QE-Like Interactions From MINERvA: What's ν?

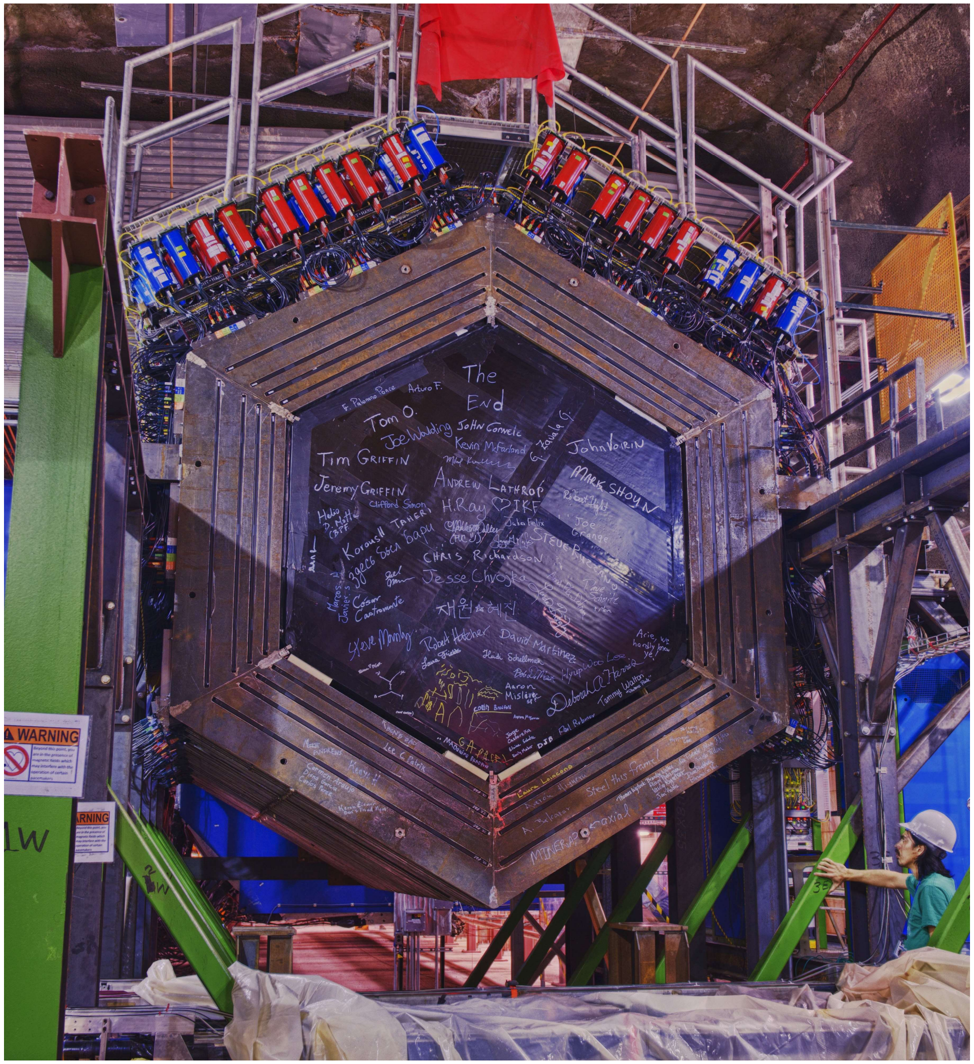
Daniel Ruterbories

on behalf of the MINERvA collaboration

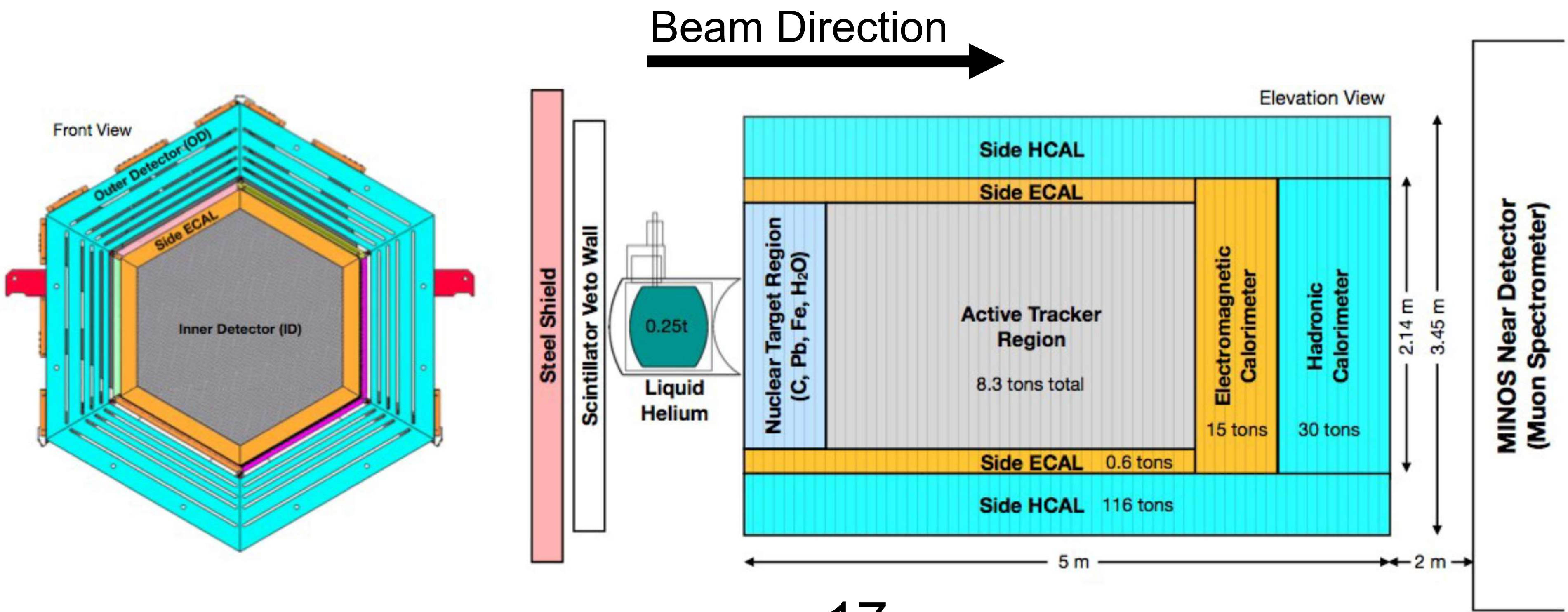
April 16th, 2024

The MINERvA Experiment

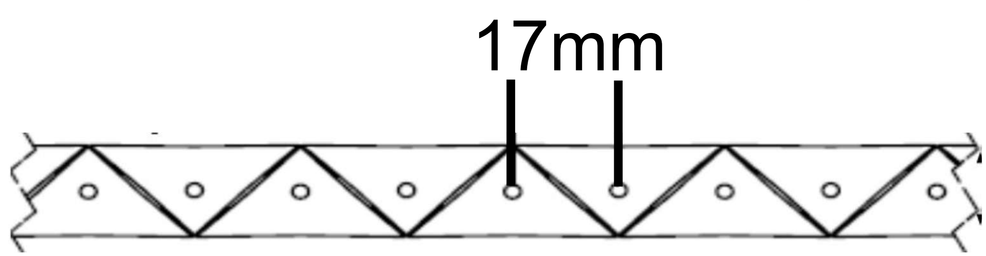
- Study neutrino-nucleus scattering at a few GeV
  - Measure the effects of the nuclear environment on neutrino scattering
  - Improve understanding of neutrino-nucleus cross section model by working with generators
  - Benefits current and future neutrino oscillation experiments



Experimental Apparatus



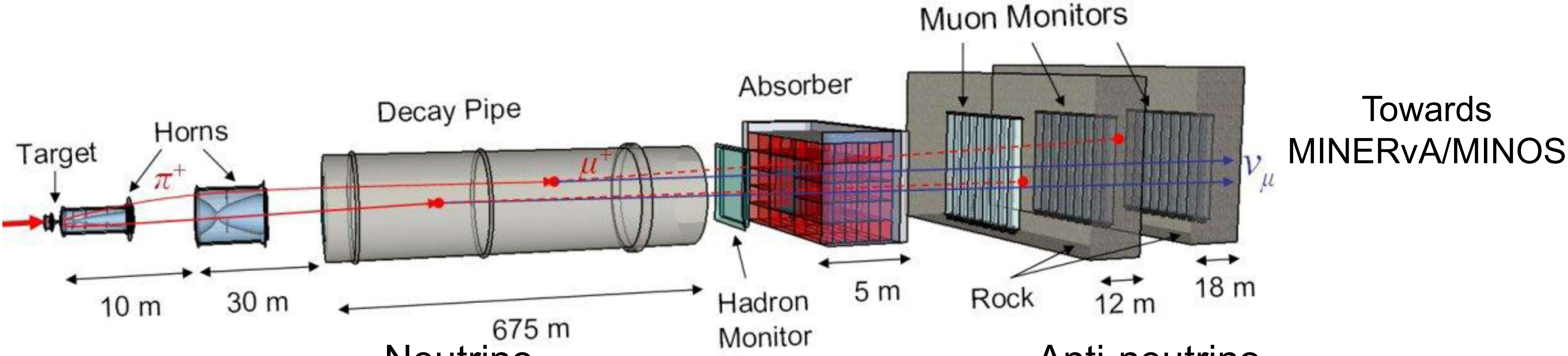
Three views:
X: Vertical
U,V: ±60

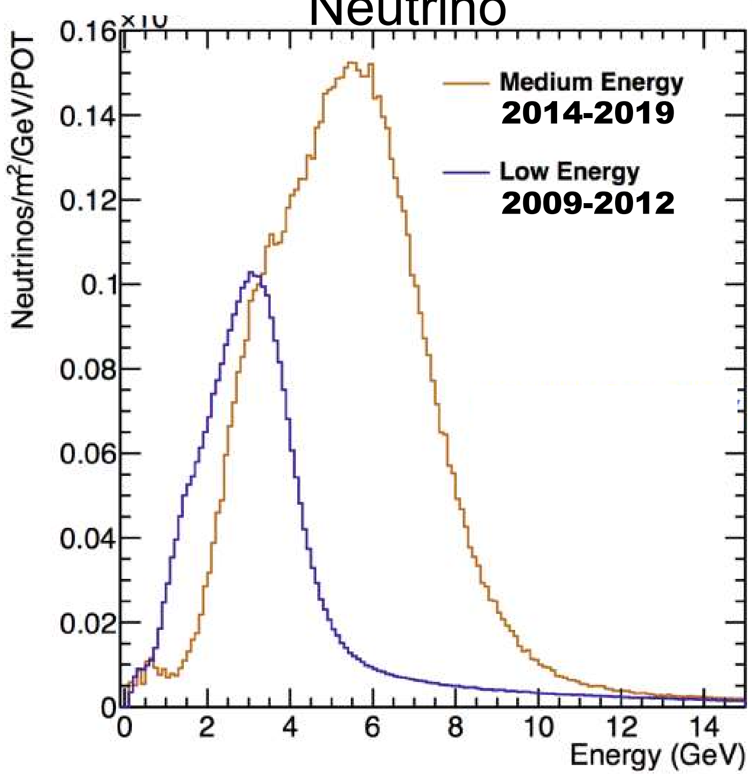


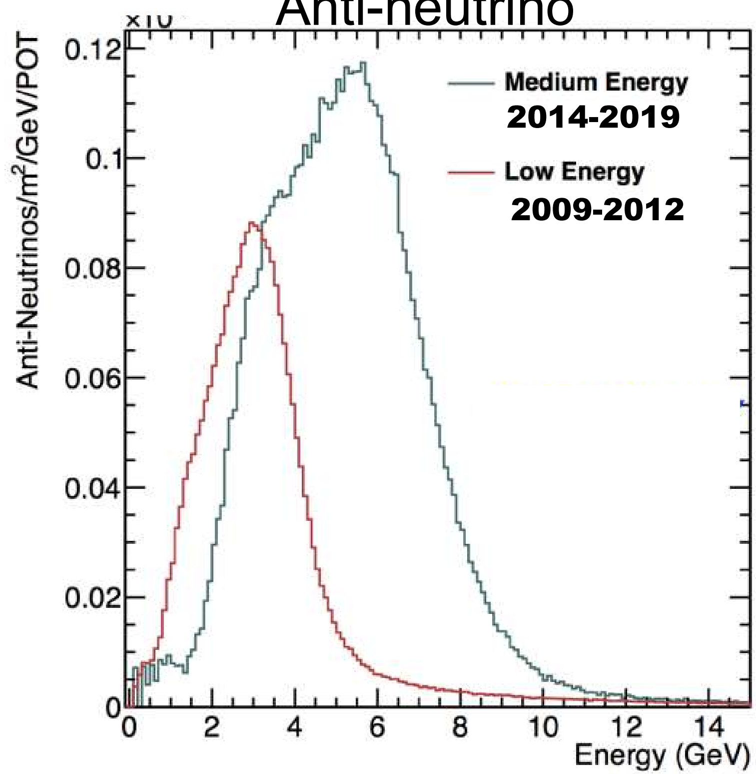
Spatial resolution ~3mm
Timing resolution ~3ns

Nucl. Inst. and Meth. A743 (2014) 130
arXiv:1305.5199

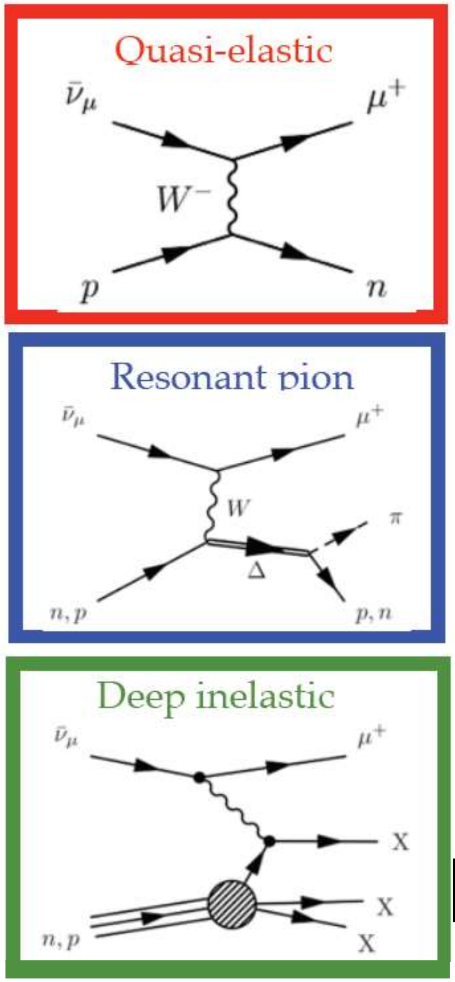
The NUMI beam







What is QE-Like? How are they selected?

