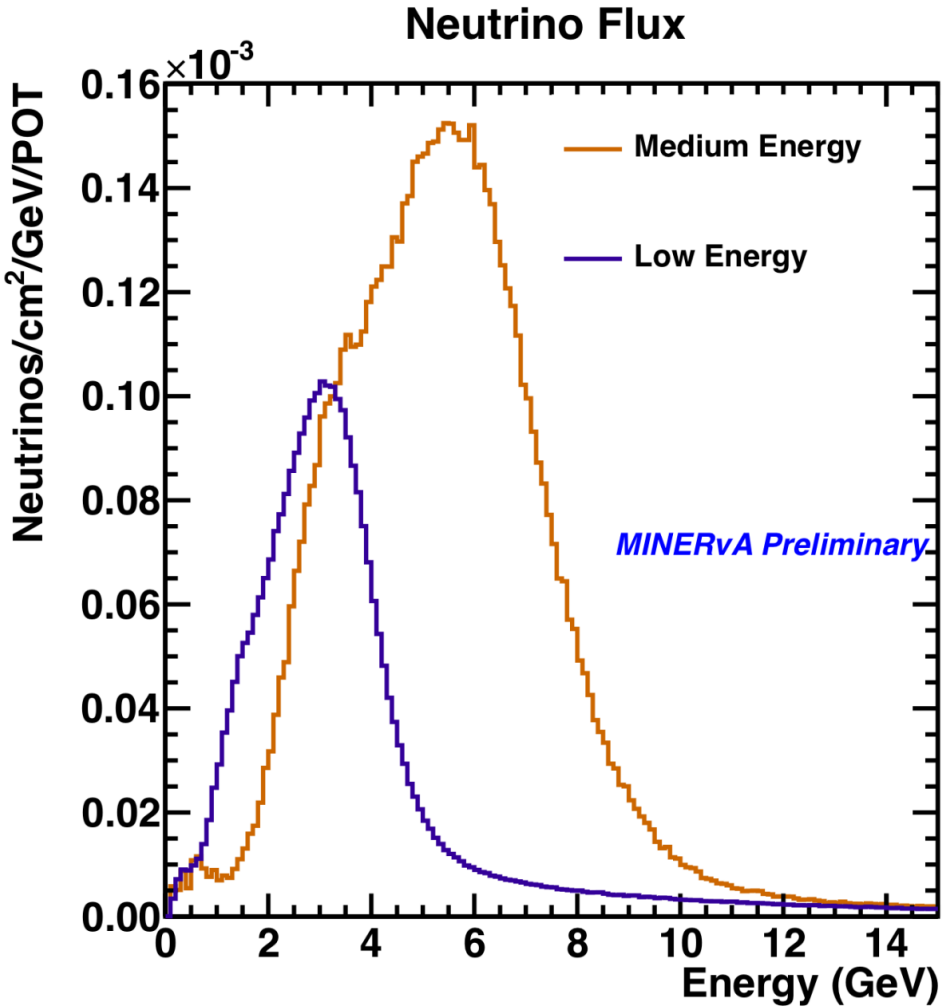
- Final State Interactions
  - change proton momentum/angle
  - pion absorption feed-in from non-QE-like to QE-like cross section
- Fermi motion & binding E
  - smear and shift muon and proton kinematics
- Measurement of A-scaling important



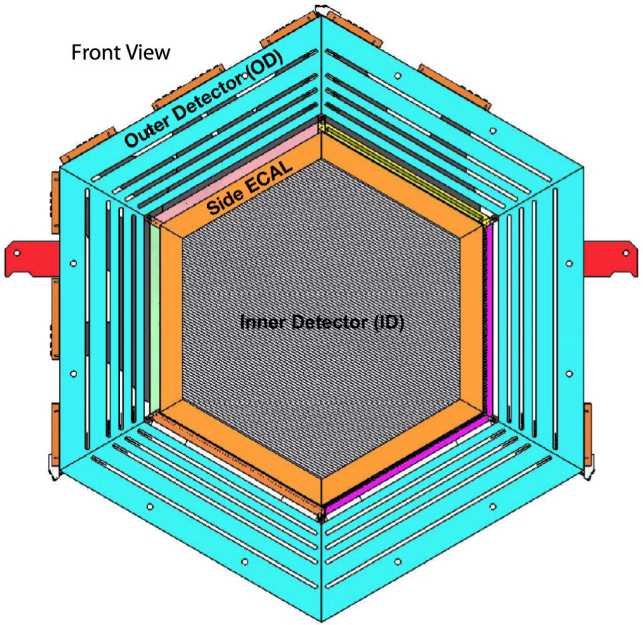
E_ν=6GeV: NuMI Flux

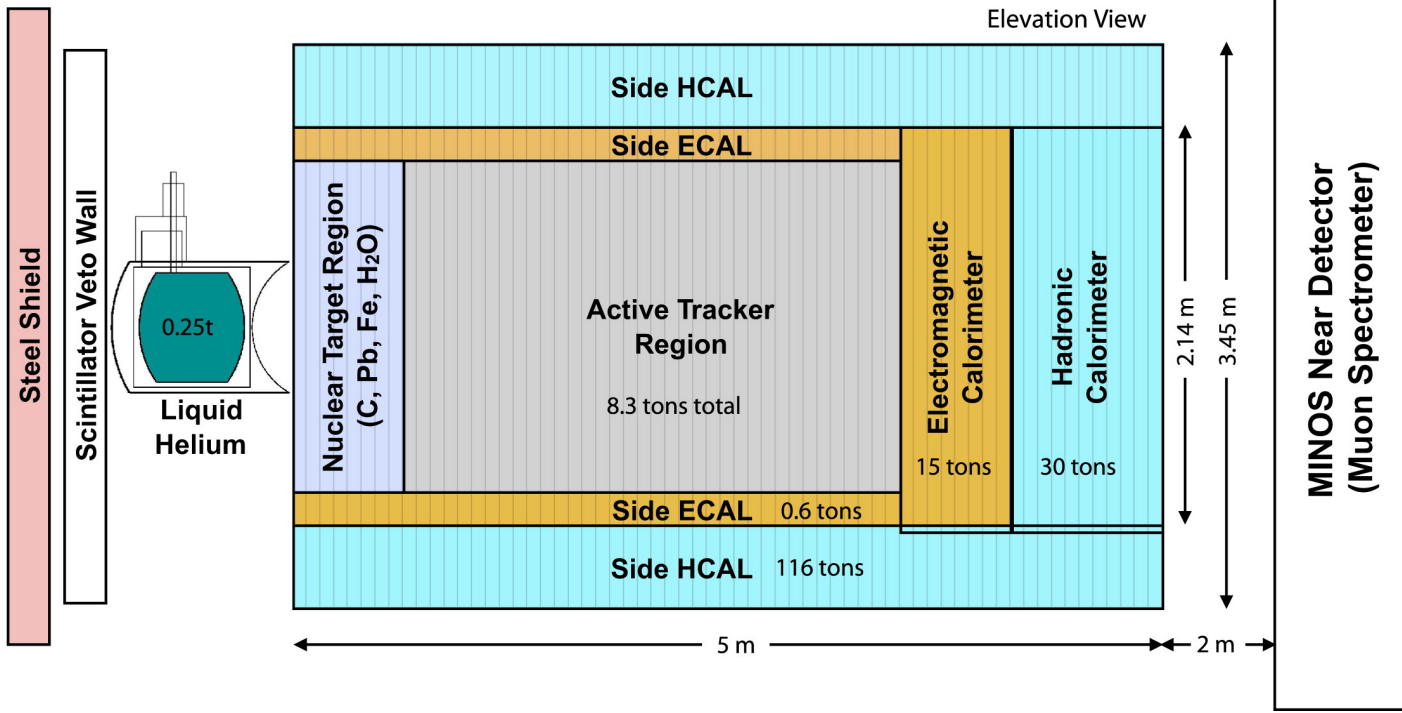




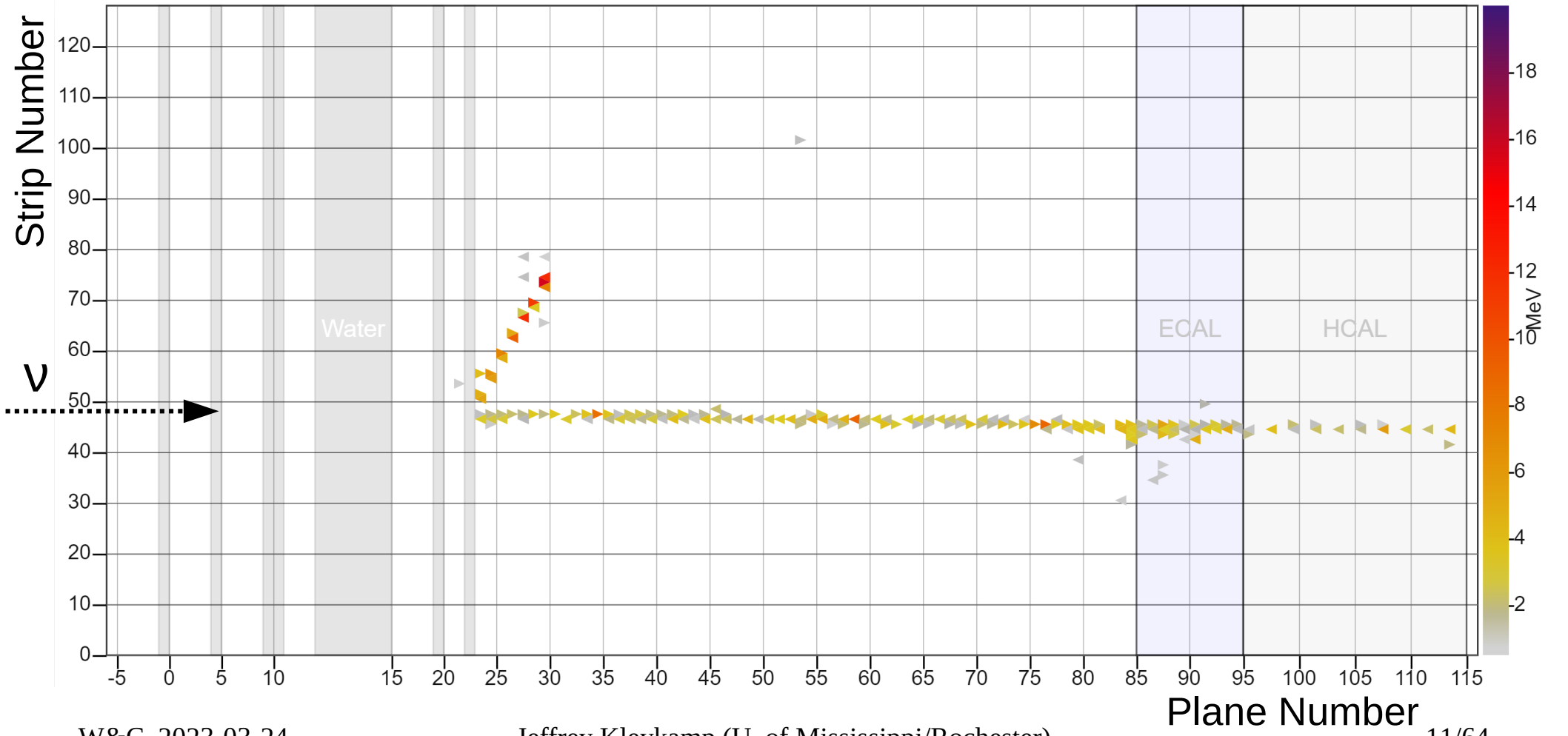


MINERvA

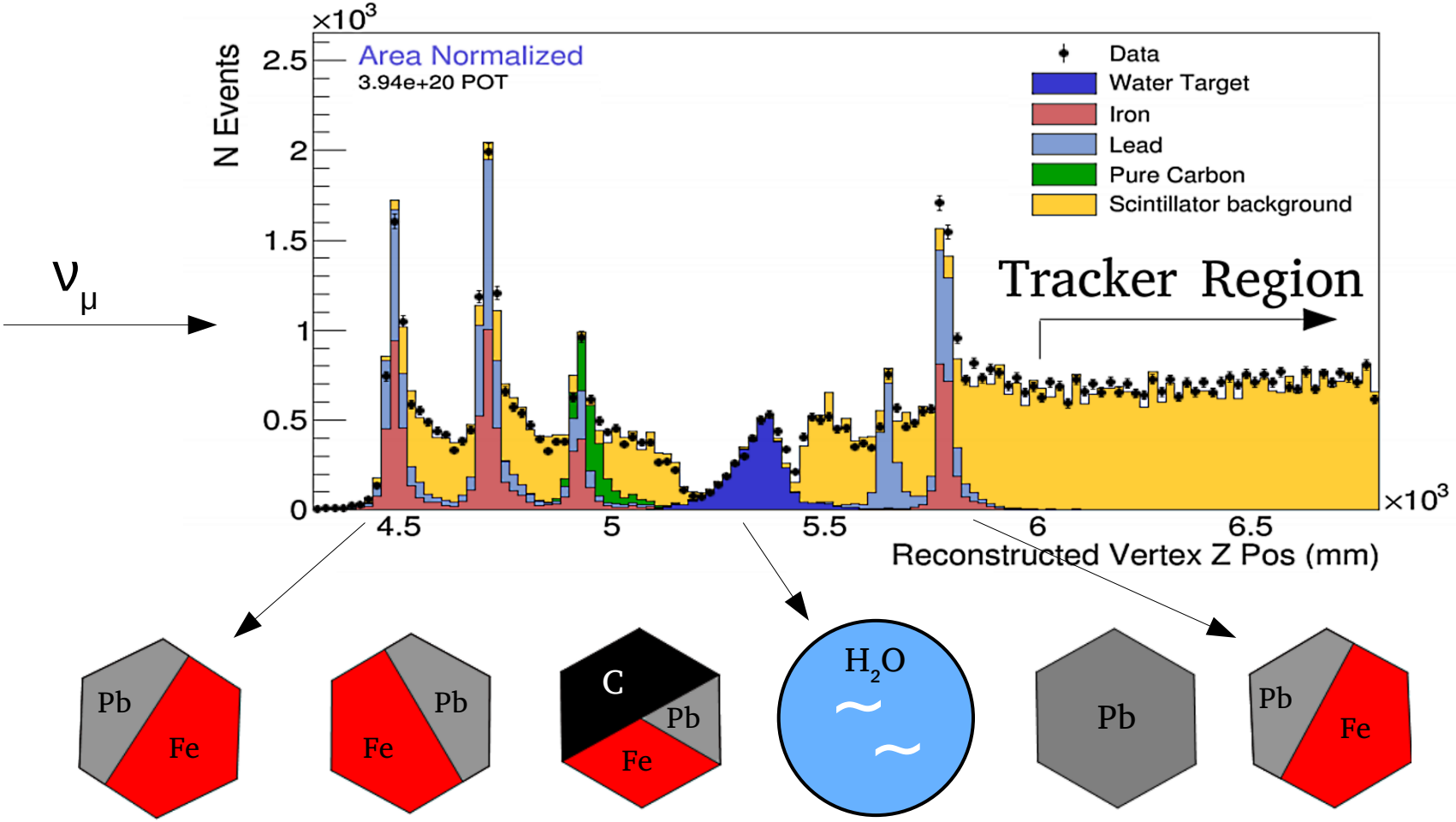

Front View
Outer Detector (OD)
Side ECAL
Inner Detector (ID)


Elevation View
Steel Shield
Scintillator Veto Wall
0.25t
Liquid Helium
Side HCAL
Side ECAL
Nuclear Target Region (C, Pb, Fe, H_2O)
Active Tracker Region
8.3 tons total
Electromagnetic Calorimeter
15 tons
Hadronic Calorimeter
30 tons
Side ECAL 0.6 tons
Side HCAL 116 tons
2.14 m
3.45 m
5 m
2 m
MINOS Near Detector (Muon Spectrometer)

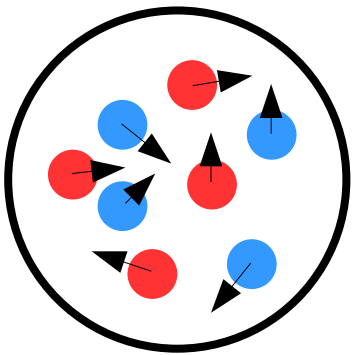
Event Display

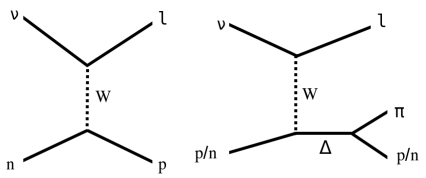


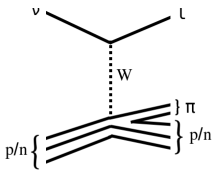
Measurement of A-scaling

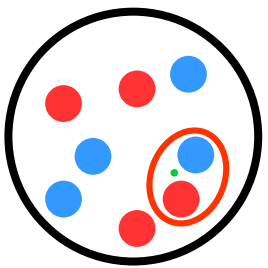


What ν oscillation cares about

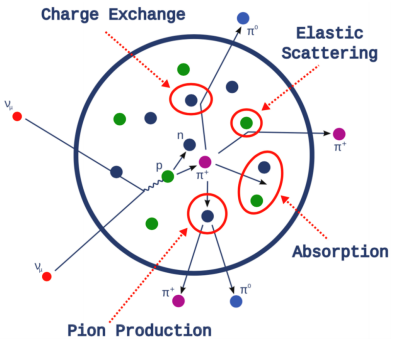




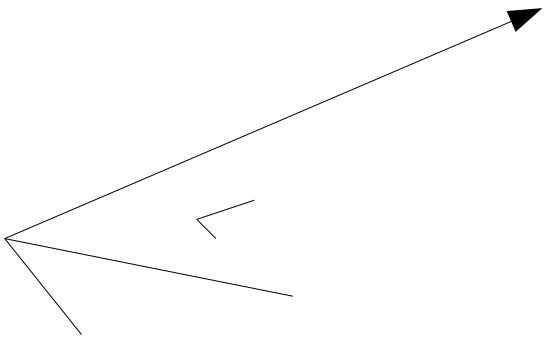




2p2h



What detectors see



What ν oscillation cares about

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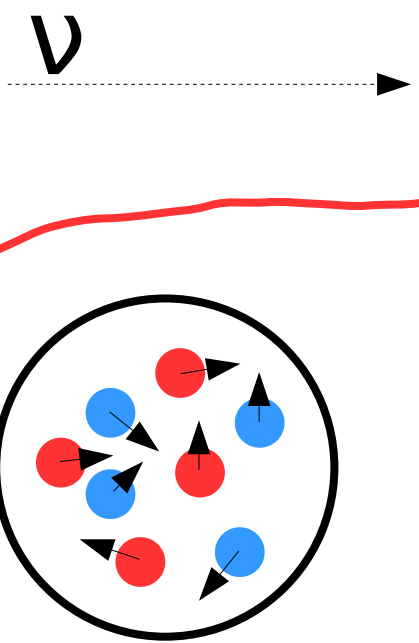
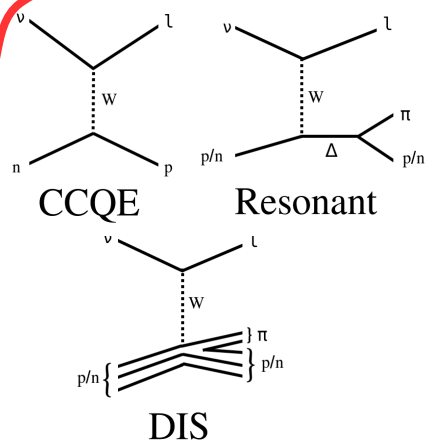
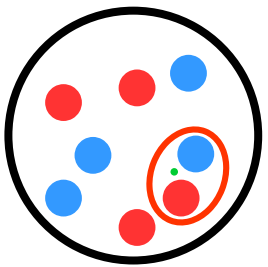
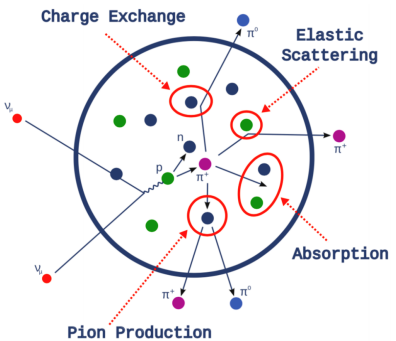
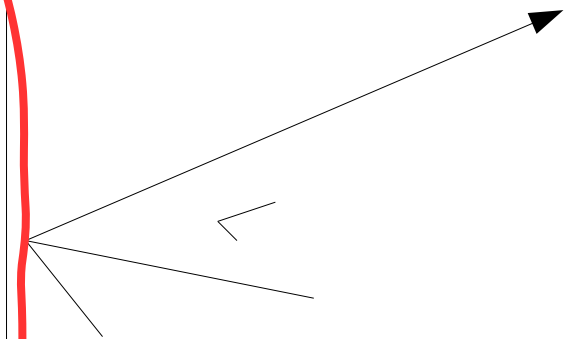






2p2h

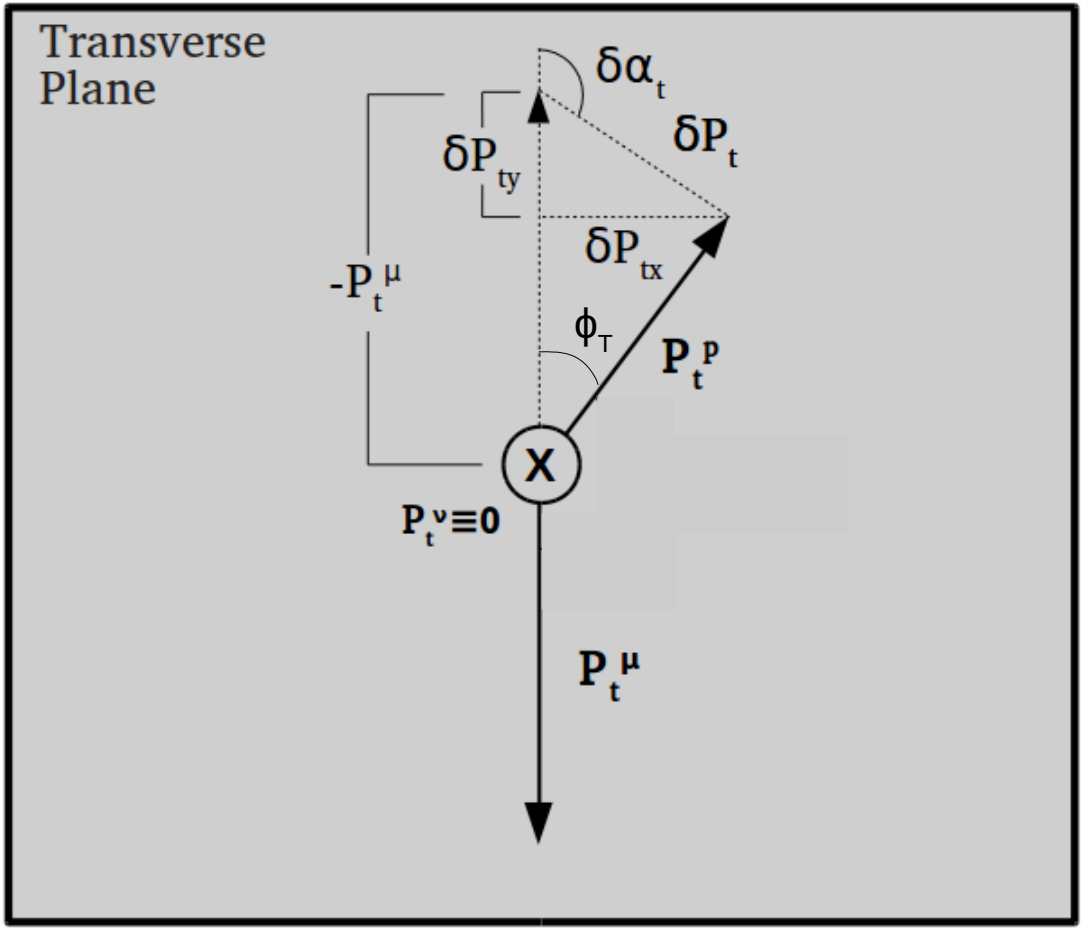




function of muon and proton kinematics

- Can measure outgoing muon
  - Not very susceptible to FSI
- Can measure outgoing proton
- Measure both at the same time for additional information
  - Transverse Kinematic Imbalance (TKI)
  - Phys. Rev. C 94 (2016) 1, 015503

function of muon and proton kinematics

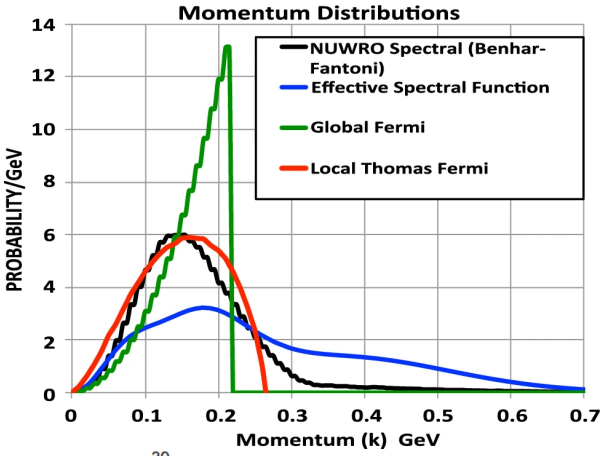


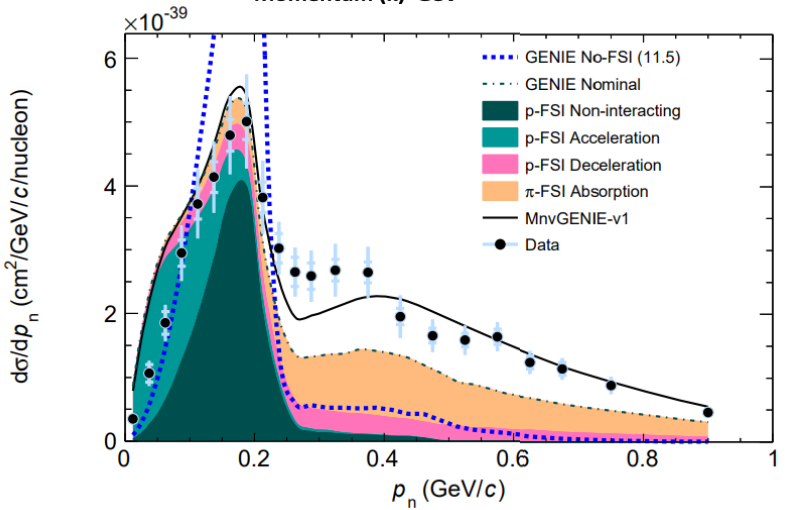
Pn definition

$$\delta P_L \equiv \frac{1}{2}R - \frac{m_{A'}^2 + \delta P_T^2}{2R}$$

$$R \equiv m_A + p_L^{\mu} - E^{\mu} - E^{P}$$

$$P_n \equiv \sqrt{{\delta P_T}^2 + {\delta P_L}^2}$$



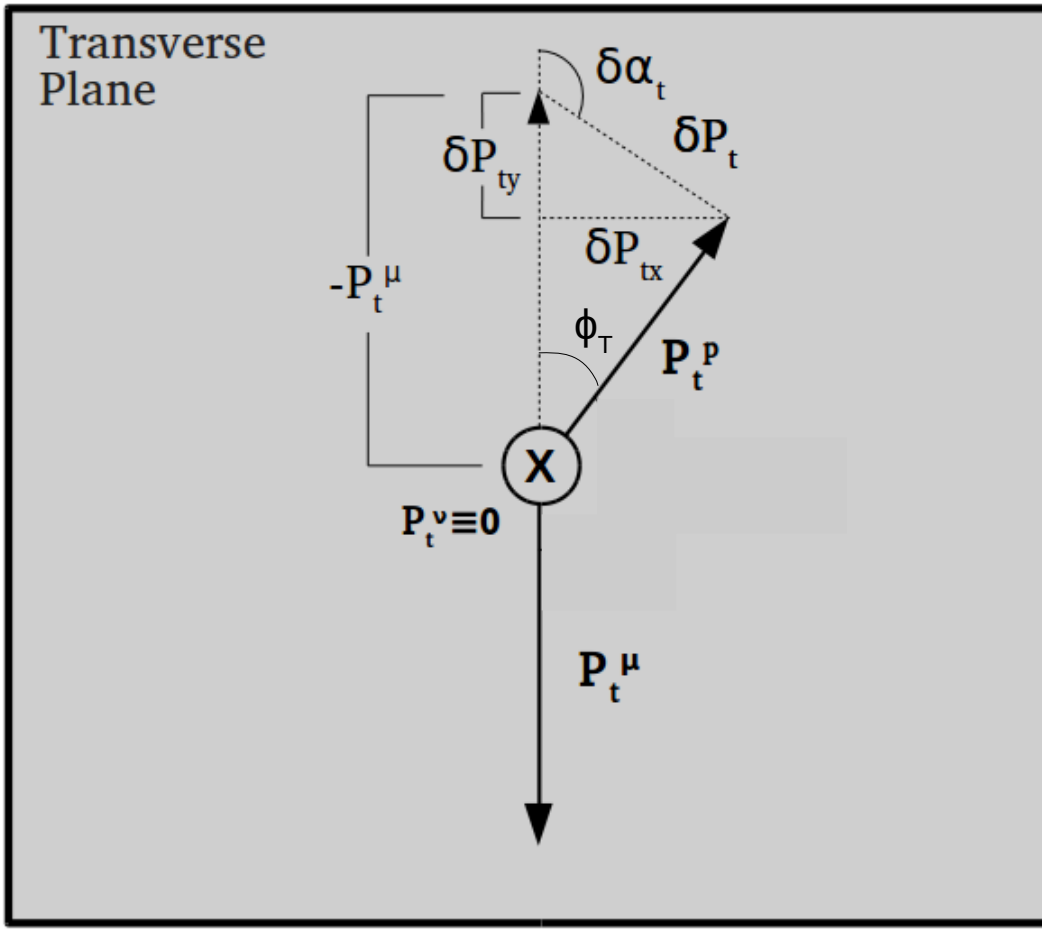


See Phys. Rev. C 95, 065501 (2017)

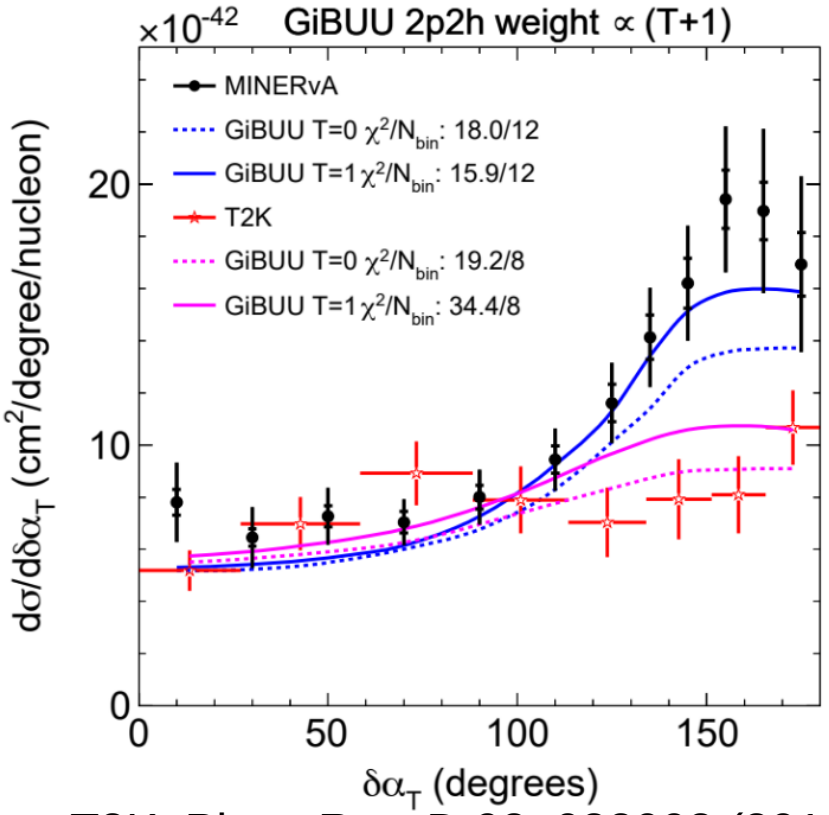
Phys. Rev. Lett. 121, 022504 (2018)

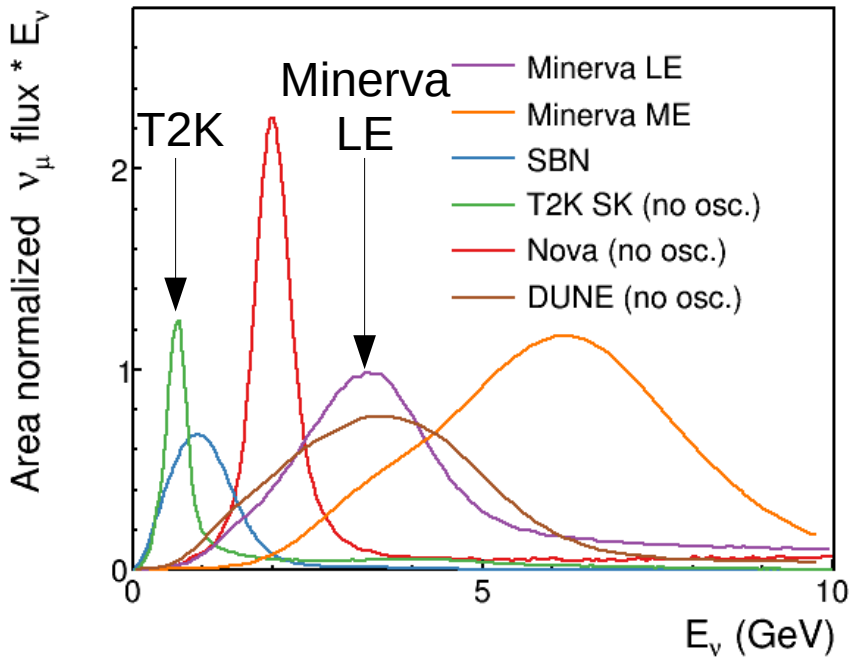
Many nuclear processes are addressed

- Proton P loss – α_T, δp_{Ty}
- Proton deflection – φ_T, δp_{Tx}
- Pion absorption – α_T, p_n
- Fermi momentum – δp_T, δp_{Tx}, δp_{Ty}, p_n
- Binding energy – δp_{Ty}
- 2p2h – φ_T, p_n



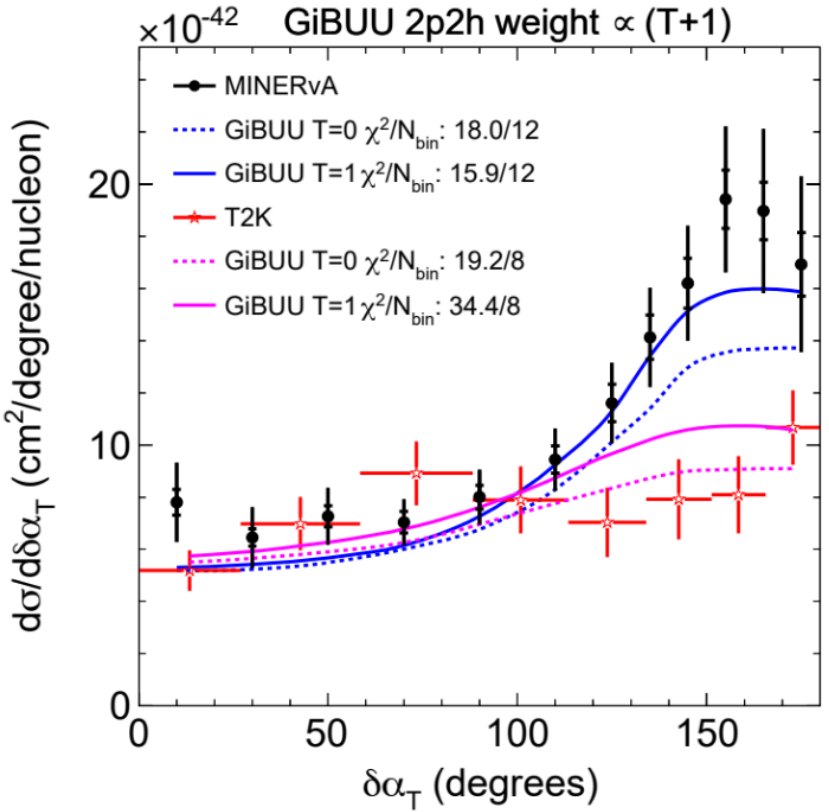
TKI in the Wild





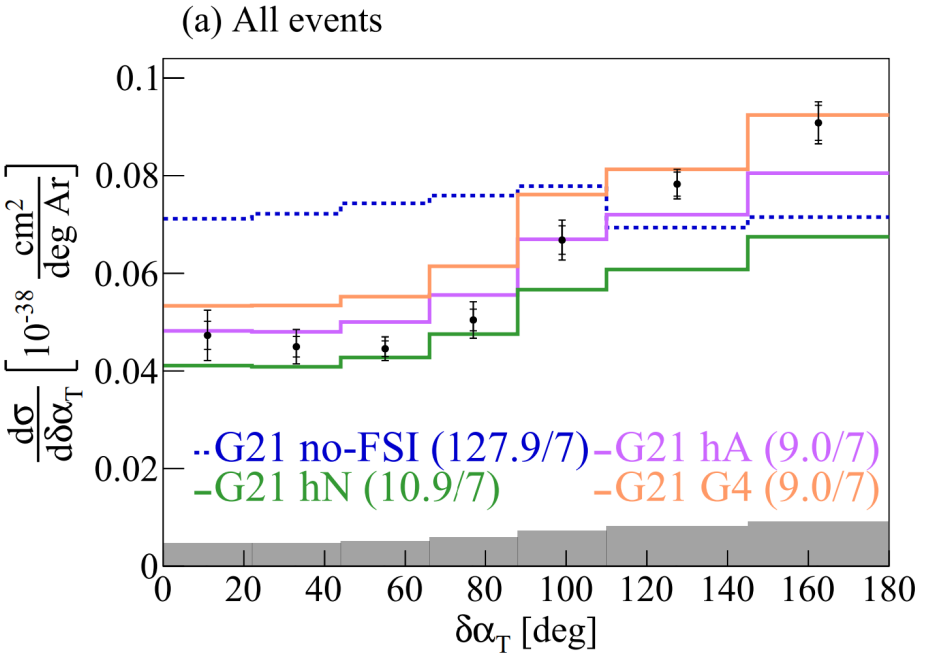
T2K: Phys. Rev. D 98, 032003 (2018)
Phys. Rev. Lett. 121, 022504 (2018)

TKI in the Wild



T2K: Phys. Rev. D 98, 032003 (2018)
Phys. Rev. Lett. 121, 022504 (2018)

Microboone



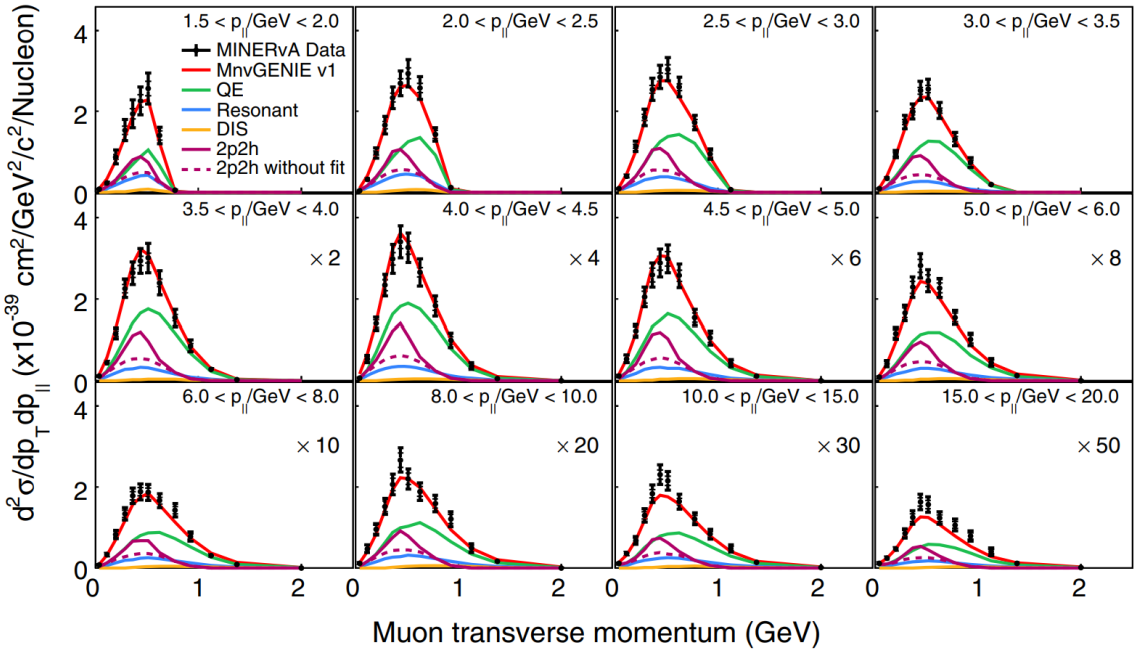
arXiv:2301.03706
arXiv:2301.03700

Analysis

MINERvA Tune v1.0.1

- Base model Genie 2.8.4
- Tuned based on MINERvA's Low Energy dataset
- Random Phase Approximation (RPA) suppression at low Q^2
- Increased Valencia 2p2h
- Aka MnvGenie

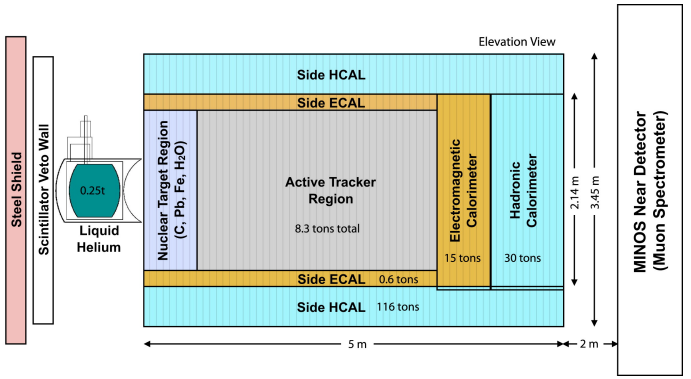
Low Energy QE-like muon cross section

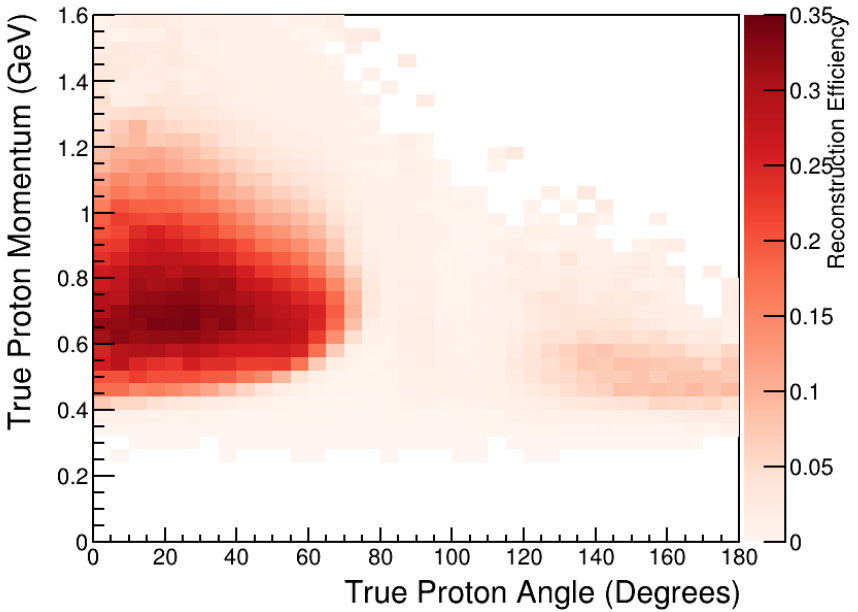


Phys. Rev. D 99, 012004 (2019)

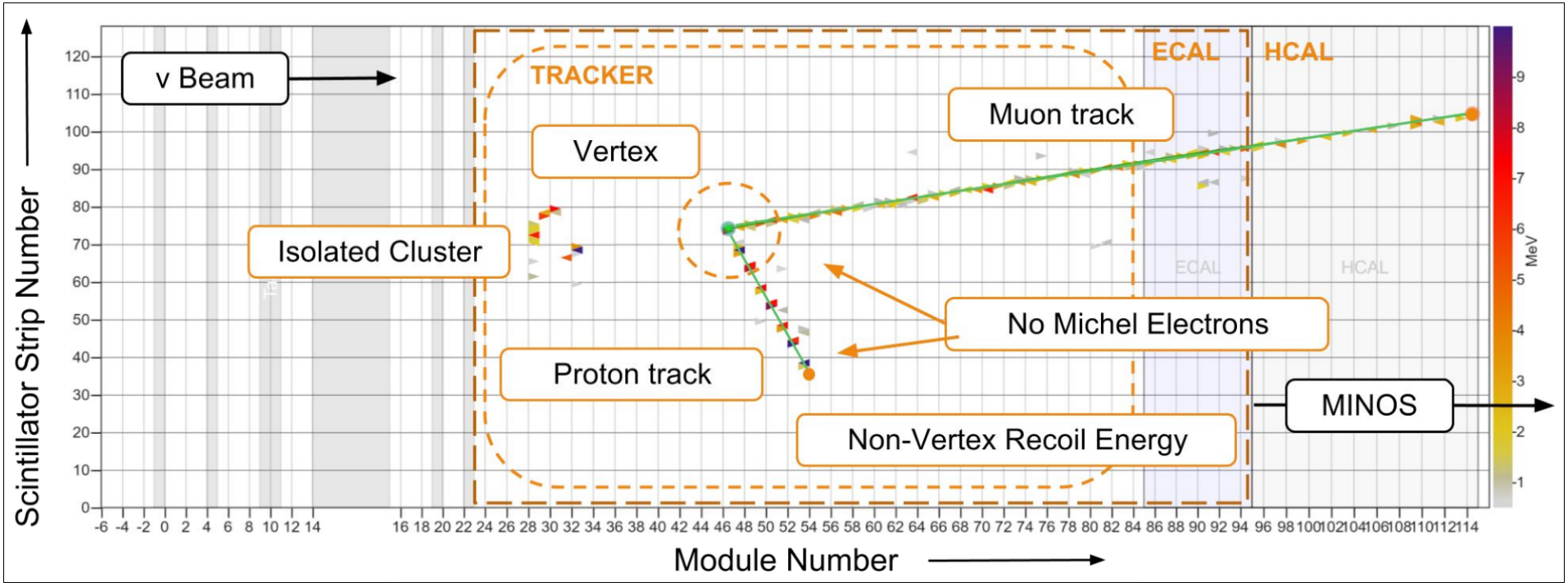
Quasielastic-like Signal Definition

- Muon
  - angle w.r.t. beam < 17 deg
  - momentum between 2-20 GeV/c
- Proton
  - angle w.r.t. beam < 70 deg
  - momentum between 500-1100 MeV/c
- No mesons (pions)
- Any number of nucleons
- No heavy baryons
- No photons above 10 MeV
- Aka CC0π1P



