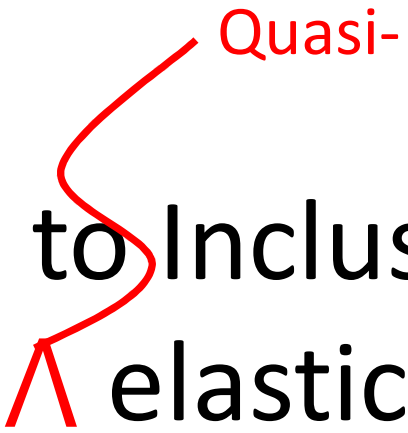
From Exclusive to Inclusive and Back Again: The Most Elastic Interactions of Neutrinos At MINERvA

Daniel Ruterbories, for the MINERvA collaboration

Fermilab Joint Experimental-Theoretical Physics Seminar

March 3rd 2017



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Road Map

Some of the BIG questions

δ_{cp} , ν mass hierarchy

Where cross sections play a role

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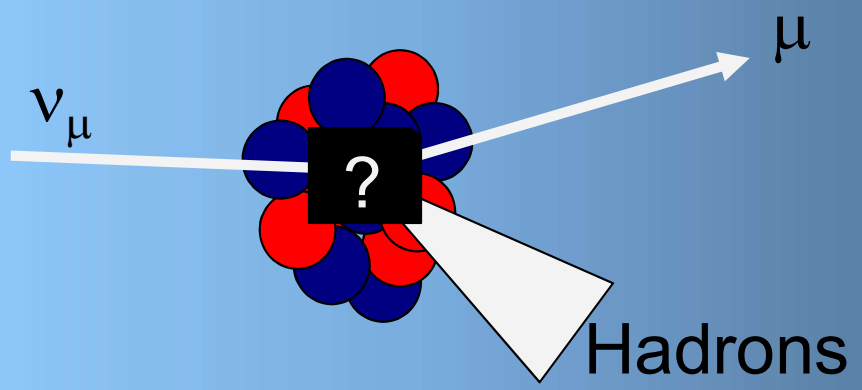
Simulating the nucleus and interactions with neutrinos



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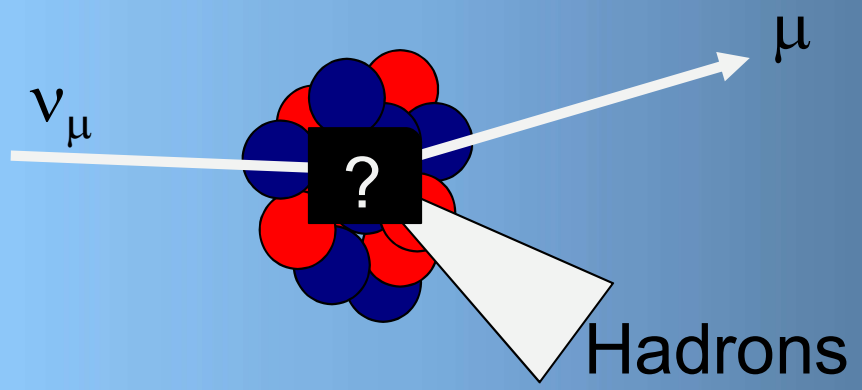

Previous MINERvA quasi-elastic (QE) and inclusive results

What did we learn?

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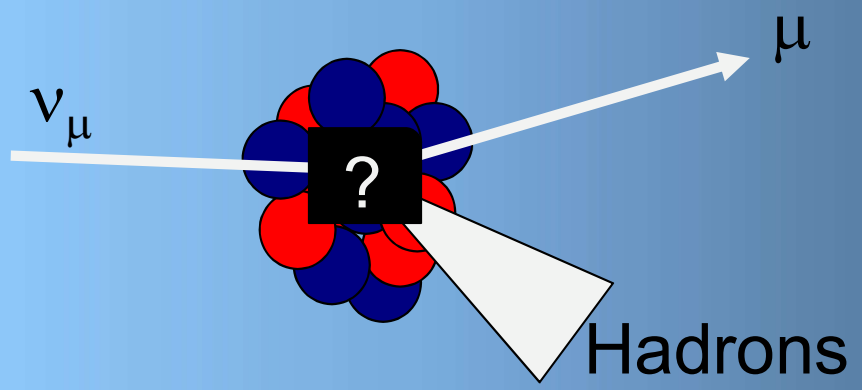

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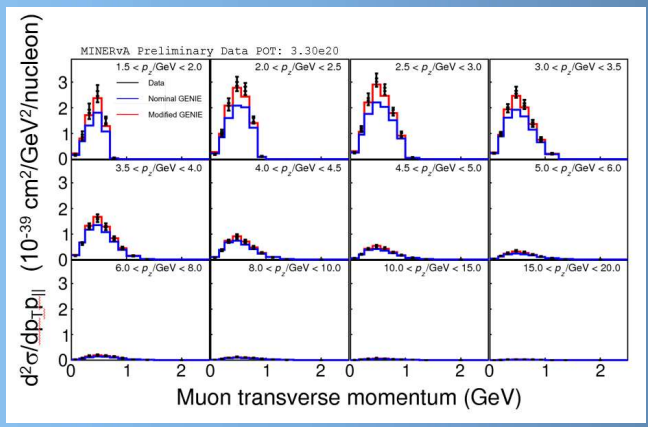
What did we learn?

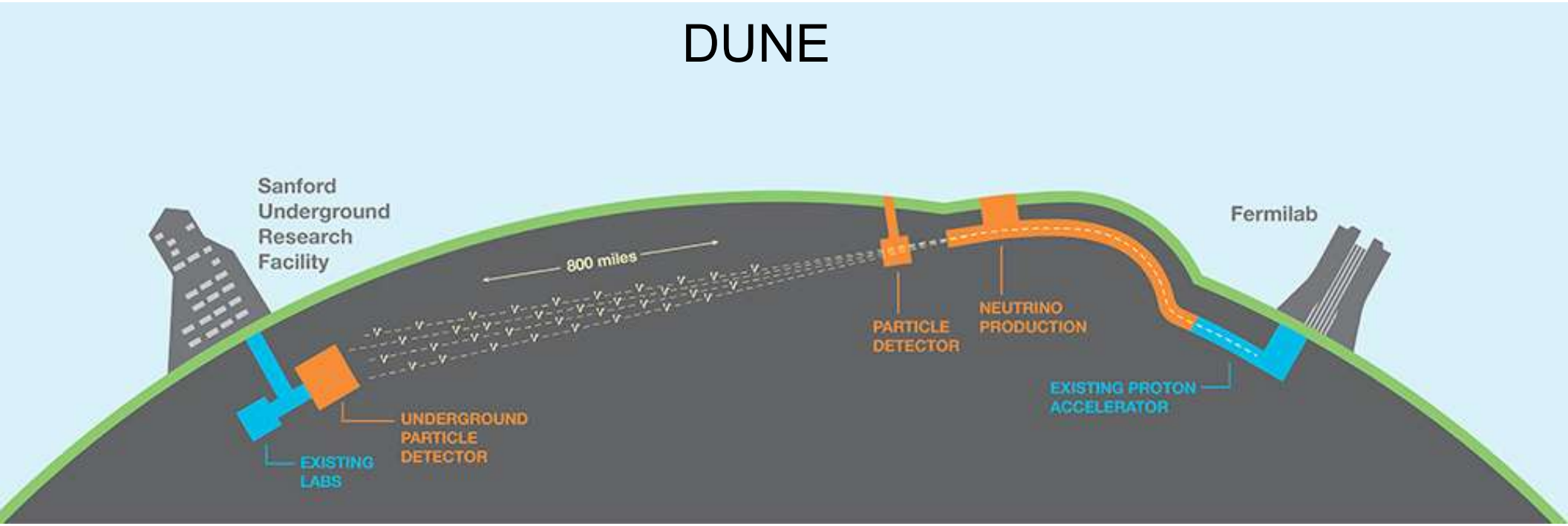
New result today!



Neutrino Oscillations and big questions

- Do neutrinos violate CP?
- Contribution to the baryon asymmetry seen in the universe.

DUNE



http://www.dunescience.org/

What do you need?

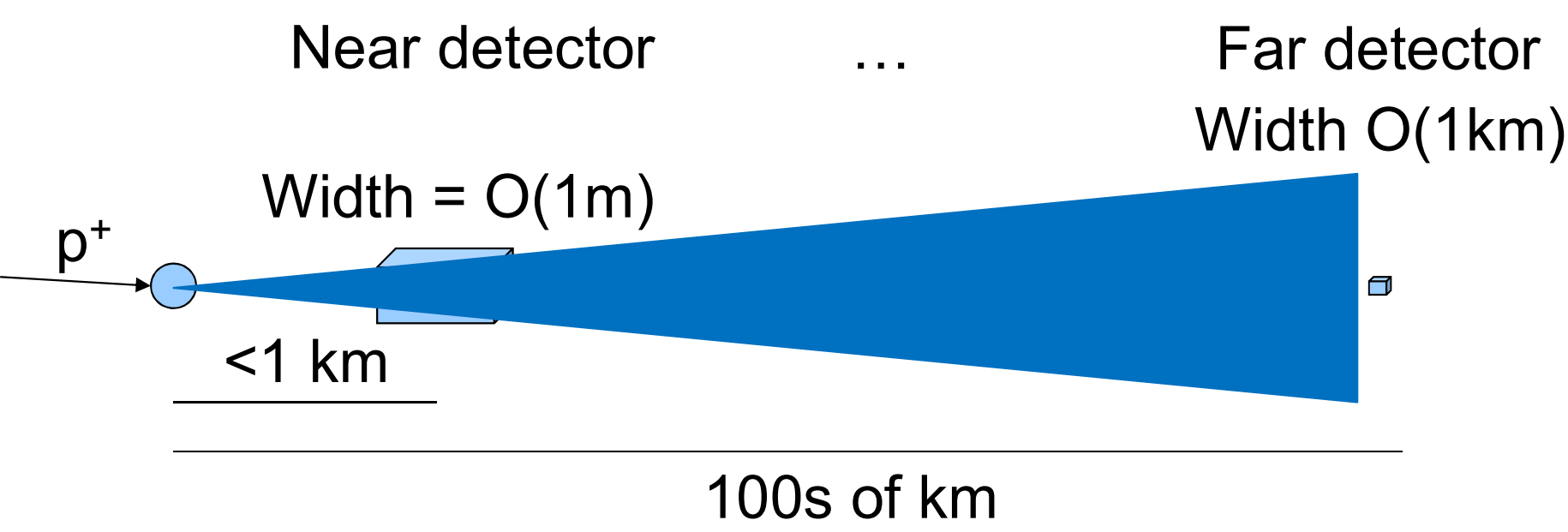
$$P(\nu_\alpha \to \nu_\beta) \approx 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{E_\nu}\right)$$

First and foremost you need an accurate measure of the rate

$$N = \Phi\sigma$$

Ingredients:

1. Flux predictions
   - Different between the near and far detector



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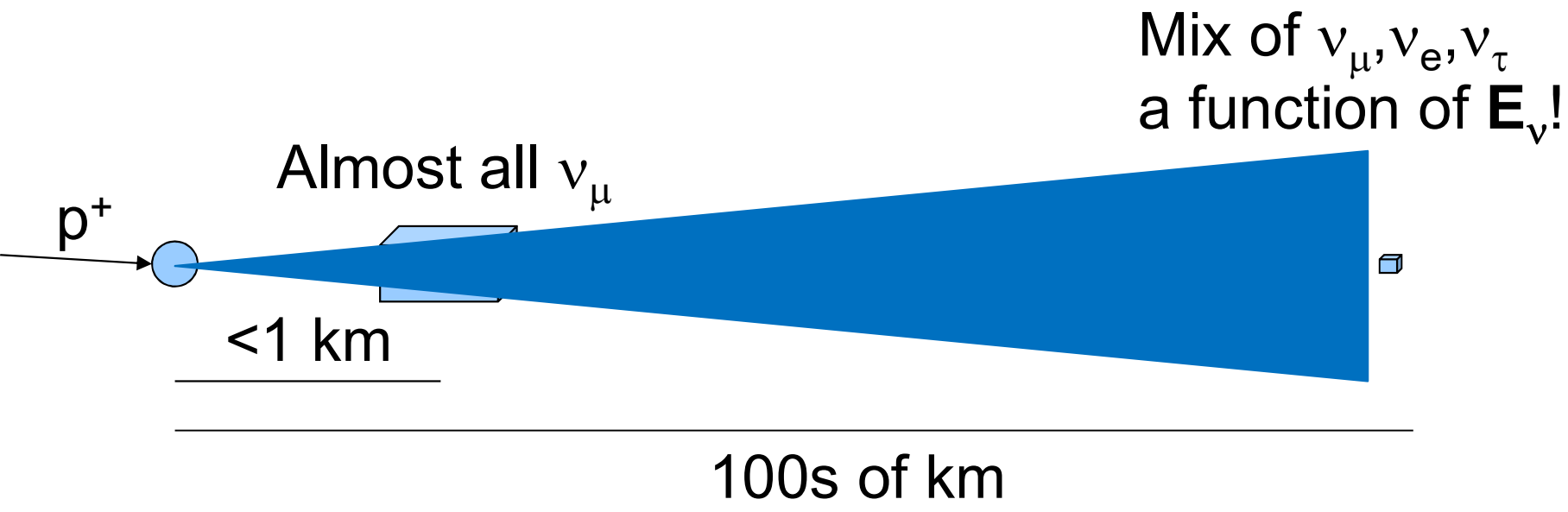

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$$N = \Phi\sigma$$

Ingredients:

2. Precise cross sections of background and signal processes

TABLE IV. Percentage change in the number of one-ring μ-like events before the oscillation fit from 1σ systematic parameter variations, assuming the oscillation parameters listed in Table III and that the antineutrino and neutrino oscillation parameters are identical.

Source of uncertainty (number of parameters)	$\delta n_{\mathrm{SK}}^{\mathrm{exp}} / n_{\mathrm{SK}}^{\mathrm{exp}}$ (%)
ND280-unconstrained cross section (6)	10.0
Flux and ND280-constrained cross section (31)	3.4
Super-Kamiokande detector systematics (6)	3.8
Pion FSI and reinteractions (6)	2.1
Total (49)	11.6

T2K Uncertainties
PRL 116, 181801 (2016)

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First and foremost you need an accurate measure of the rate

$$N = \Phi\sigma$$

Ingredients:

3. Precise understanding of acceptance

Is your model only constrained by a 2π detector and you have a 4π detector?

What do you need?

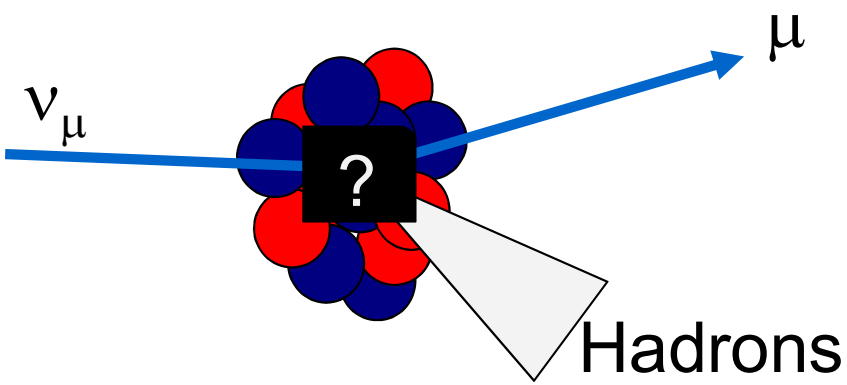
$$P(\nu_\alpha \to \nu_\beta) \approx 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{E_\nu} \right)$$

First and foremost you need an accurate measure of the rate

$$N = \Phi\sigma$$

Ingredients:

3. Nuclear effects and A-dependence?



What do you need?

$$P(\nu_\alpha \to \nu_\beta) \approx 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{E_\nu} \right)$$

First and foremost you need an accurate measure of the rate

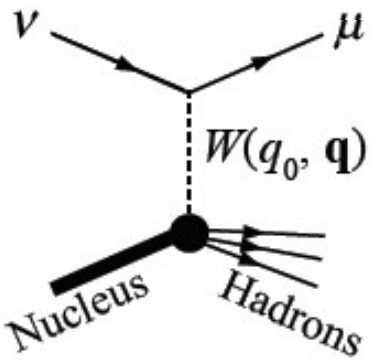
$$N = \Phi\sigma$$

Ingredients:

1) Flux prediction
2) **Precise cross sections of background and signal processes**
3) Precise understanding of acceptance
4) **Nuclear effects** and A-dependence

What else do you need?

$$P(\nu_\alpha \rightarrow \nu_\beta) \approx 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{E_\nu}\right)$$

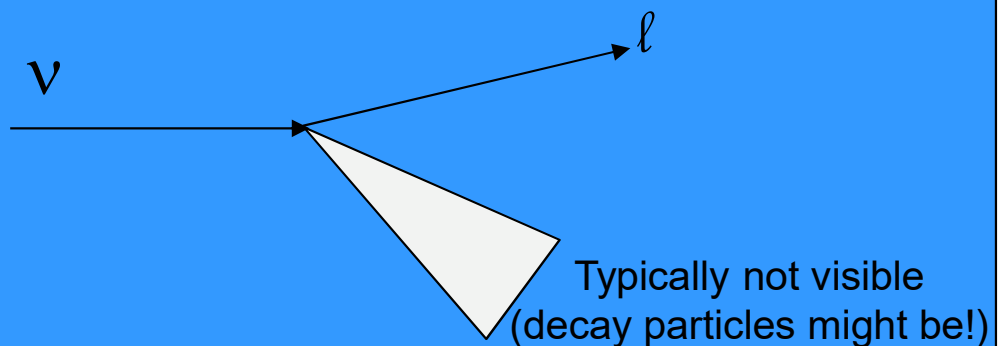


What is $\underline{E}_\nu$?

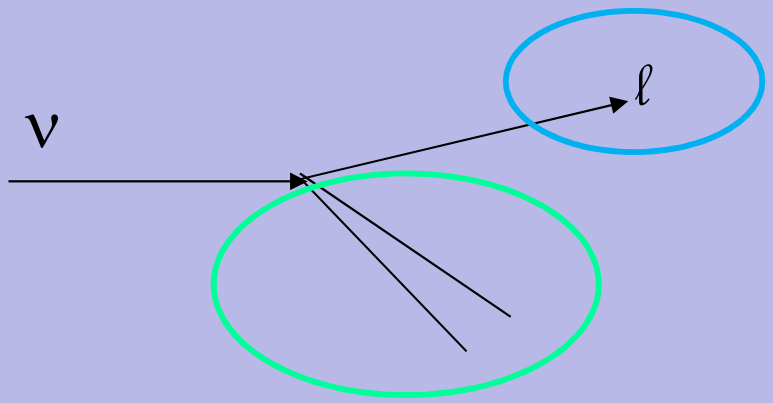
$$E_\nu = E_\mu + E_{hadrons}$$

Cherenkov Detectors

$$E_{\nu,QE} = \frac{M_n^2 - (M_p - E_b)^2 - M_\mu^2 + 2(M_p - E_b)E_\mu}{2(M_p - E_b - E_\mu + P_\mu \cos(\theta_\mu))}$$



"Fully-active" Detectors



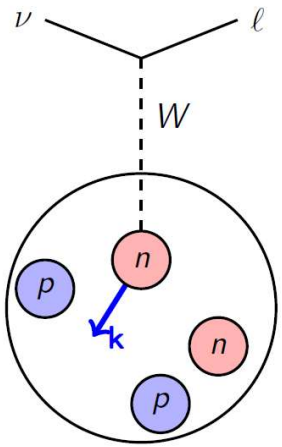
See Kevin McFarland's office

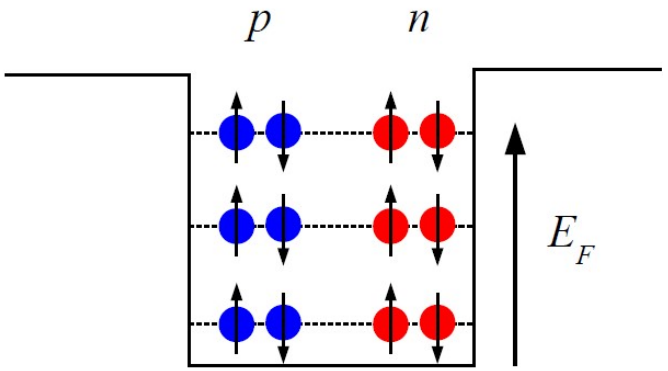
Well, let's break some rules!

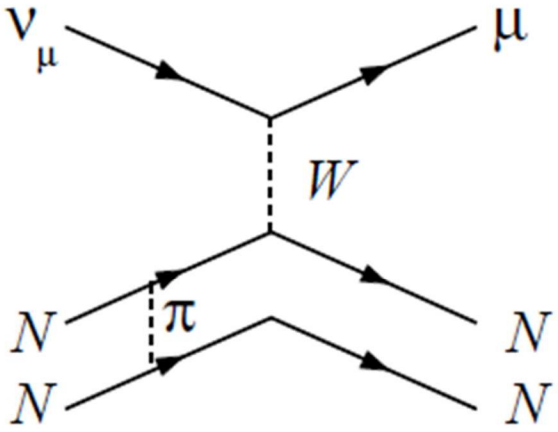
See Kevin McFarland's office

Nucleons are not free and independent particles!

- Bound and definitely not independent from their fellow nucleons
- So what… we simulate the nucleons as a **R**elativistic **F**ermi **G**as (RFG)
  - Quasi-free nucleons in a mean field
  - Includes Fermi motion, binding energy, Pauli Blocking



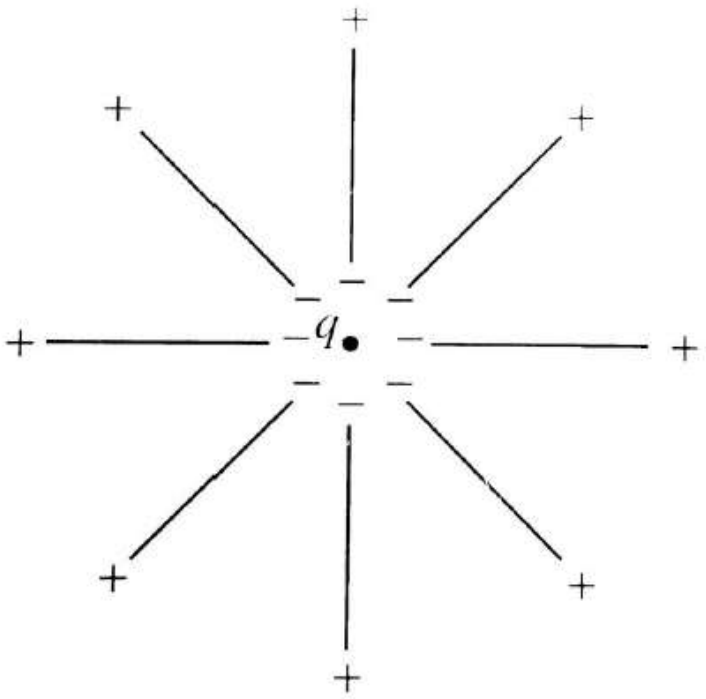




Will refer to the multi-nucleon effects generically as 2p2h

Nuclear Screening

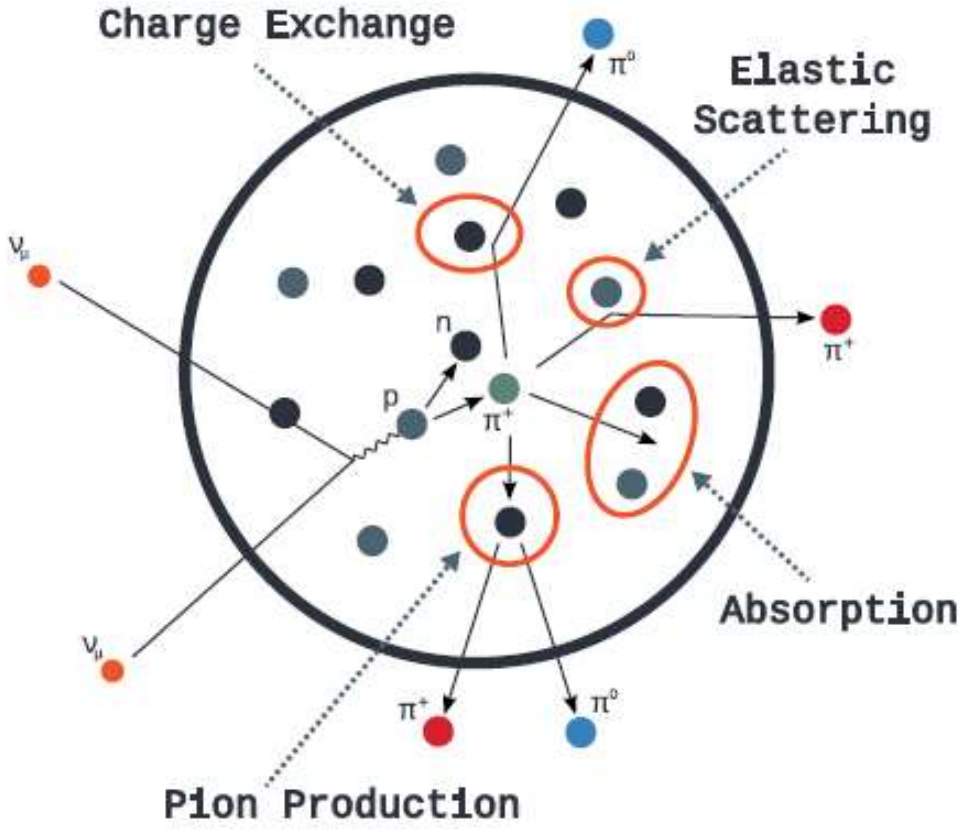
- Polarization of the nucleus screens electroweak coupling of the W



Griffiths, *Introduction to Electrodynamics*

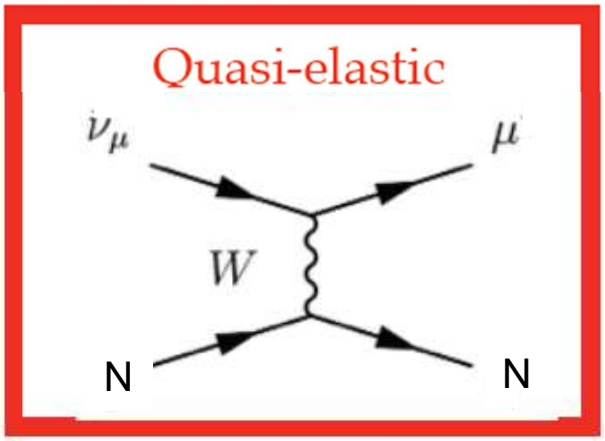
- A common analogy is screening of electric charge in a dielectric
- Calculated using **R**andom **P**hase **A**pproximation (RPA)
- Effect on cross section: Suppression at low four momentum transfer $\mathbf{Q^2}$

Final State Interactions

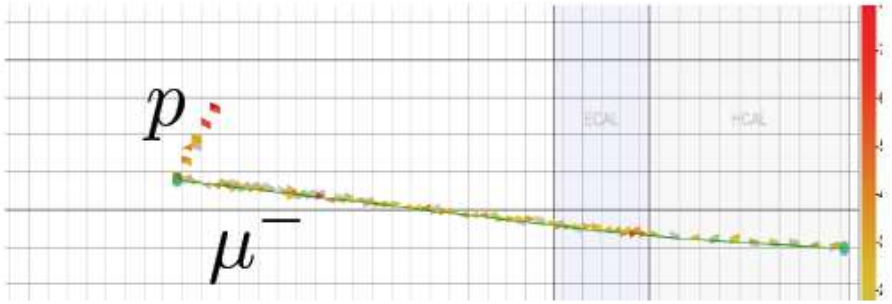


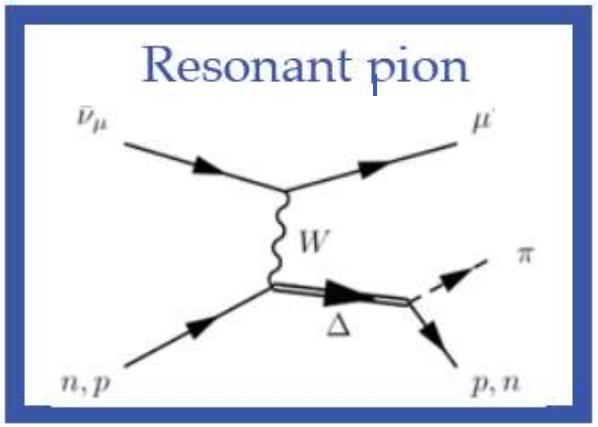
- Signal <–> Background migrations
- Energy sharing between pions and nucleons
- Particles in the detector, and thus energy deposited, is modified

Three General Types of Interactions

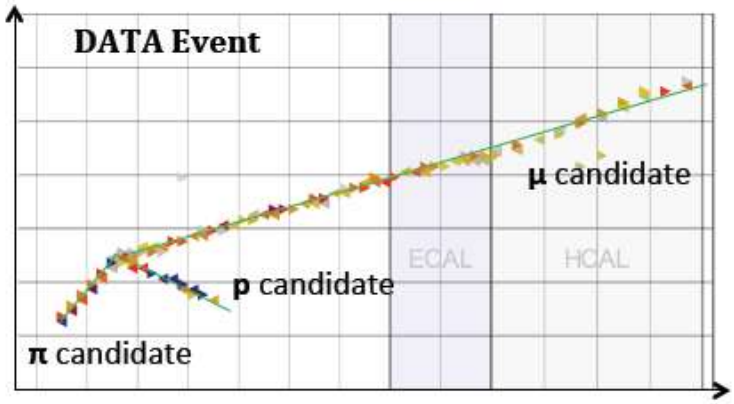


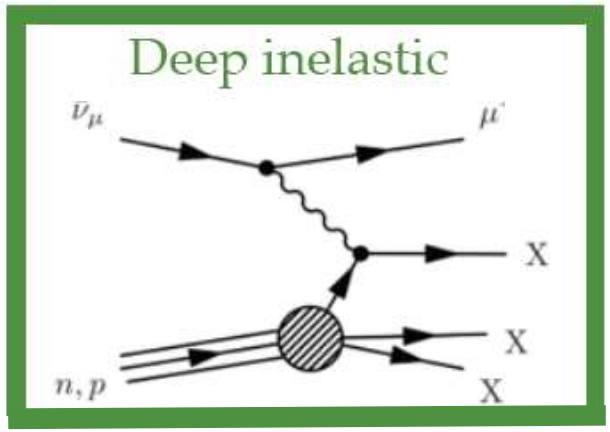
QE



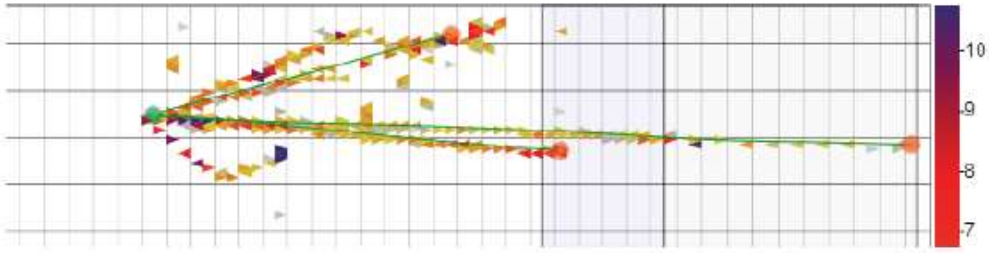


RES





DIS

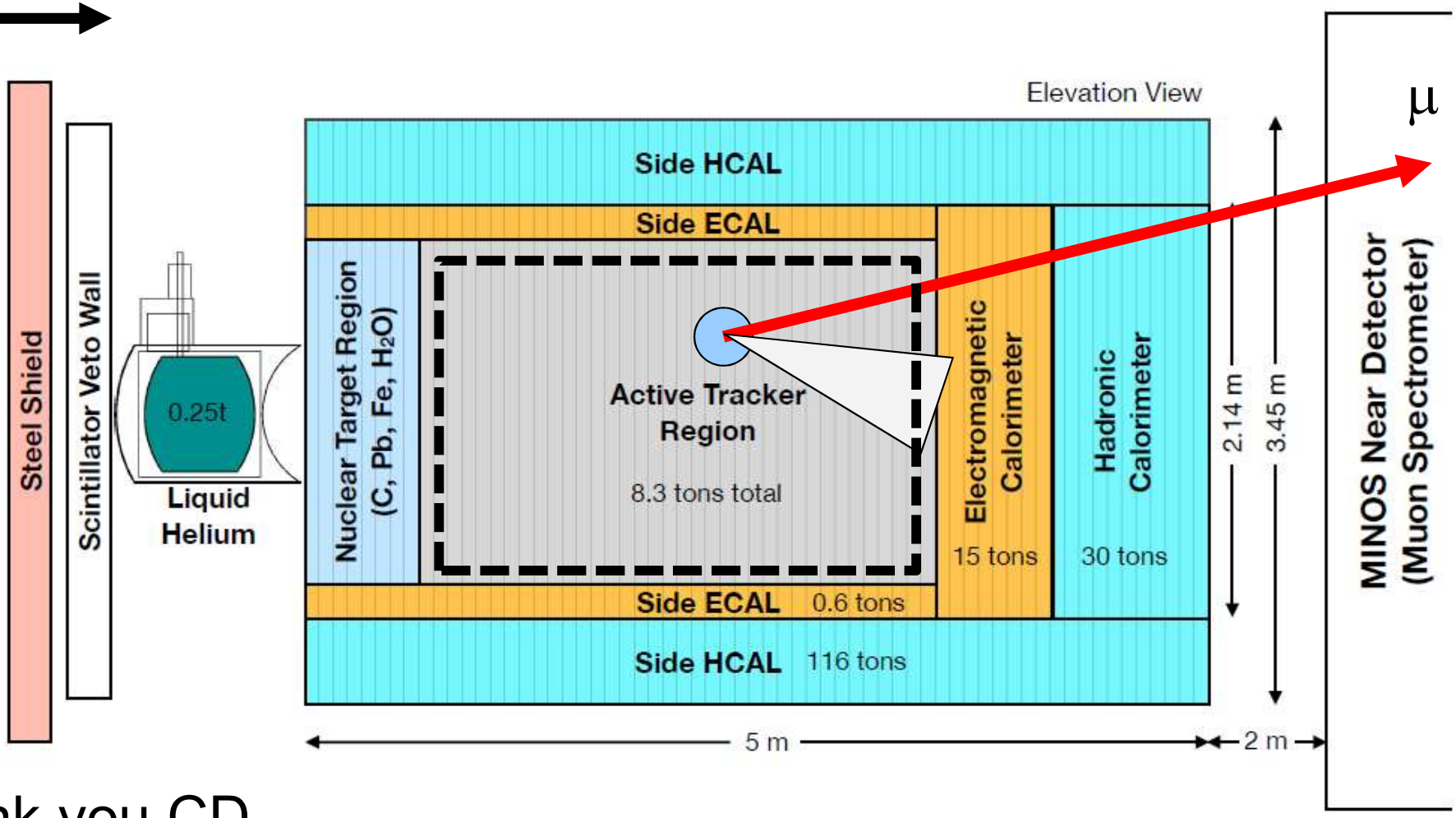


Increasing W

MINERvA Detector

Neutrino Beam
Thanks AD!!

Thanks MINOS
for your near
detector data!!



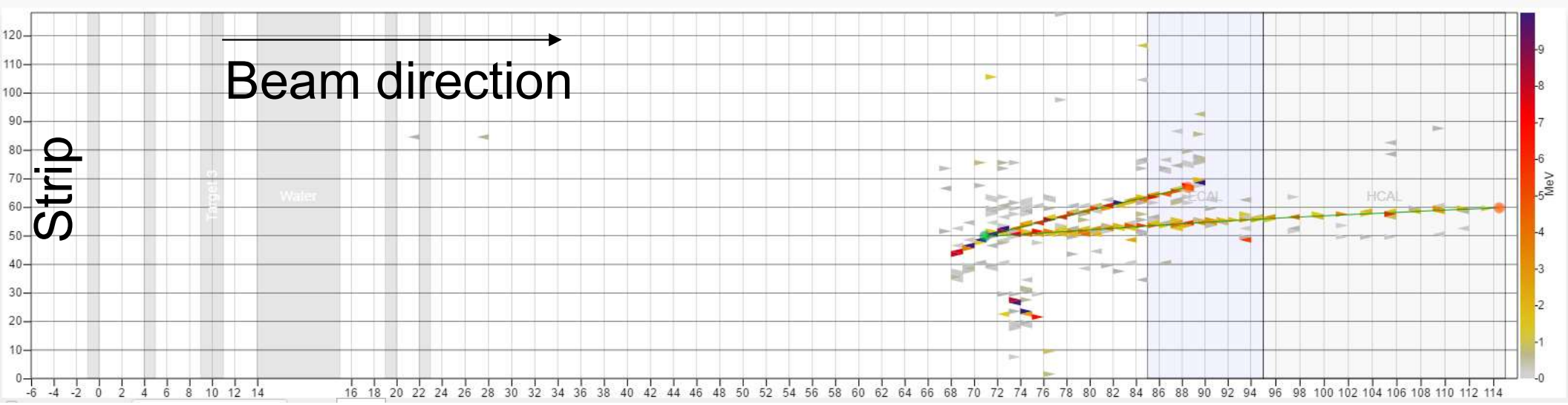
Thank you CD
for the computing
resources!!

What does MINERvA say about quasi-elastic processes?

- Strategy 1 – Use summed hadronic energy

Selection based on cutting out high recoil events

constrain background using the hadronic recoil energy



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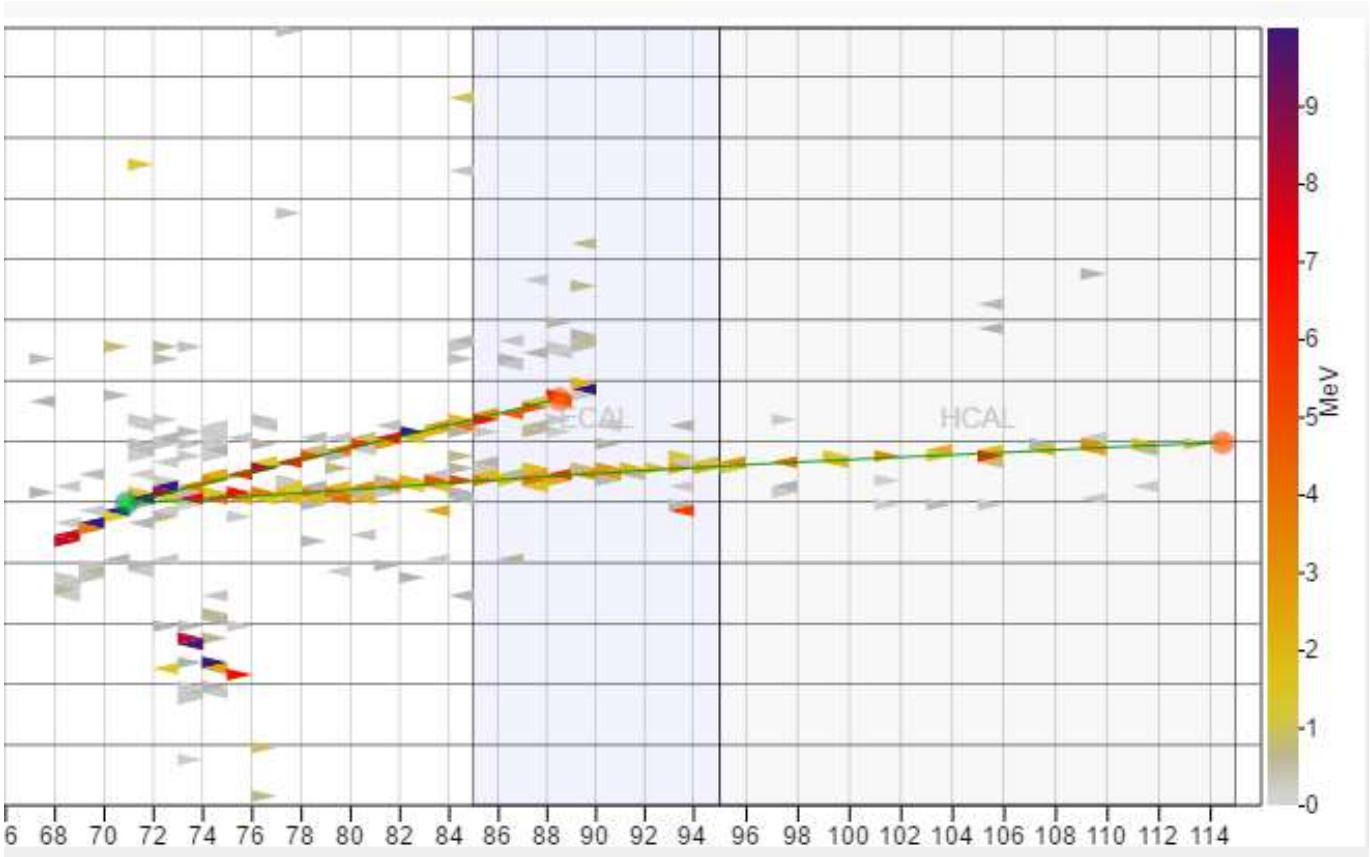

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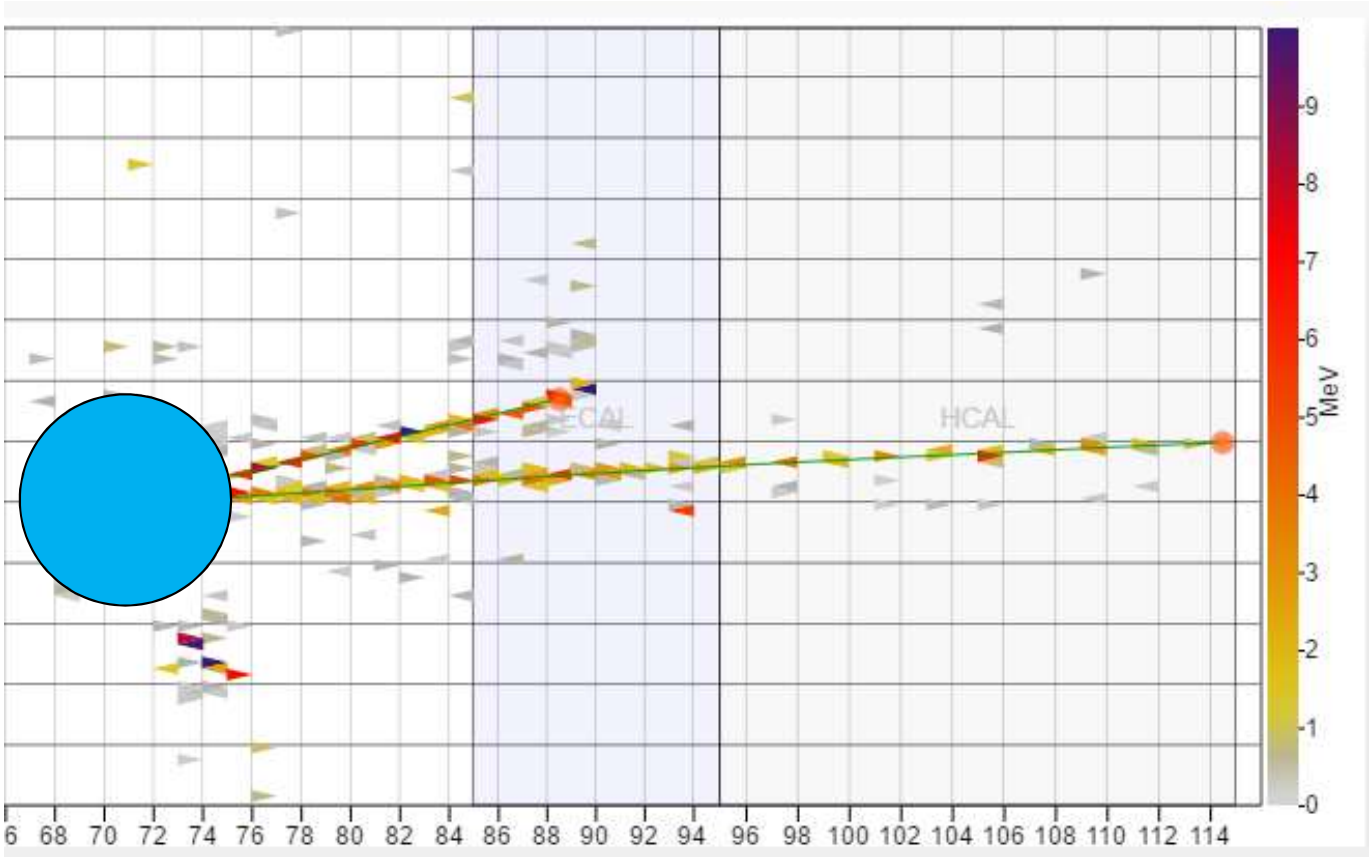

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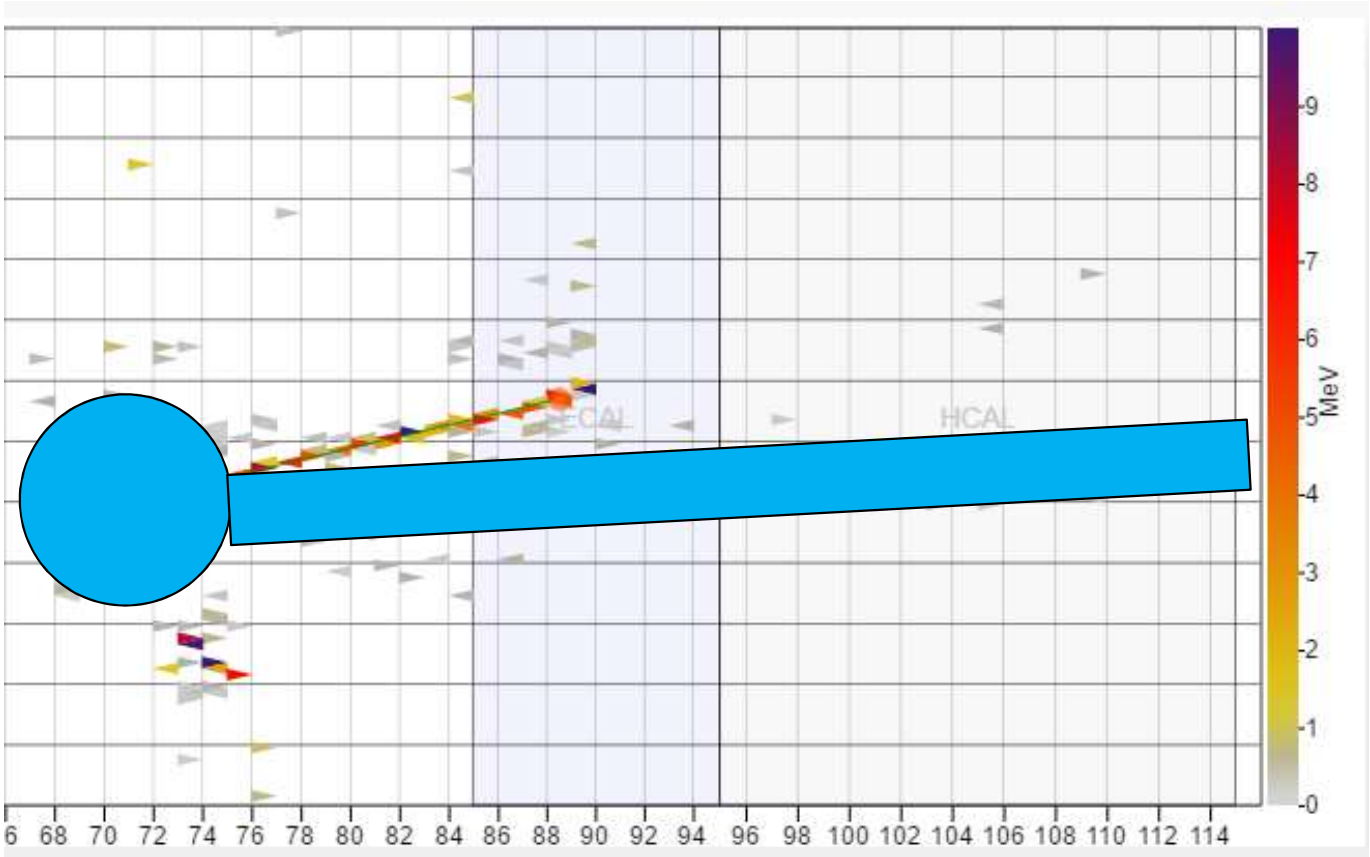

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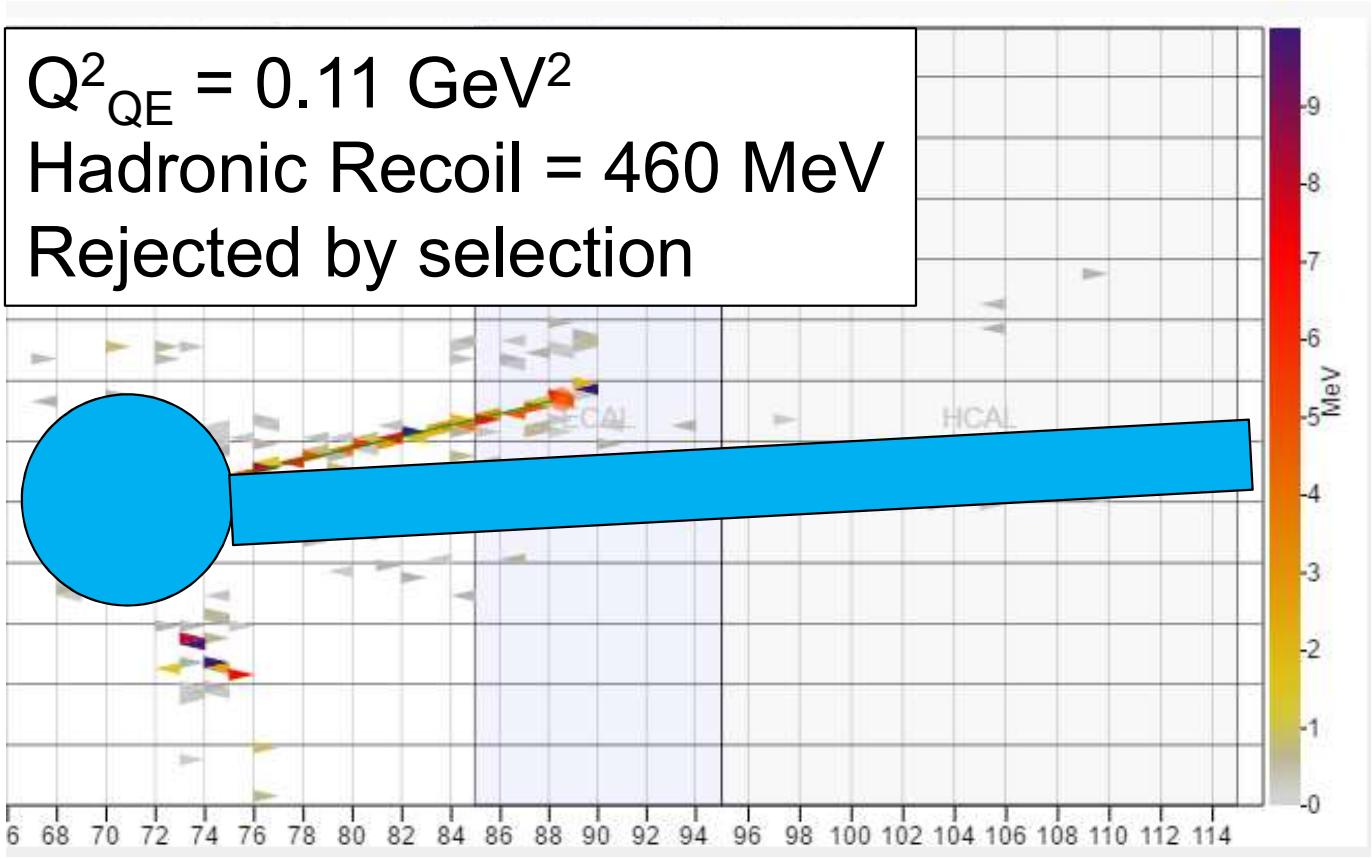
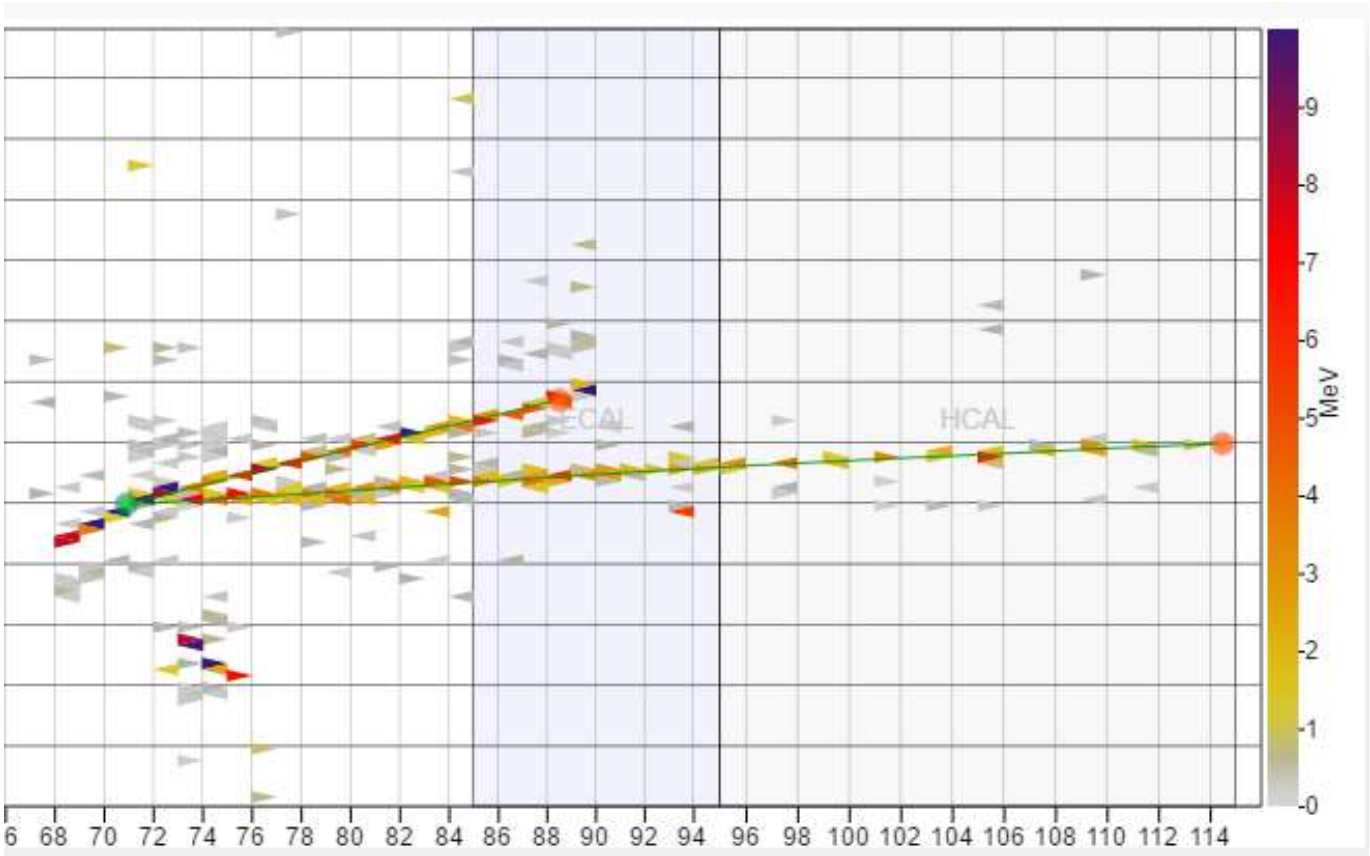


What does MINERvA say about quasi-elastic processes?

