Neutrino Scattering at a few GeV

- Motivation
- MINERvA
  - Experiment
  - Results
- Thoughts for LBNE

Mike Kordosky

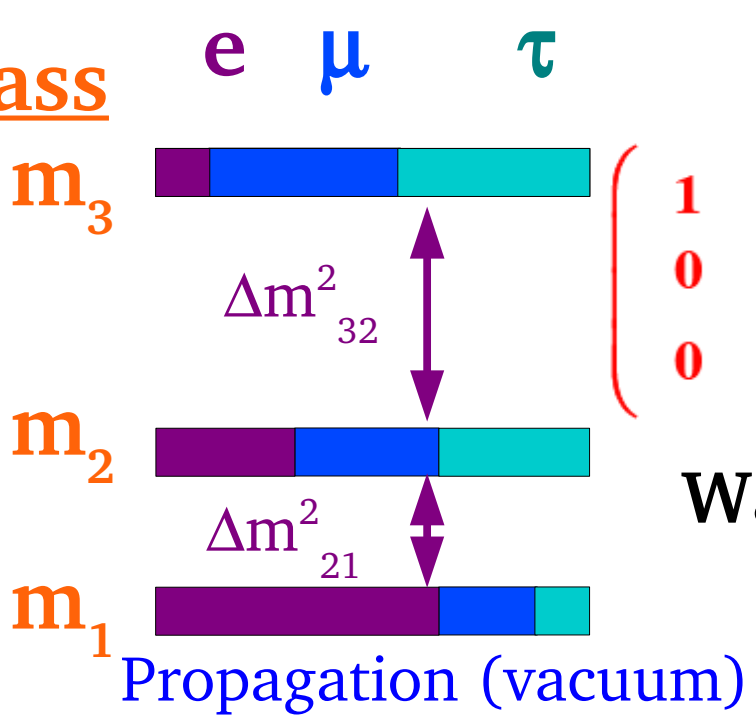
William & Mary

LBNE Physics Workshop
Santa Fe, April 25-26 2014

Motivation: ν oscillations

Flavor "Atmospheric + reactor" parts of PMNS Matrix

Mass



$\nu_\mu \leftrightarrow \nu_\mu$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$\nu_\mu \leftrightarrow \nu_e$ & $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$

$$\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix}$$

Wanted: precision, δ, mass hierarchy

flavor mass states

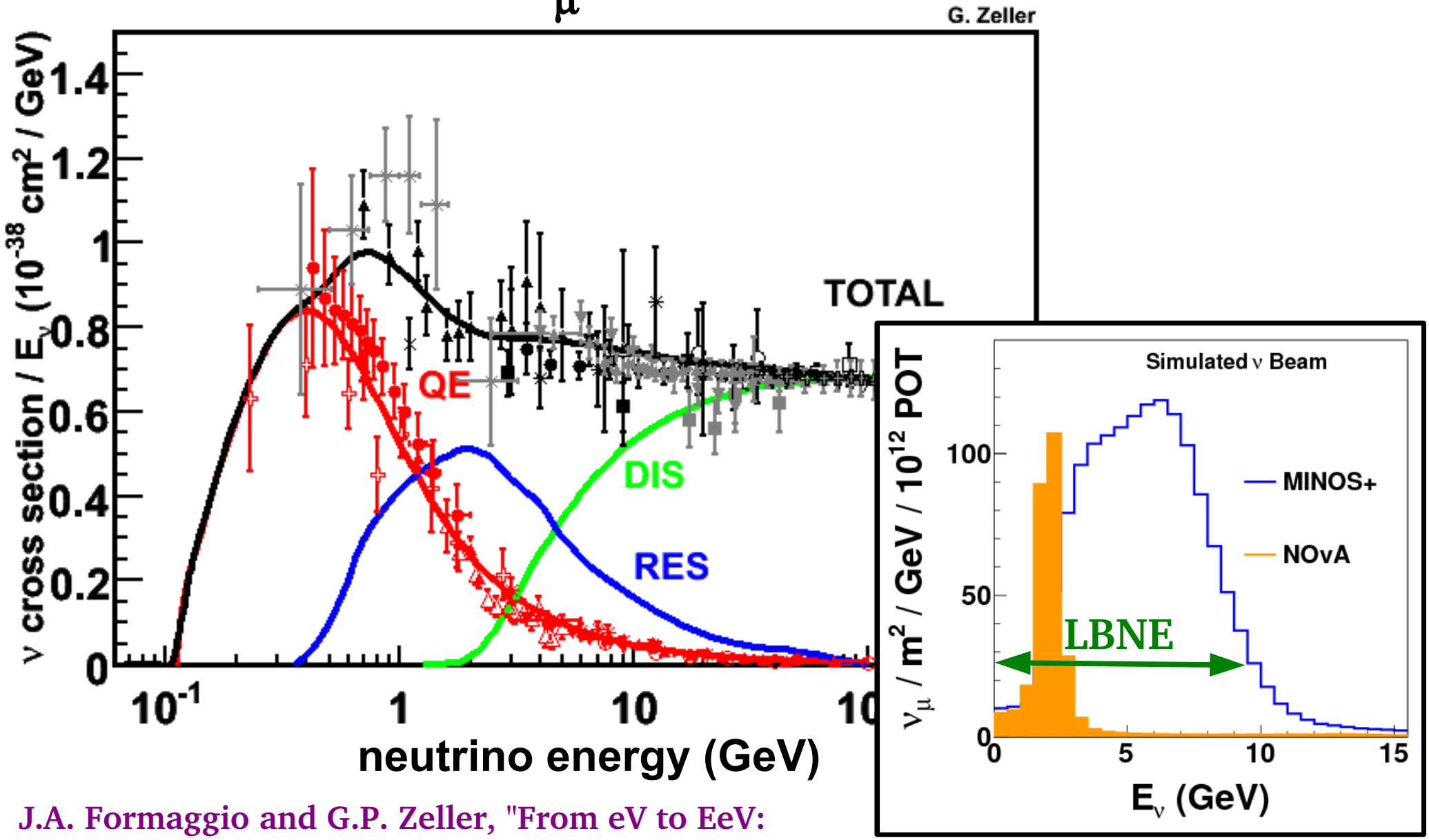
$$|\nu_\alpha(L)\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle \exp(-i L m_j^2/2p)$$

(L=distance)

Must measure

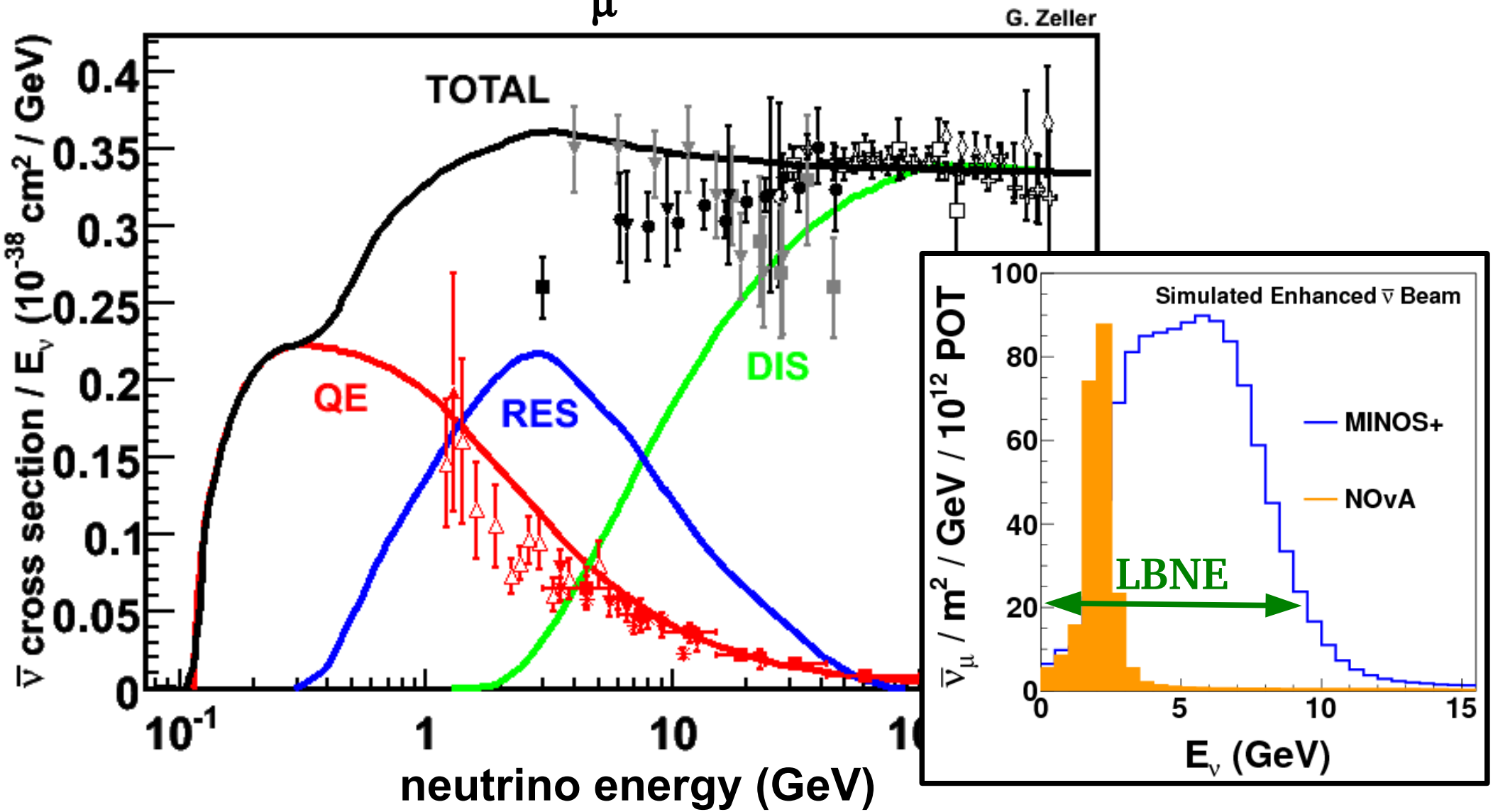
* Flavor
* Energy
* Rate

World ν_μ cross-section



J.A. Formaggio and G.P. Zeller, "From eV to EeV: Neutrino Cross Sections Across Energy Scales", Rev. Mod. Phys. 2012

World $\bar{\nu}_\mu$ cross-section

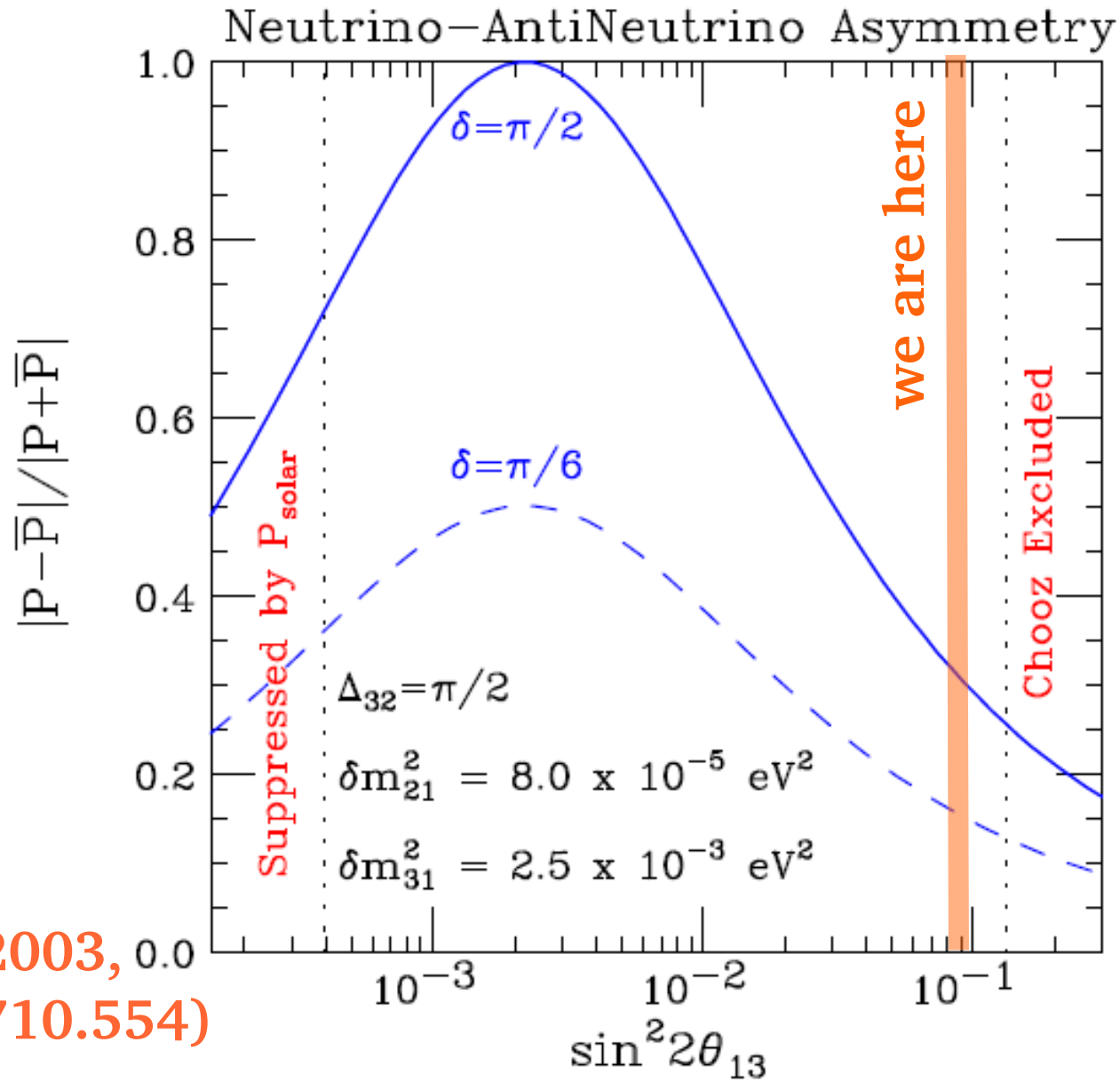


J.A. Formaggio and G.P. Zeller, "From eV to EeV: Neutrino Cross Sections Across Energy Scales", to be published in Rev. Mod. Phys. 2012

implications of large θ_{13}

Rate of $\nu_\mu \rightarrow \nu_e$ increases

but ν - $\bar{\nu}$ asymmetry decreases



(Parke 2003, arXiv:0710.554)

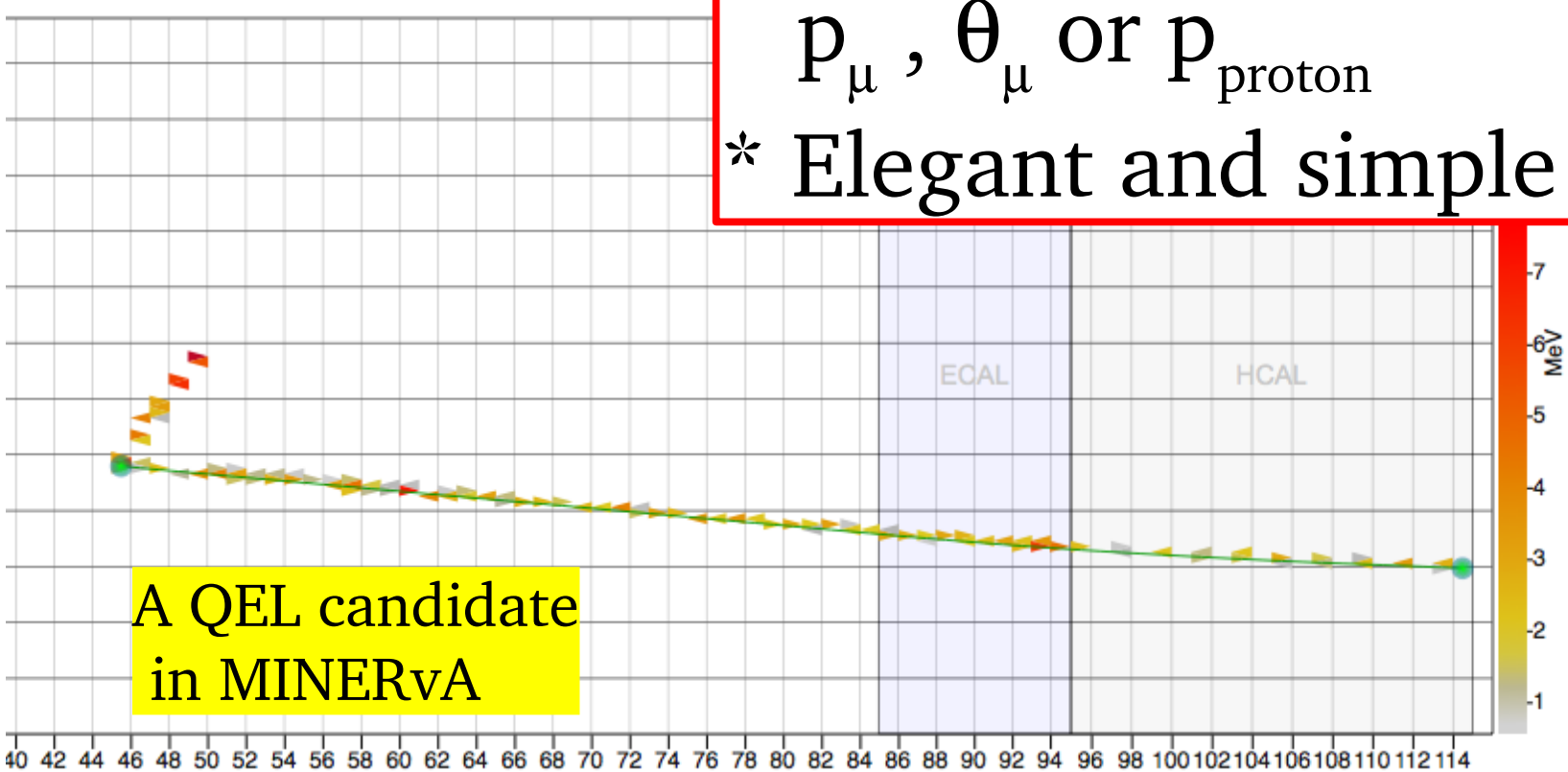
In search of a standard candle

Quasi-elastic scattering

$\nu\, n \rightarrow p\, \mu^-$

Pros:

* Low energy threshold
* No messy pions
* Energy from 2 of 3 p_μ , θ_μ or p_{proton}
* Elegant and simple



A QEL candidate in MINERvA

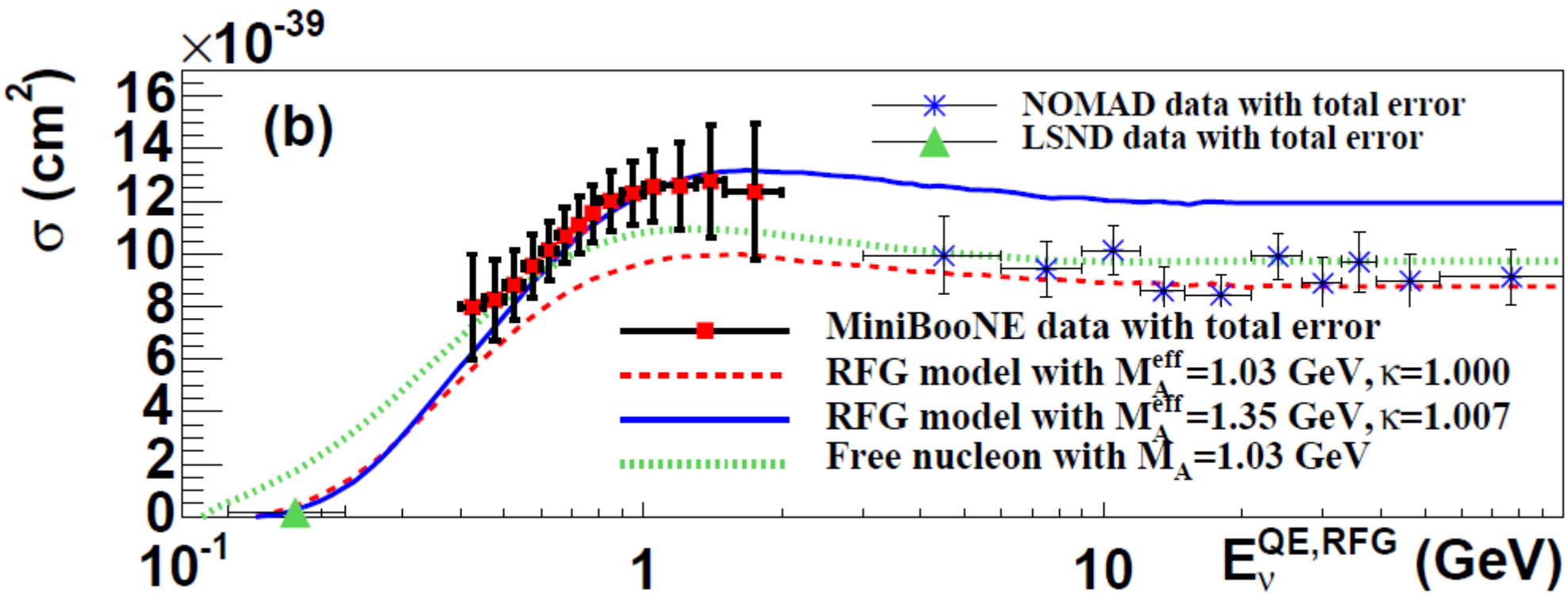
In search of a standard candle

Quasi-elastic scattering

Cons:

* We don't fully understand the energy dependence

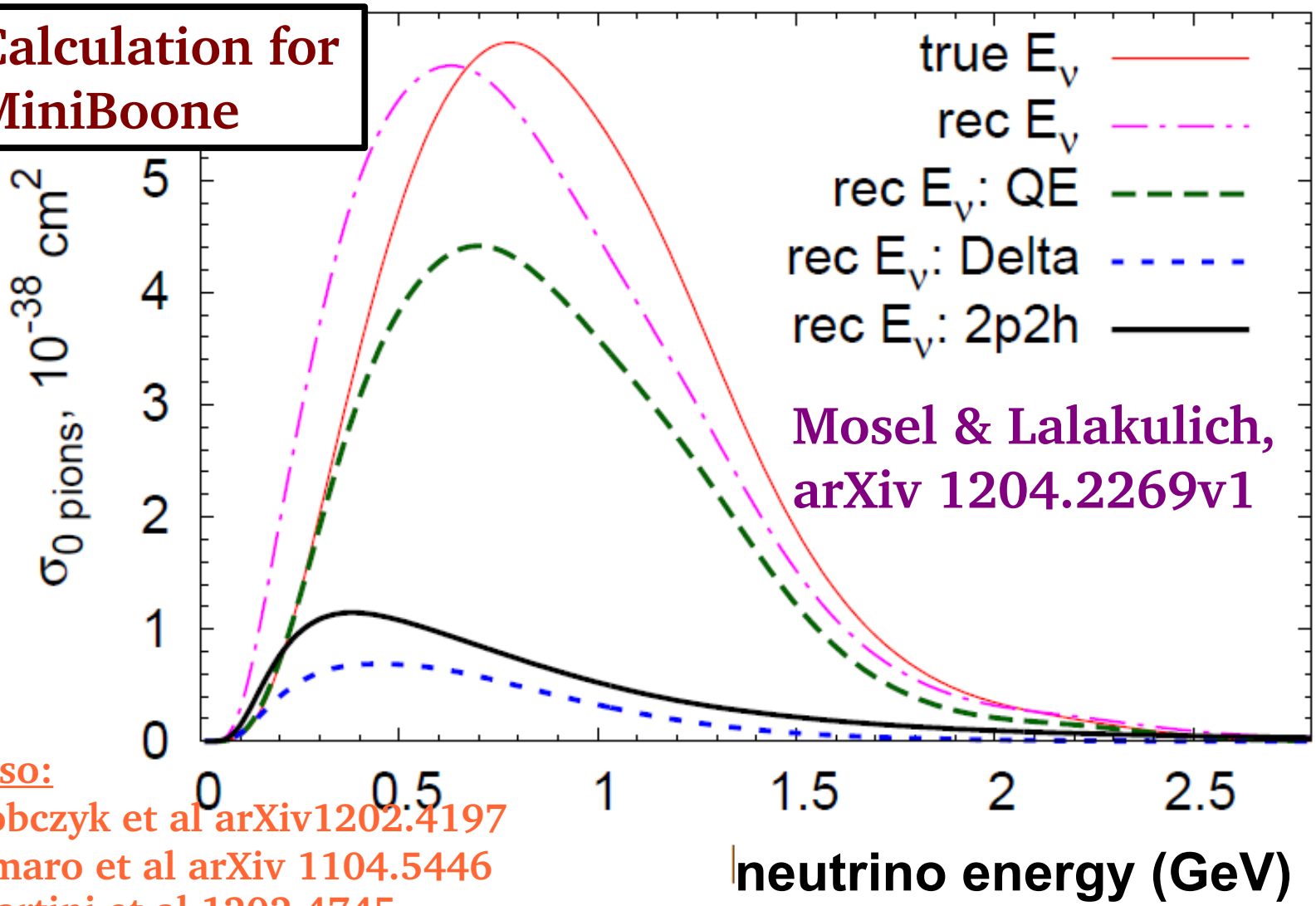
$\nu\ (A,Z) \rightarrow (A-1,Z)\ p\ \mu^-$



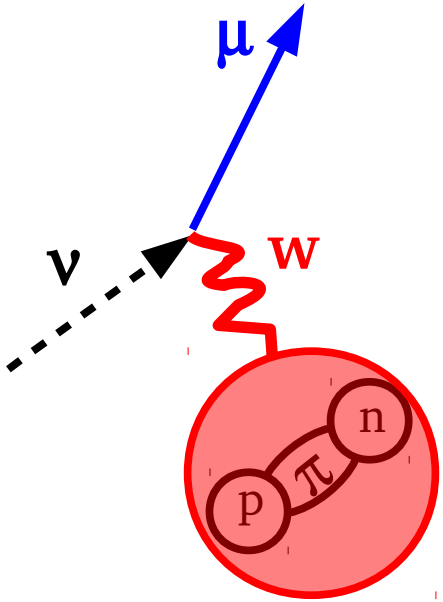
In search of a standard candle

Cons: We don't fully understand energy reconstruction

Calculation for MiniBoone



Mosel & Lalakulich, arXiv 1204.2269v1

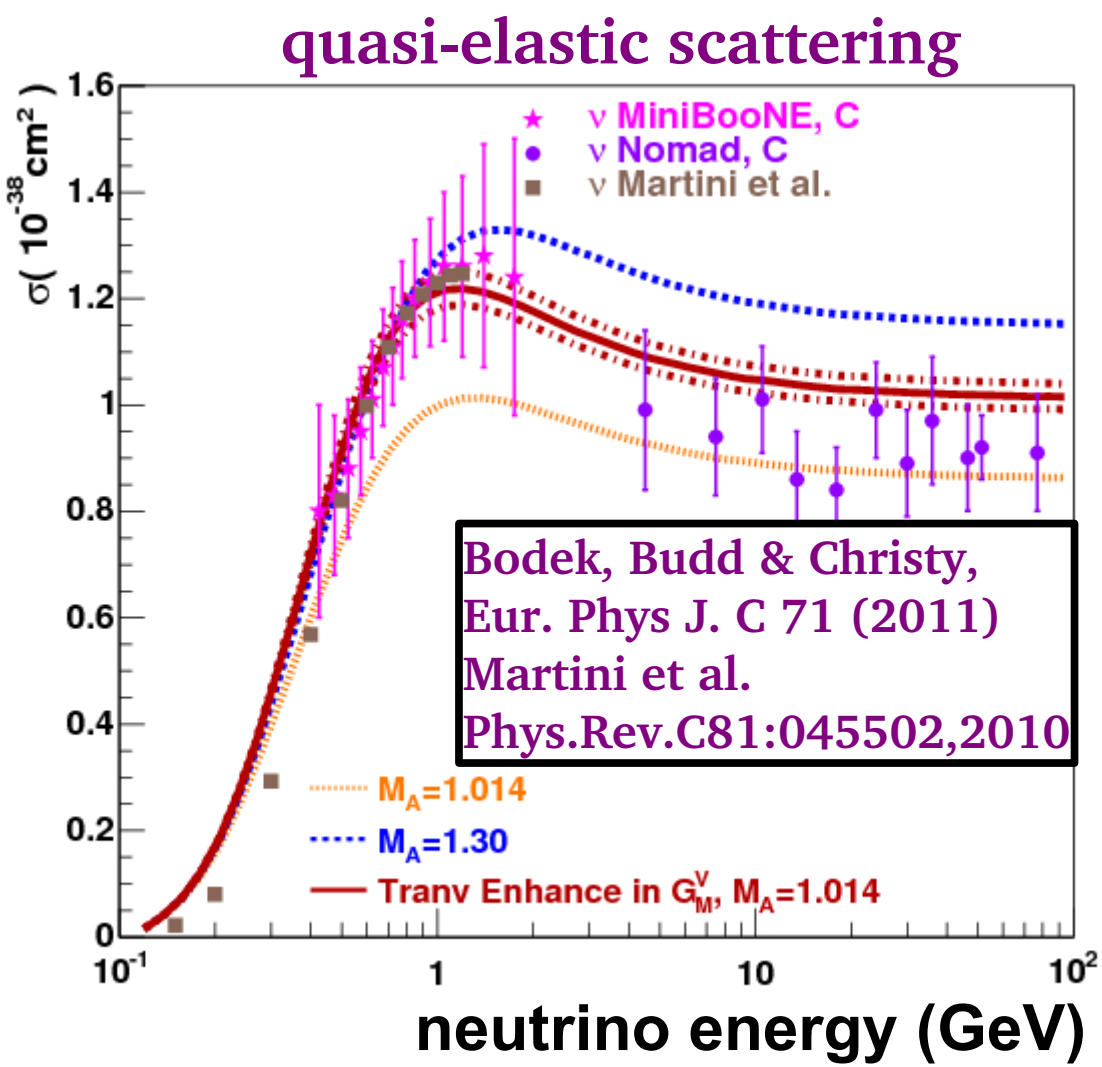


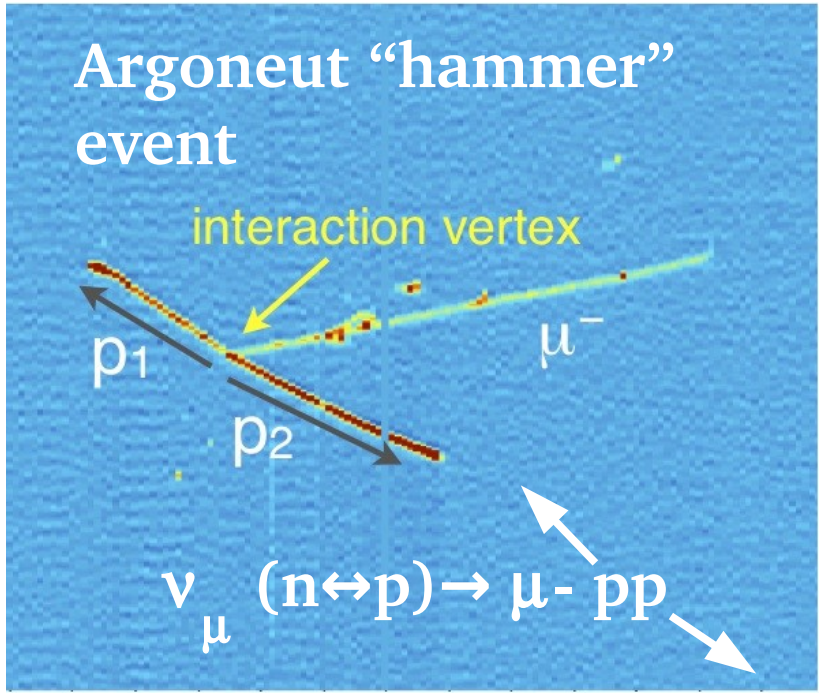
"meson exchange currents" a.k.a "2p2h"

Also:
Sobczyk et al arXiv1202.4197
Amaro et al arXiv 1104.5446
Martini et al 1202.4745
Mosel et al arXiv 1402.0297

In search of a standard candle

Cons: initial nuclear state, multi-body dynamics matter





No pions!
Looks like QEL if you can't see the protons.

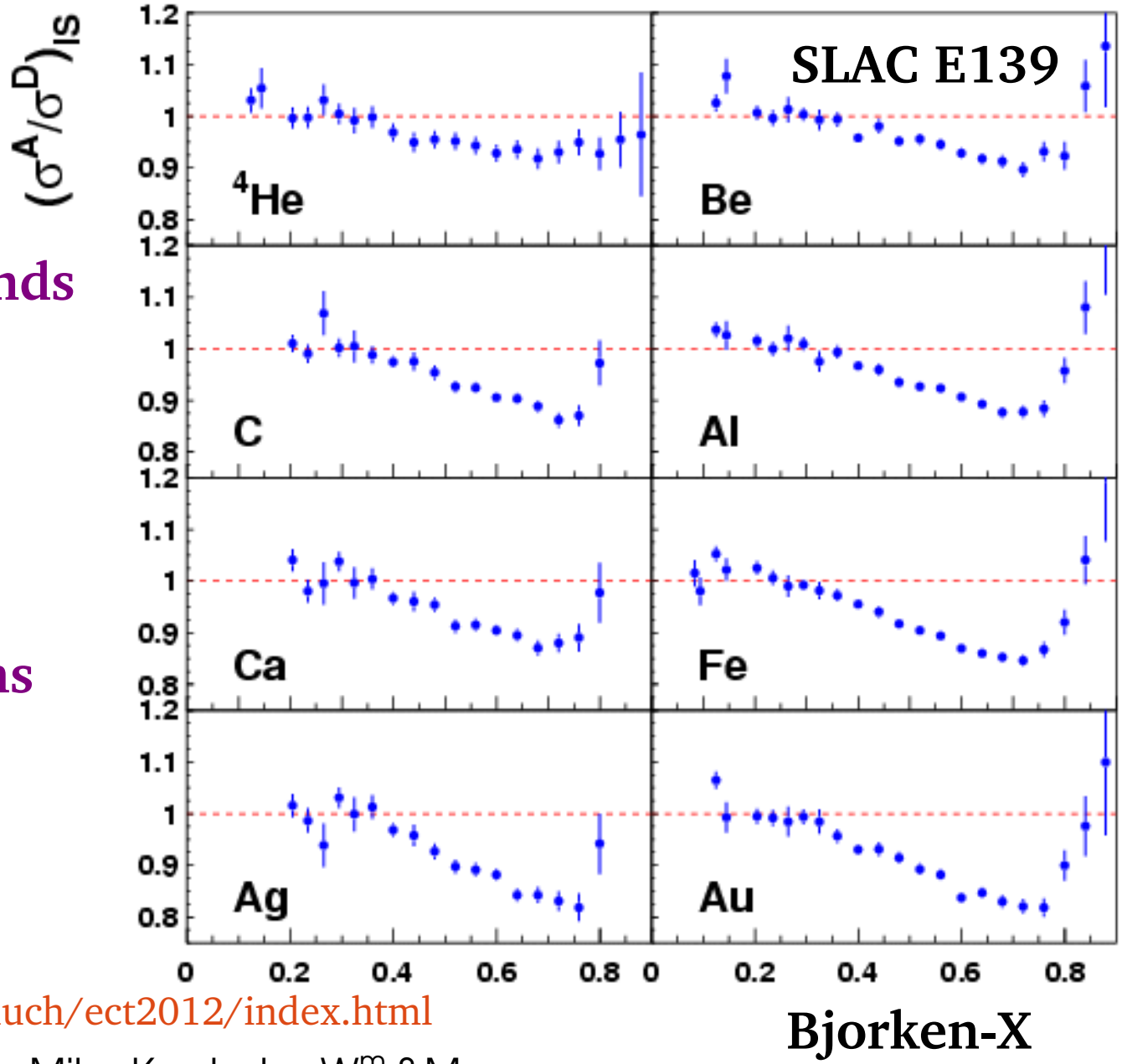
An old mystery

"EMC Effect"

x dependence of eA DIS cross-section depends on A → why?

Some evidence that νA has different behavior

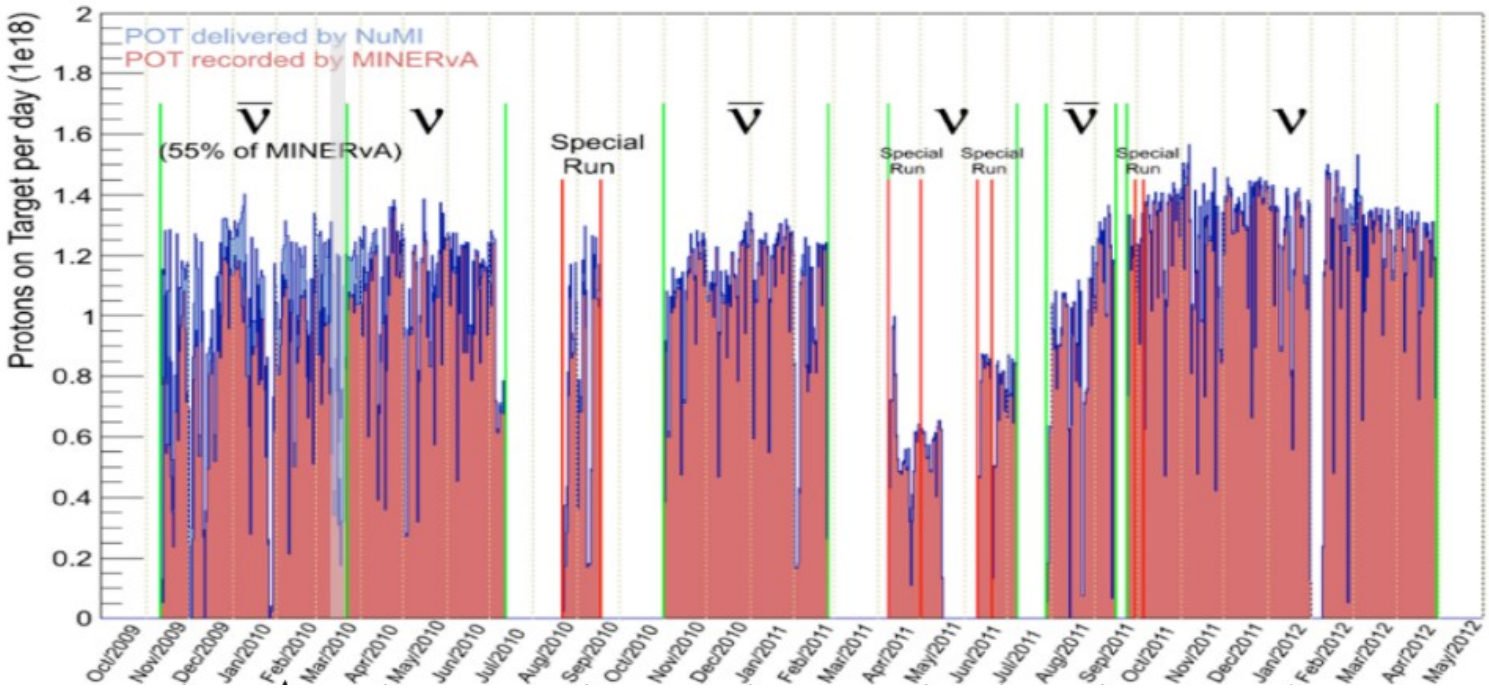
Short range correlations / multi-body dynamics ↔ EMC ?