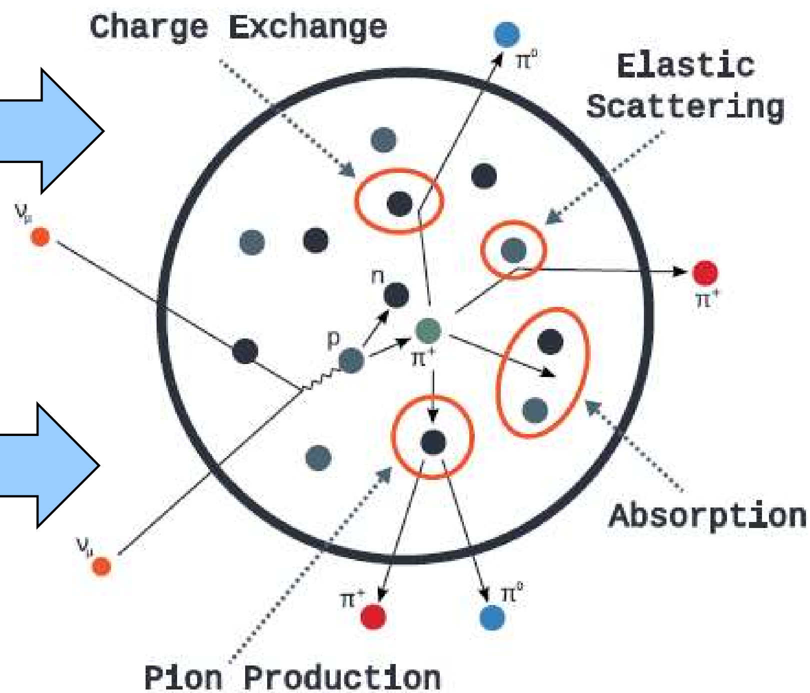


QE

RES

DIS

Initial Interaction



Final State Interactions (FSI)

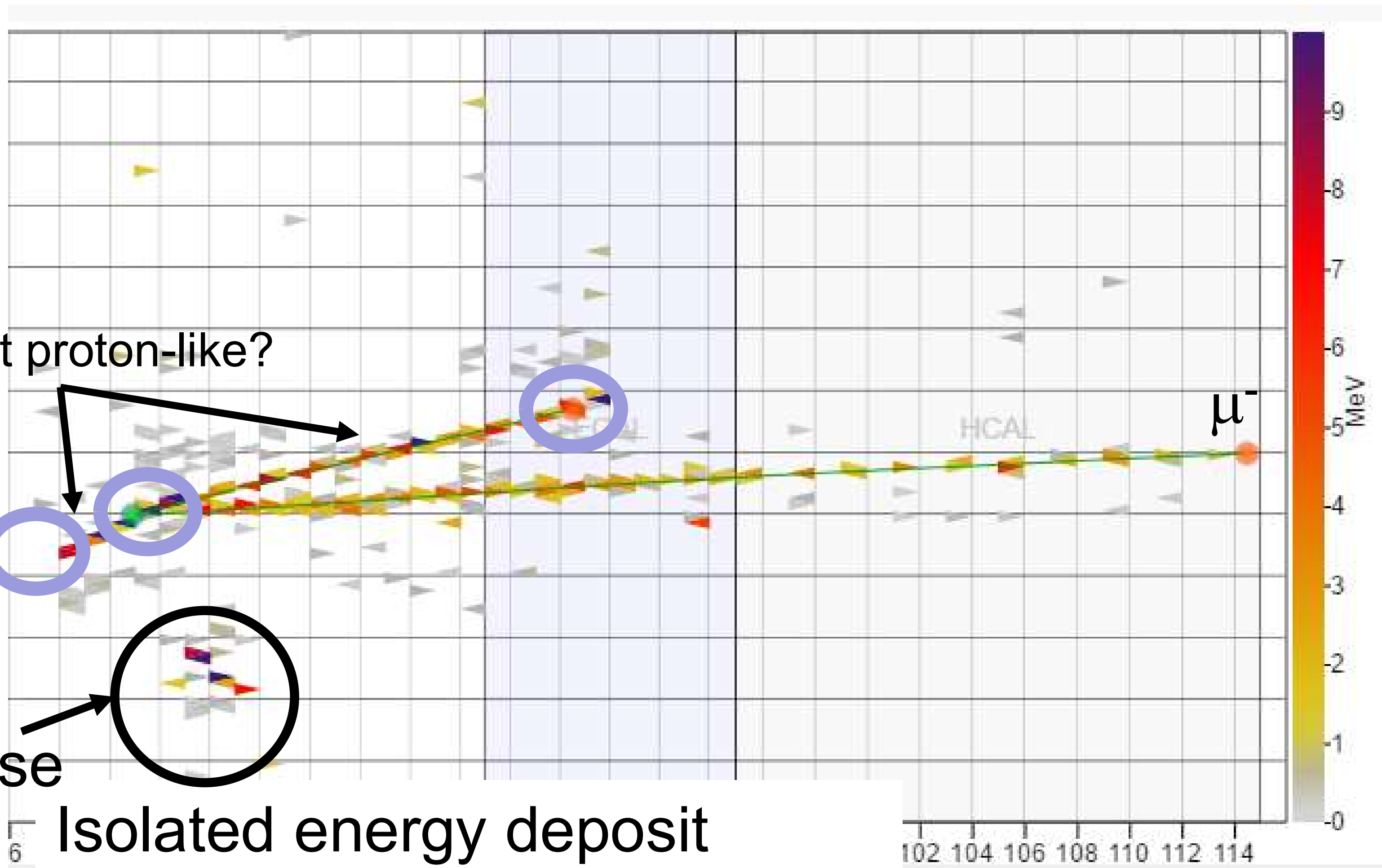
- Signal <-> Background migrations
- Energy sharing between pions and nucleons
- Particles in the detector, and thus energy deposited, is modified
- Define Signal by topology – no pion/kaons, only nucleons

Reconstruction and selection strategy

Look for Michel electrons at later times to veto π^+

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

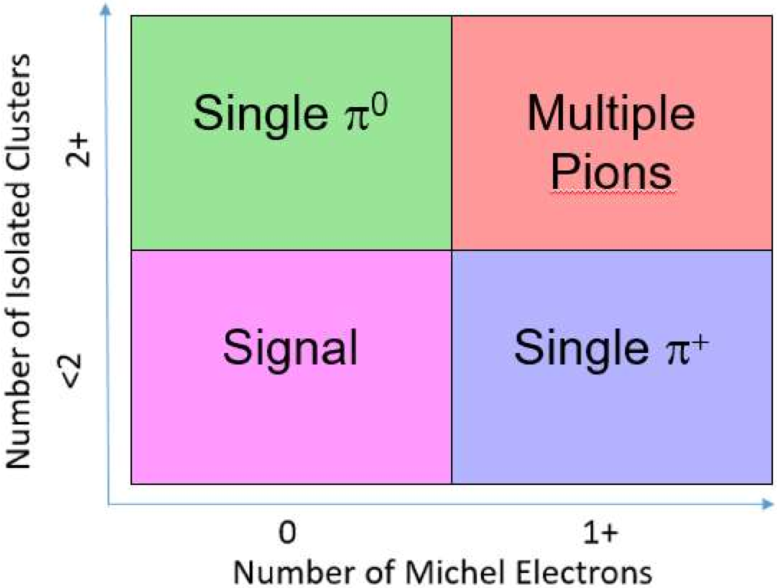
dE/dX PID. Is it proton-like?



Count these

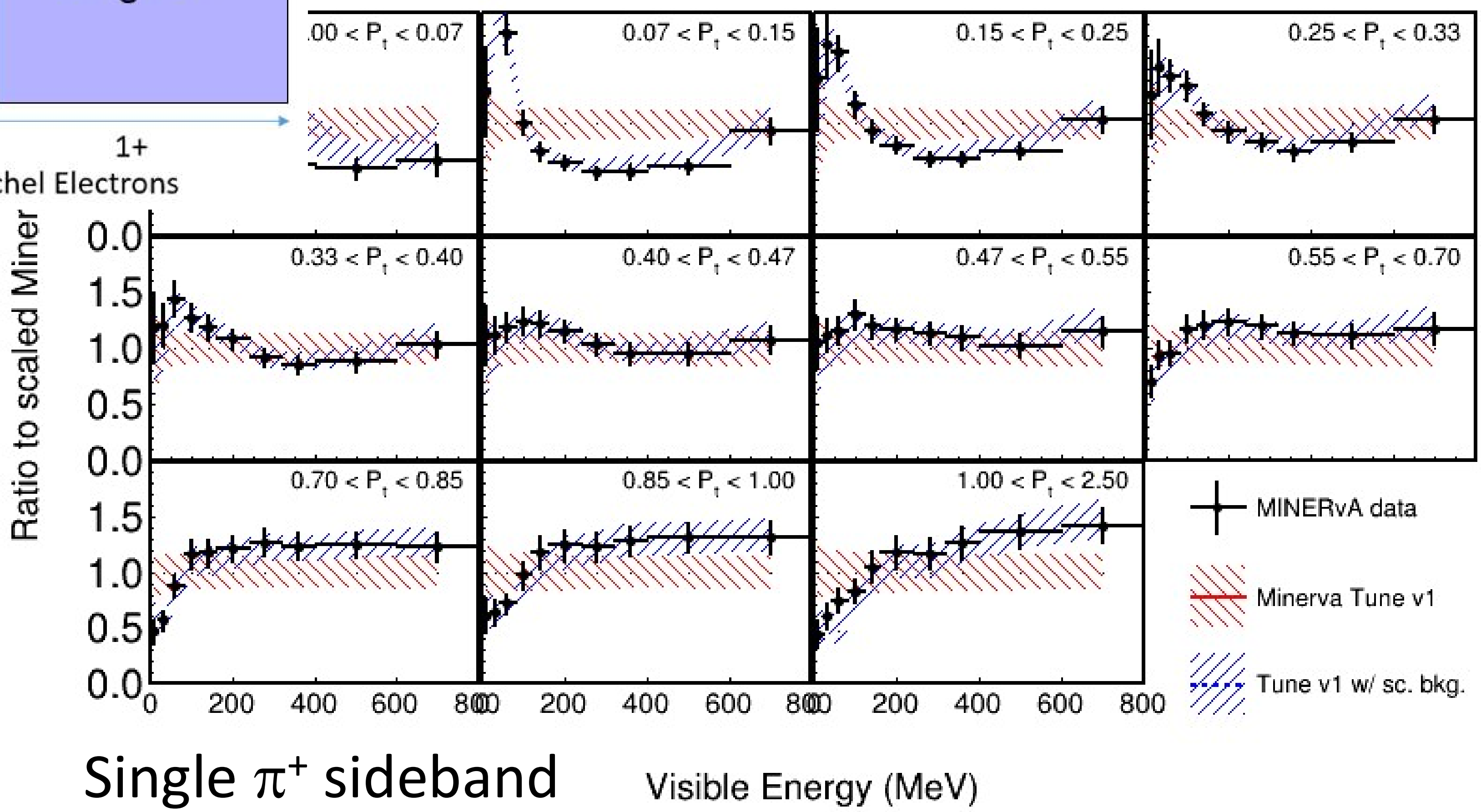
Isolated energy deposit

Background Constraints



Improved method uses a 2D SVD fitter
Bin-by-bin solutions solving the four sample space