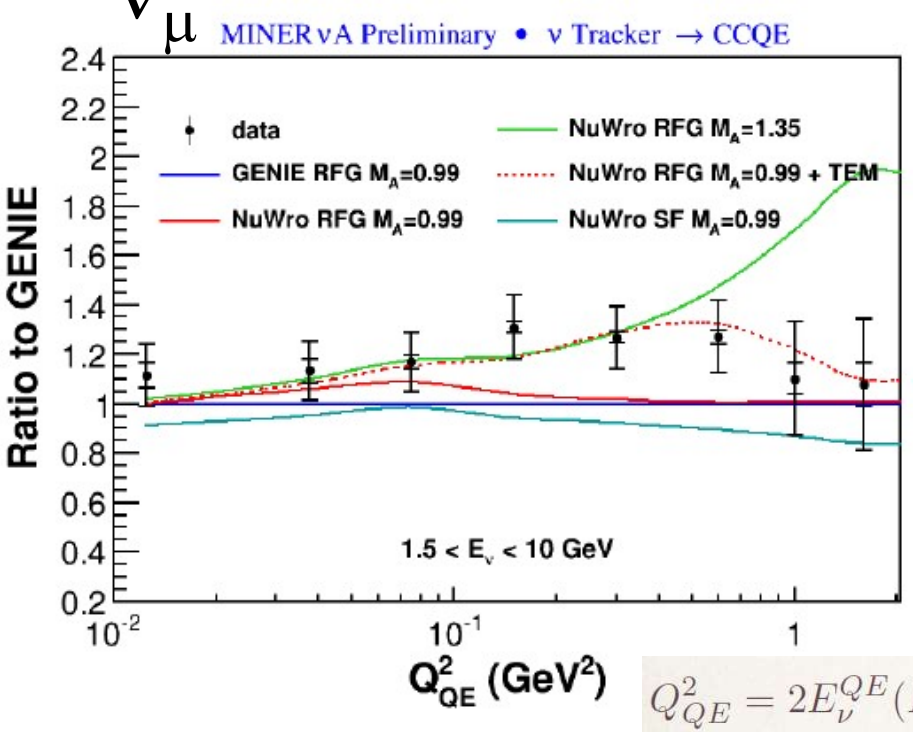
- Strategy 2 –Track pions and protons
- Select events based on particle identification
- Constrain pion background using side band fits



Strategy 1

Our first QE Results (updated to latest flux)

Phys. Rev. Lett. 111, 022502 (2013)



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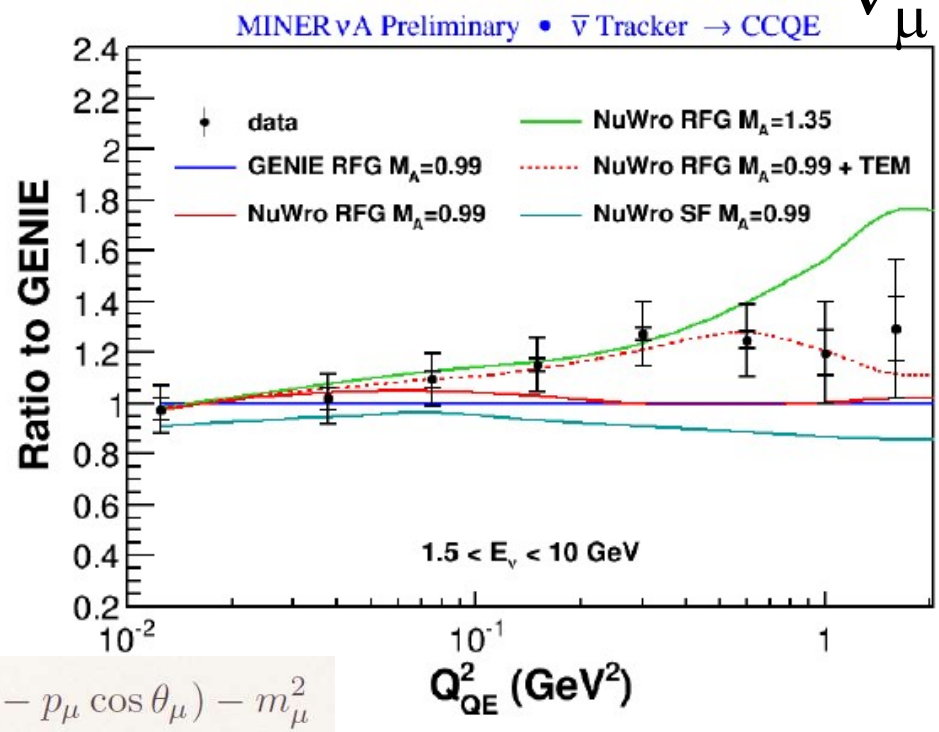

$$Q^2_{QE} = 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

<u>Both results prefer a model with a 2p2h-like enhancement</u>

TEM – Transverse Enhancement Model is an empirical model fit to electron-nucleon scattering

TEM: Eur.Phys.J. C71, 1726 (2011)
NuWro:

Strategy 1

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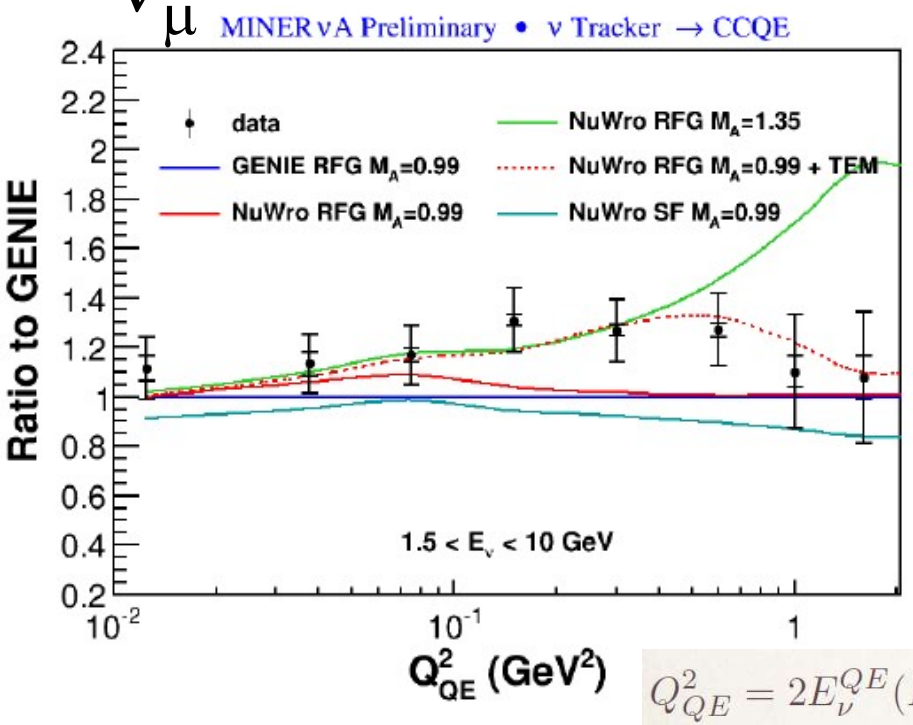
Phys. Rev. Lett. 111, 022502 (2013)



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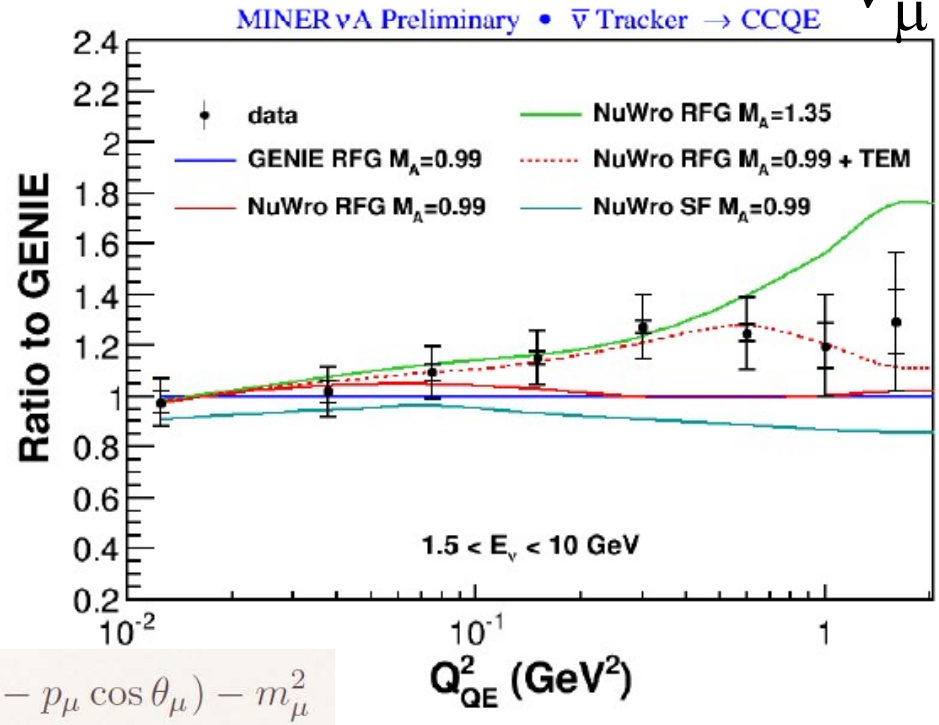
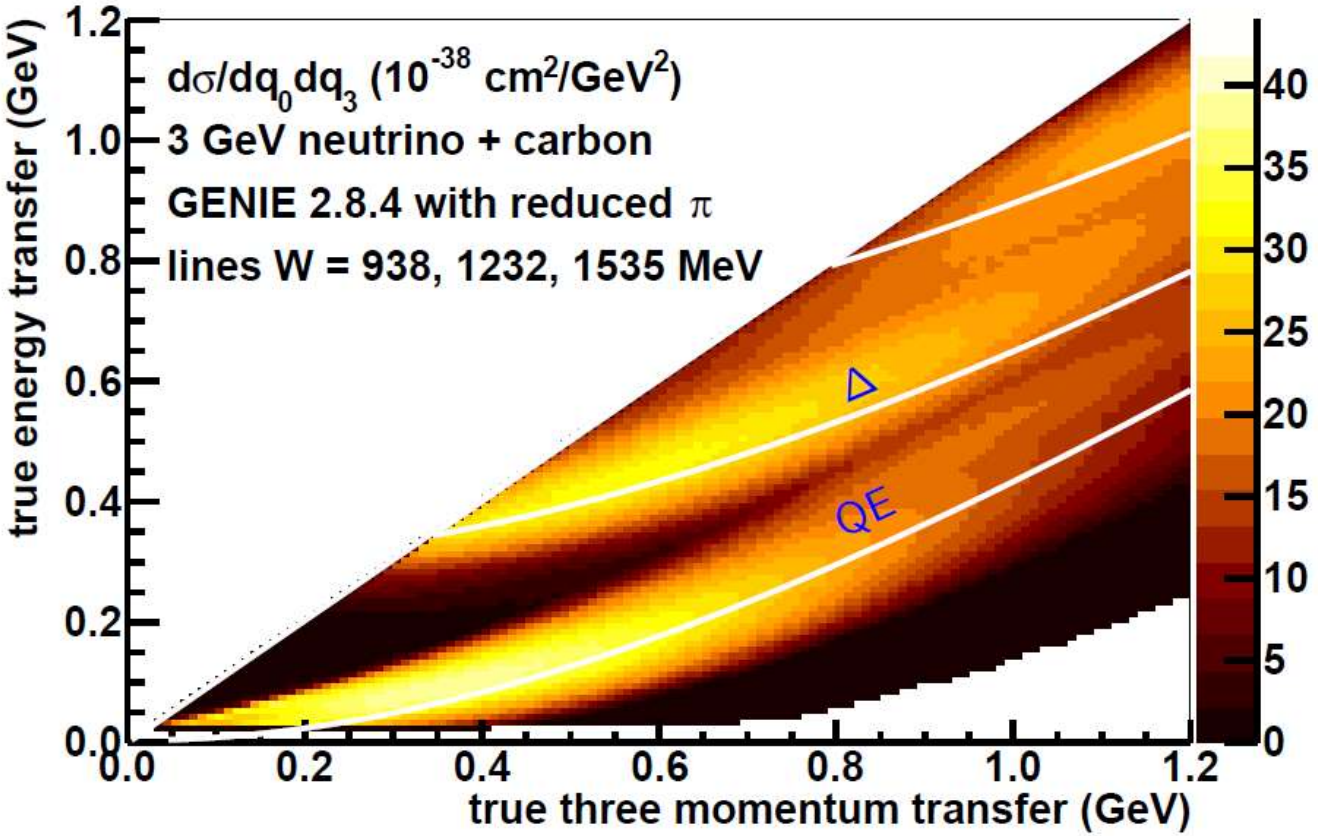


$$Q^2_{QE} = 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

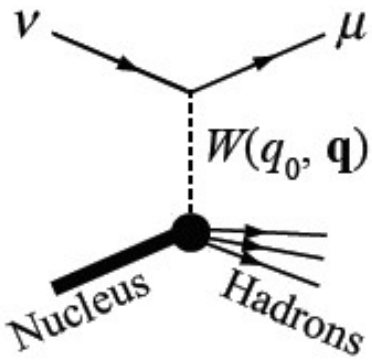
Both results prefer a model with a 2p2h-like enhancement

- Fills in low Q^2 RPA suppression
- Increases cross section in the $0.1<Q^2<1$ GeV^2 region
- Does not increase like the modified M_A curve does at high Q^2

A more inclusive approach

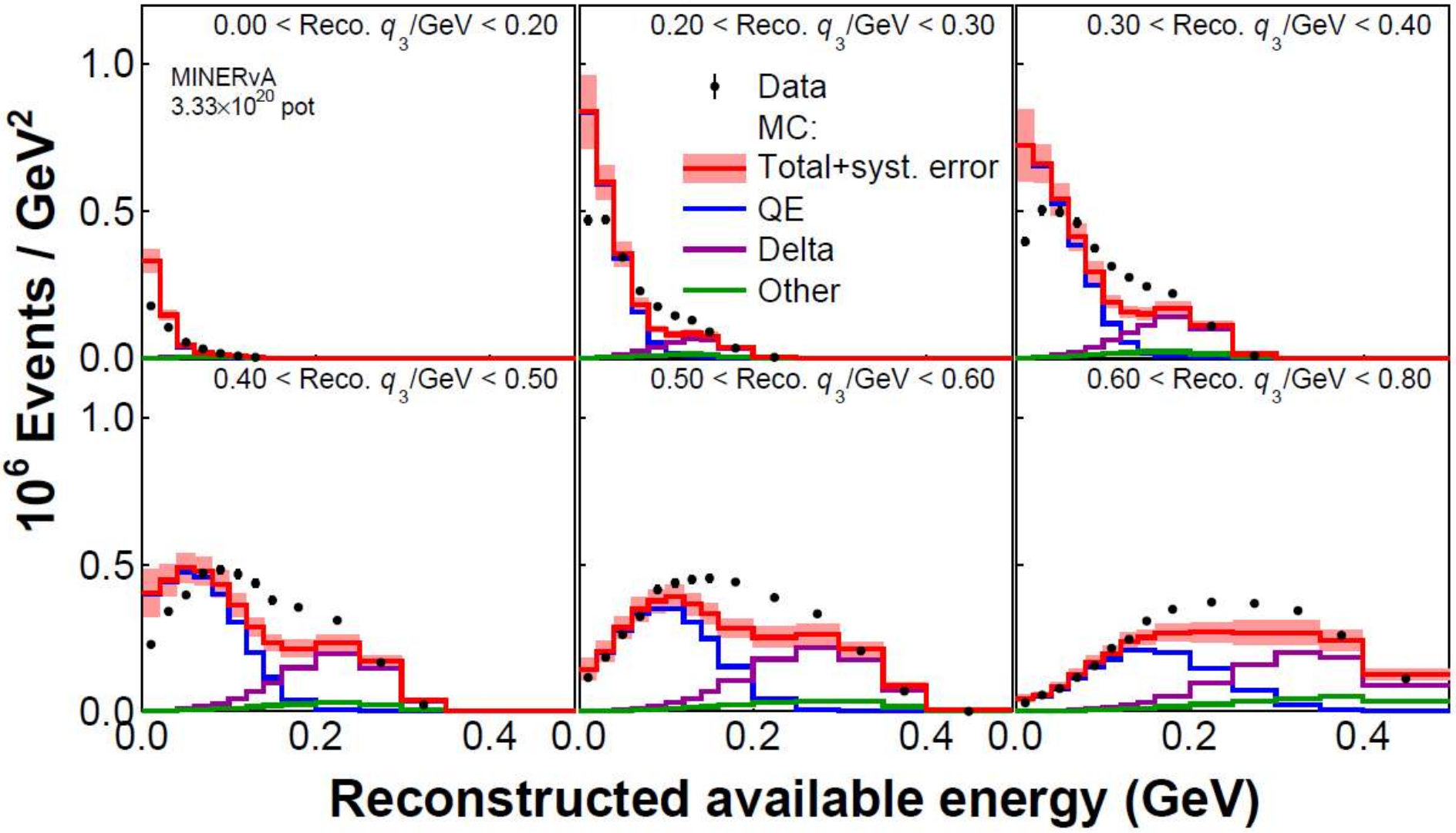


Unlike the other analyses this analysis uses information of the lepton and hadronic system together



Selected Events – Nominal GENIE w/ reduced π

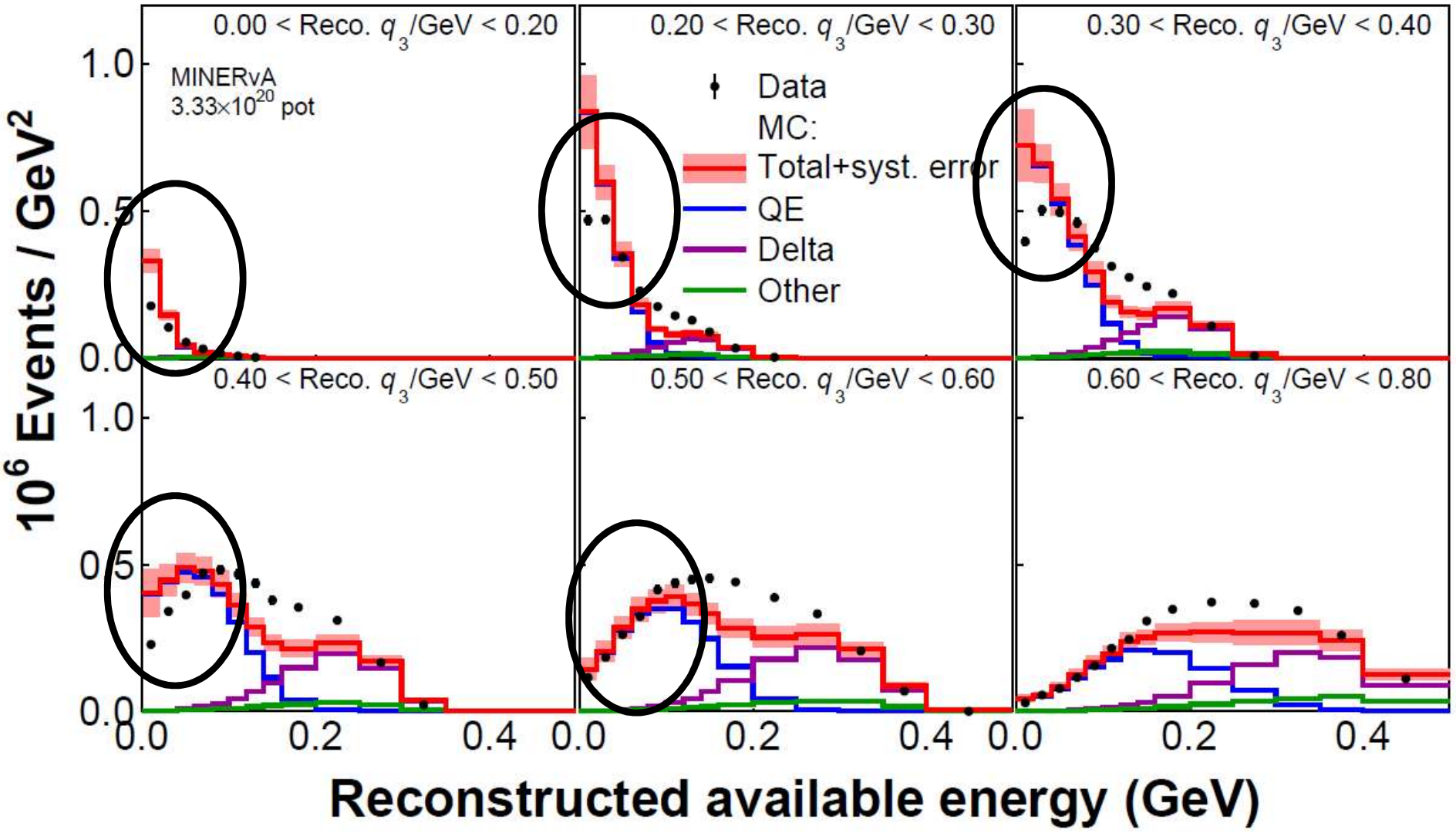
Phys. Rev. Lett. 116, 071802 (2016)



GENIE: [Nucl.Instrum.Meth.A614 (2010) 87-104], arXiv:1510.05494[hep-ph]
2p2h: PRC 70, 055503 (2004); PRC 83, 045501 (2011)
RPA: PRC 70, 055503 (2004); PRD 88, 113007 (2013)
Reduced pion: Eur. Phys. J. C (2016) 76: 474

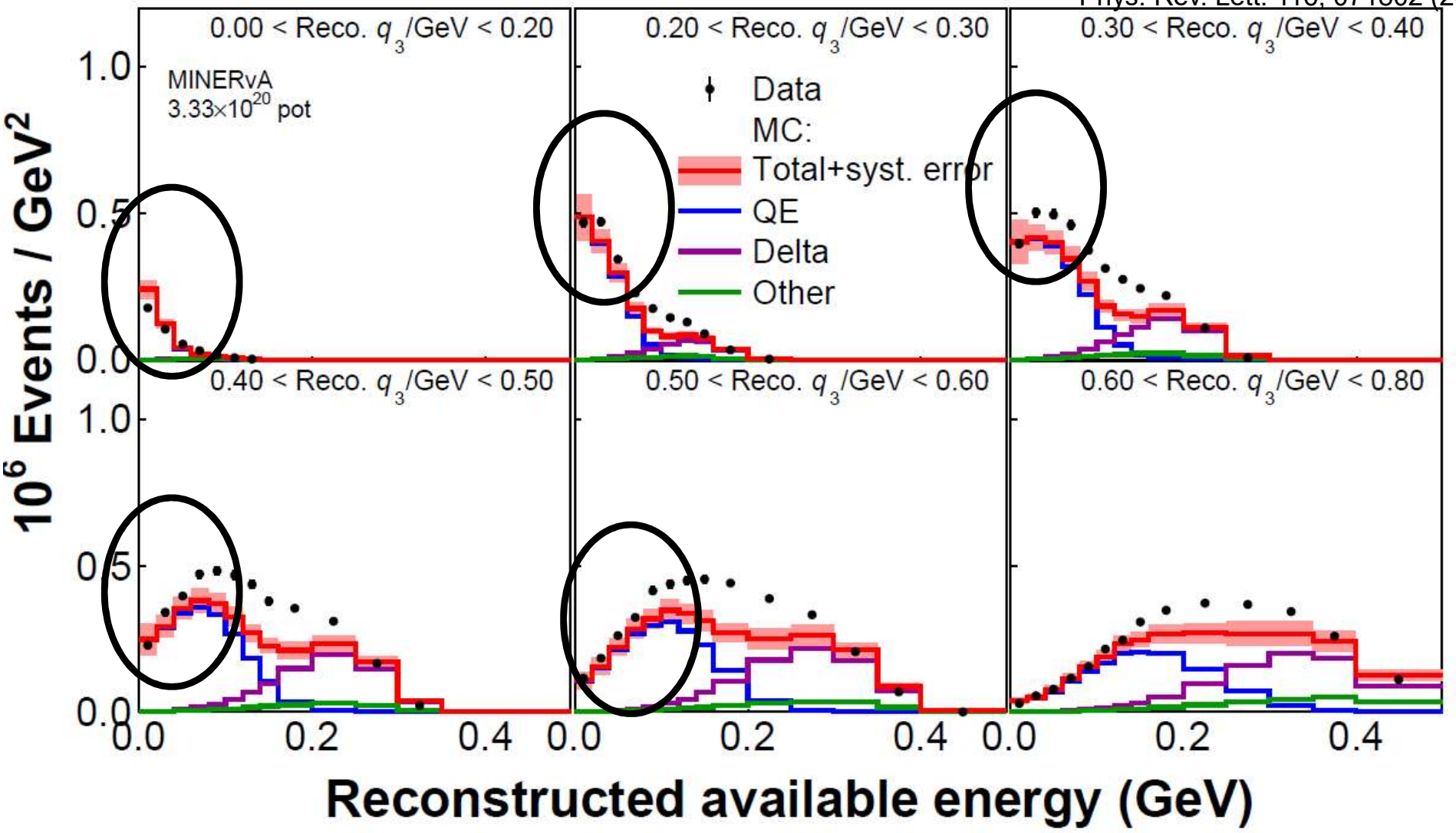
Selected Events – Nominal GENIE w/ reduced π

Phys. Rev. Lett. 116, 071802 (2016)



Selected Events
Add in Nuclear Screening

Phys. Rev. Lett. 116, 071802 (2016)



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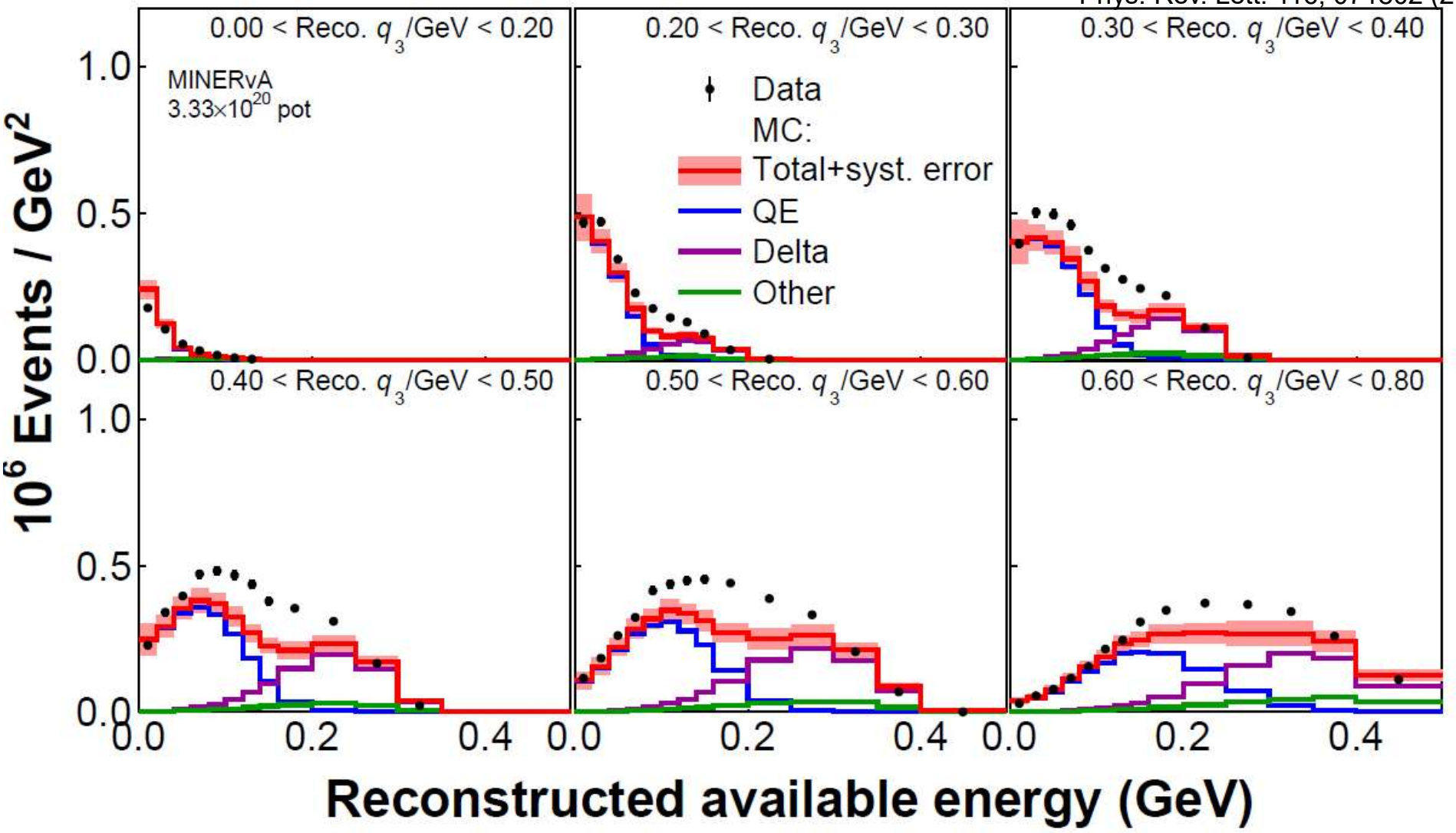

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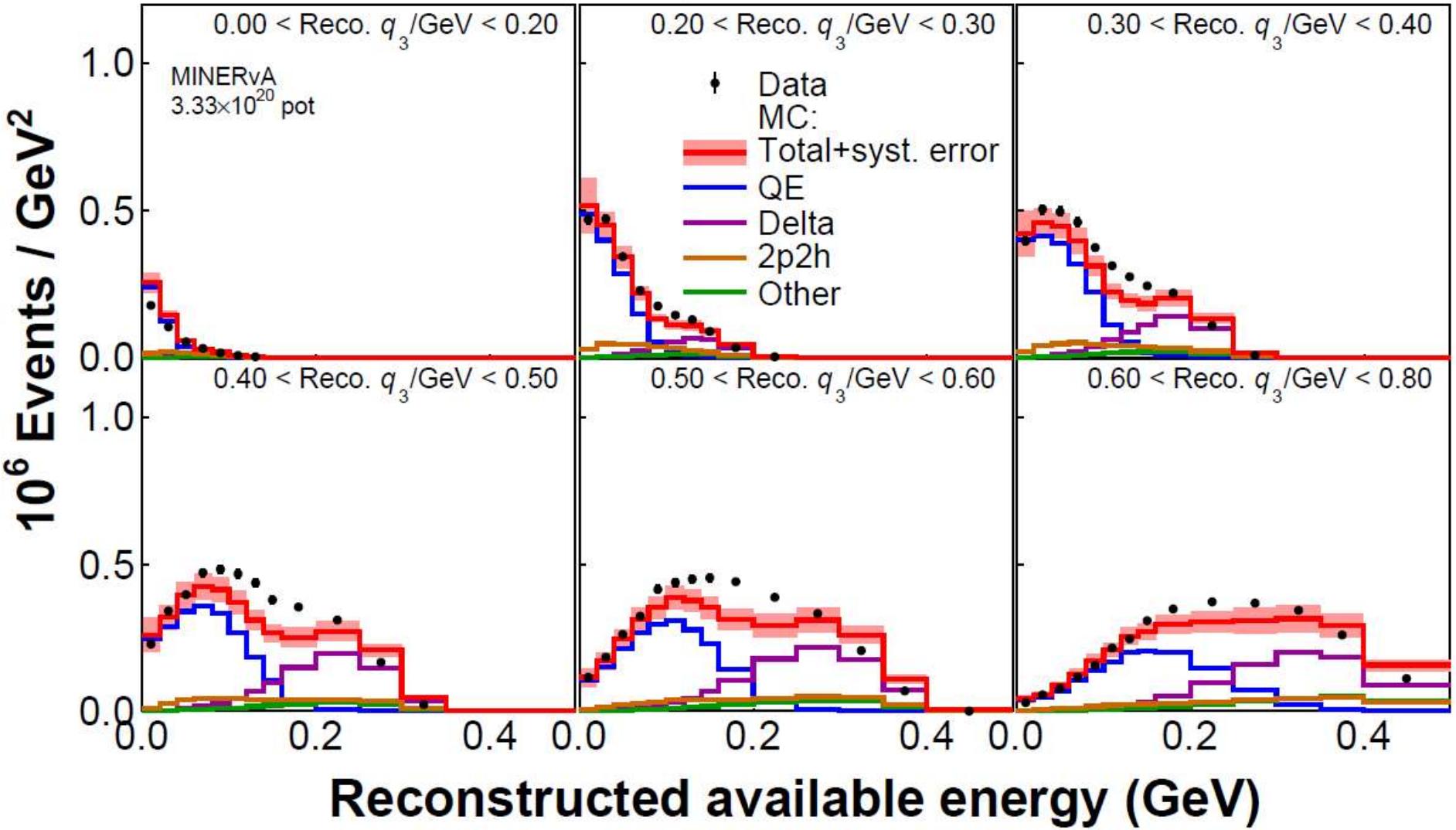
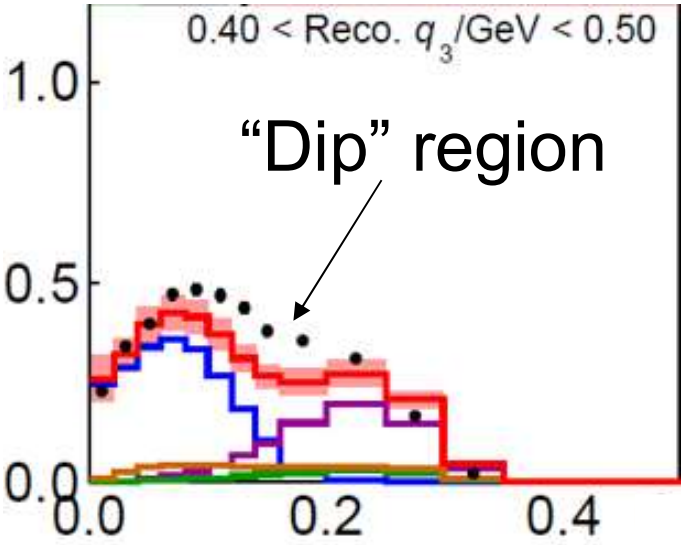


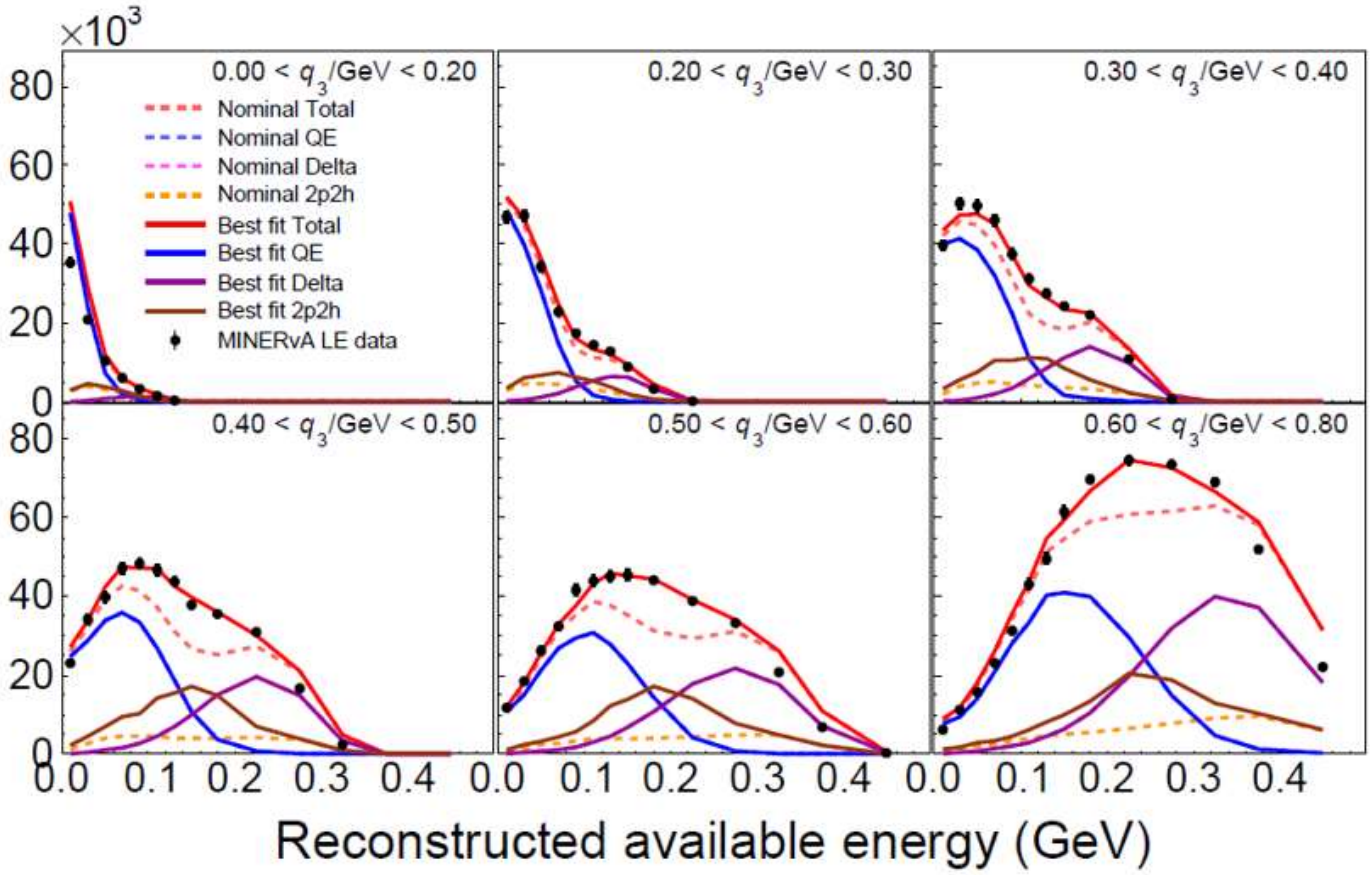
Takeaway

- Nuclear screening and 2p2h go a long way to explain the data
- BUT, not enough.
  - The dip region between QE and resonant pion production still show the simulation is not representing the data.
- So, what to do….



The low recoil fit

- Fit a 2D Gaussian in true (q_0,q_3) as a reweighting function to the 2p2h contributions to get the best agreement
- Does not scale true QE or resonant production.

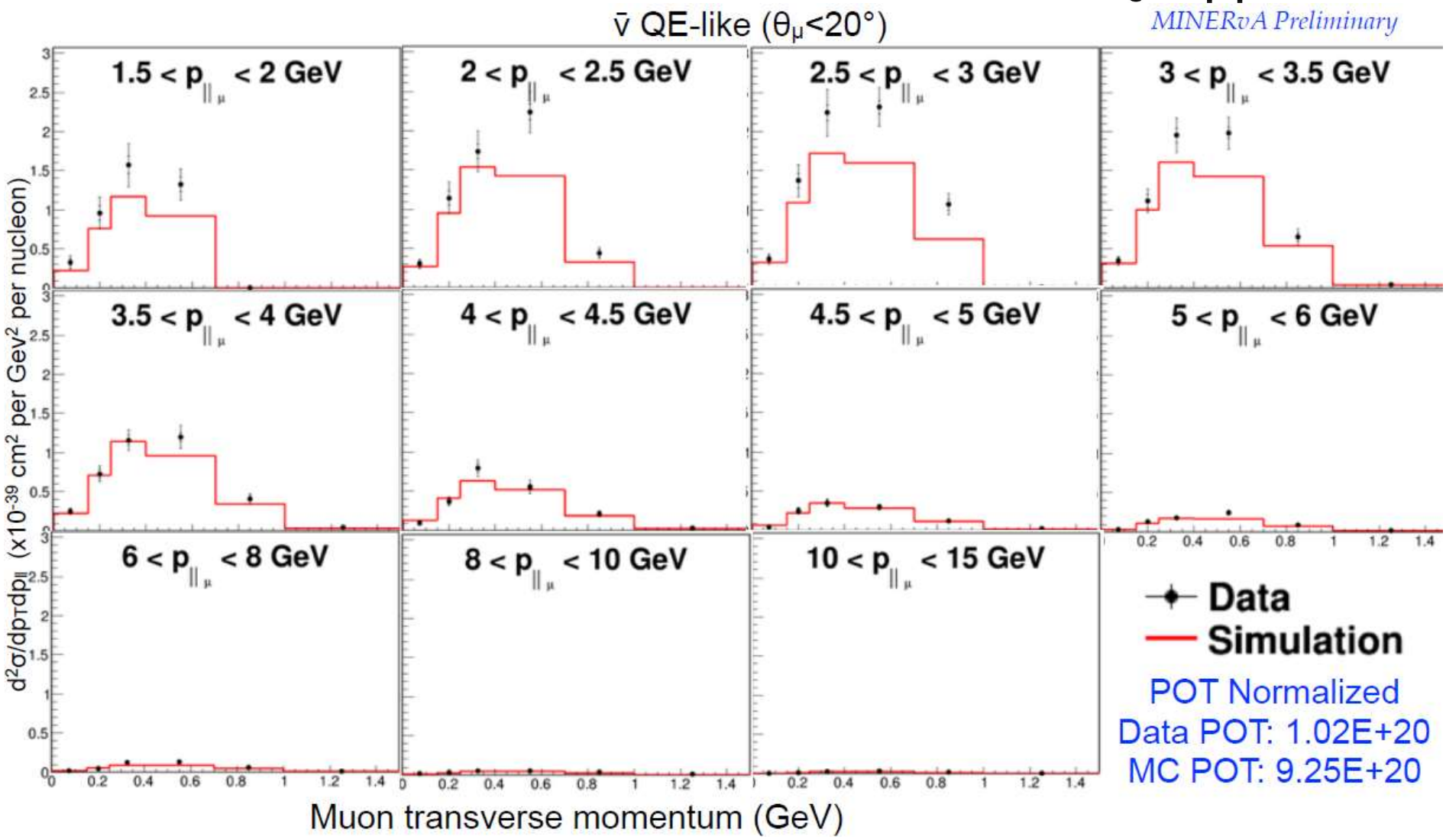


Back to exclusives!

- We now have a **modified simulation** which represents our inclusive data quite well
- Revisit the anti-neutrino result shown at JETP seminar June 17th, 2016
- Unveil the new neutrino result

Strategy 1

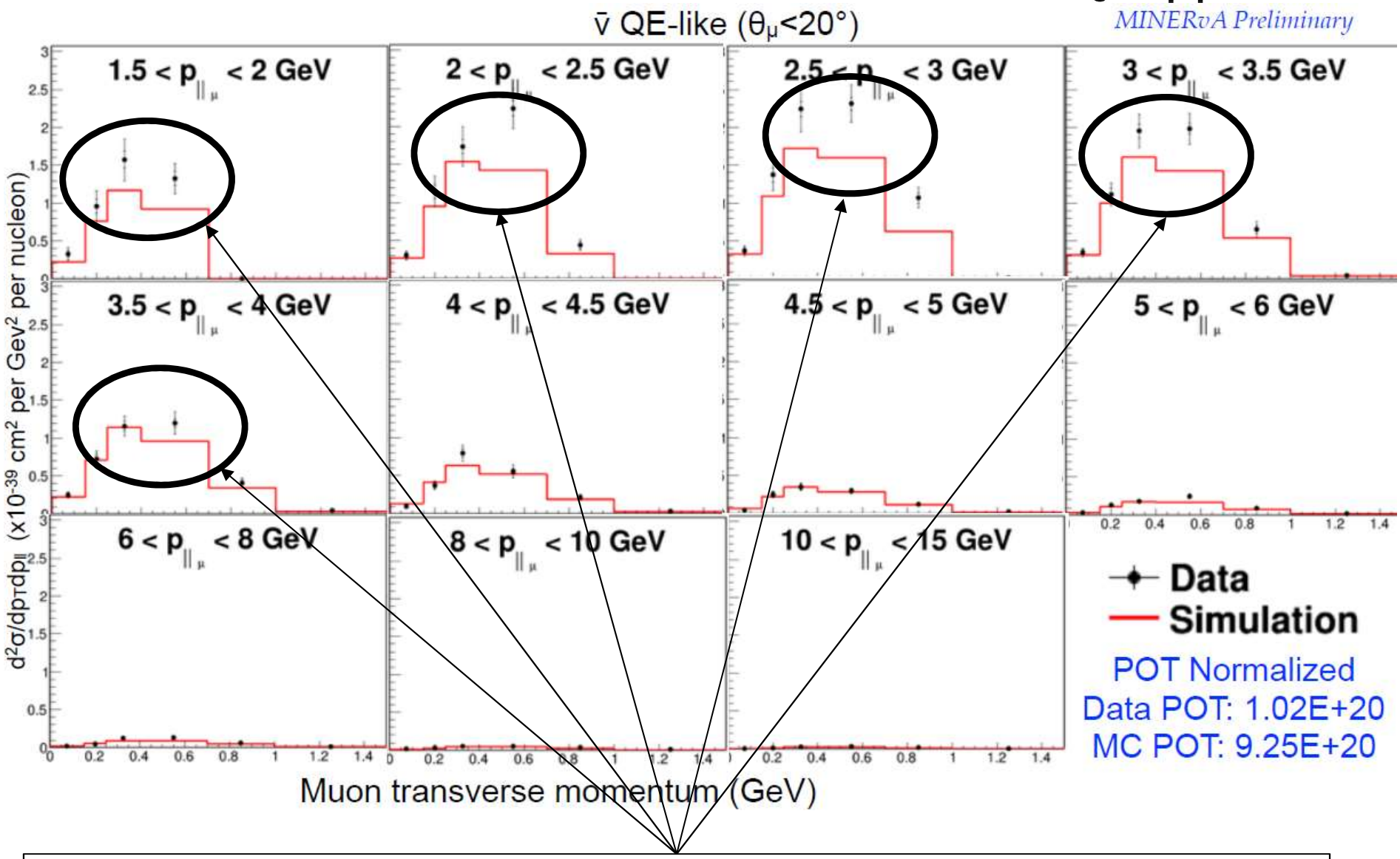
Double Differential in $P_t P_{||}$



Antineutrino Result

Strategy 1

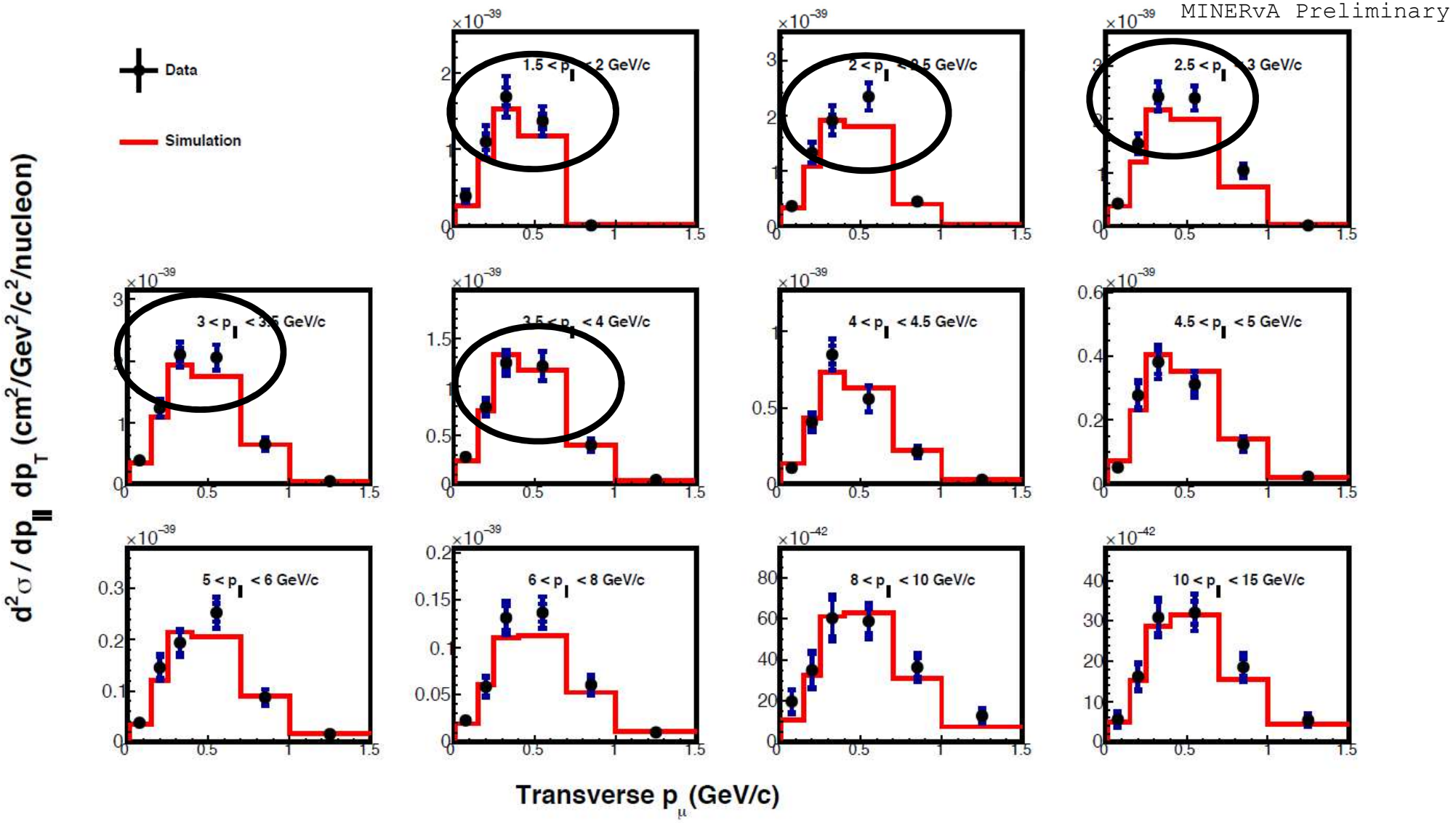
Double Differential in $P_t P_{||}$



Excess at ~0.5 GeV P_t roughly maps back to the excess regions in the inclusive NEUTRINO analysis – oh that's interesting

Strategy 1

Apply the reweight



The reweight from the inclusive neutrino fit gives improved agreement in the anti-neutrino result!

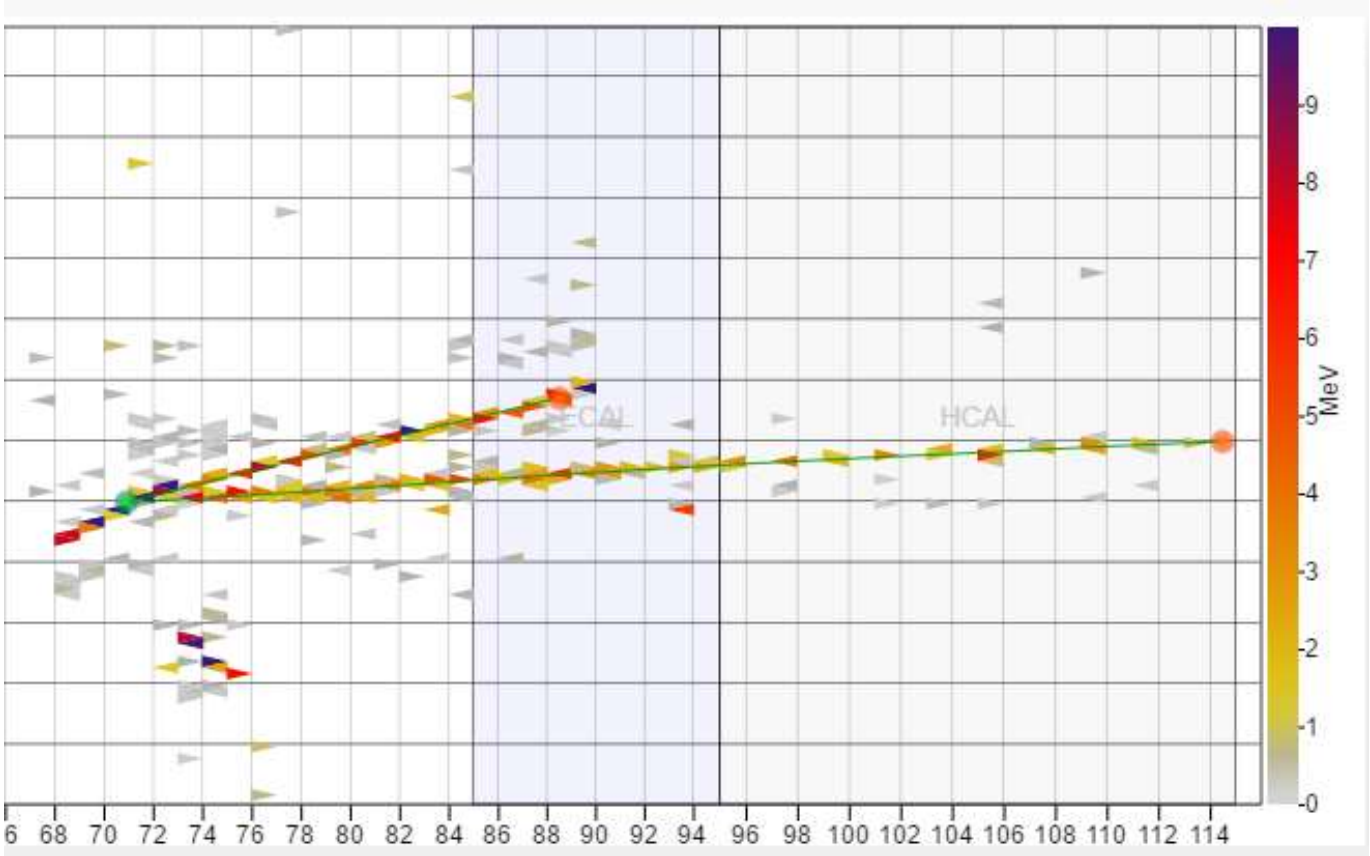
New Neutrino Results for today

Double Differential $p_t p_{||}$ cross section

Differential cross sections in $E_{\nu,QE}$ and Q^2_{QE}

What does MINERvA say about quasi-elastic processes?