Nice review talk
D. Gaskell ECT*, Trento 2012
http://www.physics.sc.edu/~strauch/ect2012/index.html

The MINERvA Experiment

NuMI Low Energy Exposure



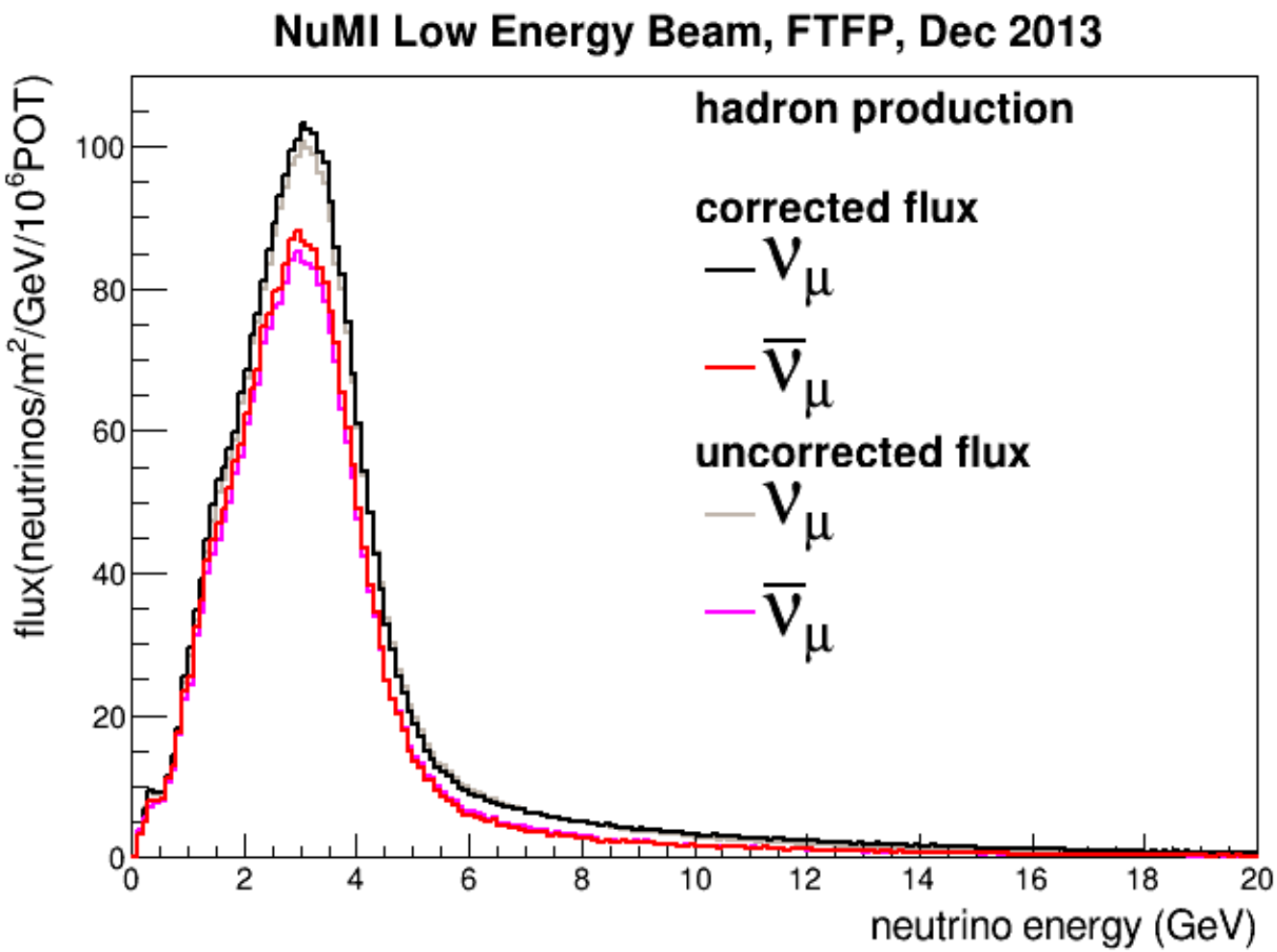
<u>Since 3/22/10</u>

ν_μ LE
3.98e20 POT

$\bar{\nu}_\mu$ LE
1.70e20 POT

special runs
4.94e19

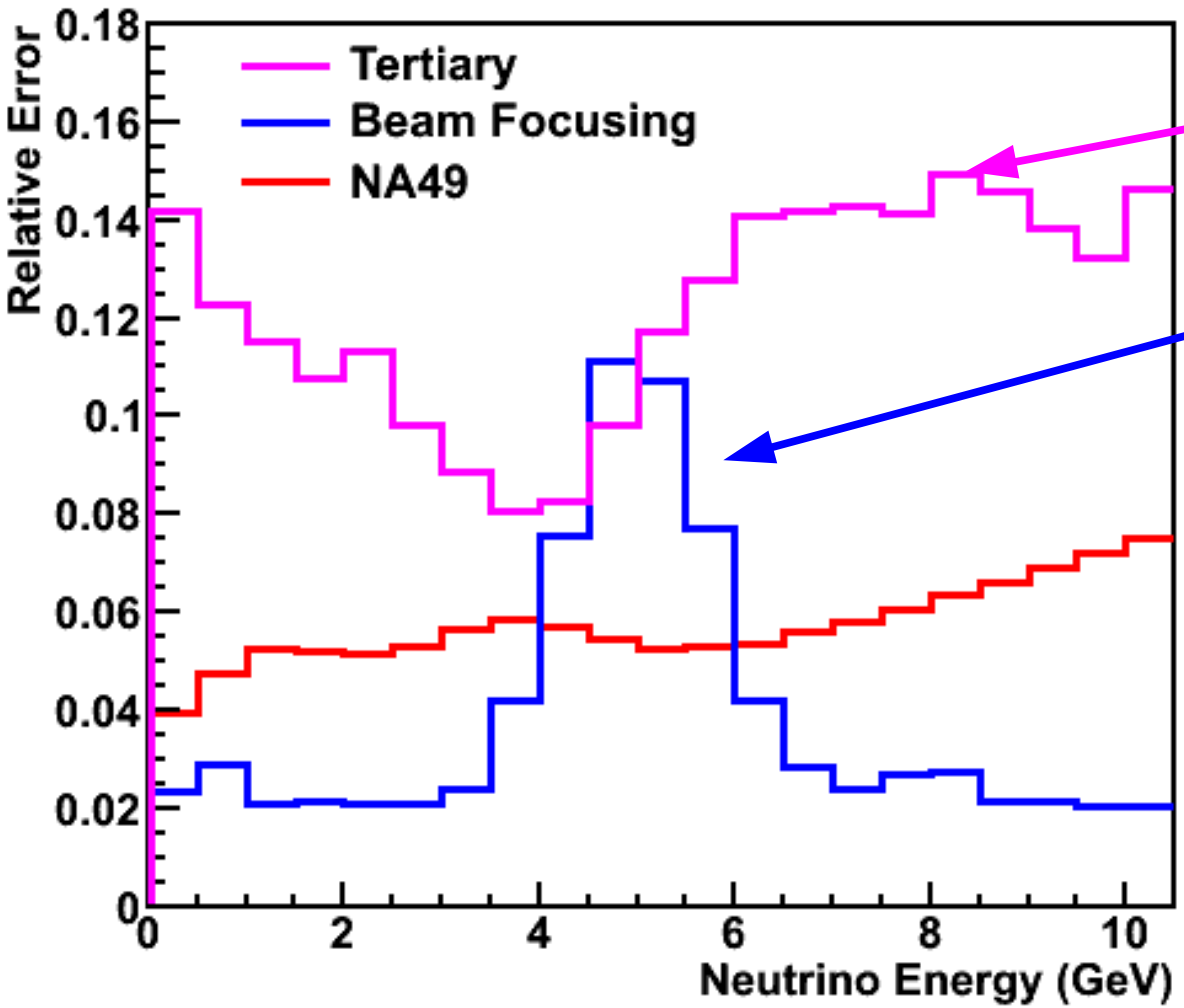
The Flux



GEANT4 based simulation of the NuMI beamline.

G4 9.4.p02
FTFP physics list

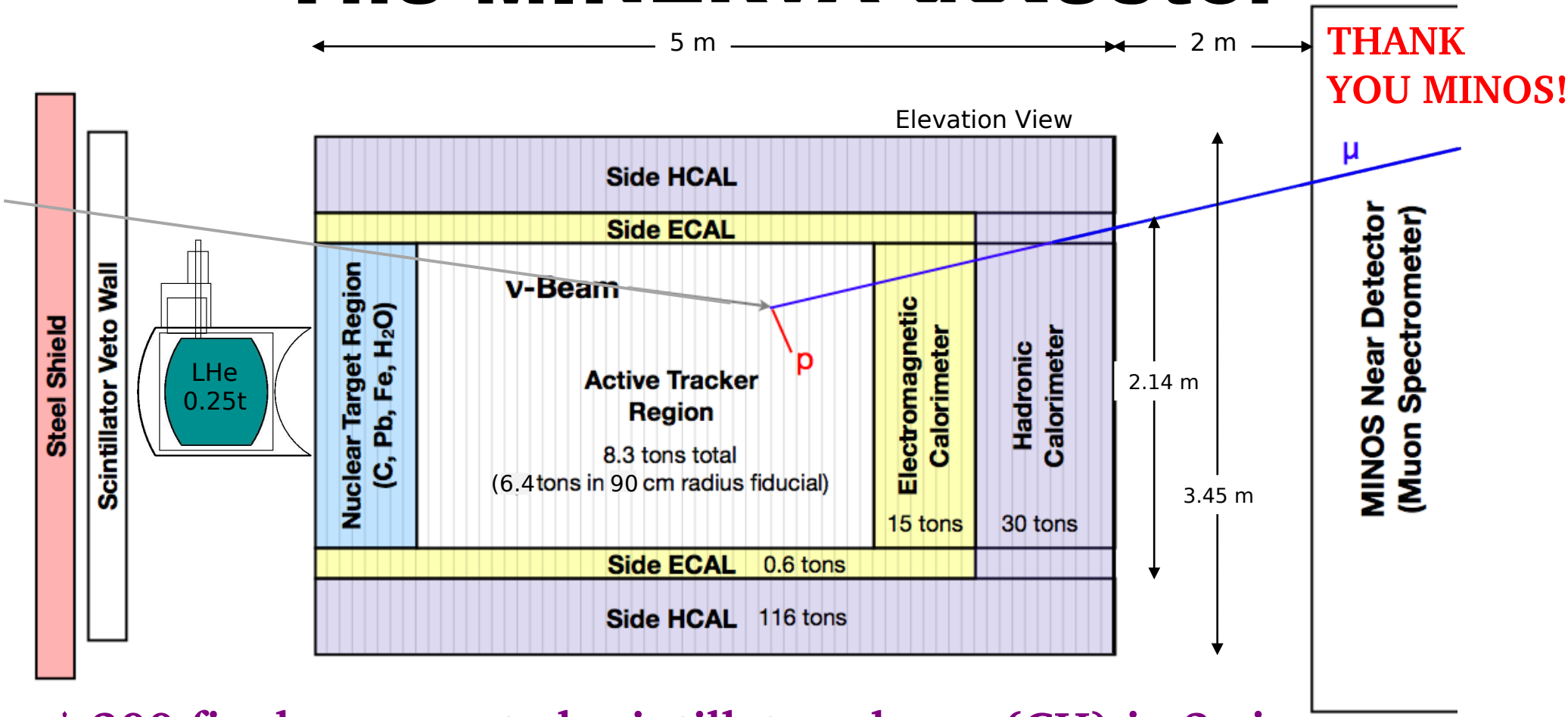
Flux Uncertainties



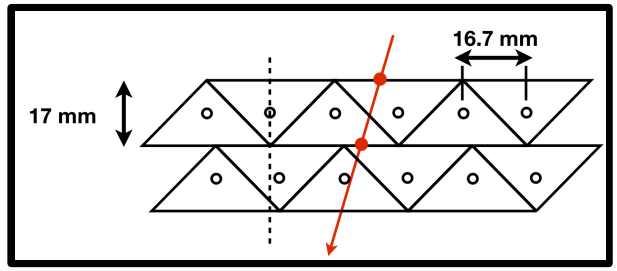
"Tertiary"
= non-NA49
model spread

Z. Pavlovic,
PhD Thesis,
Texas (2008)

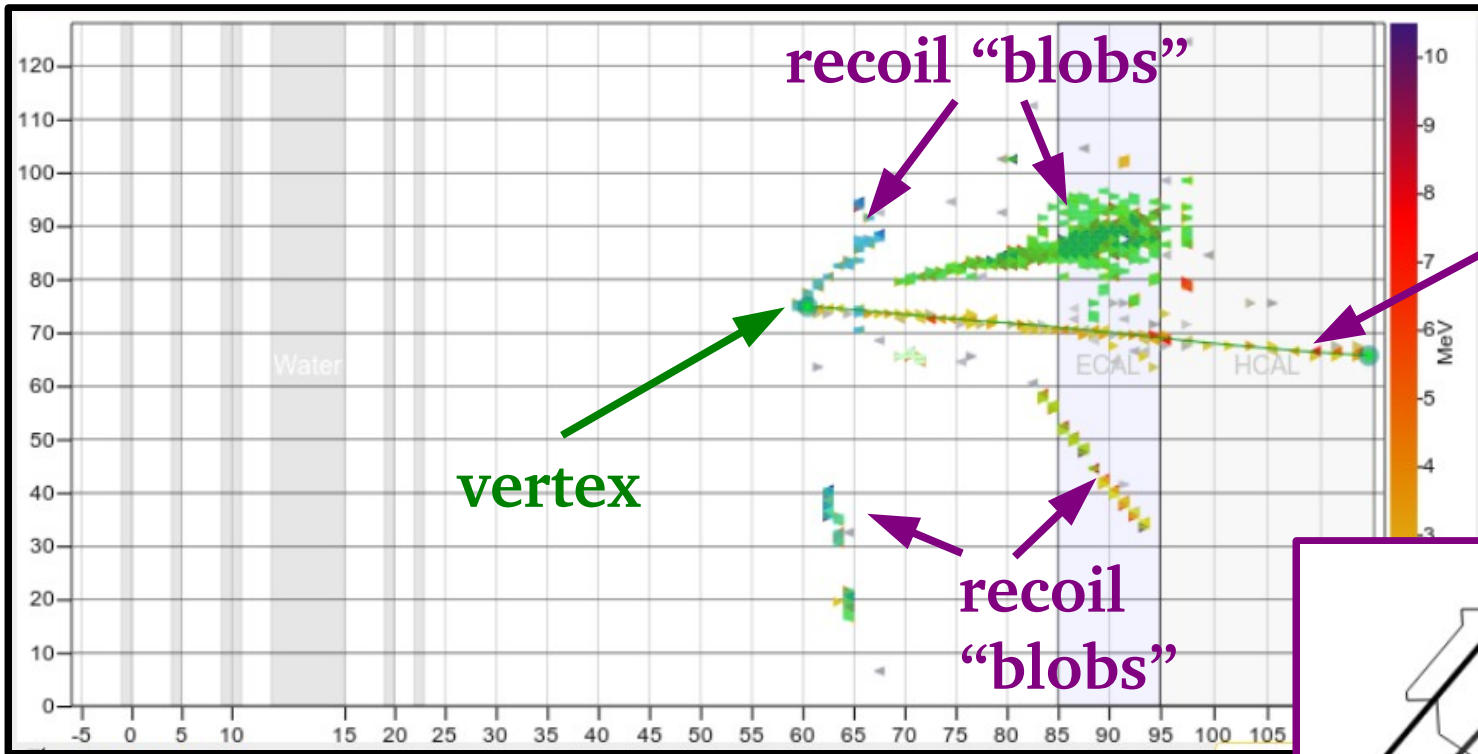
The MINERvA detector

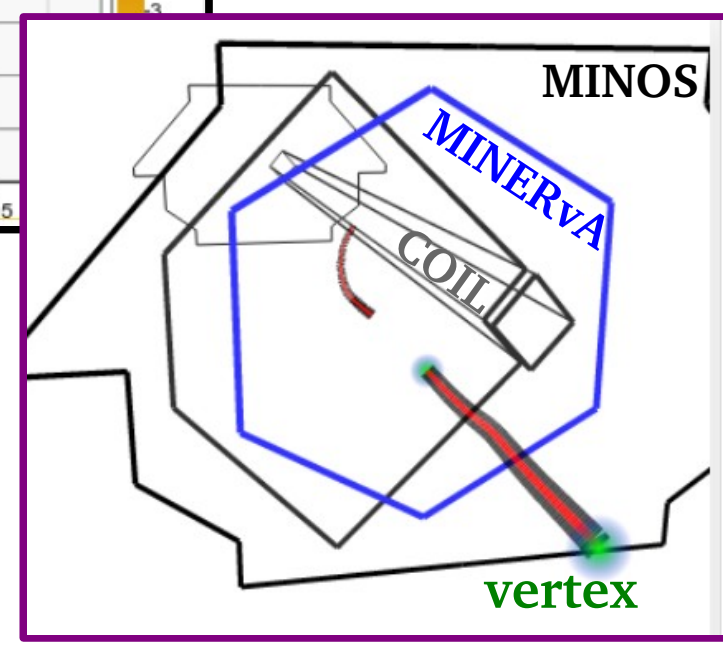


* 200 finely segmented scintillator planes (CH) in 3 views
* Calib: FEB bench tests, source mapper, LI, rock μ, Michel electrons, test-beam
* 4% channel to channel variations after calibration



Event reconstruction

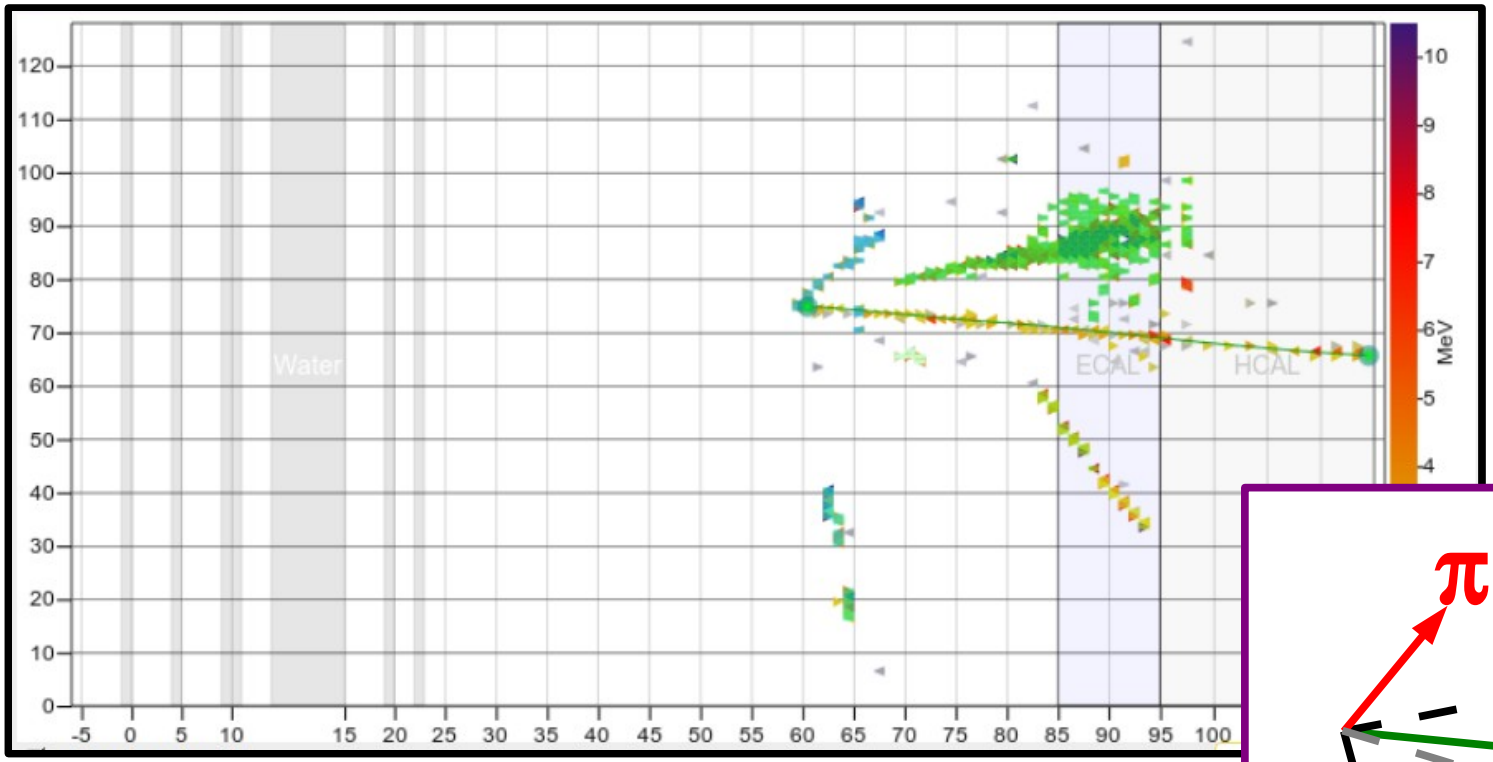




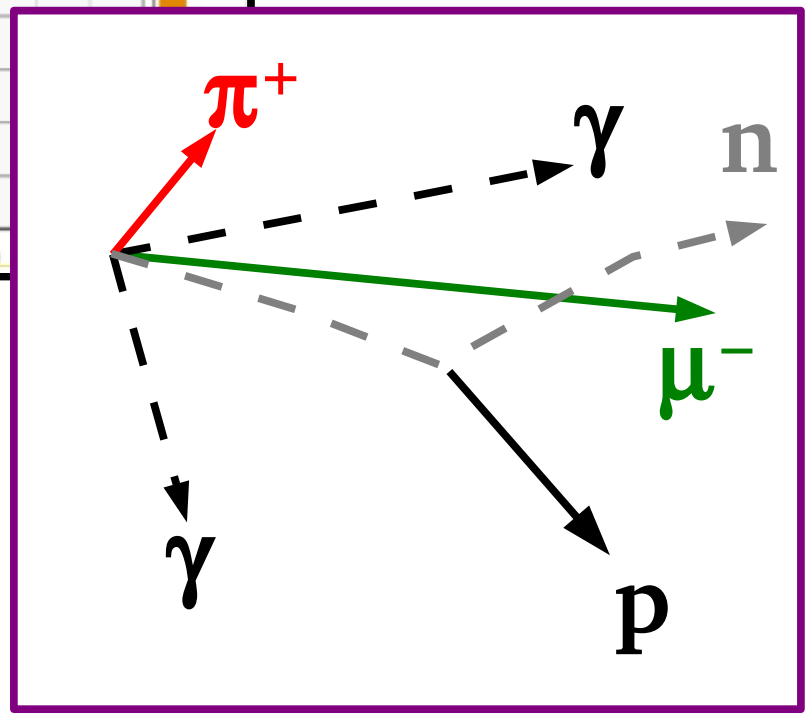
<u>Reconstructed objects</u>

MINOS tracks, other tracks, vertices, endpoints, blobs

Event reconstruction



My guess, just for fun



<u>Most important quantities:</u>

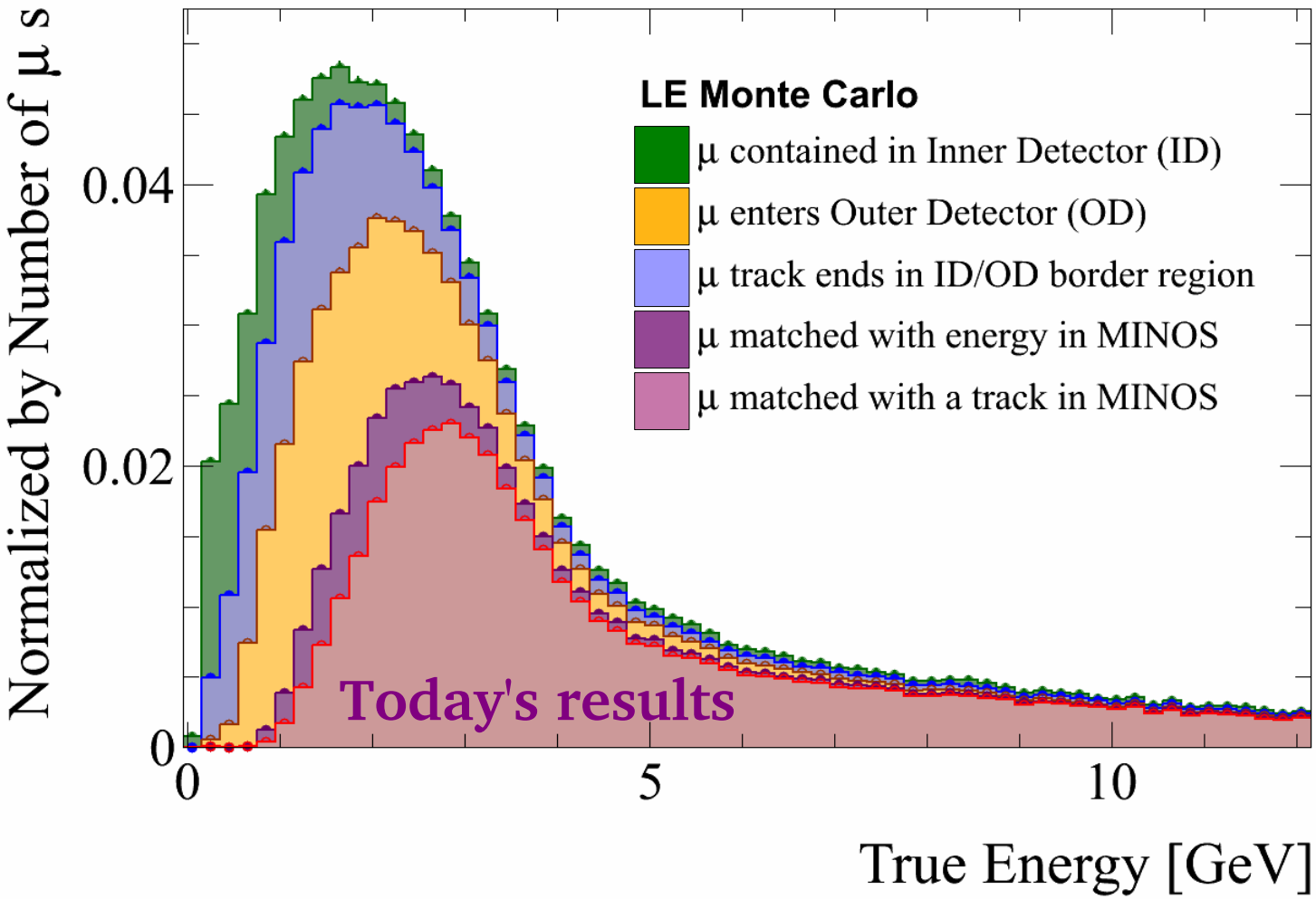
muon energy and angle

recoil energy

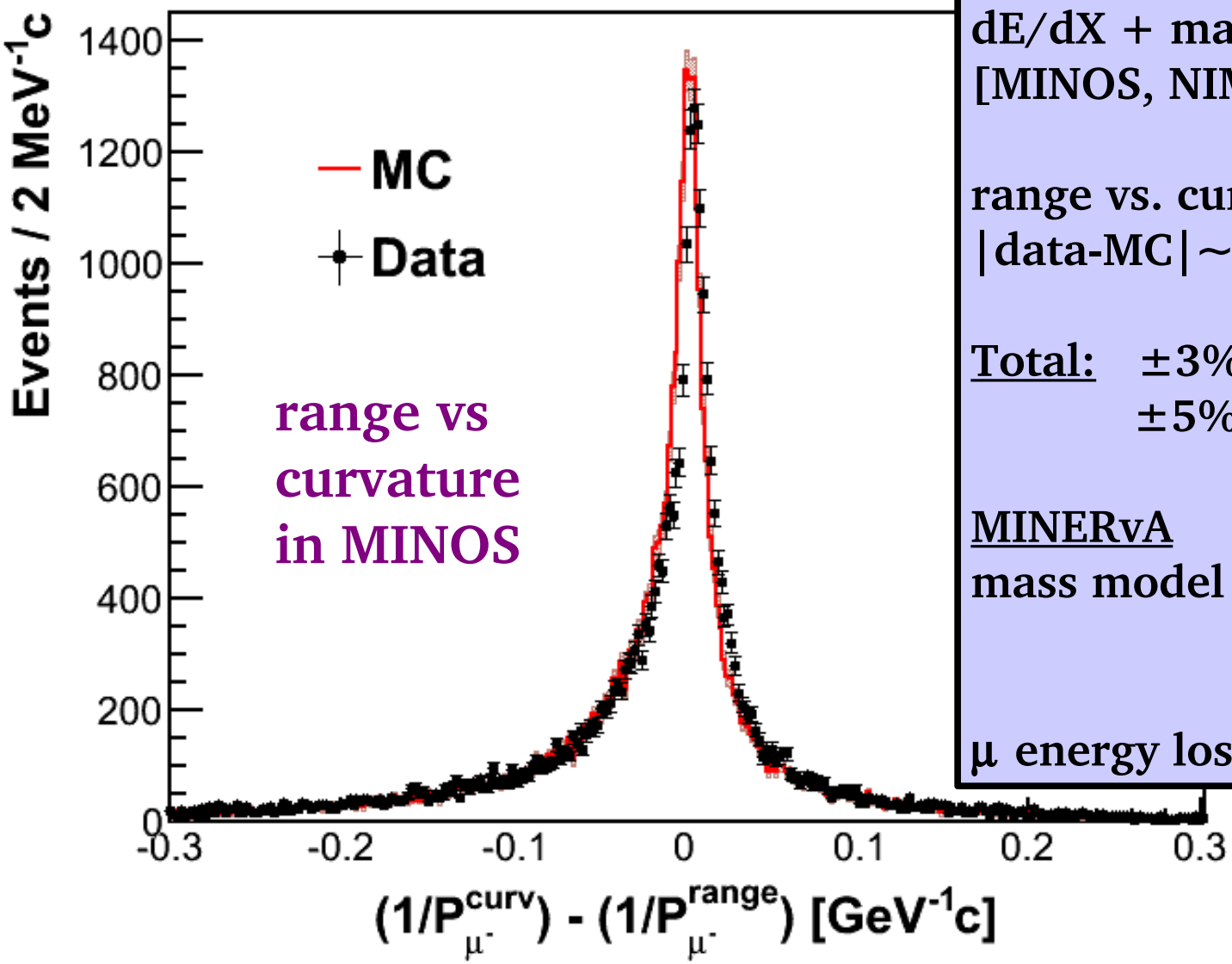
secondary tracks/blobs

Where do the muons go?

Good acceptance into MINOS for $\theta_\mu < 20°$



Muon energy uncertainty



MINOS
dE/dX + mass model = 2%
[MINOS, NIM A 596, 190 (2008)]

range vs. curvature
|data-MC|~25 MeV

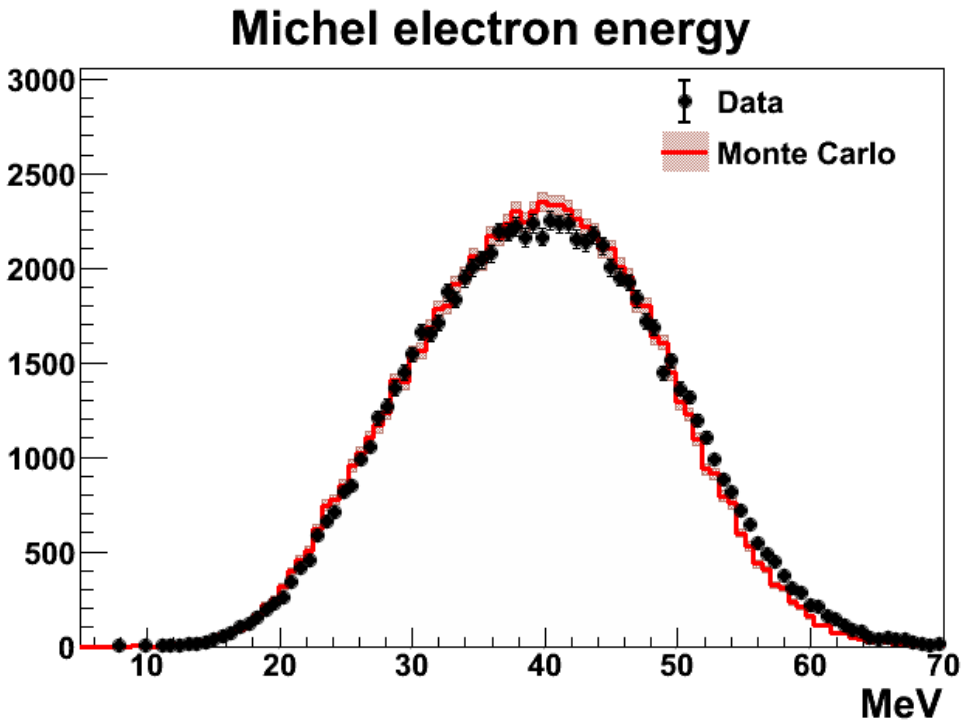
Total: ±3% p> 1.5 GeV
±5% P<1.5 GeV

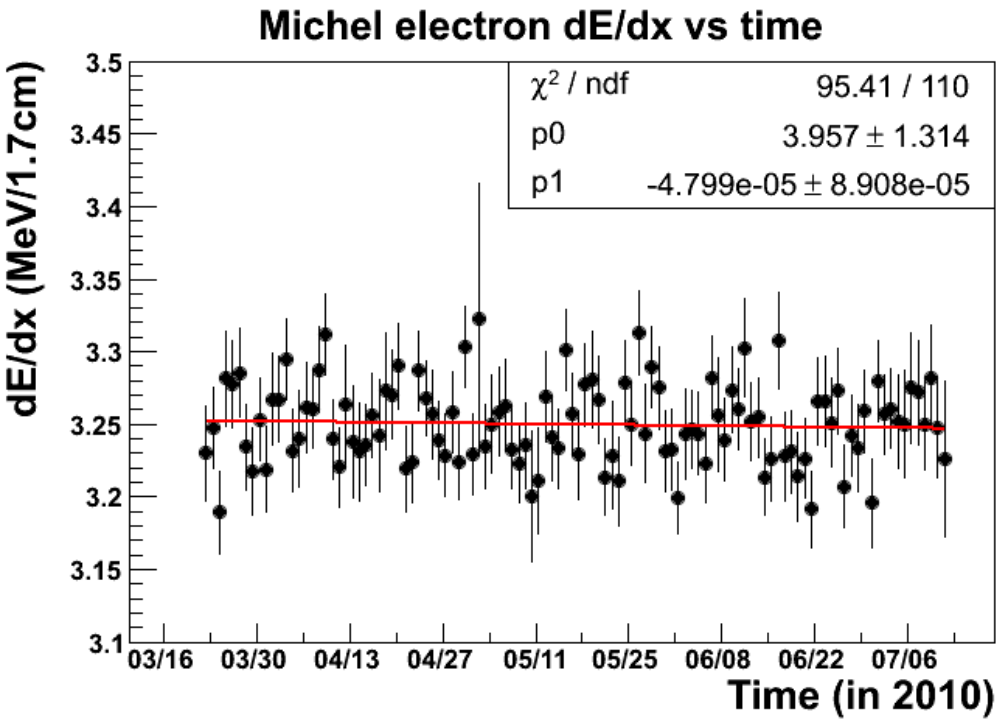
MINERvA
mass model = 11 MeV tracker
= 17 MeV Nucl. Tgts.

μ energy loss = 30 MeV

Michel electrons

Michel = $\mu \rightarrow e\,\nu\bar{\nu}$



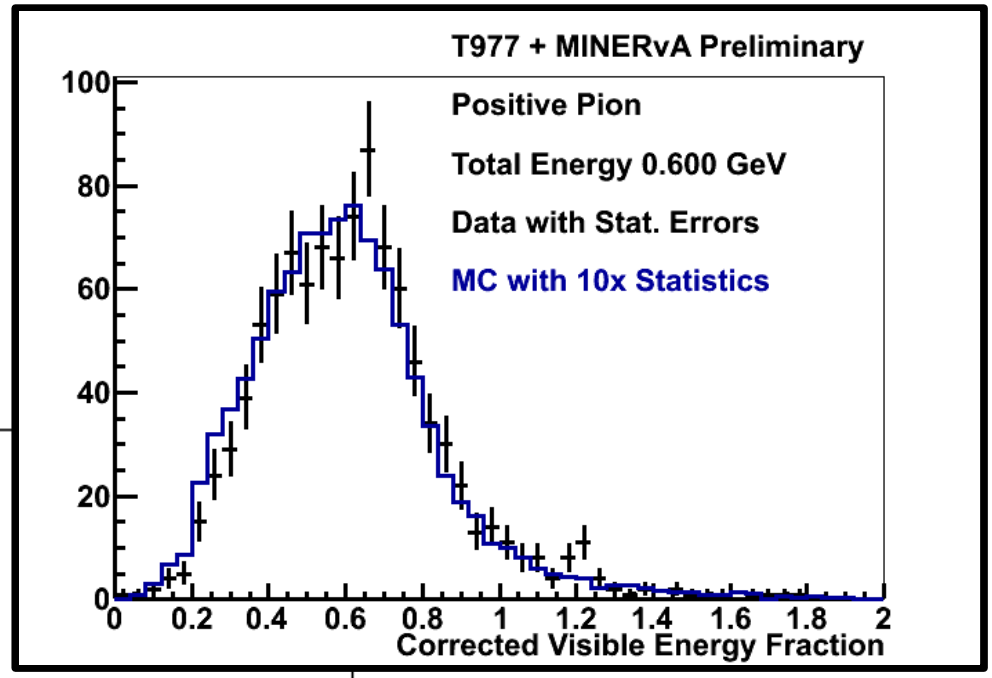


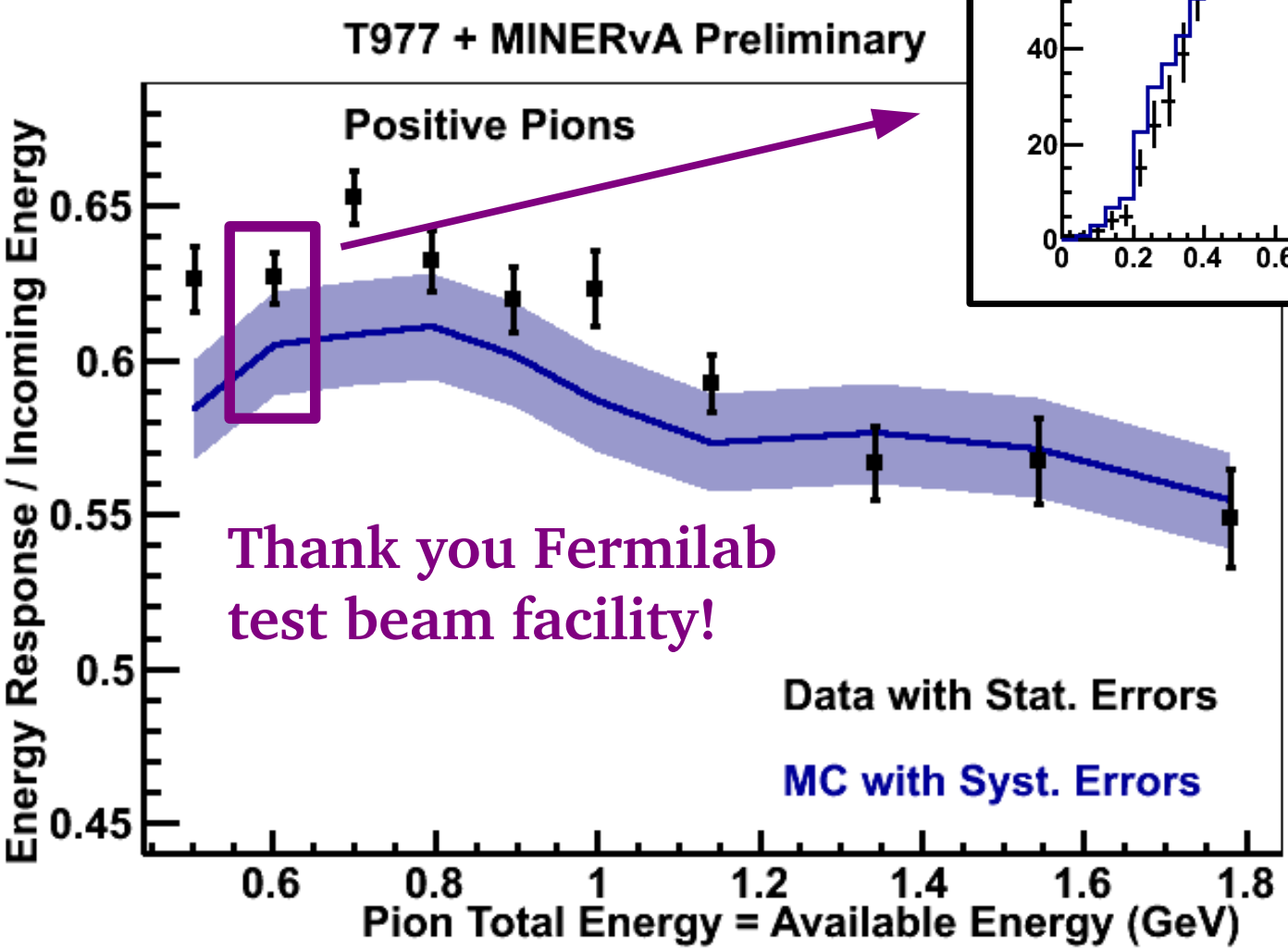
Cross-check on μ derived energy scale

EM response uncertainty = 3%

A nice stable detector!