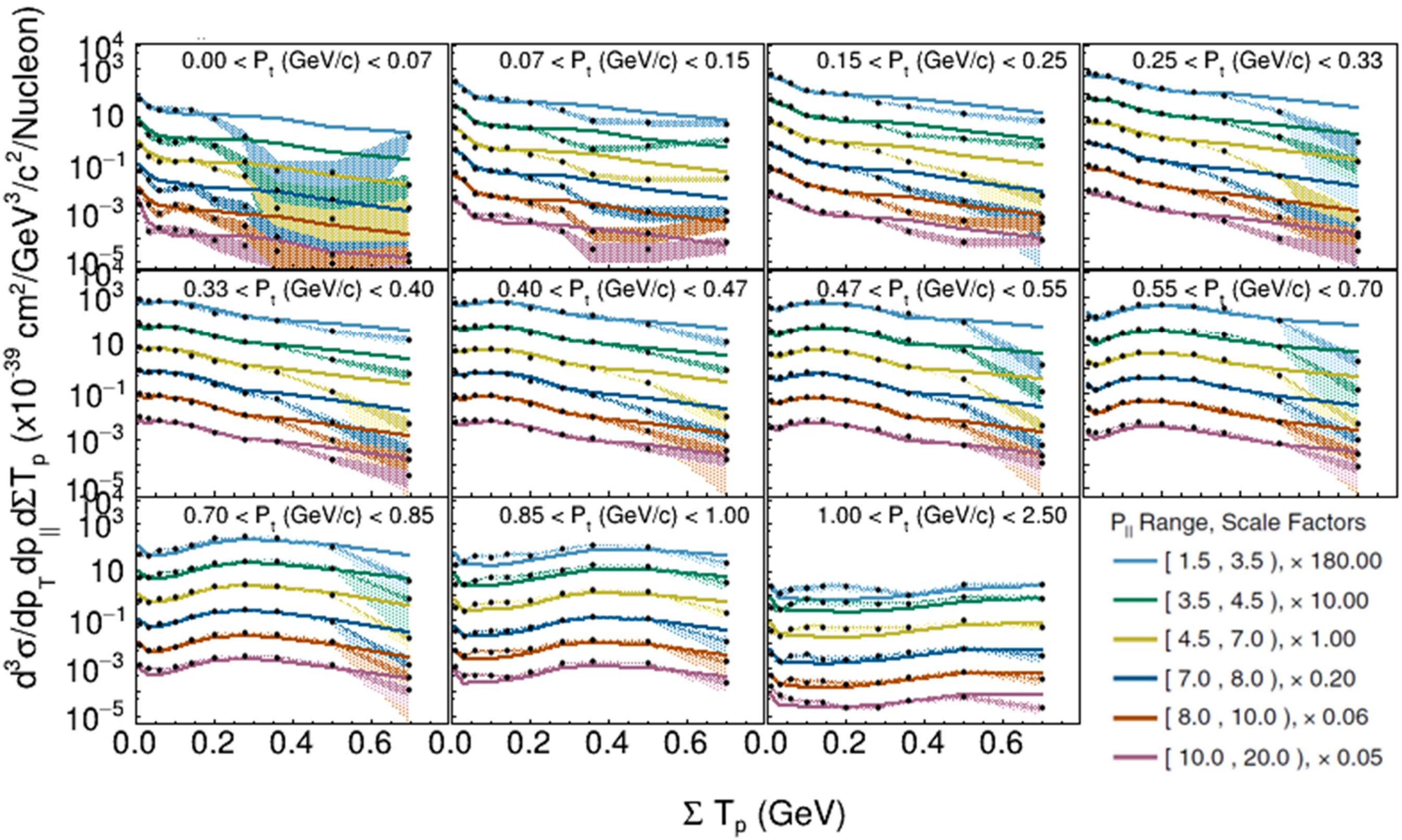
Chi2 before: 981.41 ; Chi2 after: 42.36 ; ndf = 110

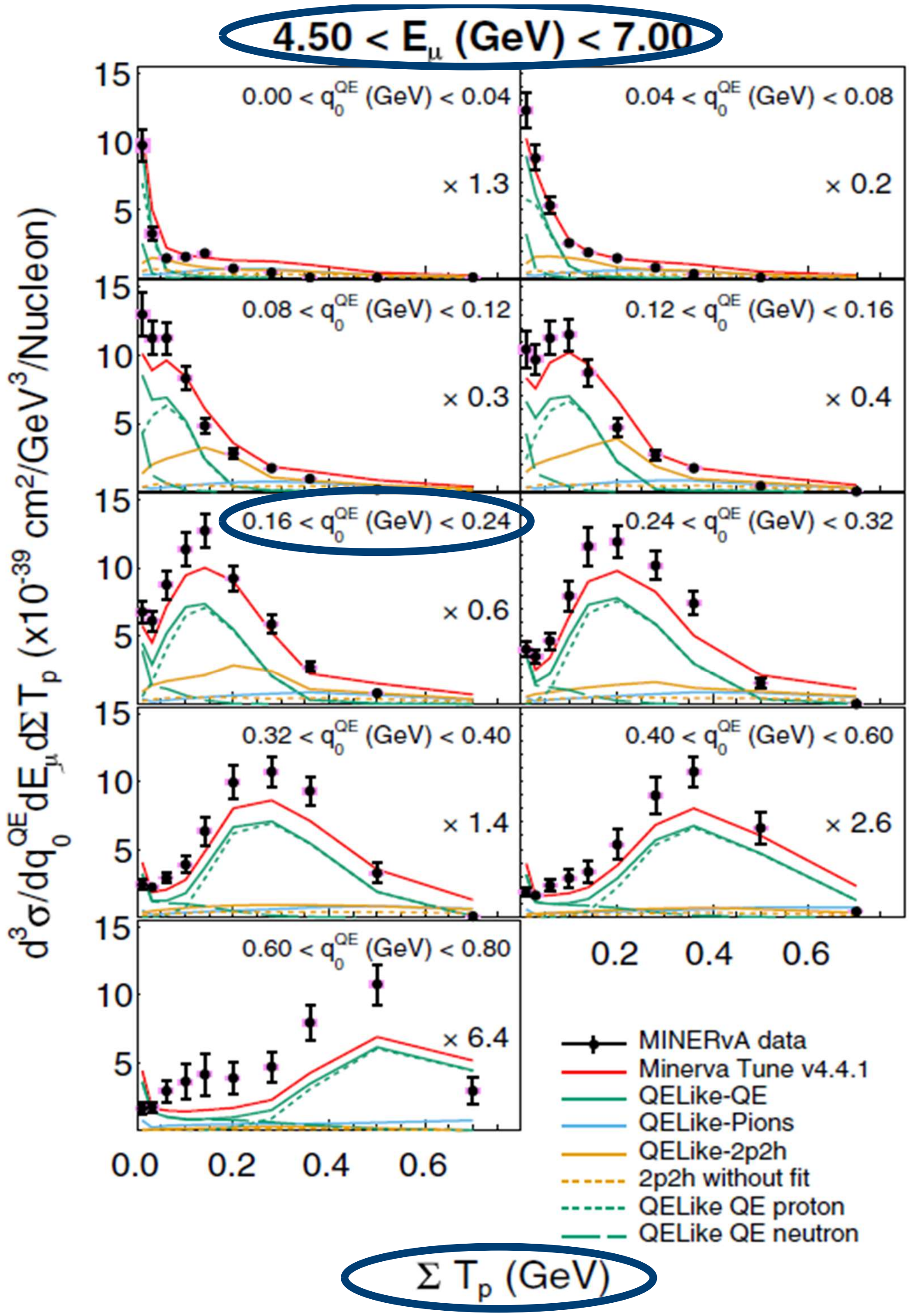


Single π^+ sideband

QE-Like in 3D

Phys.Rev.Lett. 129 (2022) 2, 021803





QE-Like in 3D

Phys.Rev.Lett. 129 (2022) 2, 021803

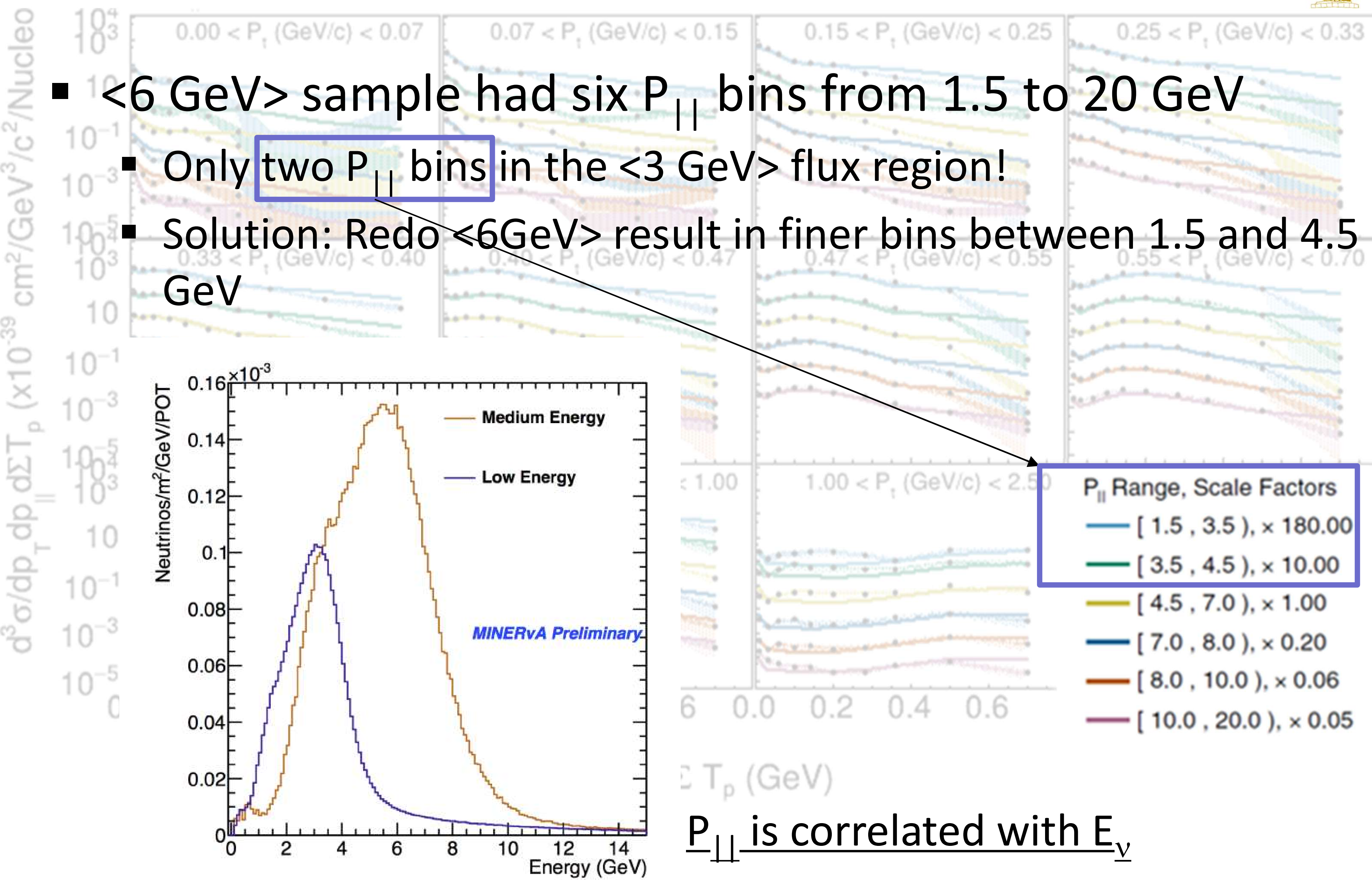
$$E_{\nu,QE} - E_\mu$$

$$q_0^{(\mathrm{QE})} \equiv \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(E_\mu - p_\mu \cos\theta_\mu)E_\mu}{2(m_n - E_b) - E_\mu + p_\mu \cos\theta_\mu}.$$

- Alternative variables akin to how oscillation experiments get at E_n
- Similar trends and observations when compared to the $p_{t,\mu}$ vs $p_{||,\mu}$ vs ΣT_p result
- **Major question: what about at lower average beam energies?**