- Strategy 2 –Track pions and protons
- Select events based on particle identification
- Constrain pion background using side band fits



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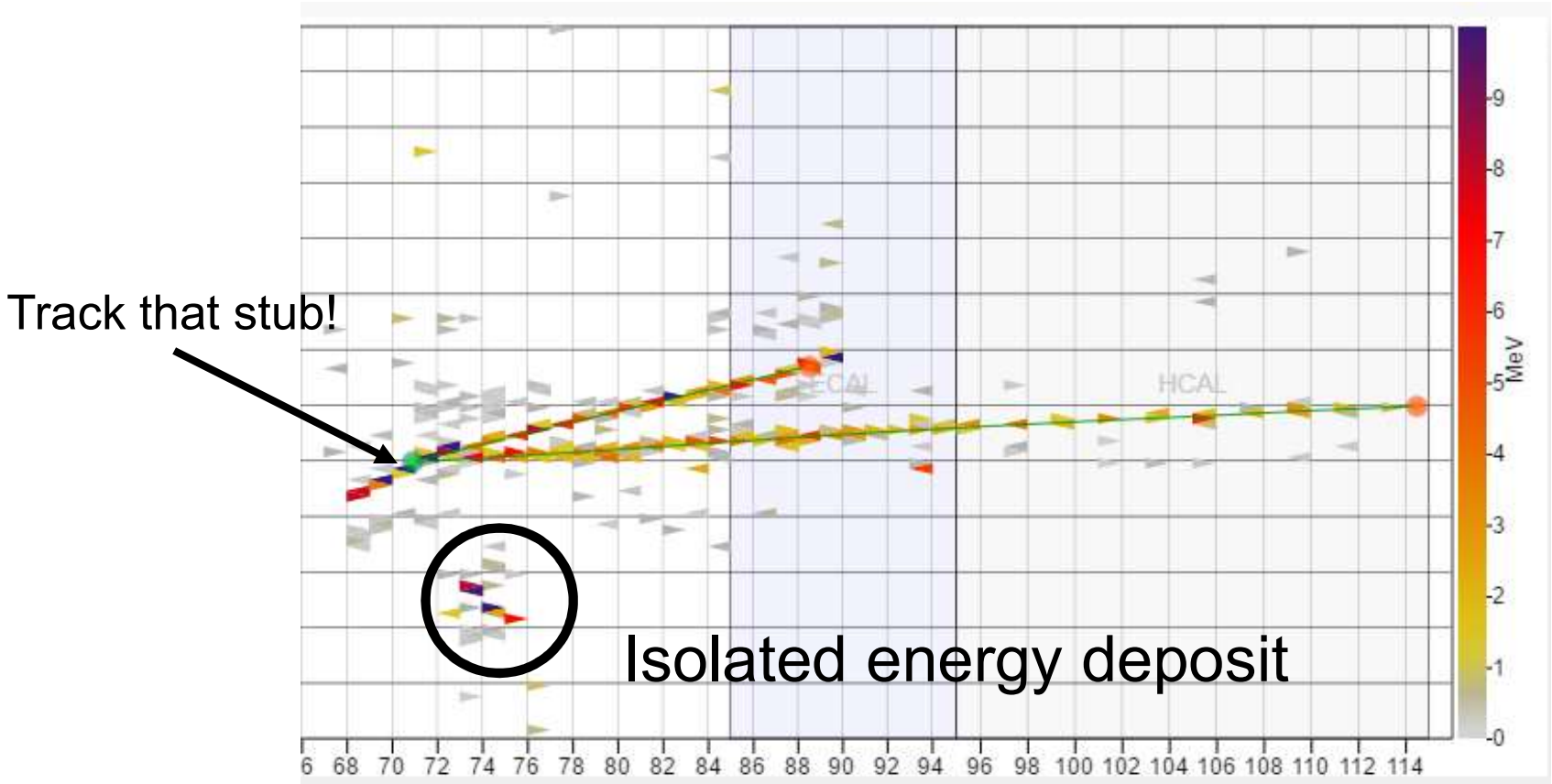

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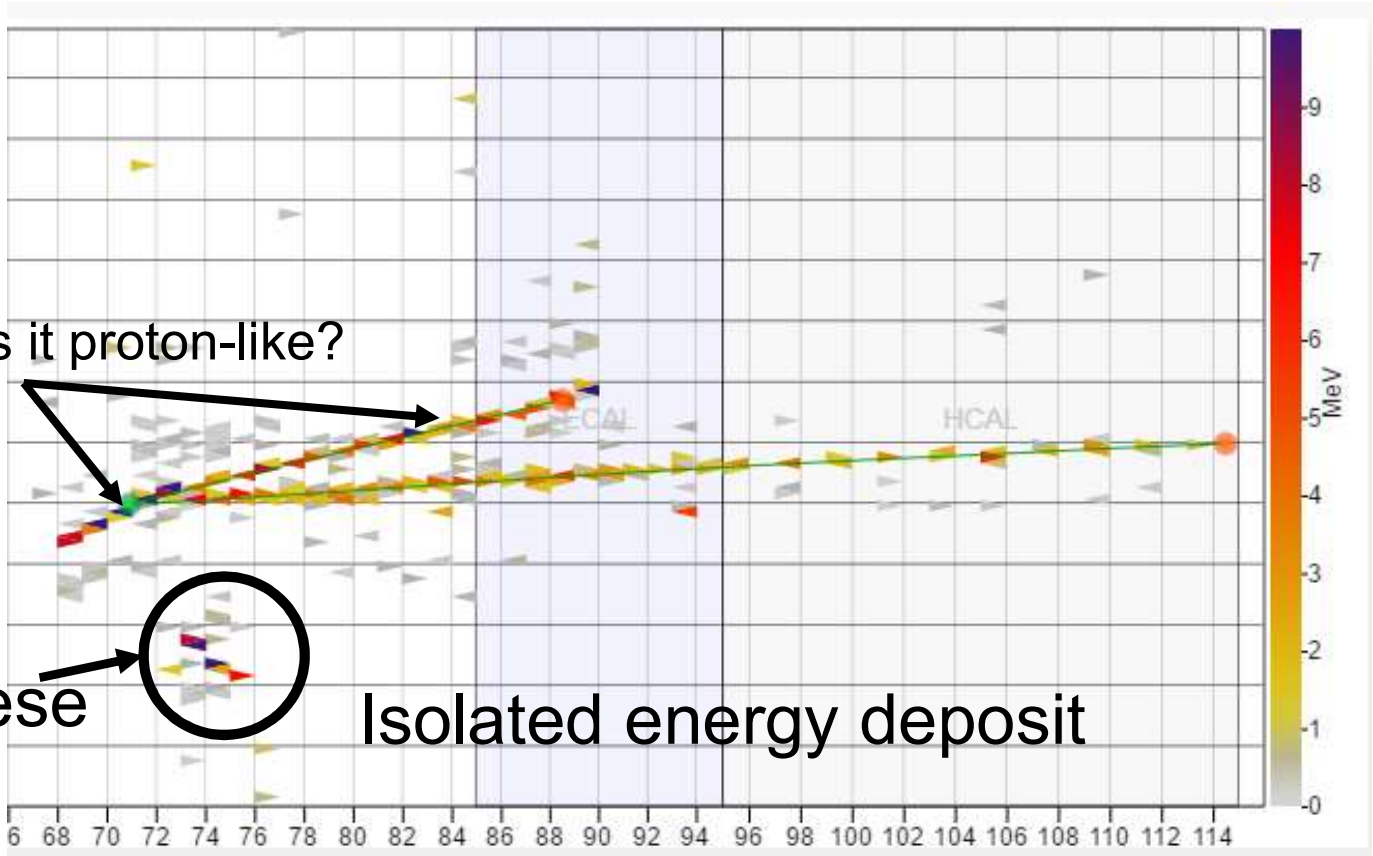

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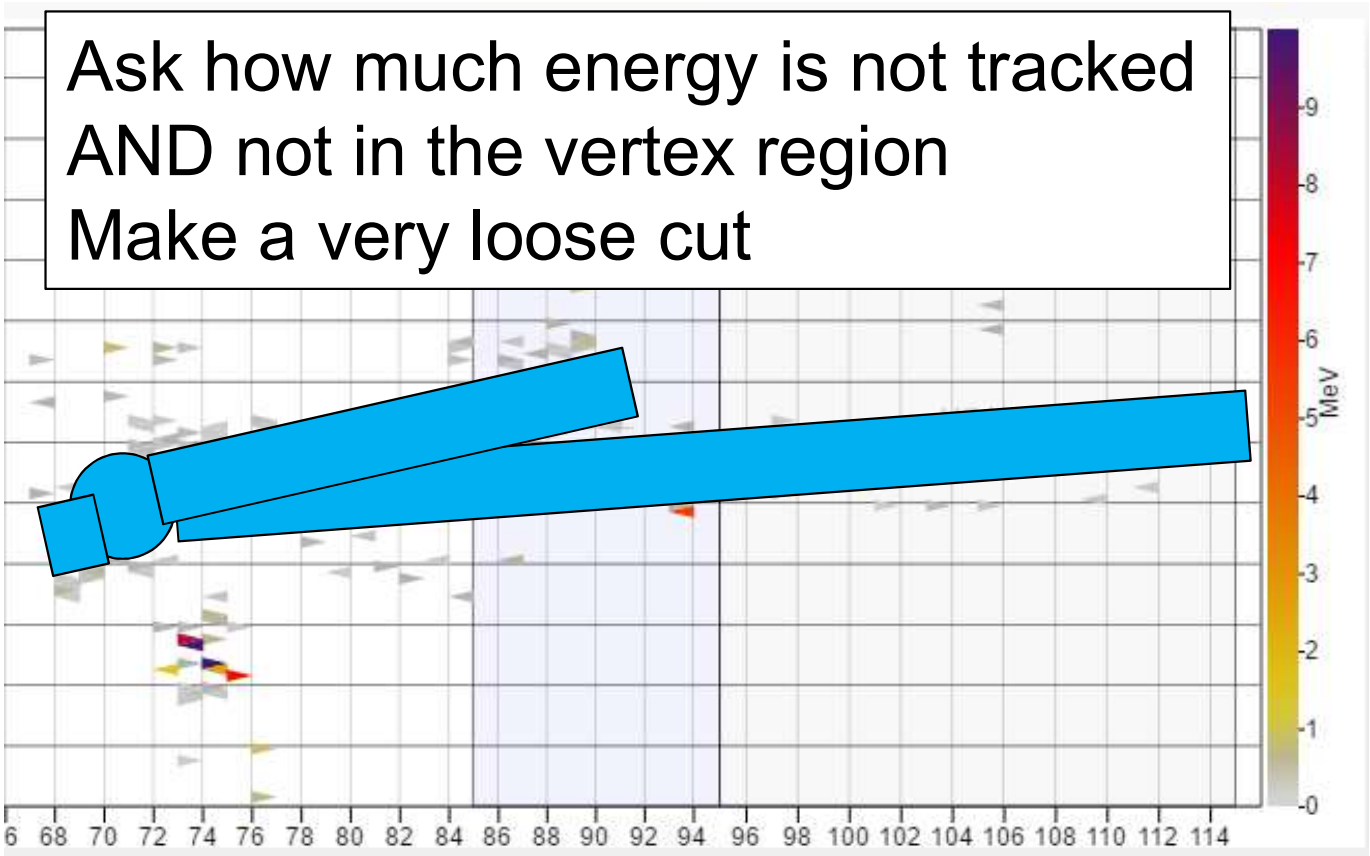

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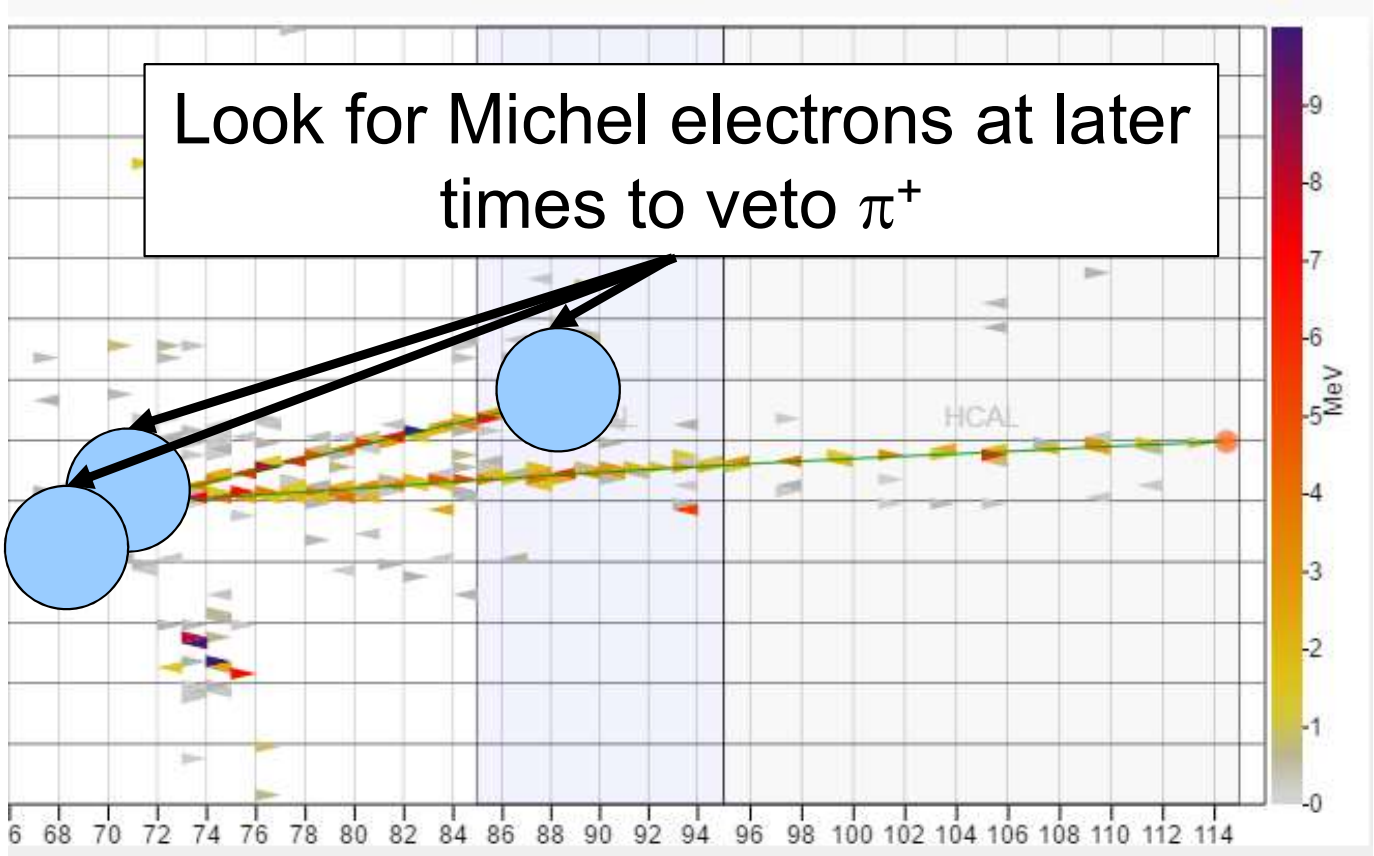


An aside.

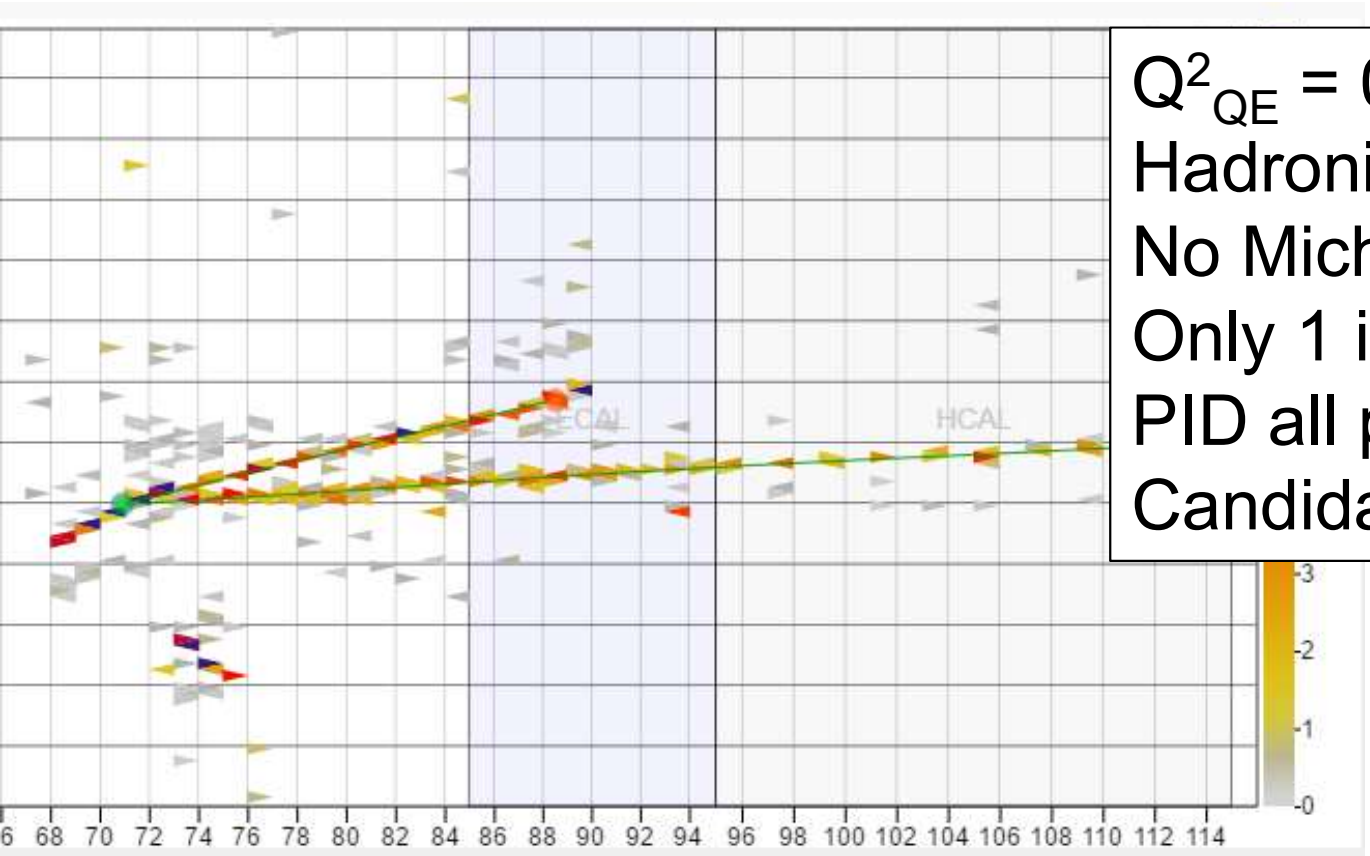
- Much harder for an anti-neutrino analysis
- Anti-neutrino interactions produce predominantly π^- which decay to μ^- which typically capture

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\mu_{\nu}}) \longrightarrow \begin{array}{l} \mu^- \rightarrow e^- \bar{\nu}_e \nu_{\mu} \\ \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_{\mu} \end{array}$$

- Therefore, no Michel electrons, bummer.

What does MINERvA say about quasi-elastic processes?

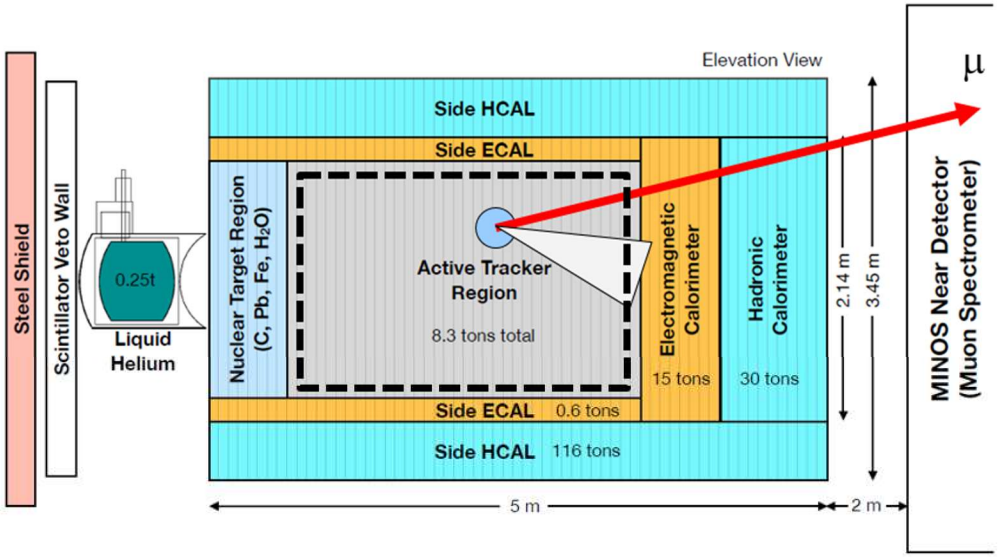
- Strategy 2 –Track pions and protons
- Select events based on particle identification
- Constrain pion background using side band fits



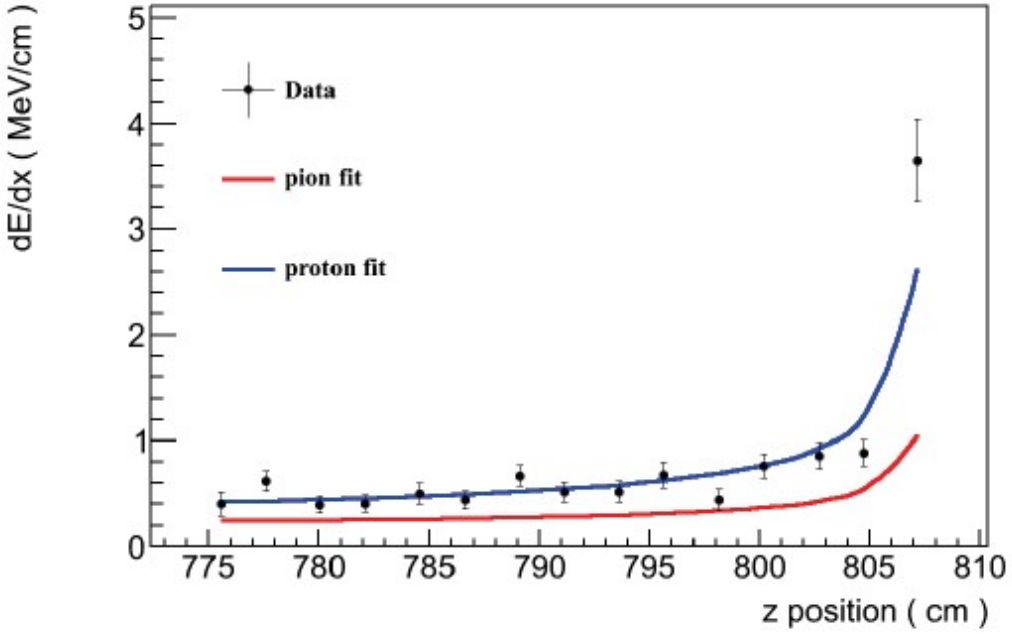
Q^2_{QE} = 0.11 GeV^2
Hadronic Recoil = 198 MeV
No Michel electrons
Only 1 isolated energy deposit
PID all proton-like
Candidate!!!

Signal definition

- QE-Like – Defined by particles exiting the nucleus
  - Any number of nucleons of all energy
  - **No pions**, heavy baryons etc
- Additional constraints
  - True muon angle <20.0 degrees because of the MINERvA-MINOS acceptance

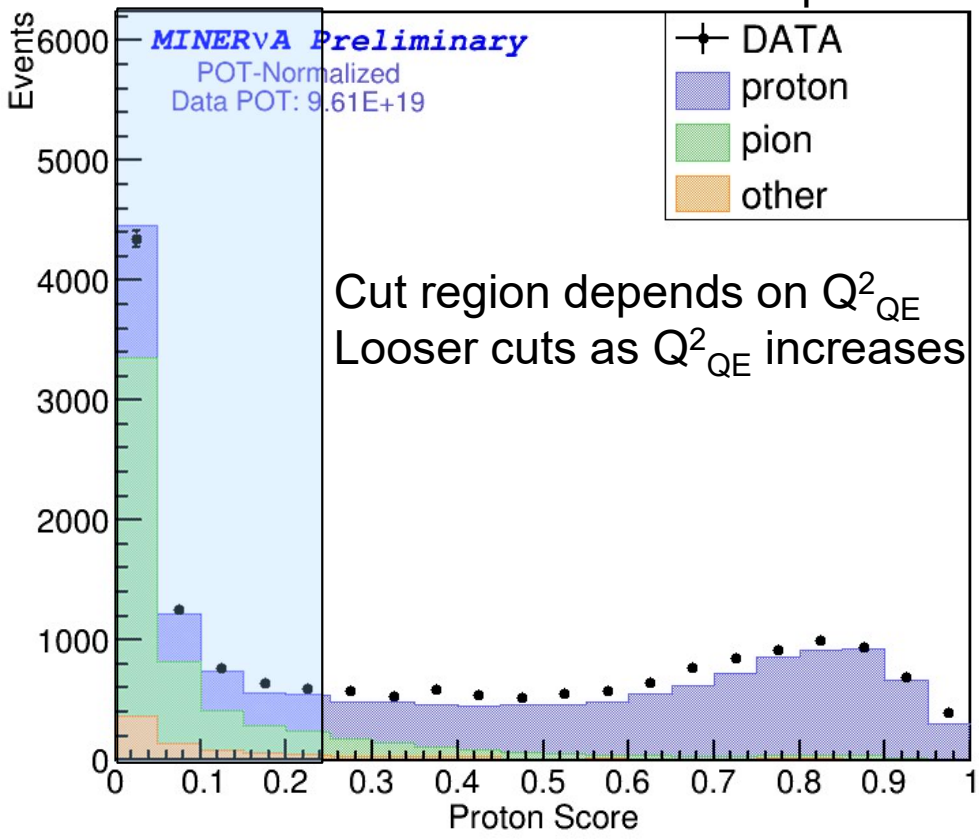


PID broken down by particle



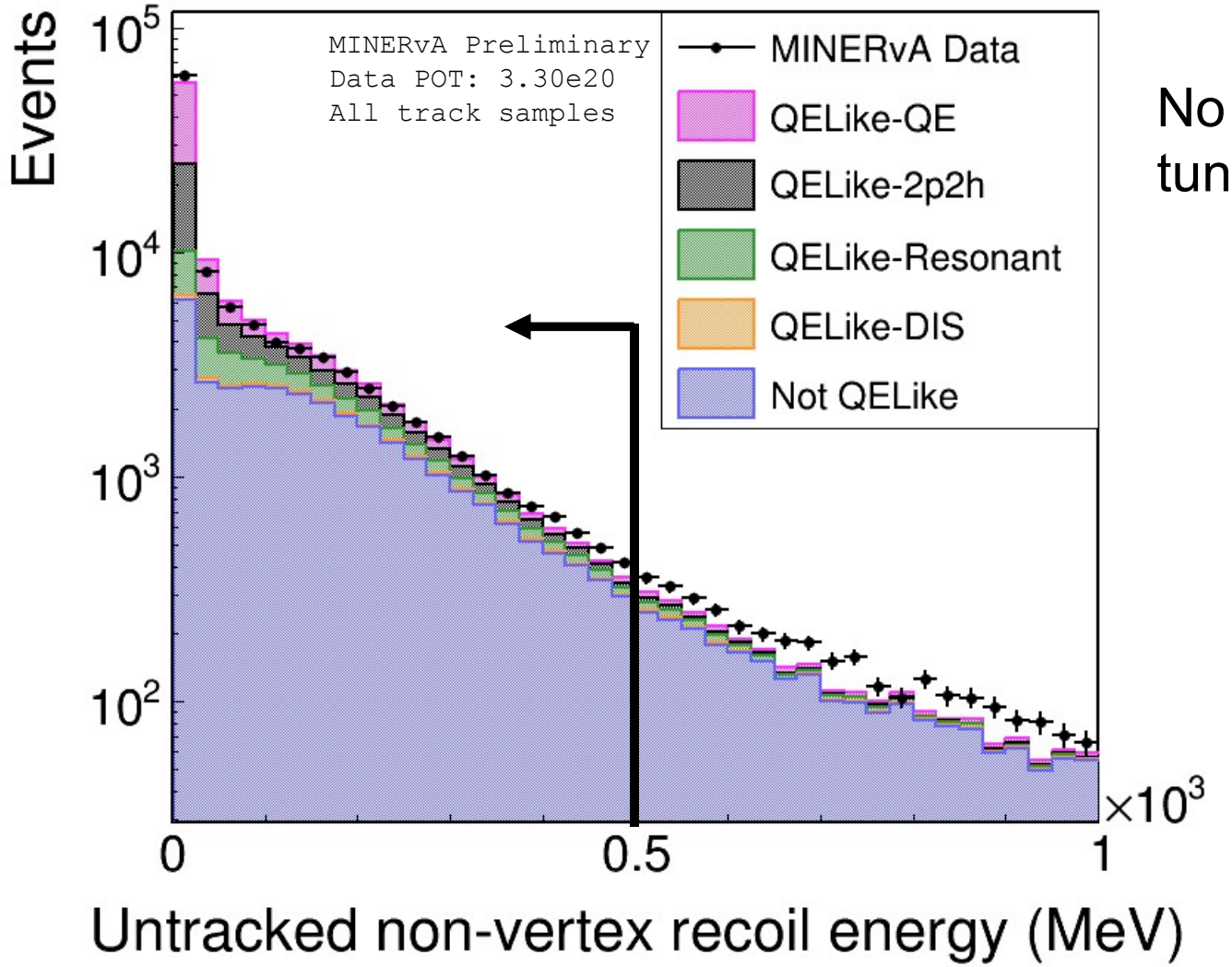
- This is applied to all tracks which are not the muon
- Loosen cut as Q^2_{QE} increases because protons are harder and interact more

Integrated over Q^2_{qe}



Hadronic Recoil

- Very loose cut on the untracked energy outside the vertex region.
- Sample here passes the rest of the selection.



No background tuning applied

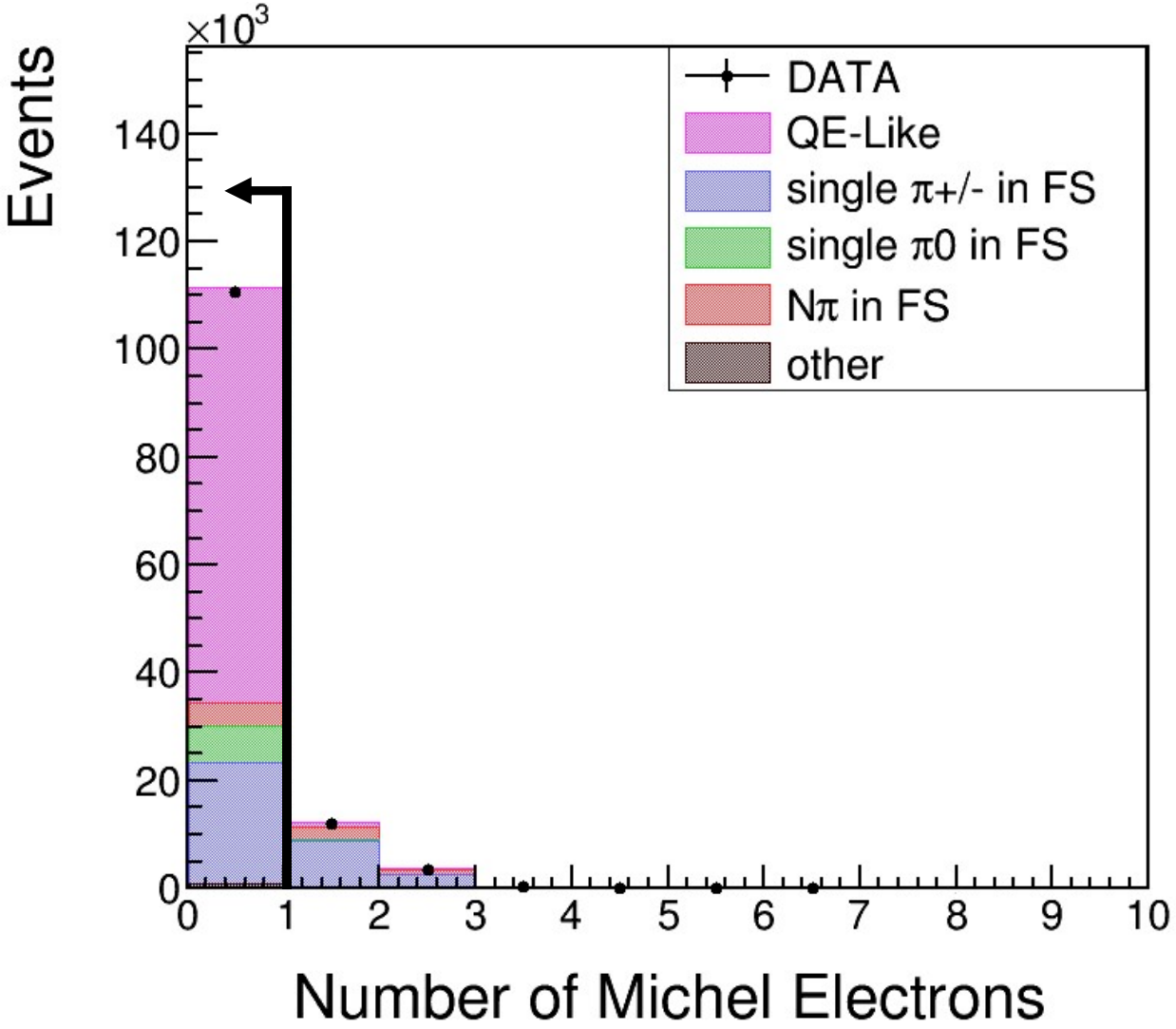
Also….

The Sidebands

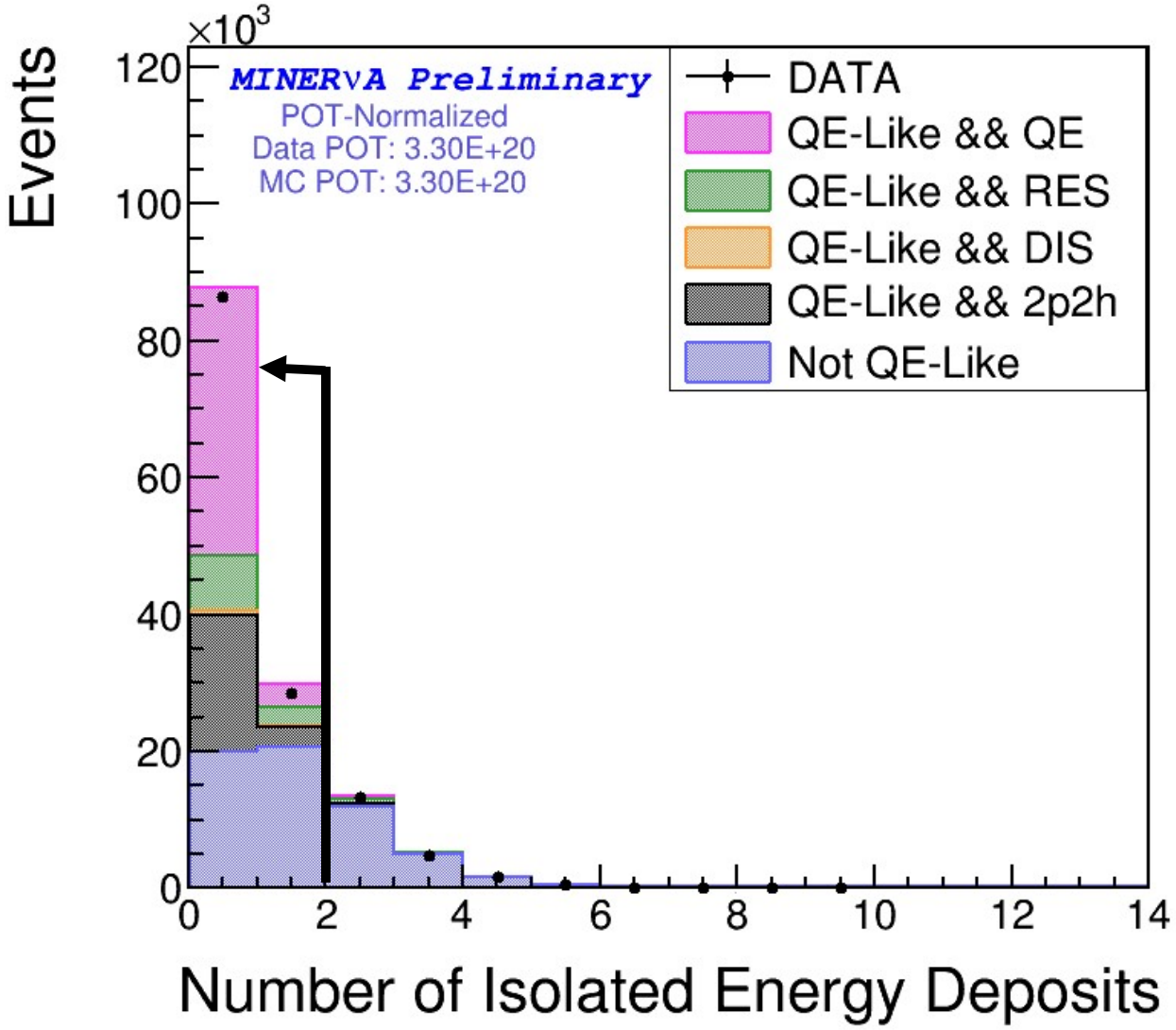
- Reject events with Michel electrons
- Reject events with 2 or more isolated clusters of energy

- In addition:
  - MINOS restricts our acceptance to about 20 degrees. Make a cut rejecting the VERY few events with angles greater than 20 degrees.

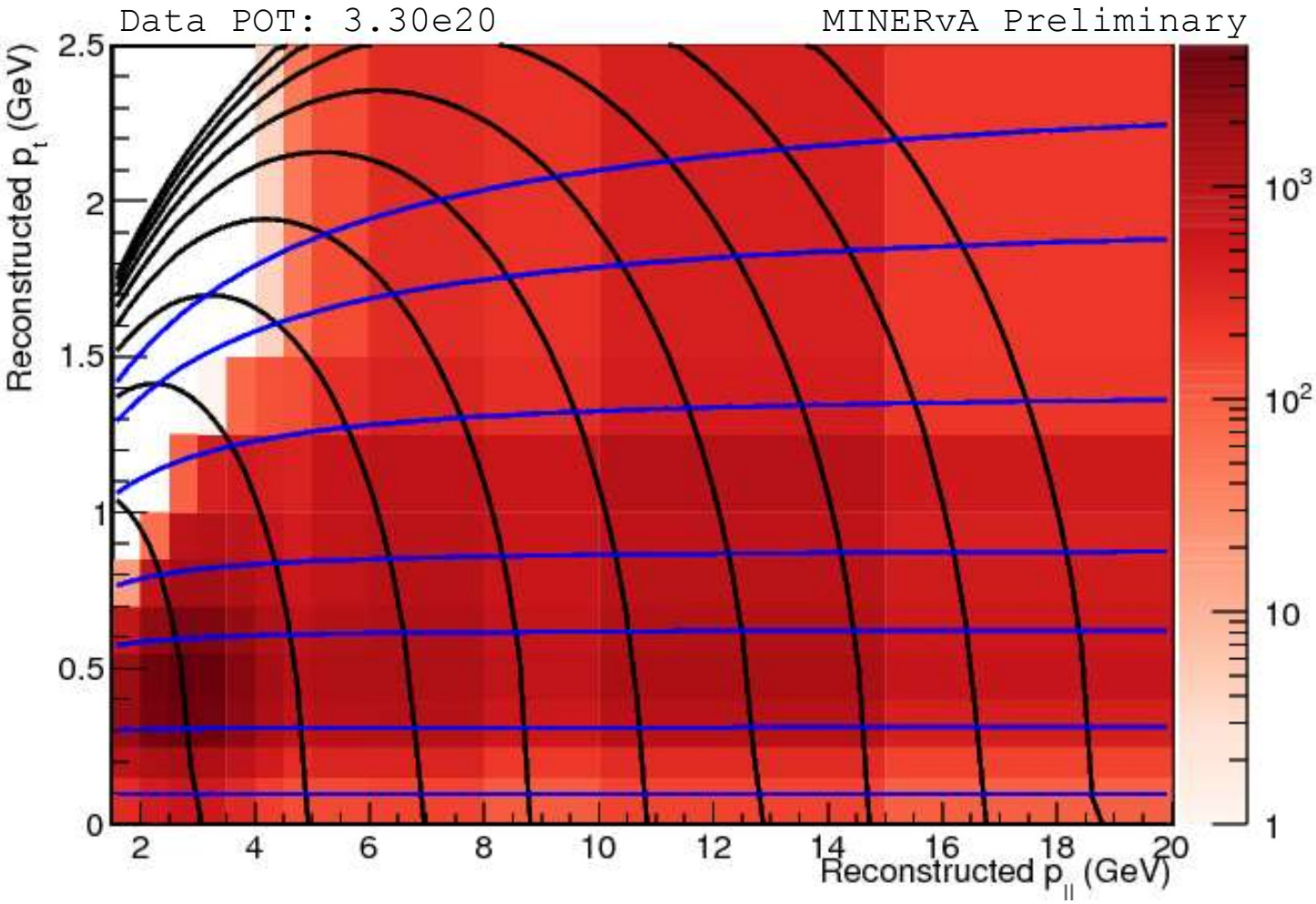
Number of Michel Electrons



Isolated energy deposits



Final Selected Sample



1-track sample
62159 events

2+track sample
46074 events

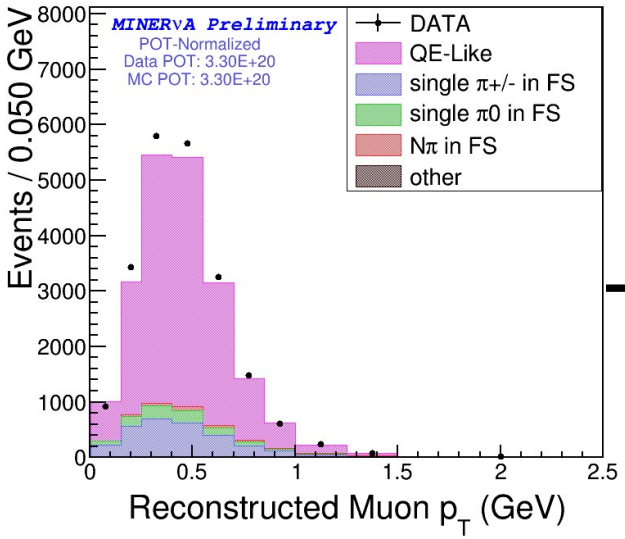
Lines of constant $E_{\nu,qe}$ [3,7,11,15,19]

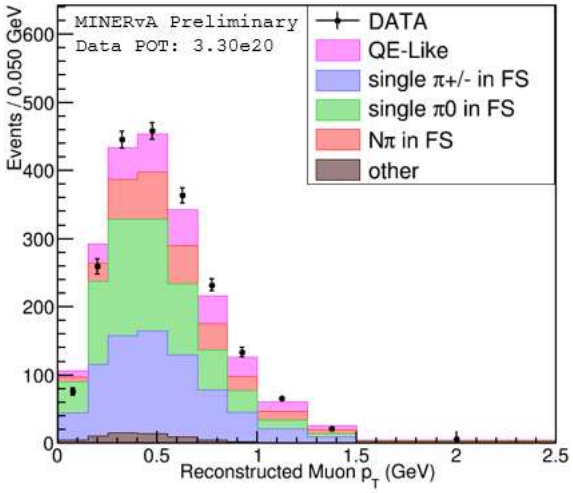
Lines of constant Q^2_{qe} [0.01,0.1,0.4,0.8,2.0,4.0,6.0]

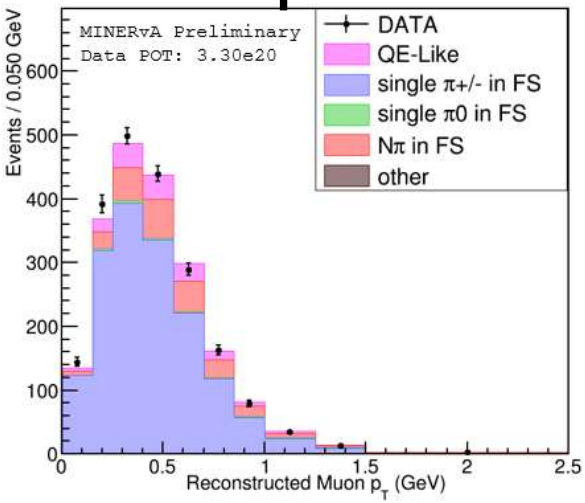
Background Subtraction Methodology

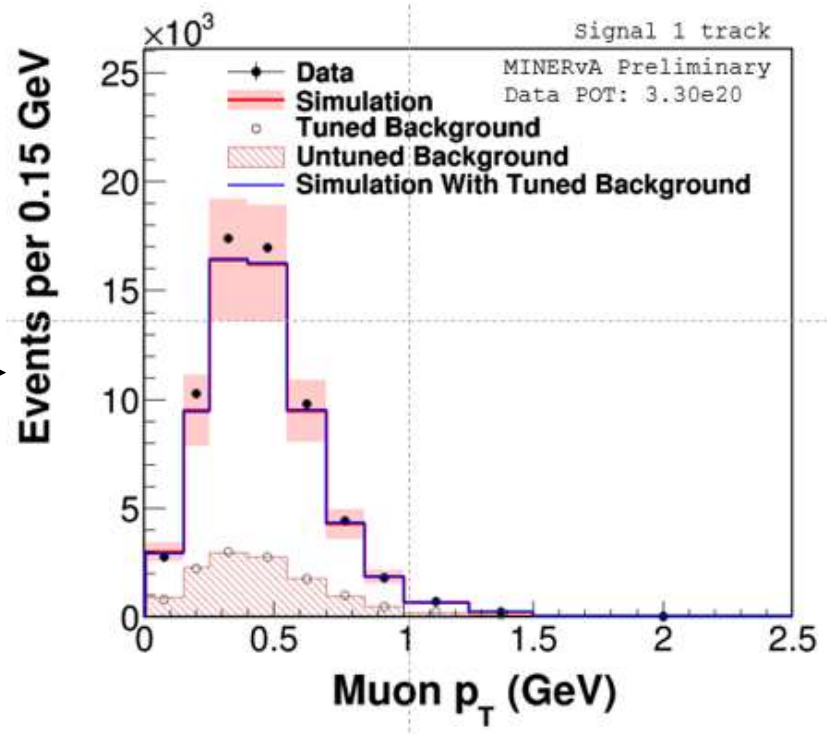
- Two side band samples:
  - Isolated energy deposits and Michel electron
- Idea is one constrains charged pions and the other neutral pions
- Extract scaling factors to apply to $\pi^{+/-}$ and π^{0}
  - In p_t, bin-by-bin or sum of bins depending on statistics

Selection and background constraint: 1-track sample

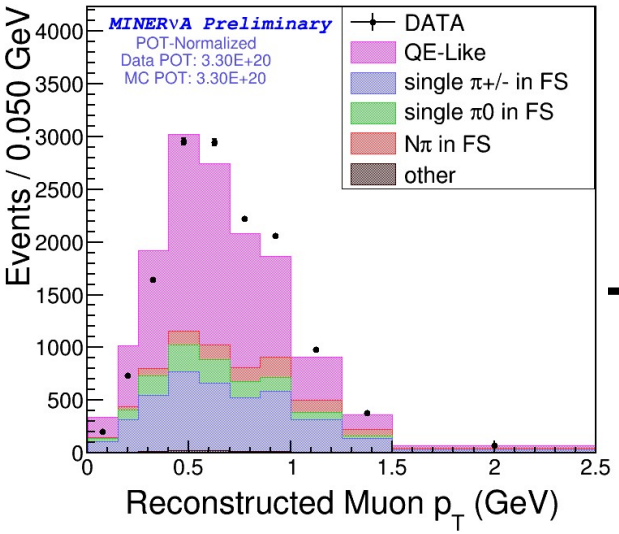


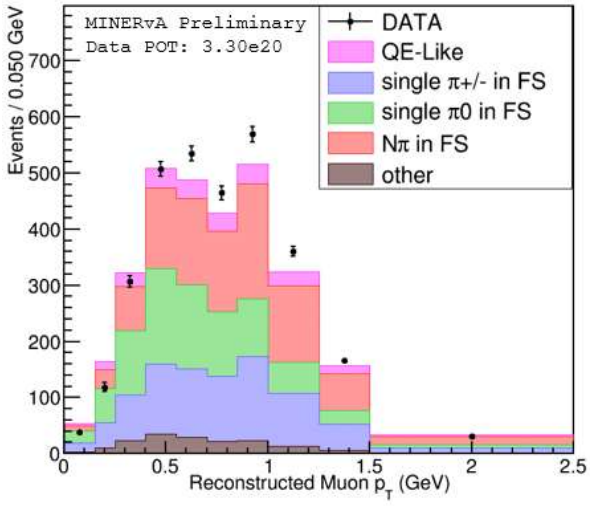


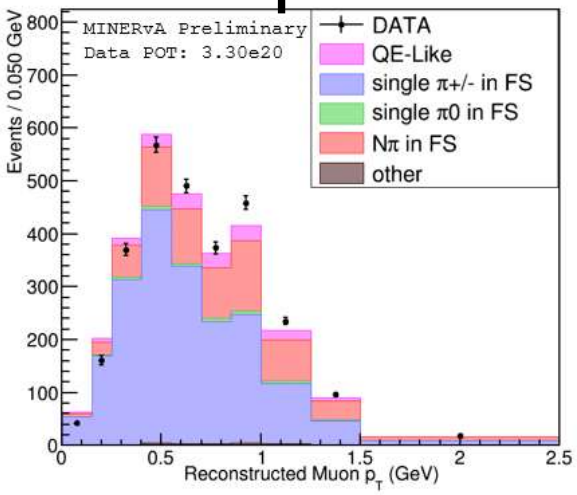


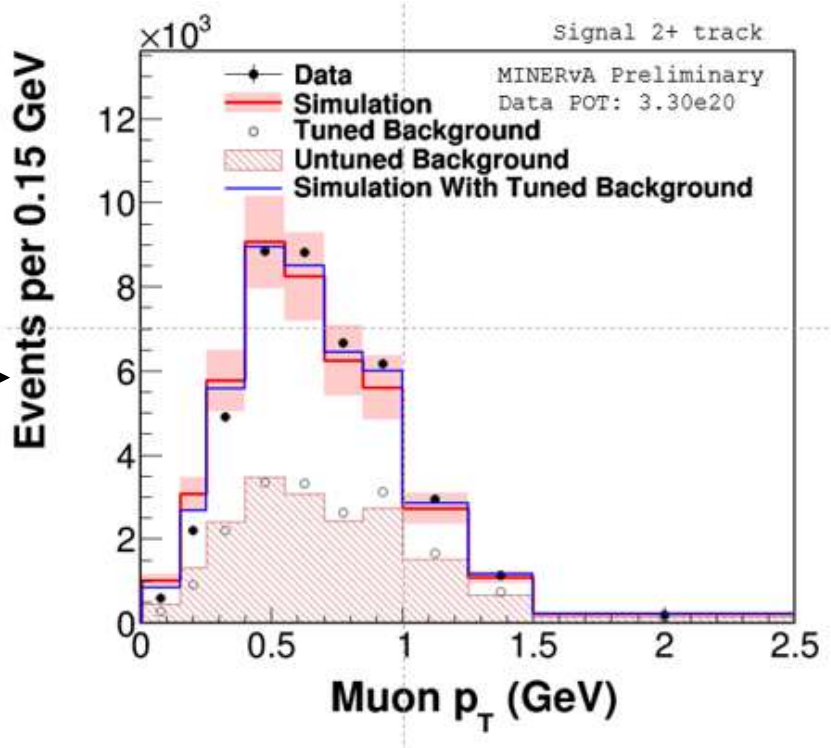


Selection and background constraint: 2+-track sample

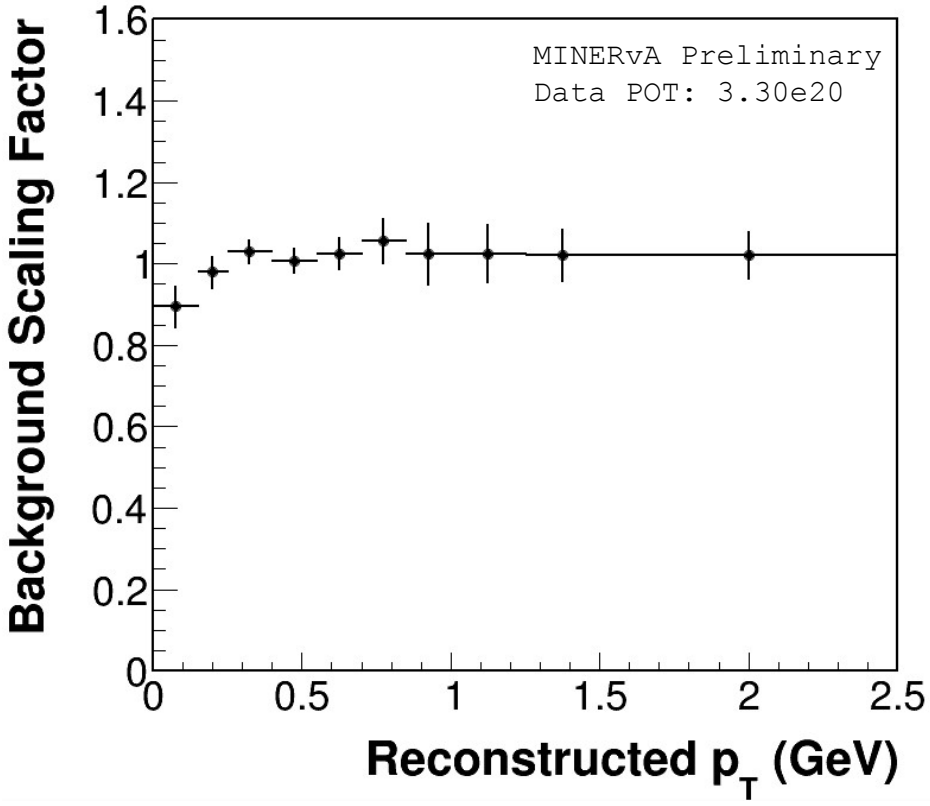




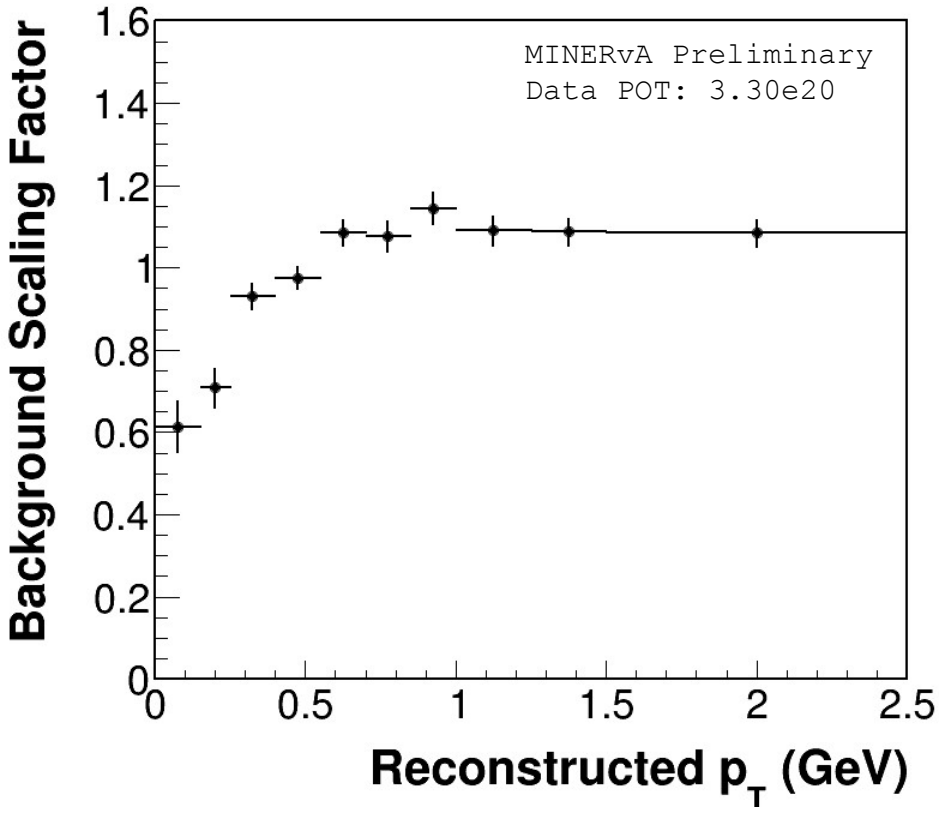




Scaling Factors

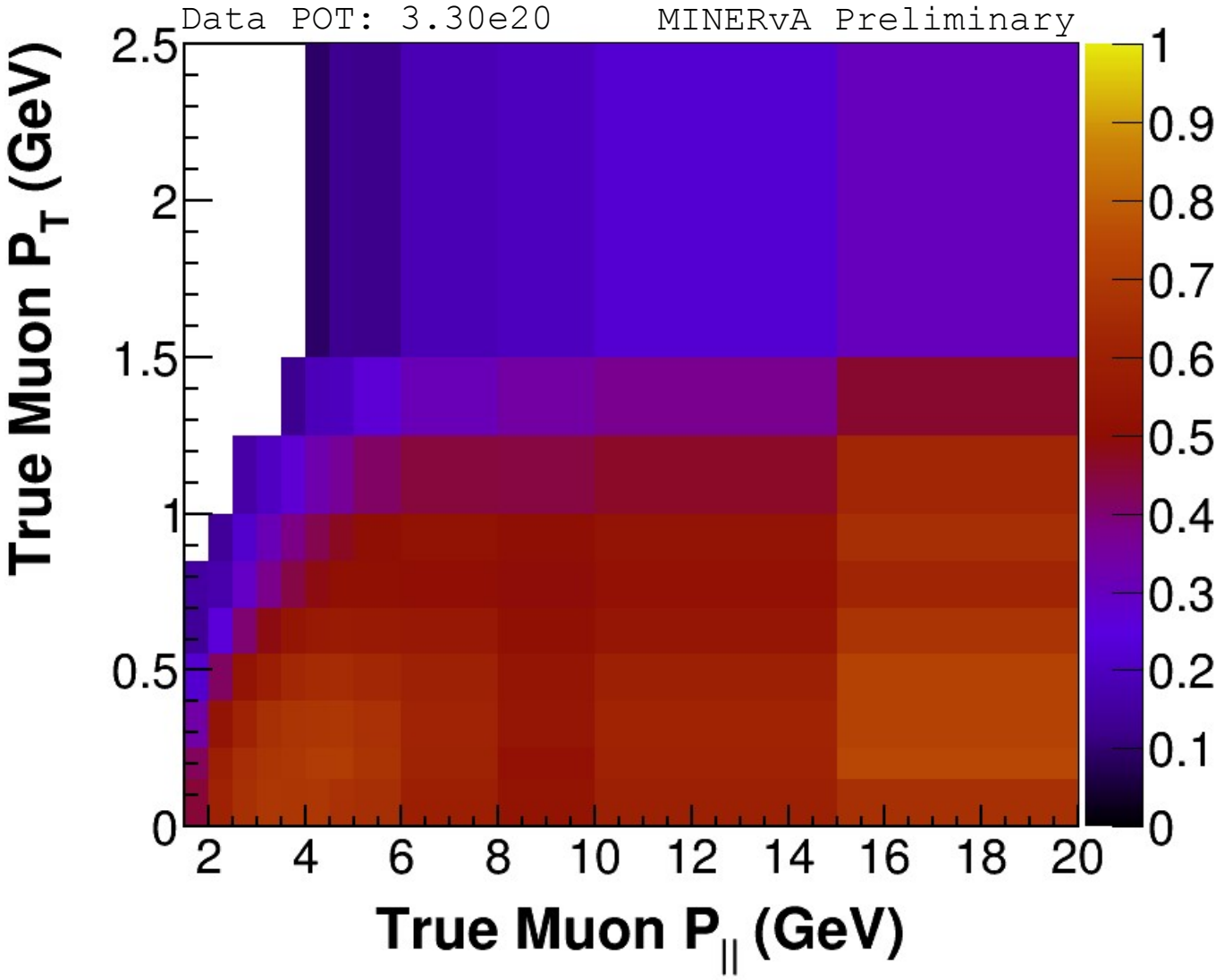


1-track sample

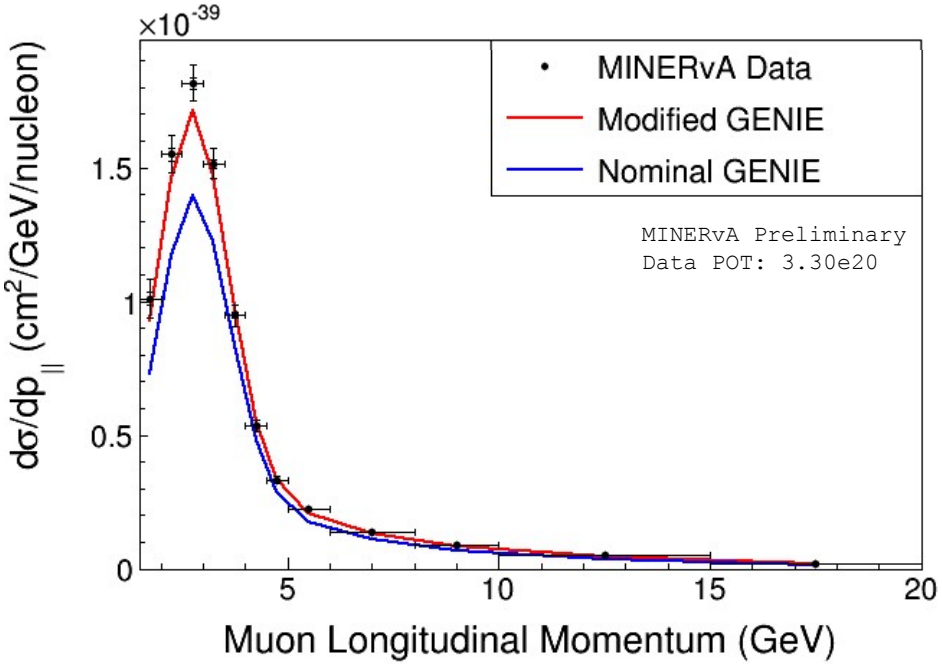


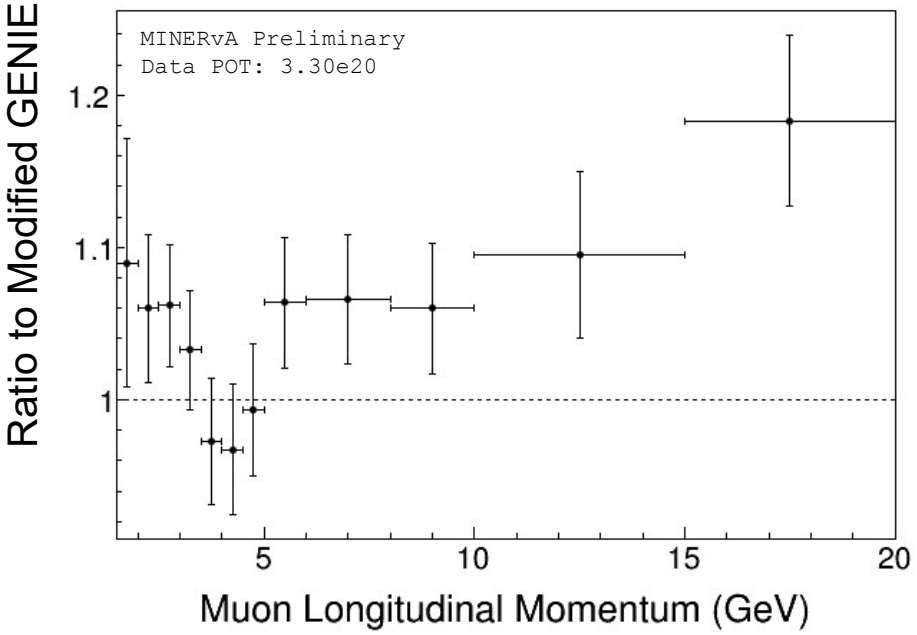
2+-track sample

Efficiency


Data POT: 3.30e20
MINERvA Preliminary
True Muon P_T (GeV)
True Muon $P_{||}$ (GeV)
0
0.5
1
1.5
2
2.5
2
4
6
8
10
12
14
16
18
20
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