FNAL-T977 Test Beam



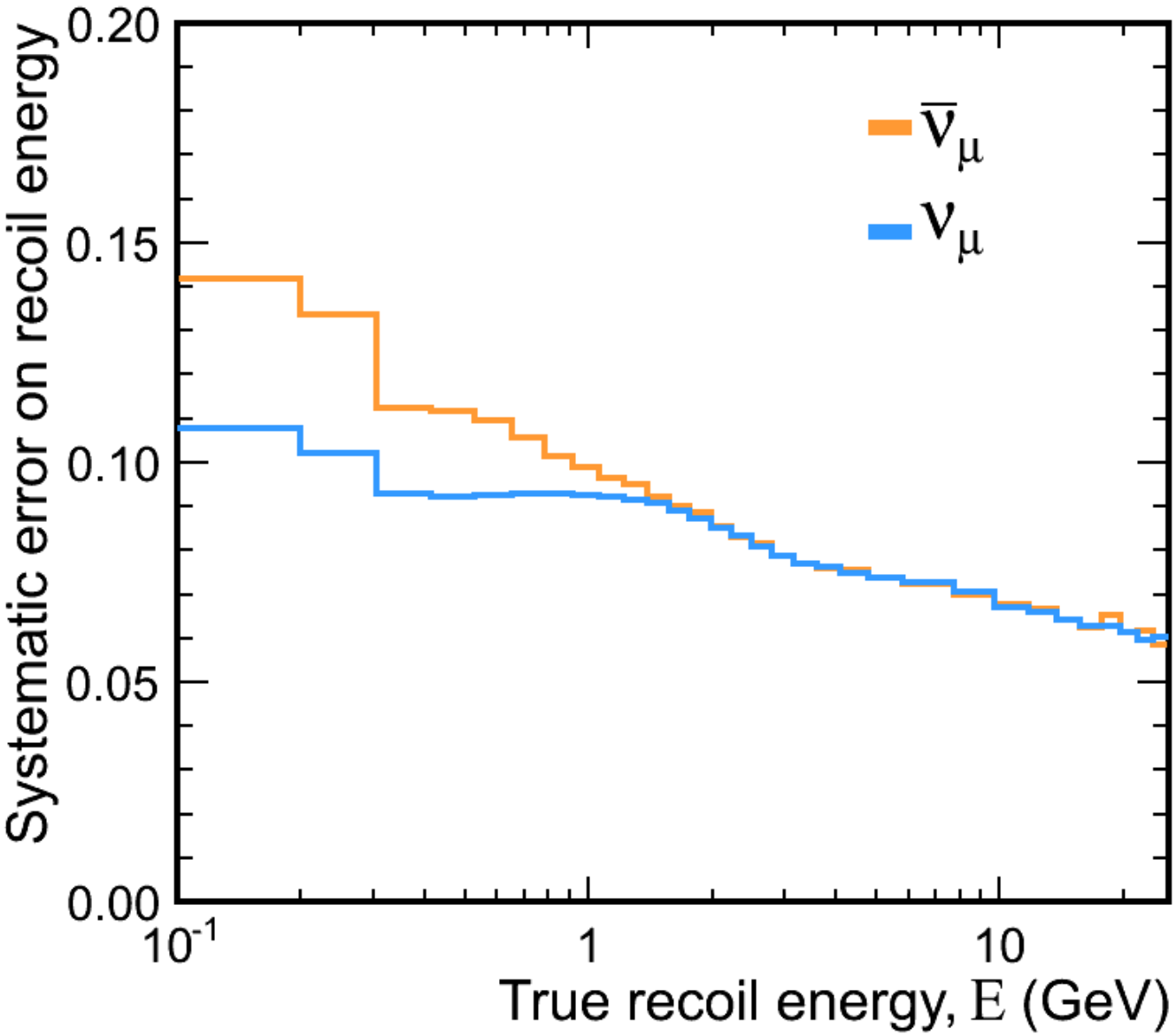


Thank you Fermilab test beam facility!

π+ agreement ~ 5%
π− a bit better
p a bit worse (10%)

Resolution well modeled

shower energy uncertainty



Convolution of single particle uncertainties

π,K = 5%

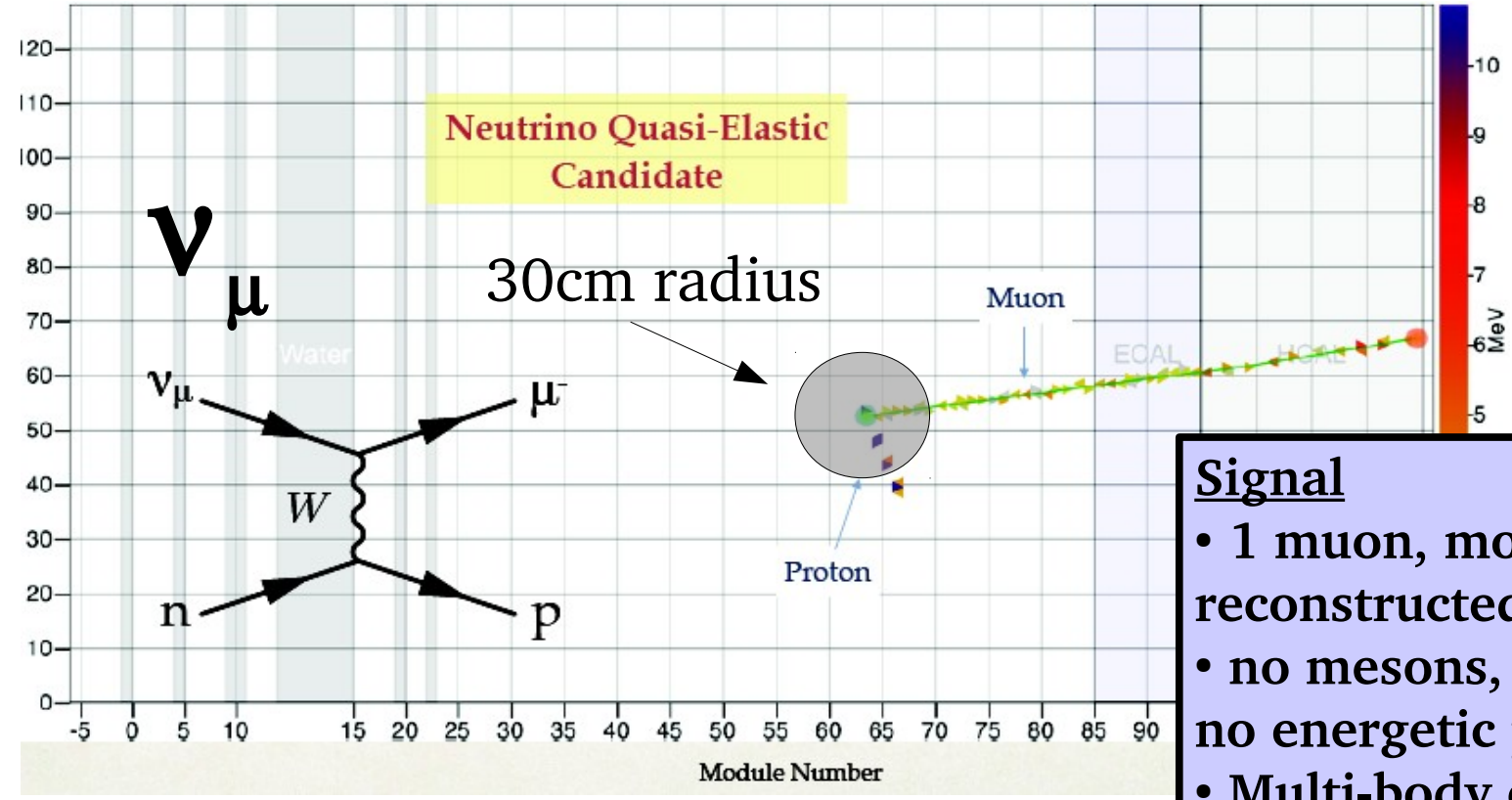
e,γ = 3%

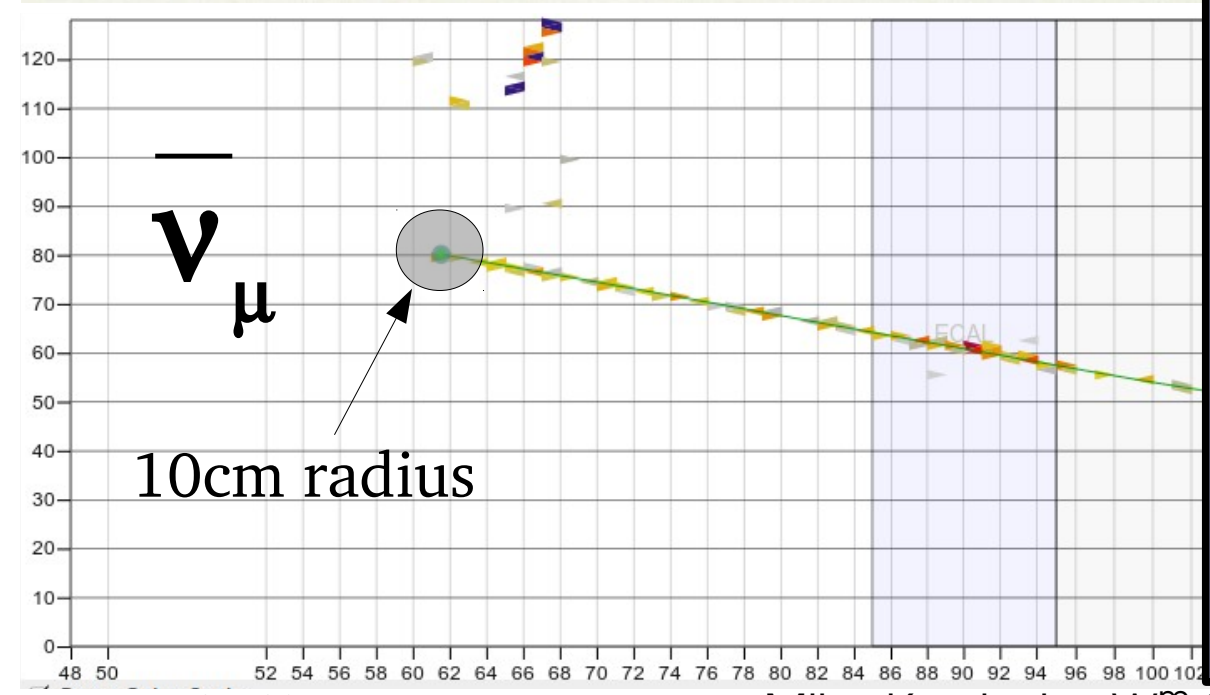
p = 10%

n = 20%

$\bar{\nu}_\mu$ Quasi-elastics

QEL event selection





Signal

- 1 muon, momentum and charge reconstructed in MINOS
- no mesons, no heavy baryons, no energetic photons
- Multi-body effects may result in multiple nucleons – allow those

Background

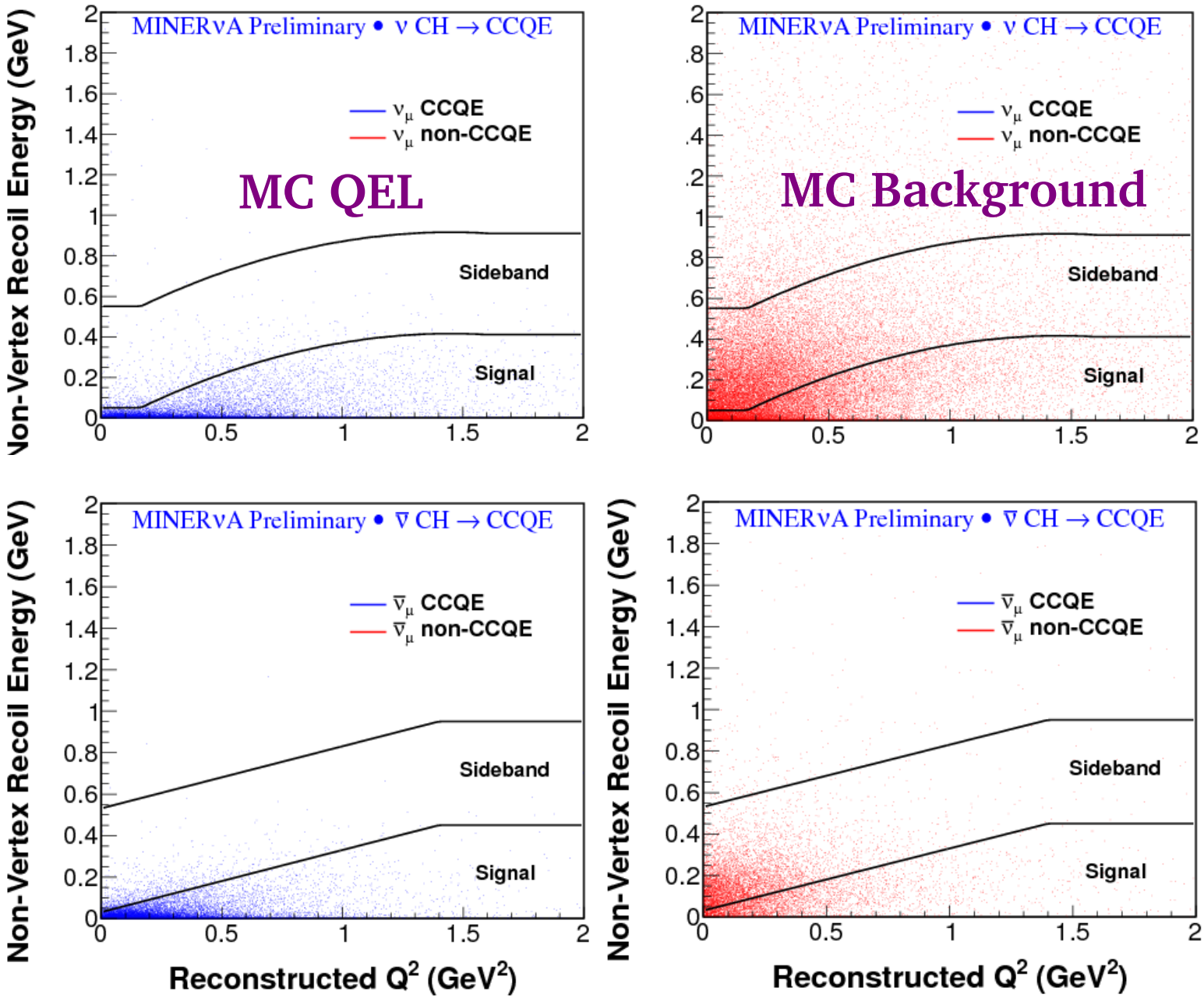
- Pions deposit energy away from the vertex → use calorimetry
- "Black out" region around the vertex
  - poorly modeled in MC
  - sensitive to multi-nucleon effects

Recoil vs. Q^2

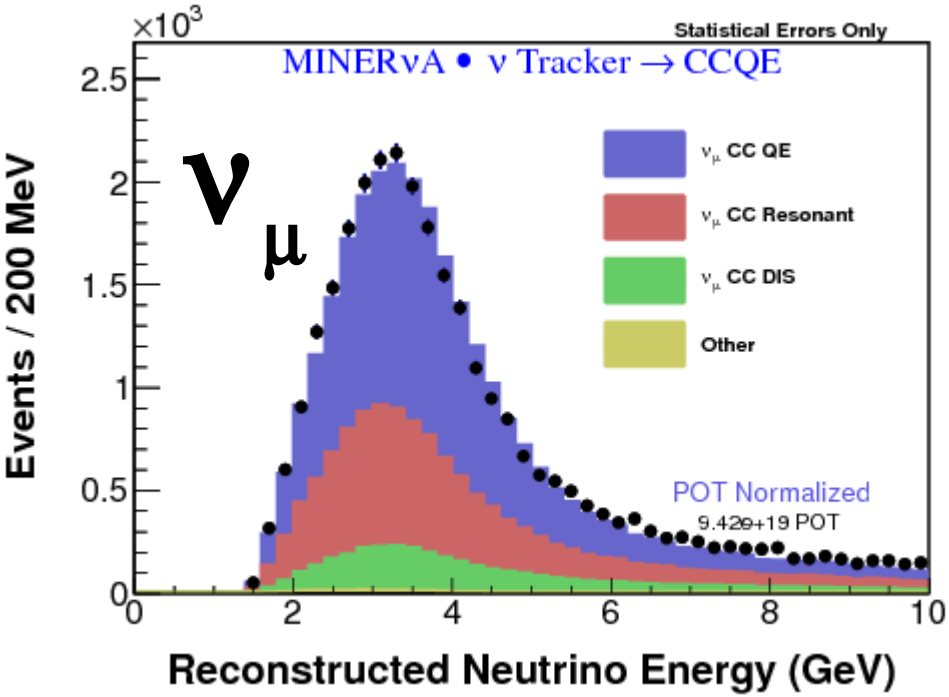
Expect $\nu = Q^2/2M_N$ for $x=1$

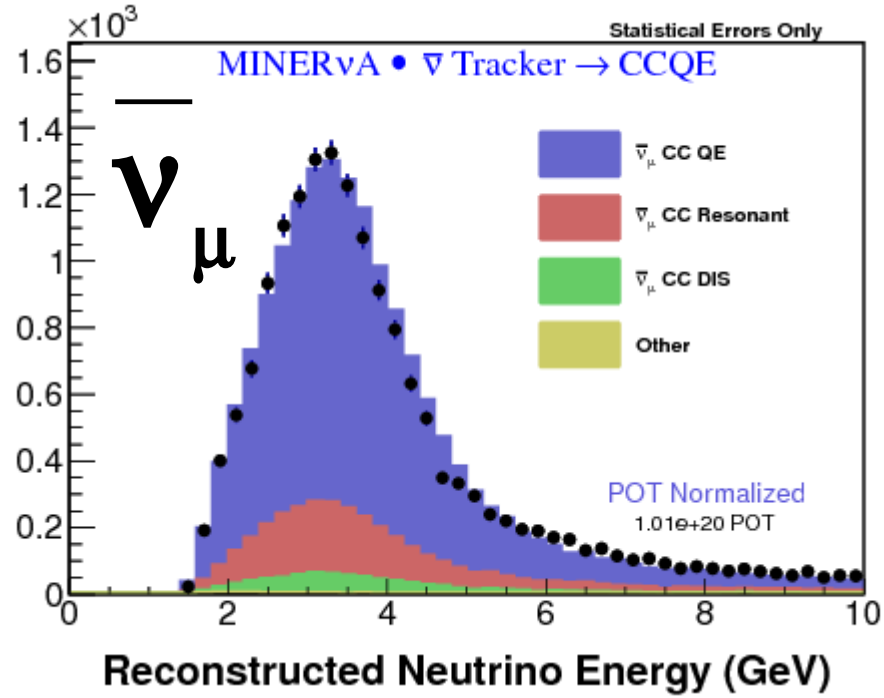
ν_μ

$\bar{\nu}_\mu$



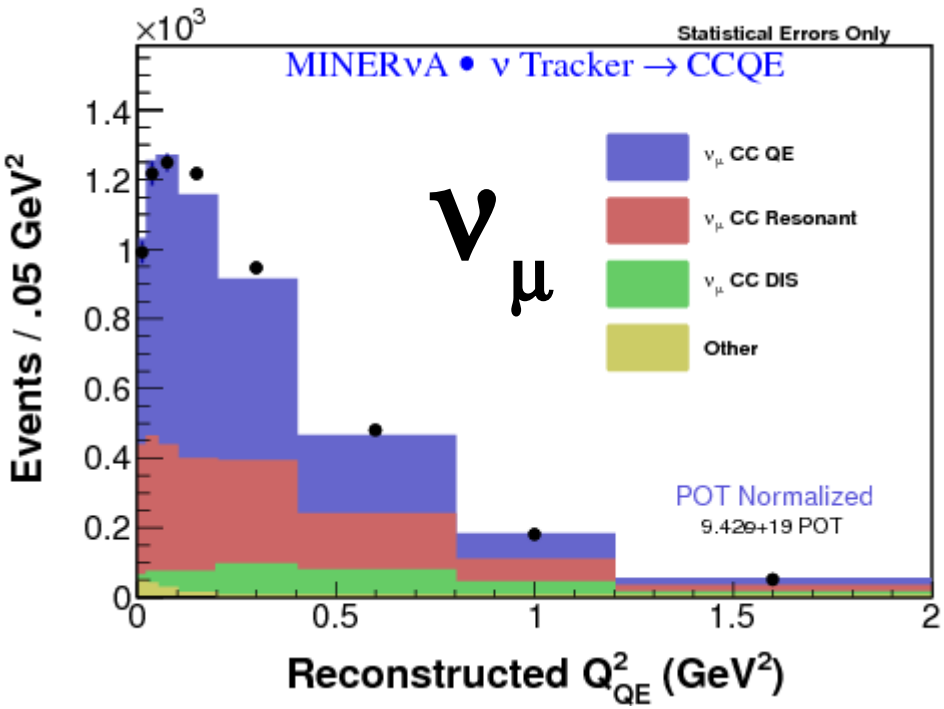
Selected samples

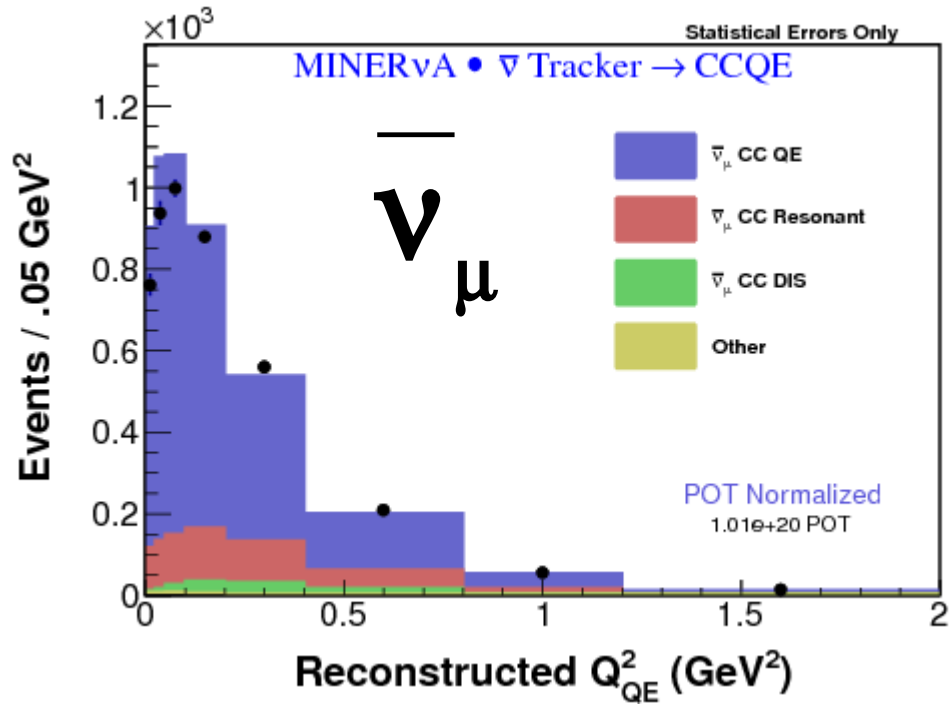




$$E_\nu = \frac{m_\mu^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

Selected Samples



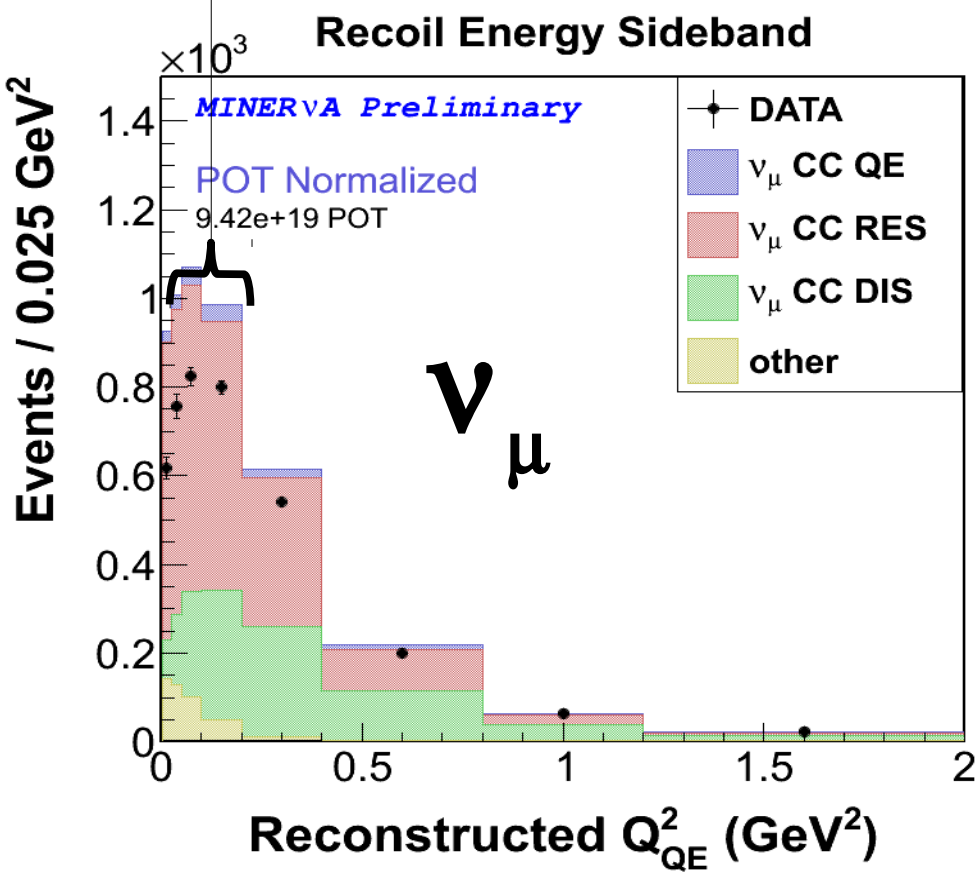


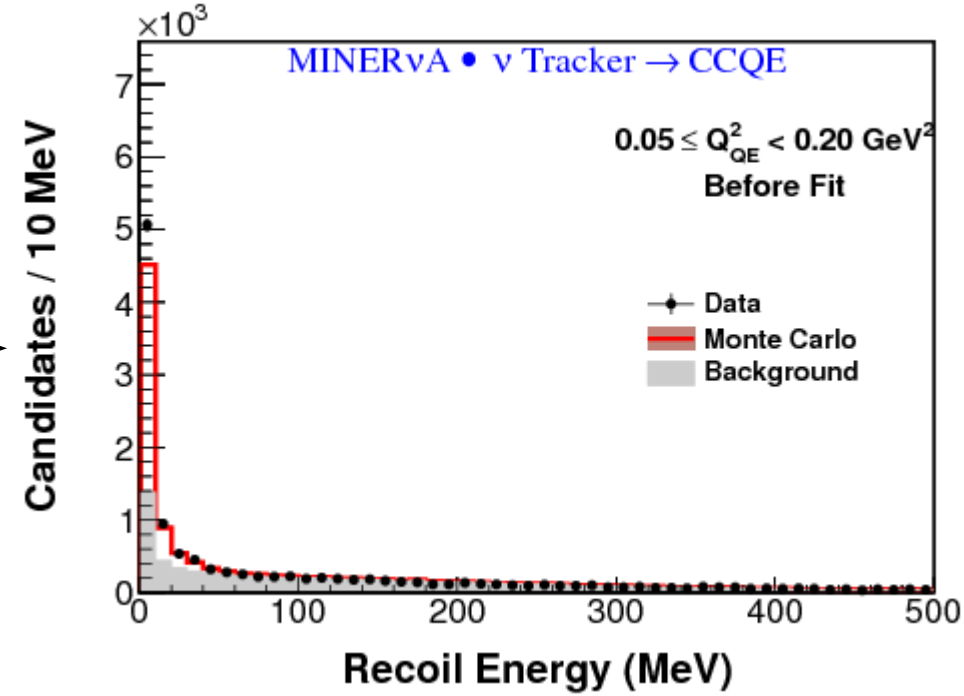
$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

29,620 events
<u>Efficiency:</u> 47%
<u>Purity:</u> 49%

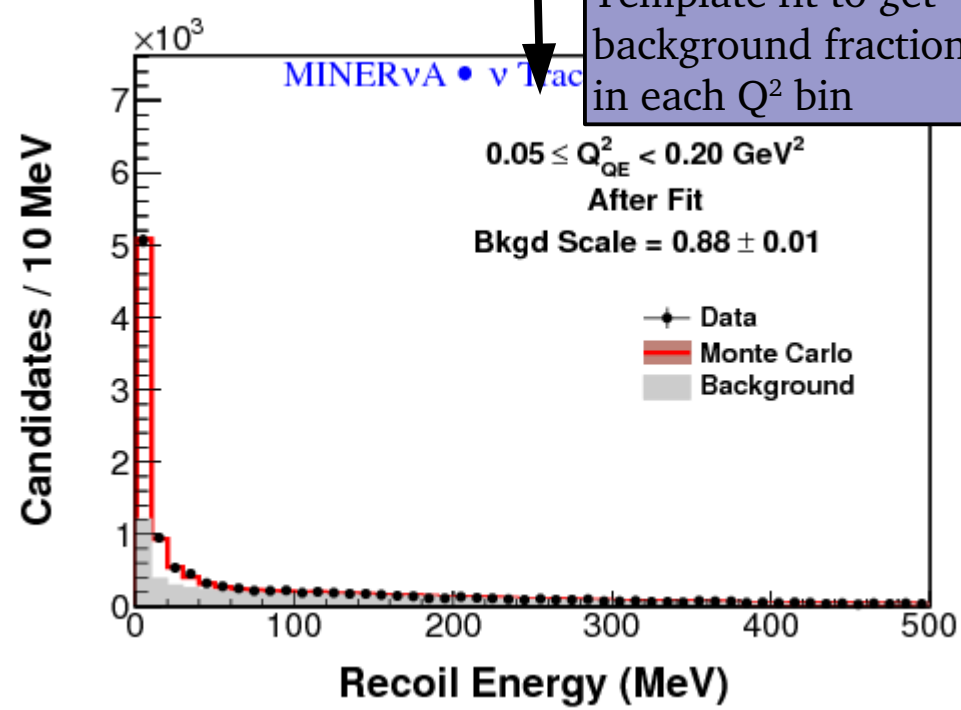
16,467 events
<u>Efficiency:</u> 54%
<u>Purity:</u> 77%

Constraining Background

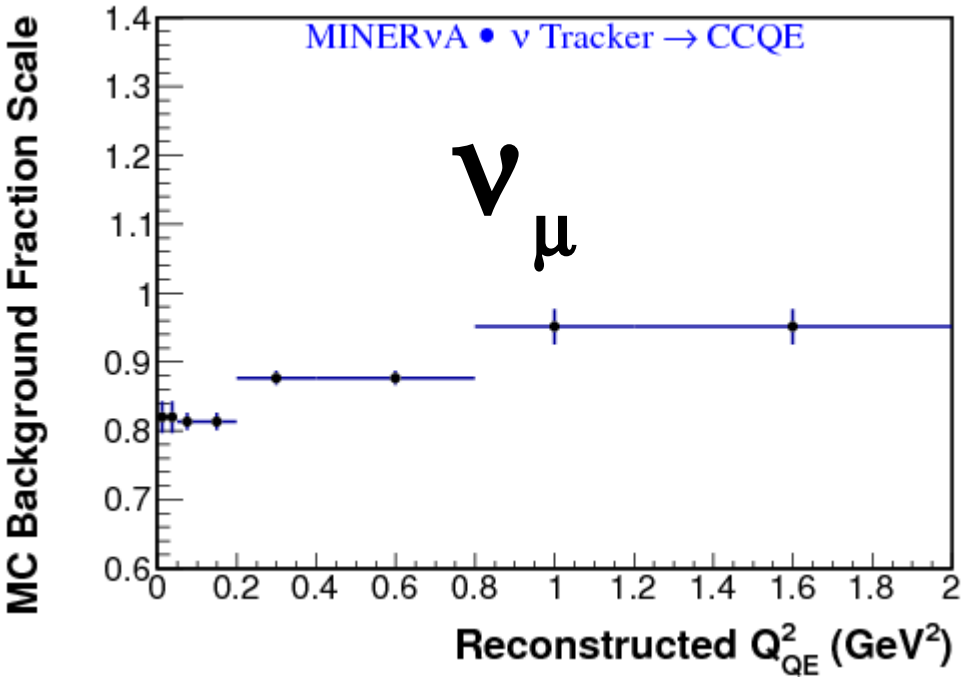


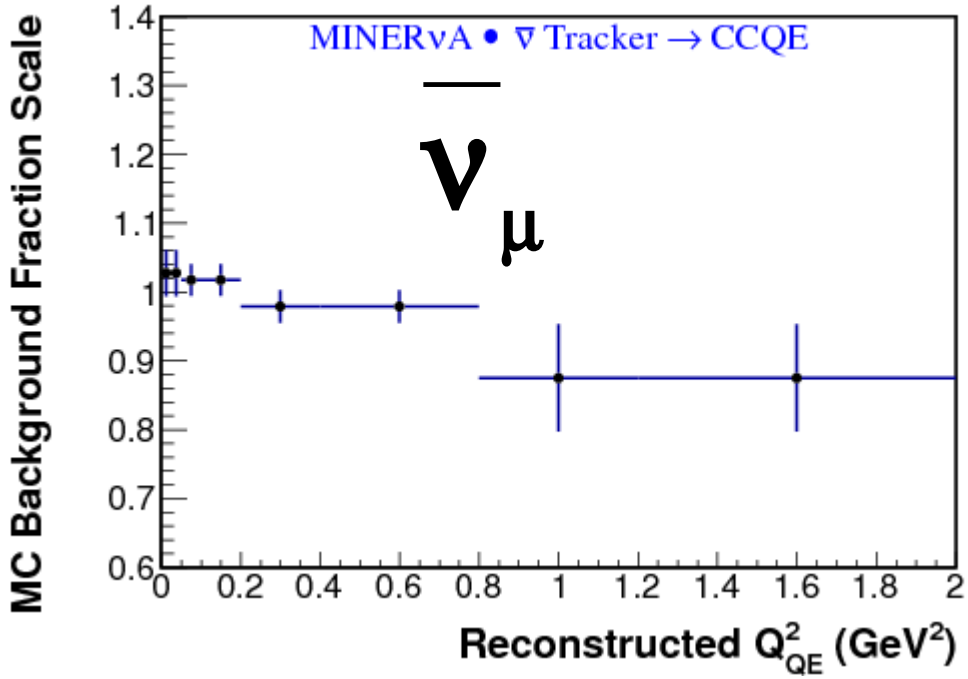


Template fit to get background fraction in each Q^2 bin



Background Scale Factors

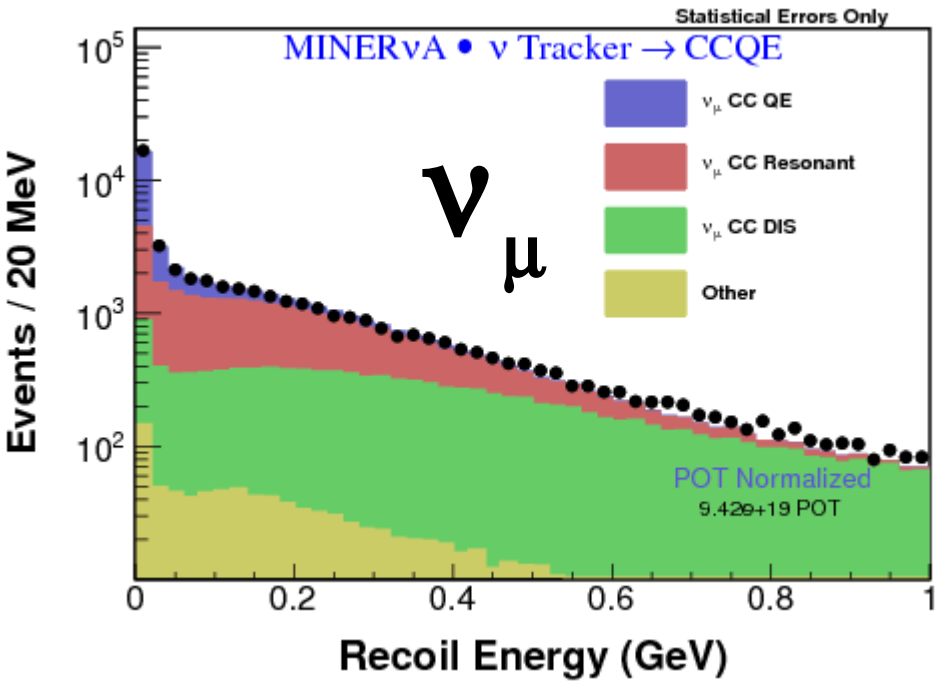


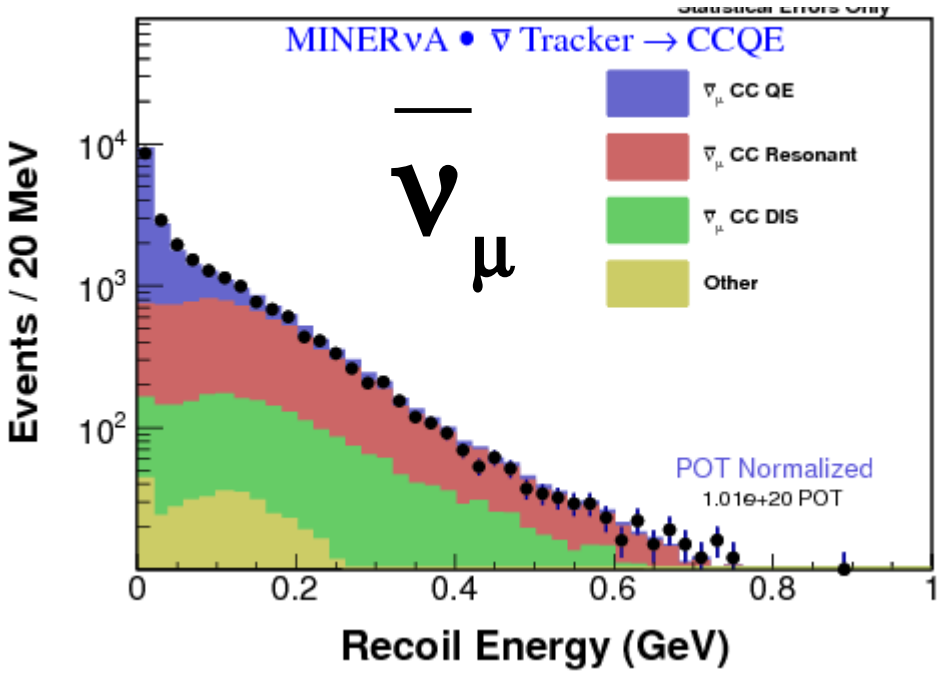


Data indicates MC background for ν_μ needs to be scaled down by 10-20% at low Q^2