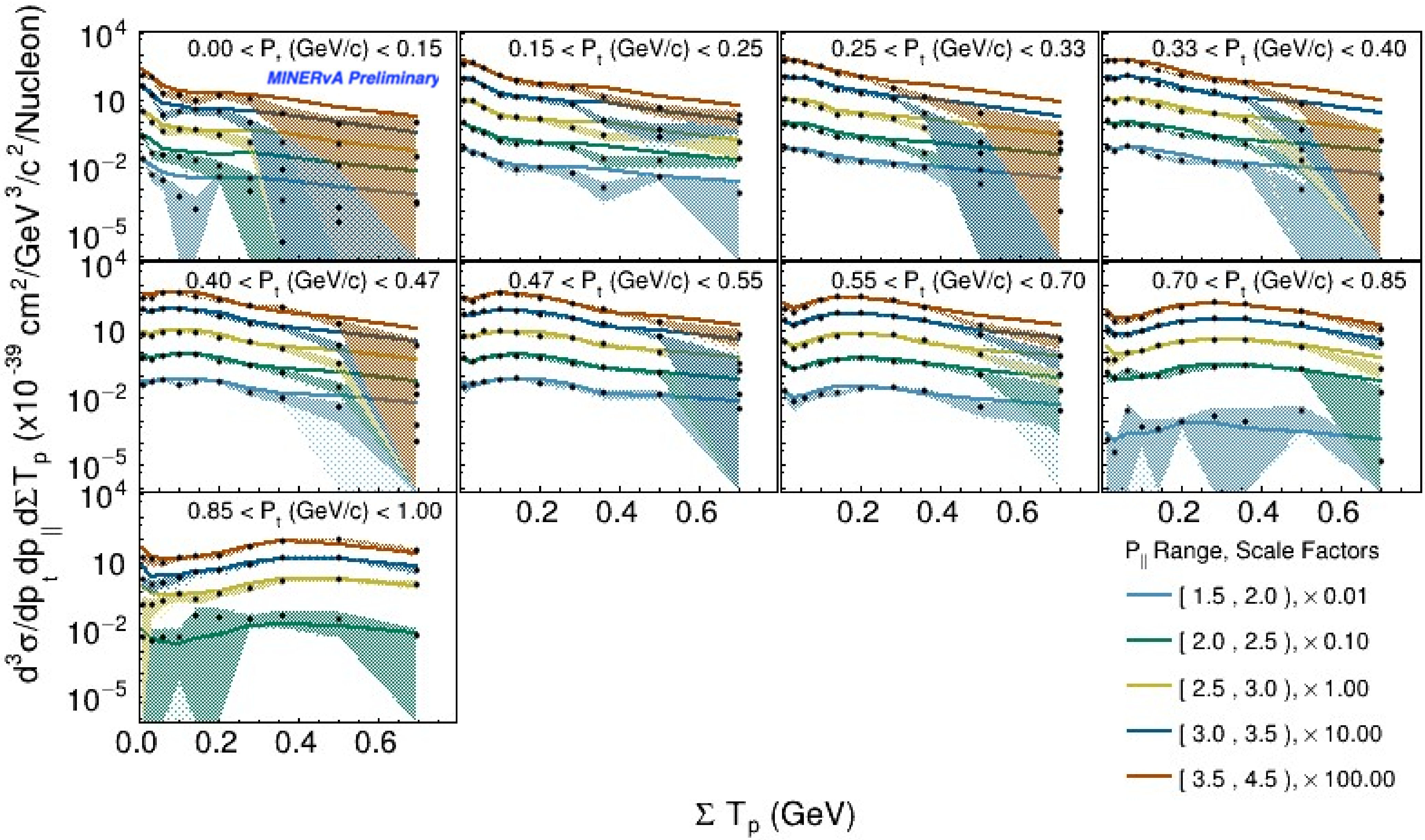
Moving to <3GeV> dataset

- <6 GeV> sample had six $P_{||}$ bins from 1.5 to 20 GeV
  - Only two $P_{||}$ bins in the <3 GeV> flux region!
  - Solution: Redo <6GeV> result in finer bins between 1.5 and 4.5 GeV



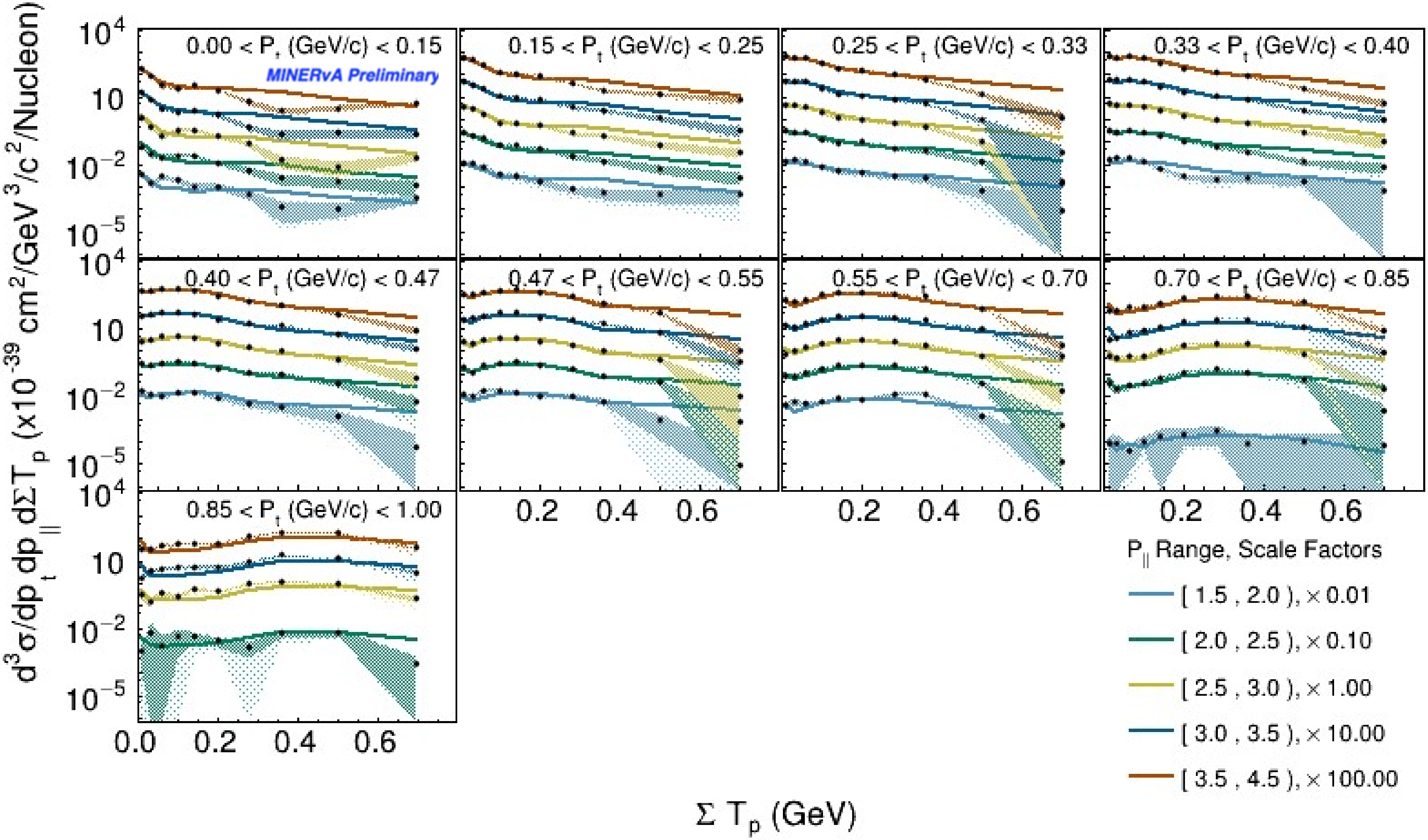
$P_{||}$ is correlated with E_{ν}

<3GeV> result



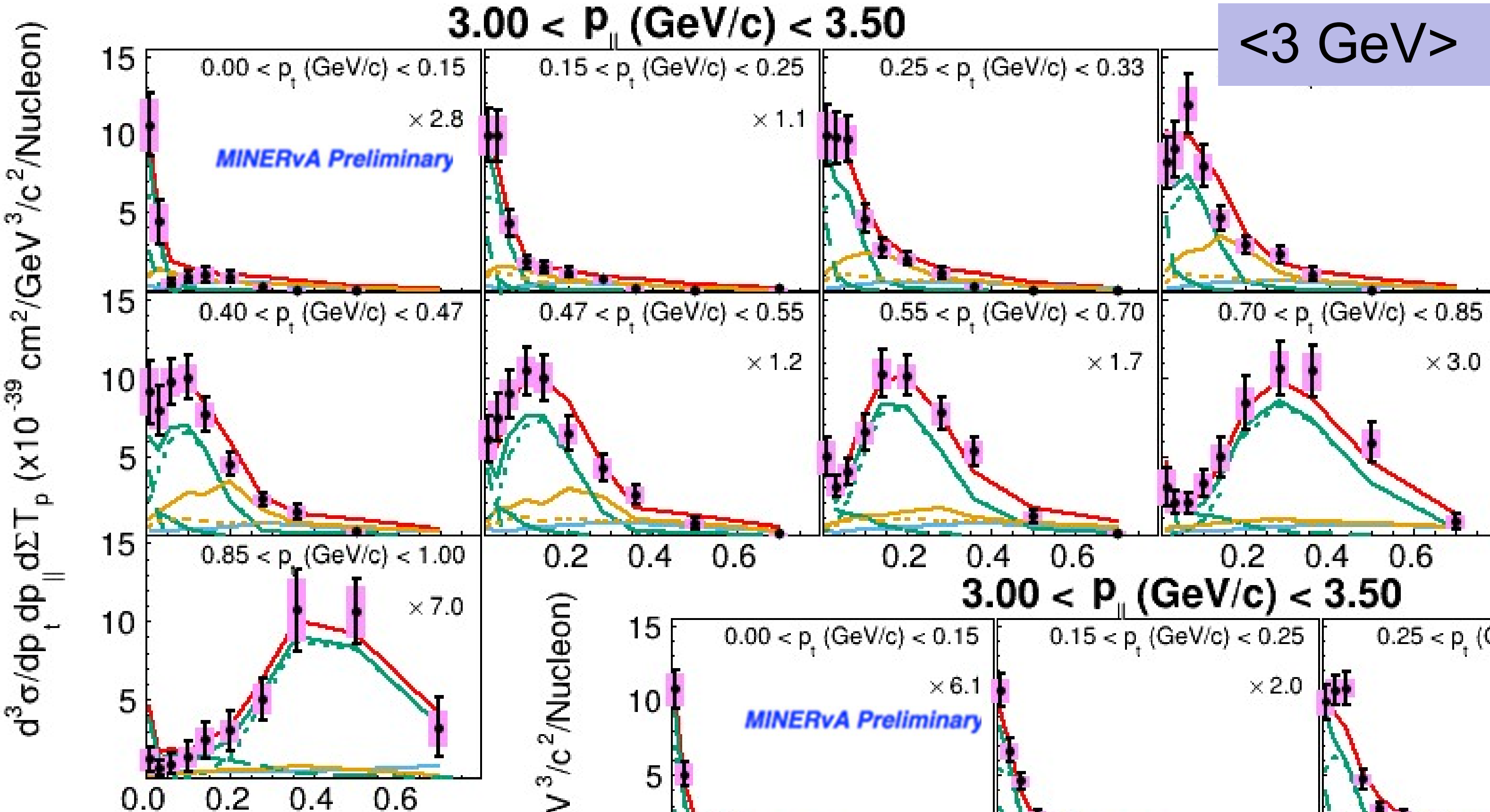
$0.00 < P_t$ (GeV/c) < 0.15
MINERvA Preliminary
$0.15 < P_t$ (GeV/c) < 0.25
$0.25 < P_t$ (GeV/c) < 0.33
$0.33 < P_t$ (GeV/c) < 0.40
$0.40 < P_t$ (GeV/c) < 0.47
$0.47 < P_t$ (GeV/c) < 0.55
$0.55 < P_t$ (GeV/c) < 0.70
$0.70 < P_t$ (GeV/c) < 0.85
$0.85 < P_t$ (GeV/c) < 1.00
$d^3\sigma/dp_t dp_{||} d\Sigma T_p$ ($\times10^{-39}$ cm^2/GeV^3/c^2/Nucleon)
ΣT_p (GeV)
$P_{||}$ Range, Scale Factors
[1.5 , 2.0), × 0.01
[2.0 , 2.5), × 0.10
[2.5 , 3.0), × 1.00
[3.0 , 3.5), × 10.00
[3.5 , 4.5), × 100.00