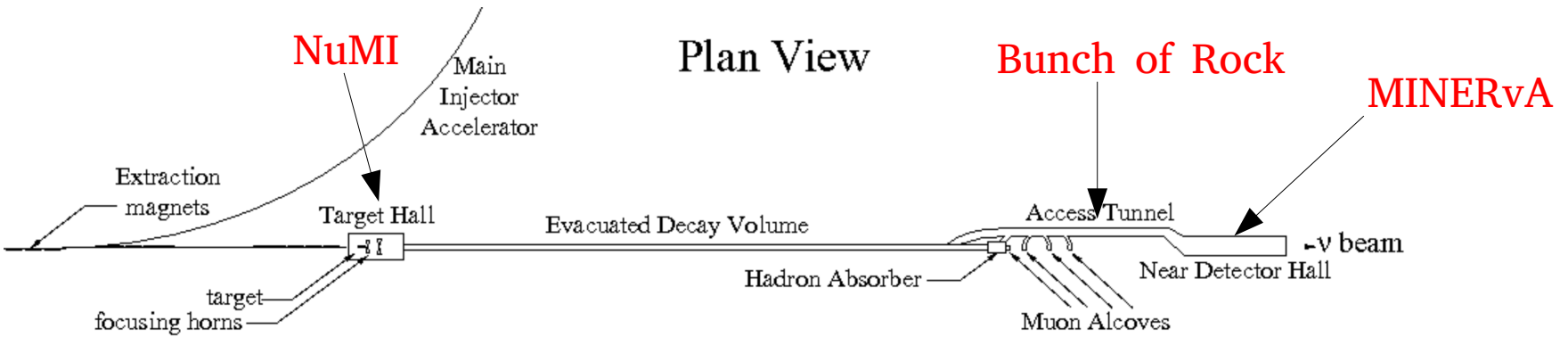


Important Cuts



Additional Considerations

- Want high momentum resolution protons
  - Reconstruct proton momentum by range
  - Reject protons which leave detector or with inelastic fate
- Also want muons which are reconstructed well inside MINOS
- Reject events from most-upstream target because of too many front-entering rock muons

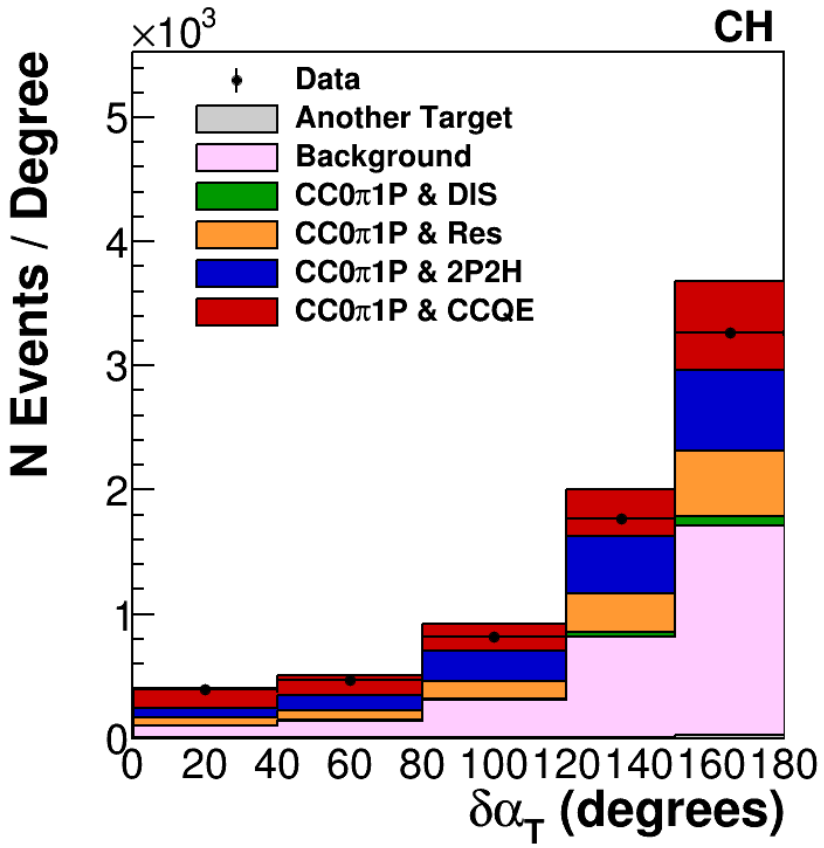


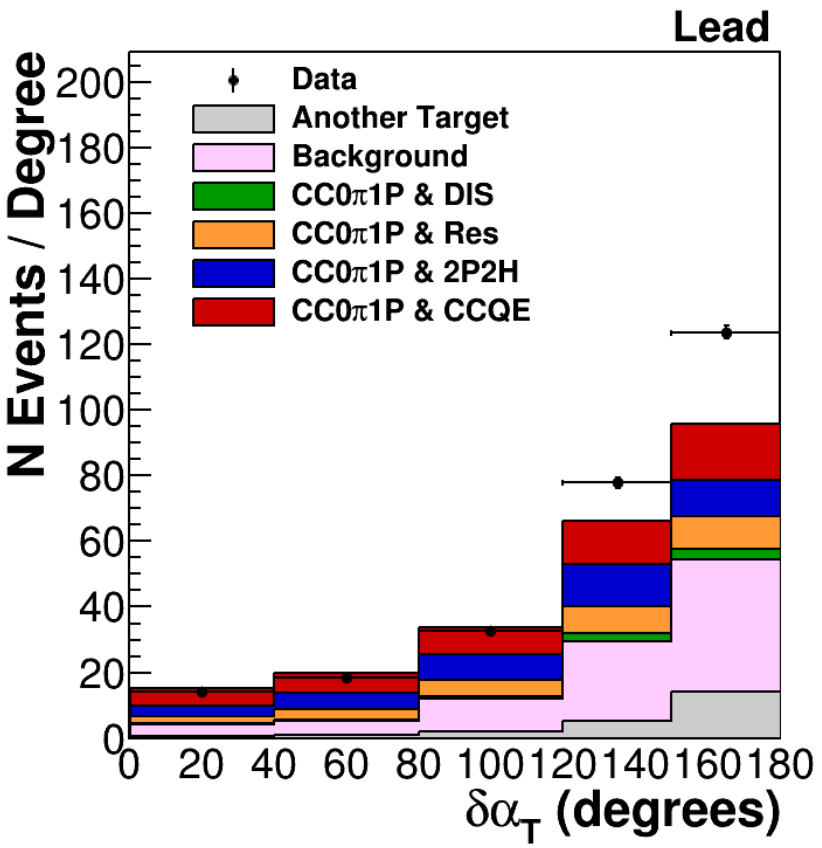
Cross Section Calculation

- Measuring cross section makes the measurement detector independent
  - Removes detector effects like resolution and efficiency effects
- Easier comparison to theory and generators

$$\frac{d\sigma}{dX}_i = \frac{\sum_j U_{ij}(N_j^{measured} - N_j^{background})}{\epsilon_i(T\Phi_i)\Delta X_i}$$

Event Rates $N^{measured}$

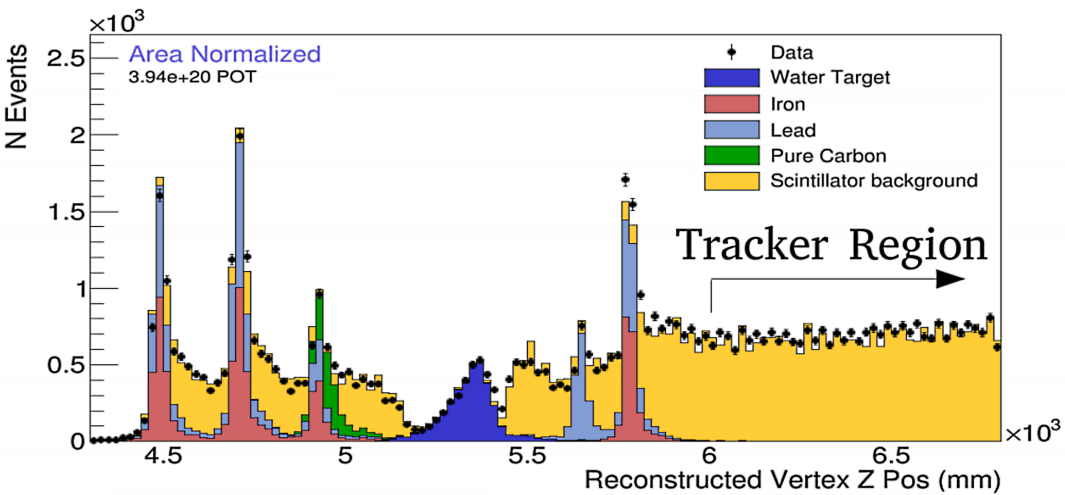




Sideband Tuning

$$\frac{d\sigma}{dX_i} = \frac{\sum_j U_{ij}(N_j^{measured} - N_j^{background})}{\epsilon_i(T\Phi_i)\Delta X_i}$$

- Don't rely on generator model
  - Instead tune based on real data by created "sidebands"
- Two types of backgrounds
  - Scintillator near targets
  - Non-signal contamination



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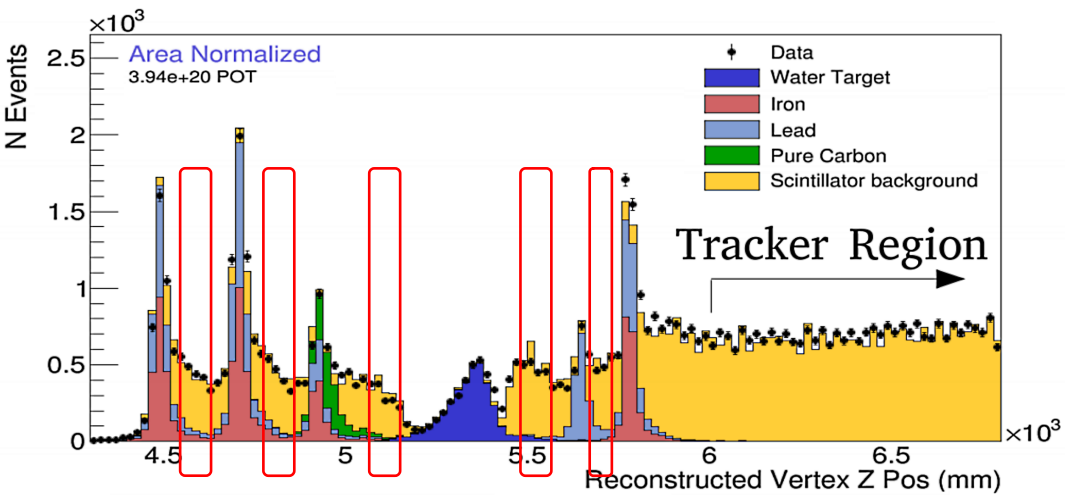

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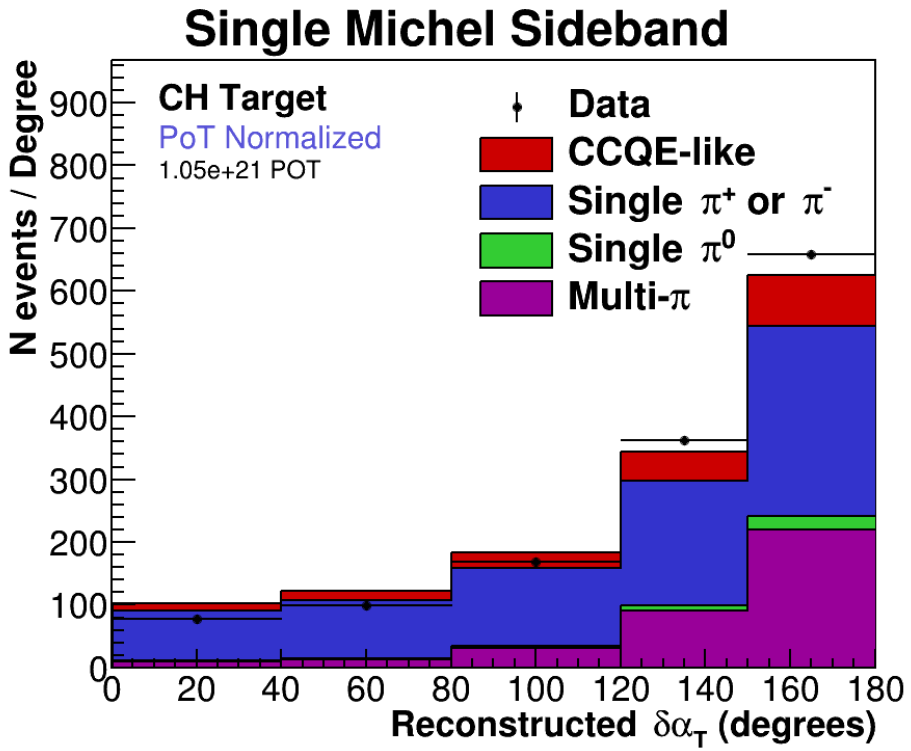
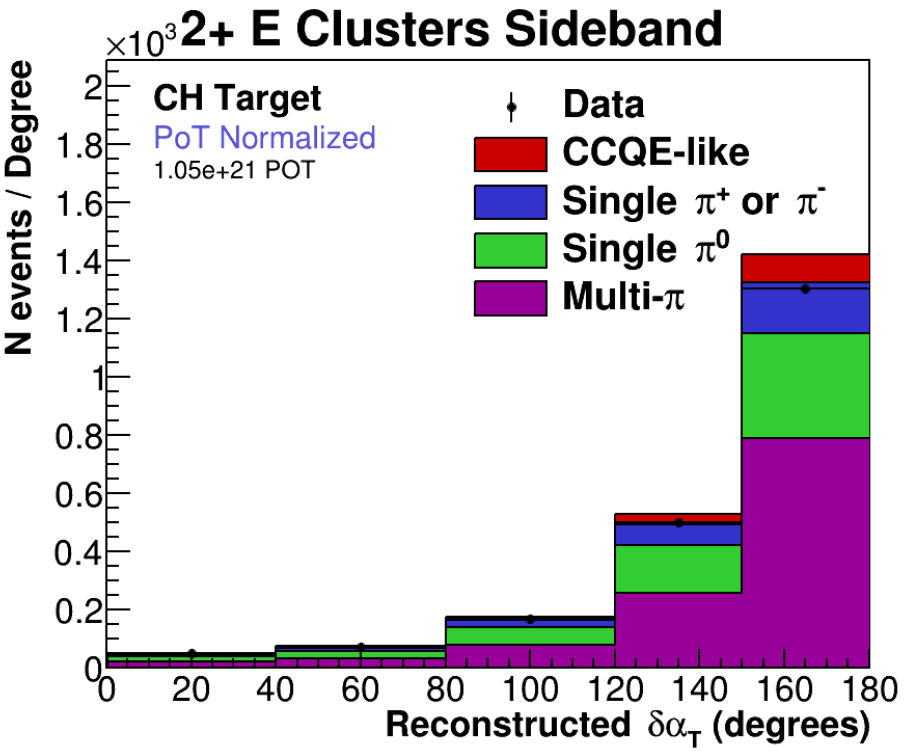
- Don't rely on generator model
  - Instead tune based on real data by created "sidebands"

Sideband 1 Has Michel electron Rich in single pion events	**Sideband 2** 2+ isolated energy clusters Rich in other backgrounds
Signal Region No michel electron 0-1 isolated energy clusters	

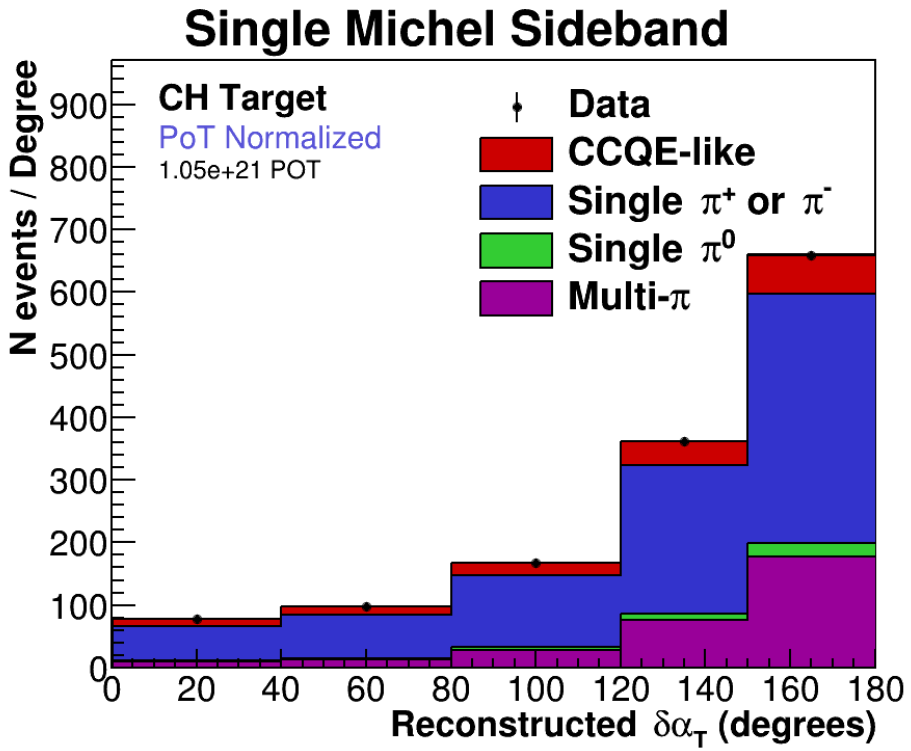
- Tune each TKI variable separately
  - Model doesn't always model variable well
  - Cross check final results
- Regularized fit

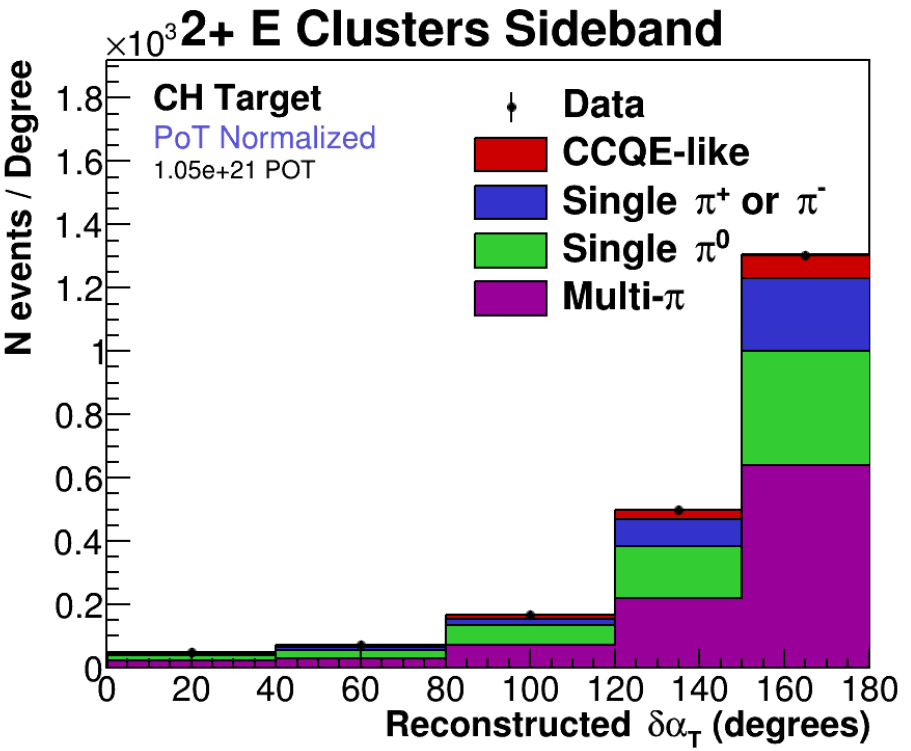
$\delta\alpha_T$, Before Tuning





$\delta\alpha_T$, After Tuning

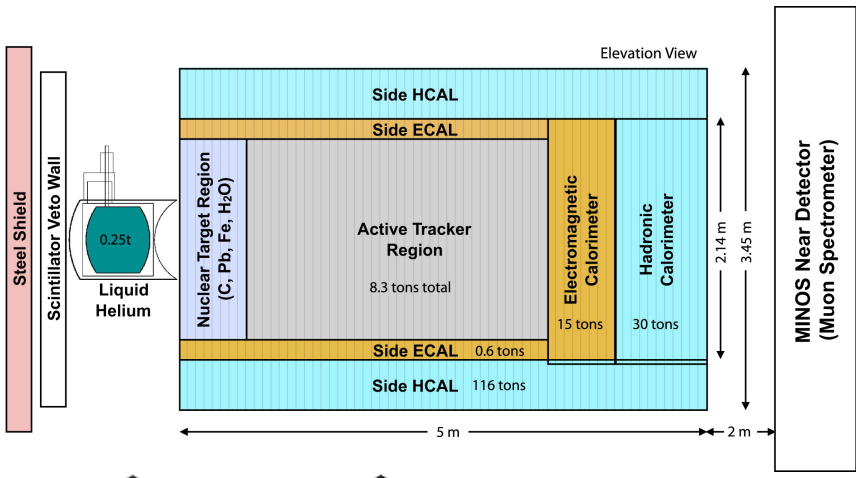


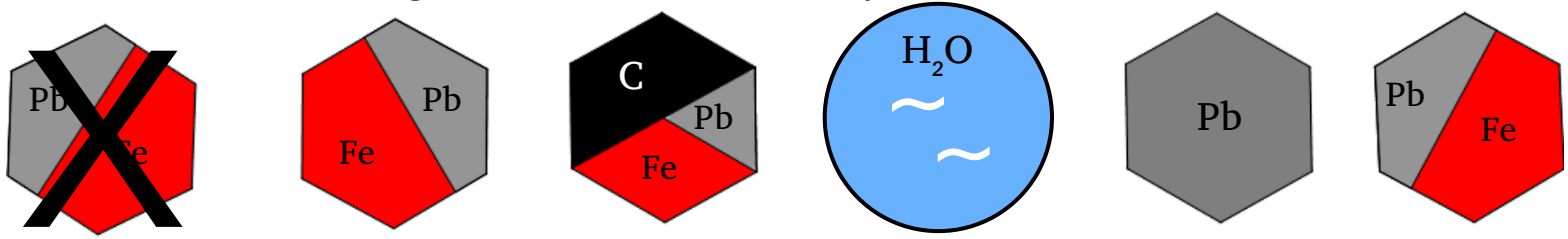


Unfolding/deconvolution, and Efficiency

$$\frac{d\sigma}{dX_i} = \frac{\sum_j U_{ij}(N_j^{measured} - N_j^{background})}{\epsilon_i (T\Phi_i)\Delta X_i}$$

- Calculated per nuclear target
  - On 4 lead targets, then add together
- D'Agostini unfolding technique
  - Number of iterations chosen per variable/target based on study

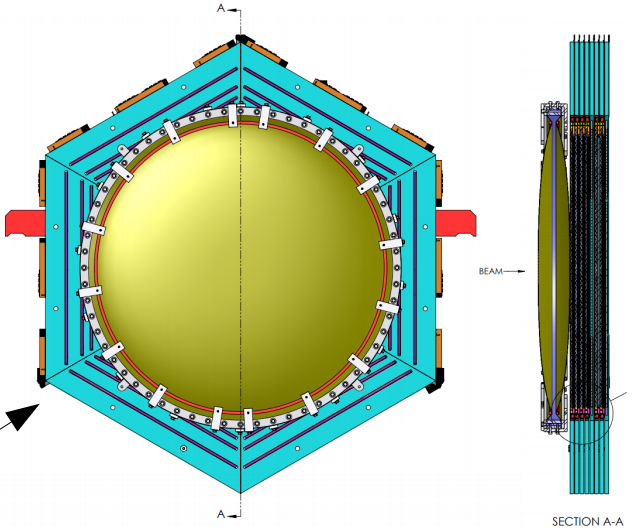


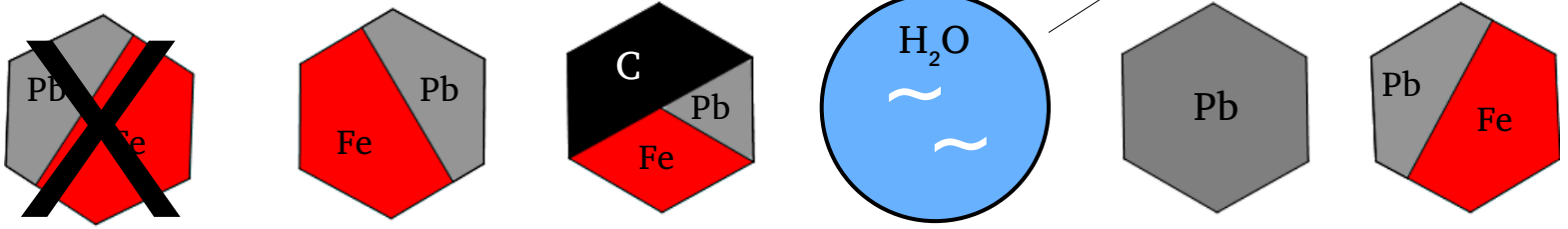


N nucleons, Flux, and Bin Width

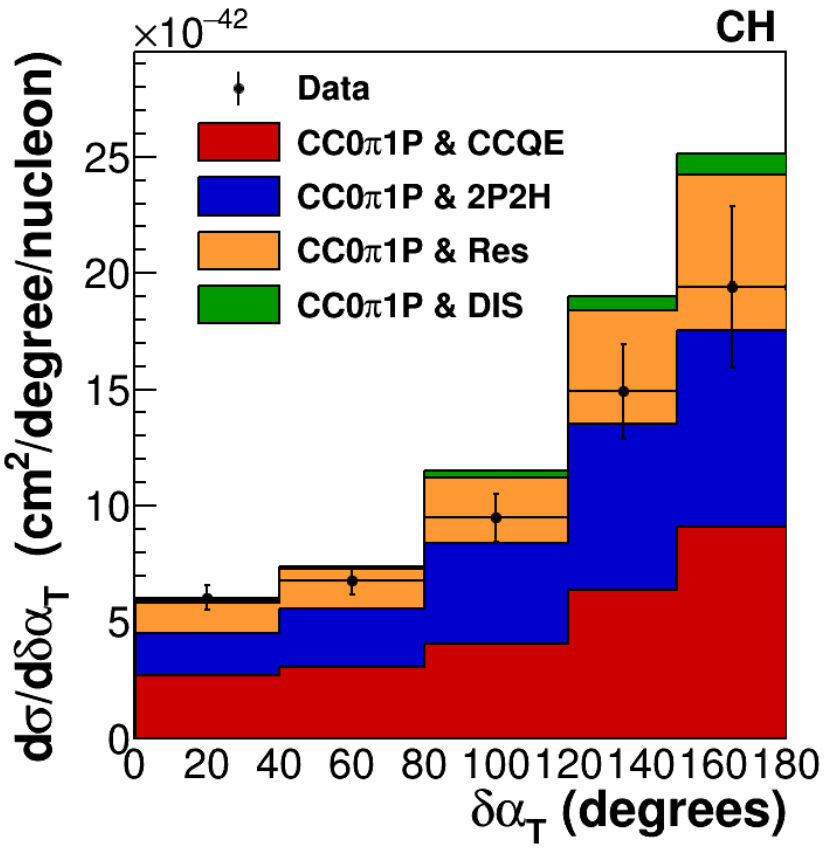
$$\frac{d\sigma}{dX_i} = \frac{\sum_j U_{ij}(N_j^{measured} - N_j^{background})}{\epsilon_i (T\Phi_i)\Delta X_i}$$

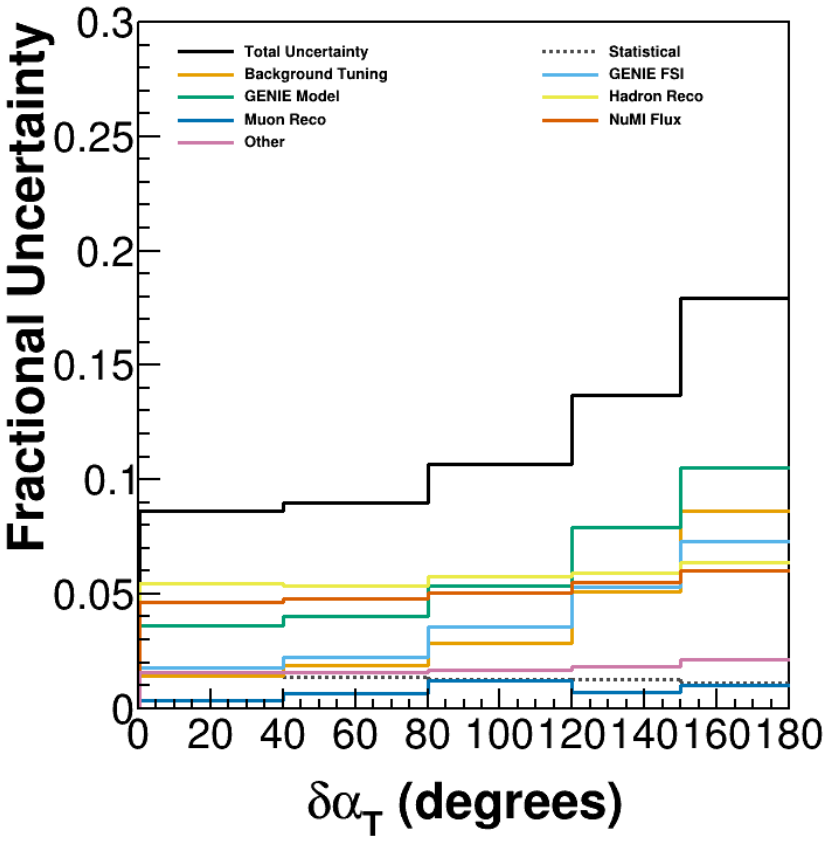
- Flux simulated
  - *ex-situ* and *in-situ* constraints
    - Phys. Rev. D 100, 092001 (2019)
- T = N nucleons from target masses
  - < 1% uncertainty



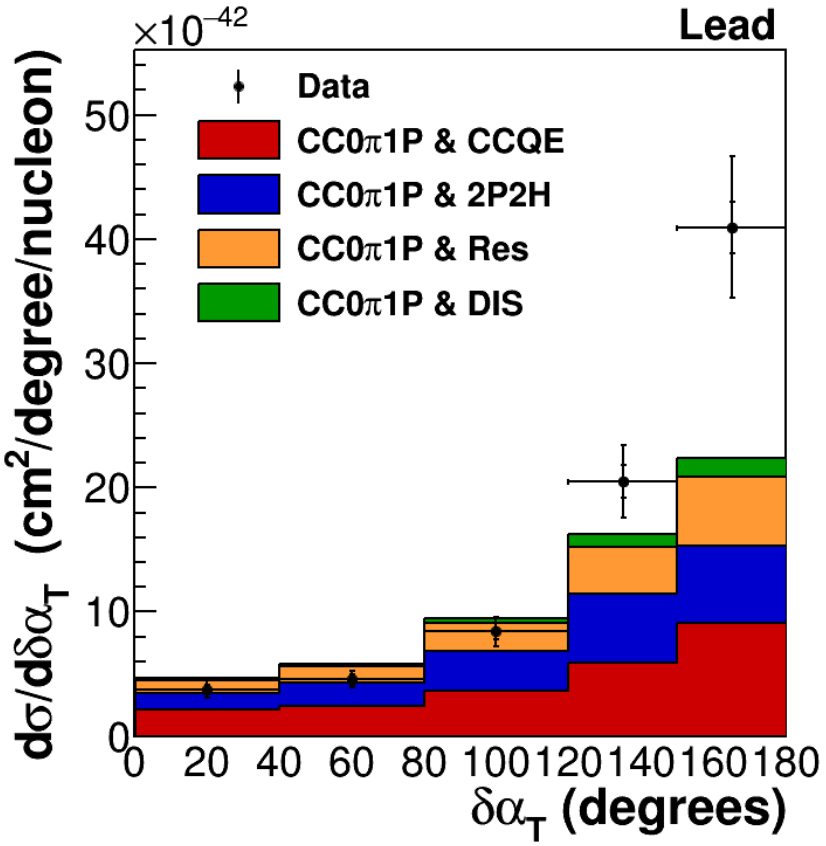


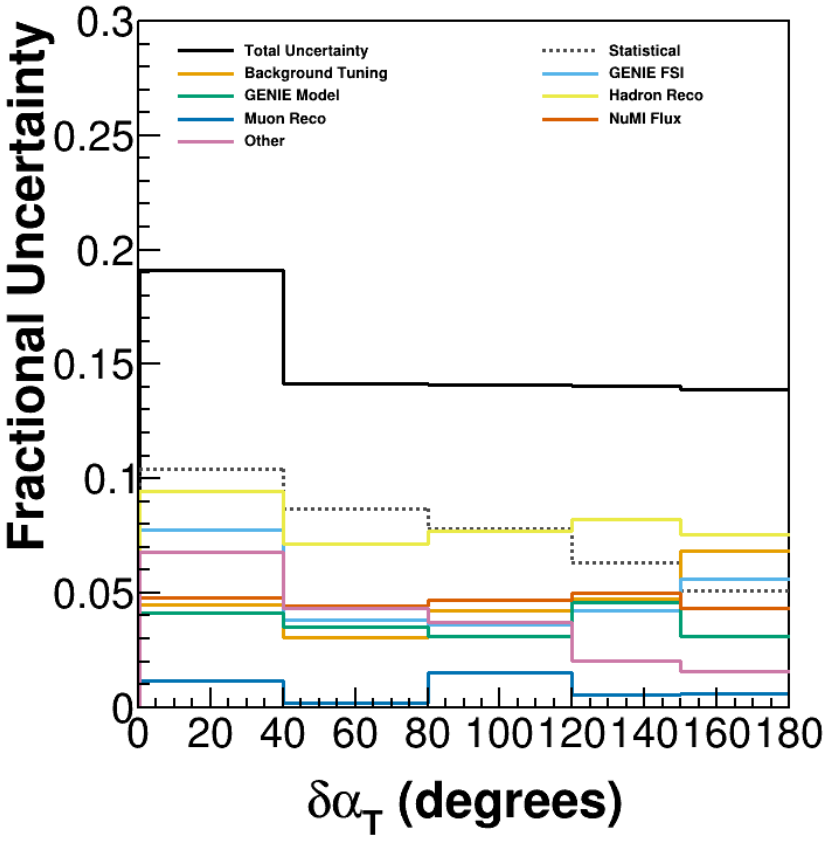
CH $\delta\alpha_T$ Cross Section





Lead $\delta\alpha_T$ Cross Section

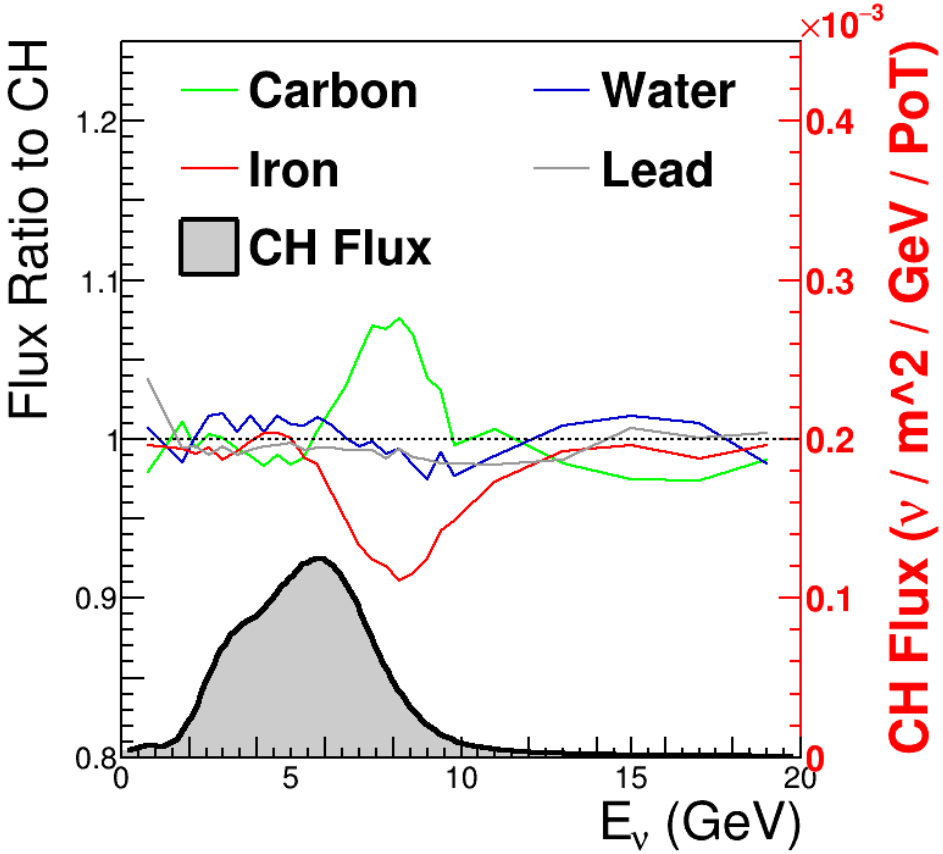


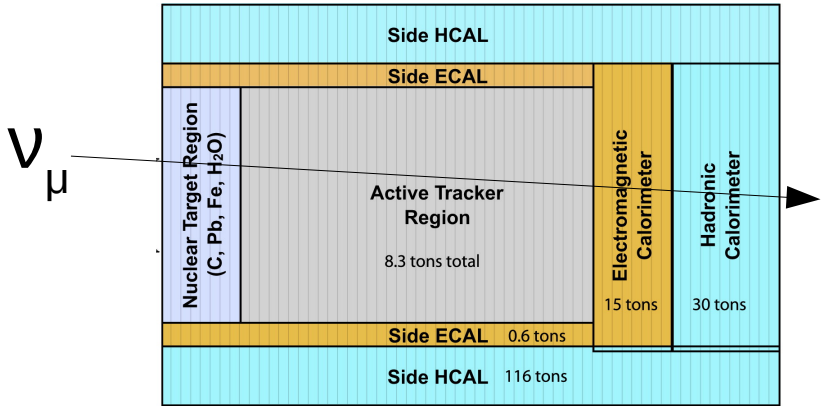


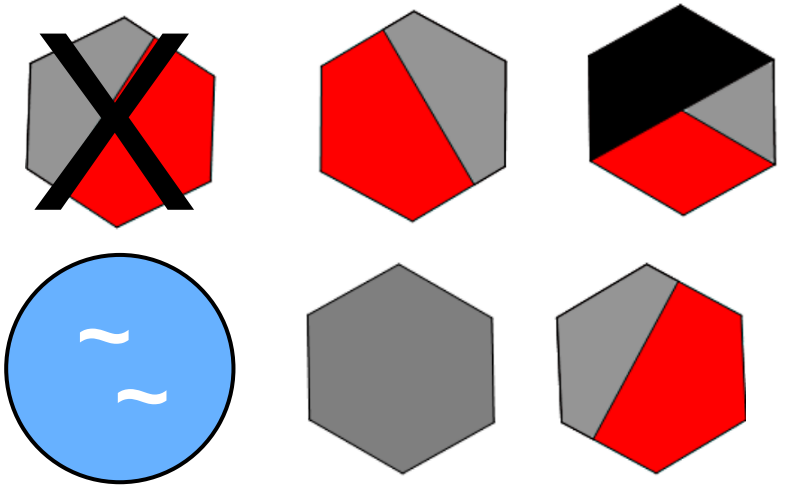
Taking Ratios

- Ratio of cross section cancels out many shared systematic uncertainties
  - Flux uncertainty
  - Muon and proton reconstruction uncertainty
  - Shared model uncertainties
- But it’s not that simple

Nuclear Target Fluxes

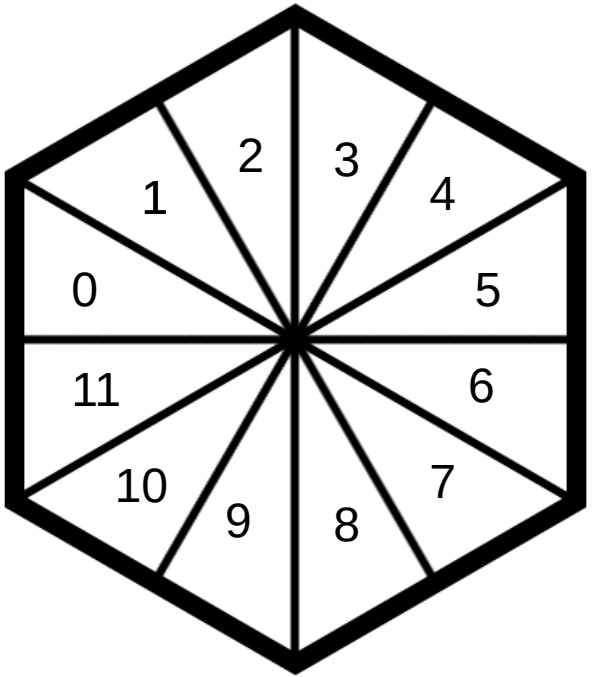


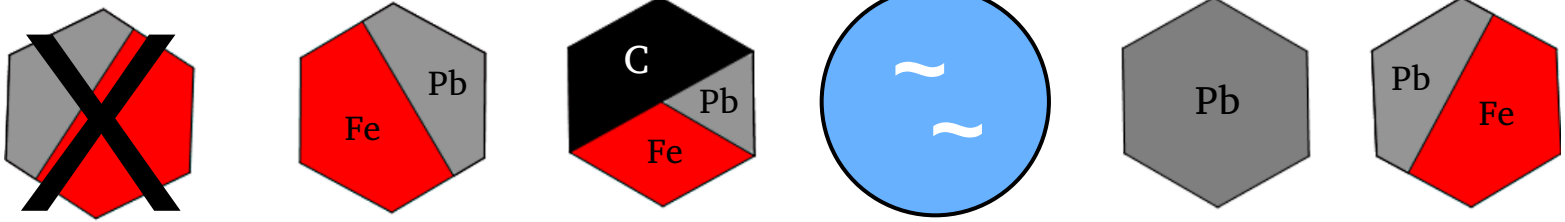




Correcting CH Flux for Nuclear Targets

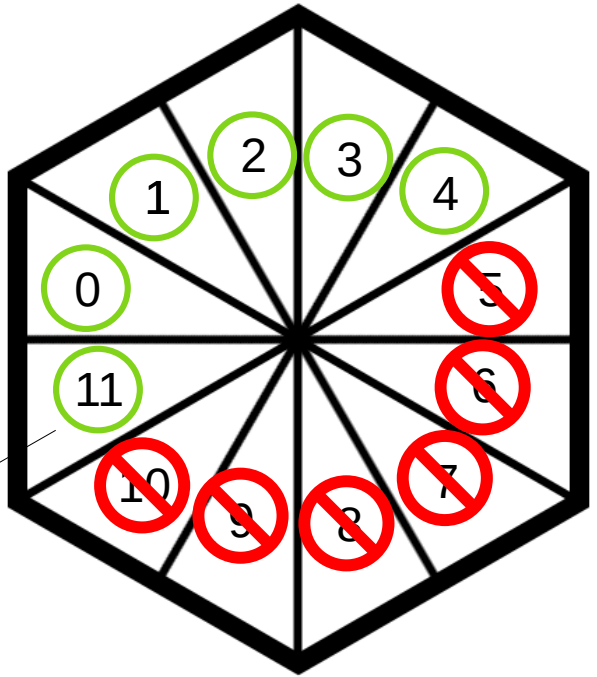
- Split the high-statistics CH region into smaller pieces
- Extract cross section for each piece

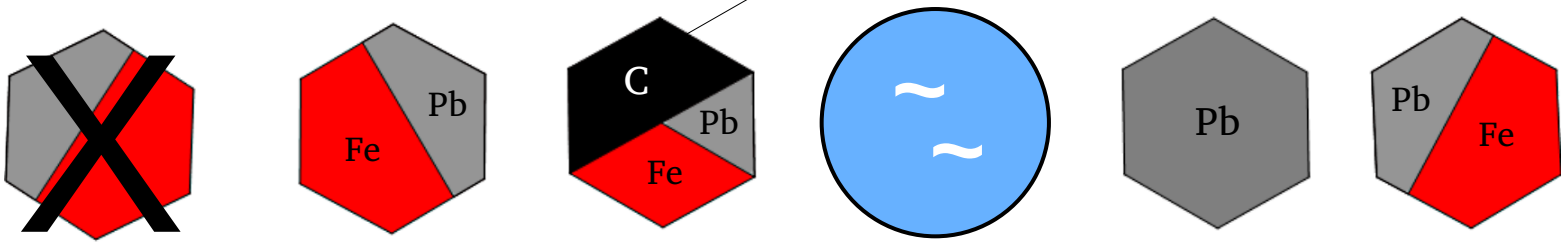




Correcting CH Flux for Nuclear Targets

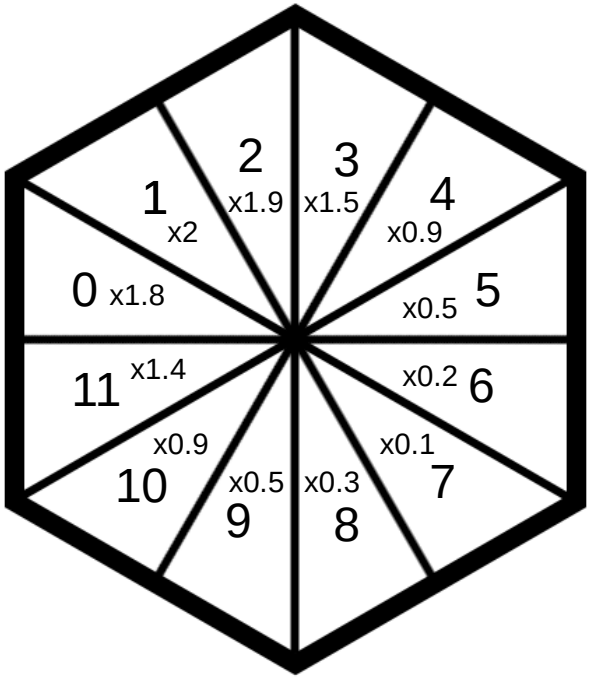
- Split the high-statistics CH region into smaller pieces
- Extract cross section for each piece
- Add together cross section pieces

