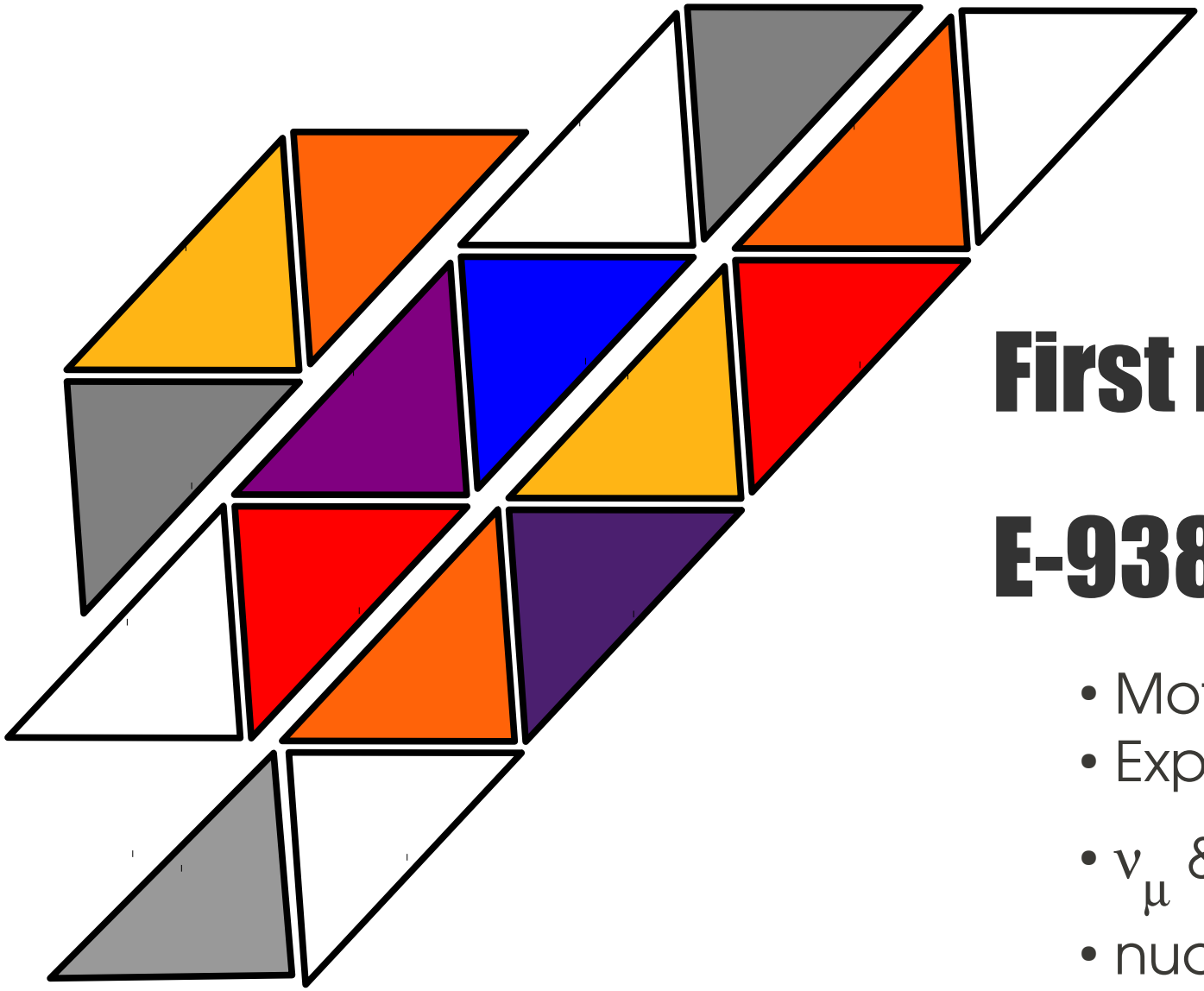


First results from E-938 "MINERvA"

- Motivation
- Experiment
- ν_μ & $\bar{\nu}_\mu$ QEL
- nuclear effects

Mike Kordosky

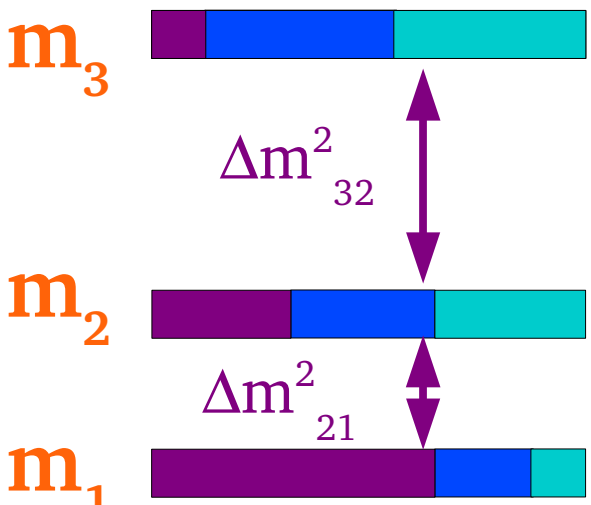
William & Mary

Fermilab Joint Experimental-Theoretical Seminar
June 1, 2012

Motivation: ν oscillations

Flavor "Atmospheric + reactor" parts of PMNS Matrix

Mass e μ τ



Propagation (vacuum)

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

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

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

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

Wanted: precision, δ, mass hierarchy

flavor mass states

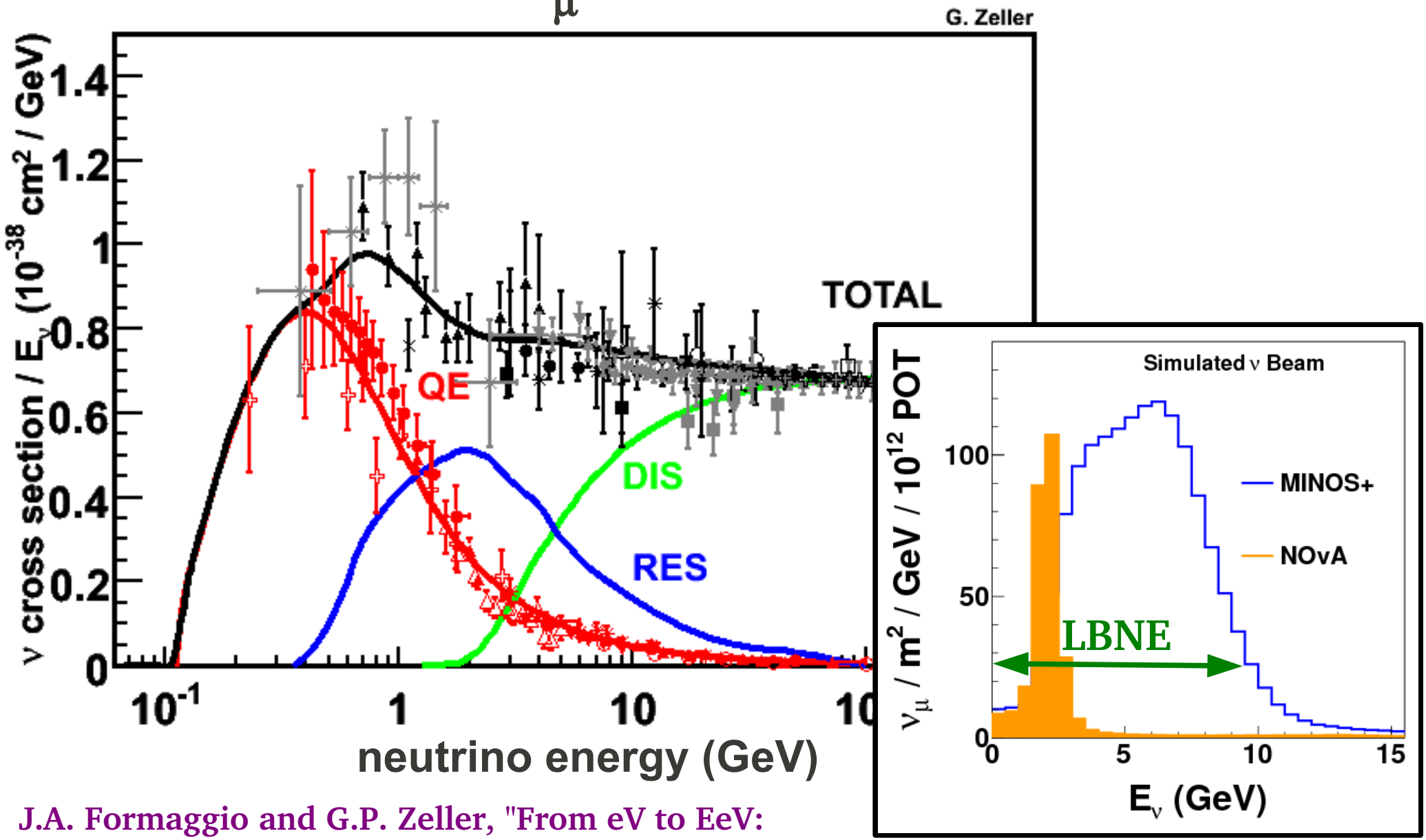
$$|\nu_\alpha(L)\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle \exp(-i L m_j^2/2p)$$

(L=distance)

Must measure

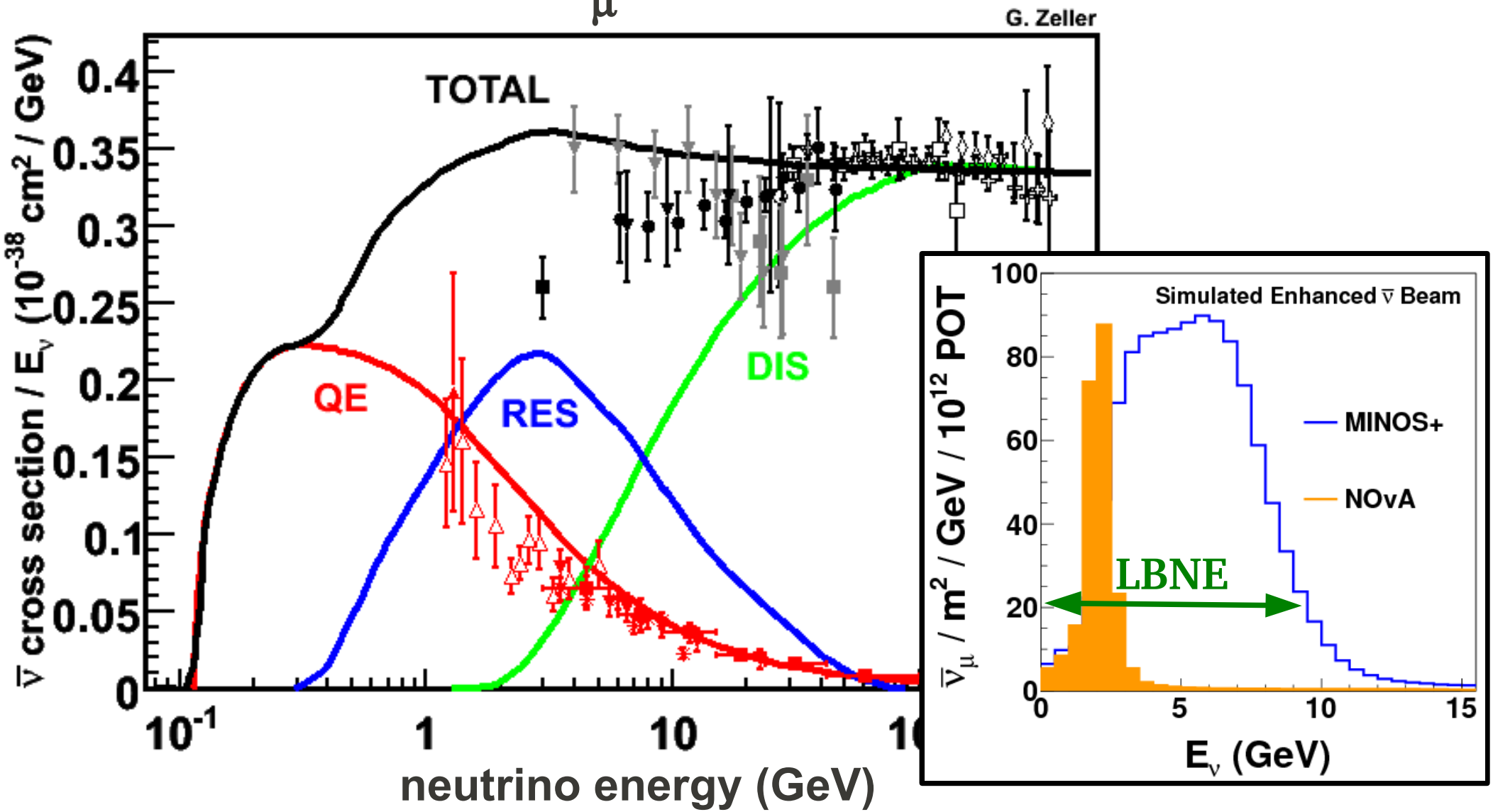
* Flavor
* Energy
* Rate

World ν_μ cross-section



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

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

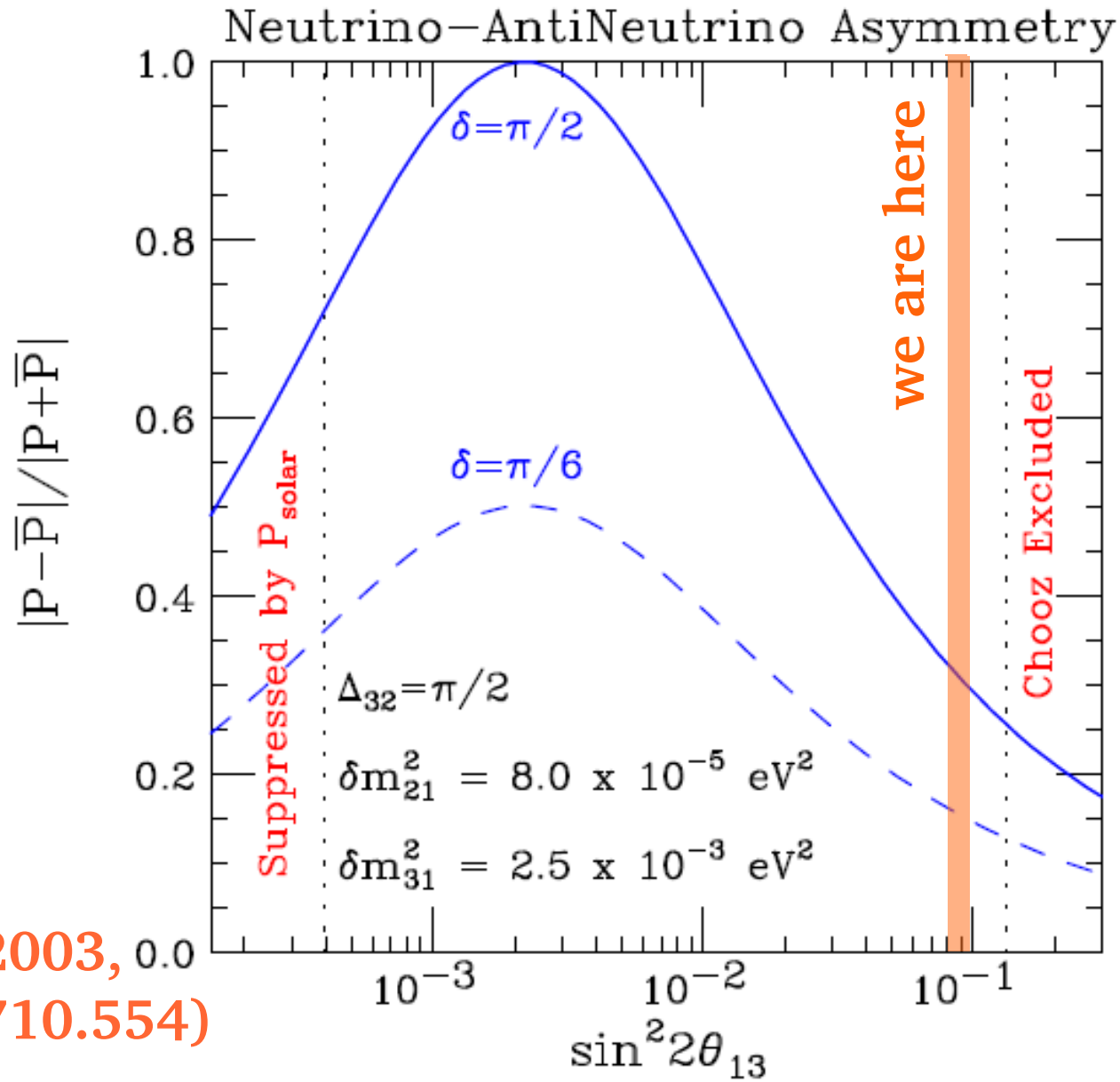


J.A. Formaggio and G.P. Zeller, "From eV to EeV: Neutrino Cross Sections Across Energy Scales", to be published in Rev. Mod. Phys. 2012

implications of large θ_{13}

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

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



(Parke 2003, arXiv:0710.554)

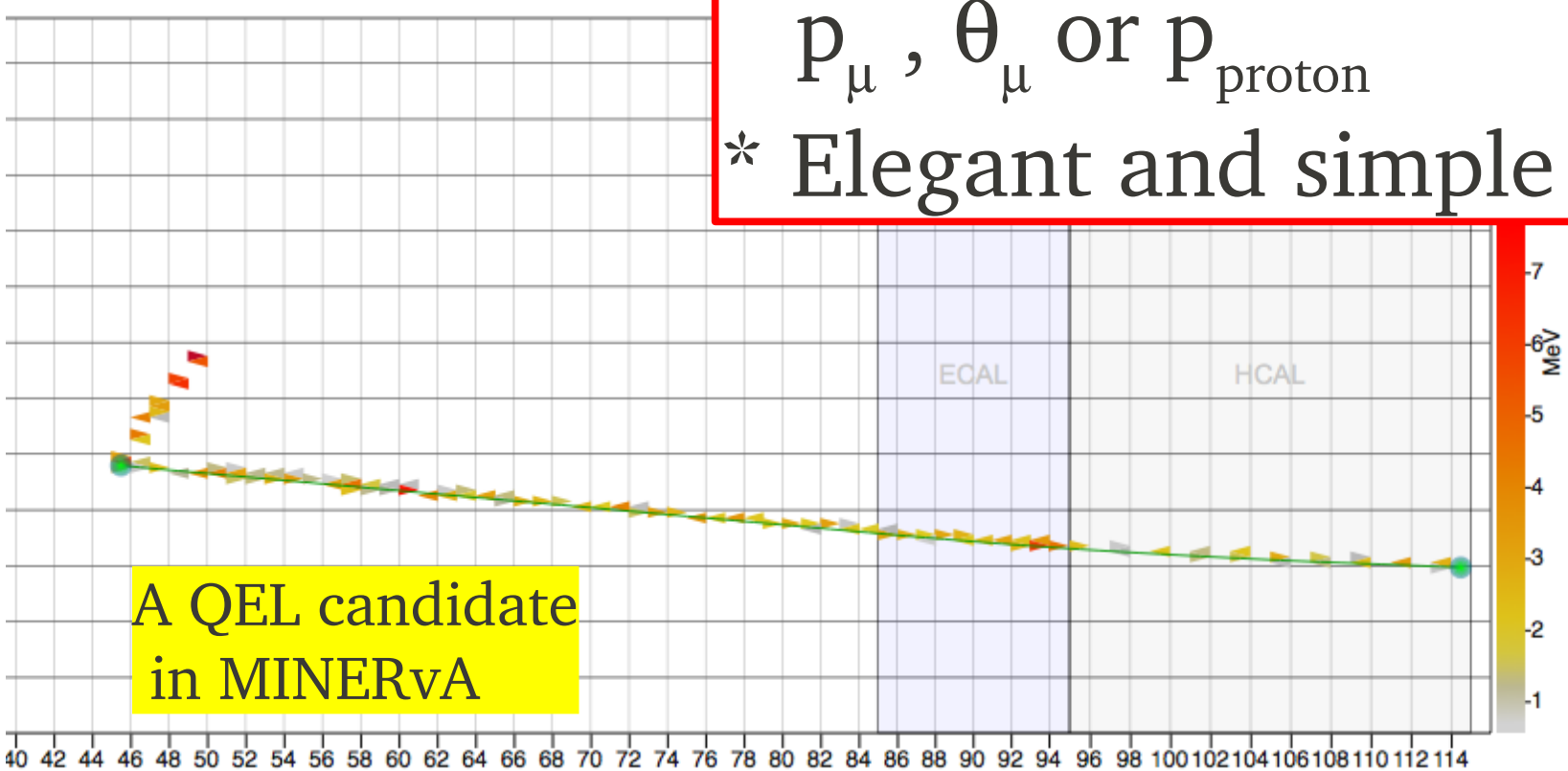
In search of a standard candle

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

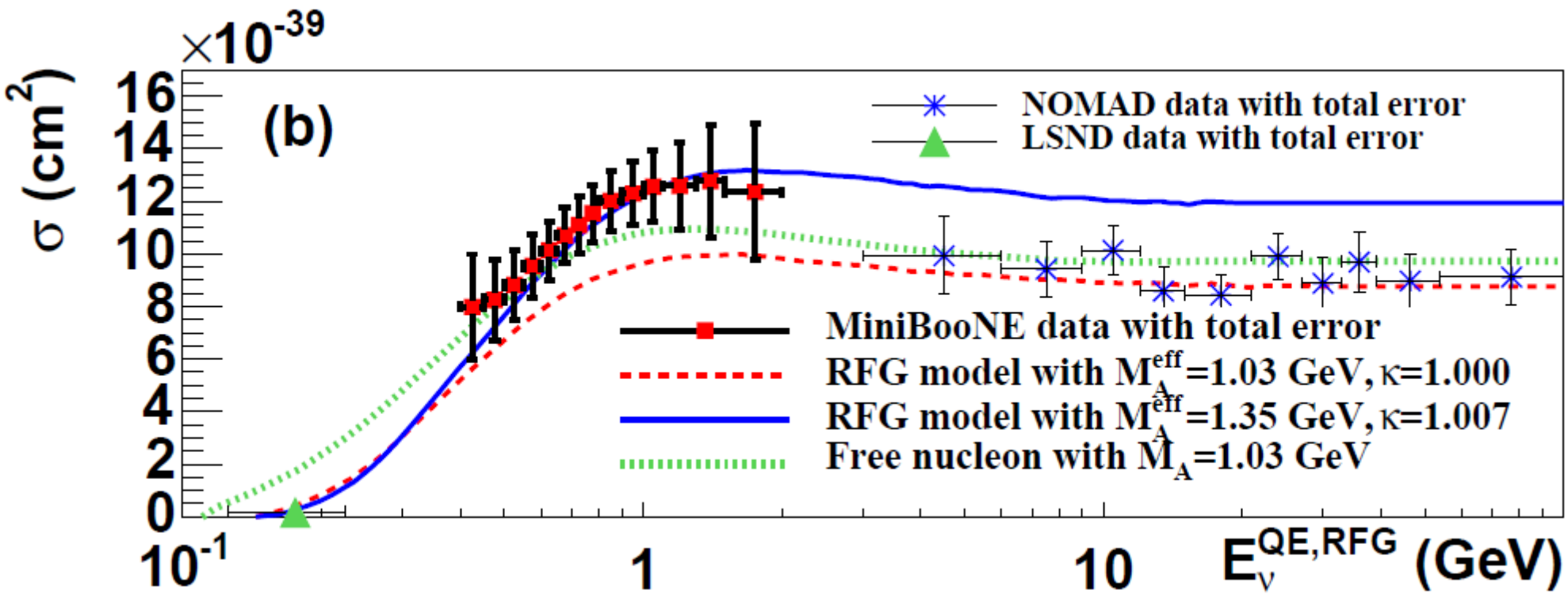
In search of a standard candle

Quasi-elastic scattering

Cons:

* We don't fully understand the energy dependence

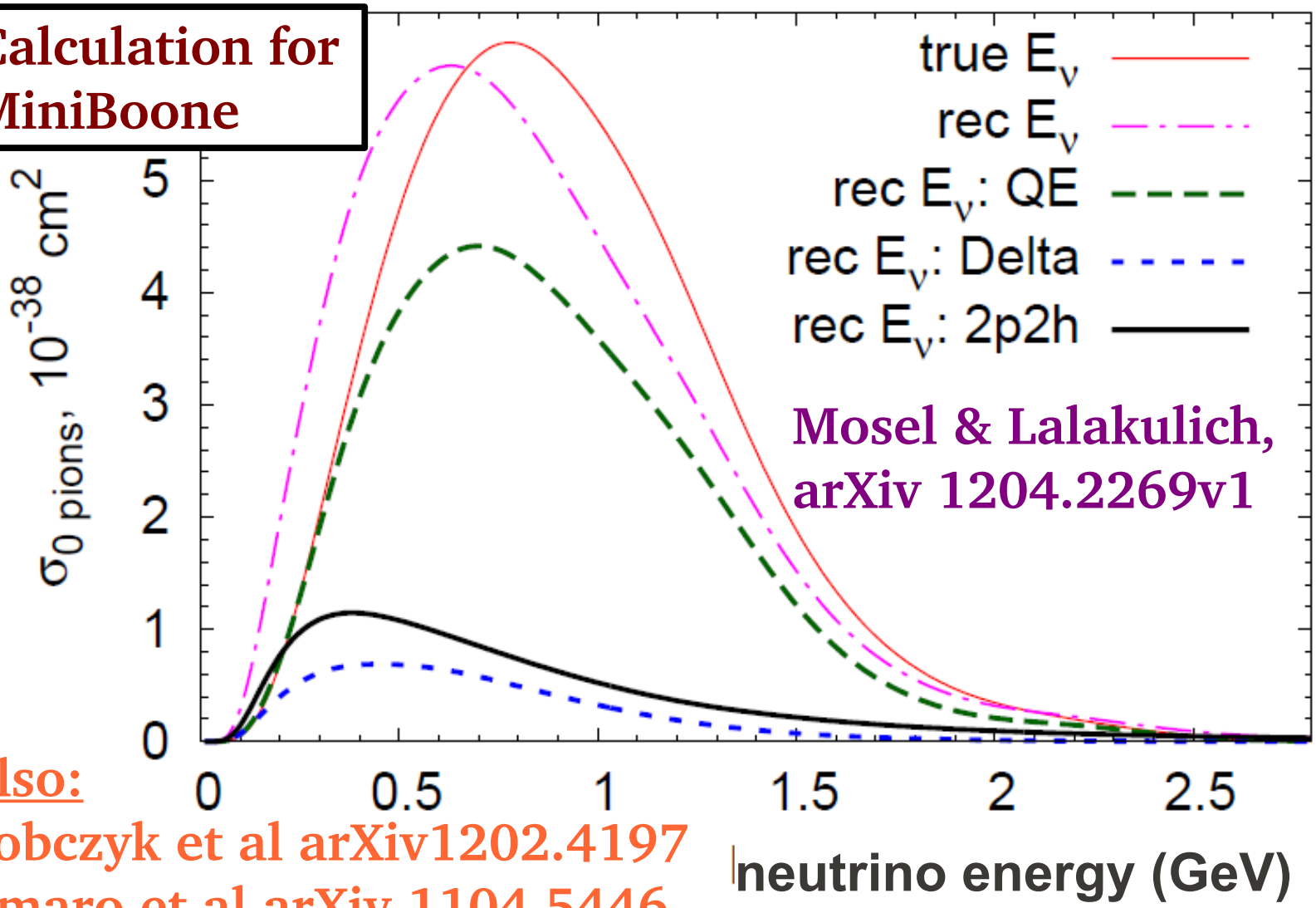
$\nu\ (A,Z) \rightarrow (A-1,Z)\ p\ \mu^-$



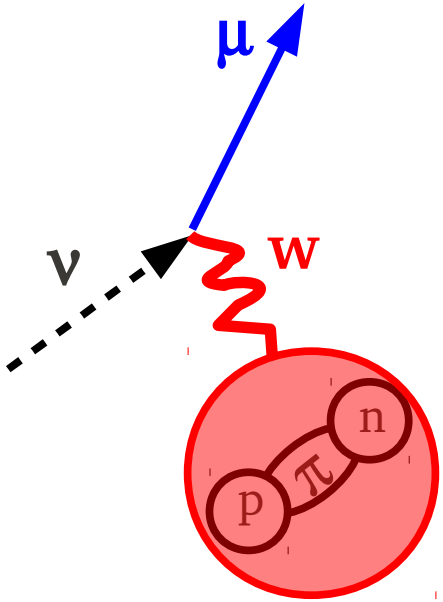
In search of a standard candle

Cons: We don't fully understand energy reconstruction

Calculation for MiniBoone



Mosel & Lalakulich, arXiv 1204.2269v1



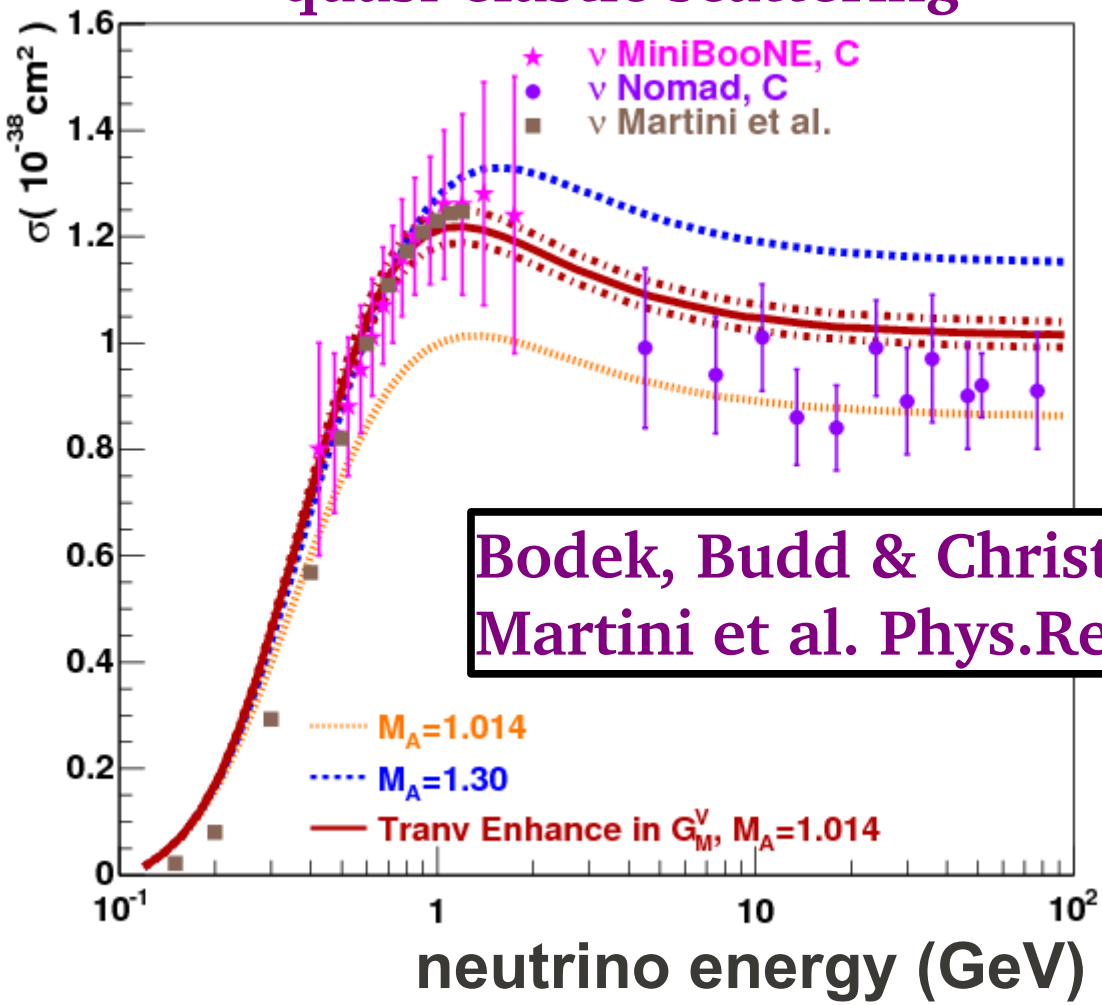
"meson exchange currents" a.k.a "2p2h"

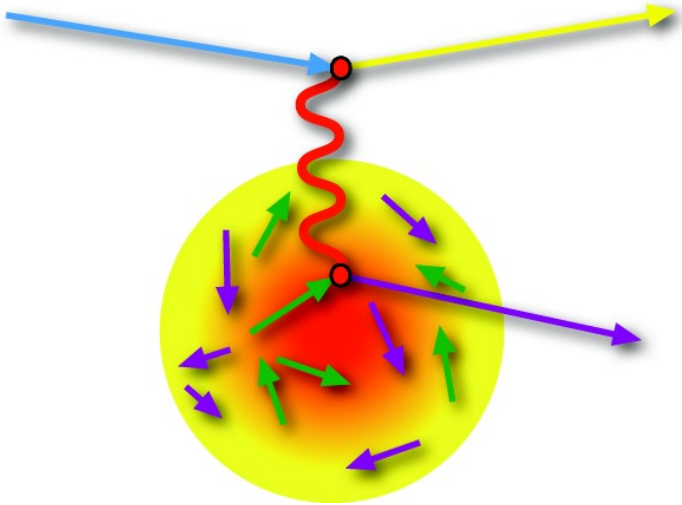
Also:
Sobczyk et al arXiv1202.4197
Amaro et al arXiv 1104.5446
Martini et al 1202.4745

In search of a standard candle

Cons: initial nuclear state, multi-body dynamics matter

quasi-elastic scattering





Bodek, Budd & Christy, Eur. Phys J. C 71 (2011)
Martini et al. Phys.Rev.C81:045502,2010

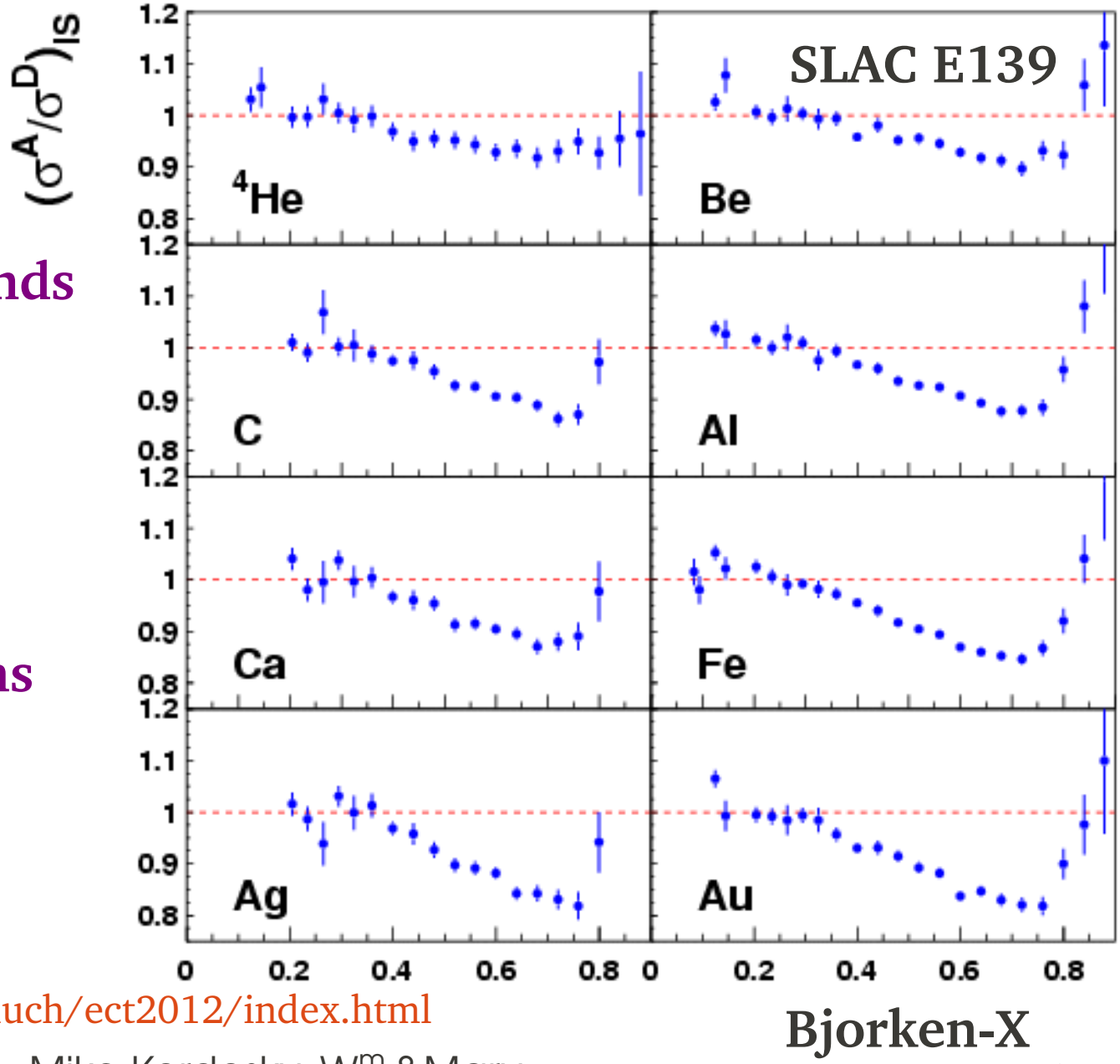
An old mystery

"EMC Effect"

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

Some evidence that νA has different behavior

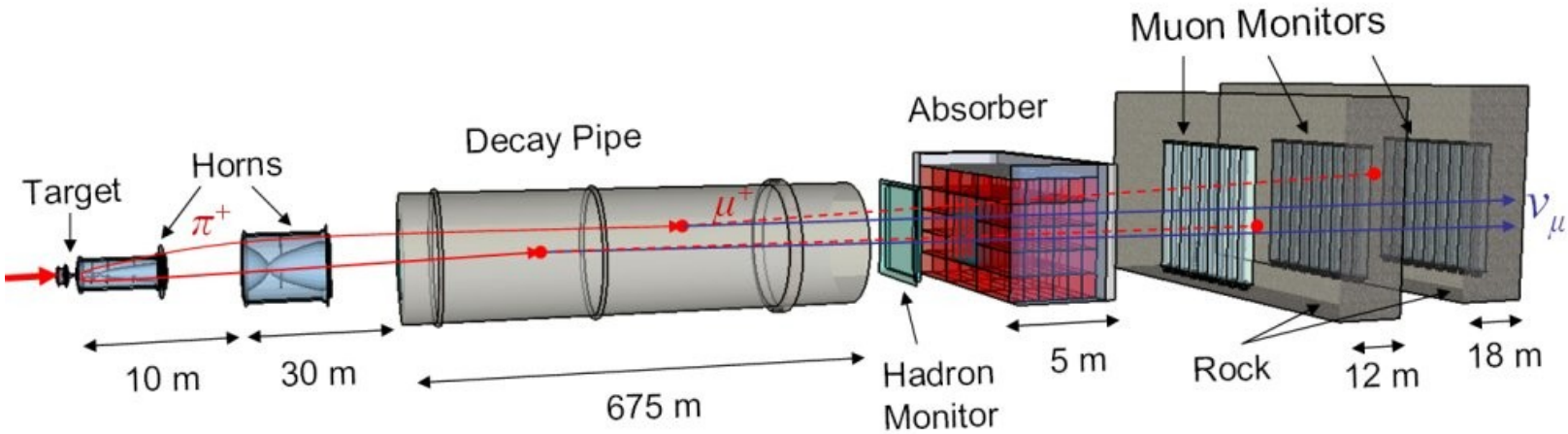
Short range correlations / multi-body dynamics ↔ EMC ?

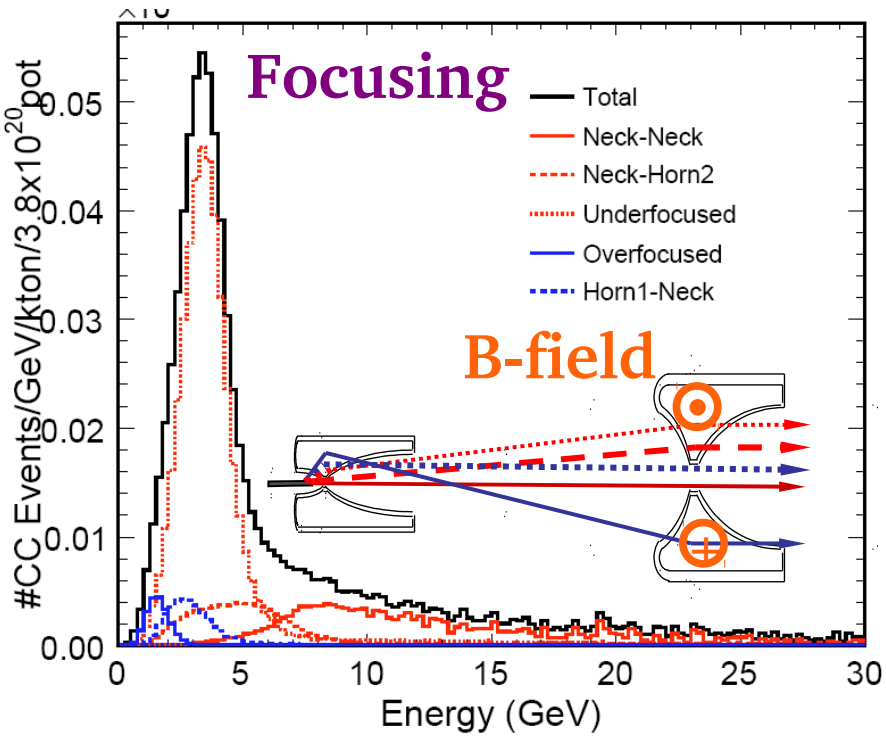


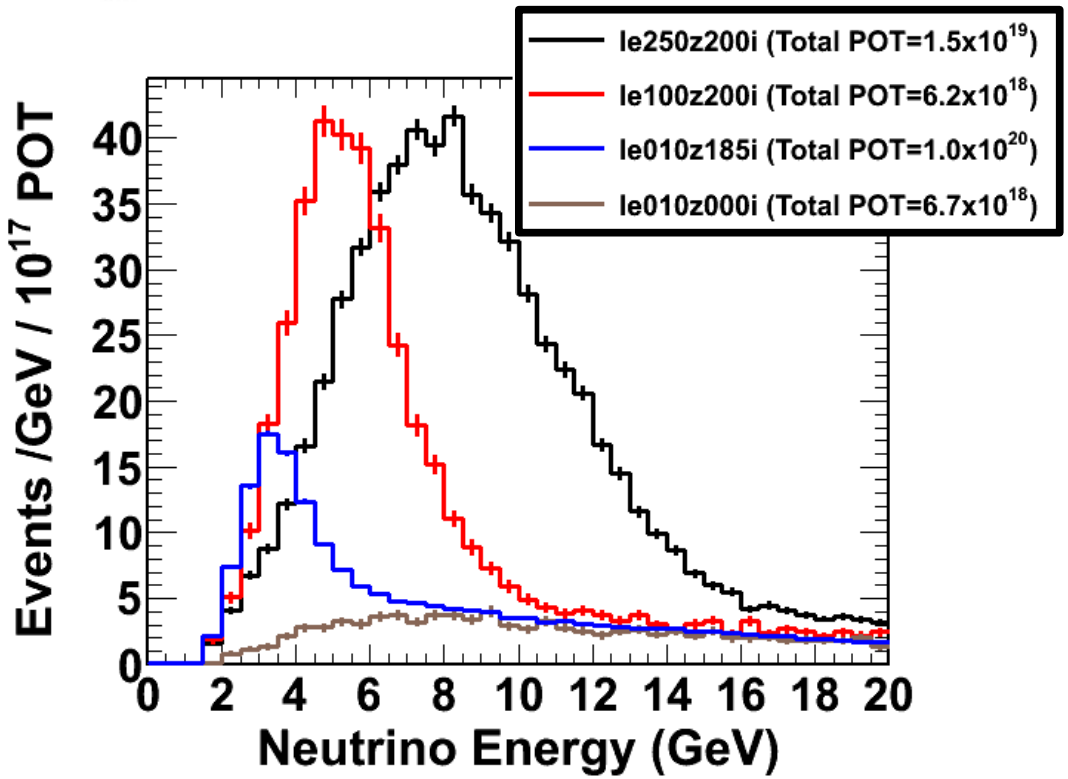
Nice review talk
D. Gaskell ECT*, Trento 2012
http://www.physics.sc.edu/~strauch/ect2012/index.html

The
MINERvA
Experiment

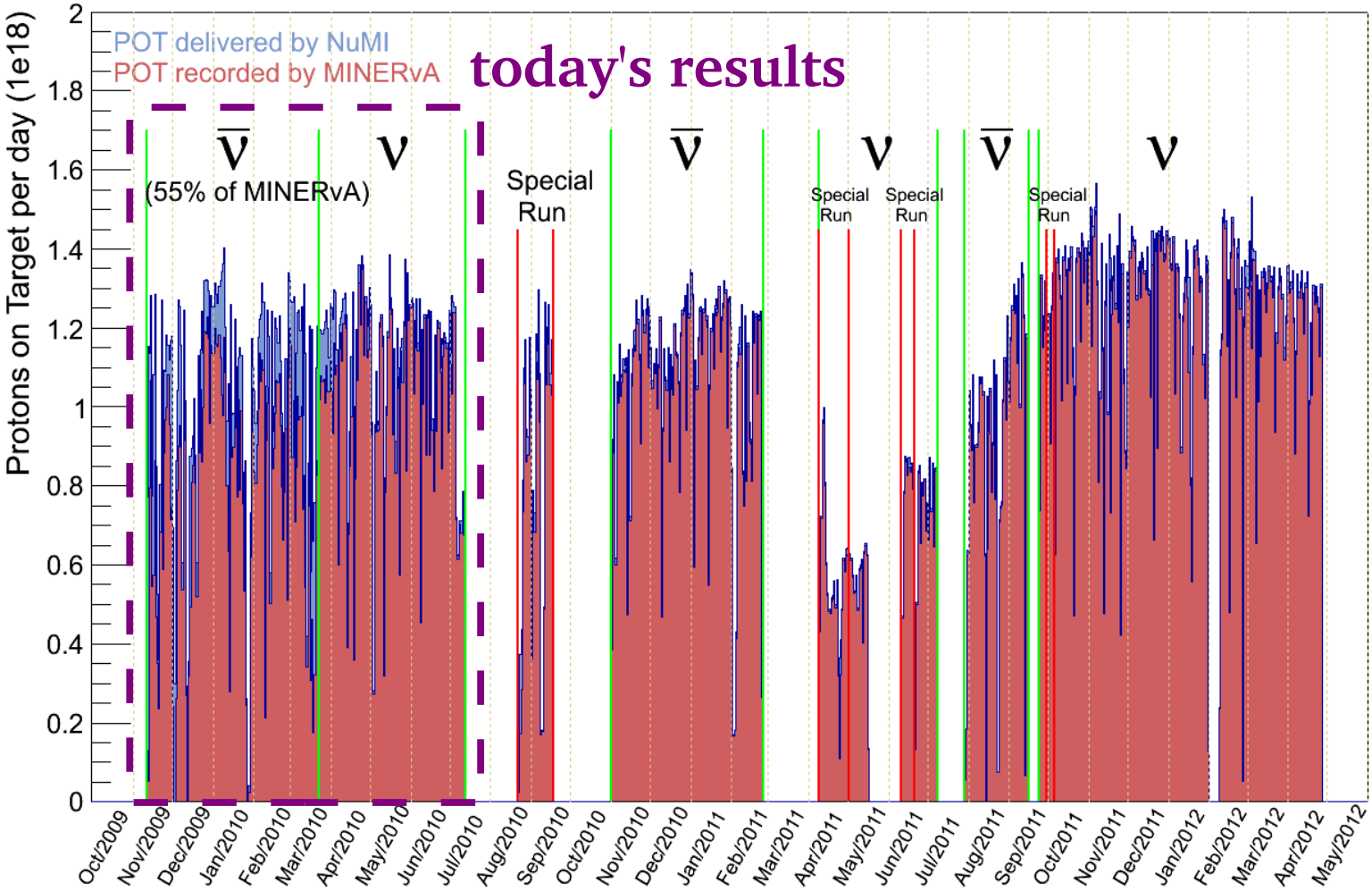
The NuMI beam







Thank you for the beam!



Since 3/22/10

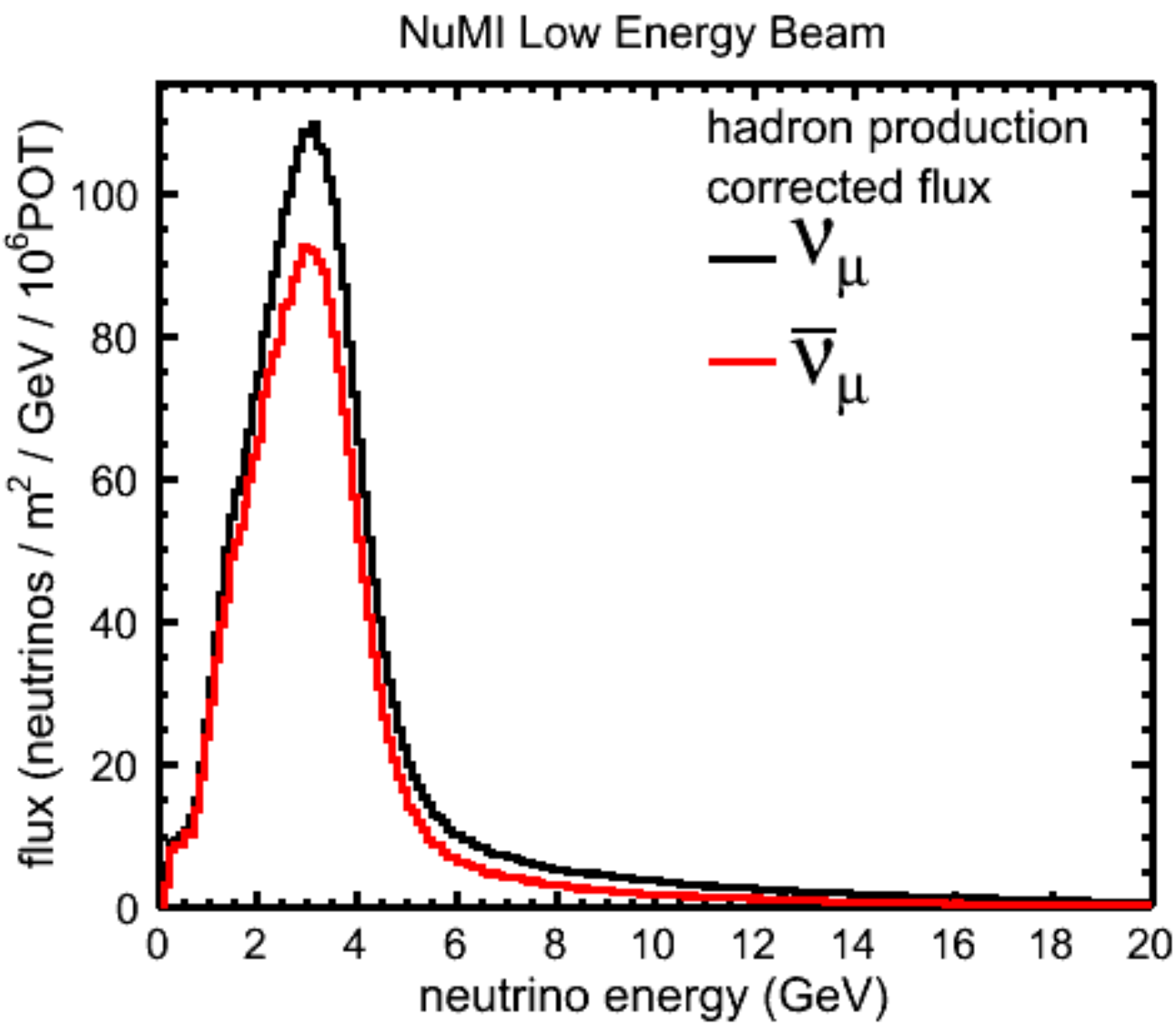
ν_μ LE 3.98e20 POT

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

special runs 4.94e19

Livetime: 97.2% MINERvA, 93.3% MINOS ND (3/22/10 – end of run)

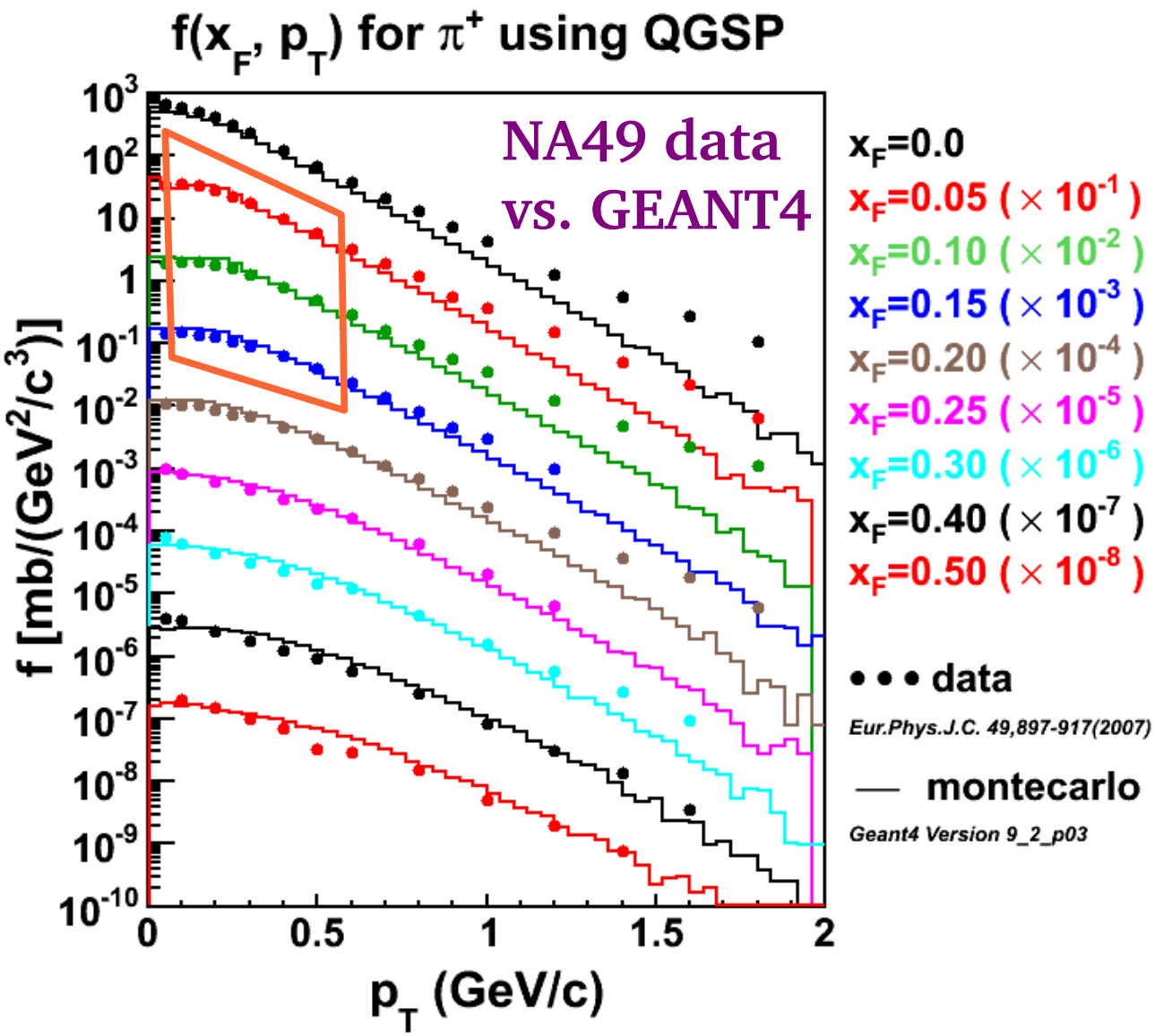
The Flux

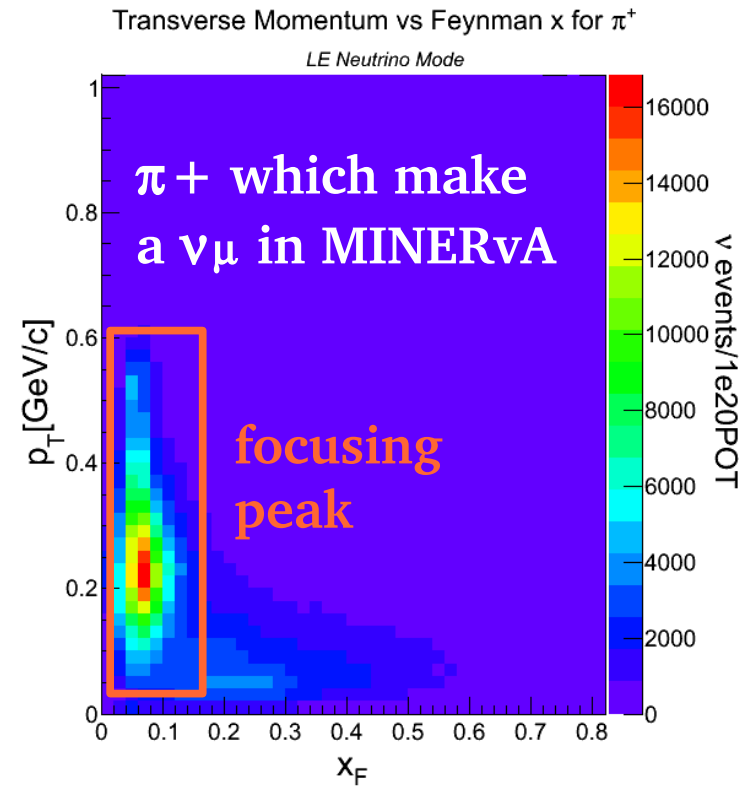


GEANT4 based simulation of the NuMI beamline.

G4 9.4.p02
QGSP physics list

Hadron production weights



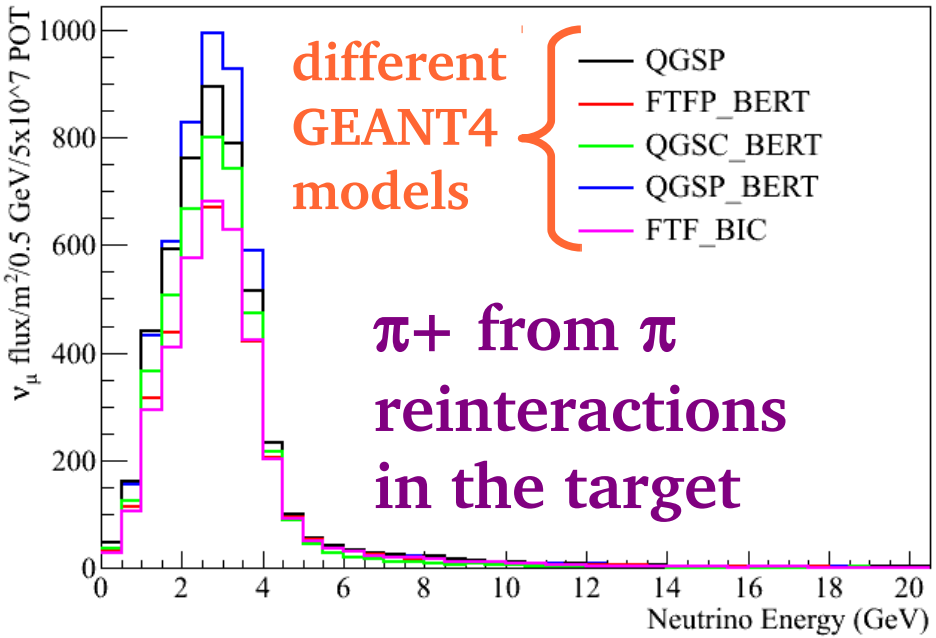


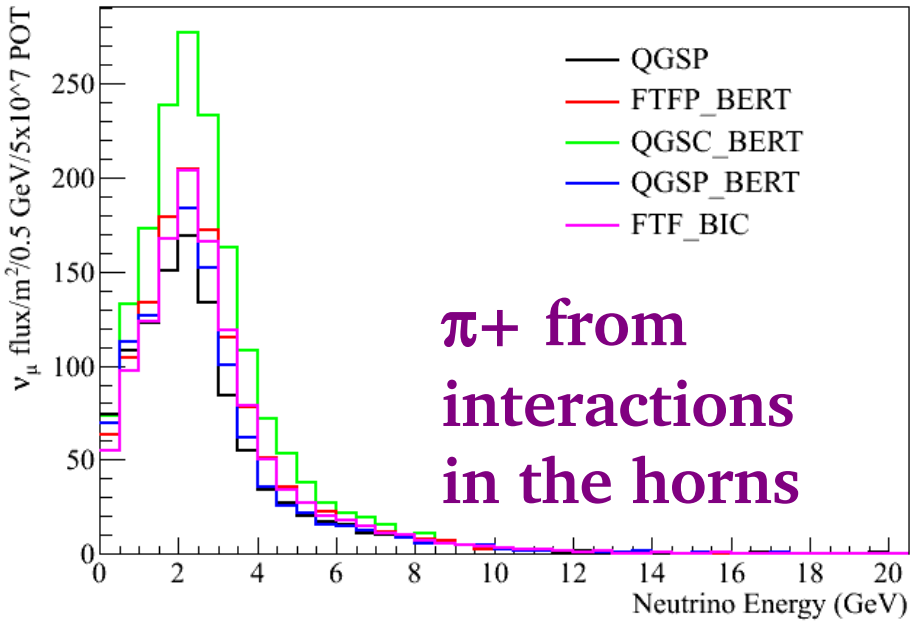
Uncertainties
7.5% systematic
2-10% statistical

Applied to
pC → π X off target

Model Spread Uncertainties

Non-NA49 uncertainties from maximum model spread





Categories

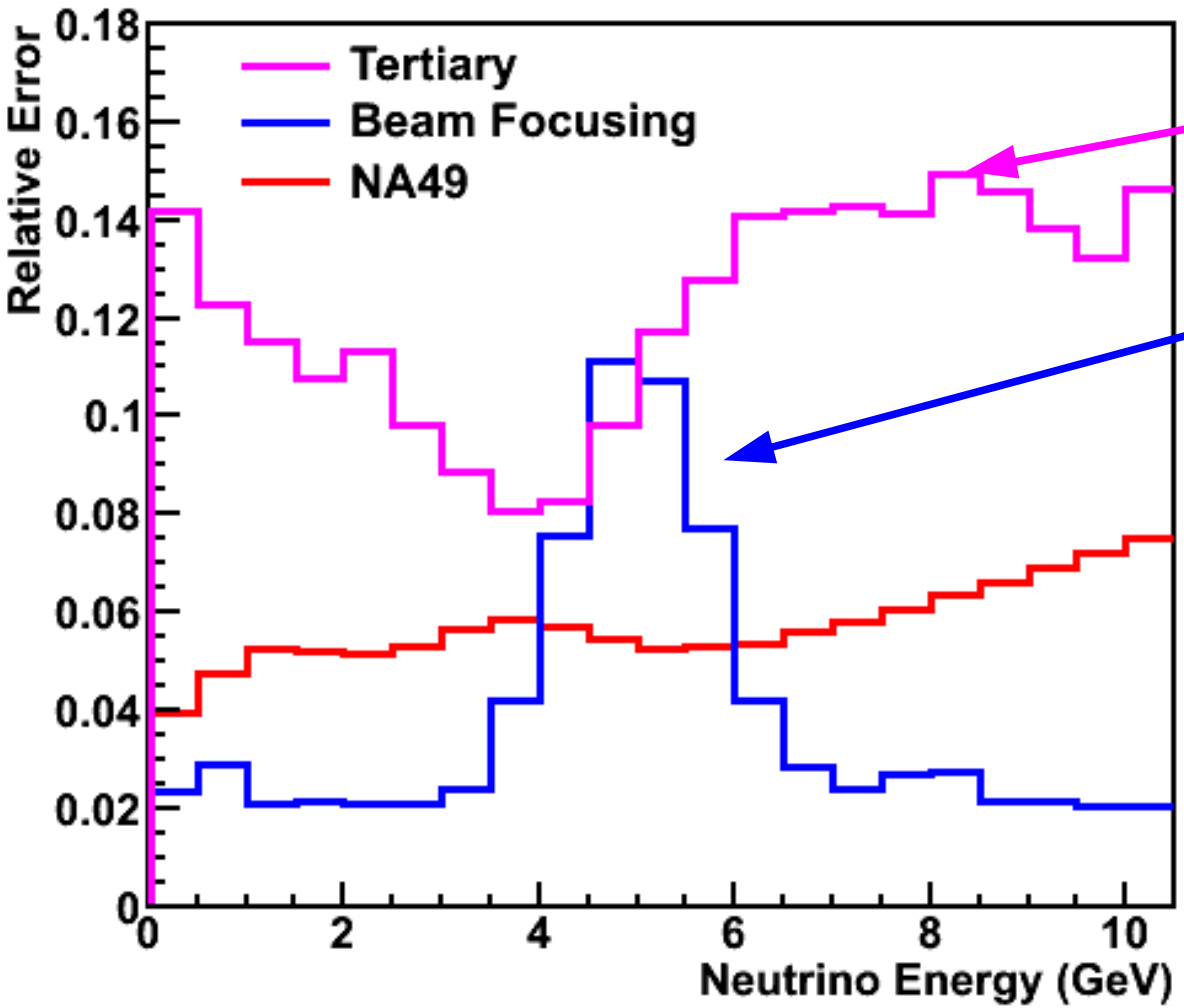
π,K,p,n,other secondary interactions in target

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

Current Flux Uncertainties

Preliminary!