Redone <6GeV> result

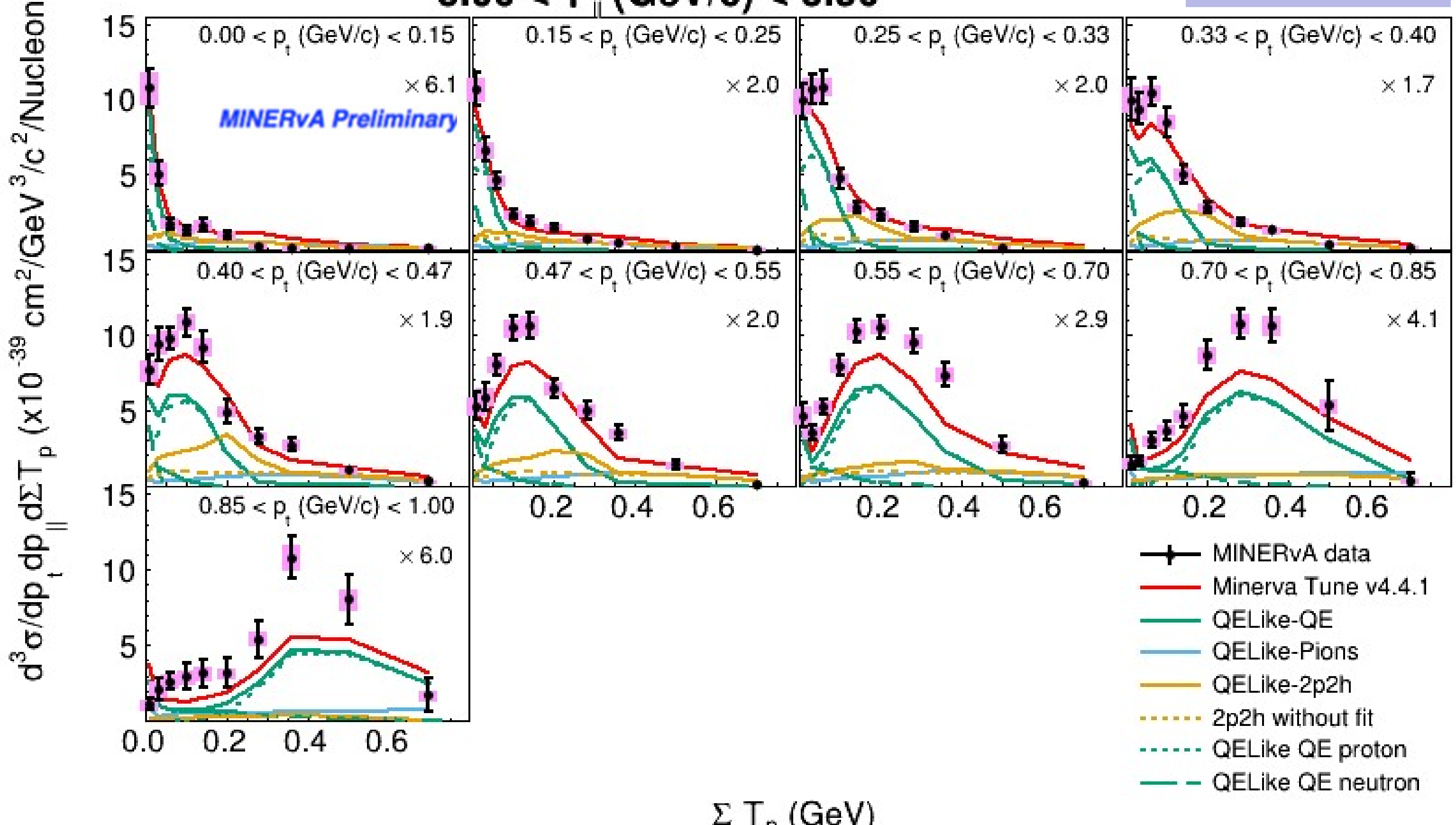


Single $P_{||}$ Slice

<3 GeV>

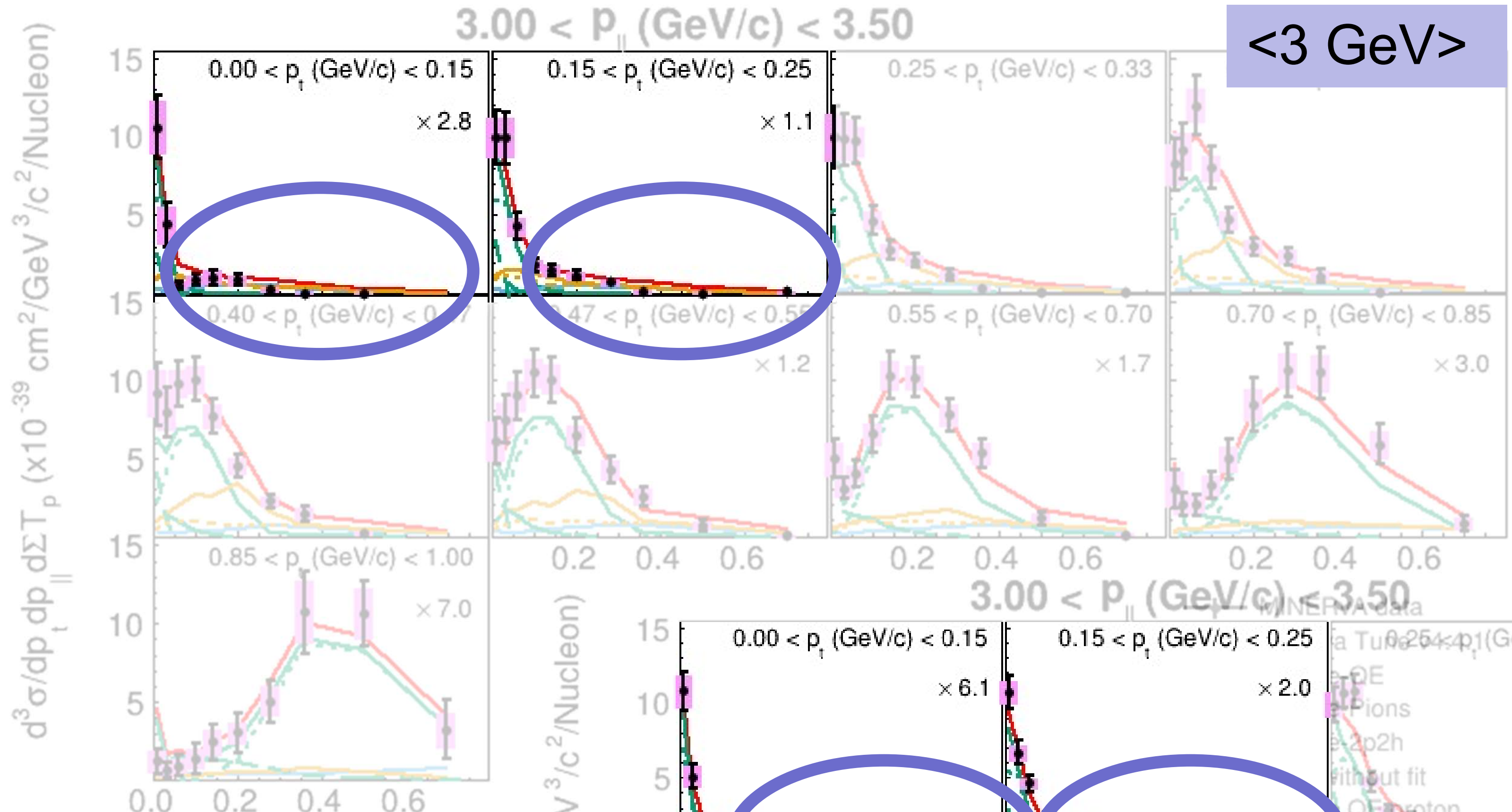


<6 GeV>

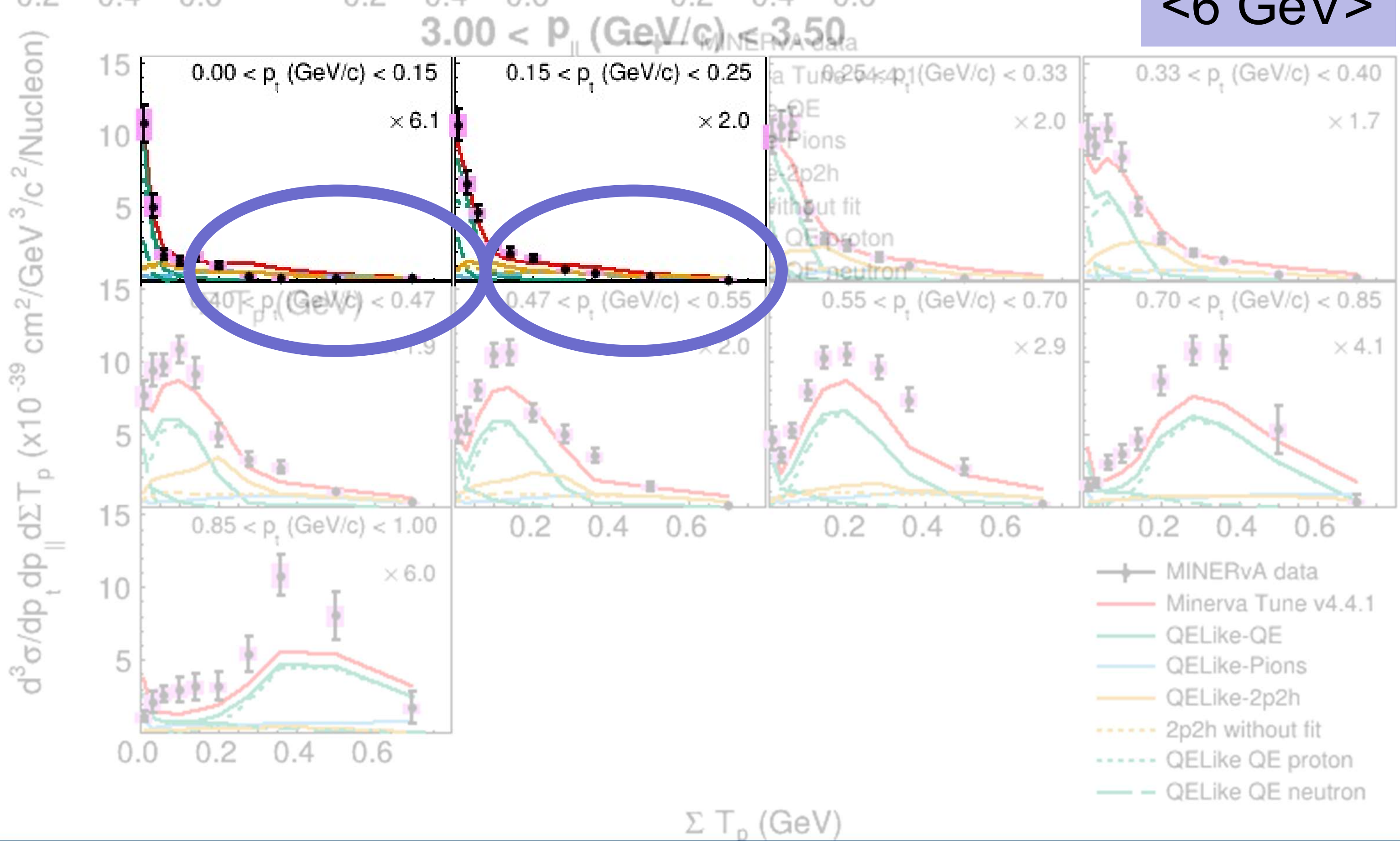


Single $P_{||}$ Slice

<3 GeV>



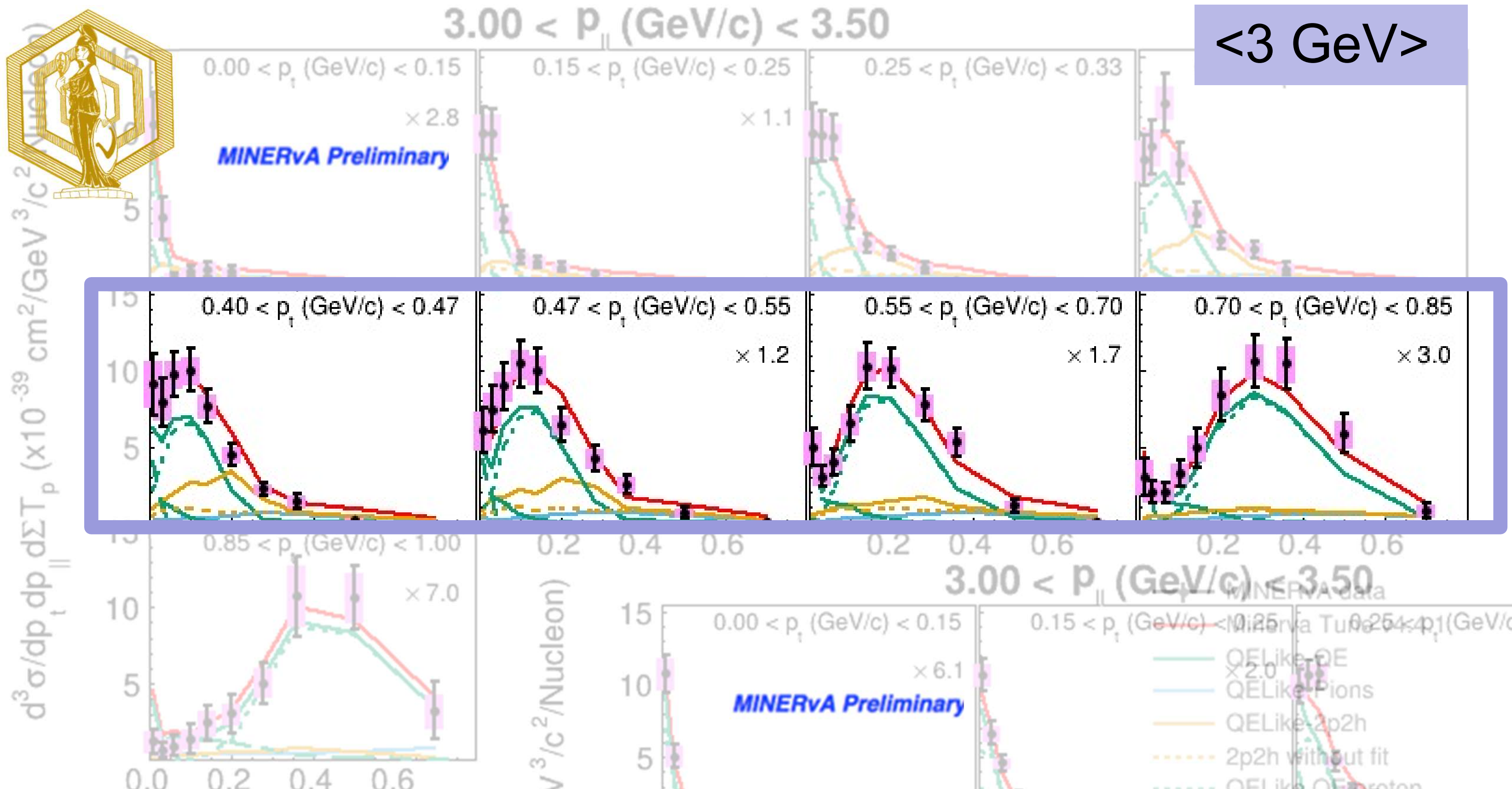
<6 GeV>



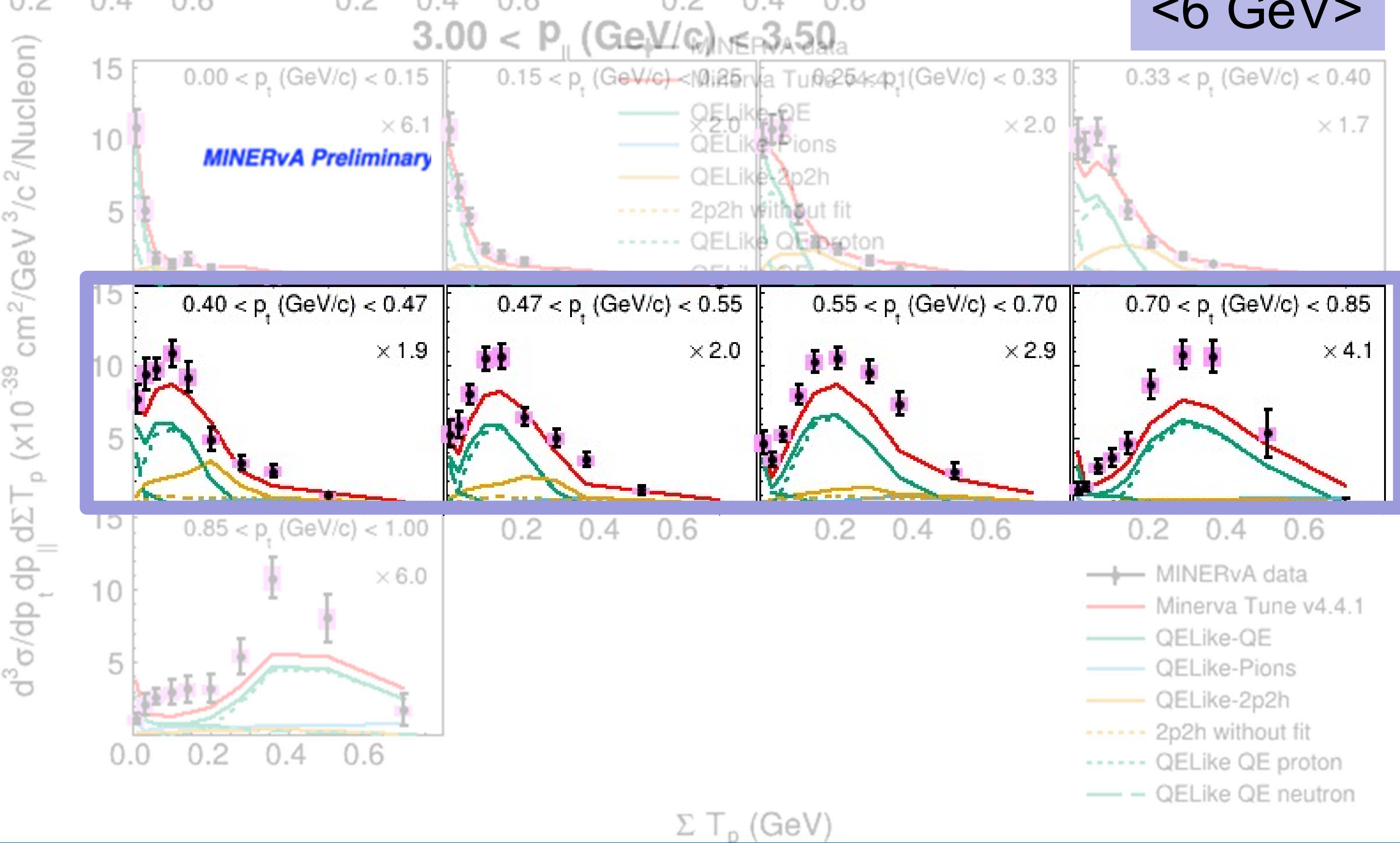