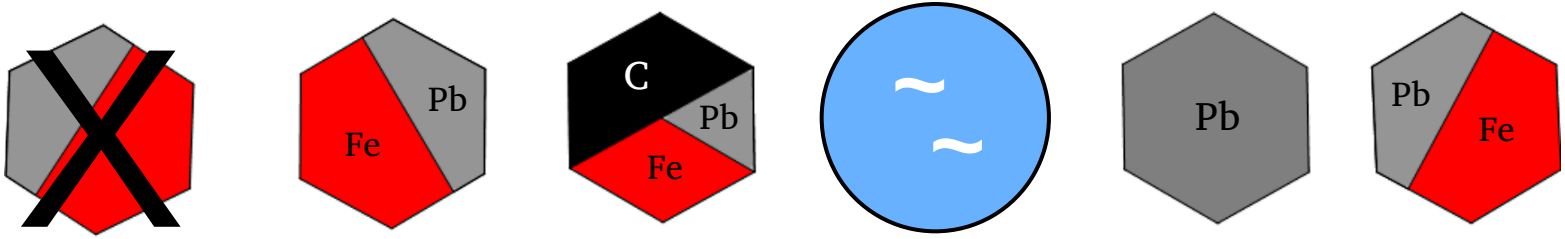




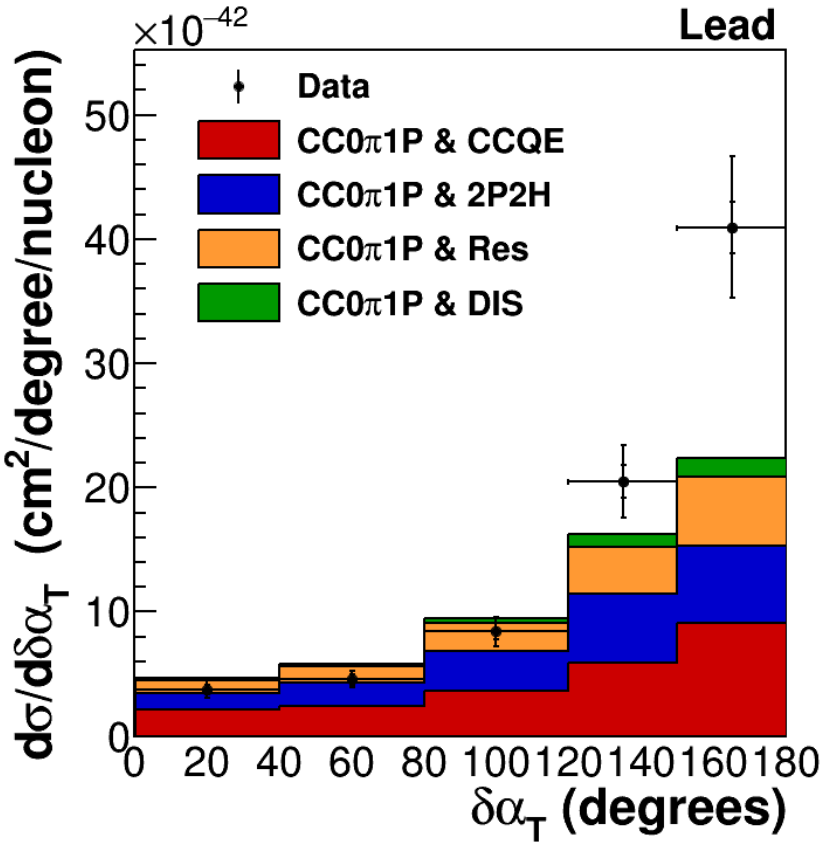
Correcting CH Flux for Nuclear Targets

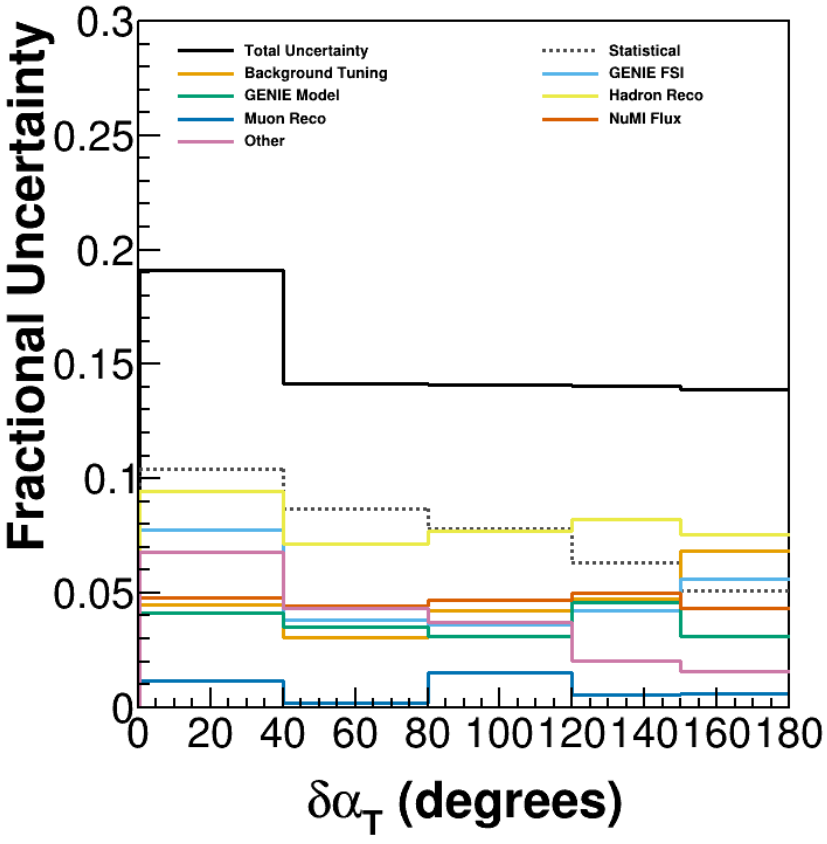
- Split the high-statistics CH region into smaller pieces
- Extract cross section for each piece
- Add together cross section pieces
- Add regularization to retain statistics



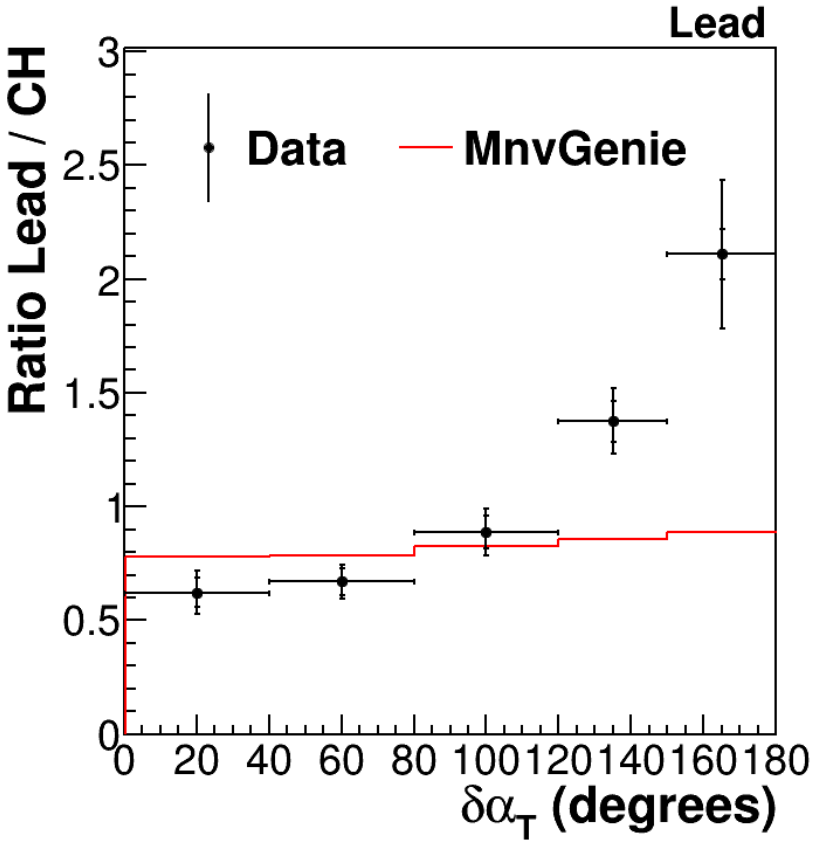


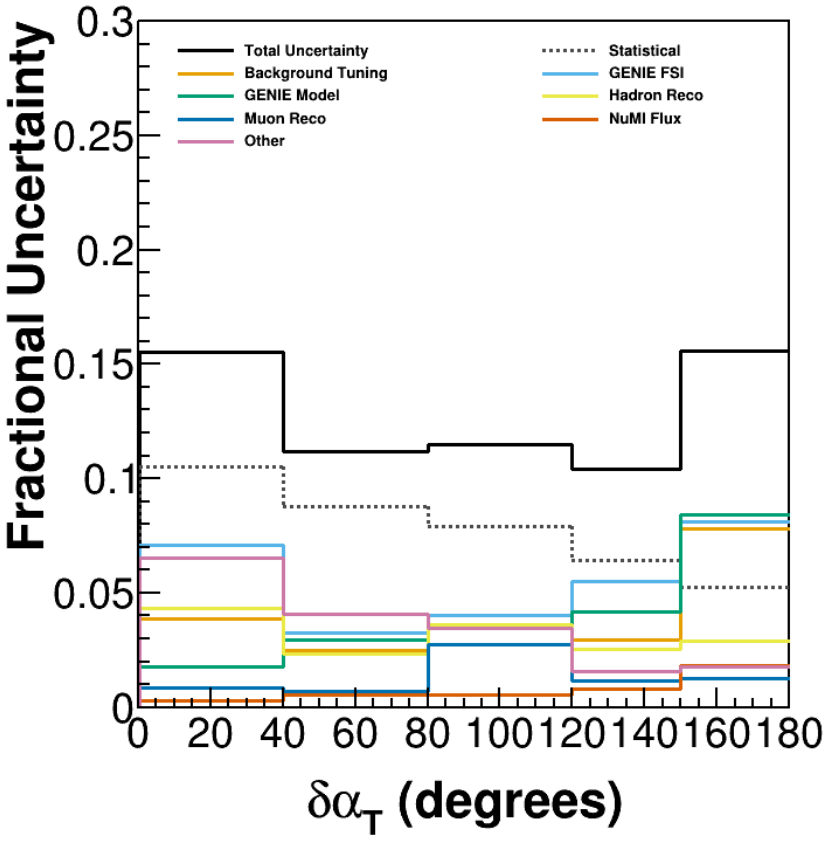
$\delta\alpha_T$ Lead Absolute Cross Section





$\delta\alpha_T$ Ratio to CH

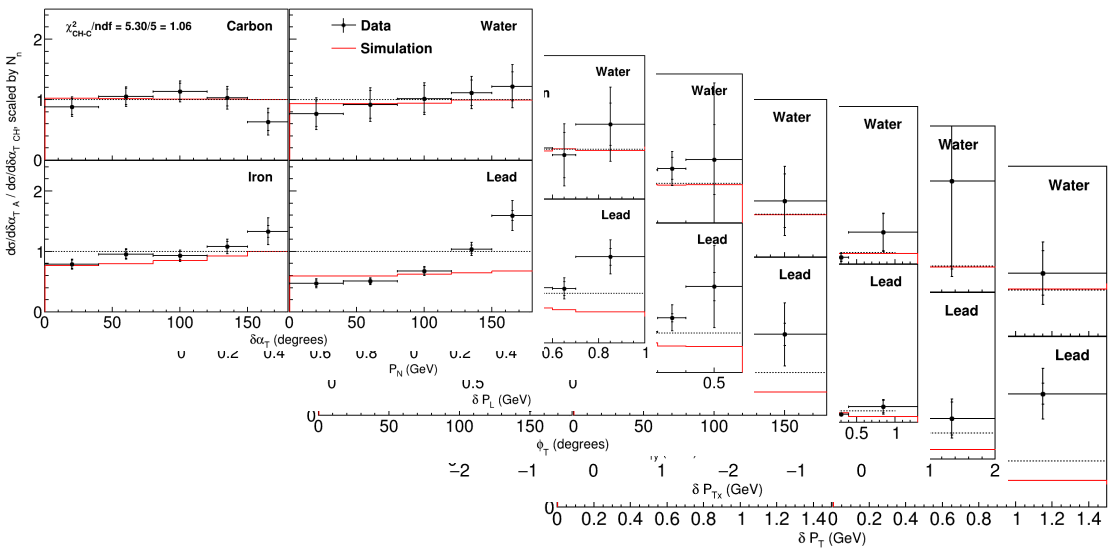




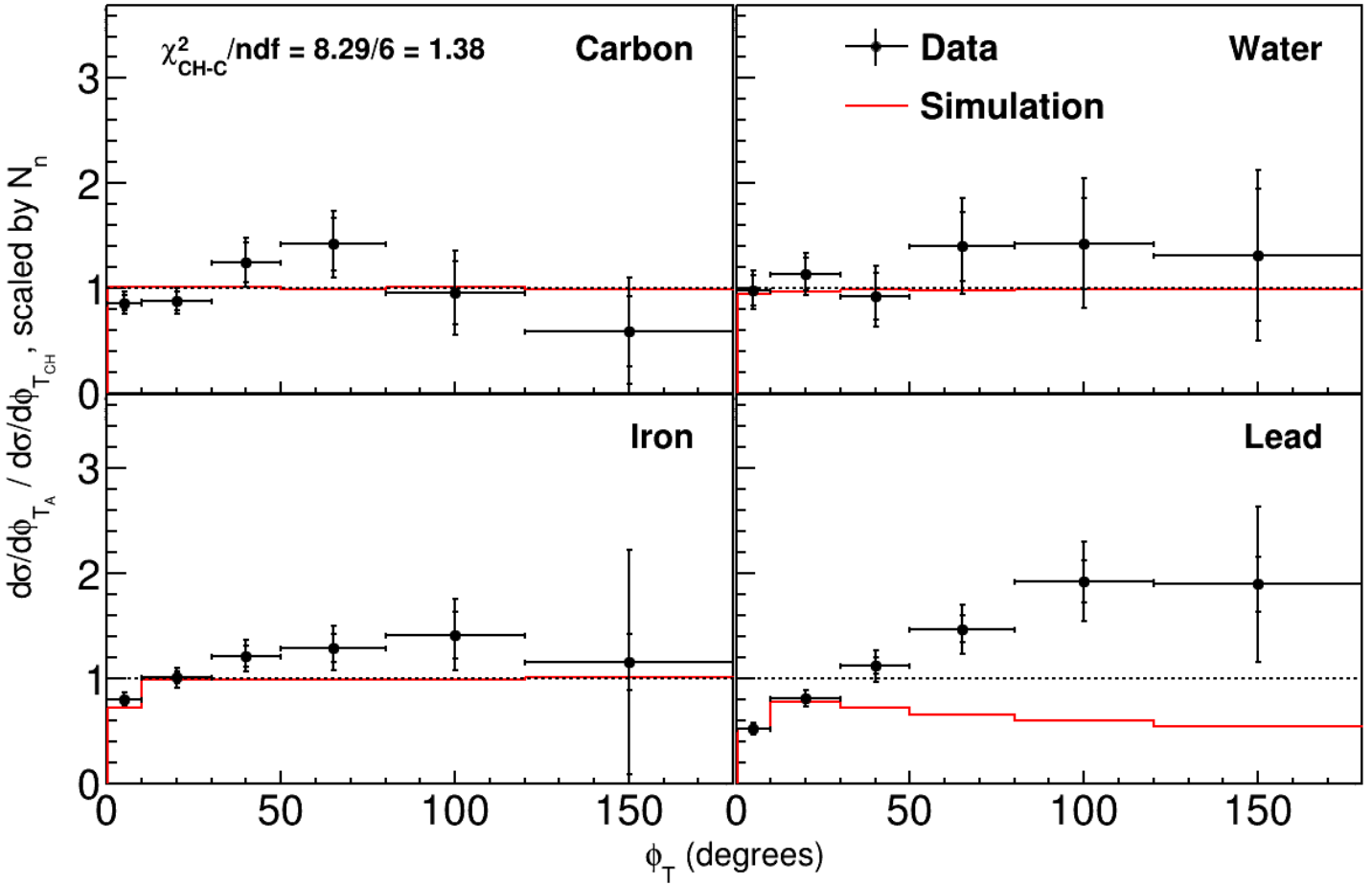
Results

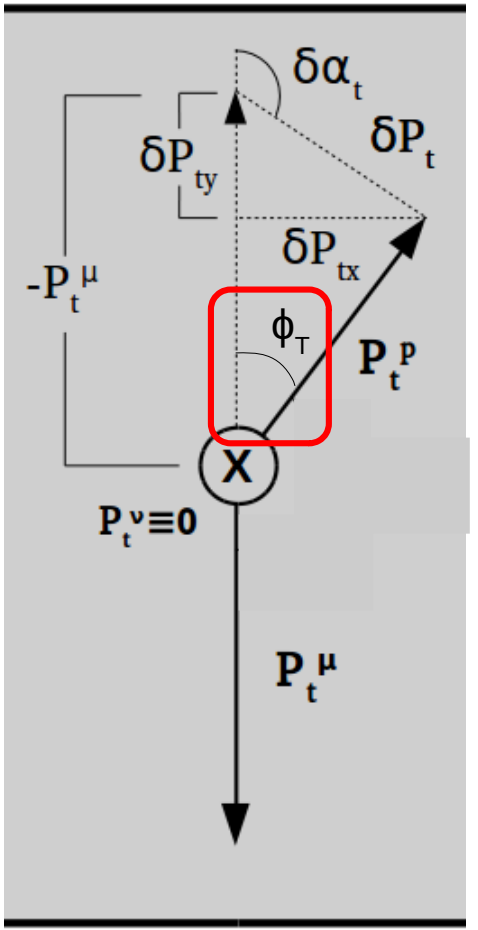
Reminder

- There are 3 muon, 3 proton, and 7 TKI cross sections across 5 nuclear targets
  - Over 200 approved plots
- Look forward to results in print

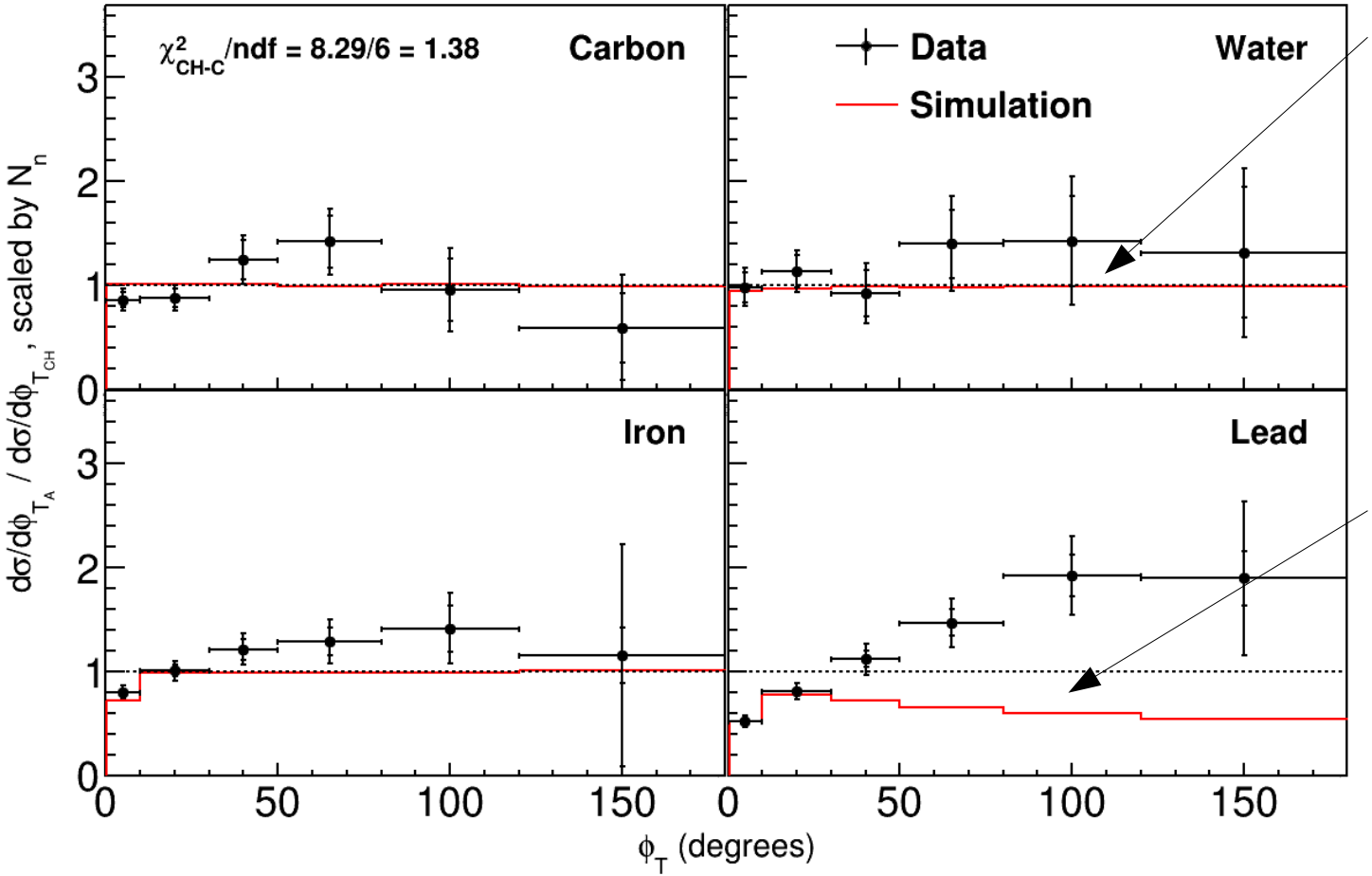


A-scaling of Proton Deflection





A-scaling of Proton Deflection



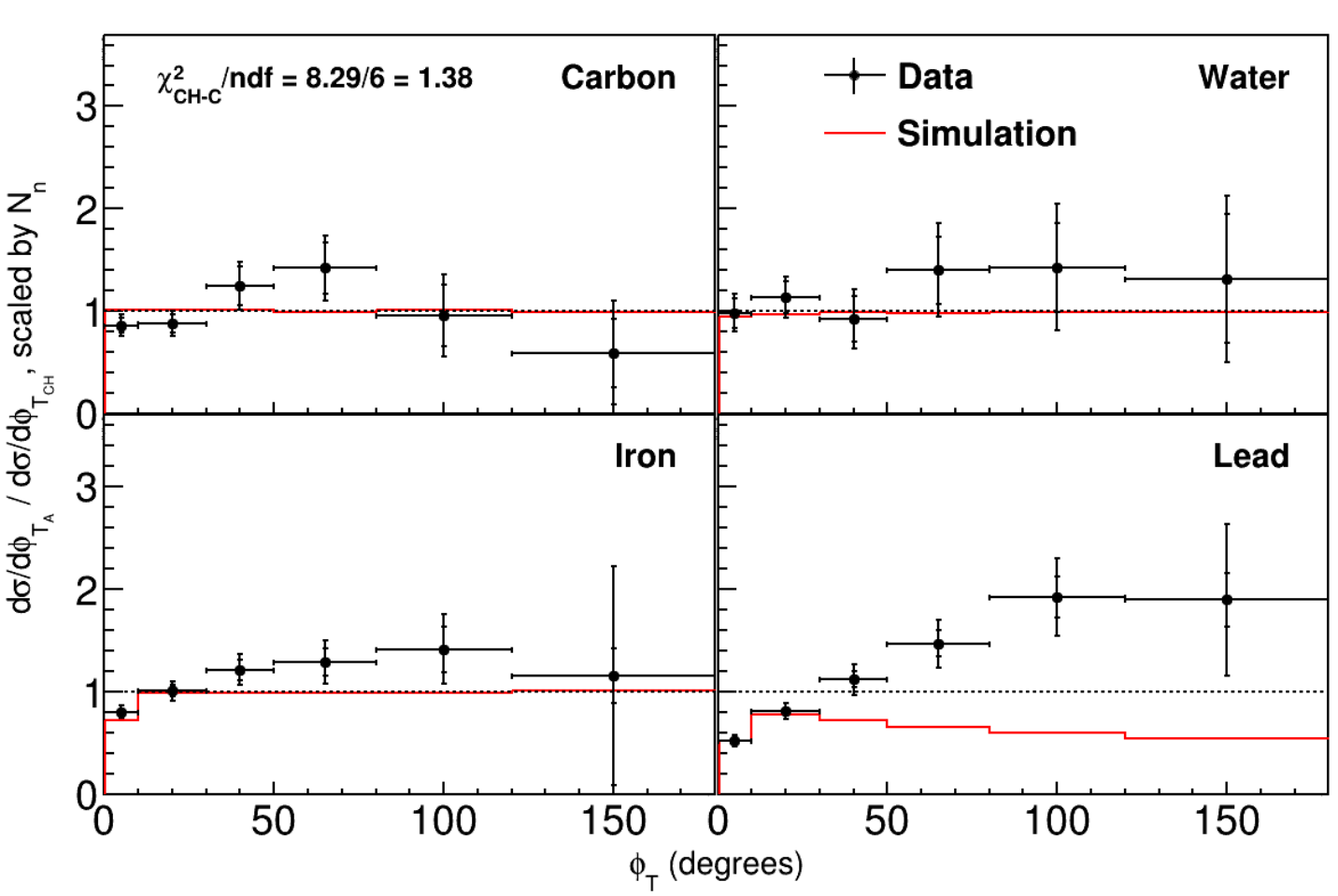
Naive scaling ~ 1

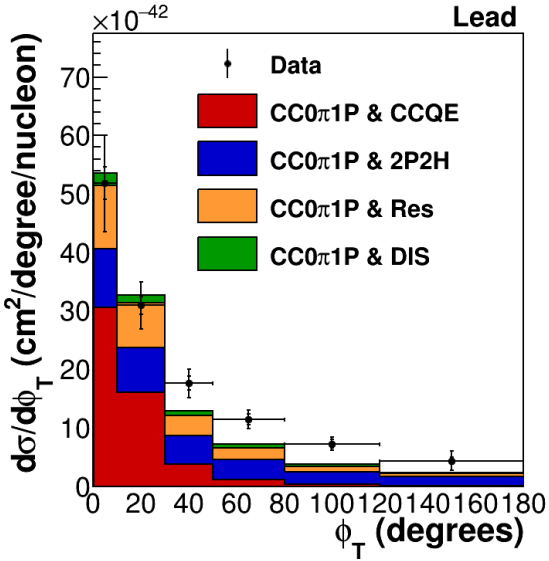
- Scaling by N neutrons
- Majority of interactions on neutrons
- 2x the neutrons, 2x the cross section

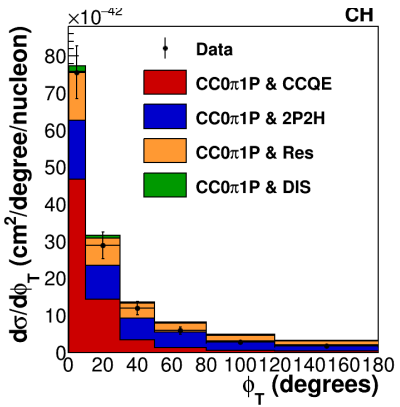
Model Scaling

- MnvTune
- Takes into account model's FSI scaling and other nuclear effects

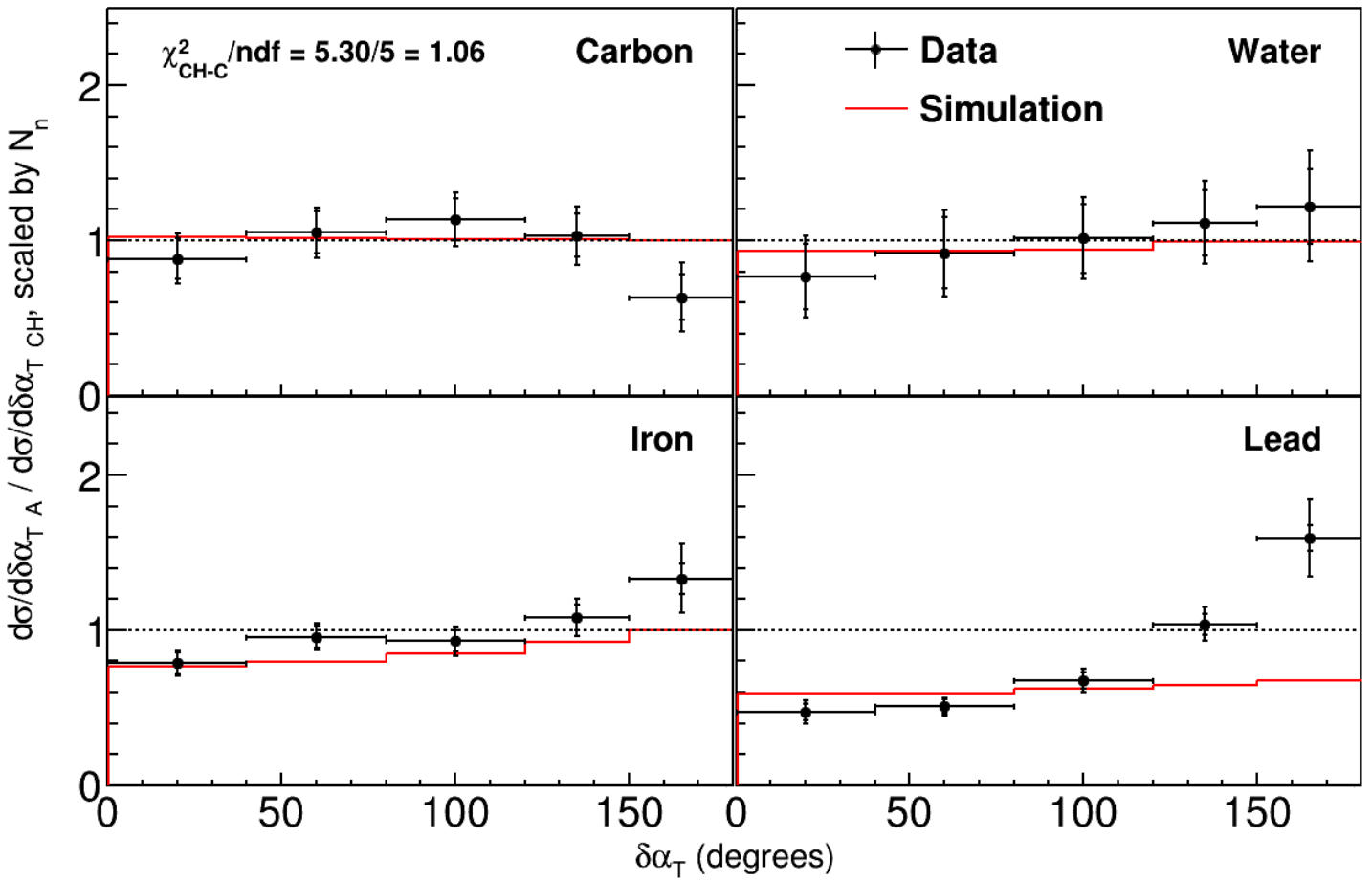
A-scaling of Proton Deflection

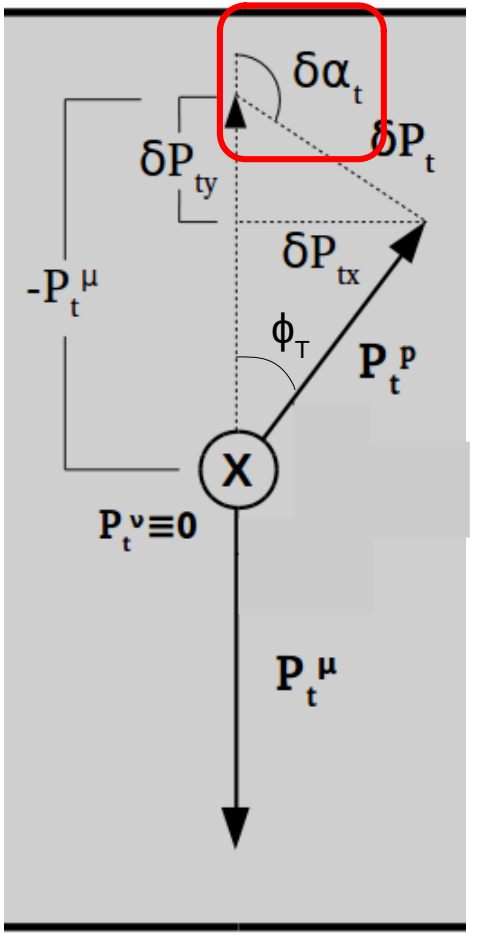




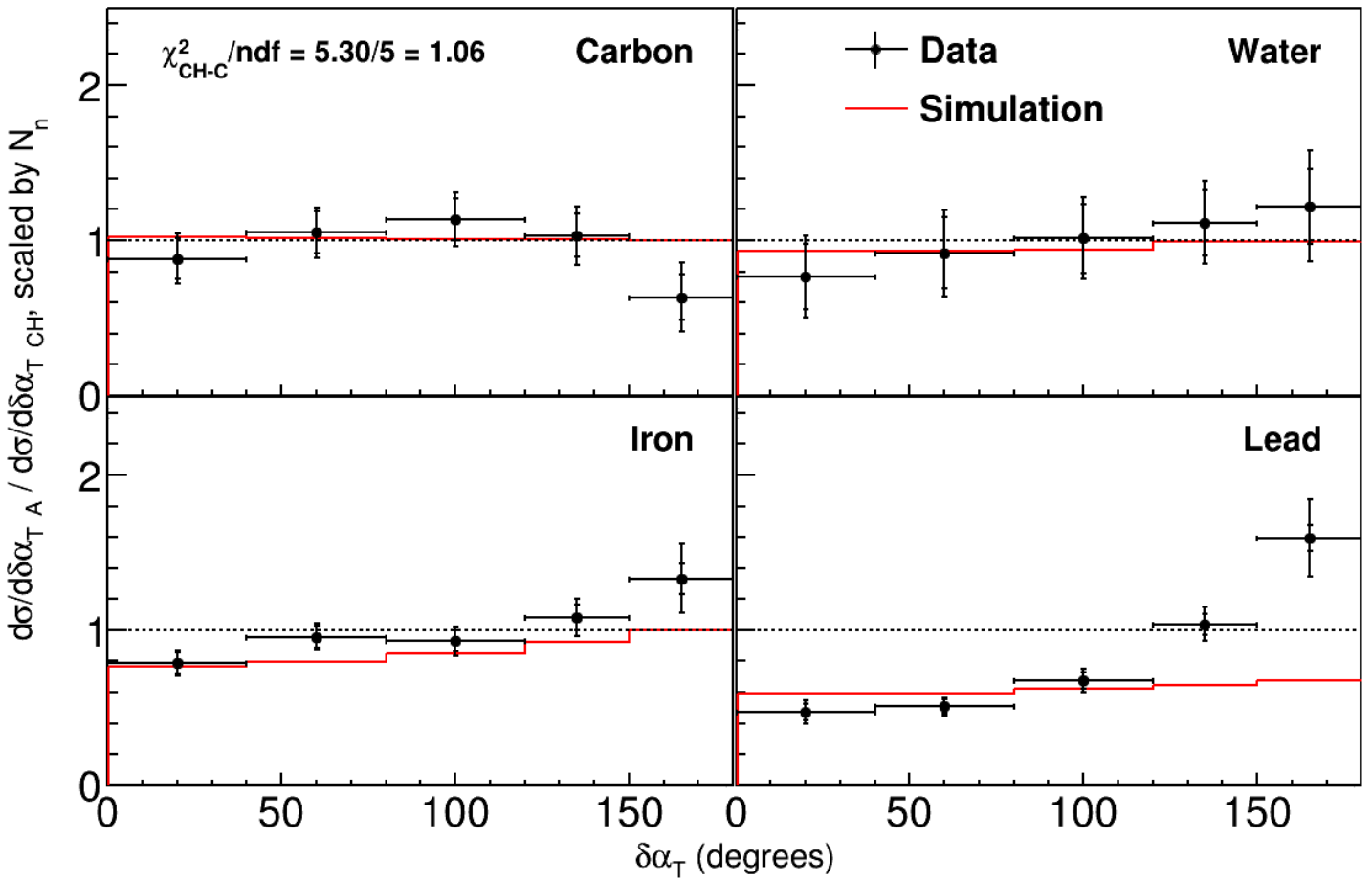


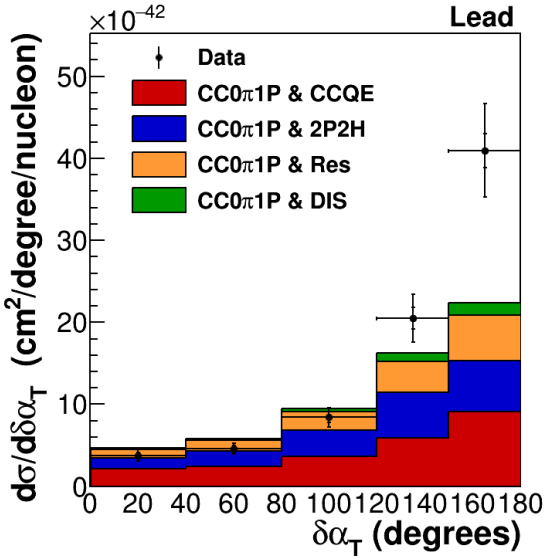
A-scaling of Proton Momentum Loss

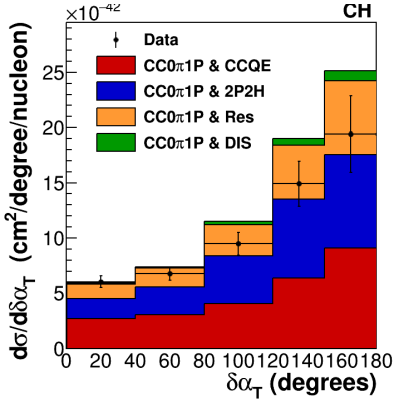




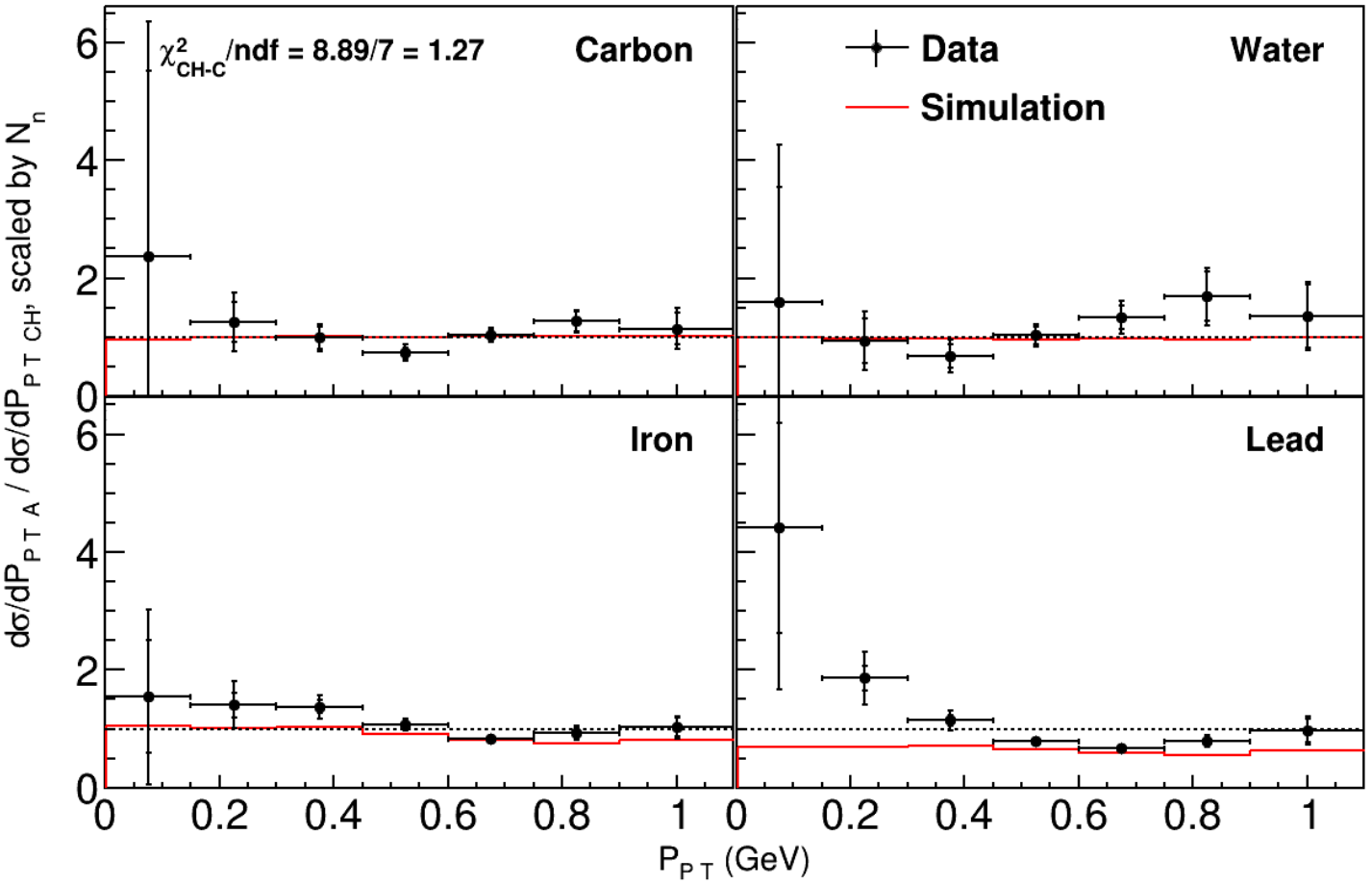
A-scaling of Proton Momentum Loss

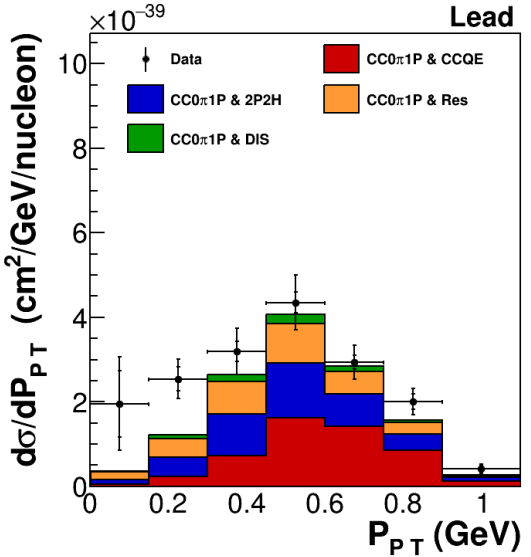


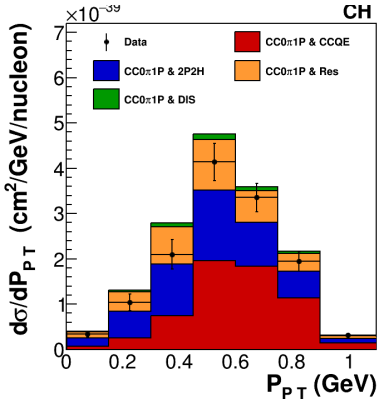




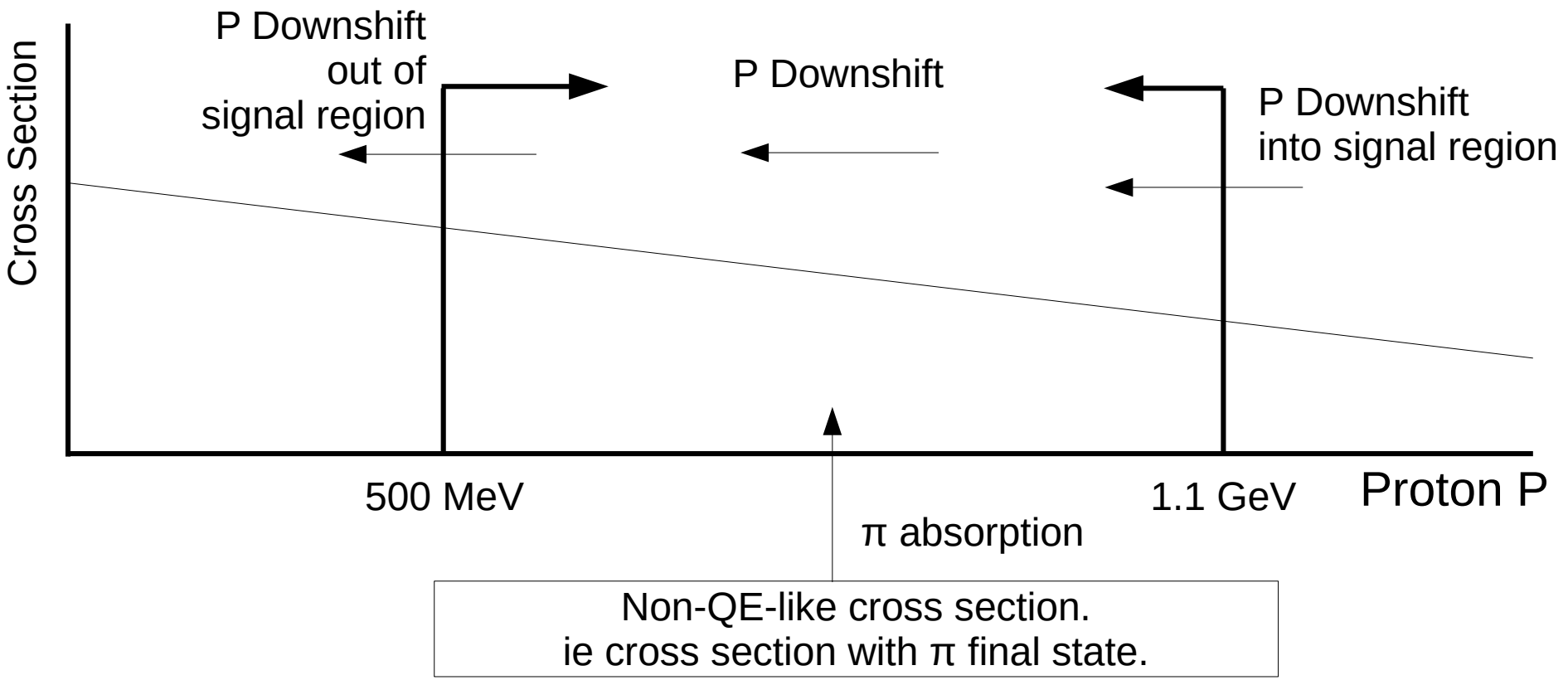
Proton Transverse Momentum



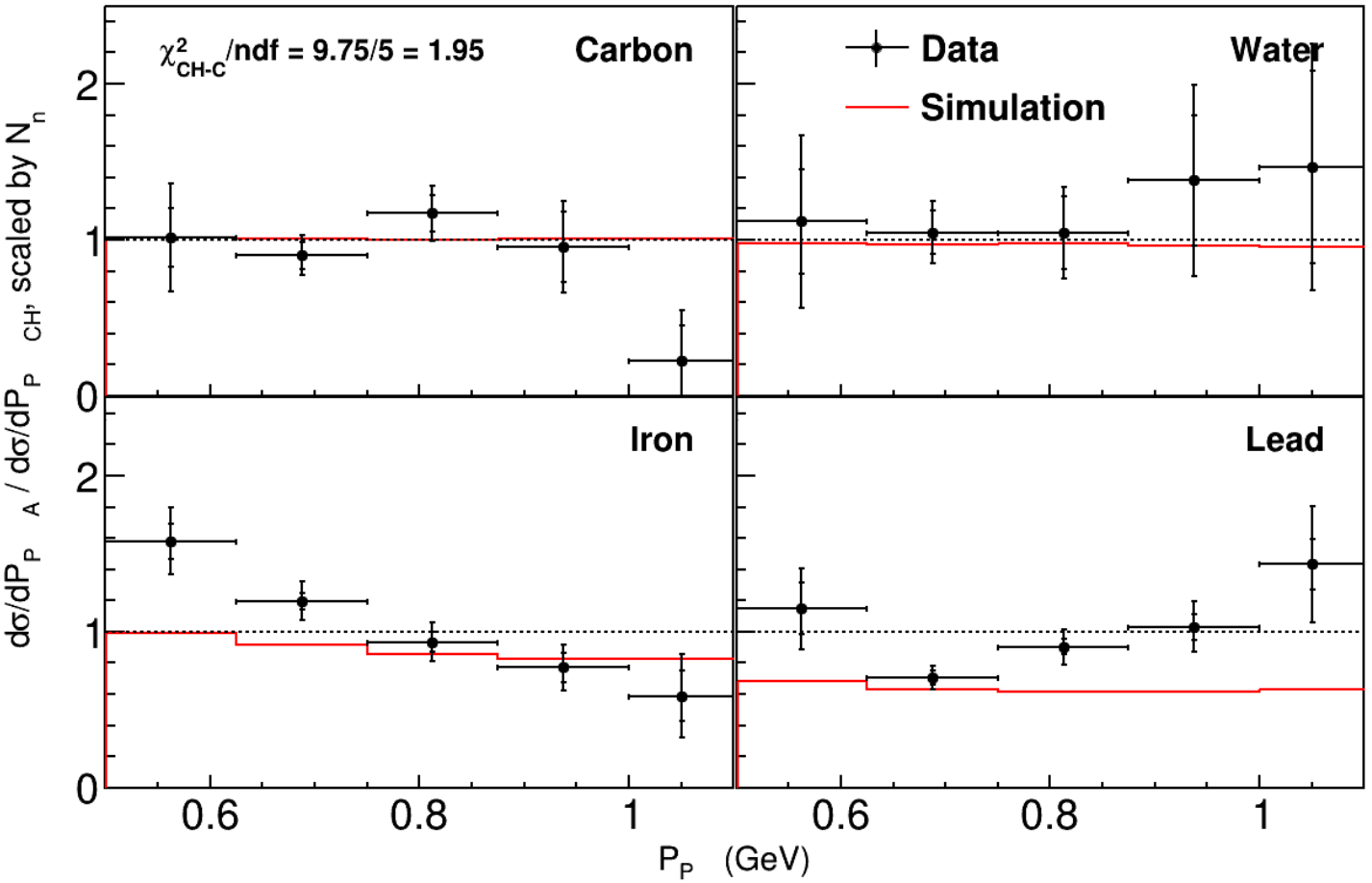


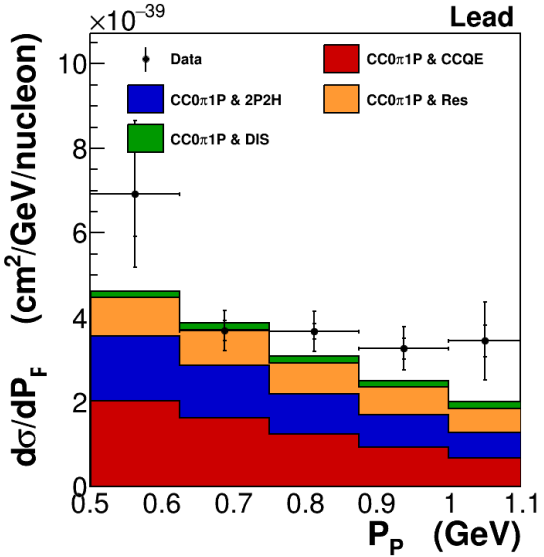


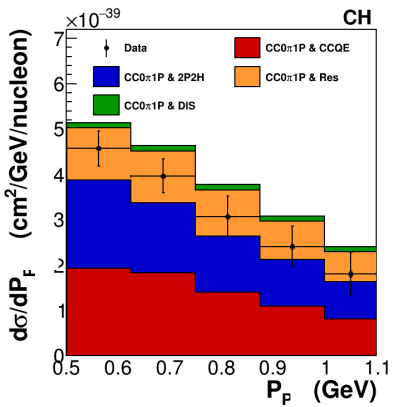
How does proton affect cross section?