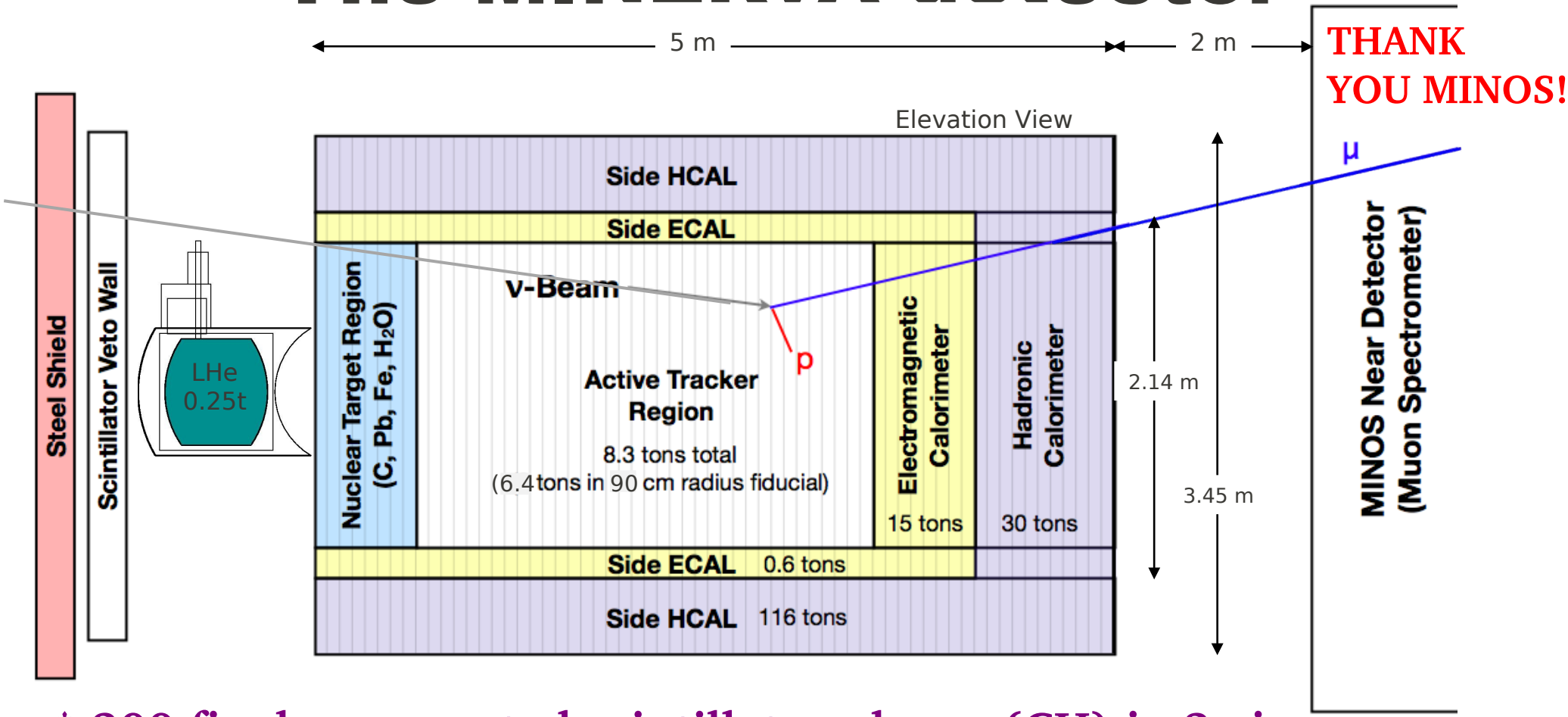


"Tertiary"
= non-NA49

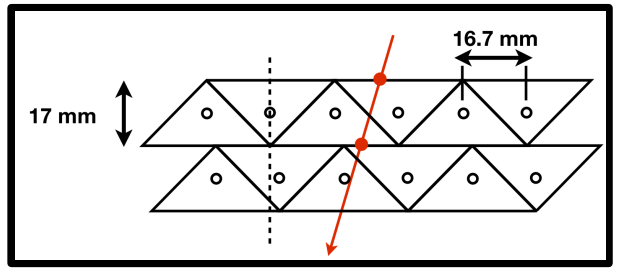
Z. Pavlovic,
PhD Thesis,
Texas (2008)

Can be improved with work!

The MINERvA detector

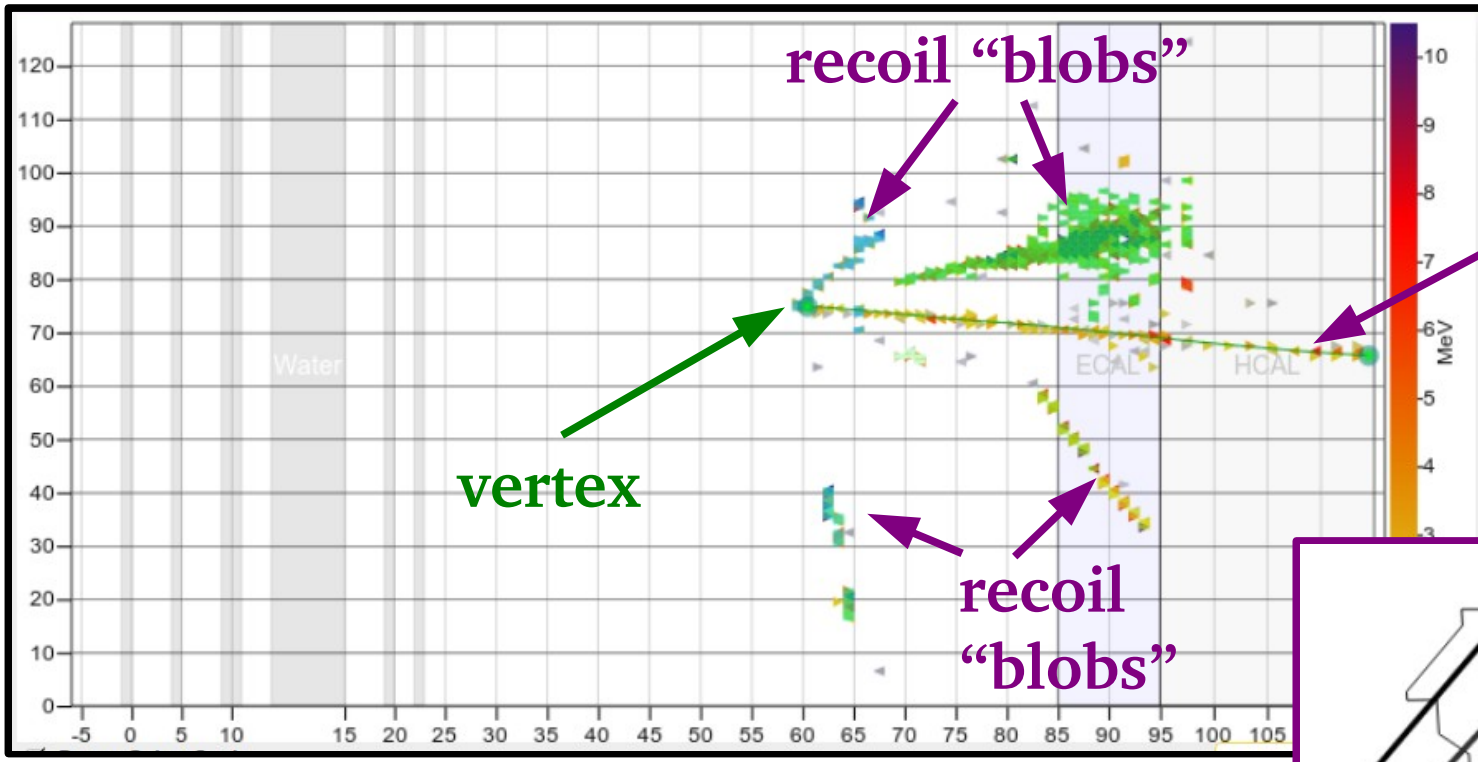


* 200 finely segmented scintillator planes (CH) in 3 views
* Calib: FEB bench tests, source mapper, LI, rock μ, Michel electrons, test-beam
* 4% channel to channel variations after calibration

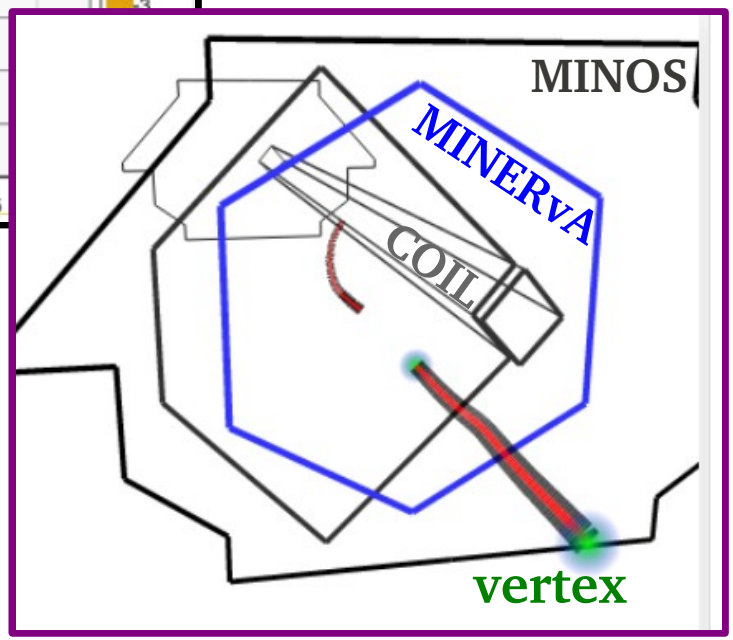


Event reconstruction

THANK YOU MINOS!



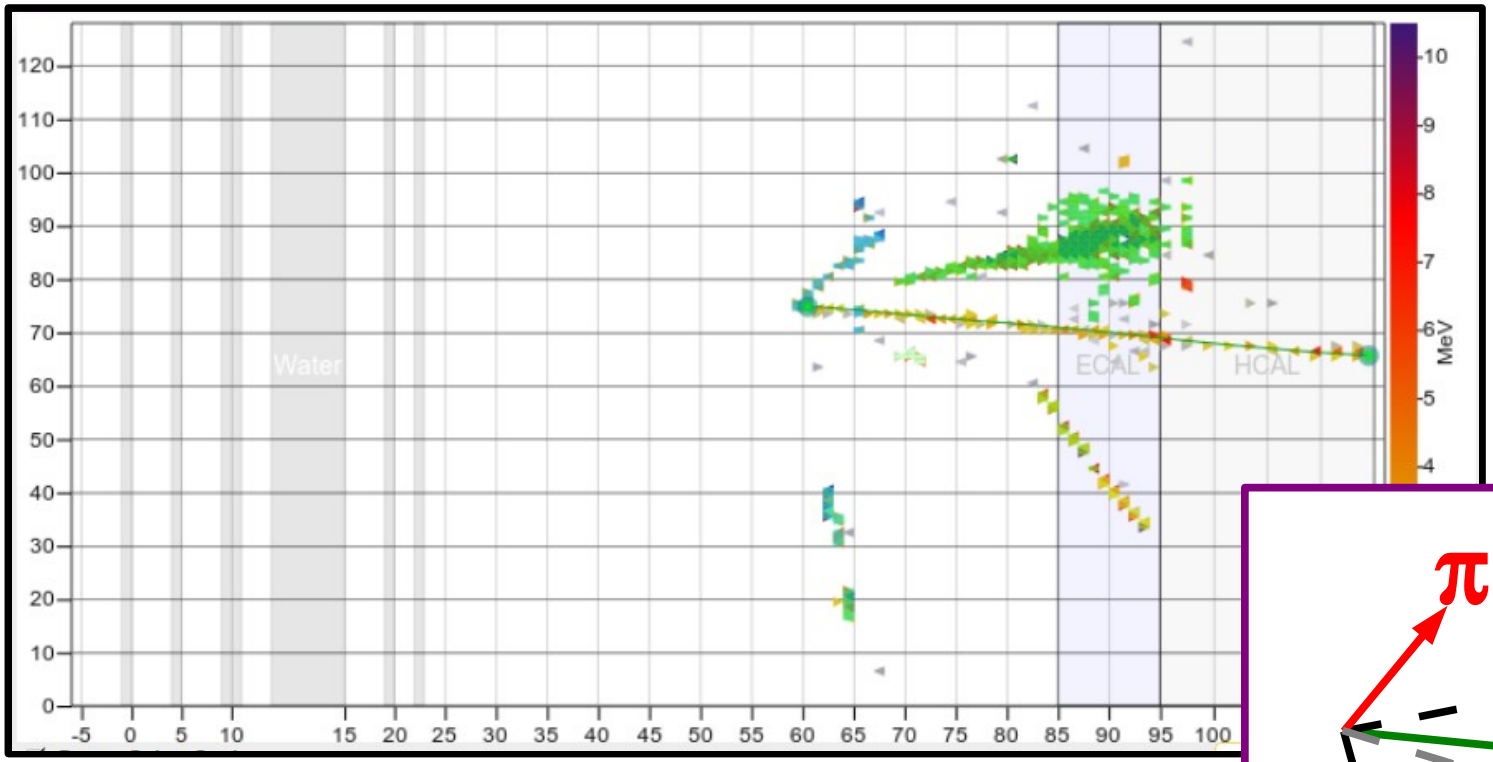
MINOS matched track



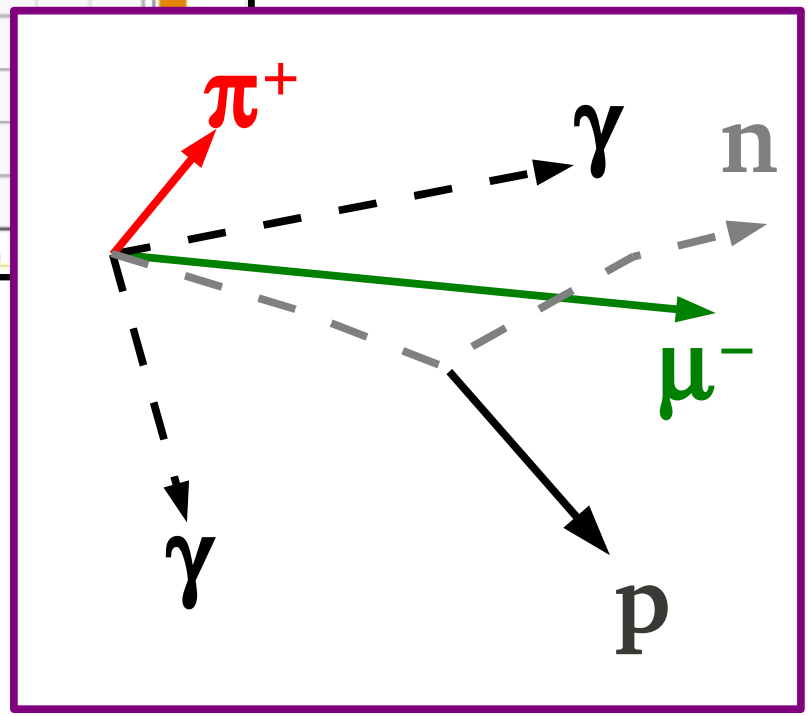
<u>Reconstructed objects</u>

MINOS tracks, other tracks, vertices, endpoints, blobs

Event reconstruction



My guess, just for fun



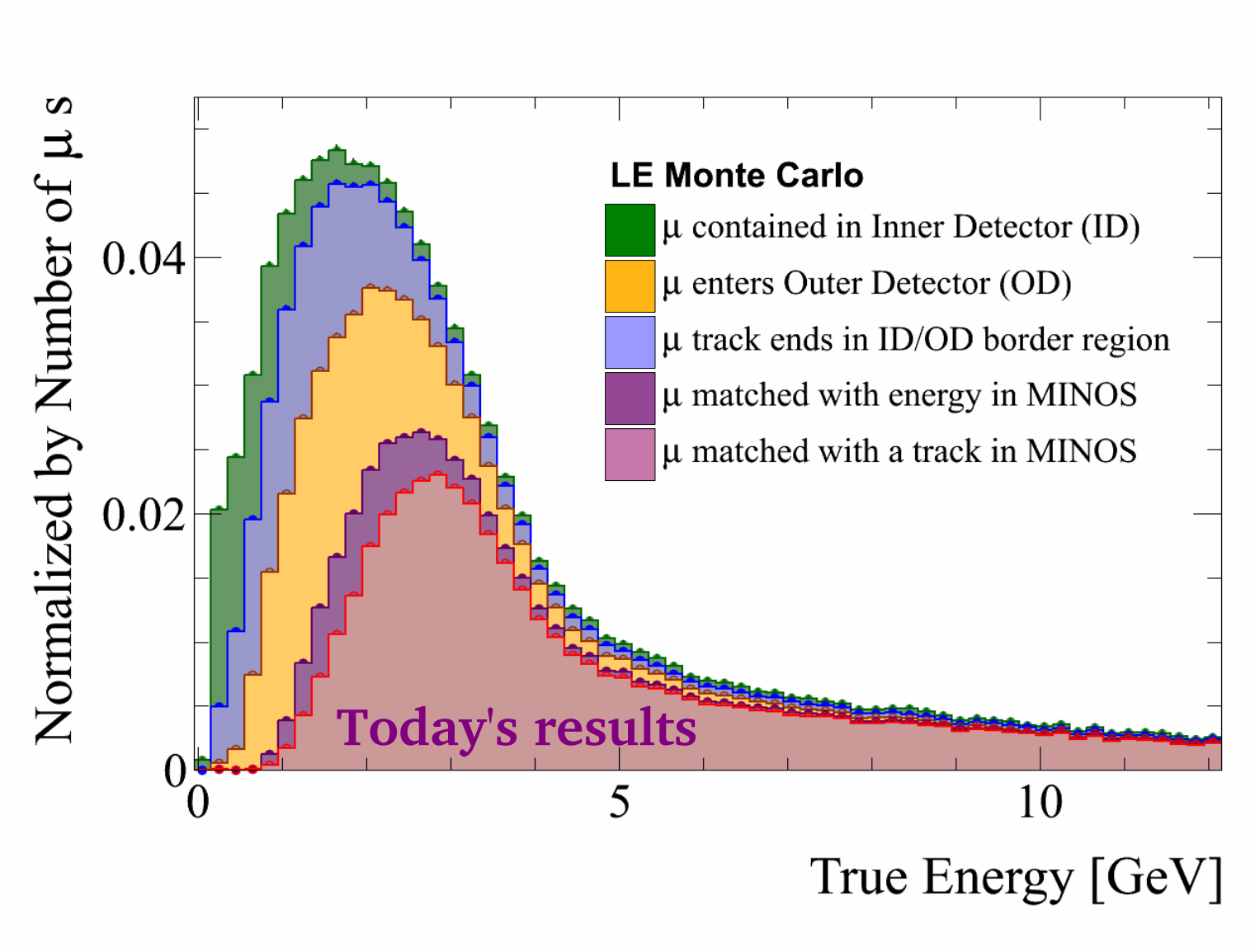
<u>Most important quantities:</u>

muon energy and angle

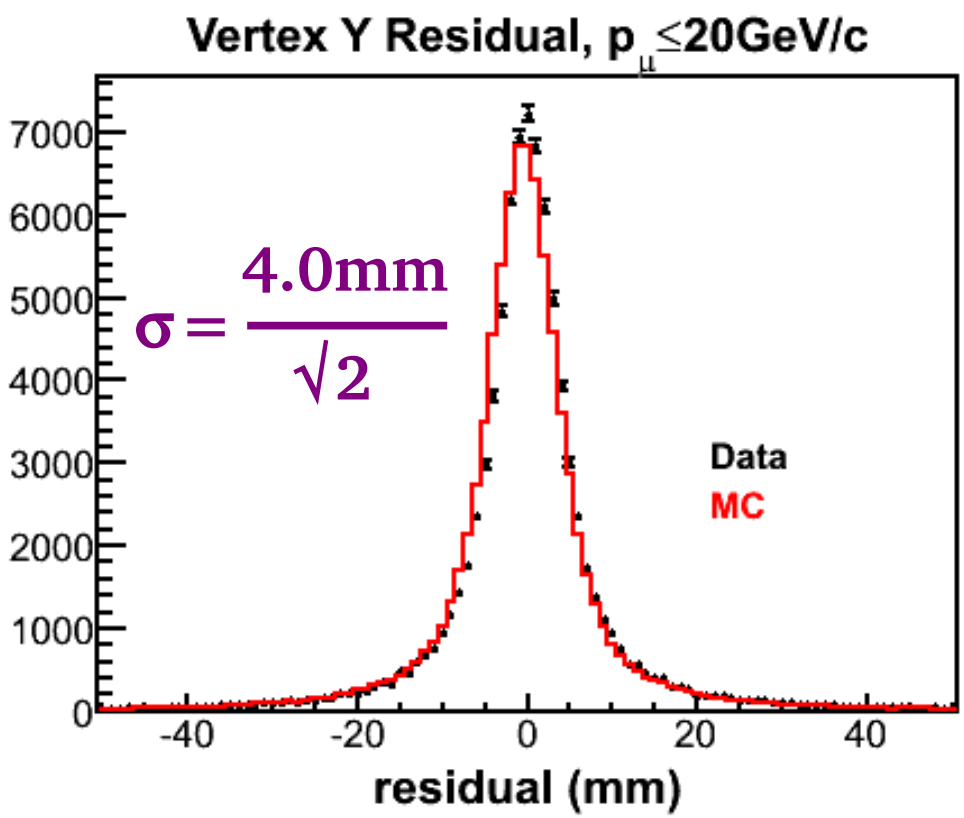
recoil energy

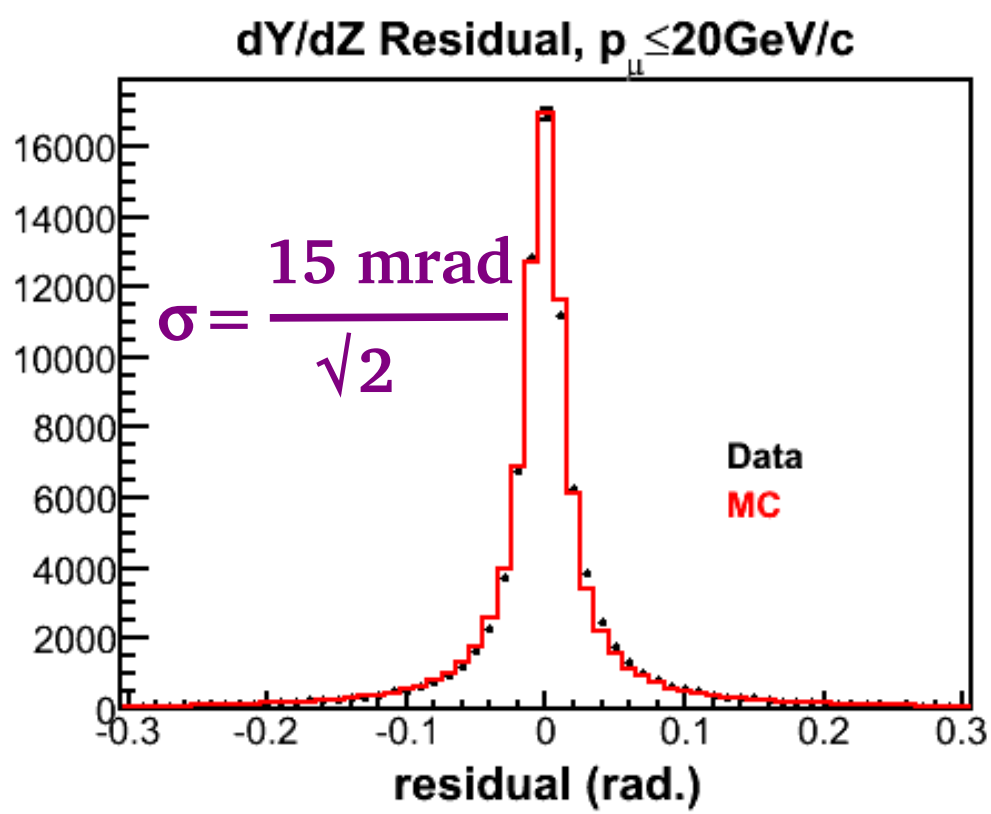
secondary tracks/blobs

Where do the muons go?



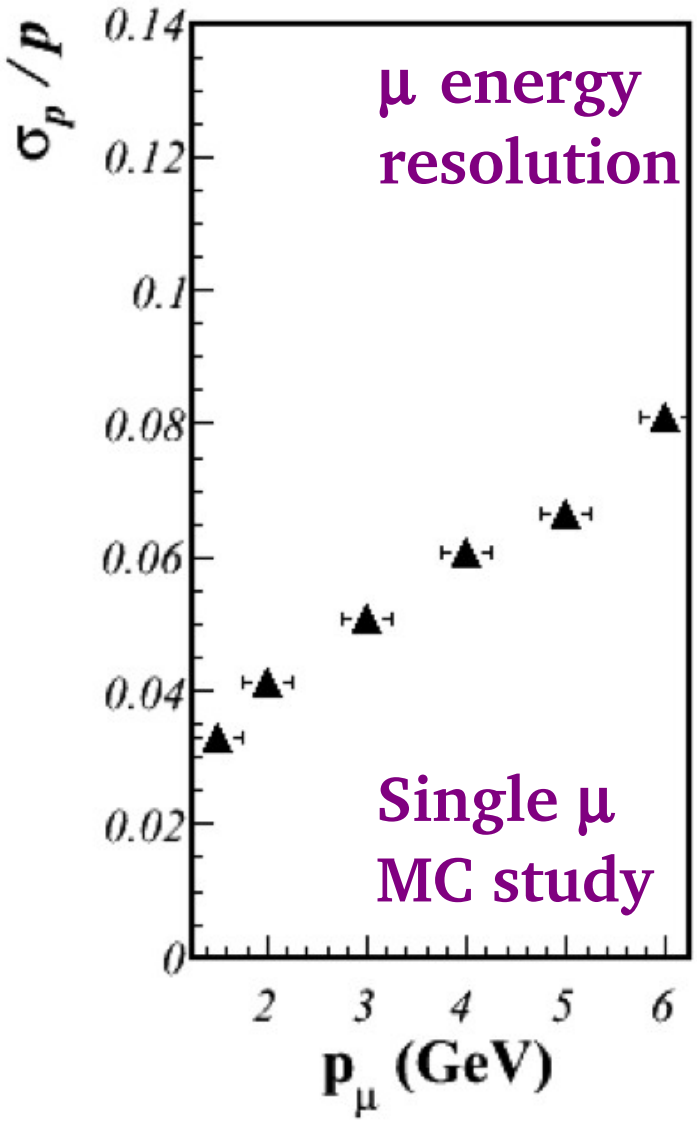
Tracking resolutions

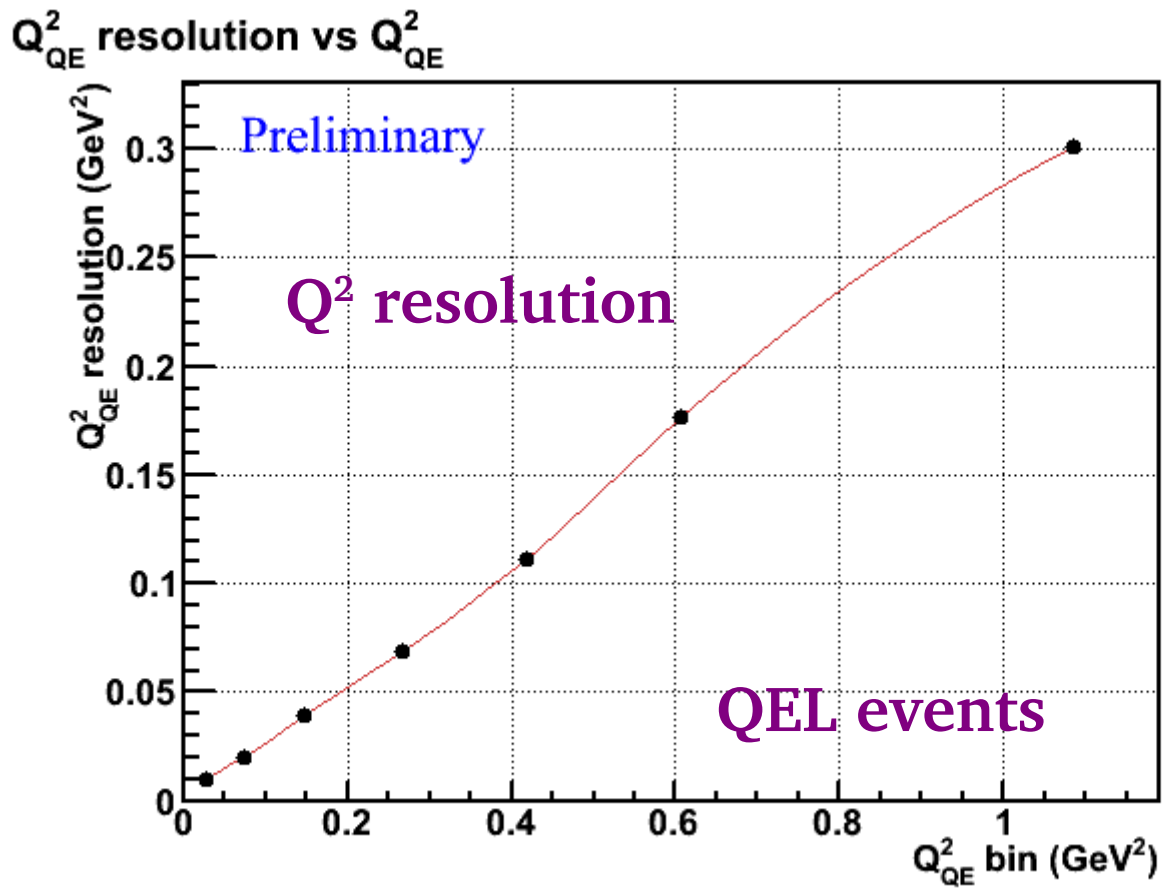




Split-track study of rock μ in tracker region

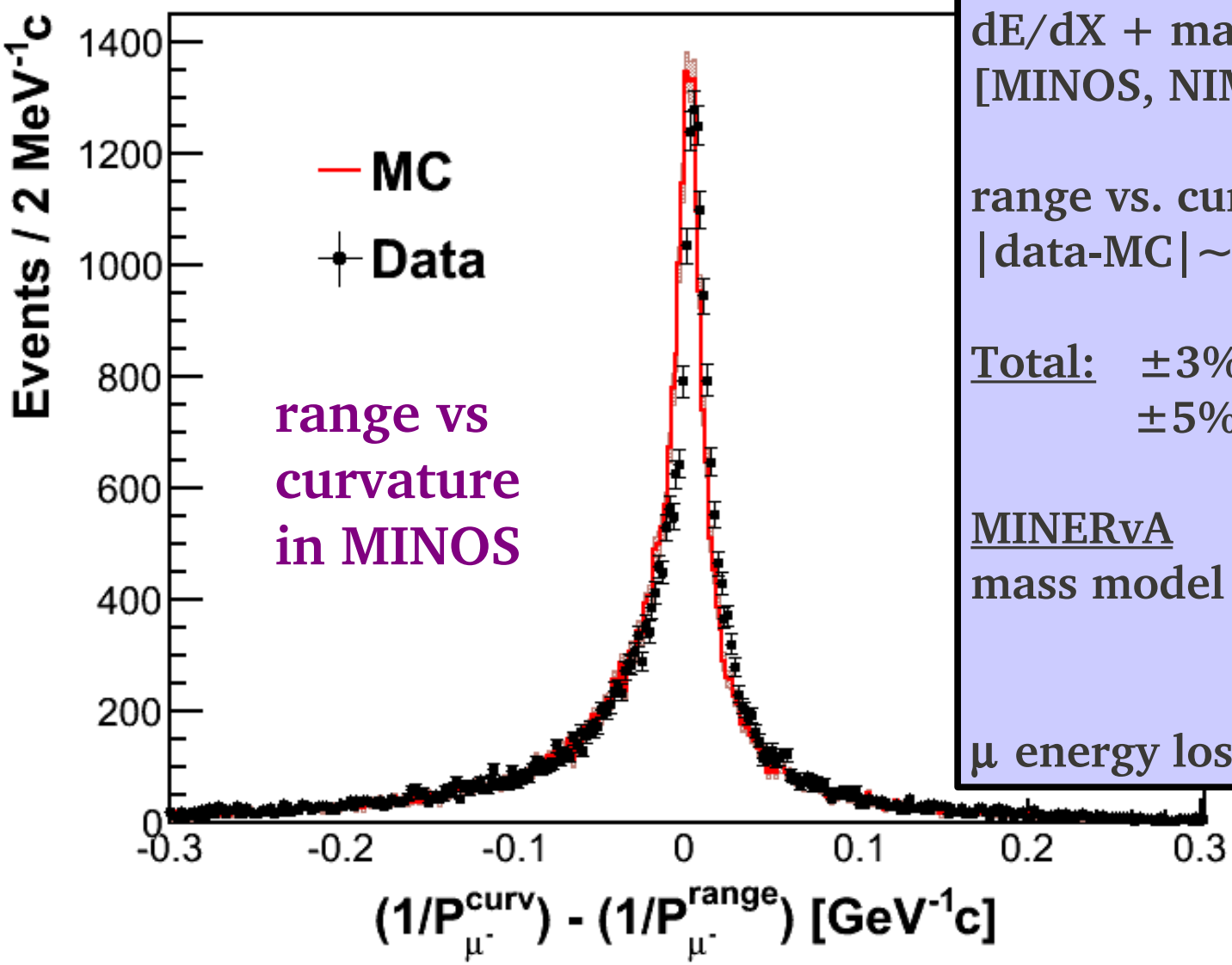
μ energy & Q^2 resolution





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

Muon energy uncertainty



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

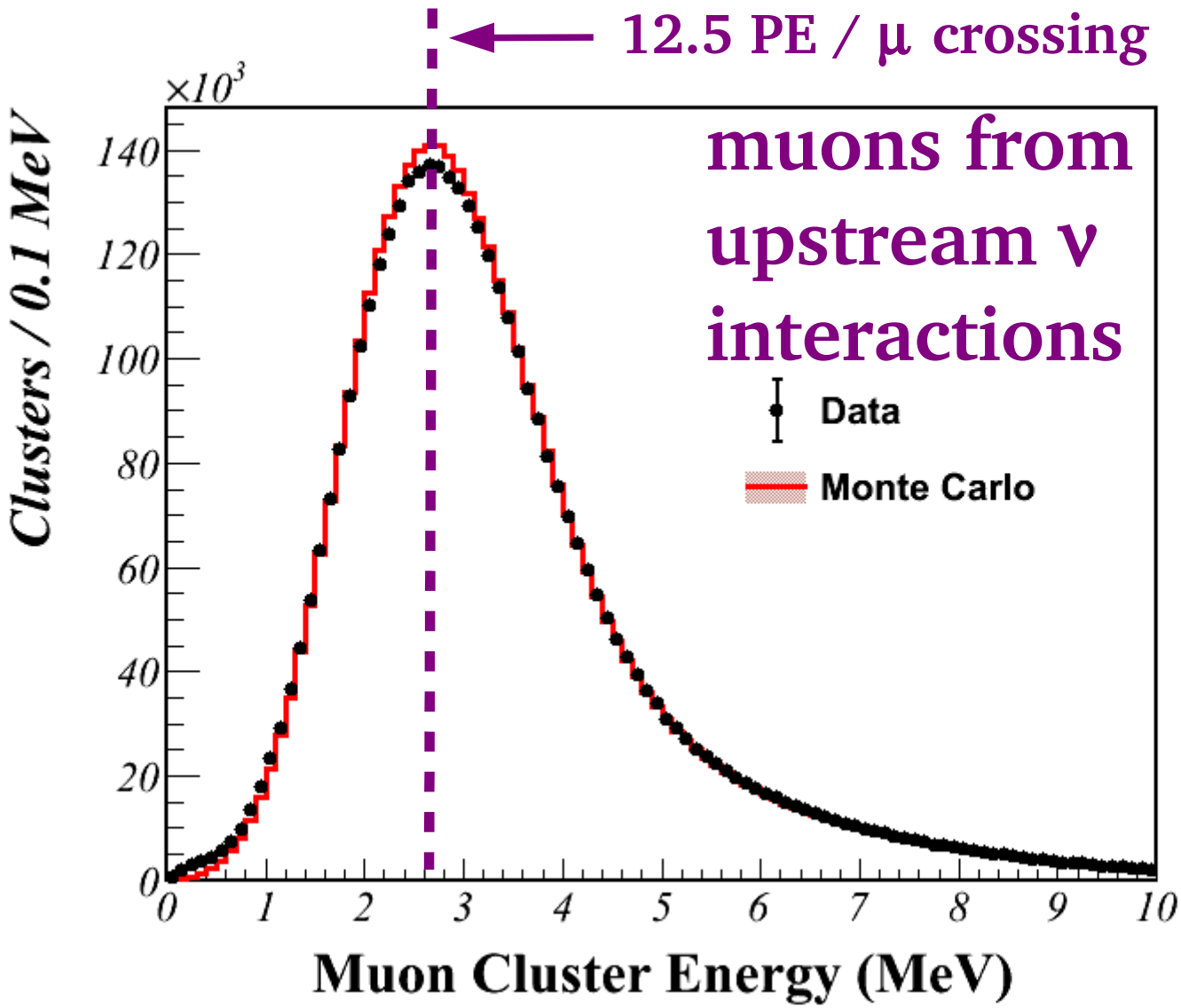
range vs. curvature
|data-MC|~25 MeV

<u>Total:</u> ±3% p> 1.5 GeV
±5% P<1.5 GeV

<u>MINERvA</u>
mass model = 11 MeV tracker
= 17 MeV Nucl. Tgts.

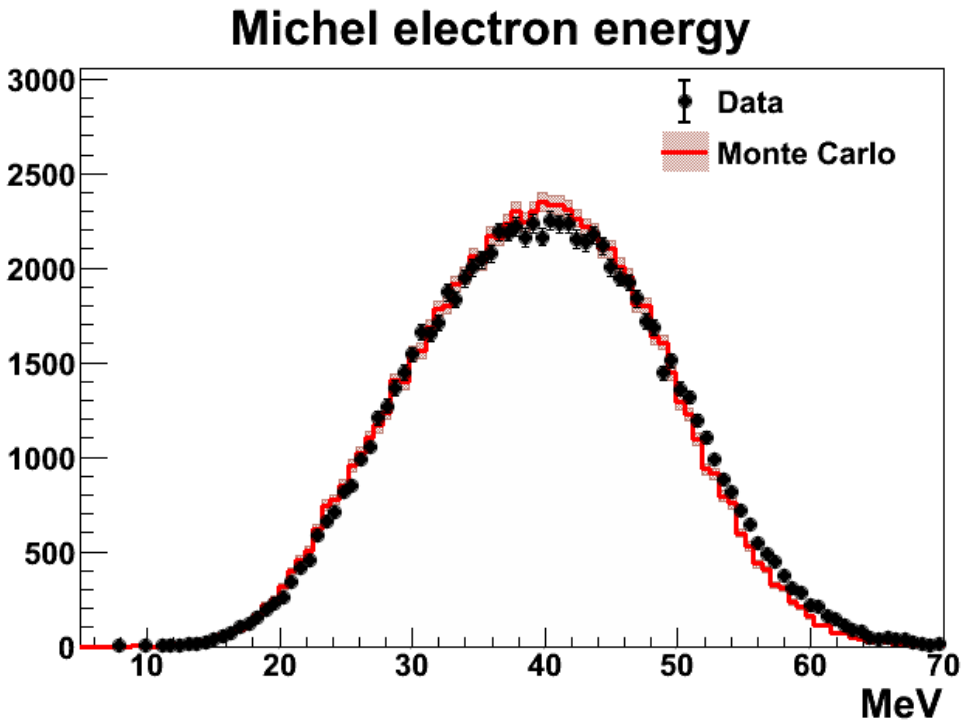
μ energy loss = 30 MeV

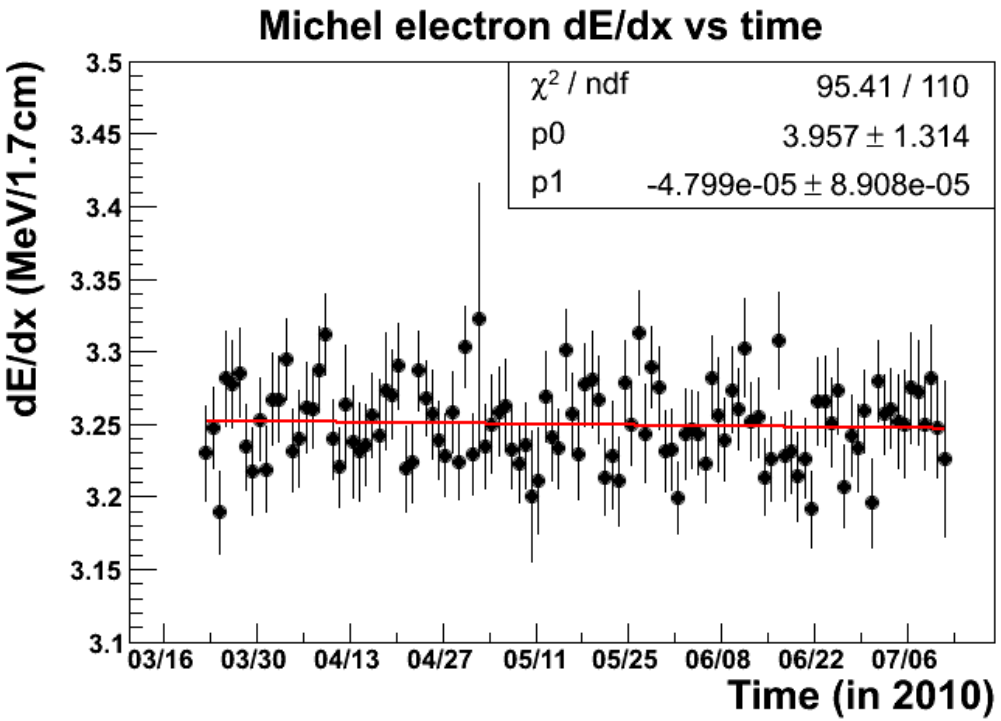
visible energy scale



Michel electrons

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





Cross-check on μ derived energy scale

EM response uncertainty = 3%

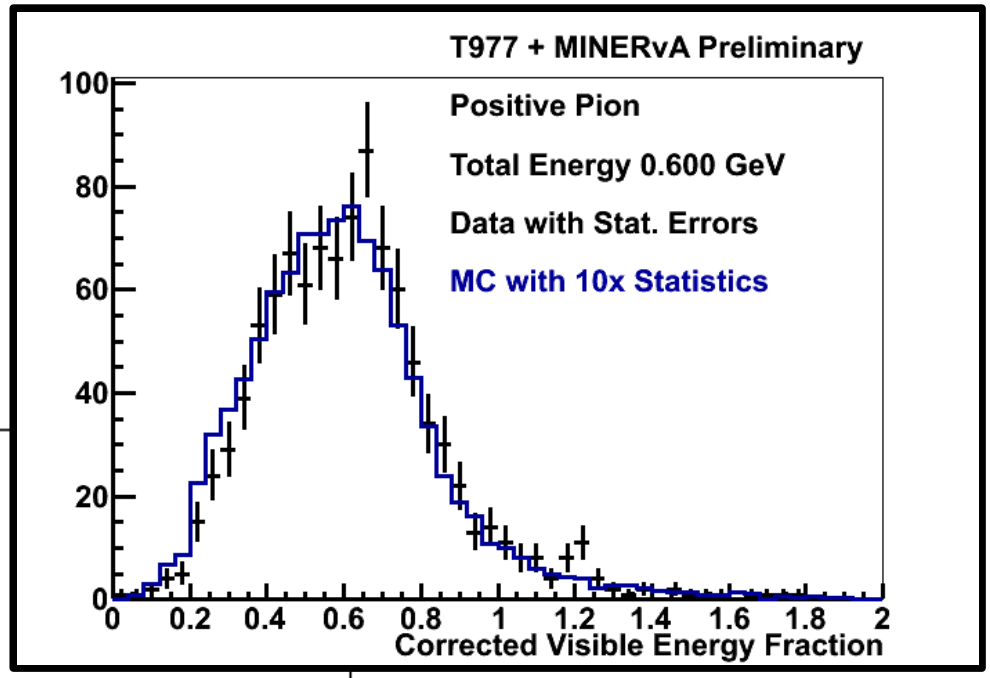
A nice stable detector!

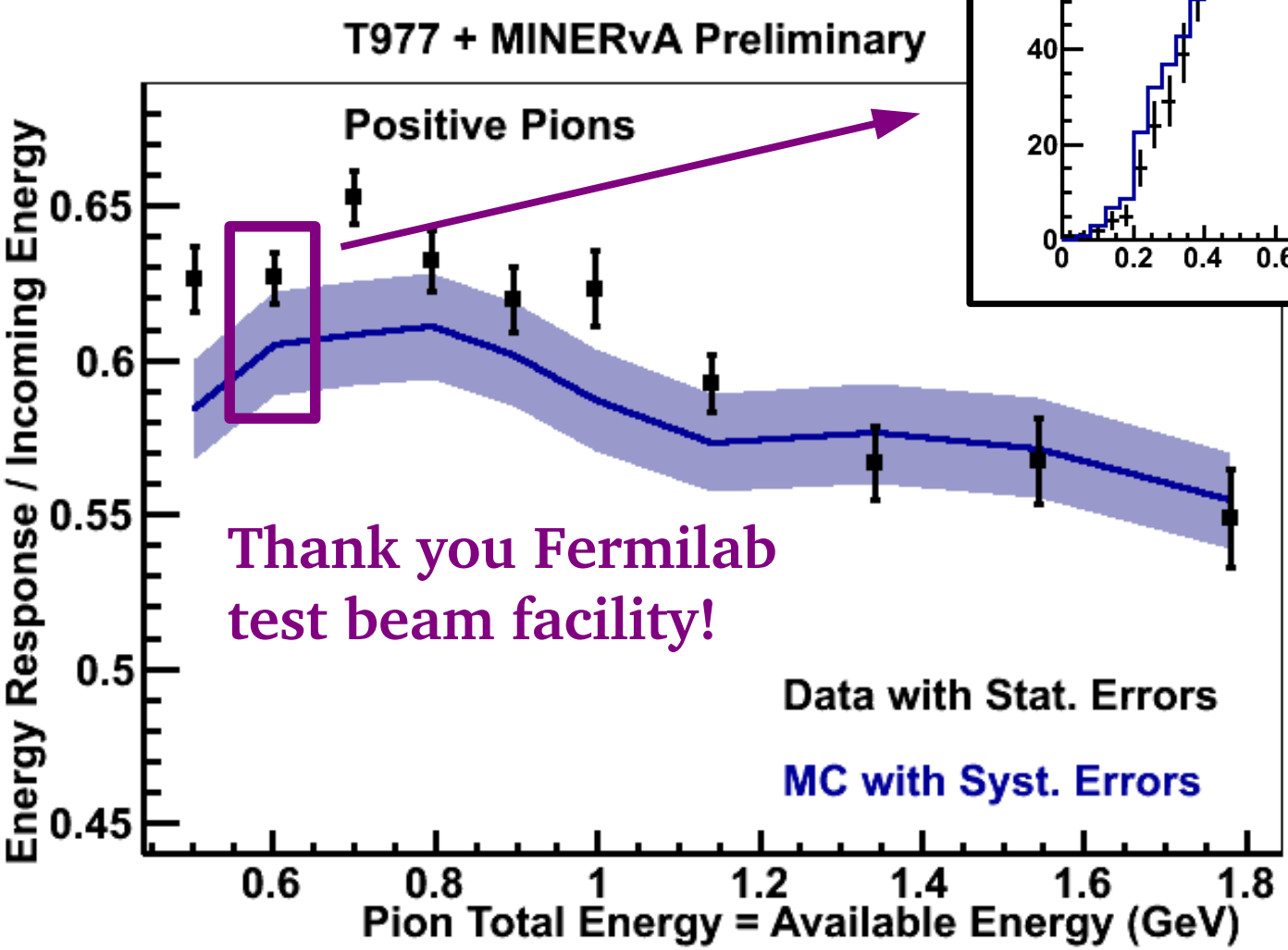
FNAL-T977 Test Beam

Mini-MINERvA + Mtest tertiary beam

Thank you Mtest staff!

FNAL-T977 Test Beam



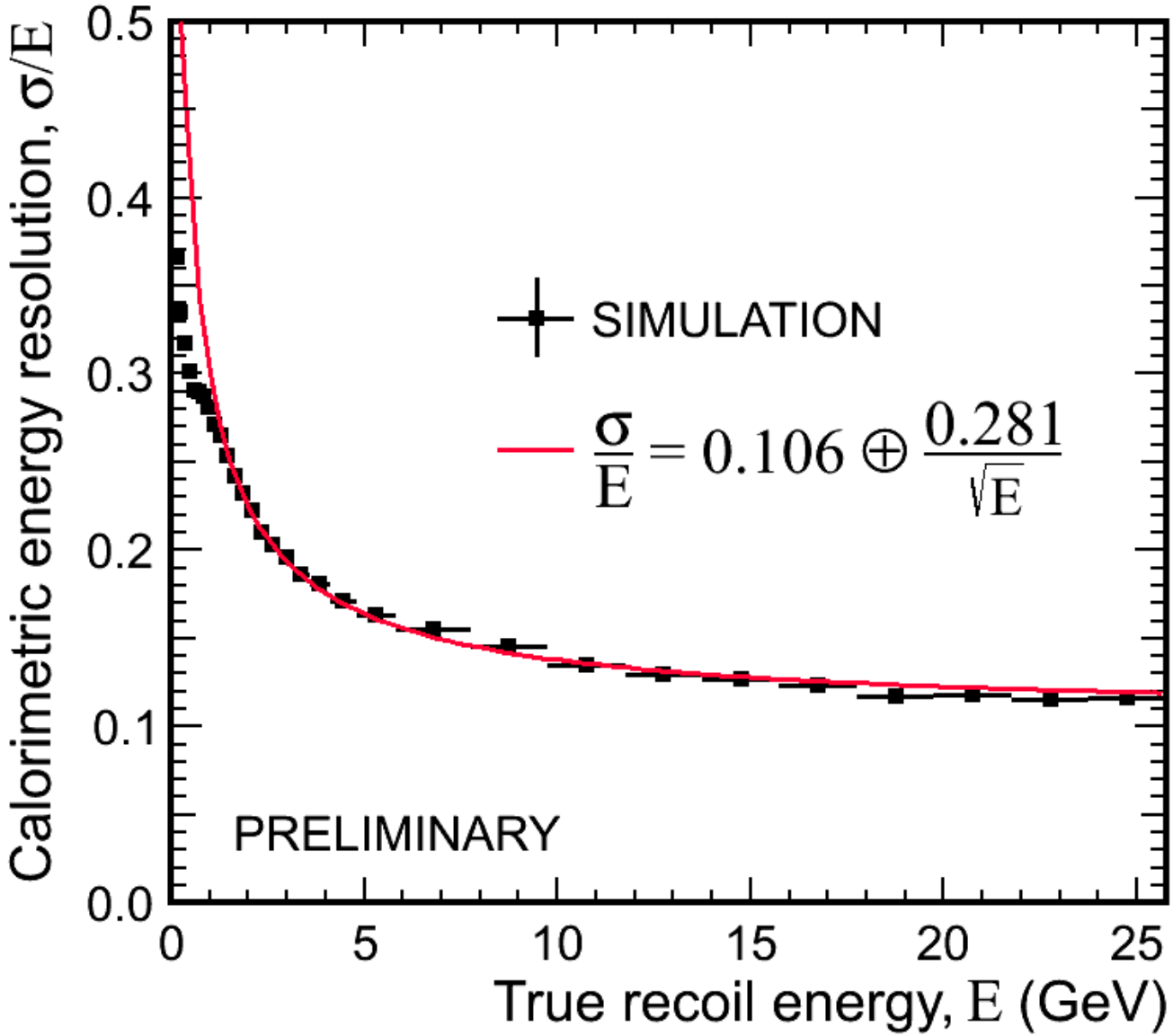


Thank you Fermilab test beam facility!