More pure anti-neutrino channel needs smaller corrections

Recoil energy after the fit

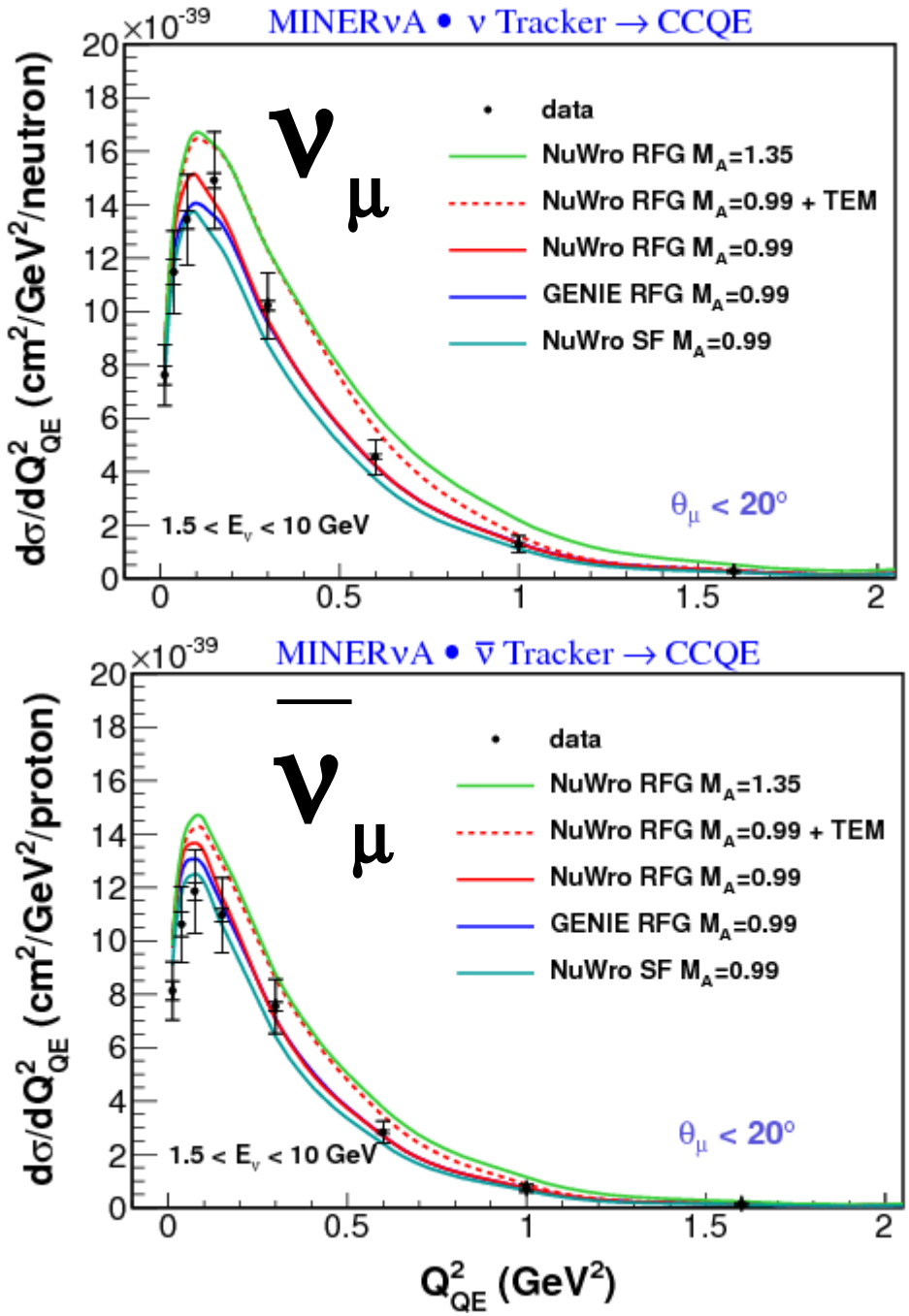




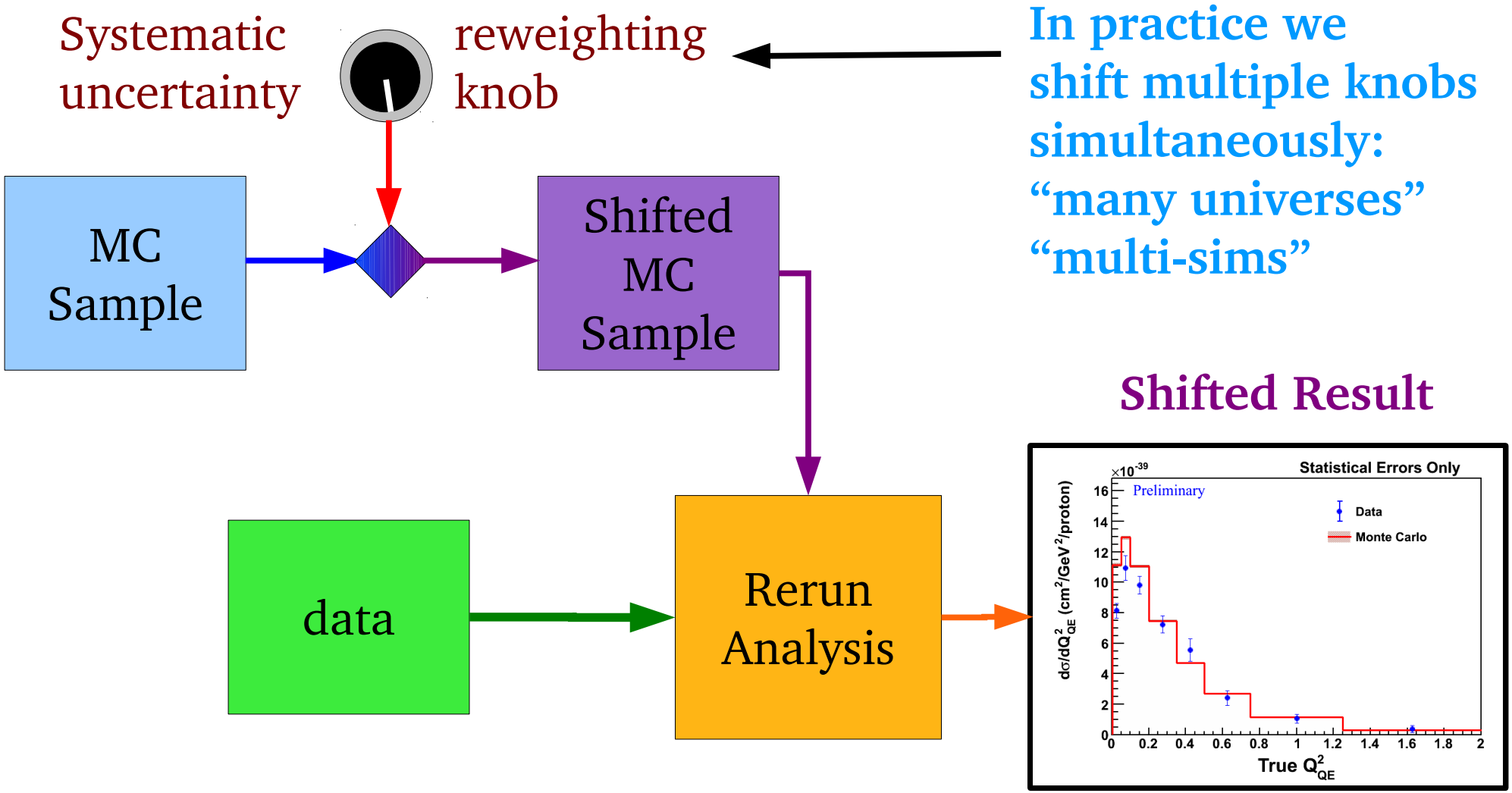
Fits successfully describe the recoil energy distribution over the whole kinematic range

Differential Cross-sections

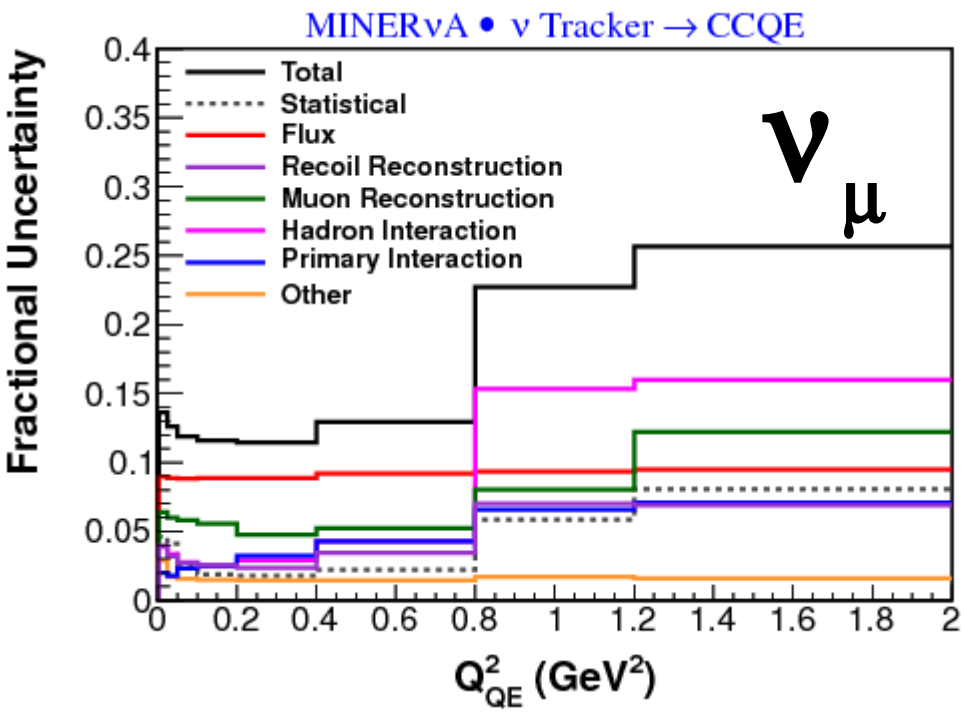
- Background subtraction
- Iterative unfolding to true Q^2 distribution
- Efficiency correction
- Fiducial mass accounting
- Incorporation of the flux

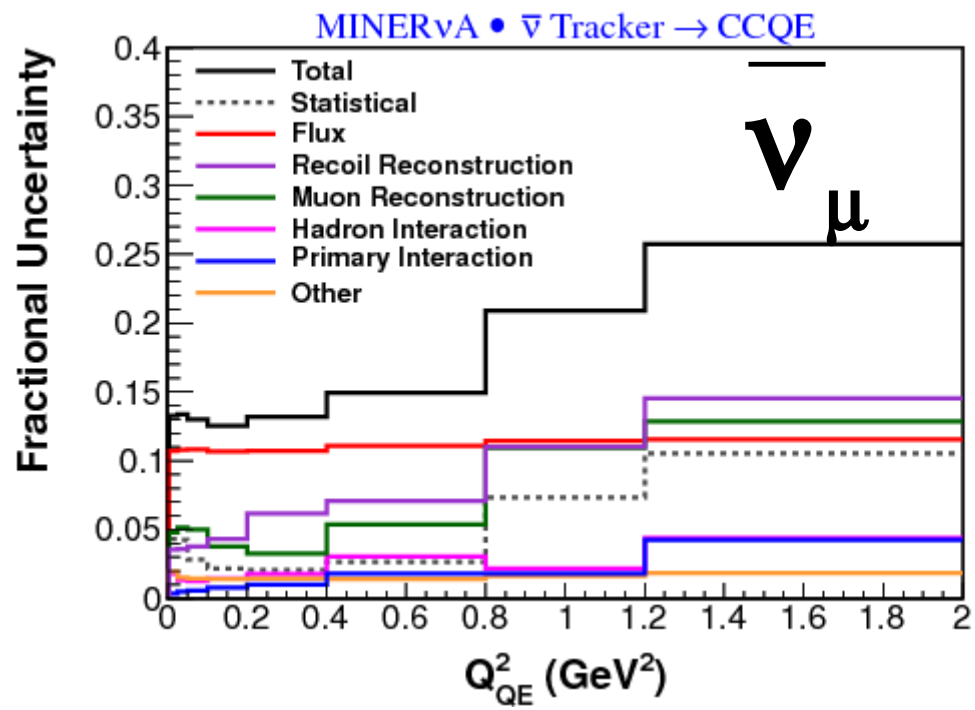


Systematic Uncertainties



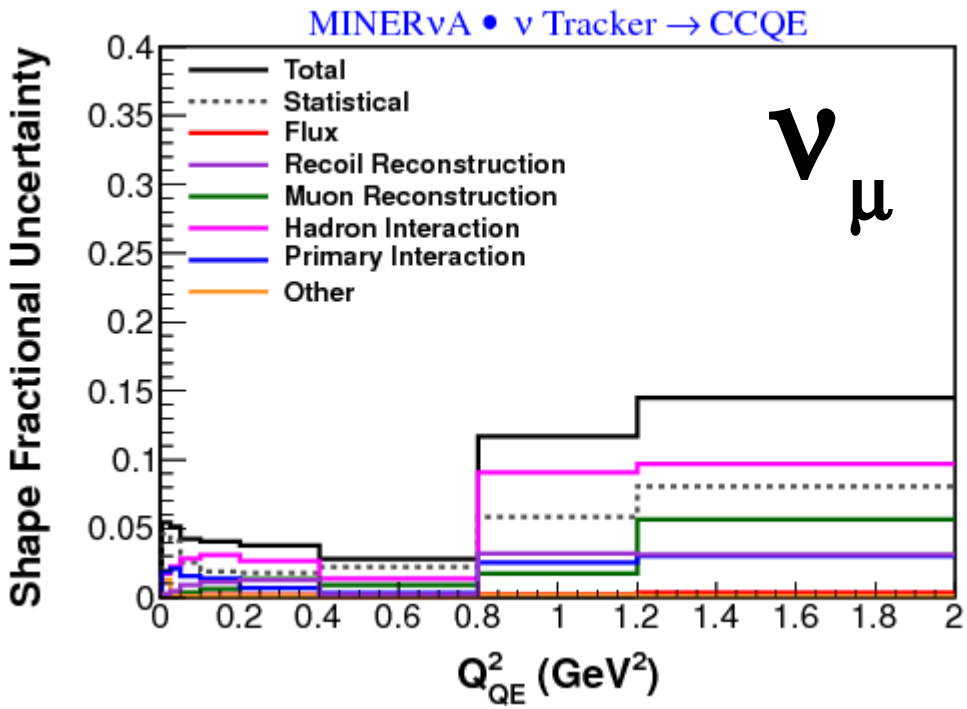
Systematic Error Bands

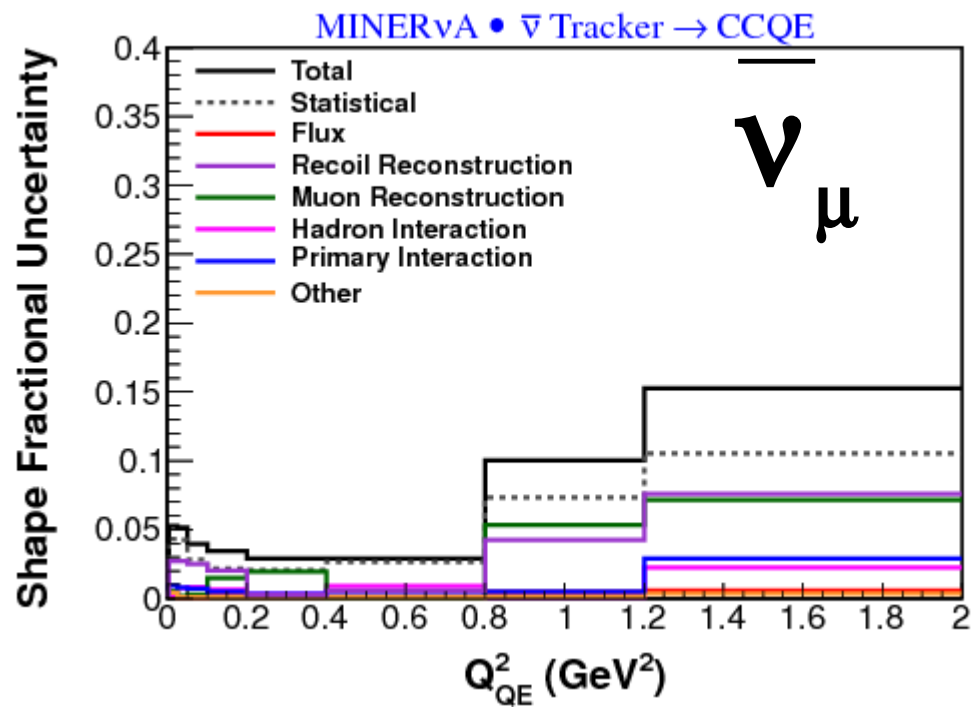




Most significant error: neutrino flux

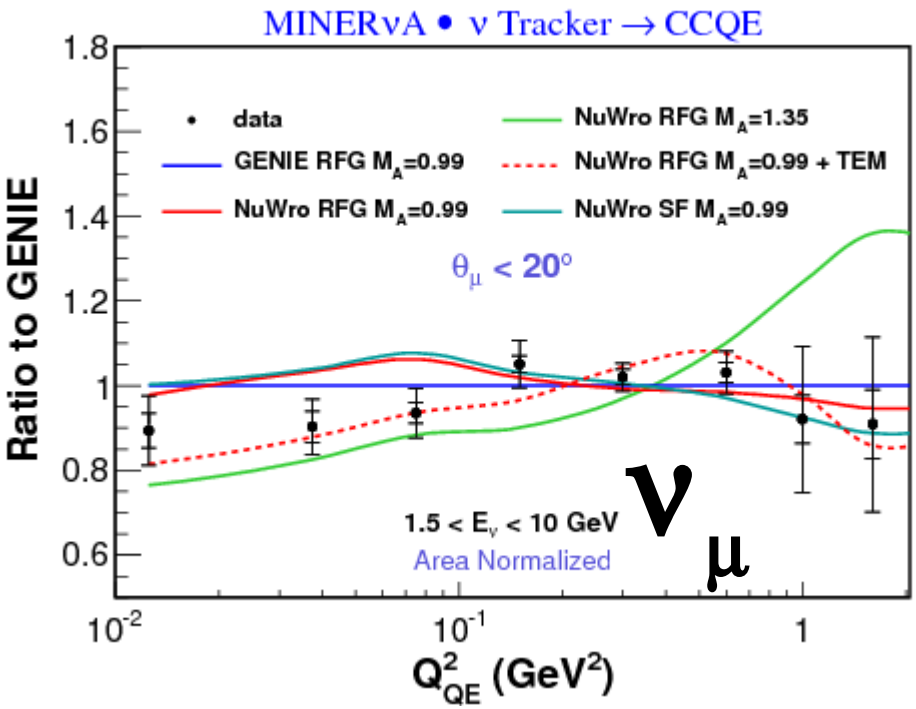
Shape uncertainties

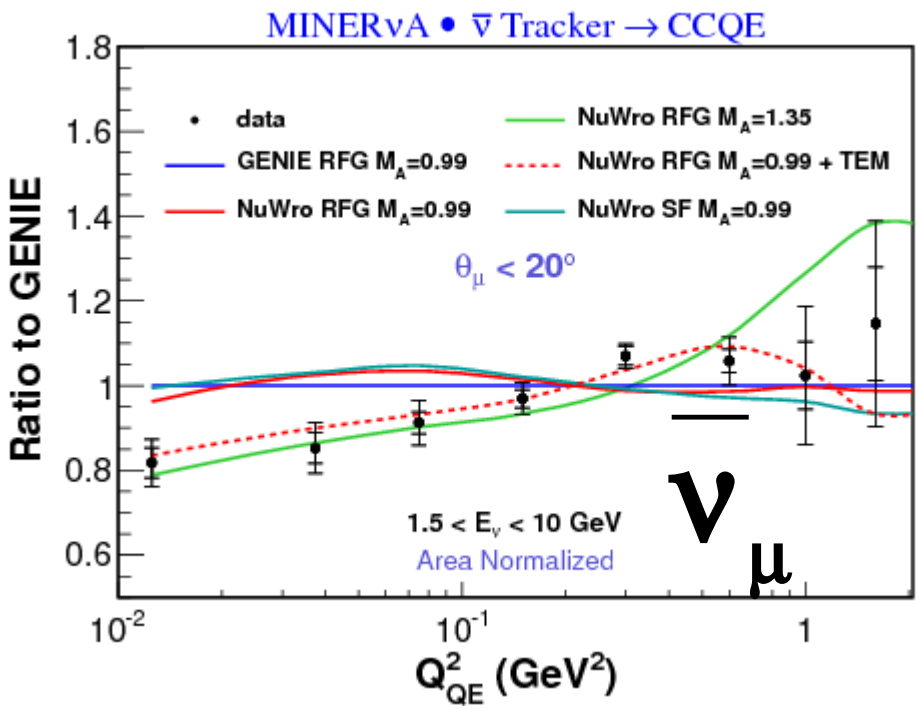




The shape of $d\sigma/dQ^2$ has smaller errors and is physics sensitive.

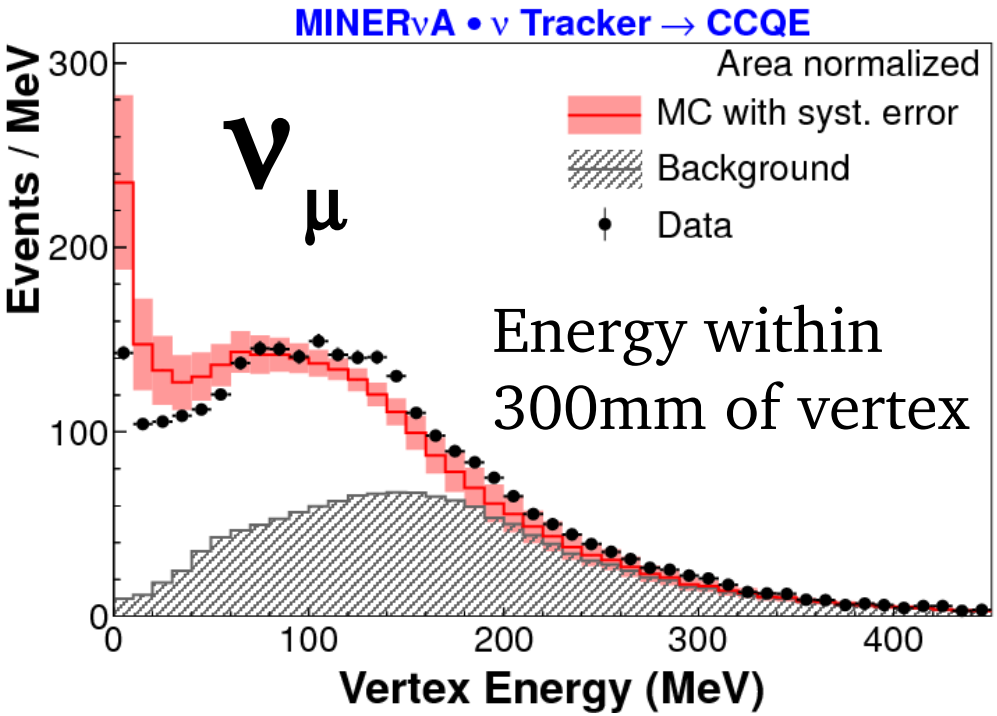
dσ/dQ² shape

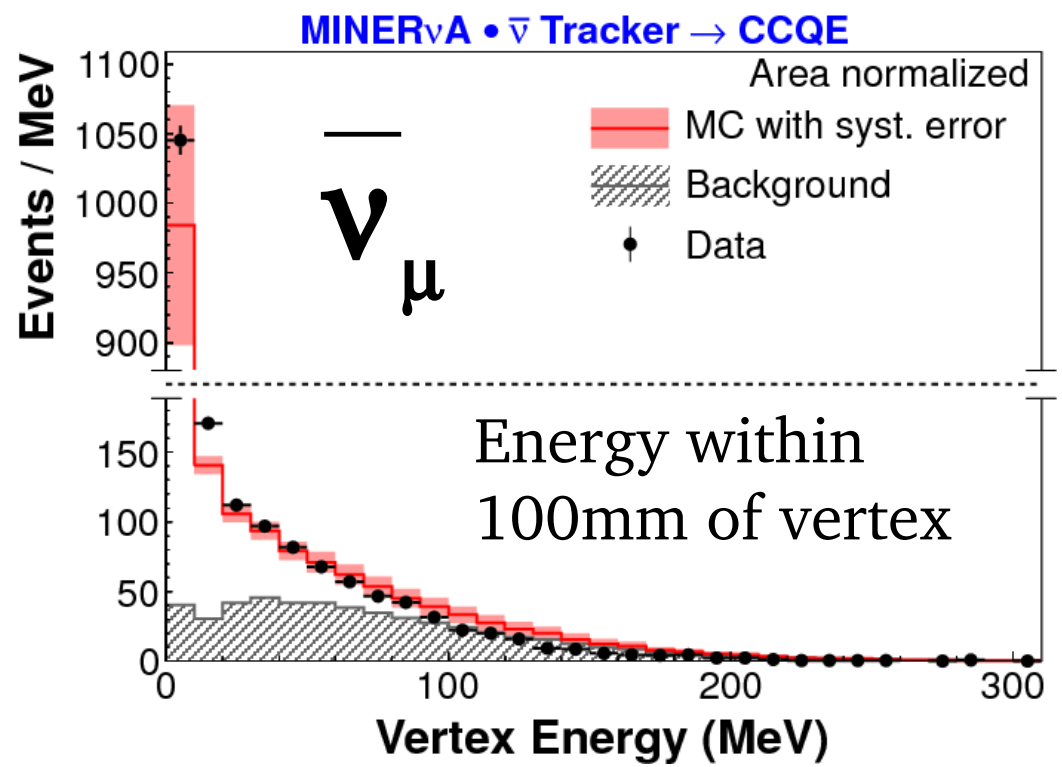




Best match is to an RFG model with MA=0.99 but with G^V_M modified in accordance with electron scattering data – "transverse enhancement" (TEM)

Vertex Energy





Excess of energy at the vertex seen in neutrino mode. Not explained by any systematic uncertainty.

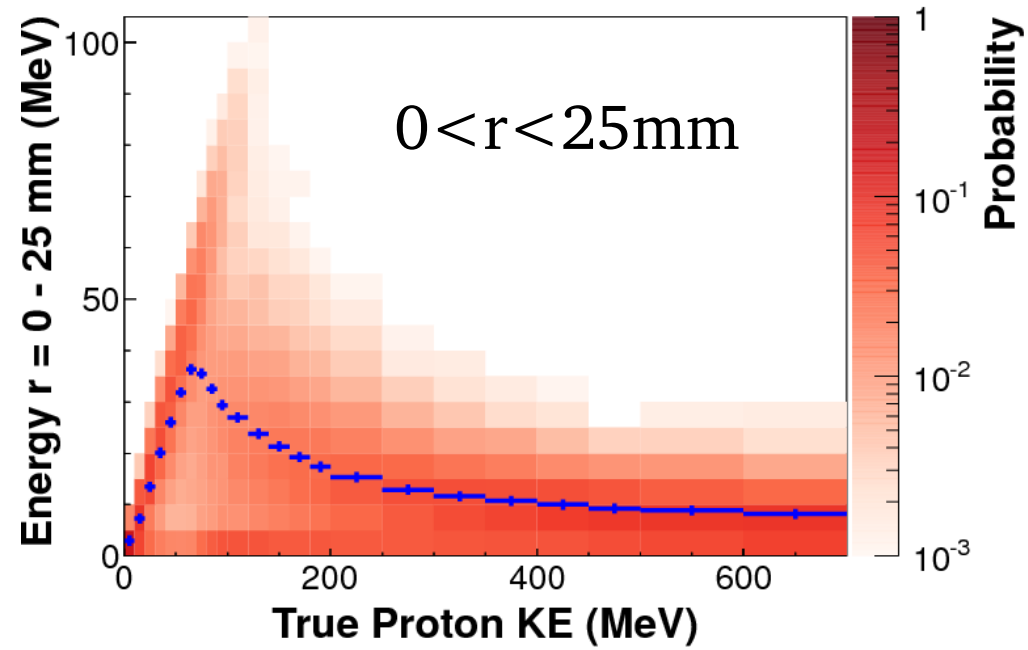
Relatively good agreement in anti-neutrino mode

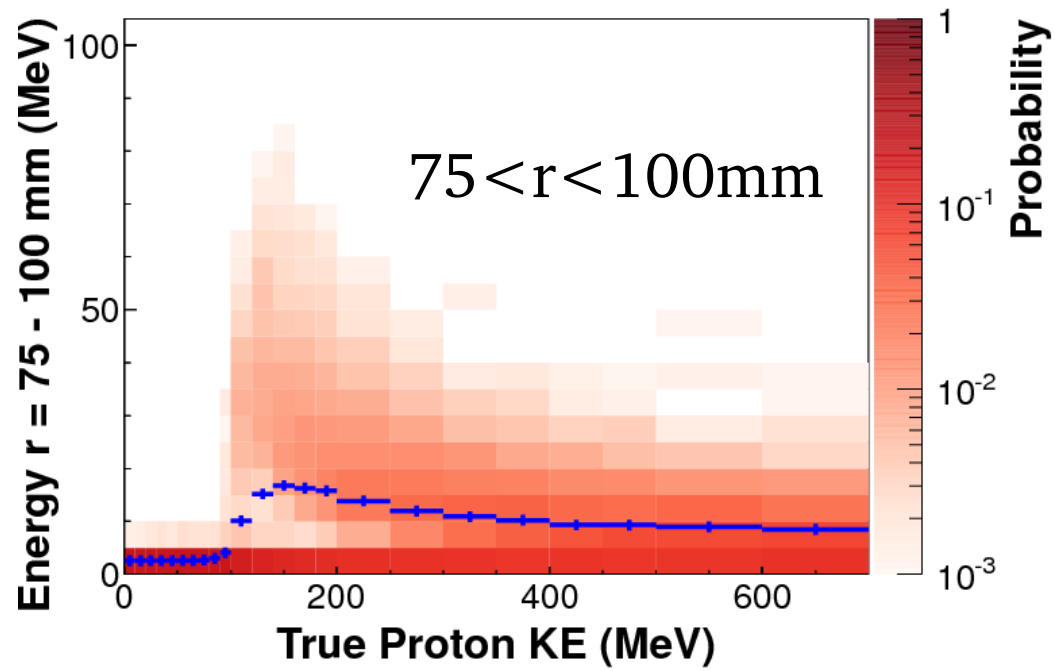
Vertex Energy Fit

Hypothesis: Some QEL-like events due to scattering on correlated np pairs.

Would result in an nn final state for anti-neutrinos but a pp pair for neutrinos.

Test this by adding in an additional proton to some events. Fit vertex energy in radial slices.



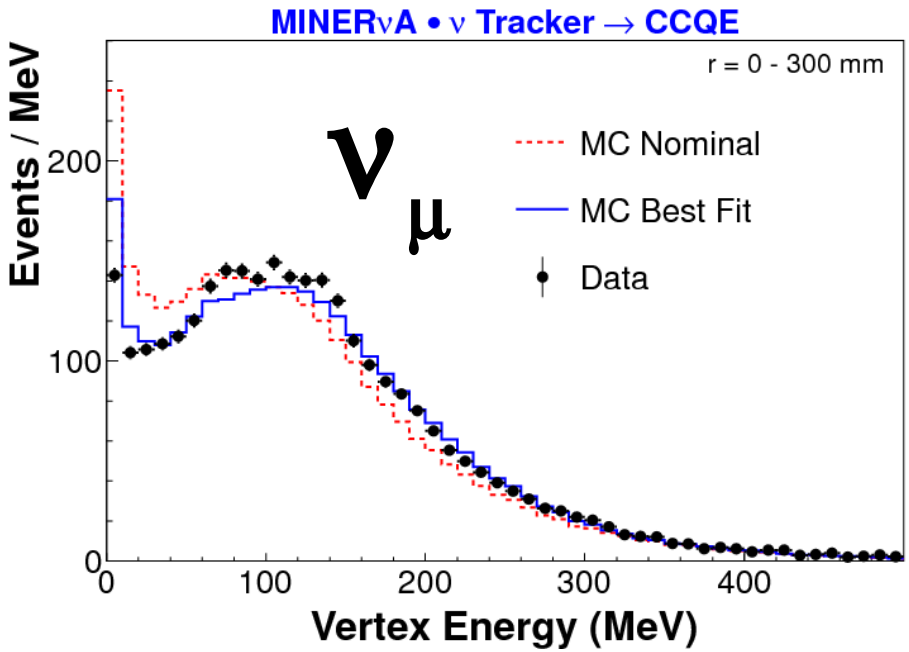


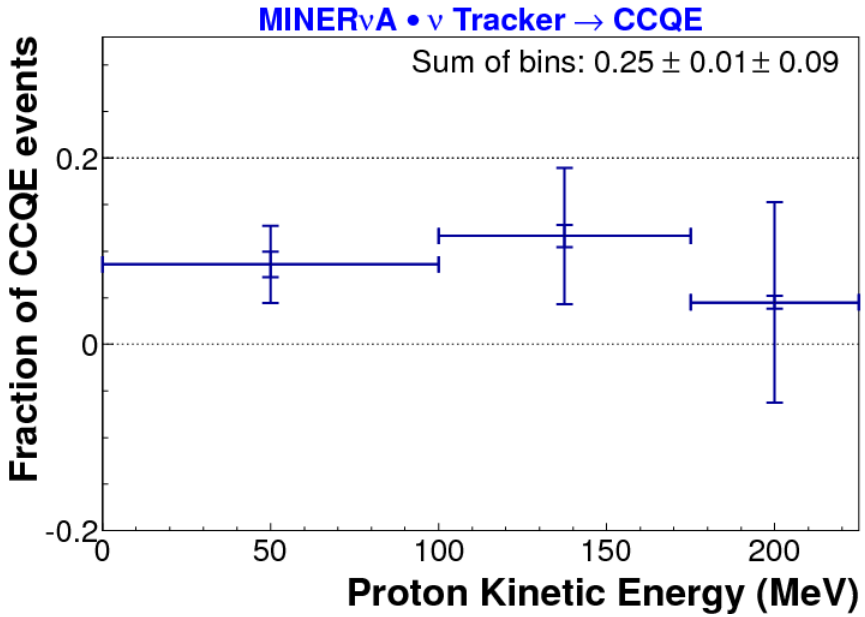
Vertex Energy Fit

Result:

Neutrinos: Best agreement if 25±9% of events have an additional proton with a flat energy distribution from $0<E_{vtx}<200$ MeV

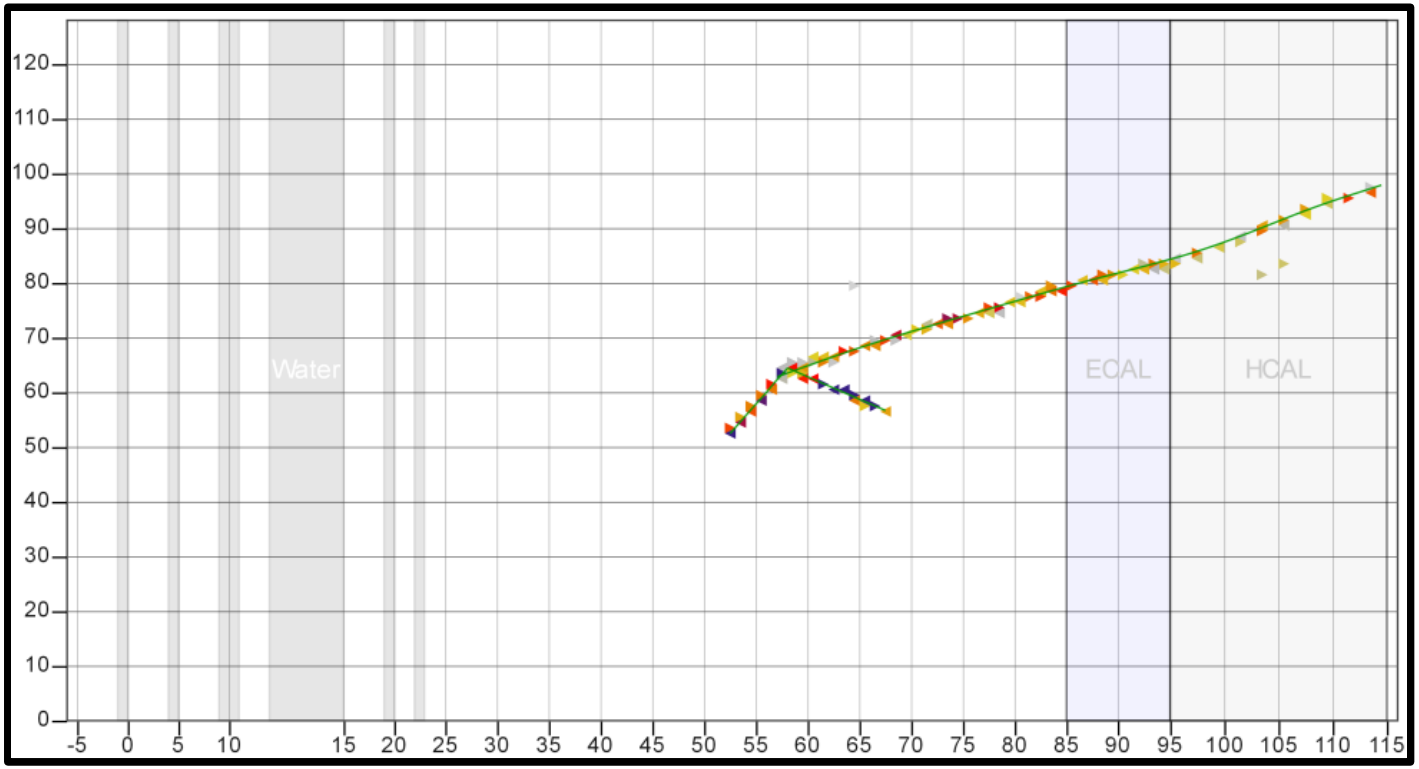
No additional protons needed in anti-neutrino mode.