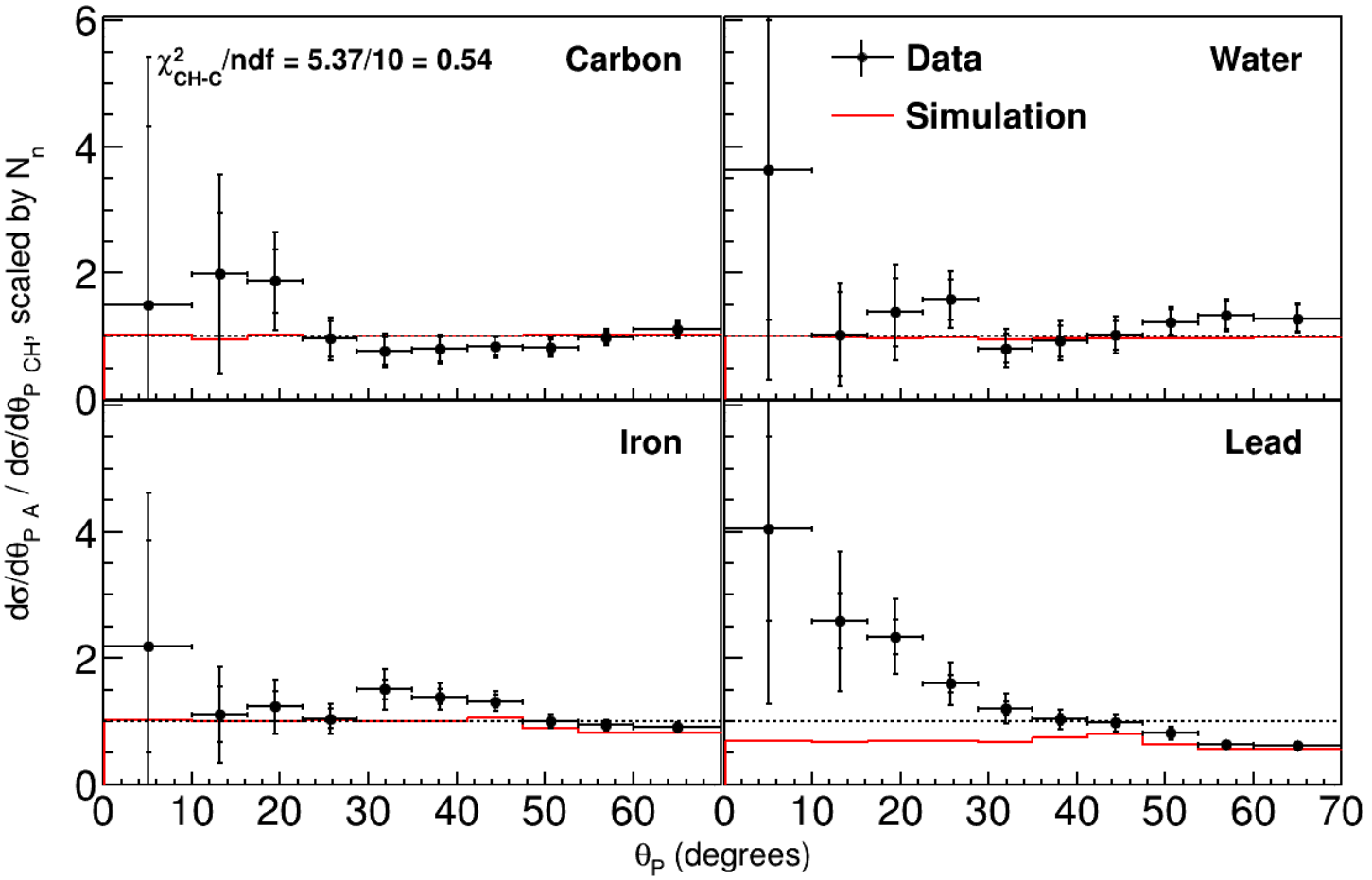
Proton Momentum

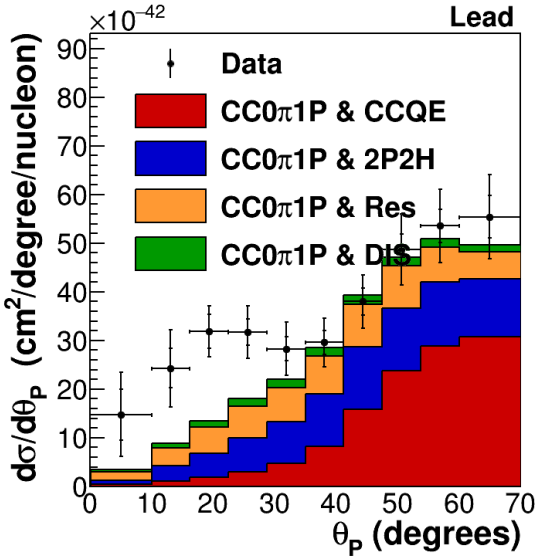


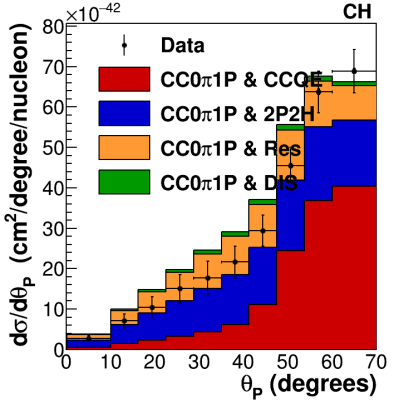




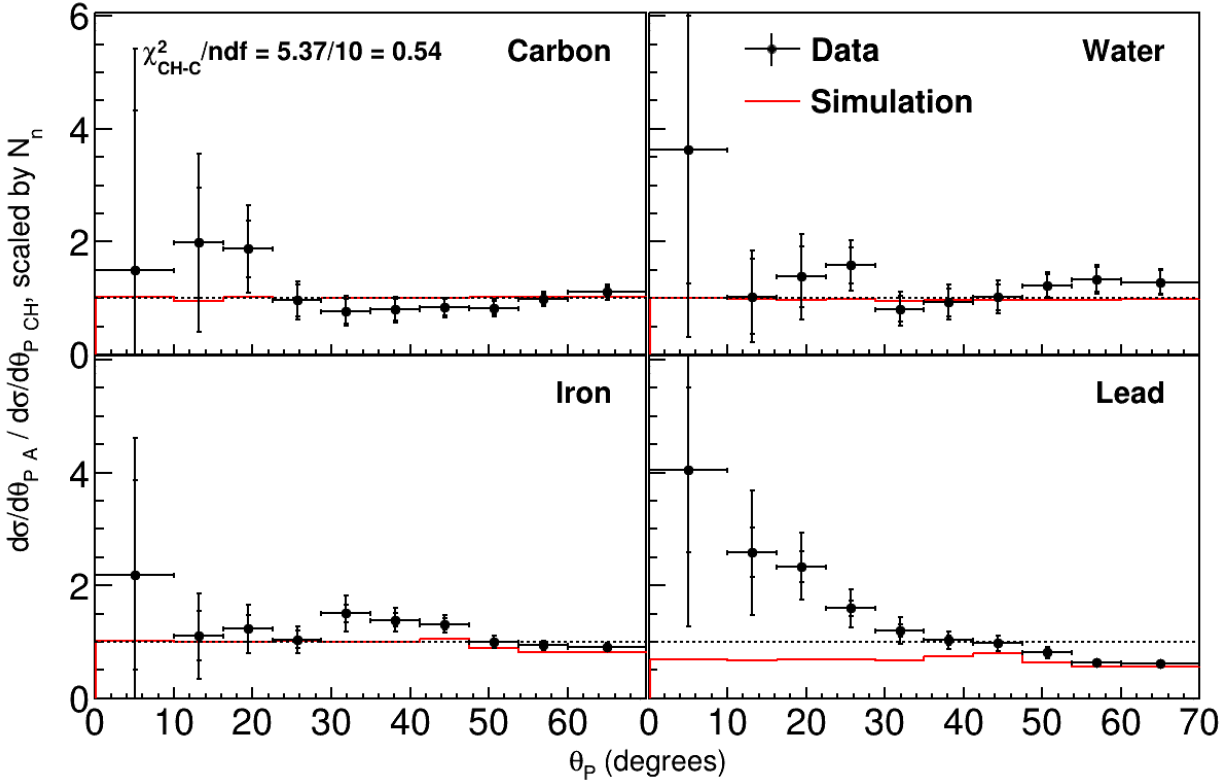
Proton Angle with Respect to Beam

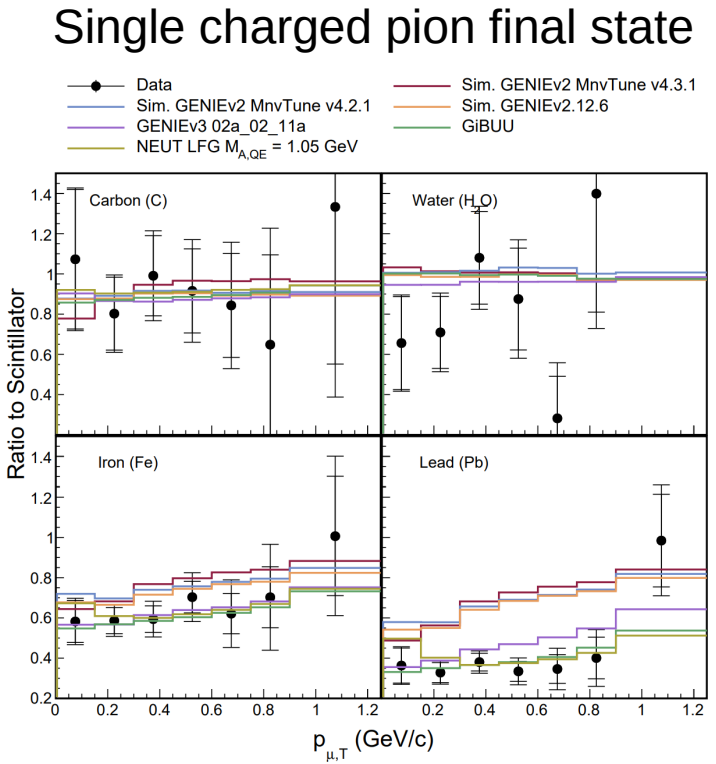






Comparing to Single Charged Pion Results

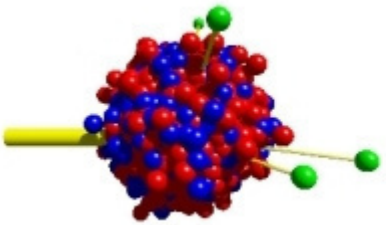




[hep-ex]:2209.07852 →

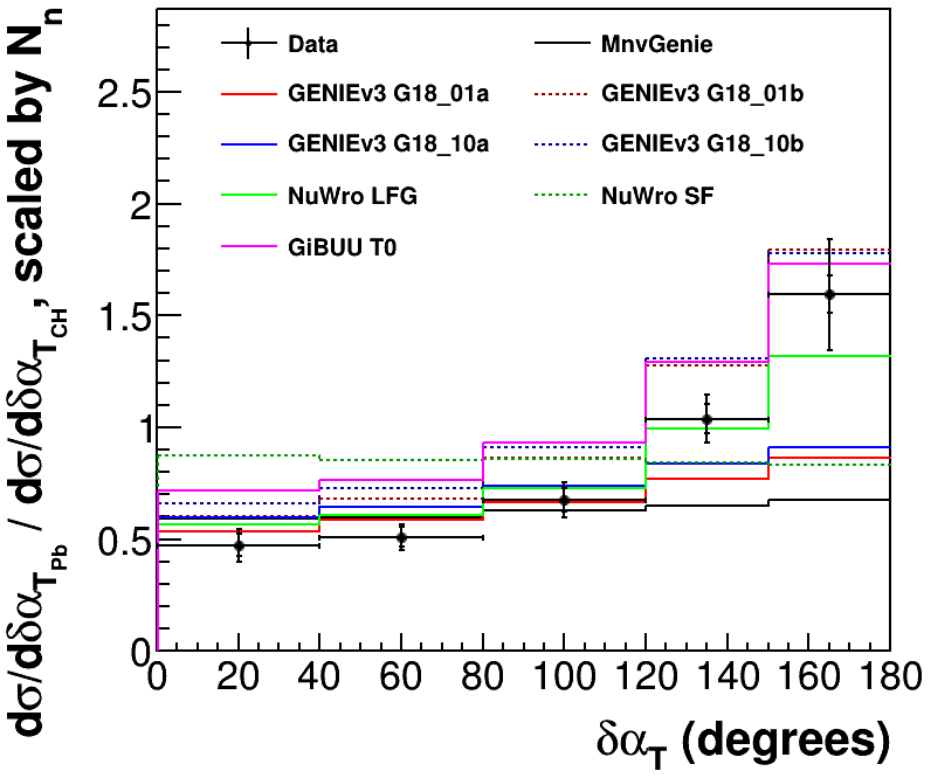
FIG. 5. Cross section ratios $(\frac{d\sigma_A}{dp_{\mu,T}})/(\frac{d\sigma_{CH}}{dp_{\mu,T}})$ for carbon, water, iron, and lead (solid points), as compared to GENIE, NEUT, and GIBUU.

Generators Introduction



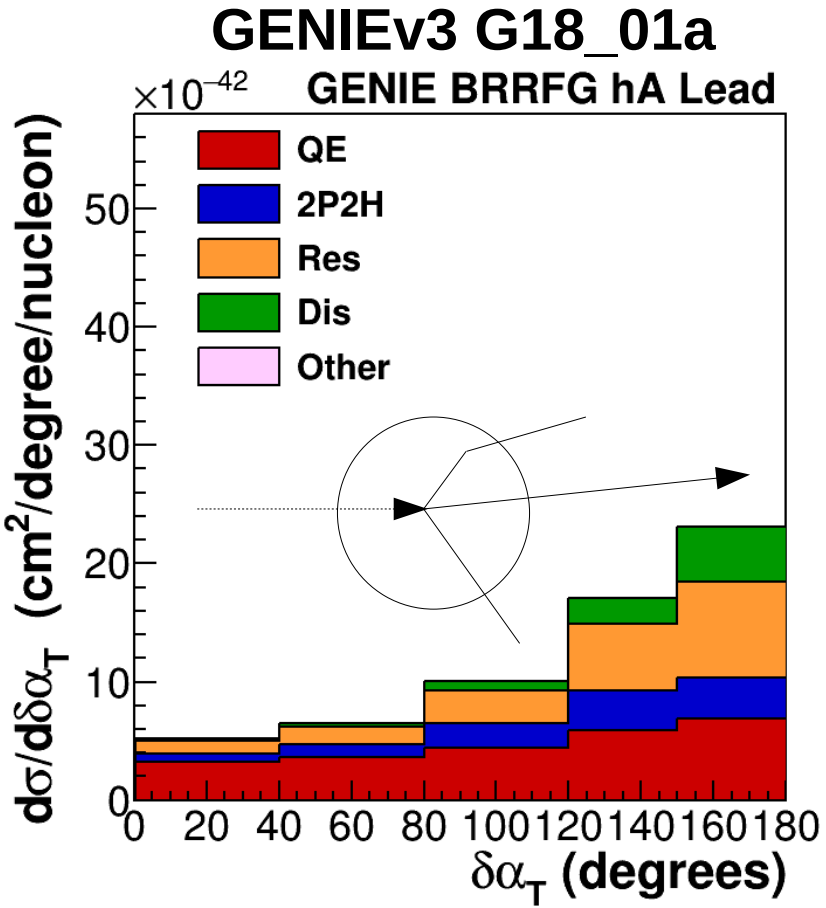
GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

Generator Comparison: $\delta\alpha_T$ in Lead

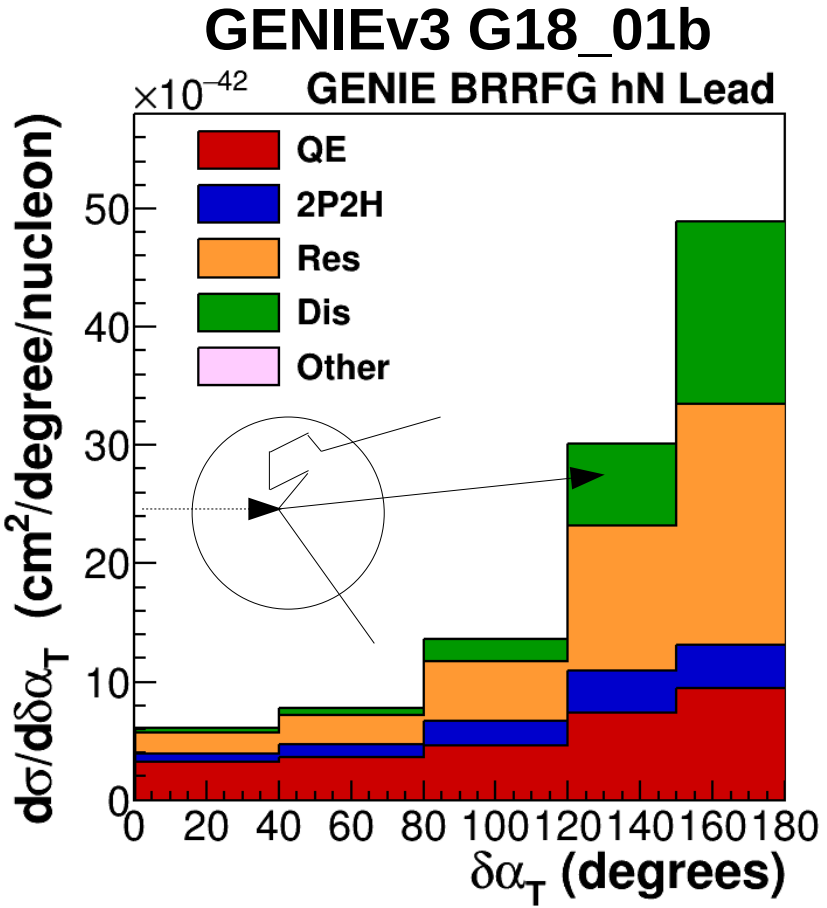


Model	χ/ndf
MnvGenie	31.25/5 = 6.25
GENIEv3 G18_01a	17.83/5 = 3.57
GENIEv3 G18_01b	12.92/5 = 2.58
GENIEv3 G18_10a	23.58/5 = 4.72
GENIEv3 G18_10b	21.14/5 = 4.23
NuWro LFG	7.07/5 = 1.41
NuWro SF	88.03/5 = 17.61
GiBUU T0	28.51/5 = 5.7

Geniev3 Predictions

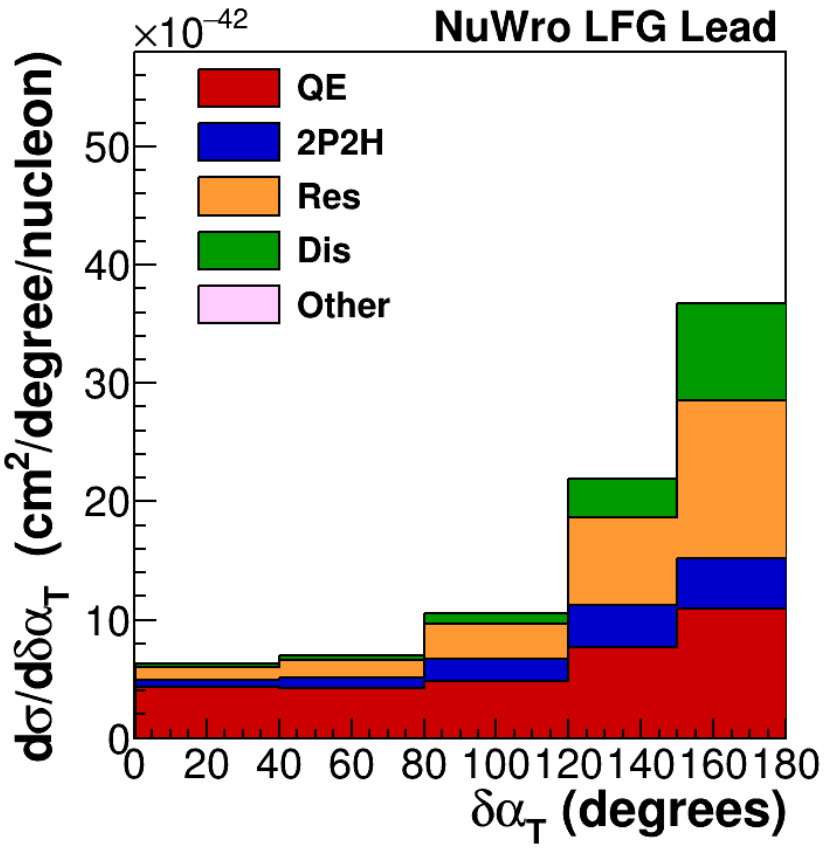


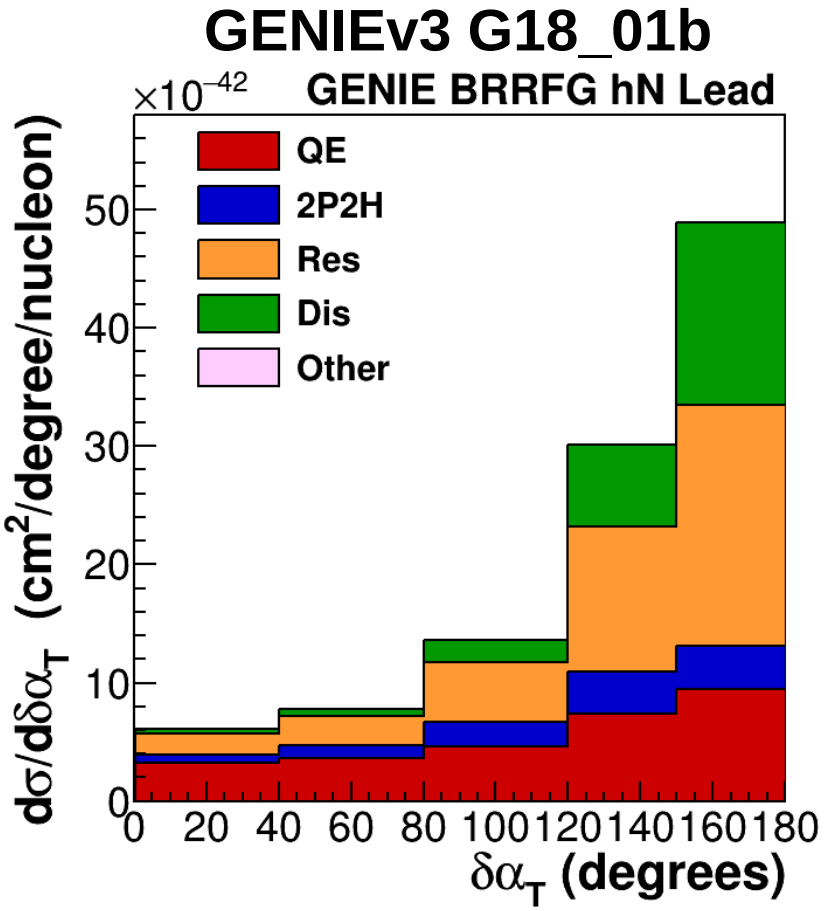
Single interaction model



Cascade model

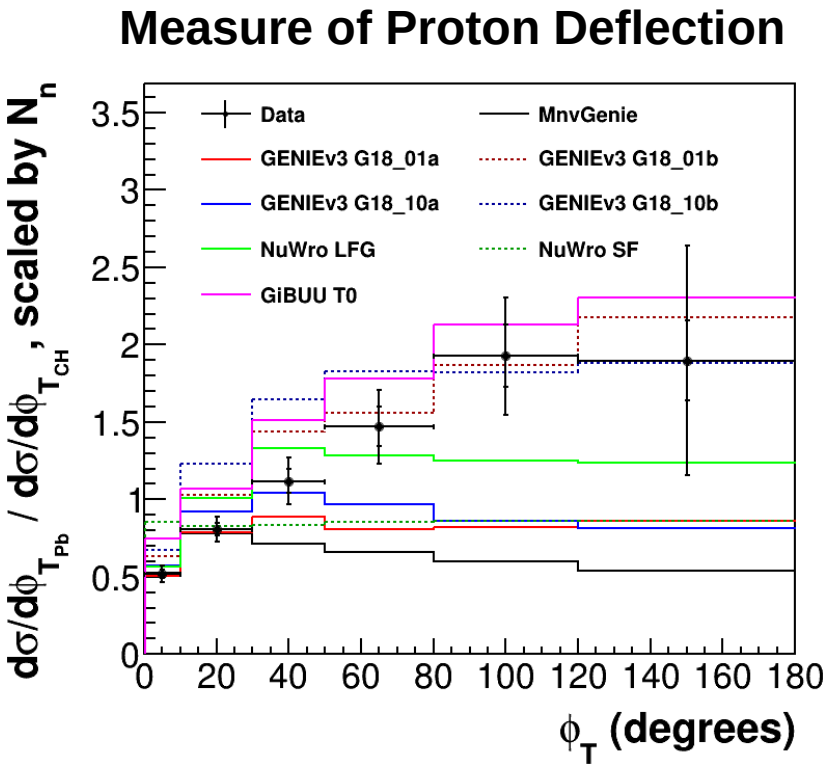
Comparison to NuWro



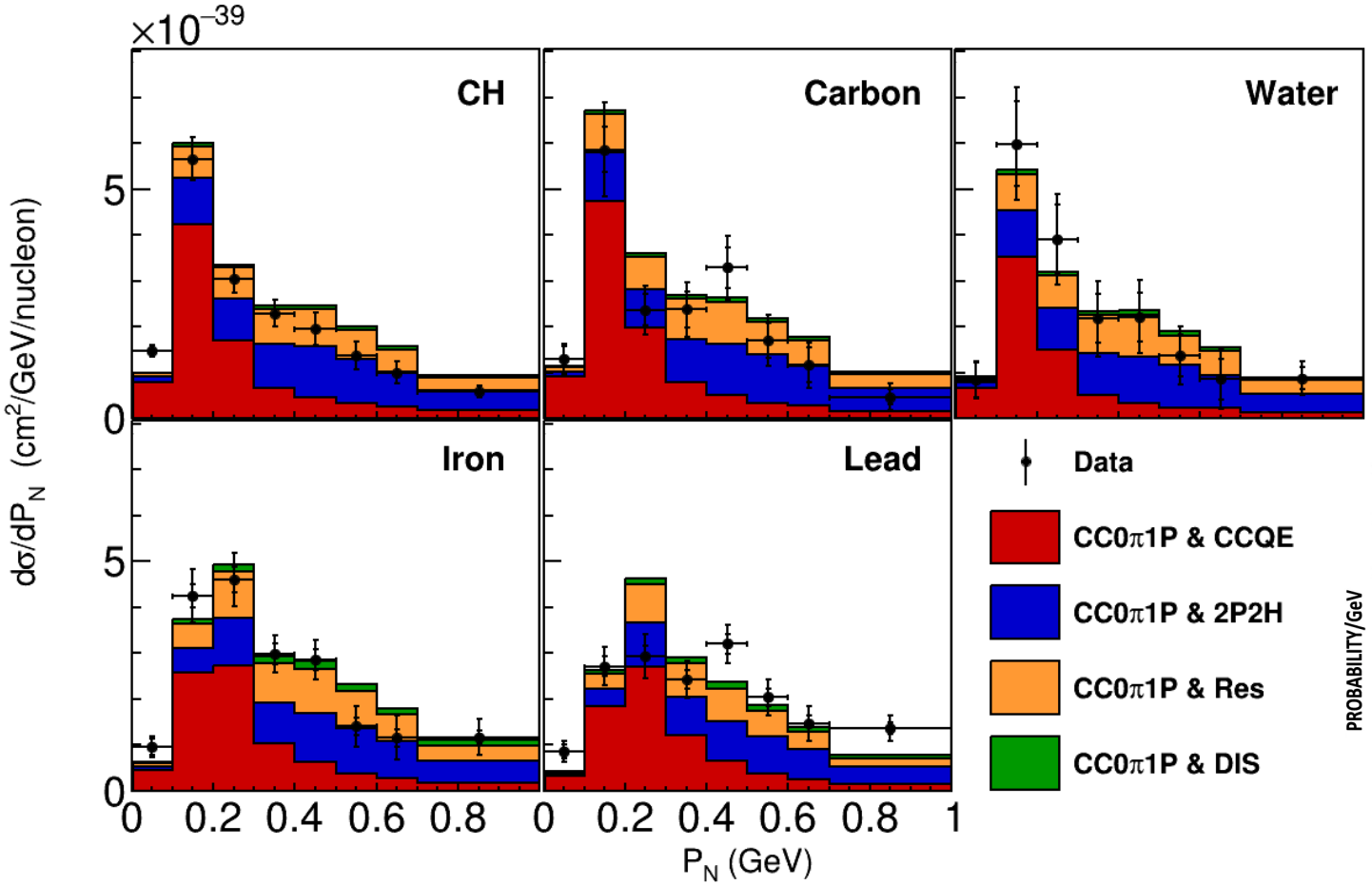


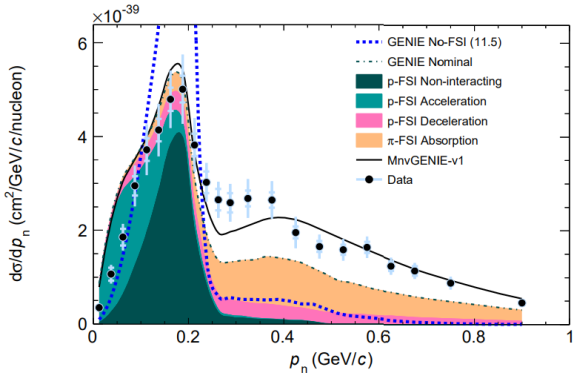
Summary so far

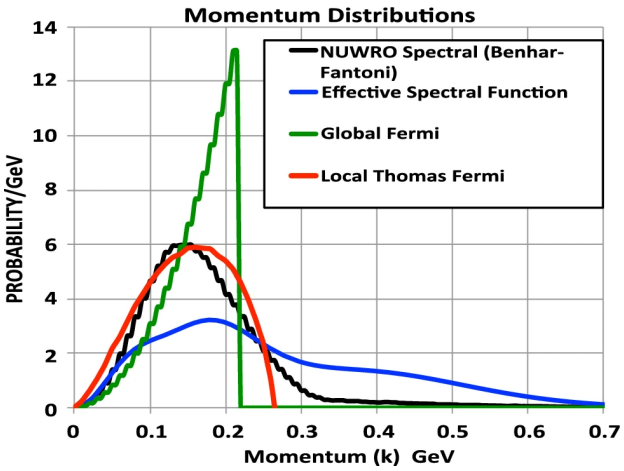
- So many variables and cross sections
  - Many generator comparisons
- No one generator is able to match the data perfectly
- Each better or worse in their own way



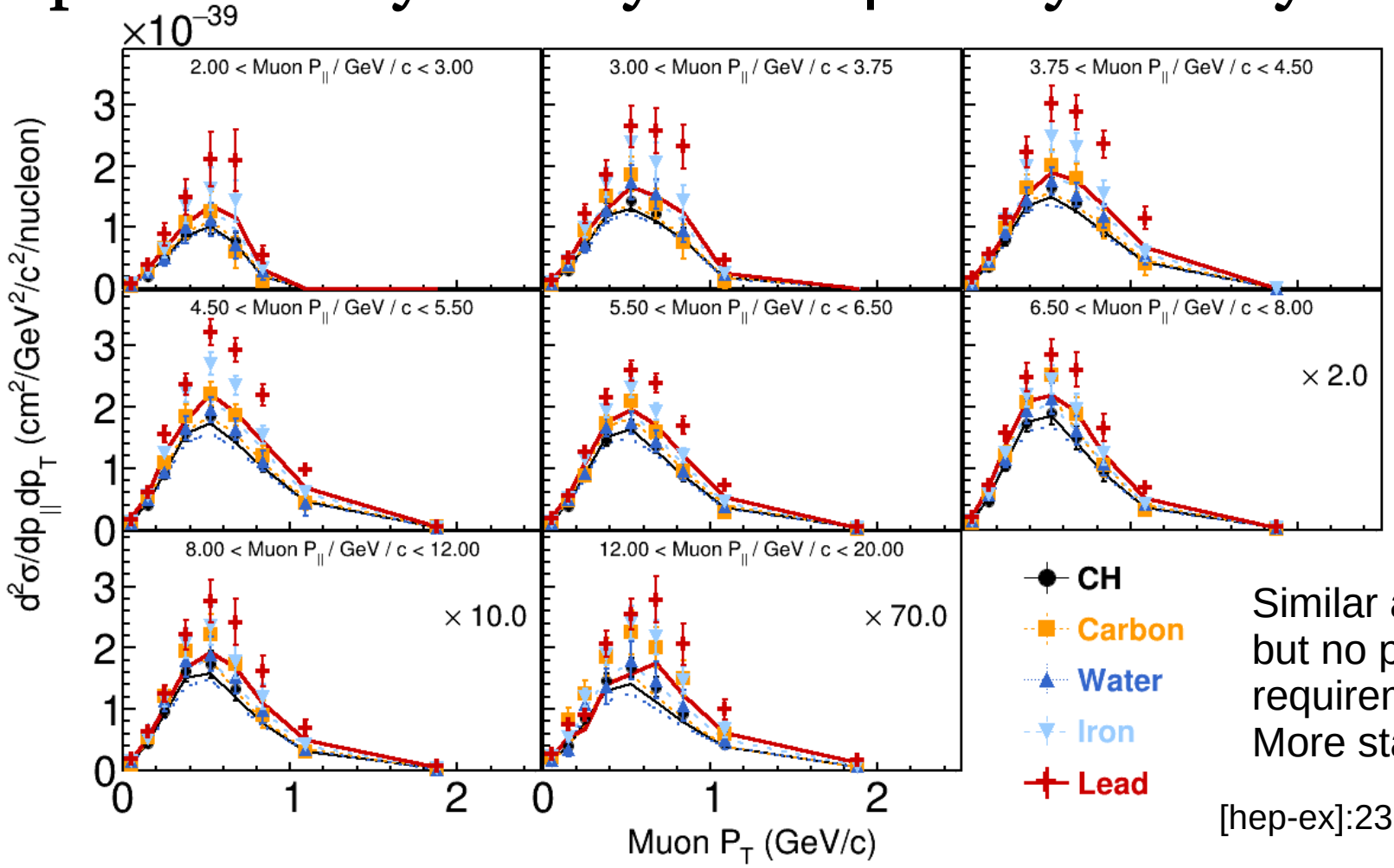
A-scaling of Reconstructed Initial Neutron P







Complementary Analysis – μ-only Analysis

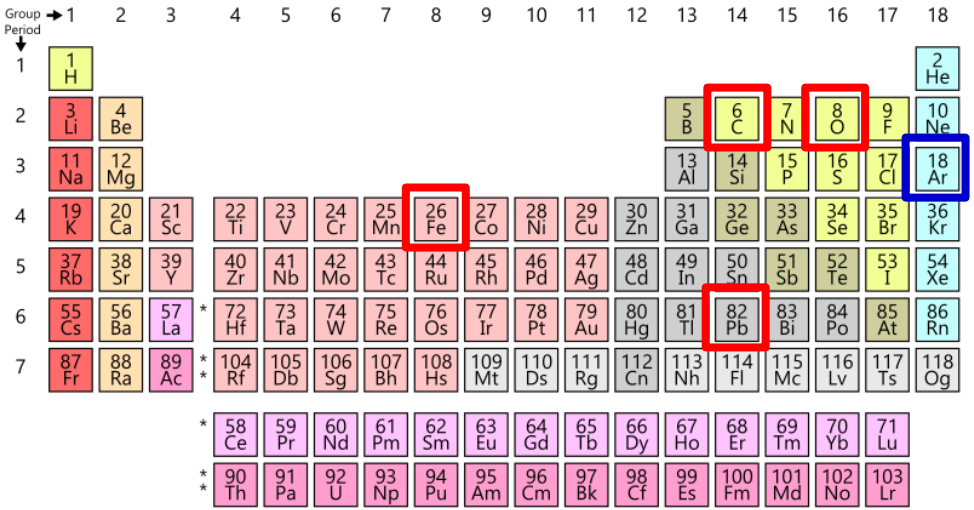


Similar analysis but no proton requirements. More statistics.

[hep-ex]:2301.02272

Conclusion

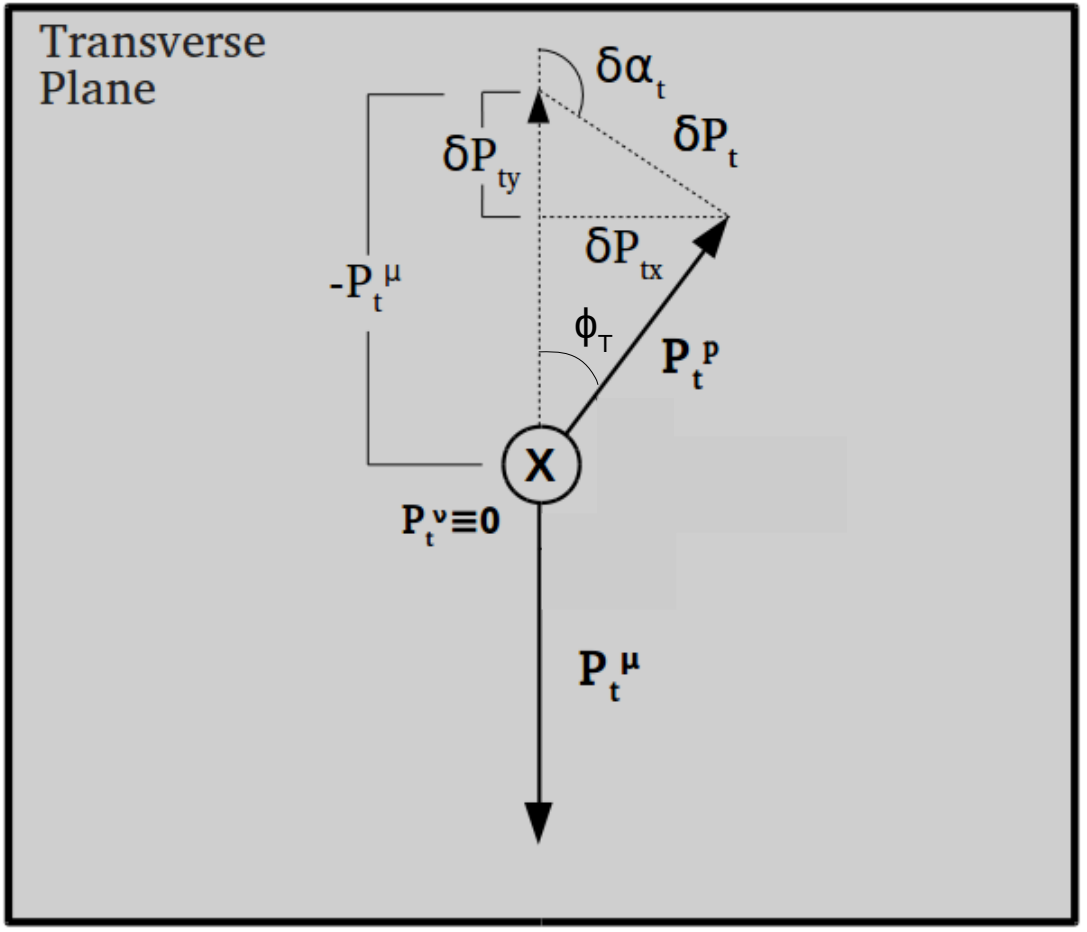
- 1st look at nucleus-by-nucleus proton behavior in ME beam
  - Proton elastic deflection or pion feed-in
  - Forward-going subset
- Generator envelope covers most variables, but no one generator gets it right
- Very rich dataset sharing same detector and flux, canceling out systematic uncertainties
  - Look forward to results in print



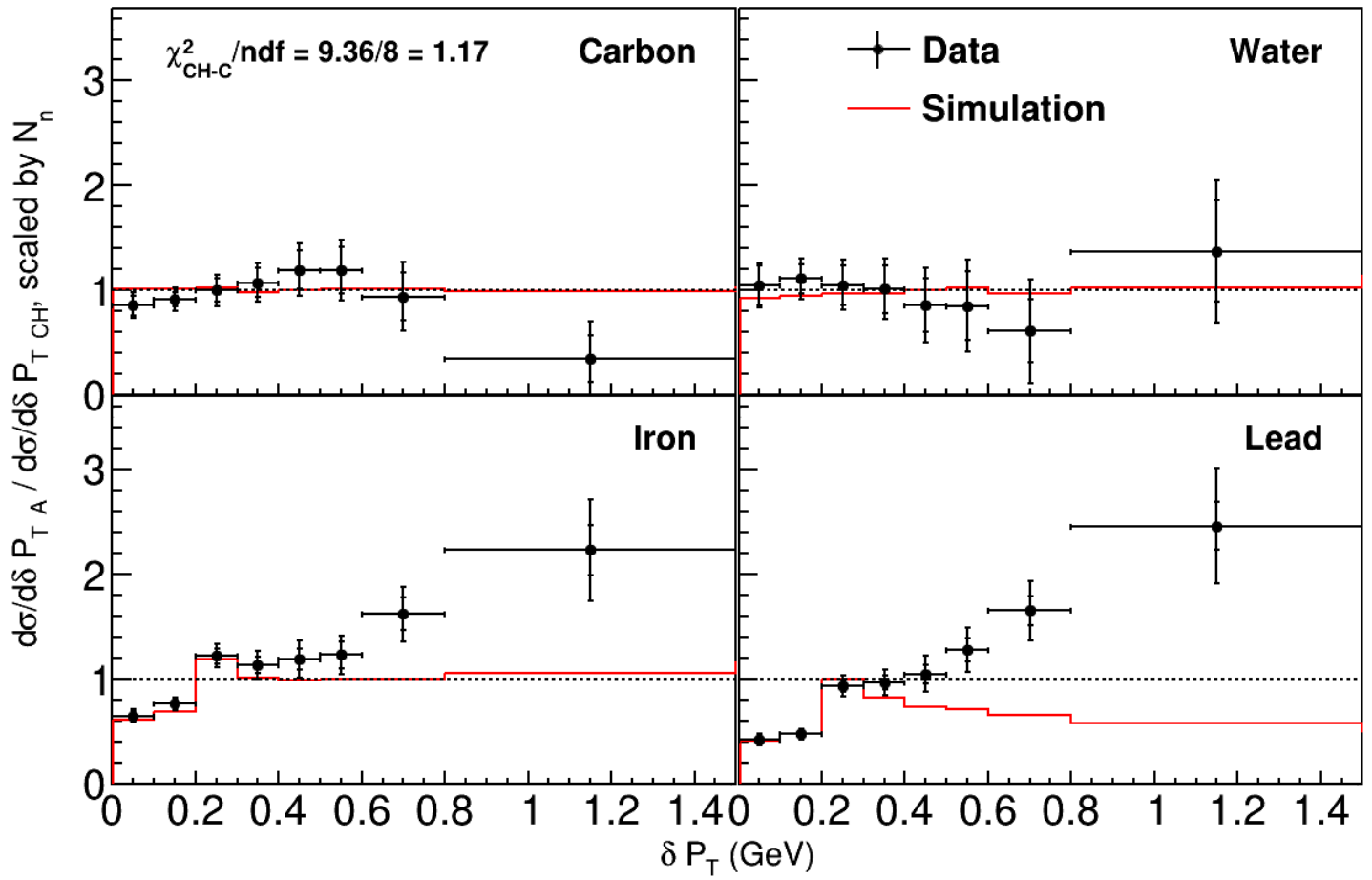
Thank You!