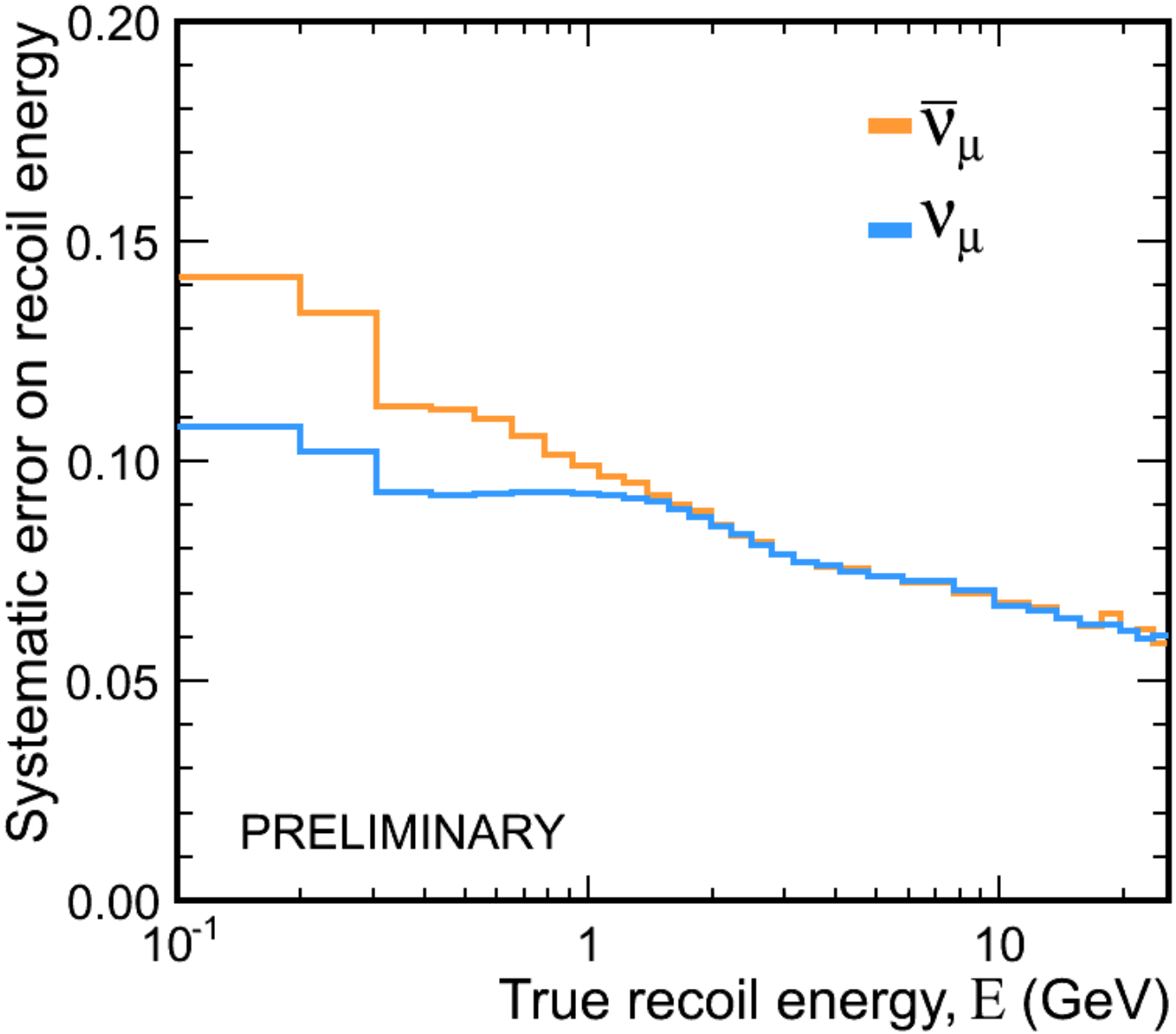
π+ agreement ~ 5%
π− a bit better
p a bit worse (10%)

Resolution well modeled

shower energy resolution



shower energy uncertainty



Convolution of single particle uncertainties

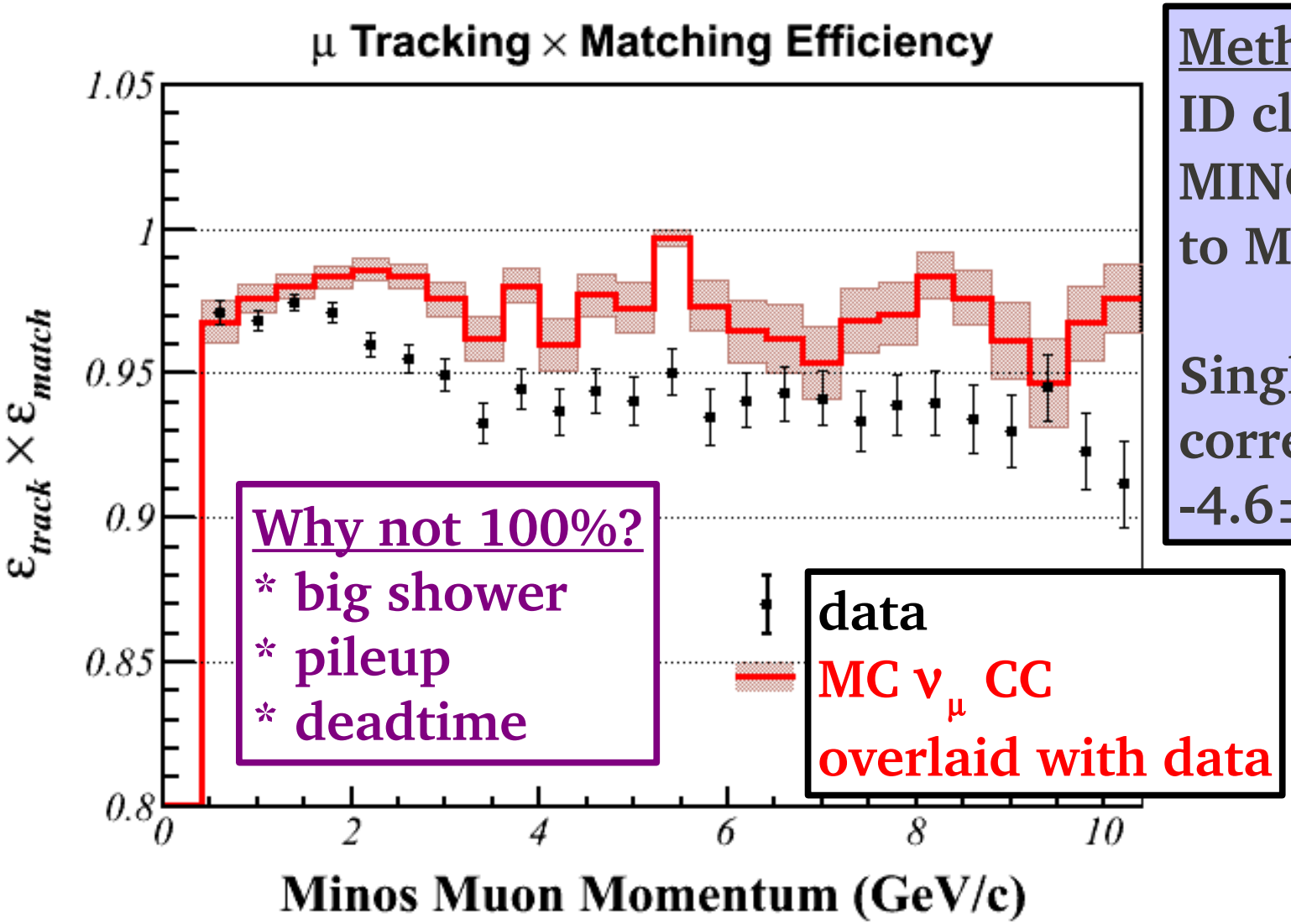
π,K = 5%

e,γ = 3%

p = 10%

n = 20%

Tracking x Matching Efficiency



Method

ID clean μ in MINOS, point back to MINERvA

Single event MC correction -4.6±2.5%

Normalization corrections

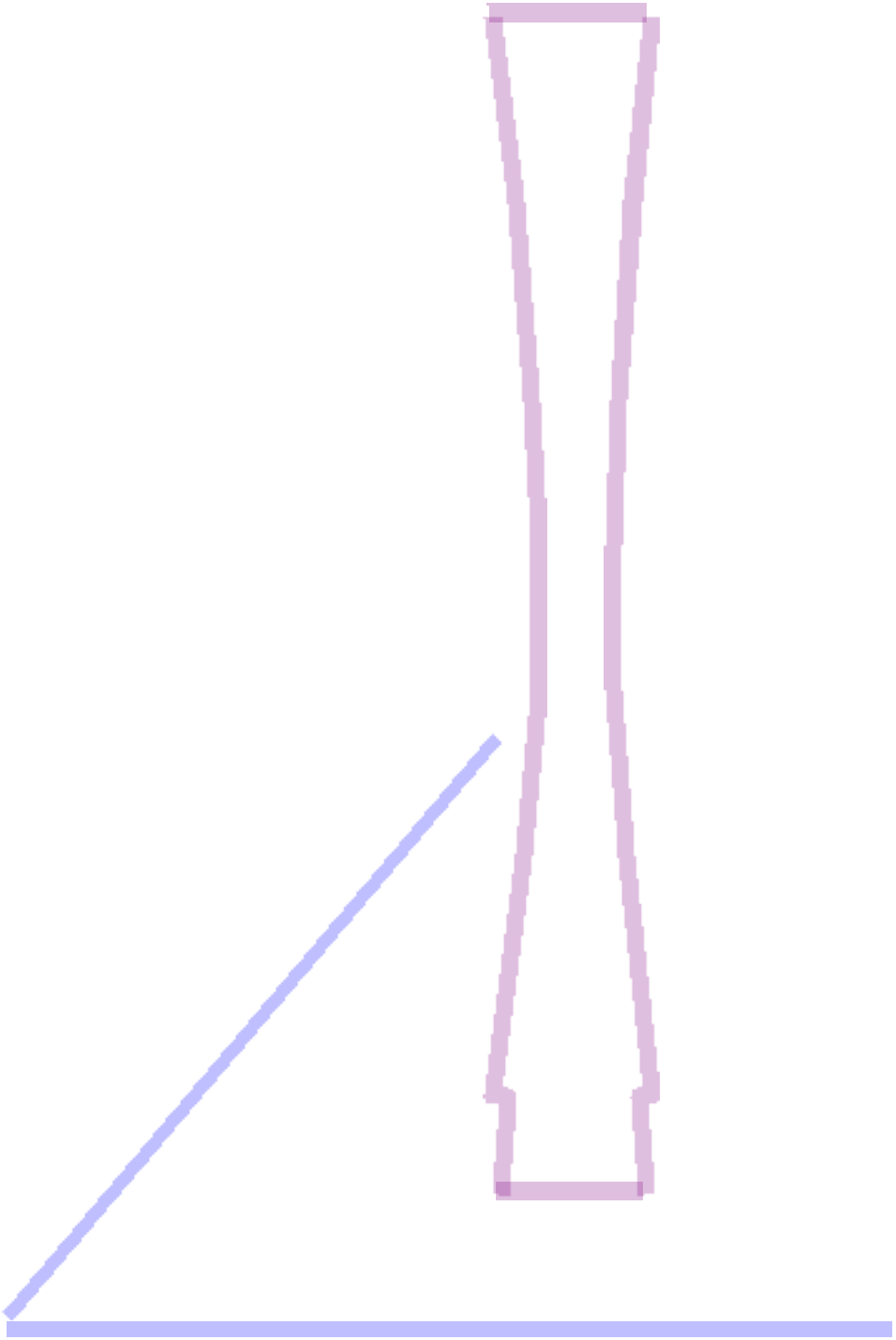
ν_μ beam

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%

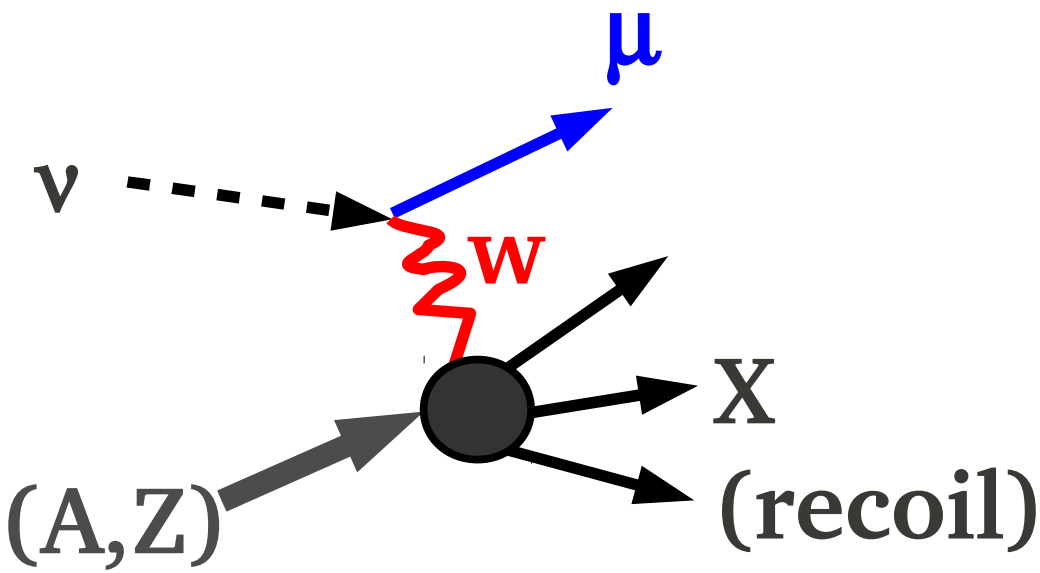
reco. effects on single event MC

*QEL analyses only

other

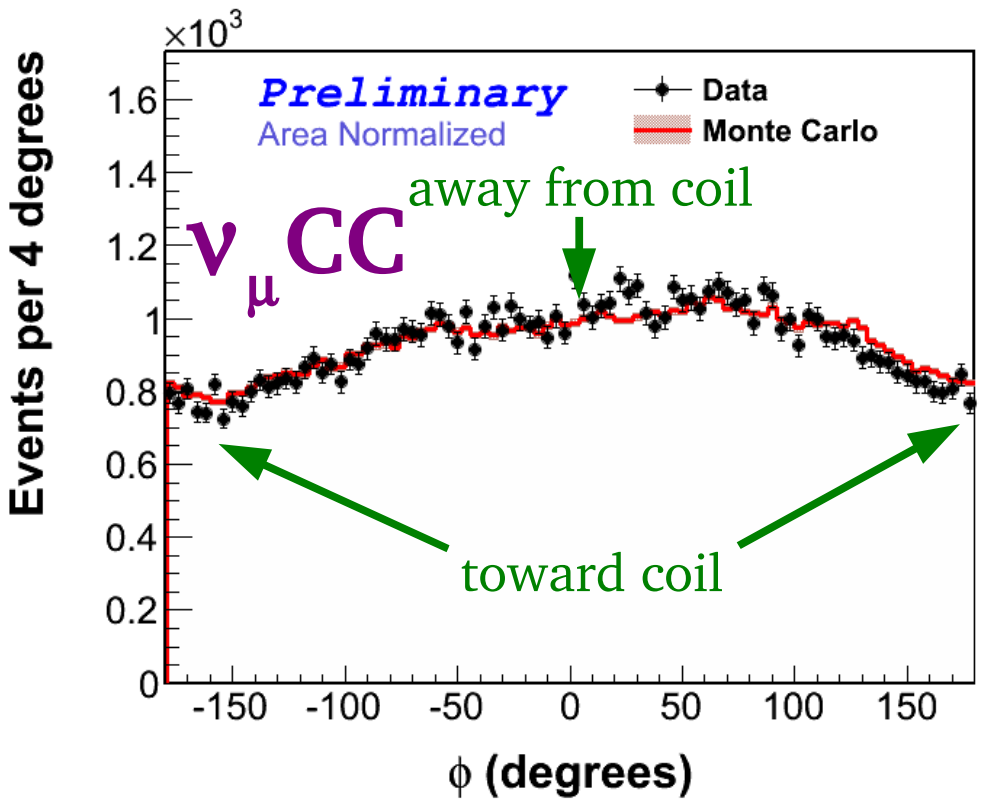


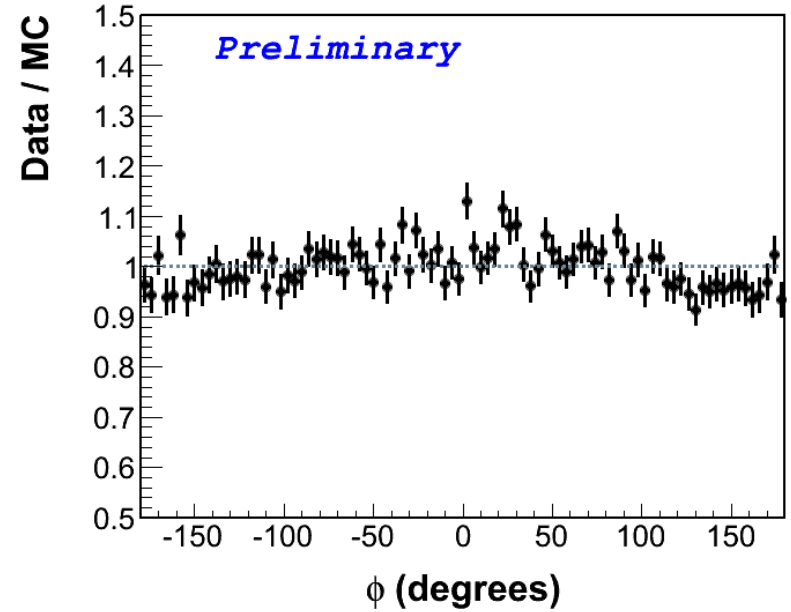
inclusive ν_μ CC scattering

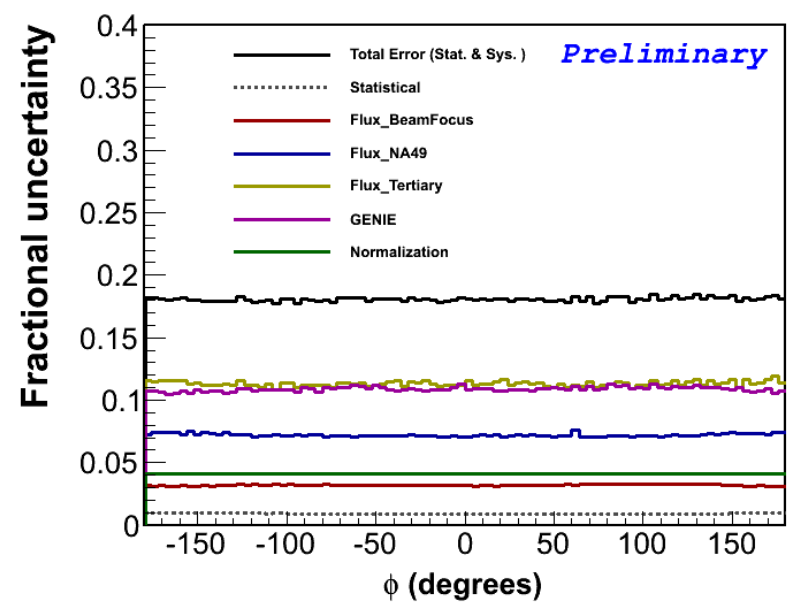


muon ϕ

ϕ probes detector acceptance and is weakly dependent on physics

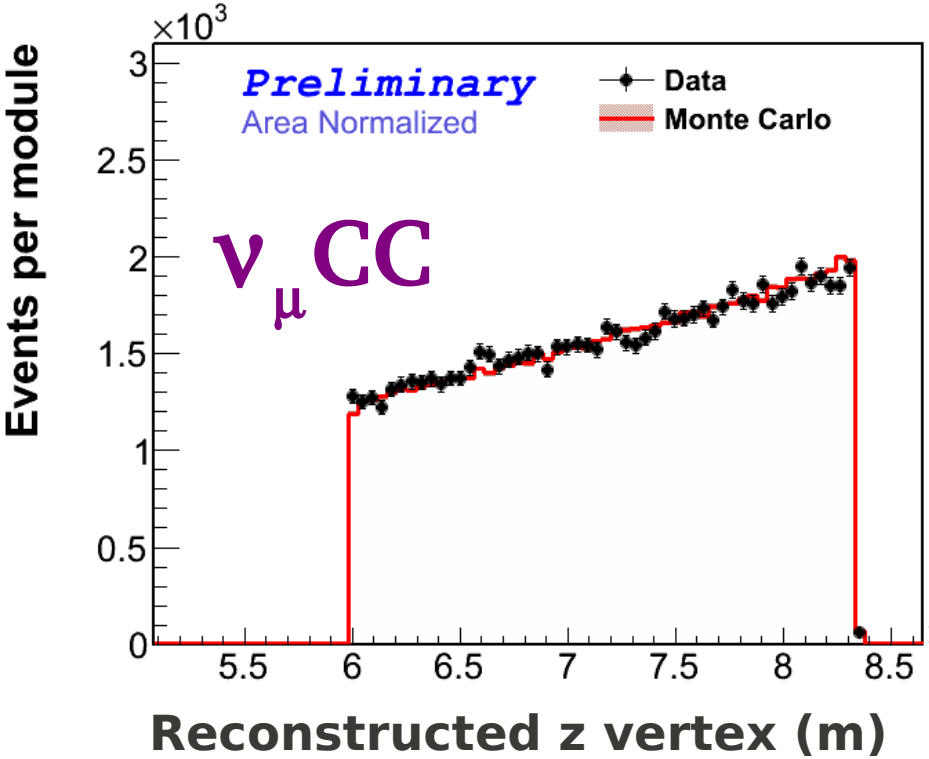




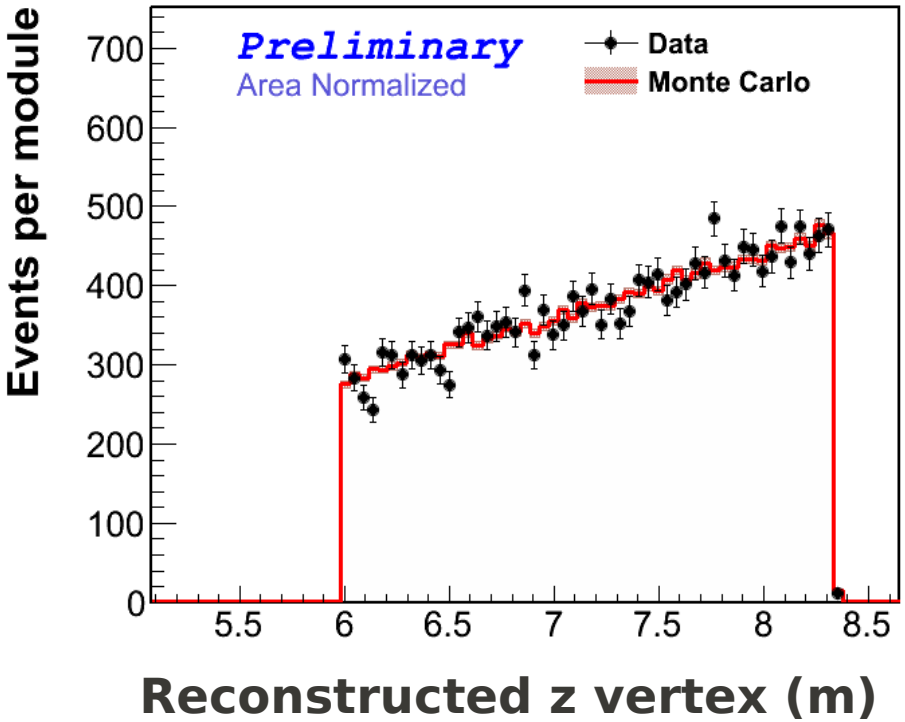


Vertex Z

probes detector acceptance,
modest physics dependence (couples to μ kinematics)

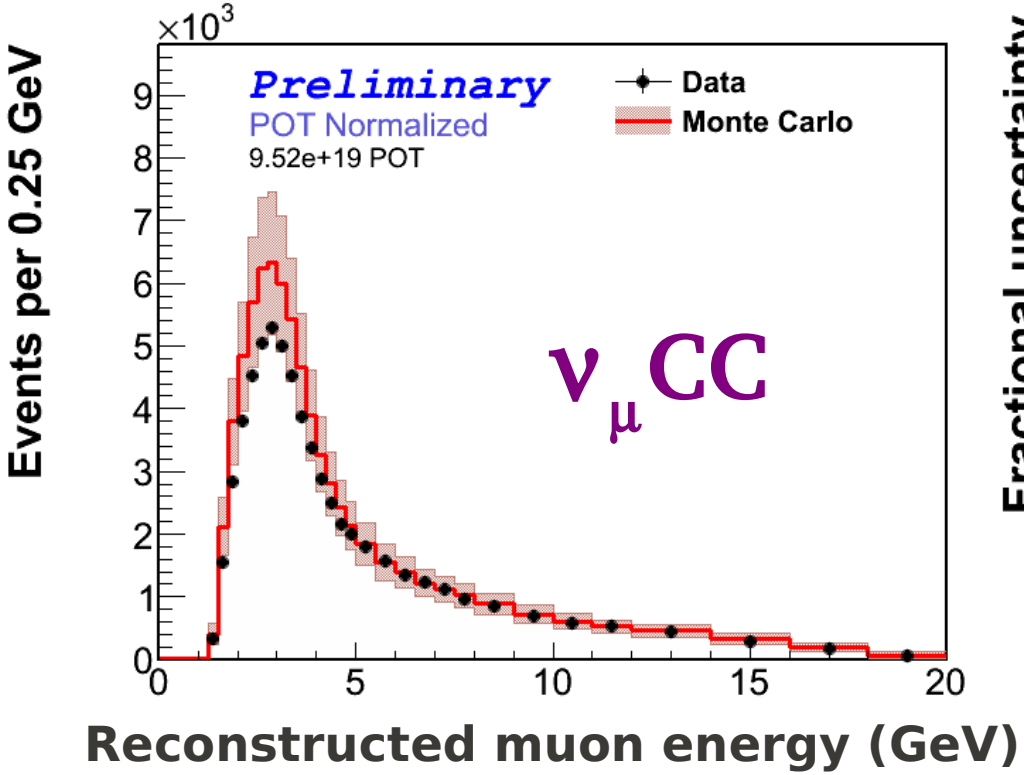


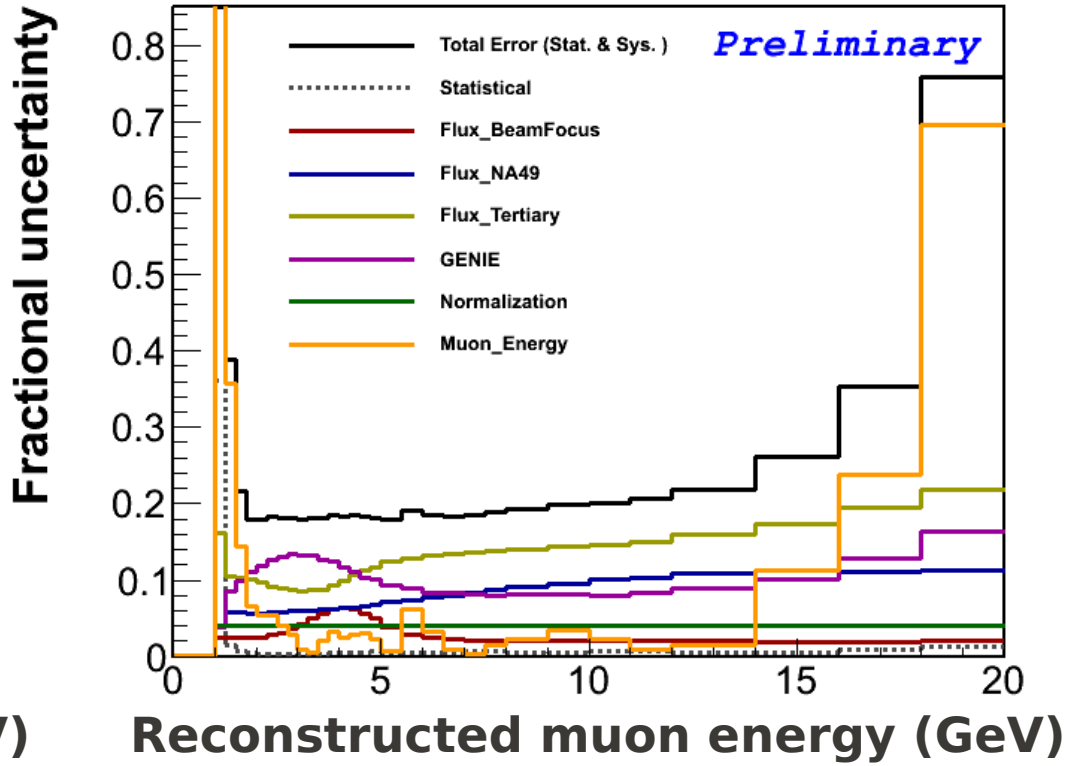
all events



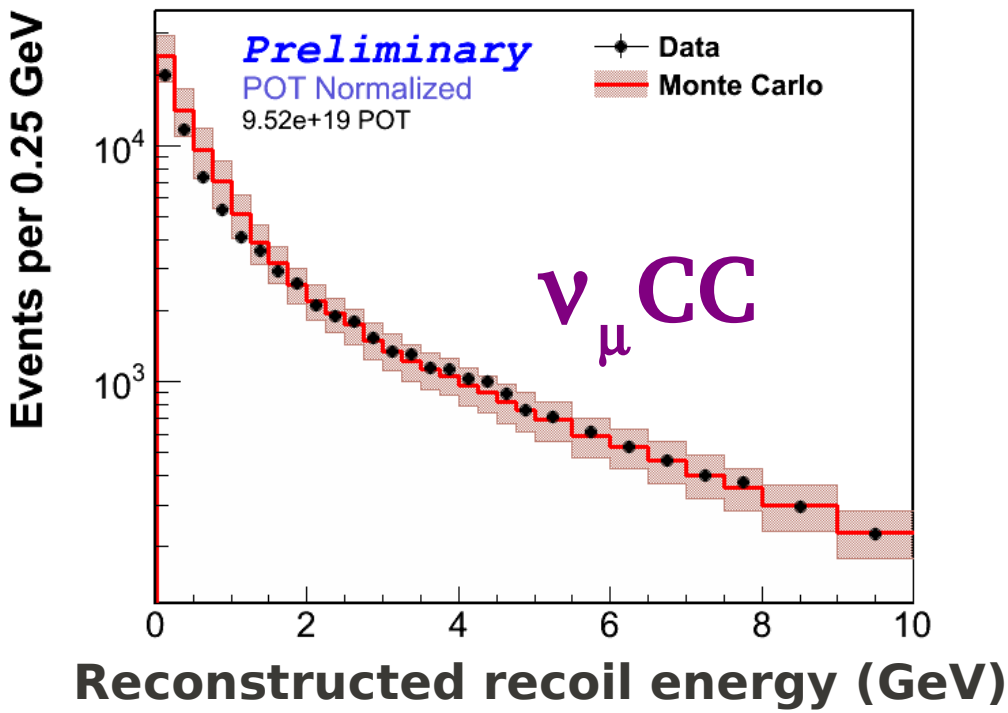
narrow slice in
μ energy

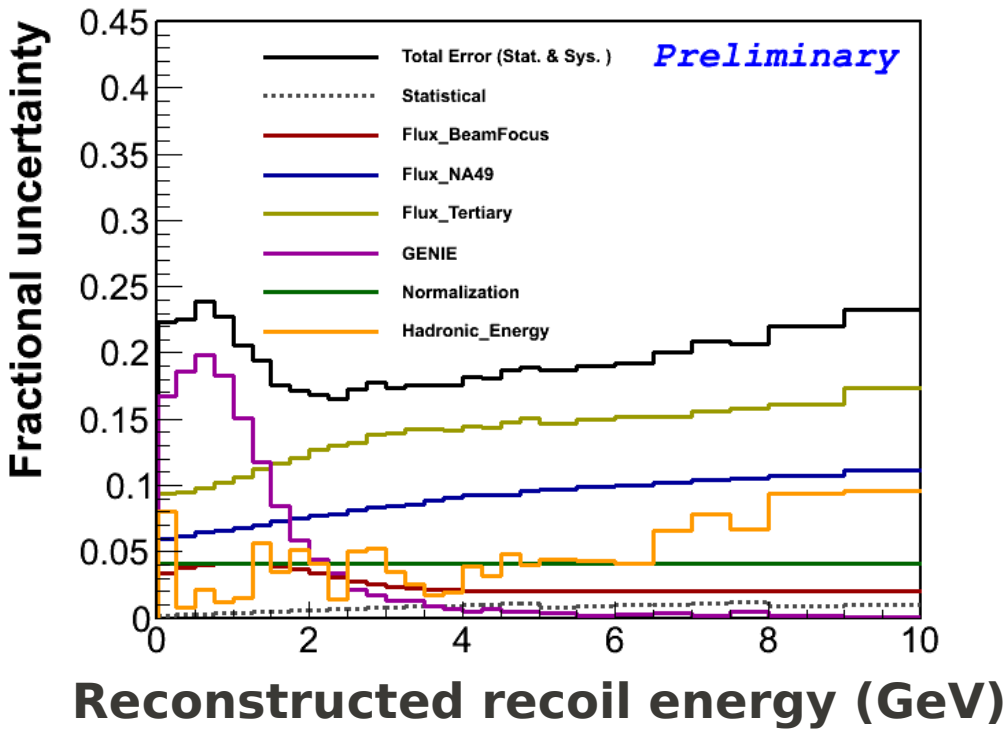
muon energy


Preliminary
POT Normalized
9.52e+19 POT
Data
Monte Carlo
ν_μCC
Events per 0.25 GeV
×10^3
Reconstructed muon energy (GeV)


Preliminary
Total Error (Stat. & Sys.)
Statistical
Flux_BeamFocus
Flux_NA49
Flux_Tertiary
GENIE
Normalization
Muon_Energy
Fractional uncertainty
Reconstructed muon energy (GeV)

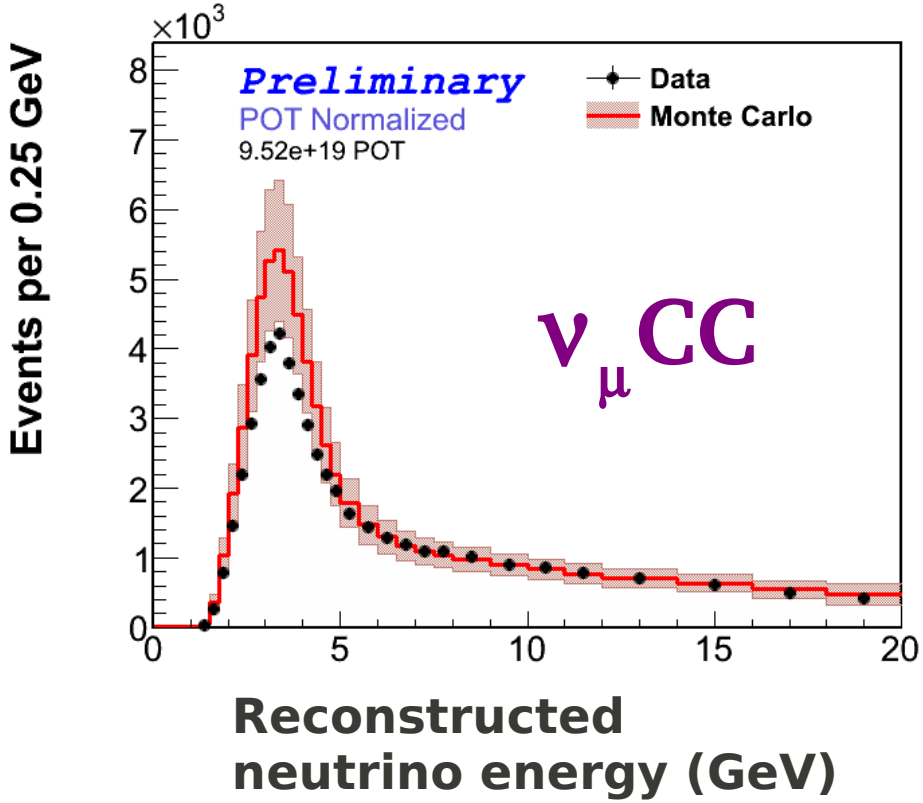
recoil energy

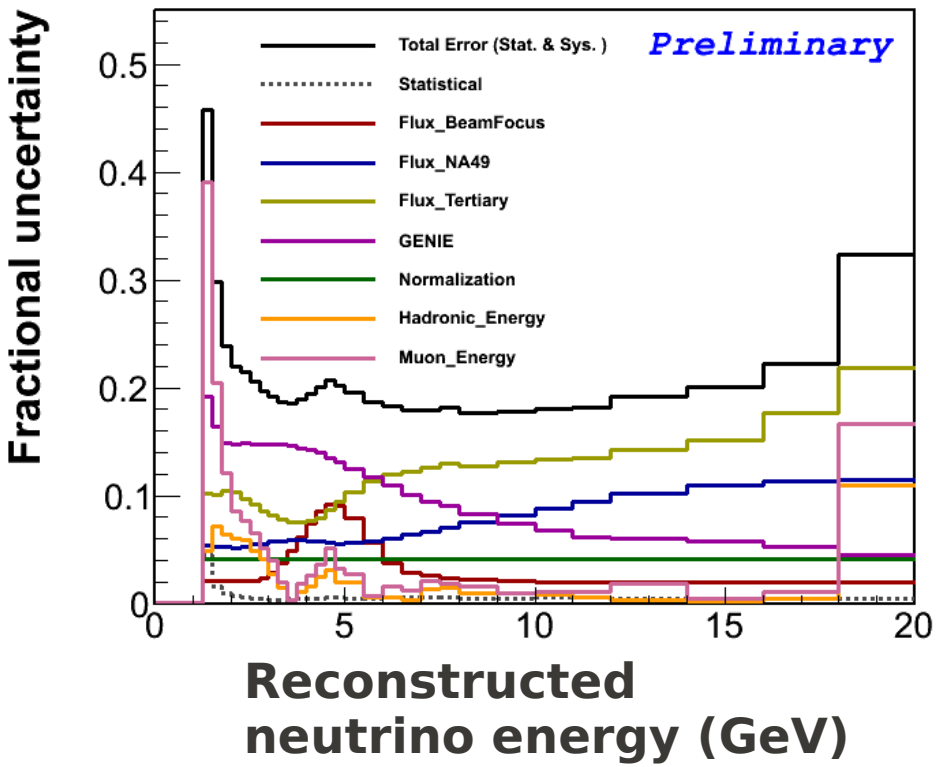




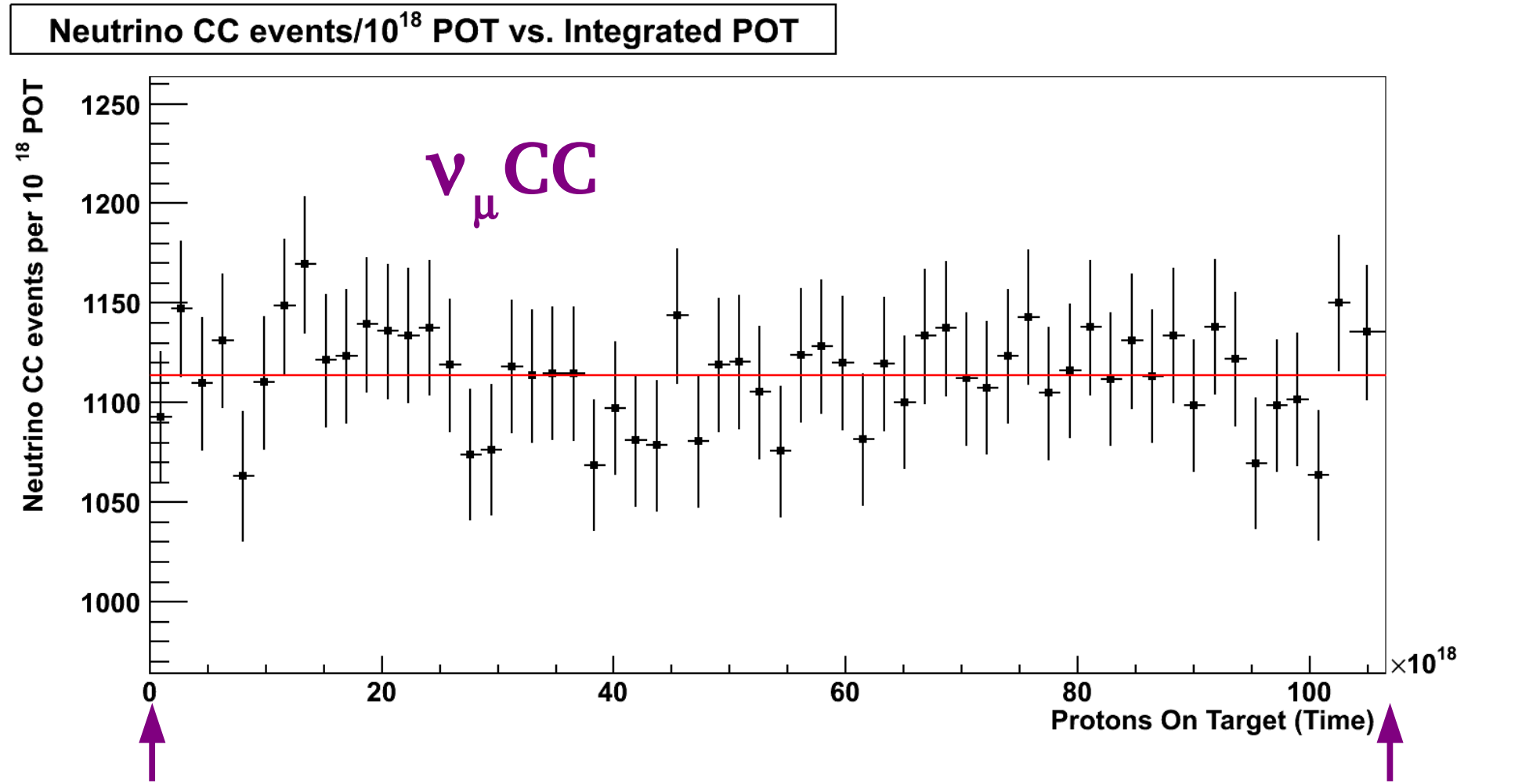
neutrino energy

$$E_\nu = E_\mu + E_{recoil}$$





Stability

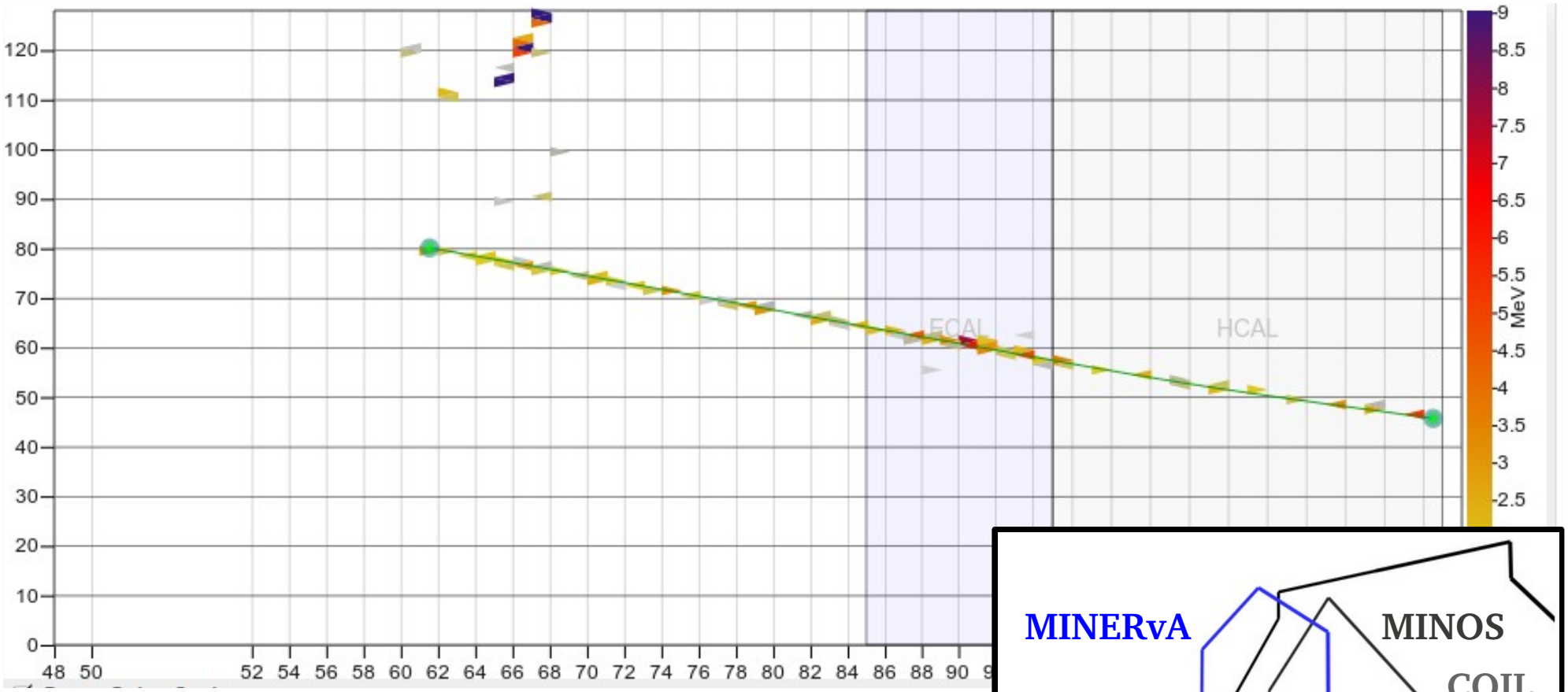


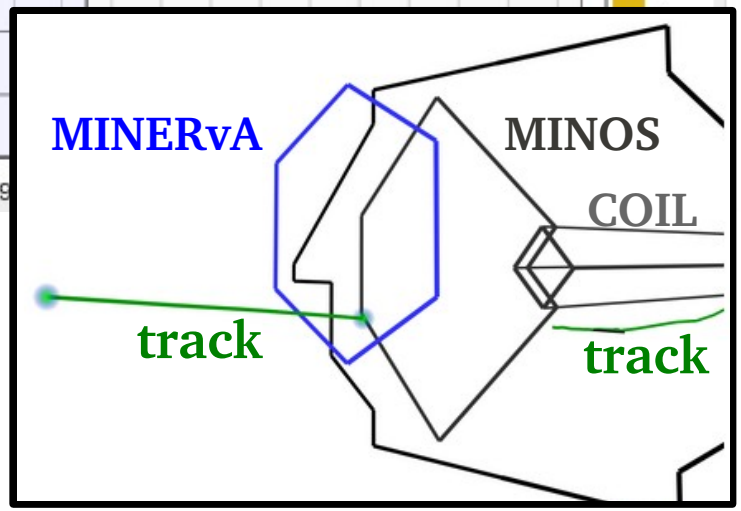
March 22, 2010

July 12, 2010

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

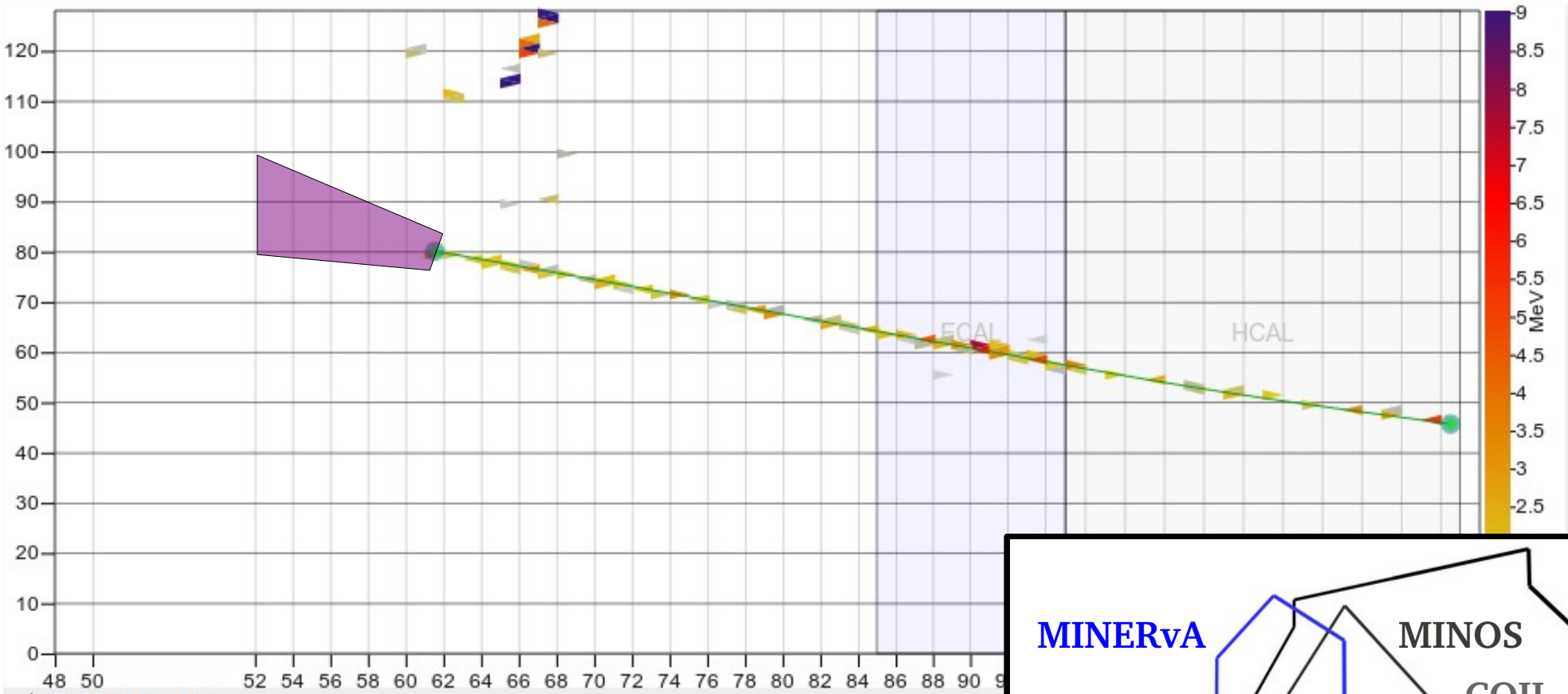
$\bar{\nu}_\mu$ QEL event selection

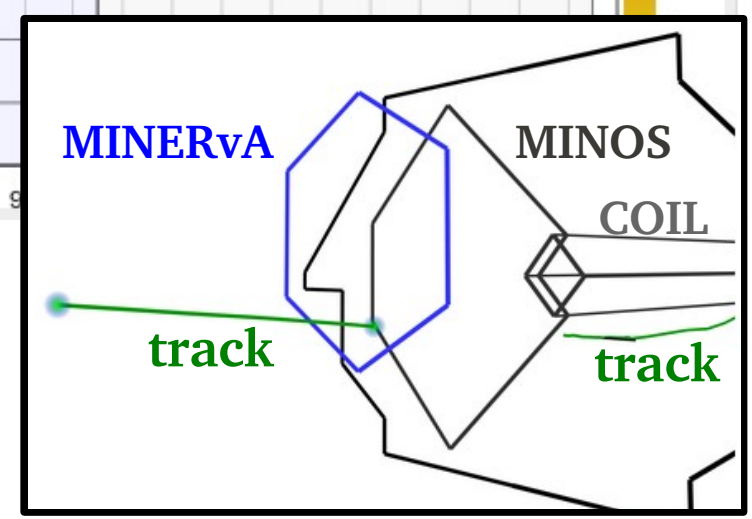




(1) μ^+ from CH tracker & matched to MINOS

$\bar{\nu}_\mu$ QEL event selection

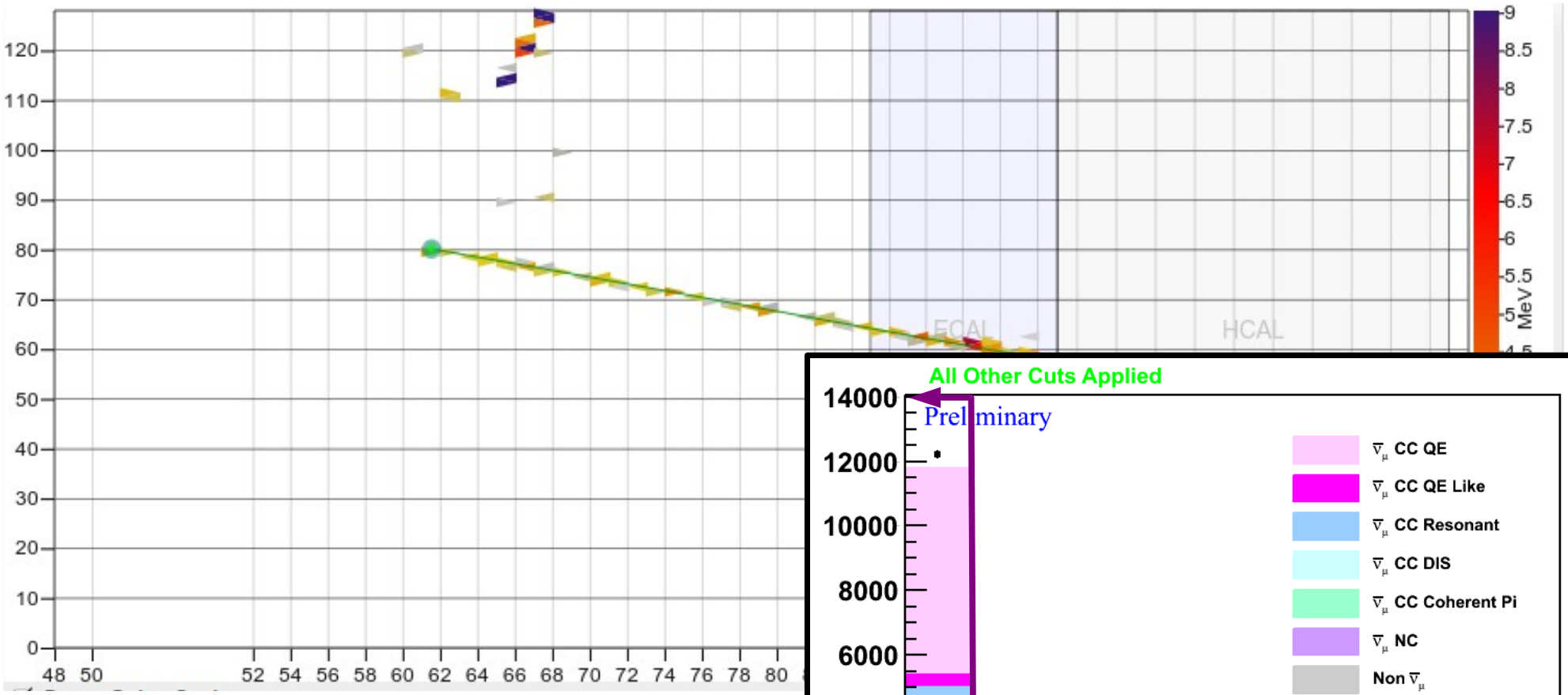




(2) Upstream live

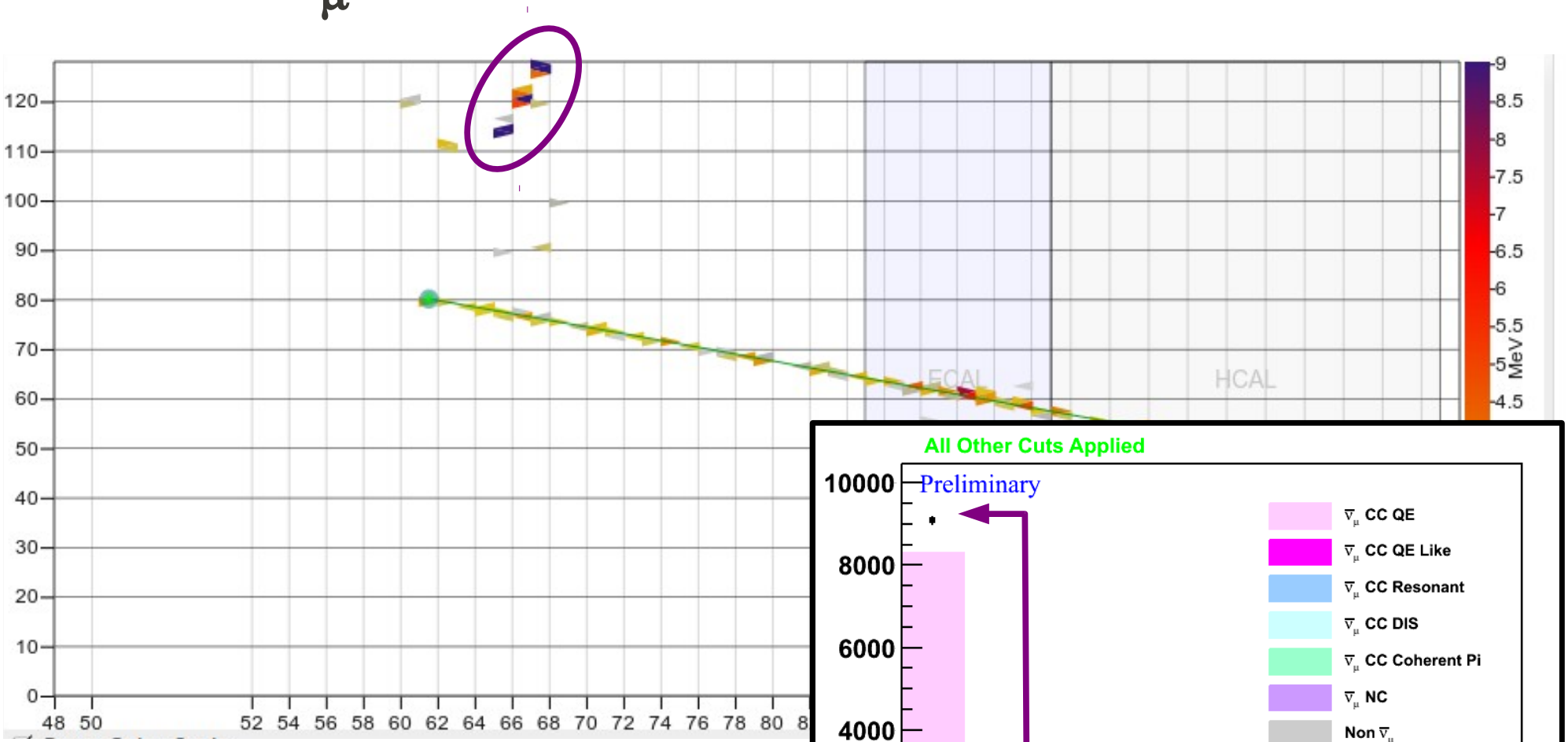
(3) No upstream activity

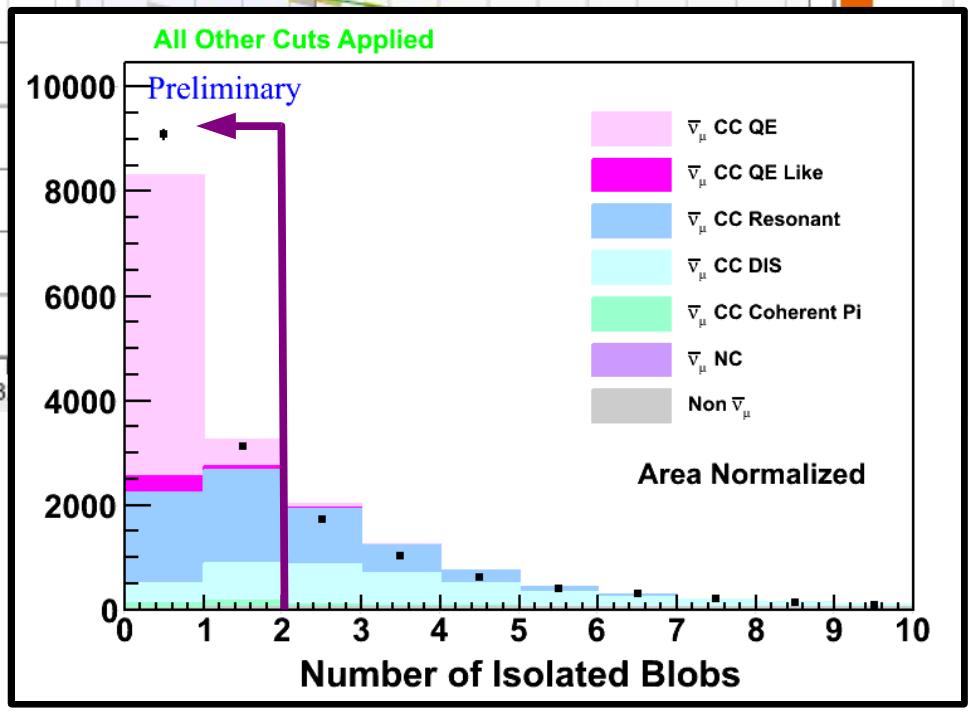
$\bar{\nu}_\mu$ QEL event selection



(4) No other tracks within +/-25ns

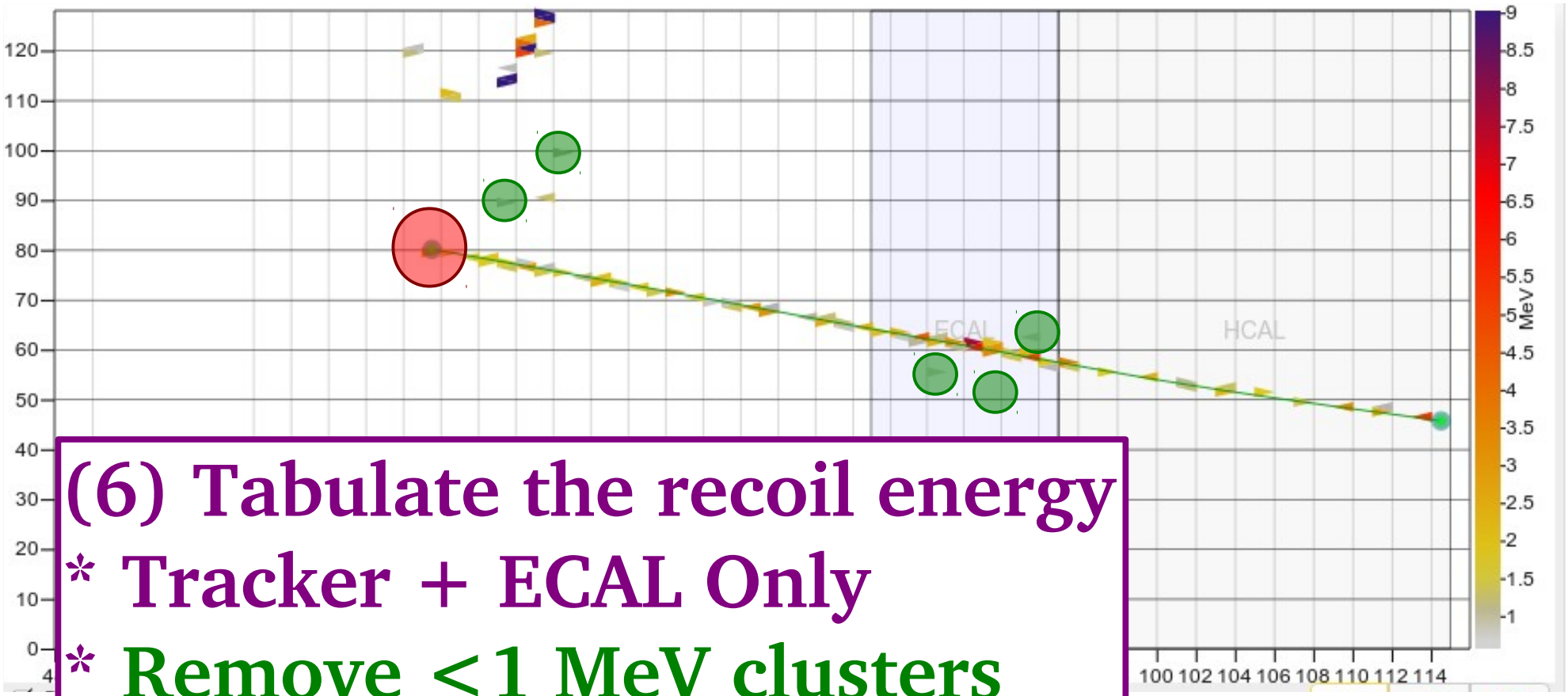
$\bar{\nu}_\mu$ QEL event selection





(5) 0 or 1 isolated shower "blobs"

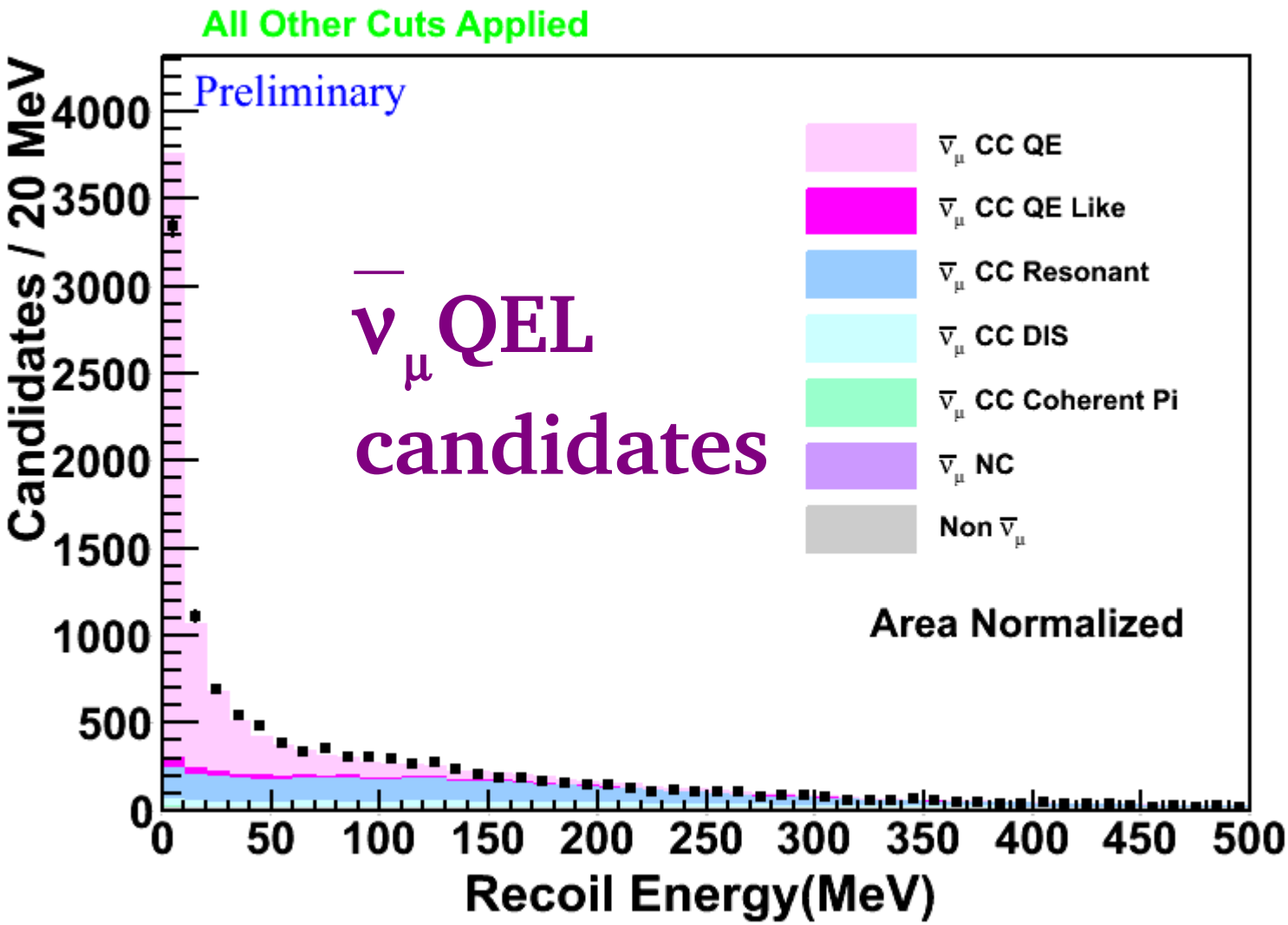
$\bar{\nu}_\mu$ QEL recoil energy



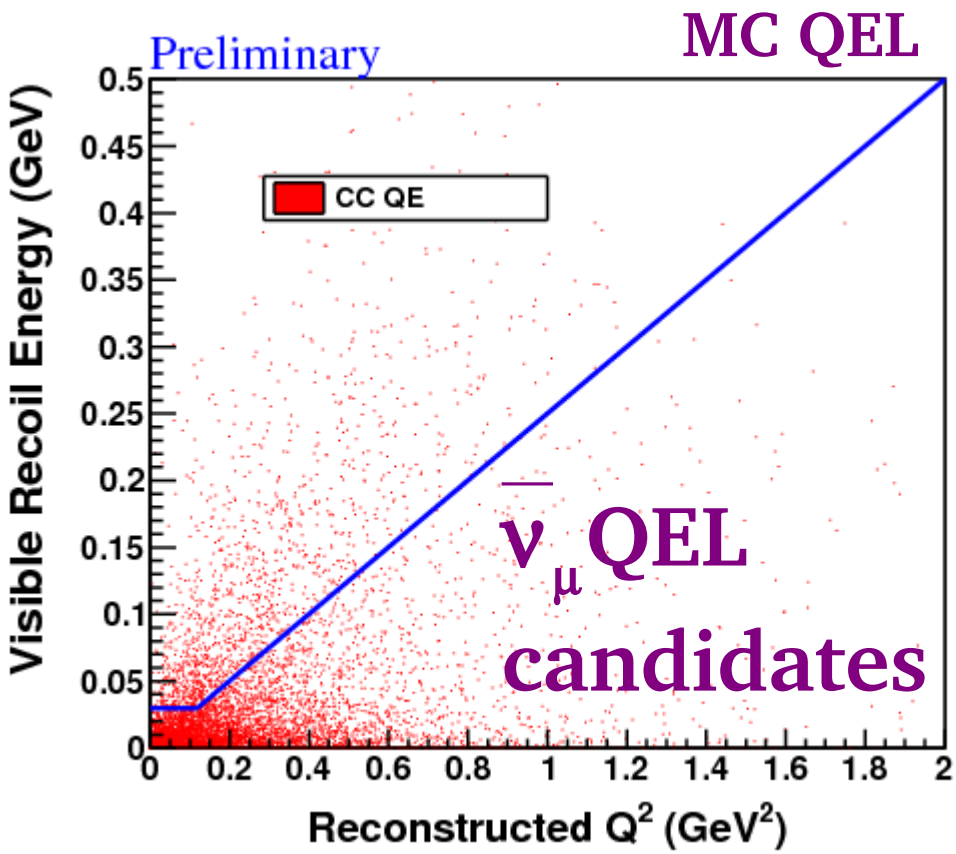
(6) Tabulate the recoil energy

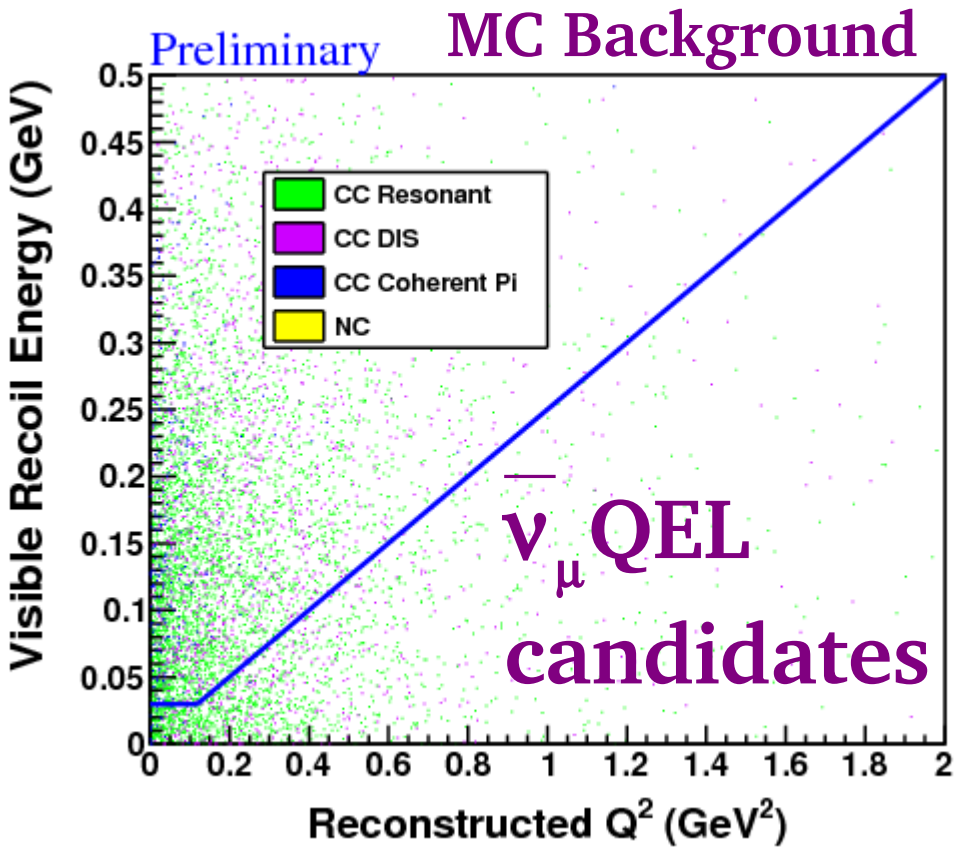
* Tracker + ECAL Only
* Remove <1 MeV clusters & likely cross-talk from μ
* Exclude 10cm vertex region