Additional Results

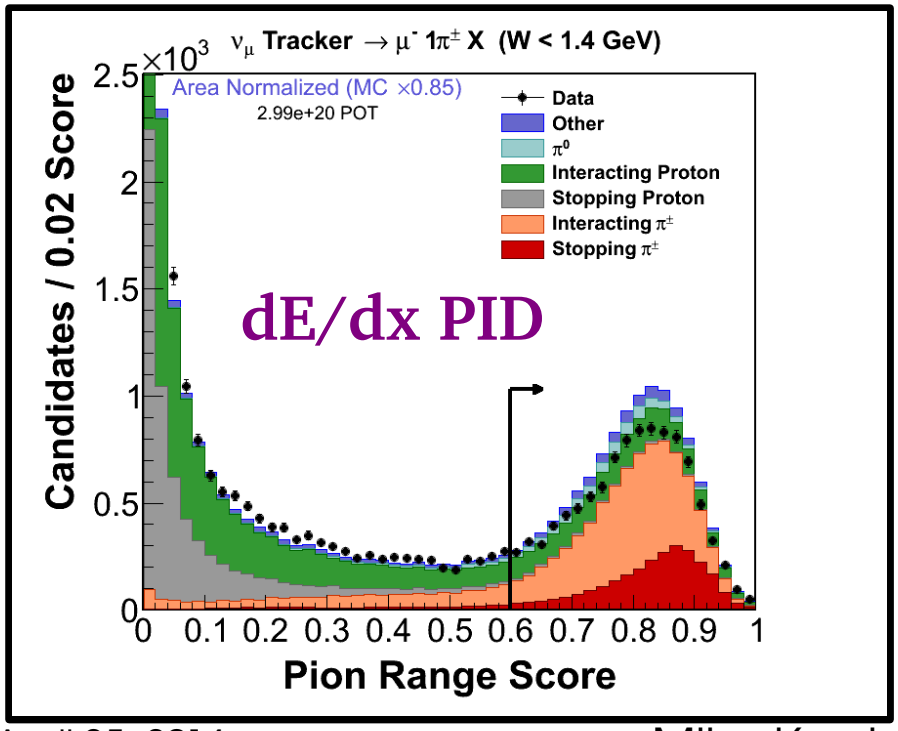
Single $\pi^{\pm}$ production

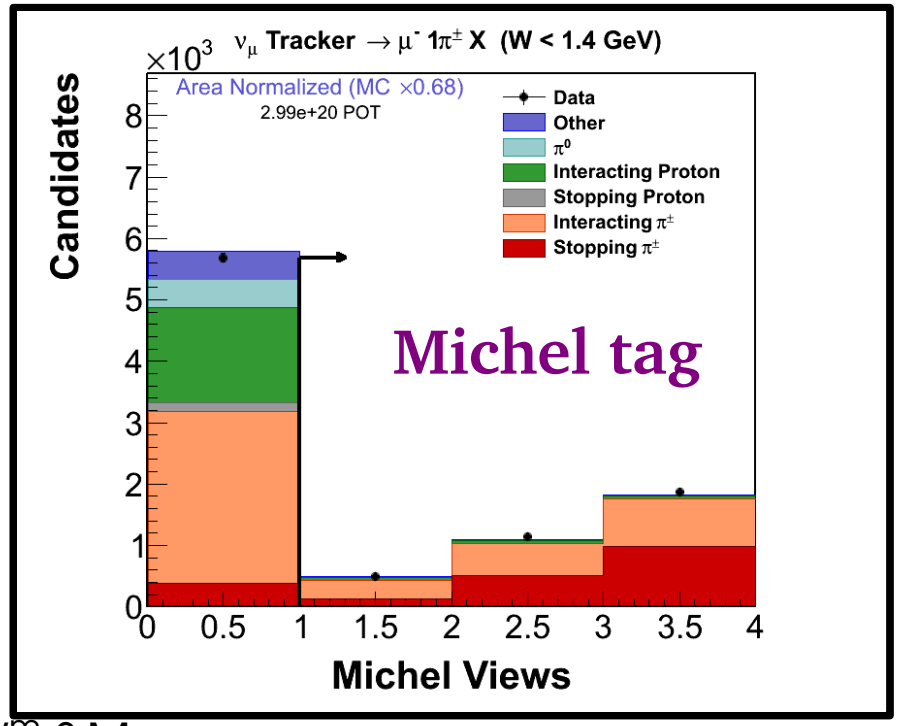


ν_μ (C,H) $\rightarrow \pi$ X

W<1.4 GeV

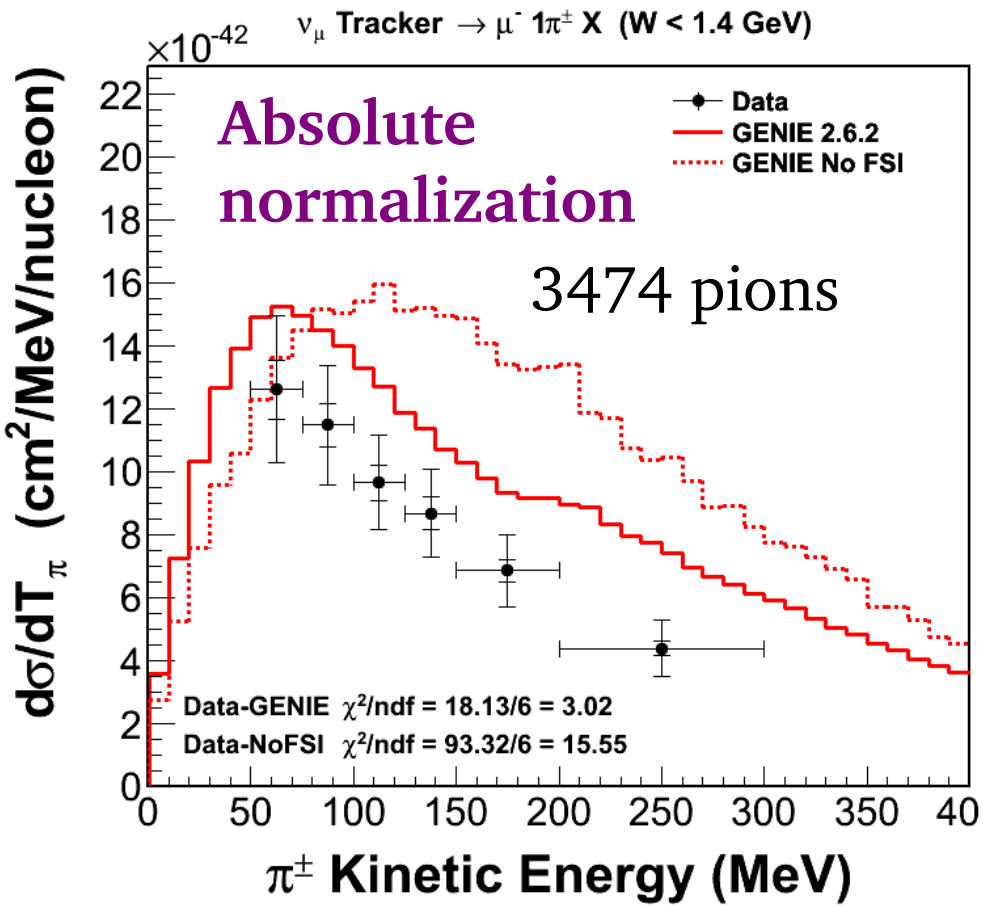
$d\sigma/dT_\pi$, $d\sigma/d\theta_\pi$

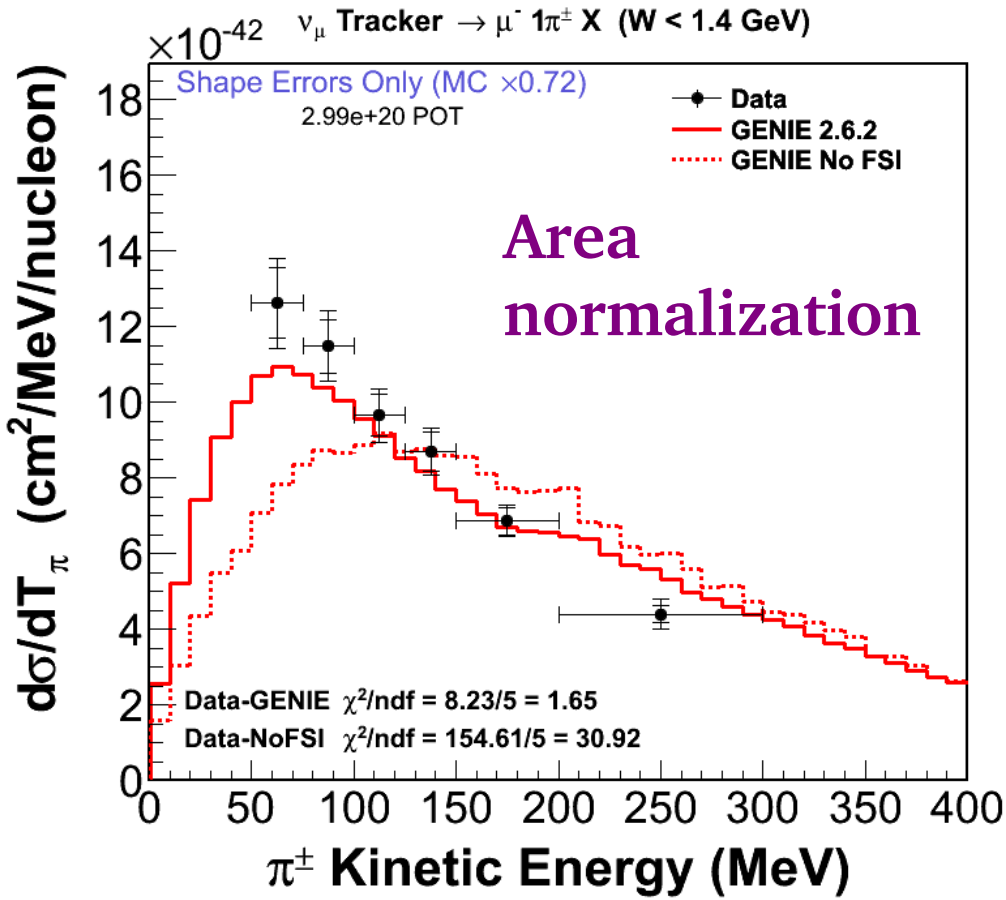




Single $\pi^{\pm}$ production

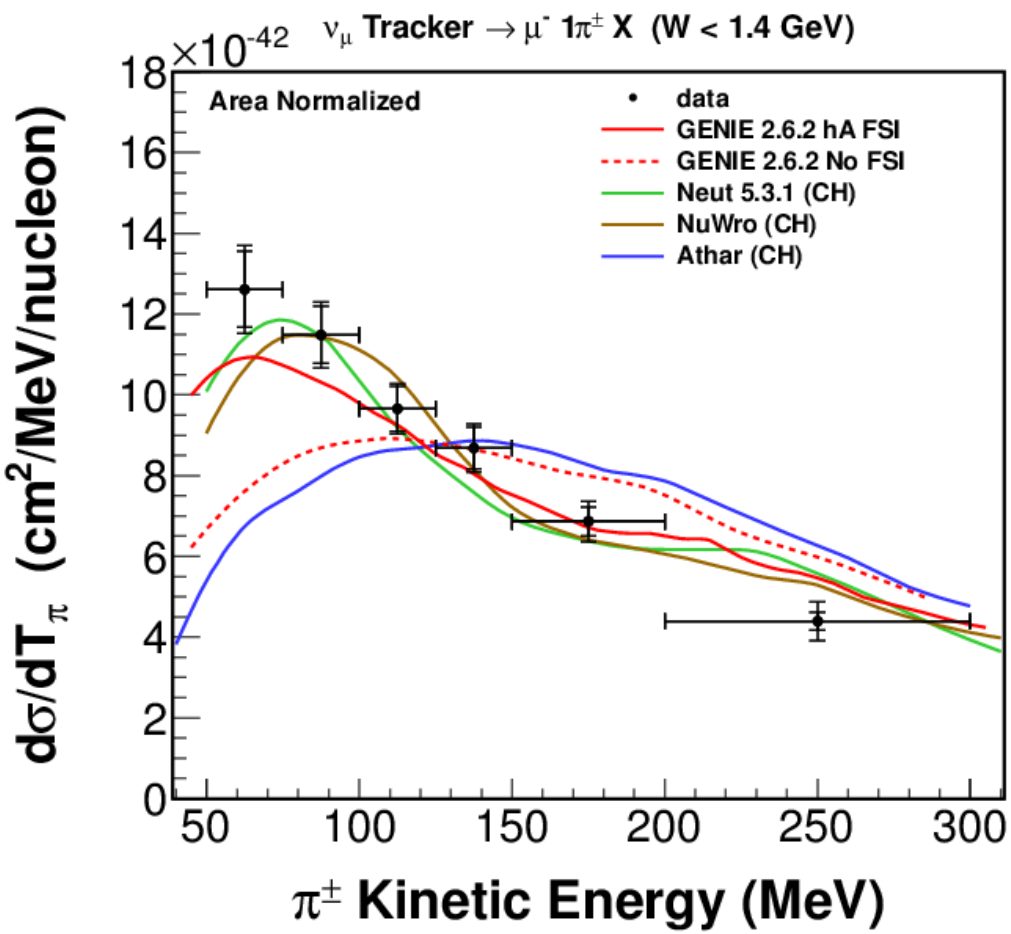
Mostly π^{+}

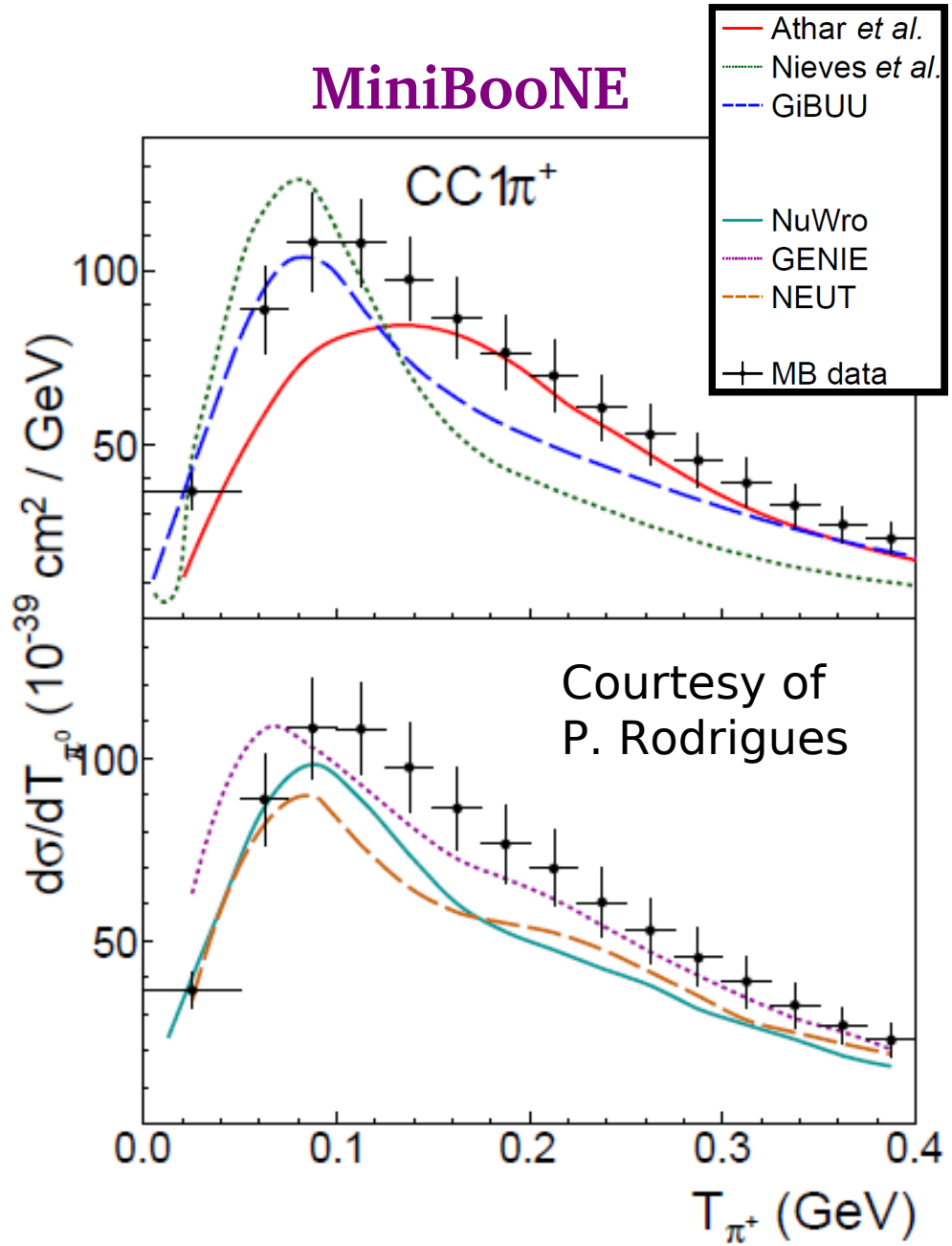




<u>Conclusion</u>: data are sensitive to FSI and provide model tests

Single π+ production

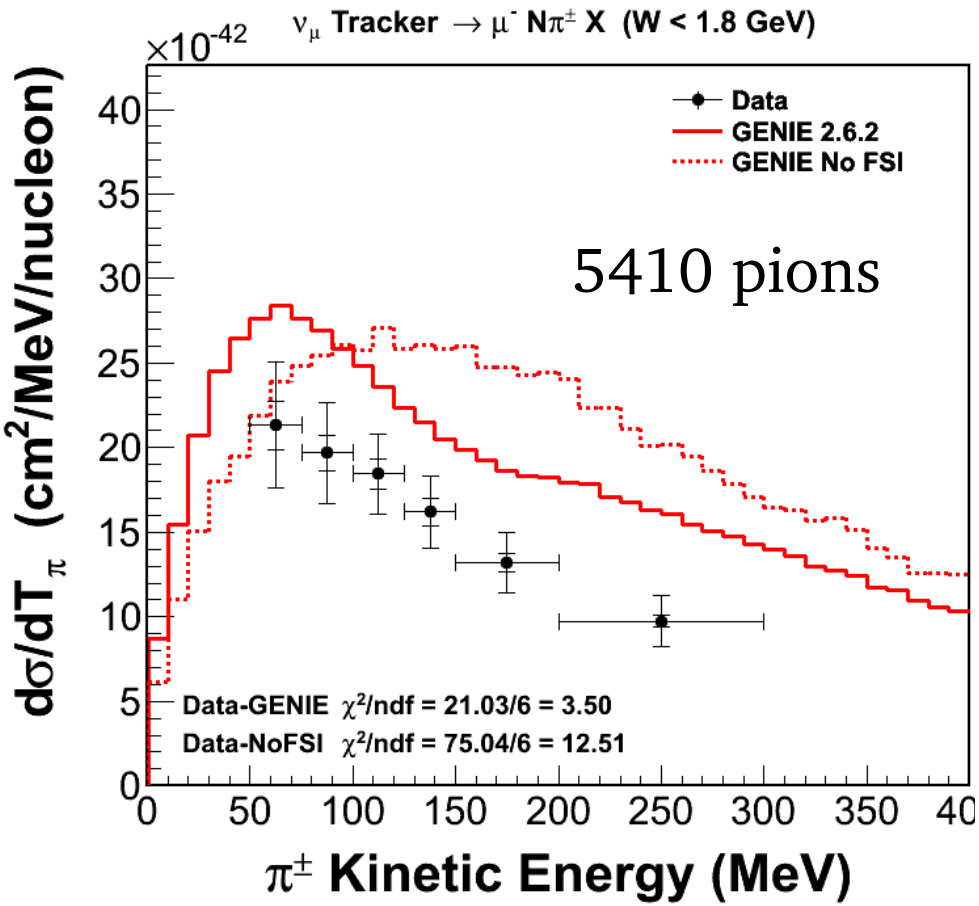


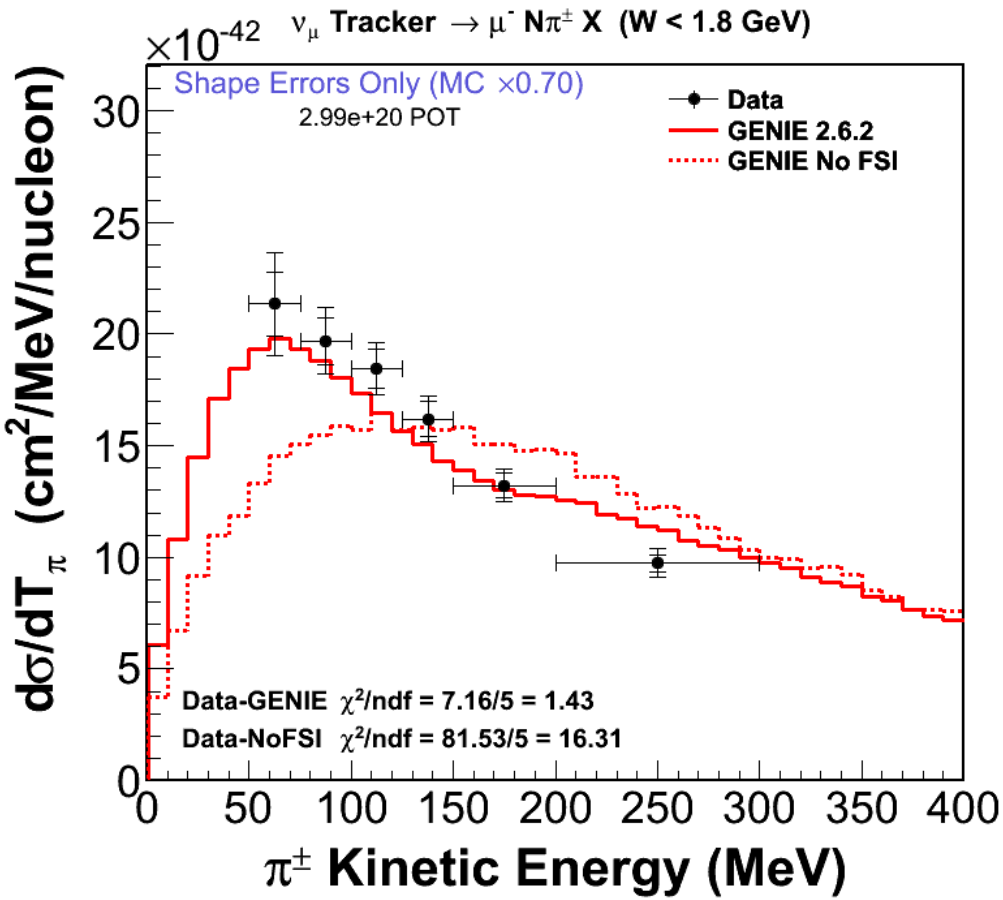


<u>Conclusion</u>: MC codes tend to agree better than micro-physical calculations *(for now…)*

Multi-$\pi^{\pm}$ production

Mostly π^{+}

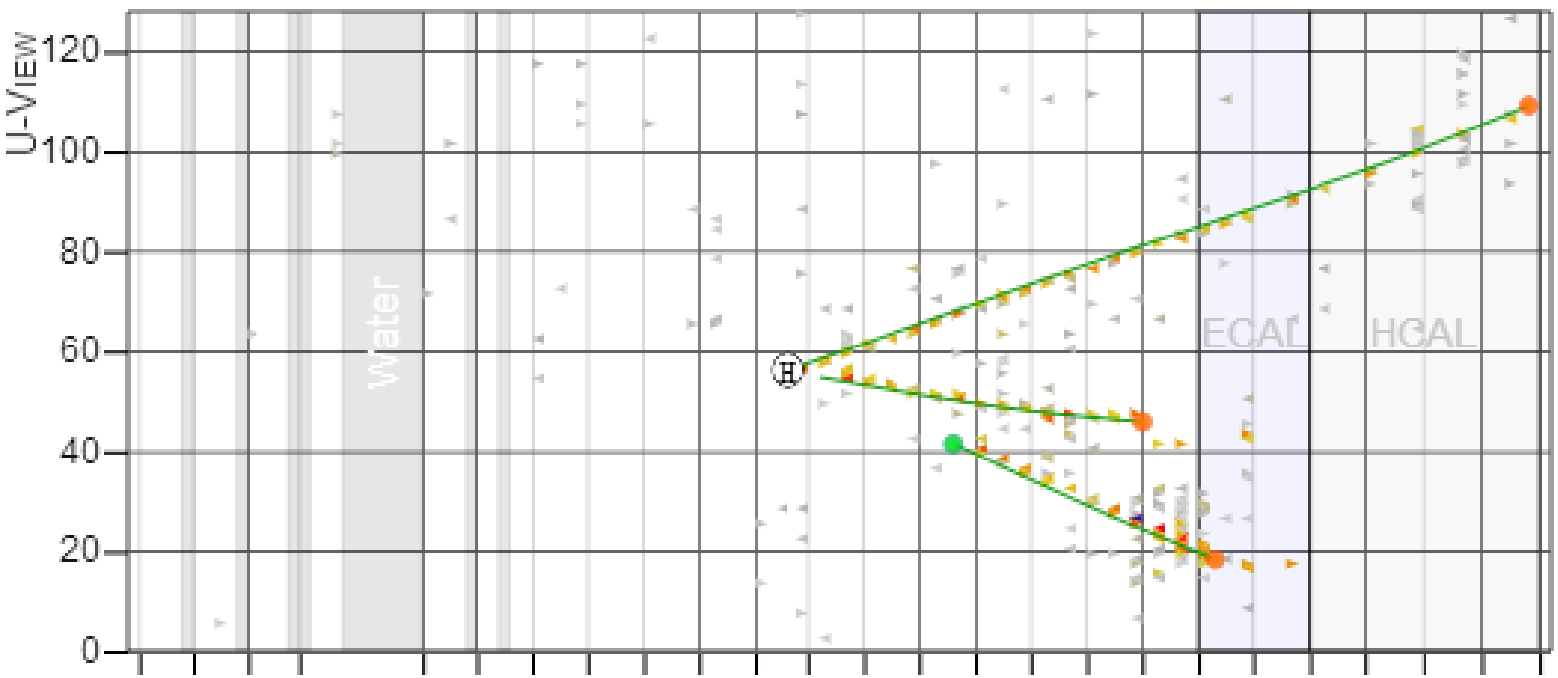




Work in progress

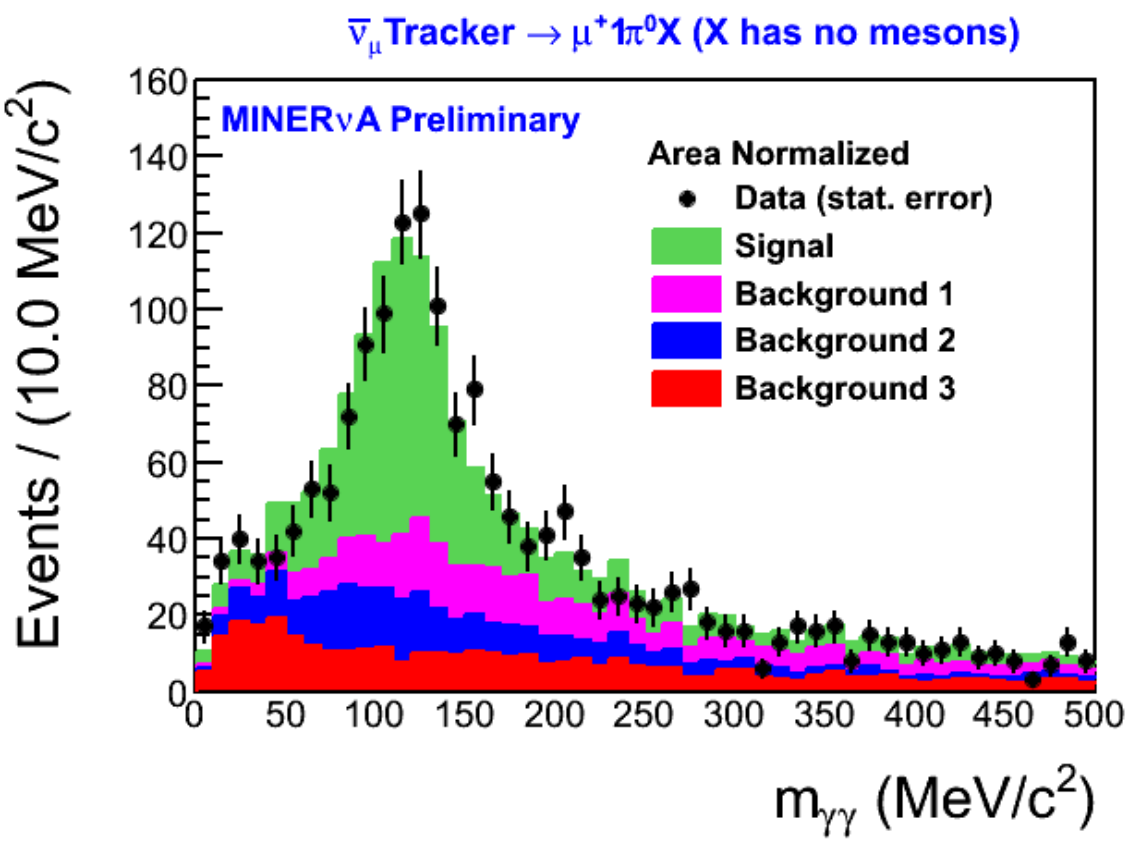
Single π^0 production

$\bar{\nu}_\mu$ (C,H) → $\mu^+ \pi^0$ + nucleons



- Single μ+ track at vertex
- Two shower "prongs"
  - displaced from vertex
  - point back to vertex

Single π^0 production



MC background breakdown:

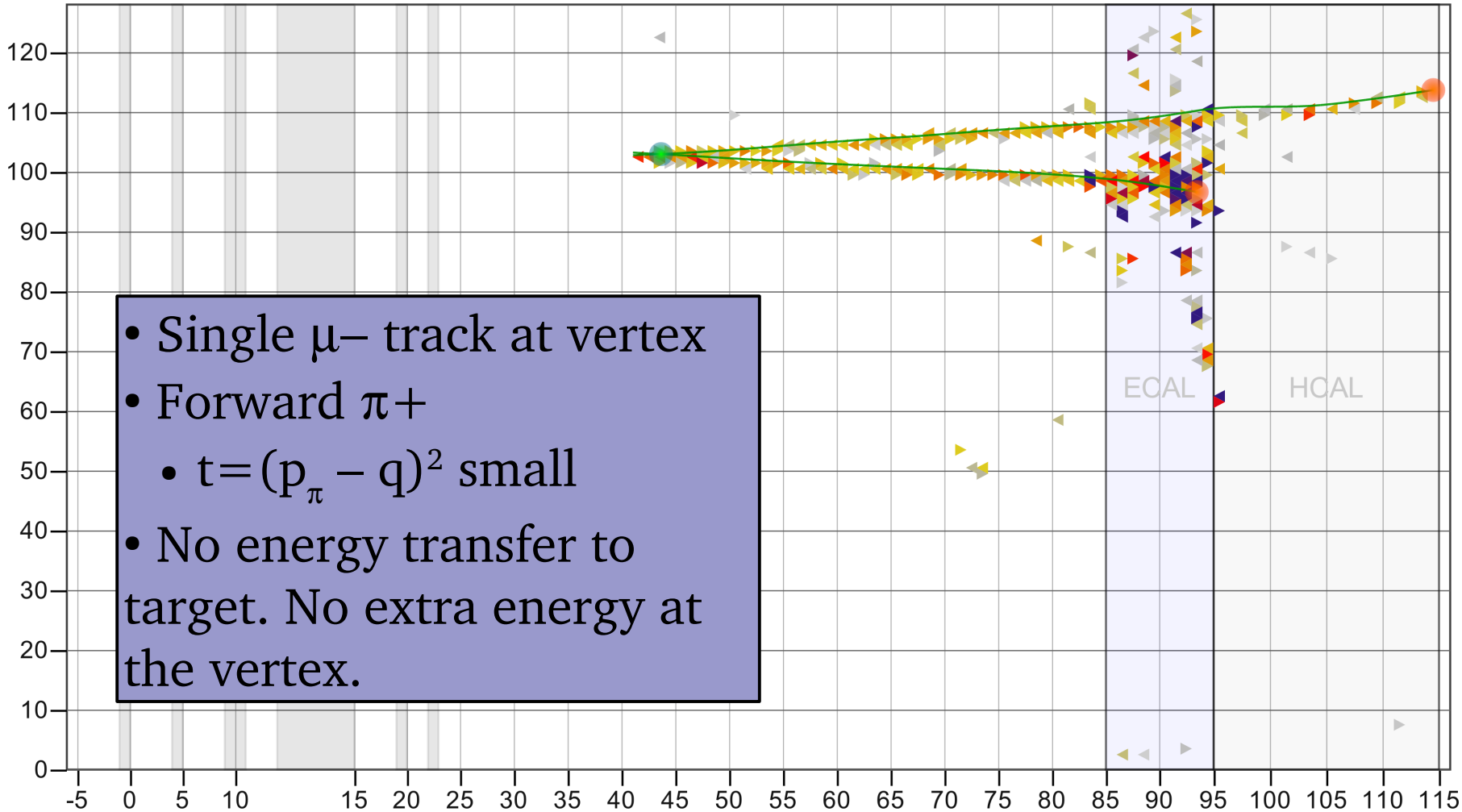
1) Background 1: events with pi0 in the final state plus charged pion (so it's not our signal)
2) Background 2: events with no final state pi0, but there is secondary pi0s, e.g., from pi-charge exchange
3) Background 3: events with no final state nor secondary pi0s

Work in progress

Coherent $\pi^{\pm}$ production

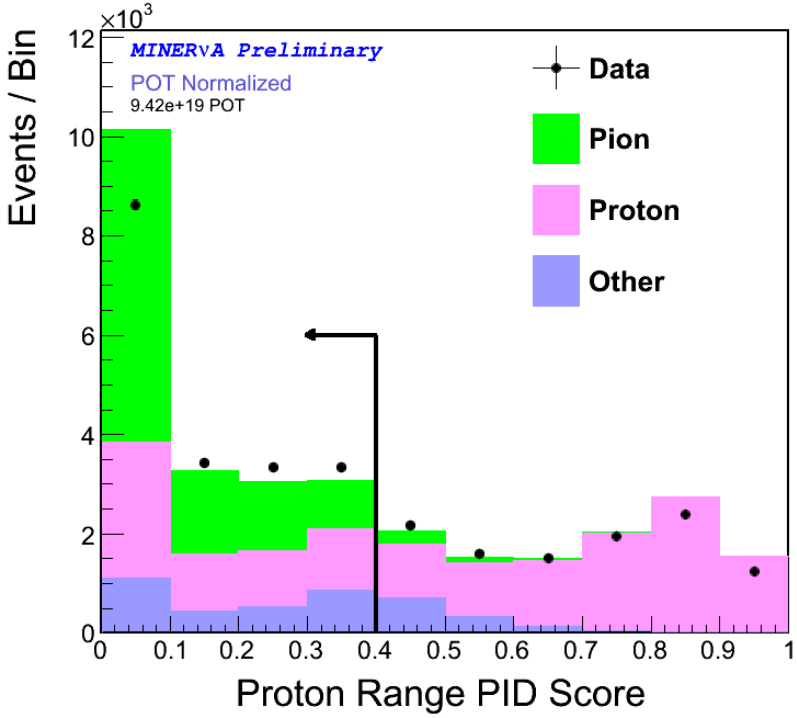
Work in progress

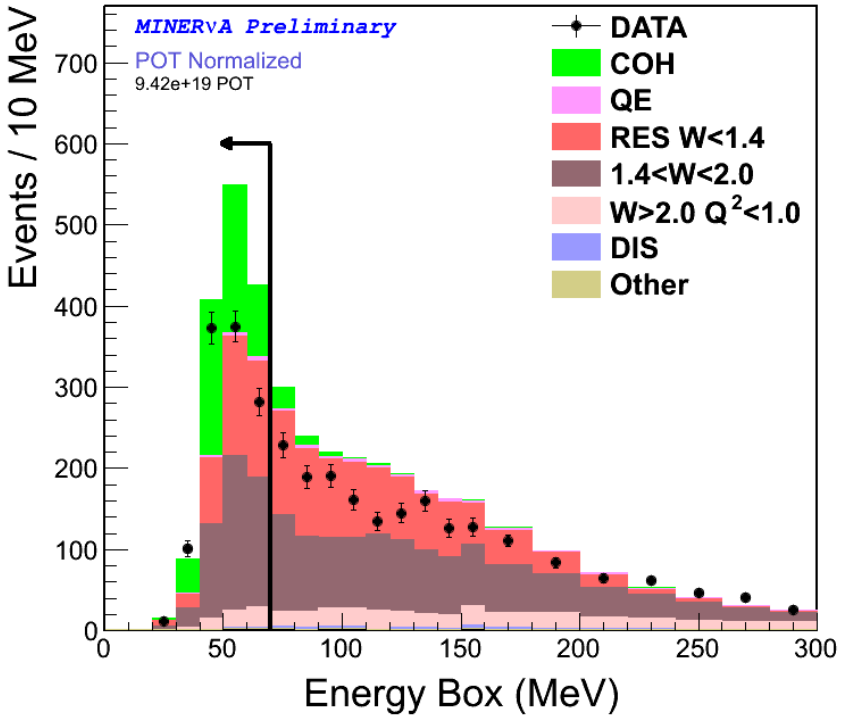
$$\nu_\mu C \rightarrow \mu^- \pi^+ C$$

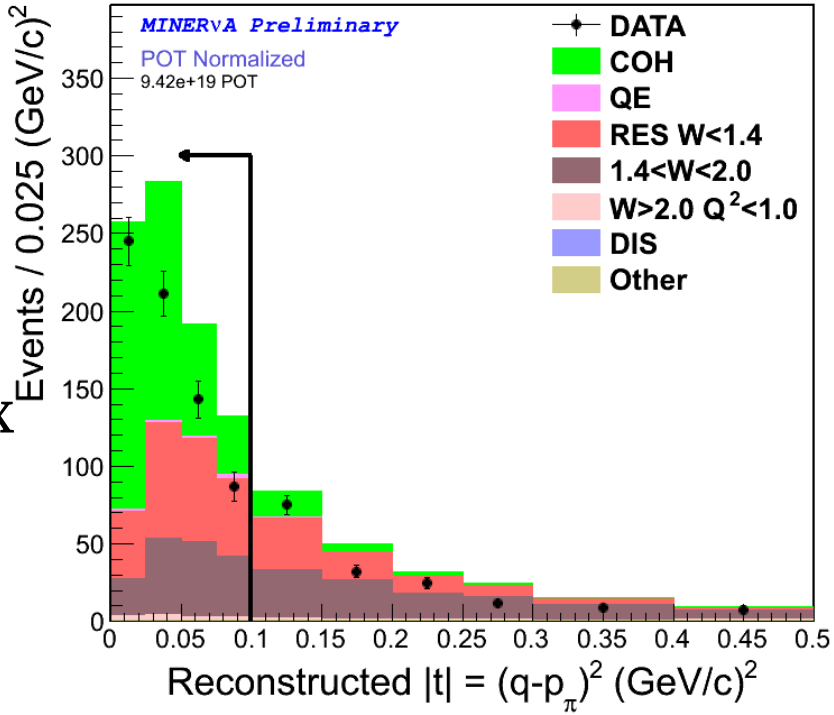


- Single $\mu-$ track at vertex
- Forward $\pi+$
  - $t=(p_\pi - q)^2$ small
- No energy transfer to target. No extra energy at the vertex.