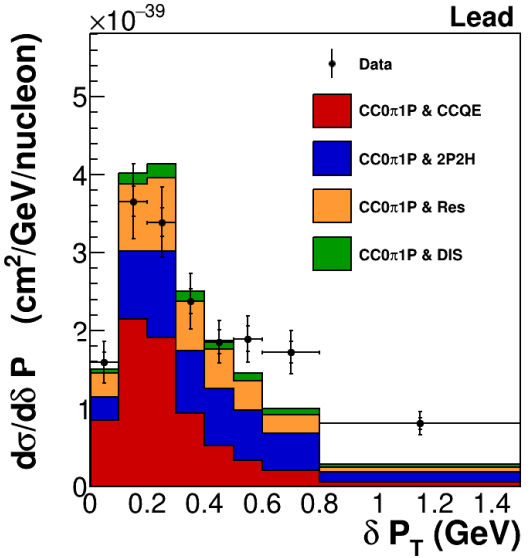
Backup

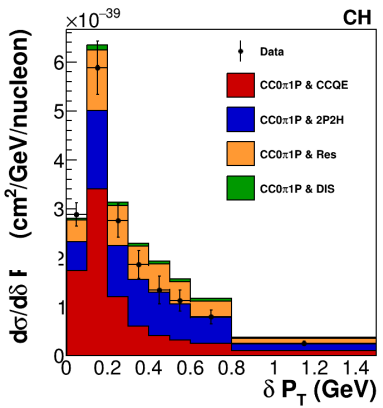
TKI Reminder



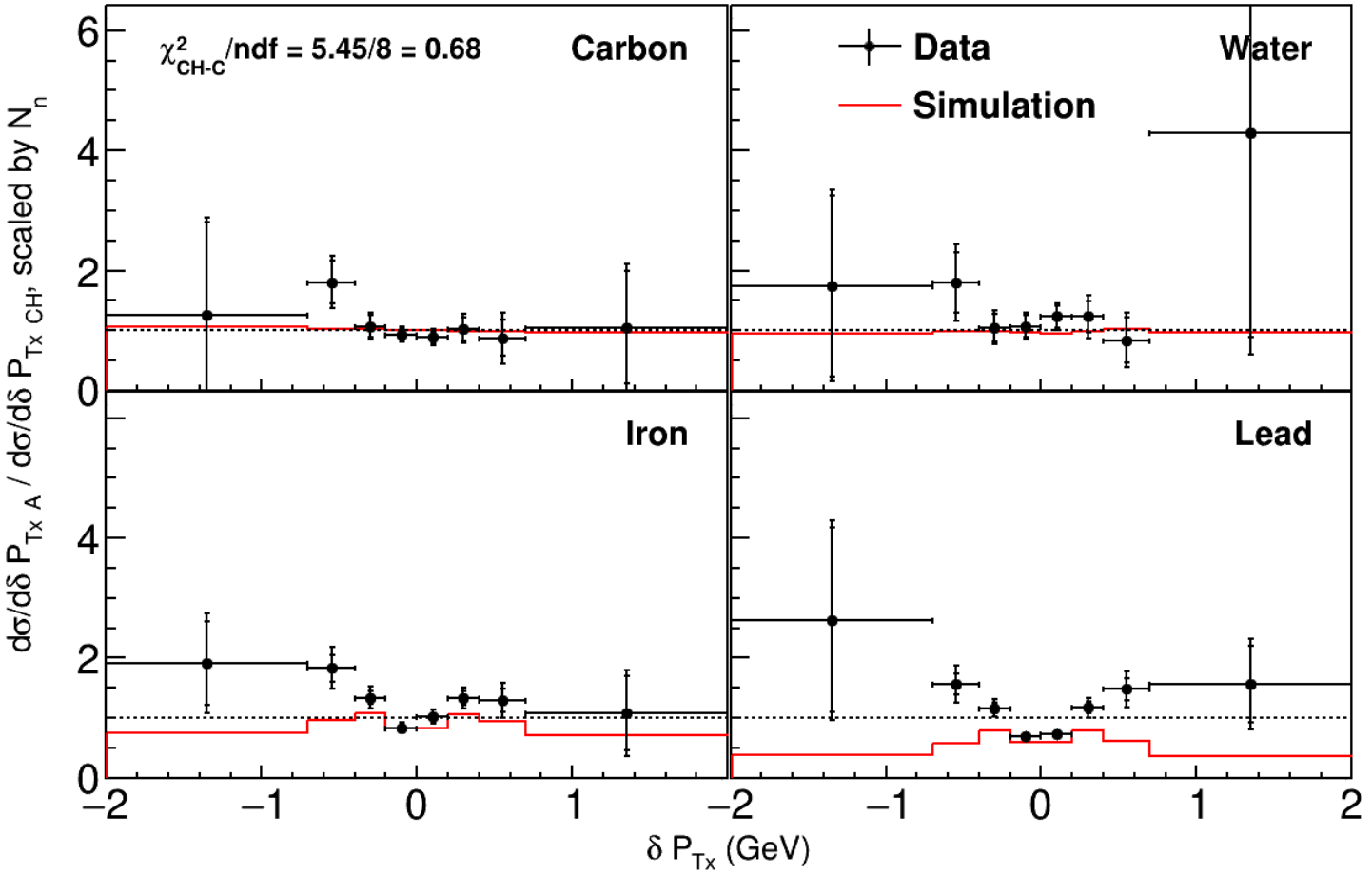
dpt

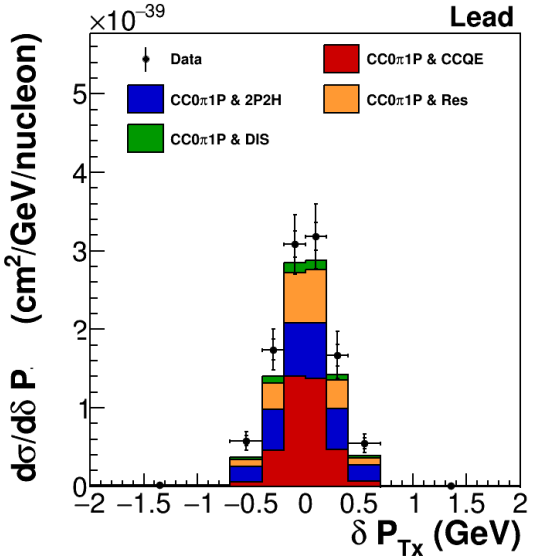

χ^2_{CH-C}/ndf = 9.36/8 = 1.17
Carbon
Water
Iron
Lead
Data
Simulation
$d\sigma/d\delta\ P_{T\ A}$ / $d\sigma/d\delta\ P_{T\ CH}$, scaled by N_n
$\delta\ P_T$ (GeV)

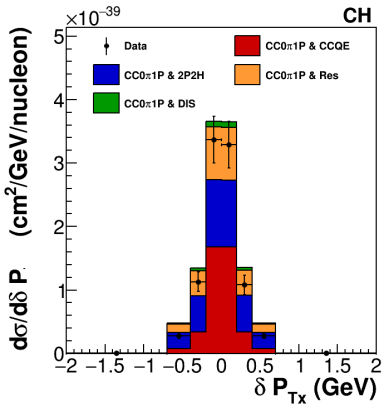

Lead
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
$d\sigma/d\delta\ P$ (cm^2/GeV/nucleon)
$\delta\ P_T$ (GeV)


CH
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
(cm^2/GeV/nucleon)
$\delta\ P_T$ (GeV)

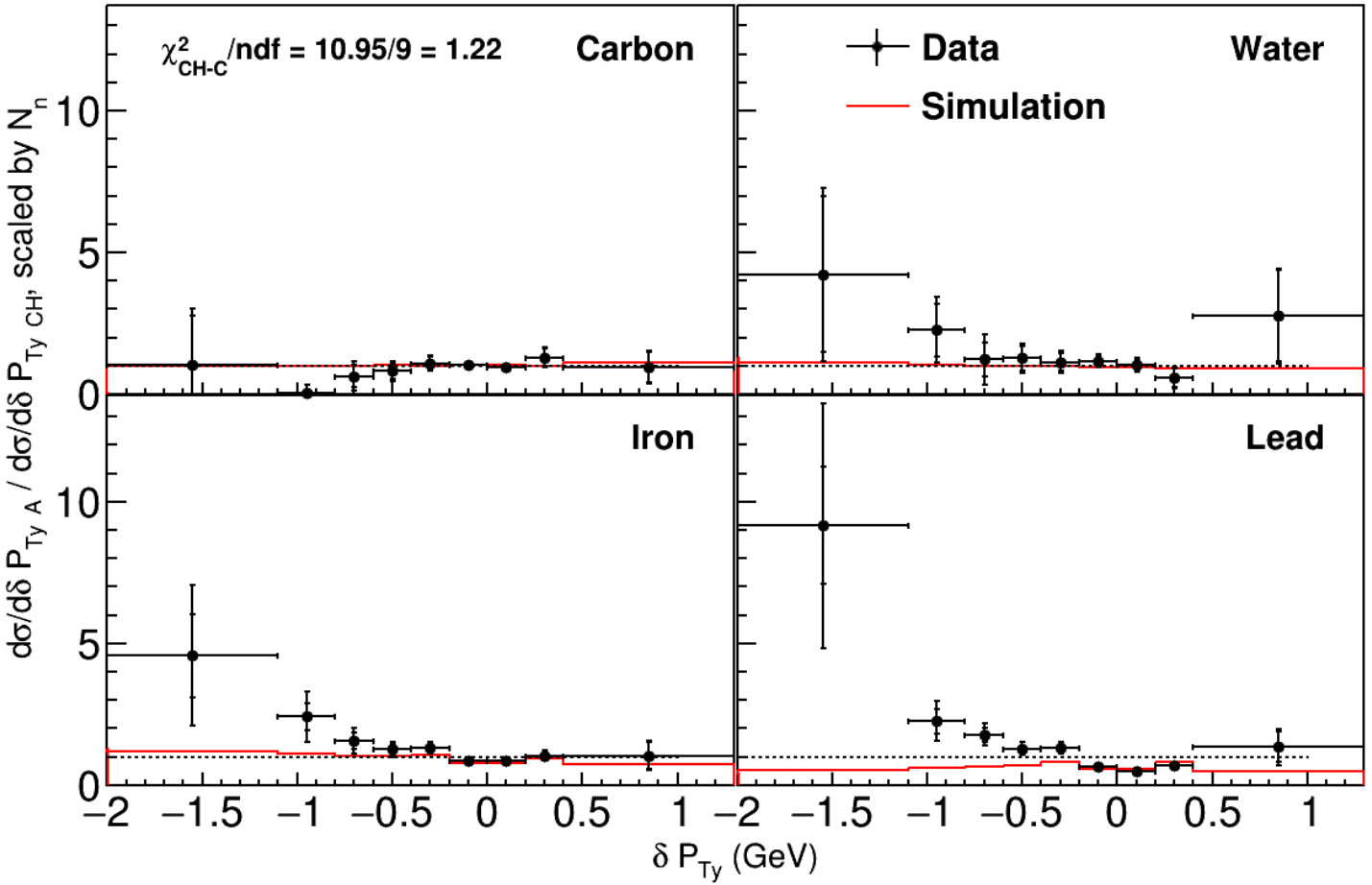
dptx

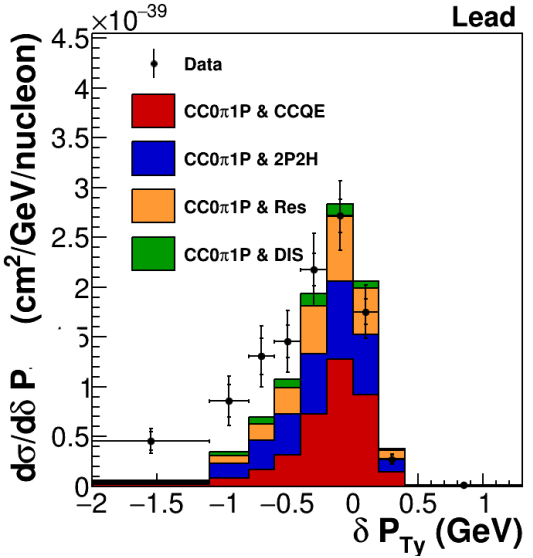

χ^2_{CH-C}/ndf = 5.45/8 = 0.68
Carbon
Data
Simulation
Water
Iron
Lead
$d\sigma/d\delta\ P_{Tx\ A}$ / $d\sigma/d\delta\ P_{Tx\ CH}$, scaled by N_n
$\delta\ P_{Tx}$ (GeV)

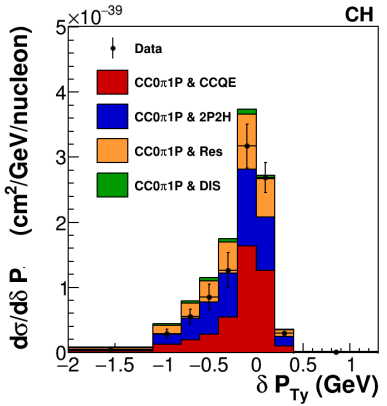

Lead
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
$d\sigma/d\delta\ P_{Tx}$ (cm^2/GeV/nucleon)
$\delta\ P_{Tx}$ (GeV)


CH
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
$d\sigma/d\delta\ P_{Tx}$ (cm^2/GeV/nucleon)
$\delta\ P_{Tx}$ (GeV)

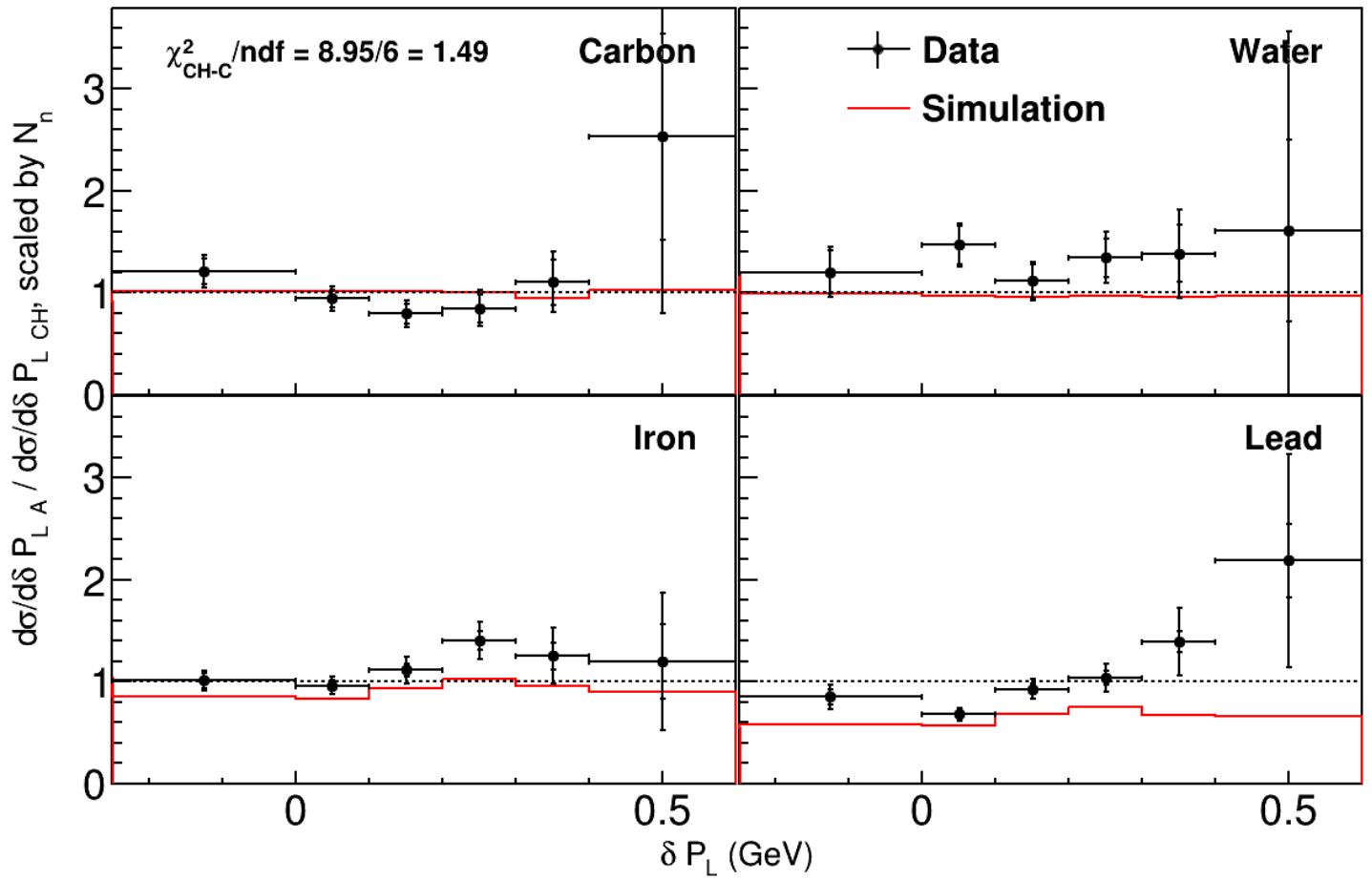
dpty

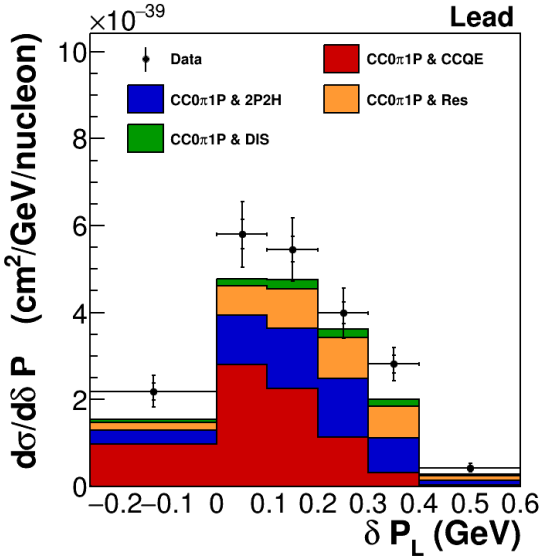

χ^2_{CH-C}/ndf = 10.95/9 = 1.22
Carbon
Data
Simulation
Water
Iron
Lead
dσ/dδ P_Ty A / dσ/dδ P_Ty CH, scaled by N_n
δ P_Ty (GeV)

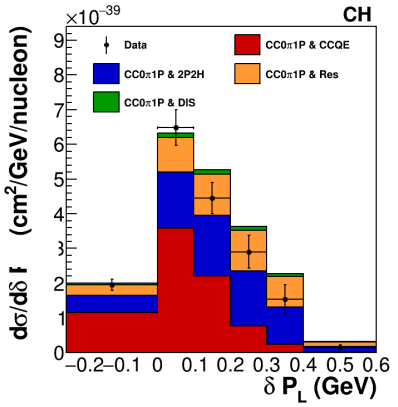

×10⁻³⁹
Lead
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
dσ/dδ P (cm²/GeV/nucleon)
δ P_Ty (GeV)


×10⁻³⁹
CH
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
dσ/dδ P (cm²/GeV/nucleon)
δ P_Ty (GeV)

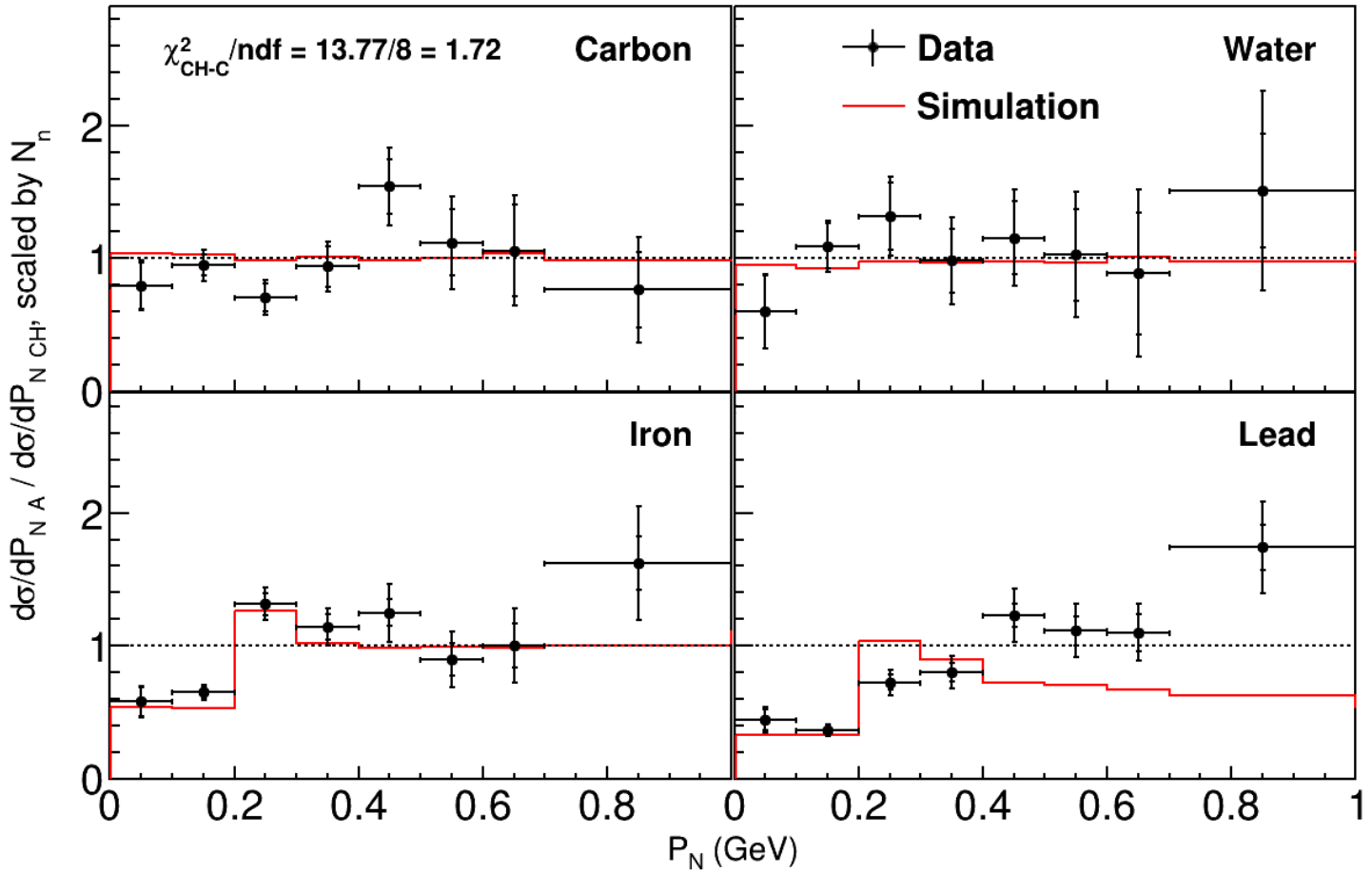
Pl

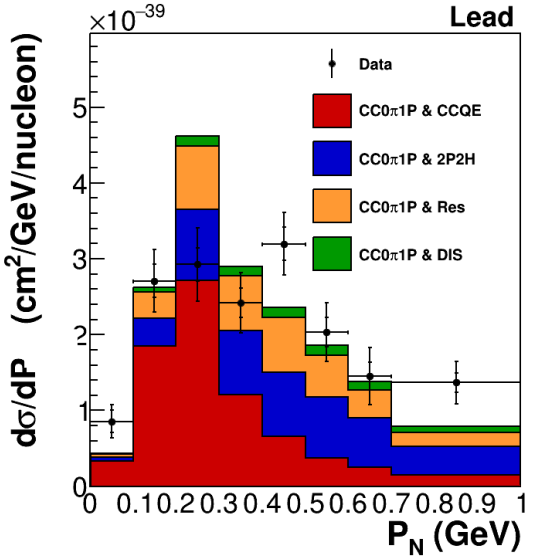

χ^2_{CH-C}/ndf = 8.95/6 = 1.49
Carbon
Water
Iron
Lead
Data
Simulation
dσ/dδ P_L A / dσ/dδ P_L CH, scaled by N_n
δ P_L (GeV)

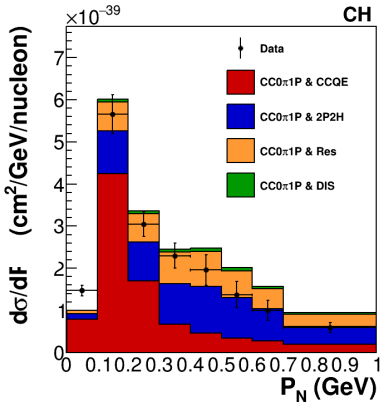

Lead
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
dσ/dδ P (cm²/GeV/nucleon)
δ P_L (GeV)


CH
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
δ P_L (GeV)

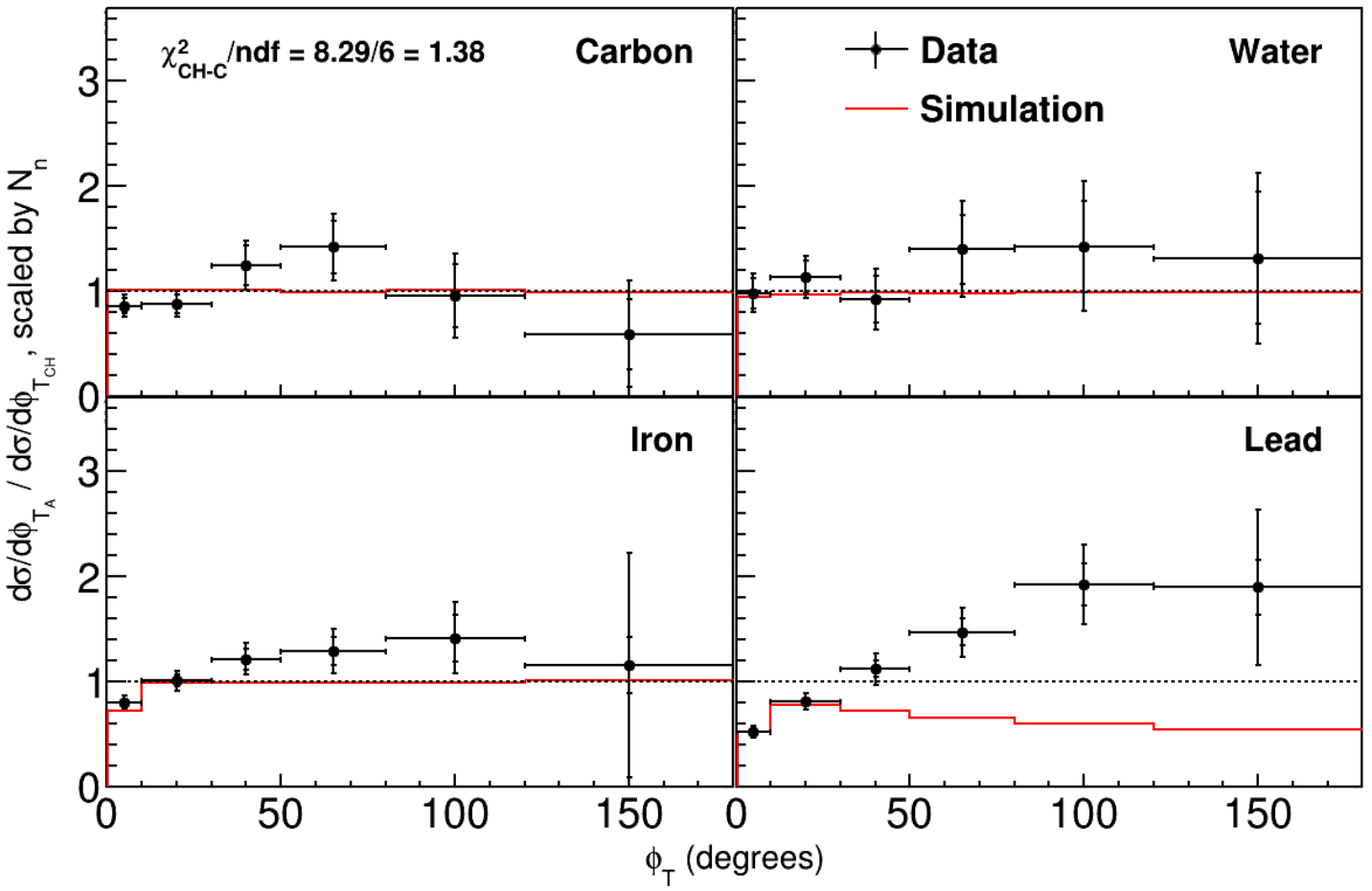
Pn

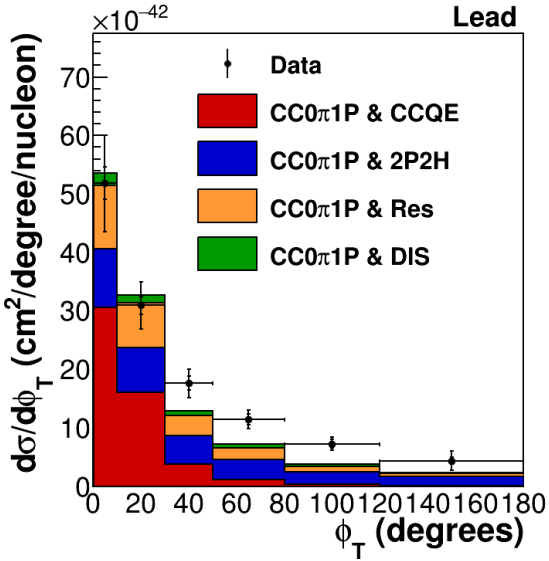

χ^2_{CH-C}/ndf = 13.77/8 = 1.72
Carbon
Data
Simulation
Water
Iron
Lead
$d\sigma/dP_{N\,A}$ / $d\sigma/dP_{N\,CH}$, scaled by N_n
P_N (GeV)

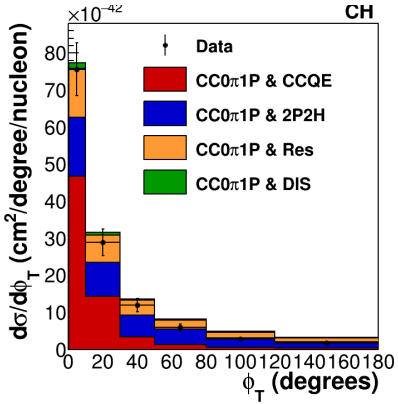

Lead
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
$d\sigma/dP$ (cm^2/GeV/nucleon)
P_N (GeV)


CH
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
$d\sigma/dP$ (cm^2/GeV/nucleon)
P_N (GeV)

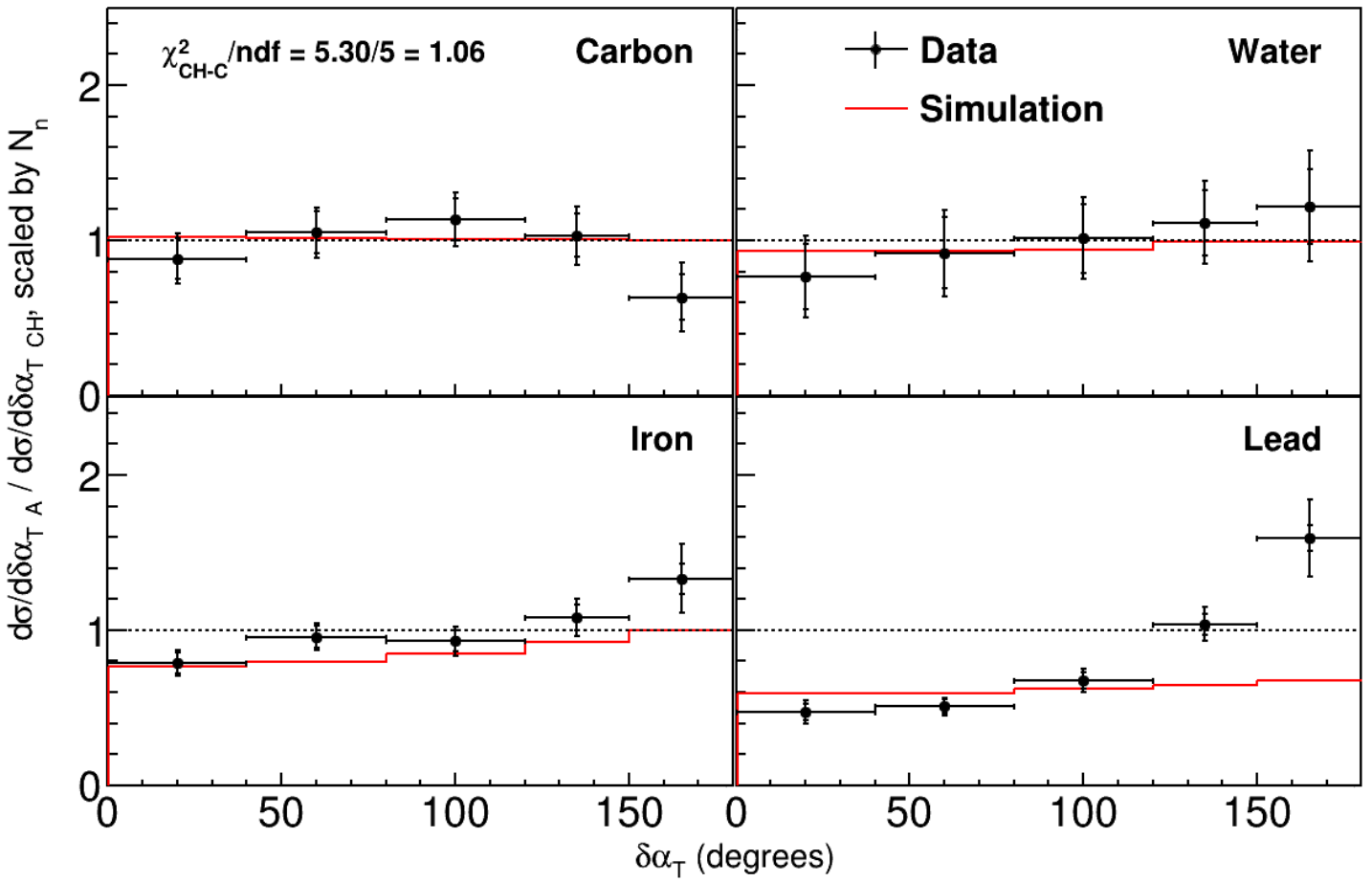
A-scaling of Proton Deflection

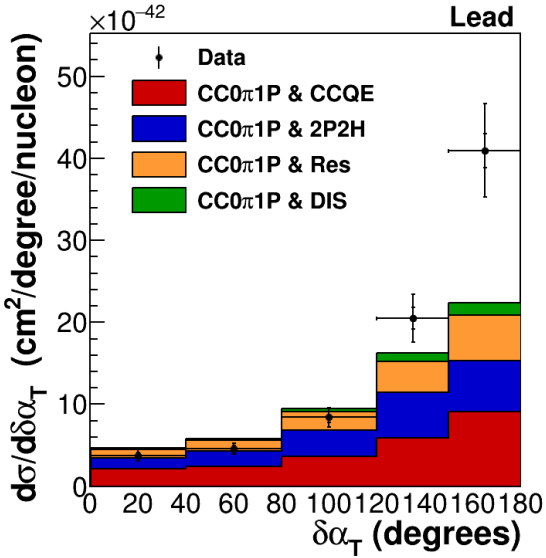


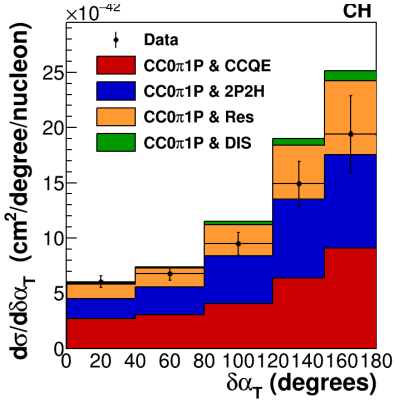




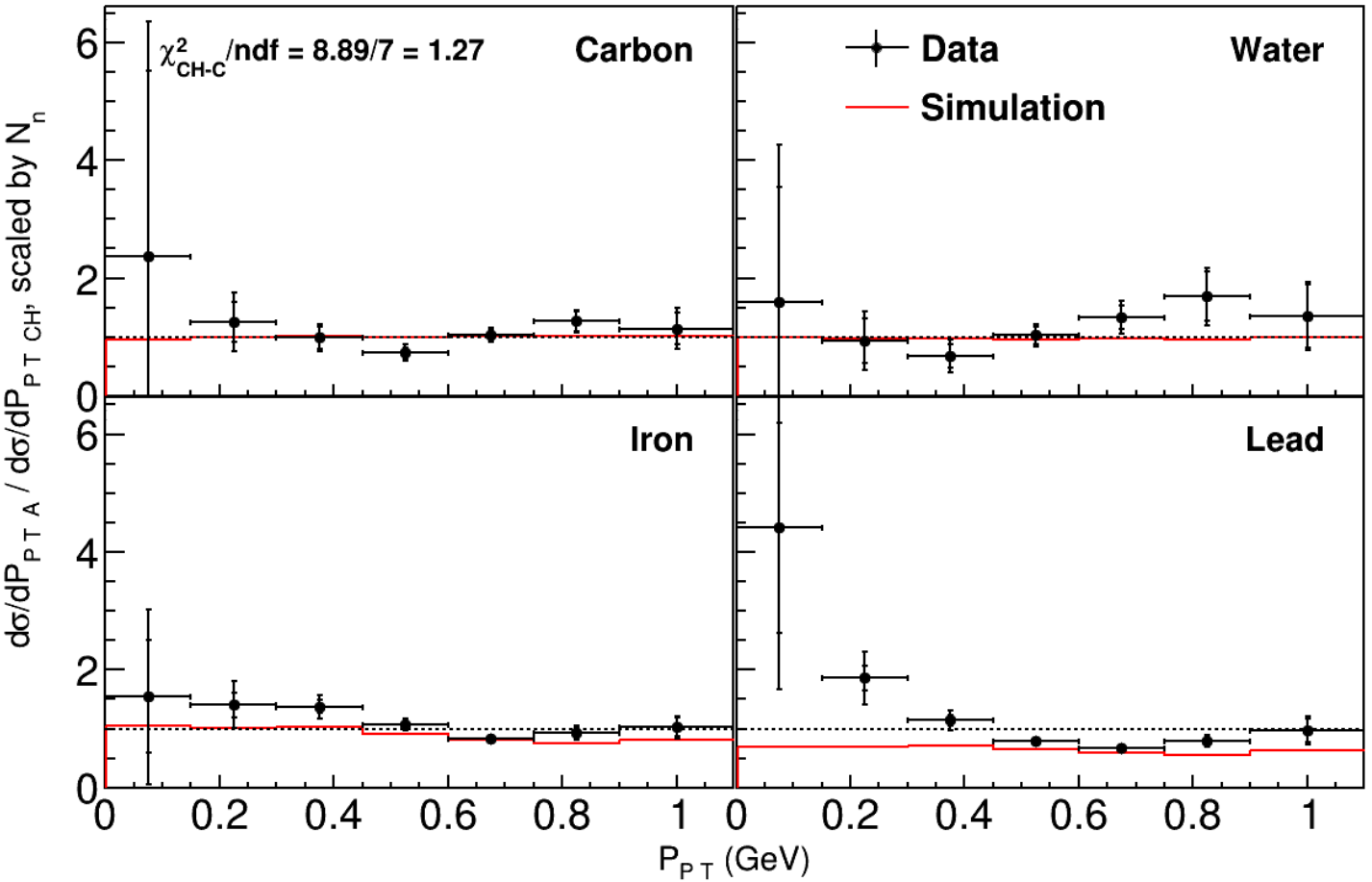
A-scaling of Proton Momentum Loss

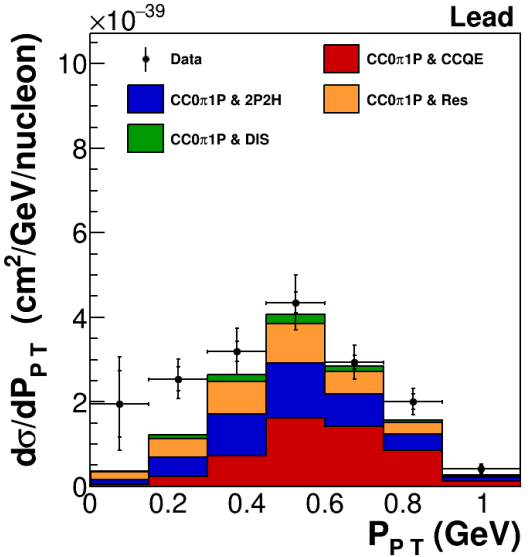


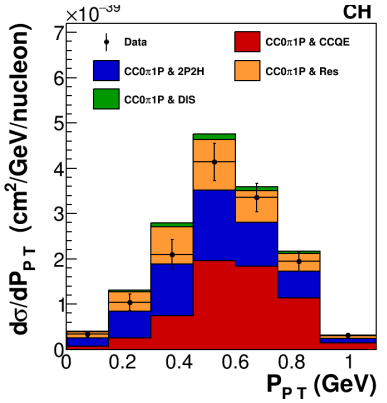




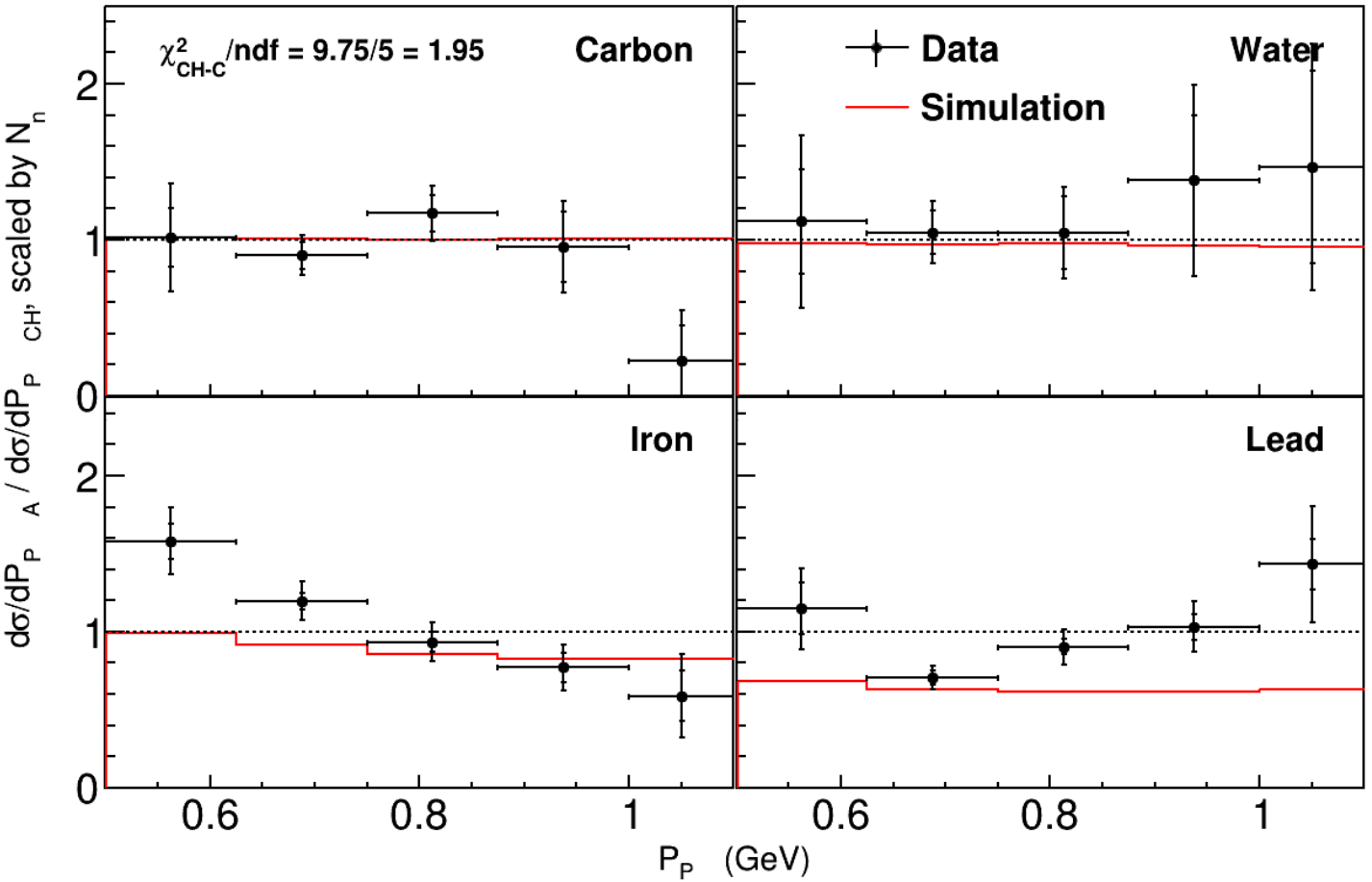
Proton P_T

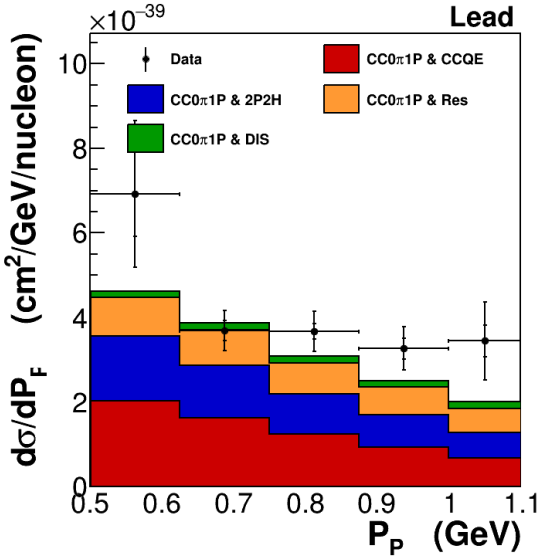

χ^2_{CH-C}/ndf = 8.89/7 = 1.27
Carbon
Data
Simulation
Water
Iron
Lead
$d\sigma/dP_{PT\,A}$ / $d\sigma/dP_{PT\,CH}$, scaled by N_n
P_{PT} (GeV)

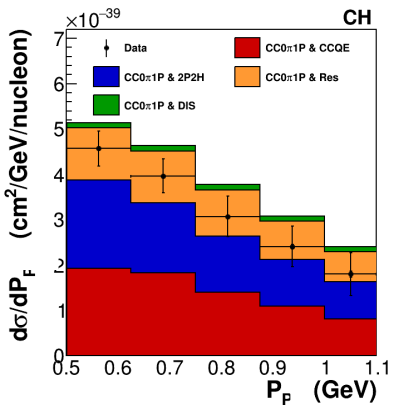

Lead
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
$d\sigma/dP_{PT}$ (cm^2/GeV/nucleon)
P_{PT} (GeV)


CH
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
$d\sigma/dP_{PT}$ (cm^2/GeV/nucleon)
P_{PT} (GeV)

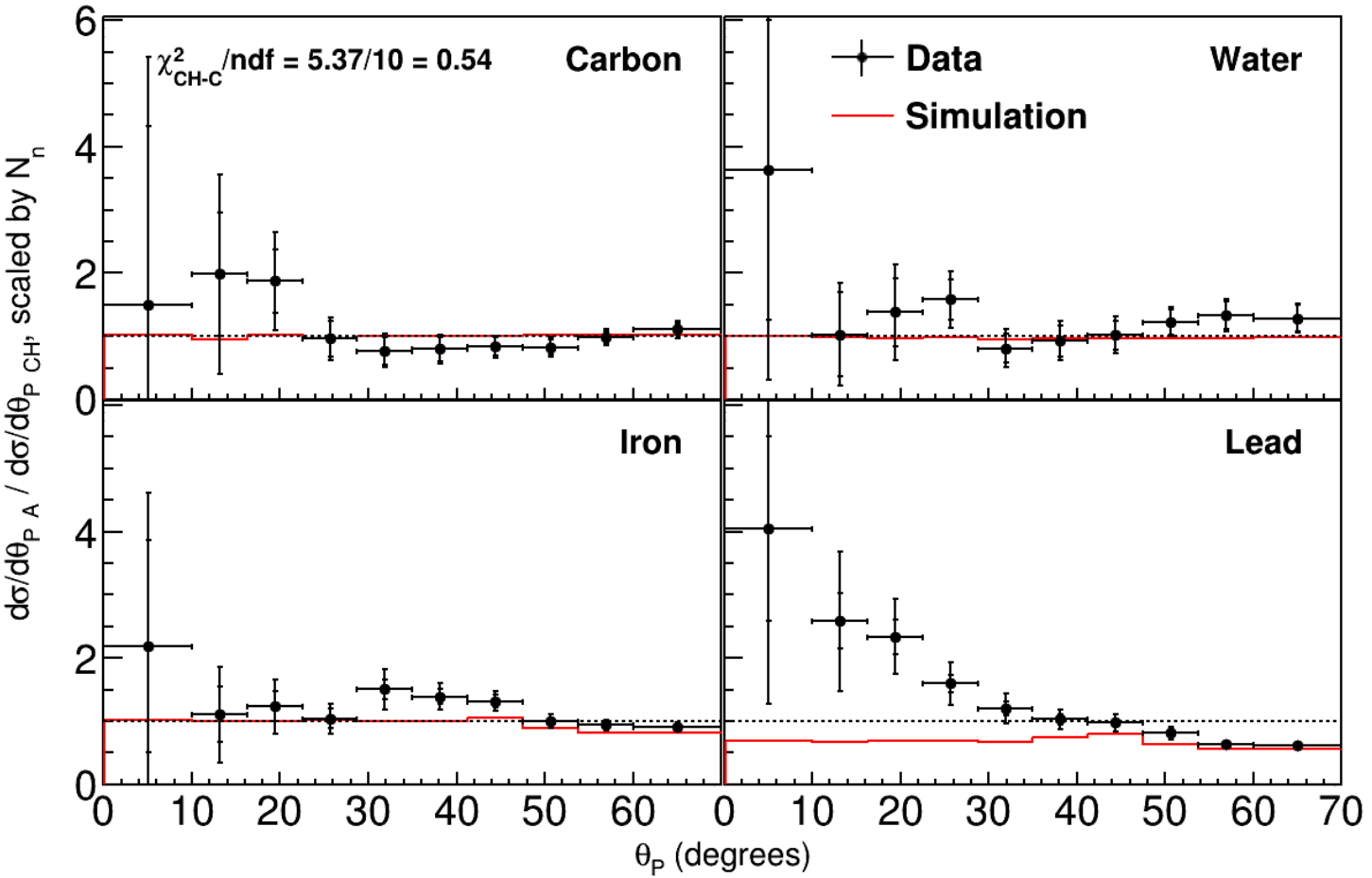
Proton P

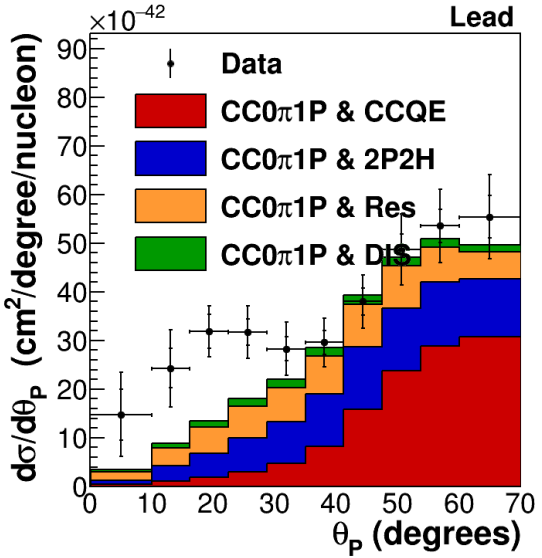

χ^2_{CH-C}/ndf = 9.75/5 = 1.95
Carbon
Water
Iron
Lead
Data
Simulation
$d\sigma/dP_P$ $_A$ / $d\sigma/dP_P$ $_{CH}$, scaled by N_n
P_P (GeV)