$\bar{\nu}_\mu$ QEL recoil energy



Recoil vs. Q^2


Preliminary
MC QEL
CC QE
$\bar{\nu}_\mu$ QEL candidates
Visible Recoil Energy (GeV)
Reconstructed Q^2 (GeV^2)


Preliminary
MC Background
CC Resonant
CC DIS
CC Coherent Pi
NC
$\bar{\nu}_\mu$ QEL candidates
Visible Recoil Energy (GeV)
Reconstructed Q^2 (GeV^2)

GENIE

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

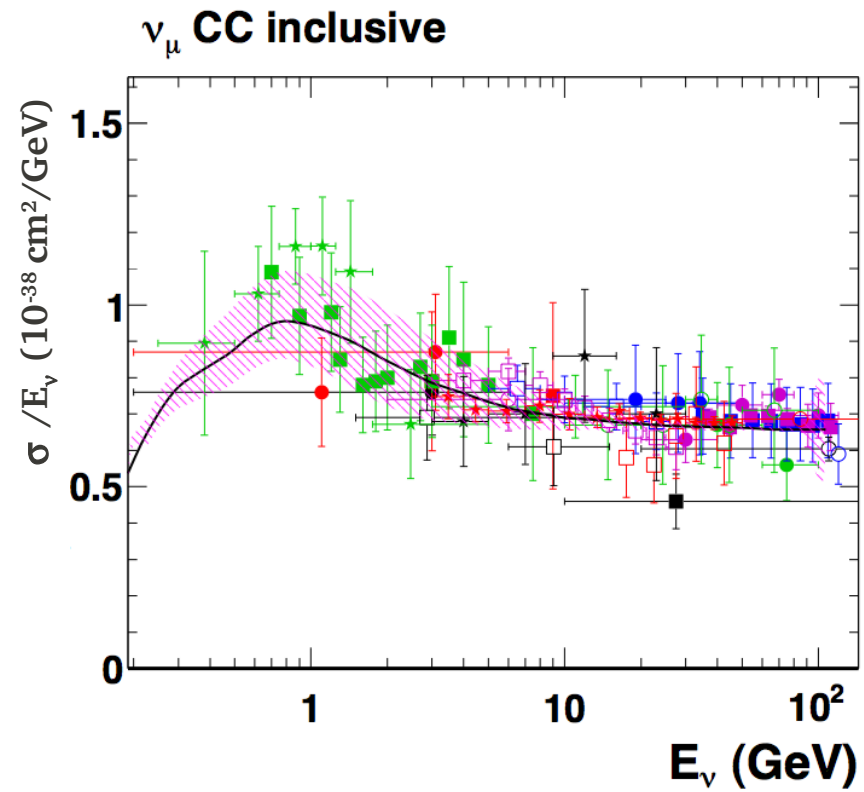
Resonance: Rein & Sehgal (K, ρ, η production, Δ-Nγ)

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

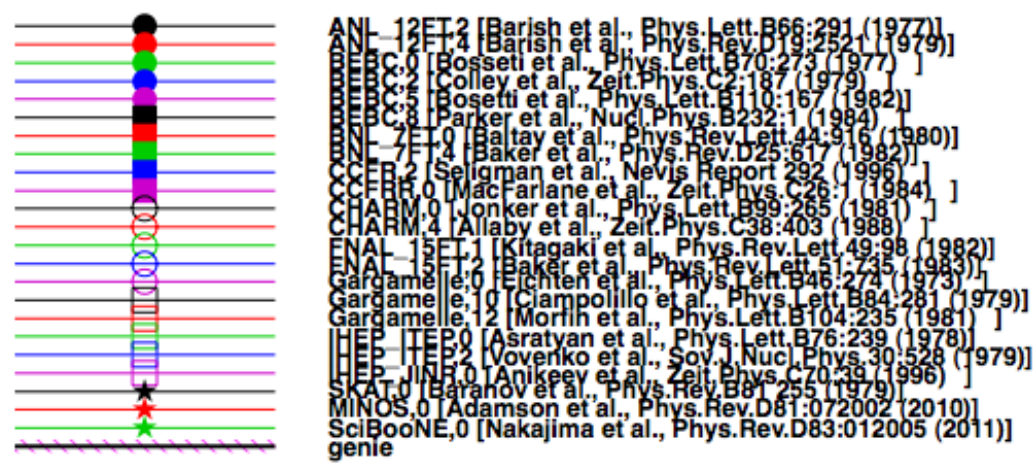
T. Yang, AIP Conf. Proc.967:269-275 (2007)

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*

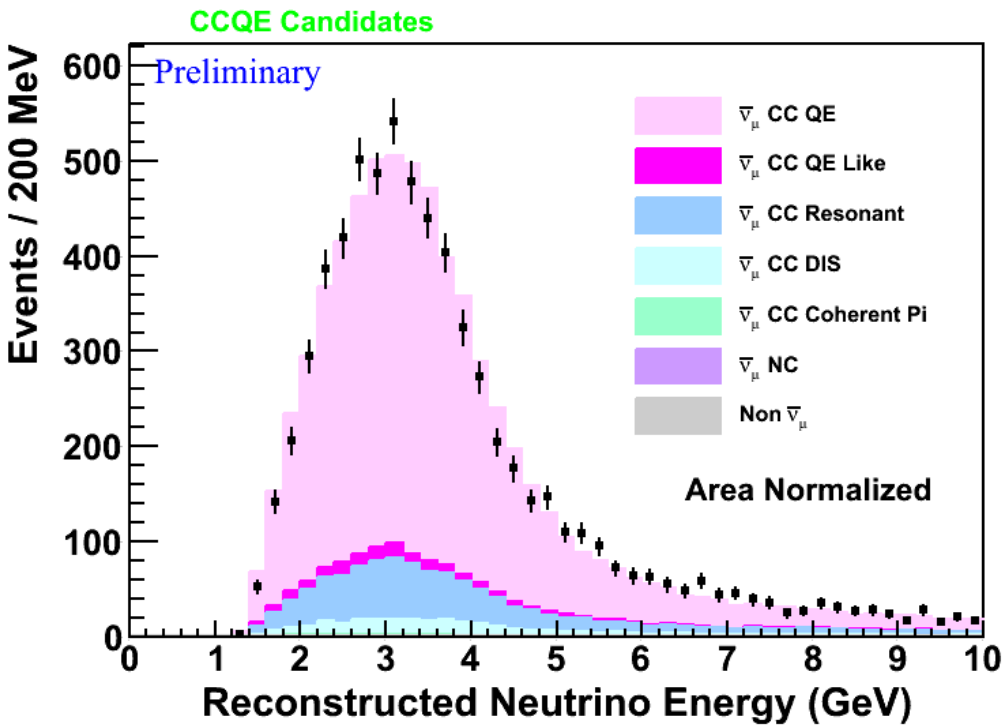
anchored to π,p/n-Fe data, scaled to all nucl

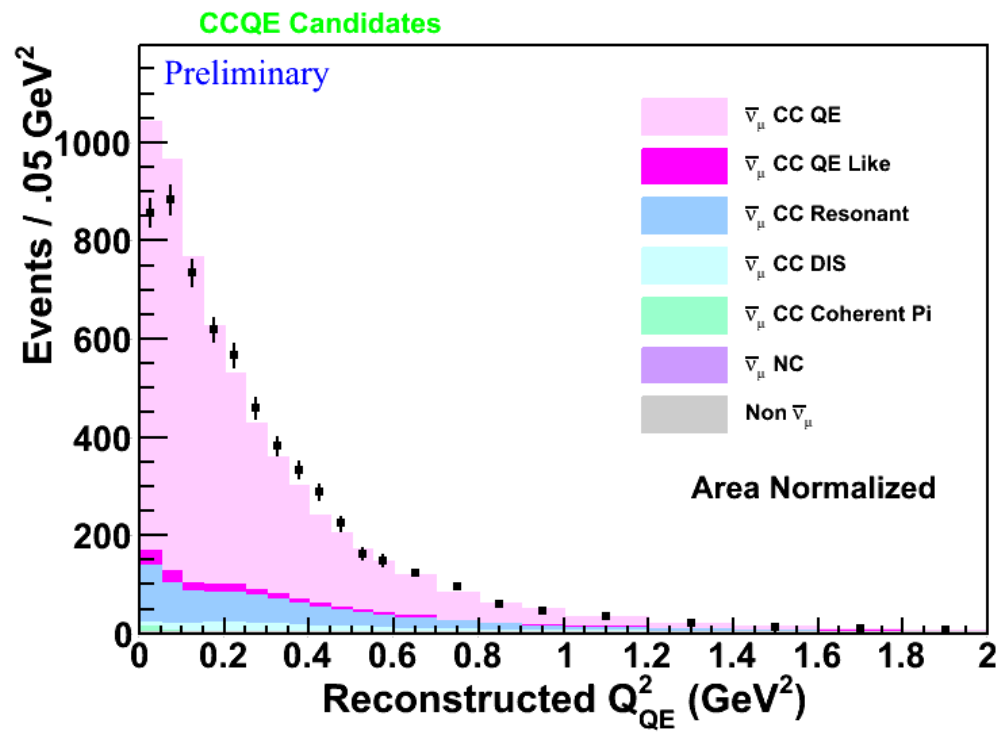


www.genie-mc.org; NIM A614 (2010) 87-104

neutrino energy & Q^2

$\bar{\nu}_\mu$ QEL candidates



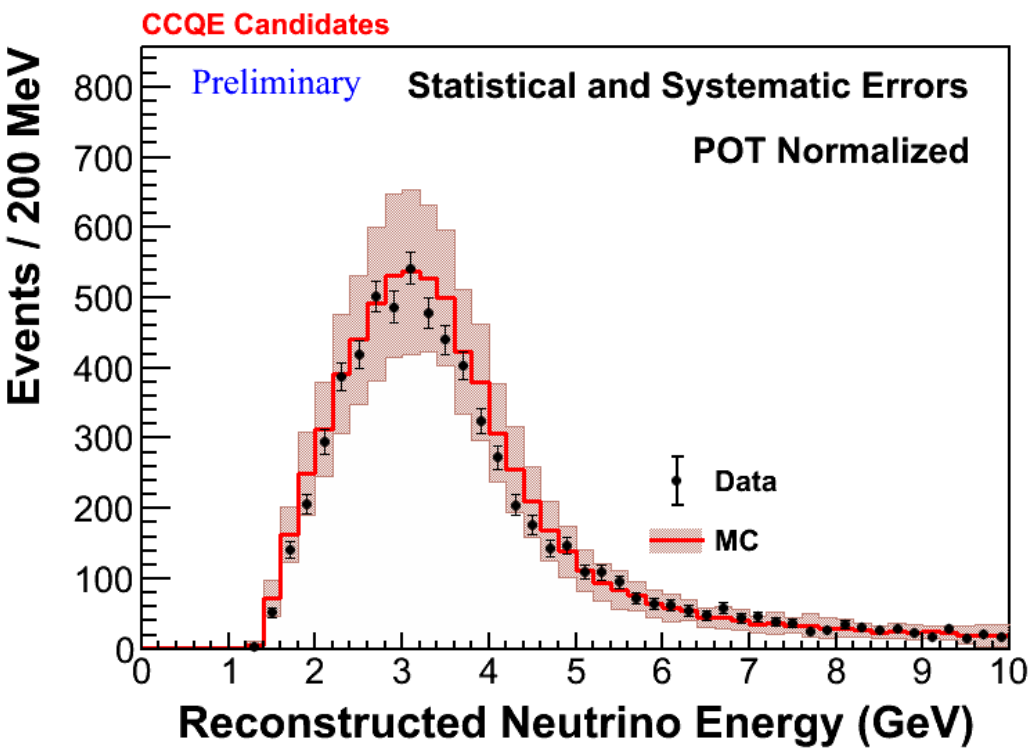


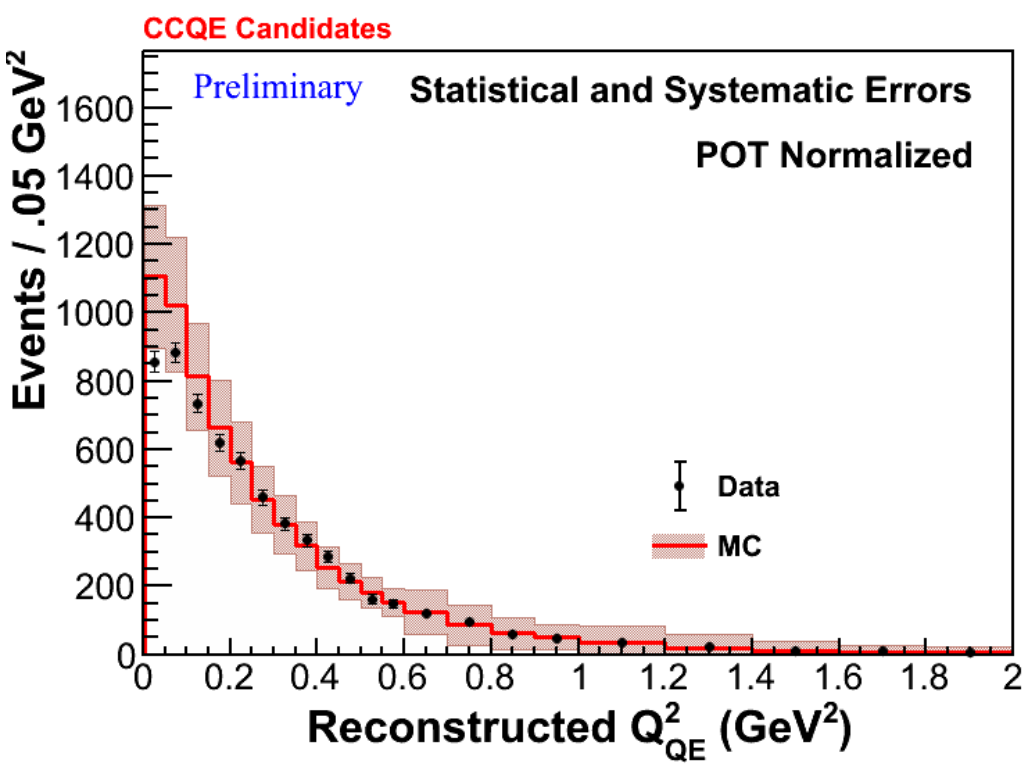
$$E_\nu = \frac{m_\mu^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

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

neutrino energy & Q^2

$\bar{\nu}_\mu$ QEL candidates

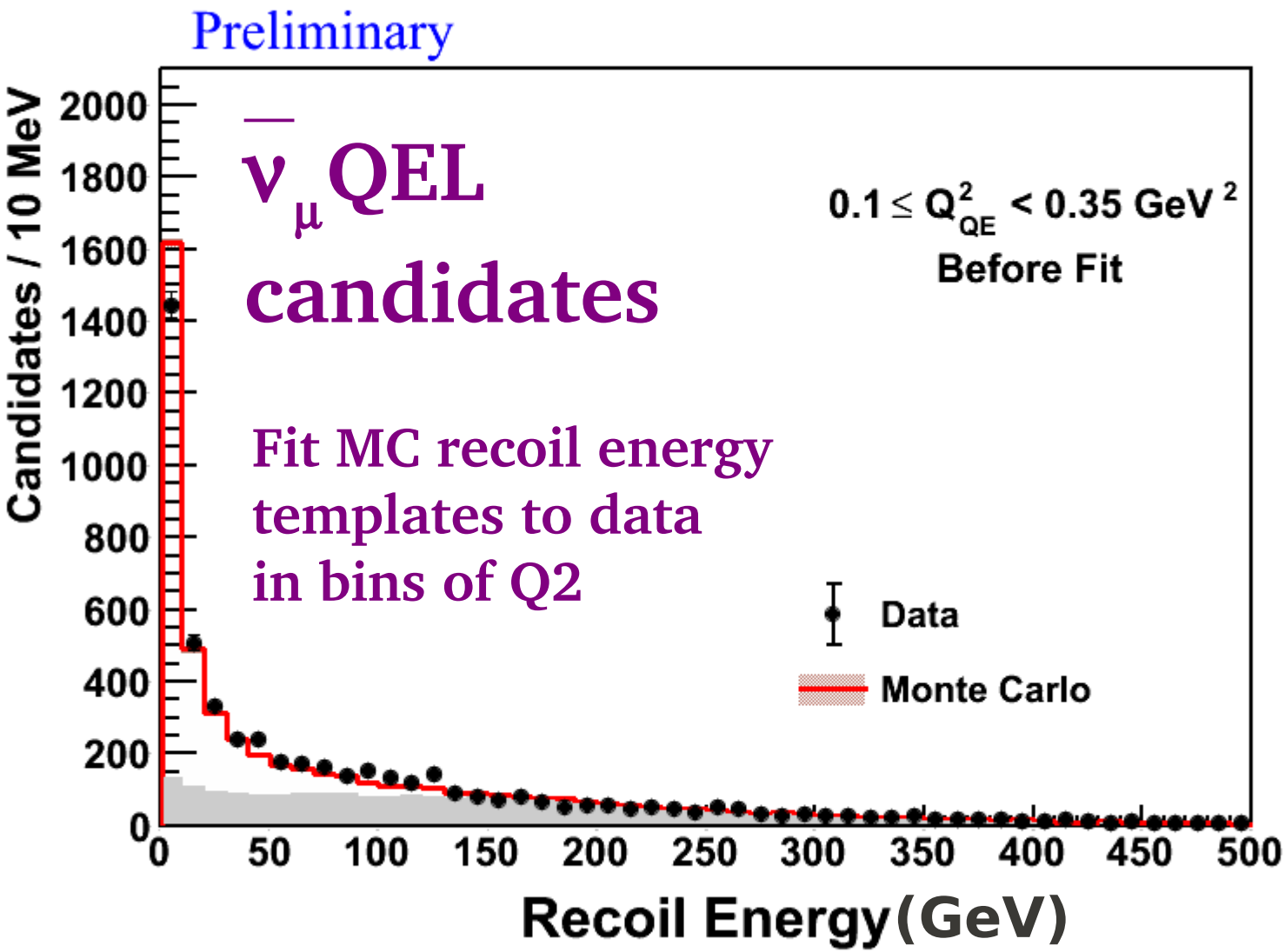




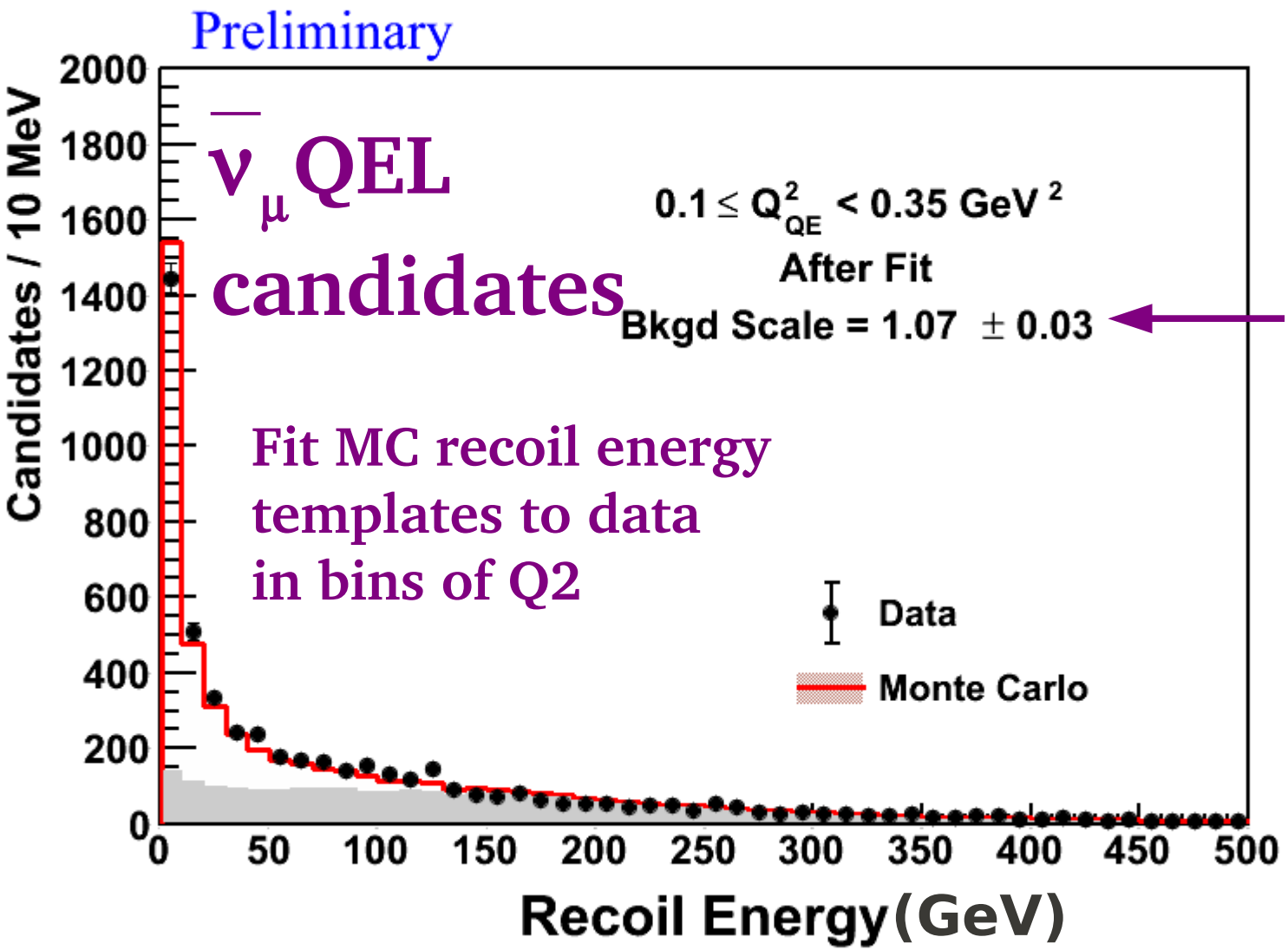
$$E_\nu = \frac{m_\mu^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

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

Background Subtraction

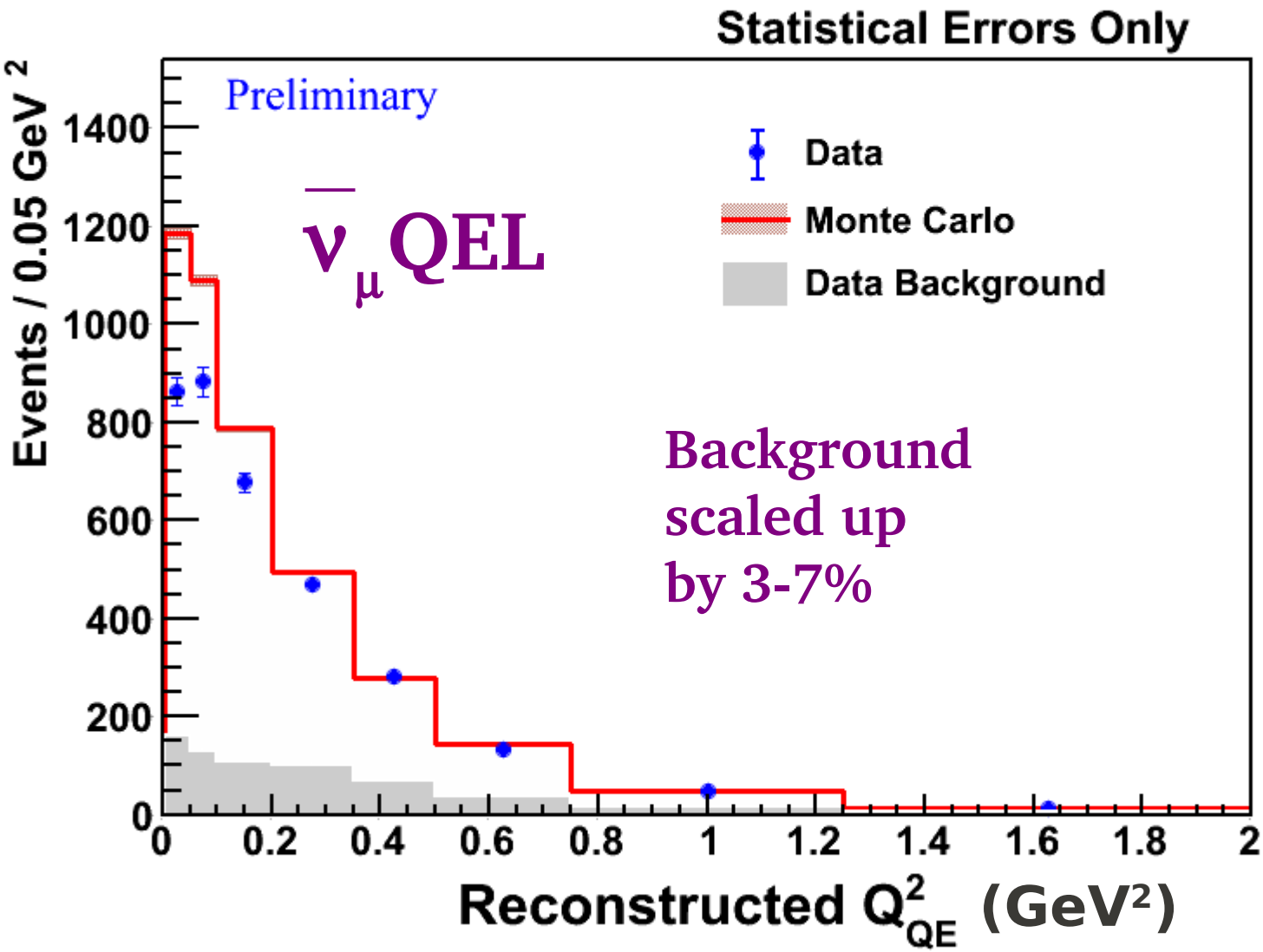


Background Subtraction

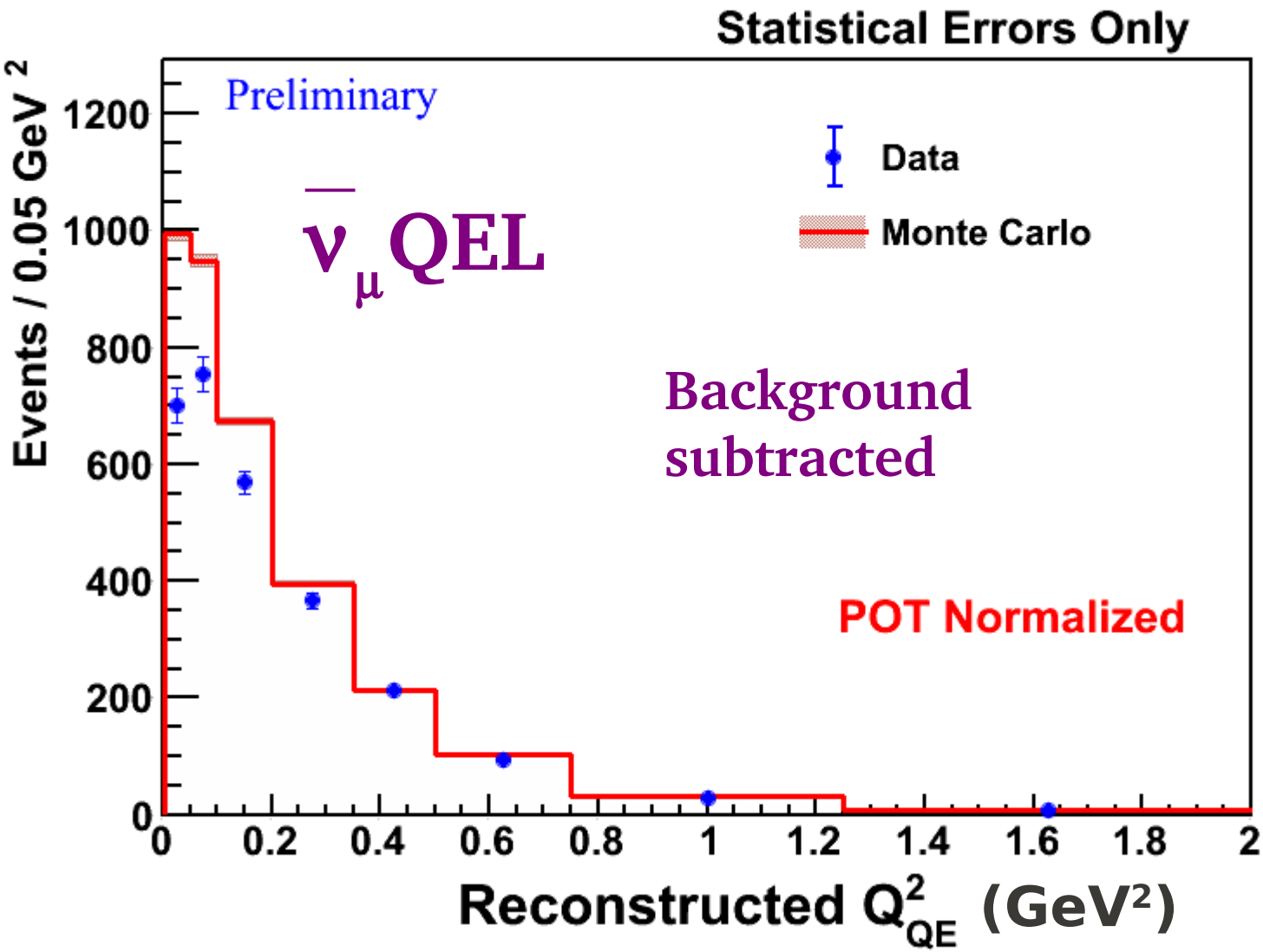


small correction

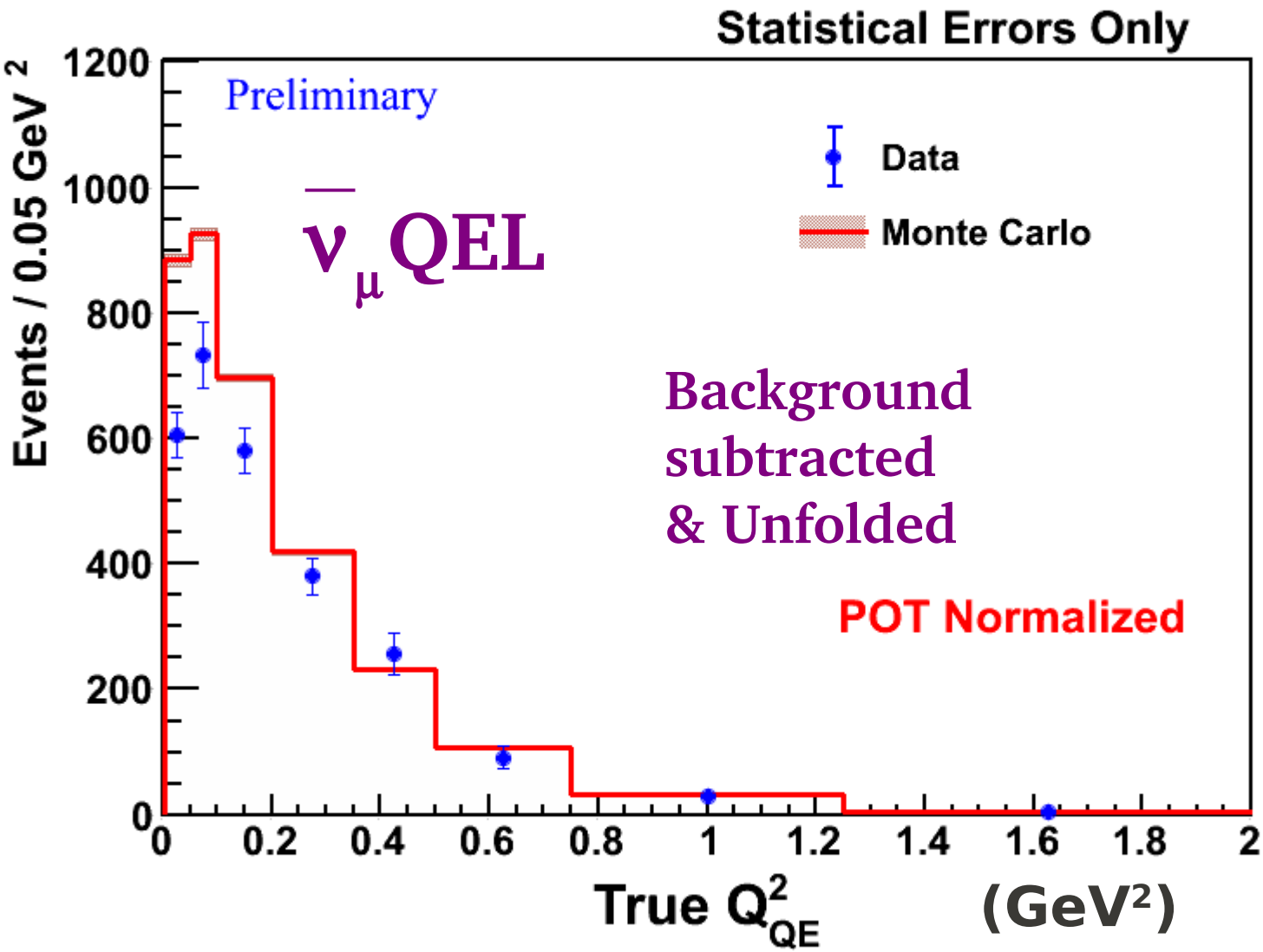
Background Subtraction



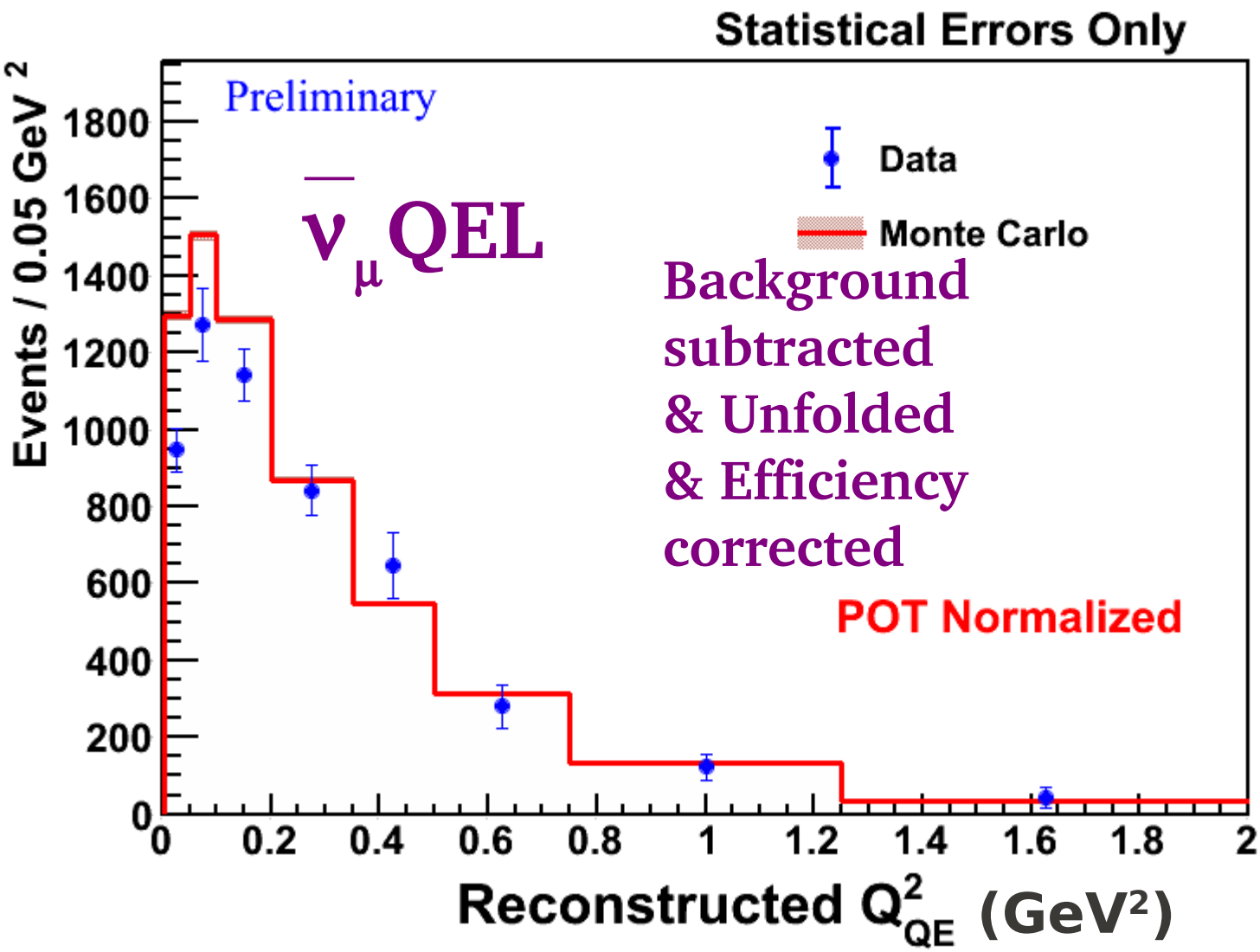
Background Subtraction



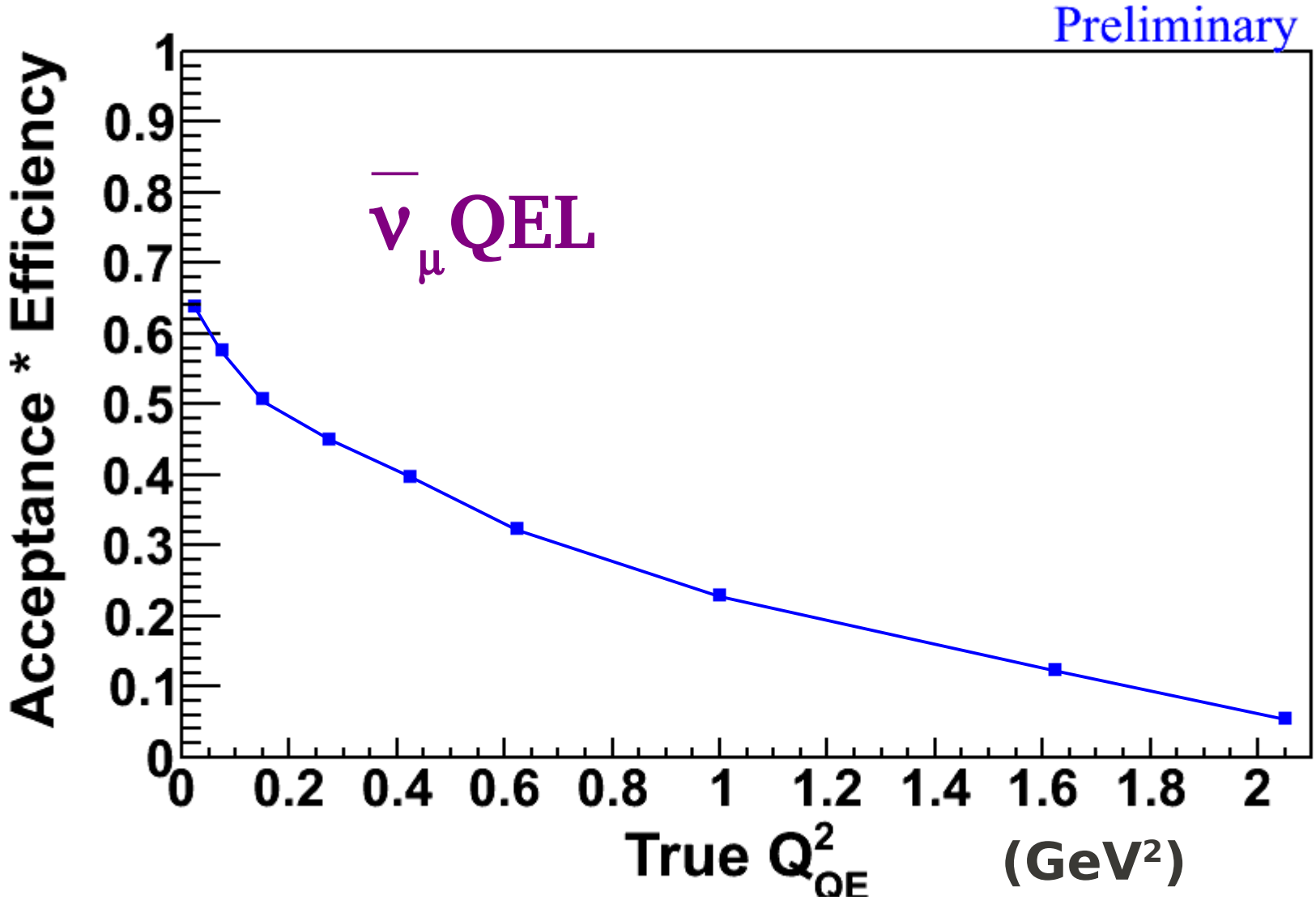
Unfolded


Statistical Errors Only
Preliminary
Data
Monte Carlo
$\bar{\nu}_\mu$ QEL
Background subtracted & Unfolded
POT Normalized
Events / 0.05 GeV ^{2}
True Q^2_{QE} (GeV^2)
0
200
400
600
800
1000
1200
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

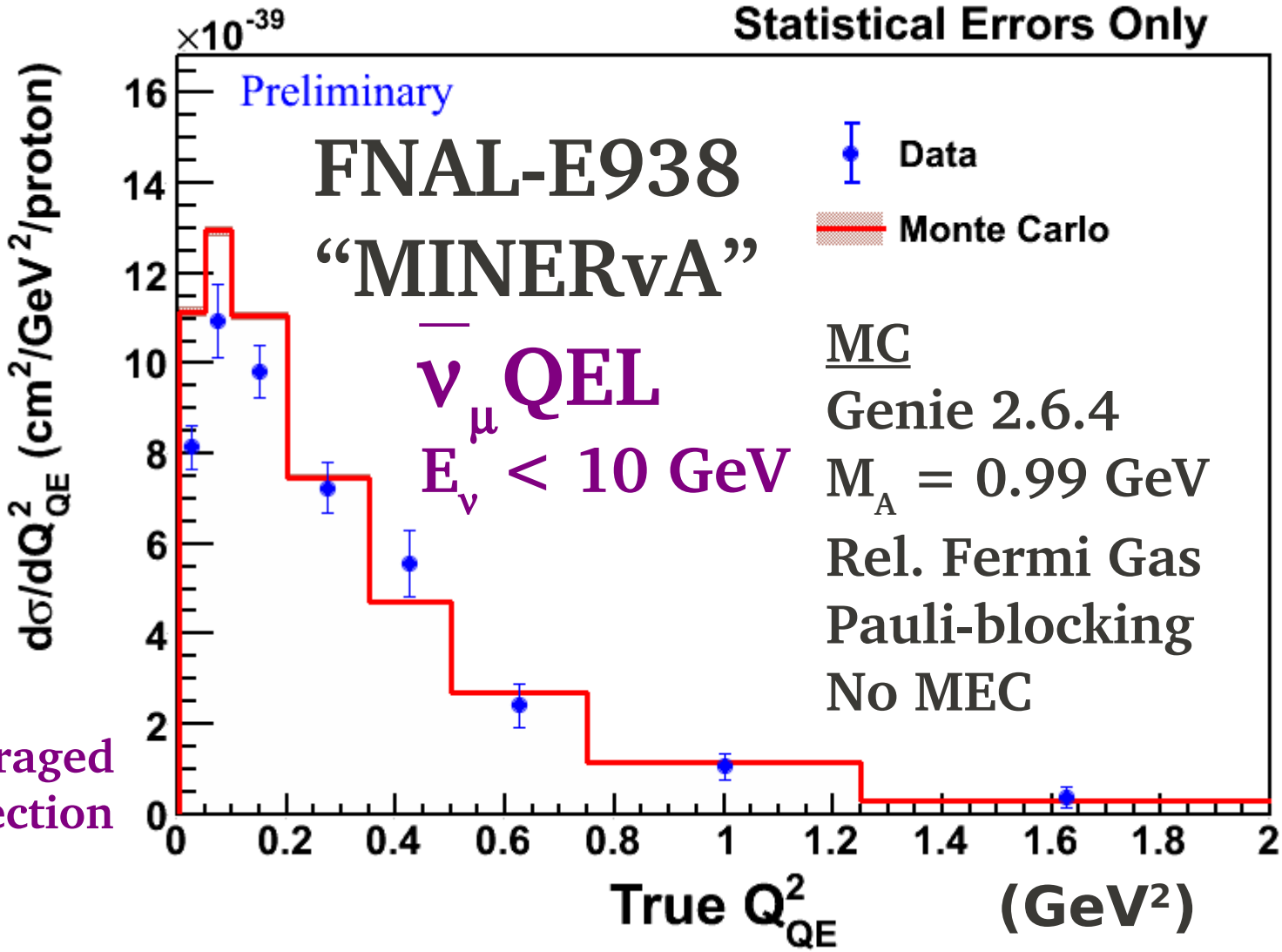
Efficiency Corrected



Efficiency

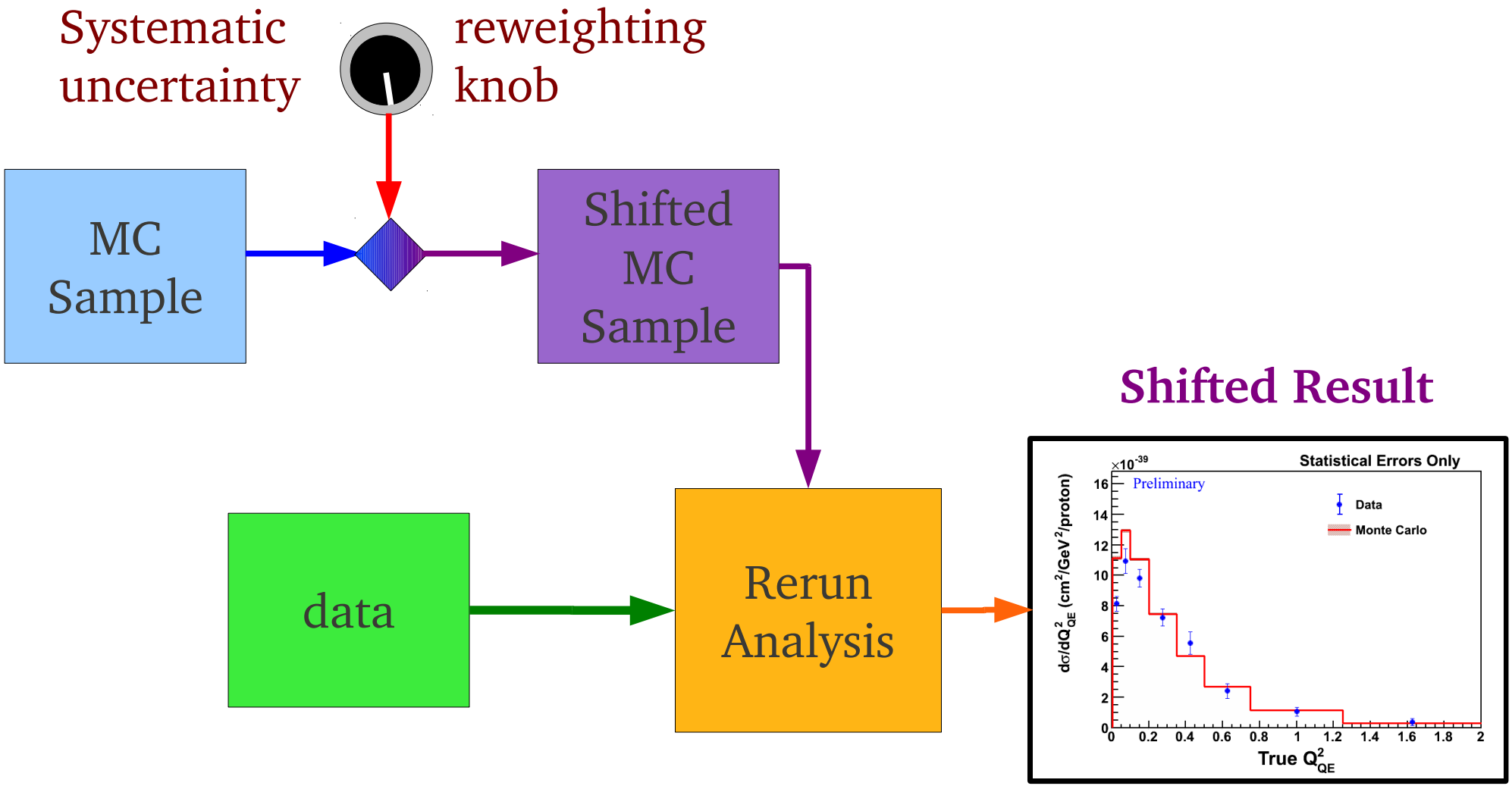

Preliminary
$\bar{\nu}_\mu$ QEL
Acceptance * Efficiency
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
True Q^2_{QE} (GeV²)

Differential Cross-section



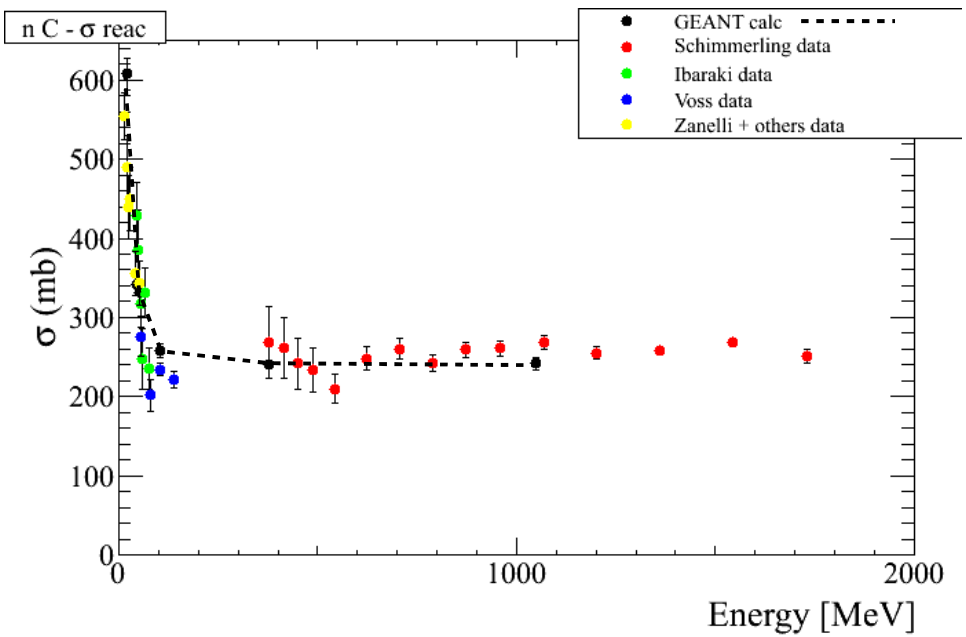
Note:
bin averaged cross-section

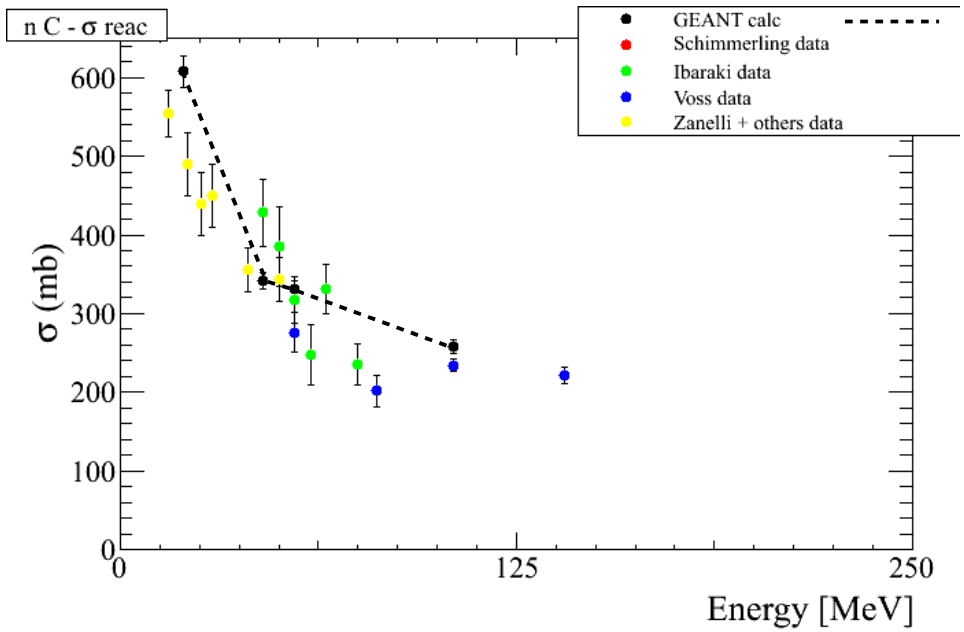
Systematic Uncertainties



Example: nC cross-section

Uncertainty in the nC cross-section causes uncertainty on the recoil distribution for signal and background.