Coherent $\pi^{\pm}$ production







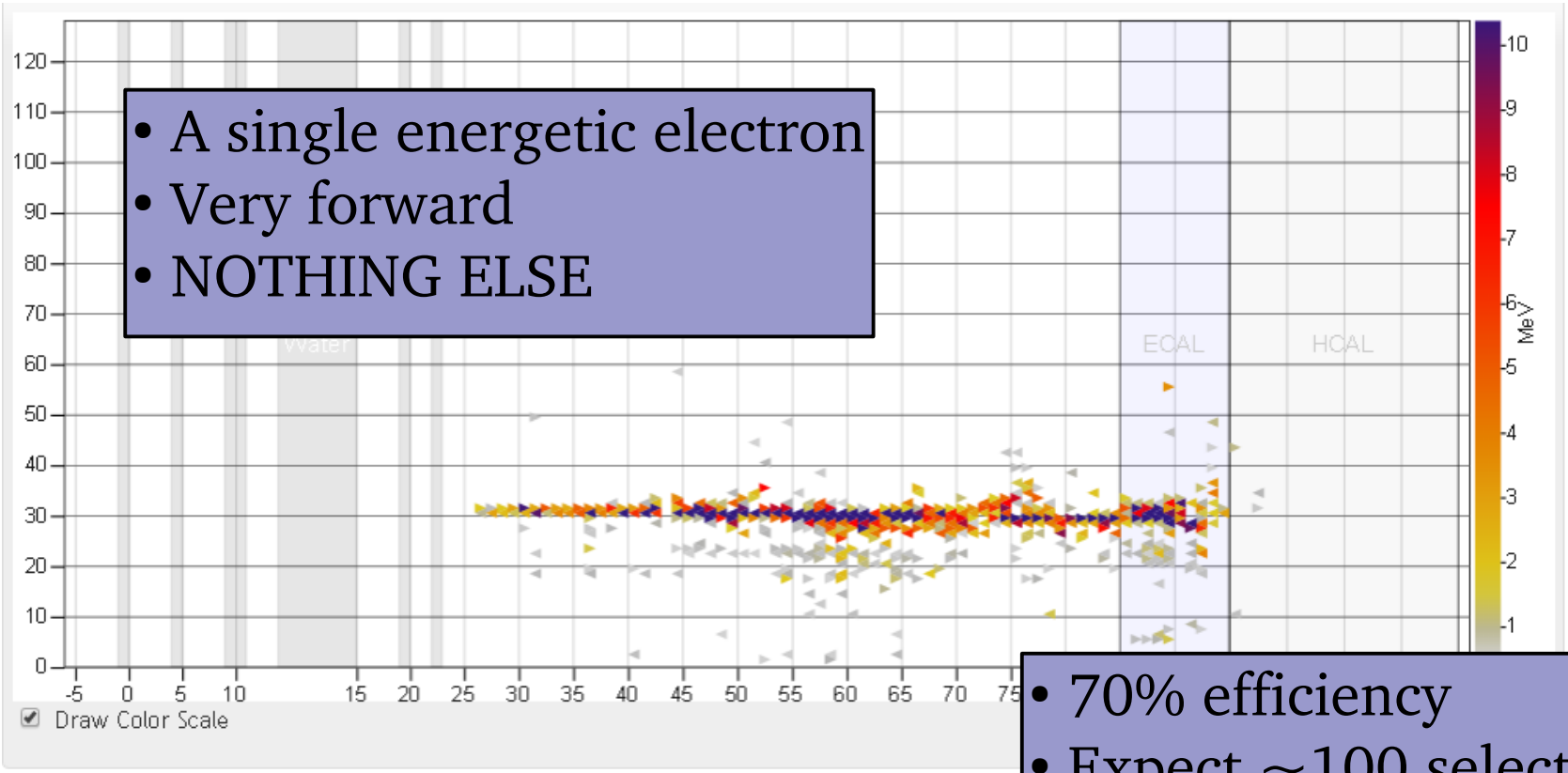
Work in progress

Major effort is on understanding the vertex energy and constraining the background with sidebands in t.

ν – electron scattering

Standard candle cross-section, precisely predicted by the SM

$$\frac{d\sigma(\nu_\mu e^- \to \nu_\mu e^-)}{dy} = \frac{G_F{}^2 m_e E_\nu}{2\pi}\left[\left(\frac{1}{2} - \sin^2\theta_W\right)^2 + \sin^4\theta_W (1-y)^2\right]$$



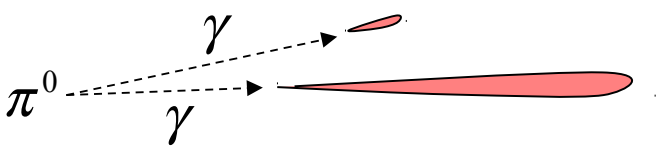
- A single energetic electron
- Very forward
- NOTHING ELSE

- 70% efficiency
- Expect ~100 selected events for 3.43e20 POT in the NuMI LE beam

ν – electron scattering

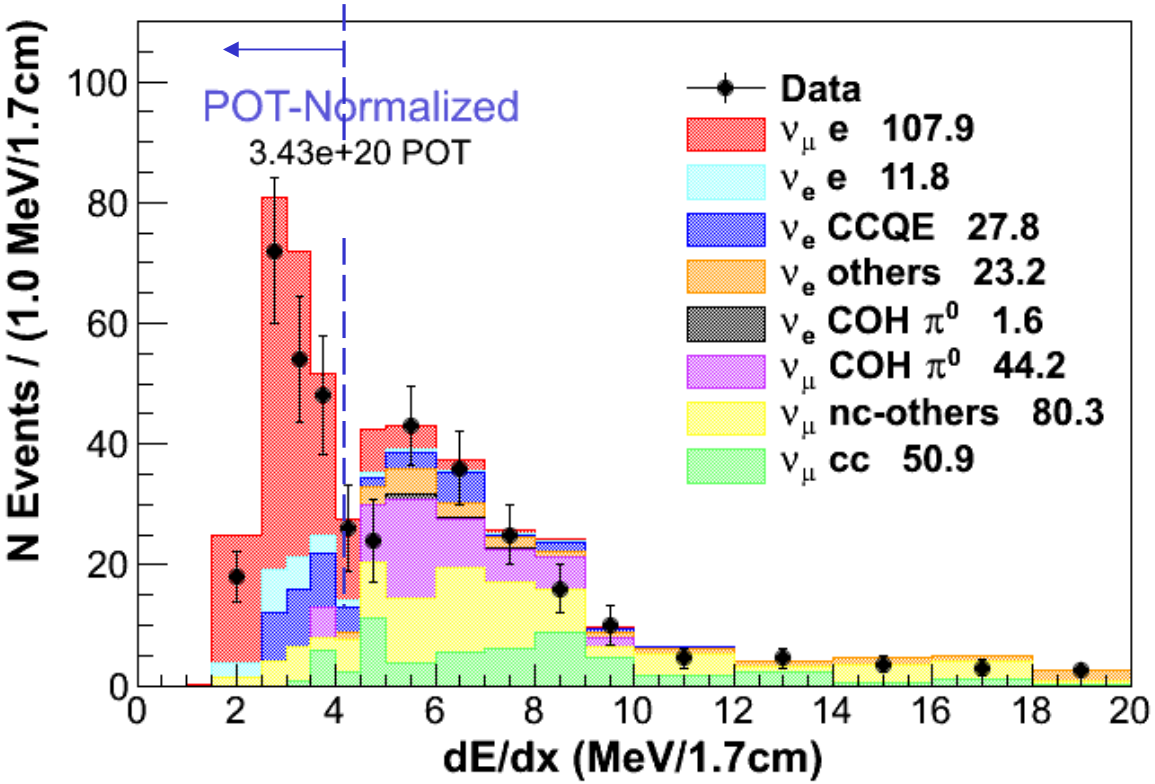
Major background from events with a π^0 where 1 γ is lost

$\nu_\mu A \rightarrow \nu_\mu A \pi^0$	NC-coherent π^0
$\nu_\mu N \rightarrow \nu_\mu N \pi^0$	NC-resonant π^0



<u>Background rejection</u>
Look at dE/dx near the start of the shower

electron = 1 MIP
gamma = 2 MIPs

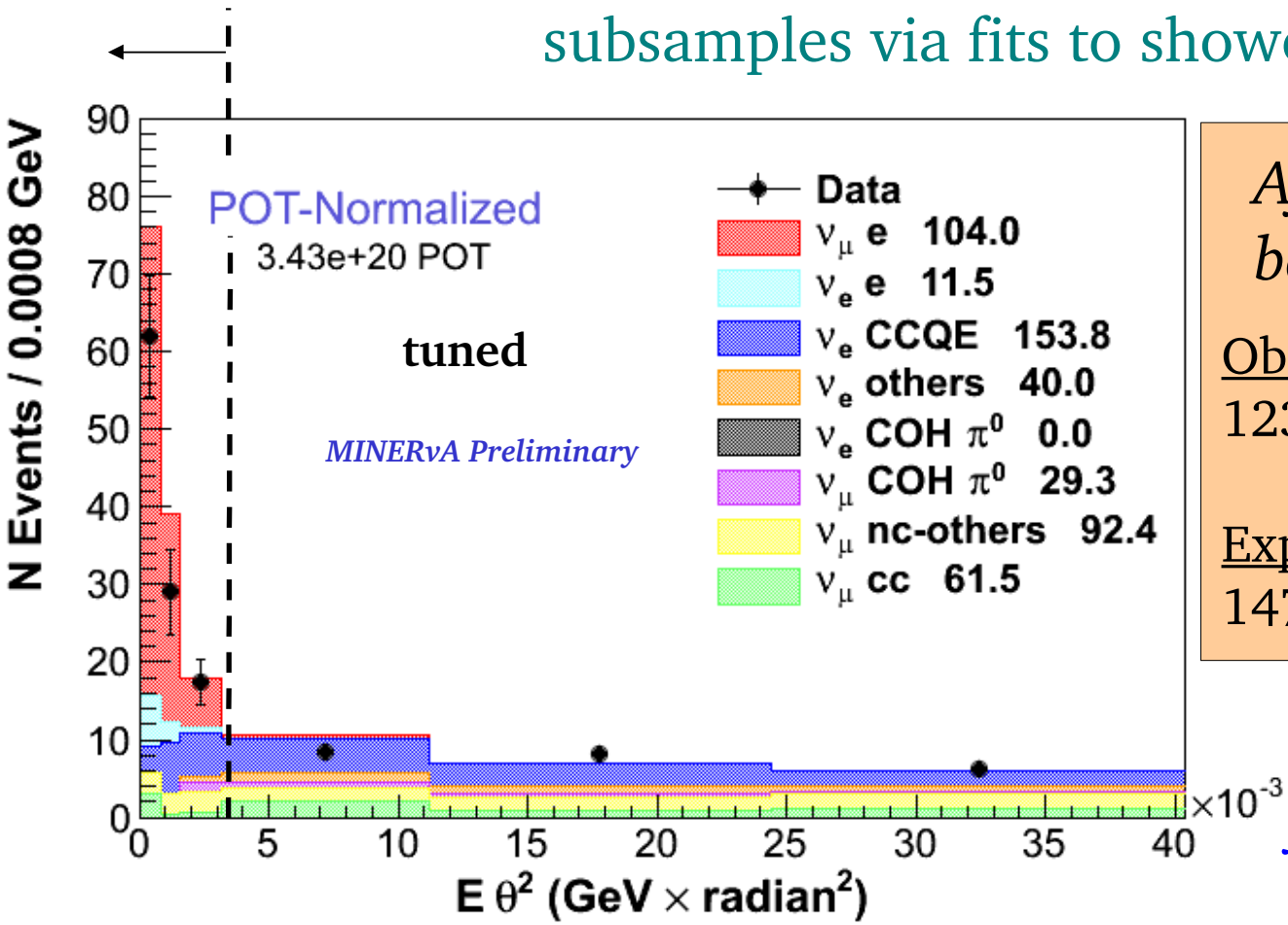


ν – electron scattering

Background from ν_e CC interactions removed via $E\theta^2$ cut

Data driven background constraint via sidebands in dE/dx, $E\theta^2$. Sensitivity to subsamples via fits to shower topological variables.

$E\theta^2 < 0.0032\,\mathrm{GeV}\cdot\mathrm{rad}^2$



After efficiency and background corrections

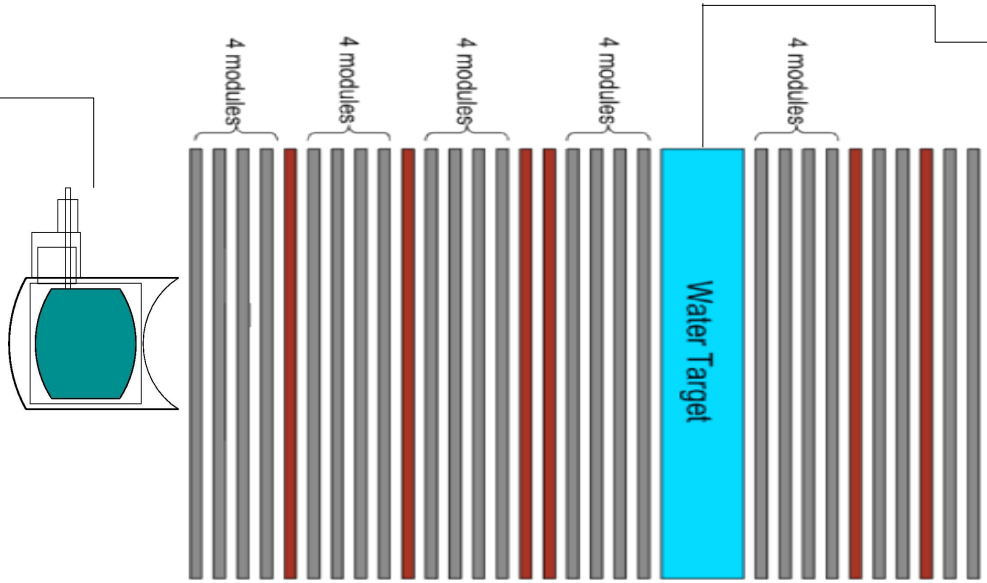
<u>Observed</u>
123.8 ± 17.0 (stat) ± 9.1 (syst)

<u>Expected</u>
147.5 ± 22.9 (flux)

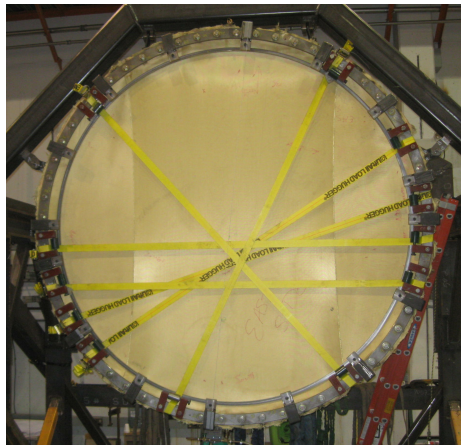
Gives a constraint on the flux comparable to current uncertainty.

nuclear targets

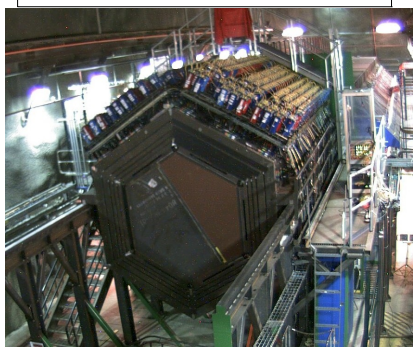
250 kg
Liquid He



500kg
Water

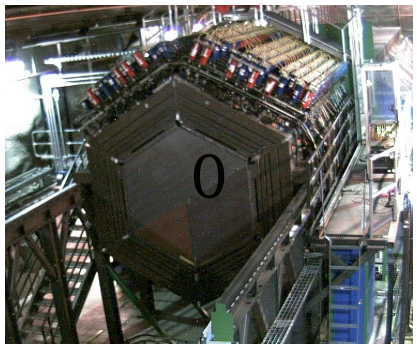


1.0” Fe / 1.0” Pb

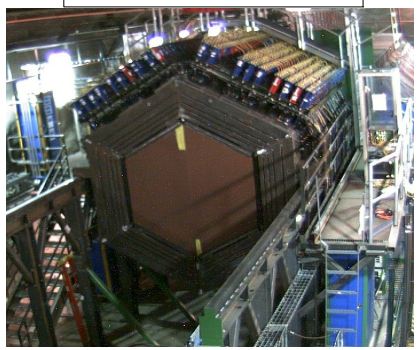


1.0” Pb / 1.0” Fe

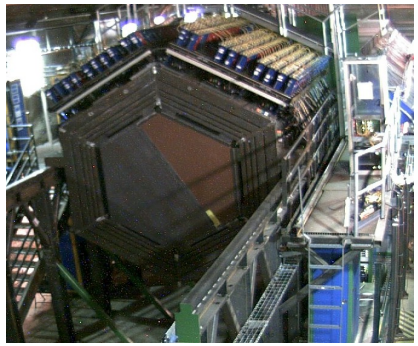
3.0” C / 1.0” Fe / 1.0” Pb



0.3” Pb



0.5” Fe / 0.5” Pb



Nuclear Target Observables

$$\frac{\sigma(E)_{Pb}}{\sigma(E)_{CH}} \quad \frac{\sigma(E)_{Fe}}{\sigma(E)_{CH}} \quad \frac{\sigma(E)_{C}}{\sigma(E)_{CH}}$$

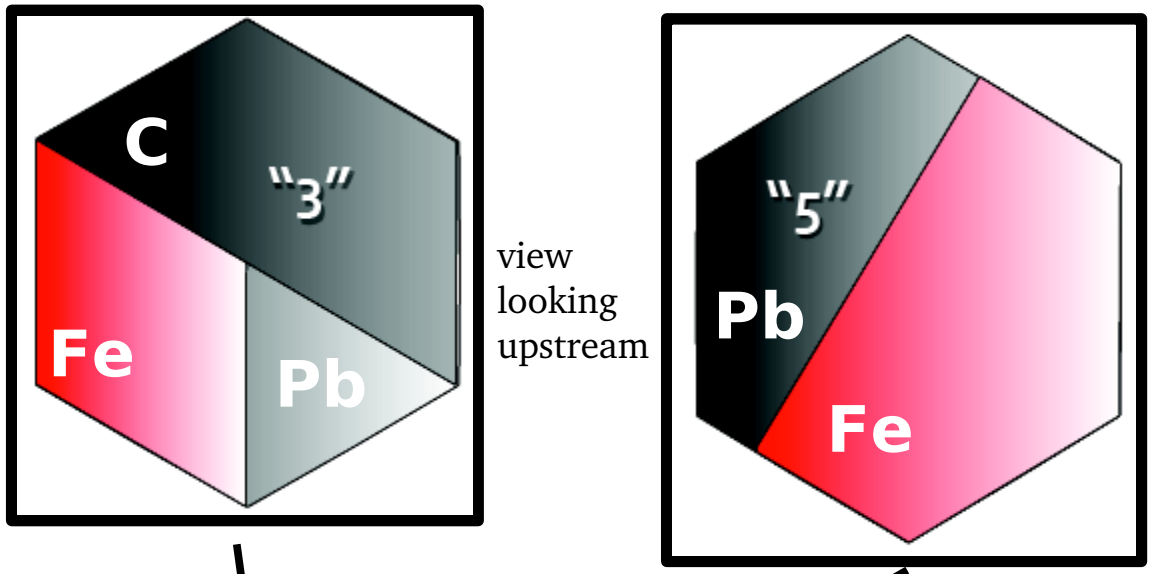
Ratio of the ν_μ CC cross-section as a function of energy

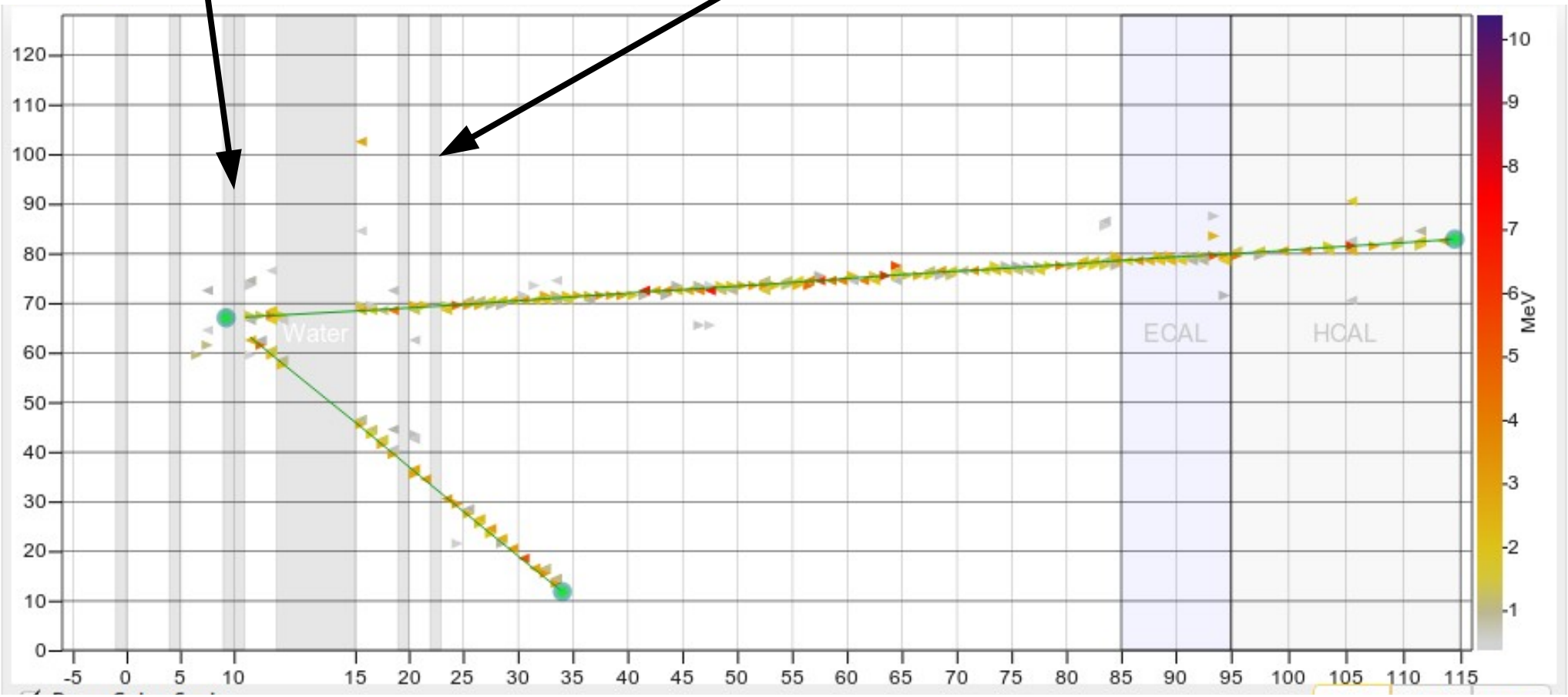
… and as a function of Bjorken-x

$$x_{Bj} = Q^2/2m\nu$$

$$\frac{\frac{d\sigma_{Pb}}{dx}}{\frac{d\sigma_{CH}}{dx}} \quad \frac{\frac{d\sigma_{Fe}}{dx}}{\frac{d\sigma_{CH}}{dx}} \quad \frac{\frac{d\sigma_{C}}{dx}}{\frac{d\sigma_{CH}}{dx}}$$

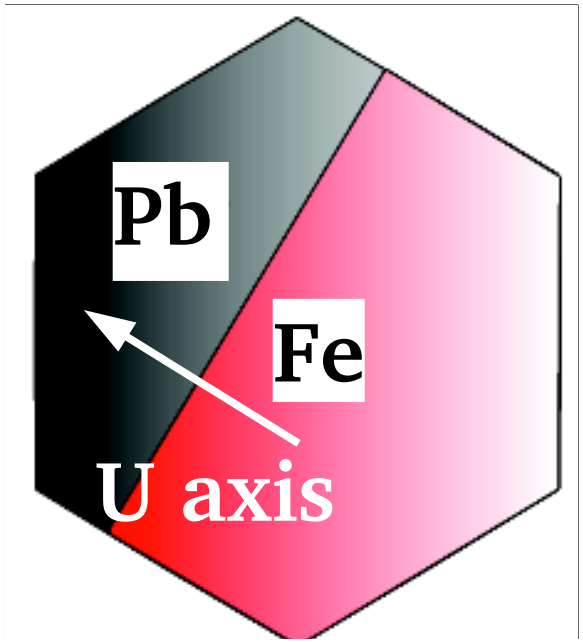
An event from target 3

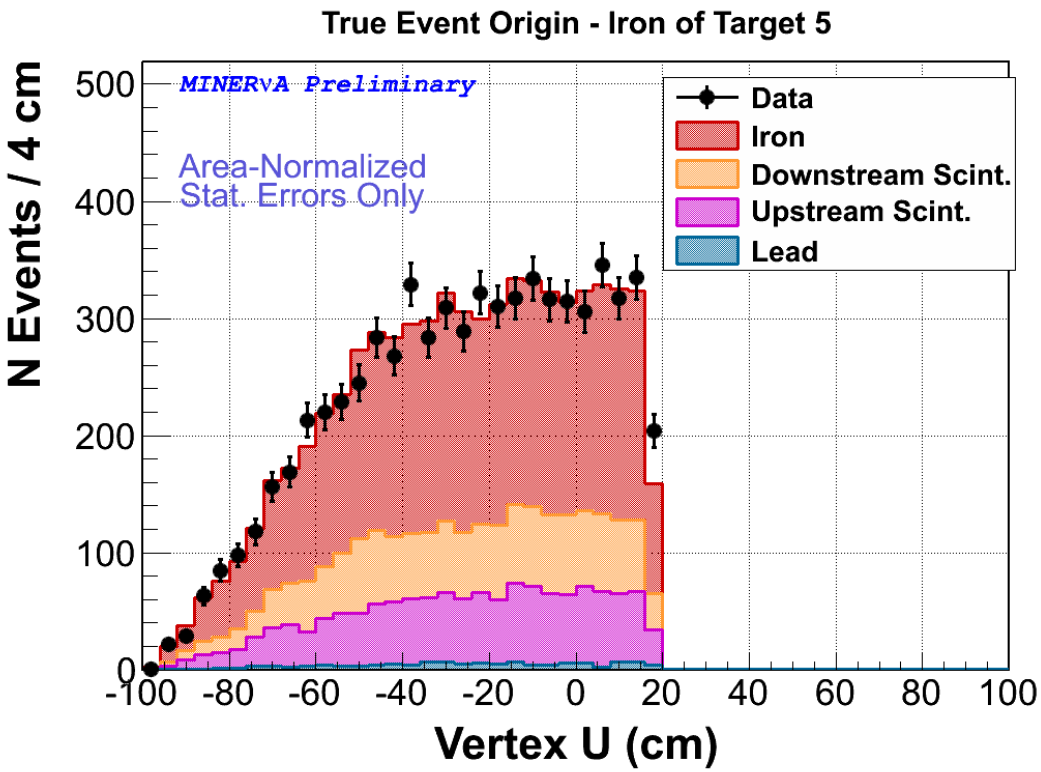


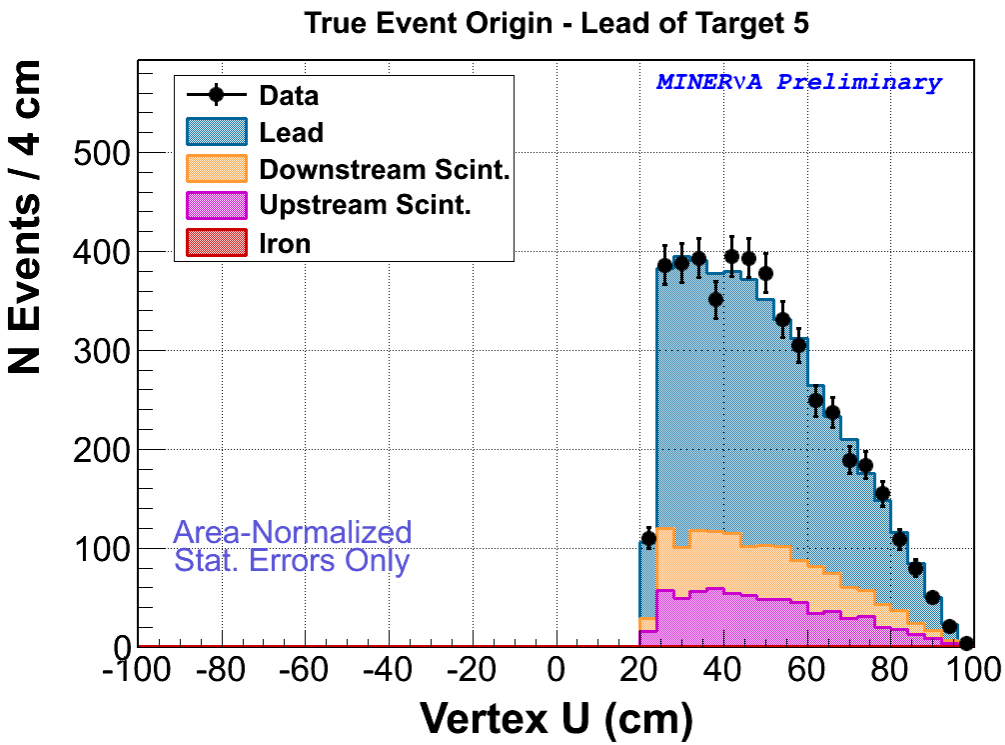


Selection of Fe and Pb

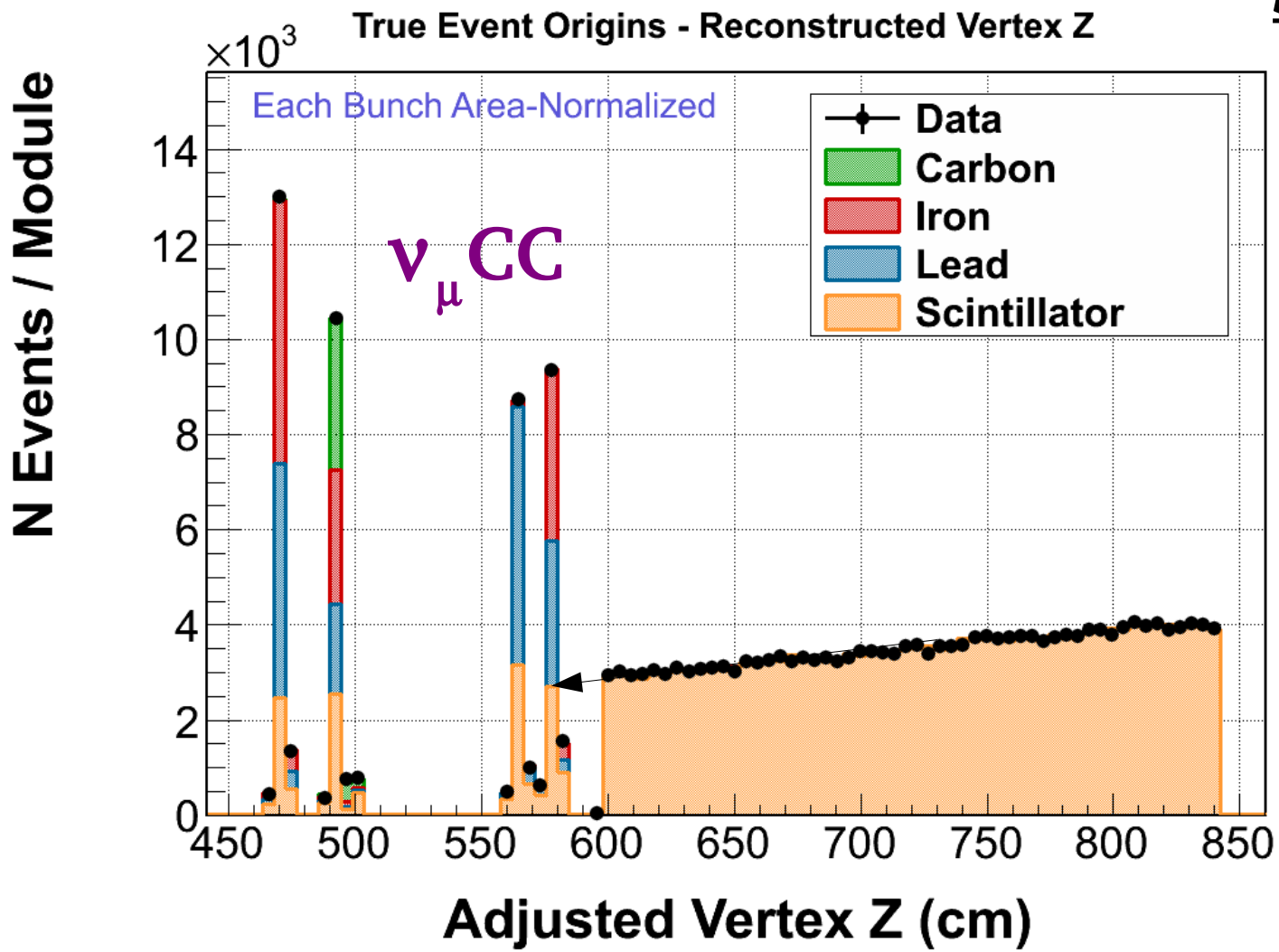
Target #5 ν_μCC







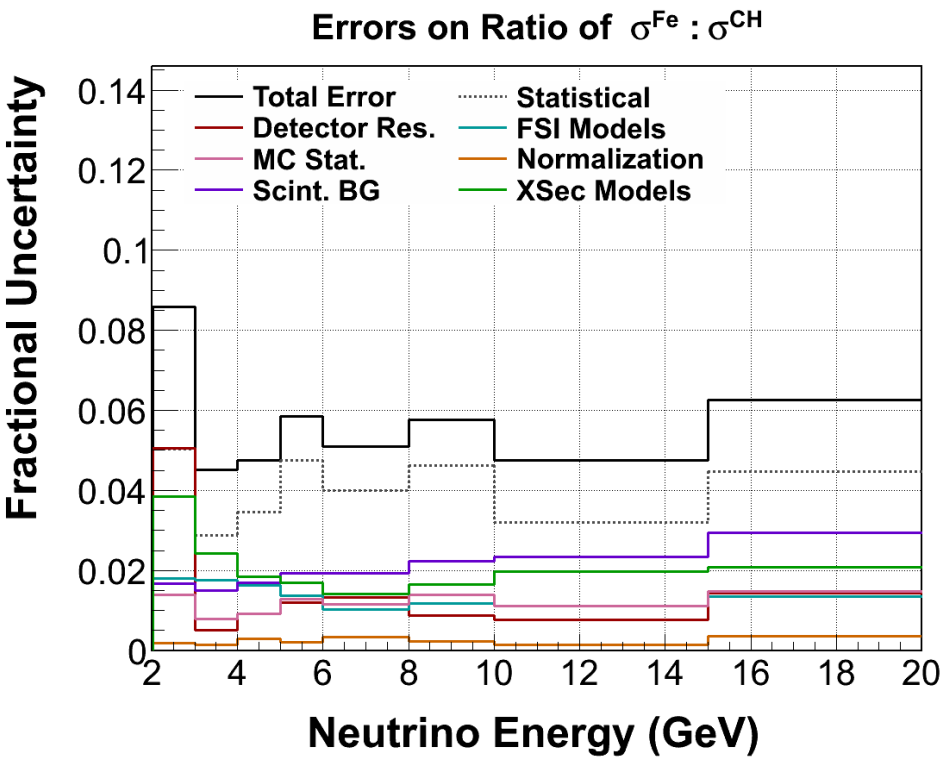
Constraining Plastic Background

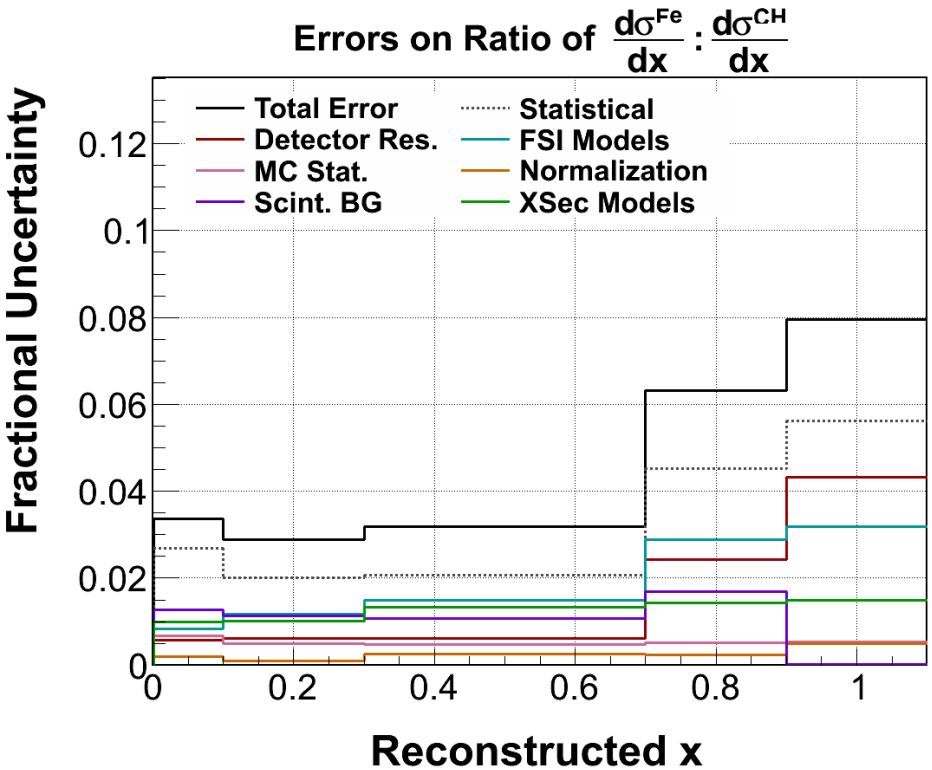


Strategy, in brief

- Use the observed event rate in the scintillator tracker region to predict the event rate at each of the targets
- Use the MC to correct for acceptance and efficiency differences between the two locations