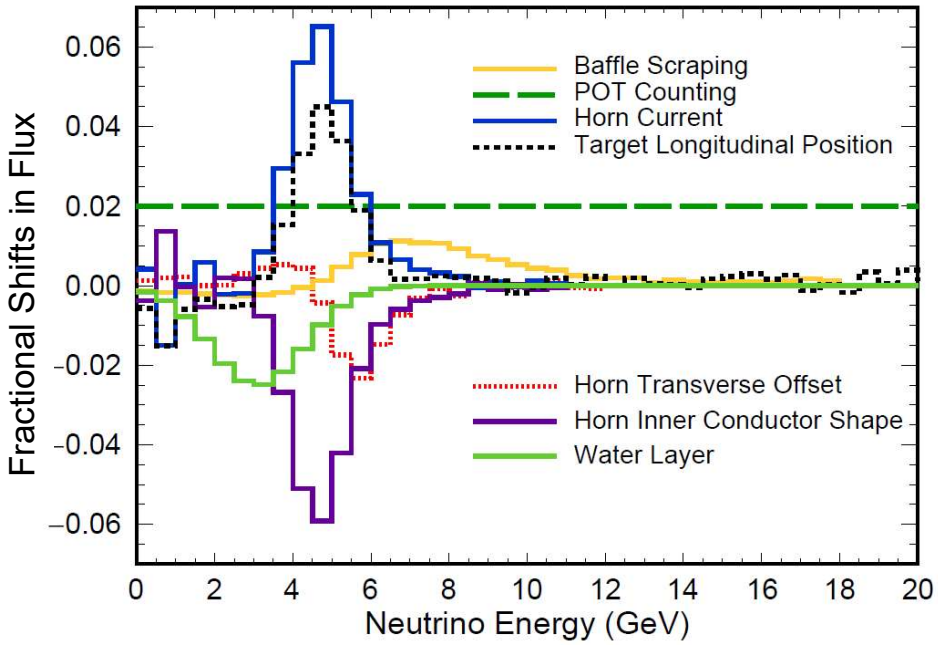
Quickly look at 1D versions

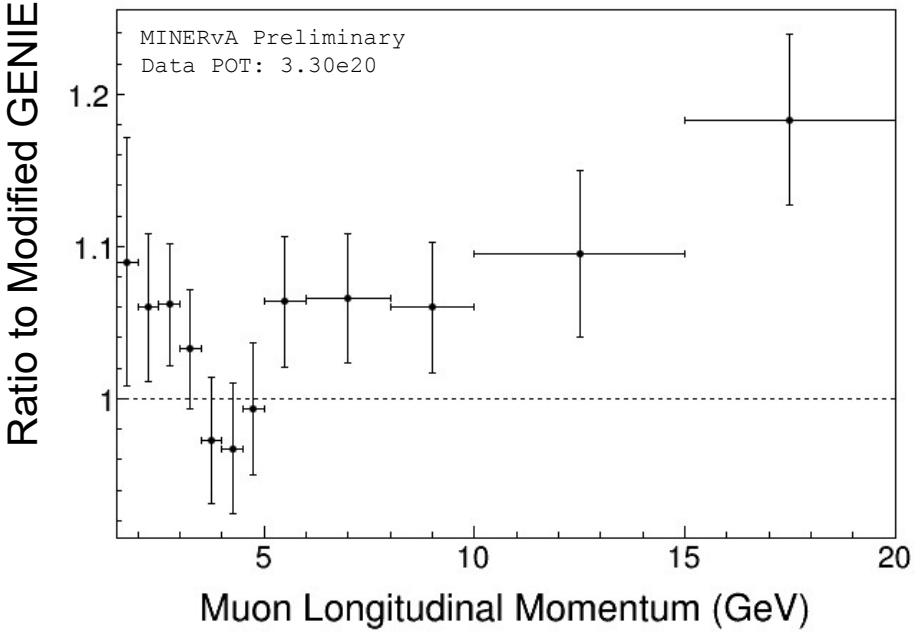




- In the ~3-5 GeV region the flux focusing systematics dominate
- This is right at the falling edge of the flux peak

Quickly look at 1D versions





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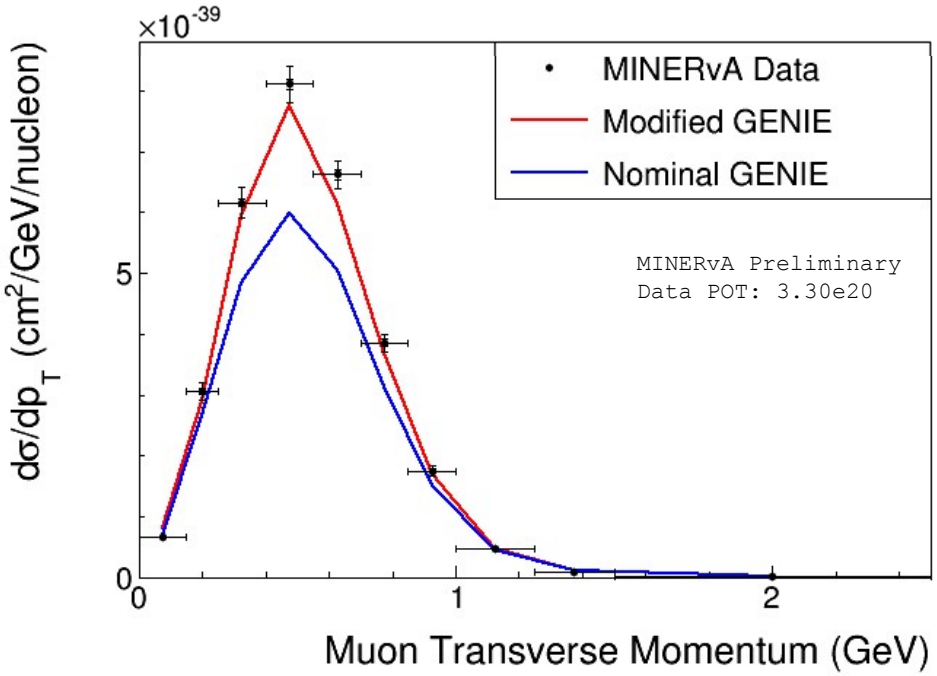
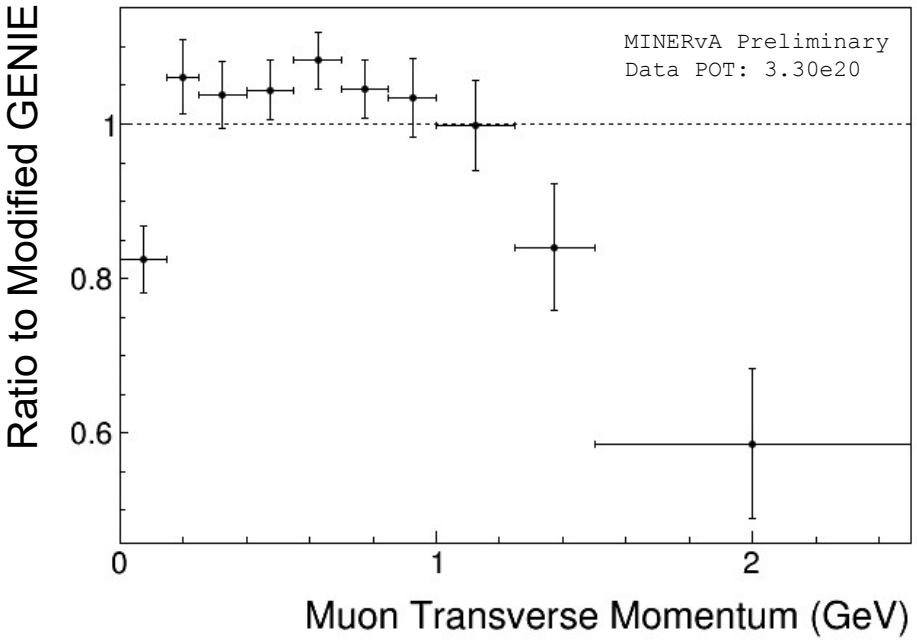
The focusing uncertainties are sufficient to cover this deviation

Quickly look at 1D versions





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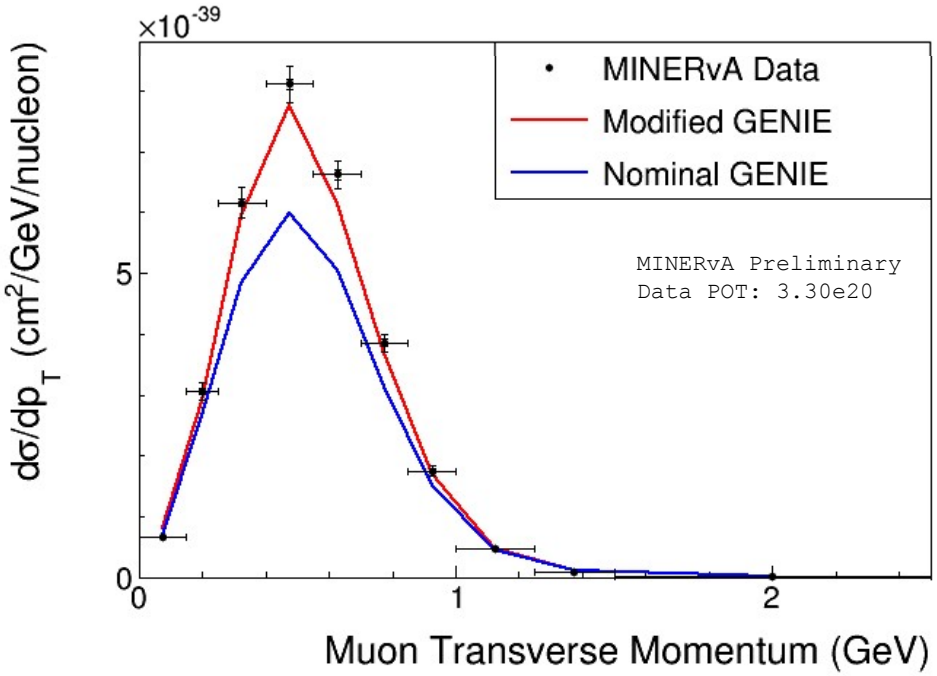
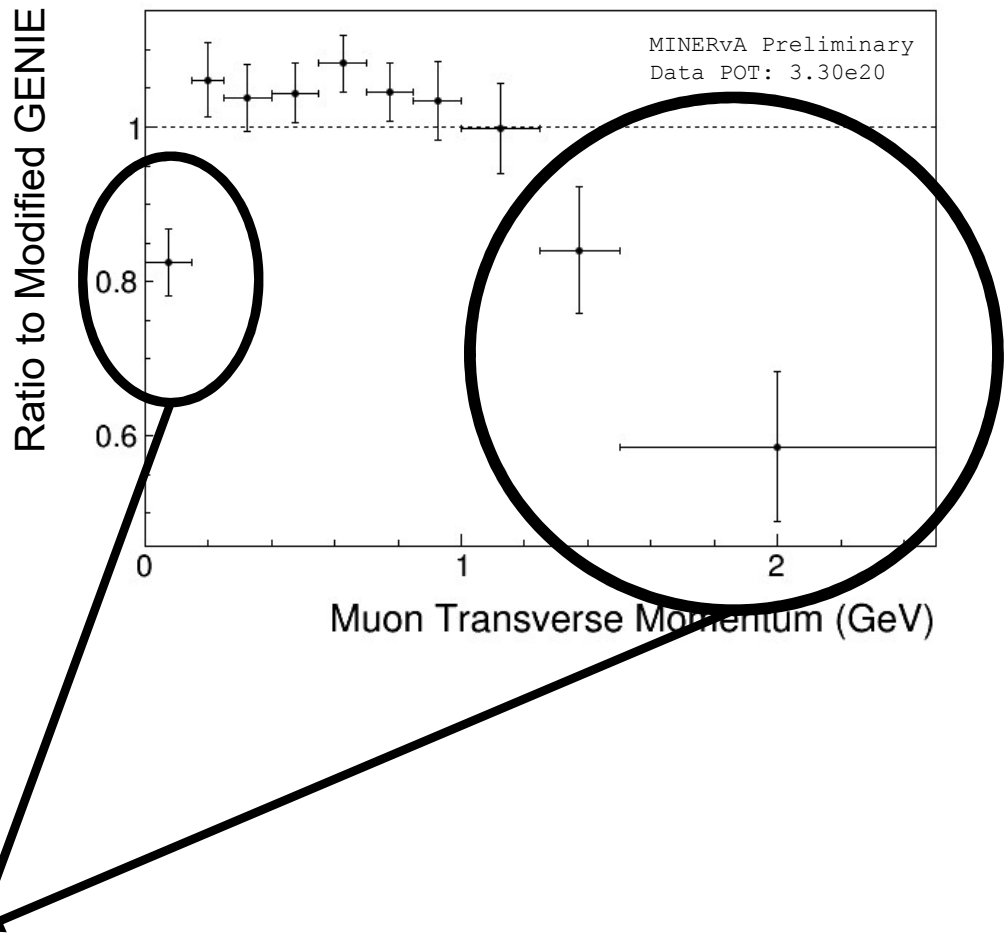
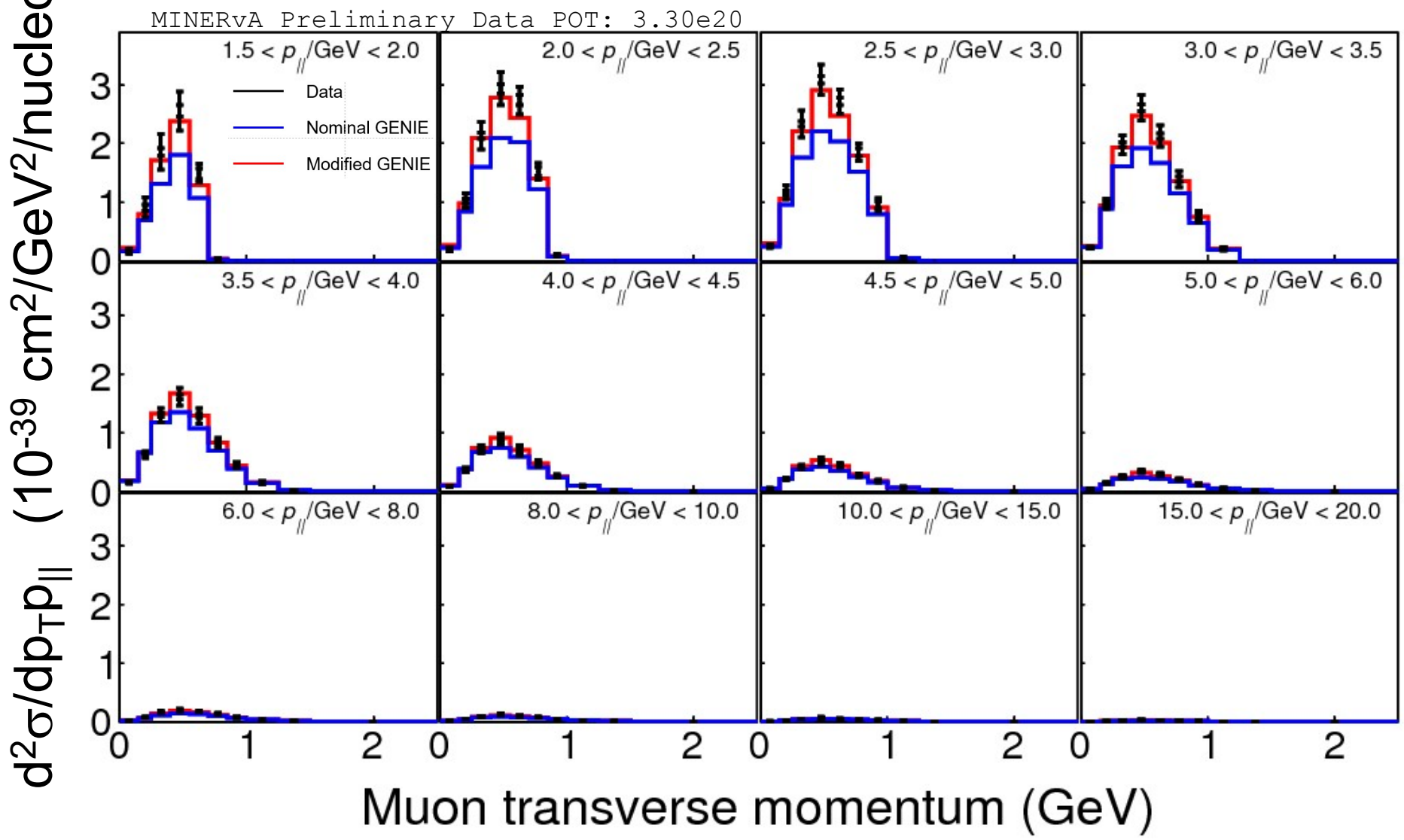


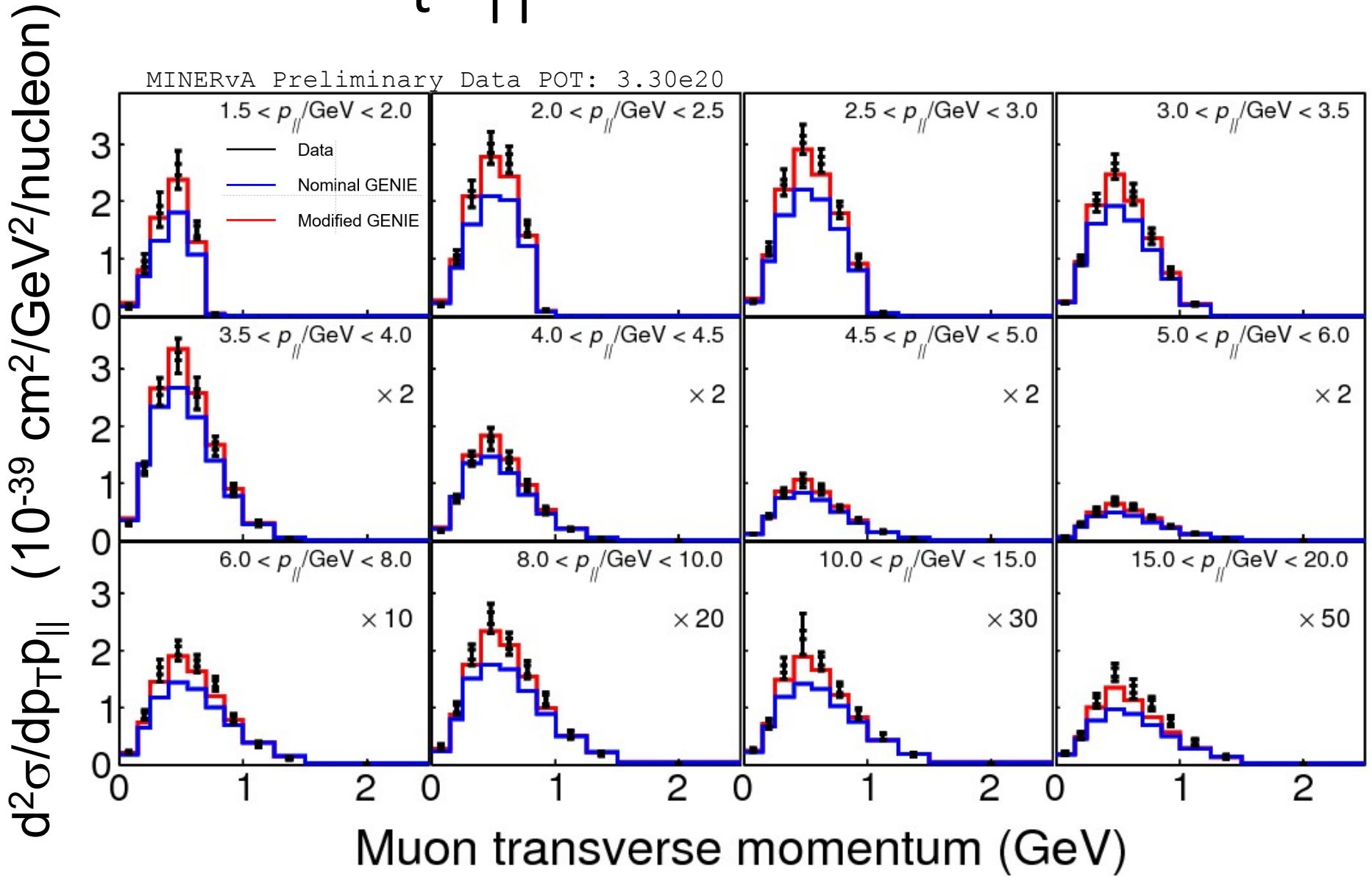


Let's go look at these in the 2D cross section

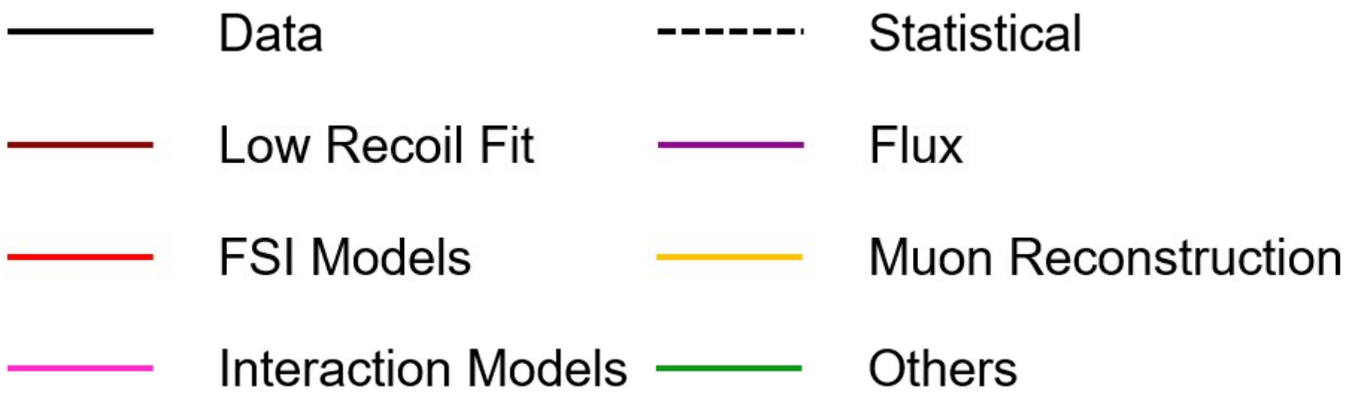
$P_t P_{||}$ Cross Section



$P_t P_{||}$ Cross Section



Systematic Uncertainties



- Low Recoil fit – Do the fit but varying only nn or np or QE components. Add in quadrature. Dominant in mid P_t bins which have the highest fraction of 2p2h events

Systematic Uncertainties

- Muon Reconstruction-
  - 11MeV shift from MINERvA material assay
  - 30 MeV shift from energy deposition per cm
  - 2% for energy by range MINOS
  - 0.6% > 1GeV or 2.5% <1GeV if measured by curvature
  - Added in quadrature

Systematic Uncertainties

- FSI Models- what particles get out of the nucleus and energy sharing between nucleons and pions
- Dominated by pion absorption
  - Background–>signal migration strength

Systematic Uncertainties

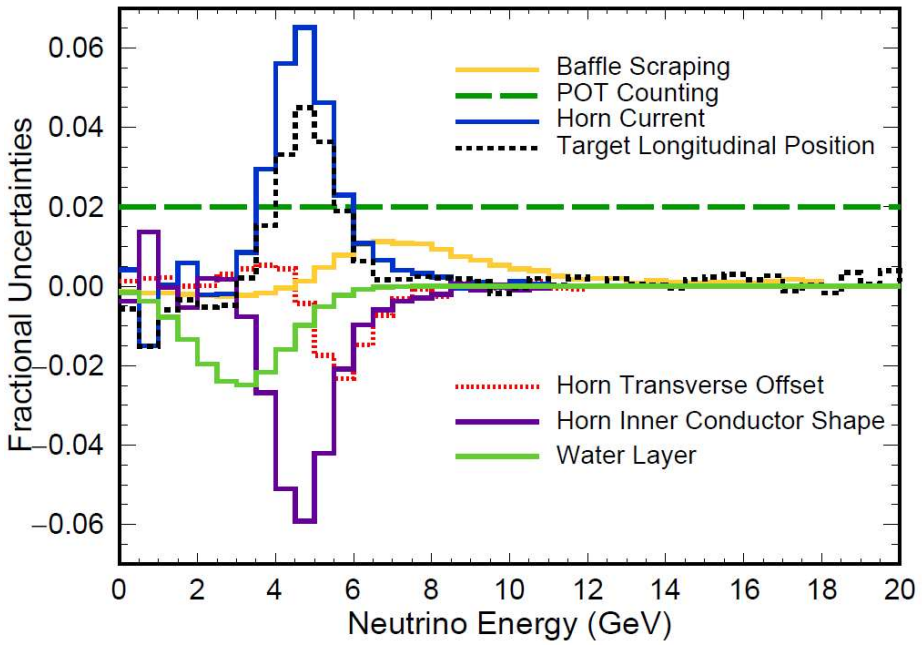
- Interaction Models – These are the GENIE model parameters' uncertainties.
- In general small (good!) but as p_T increases the data constraint on backgrounds isn't as good and we start depending on the model more

Systematic Uncertainties

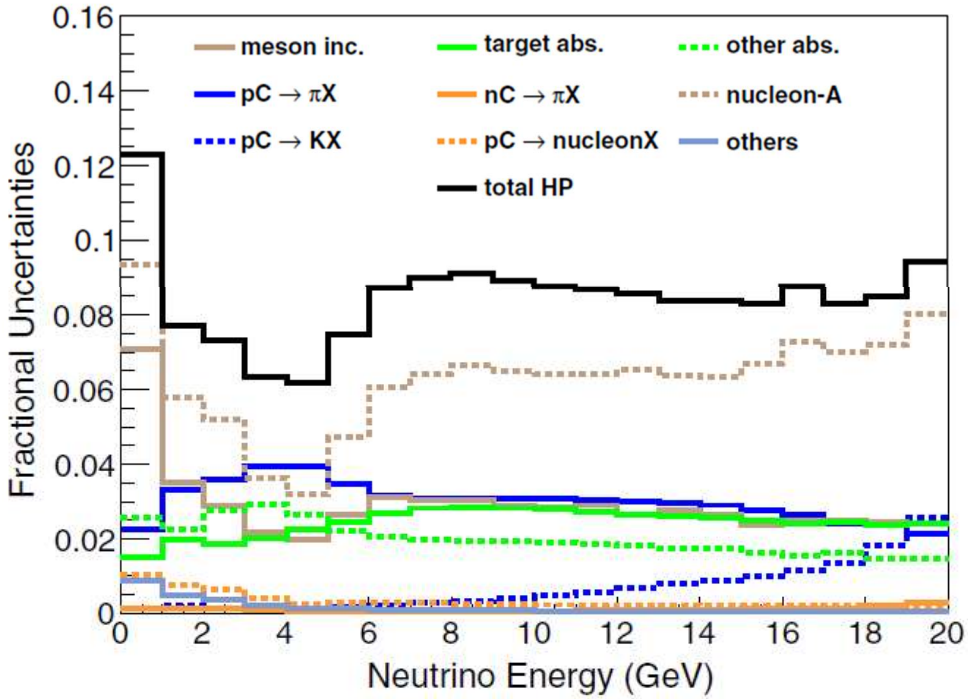
Data
Statistical
Low Recoil Fit
Flux
FSI Models
Muon Reconstruction
Interaction Models
Others

- Flux – See Phys. Rev. D 94, 092005 (2016)

Focusing Uncertainties



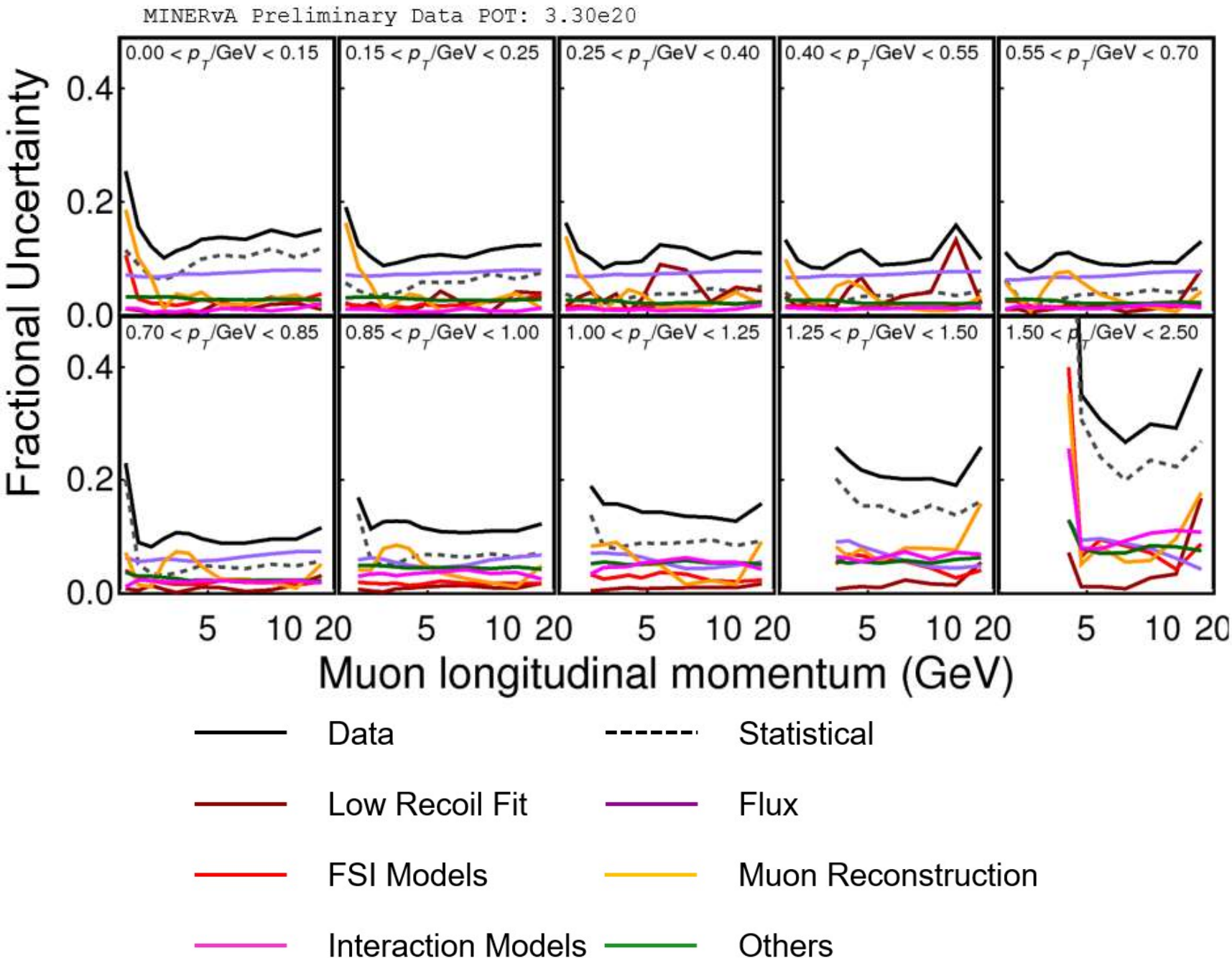
Hadron Production Uncertainties



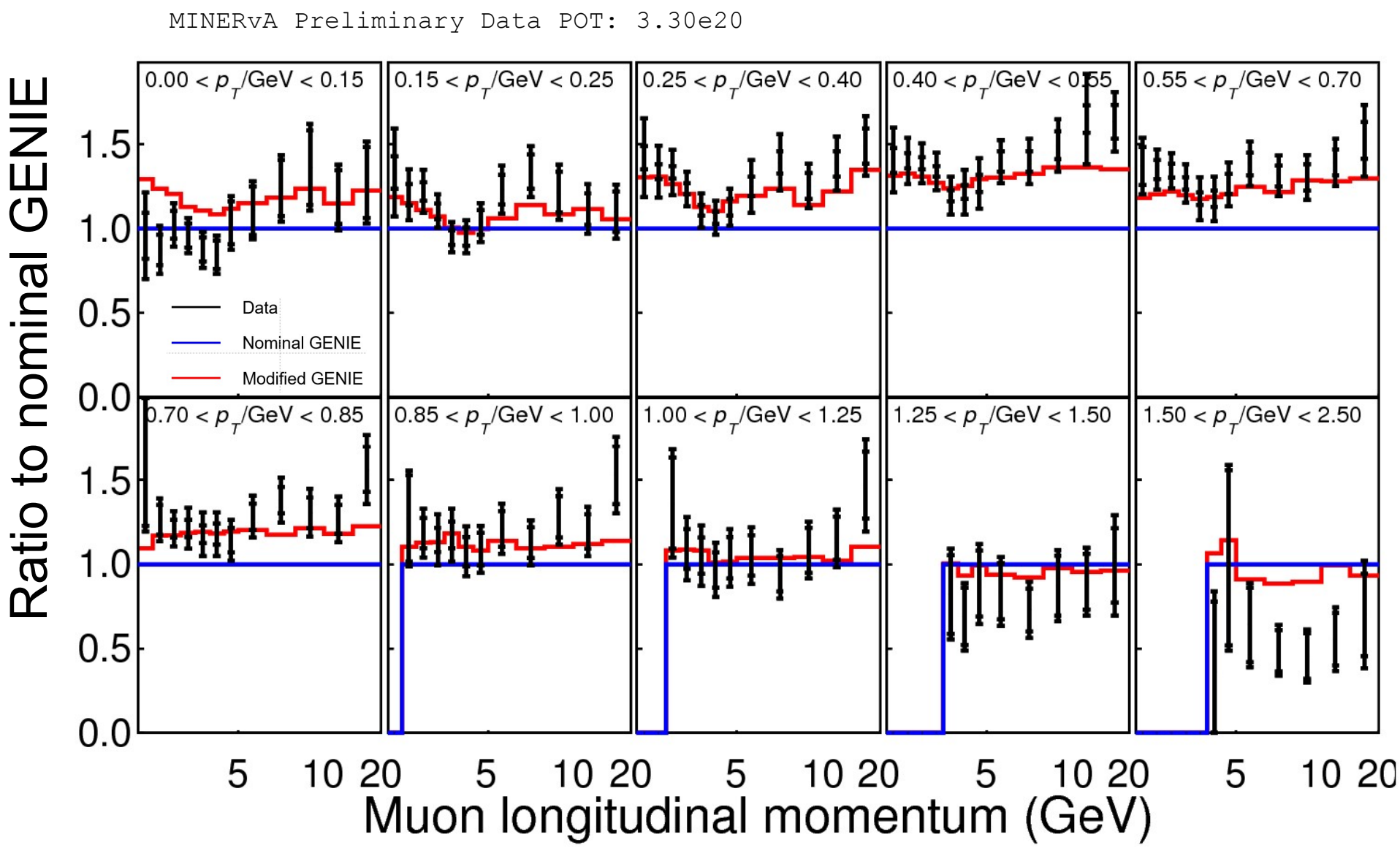
Systematic Uncertainties

- Others – Summation of many small uncertainties
- Includes – **particle response in detector**, energy of hits, number of targets, matching efficiencies between MINOS and MINERvA, Bethe-Bloch.

Systematic Uncertainties



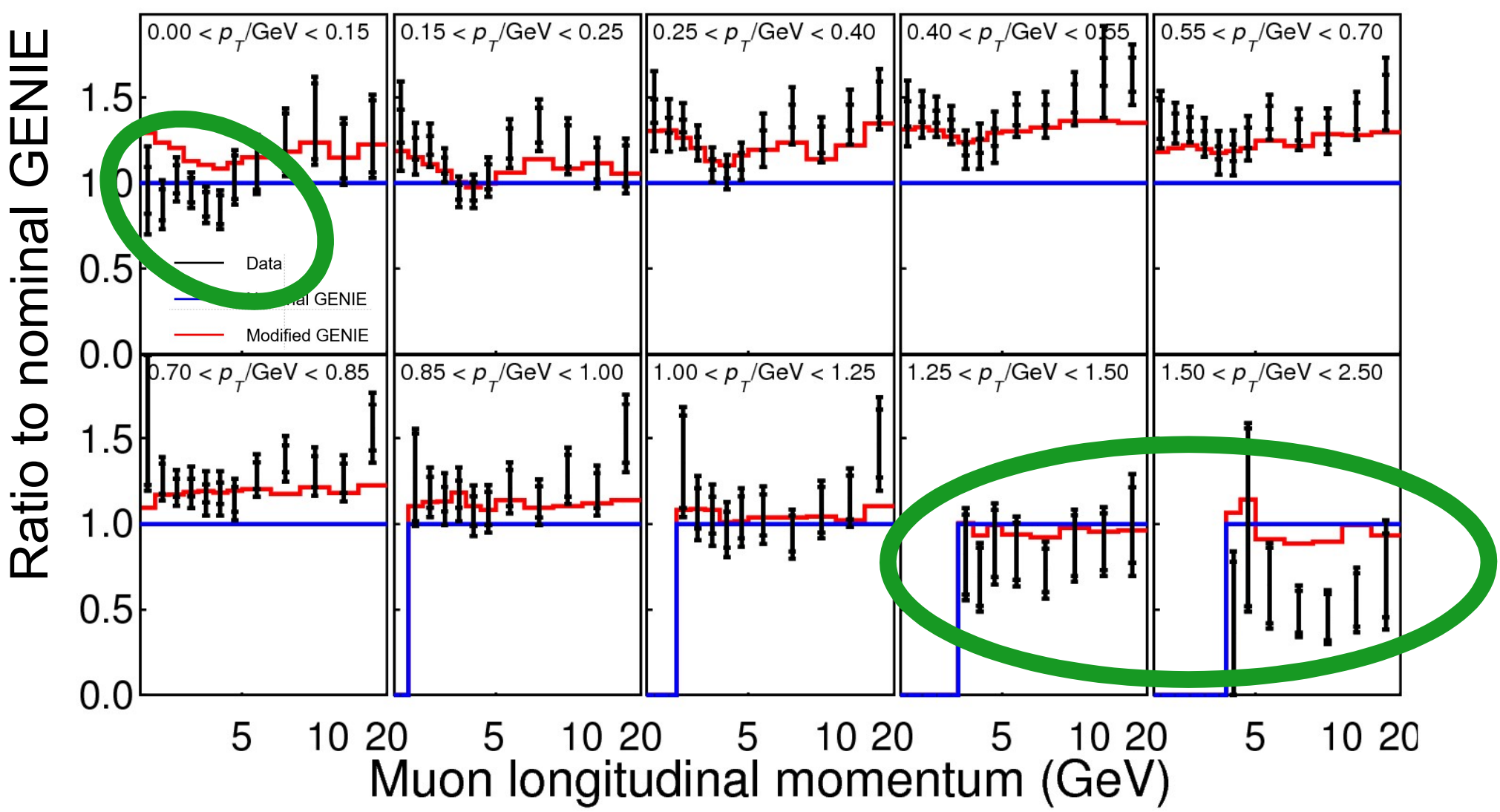
Comparison To Nominal GENIE



Modified GENIE χ^2=170 (stat.+sys, 120 dof)

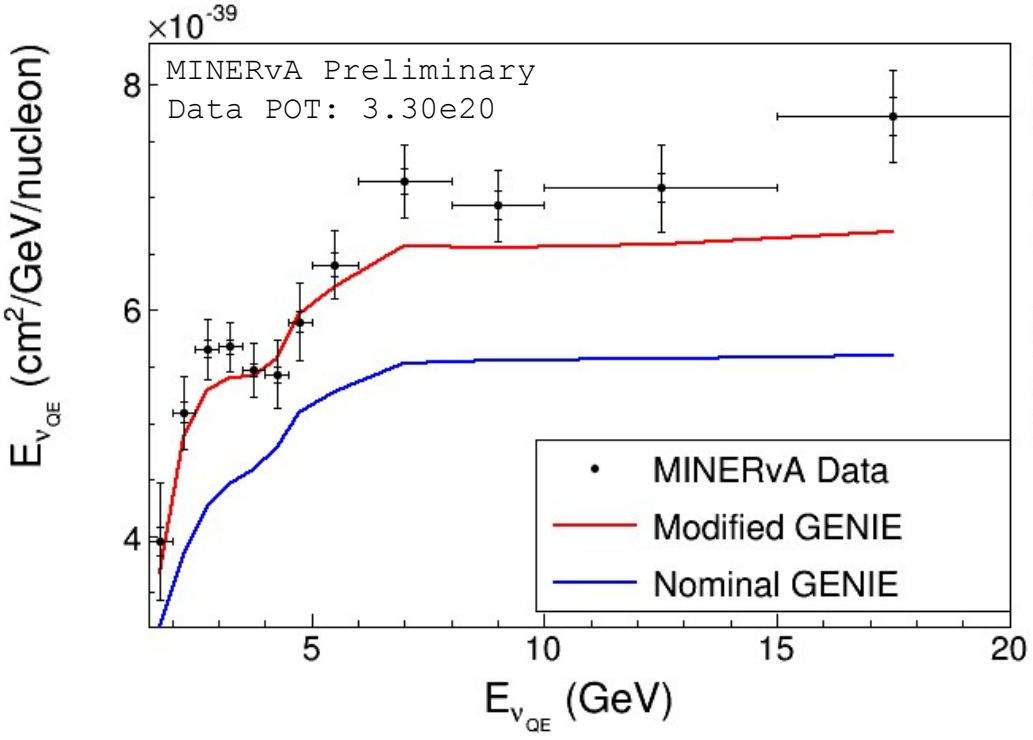
Nominal GENIE χ^2=220 (stat.+sys, 120 dof)

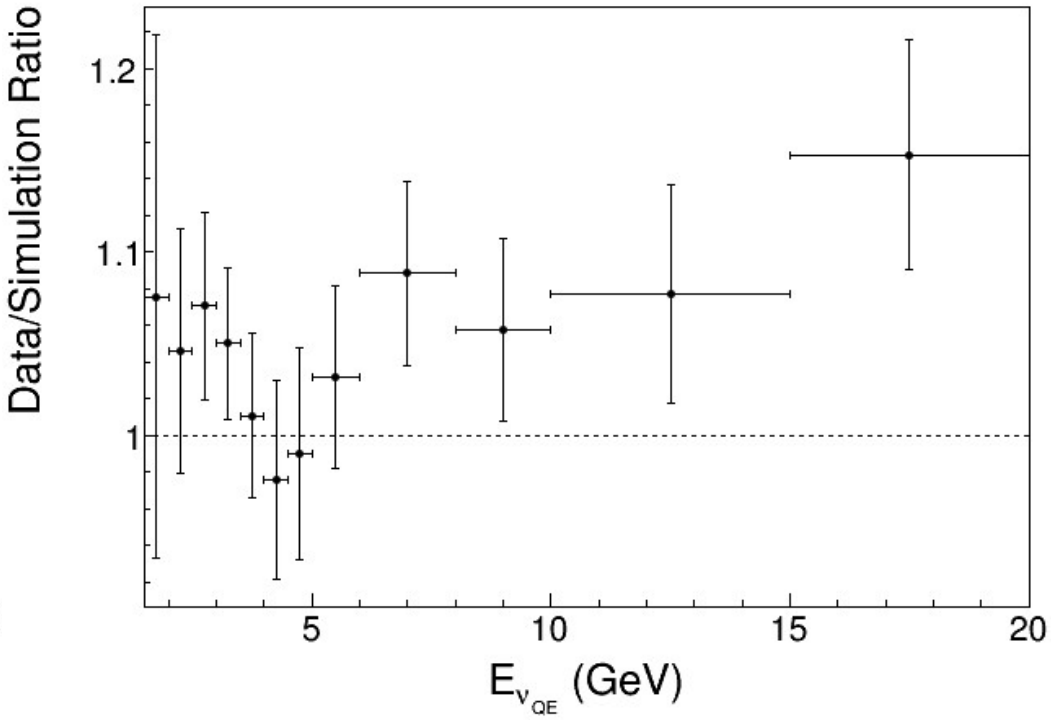
Comparison To Nominal GENIE



Two interesting regions which will pop up later in the Q^2_{QE} section

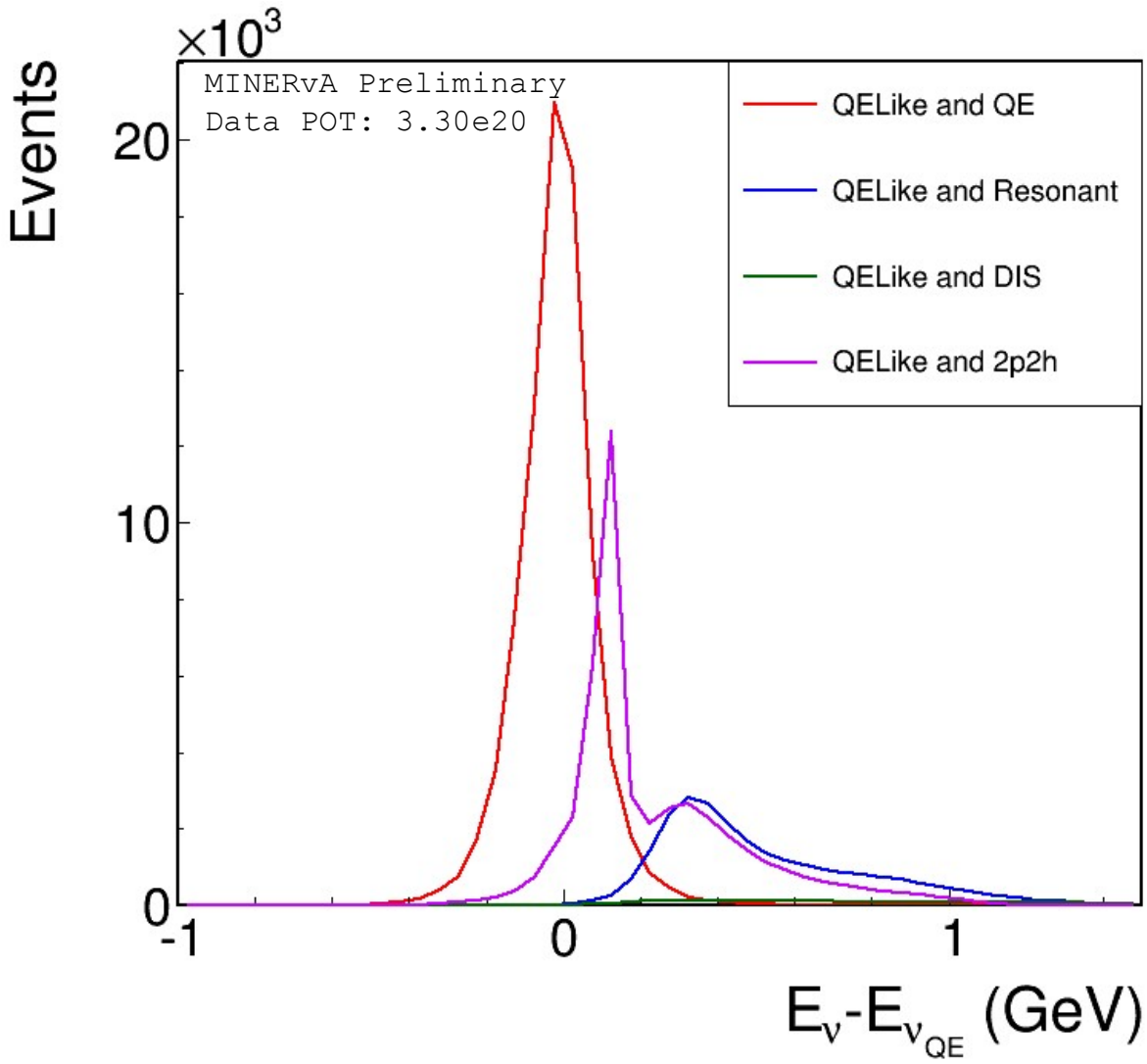
“σ”($E_{\nu,QE}$)





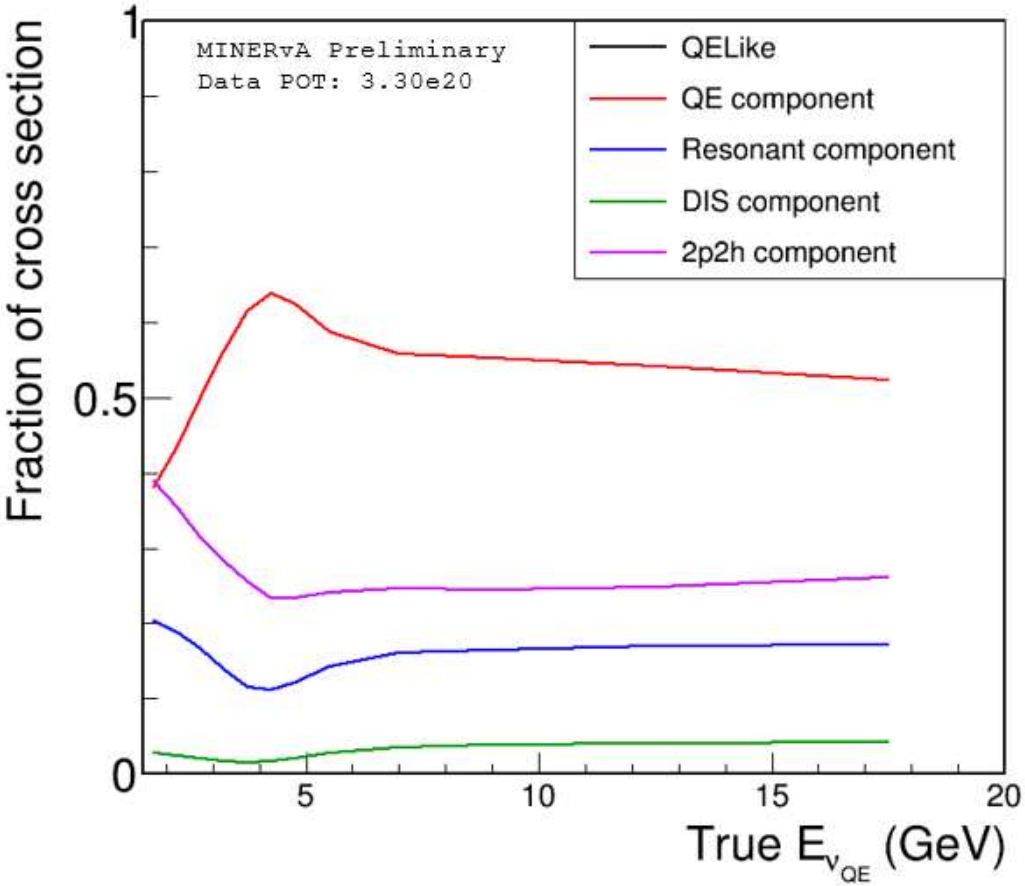
- This is NOT true E_ν
- But, we normalize in bins of true E_ν
- What is the difference?