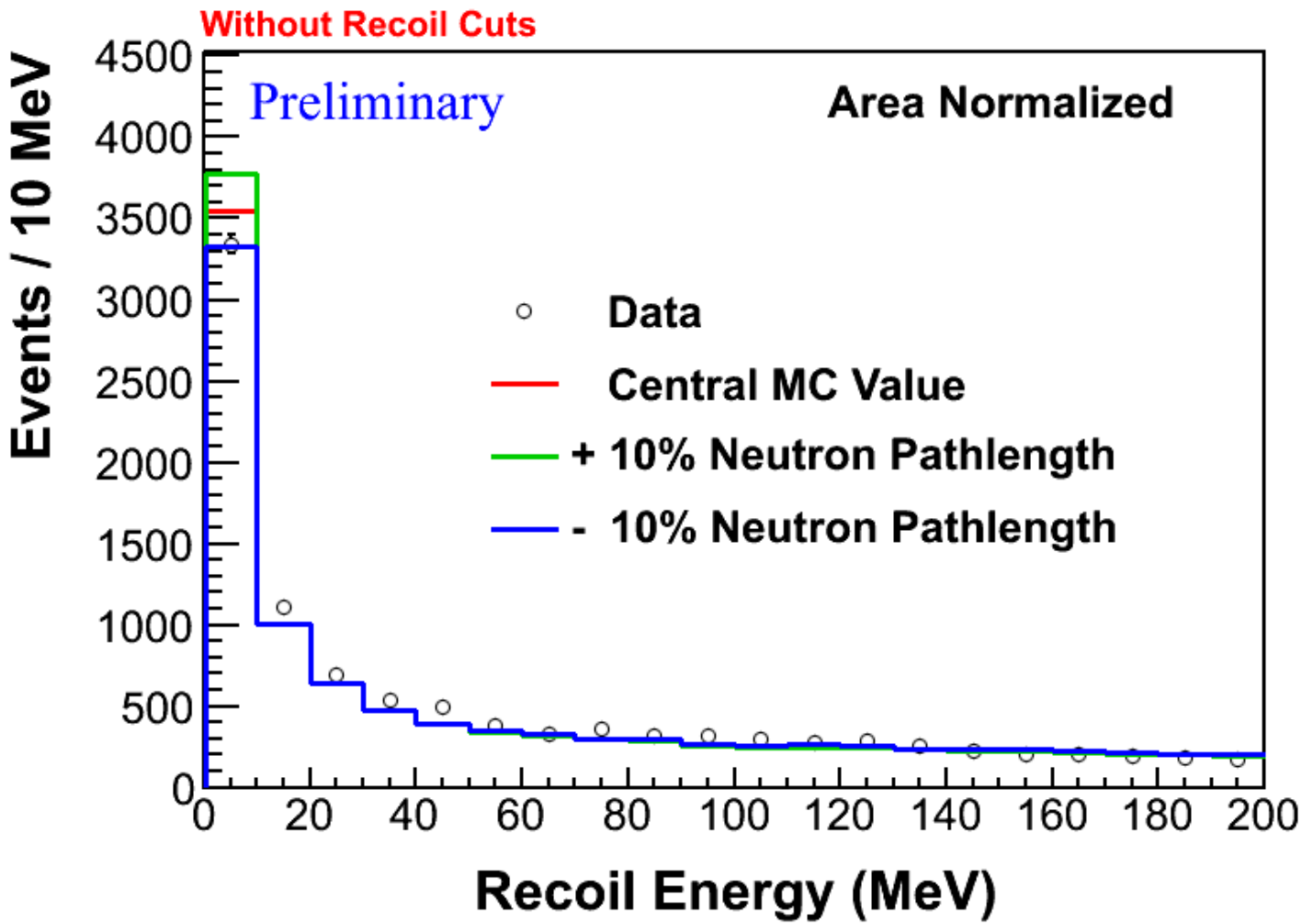




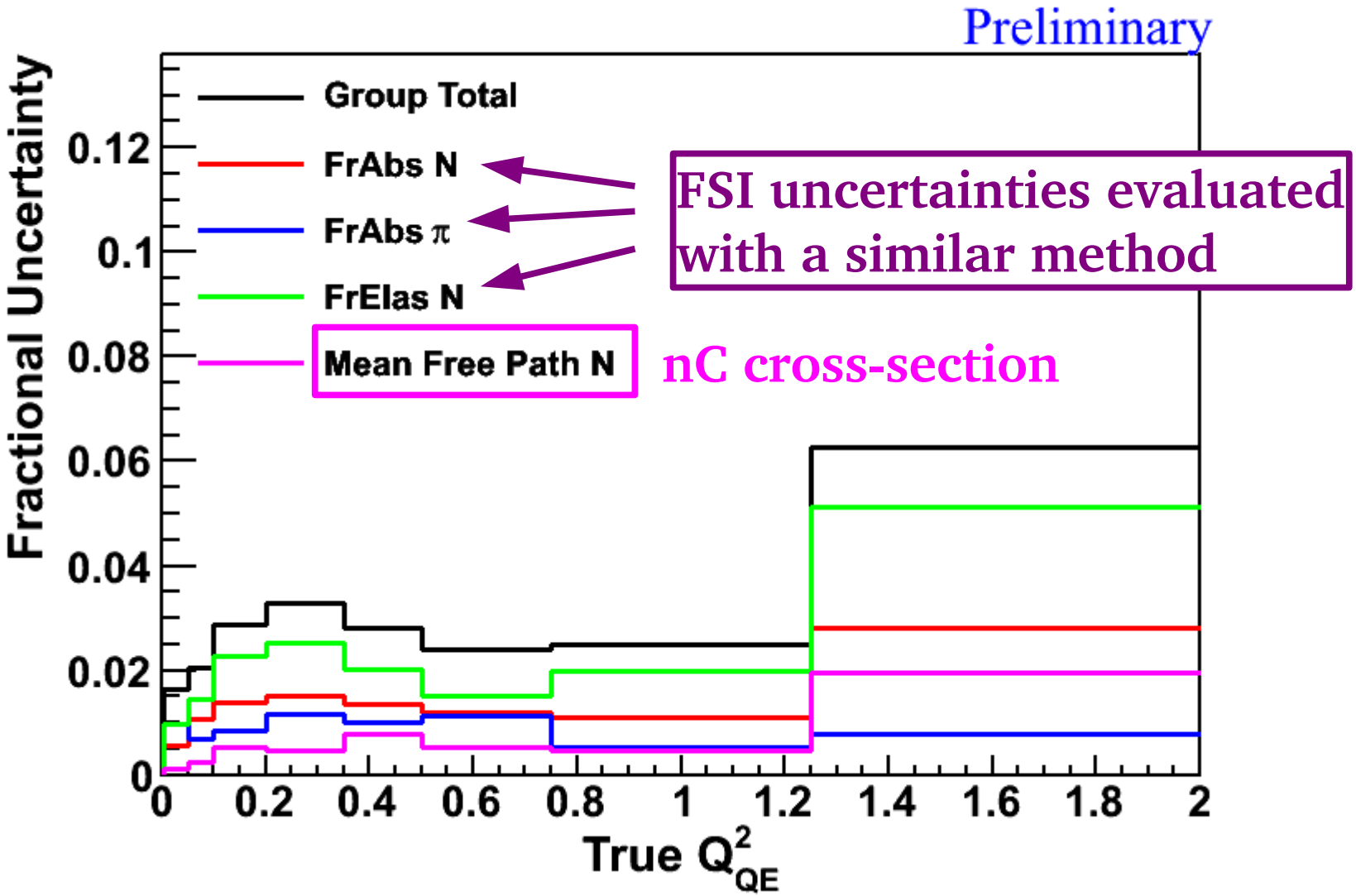
Comparison of GEANT with world data suggests a 10% uncertainty on the nC reaction cross-section

Example: nC cross-section

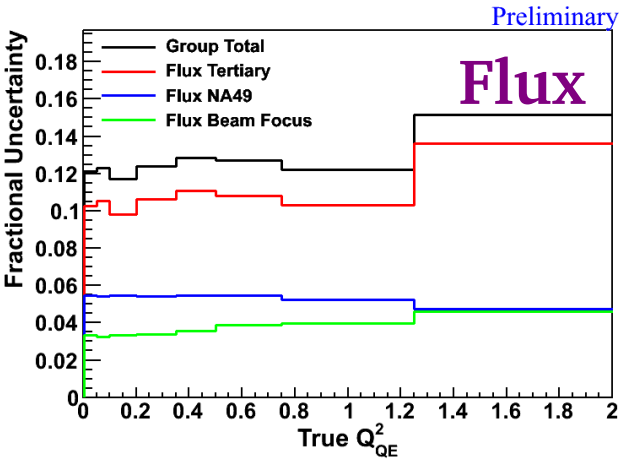
We tabulate the n scattering distance in each event and reweight it for a larger/smaller cross-section

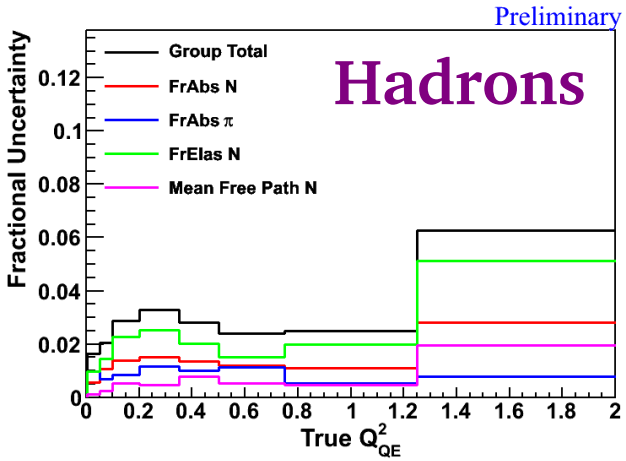


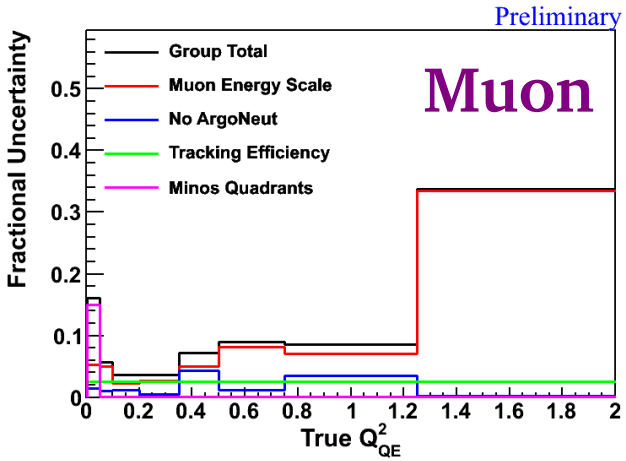
Example: nC cross-section

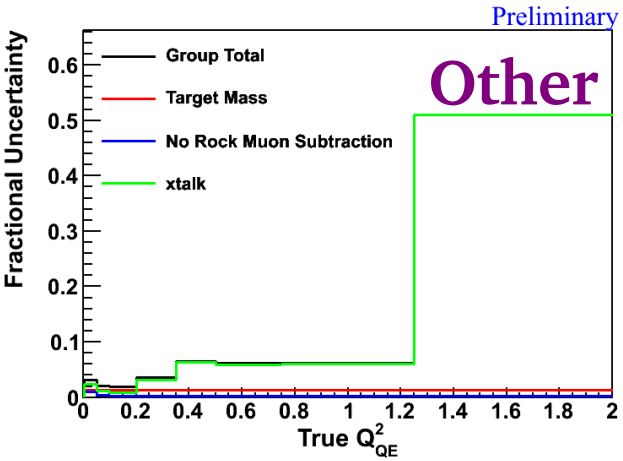


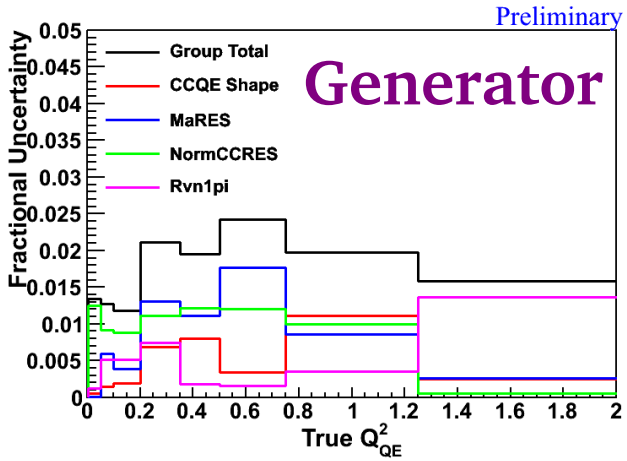
All systematics

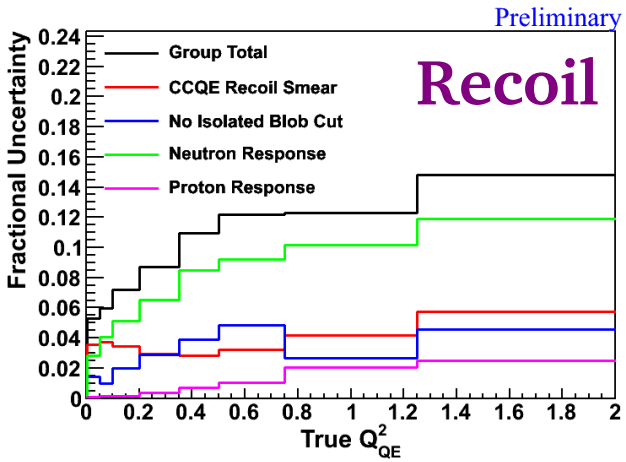




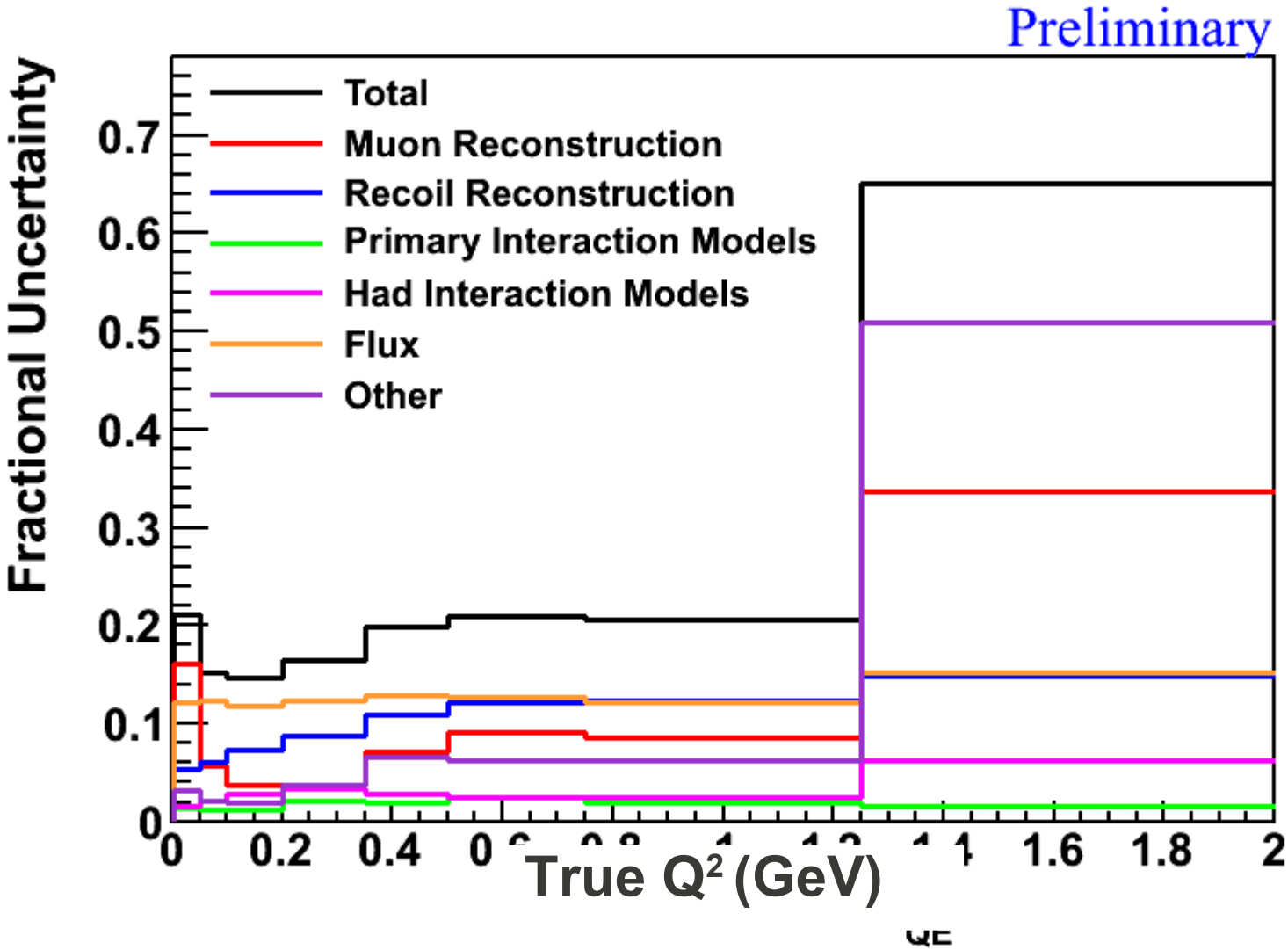




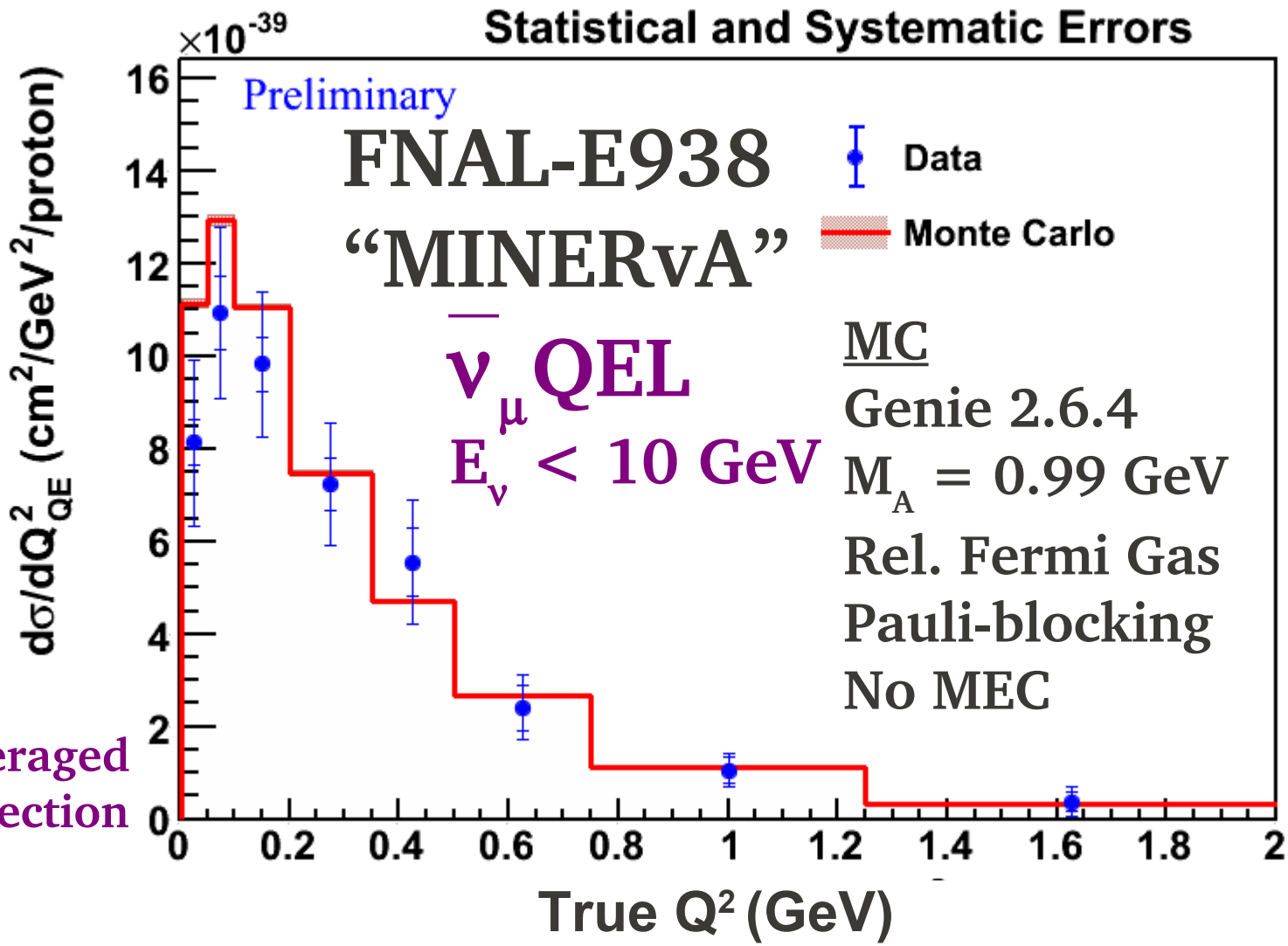




Systematics Summary

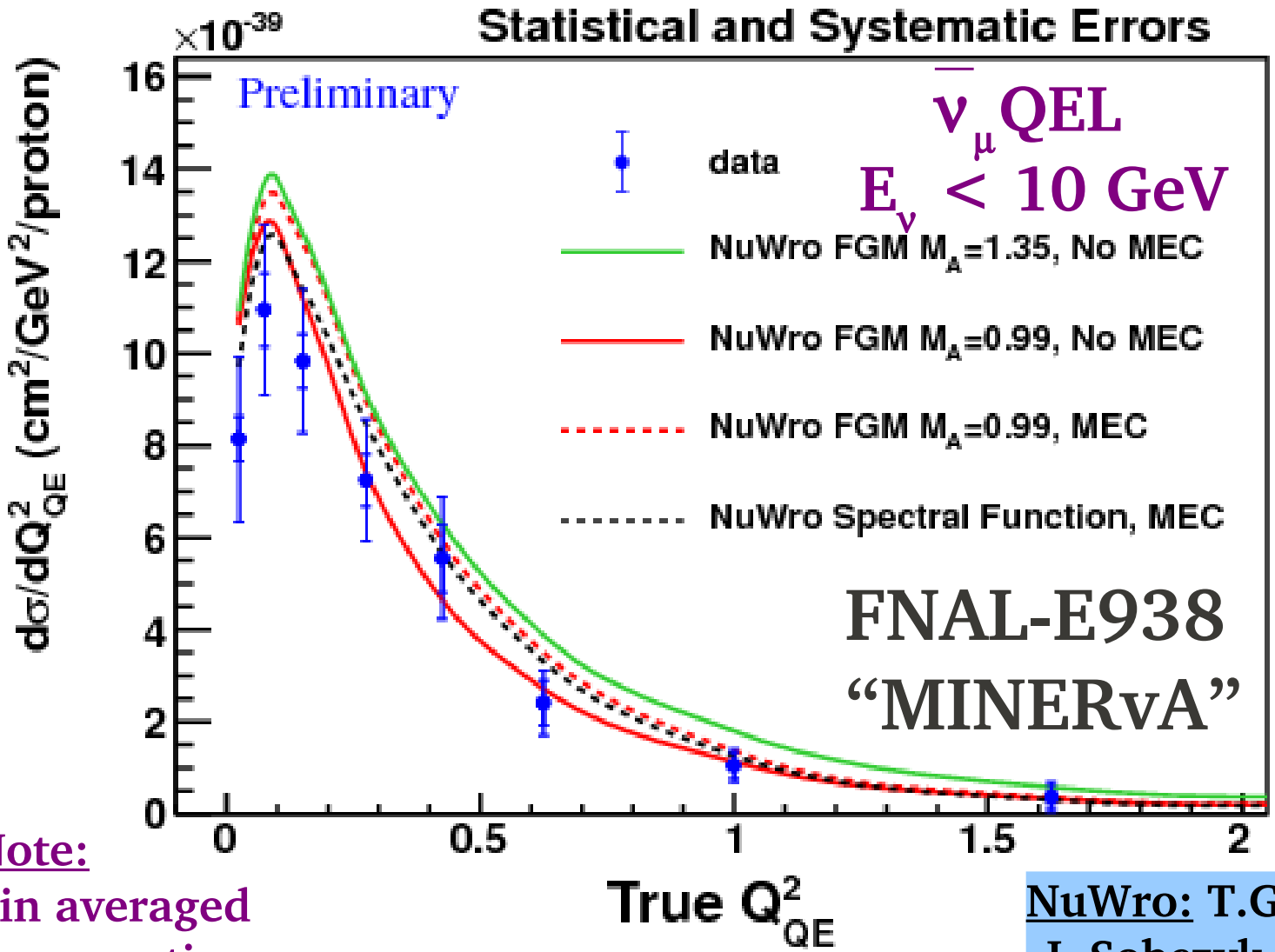


Cross-section with systematics



Note:
bin averaged
cross-section

Model Comparisons



$\bar{\nu}_\mu$ QEL

$E_\nu < 10$ GeV

FNAL-E938

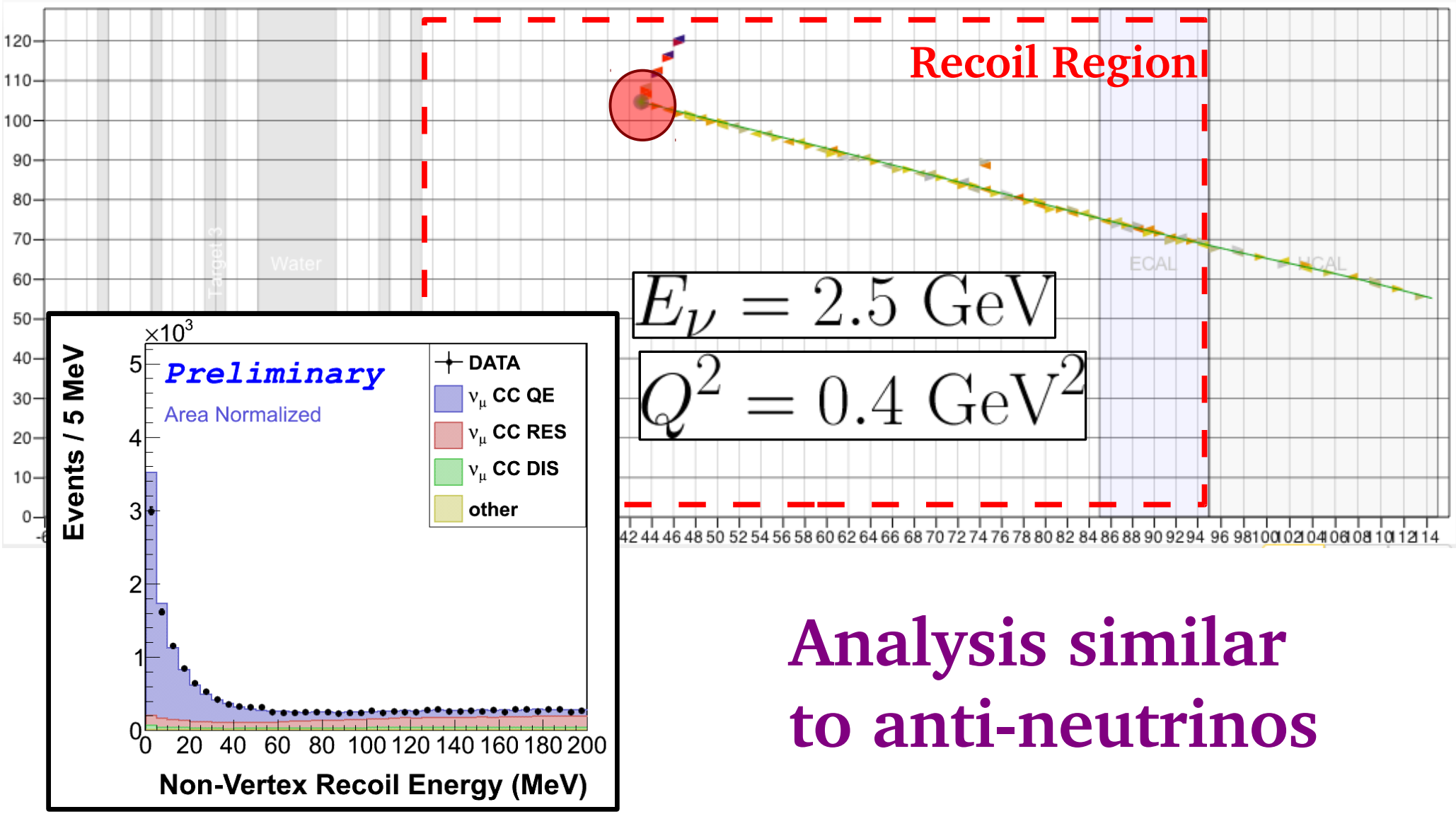
"MINERvA"

Note:
bin averaged cross-section

NuWro: T.Golan, C. Juszczak, J. Sobczyk. arXiv:1202.4197

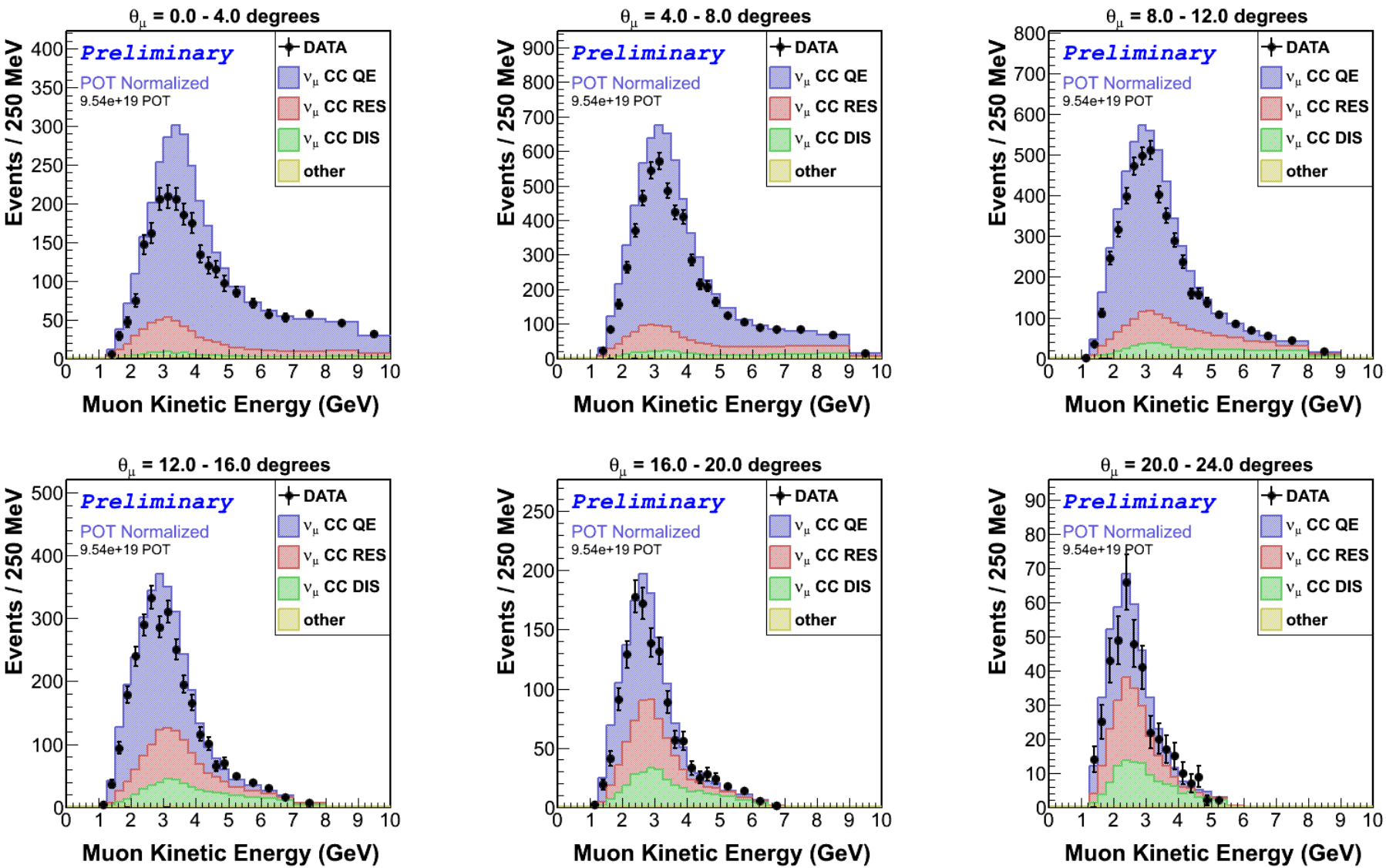
ν_μ Quasi-elastics

ν_μ Quasi-elastics

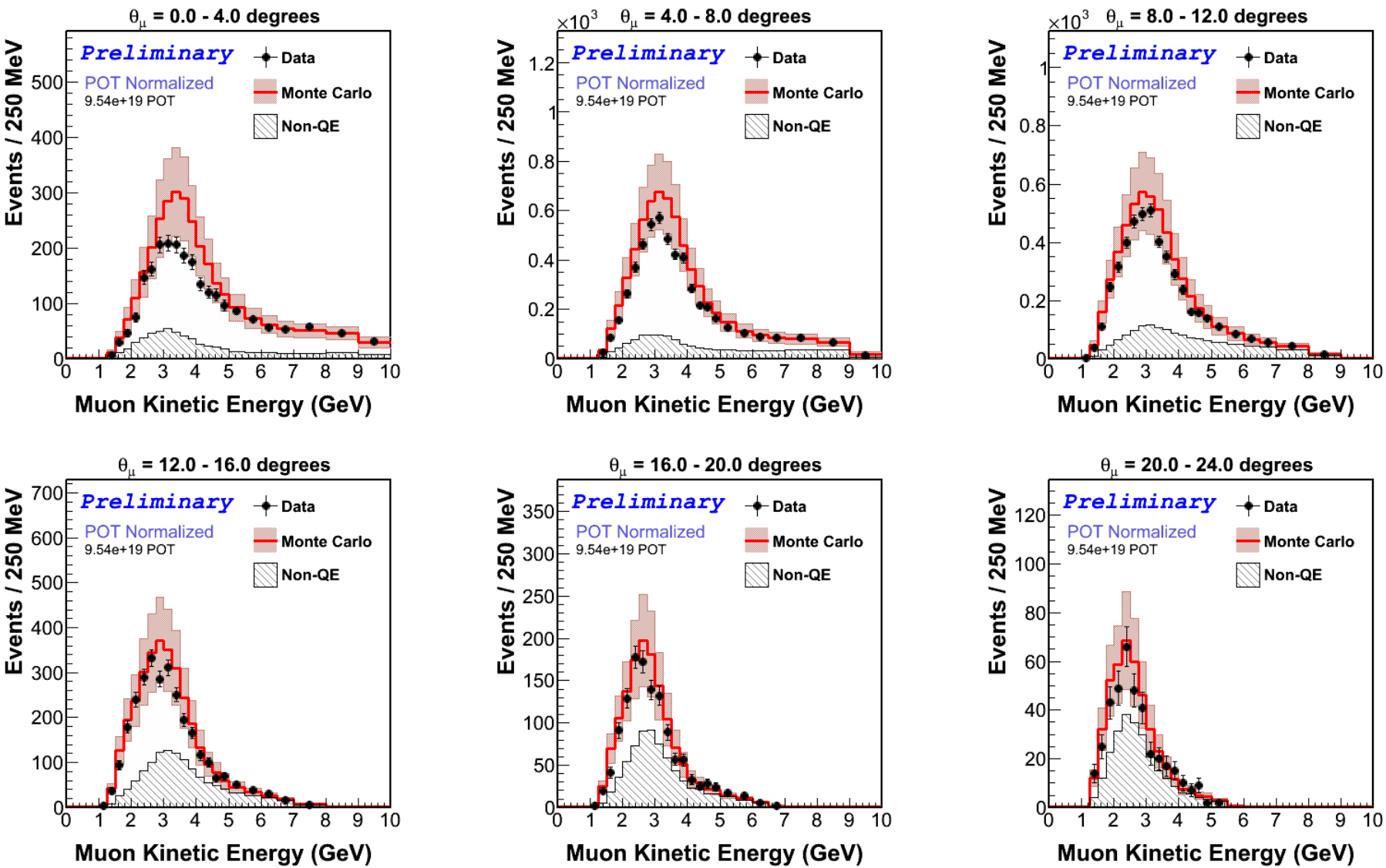


Analysis similar to anti-neutrinos

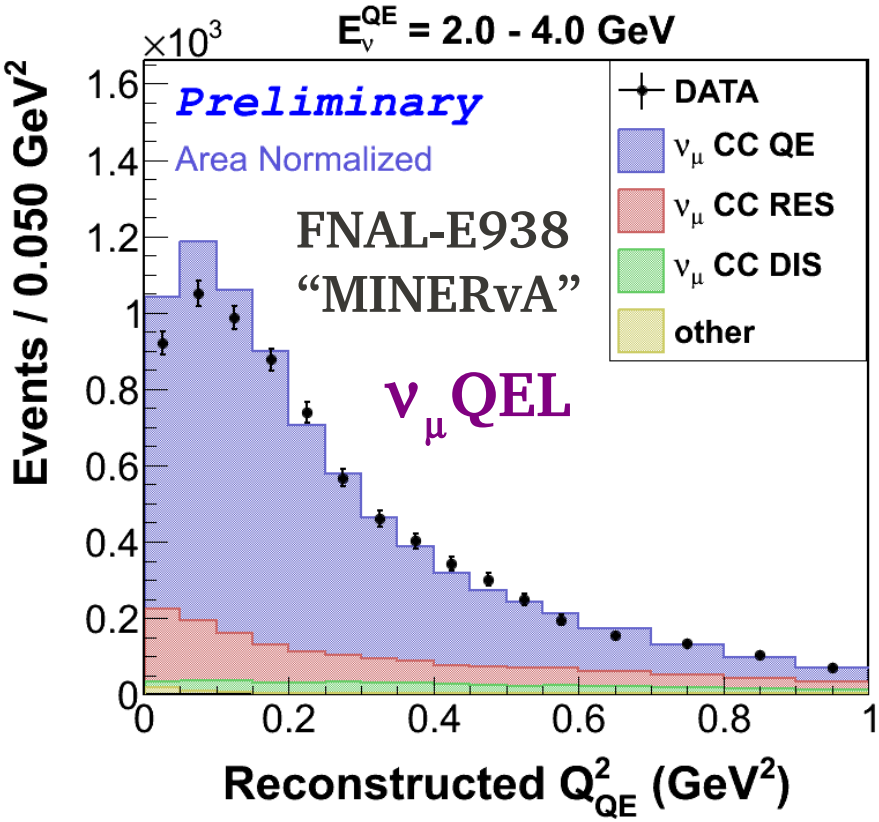
ν_μ Quasi-elastics

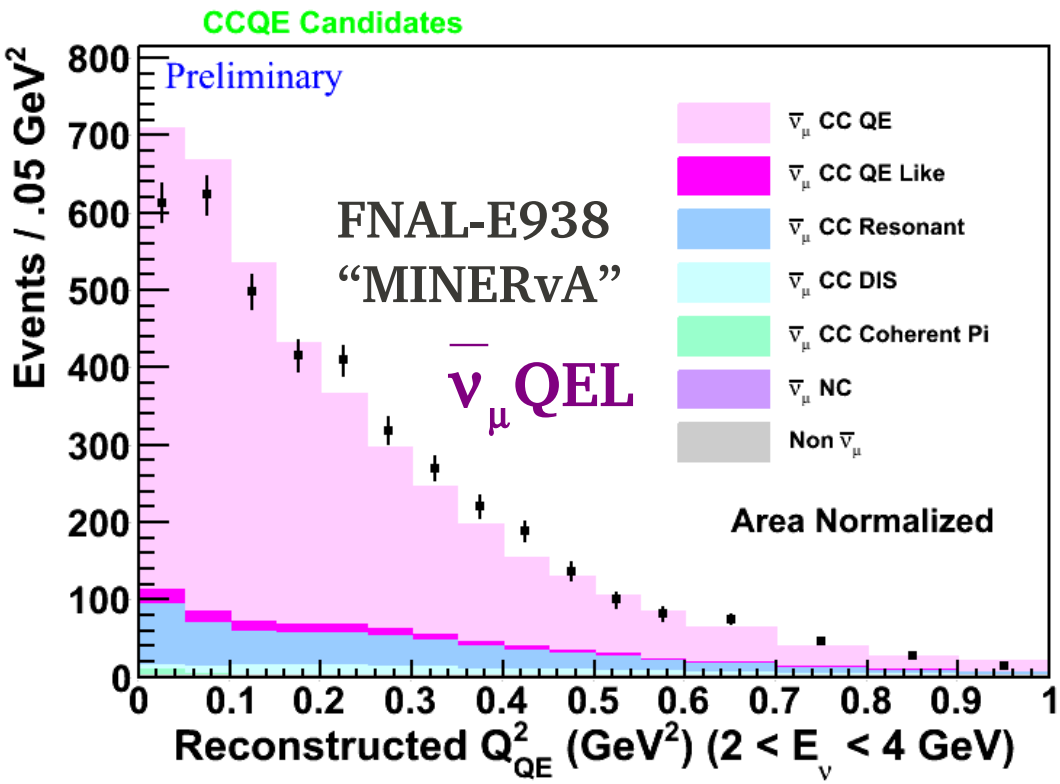


ν_μ Quasi-elastics

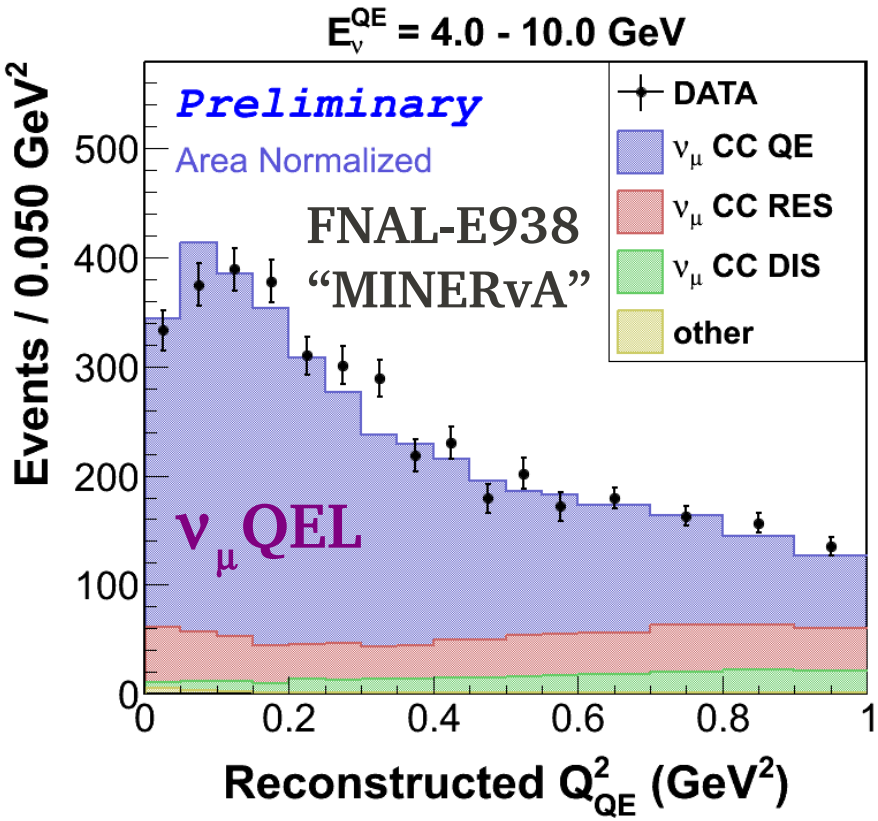


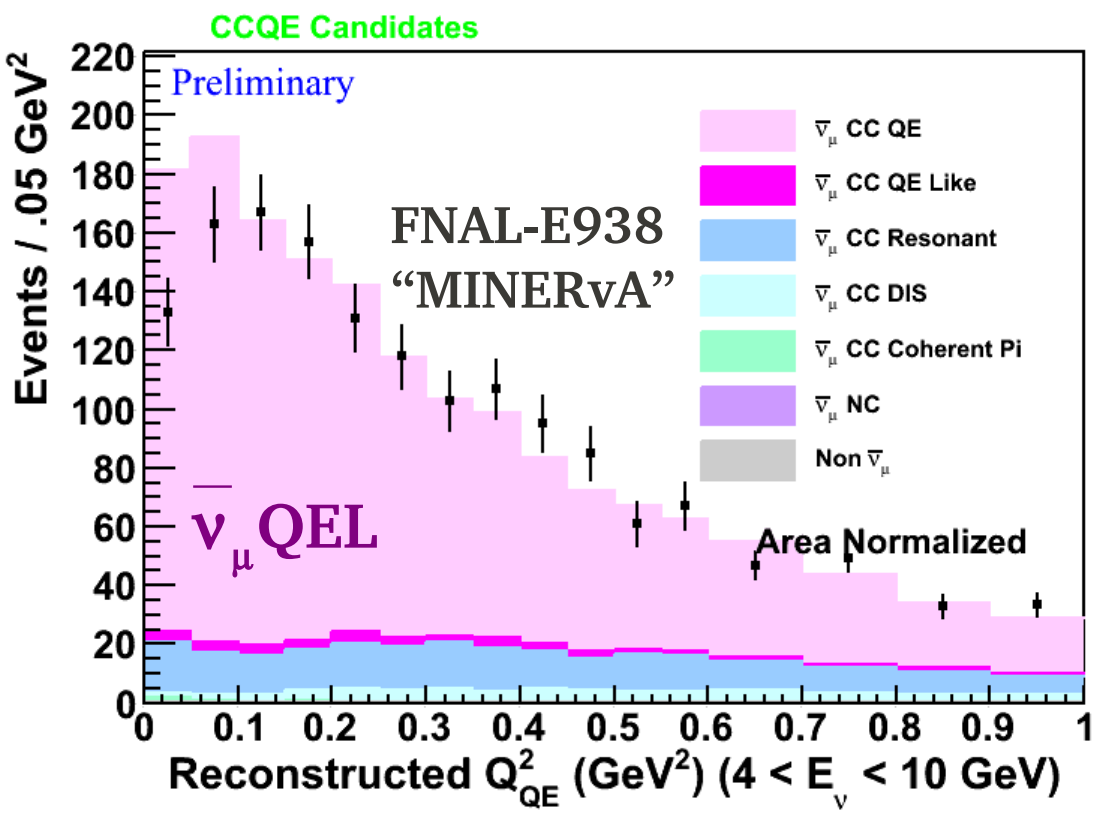
ν_μ and $\bar{\nu}_\mu$ compared

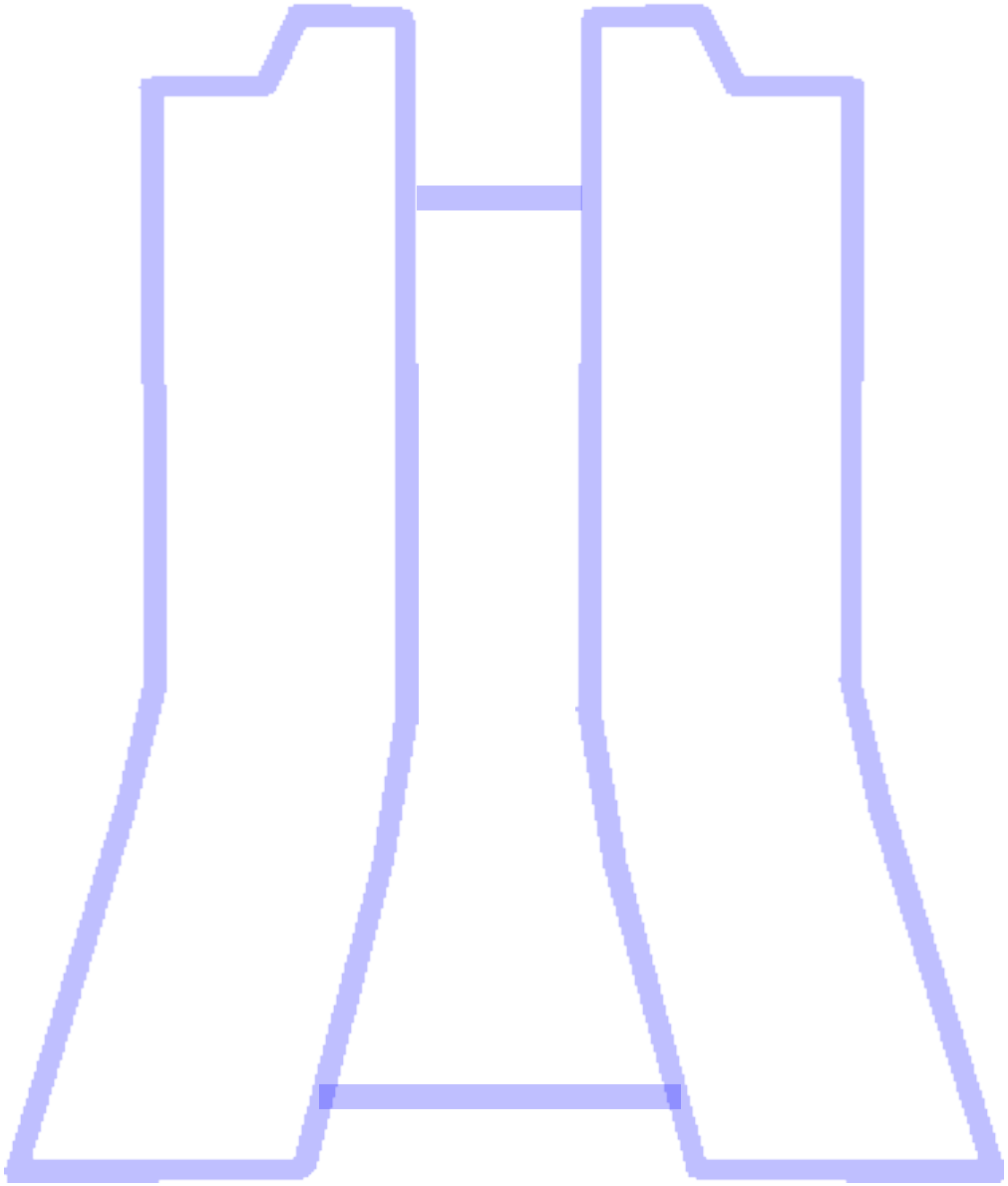




ν_μ and $\bar{\nu}_\mu$ compared



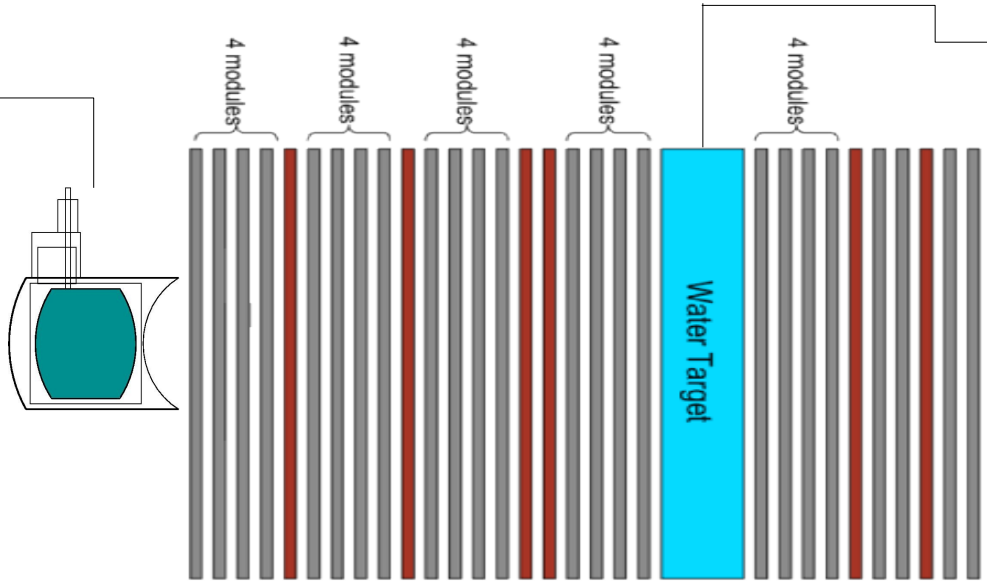




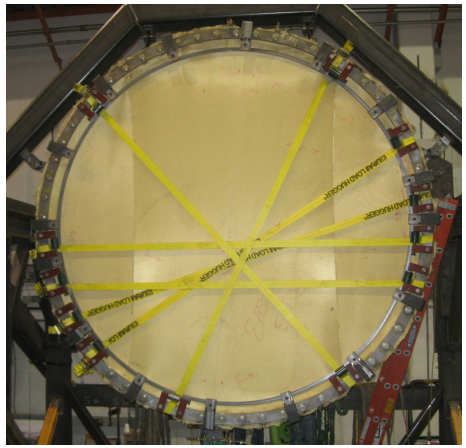
Nuclear Targets

nuclear targets

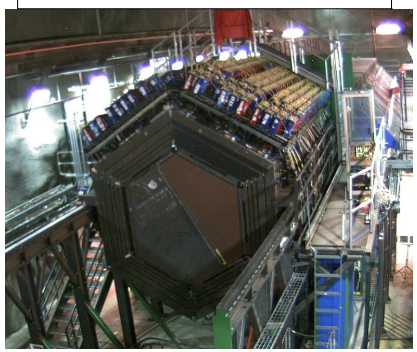
250 kg
Liquid He



500kg
Water

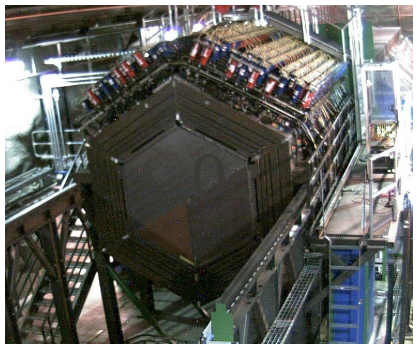


1.0” Fe / 1.0” Pb

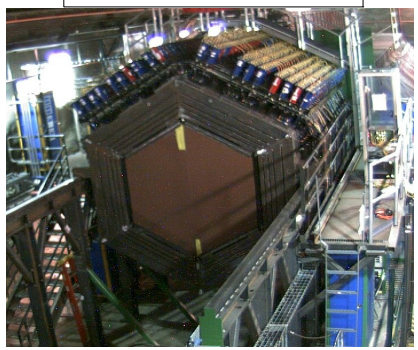


1.0” Pb / 1.0” Fe

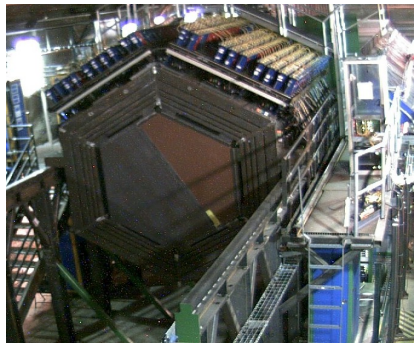
3.0” C / 1.0” Fe / 1.0” Pb



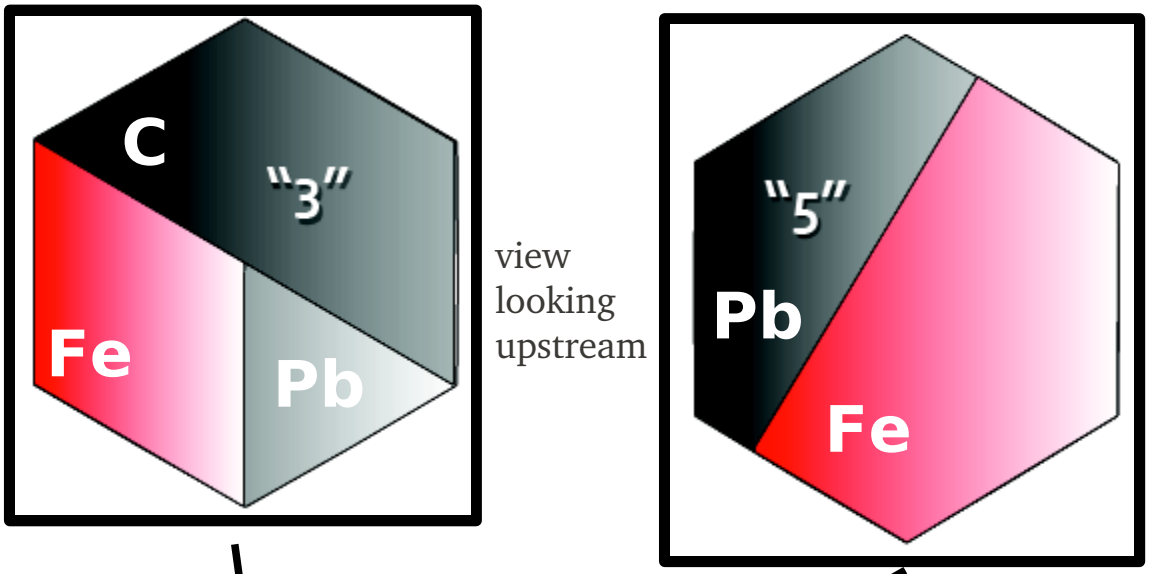
0.3” Pb

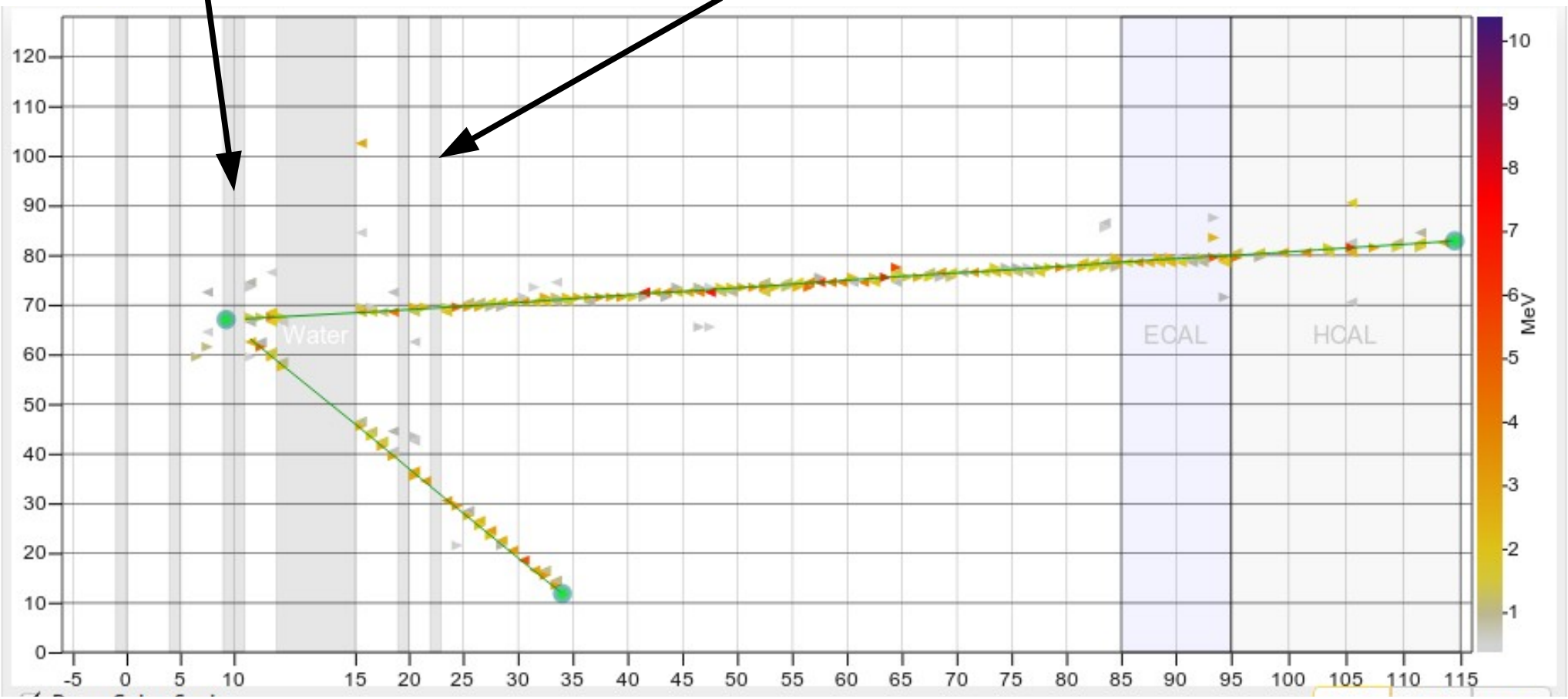


0.5” Fe / 0.5” Pb

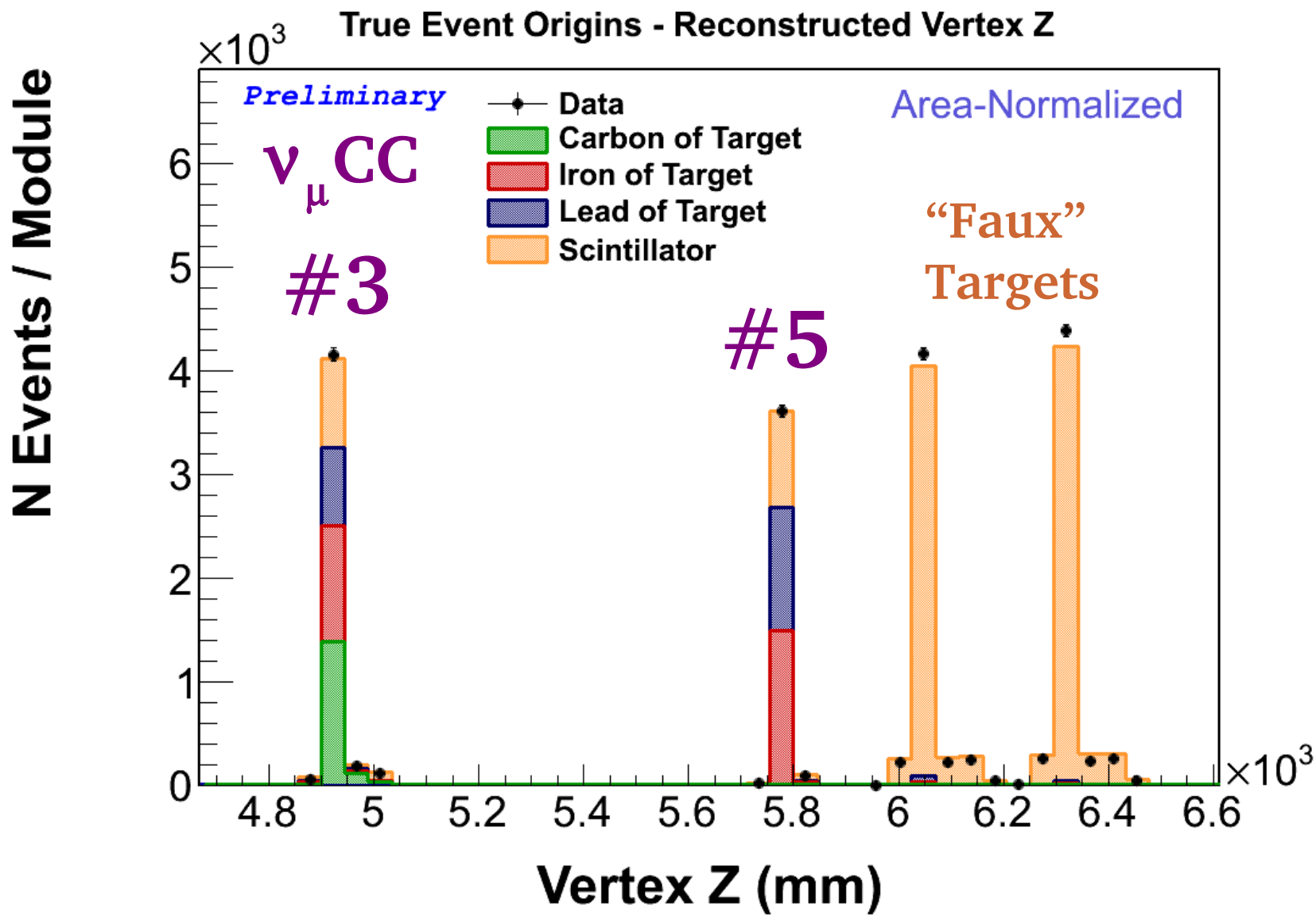


An event from target 3



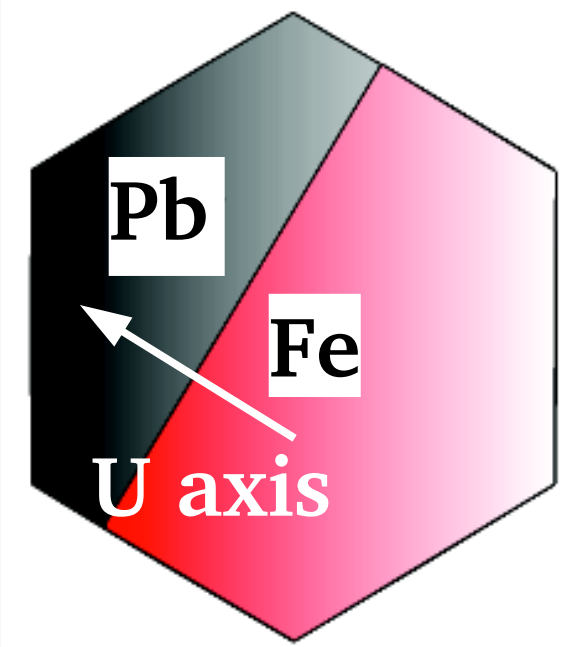


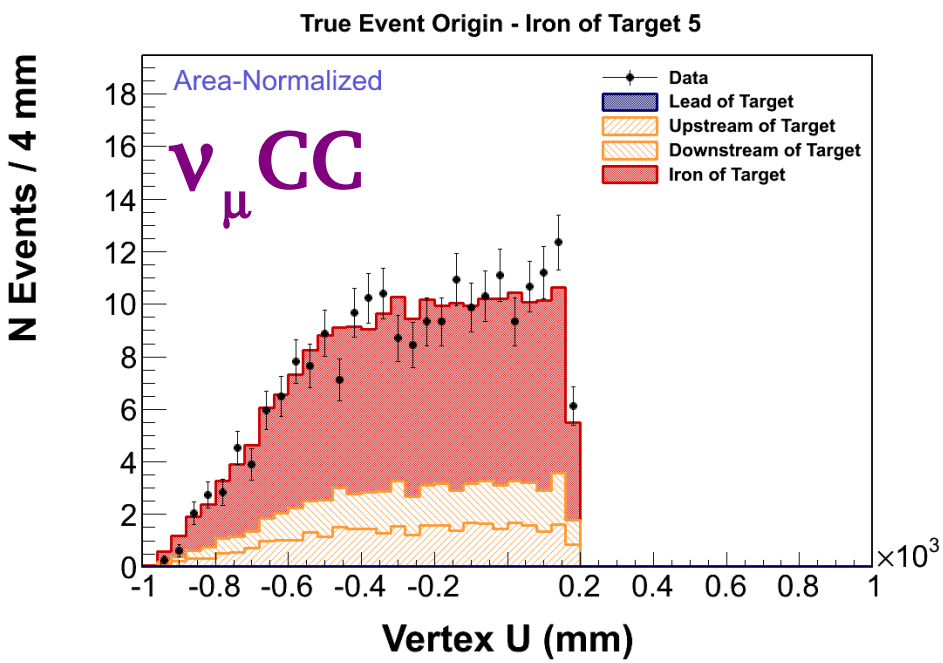
Z vertex distribution

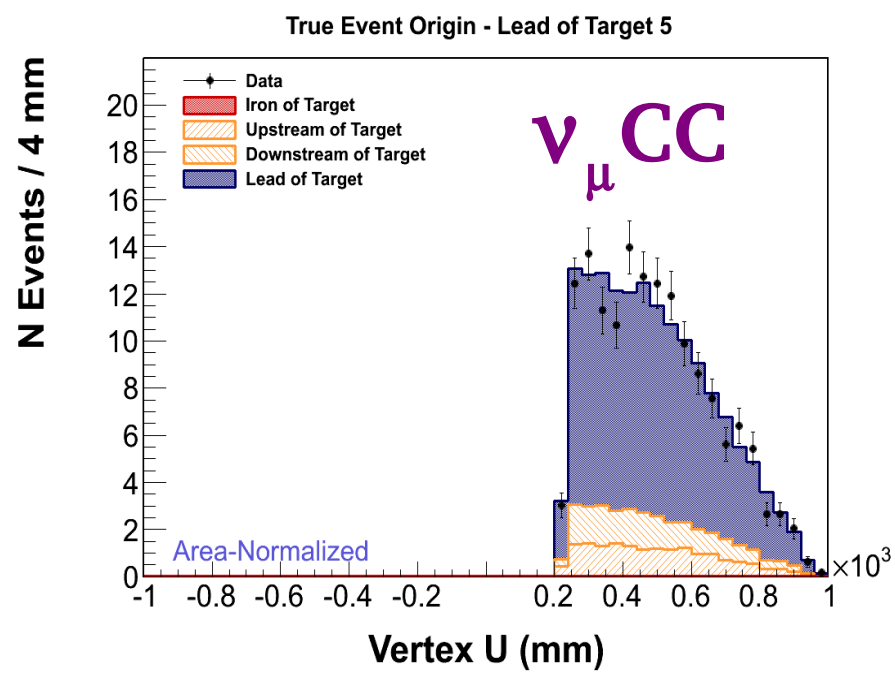


Selection of Fe and Pb

Target #5







Analysis Strategy

Wanted

Bin averaged differential cross-section

$$\frac{d\sigma^A}{dX_i} = \frac{S_i^A}{\Phi_i^A \, \Delta X_i \, M^A}$$

Analysis Strategy

Known bin width in variable X and # target nuclei

$$\frac{d\sigma^A}{dX_i} = \frac{S_i^A}{\Phi_i^A \, \Delta X_i \, M^A}$$

Analysis Strategy

Flux for bin i has significant uncertainties

$$\frac{d\sigma^A}{dX_i} = \frac{S_i^A}{\Phi_i^A \, \Delta X_i \; M^A}$$

Would like to mitigate them

Analysis Strategy

signal events

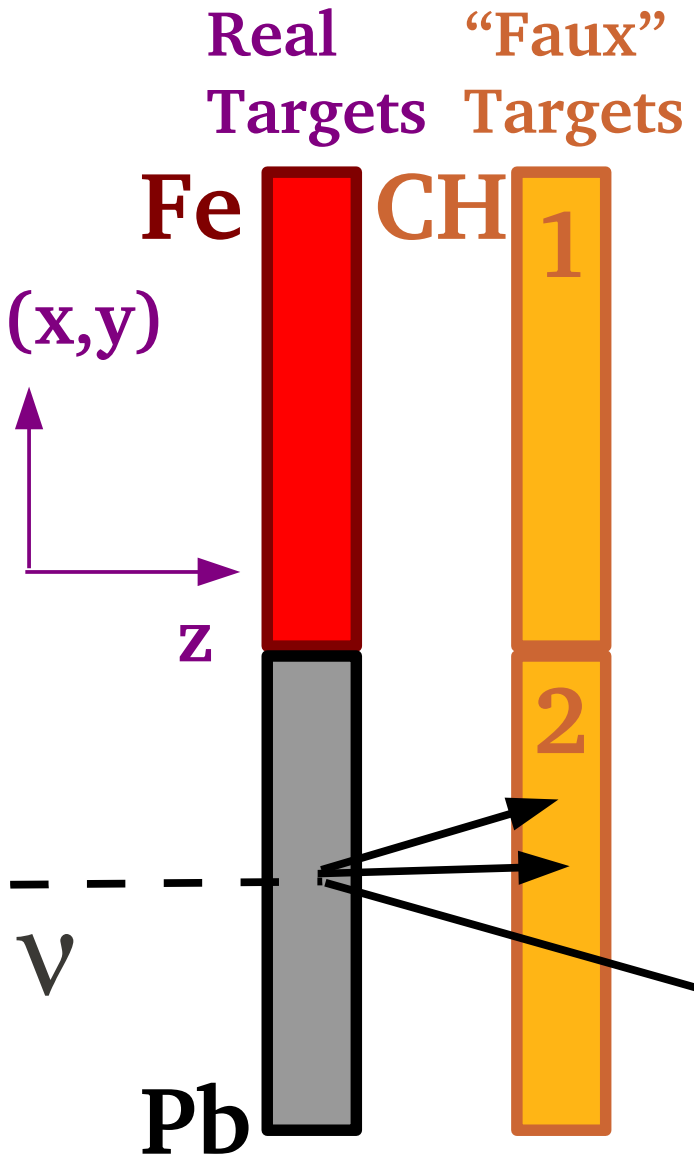
Correct selected events

* backgrounds from other nuclei
* efficiencies

$$S_i^A = \frac{N_i^A - B_i^A}{[\epsilon_{xy}^A \; \epsilon_z^A \; \epsilon_{\text{other}}^A]_i}$$

$$\frac{d\sigma^A}{dX_i} = \frac{S_i^A}{\Phi_i^A \; \Delta X_i \; M^A}$$

Ratios mitigate uncertainties

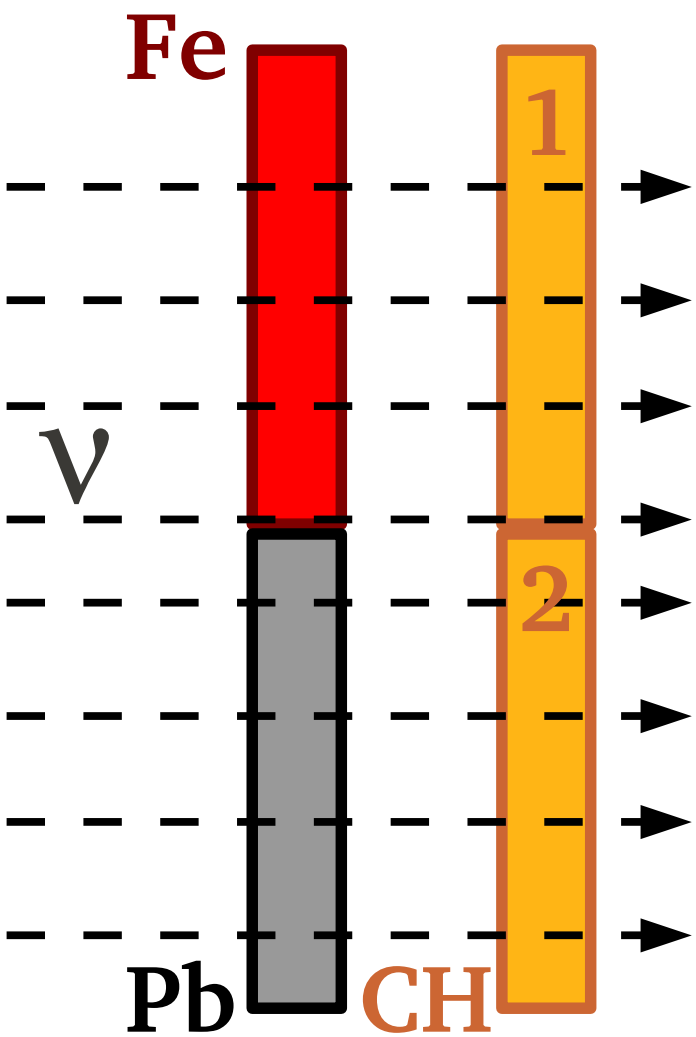


Study interactions on passive nuclear targets and downstream active (CH) targets covering the same (x,y) region