Gross overprediction at low P_t but large ΣT_p

Single $P_{||}$ Slice

<3 GeV>

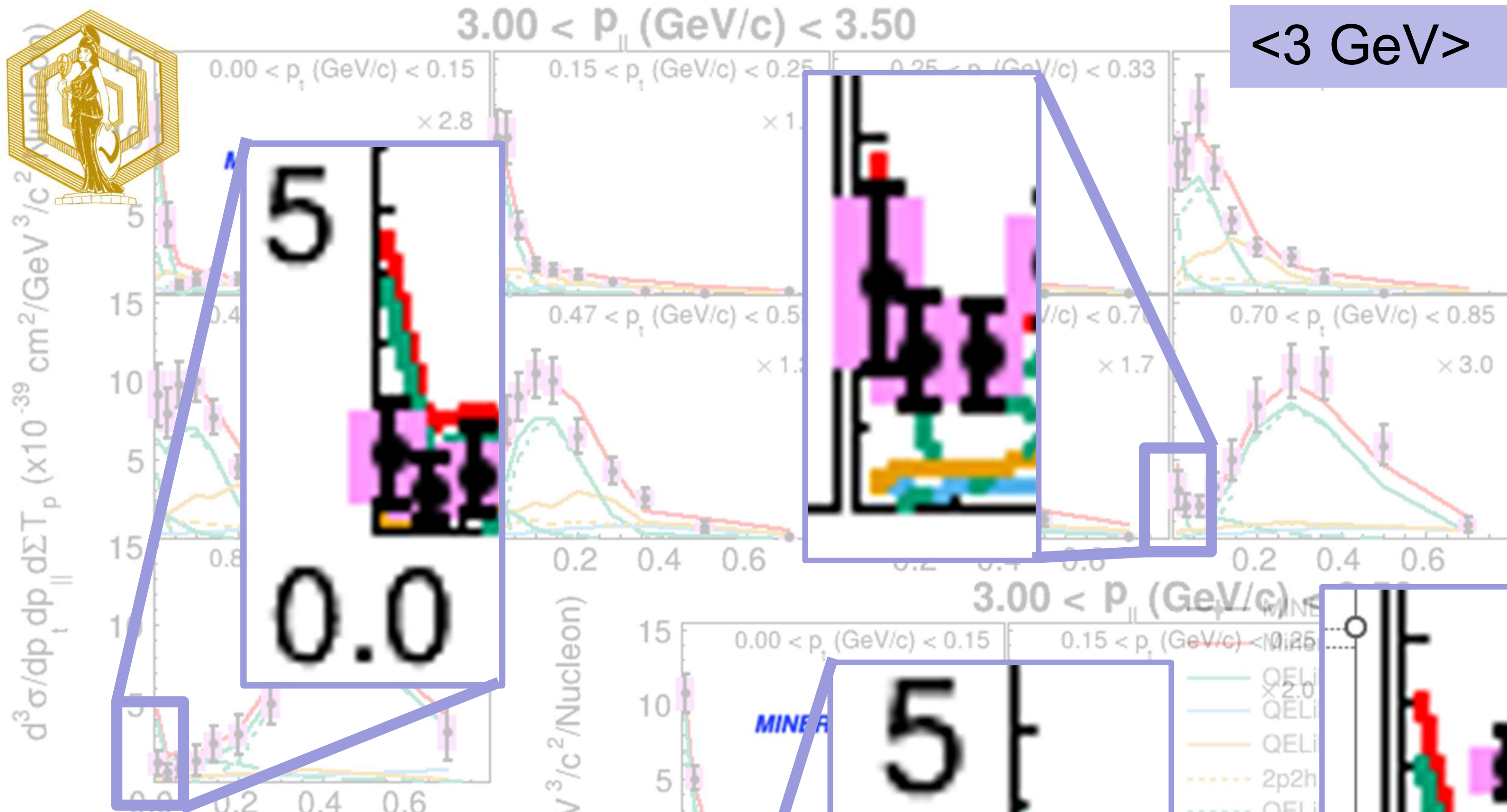


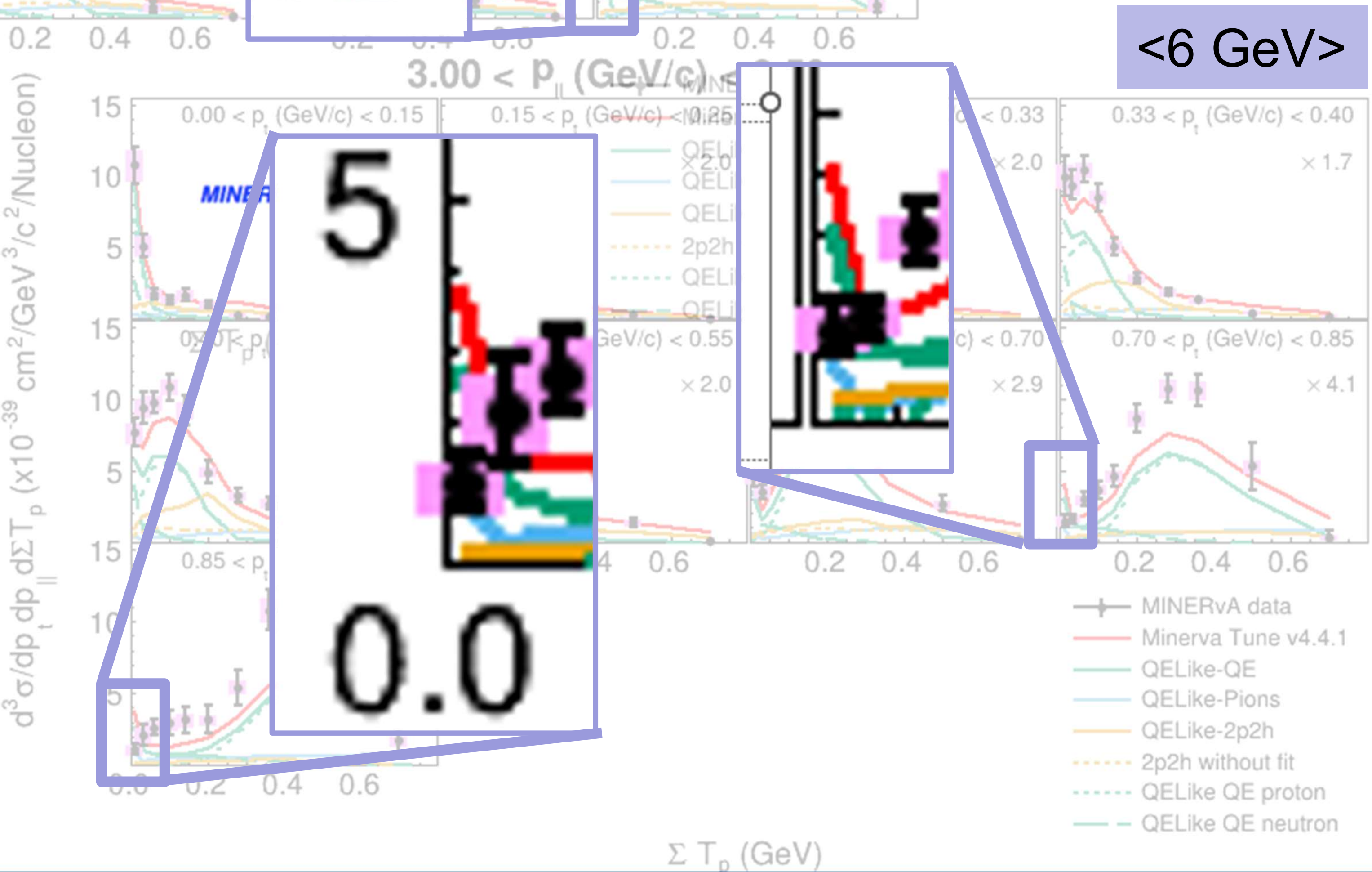
<6 GeV>



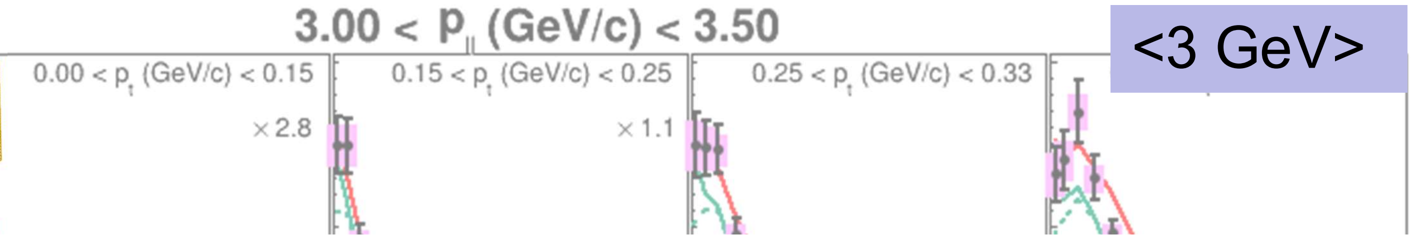
Peak differences as well as normalization differences between data/MC and datasets