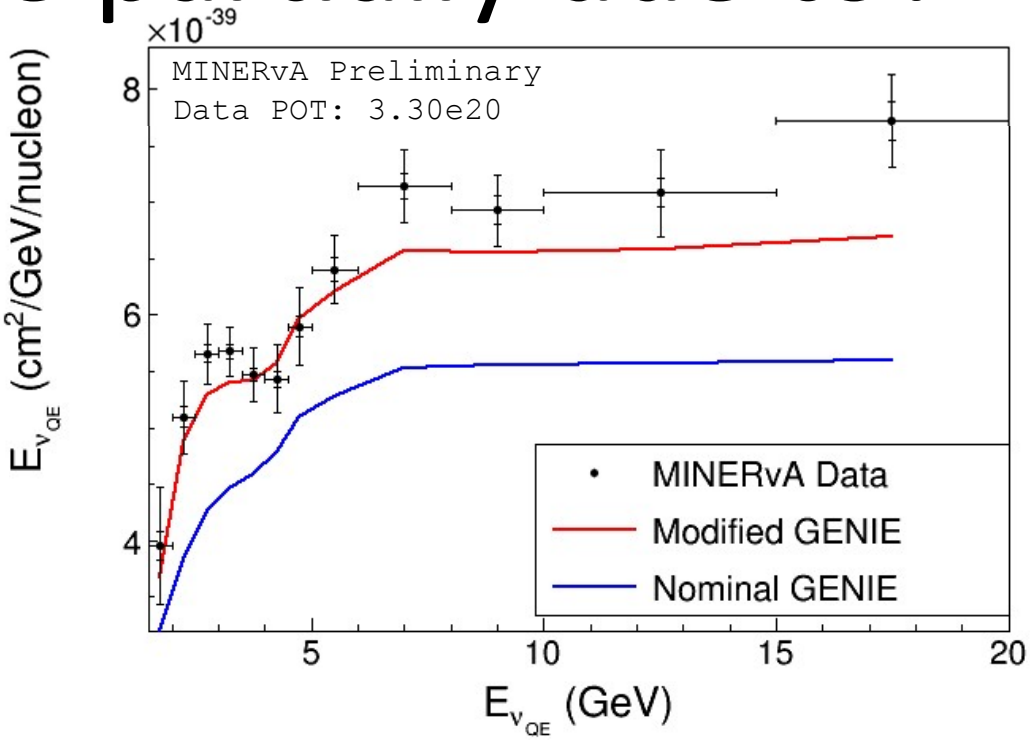
QELike-components: $E_\nu - E_{\nu,QE}$



What's the wiggle partially due to?

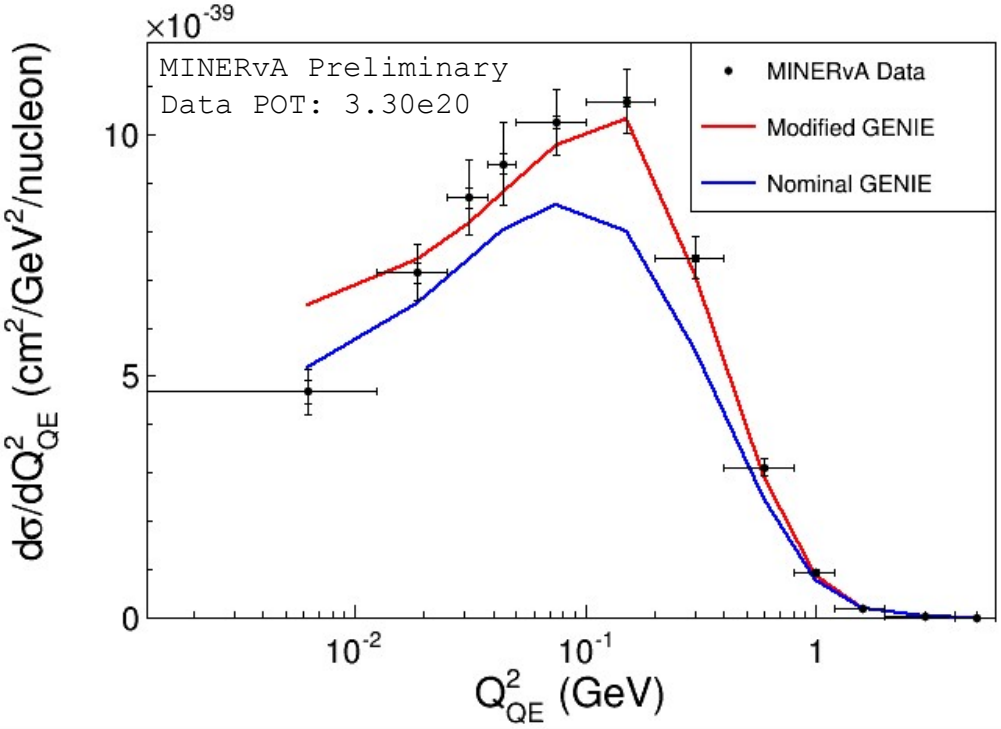
Rapidly changing fractions of non-QE components with biased $E_{\nu,QE}$

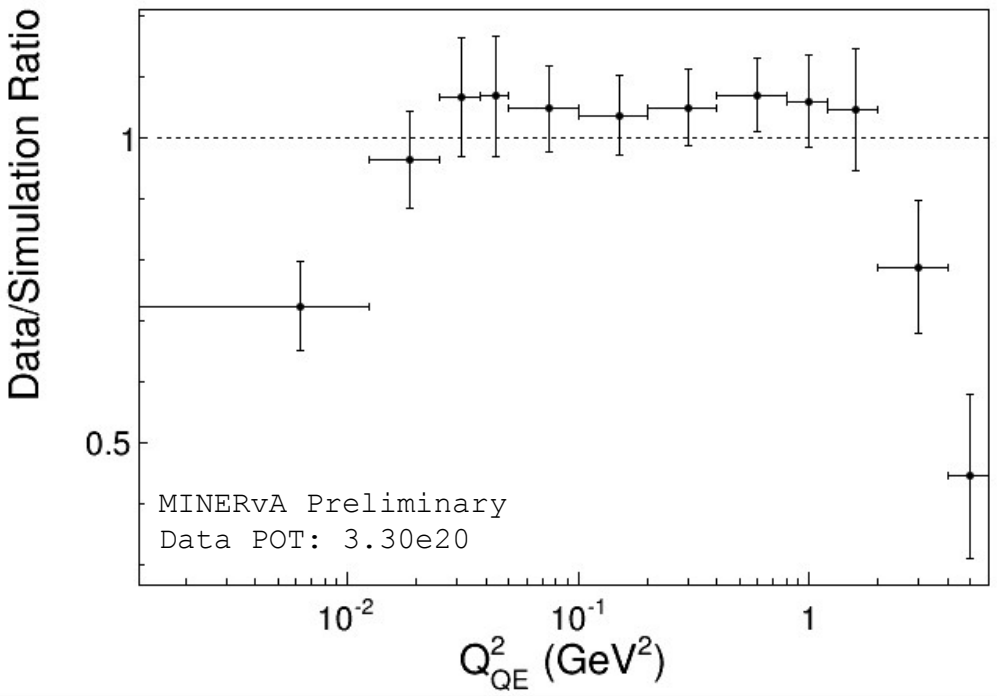




Why only partially? We see a wiggle, smaller, in $p_{||}$. This is thought to be part of a mismodeling of the falling edge of the focusing peak.

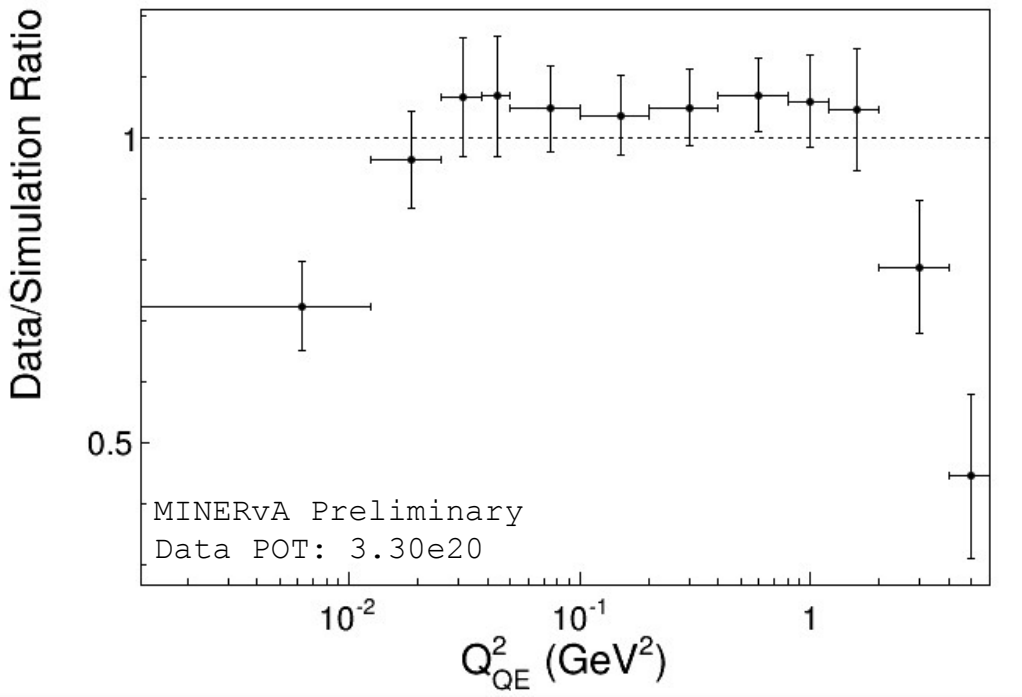
Q^2_{QE} Cross Section

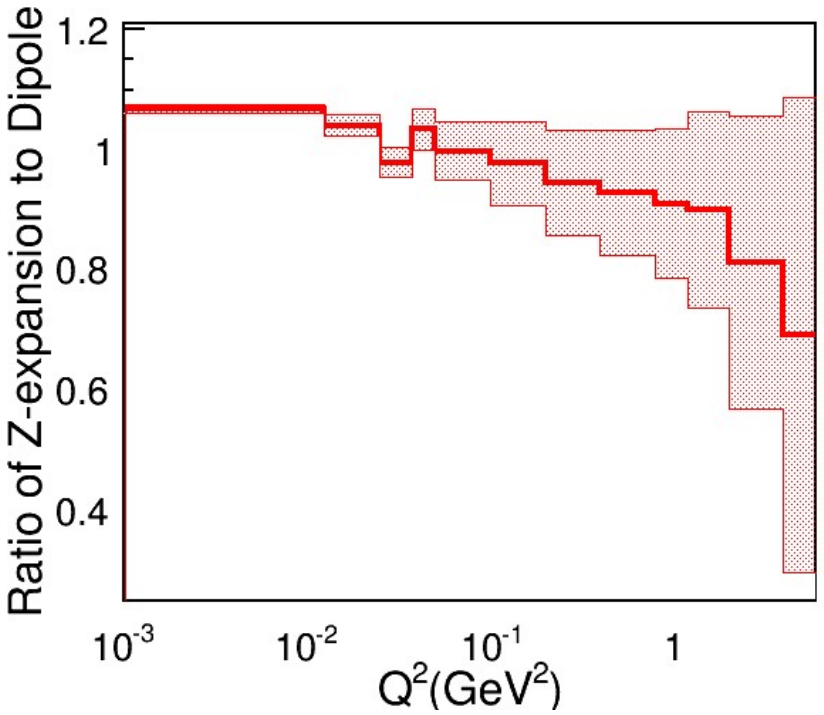




- The low Q^2_{QE} bin shows up in the low recoil analysis as well.
- The high Q^2_{QE} discrepancy is potentially due to the dipole axial form factor we use.

Z-expansion of Form Factors

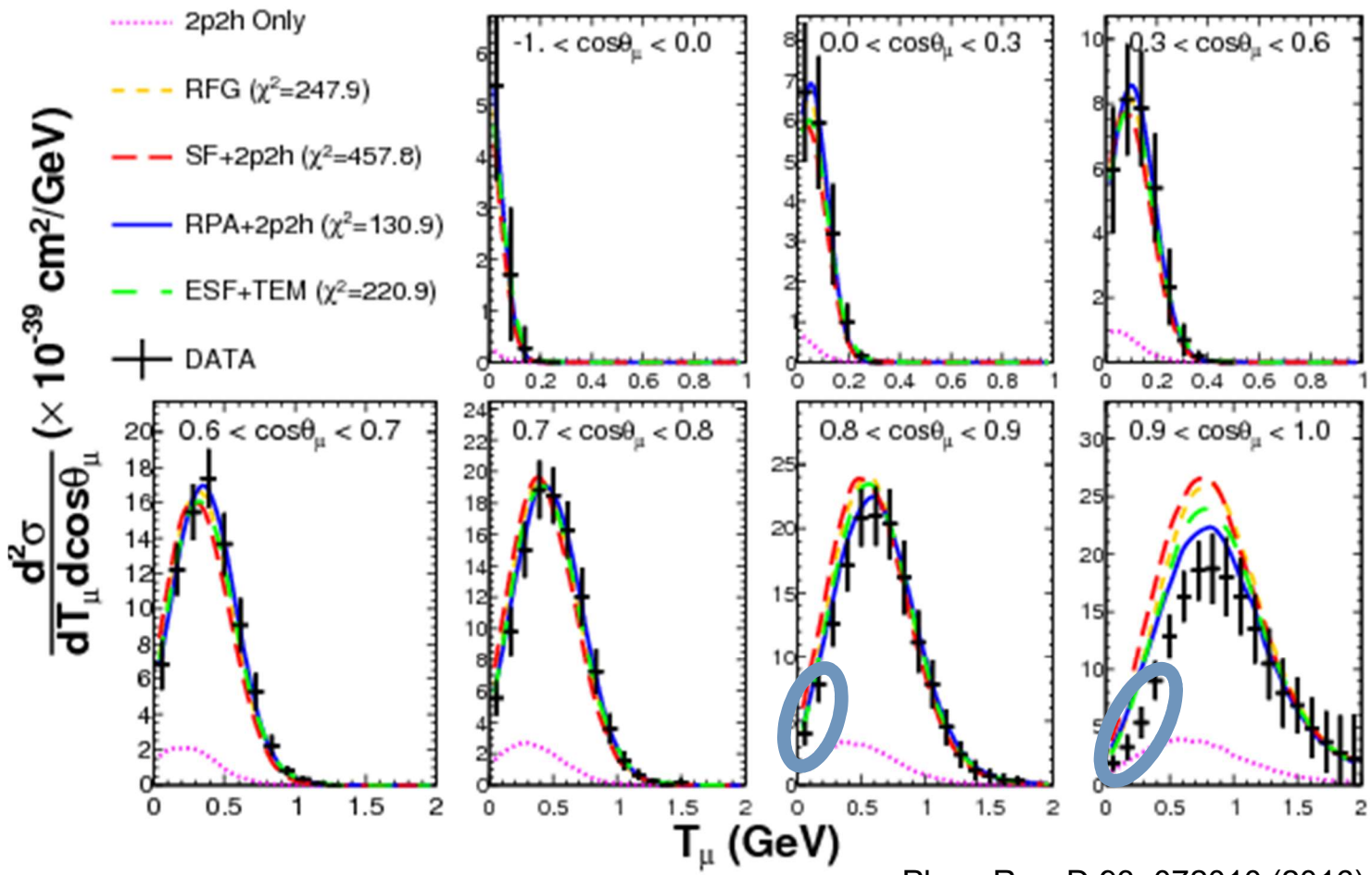




Phys.Rev. D84, 073006 (2011)
Phys.Rev. D93, 113015 (2016)

- Z-expansion is a model independent axial form factor
- This is interesting, but it not a 1 to 1 comparison
- The Z-expansion plot is true Q^2 and true QE

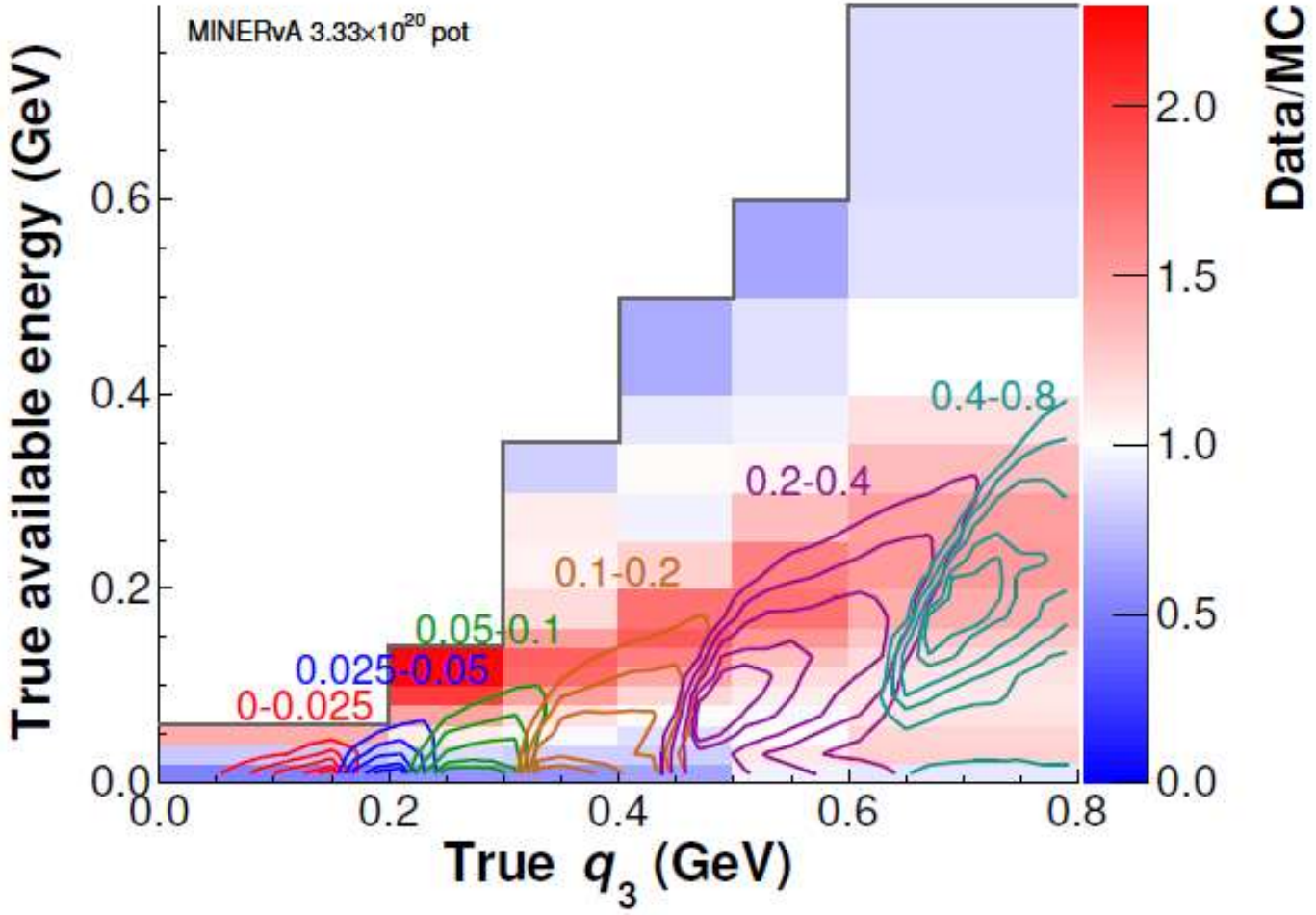
Where does our low Q^2_{QE} reside in MiniBooNE phase space?



Phys. Rev. D 93, 072010 (2016)
Phys. Rev. D 81, 092005 (2010)

Assumes contribution is all CCQE

Where does this reside in our inclusive result?



GENIE predicts about 1/3 of the rate in the p_T /$p_{||}$ bins are from true QE.
The result above also see these contributions (along the diagonal)
Low Q^2 predictions of the non-QE component are difficult.

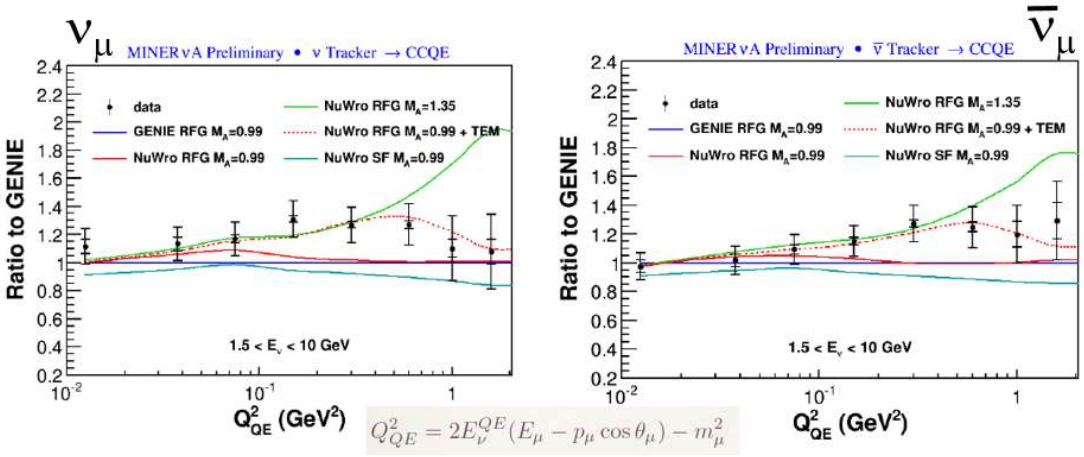
Recap

- As we utilize better models our agreement with data improves, but there is still work to be done!
- The p_T $p_{||}$ result will be useful to the model building community, with new components necessary to better reproduce the data
- MINERvA can access larger Q^2 which is interesting when comparing to the Z-expansion
- $E_{\nu,QE}$ is a variable which depends on your model.
  - Better get that model correct!

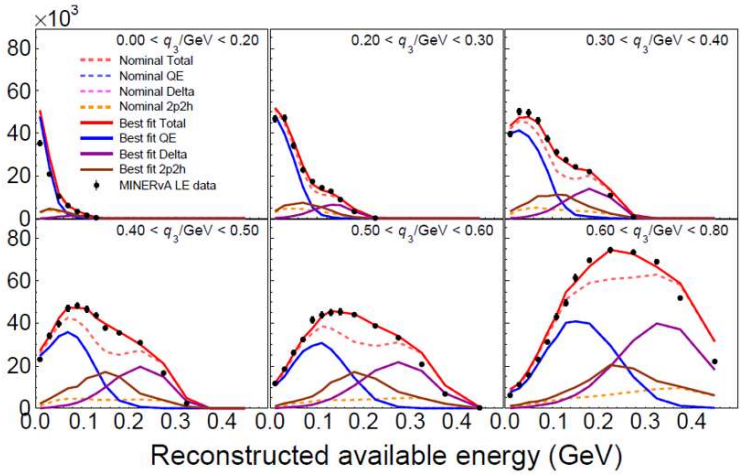
Looking to the future

- MINERvA has a very large dataset from the NOvA era neutrino run. What can we do?
  - Explore that higher Q^2_{QE} space which is currently limited in statistics
  - Slice the data in more ways.
- Continue to utilize better models as they become available. Test them.
- Continue to study FSI and A-dependence using our C, Fe, Pb targets.

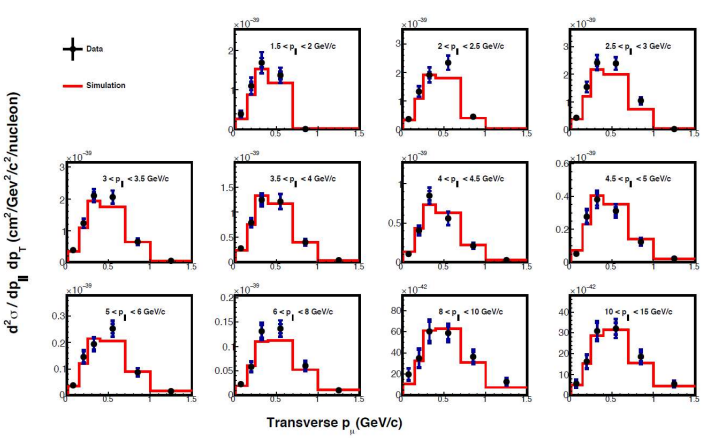
Conclusions

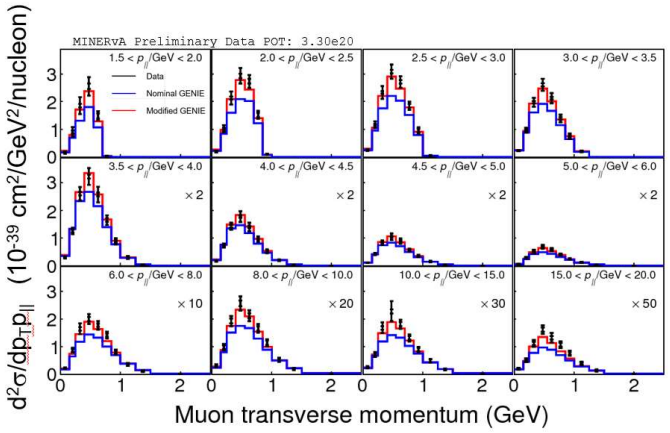


We need 2p2h-like models in our simulation!



We have a model + ad hoc corrections to describe the inclusive data





Works on neutrino ***AND*** antineutrino exclusive channels!

This is CC0π – just like the primary signal region in T2K

We have a prescription which can be directly applied to oscillation experiments.

Backups

Previous CCQE(like) Results

Old CCQE Results Model Comp

χ^2

	Both Modes	Neutrinos	Antineutrinos
GENIE	40.5	27.6	24.0
$NuWro(M_A = 0.99)$	52.6	38.1	26.9
$NuWro(M_A = 1.35)$	56.8	50.9	25.4
$NuWro(M_A = 0.99)TEM$	26.8	21.1	7.6
$NuWro(M_A = 0.99)SLF$	44.8	39.5	27.8
$NuWro(M_A = 0.99)RPA$	101.8	109.8	39.6

Reconstruction Variables

- $q_0 \equiv \nu$ = Calorimetric Hadronic Energy
- $E_\nu = E_\mu + q_0$
- $Q^2 = 2E_\nu\left(E_\mu - p_\mu cos\theta_\mu\right) - M_\mu^2$
- $q_3 \equiv |\boldsymbol{q}| = \sqrt{Q^2 - q_0^2}$

$$E_{\text{avail}} = \sum(\text{Proton and } \pi^{\pm} \text{ KE}) + (\text{Total } E \text{ of other particles except neutrons})$$

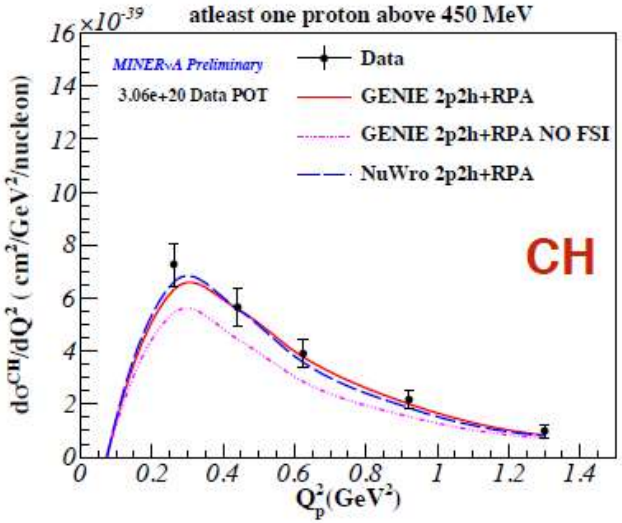
How about the hadron side of things?

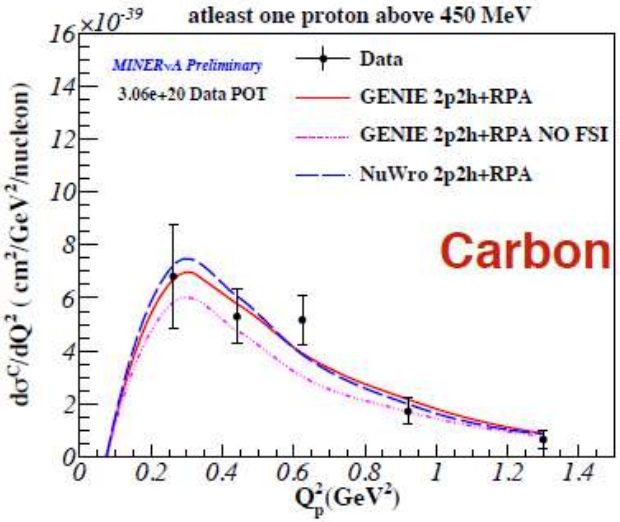
- Select two track events in the tracker and also isolate a sample in the nuclear targets
- Does not require a MINOS match – because…

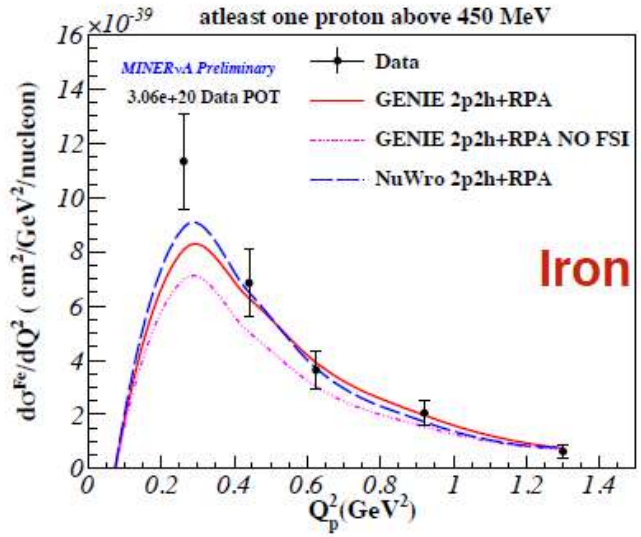
$$Q^2 = (M')^2 - M_p^2 + 2M'(T_p + M_p - M')$$

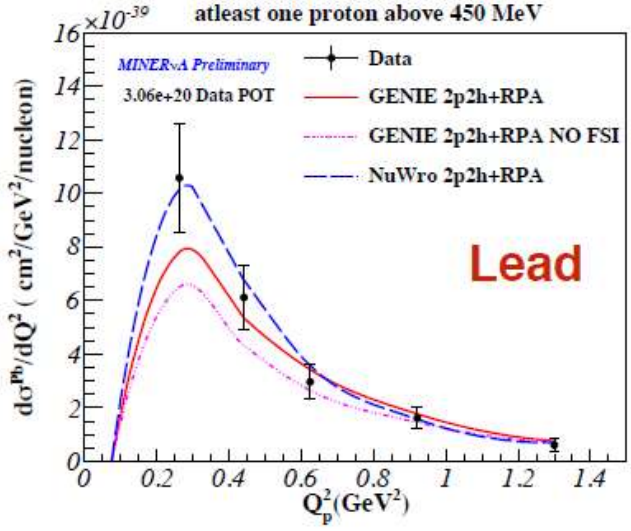
- Nuclear targets provide A-dependent measurements on C, Fe, Pb

What does the proton say?









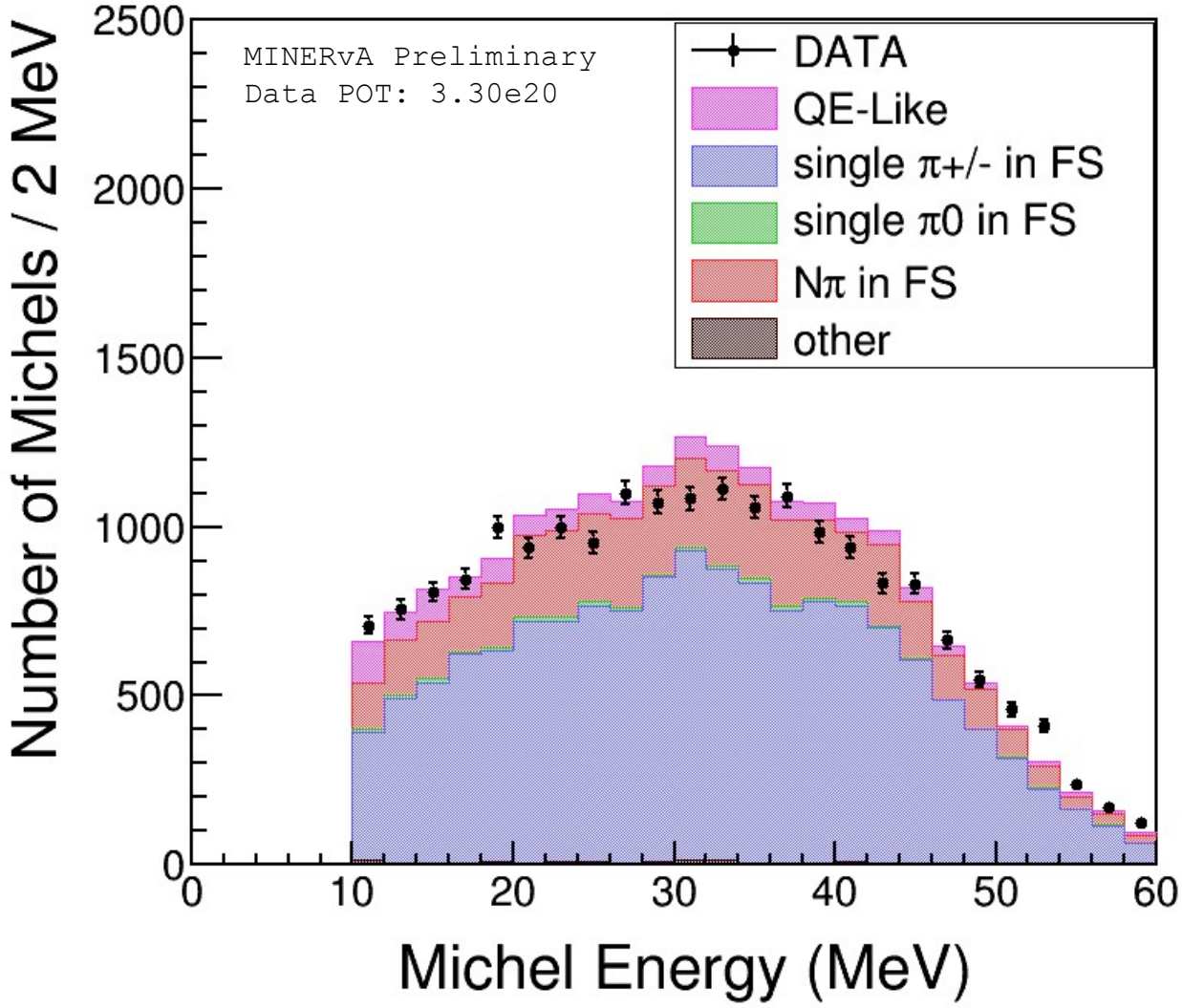
It says…

- GENIE 2p2h+RPA models an analysis off the CH target in the track and the C target in the nuclear region
- A dependence simulation in NuWro better represents the data

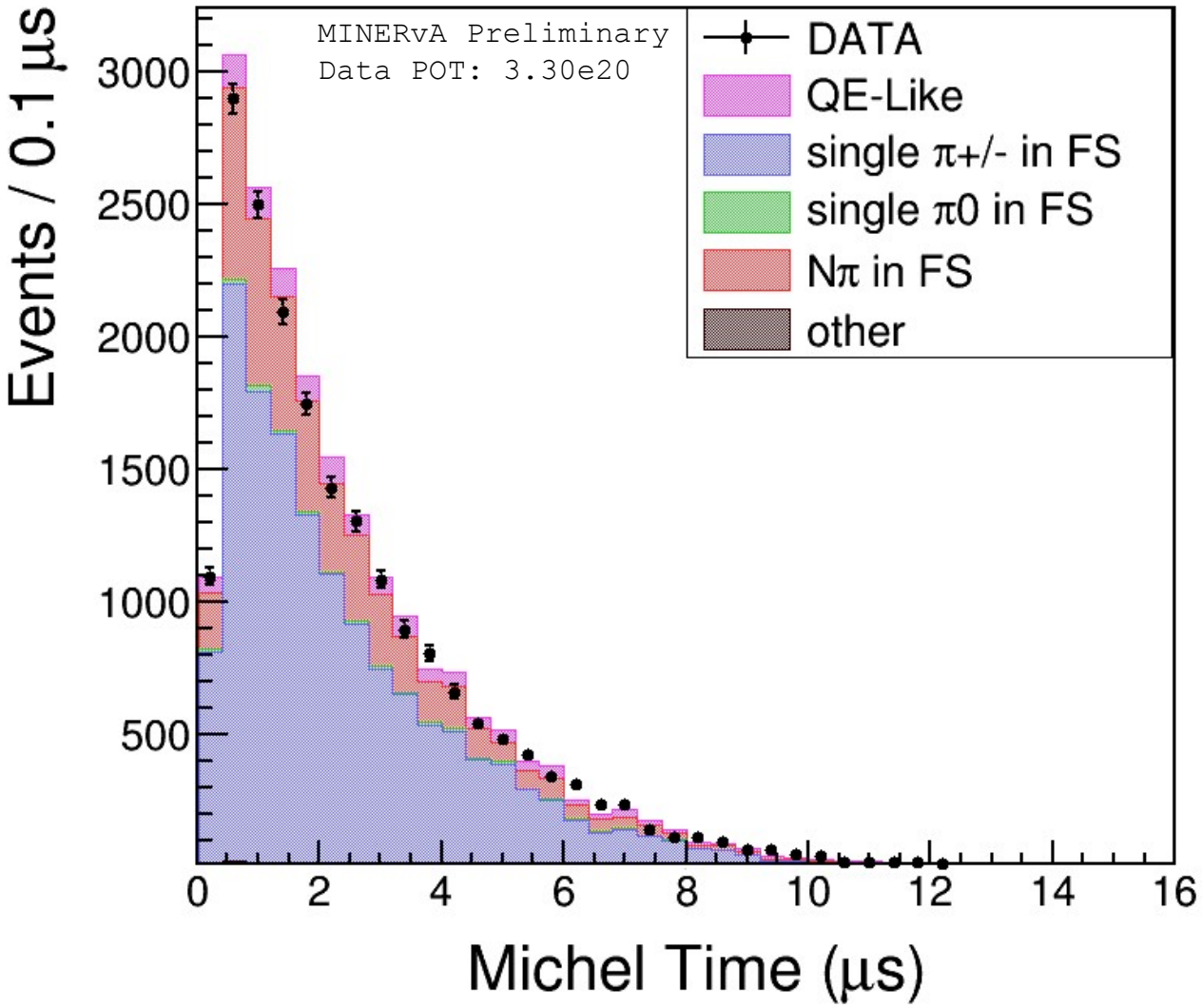
	carbon	iron	lead
GENIE	5.9/5	19.9/5	17.5/5
NuWro	6/5	14.6/5	11.1/5

Michel

Michel Energy Spectrum

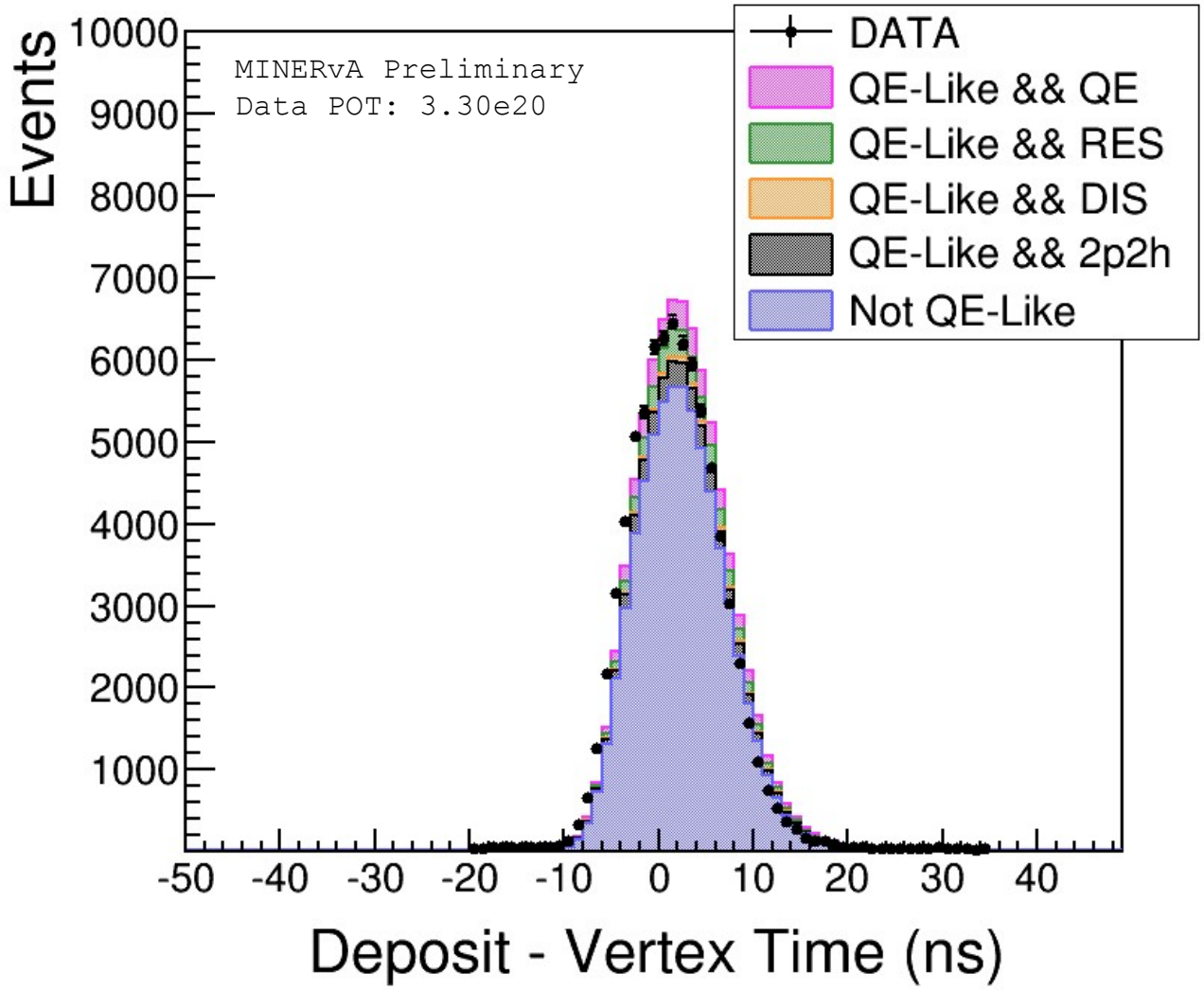


Michel Decay Time



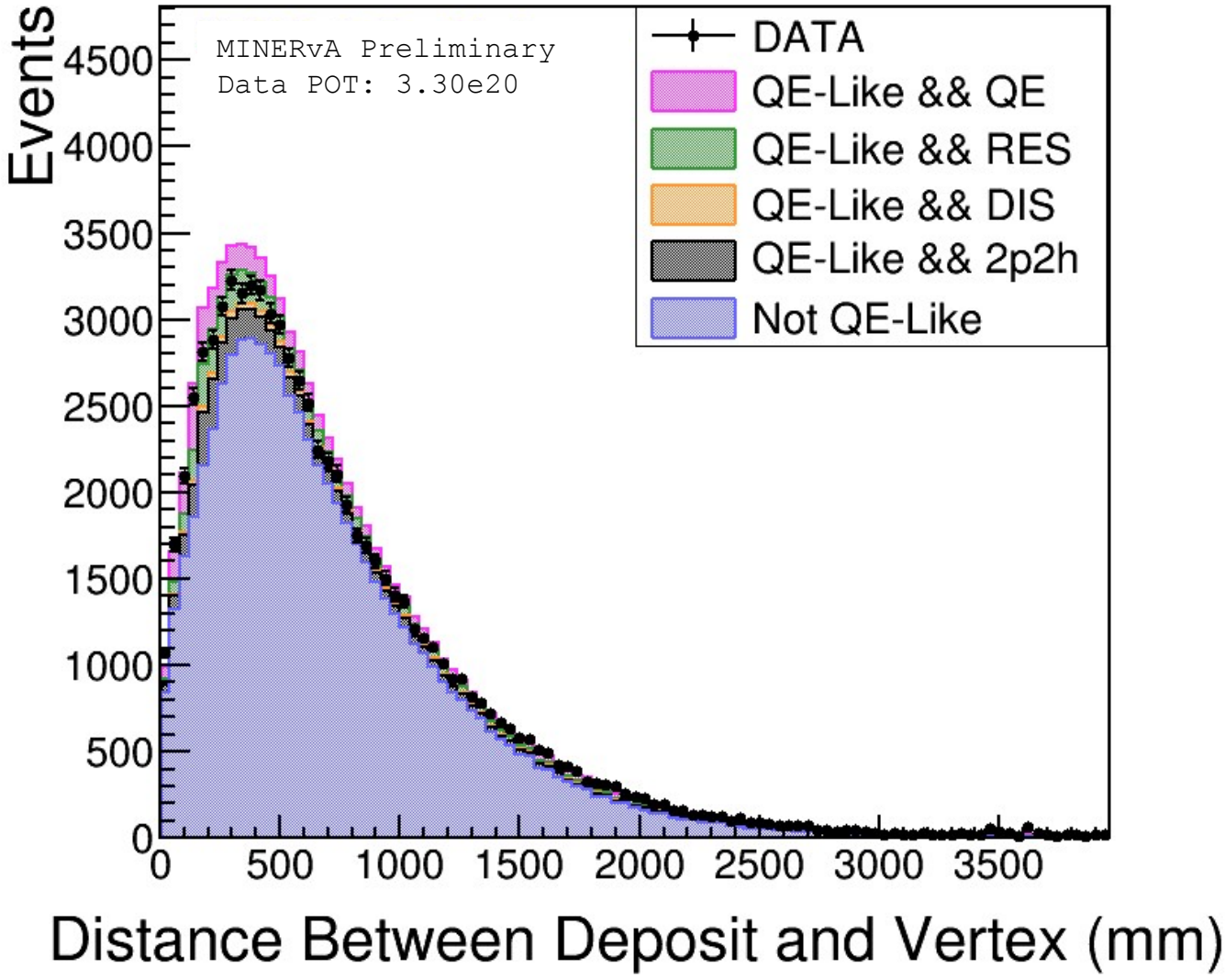
Isolated Energy Deposits

Time difference between deposit and vertex



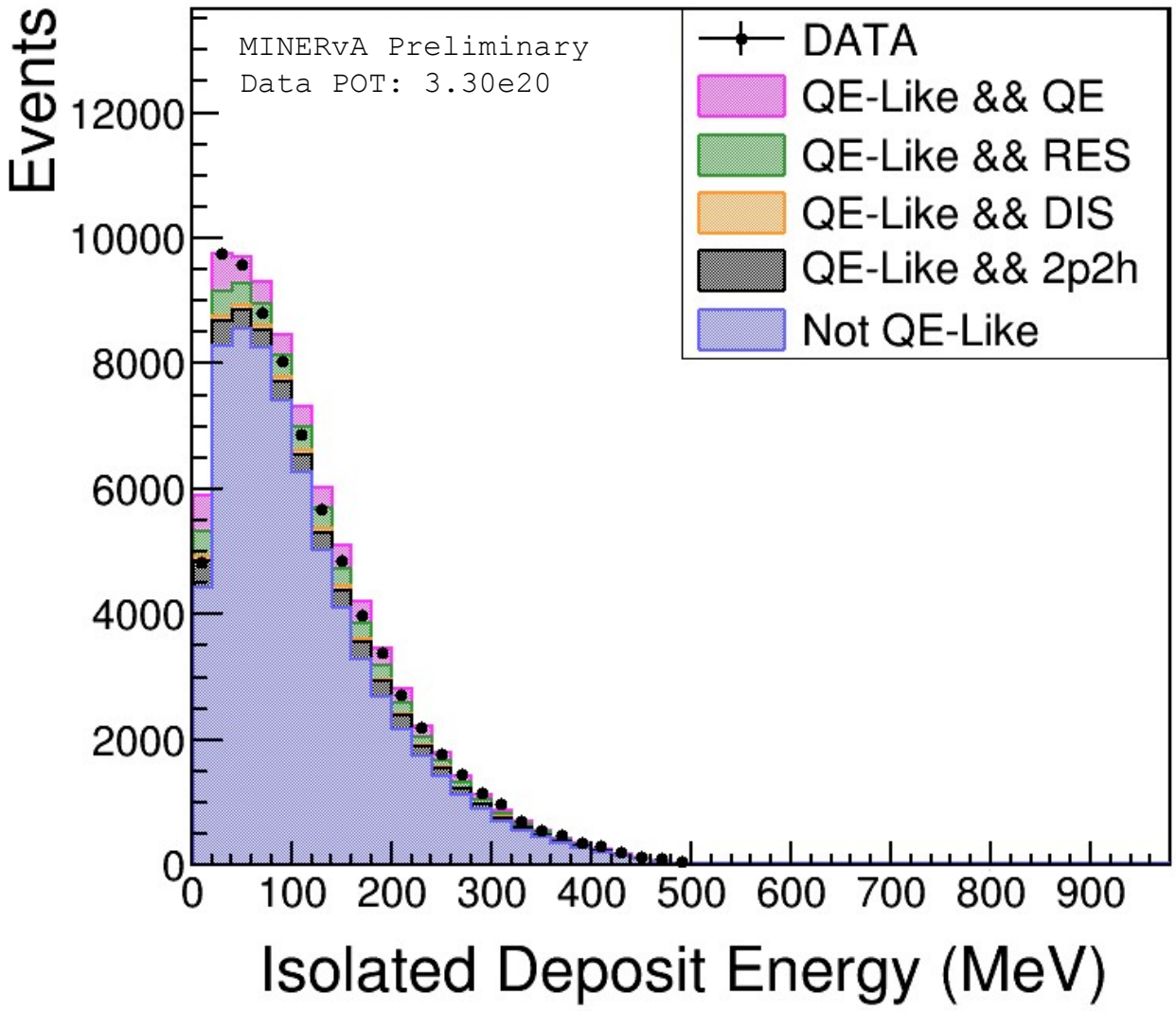
Sample passes all non-isolated deposit related cuts
Sample here is 1+ deposits
(the signal sample would keep the 1 deposit case)

Distance from the vertex to the deposit



Sample passes all non-isolated deposit related cuts
Sample here is 1+ deposits
(the signal sample would keep the 1 deposit case)

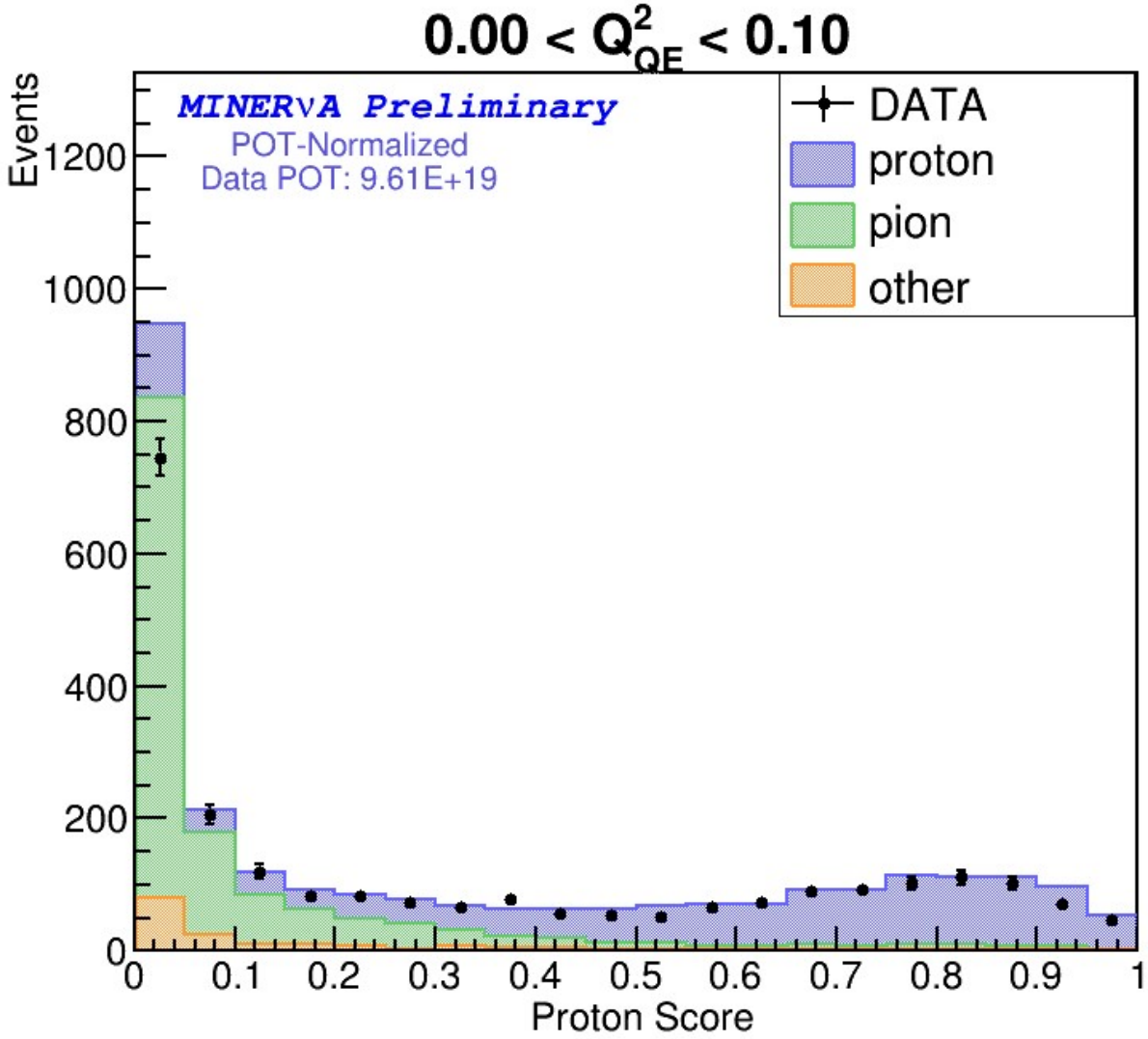
Isolated deposit's energy



Sample passes all non-isolated deposit related cuts
Sample here is 1+ deposits
(the signal sample would keep the 1 deposit case)