Pb/Fe ratio with small uncertainties from

$$\frac{\left[\dfrac{\text{Pb}}{\text{CH \#2}}\right]}{\left[\dfrac{\text{Fe}}{\text{CH \#1}}\right]}$$

Ratios mitigate uncertainties



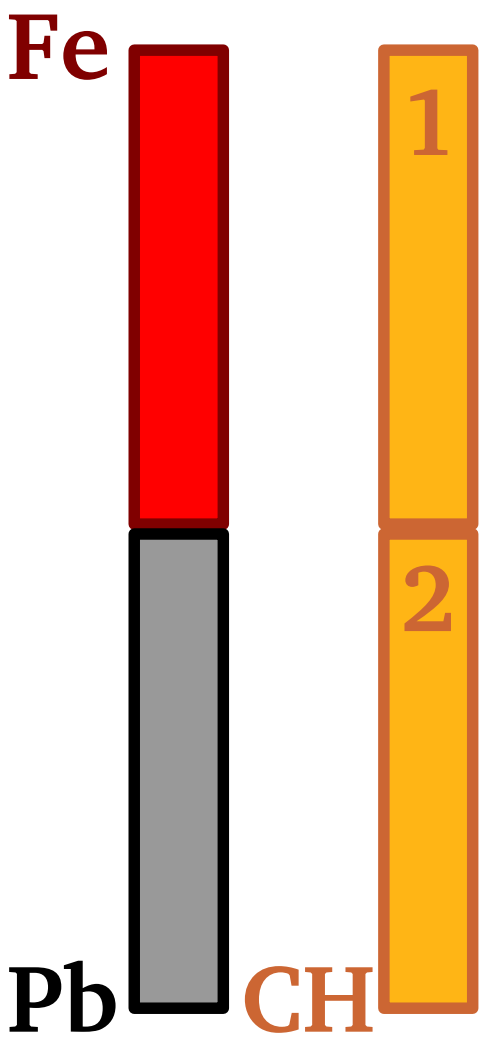
Flux is nearly the same for all regions

$$\frac{d\sigma^A}{dX_i} = \frac{S_i^A}{\Phi_i^A \, \Delta X_i \, M^A}$$

Especially for regions covering the same (x,y) region.

$$\left[\frac{\text{Pb}}{\text{CH \#2}}\right] \qquad \left[\frac{\text{Fe}}{\text{CH \#1}}\right]$$

Ratios mitigate uncertainties



MINOS acceptance causes efficiency to depend on vertex position in (x,y)

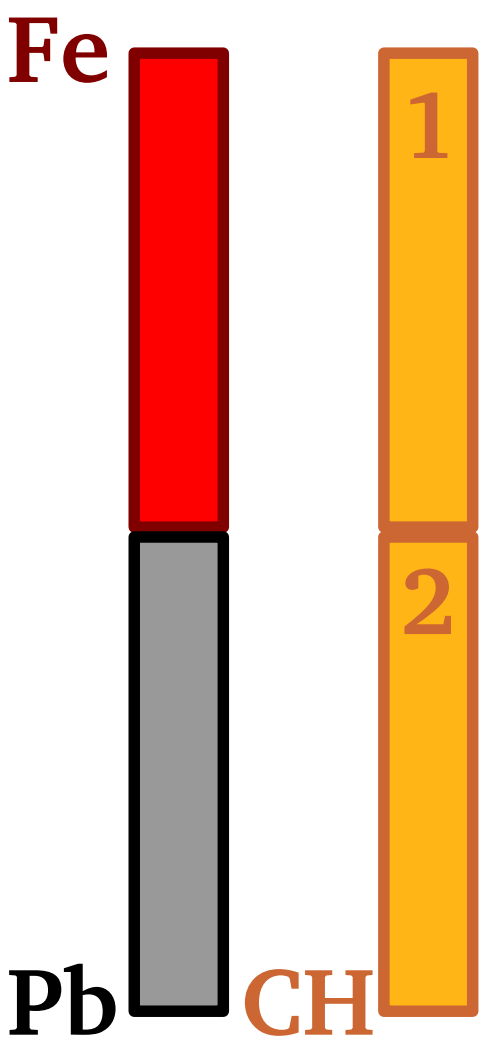
$$S_i^A = \frac{N_i^A - B_i^A}{[\epsilon_{xy}^A \, \epsilon_z^A \, \epsilon_{\text{other}}^A]_i}$$

cancels in ratios

$$\left[\frac{\text{Pb}}{\text{CH \#2}}\right] \qquad \left[\frac{\text{Fe}}{\text{CH \#1}}\right]$$

MINOS

Ratios mitigate uncertainties

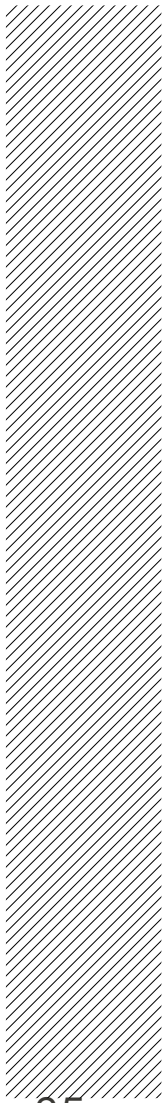


MINOS acceptance causes efficiency to depend on vertex position in z

$$S_i^A = \frac{N_i^A - B_i^A}{[\epsilon_{xy}^A \, \epsilon_z^A \, \epsilon_{\text{other}}^A]_i}$$

cancels in ratios

$$\left[\frac{\text{Pb}}{\text{Fe}}\right] \qquad \left[\frac{\text{CH \#1}}{\text{CH \#2}}\right]$$



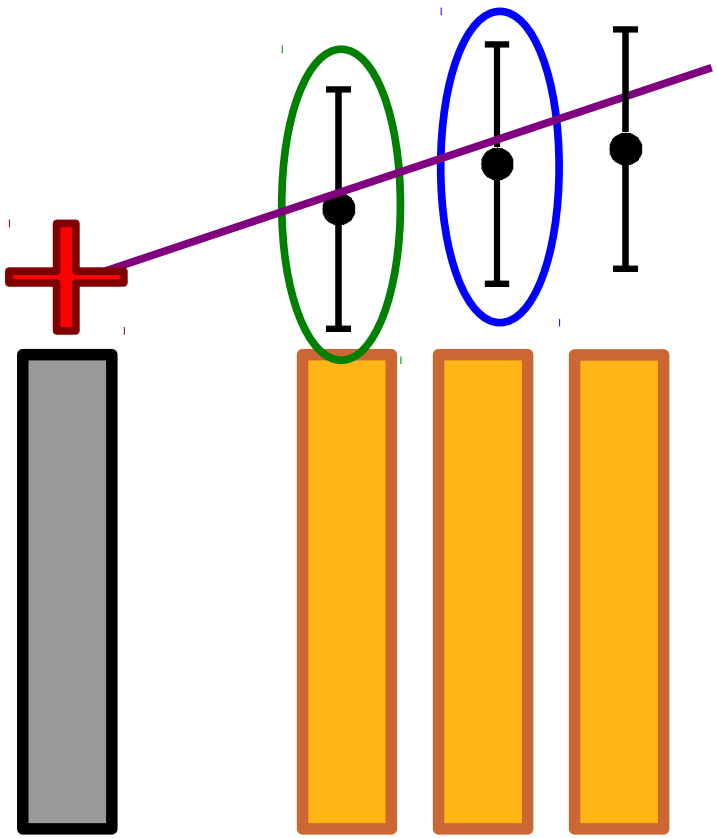
Background correction

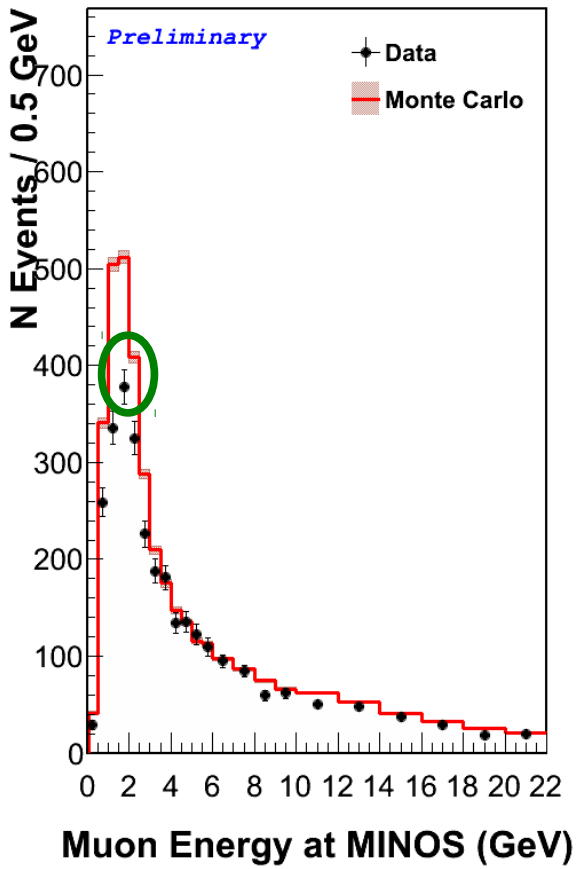
Dominant source of background
for Fe & Pb is from interactions in CH

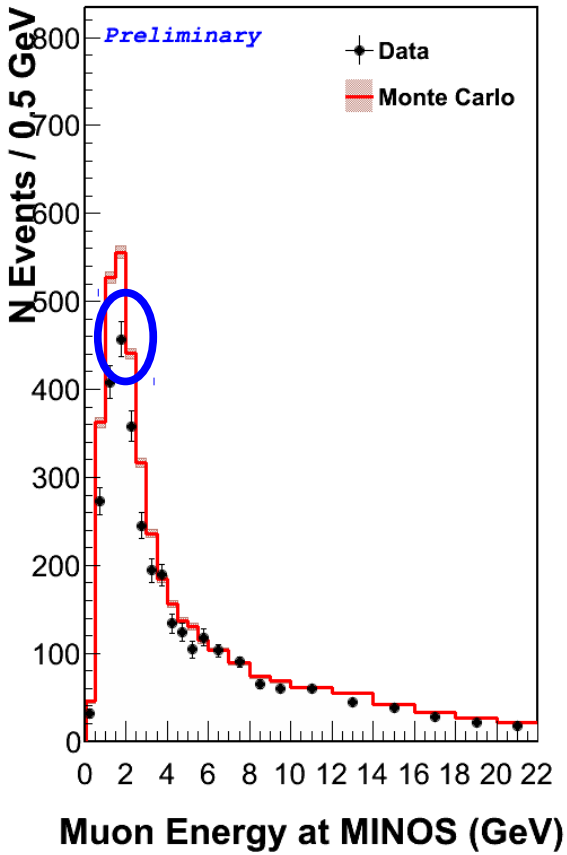
$$S_i^A = \frac{N_i^A - B_i^A}{[\epsilon_{xy}^A \; \epsilon_z^A \; \epsilon_{\text{other}}^A]_i}$$

Background correction

Use upstream CH regions to predict CH rate if passive target was CH

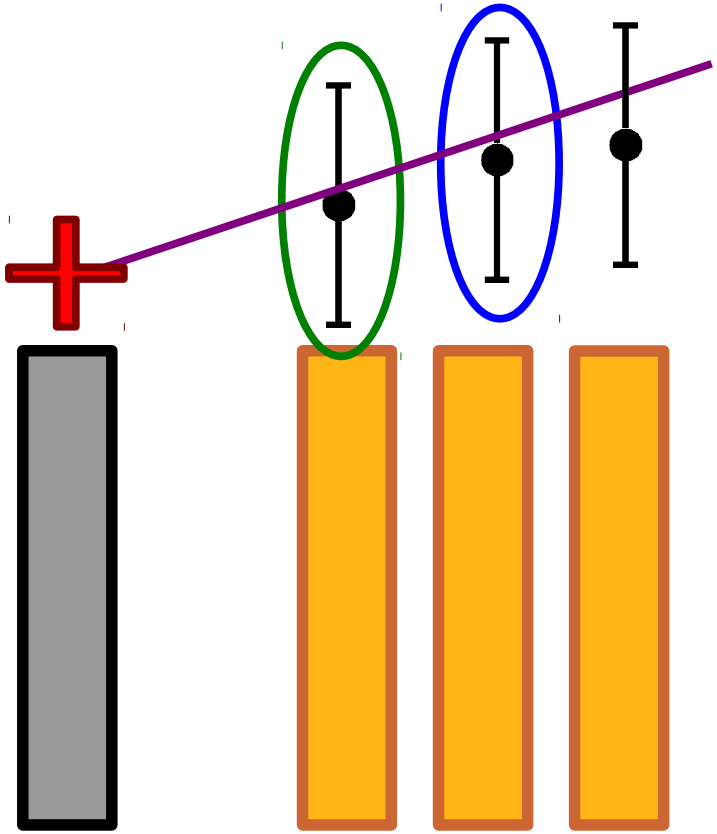


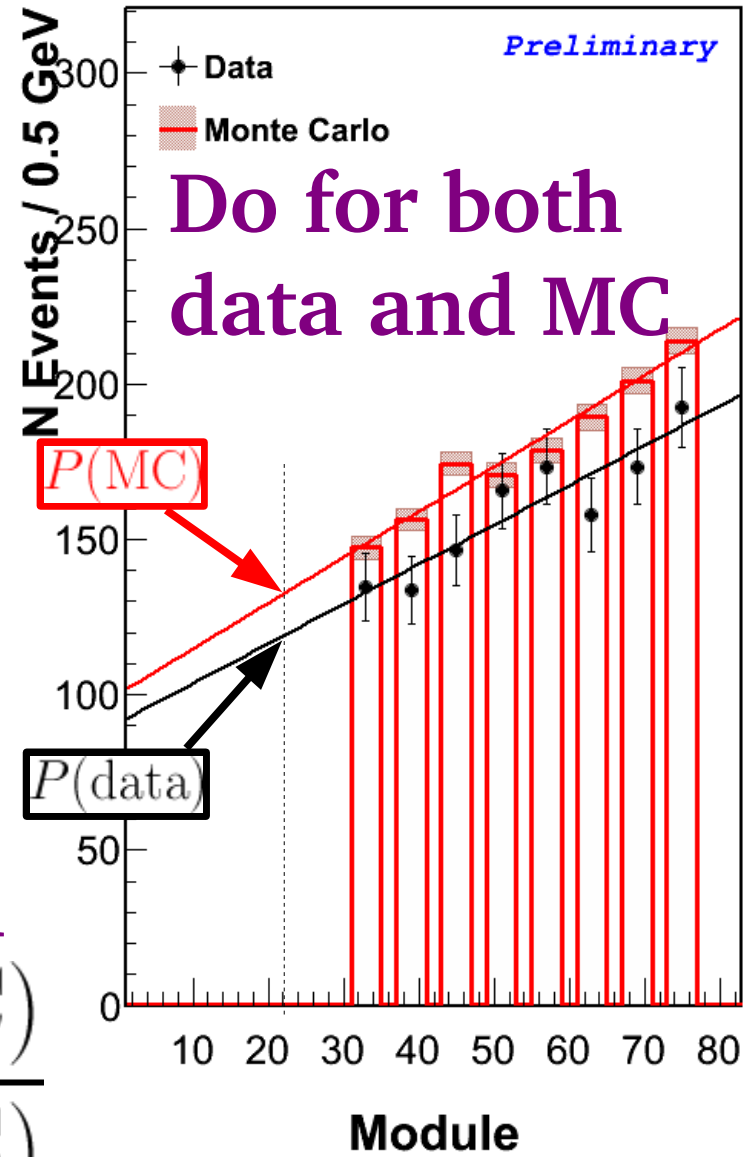




Do this in bins of muon momentum

Background correction



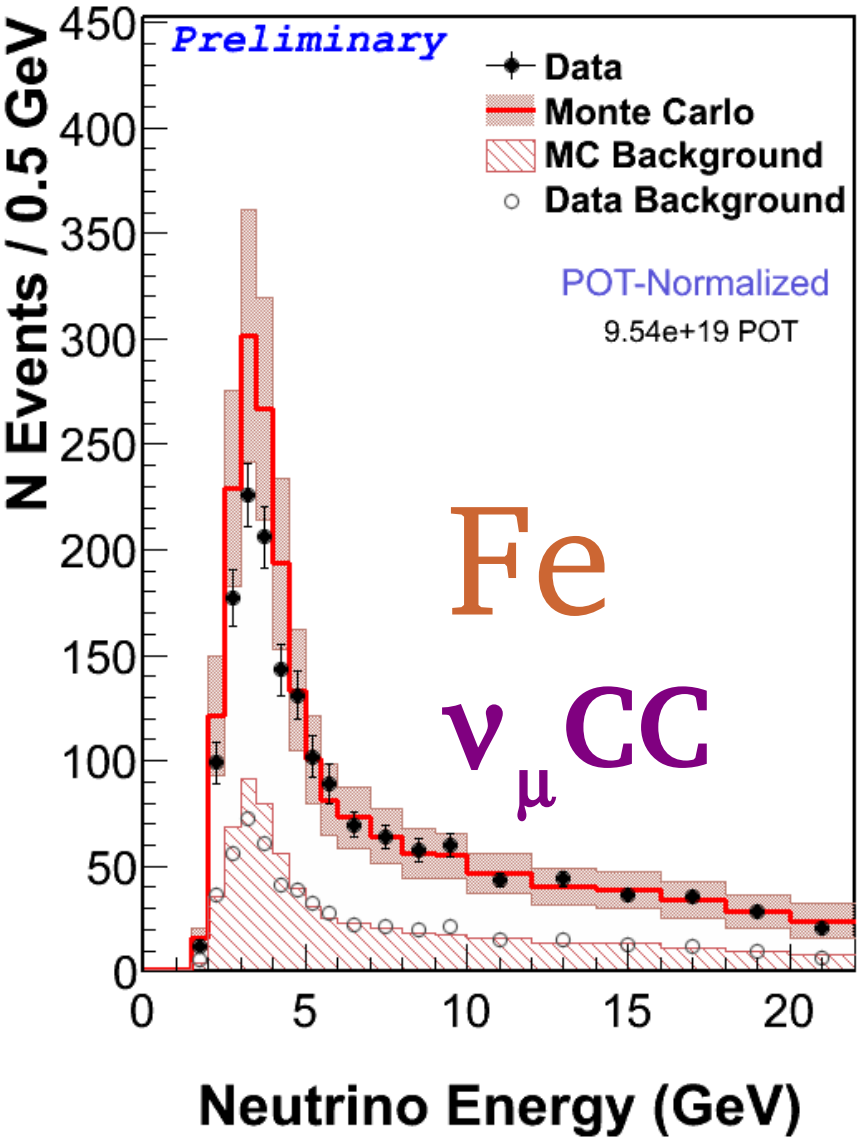


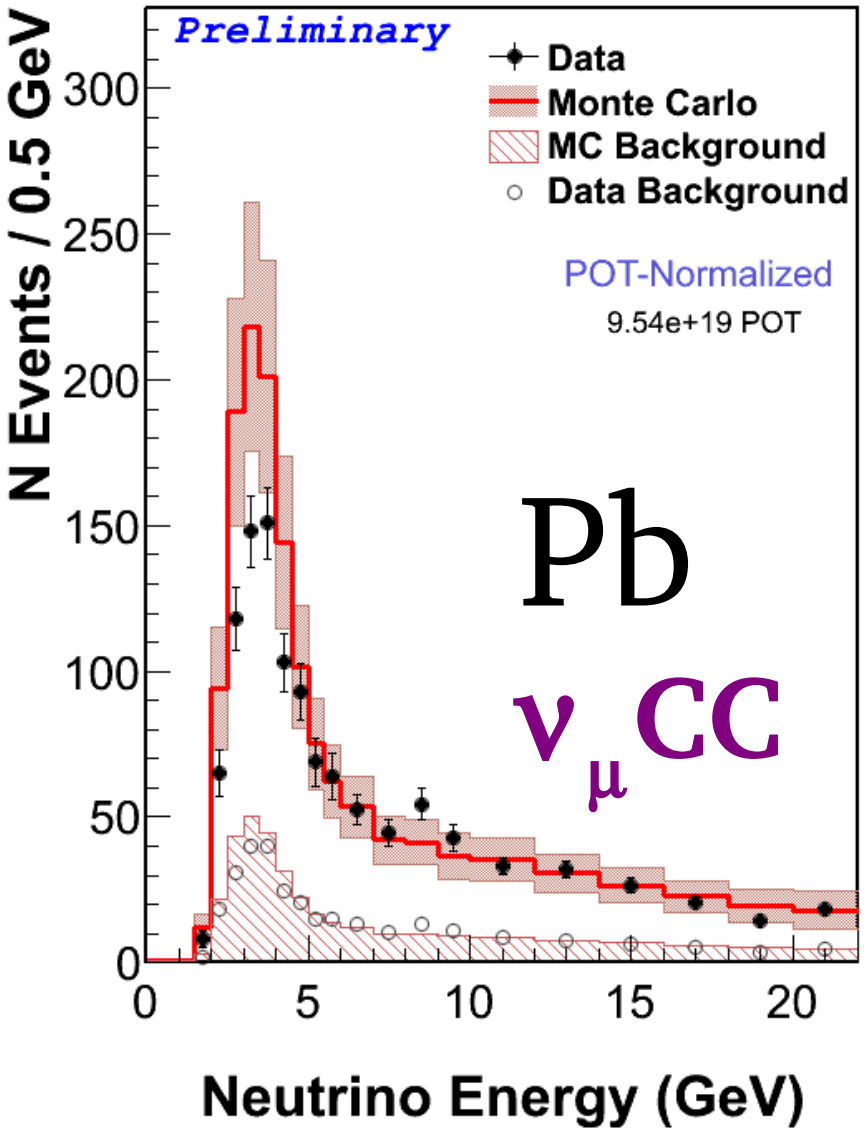
Do for both data and MC

Estimate background in data

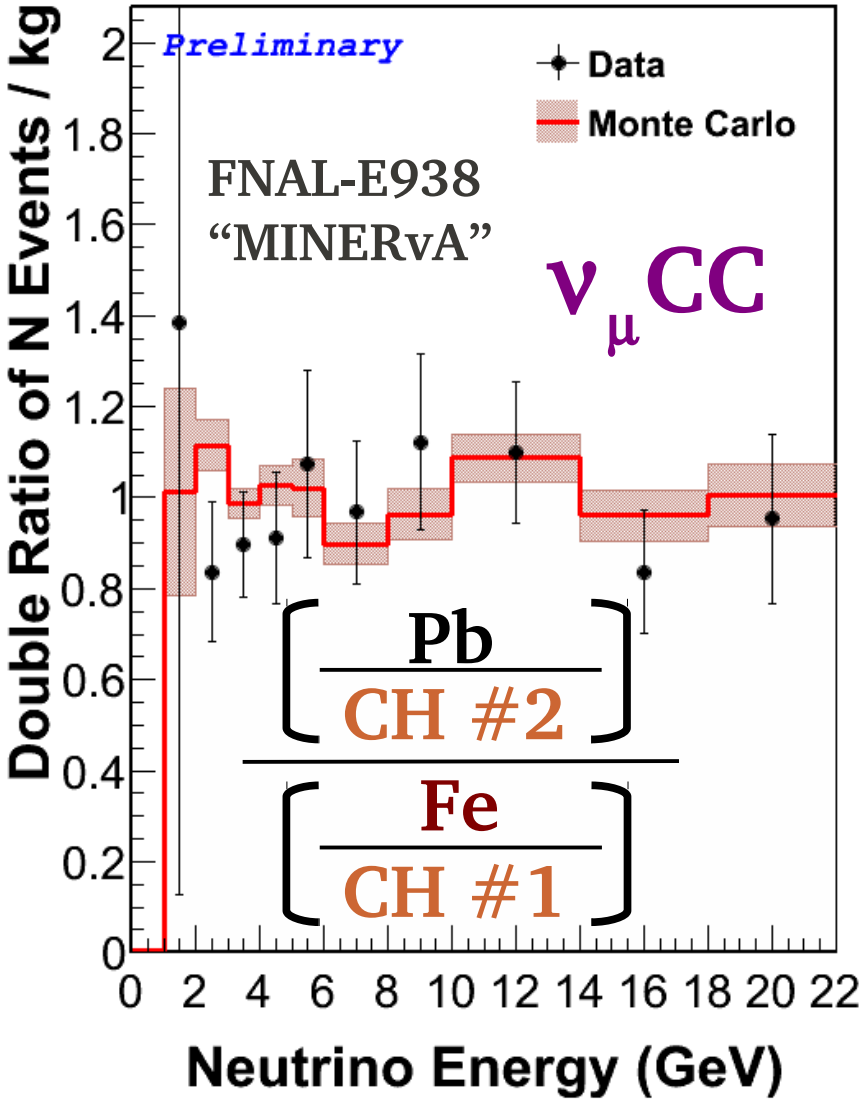
$$B(\text{data}) = P(\text{data})\frac{B(\text{MC})}{P(\text{MC})}$$

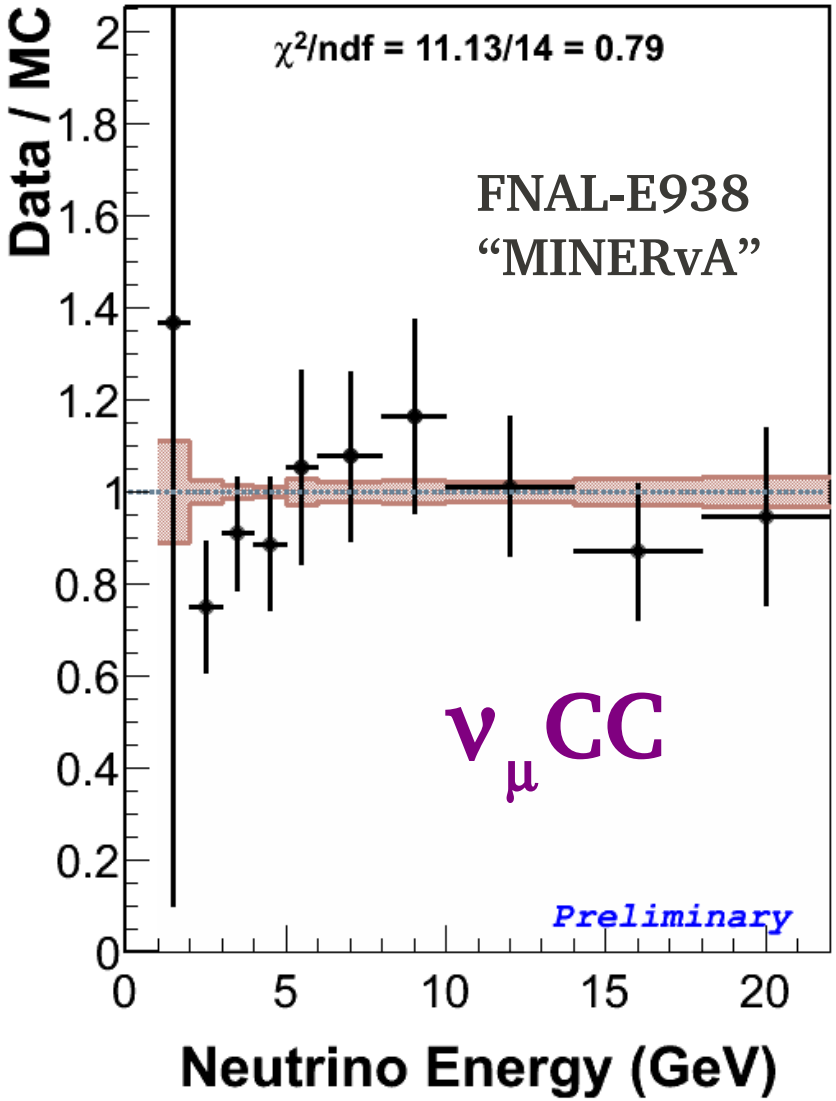
Target #5 Results





Target #5 Results

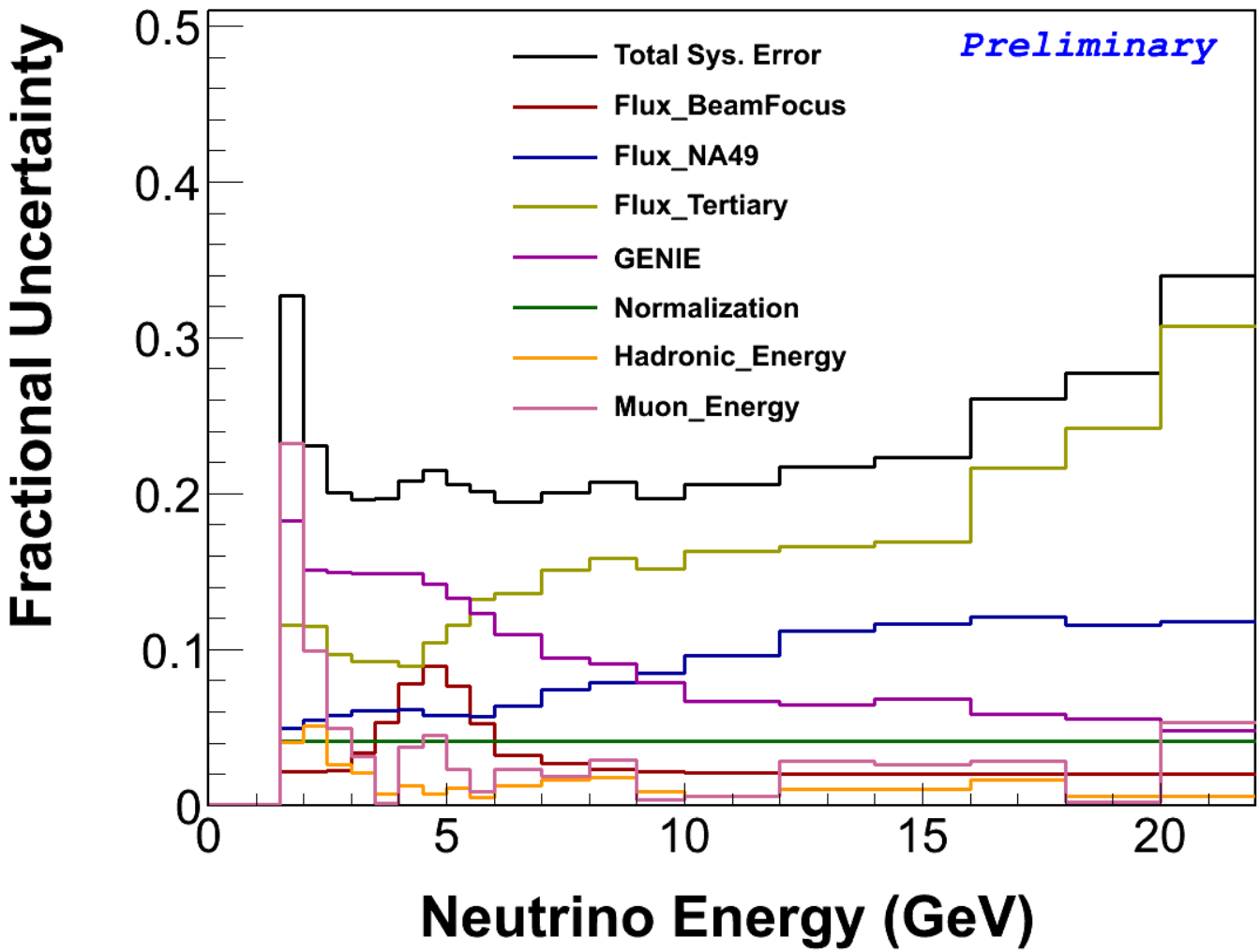




Proof of principle → more data → Bjorken-x, Q^2

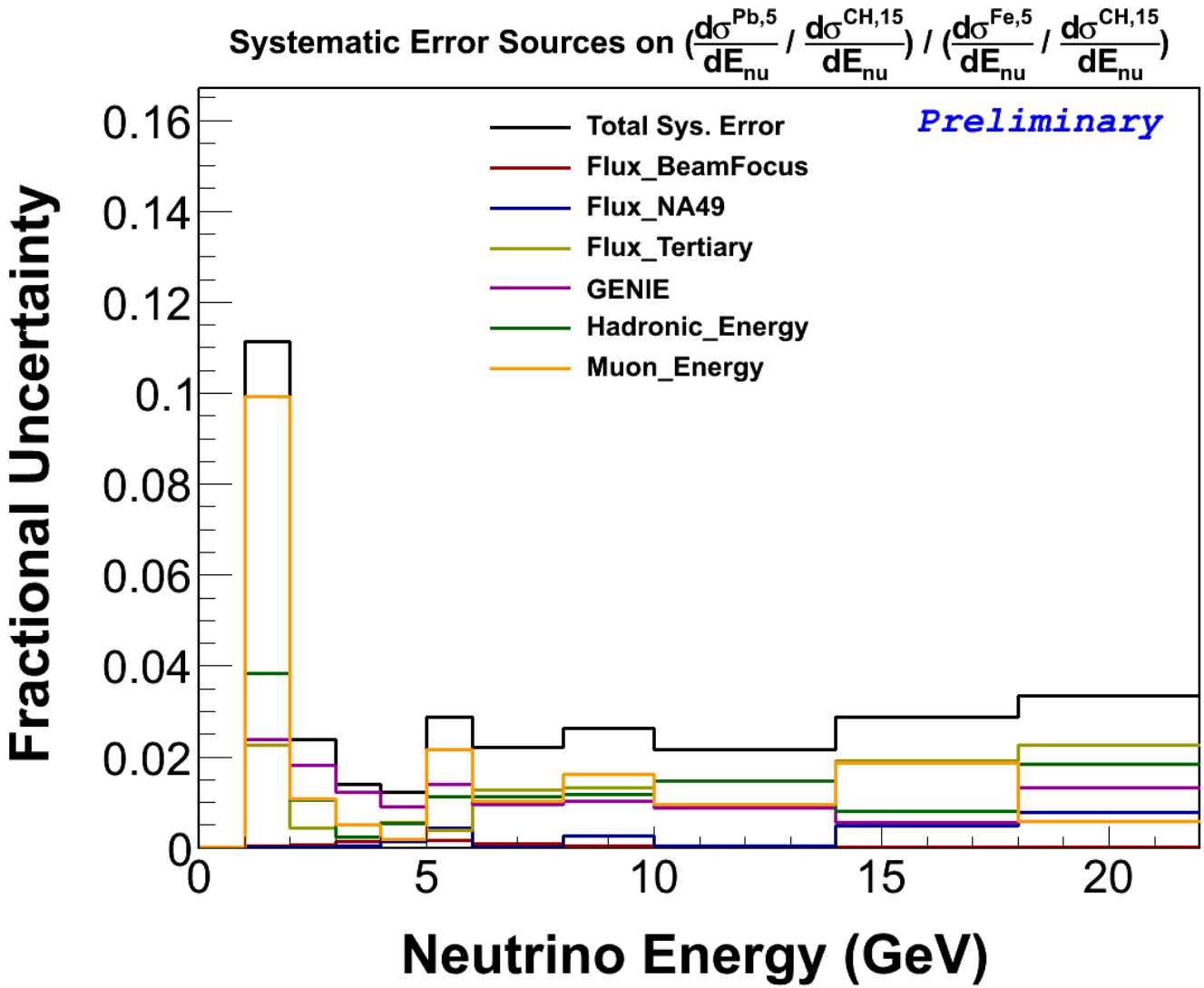
Systematic Uncertainties

Uncertainty on the energy spectrum from Fe



Systematic Uncertainties

Uncertainty on the ratio



Summary: update → results!

- Preliminary $d\sigma/dQ^2$ for $\bar{\nu}_\mu$ quasi-elastics!
  - Already able to inform/constrain models
  - Bridge NOMAD & MiniBooNE → need for lower E
- Promising nuclear target ratios method
  - small systematics,
  - data hungry, additional targets available → ME run
- neutrino QEL very close, (many) other analyses in progress
- 3x more data for ν and $\bar{\nu}$ in the can
- Identified portfolio of systematics
  - clear path for improvements & MC tuning
  - Flux program: HP data (NA61) + multi-beam + μ monitors

University of Athens
University of Texas at Austin
Centro Brasileiro de Pesquisas Físicas
Fermilab
University of Florida
Universidad de Guanajuato
Hampton University
Inst. Nucl. Reas. Moscow
Mass. Col. Lib. Arts
Northwestern University
Otterbein University
Pontificia Universidad Catolica del Peru
University of Pittsburgh
University of Rochester
Rutgers University
Tufts University
University of California at Irvine
University of Minnesota at Duluth
Universidad Nacional de Ingeniería
Universidad Técnica Federico Santa María
William and Mary

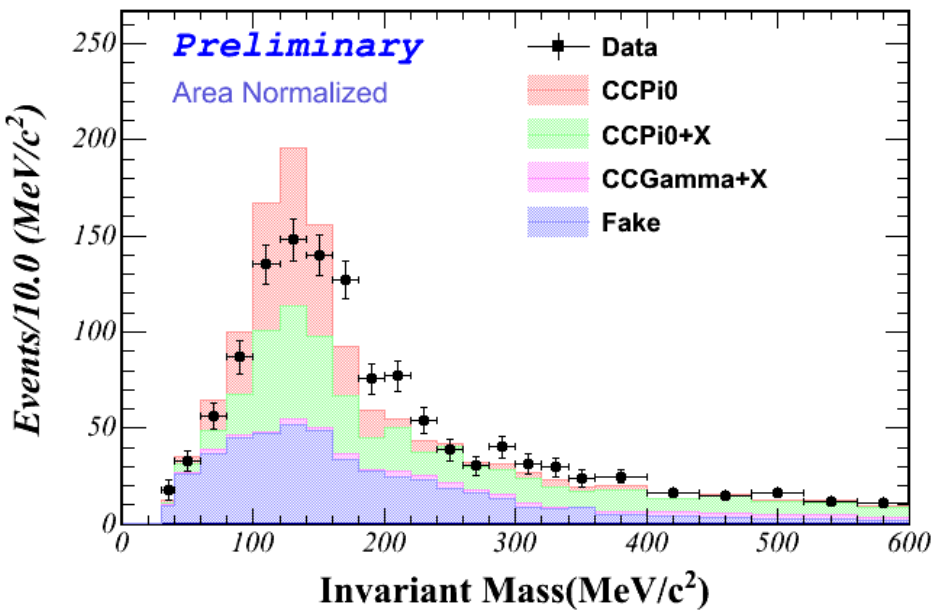
Love neutrinos?

Love accelerators??

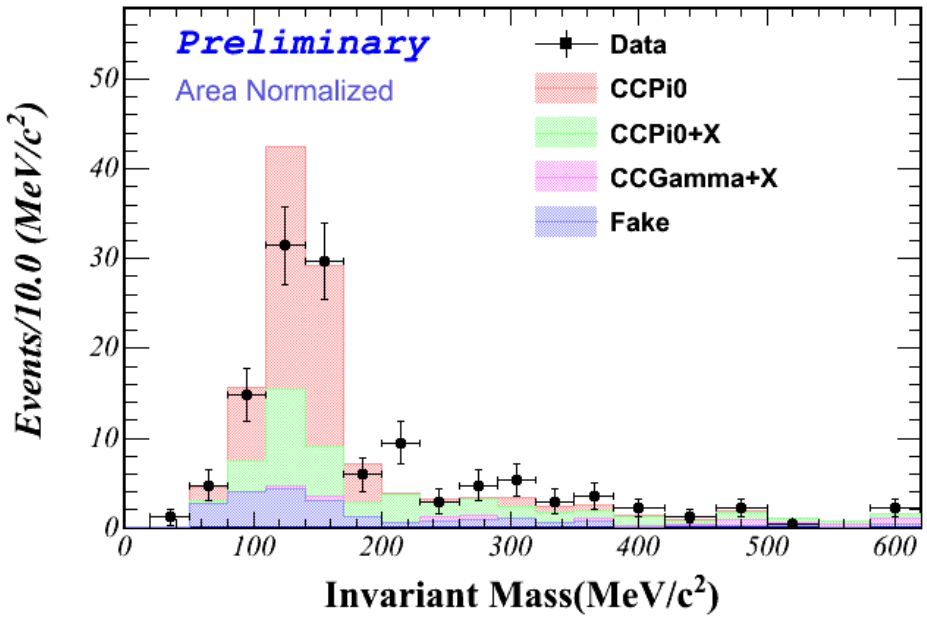
Love tricorne hats???

π^0 reconstruction

Report from a work in progress

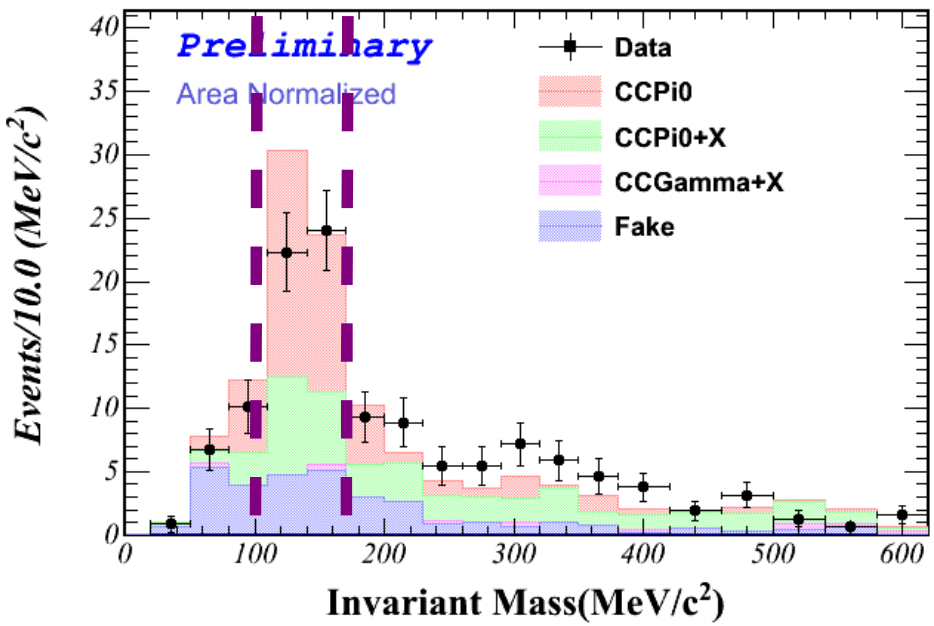


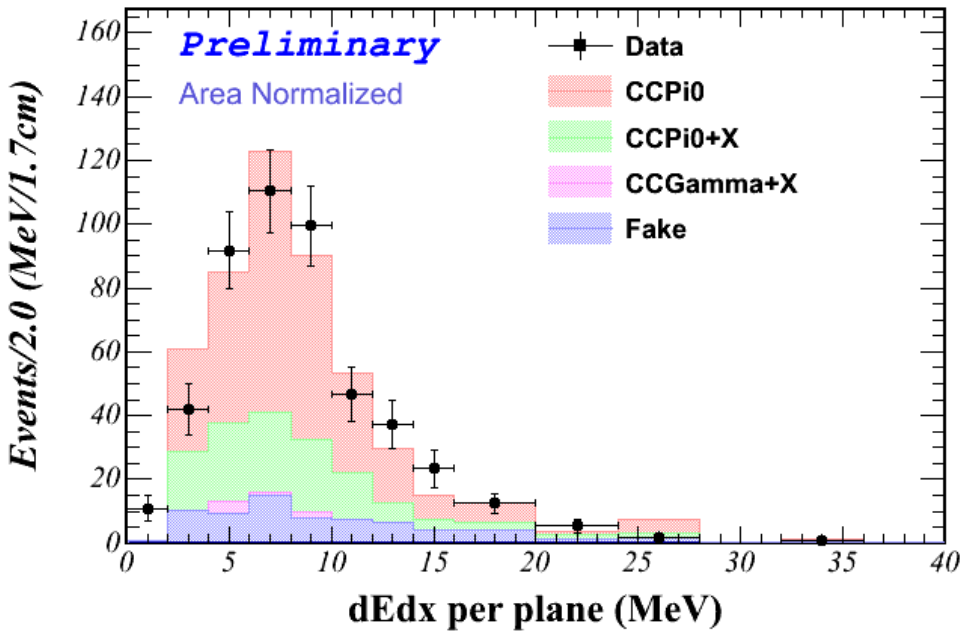
μ^+ and 2 isolated blobs
opening angle > 25°



μ^+ and 2 isolated blobs
opening angle > 25°
vertex energy<40 MeV
2<γ dE/dx<12 MeV/plane

π^0 dE/dx

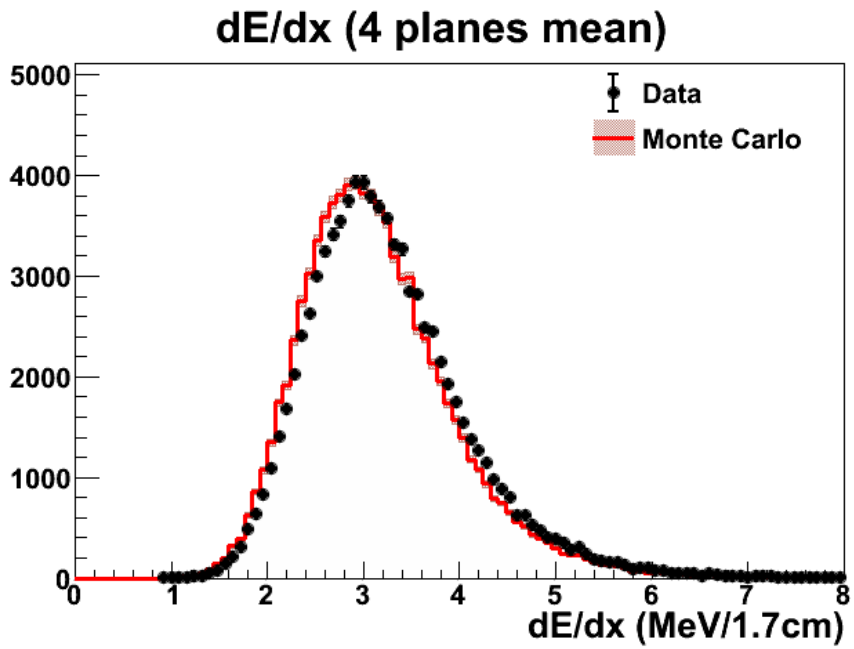


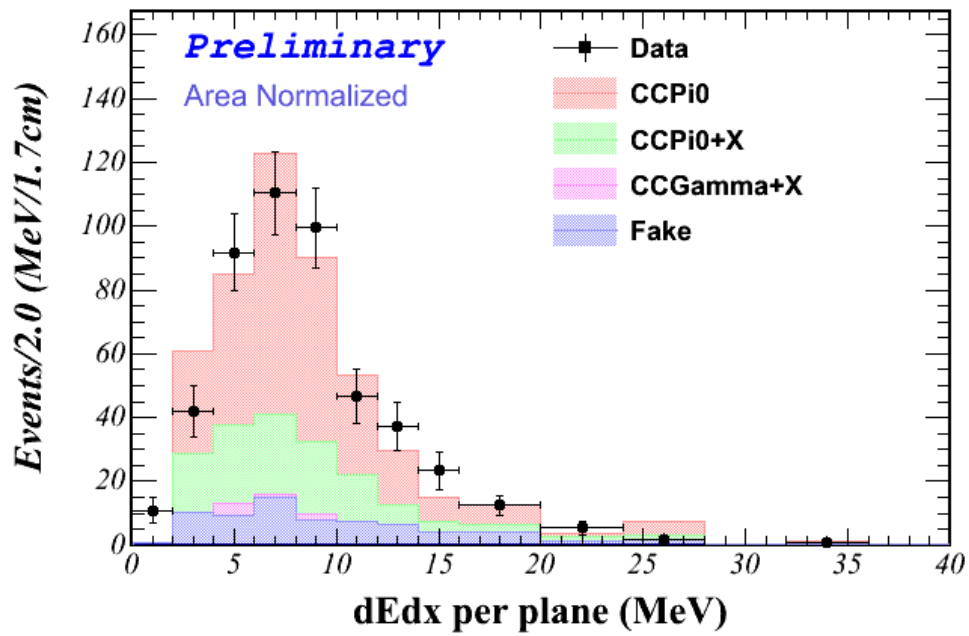


μ^+ and 2 isolated blobs
opening angle > 25°
vertex energy<40 MeV
E1>100MeV, E2>50MeV
$\theta 1, \theta 2 < 50°$