Single $P_{||}$ Slice



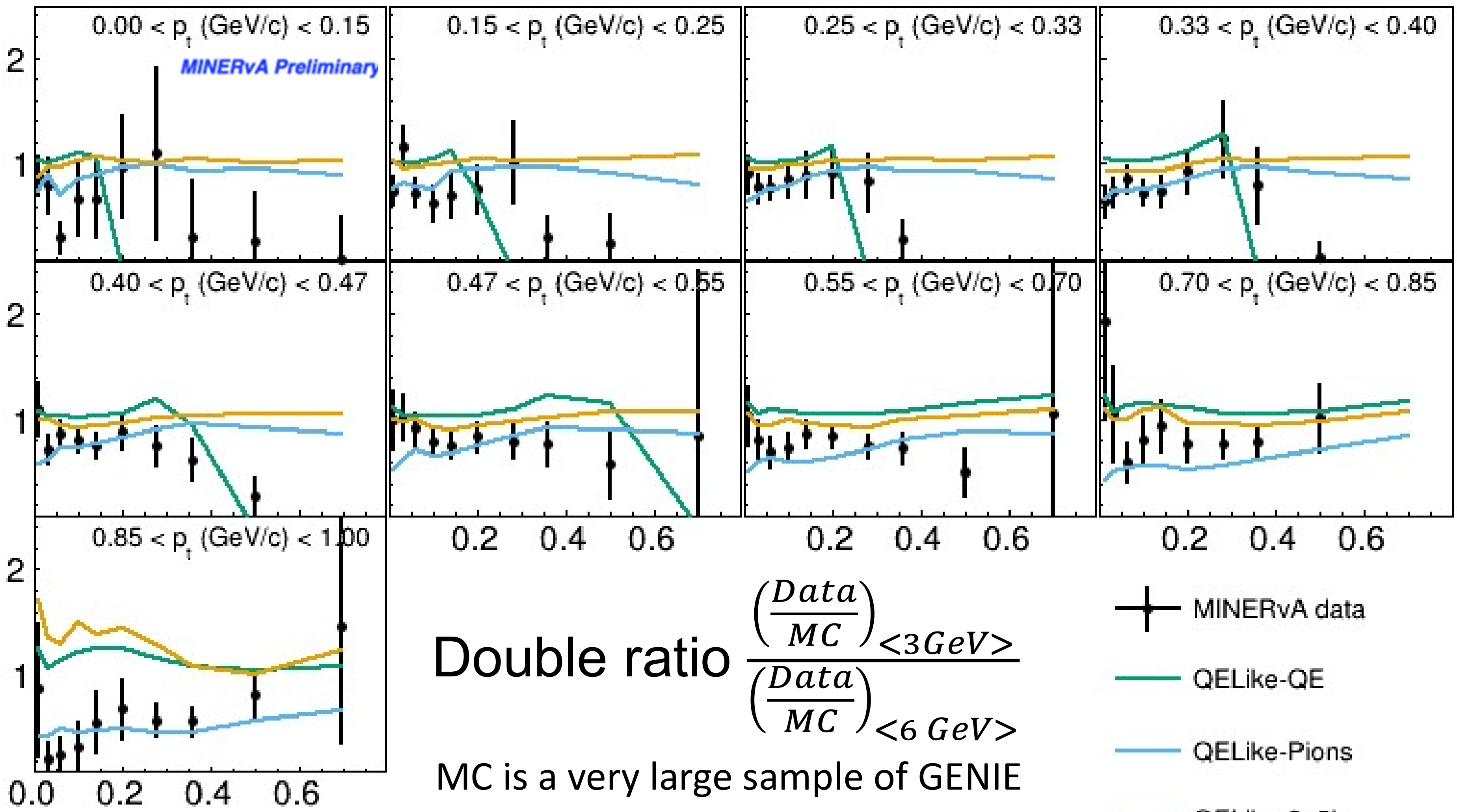


Data/MC differences in regions with FSI p->n QE events



<3 GeV>

Single P|| Slice



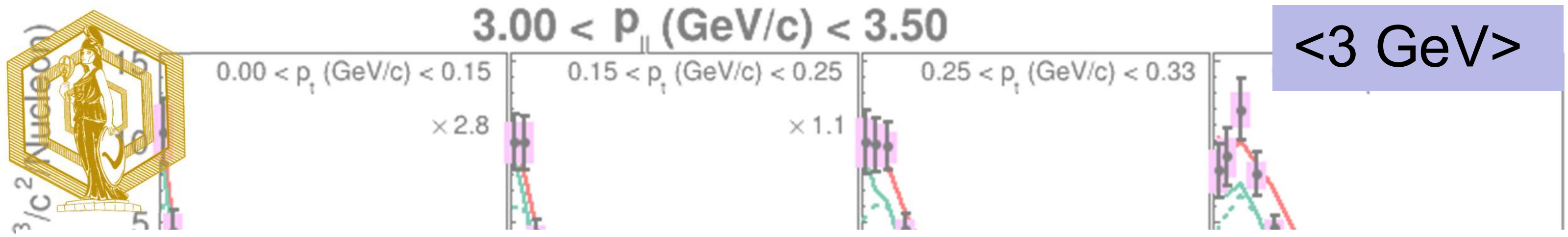
Double ratio $\frac{\left(\frac{Data}{MC}\right)_{<3GeV>}}{\left(\frac{Data}{MC}\right)_{<6\ GeV>}}$

MC is a very large sample of GENIE v3_06 10a

$\Sigma\ T_p$ (GeV)

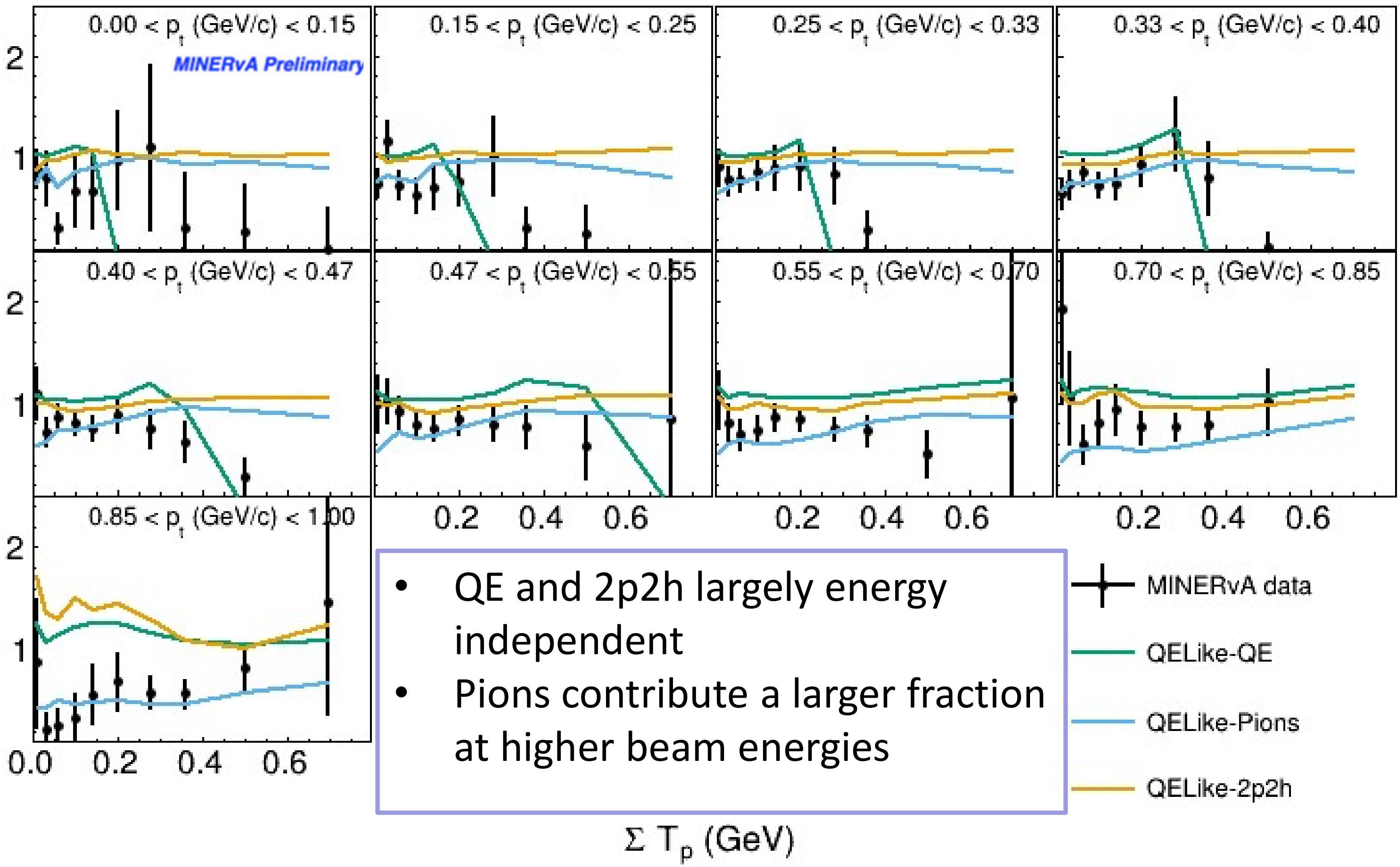
QELike QE neutron

$\Sigma\ T_p$ (GeV)



<3 GeV>

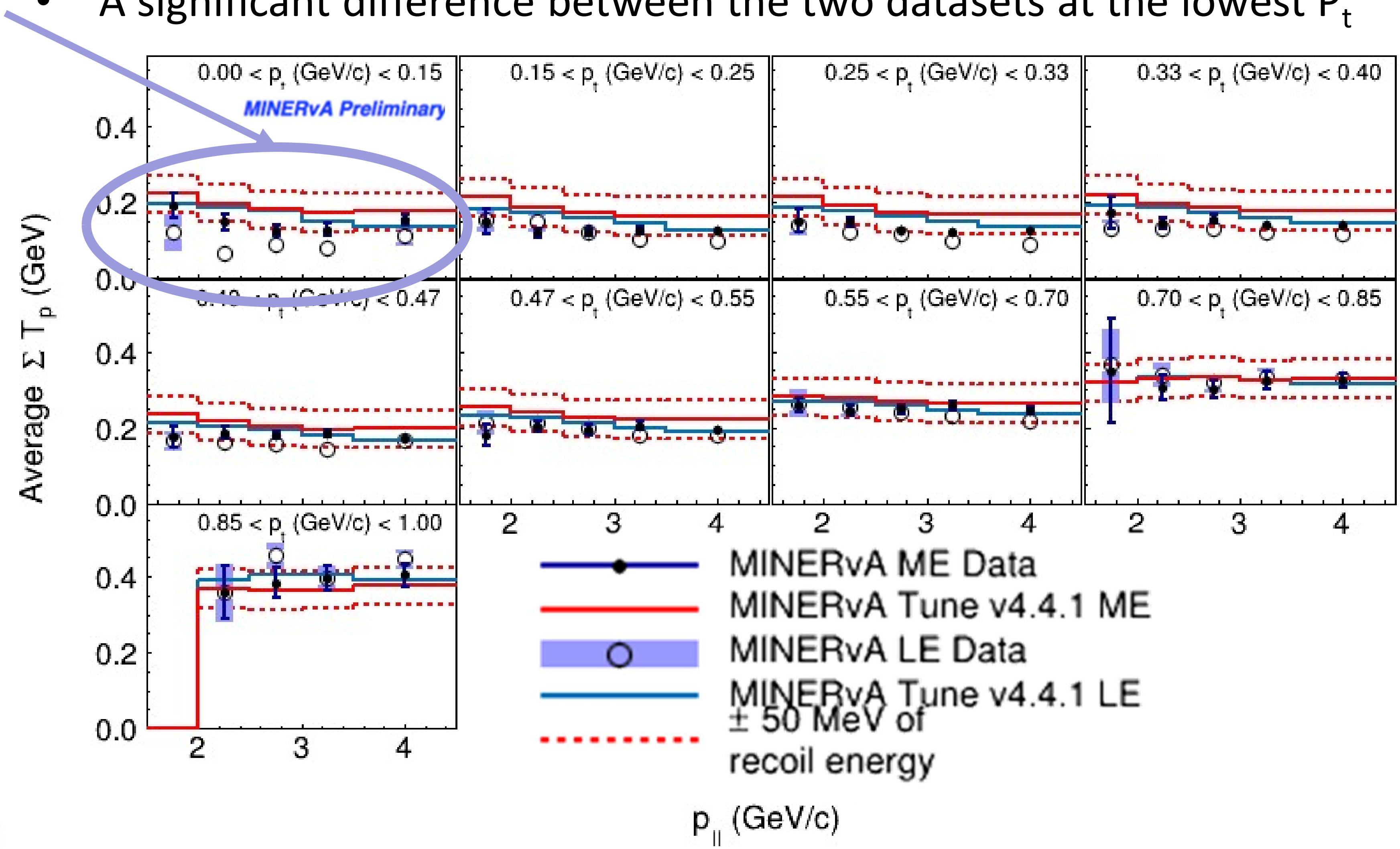
Single P|| Slice



- QE and 2p2h largely energy independent
- Pions contribute a larger fraction at higher beam energies

Average Recoil

- Similar trends for <3GeV> and <6GeV> datasets – prefer a lower average recoil energy
  - A significant difference between the two datasets at the lowest P_t