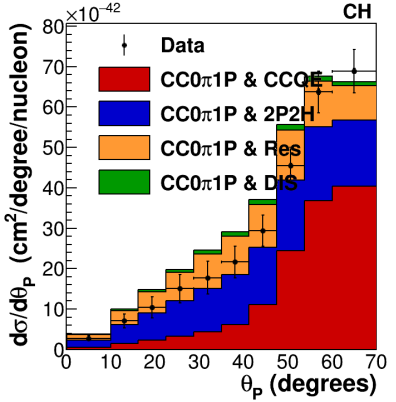

Lead
$\times 10^{-39}$
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
$d\sigma/dP_P$ (cm^2/GeV/nucleon)
P_P (GeV)


CH
$\times 10^{-39}$
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
$d\sigma/dP_P$ (cm^2/GeV/nucleon)
P_P (GeV)

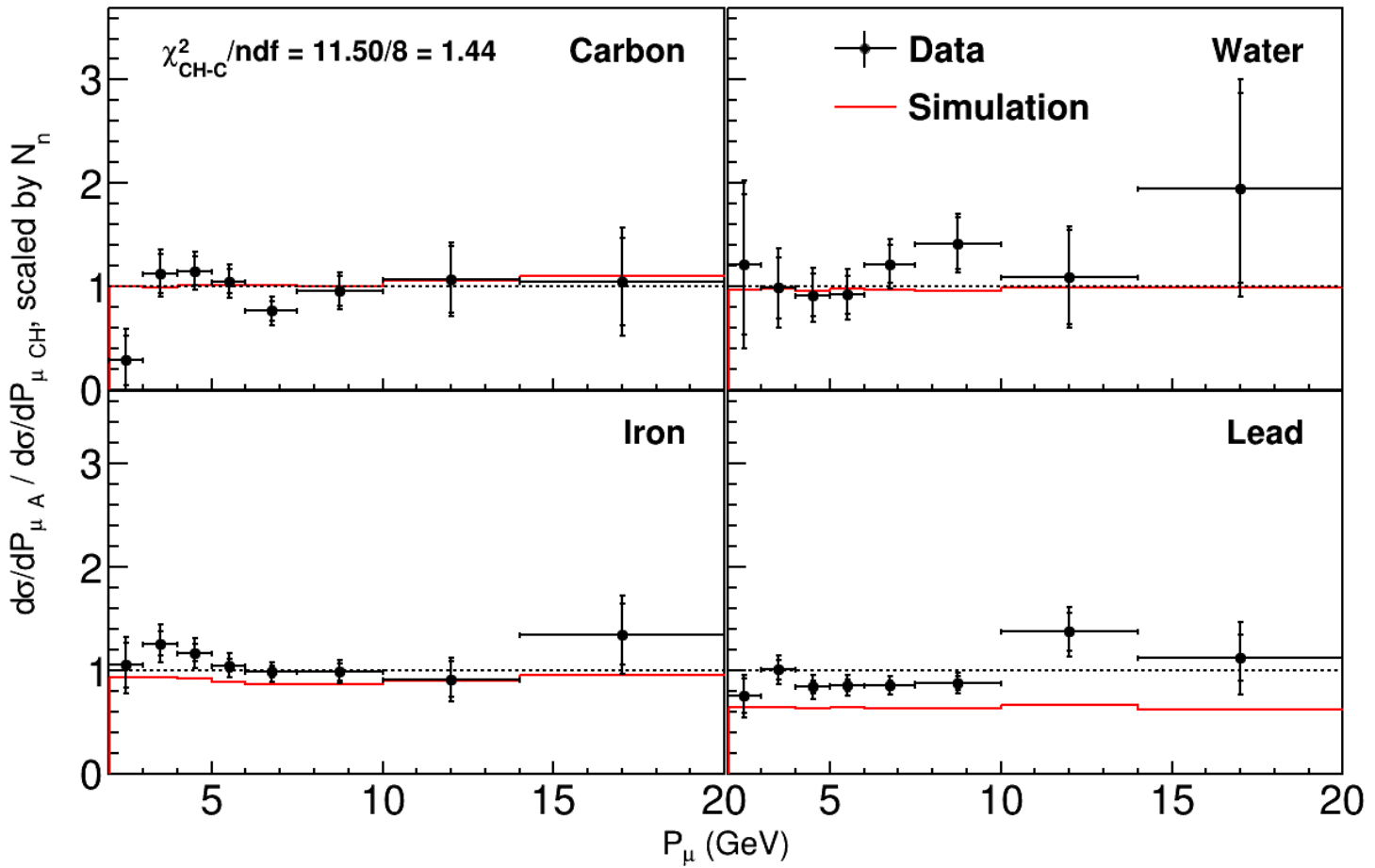
Proton Theta

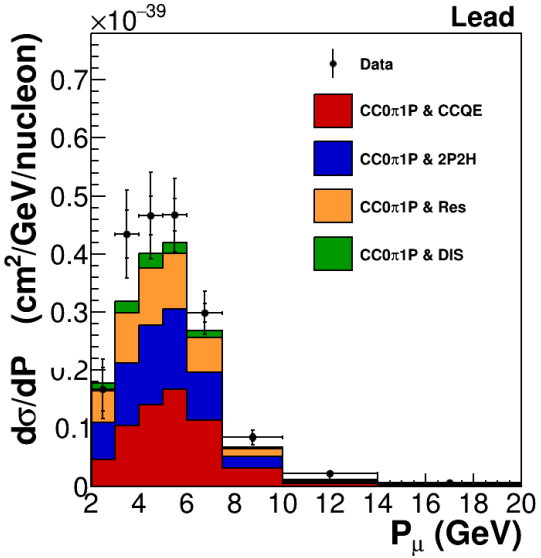


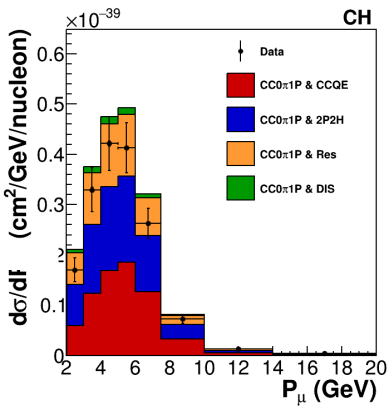




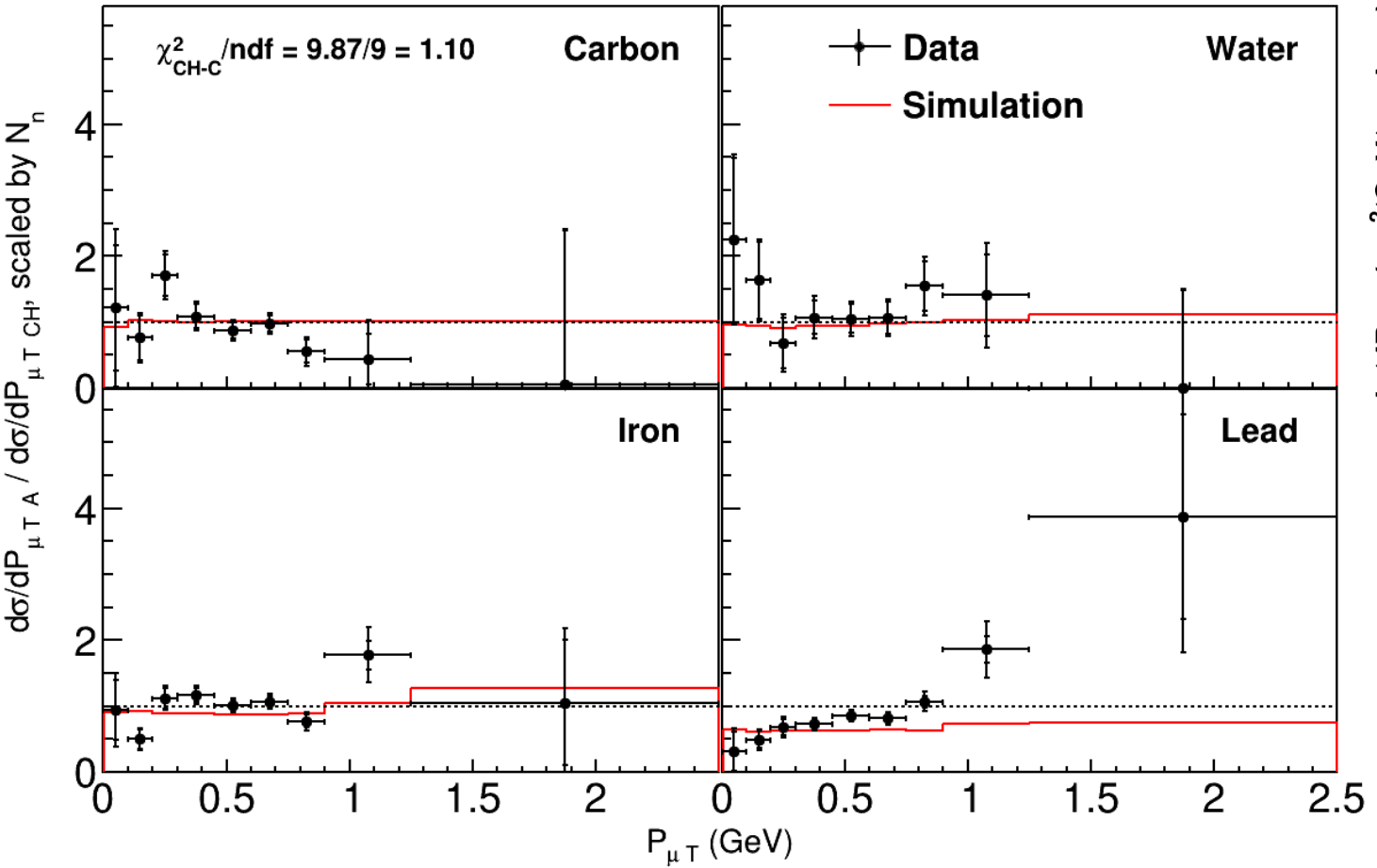
Muon P

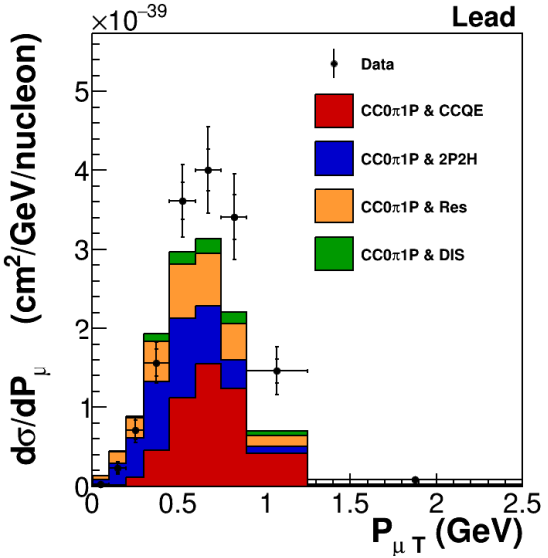

χ^2_{CH-C}/ndf = 11.50/8 = 1.44
Carbon
Water
Iron
Lead
Data
Simulation
$d\sigma/dP_{\mu\ A}$ / $d\sigma/dP_{\mu\ CH}$, scaled by N_n
P_μ (GeV)

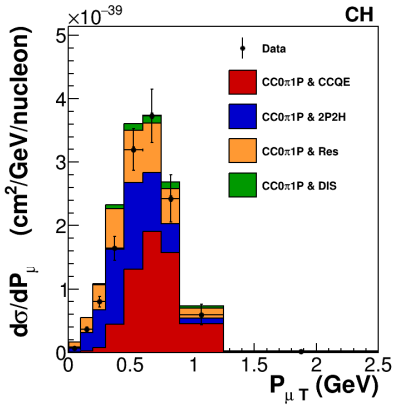

Lead
$\times 10^{-39}$
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
$d\sigma/dP$ (cm^2/GeV/nucleon)
P_μ (GeV)


CH
$\times 10^{-39}$
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
(cm^2/GeV/nucleon)
P_μ (GeV)

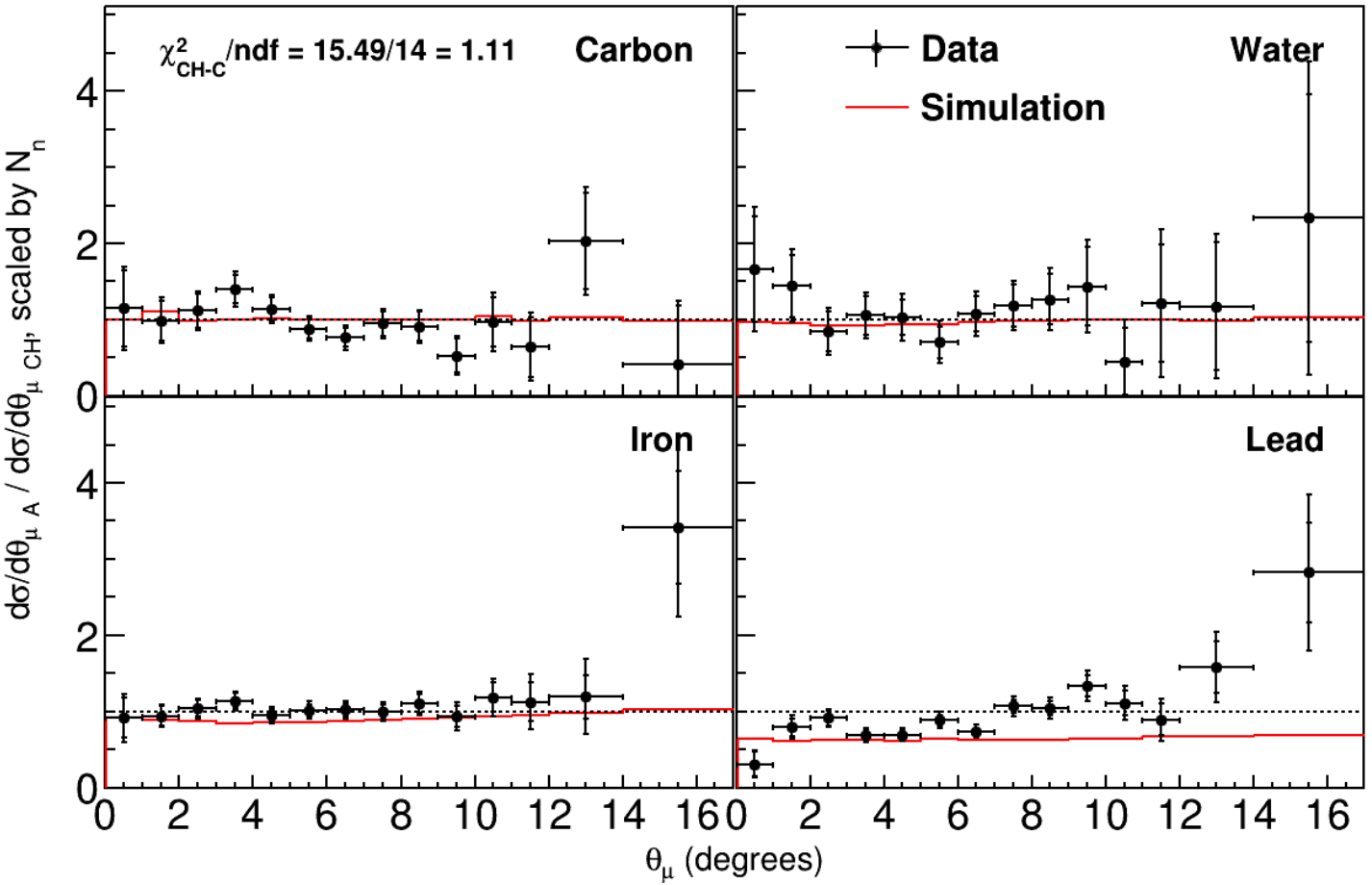
Muon P_T

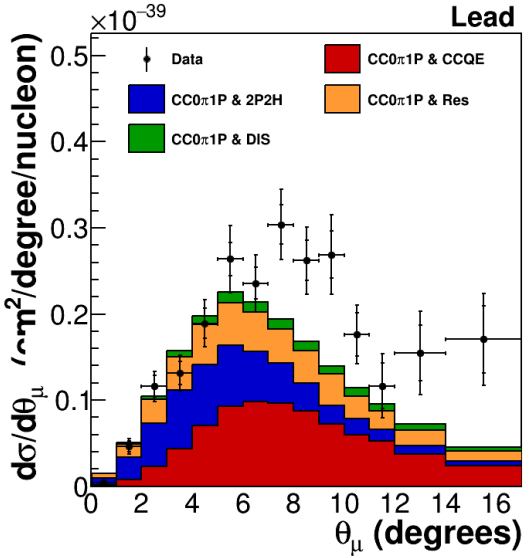

χ^2_{CH-C}/ndf = 9.87/9 = 1.10
Carbon
Data
Simulation
Water
Iron
Lead
$d\sigma/dP_{\mu T A} / d\sigma/dP_{\mu T CH}$, scaled by N_n
$P_{\mu T}$ (GeV)

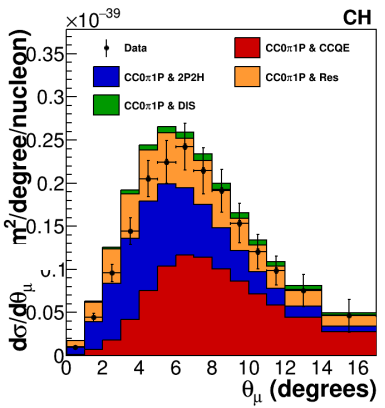

Lead
$\times 10^{-39}$
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
$d\sigma/dP_{\mu}$ (cm^2/GeV/nucleon)
$P_{\mu T}$ (GeV)


CH
$\times 10^{-39}$
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
$d\sigma/dP_{\mu}$ (cm^2/GeV/nucleon)
$P_{\mu T}$ (GeV)

Muon Theta

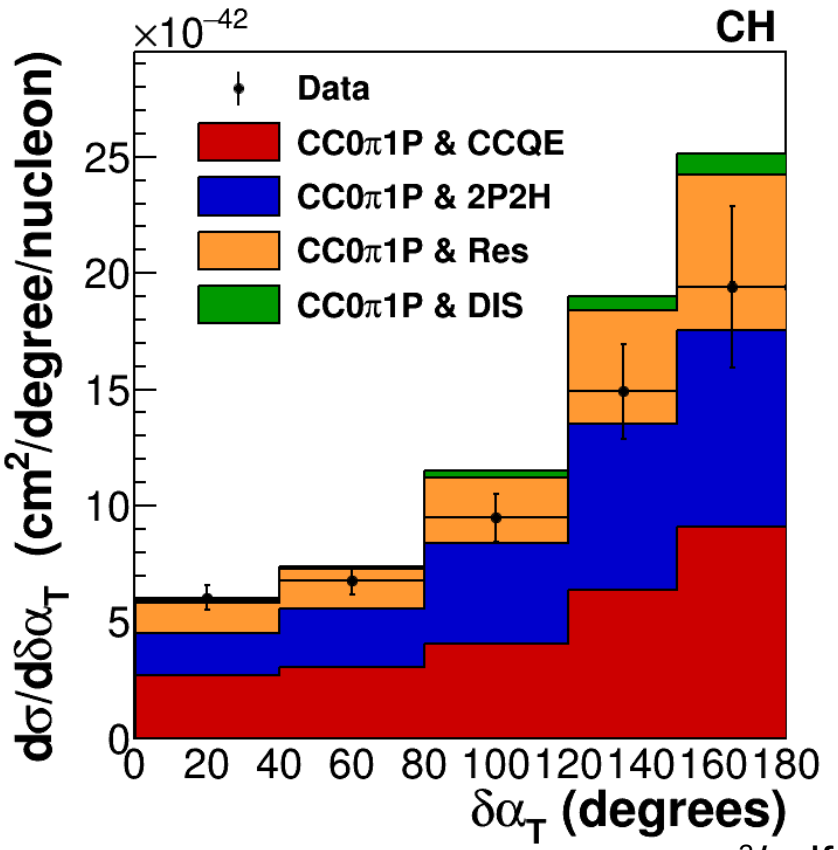

χ^2_{CH-C}/ndf = 15.49/14 = 1.11
Carbon
Data
Simulation
Water
Iron
Lead
$d\sigma/d\theta_{\mu\ A}$ / $d\sigma/d\theta_{\mu\ CH}$, scaled by N_n
θ_μ (degrees)

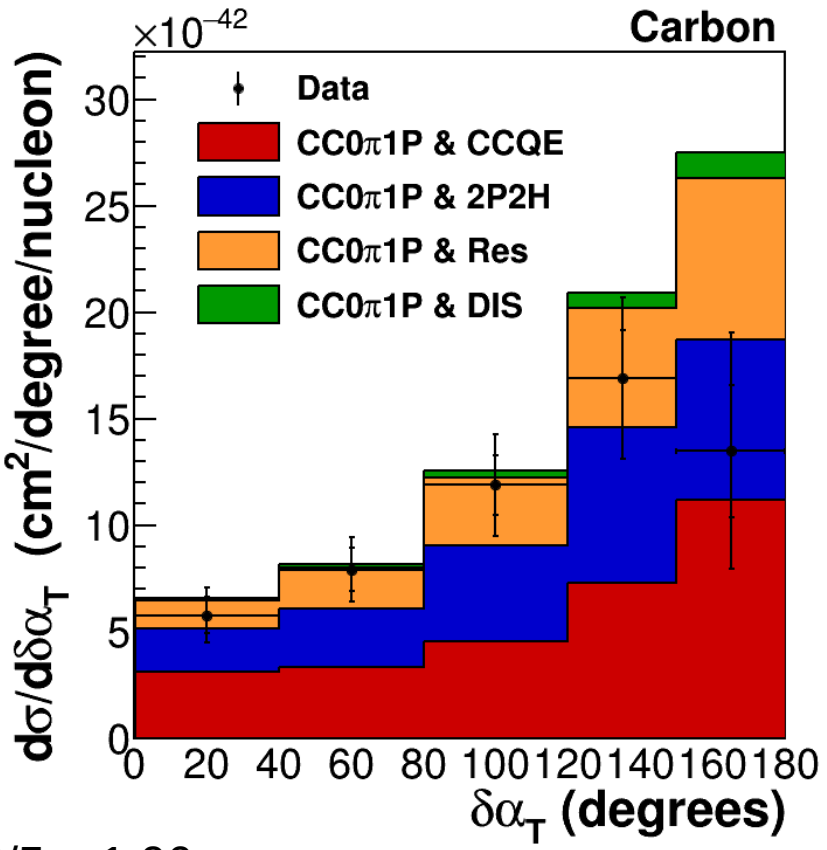

Lead
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
$d\sigma/d\theta_\mu$
θ_μ (degrees)


CH
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
$d\sigma/d\theta_\mu$
θ_μ (degrees)

Additional Information

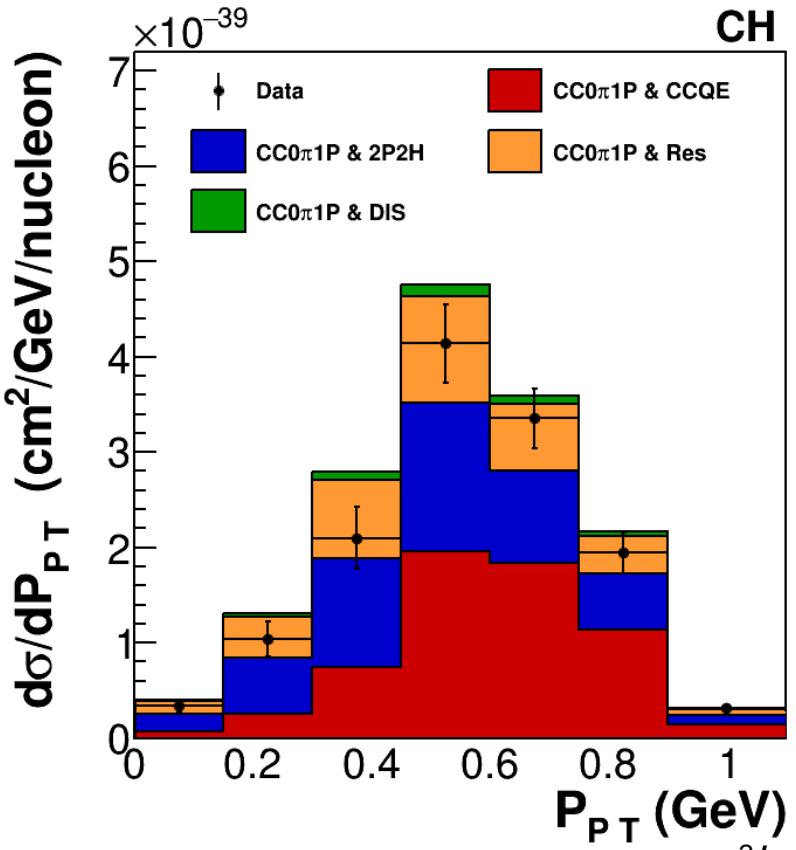
Consistency between CH and C

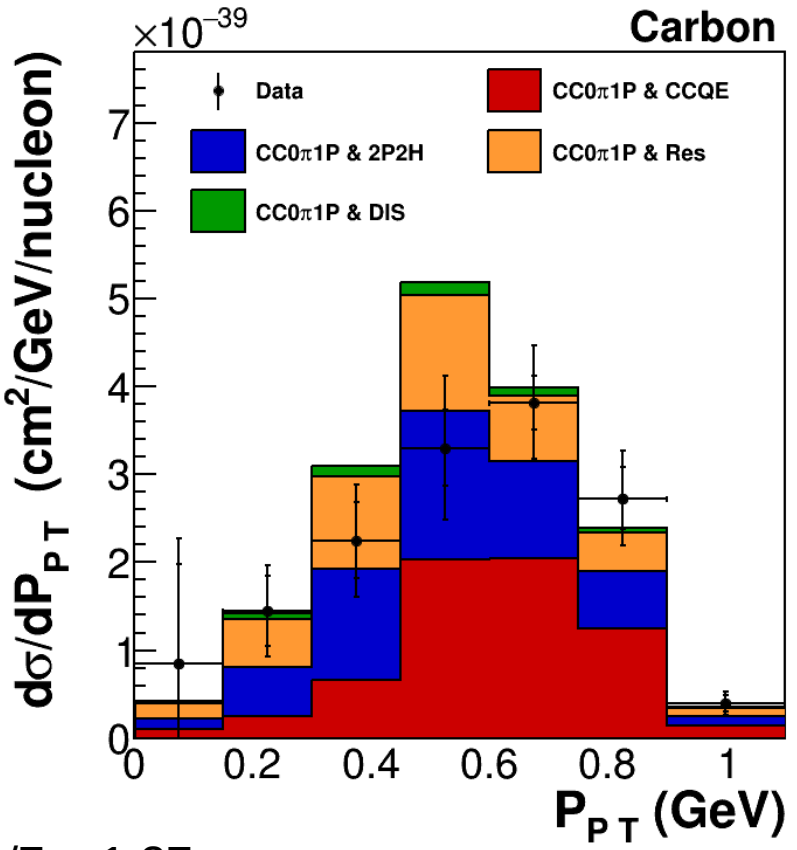




$\chi^2/ndf = 5.30/5 = 1.06$

Consistency between CH and C

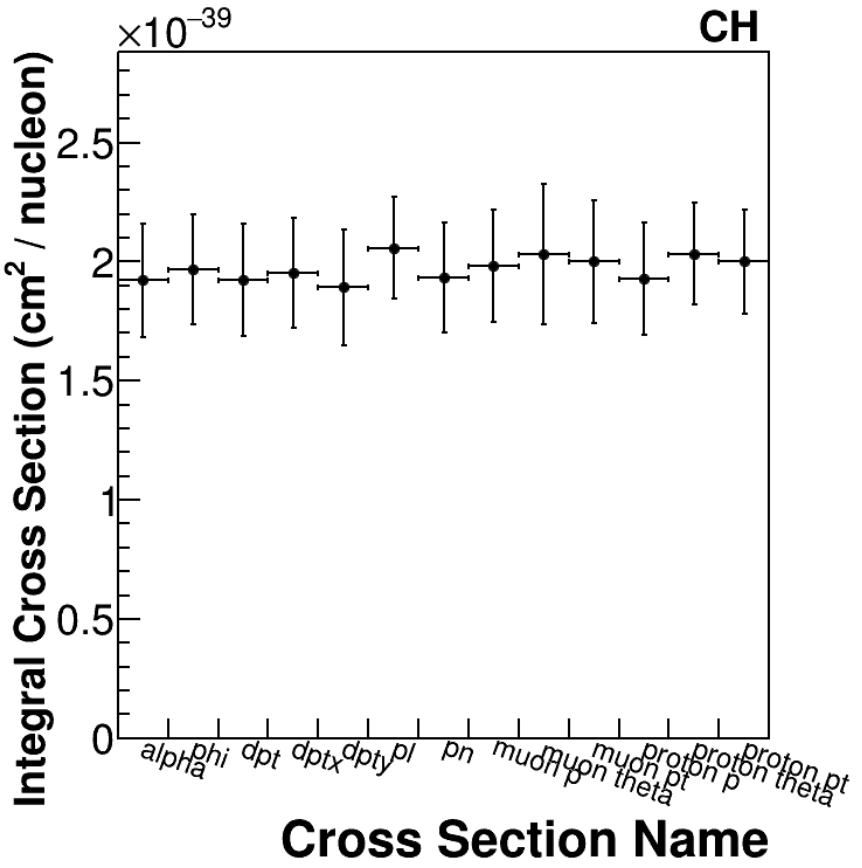




χ^2/ndf = 8.89/7 = 1.27

Sideband Tuning Consistency

- Genie 2.12 modeling of TKI variables is not always the best
- Tuning per TKI variable
- Could lead to different total cross section
- Check that the total cross section is same within error
  - Here inner error bar is stat error, outer error bar is total sideband tuning error



Sideband Tuning Consistency

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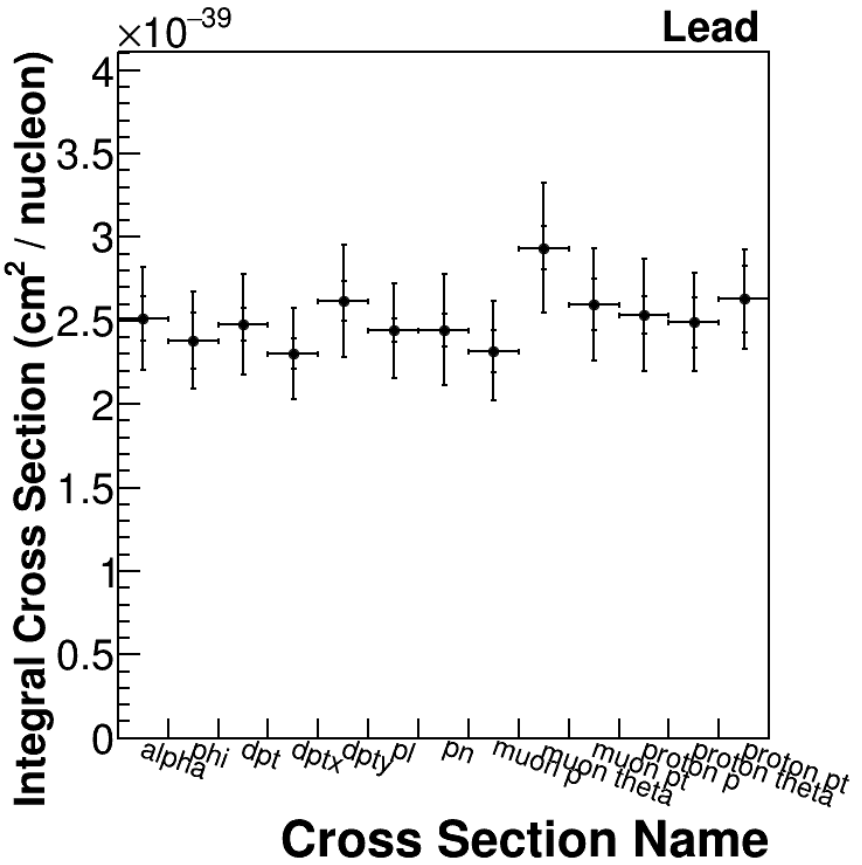
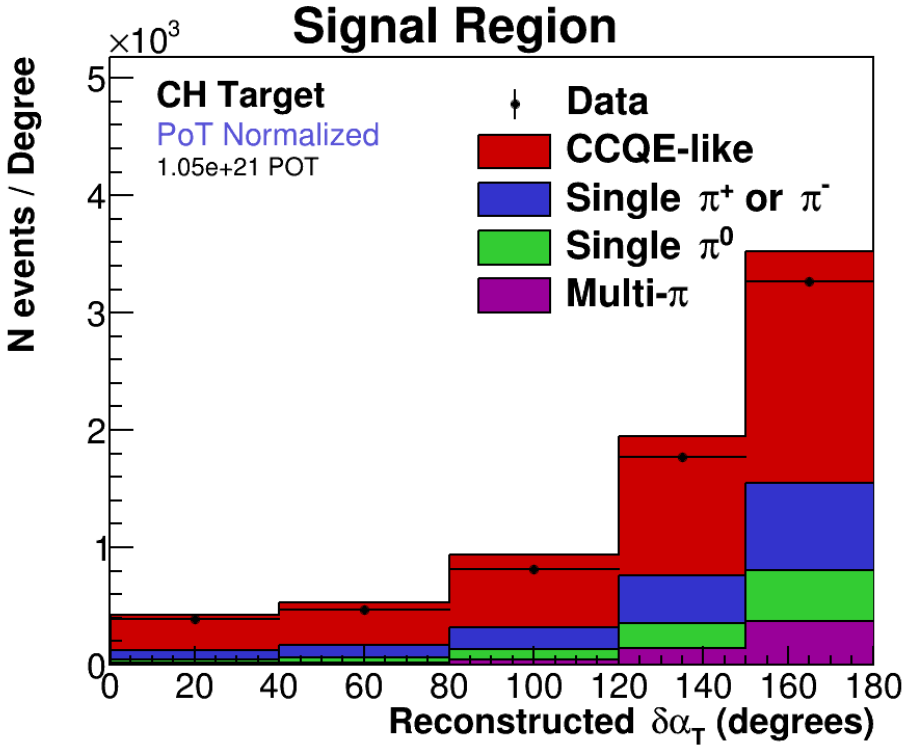
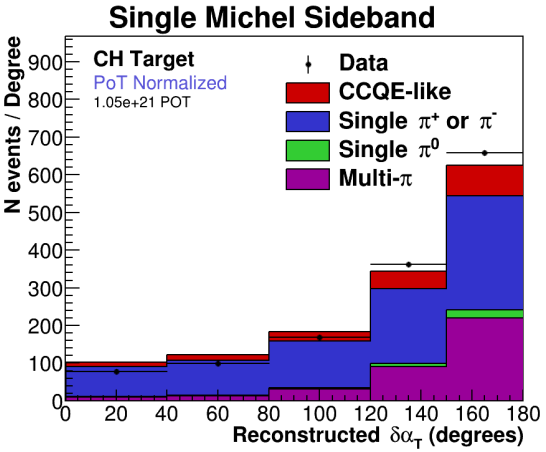
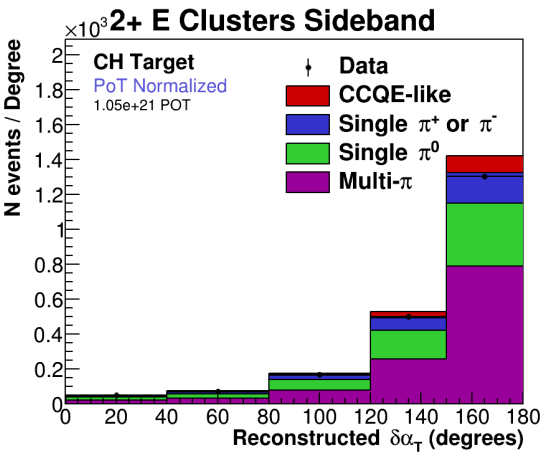
  - Here inner error bar is stat error, outer error bar is total sideband tuning error



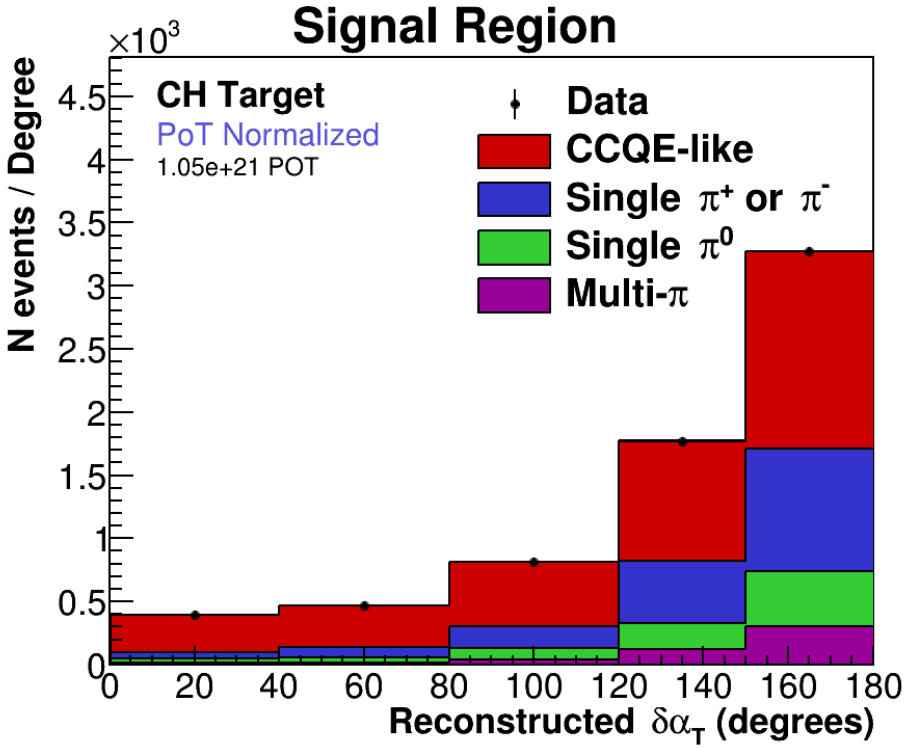
Before


Signal Region
×10³
N events / Degree
CH Target
PoT Normalized
1.05e+21 POT
Data
CCQE-like
Single π⁺ or π⁻
Single π⁰
Multi-π
Reconstructed δα_T (degrees)

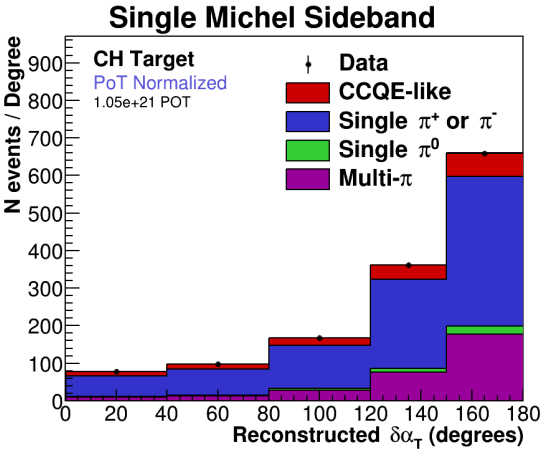

Single Michel Sideband
N events / Degree
CH Target
PoT Normalized
1.05e+21 POT
Data
CCQE-like
Single π⁺ or π⁻
Single π⁰
Multi-π
Reconstructed δα_T (degrees)

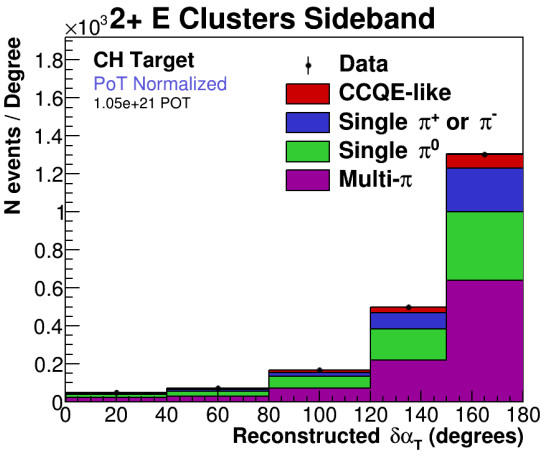

2+ E Clusters Sideband
×10³
N events / Degree
CH Target
PoT Normalized
1.05e+21 POT
Data
CCQE-like
Single π⁺ or π⁻
Single π⁰
Multi-π
Reconstructed δα_T (degrees)

After



Signal region allowed to float in tune, but tune not used in MnvTune





Single π0 tuning explanation

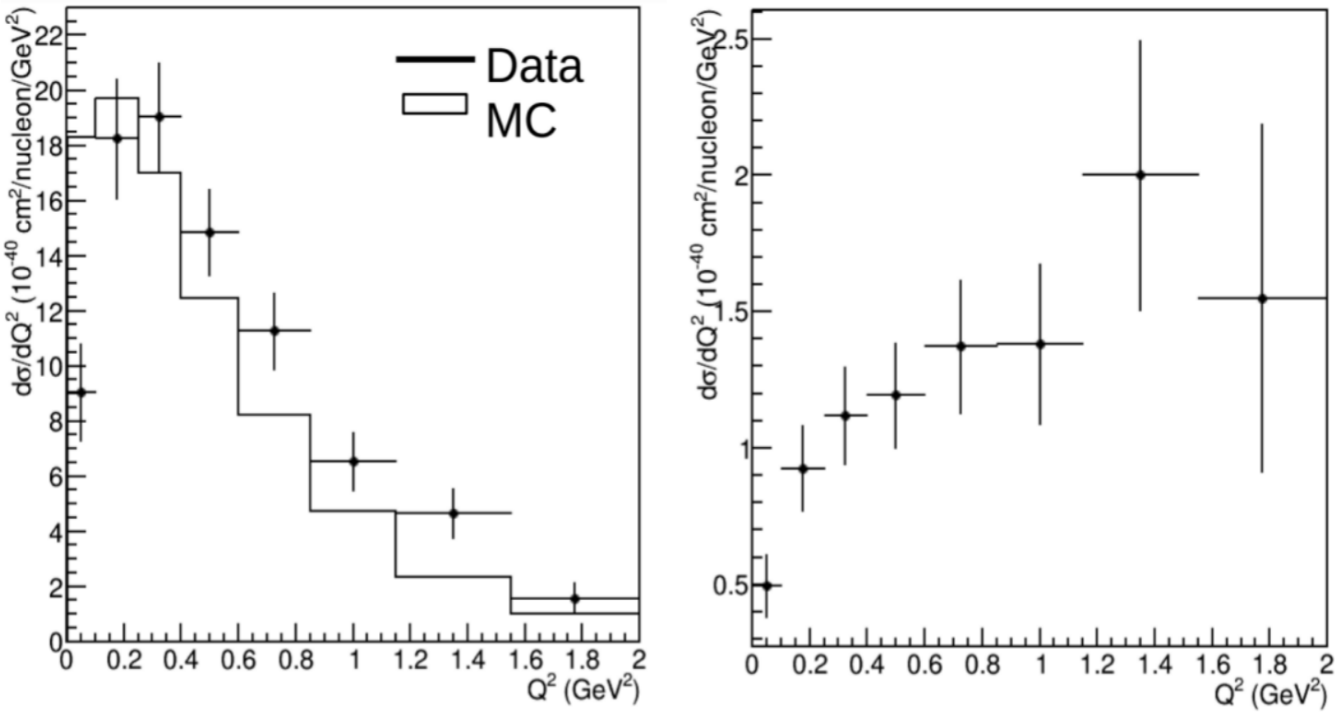
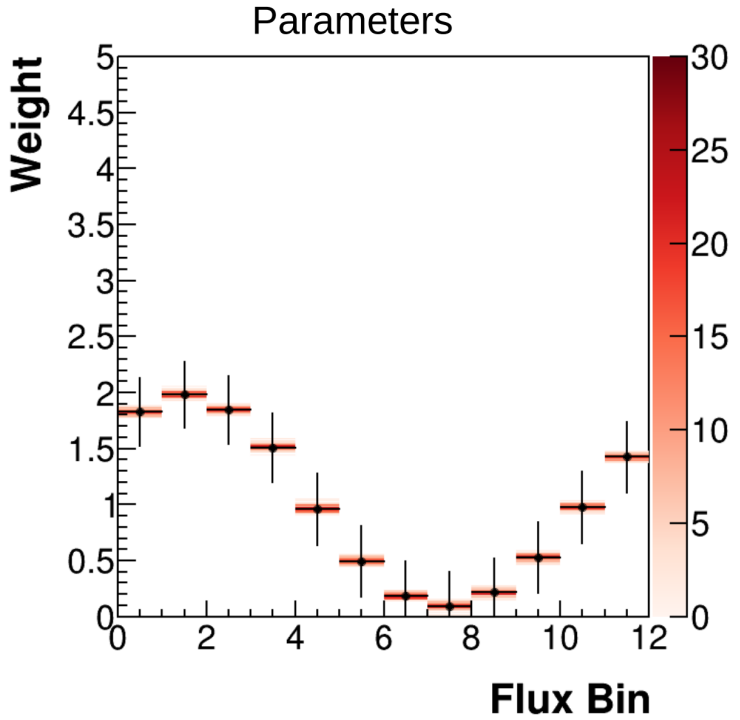
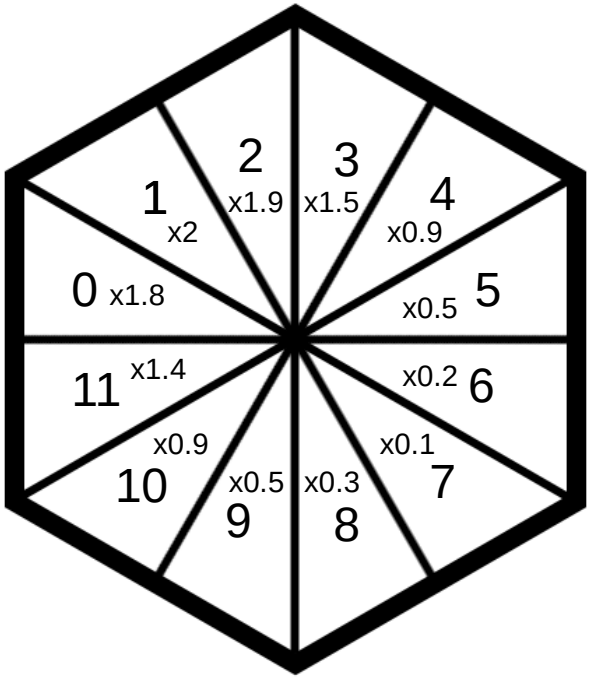
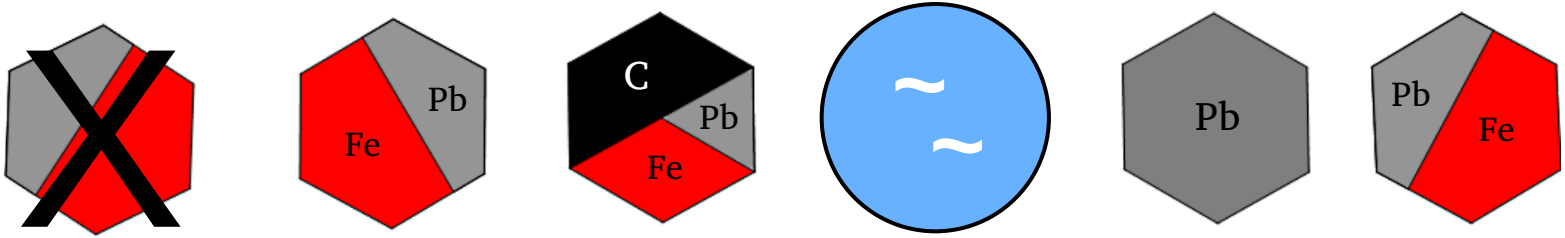


Figure 5.13: A comparison of the data and simulation of $\nu_\mu + CH \to \mu^- + \pi^0 + X$ cross section (left). The ratio used for tuning (right). Left plot is reproduced from Ref. [83].