γ dE/dx

e vs γ dE/dx

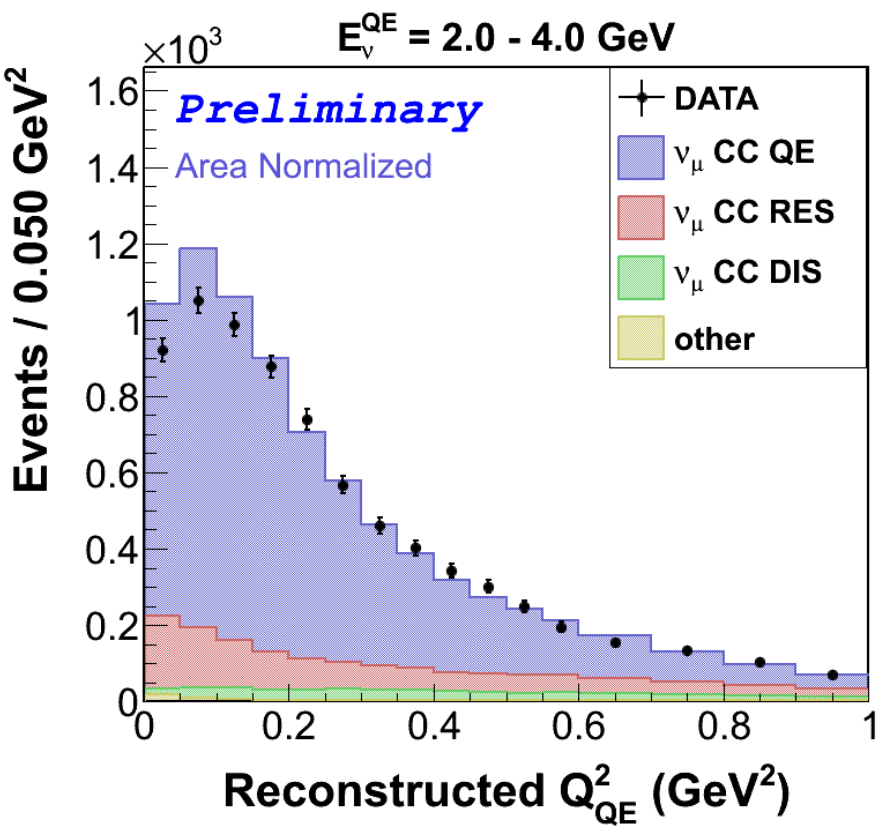


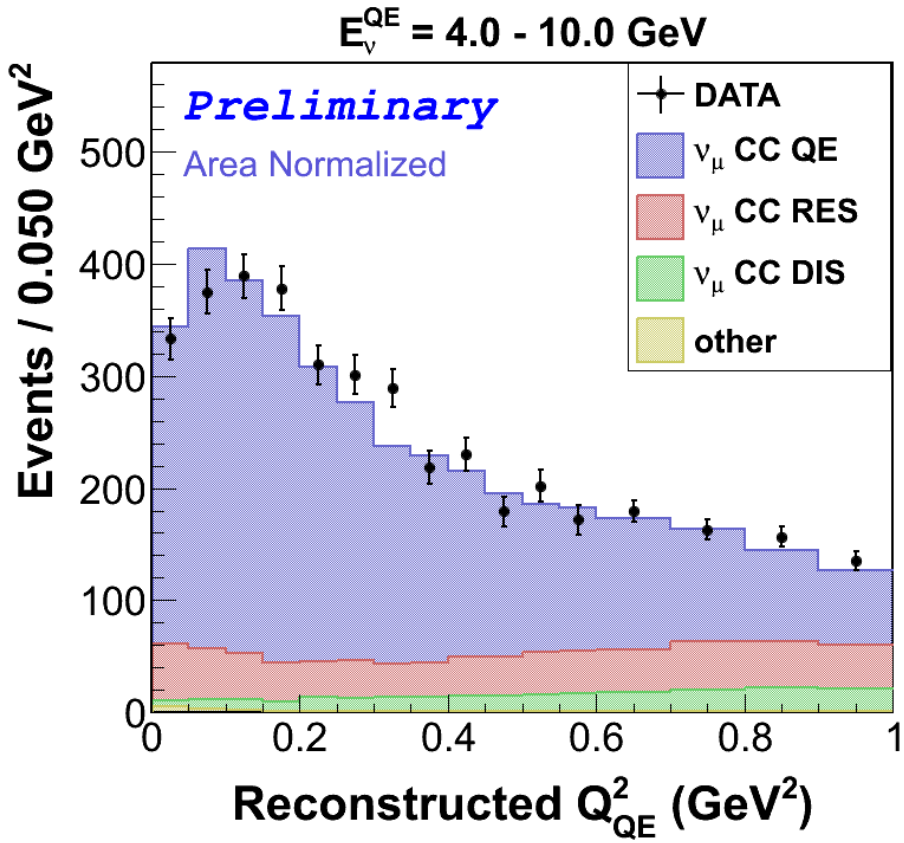


Michel electron dE/dx

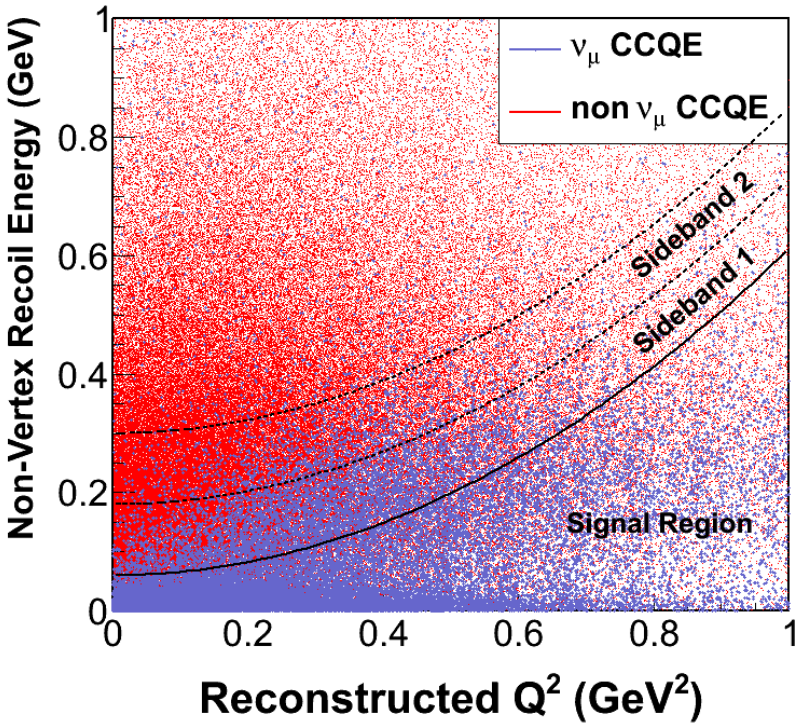
γ from π^0 dE/dx

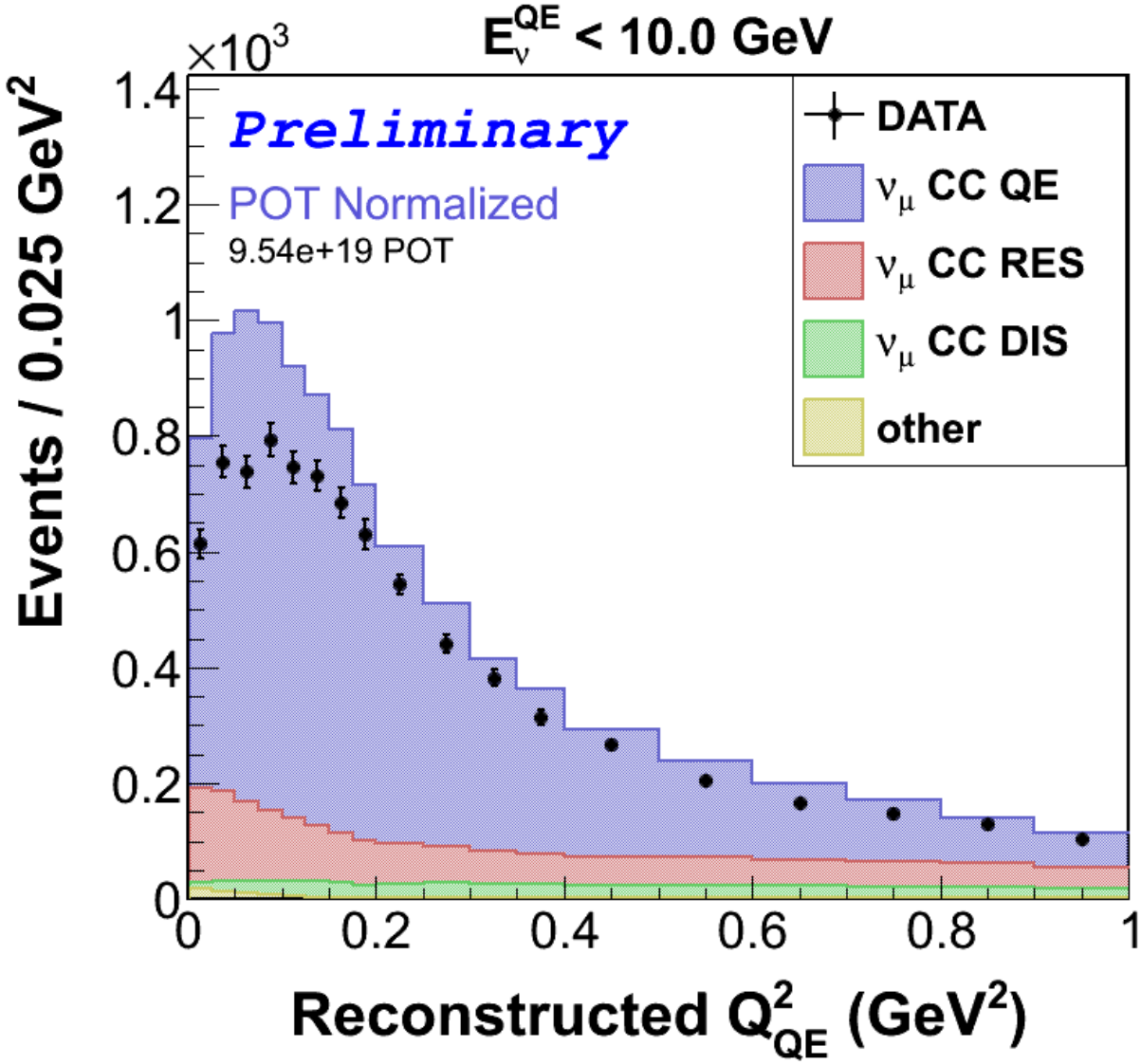
ν_μ Quasi-elastics



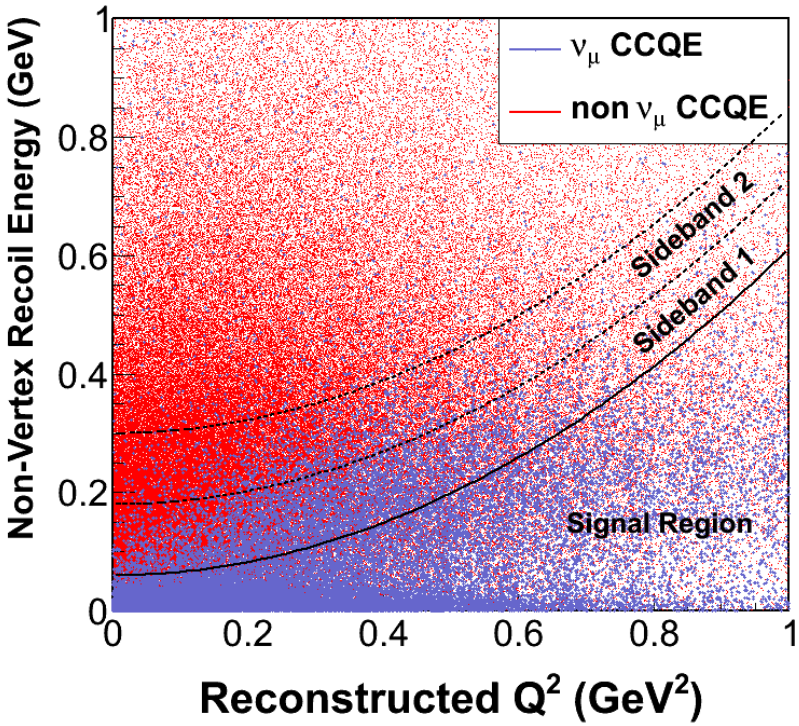


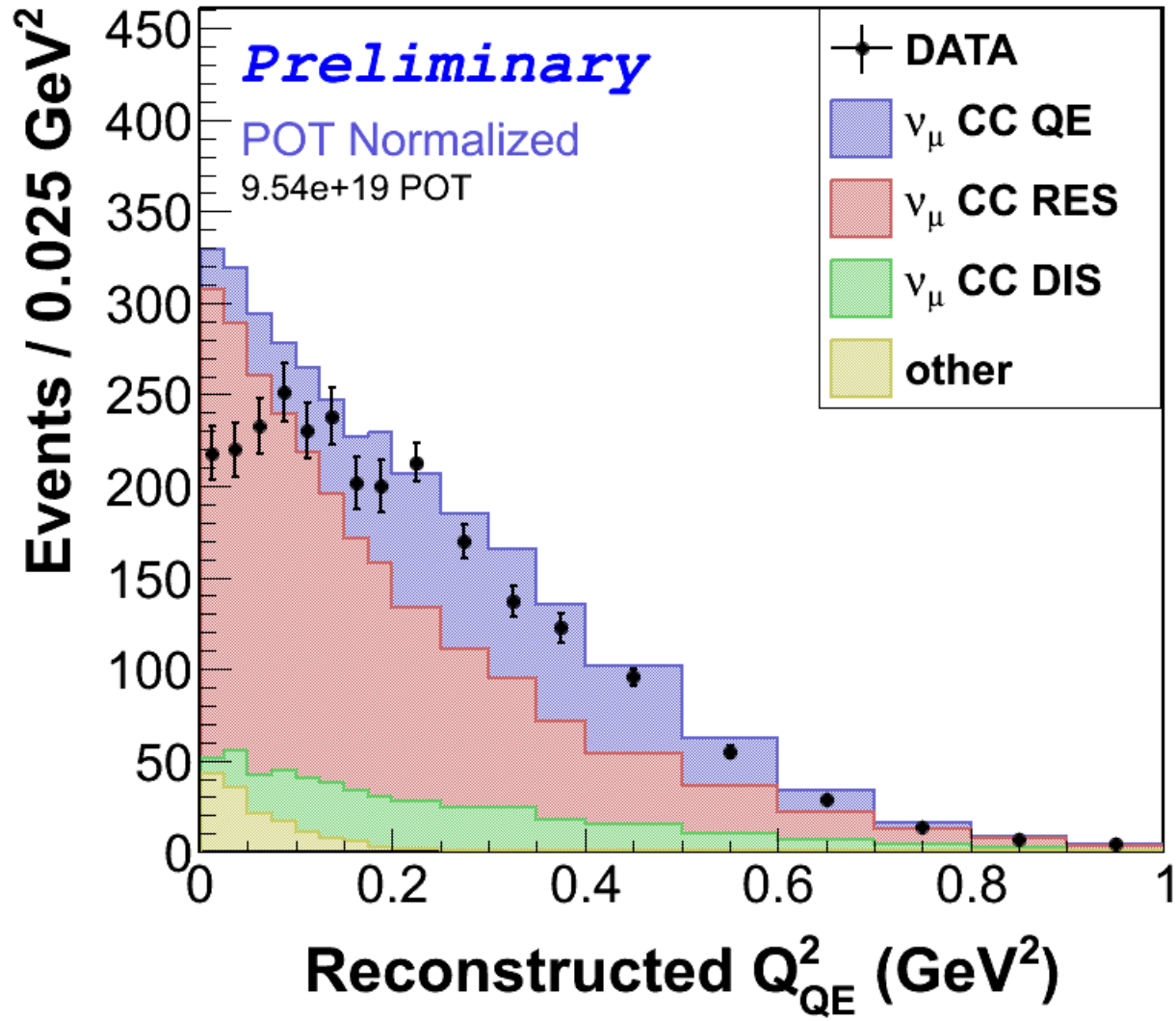
ν_μ QEL signal region



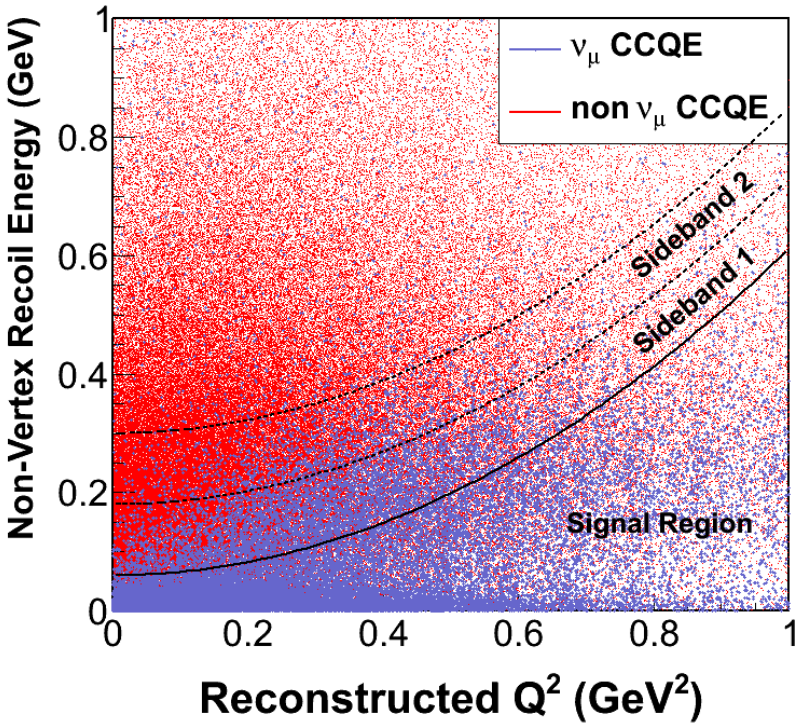


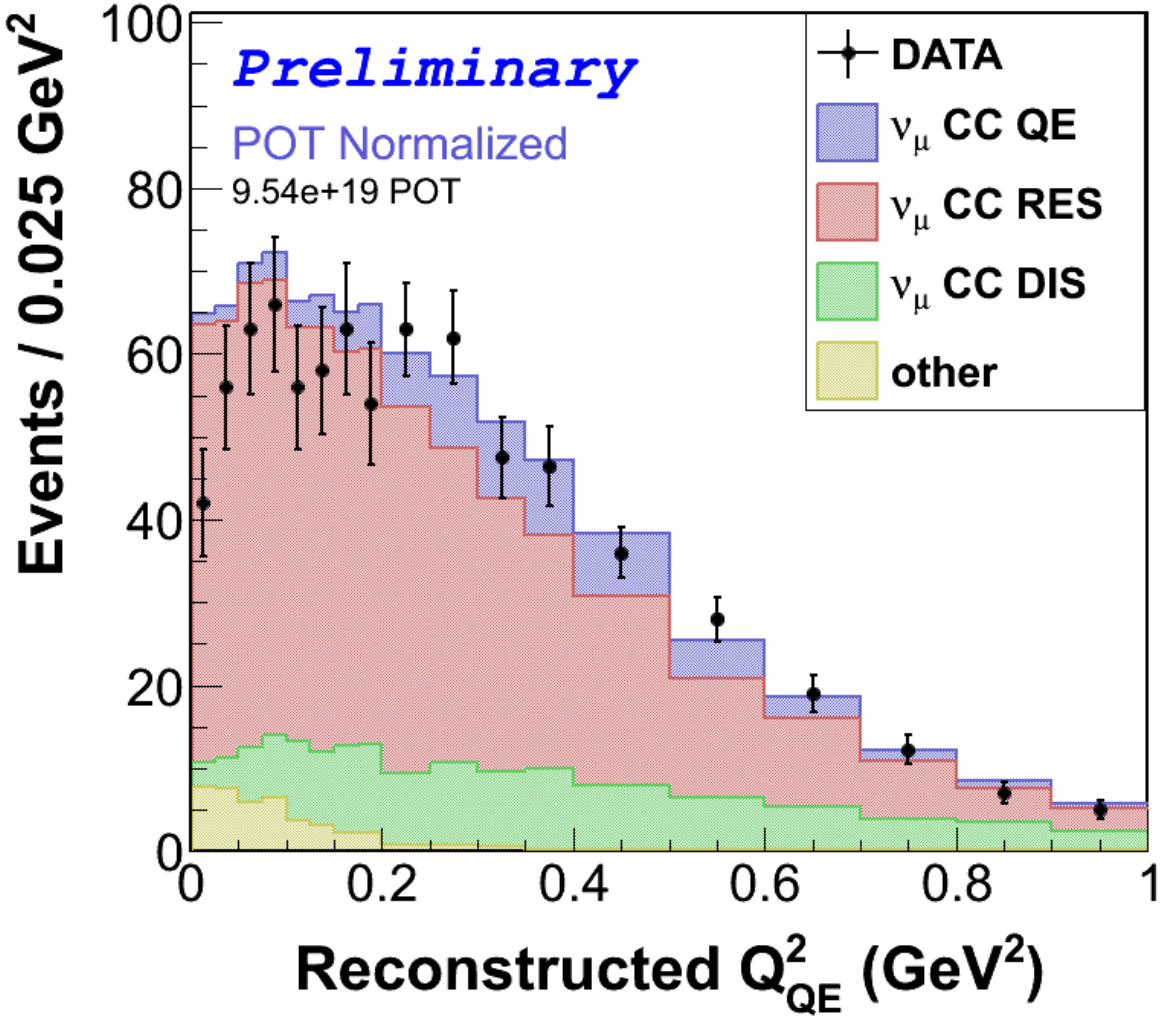
ν_μ QEL sideband #1





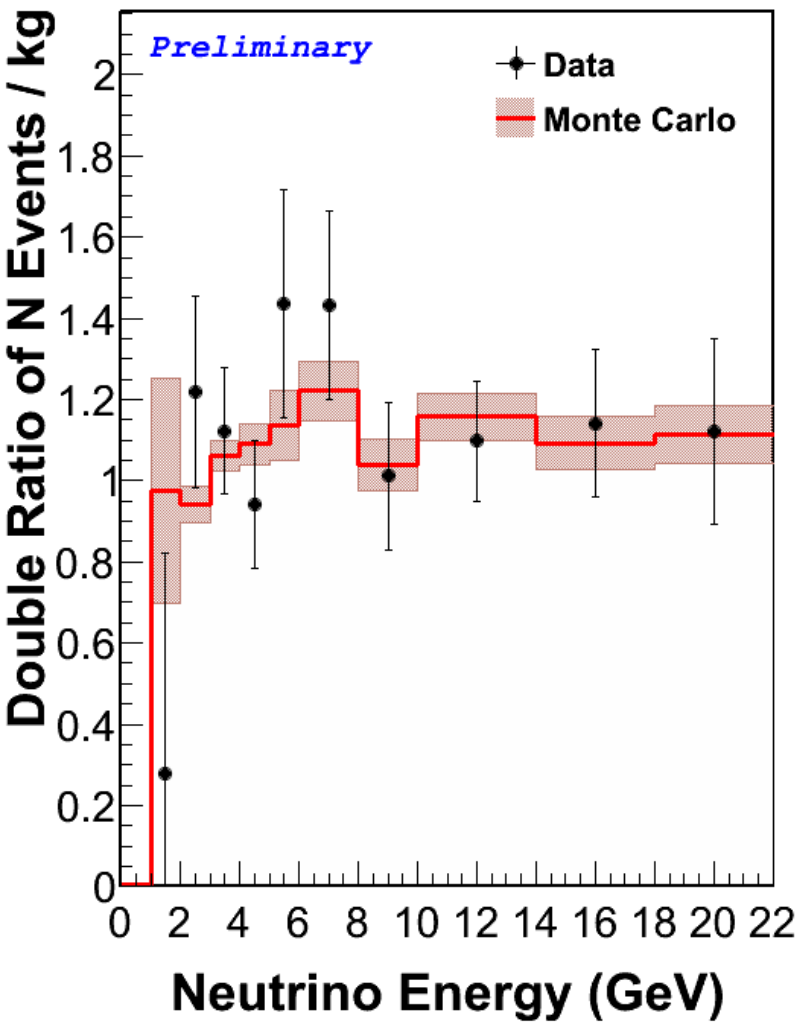
ν_μ QEL sideband #2

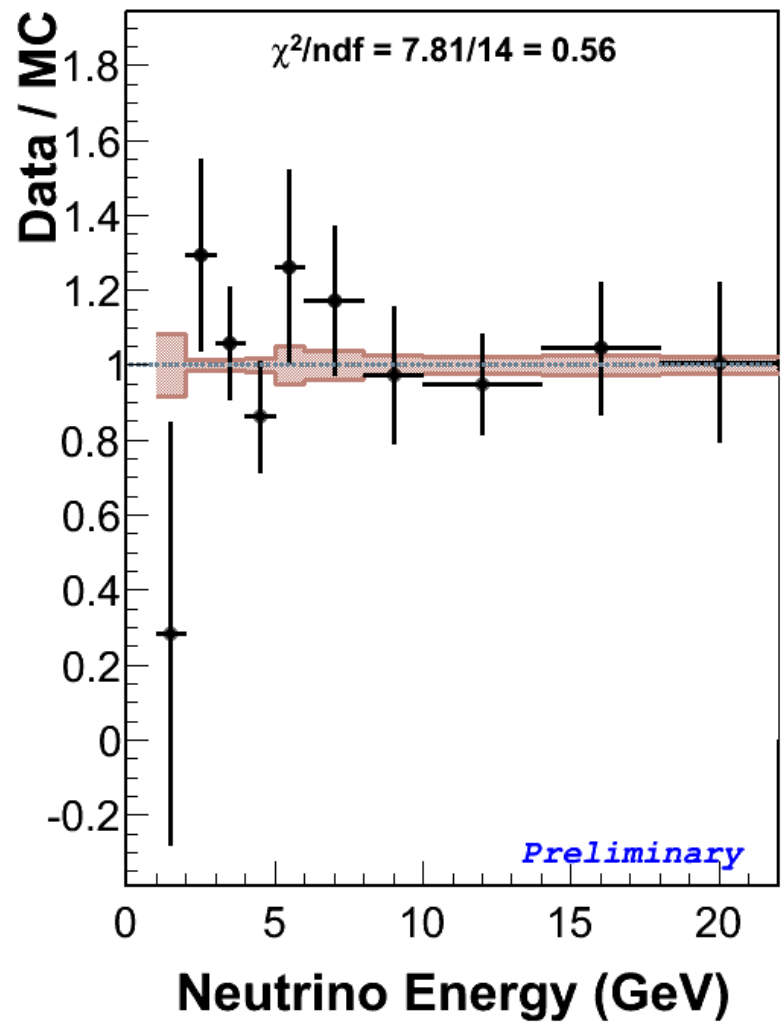




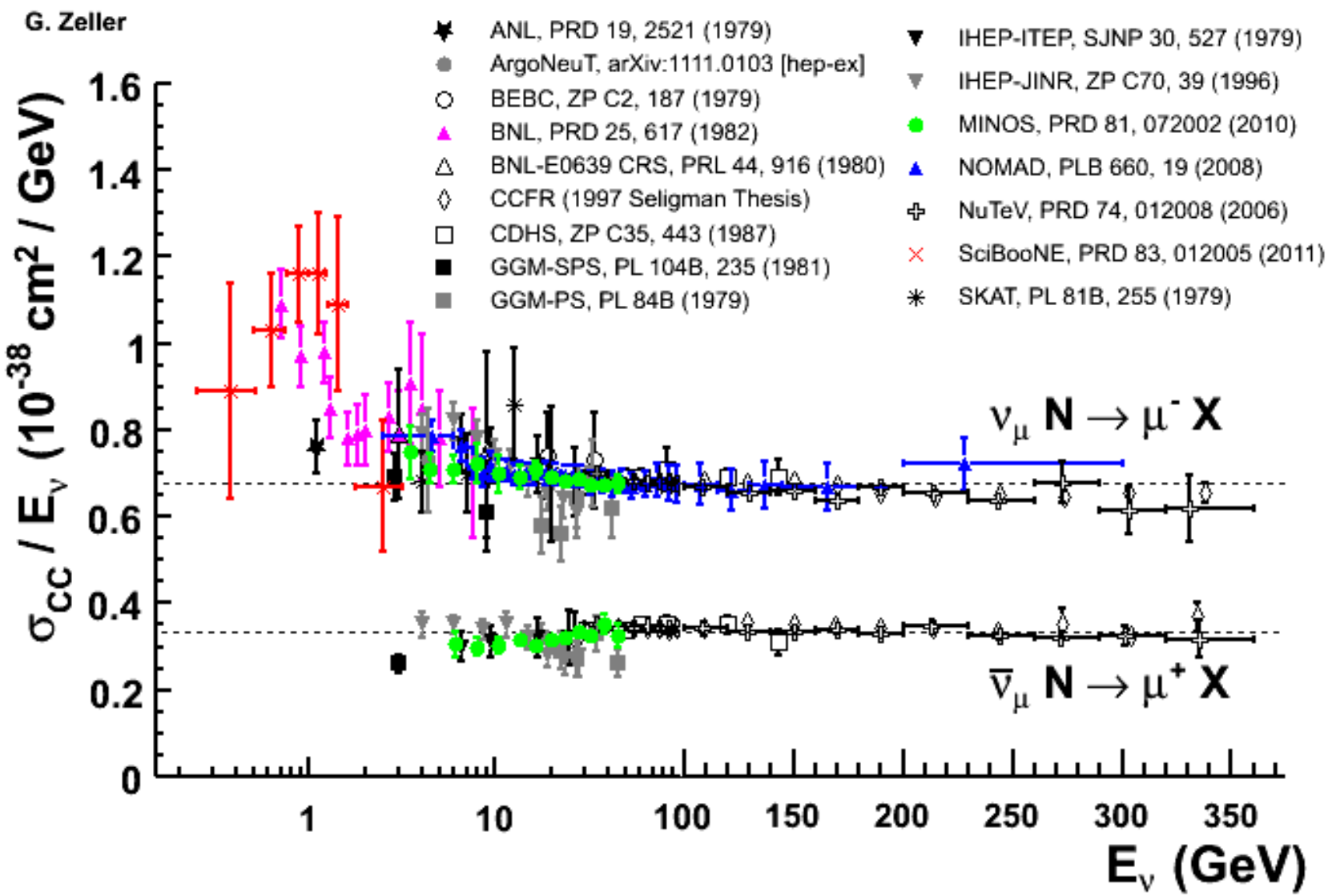
Target #3, C/Fe ratio

$$\left(\frac{d\sigma^{C,3}}{dE_{nu}} / \frac{d\sigma^{CH,13}}{dE_{nu}}\right) / \left(\frac{d\sigma^{Fe,3}}{dE_{nu}} / \frac{d\sigma^{CH,13}}{dE_{nu}}\right)$$





Cross-section plot w/ refs



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%

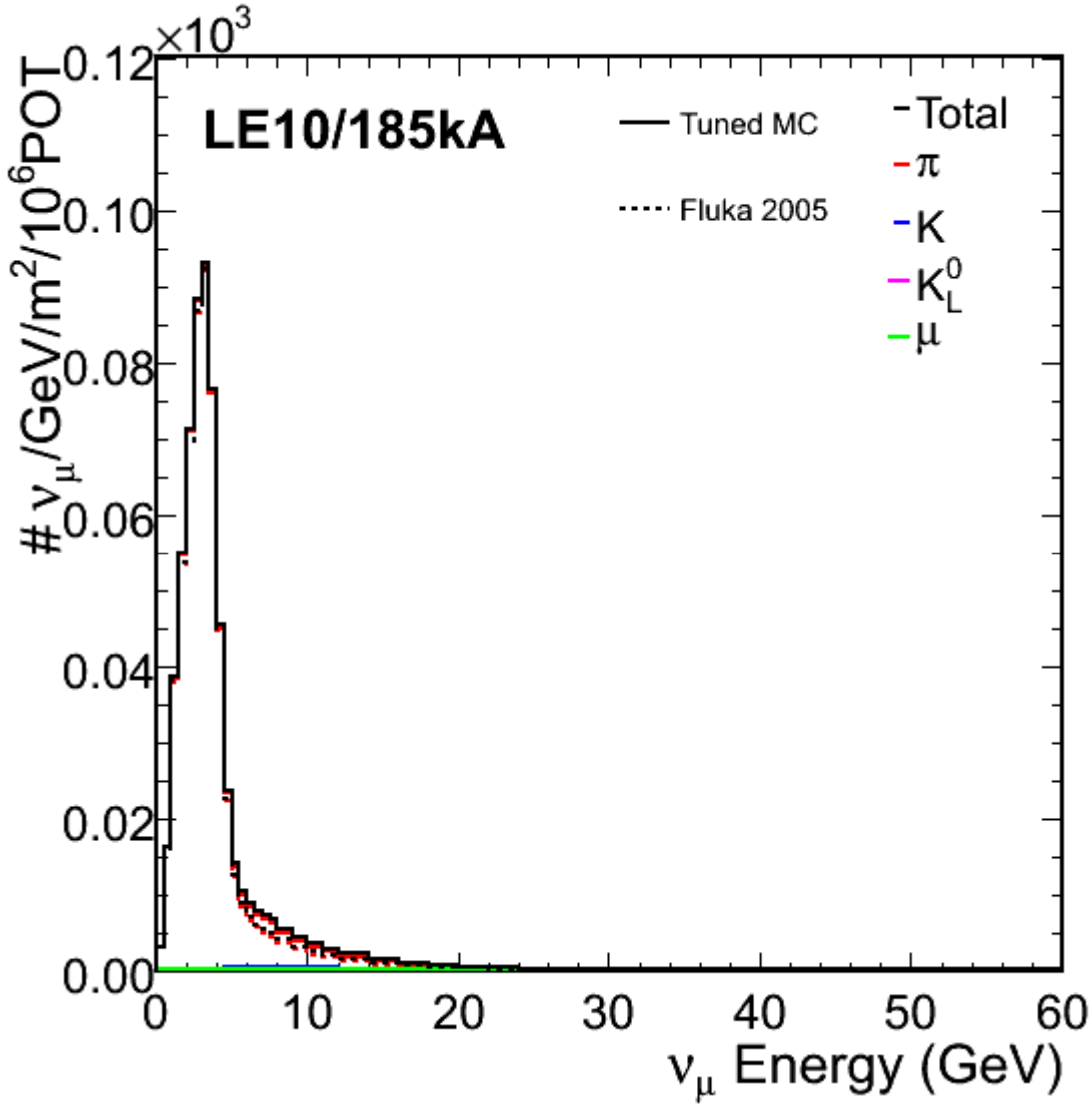
References: (1) www.genie-mc.org, (2) arXiv:0806.2119, (3) D. Bhattacharya, Ph. D Thesis (U. Pittsburgh) 2009.

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

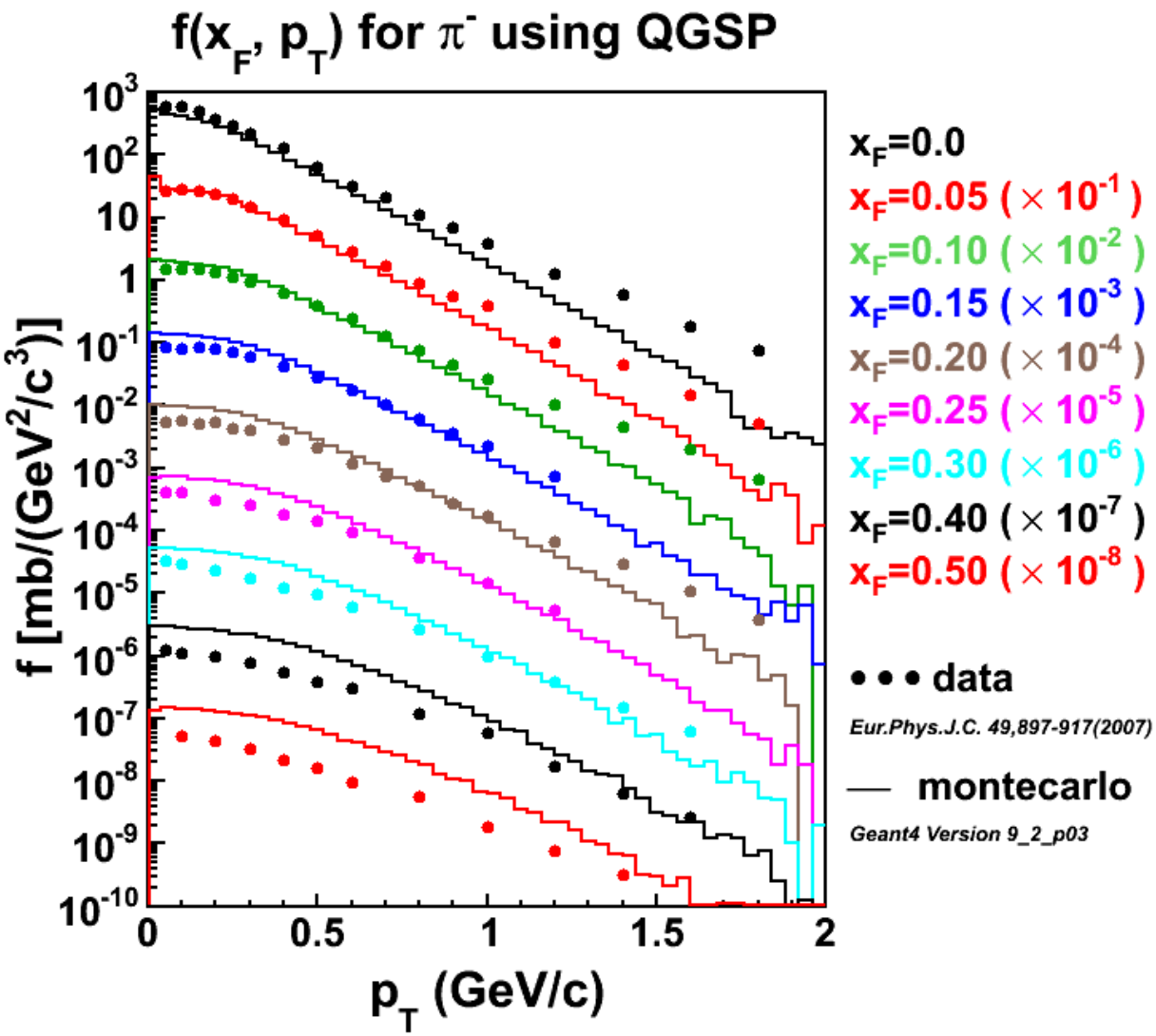
GENIE 2.6, FLUKA08, 90cm radius, 116 tracker modules

MINOS G3/FLUKA05 flux

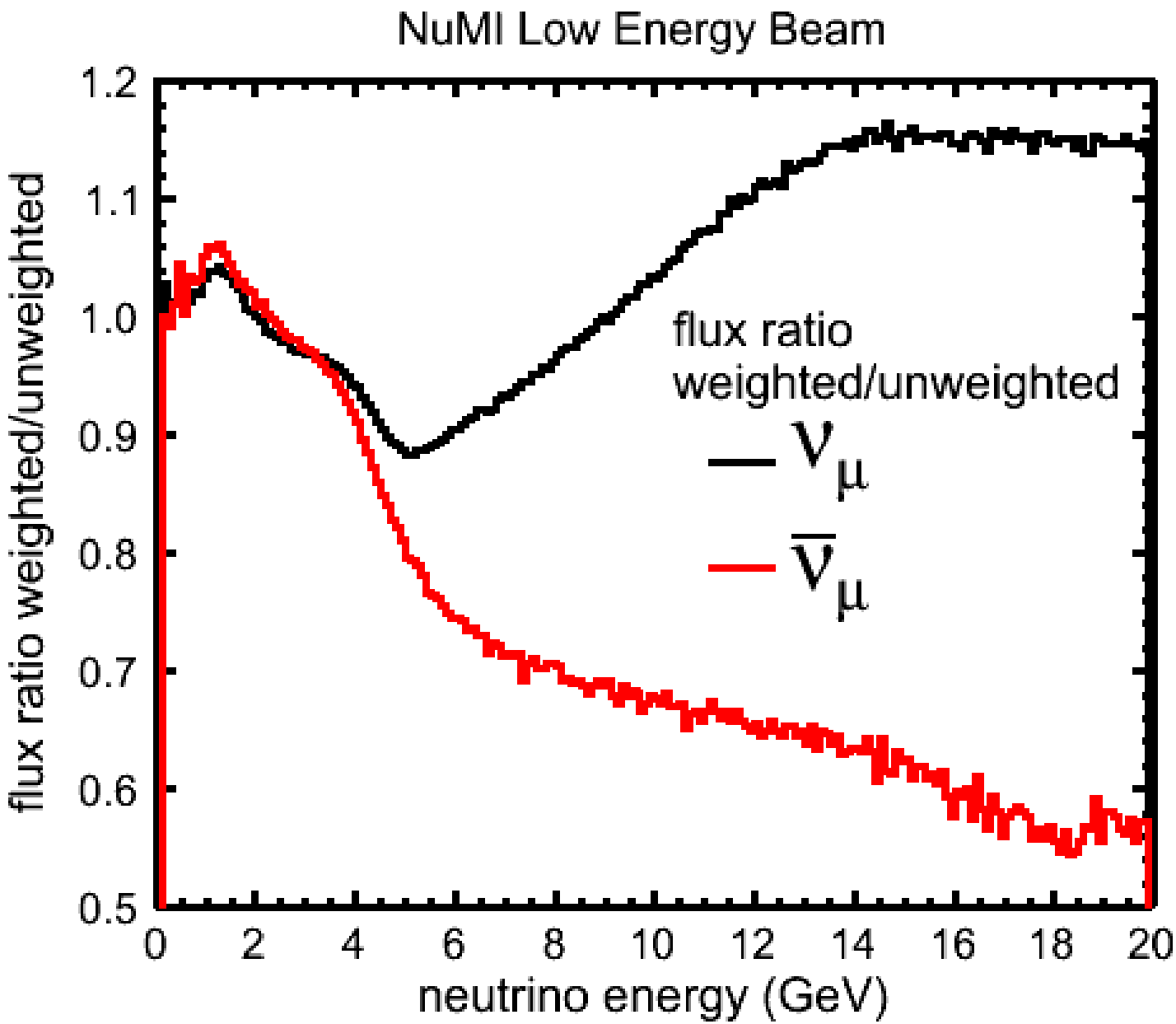


http://www.hep.utexas.edu/~zarko/wwwgnumi/v19/

NA49 π^- vs G4 QGSP

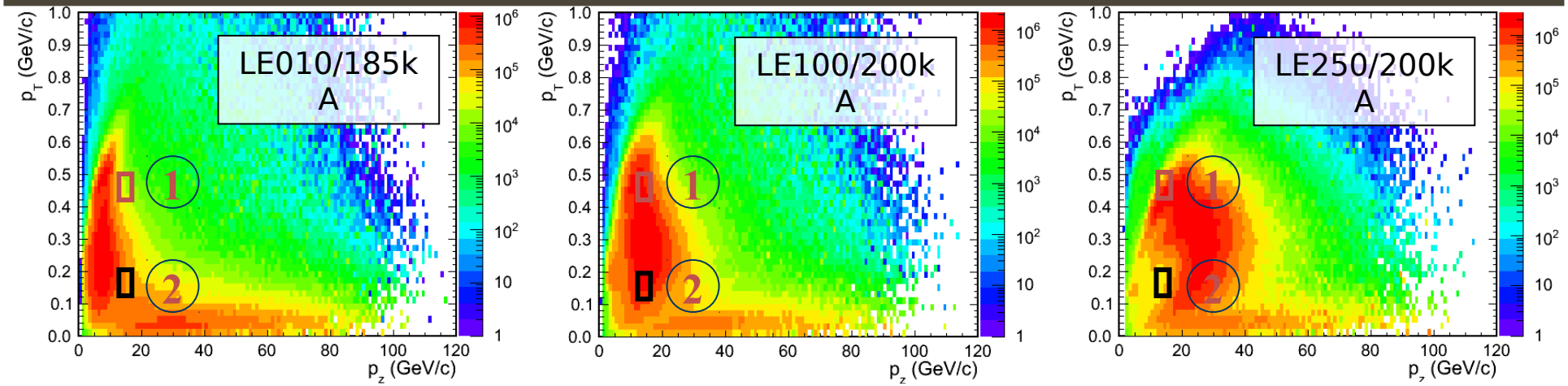


NA49 flux tuning

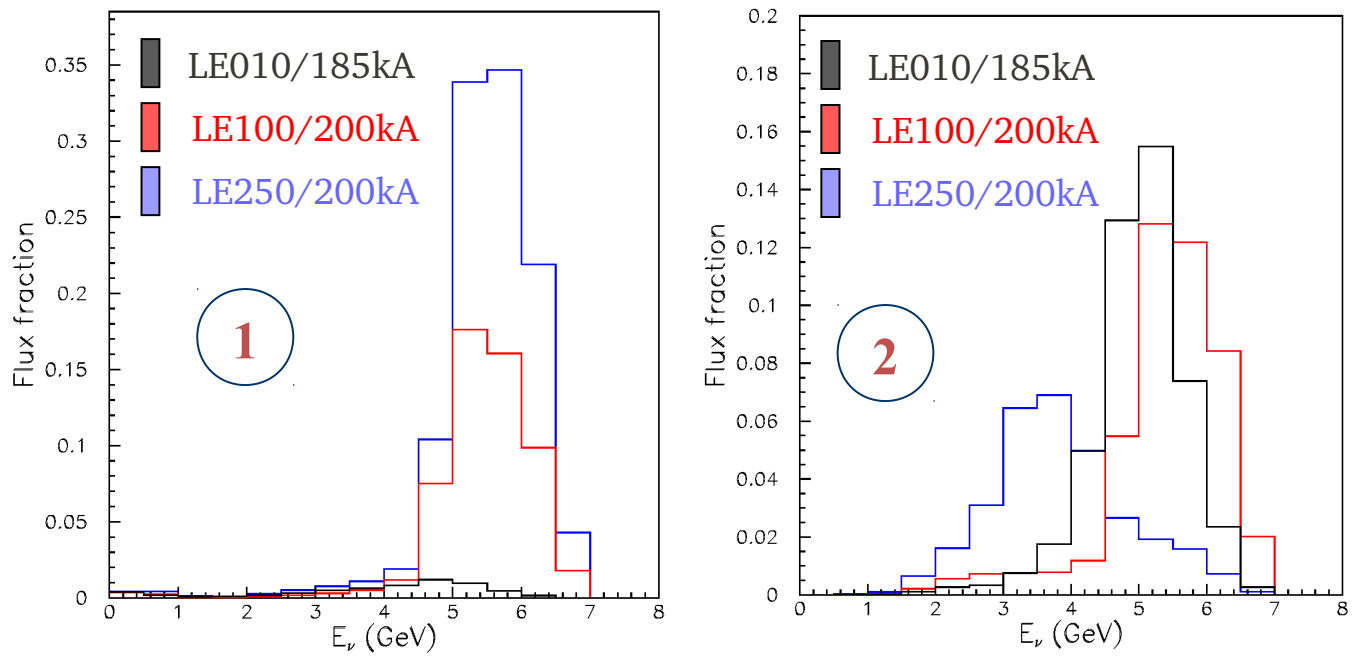


Using neutrino data

Flexible beam configurations permit *tuning* hadron production yields to match data.



Each (*x*F,*p*T) bin contributes with different weight in each beam configuration

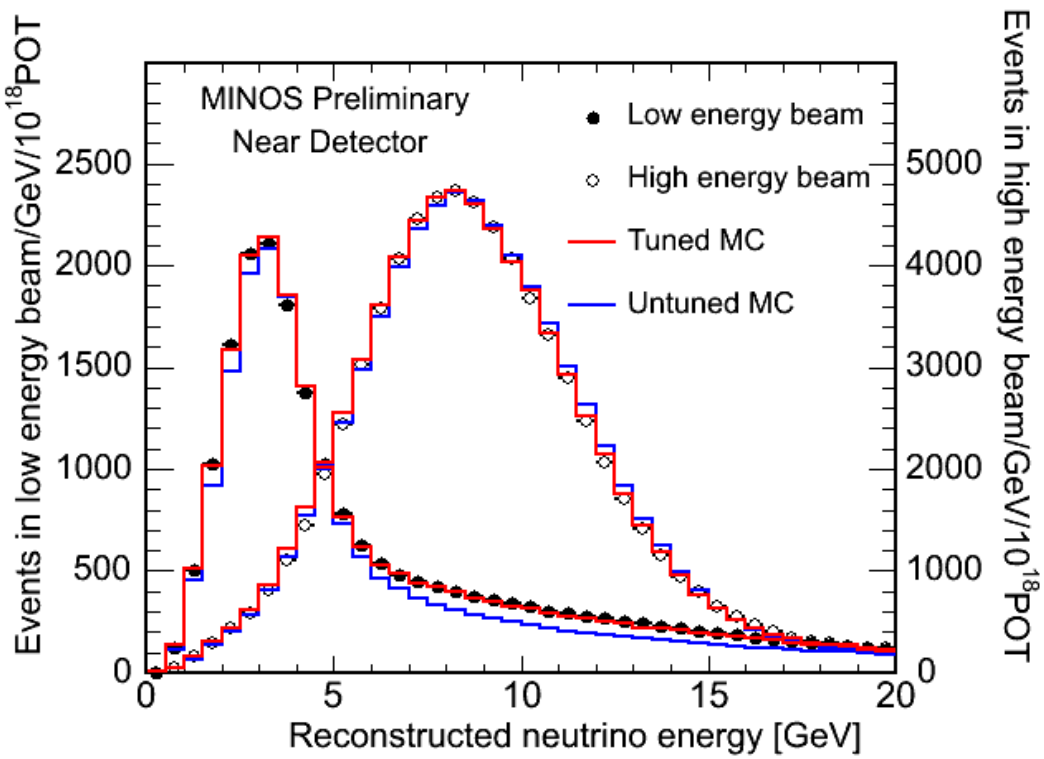


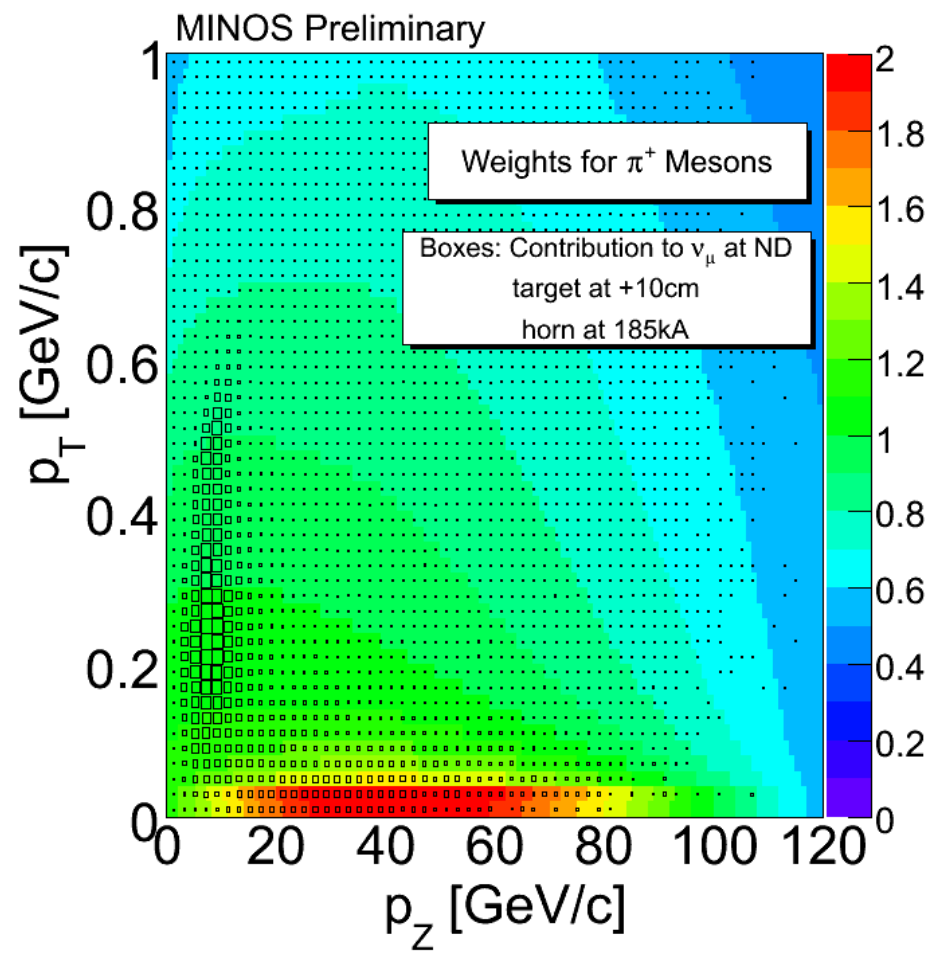
Using neutrino data

Fit MC to Data by tuning weights in π,K (*x*F,*p*T) plane
In MINOS, ν_μ-CC inclusive were used → MINERvA must do better

Phys. Rev. D77, 072002 (2008).

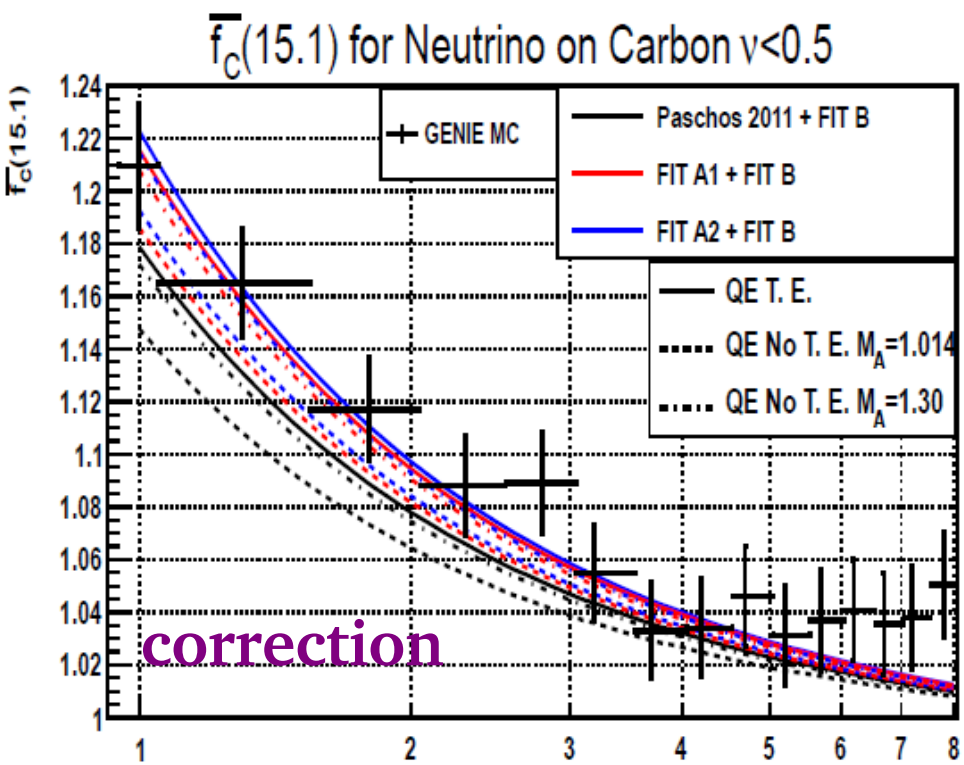
$$weight = \frac{(d^2N/dx_F\,dp_T)_{tuned}}{(d^2N/dx_F\,dp_T)_{MC}}$$

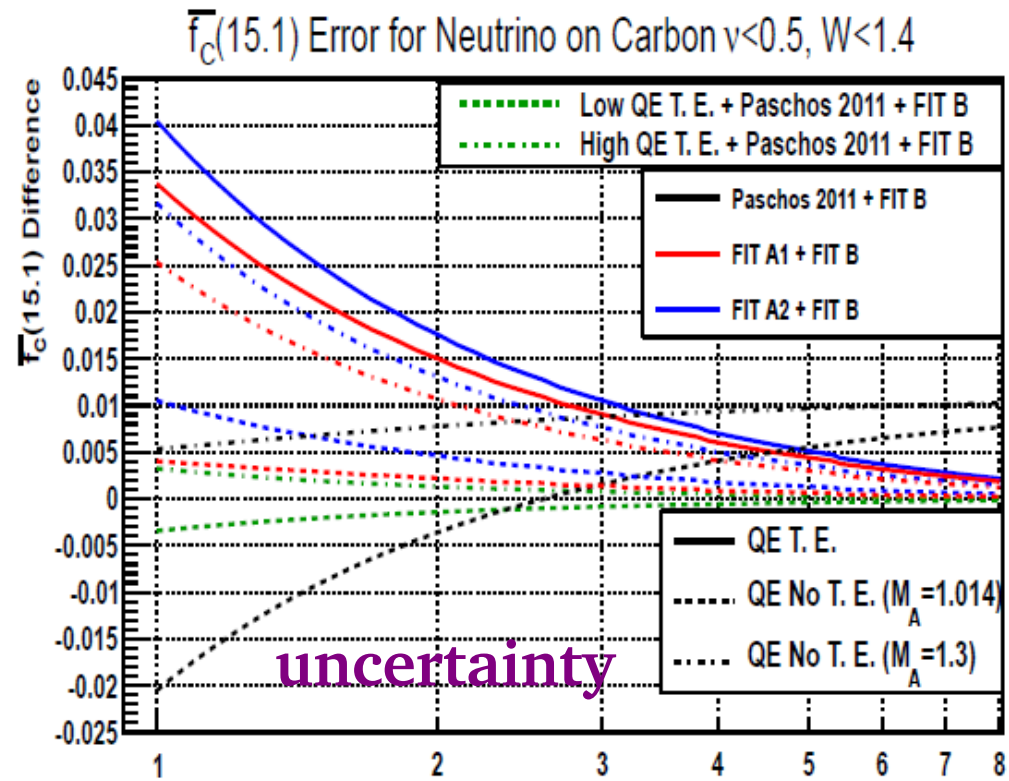




Low-ν flux method

Recent work: Bodek et al, Eur.Phys.J. C72 (2012) 1973
MINOS, Phys.Rev. D 81 (2010) 072002



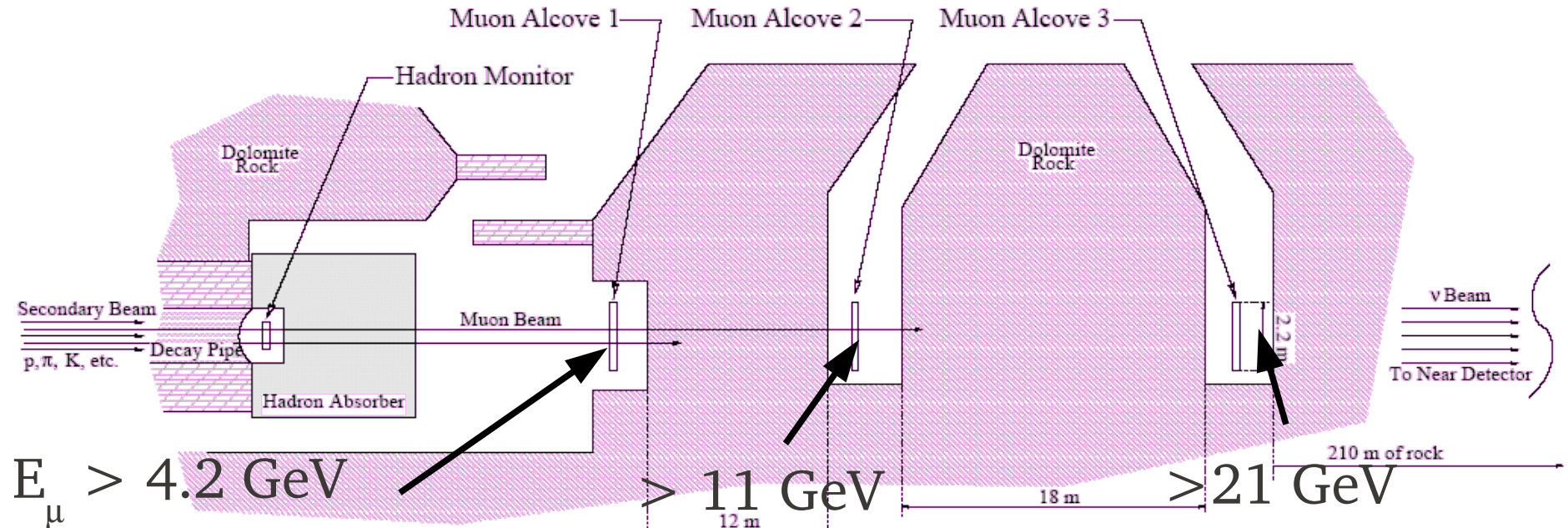


neutrino energy (GeV)

0th order: cross-section of low ν events is constant w/ energy
Higher orders: the correction and uncertainties above.
→ Combine with multiple beam configurations, HP and μ-mons

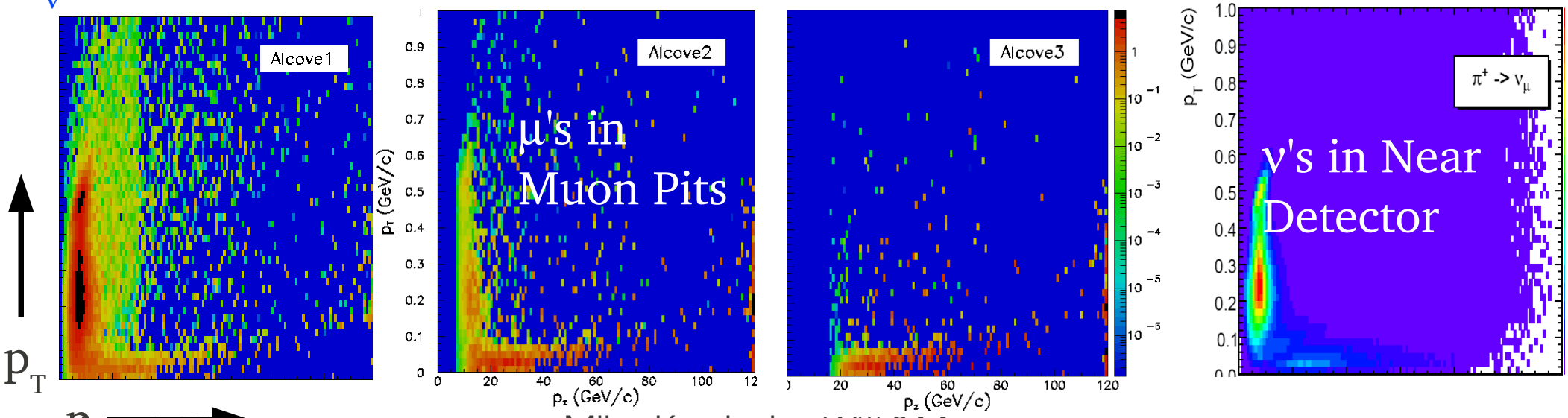
Using monitors

L. Loiacono, "Measurement of the Muon Neutrino Inclusive Charged Current Cross Section on Iron Using the MINOS Detector," PhD Thesis, UT Austin 2010