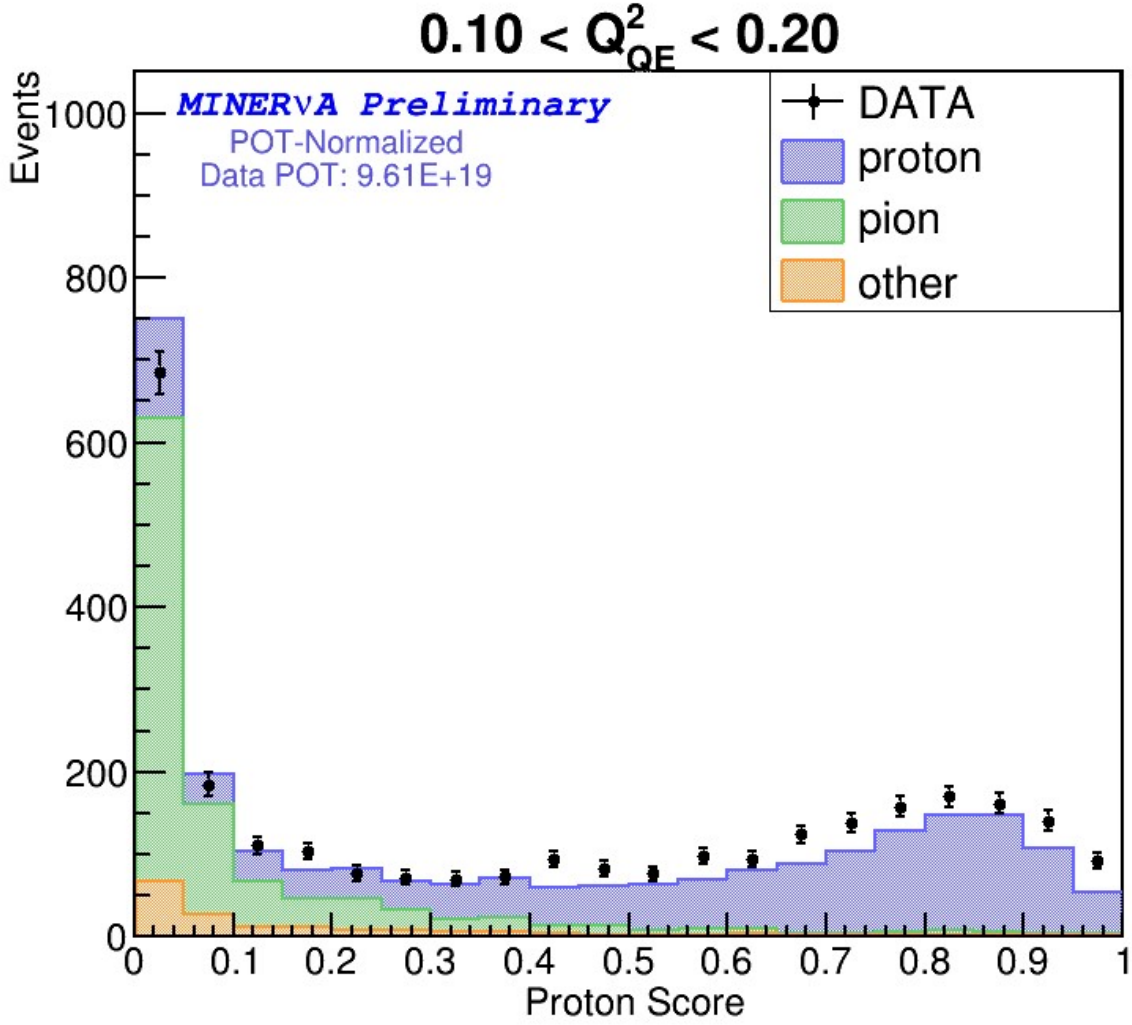
PID

PID broken down by particle



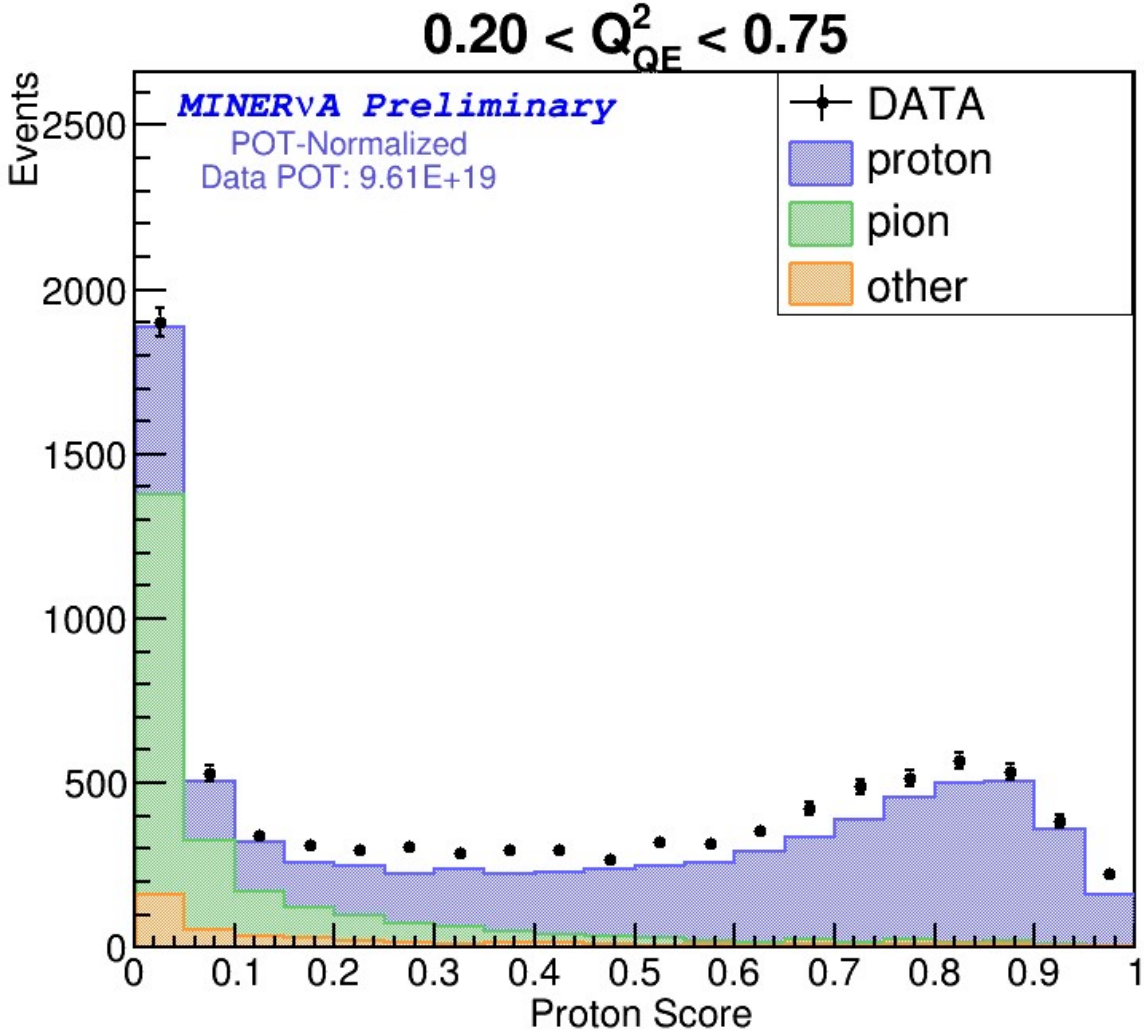
Full event selection except for PID cut, 2-tracks only,

PID broken down by particle



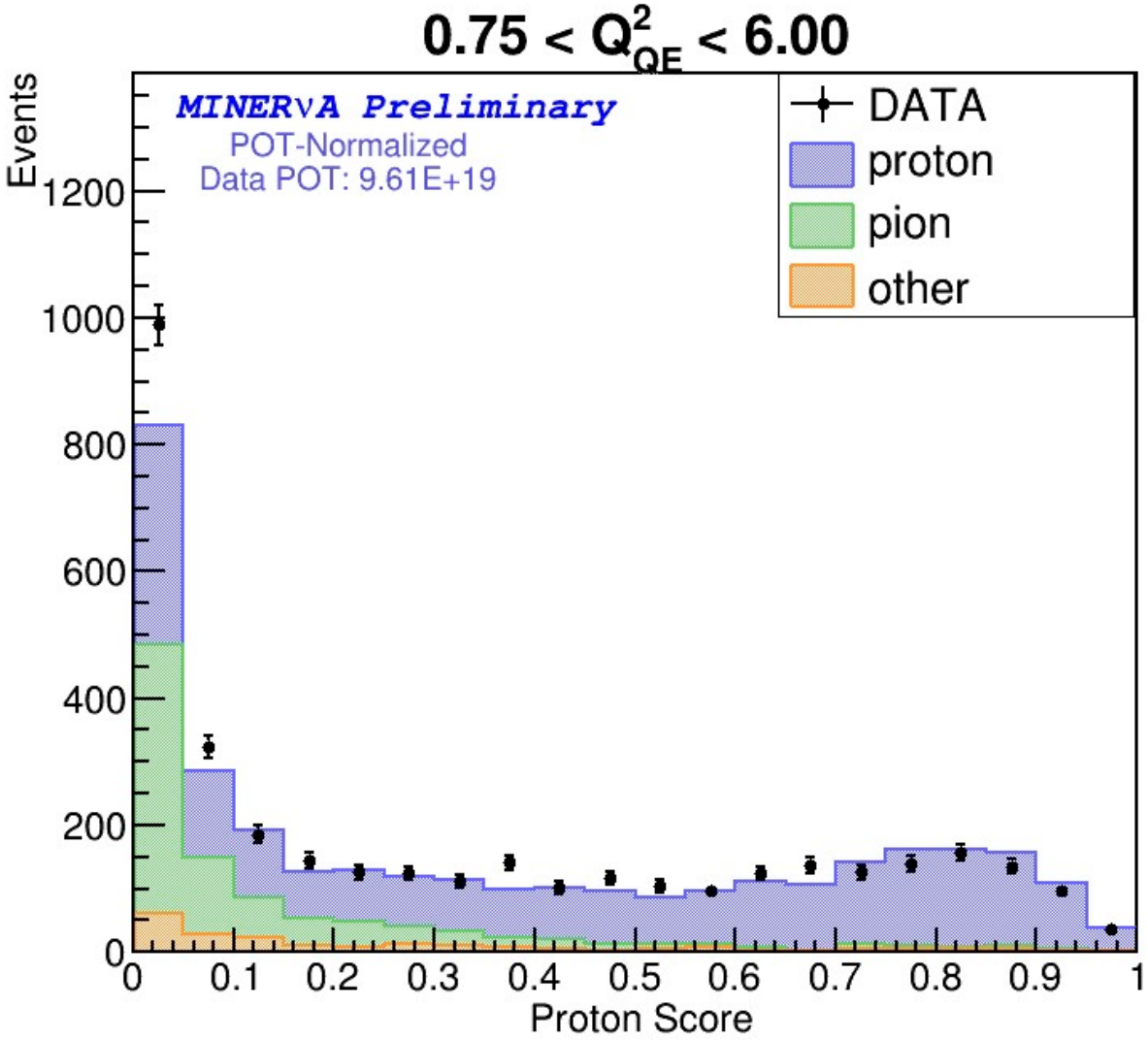
Full event selection except for PID cut, 2-tracks only,

PID broken down by particle



Full event selection except for PID cut, 2-tracks only,

PID broken down by particle

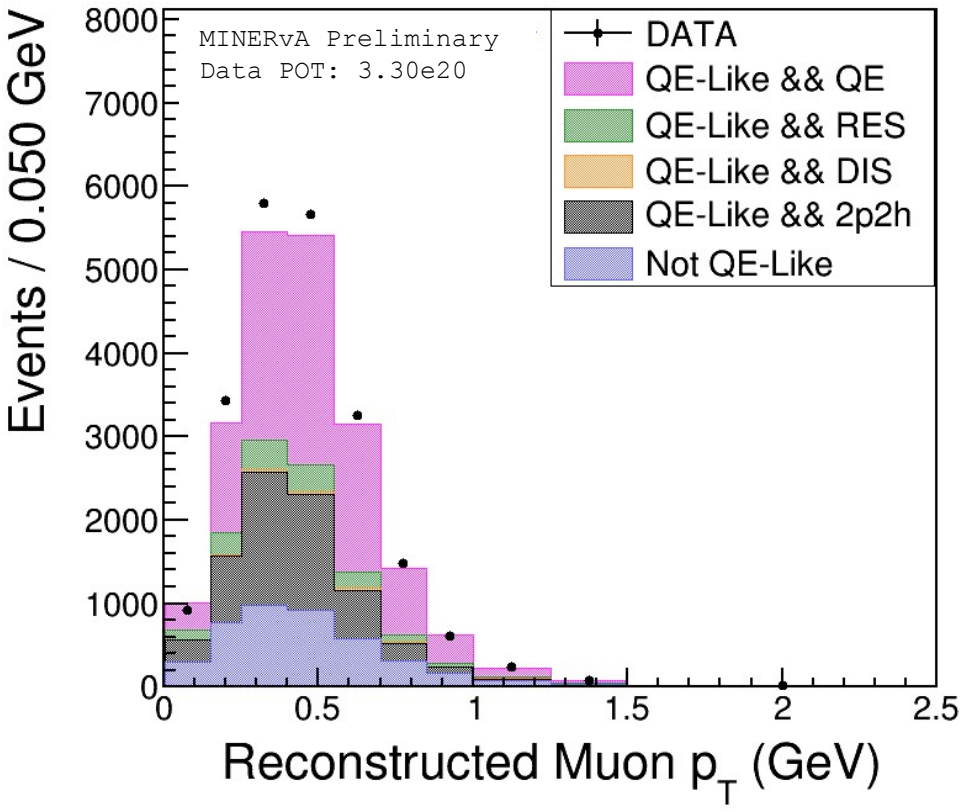


Full event selection except for PID cut, 2-tracks only,

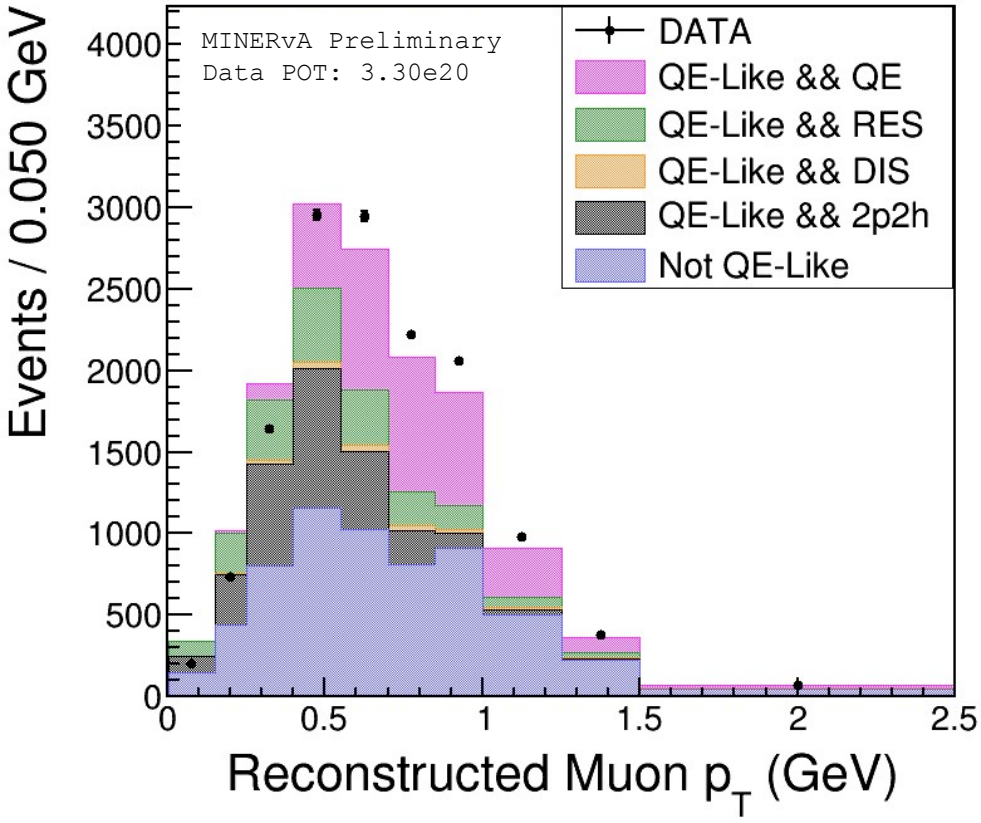
Background Constraint

Signal Before Tuning

Sample passes ALL selection criteria



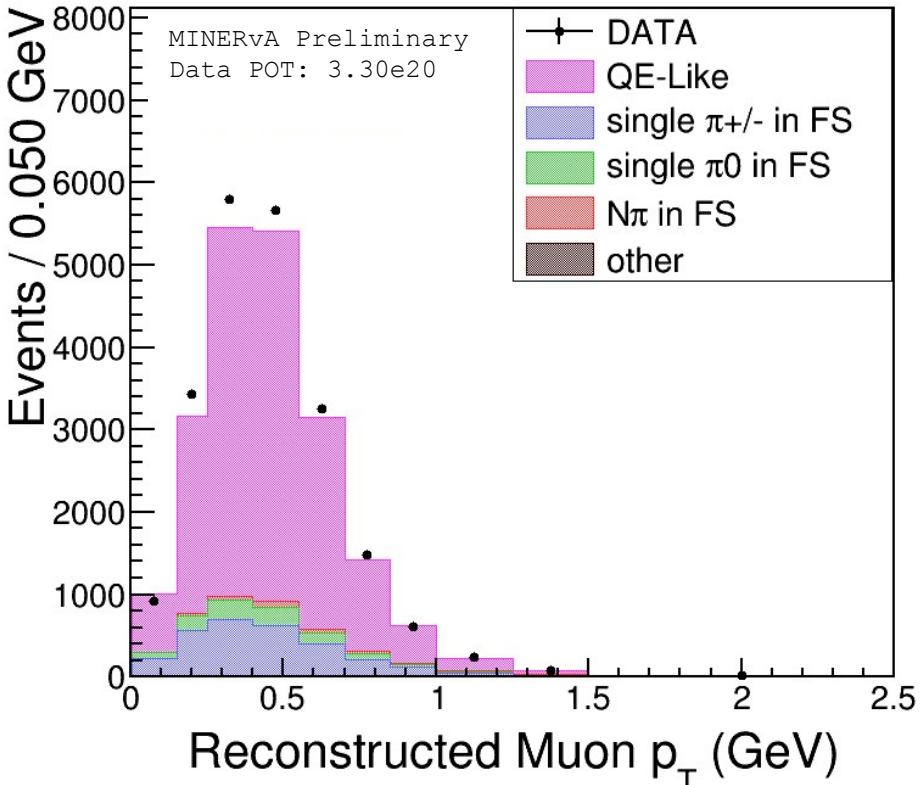
1-track sample



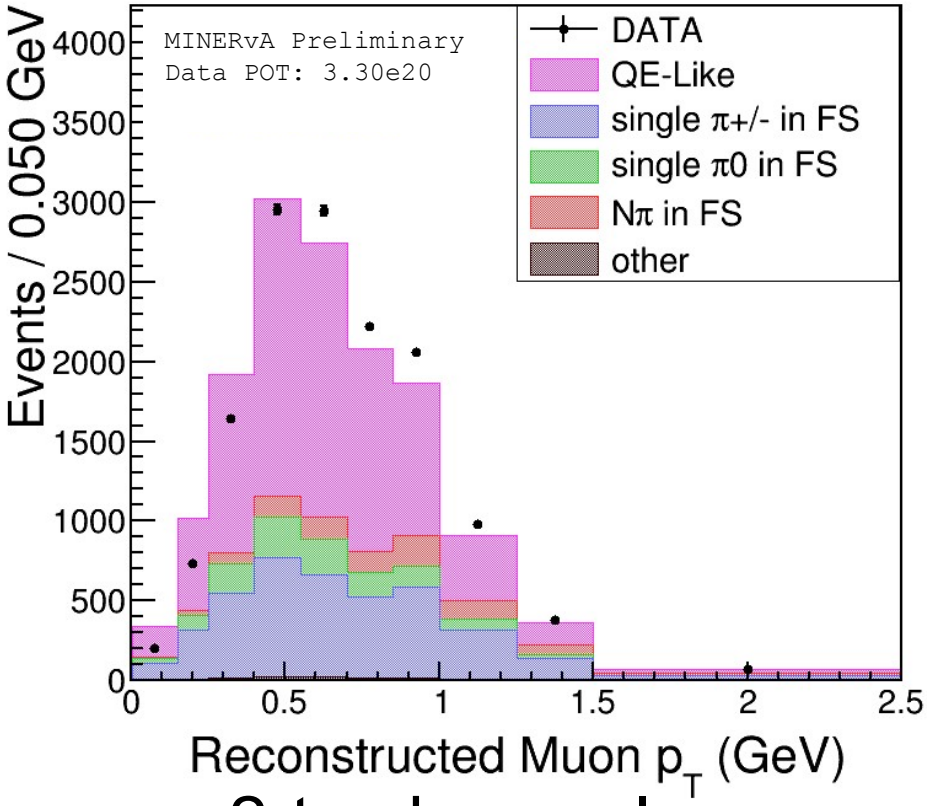
2-track sample

Signal Before Tuning

Sample passes ALL selection criteria



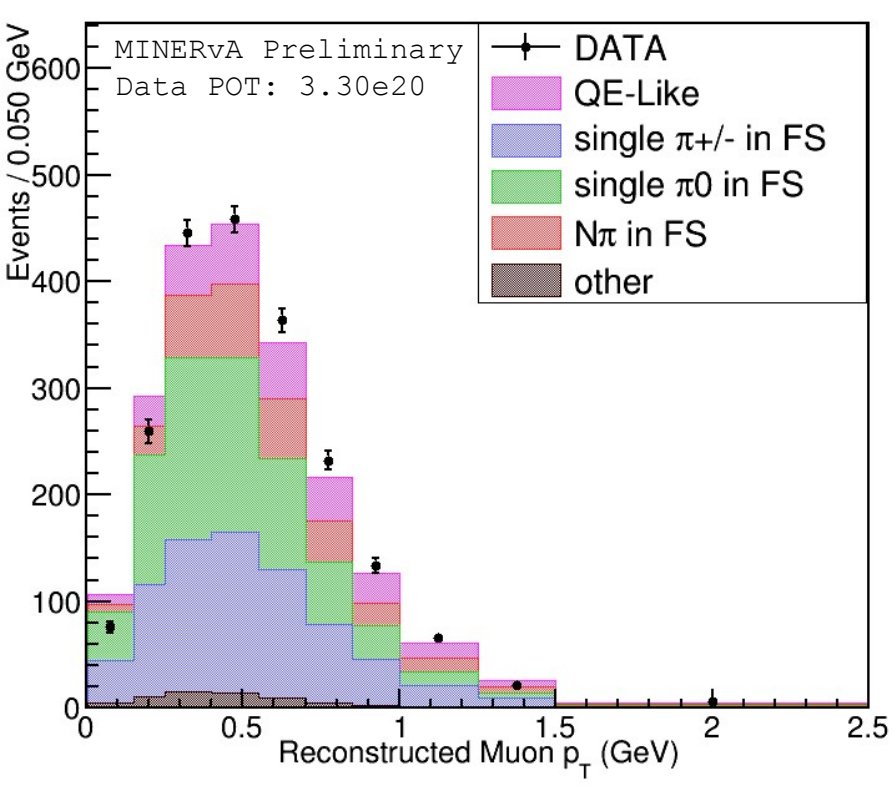
1-track sample

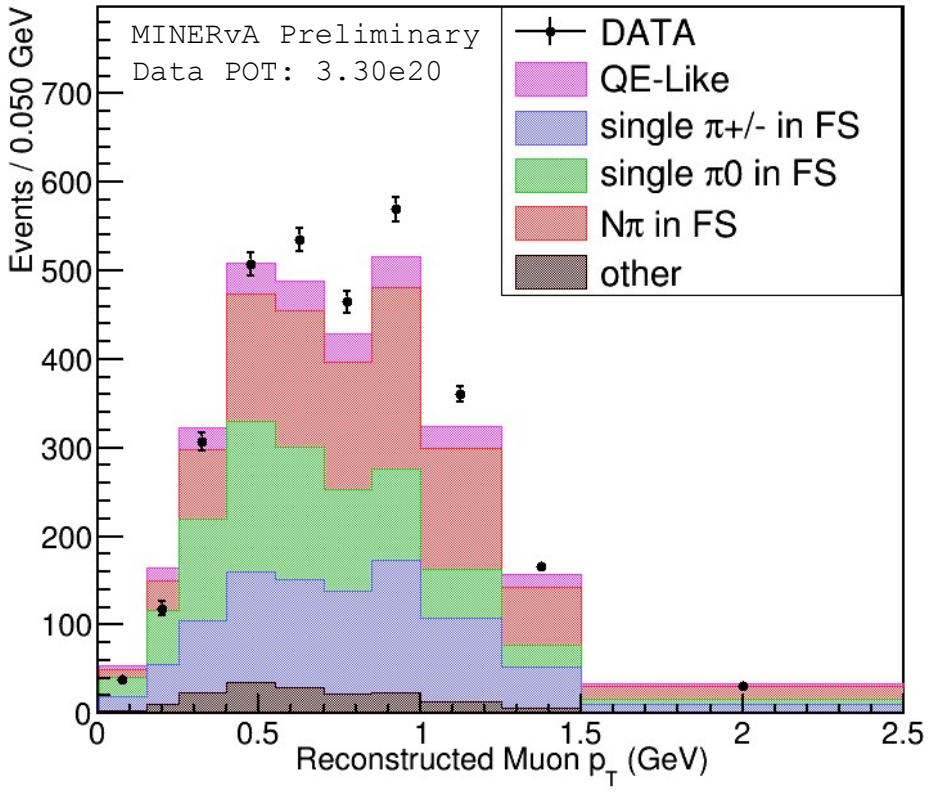


2-track sample

Sideband Inputs

Sample passes ALL other cuts but has 2 or more isolated clusters





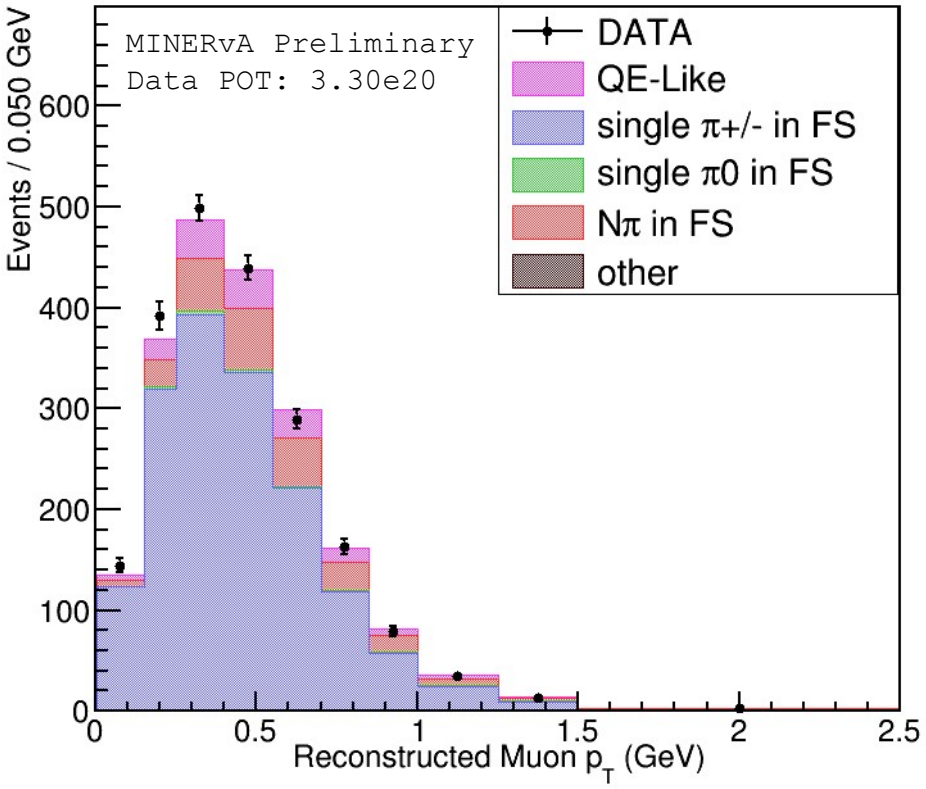
1-track sample

2-track sample

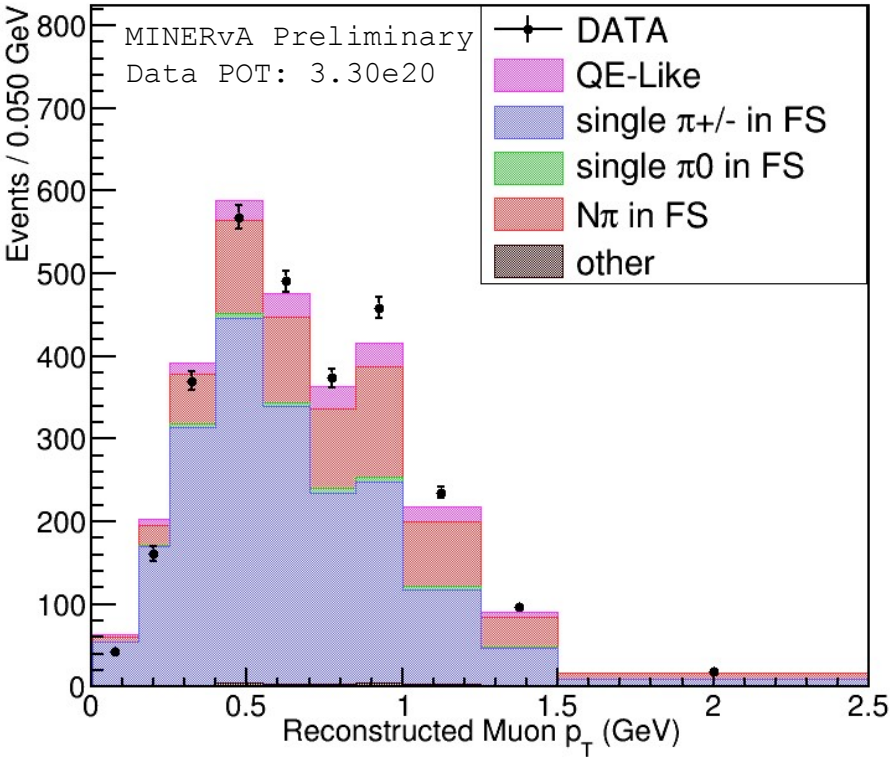
Jump at 0.8-1.0 GeV P_T in the 2-track sample is because of the PID cut which stops cutting in that region and beyond