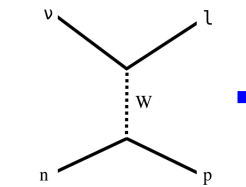
Correcting CH Flux for Nuclear Targets





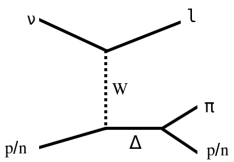


Interaction Types vs Observable Signals

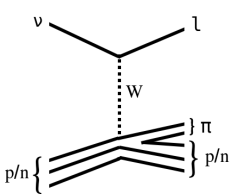


CCQE

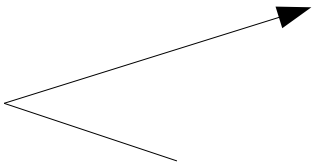
2p2h



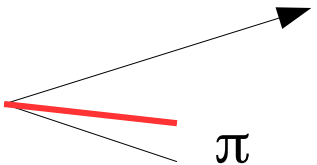
Resonant



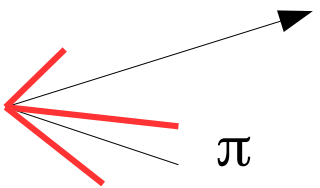
DIS



CCQE-like
1 Muon
0 Pions

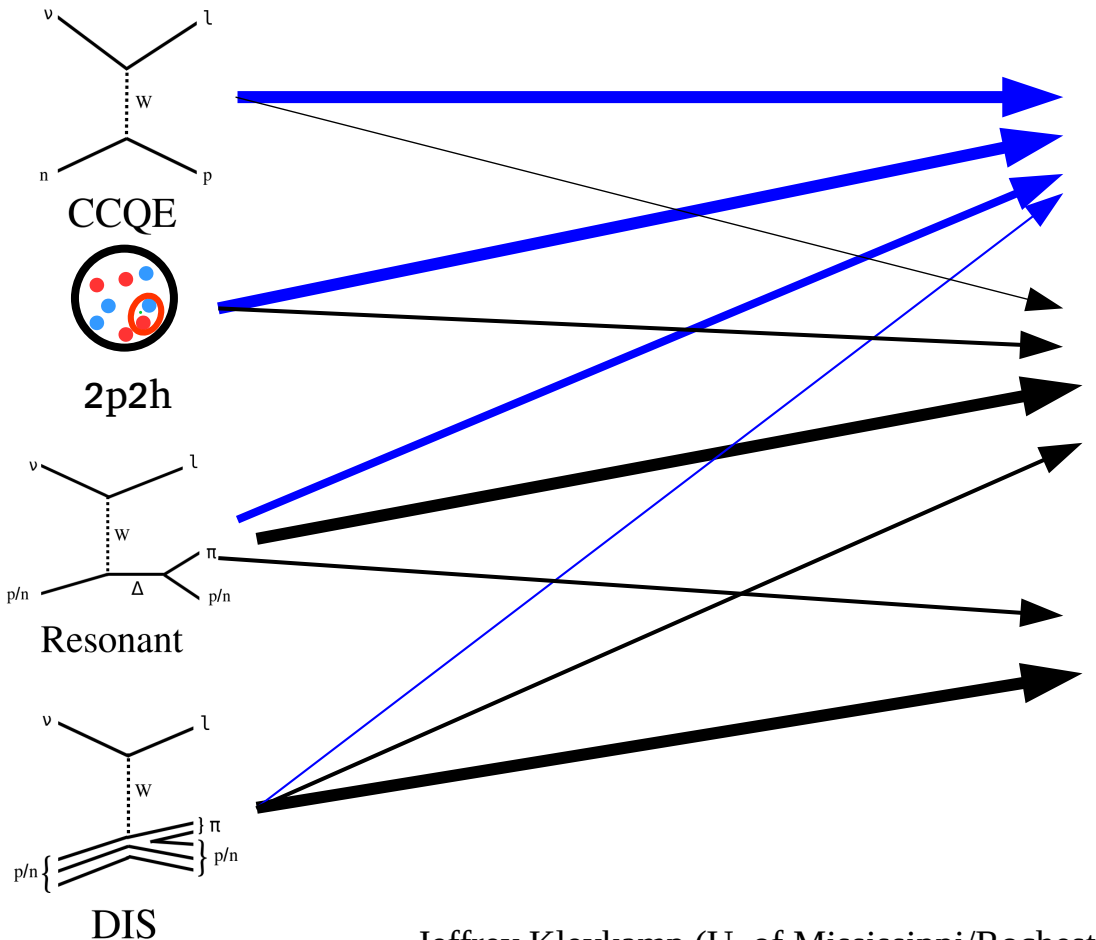


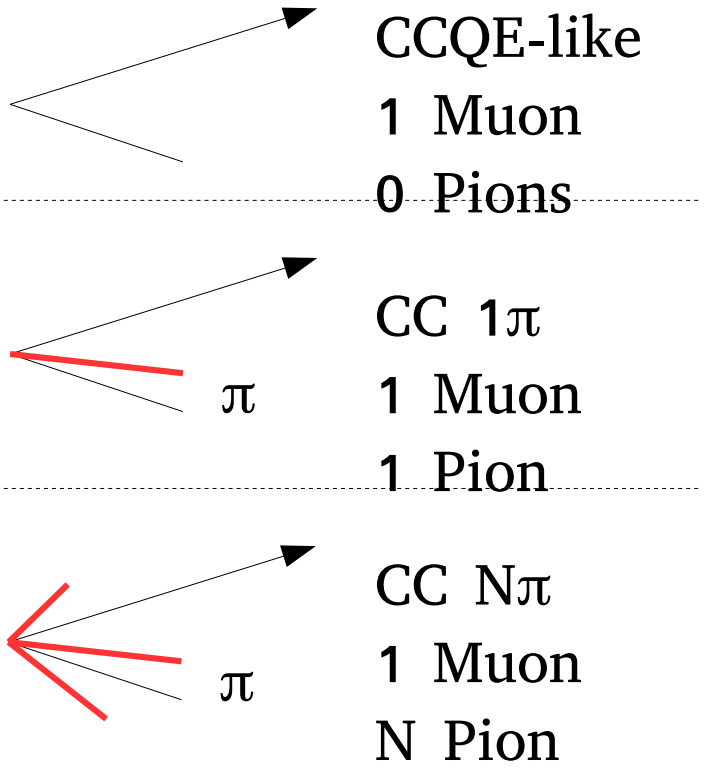
CC 1π
1 Muon
1 Pion



CC Nπ
1 Muon
N Pion

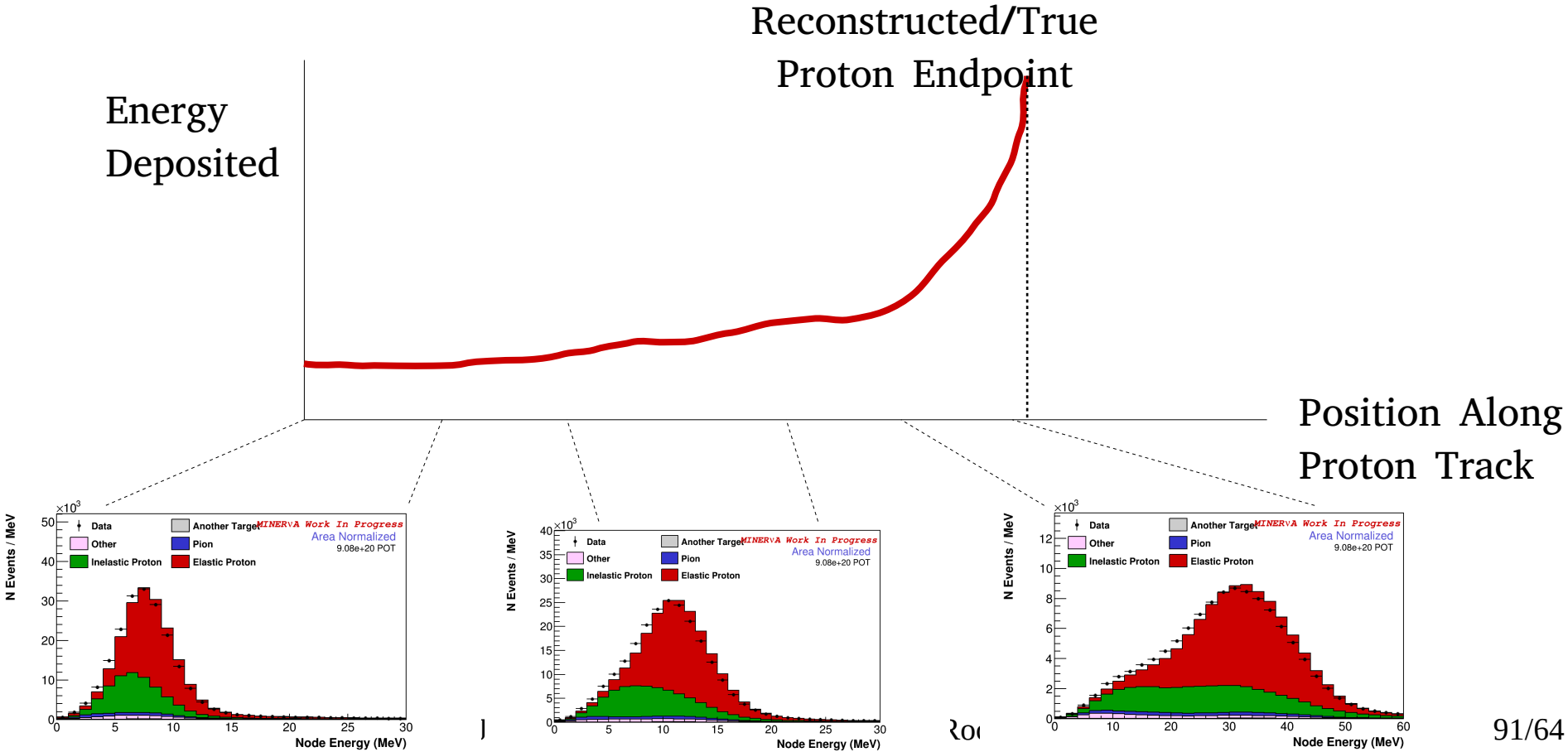
Interaction Types vs Observable Signals





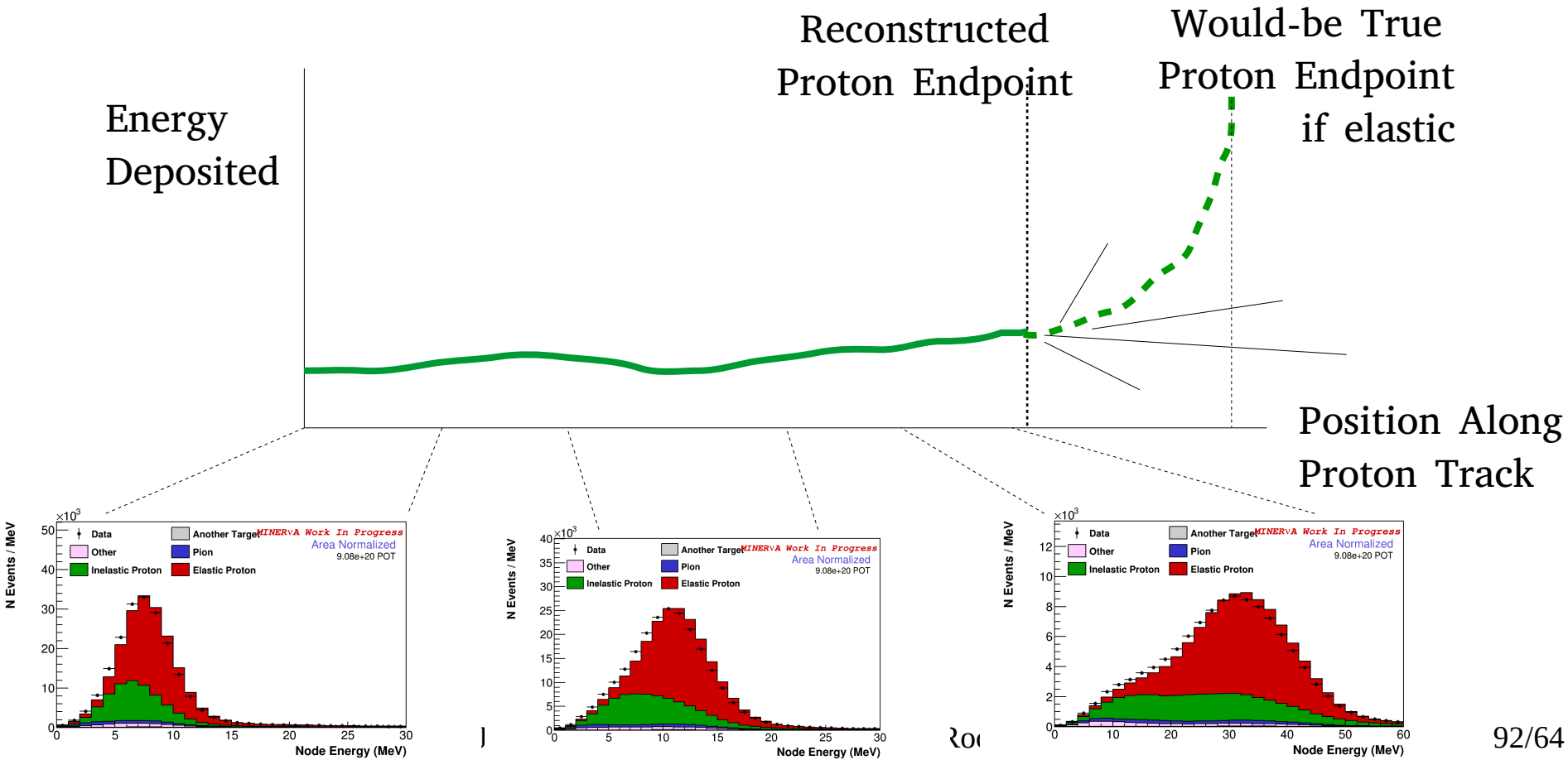
Elastic Example

- Elastic-Scattering Contained (ESC) Proton Cut

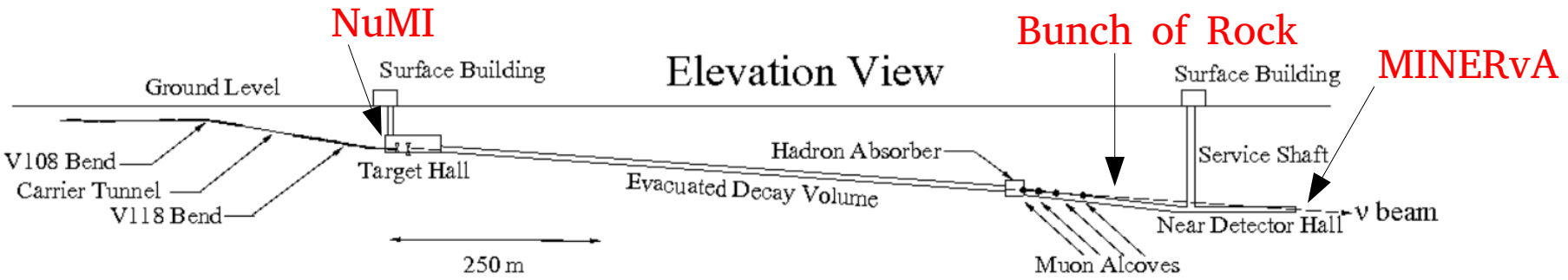


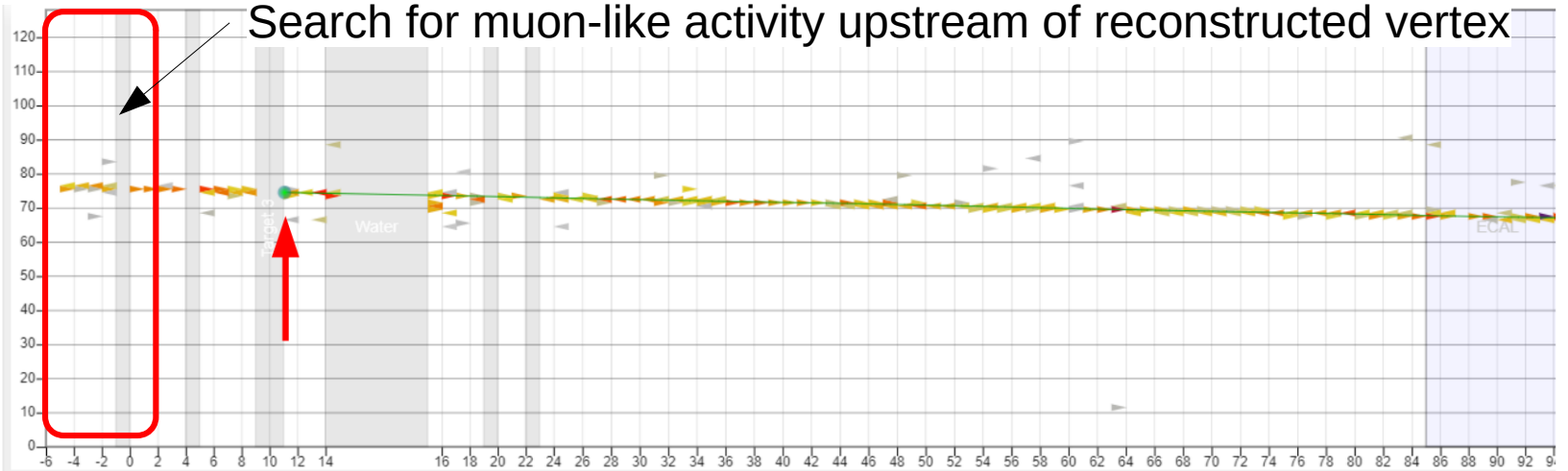
Inelastic Example

- Elastic-Scattering Contained (ESC) Proton Cut



Rock Muons





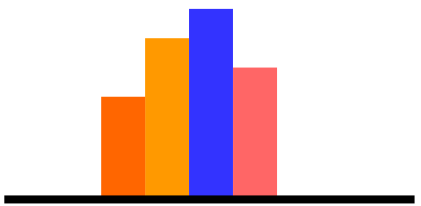
Rejected target 1 events because of too much rock muon contamination

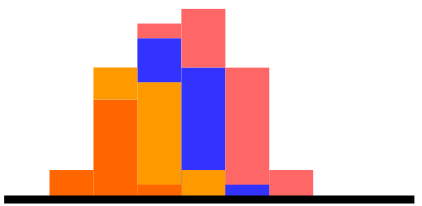
Unfolding/deconvolution

$$\frac{d\sigma}{dX}_i = \frac{\sum_j U_{ij}\left(N_j^{measured} - N_j^{background}\right)}{\epsilon_i\left(T\Phi_i\right)\Delta X_i}$$

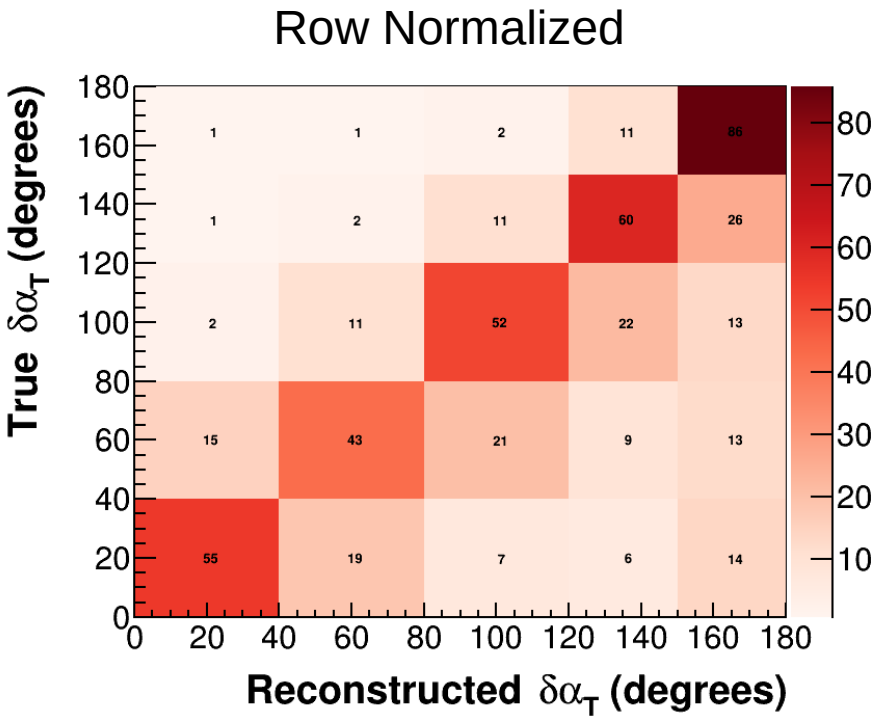
Easy

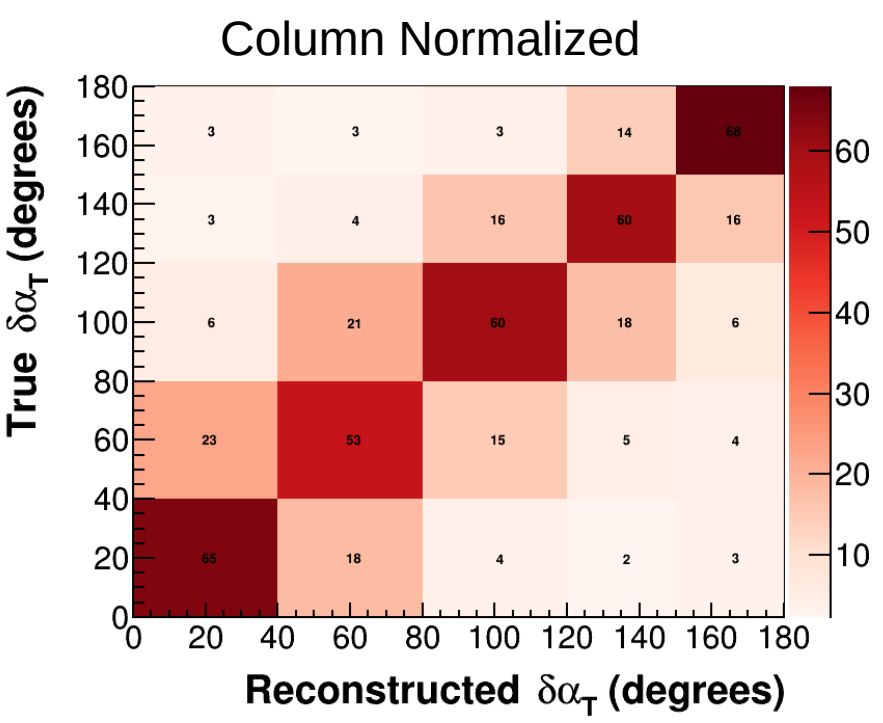
Difficult



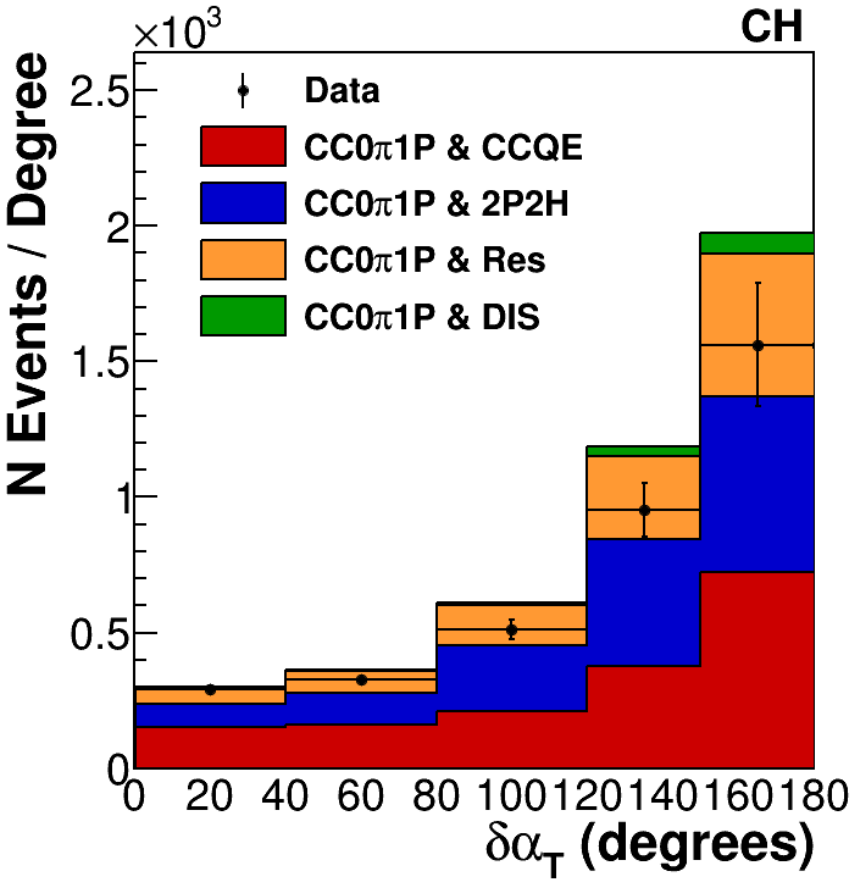


Unfolding Matrix U_{ij}



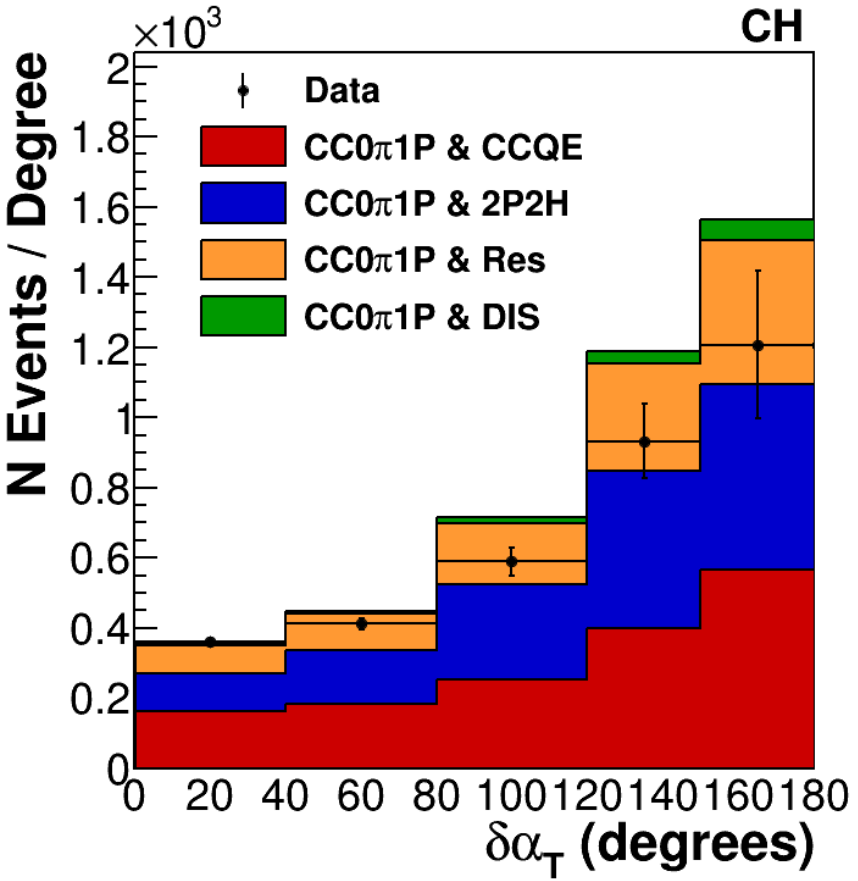


Background Subtracted

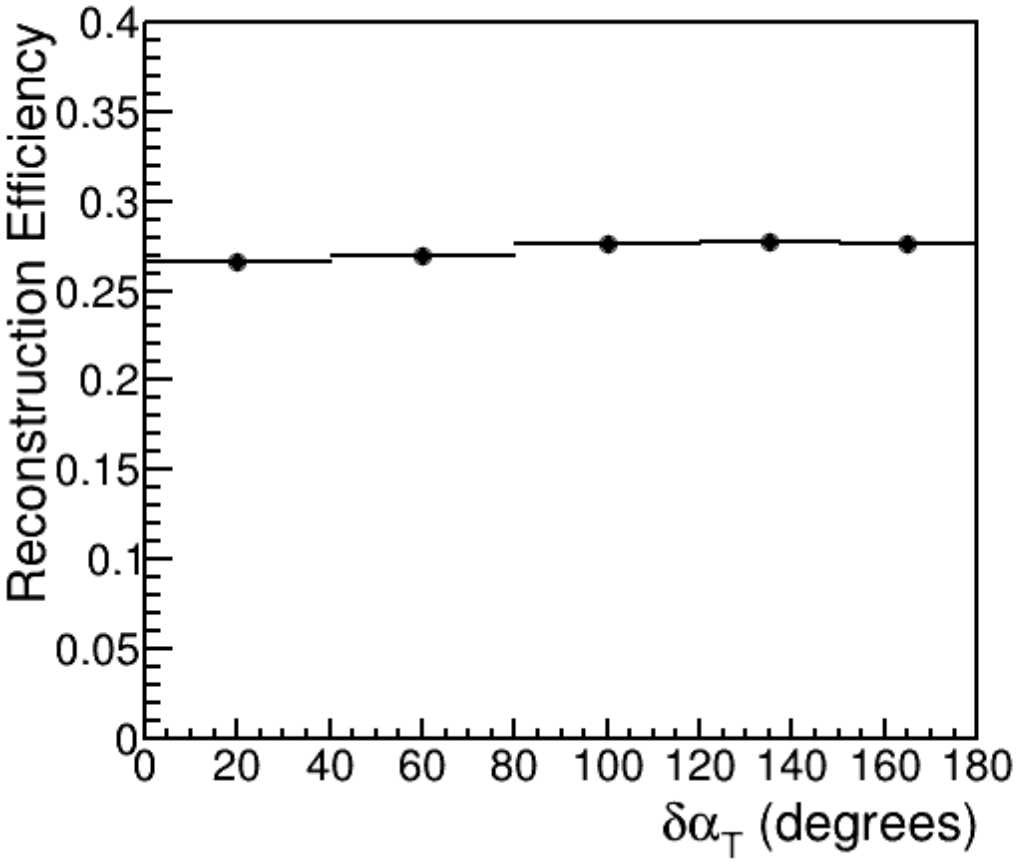


$(N_j^{measured} - N_j^{background})$

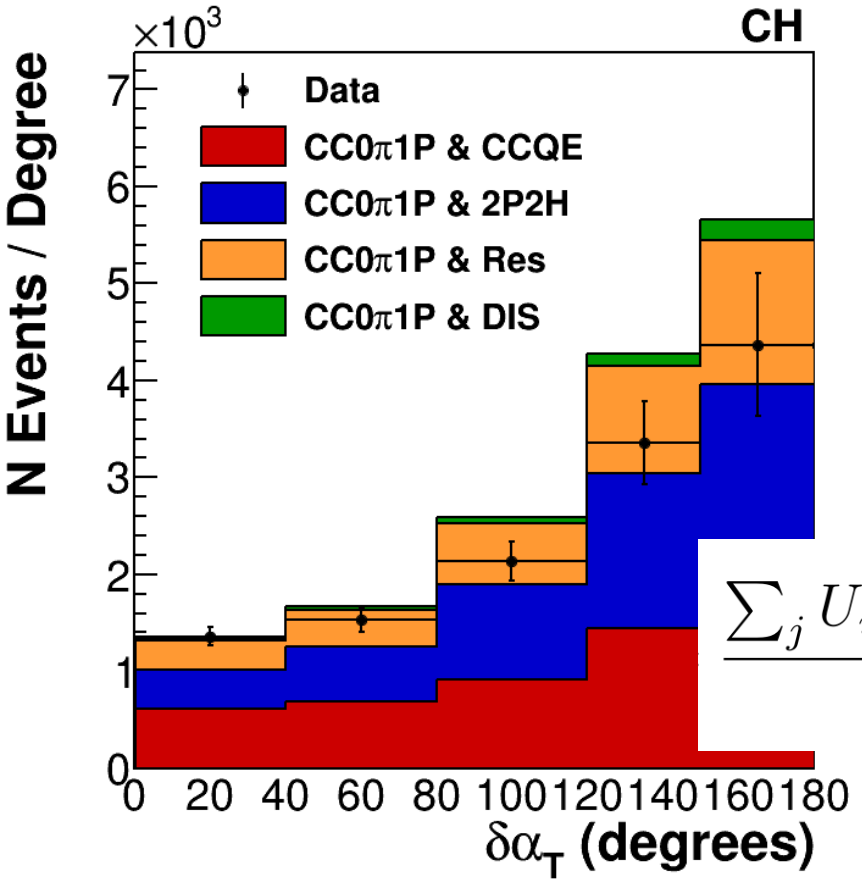
Unfolded $\sum_j U_{ij}(N_j^{measured} - N_j^{background})$



Reco eff


Reconstruction Efficiency
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
20
40
60
80
100
120
140
160
180
δα_T (degrees)

Eff corrected



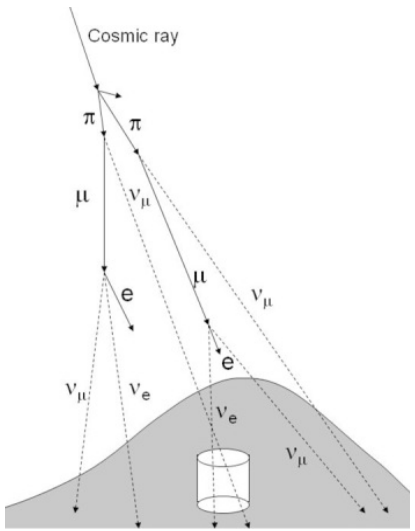
$$\frac{\sum_j U_{ij}(N_j^{measured} - N_j^{background})}{\epsilon_i}$$

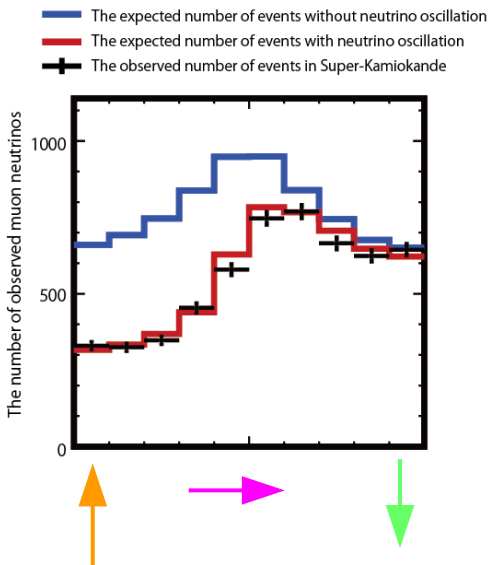
Why are neutrinos interesting

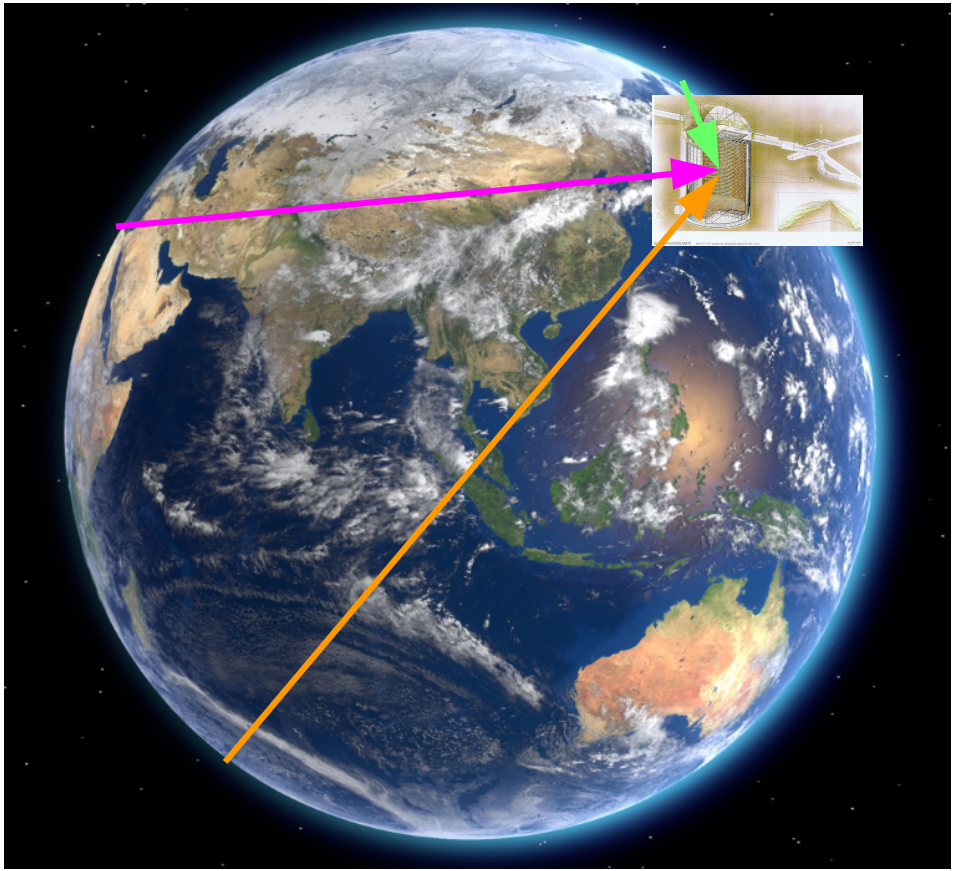
- No charge or color charge
  - No electromagnetic or strong interactions
  - weak force only → “Ghost particles”
  - understand weak force
- Neutrinos are everywhere
  - Passing through you right now
- Neutrinos play roles in supernovae and right after the big bang

Neutrino Oscillations

- When neutrinos travel, they change neutrino flavors
  - $\nu_\mu \rightarrow \nu_{e,\tau}$
- Not predicted by the SM



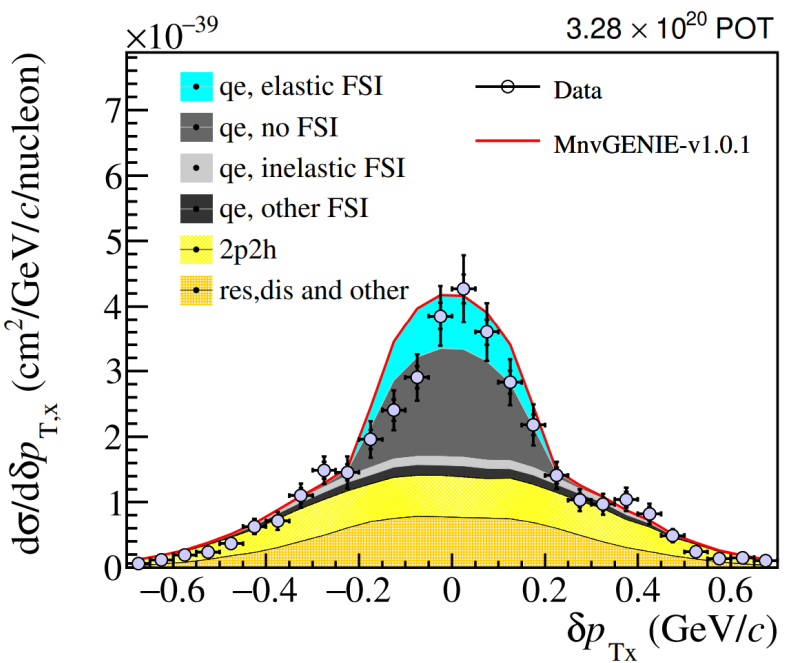


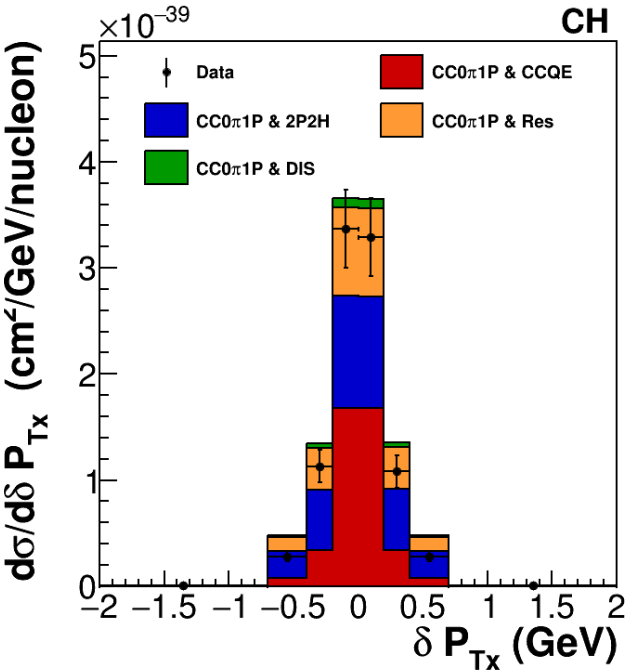


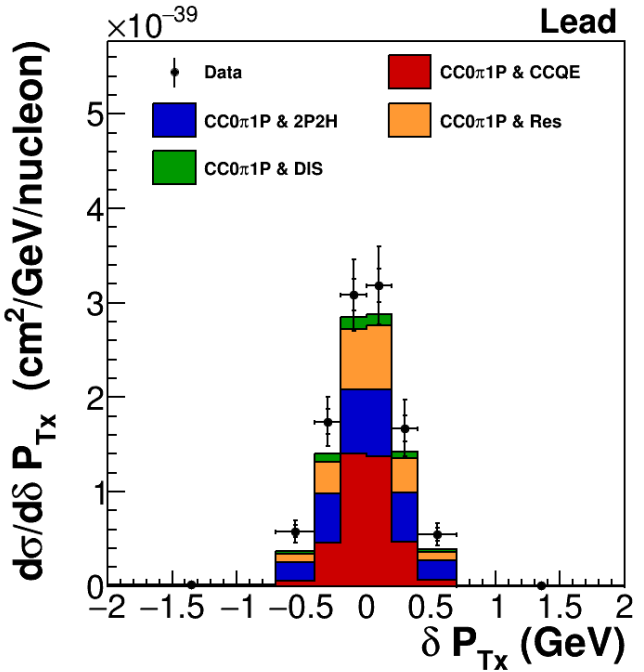
dptx asymmetry – not seen

- Wider binning, dptx sideband tuning reduces pi background effects, higher P energy threshold (450 MeV → 500 MeV)

Phys. Rev. D 101, 092001 (2020)