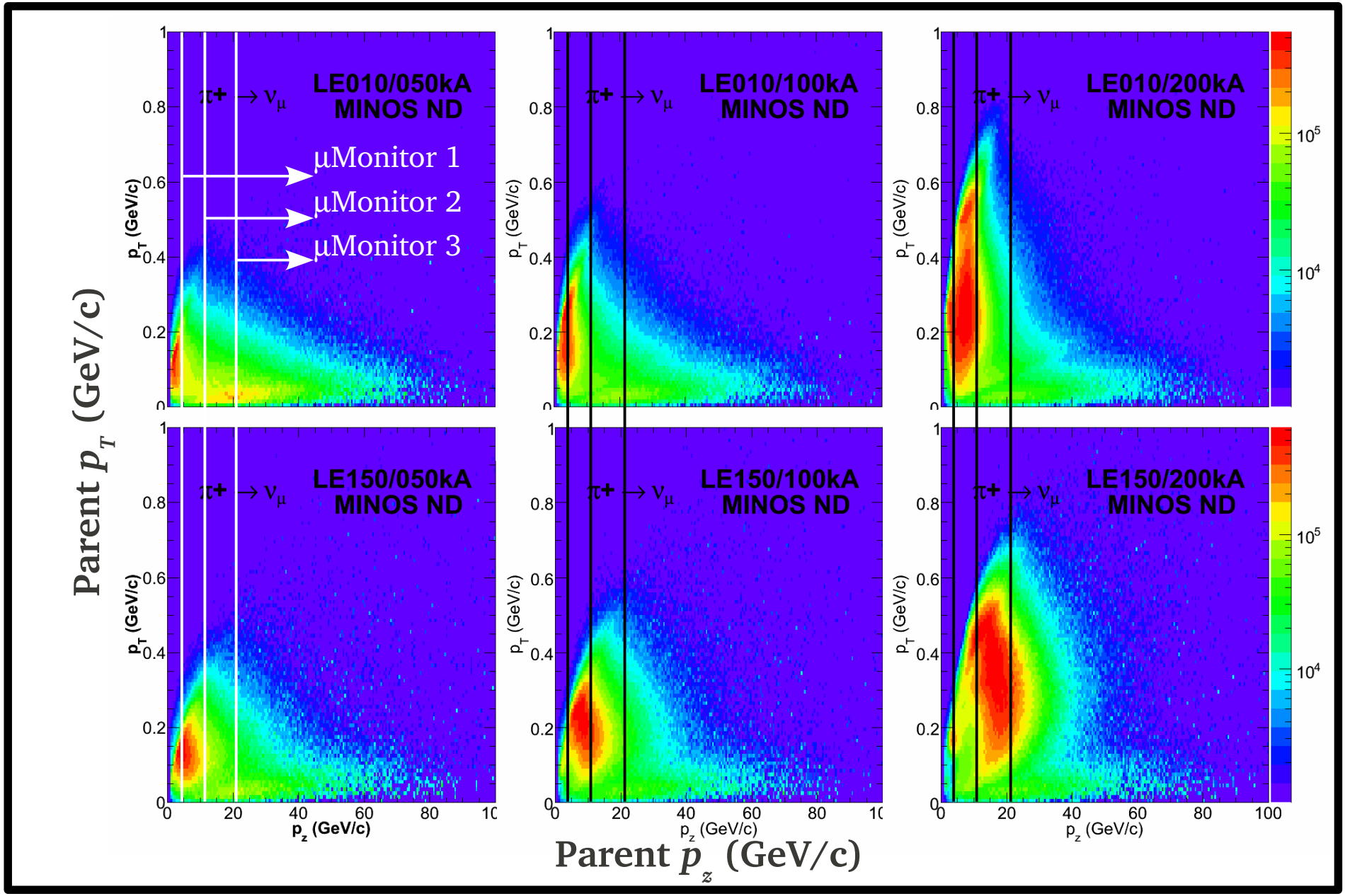


E_μ > 4.2 GeV > 11 GeV >21 GeV

E_ν > 1.8 GeV > 4.7 GeV > 9.0 GeV

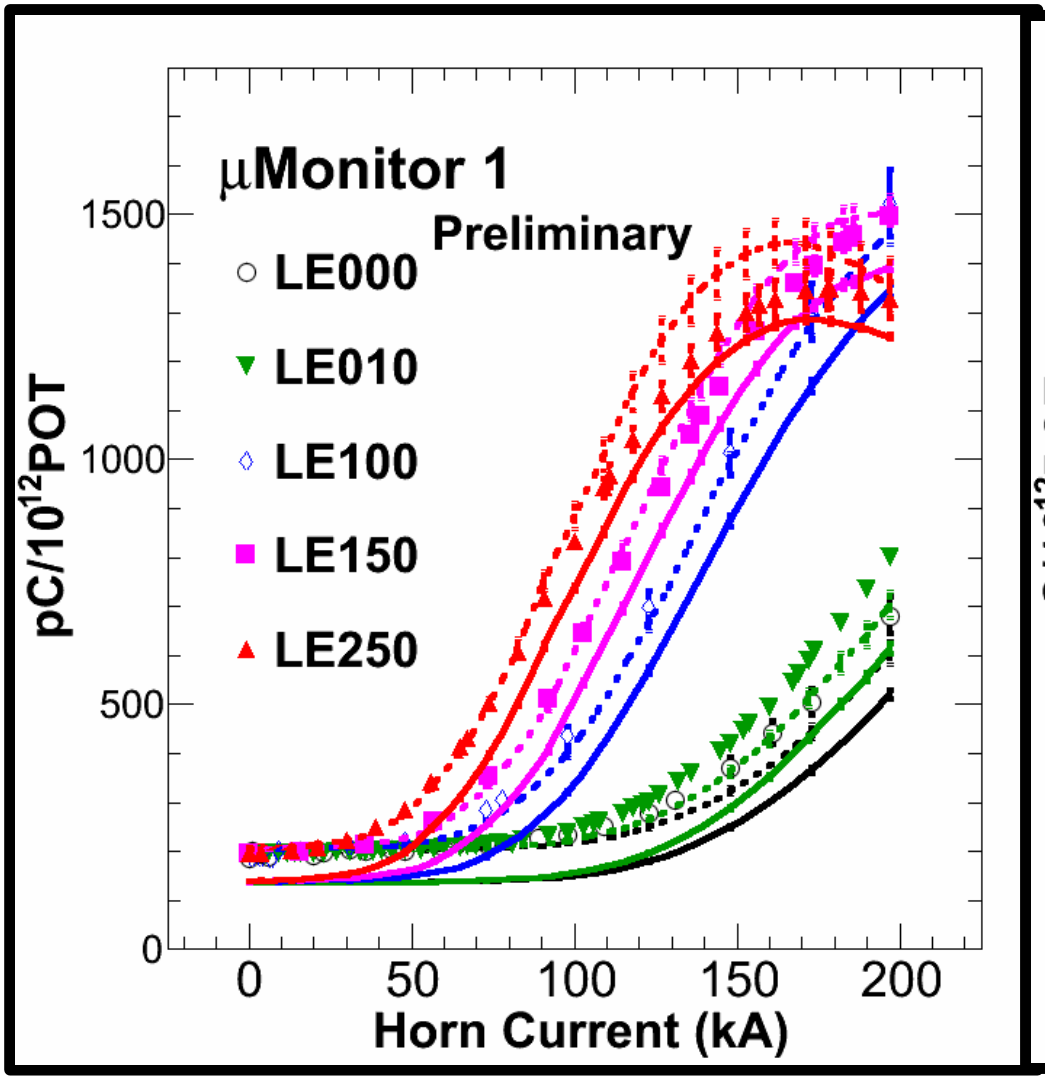


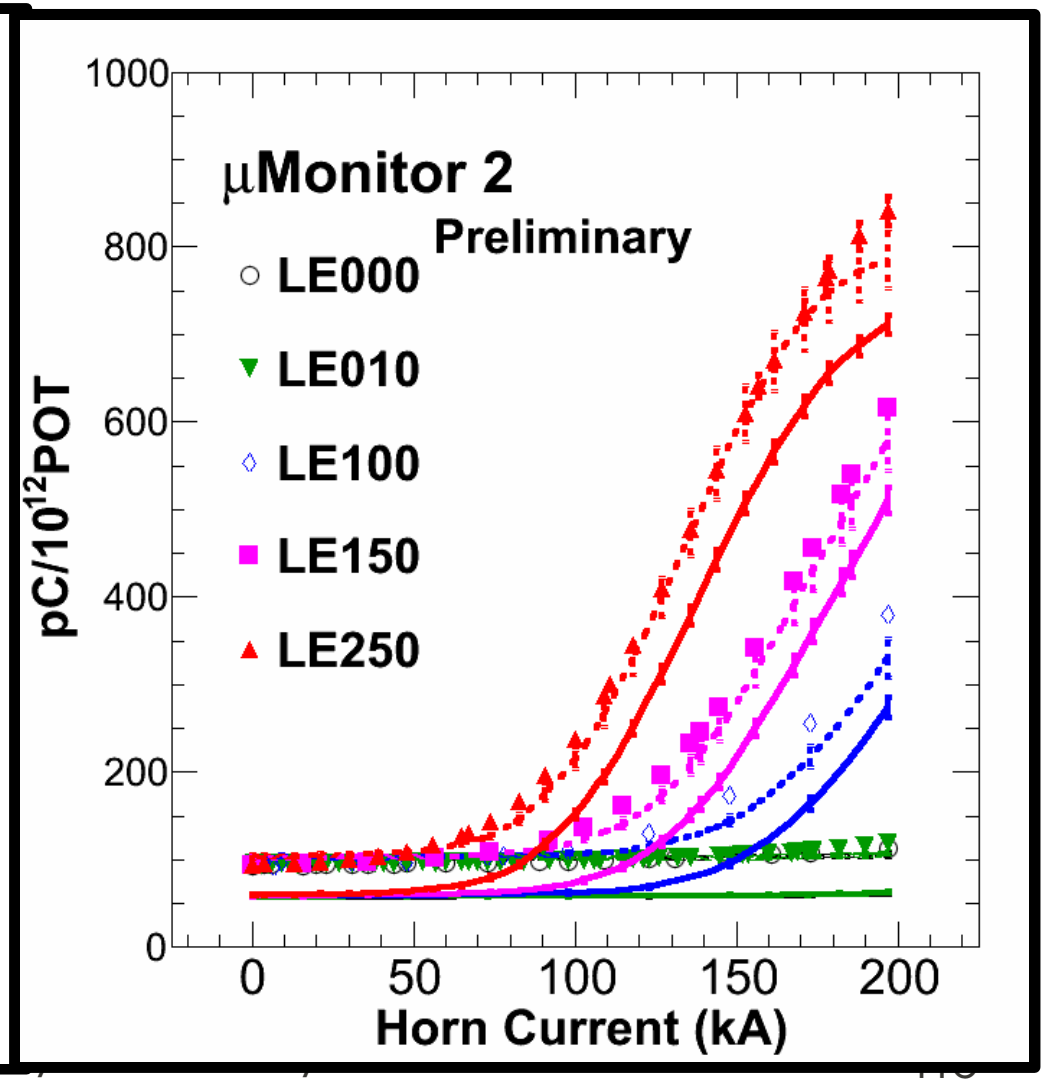
Using monitors



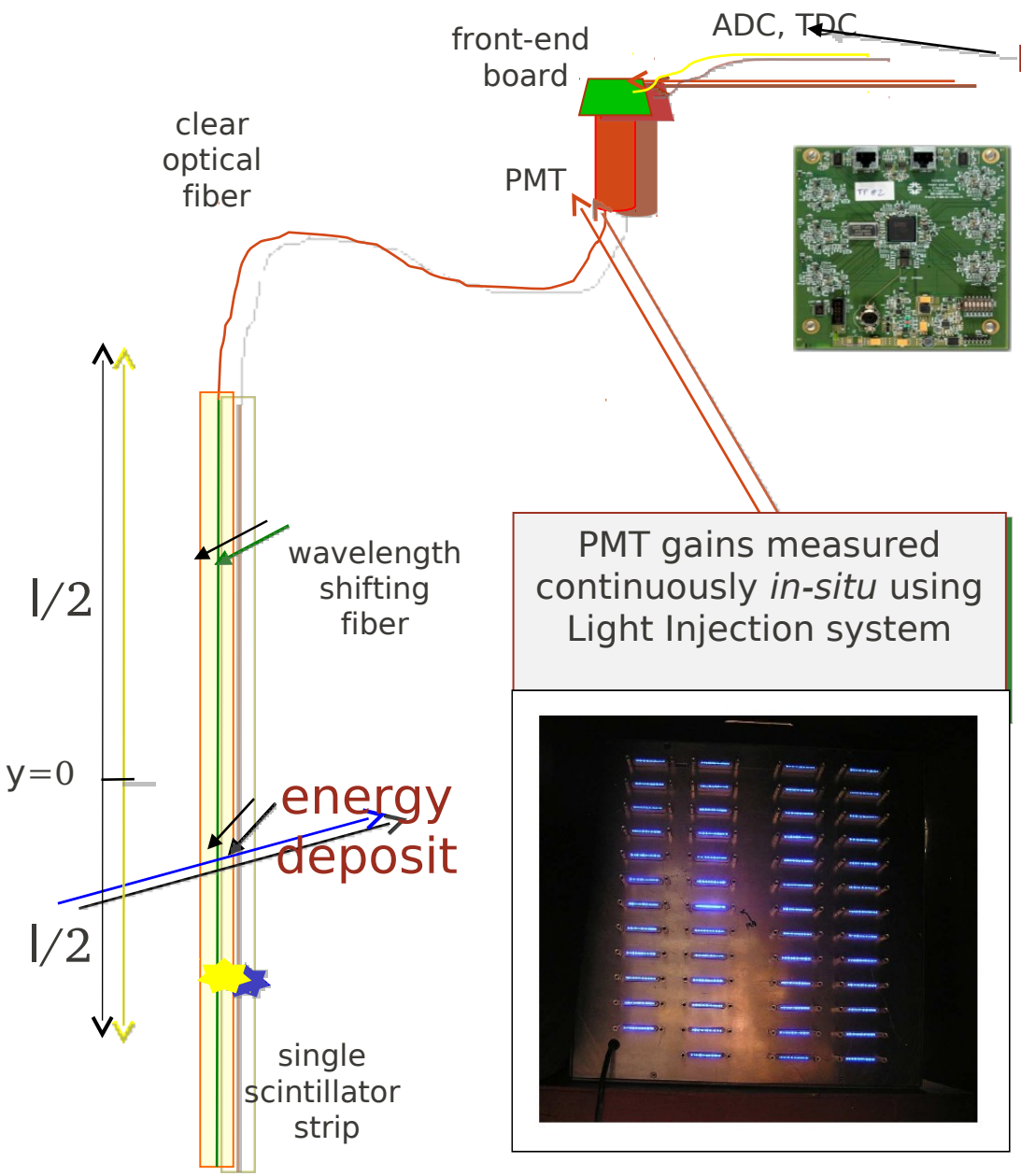
Using monitors

○ Data — Monte-Carlo - - - Tuned Monte-Carlo



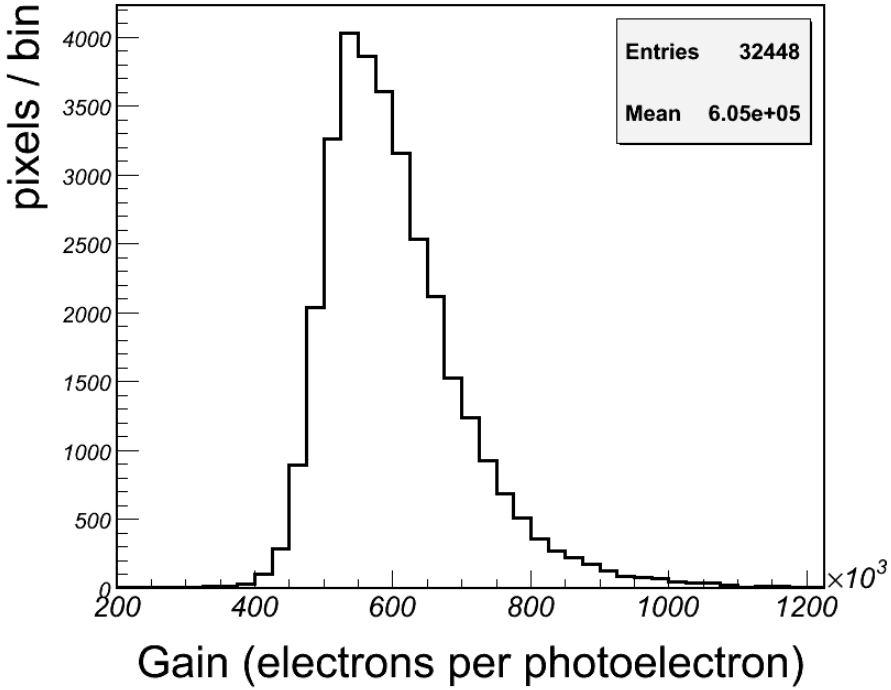


Detector Calibration

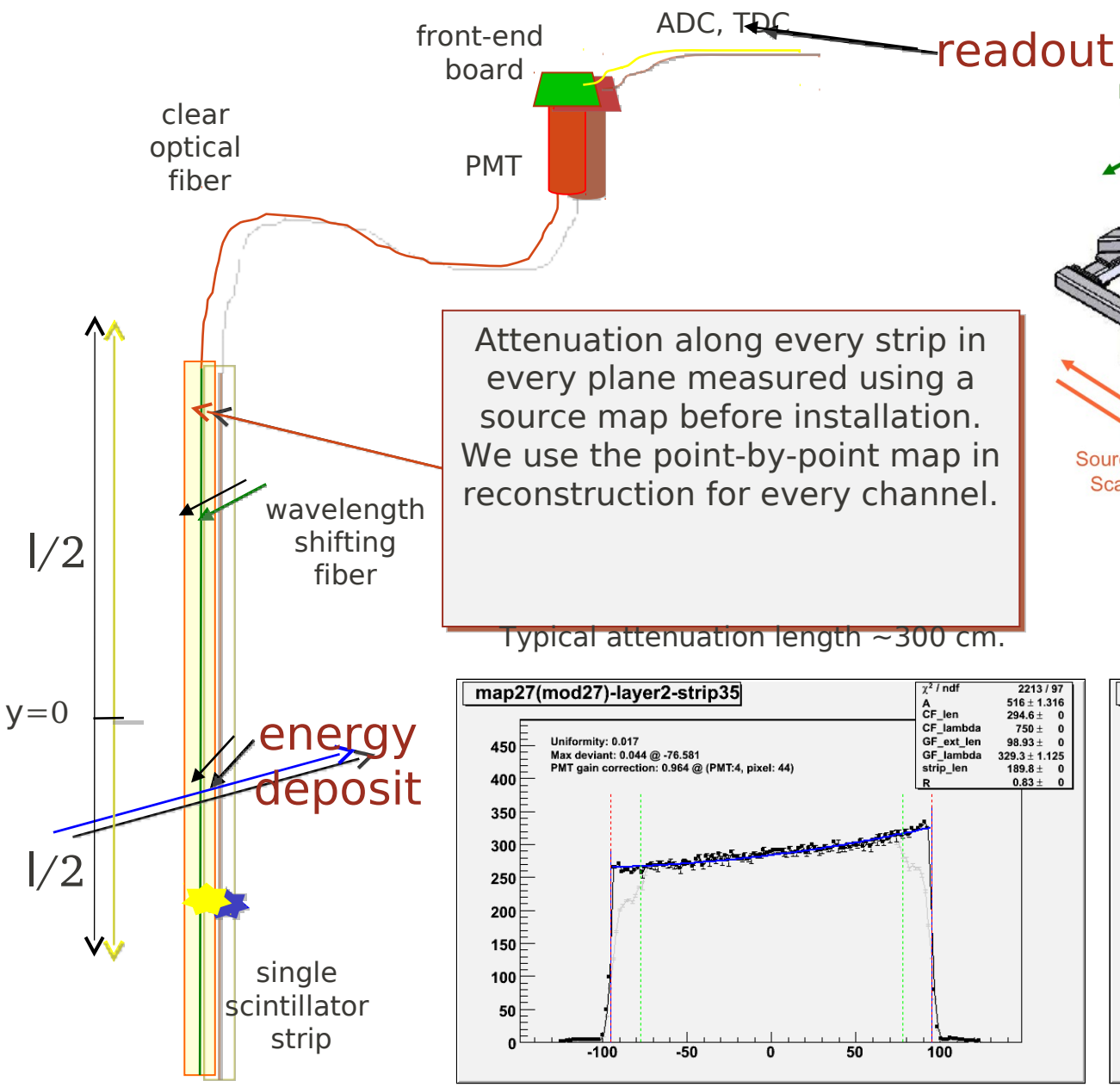


Charge to ADC conversion function measured on a test stand for every channel on every board before installation on the detector

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

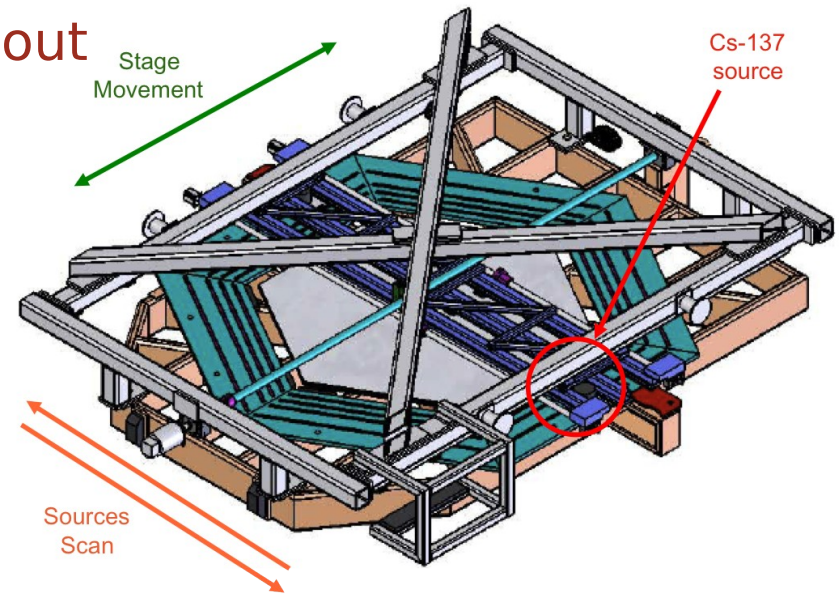


Detector Calibration

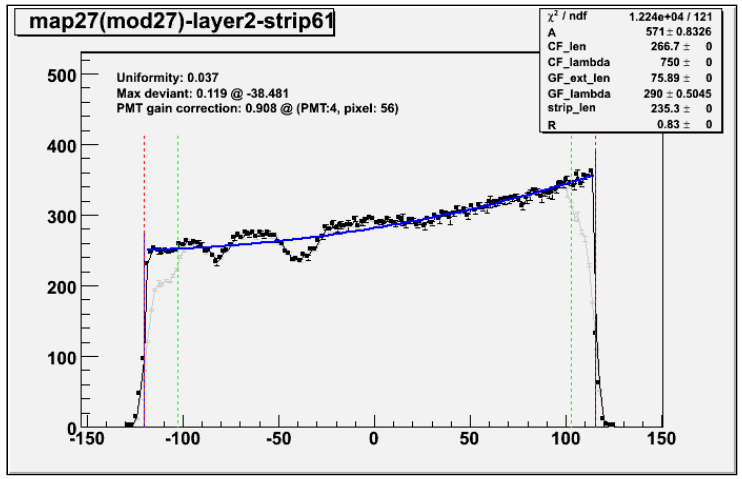


Attenuation along every strip in every plane measured using a source map before installation. We use the point-by-point map in reconstruction for every channel.

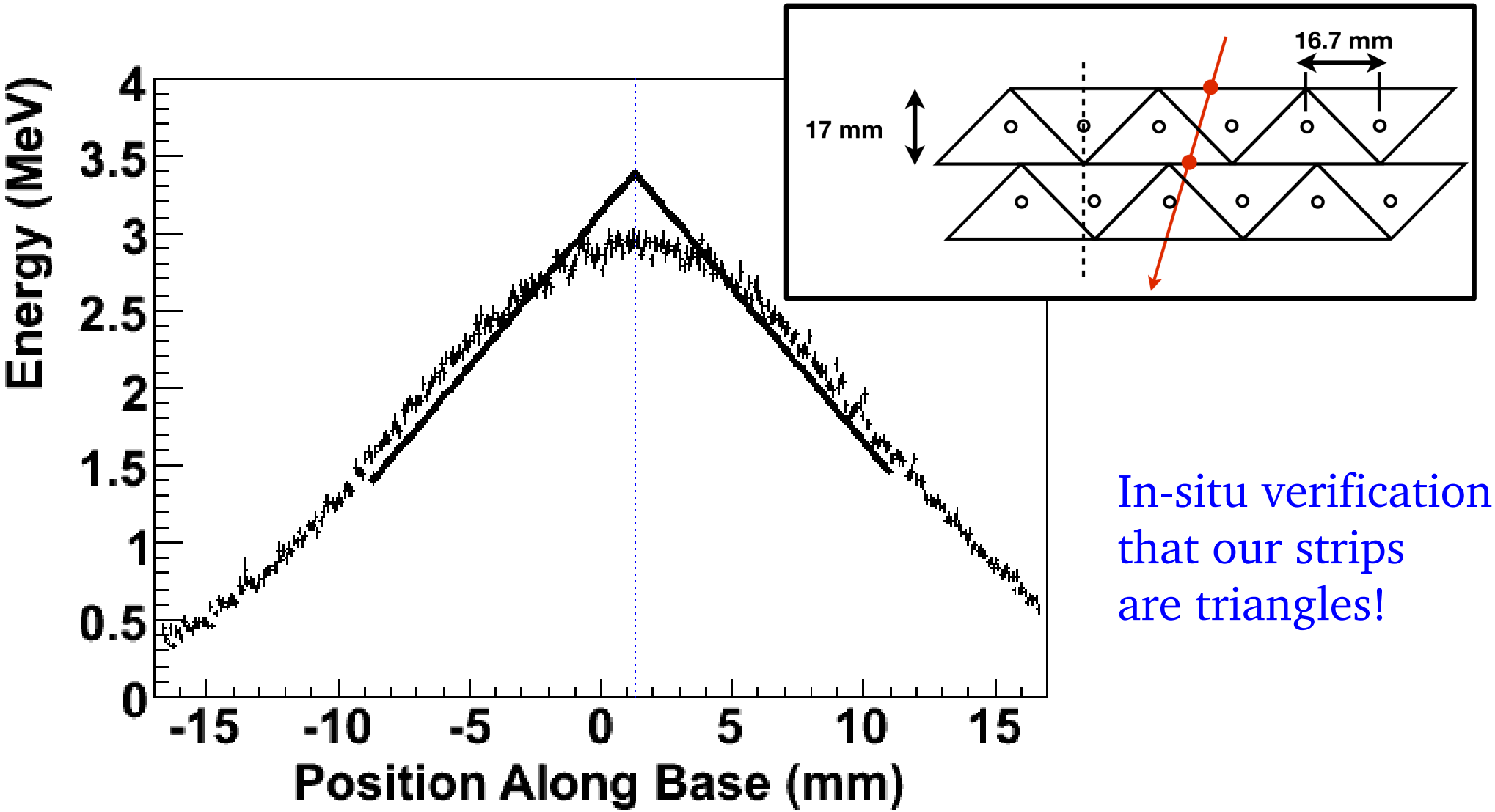
Typical attenuation length ~300 cm.



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



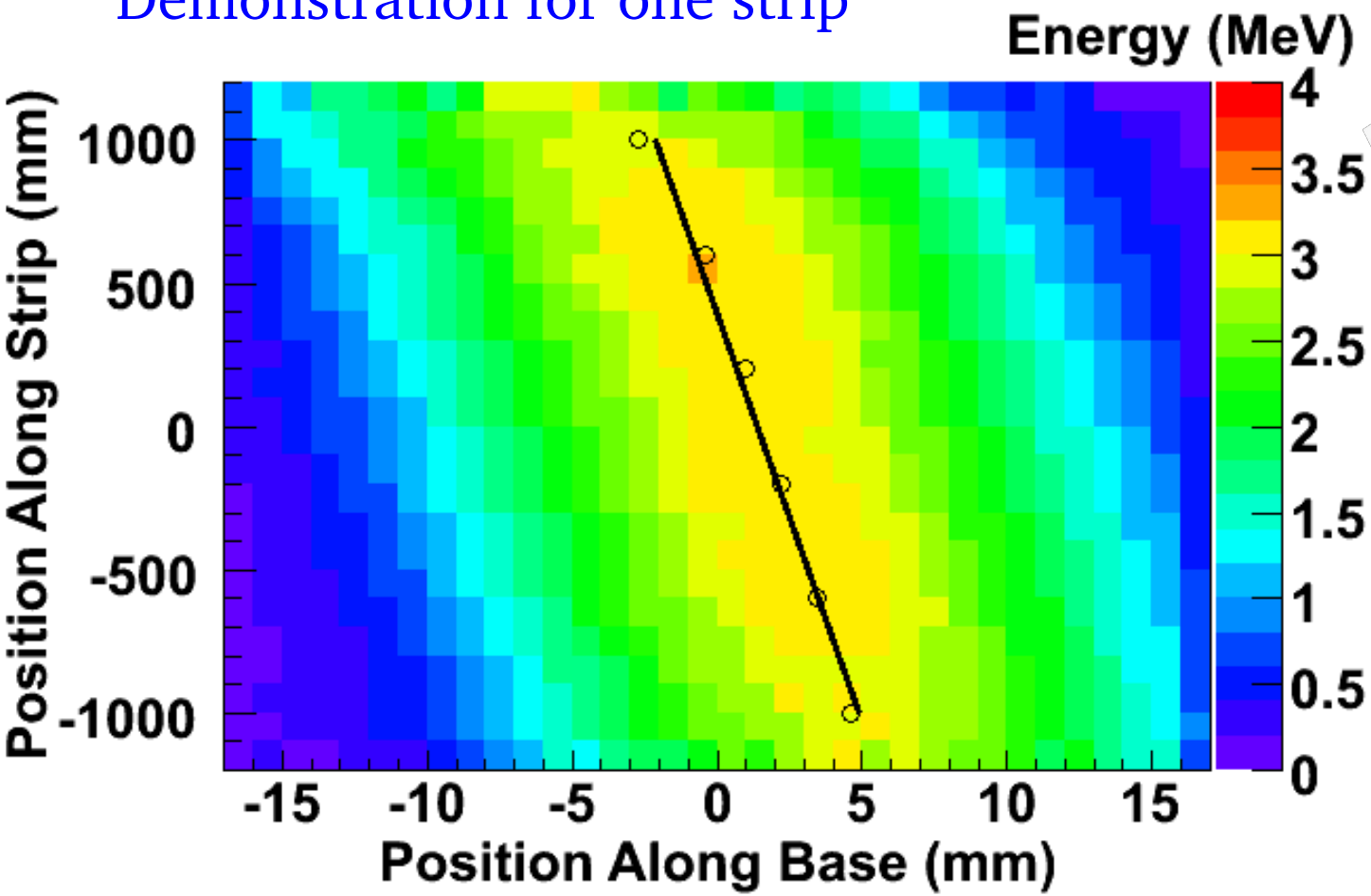
Alignment and strip response

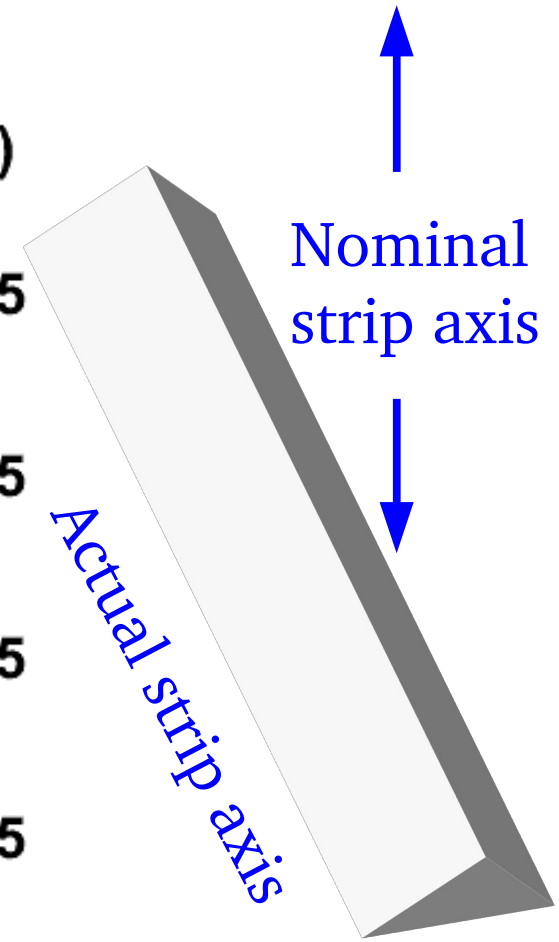


In-situ verification that our strips are triangles!

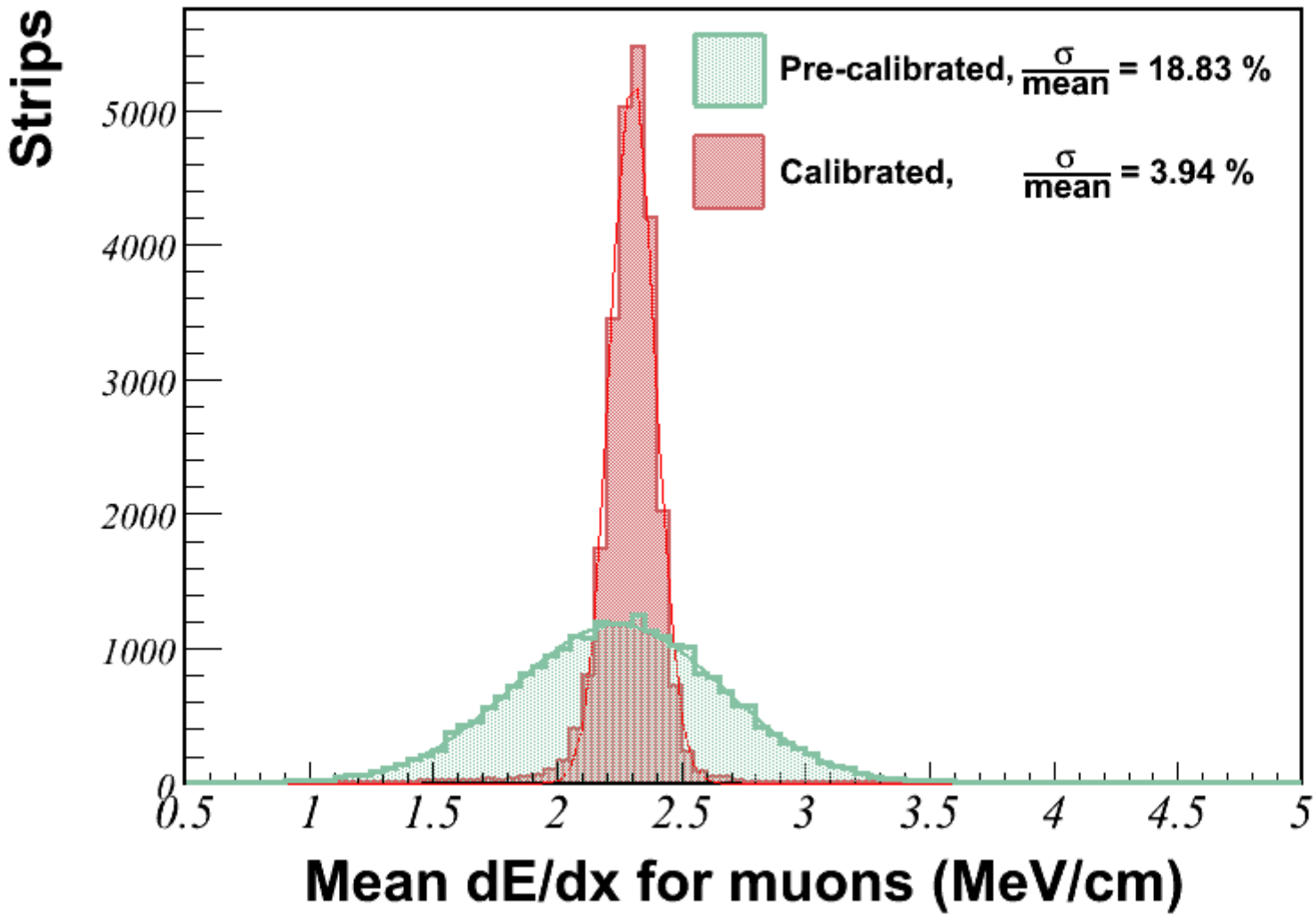
Alignment and strip response

Demonstration for one strip

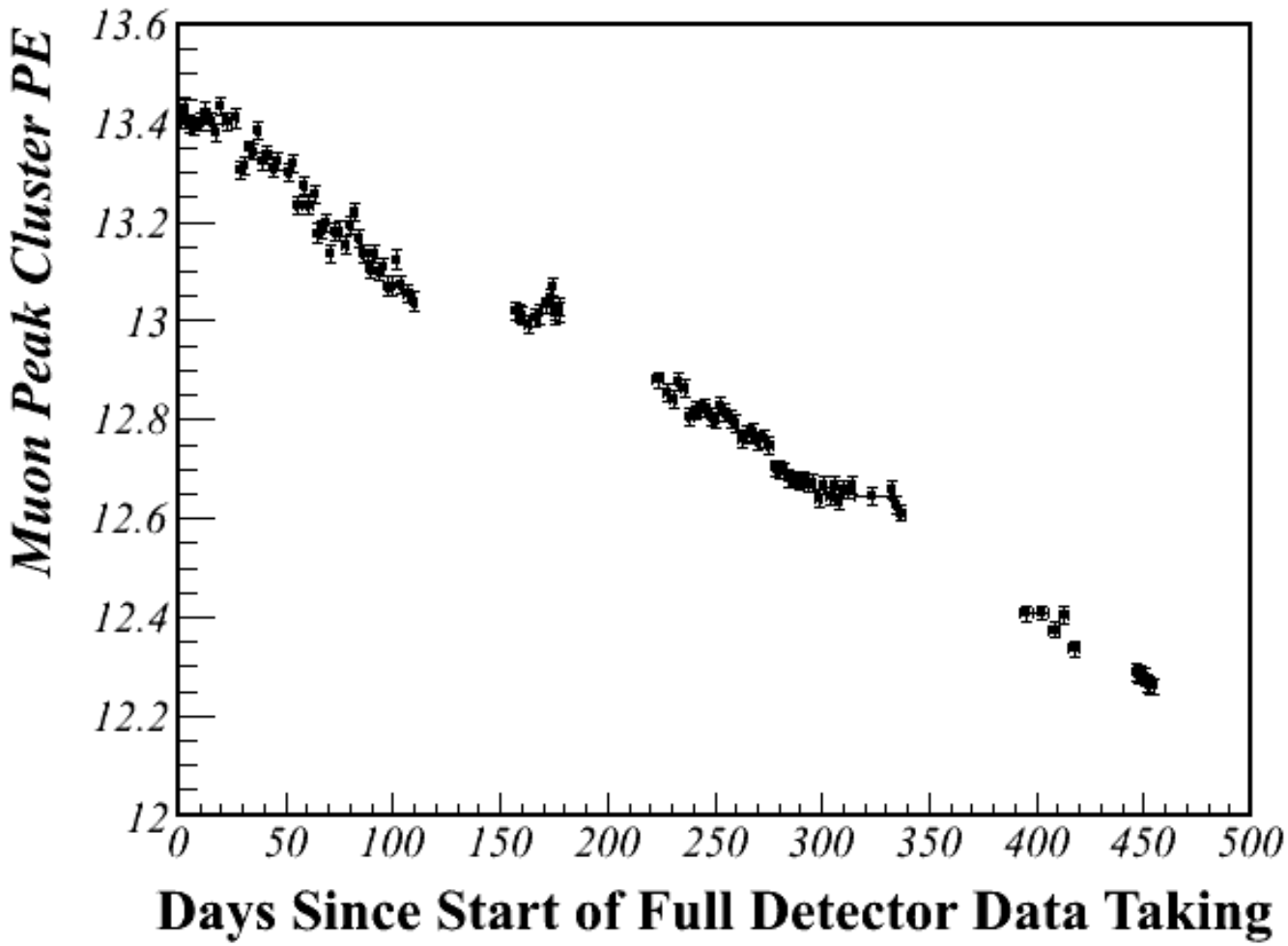




Alignment and strip response



Response vs. Time



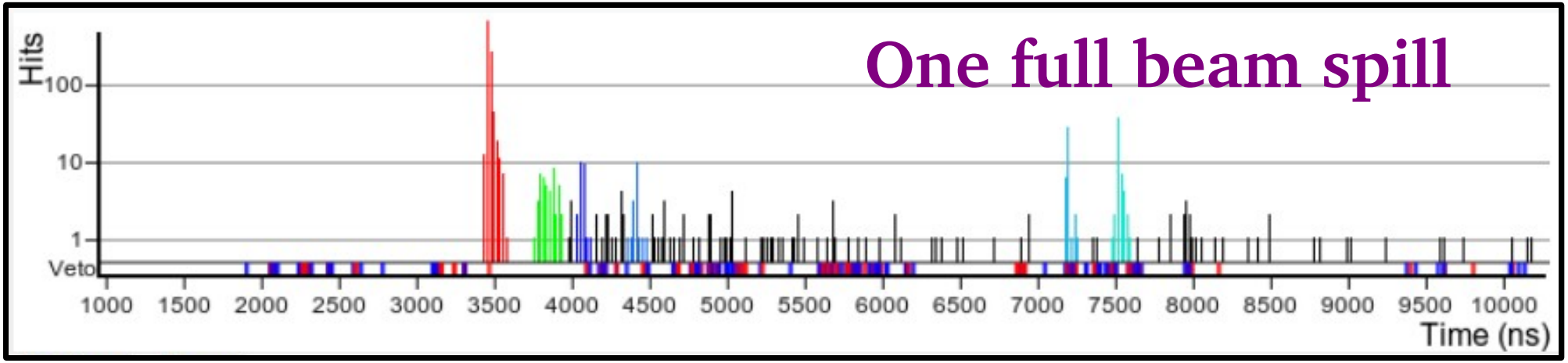
Minerva 1 (days 0-107): light loss = 10.1% per year
Minerva 5 (days 222-335): light loss = 7.1% per year

Thank you for the beam!

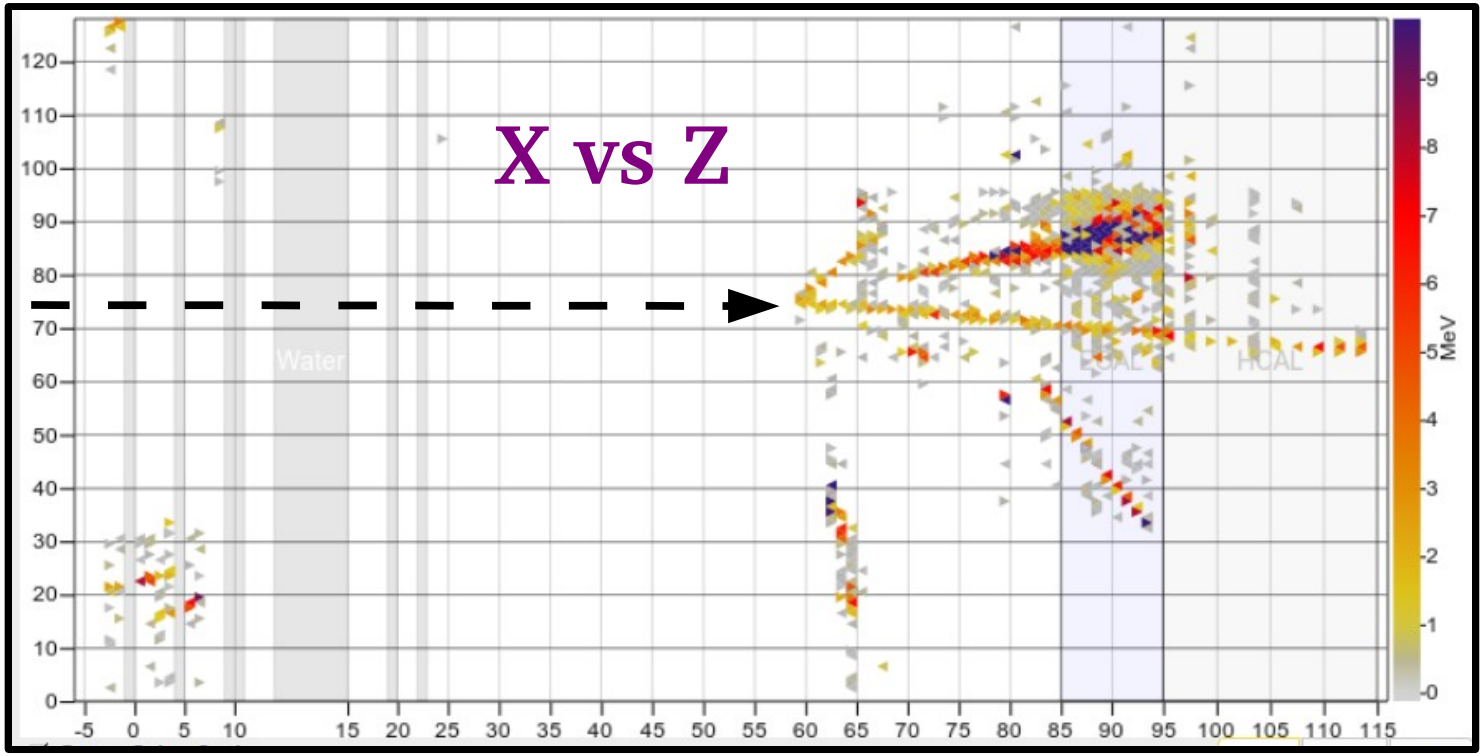
From 3/22/2010	nu	nub	total
nu -LE	3.98E+20		
nu-0 current	7.38E+18		
nu-ME	1.47E+19		
nu-HE	8.15E+18		
nub-LE		1.70E+20	
nub-ME		1.92E+19	
Total Special	3.02E+19	1.92E+19	4.94E+19
total	4.29E+20	1.89E+20	6.18E+20
He Filled	1.90E+20		
He Empty	5.50E+19		
Water Target	1.96E+20		

Livetime: 97.2% MINERvA, 93.3% MINOS ND (3/22/10 – end of run)

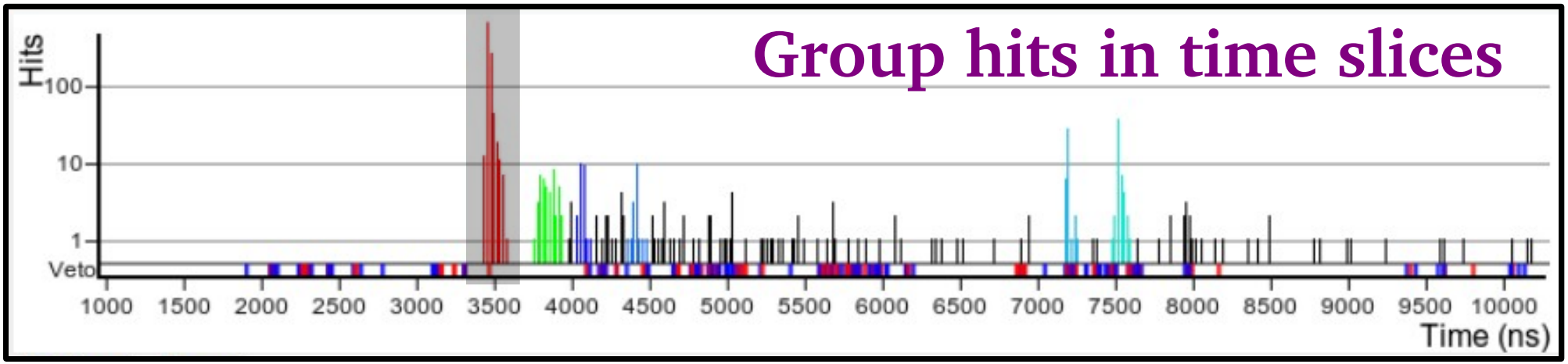
Event reconstruction

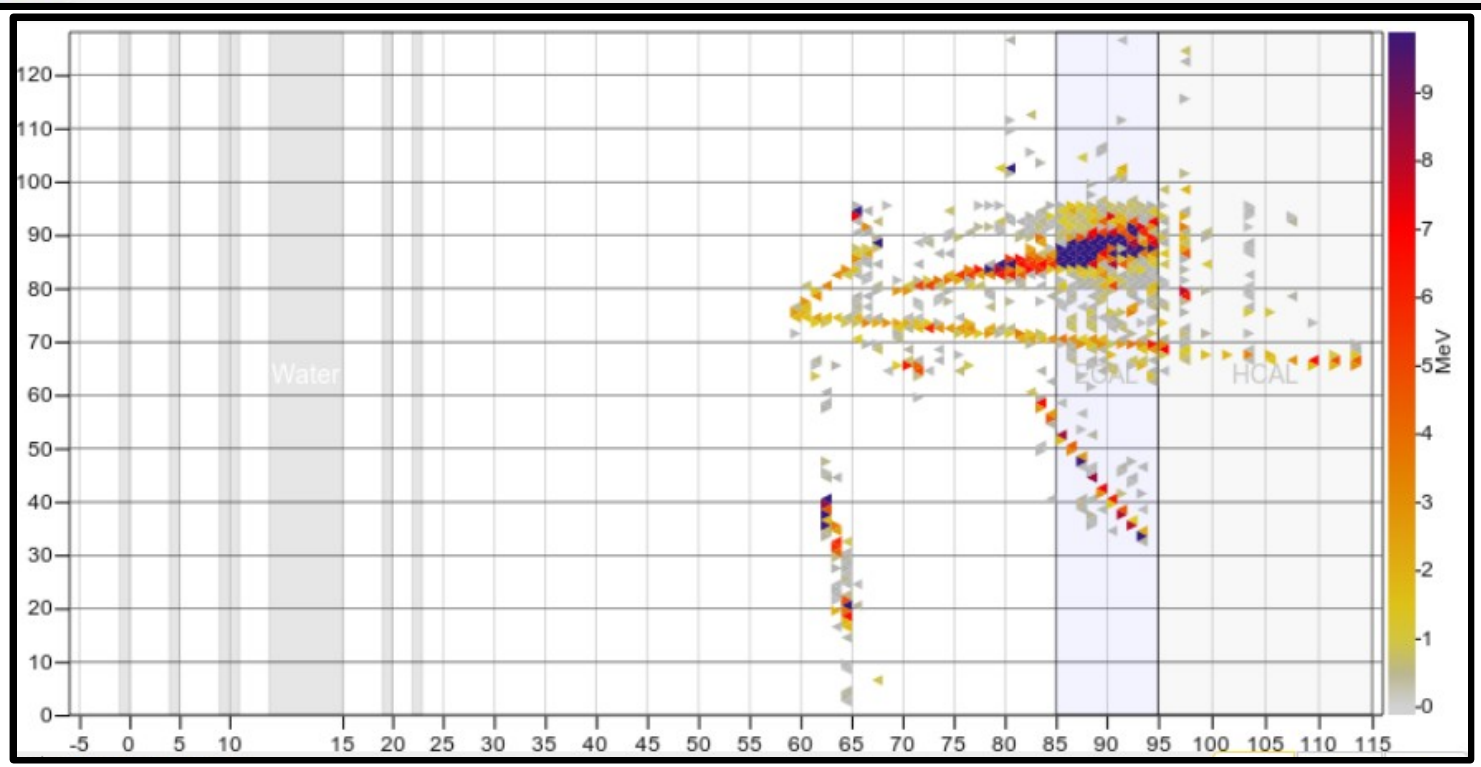


ν_μ

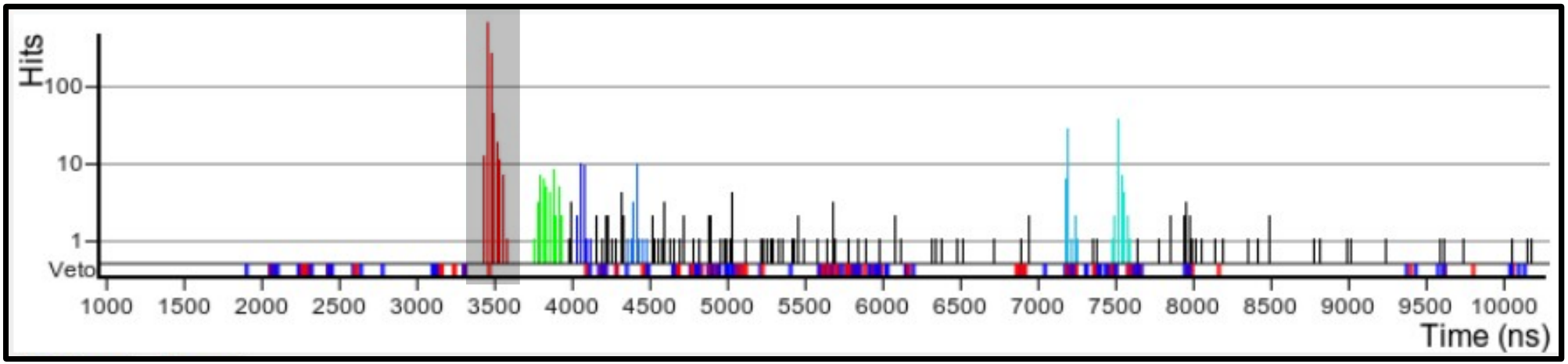


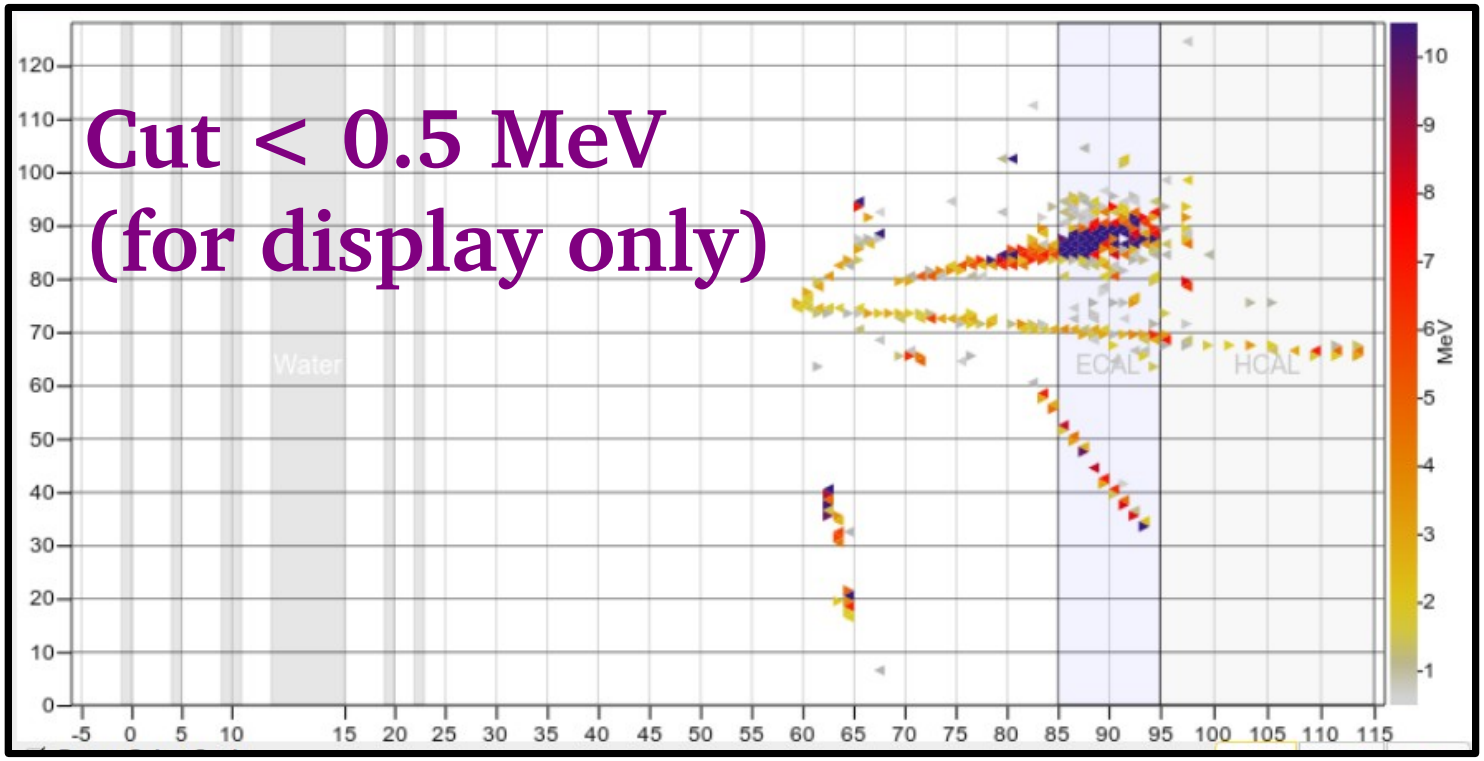
Event reconstruction



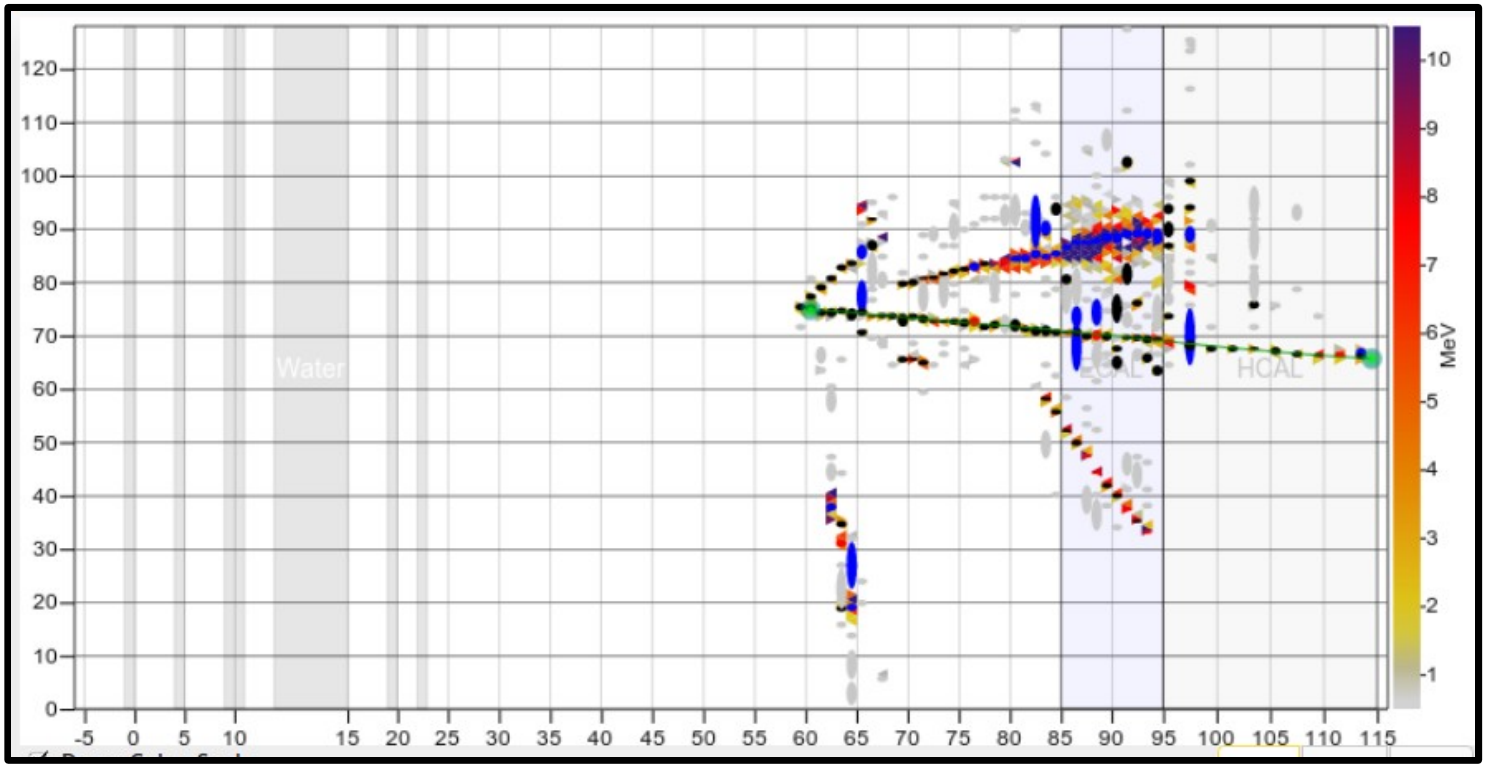


Event reconstruction





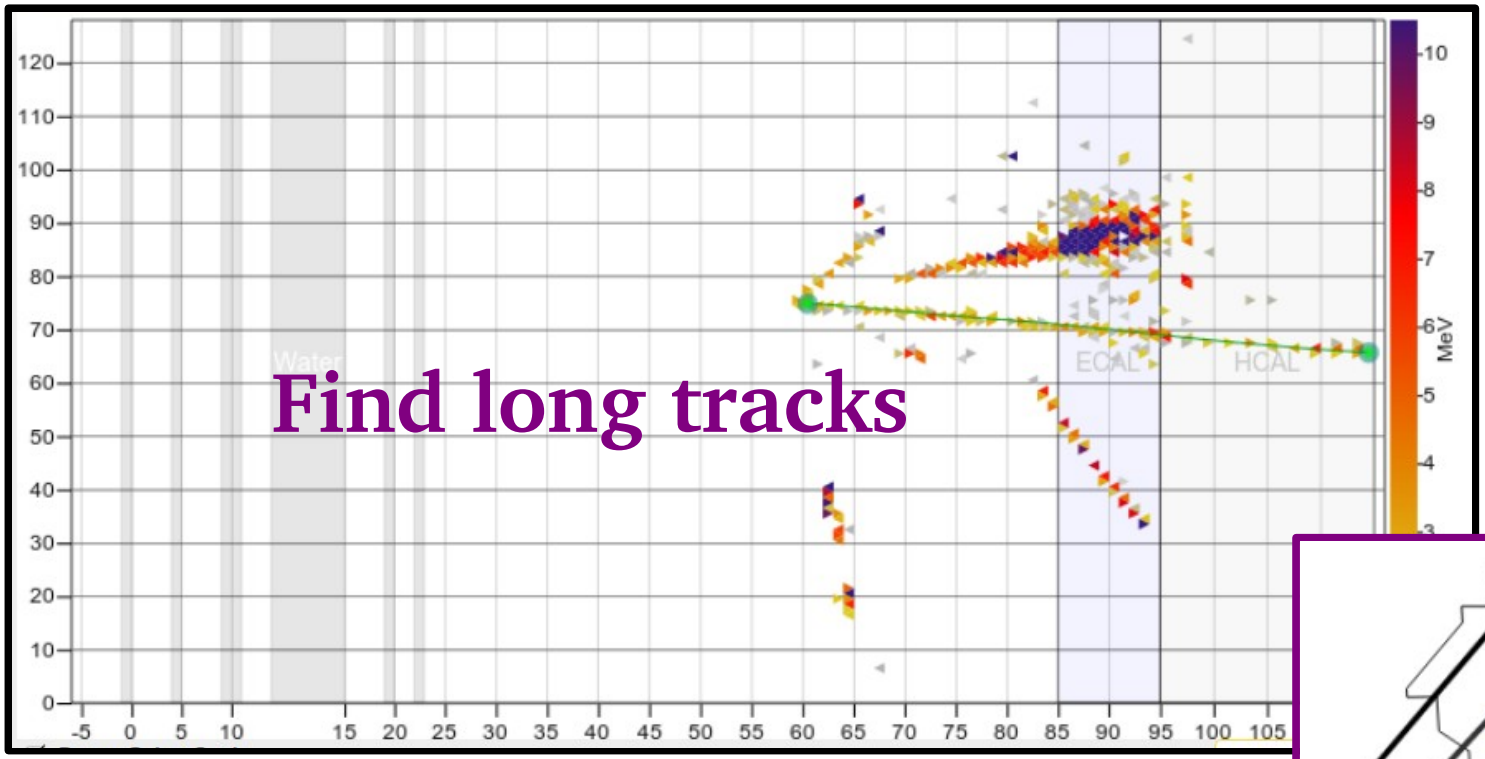
Event reconstruction



Form clusters to aid pattern recognition

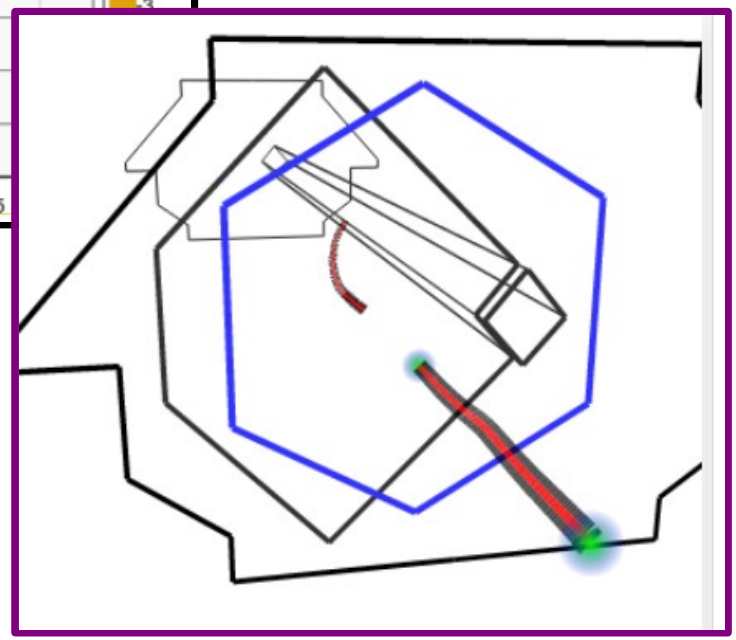
black=track-like, blue=shower-like, gray=low activity

Event reconstruction



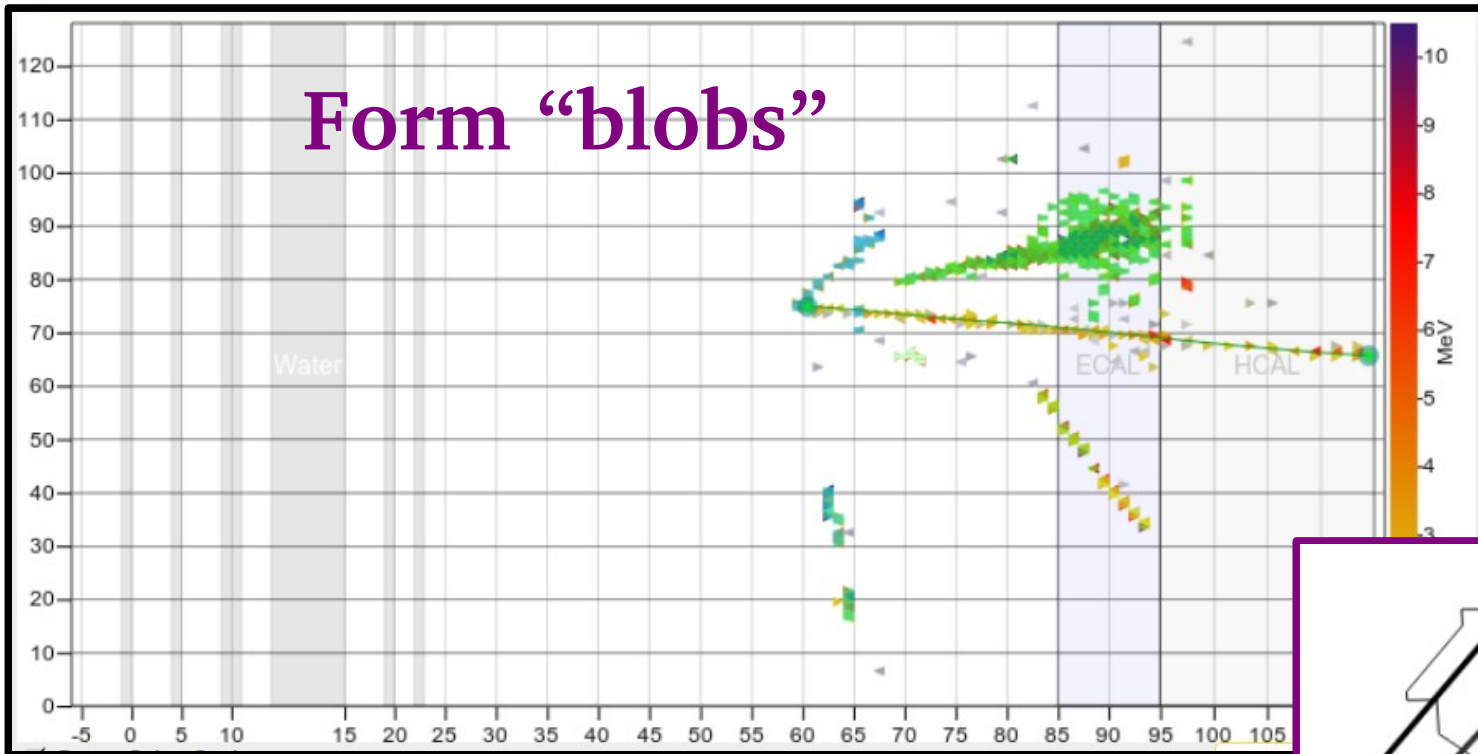
Find long tracks

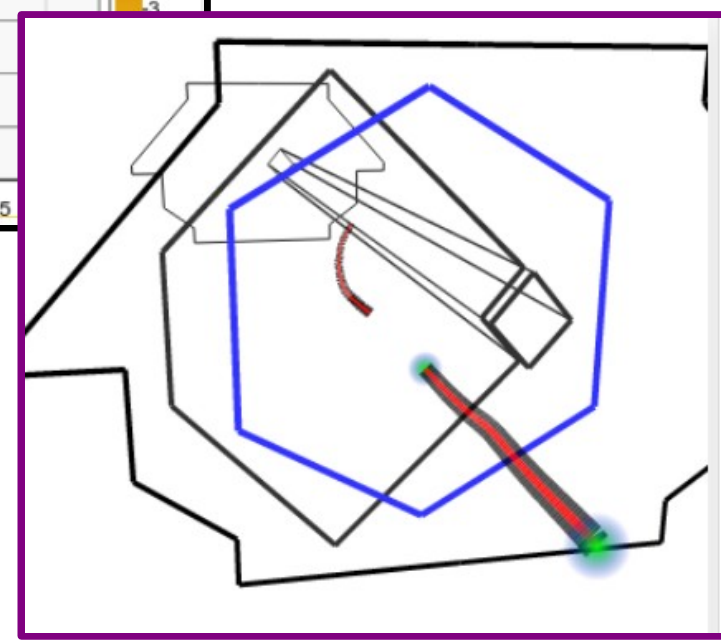
Match to MINOS



Use MINOS matched μ to define event vertex

Event reconstruction





<u>Reconstructed objects</u>

MINOS tracks, other tracks, vertices, endpoints, blobs