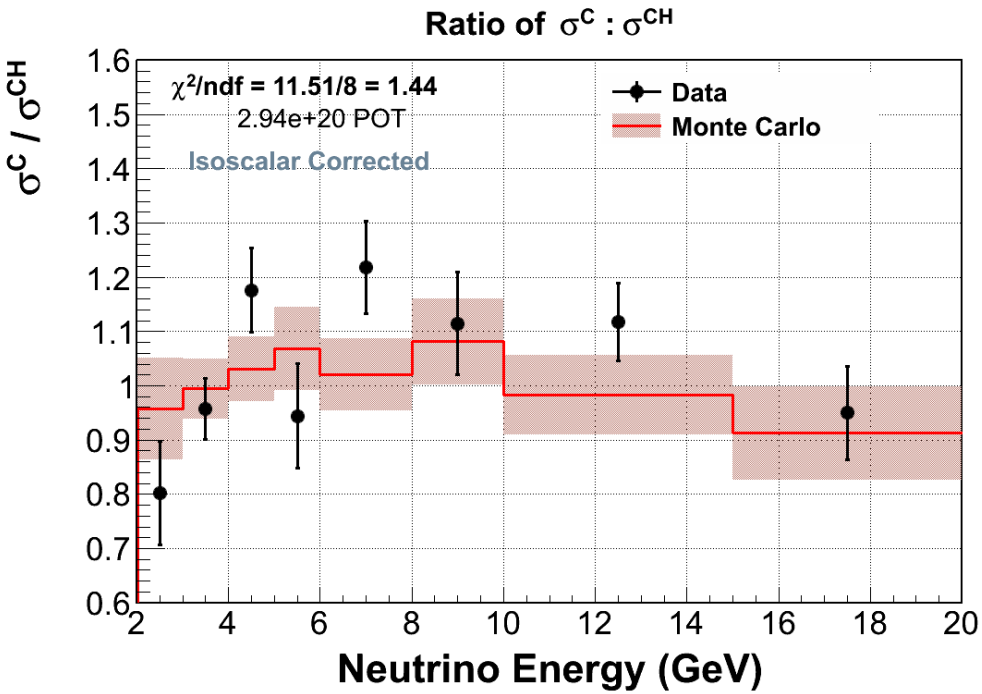
Systematic Uncertainties

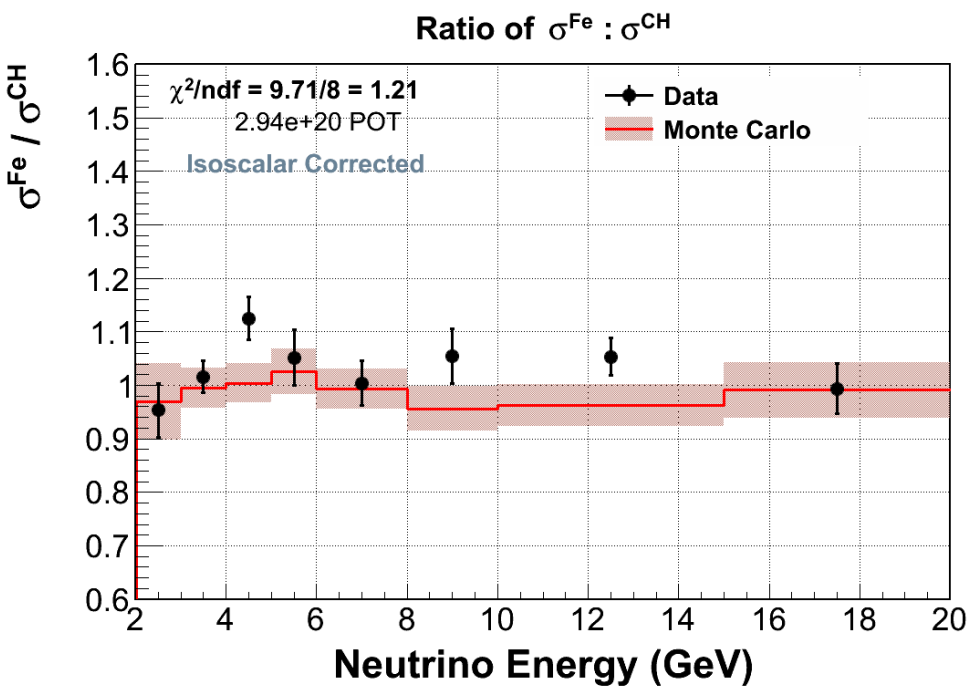


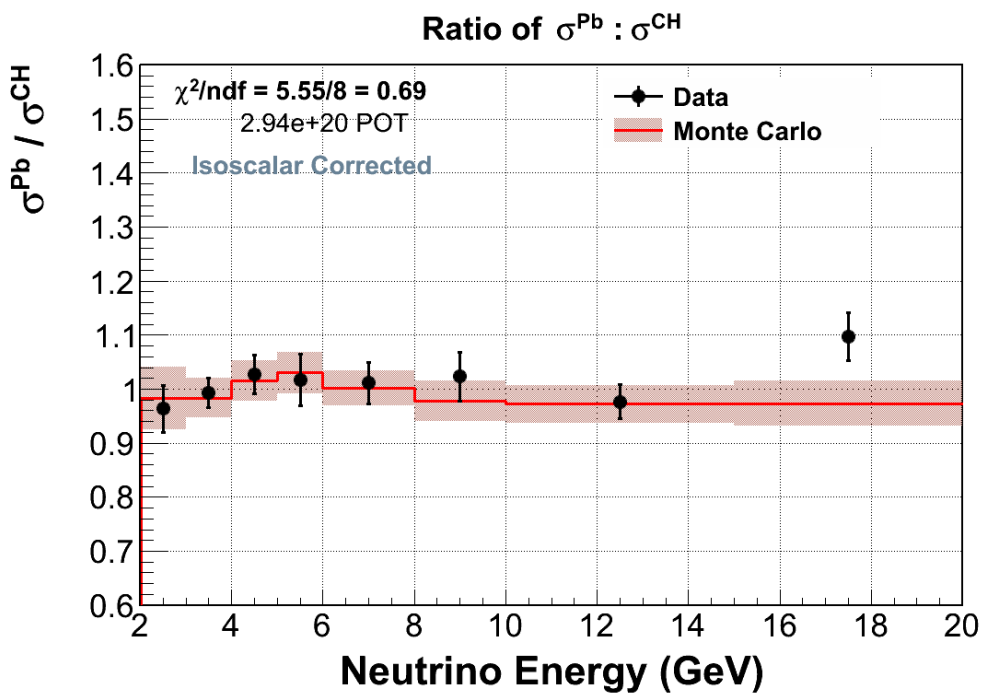


Uncertainties on the cross-section ratios are at the few % level

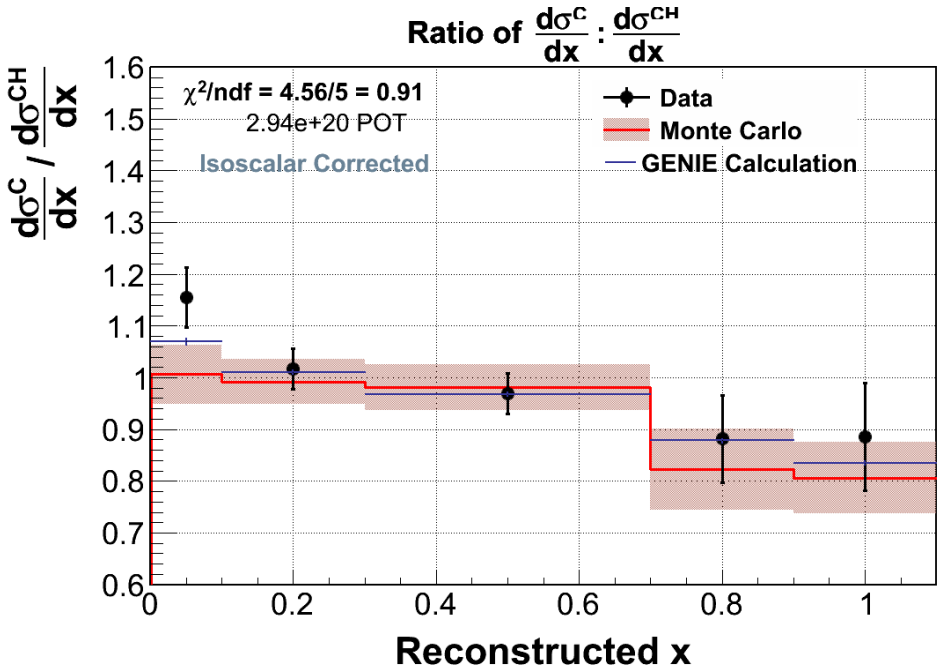
Energy Dependence



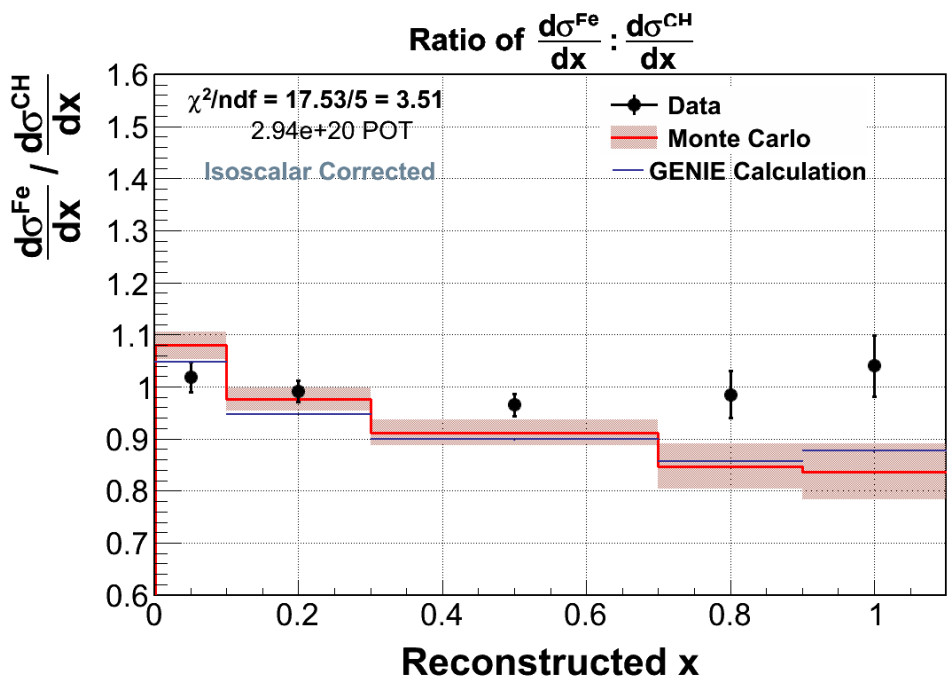


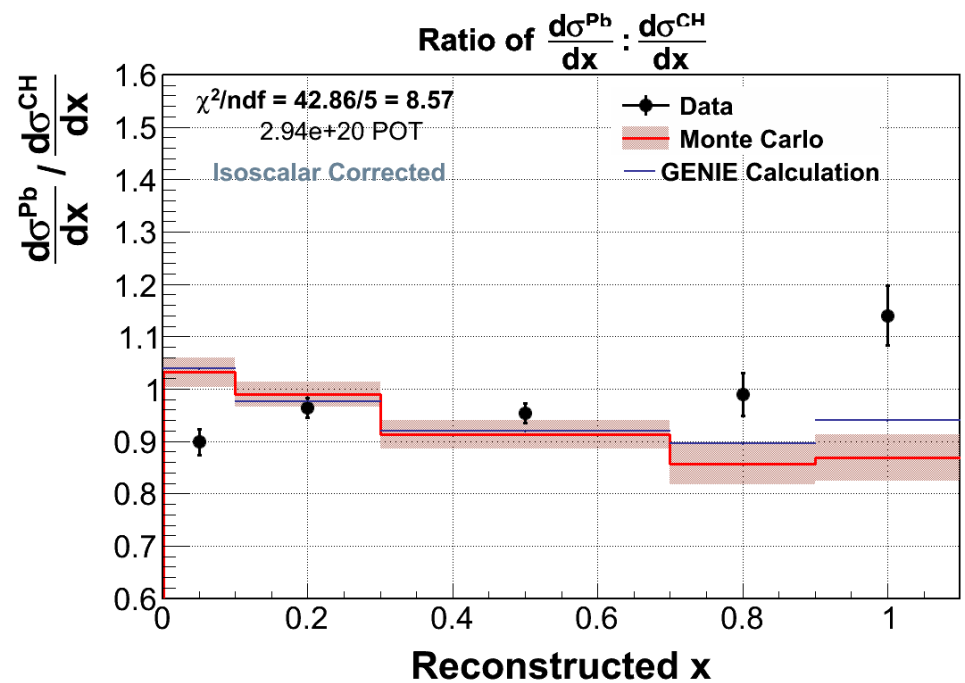


X_{Bj} Dependence



- *Heavy smearing in x → no unfolding done, instead publish smearing matrix.*
- **A** *dependent deficit (excess) at low (high) x not in simulation*





Other analyses in progress

- QEL:
  - two tracks. Q^2 reco with muon and proton arms compared
  - $d^2\sigma/d\theta_\mu\, dp_\mu$ for numu and numubar
  - Michel tag to remove inelastic background
  - nuclear targets
- ν_e QEL, K production, Inclusive CC, DIS target ratios, & the flux
- Many additional channels (e.g., all νA NC) and the ME beam adds kinematic reach to existing measurements.
- Also, for LBNE I hope the community will engage in a generator tuning effort similar to that of the collider program.

MINERνA has more channels to measure than people to do the work.

Analysis infrastructure is well developed.

Room for additional LBNE collaborators to get involved, measure cross-sections of interest, and train the next generation.

Discussion

- Flux
  - Understanding the flux is really an experiment unto itself: hadron production, mu mons, in-situ
- Test beam
  - We use the testbeam data over and over and are considering collecting more → CAPTAIN / LArIAT
- Systematic infrastructure
  - Many universes very powerful
  - Needs to be designed in early on
  - Lots of accounting (e.g., for detector systematics)
- Exiting energy
  - I wish we had better muon coverage and we clearly lose some energy from neutrons

Centro Brasileiro de Pesquisas Físicas
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Mass. Col. Lib. Arts
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Pontificia Universidad Catolica del Peru
University of Pittsburgh
University of Rochester
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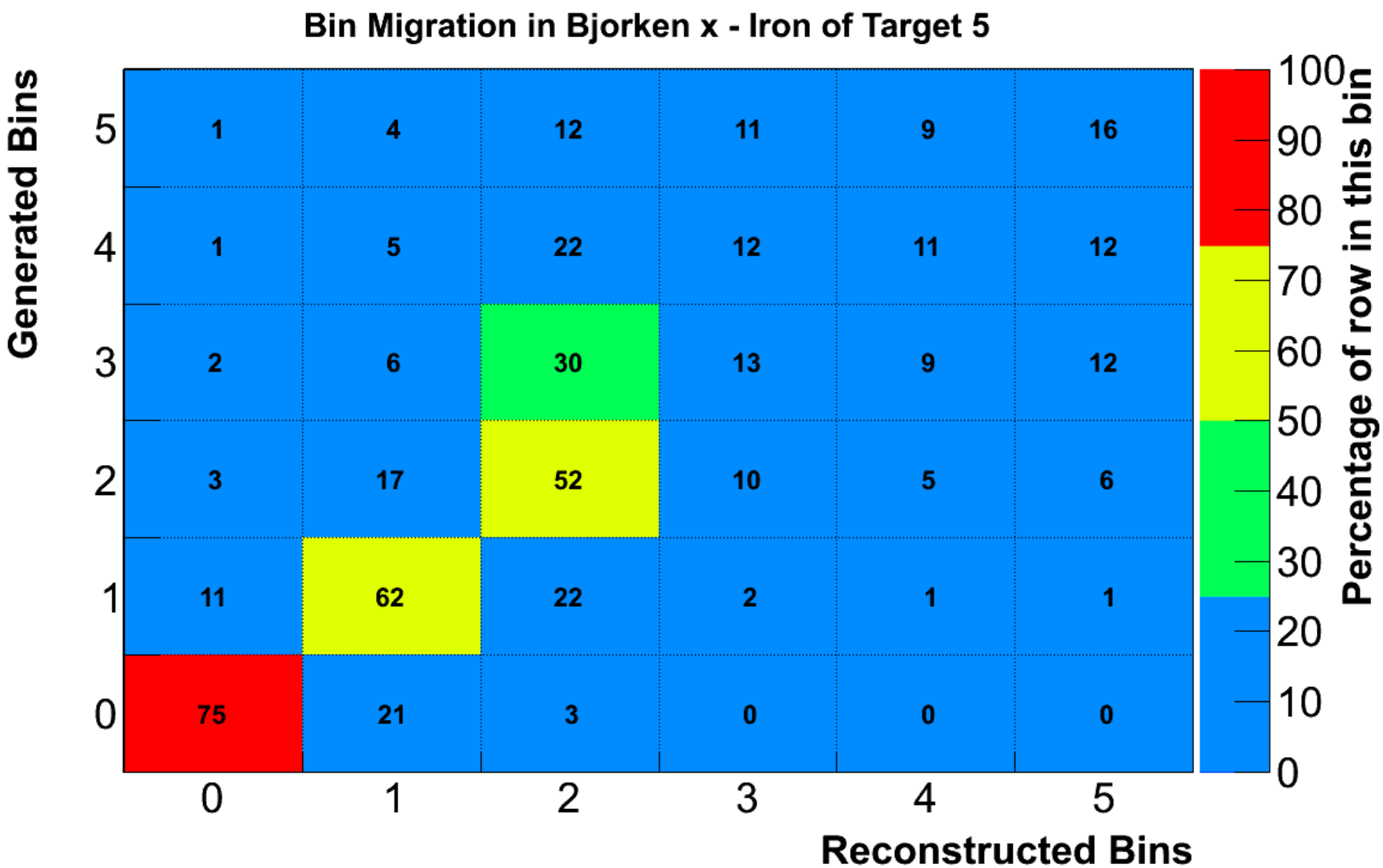
University of Minnesota at Duluth
Universidad Nacional de Ingeniería
Universidad Técnica Federico Santa María
William and Mary

X_{Bj} smearing



Cross Section Model Uncertainties

Uncertainty	1 σ
M_A (Elastic Scattering)	± 25%
Eta (Elastic scattering)	± 30%
M_A (CCQE Scattering)	+25% –15%
CCQE Normalization	+20% –15%
CCQE Vector Form factor model	on/off
CC Resonance Normalization	± 20%
M_A (Resonance Production)	± 20%
M_V (Resonance Production)	± 10%
1pi production from $\nu p / \bar{\nu} n$ non-resonant interactions	± 50%
1pi production from $\nu n / \bar{\nu} p$ non-resonant interactions	± 50%
2pi production from $\nu p / \bar{\nu} n$ non-resonant interactions	± 50%
2pi production from $\nu n / \bar{\nu} p$ non-resonant interactions	± 50%
Modfiy Pauli blocking (CCQE) at low Q^2 (change PB momentum threshold)	± 30%

Intranuclear Rescattering Uncertainties

Uncertainty	1 σ
Pion mean free path	± 20%
Nucleon mean free path	± 20%
Pion fates – absorption	± 30%
Pion fates – charge exchange	± 50%
Pion fates – Elastic	± 10%
Pion fates – Inelastic	± 40%
Pion fates – pion production	± 20%
Nucleon fates – charge exchange	± 50%
Nucleon fates – Elastic	± 30%
Nucleon fates – Inelastic	± 40%
Nucleon fates – absorption	± 20%
Nucleon fates – pion production	± 20%
AGKY hadronization model – x_F distribution	± 20%
Delta decay angular distribution	On/off
Resonance decay branching ratio to photon	± 50%

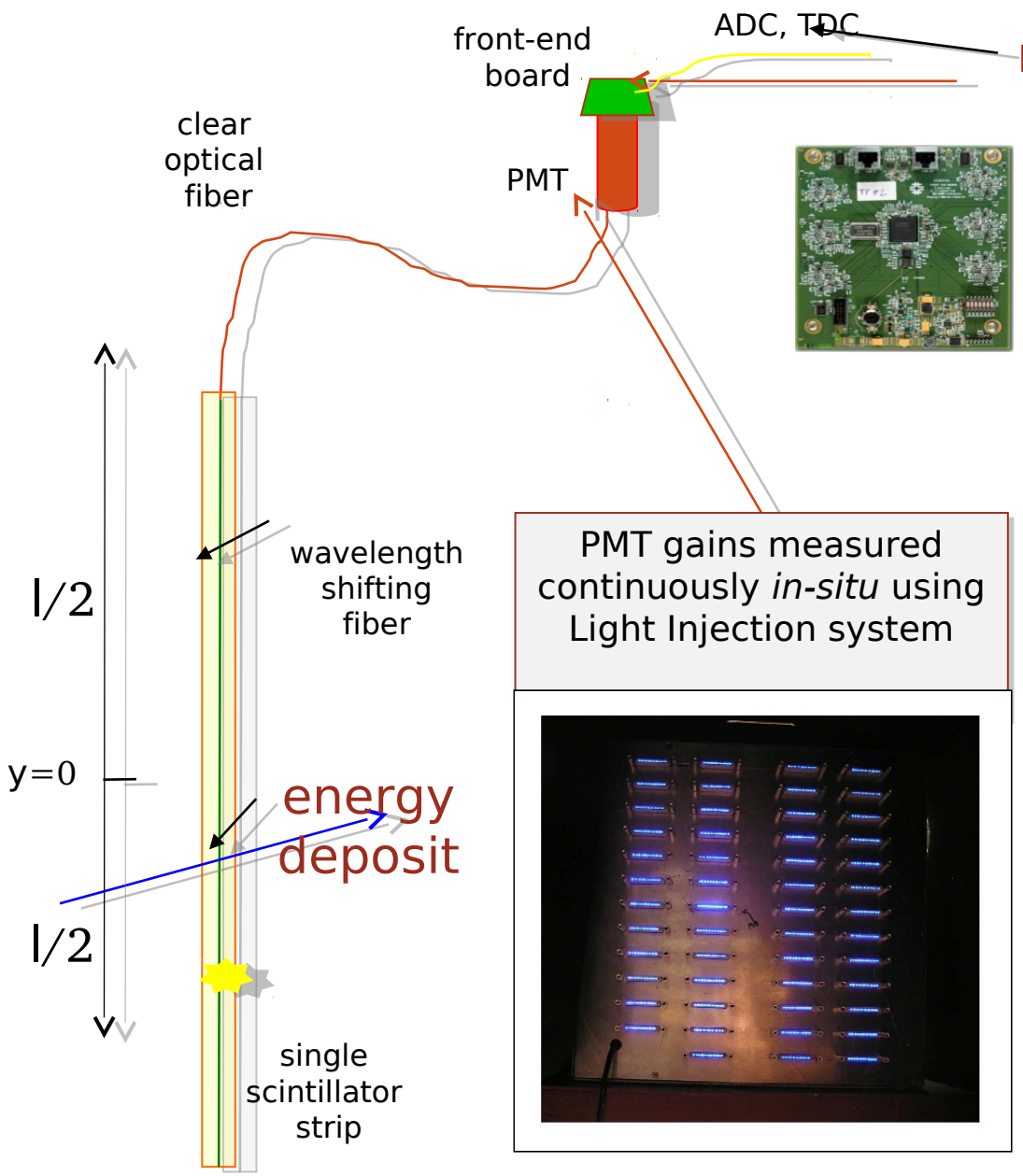
References: (1) www.genie-mc.org, (2) arXiv:0806.2119, (3) D. Bhattacharya, Ph. D Thesis (U. Pittsburgh) 2009.

Nuclear Target Event Rates

Target	Fiducial Mass	ν_μ CC Events in 1.0e20 P.O.T.
Plastic	6.43 tons	340k
Helium	0.25 tons	14k
Carbon	0.17 tons	9.0k
Water	0.39 tons	20k
Iron	0.97 tons	54k
Lead	0.98 tons	57k

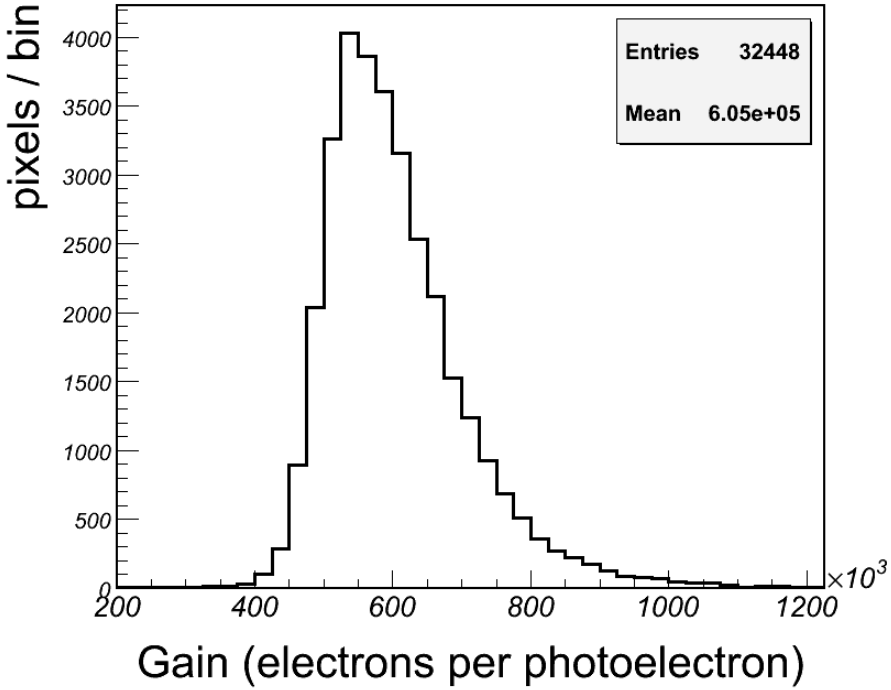
GENIE 2.6, FLUKA08, 90cm radius, 116 tracker modules

Detector Calibration

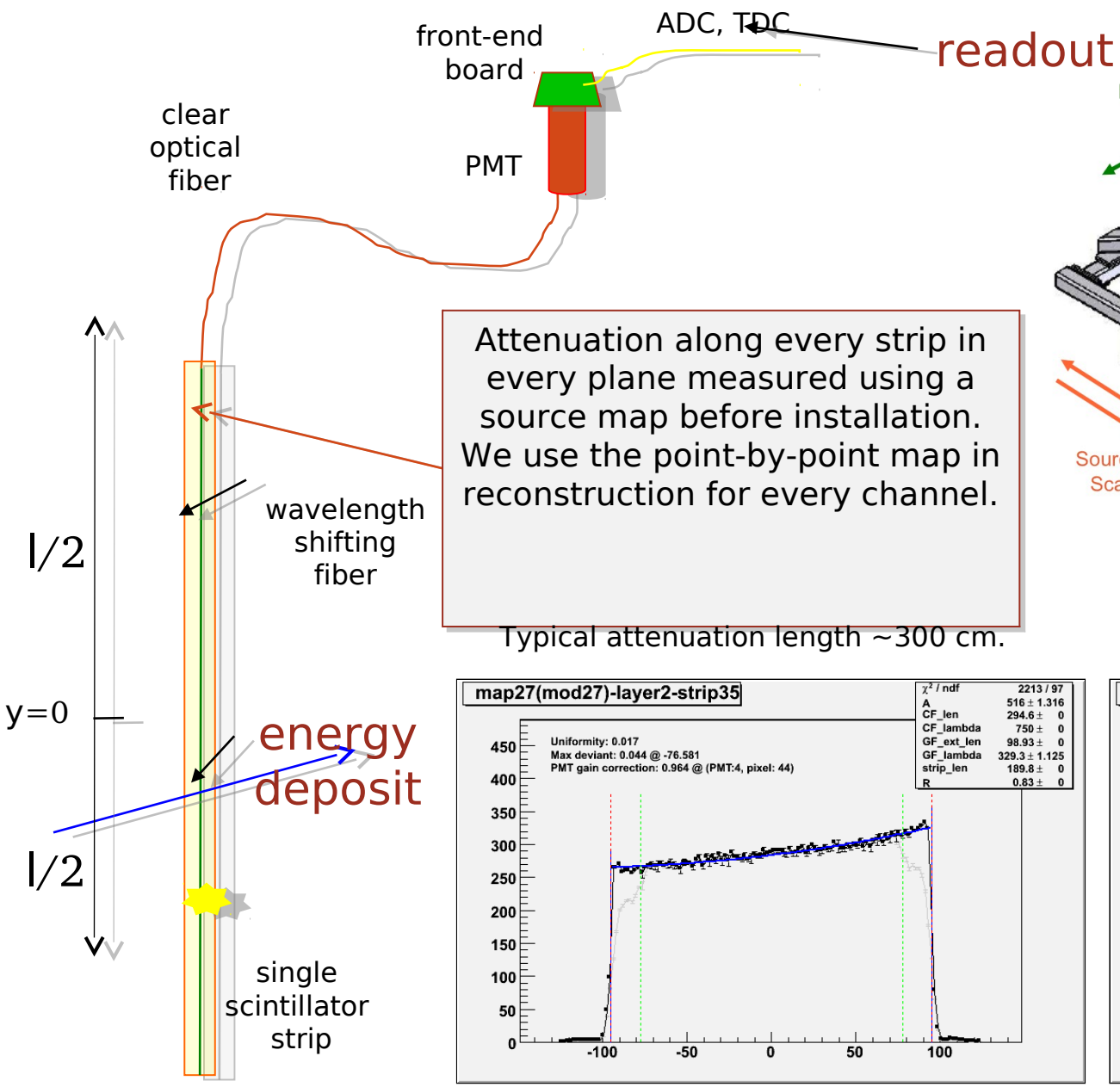


Charge to ADC conversion function measured on a test stand for every channel on every board before installation on the detector

PMT gains measured continuously *in-situ* using Light Injection system

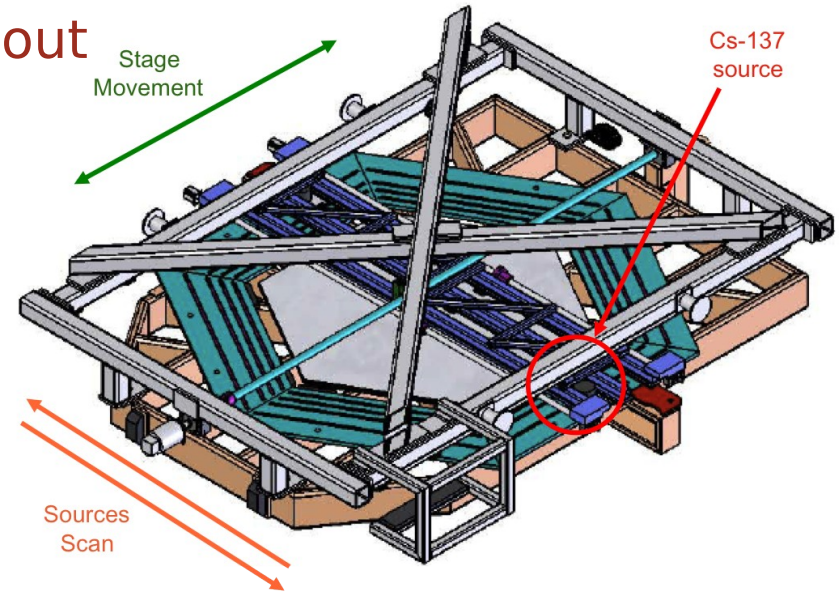


Detector Calibration

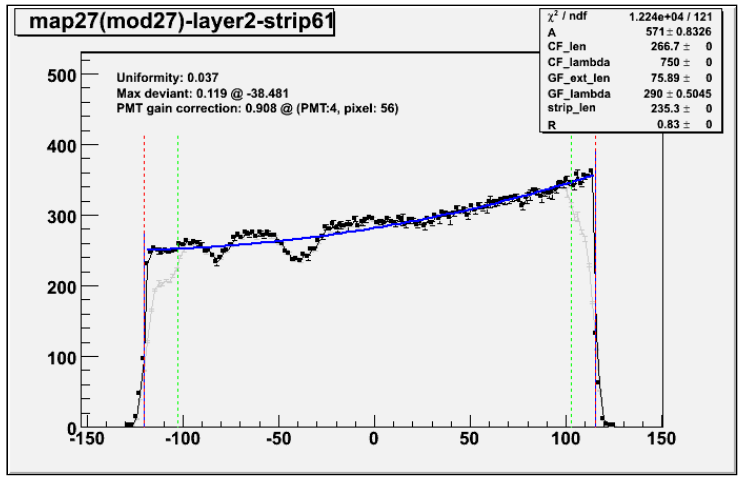


Attenuation along every strip in every plane measured using a source map before installation. We use the point-by-point map in reconstruction for every channel.

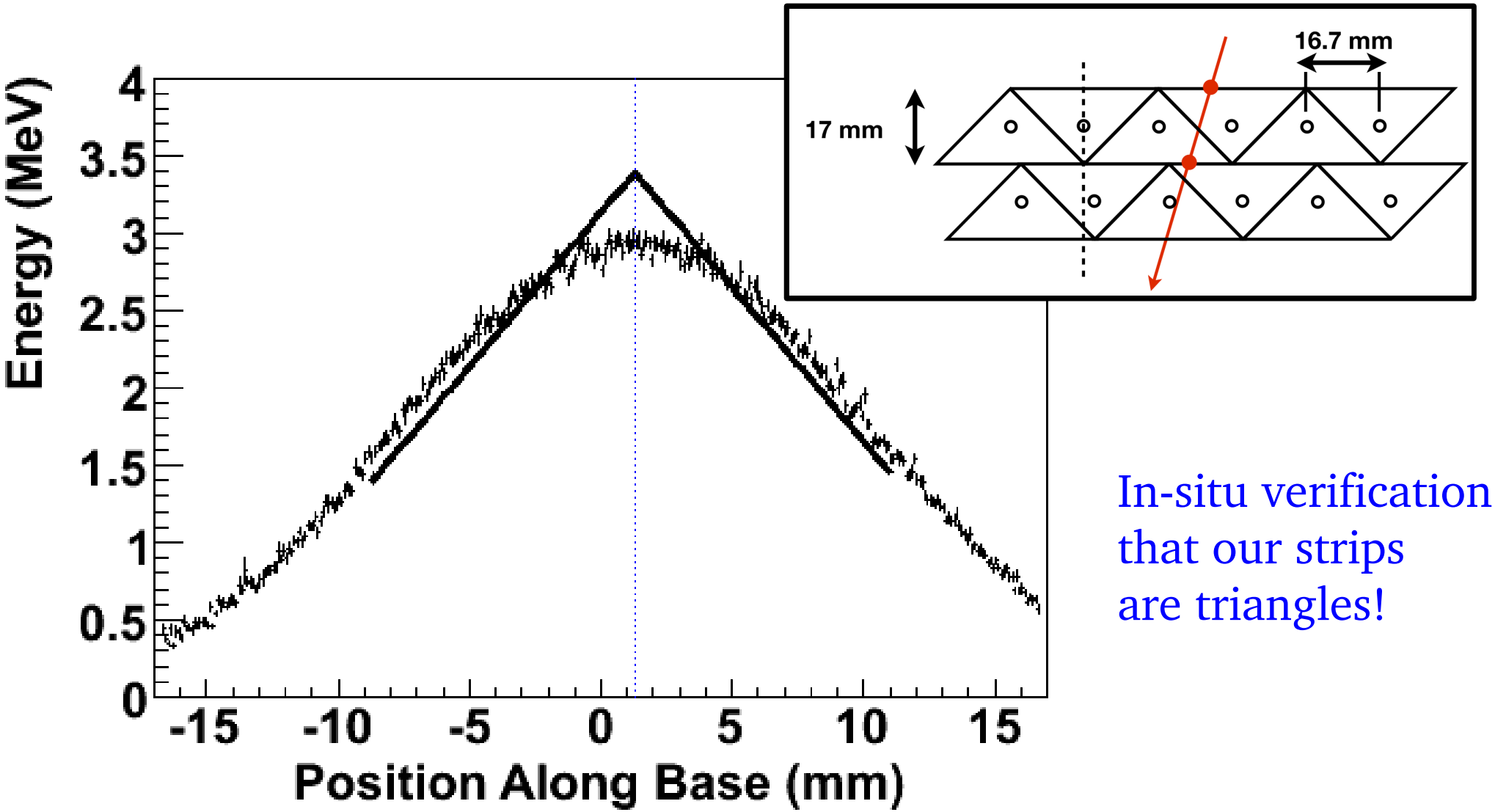
Typical attenuation length ~300 cm.



Map can find non-uniformities along the strip (e.g. air pockets in glue)



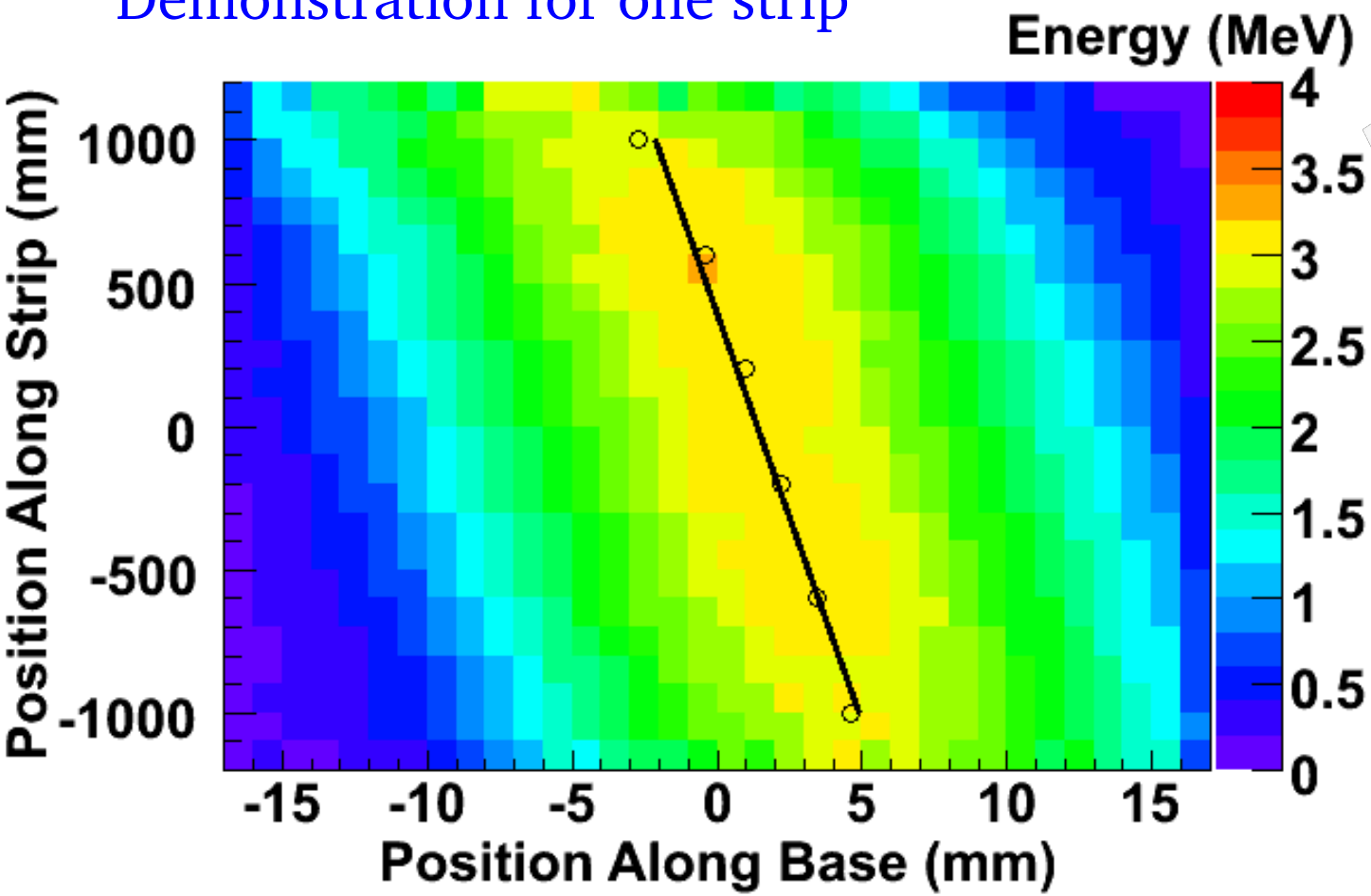
Alignment and strip response

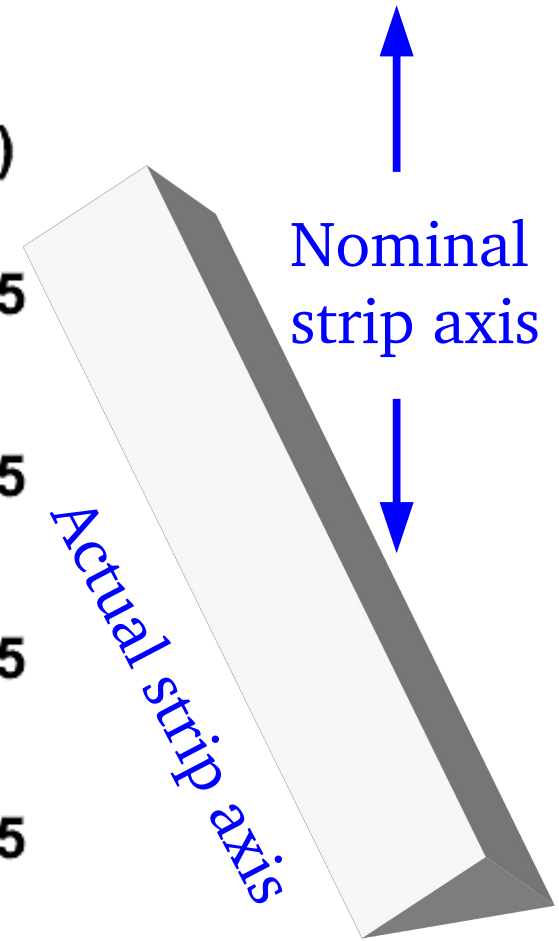


In-situ verification that our strips are triangles!