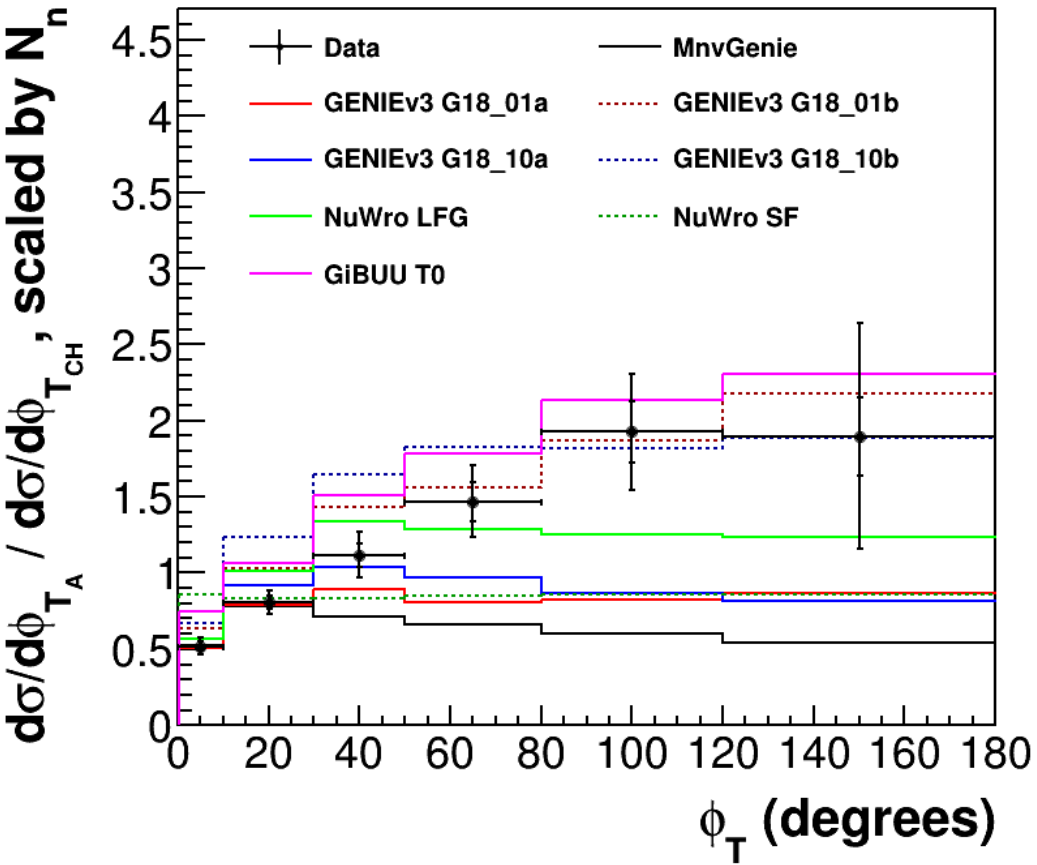






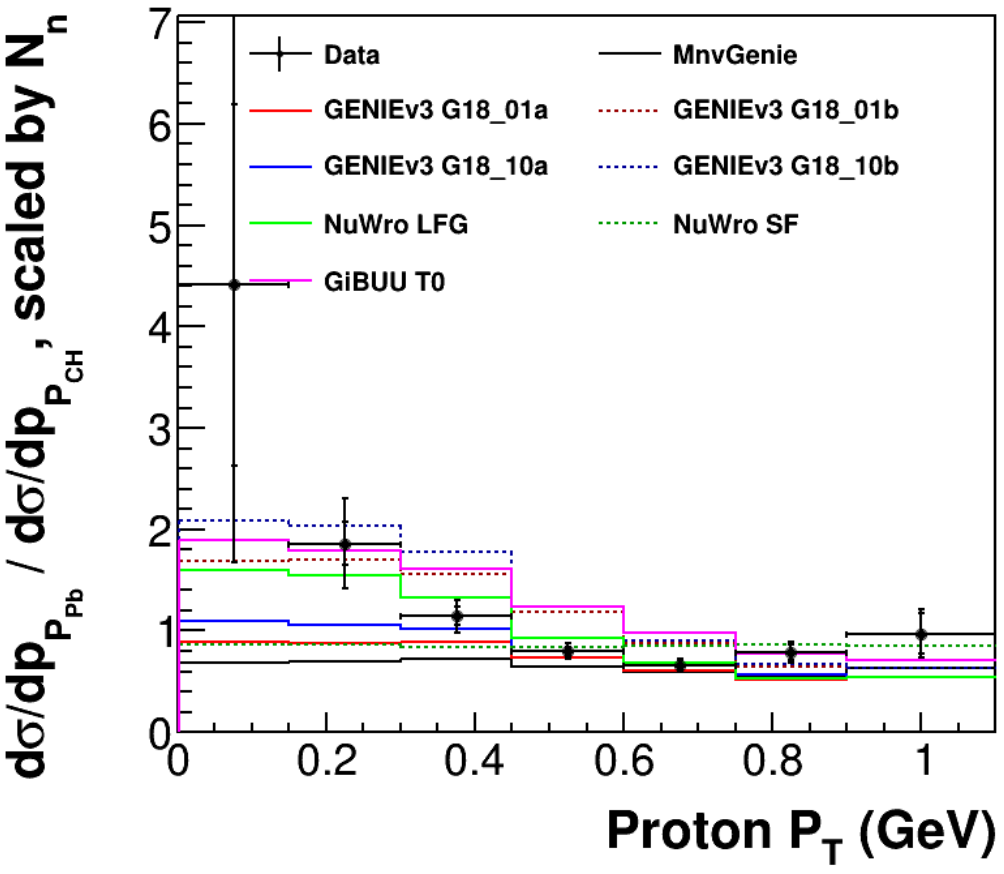
Additional Comparisons

Lead



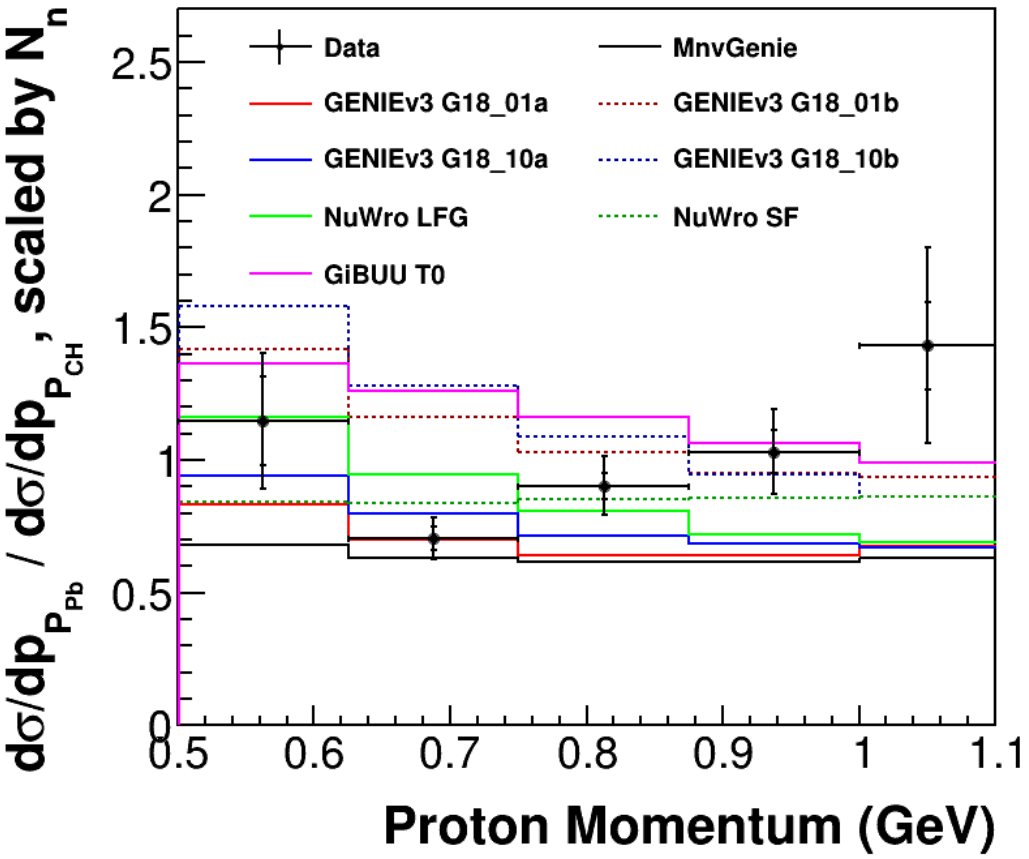
Model	χ/ndf
MnvGenie	20.55/6 = 3.42
GENIEv3 G18_01a	14.35/6 = 2.39
GENIEv3 G18_01b	14.03/6 = 2.34
GENIEv3 G18_10a	20.16/6 = 3.36
GENIEv3 G18_10b	45.86/6 = 7.64
NuWro LFG	24.1/6 = 4.02
NuWro SF	48.18/6 = 8.03
GiBUU T0	24.42/6 = 4.07

Lead



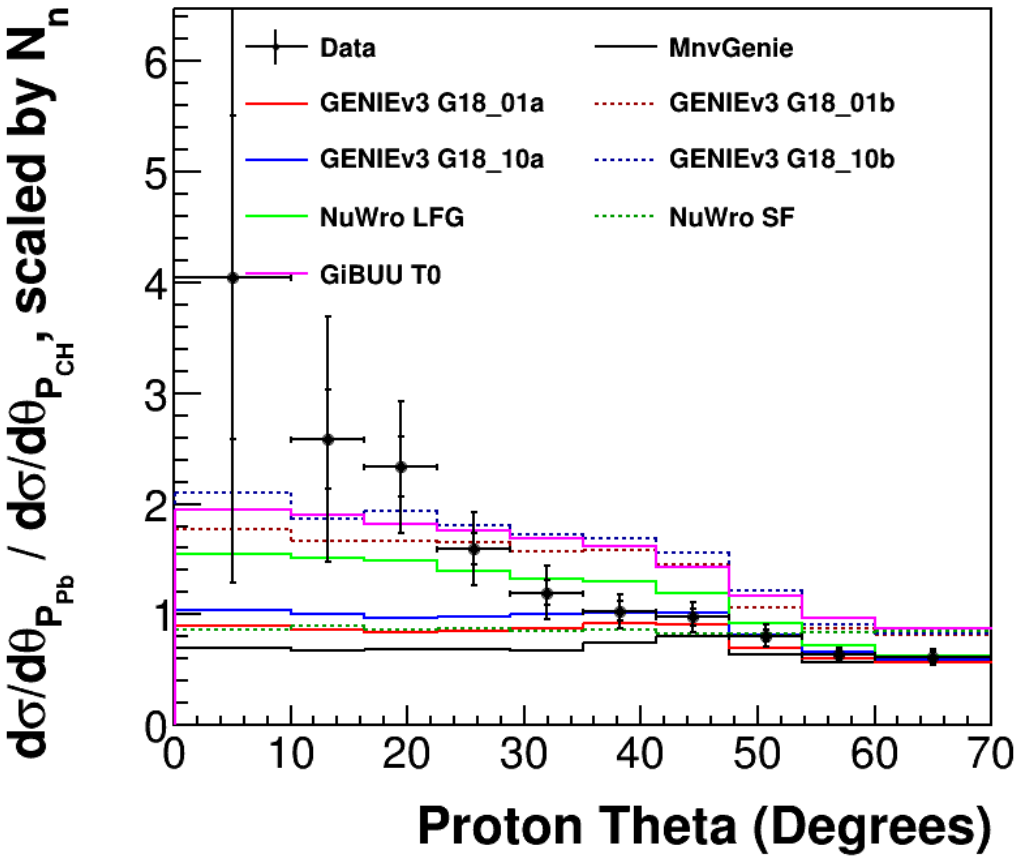
Model	χ/ndf
MnvGenie	14.21/7 = 2.03
GENIEv3 G18_01a	11.81/7 = 1.69
GENIEv3 G18_01b	45.37/7 = 6.48
GENIEv3 G18_10a	9.97/7 = 1.42
GENIEv3 G18_10b	56.5/7 = 8.07
NuWro LFG	17.4/7 = 2.49
NuWro SF	22.46/7 = 3.21
GiBUU T0	54.93/7 = 7.85

Lead



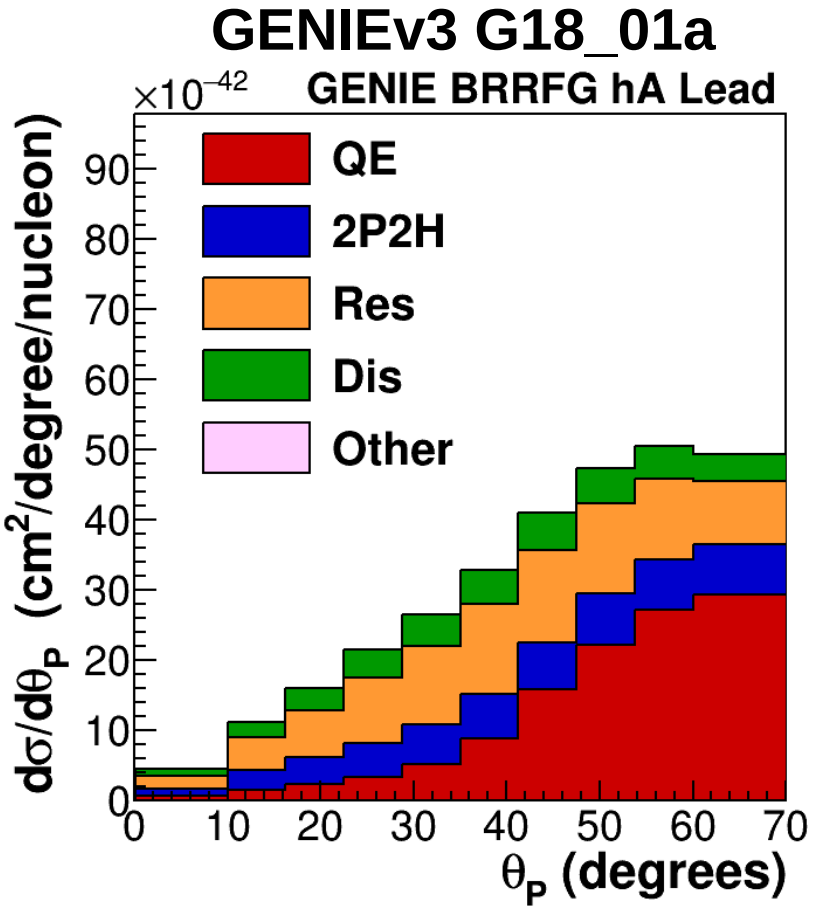
Model	χ/ndf
MnvGenie	11.34/5 = 2.27
GENIEv3 G18_01a	12.64/5 = 2.53
GENIEv3 G18_01b	62.77/5 = 12.56
GENIEv3 G18_10a	17.42/5 = 3.48
GENIEv3 G18_10b	97.43/5 = 19.49
NuWro LFG	34.04/5 = 6.81
NuWro SF	13.49/5 = 2.7
GiBUU T0	82.27/5 = 16.45

Lead

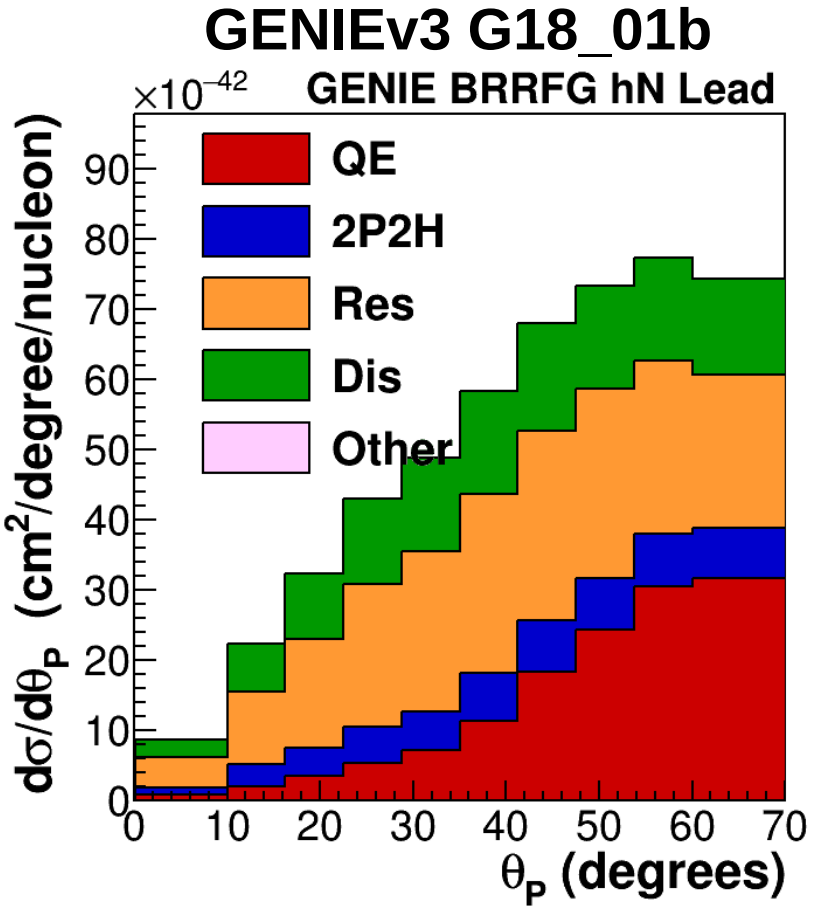


Model	χ/ndf
MnvGenie	22.1/10=2.2
GENIEv3 G18_01a	21.5/10=2.1
GENIEv3 G18_01b	60.7/10=6.1
GENIEv3 G18_10a	24.1/10=2.4
GENIEv3 G18_10b	68.3/10=6.8
NuWro LFG	18.4/10=1.8
NuWro SF	35.7/10=3.6
GiBUU T0	26.4/10=2.6

Geniev3 Predictions



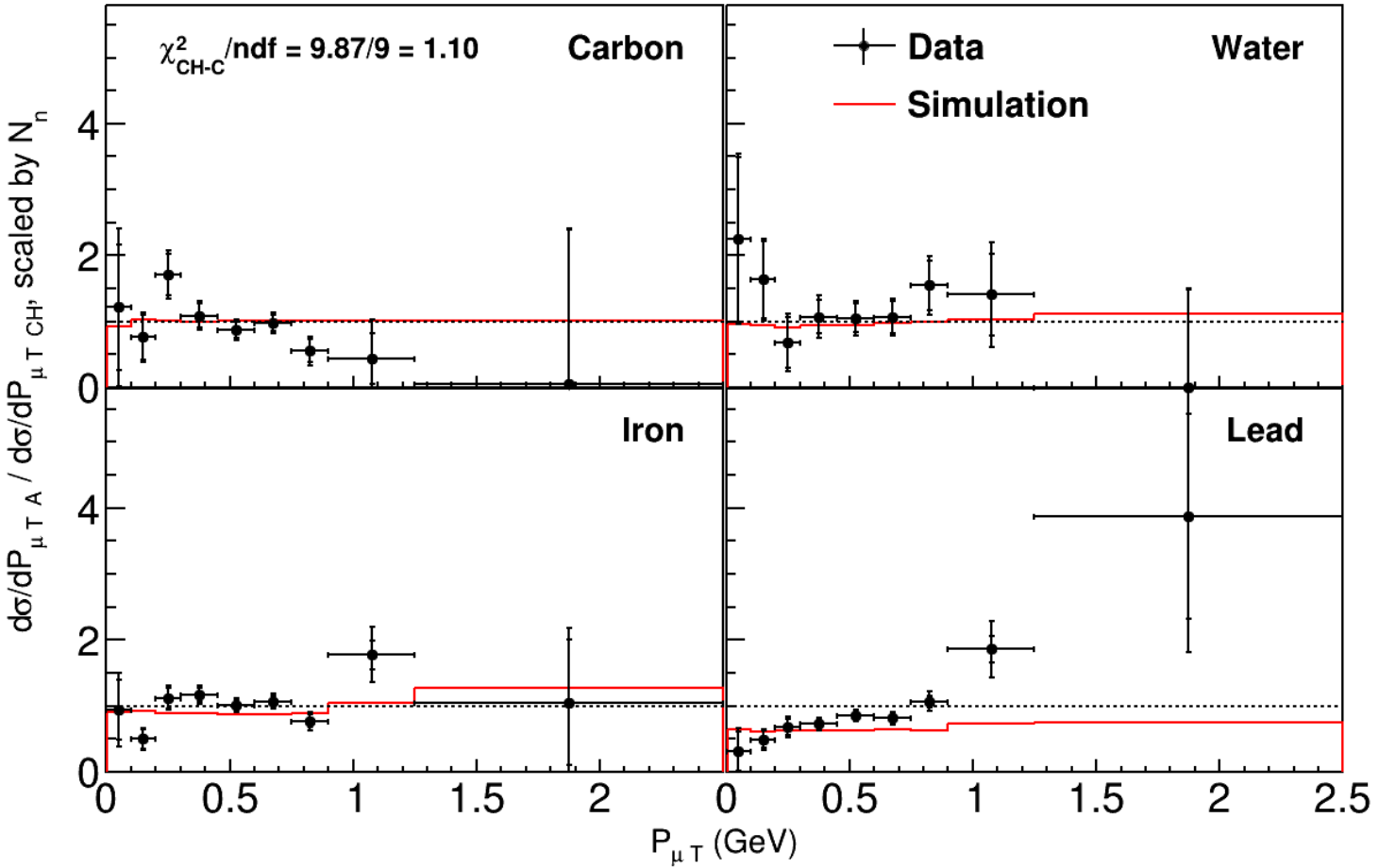
Single interaction model

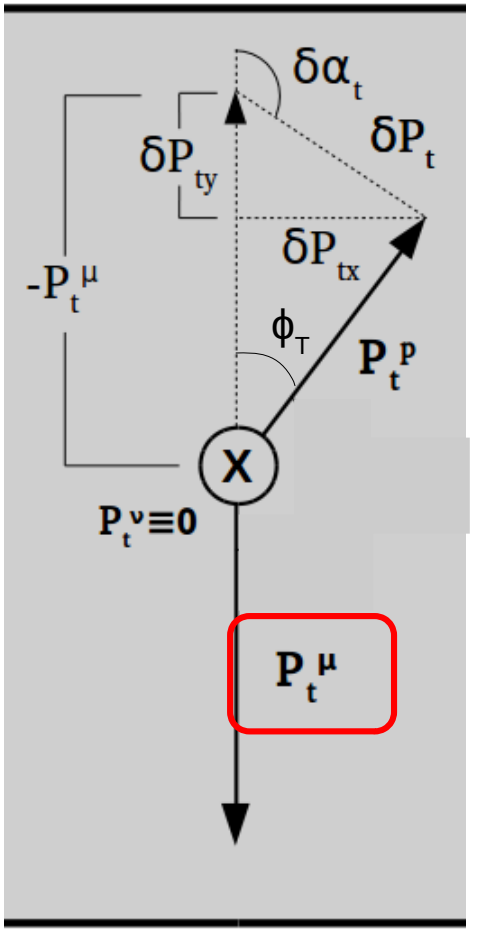


Cascade model

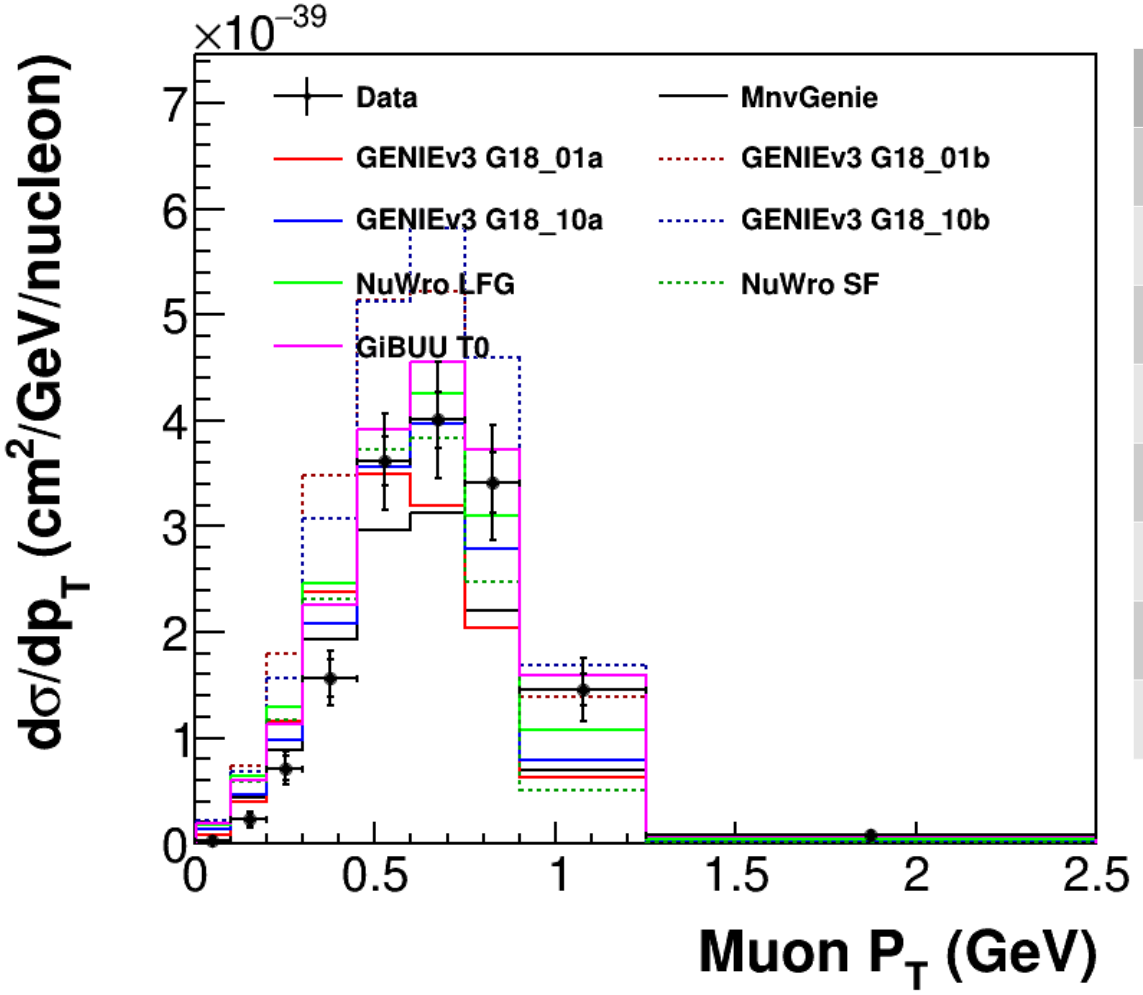
What else can we learn?

Muon P_T


χ^2_{CH-C}/ndf = 9.87/9 = 1.10
Carbon
Data
Simulation
Water
Iron
Lead
$d\sigma/dP_{\mu T A}$ / $d\sigma/dP_{\mu T CH}$, scaled by N_n
$P_{\mu T}$ (GeV)


$\delta\alpha_t$
δP_t
δP_{ty}
δP_{tx}
$-P_t^{\mu}$
ϕ_T
P_t^{p}
X
$P_t^{\nu}\equiv 0$
P_t^{μ}

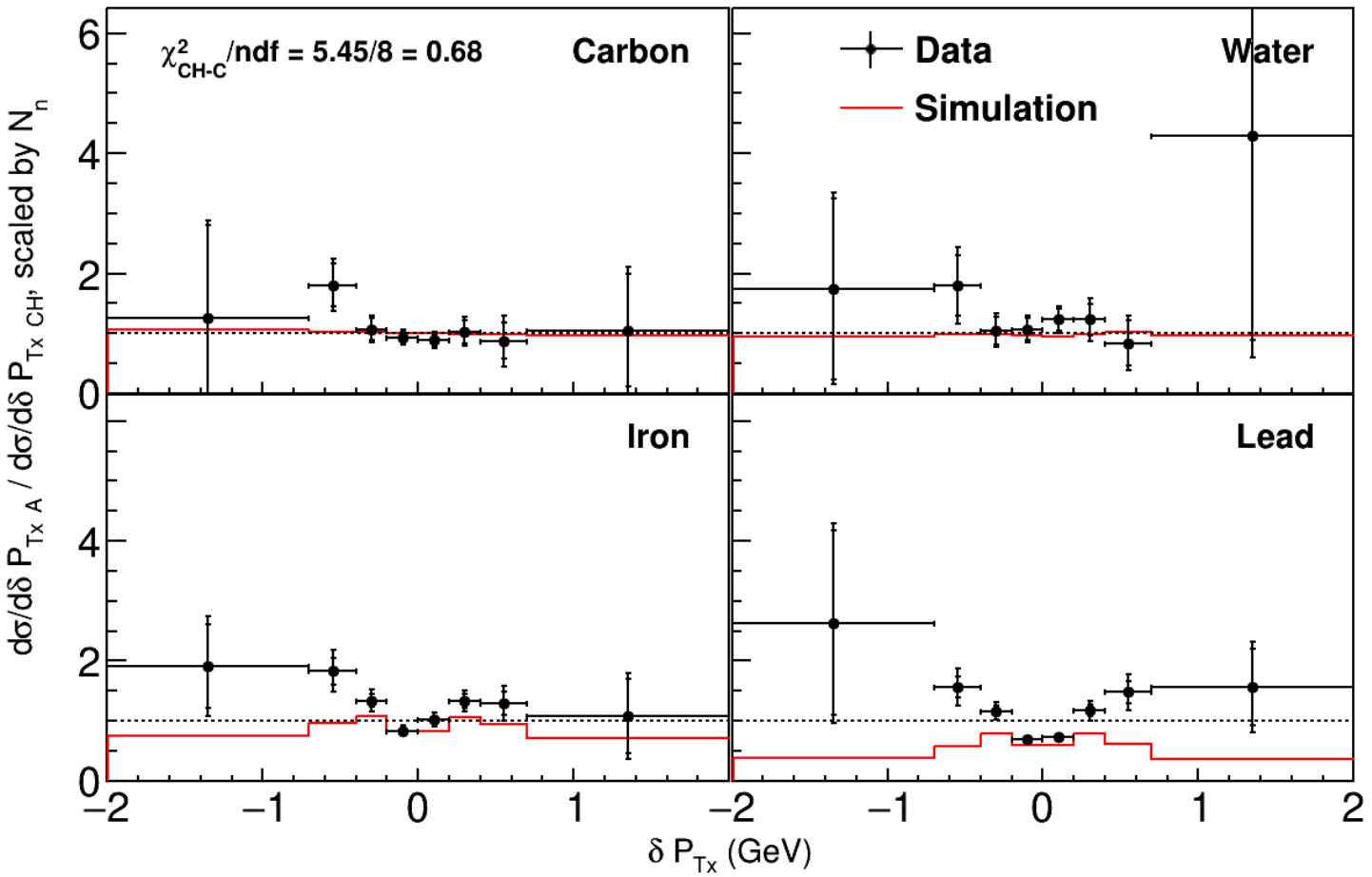
Lead Muon P_T

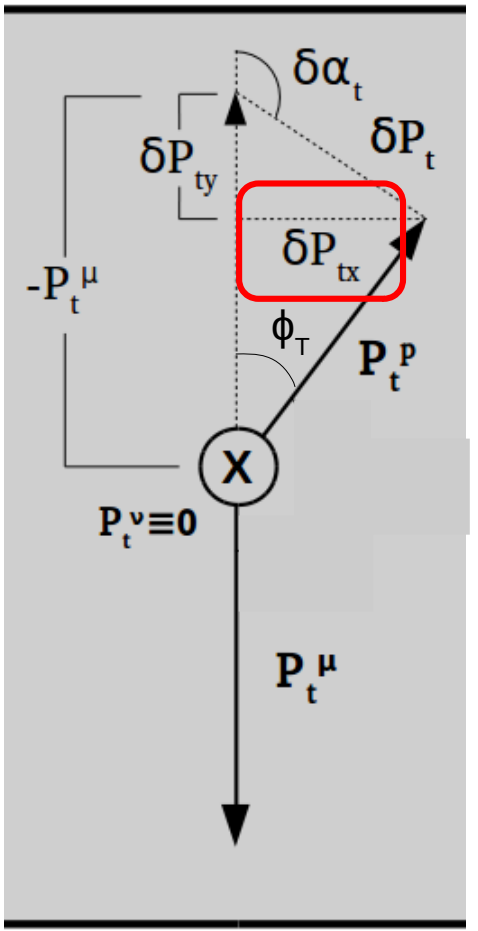


Model	χ/ndf
MnvGenie	45.1/10=4.5
GENIEv3 G18_01a	65.5/10=6.6
GENIEv3 G18_01b	166.7/10=16.7
GENIEv3 G18_10a	43.4/10=4.3
GENIEv3 G18_10b	105.9/10=10.6
NuWro LFG	82.7/10=8.3
NuWro SF	96/10=9.6
GiBUU T0	53/10=5.3

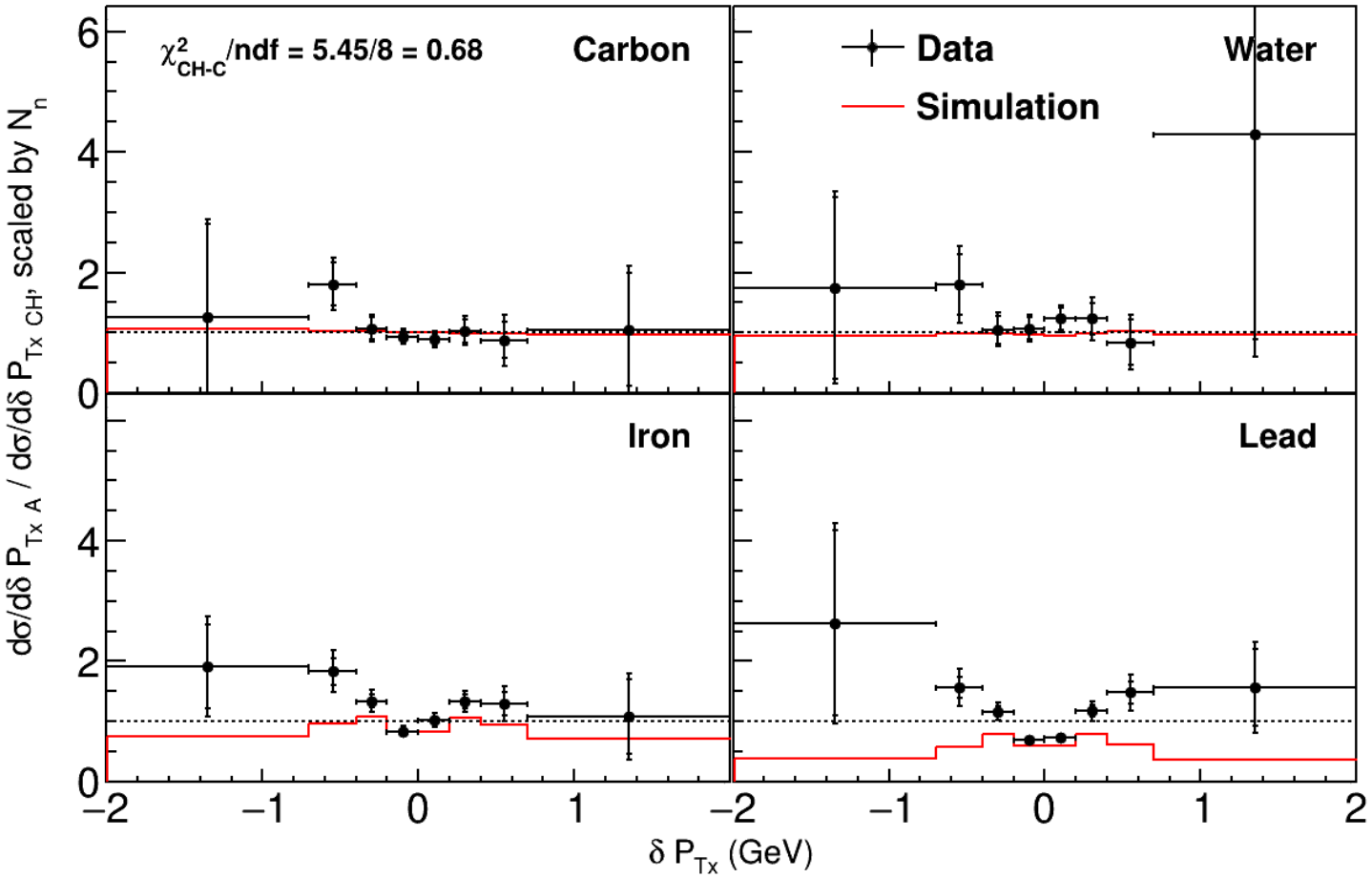
Keep in mind that we're measuring the subset of muons with a proton in the final state.

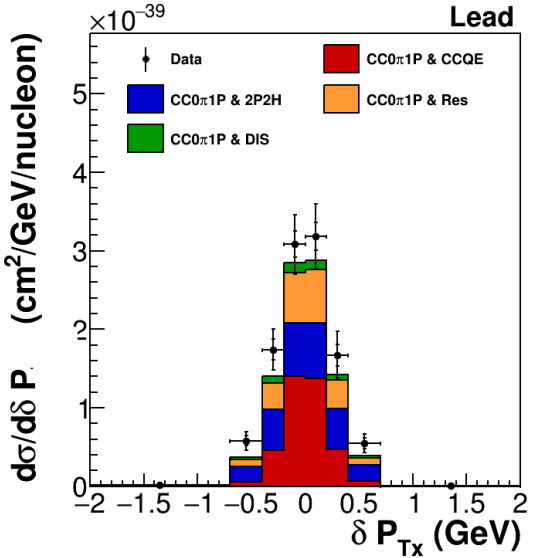
dptx

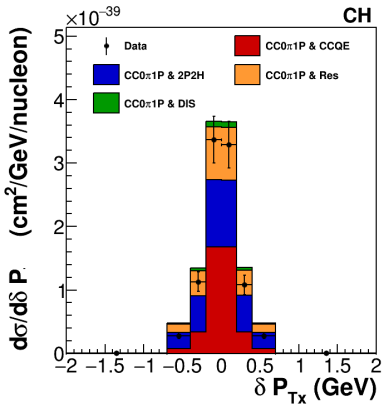

χ^2_{CH-C}/ndf = 5.45/8 = 0.68
Carbon
Data
Simulation
Water
Iron
Lead
dσ/dδ P_Tx A / dσ/dδ P_Tx CH, scaled by N_n
δ P_Tx (GeV)


δα_t
δP_t
δP_ty
δP_tx
-P_t^μ
φ_T
P_t^p
X
P_t^ν≡0
P_t^μ

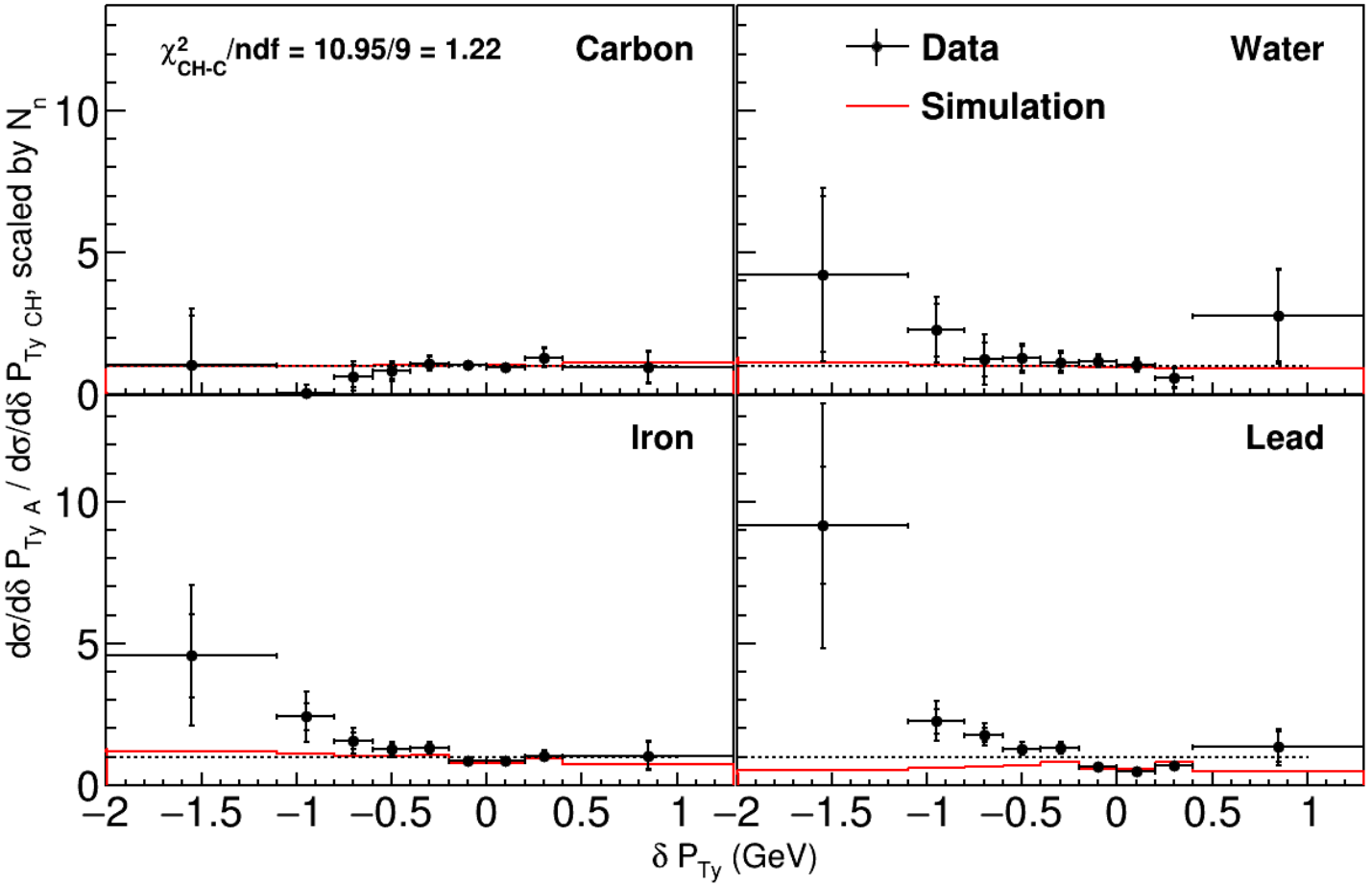
dptx

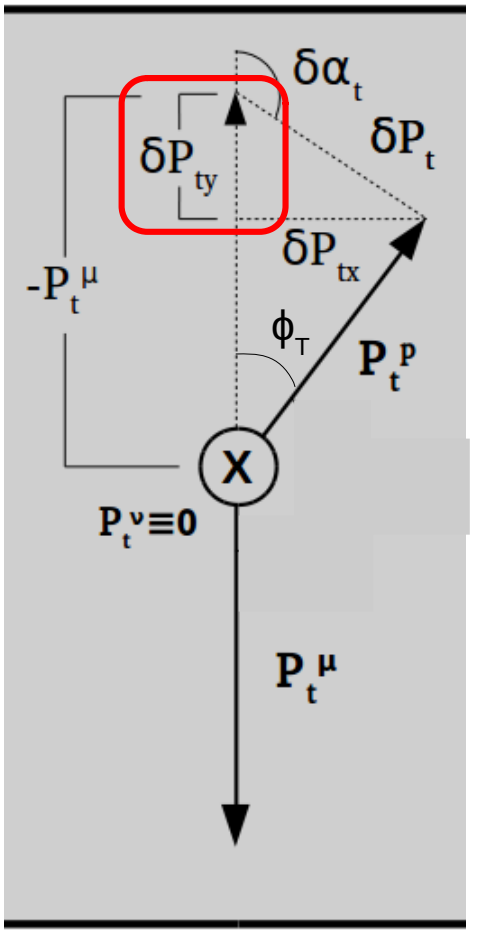

χ^2_{CH-C}/ndf = 5.45/8 = 0.68
Carbon
Data
Simulation
Water
Iron
Lead
$d\sigma/d\delta\ P_{Tx\ A}$ / $d\sigma/d\delta\ P_{Tx\ CH}$, scaled by N_n
$\delta\ P_{Tx}$ (GeV)


Lead
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
$d\sigma/d\delta\ P_{Tx}$ (cm²/GeV/nucleon)
$\delta\ P_{Tx}$ (GeV)

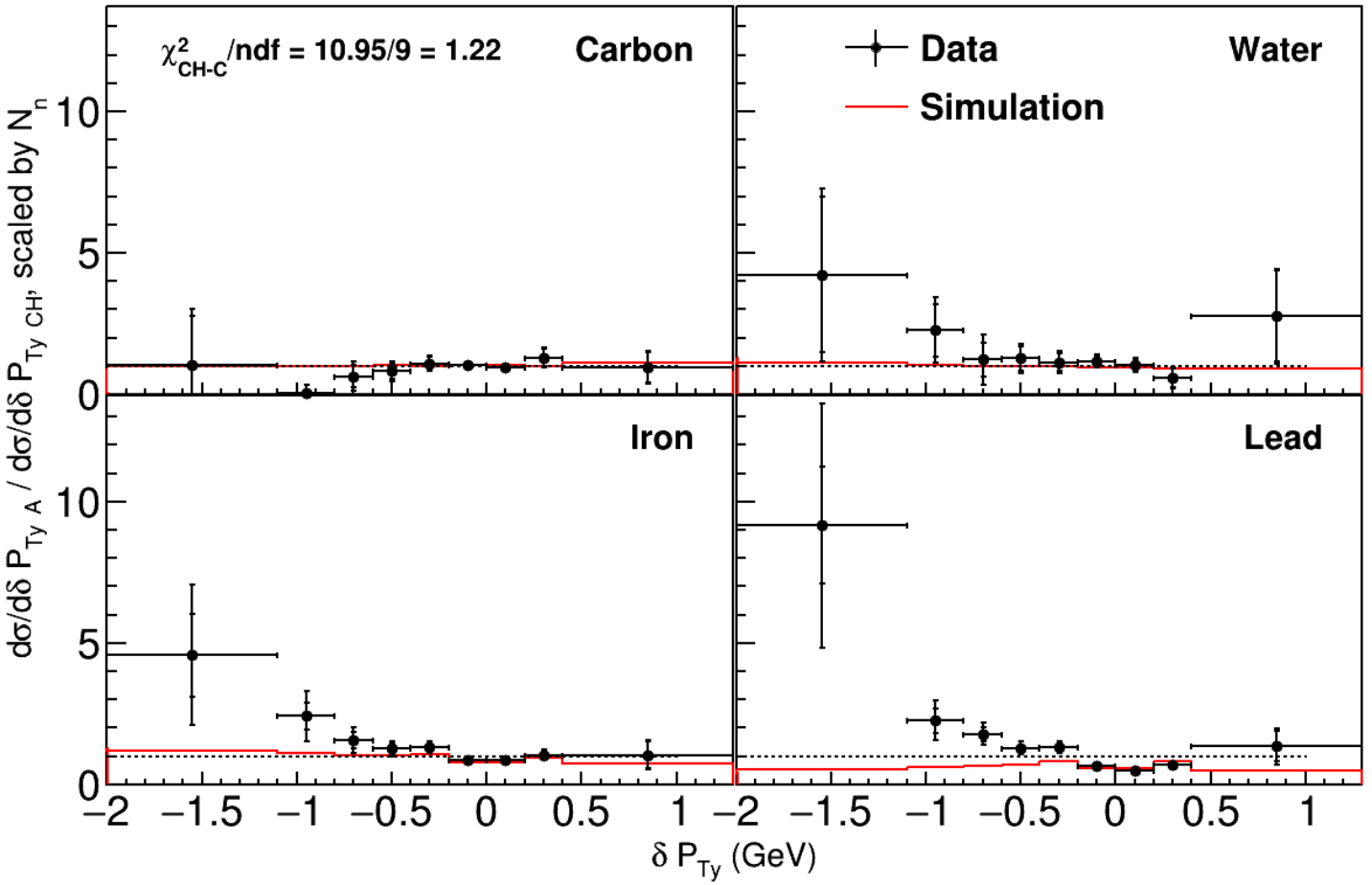

CH
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
$d\sigma/d\delta\ P_{Tx}$ (cm²/GeV/nucleon)
$\delta\ P_{Tx}$ (GeV)

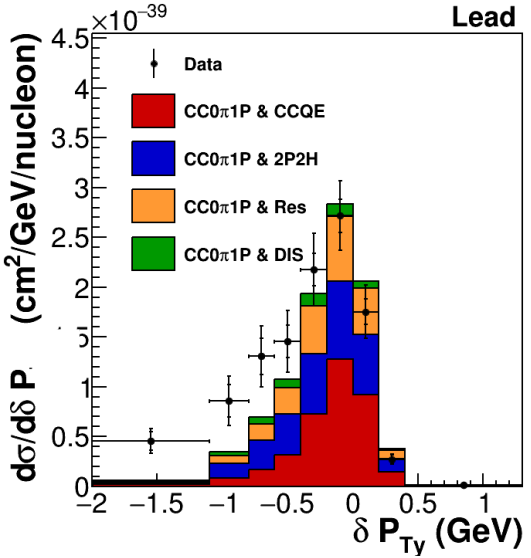
dpty

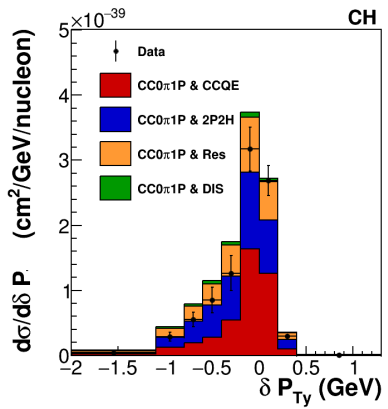

χ^2_{CH-C}/ndf = 10.95/9 = 1.22
Carbon
Data
Simulation
Water
Iron
Lead
dσ/dδ P_Ty A / dσ/dδ P_Ty CH, scaled by N_n
δ P_Ty (GeV)


δα_t
δP_t
δP_ty
δP_tx
-P_t^μ
φ_T
P_t^p
X
P_t^ν≡0
P_t^μ

dpty


χ^2_{CH-C}/ndf = 10.95/9 = 1.22
Carbon
Data
Simulation
Water
Iron
Lead
dσ/dδ P_Ty A / dσ/dδ P_Ty CH, scaled by N_n
δ P_Ty (GeV)


×10⁻³⁹
Lead
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
dσ/dδ P (cm²/GeV/nucleon)
δ P_Ty (GeV)


×10⁻³⁹
CH
Data
CC0π1P & CCQE
CC0π1P & 2P2H
CC0π1P & Res
CC0π1P & DIS
dσ/dδ P (cm²/GeV/nucleon)
δ P_Ty (GeV)