Sideband Inputs

Sample passes ALL cuts but has an associated Michel

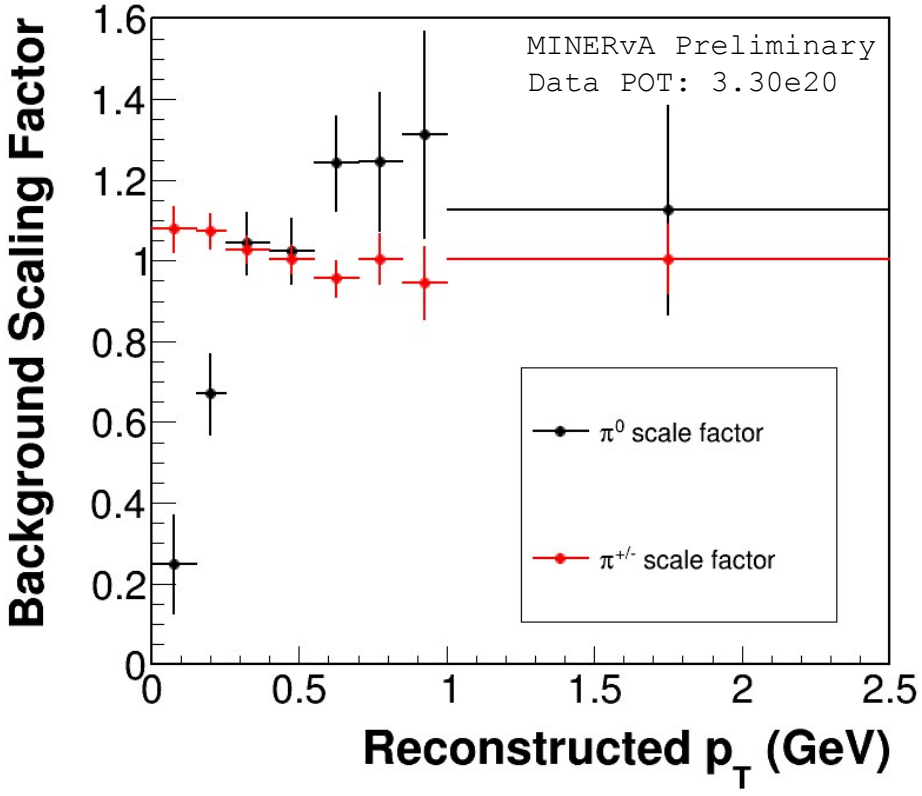


1-track sample

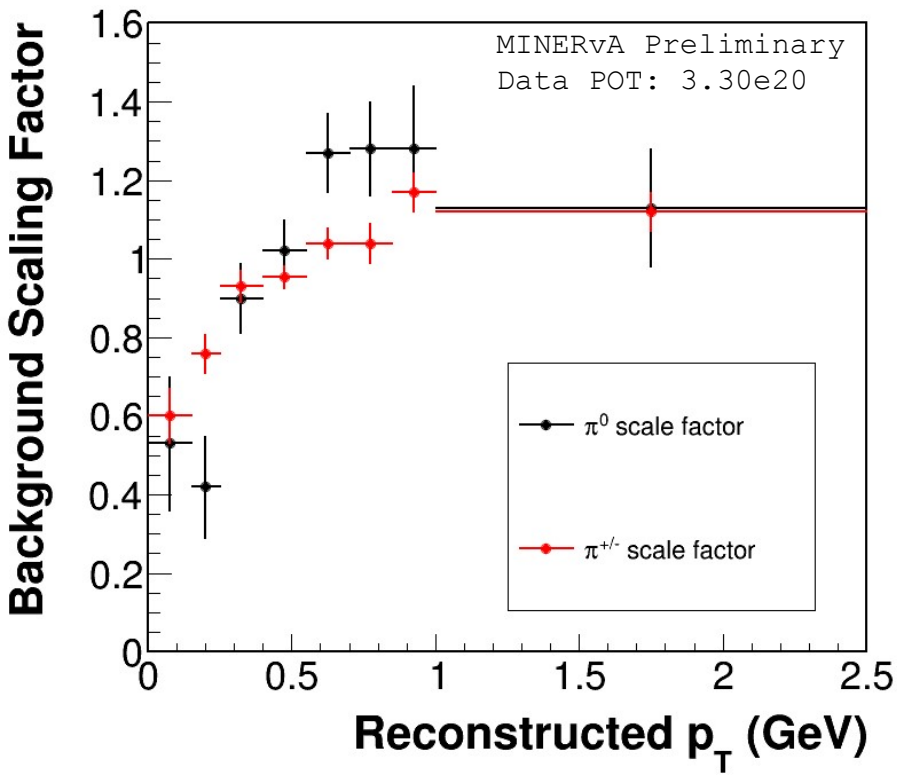


2-track sample

Scaling Factors

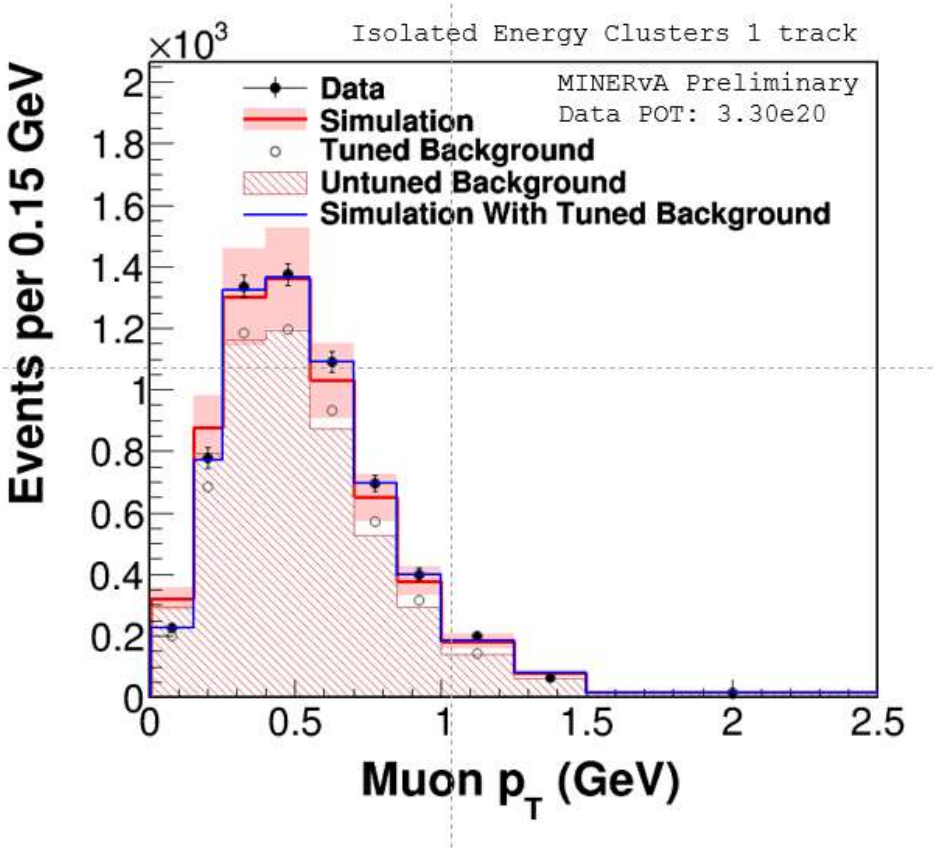


1-track sample

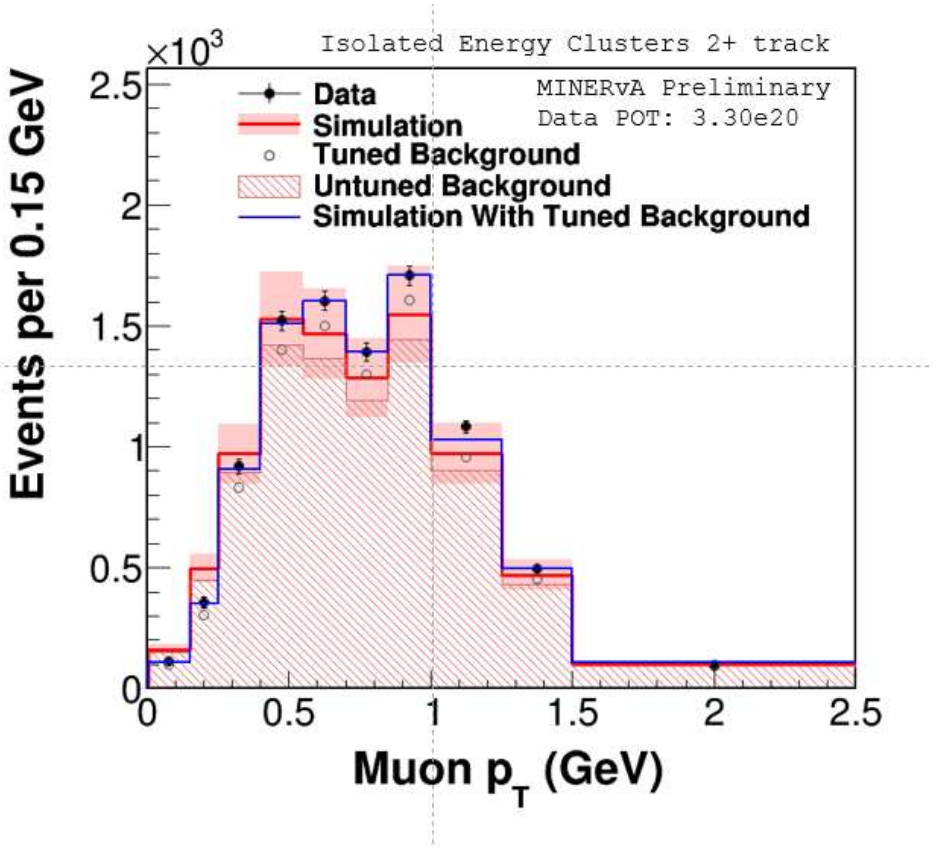


2-track sample

Tuned Sideband
Isolated Energy Deposits

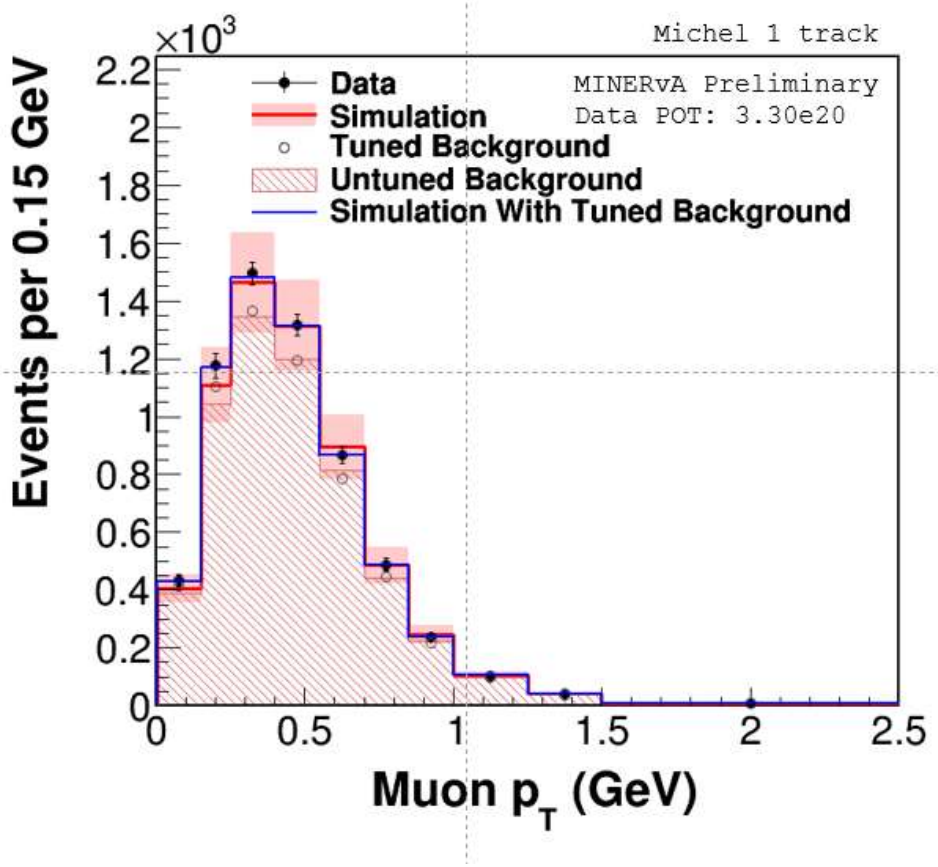


1-track sample

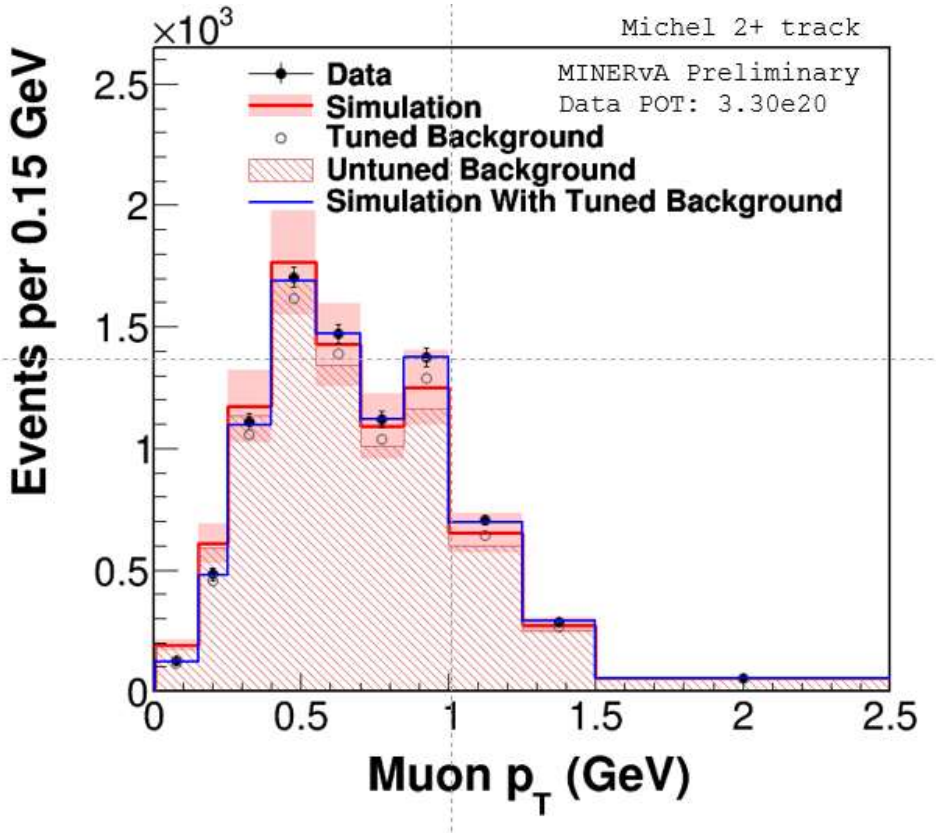


2-track sample

Tuned Sideband Michels

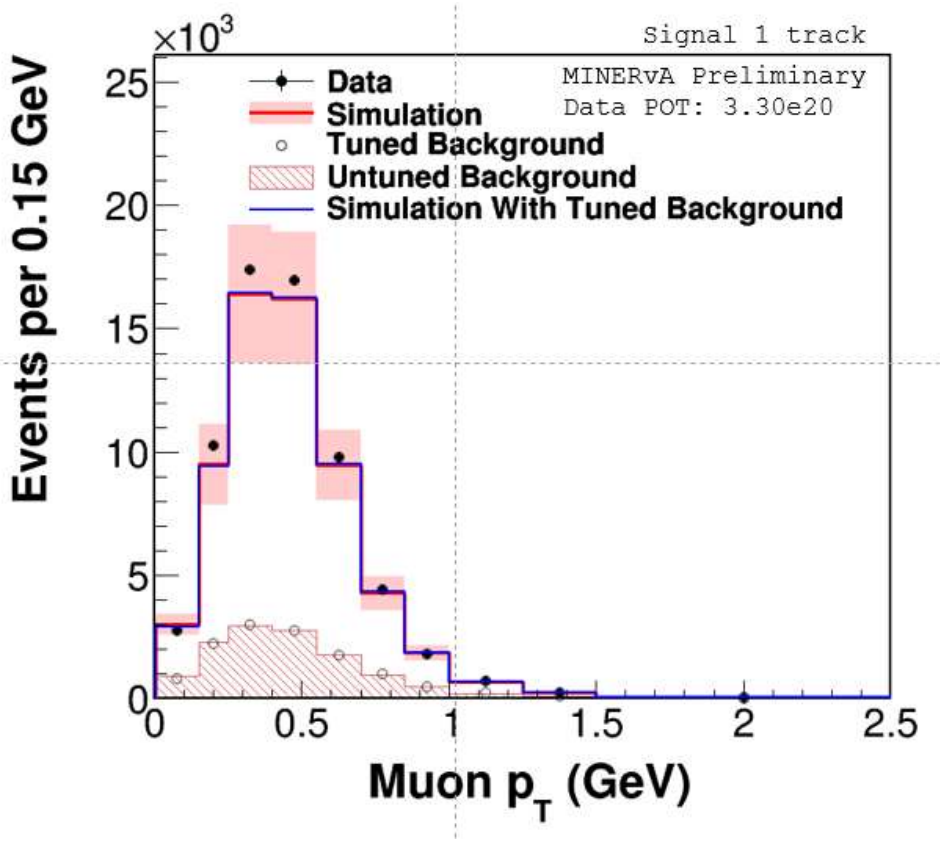


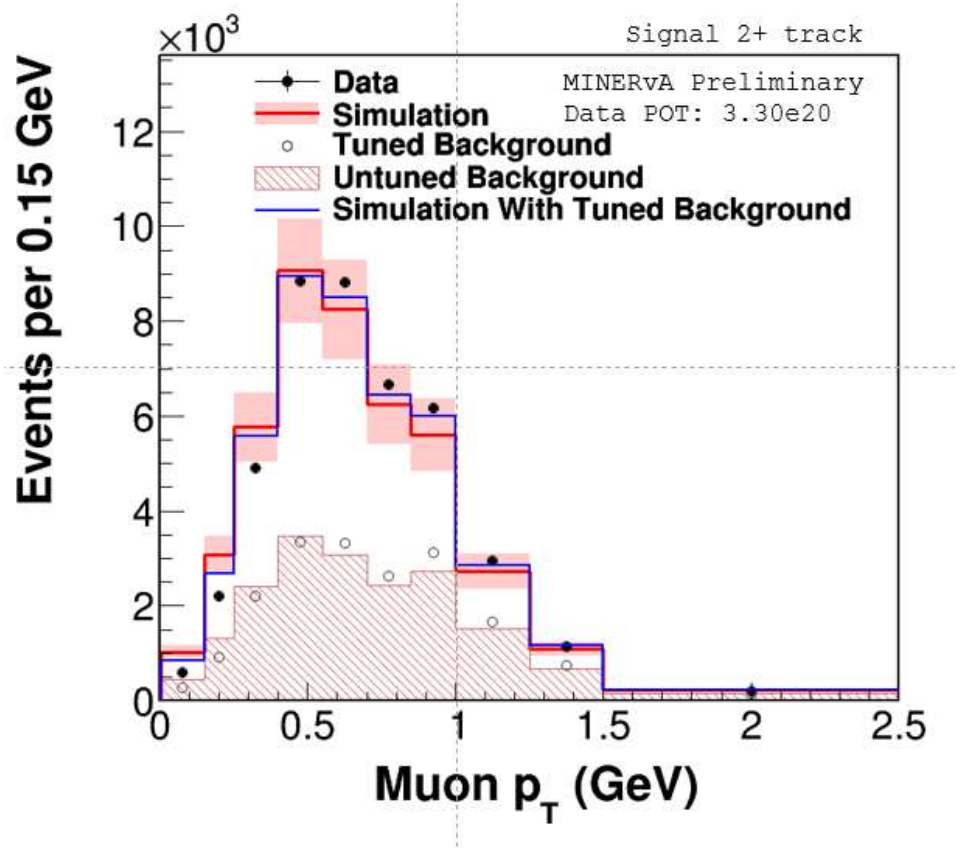
1-track sample



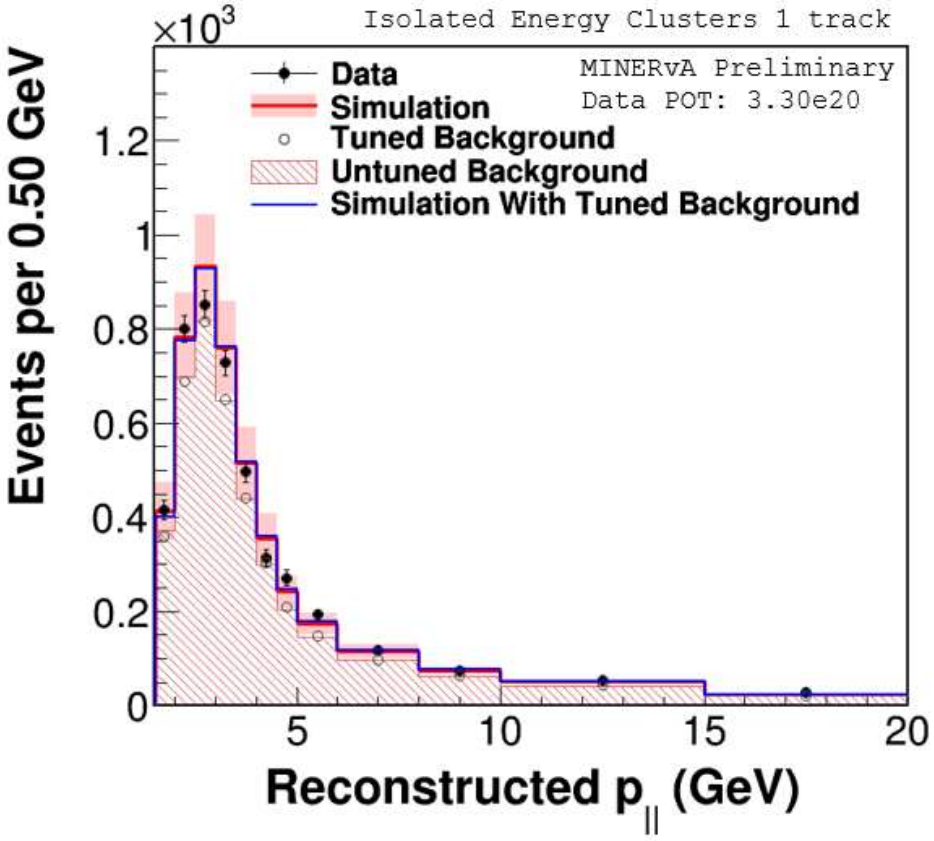
2-track sample

Tuned Signal Sample

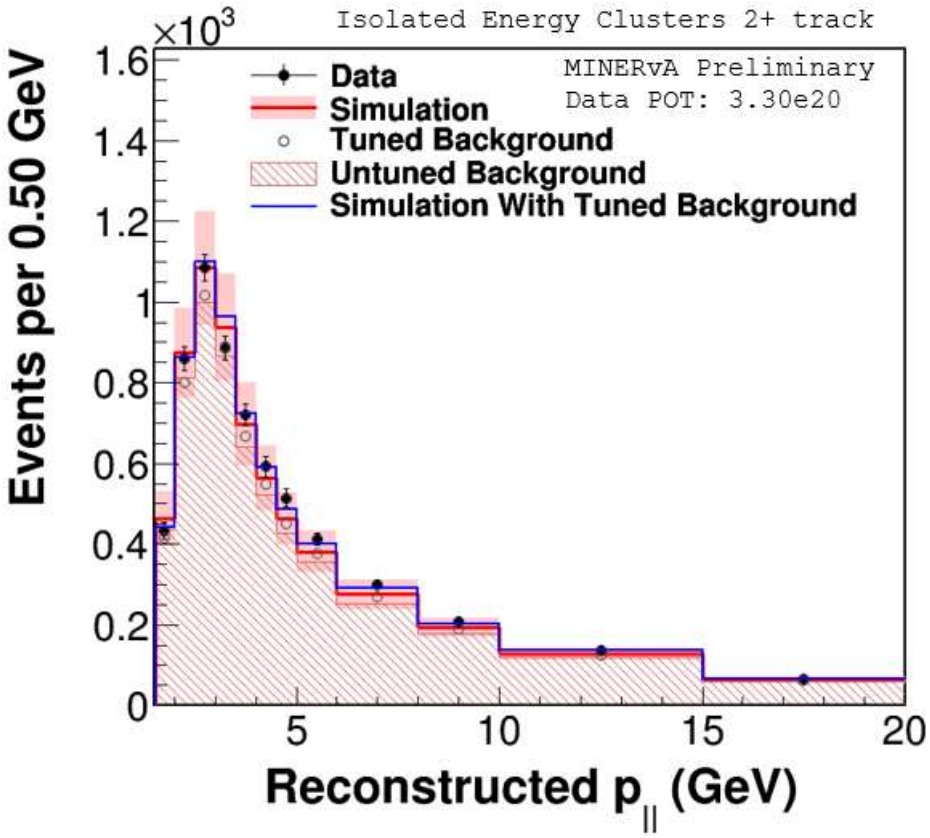




Tuned Sideband
Isolated Energy Deposits

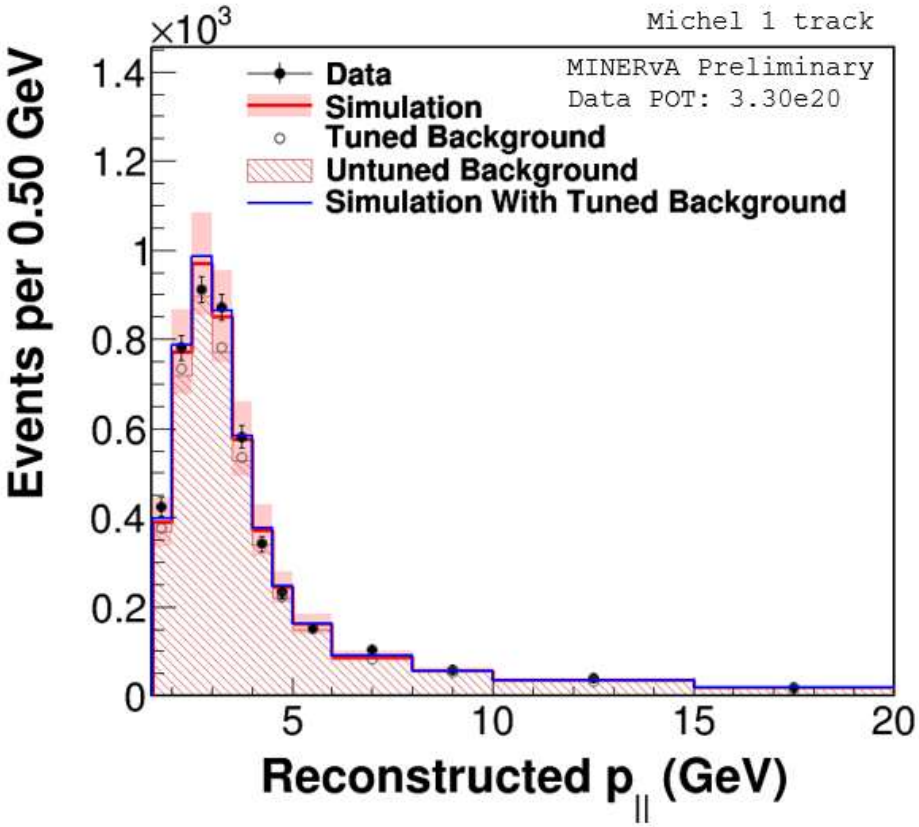


1-track sample

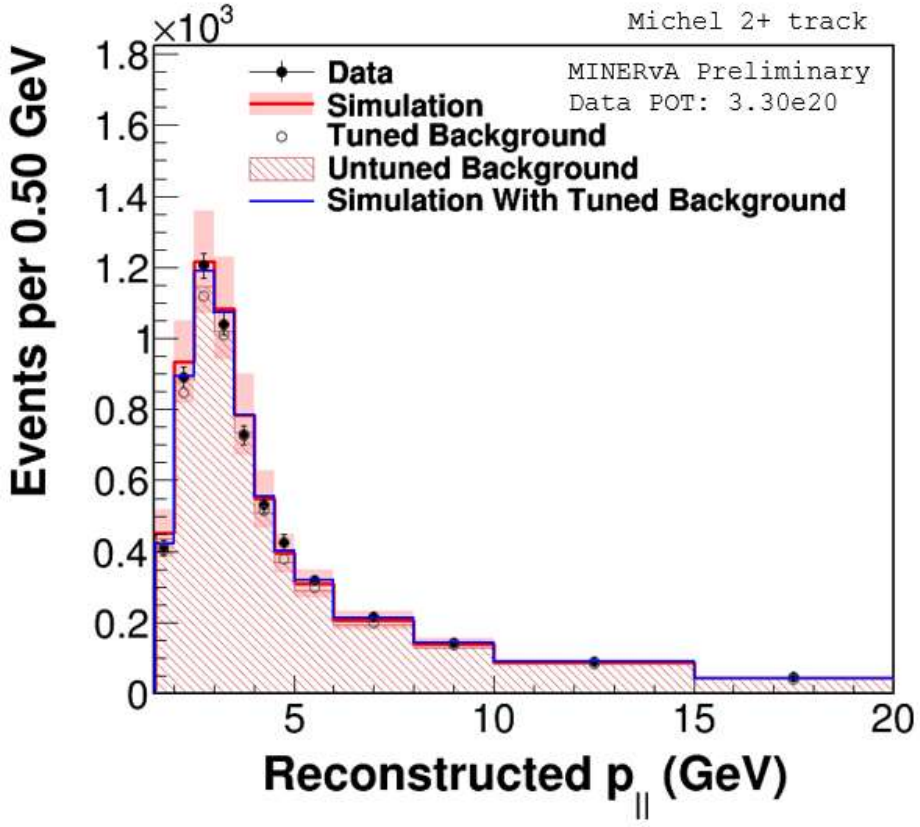


2-track sample

Tuned Sideband Michels

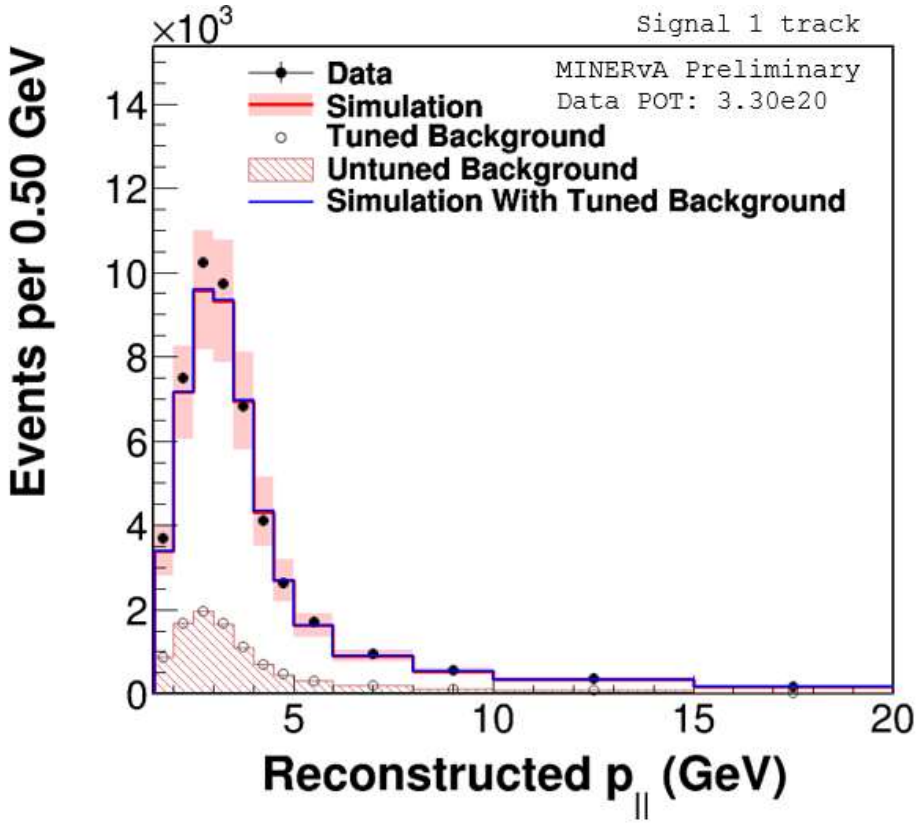


1-track sample

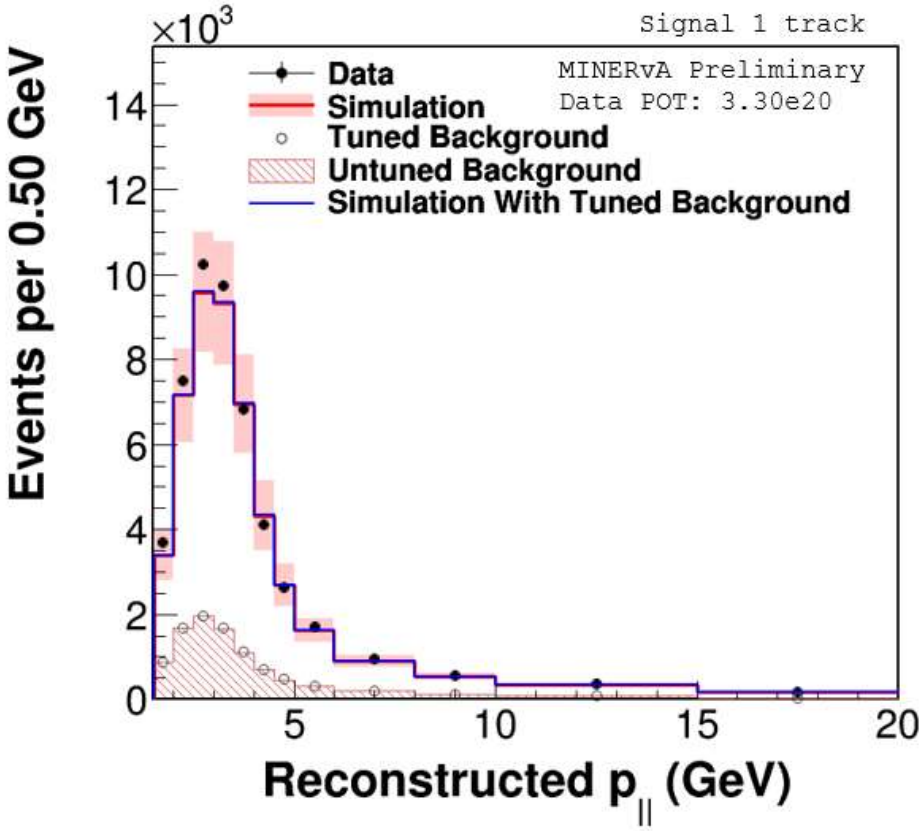


2-track sample

Tuned Signal Sample



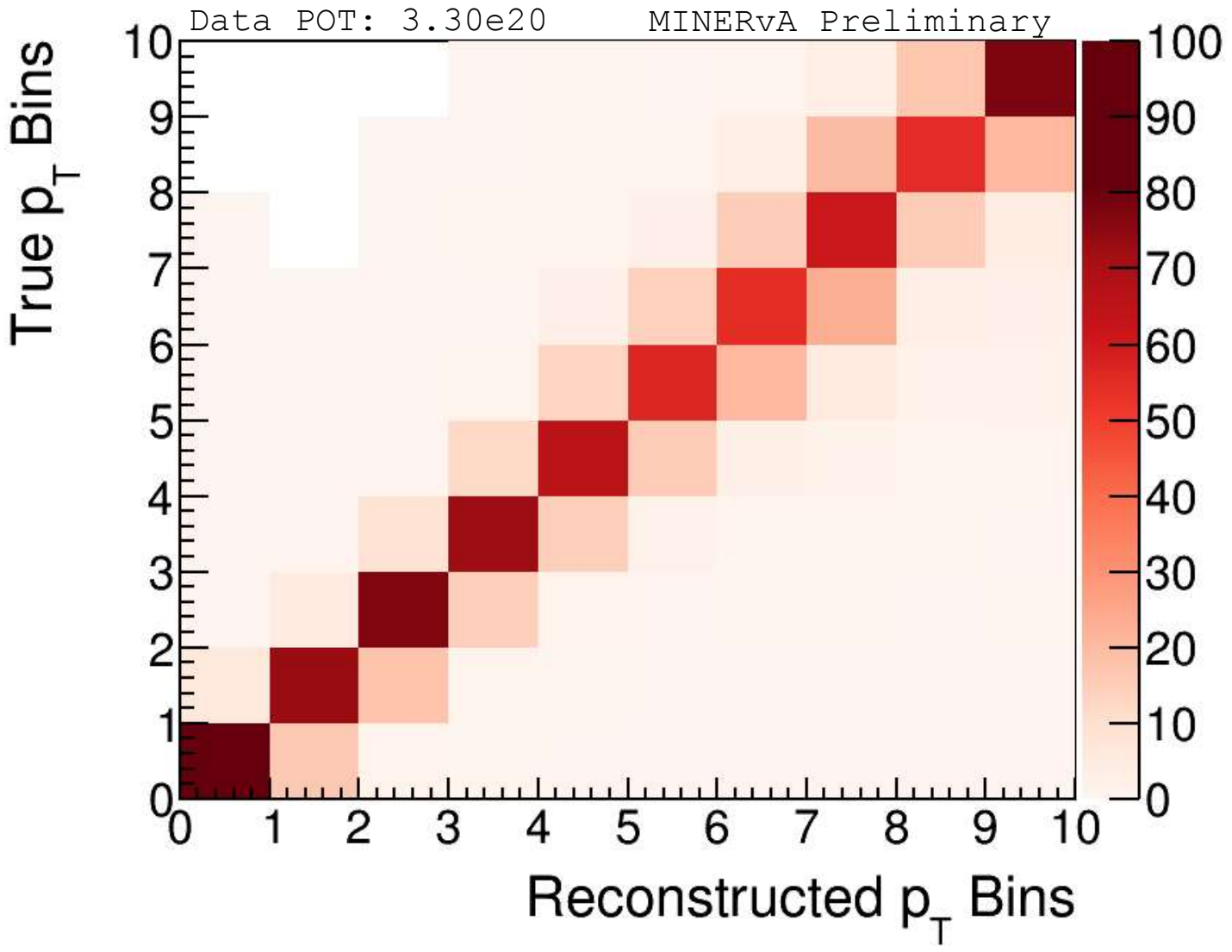
1-track sample



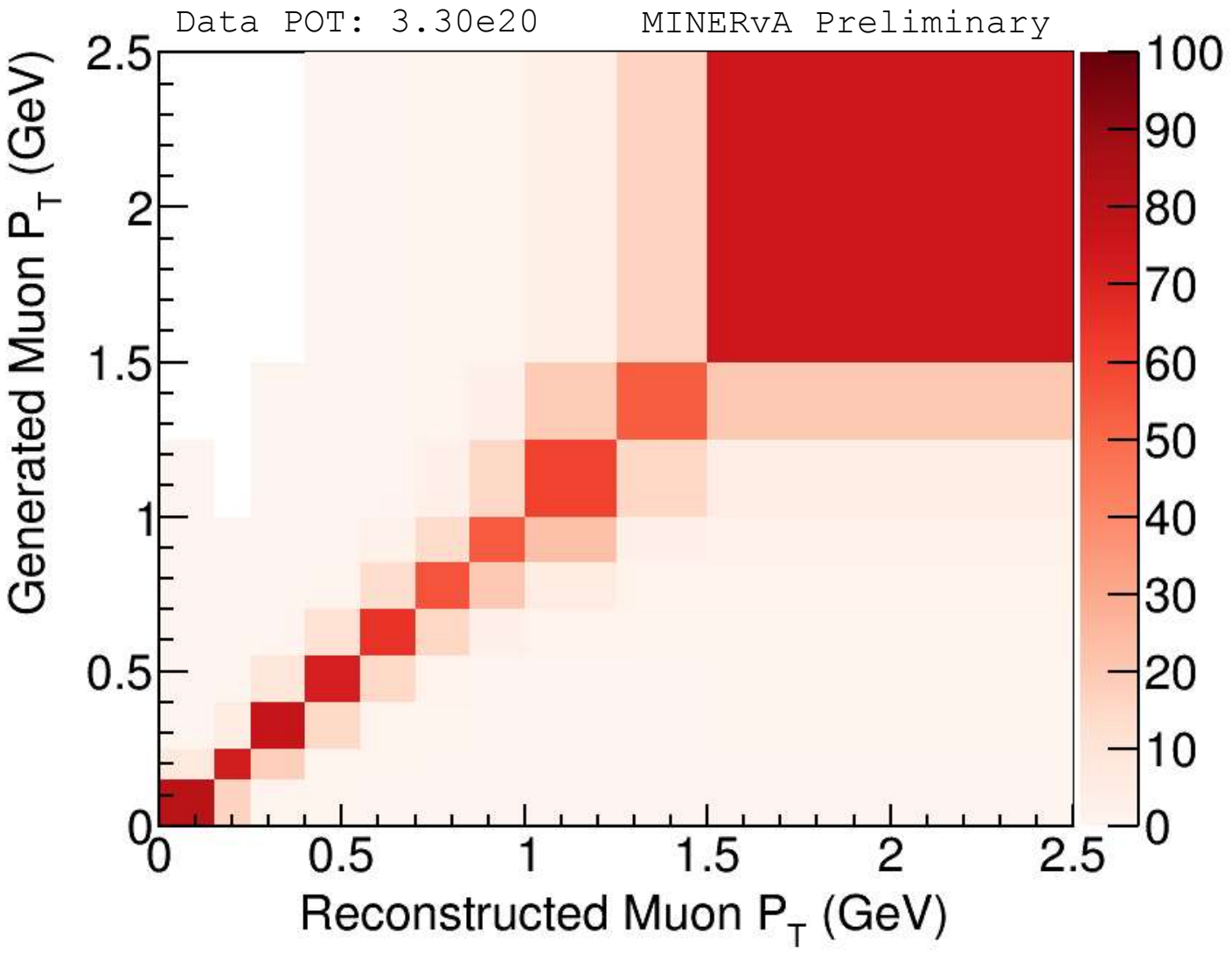
2-track sample

Migration

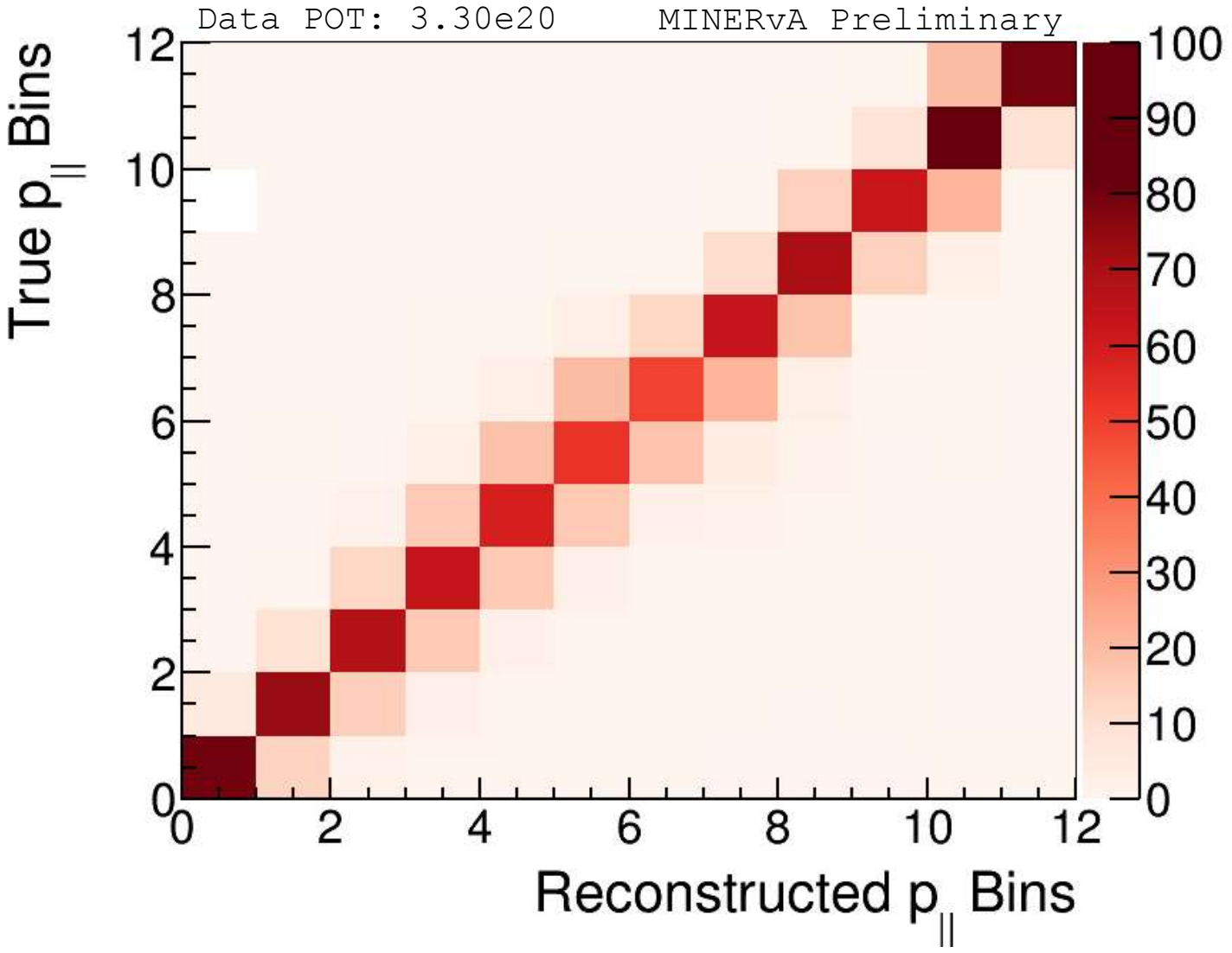
Migration Matrix P_t



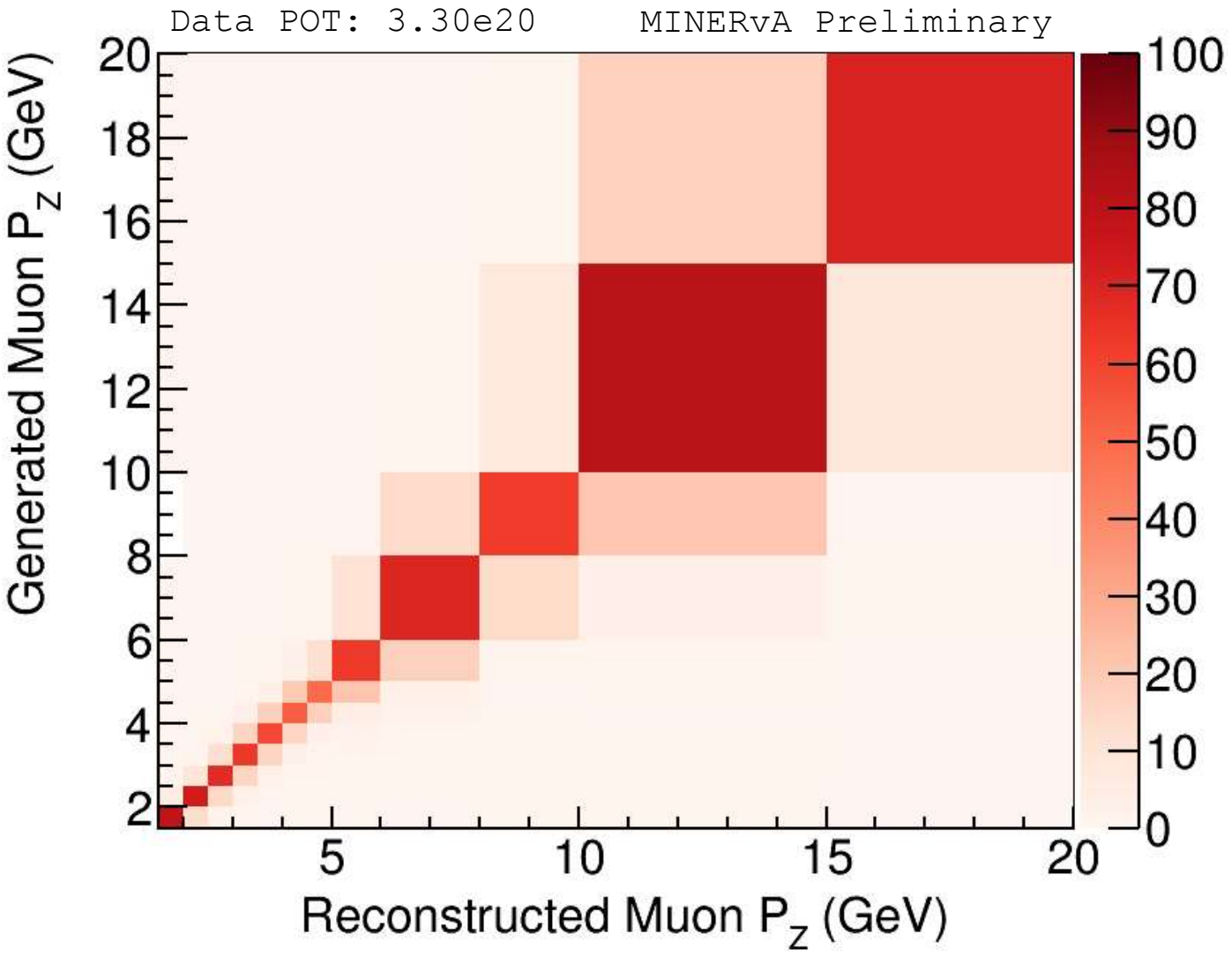
Migration Matrix P_t



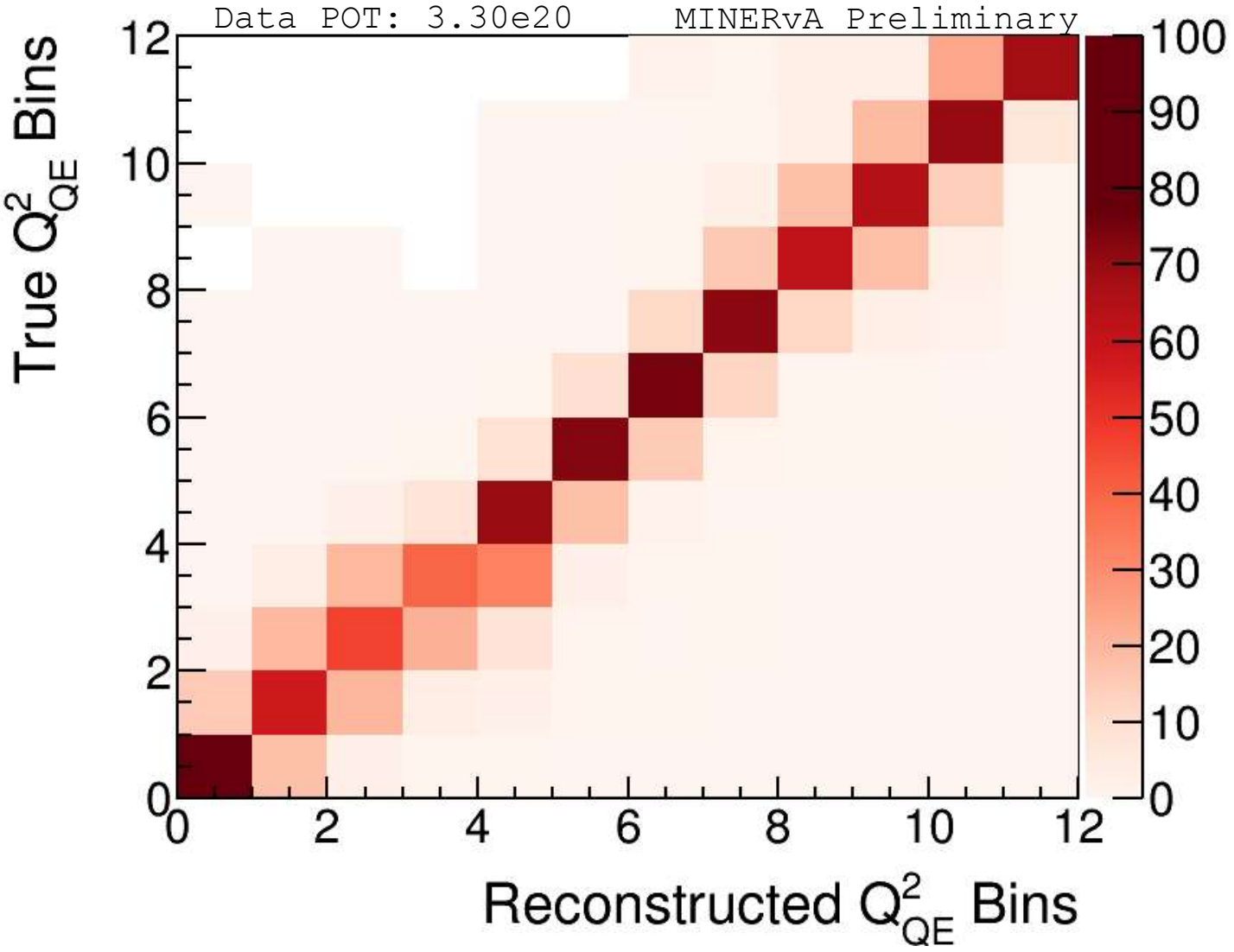
Migration Matrix $P_{||}$



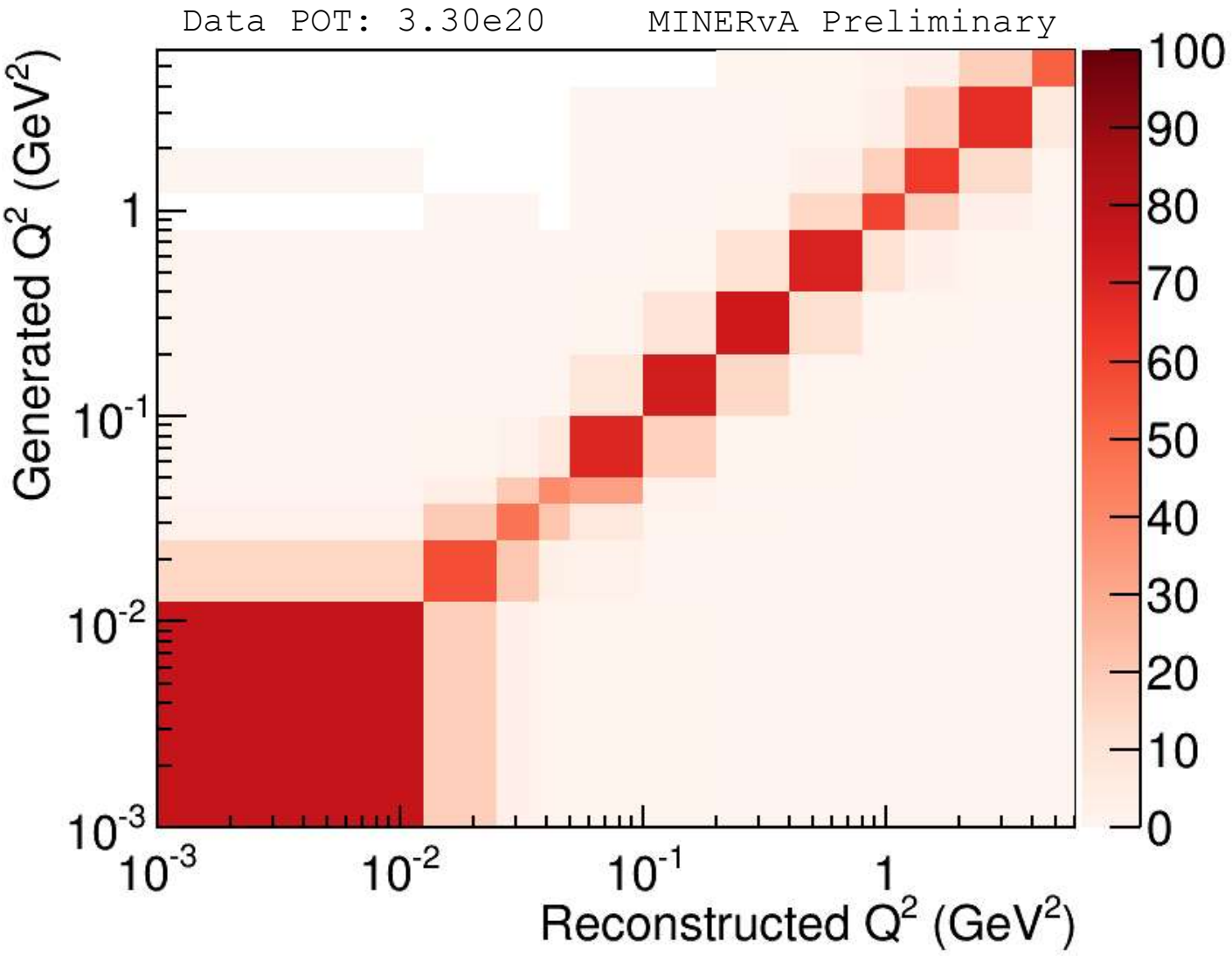
Migration Matrix $P_{||}$



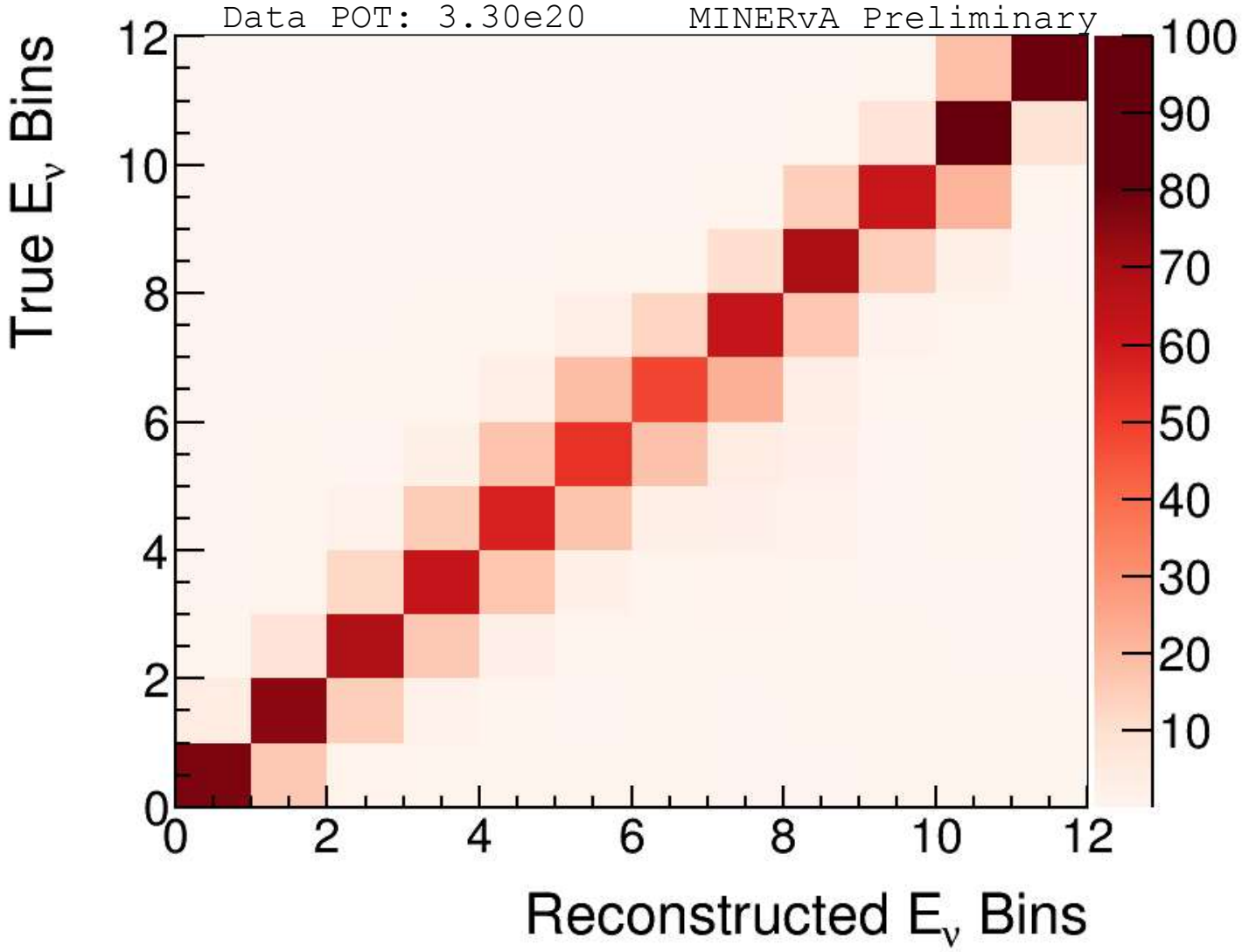
Migration Matrix Q^2_{QE}



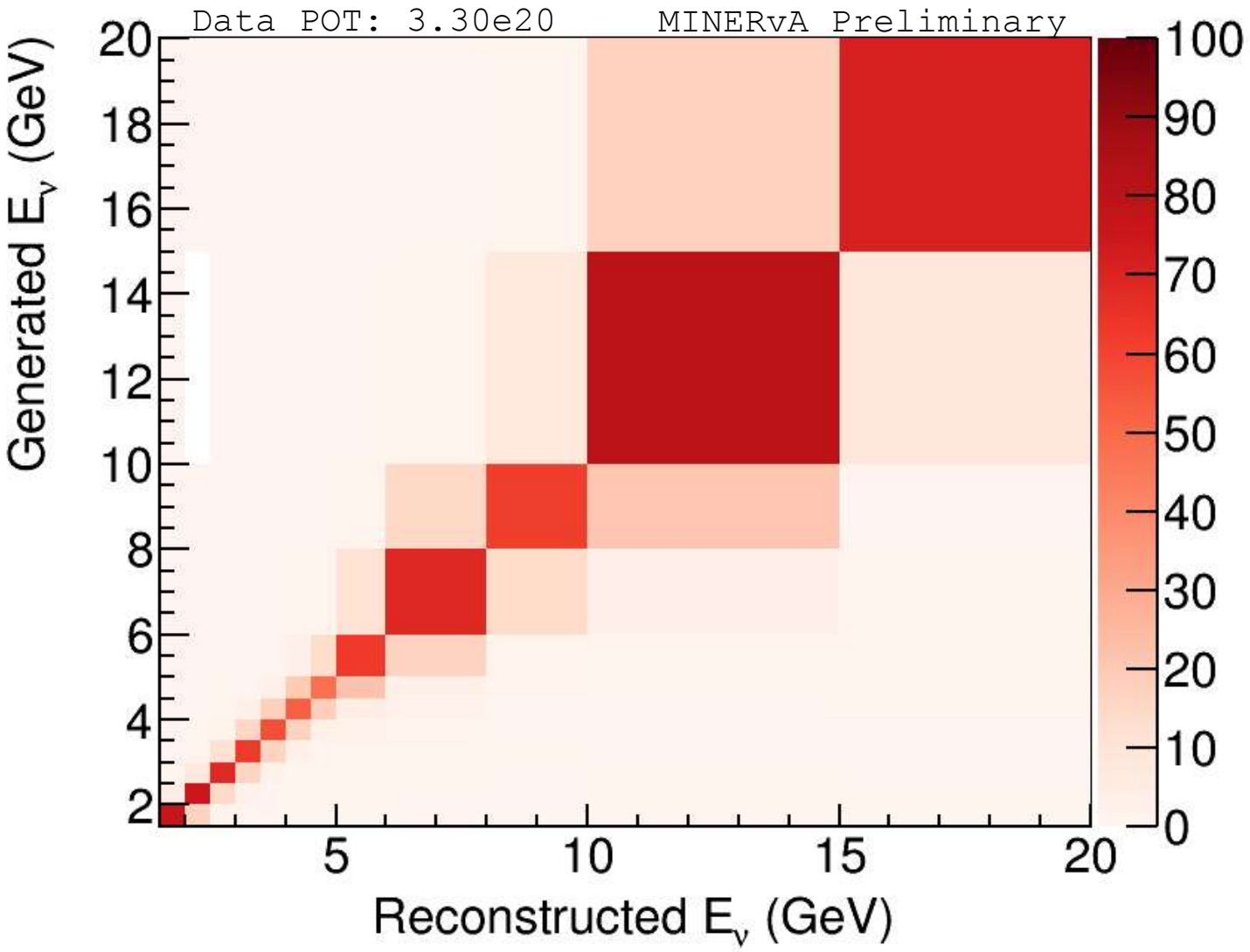
Migration Matrix Q^2_{QE}



Migration Matrix E_ν

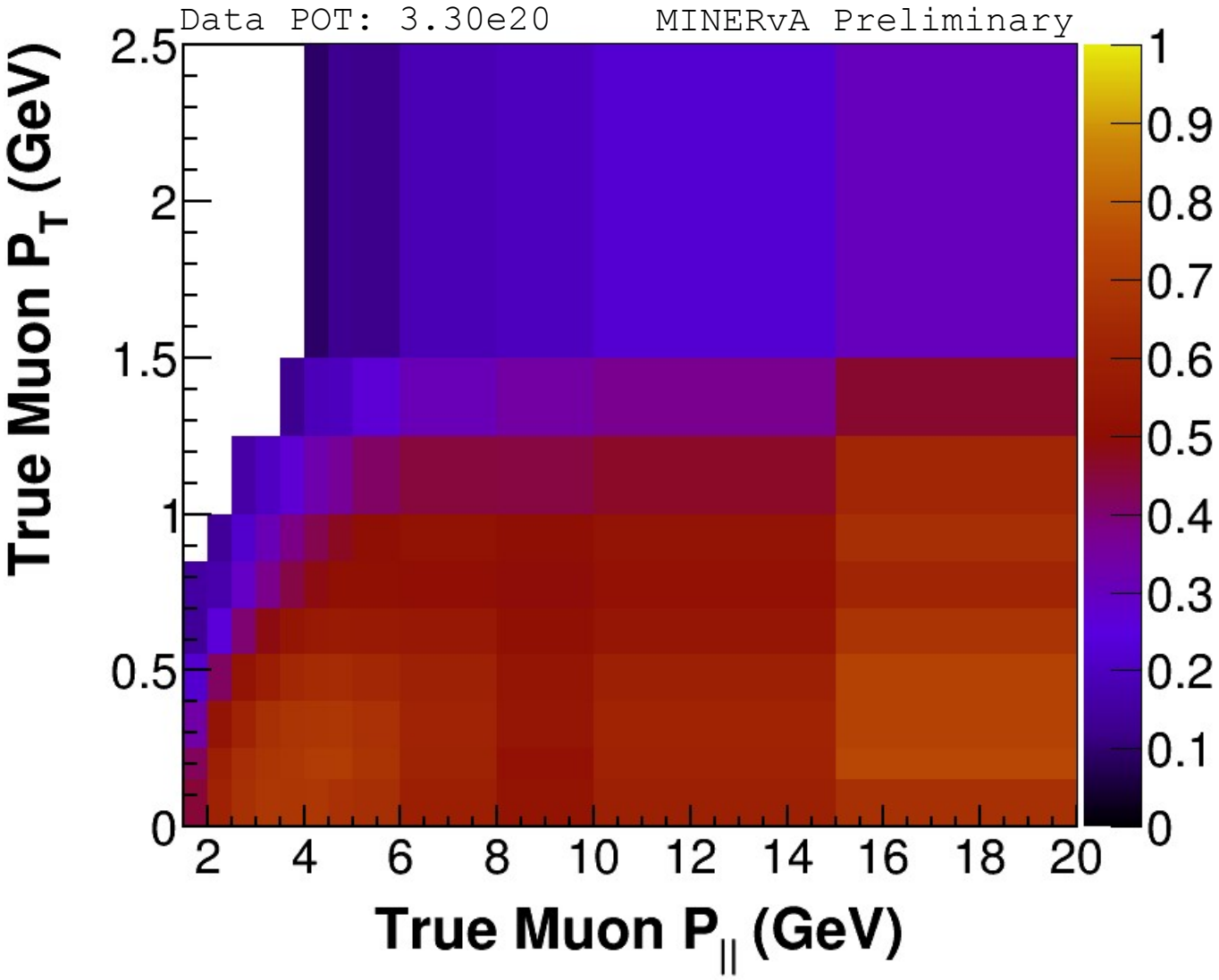


Migration Matrix E_ν

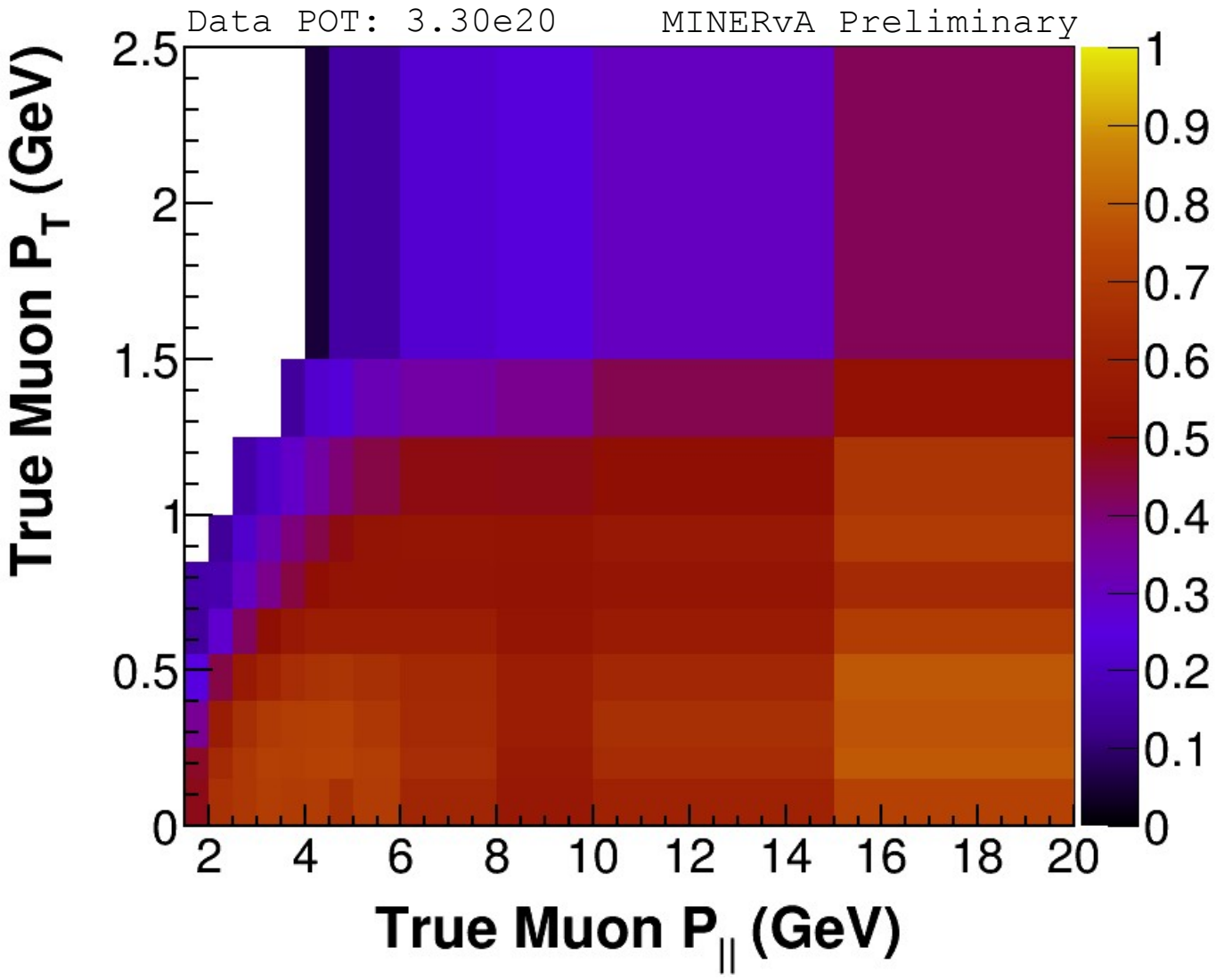


Efficiency and Purity

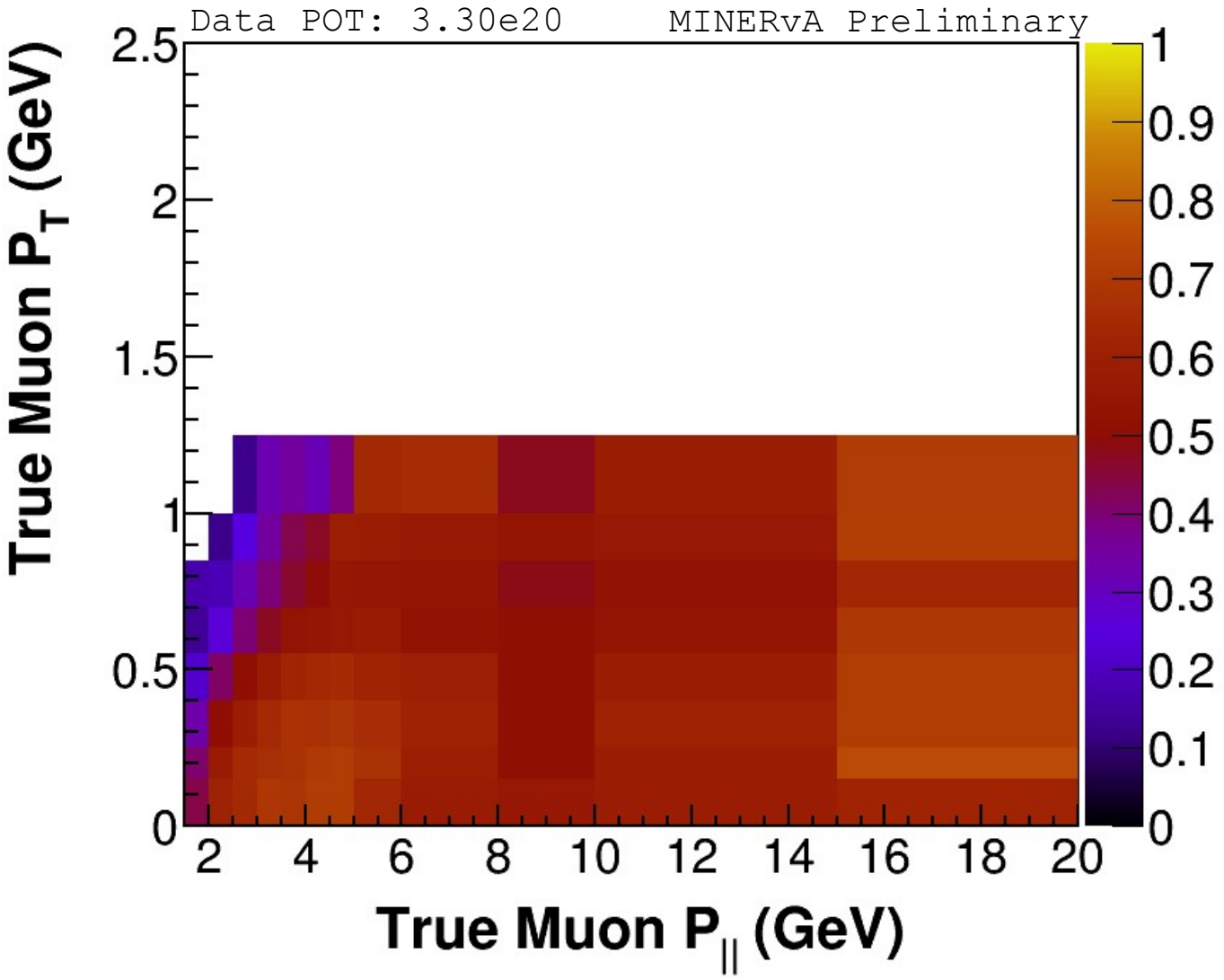
Efficiency - QELike



Efficiency- QE

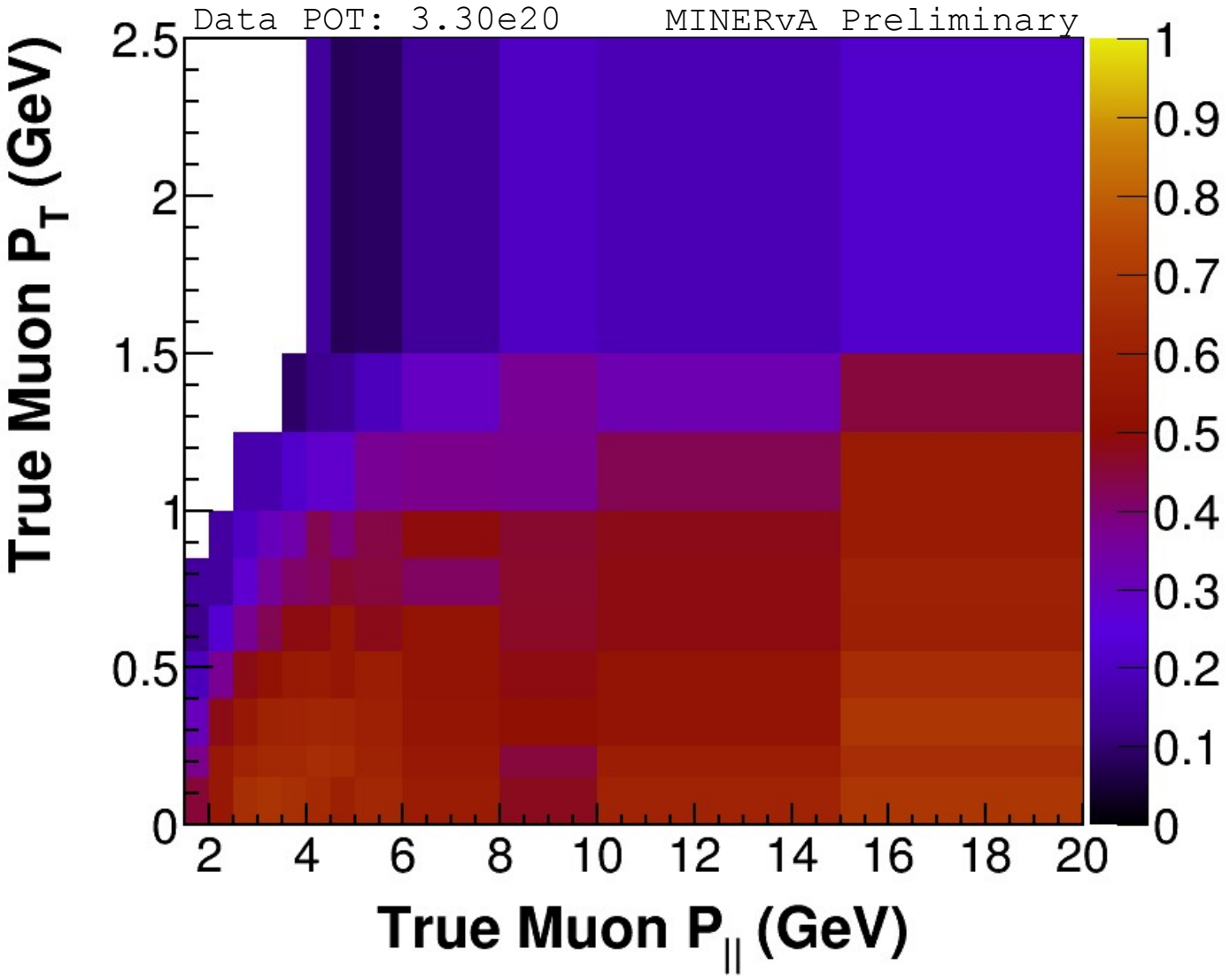


Efficiency – QELike – 2p2h

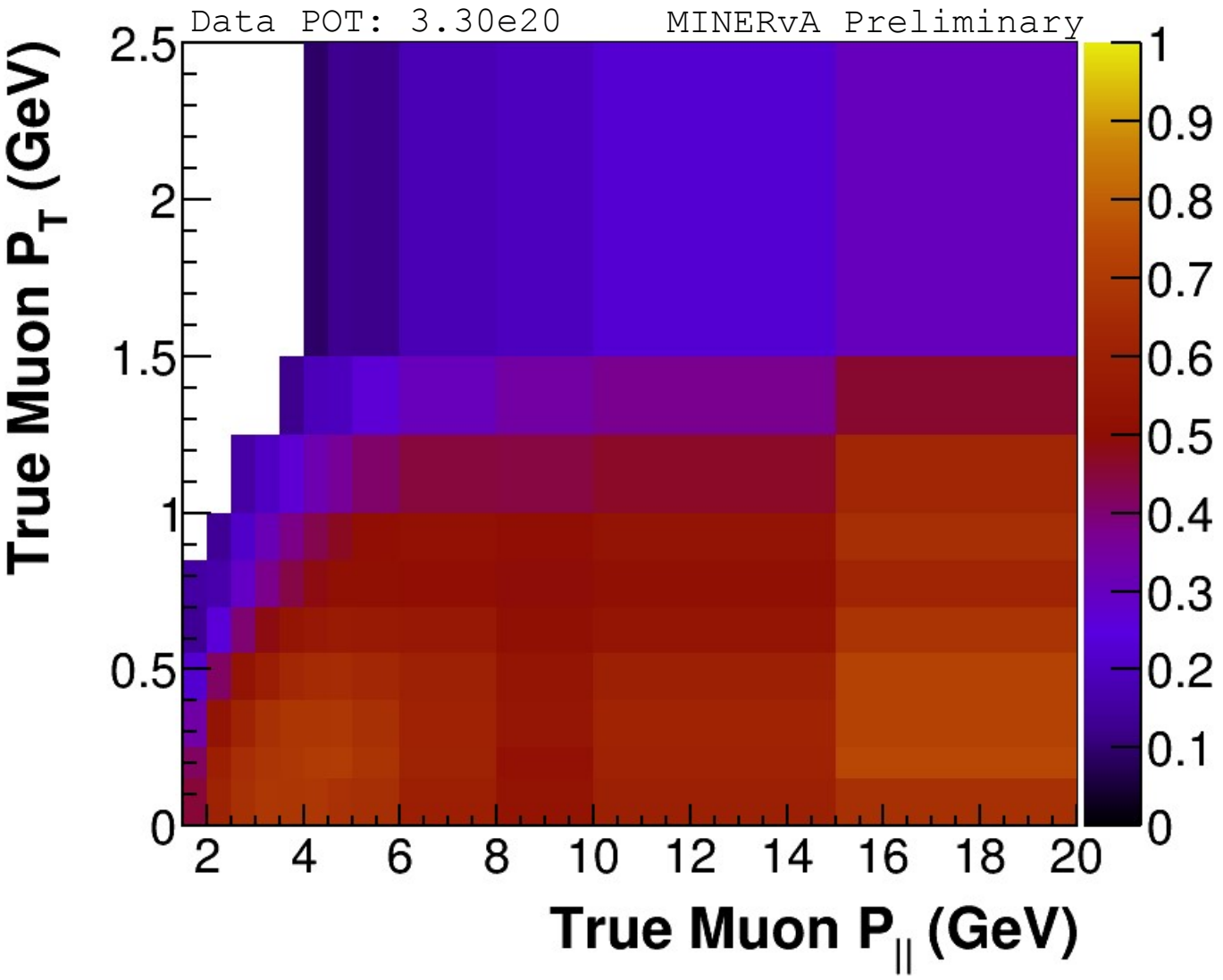


The cutoff is due to the model cutting out at q_3=1.2 GeV

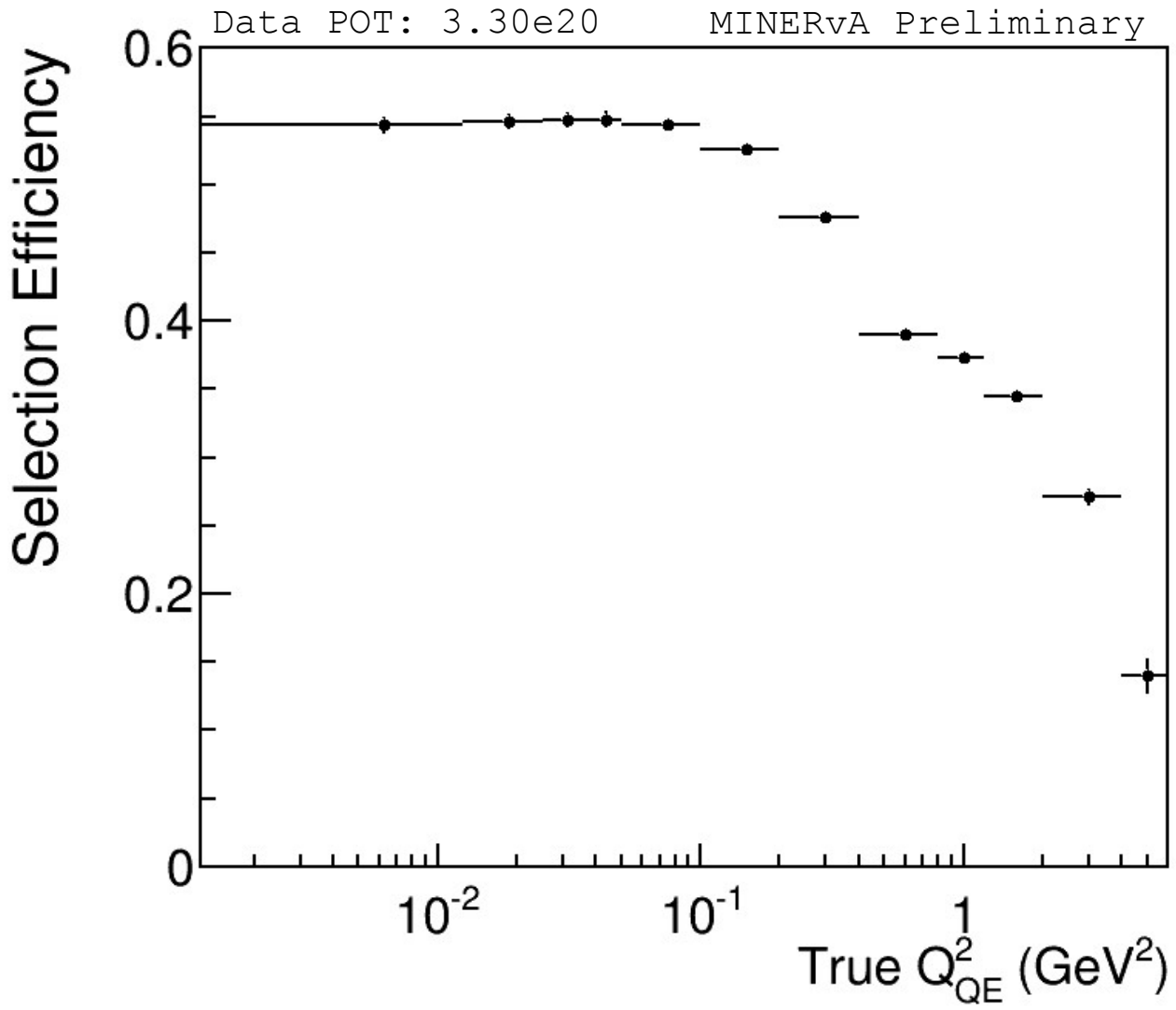
Efficiency – QELike - Resonant



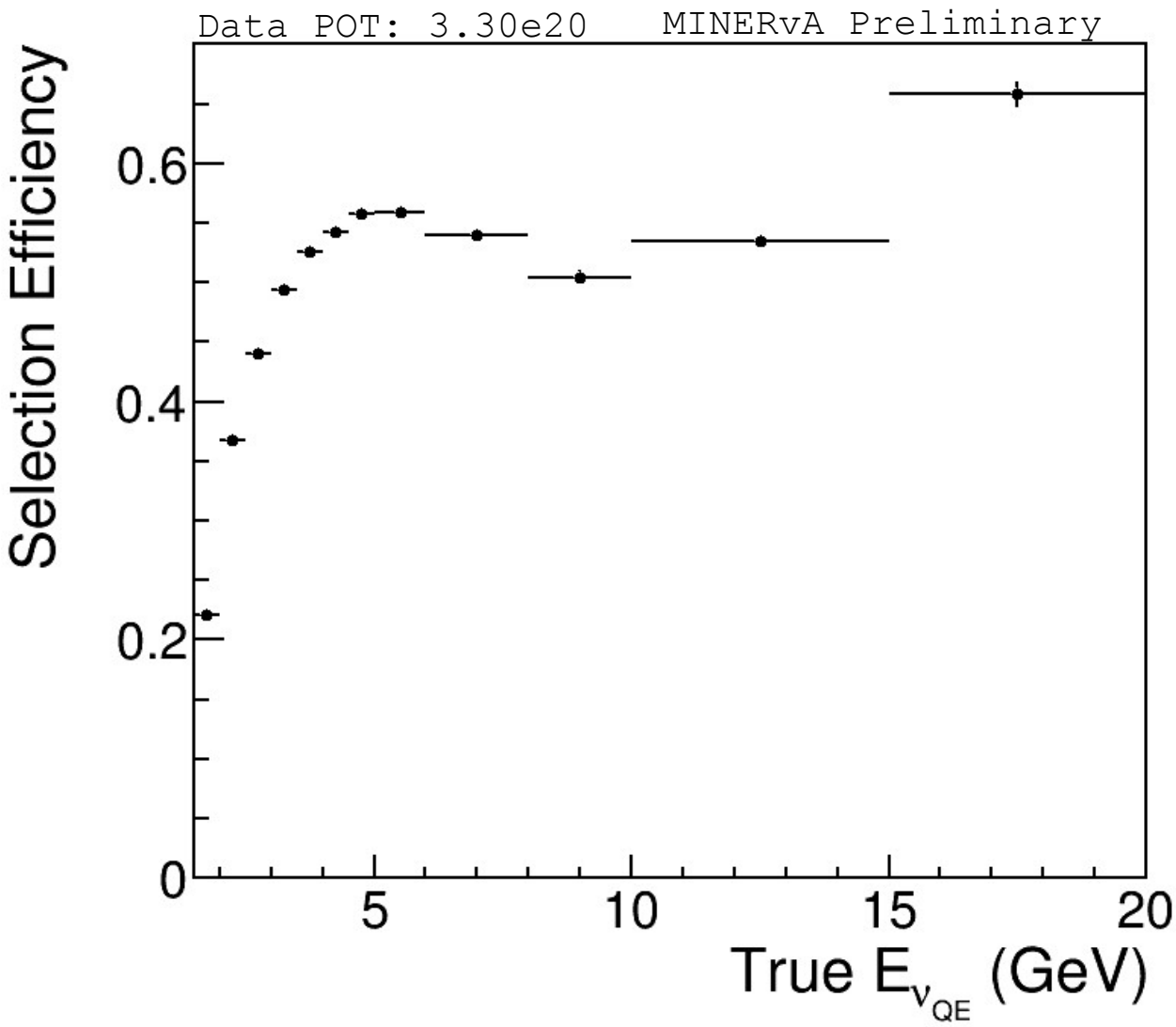
Purity


Data POT: 3.30e20
MINERvA Preliminary
True Muon P_T (GeV)
True Muon $P_{||}$ (GeV)
0
0.5
1
1.5
2
2.5
2
4
6
8
10
12
14
16
18
20
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Efficiency – Q^2_{QE}