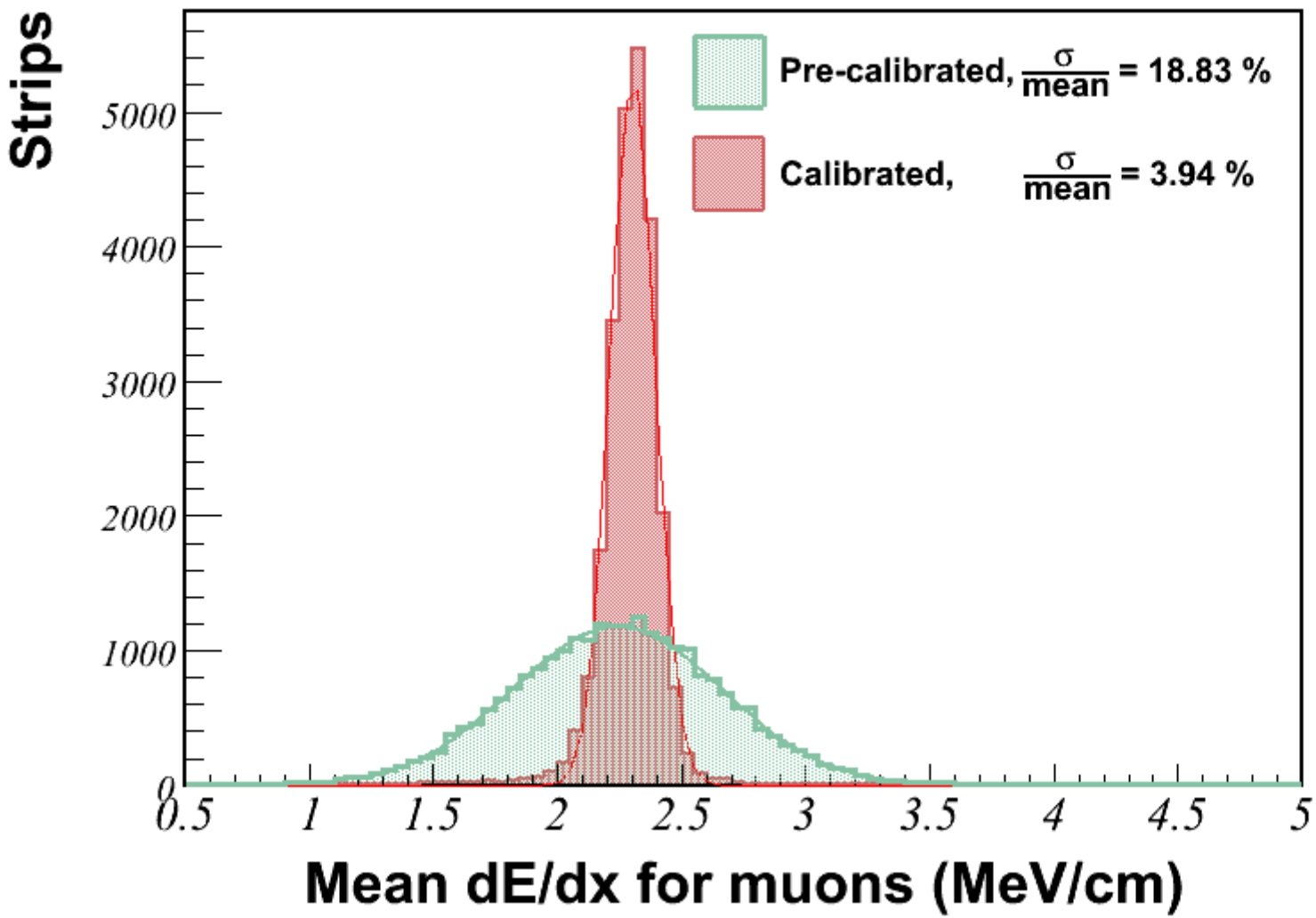
Alignment and strip response

Demonstration for one strip

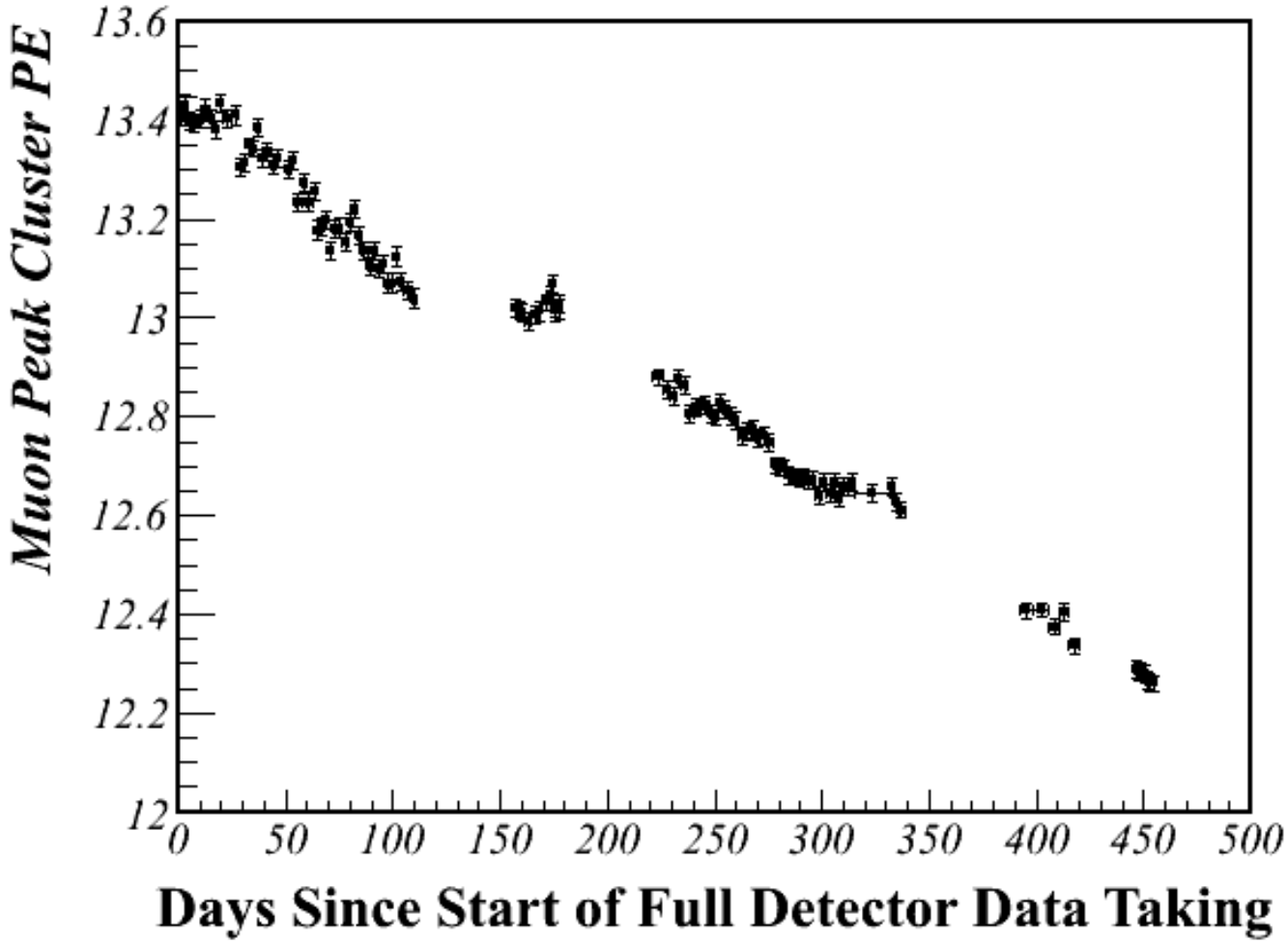




Alignment and strip response



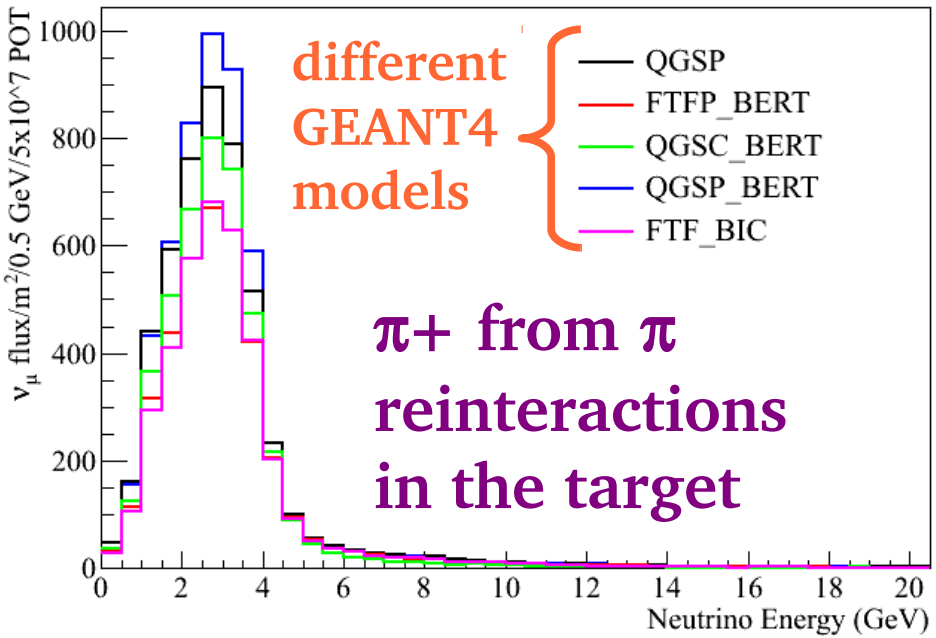
Response vs. Time

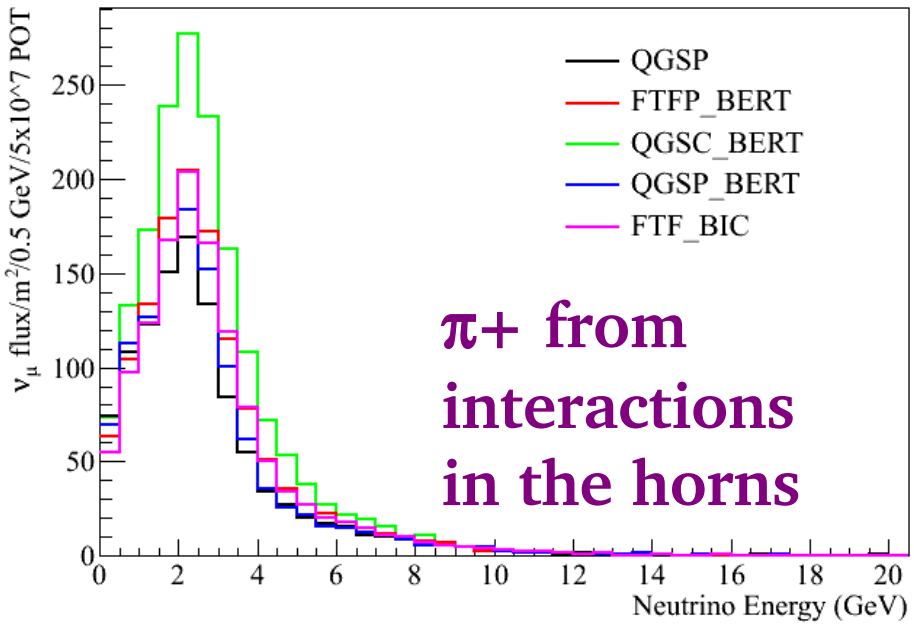


Minerva 1 (days 0-107): light loss = 10.1% per year
Minerva 5 (days 222-335): light loss = 7.1% per year

Model Spread Uncertainties

Non-NA49 uncertainties from maximum model spread





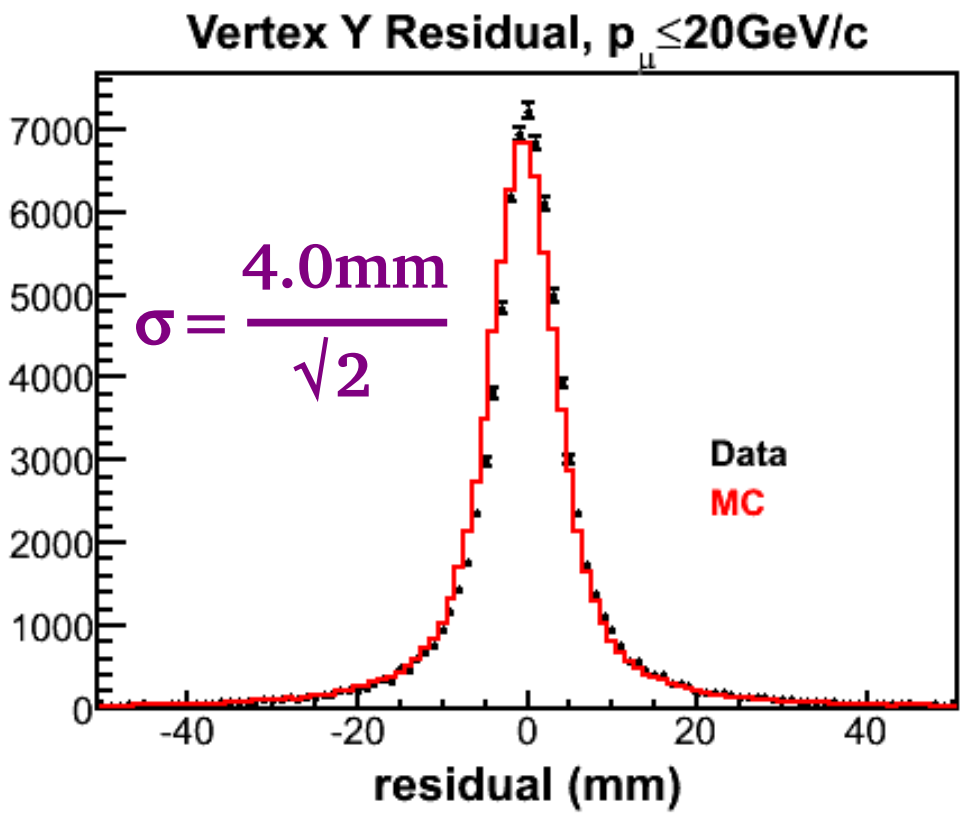
Categories

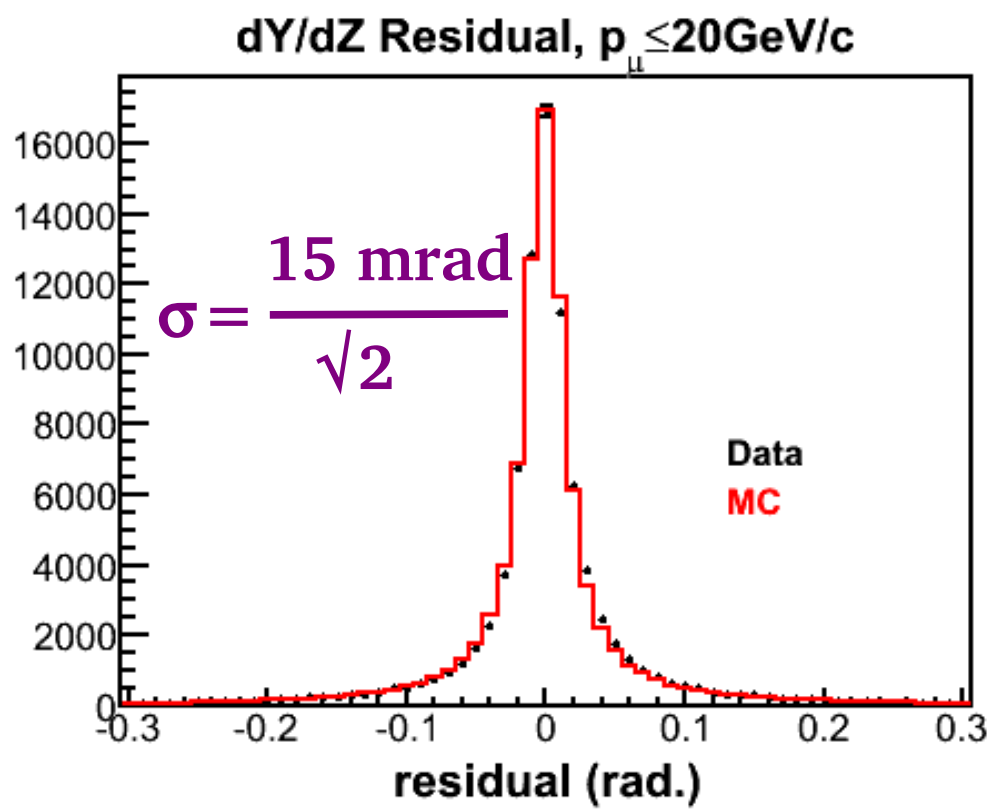
π,K,p,n,other secondary interactions in target

production in horns, decay pipe walls& He, target hall chase

Large project to
(a) add more models
(b) gradually replace model spread with existing and new data

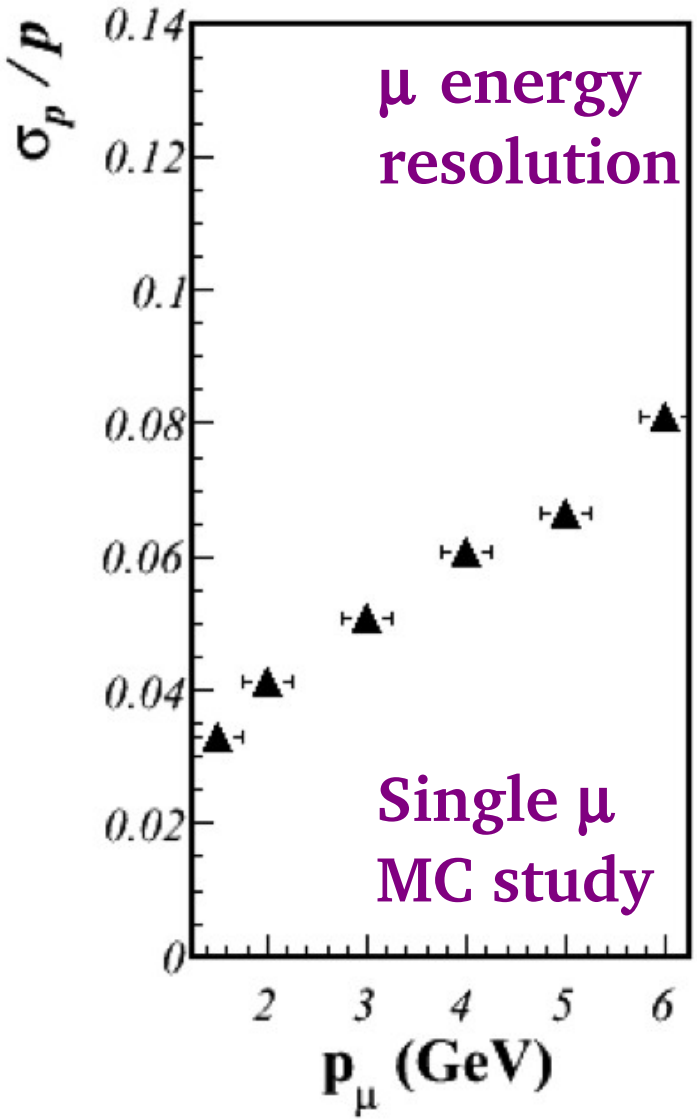
Tracking resolutions

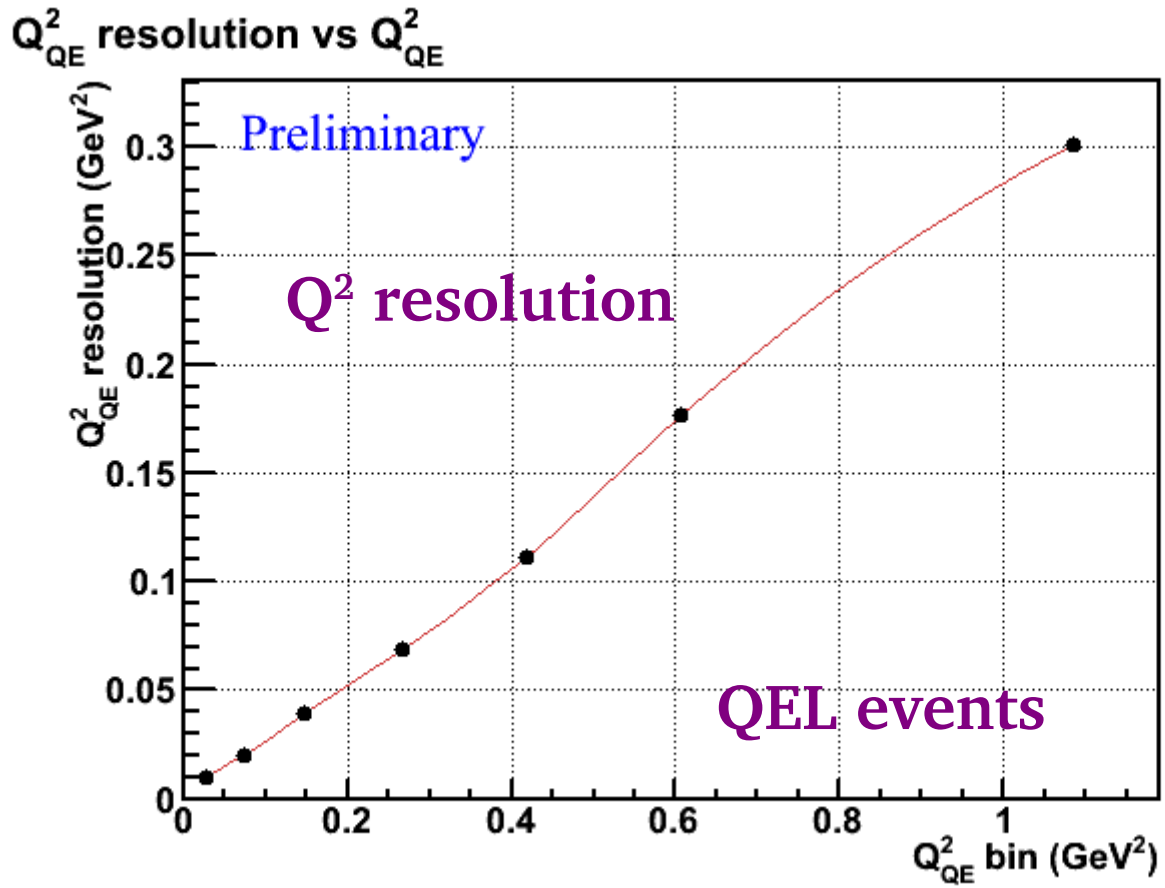




Split-track study of rock μ in tracker region

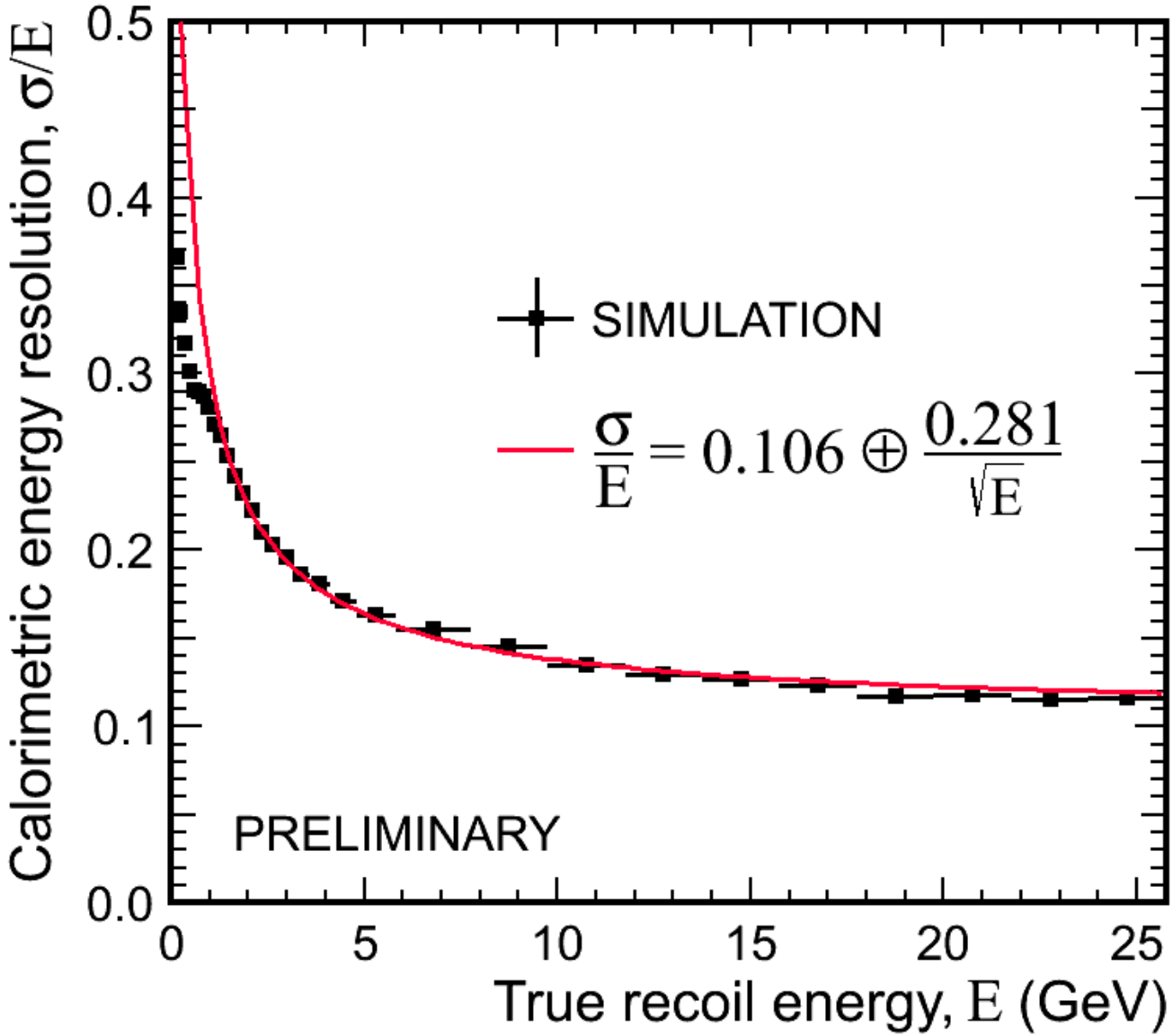
μ energy & Q^2 resolution



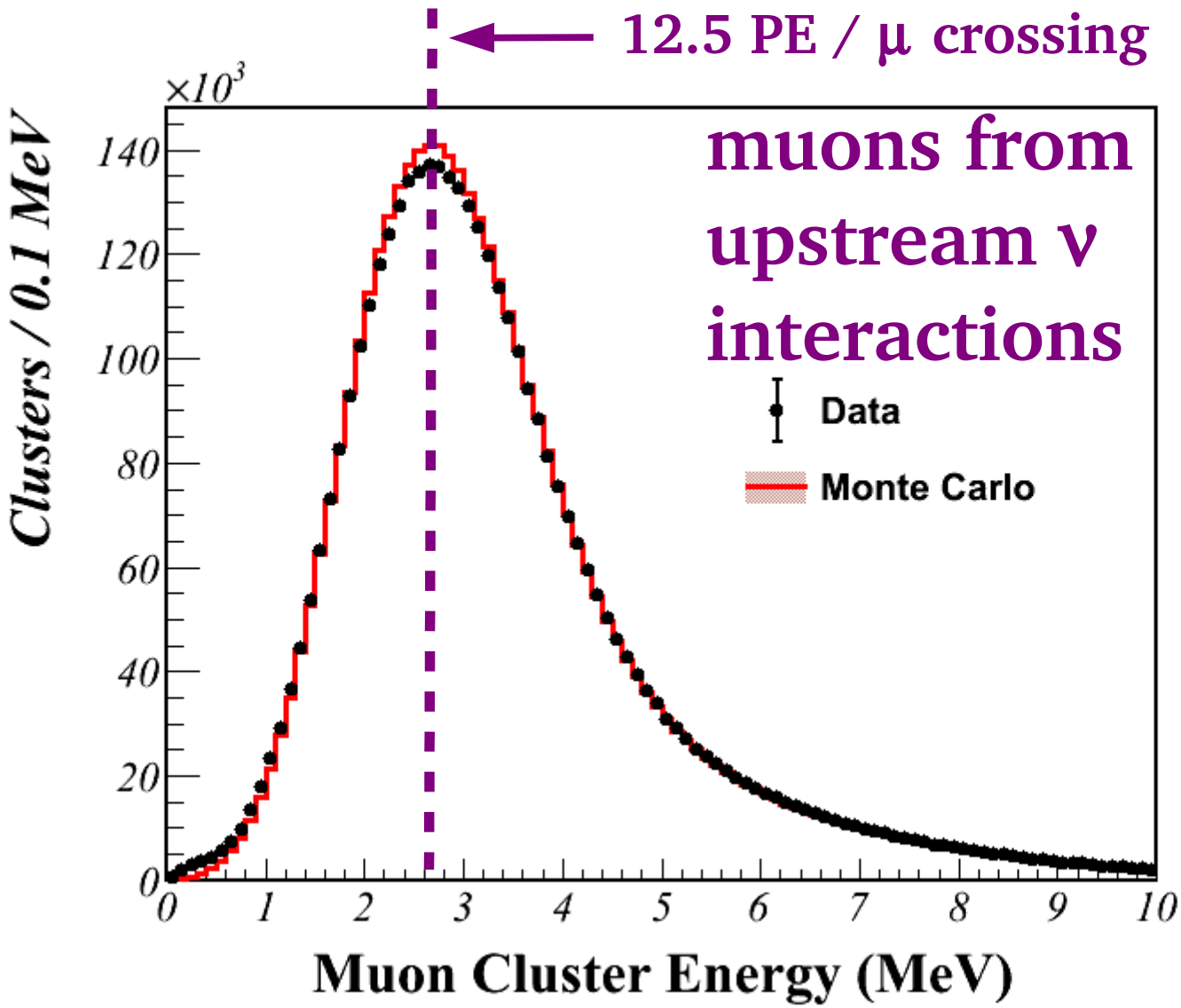


Q^2 = (4-momentum transfer)^2

shower energy resolution



visible energy scale



GENIE

QEL: BBBA05 FF, M_A is 0.99 GeV/c^2

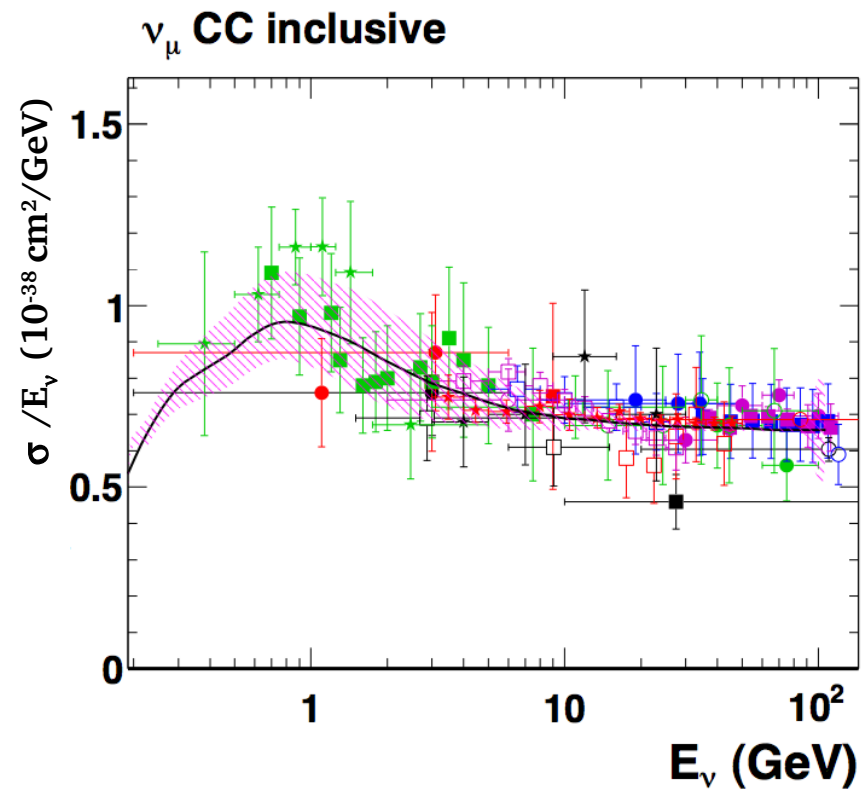
Resonance: Rein & Sehgal (K, ρ, η production, Δ-Nγ)

Coherent-π: Rein-Sehgal

DIS: GRV94/GRV98 with Bodek-Yang

DIS and QEL charm (S.G.Kovalenko, Sov.J.Nucl.Phys.52:934 (1990))

1π and 2π channels tuned in transition region to electron scattering and neutrino data.



Nuclear Model: RFGM with NN correlations

Hadronization Model: AGKY – transitions between KNO-based and JETSET

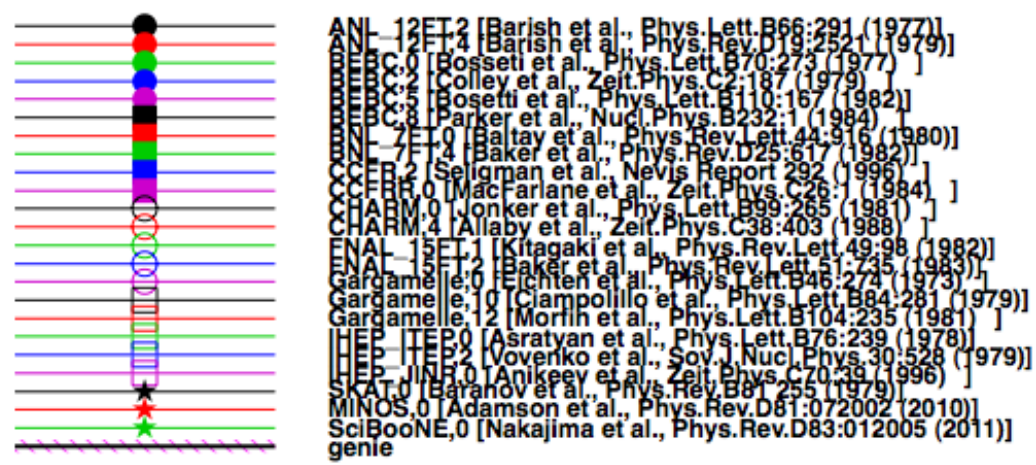
T. Yang, AIP Conf. Proc.967:269-275 (2007)

Formation zone: SKAT μ^2=0.08 GeV^2

Intranuclear Rescattering: cascade model

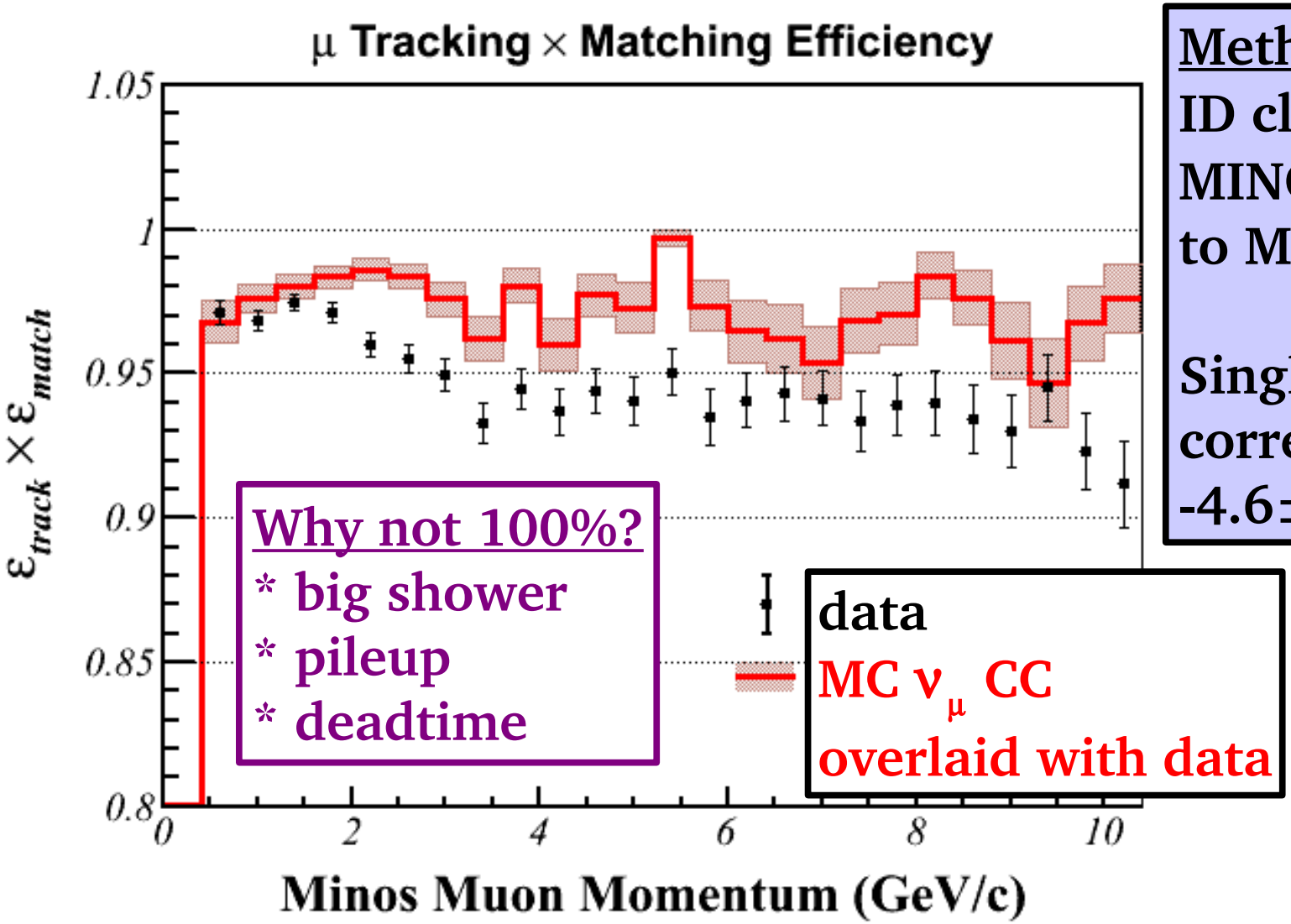
INTRANUKE-hA (*S. Dytman, AIP Conf Proc, 896, pp. 178-184 (200*

anchored to π,p/n-Fe data, scaled to all nucl



www.genie-mc.org; NIM A614 (2010) 87-104

Tracking x Matching Efficiency



Method

ID clean μ in MINOS, point back to MINERvA

Single event MC correction -4.6±2.5%

Normalization corrections

ν_μ beam

Source	MC scale factor	uncertainty
MINERvA tracking efficiency	0.956	2.5%
MINOS μ acceptance	0.975	2.5%
MINOS pileup	0.972	0.6%
Catastrophic dead time	0.983	1.0%
Signal removed by deadtime cuts*	0.970	0.1%
Mass Model	1.000	1.4%
POT scale	1.000	2.0%
Total	f=0.865	4.0%

reco. effects on single event MC

*QEL analyses only

other