Efficiency – $E_{\nu,QE}$

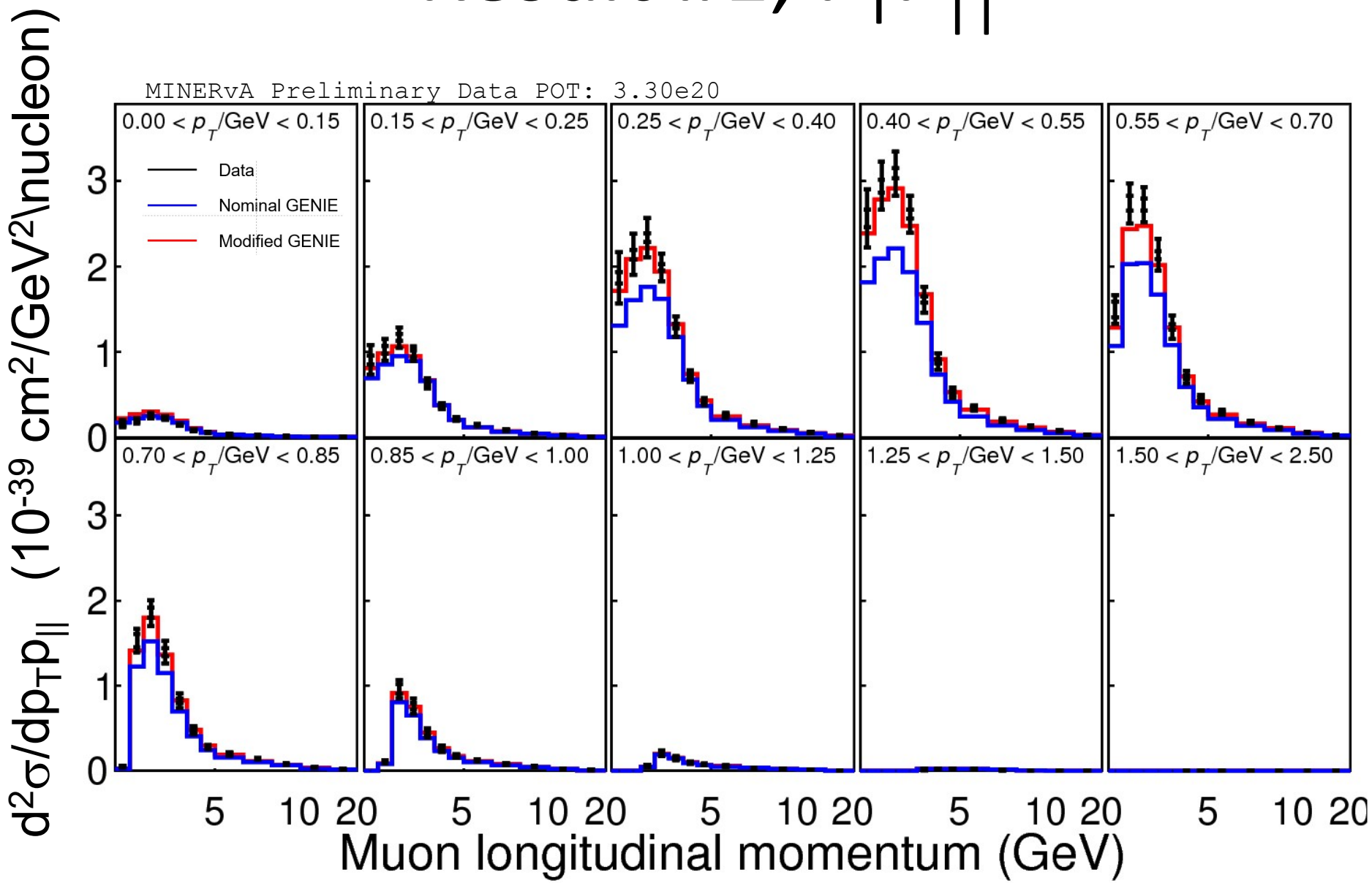


Results

Signal definition

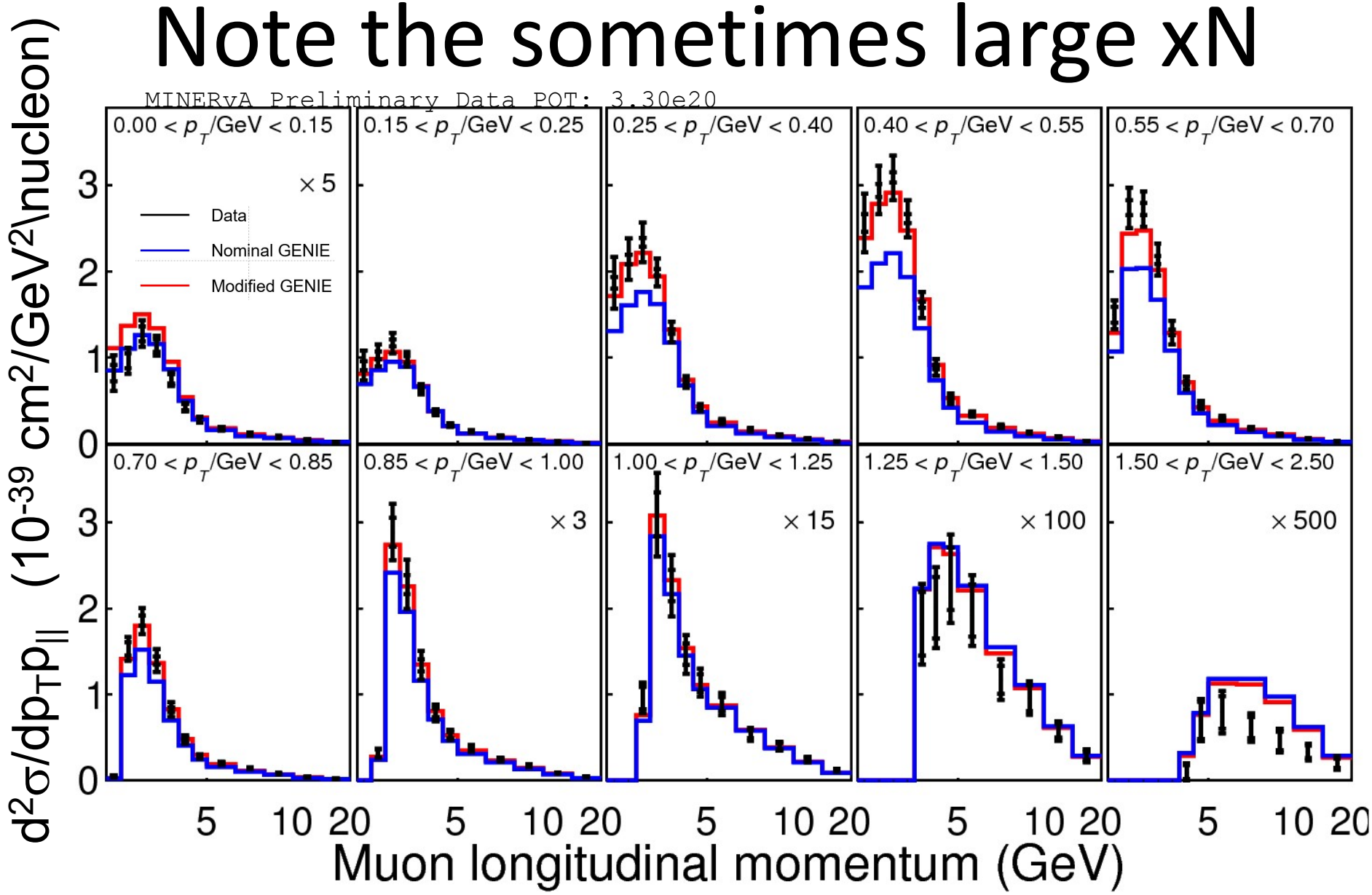
- QELike – Defined by final state particles
  - Any number of nucleons of all energy
  - No pion, heavy baryons etc
  - No gammas > 10MeV
- Additional constraints
  - True muon angle <20.0
- We do not simulate radiative CCQE but will not cut it out of the sample in data (mostly collinear with muon)
  - Basically we assume selection efficiency of this process is the same as everything else…

Result #1, $P_T P_{||}$



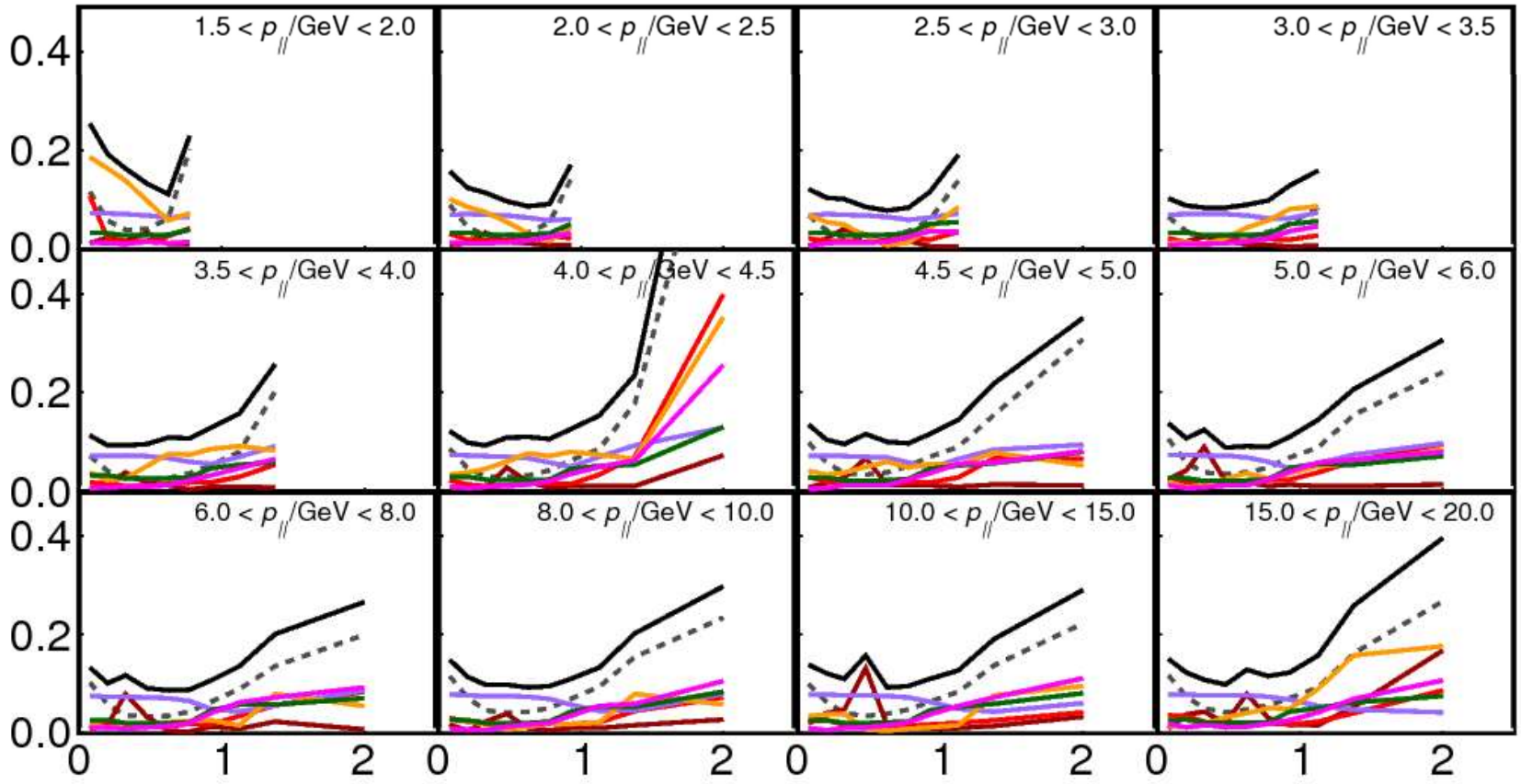
Note: x-axis is not linear. High $P_{||}$ is squashed to allow everyone to see the lower $P_{||}$

Result #1 $P_T P_{||}$
Note the sometimes large xN



Note: x-axis is not linear. High $P_{||}$ is squashed to allow everyone to see the lower $P_{||}$

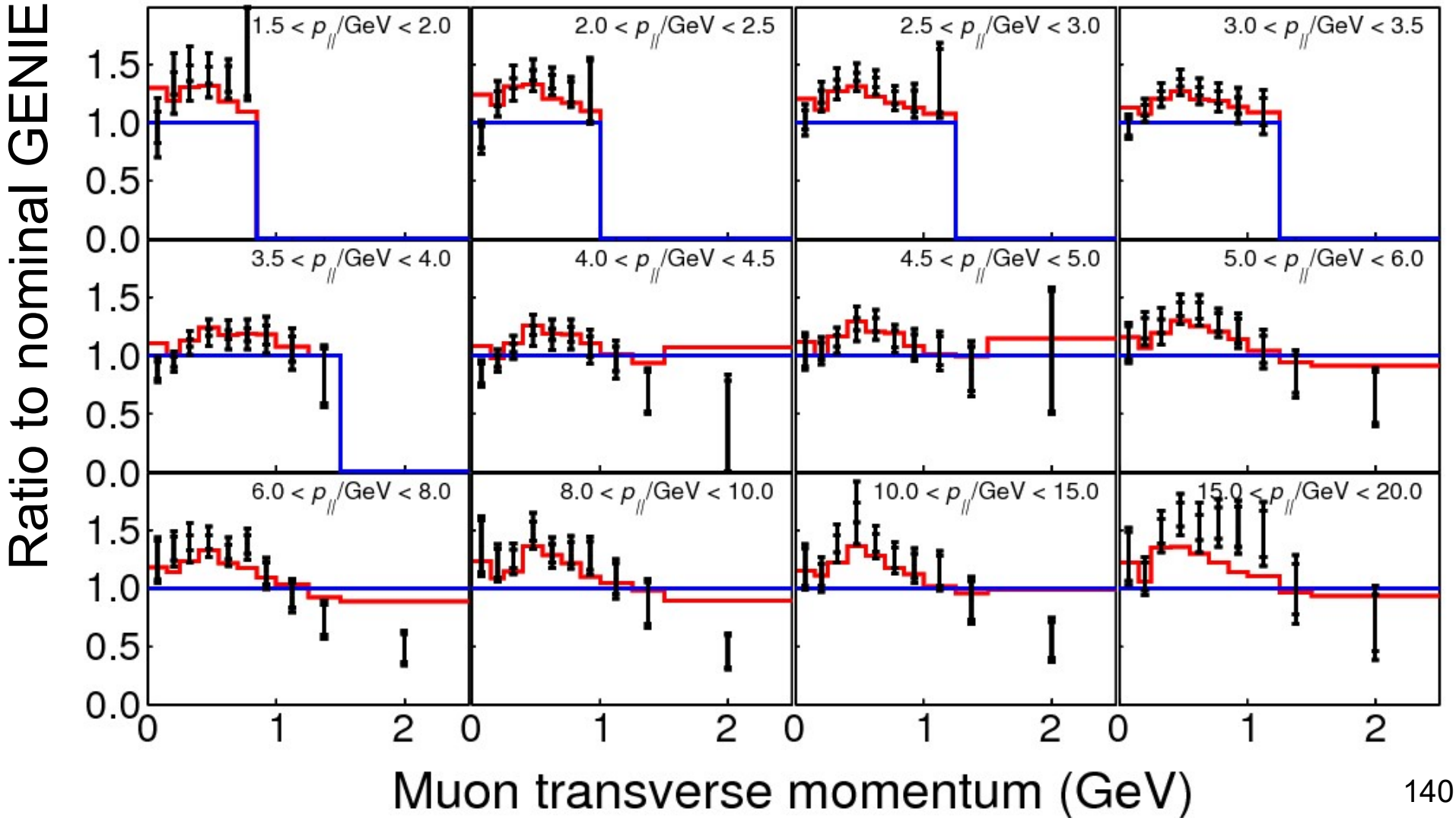
Systematics



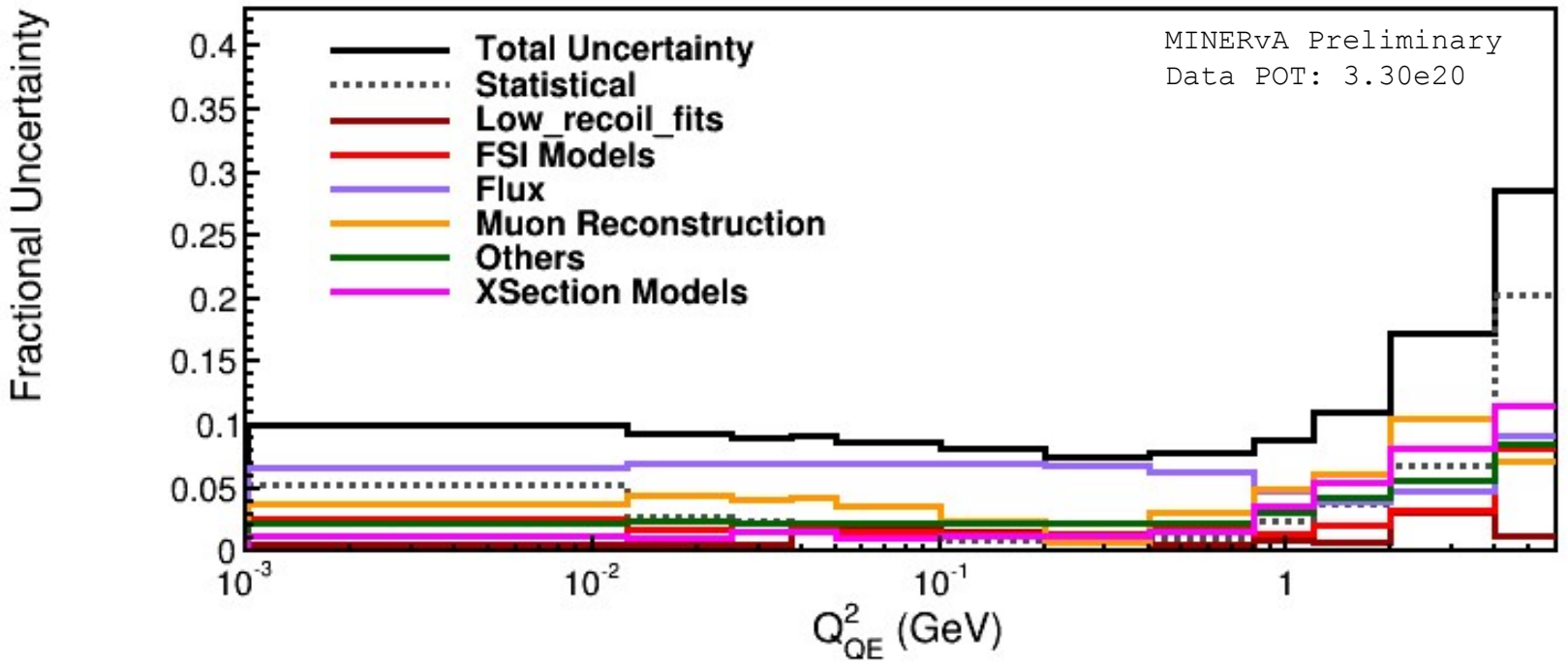
Comparison

Data — Modified GENIE — Nominal GENIE

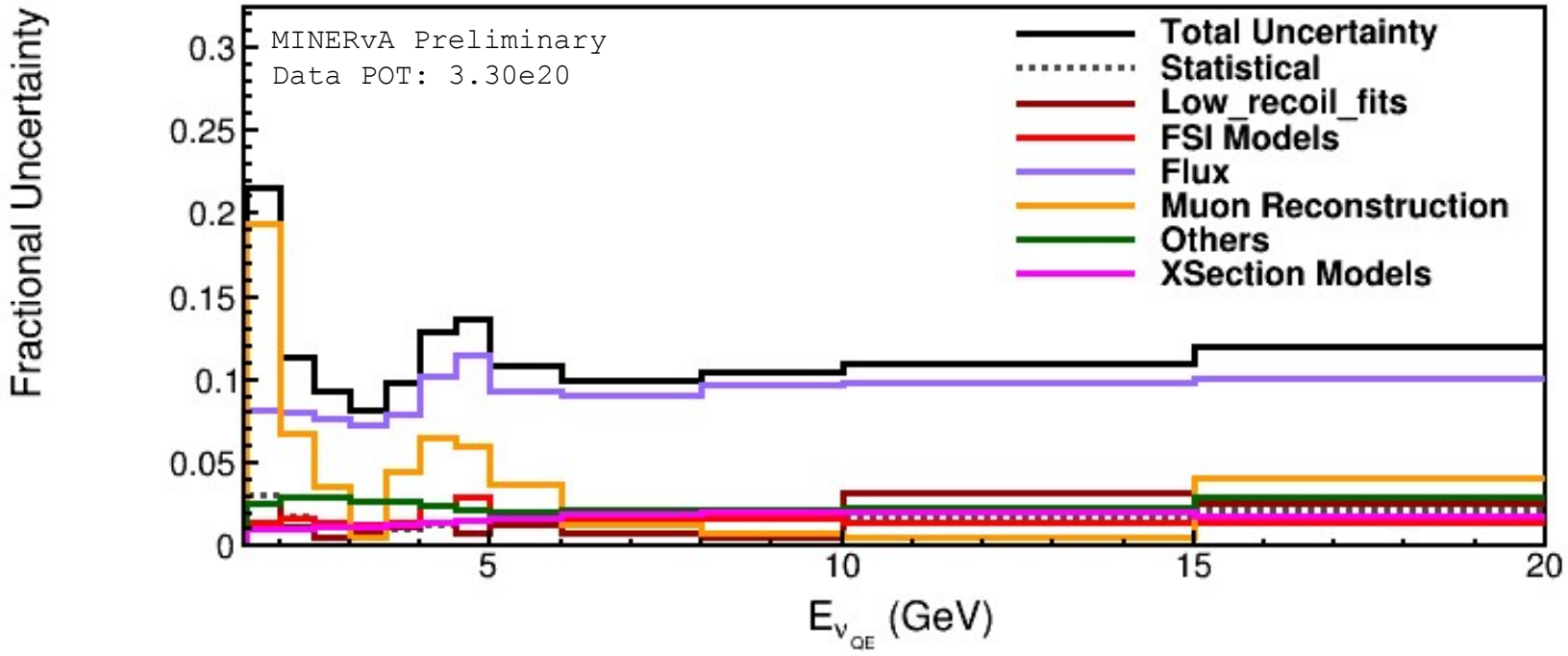
MINERvA Preliminary Data POT: 3.30e20



Q^2_{QE} systematic errors



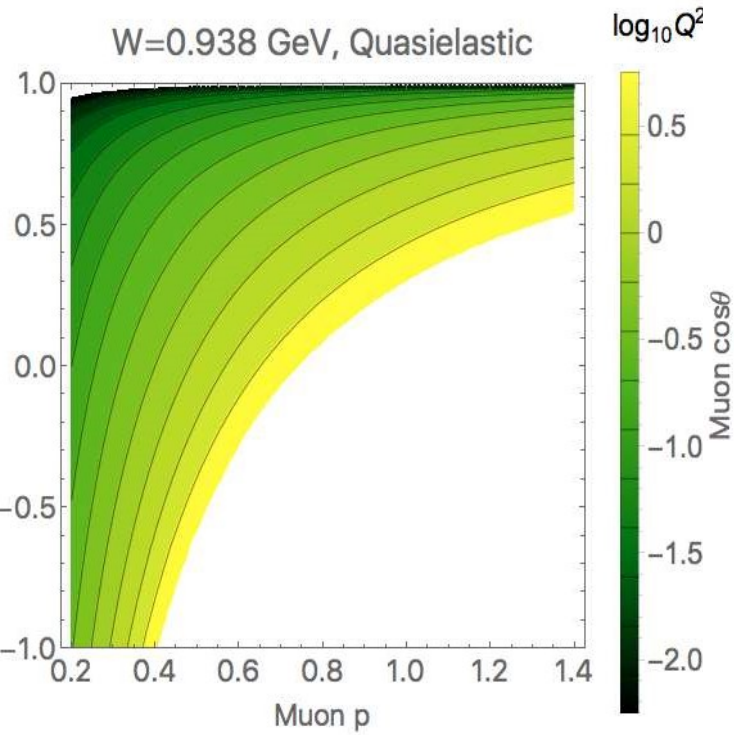
$E_{\nu,QE}$ systematic errors

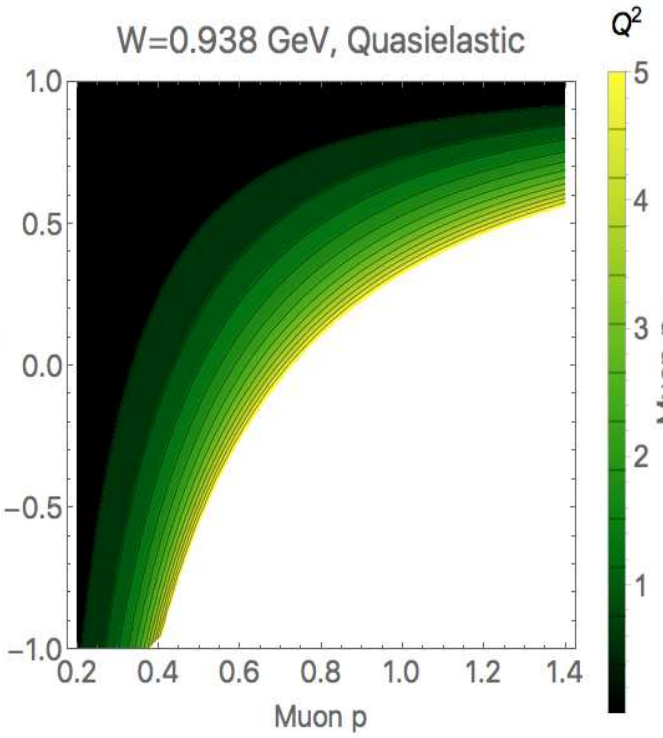


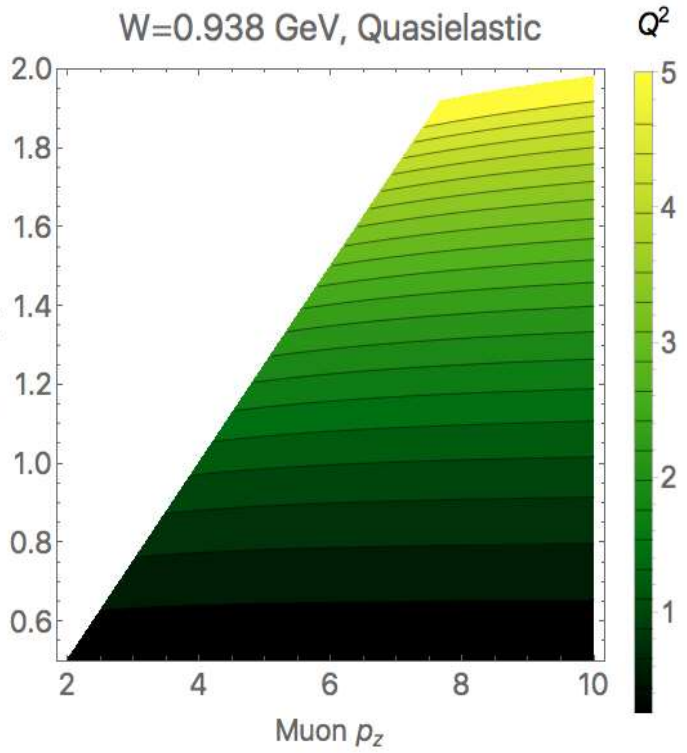
MiniBooNE Comparison

MiniBooNE and MINERvA Kinematics

- MiniBooNE and MINERvA variables at high Q^2

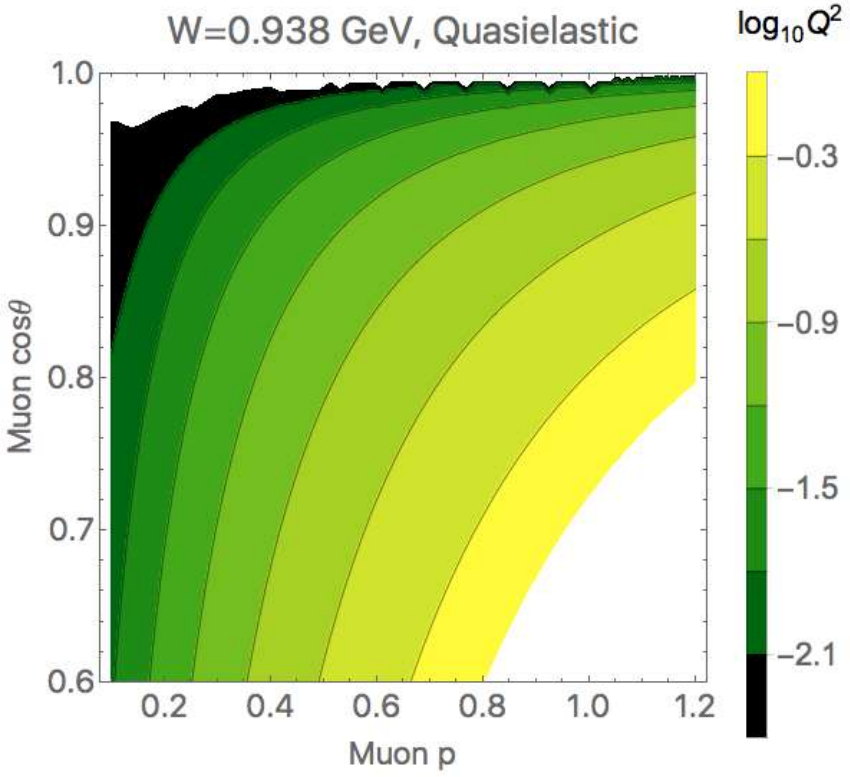


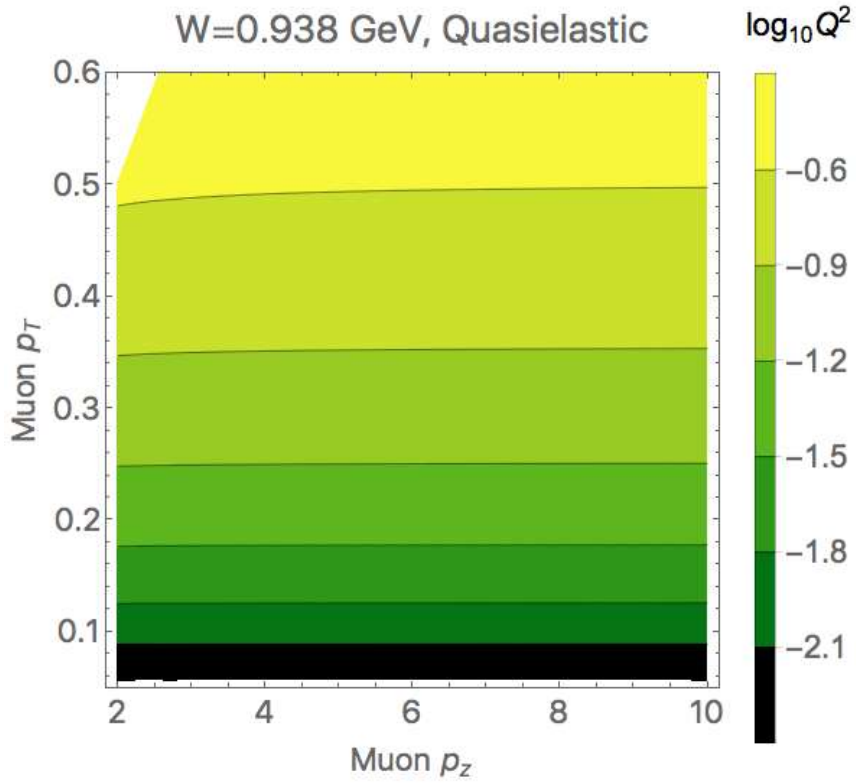




MiniBooNE and MINERvA Kinematics

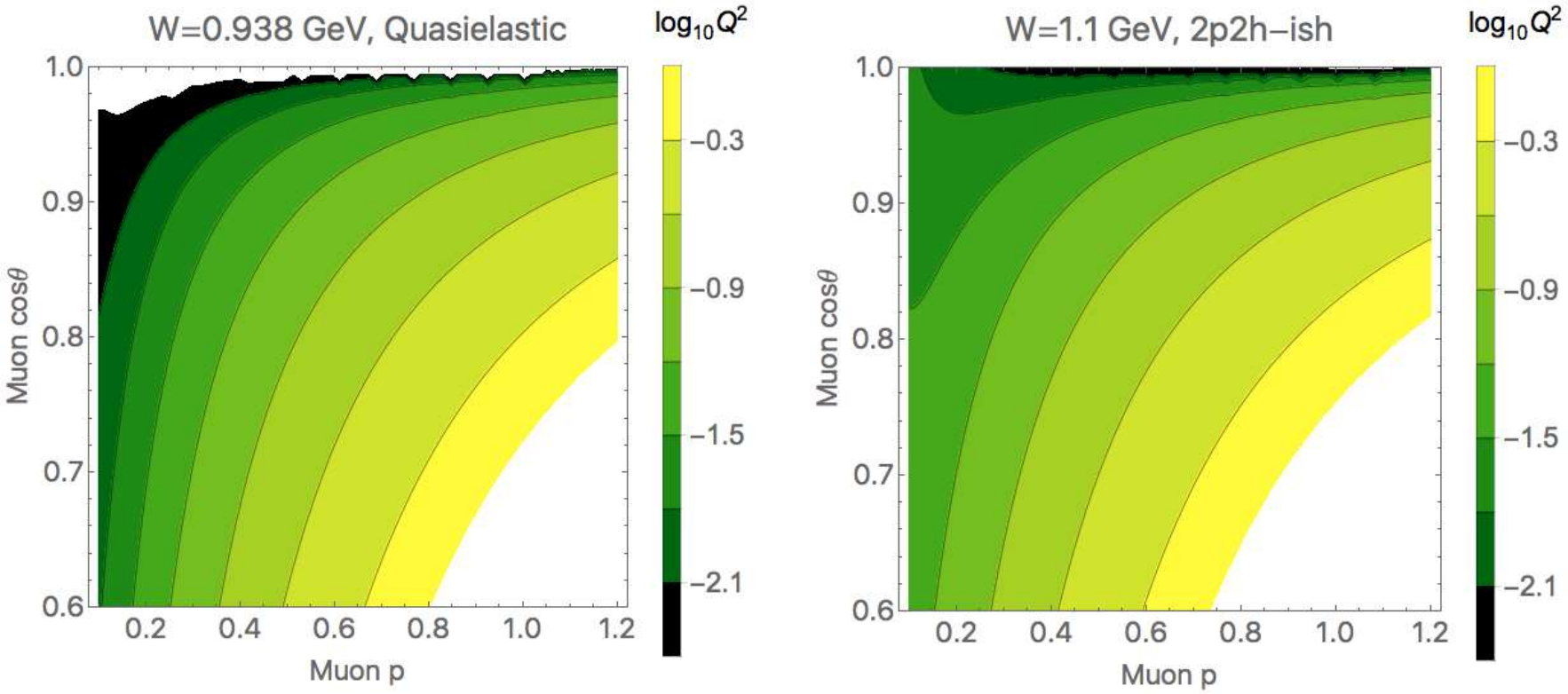
- At low Q^2 for MINERvA, $Q^2 \approx p_T^2$



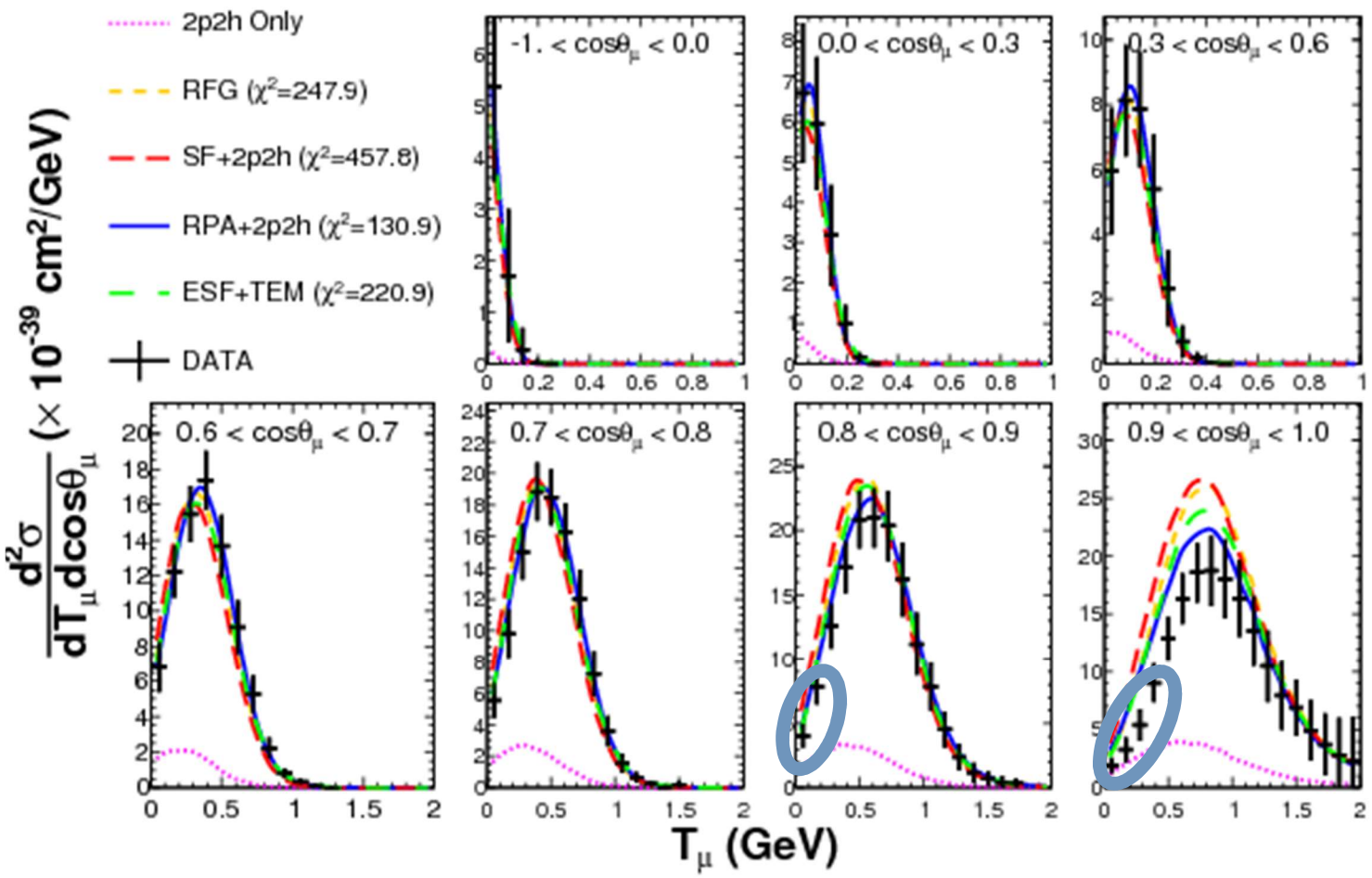


MiniBooNE and MINERvA Kinematics

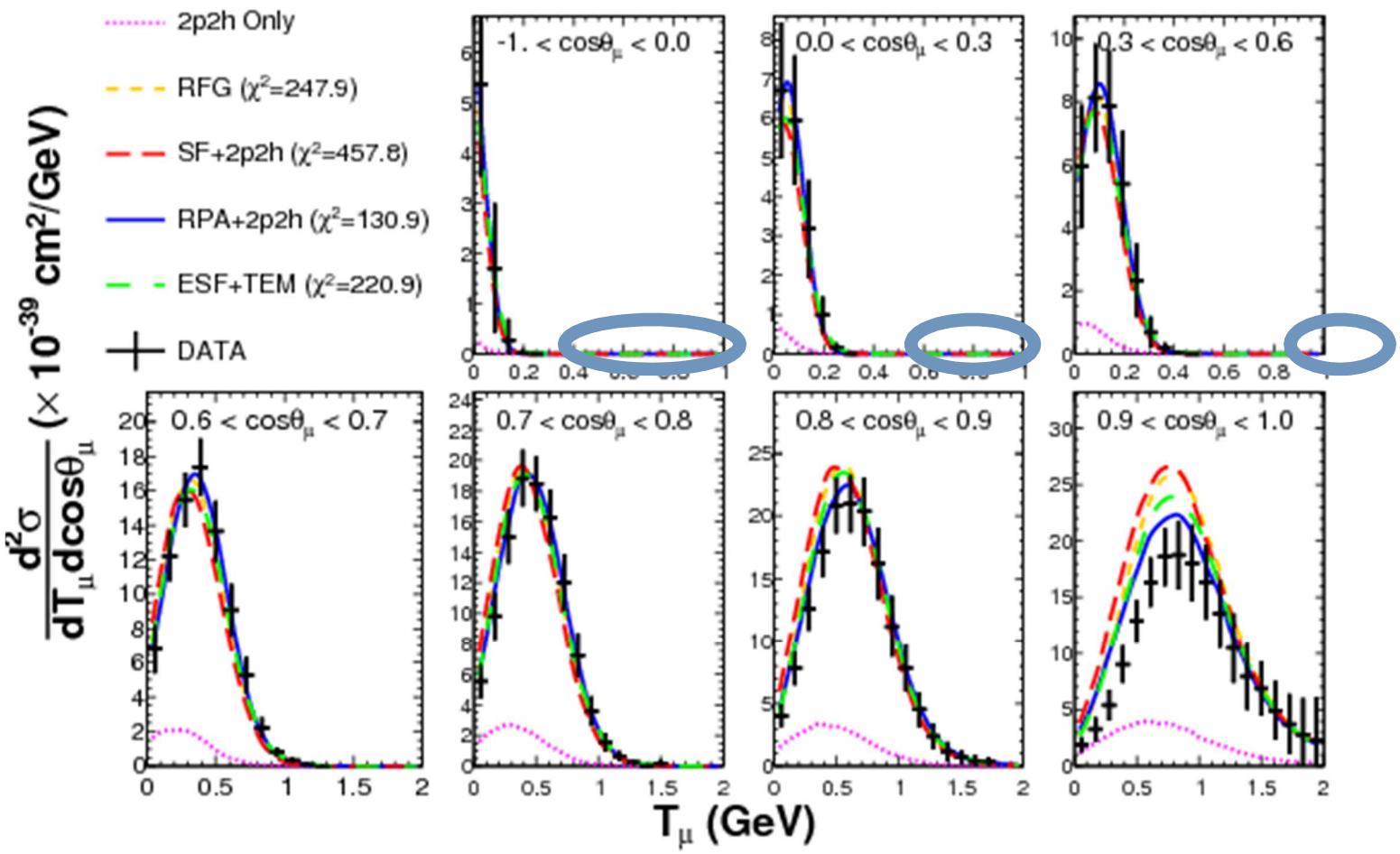
- True CCQE and 2p2h like W. Note migration of 2p2h to higher Q^2



MiniBooNE data, our lowest Q^2, <.0125 GeV^2

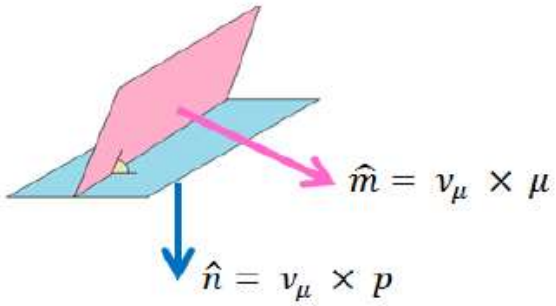


MiniBooNE data, our high Q^2, >2 GeV^2

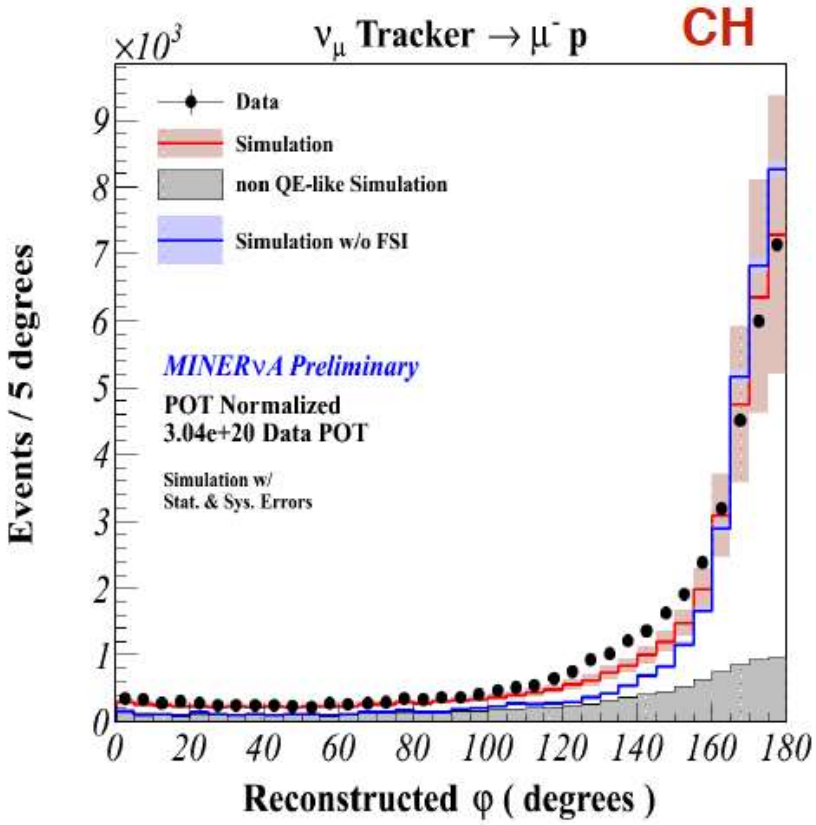


Coplanarity Angle

- Protons are very sensitive to final state interactions
- A clear effect of final state interactions can be shown with the coplanarity angle, which is the angle between the ν-muon and ν-proton plane



$$\varphi = \cos^{-1}\left(\frac{(\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_\mu) \cdot (\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_p)}{|\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_\mu||\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_p|}\right)$$



- Detector resolution on φ is 3.8 degrees, the width is due to Fermi motion, inelastic scattering and FSI effects

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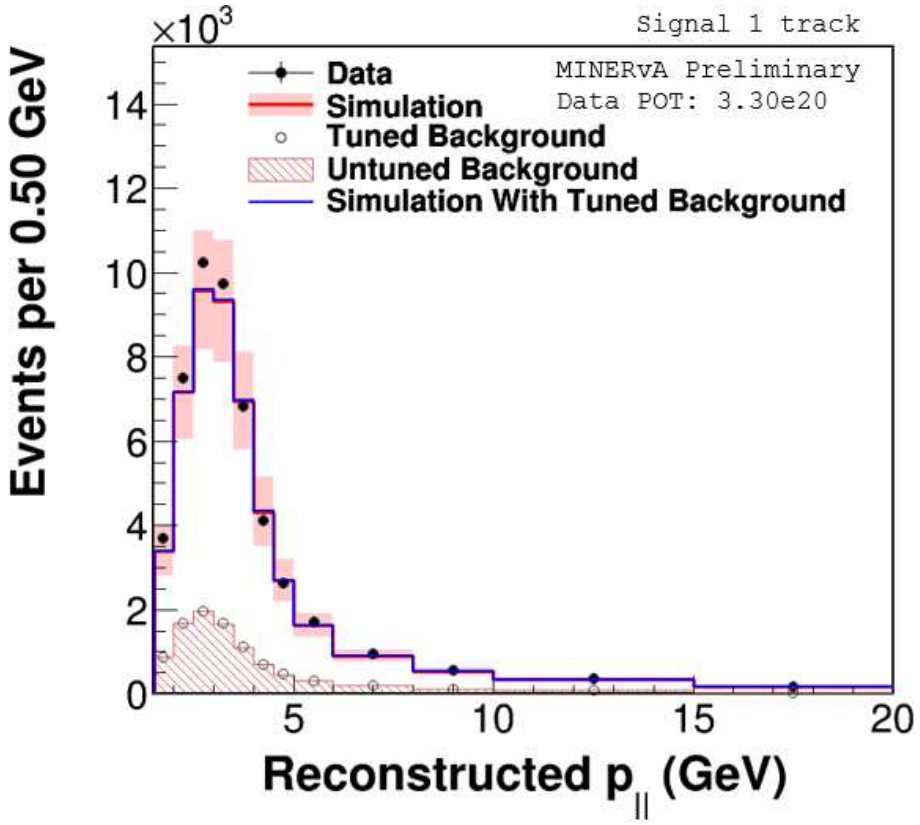
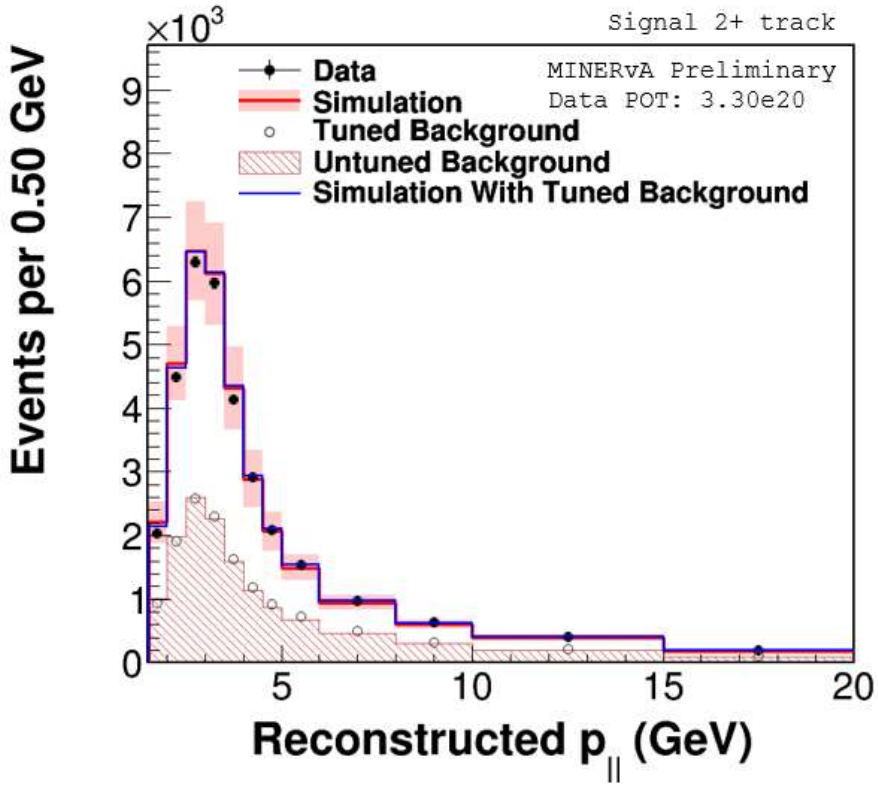
Tuned Signal Sample



1-track sample



2-track sample

σ vs. E_ν: The Teppei plot

- Because of the difference between CCQE-like and true CCQE and the problem with ${E_\nu}^{CCQE}$