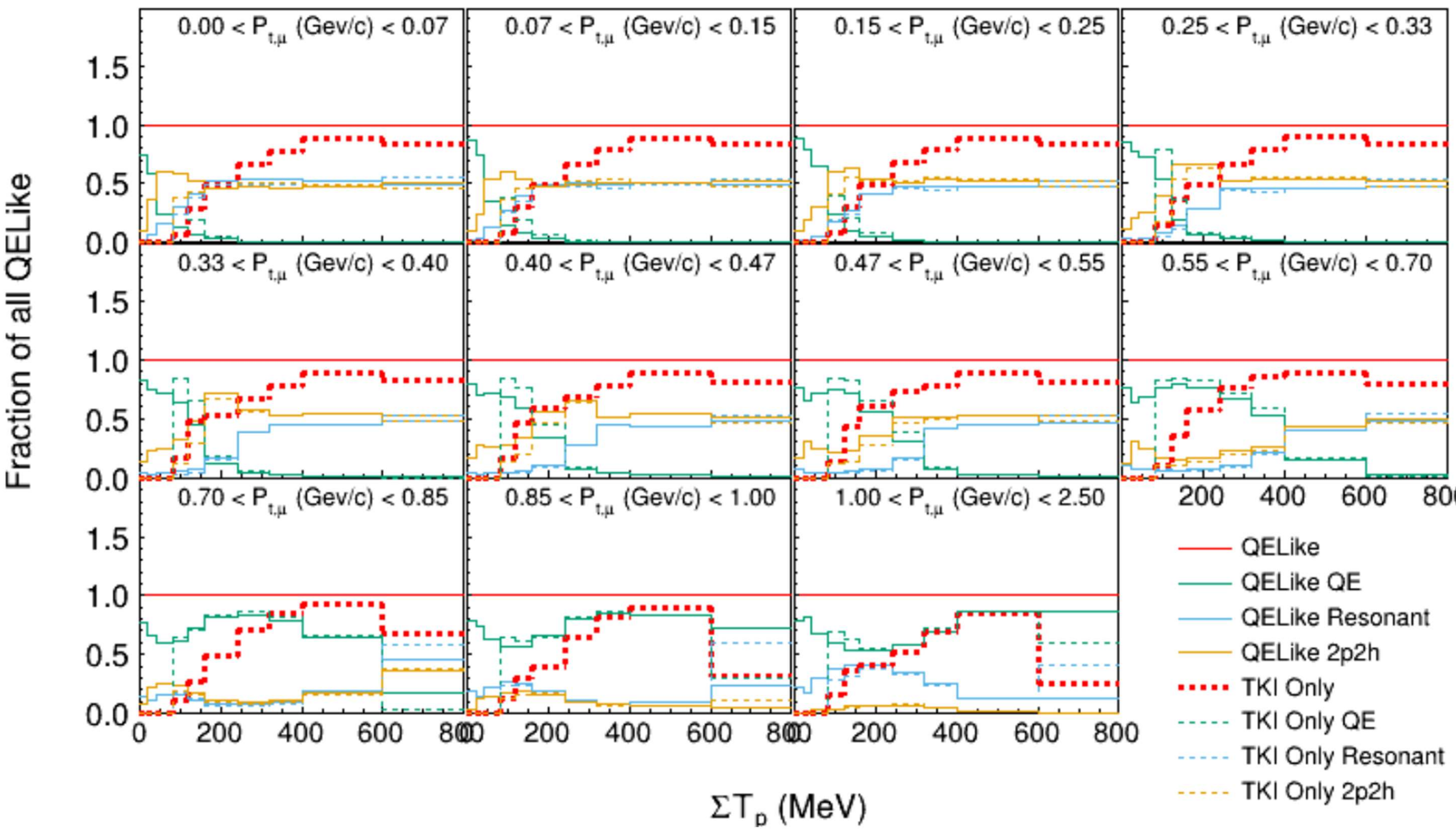


Conclusions

- Low P_t has over prediction at higher ΣT_p
- Interesting peak differences at moderate P_t
- At High P_t , low ΣT_p continue to observe MC-data differences. A region with have large FSI effects.
- Resonant pion production contributes a larger fraction of events at <6GeV> compared to <3GeV>
- There is a significant different in average recoil between the two datasets at the lowest P_t

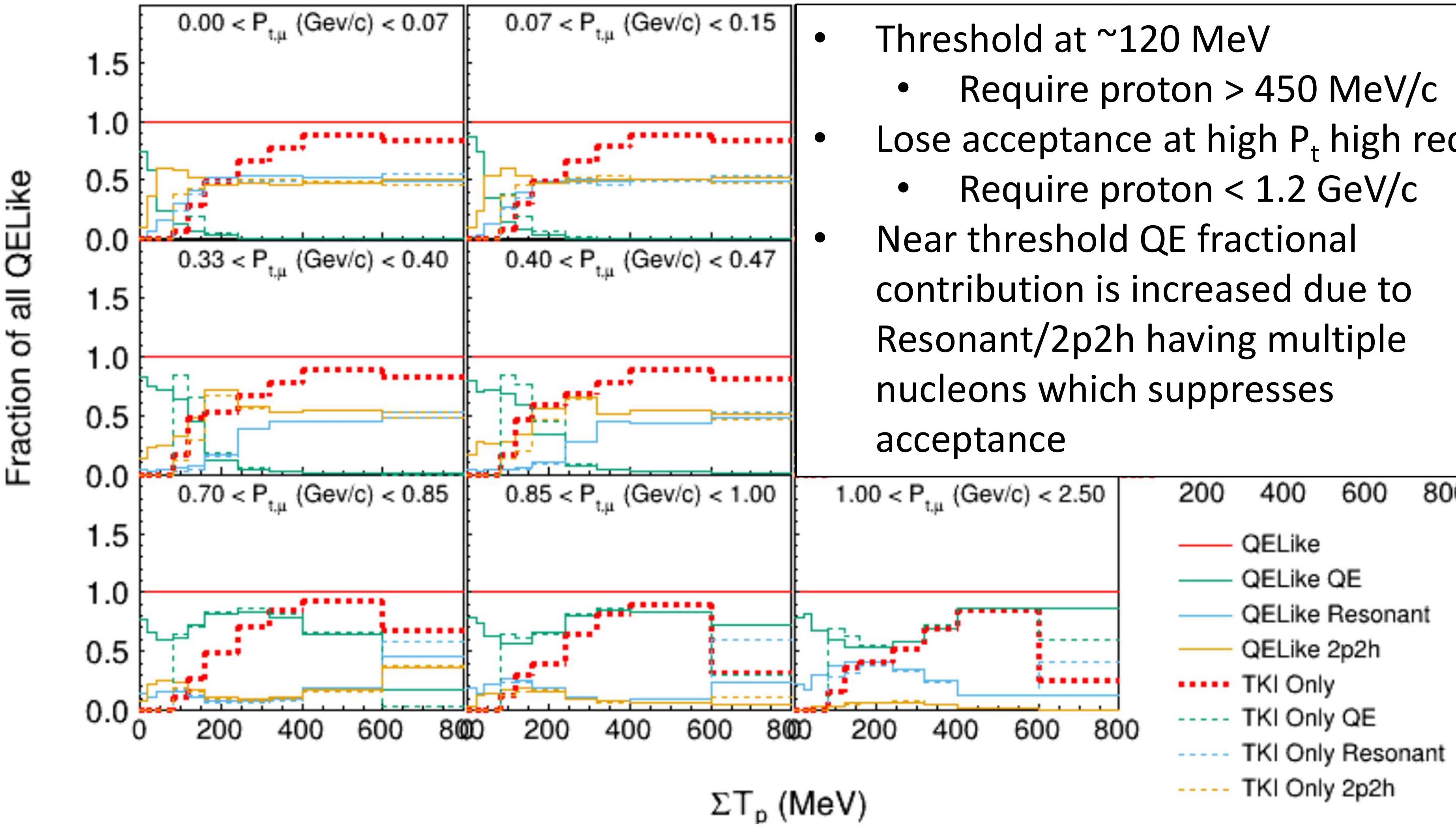
Move from an inclusive QE-Like

Transverse Kinematic Imbalance (TKI)



Move from an inclusive QE-Like

Transverse Kinematic Imbalance (TKI)



- Threshold at ~120 MeV
  - Require proton > 450 MeV/c
- Lose acceptance at high P_t high recoil
  - Require proton < 1.2 GeV/c
- Near threshold QE fractional contribution is increased due to Resonant/2p2h having multiple nucleons which suppresses acceptance

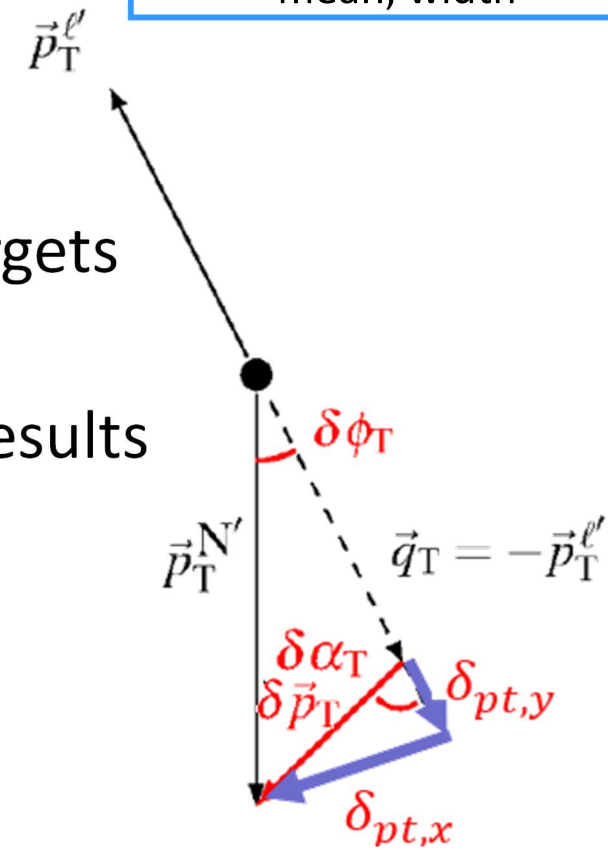
Transverse Kinematic Imbalance

Sensitive to the “interaction energy” – call back to Moniz name.

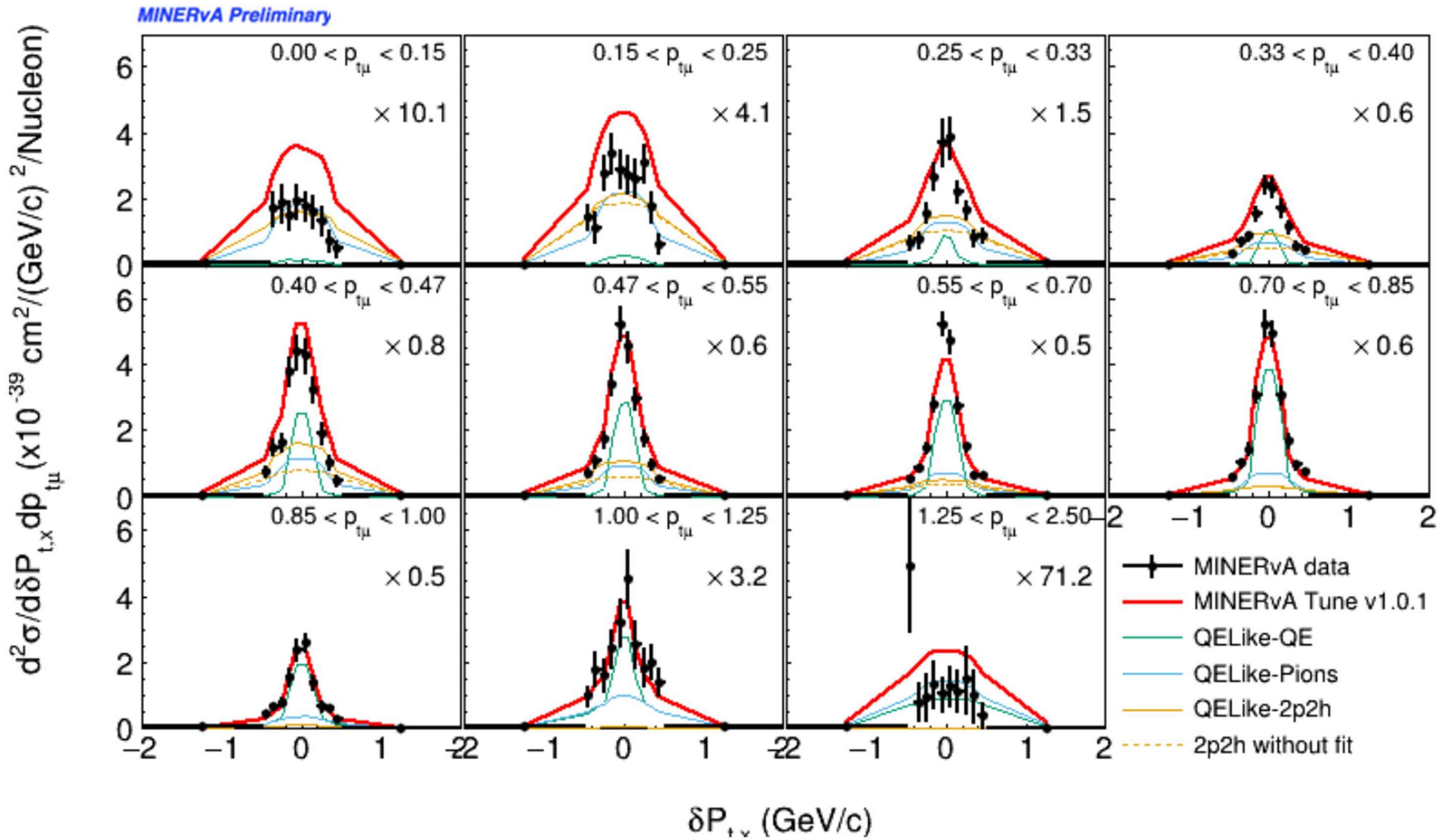
Width sensitive to the Fermi momentum spectrum

Interest in asymmetry, mean, width

- <3 GeV> results – single differential
  - See - *Phys.Rev.D* 101 (2020) 9, 092001
    Phys.Rev.Lett. 121 (2018) 2, 022504
  - $\delta_{a,t}$, $\delta_{\phi,t}$, $\delta_{p,t}$, p_n, $\delta_{pt,y}$, $\delta_{pt,x}$
- <6 GeV> results
  - Last NuInt – MINERvA TKI on nuclear targets
    - Publication in progress
  - *Today* - Introduce Double Differential Results
  - Challenge – What variables ?
    - Choose $P_{t,\mu}$ vs TKI Vars *PLUS* , $\delta_{p,l}$, T_p, θ_p
    - Choose $\delta_{pt,x}$ vs $\delta_{pt,y}$
    - Introduce new variable – k_x



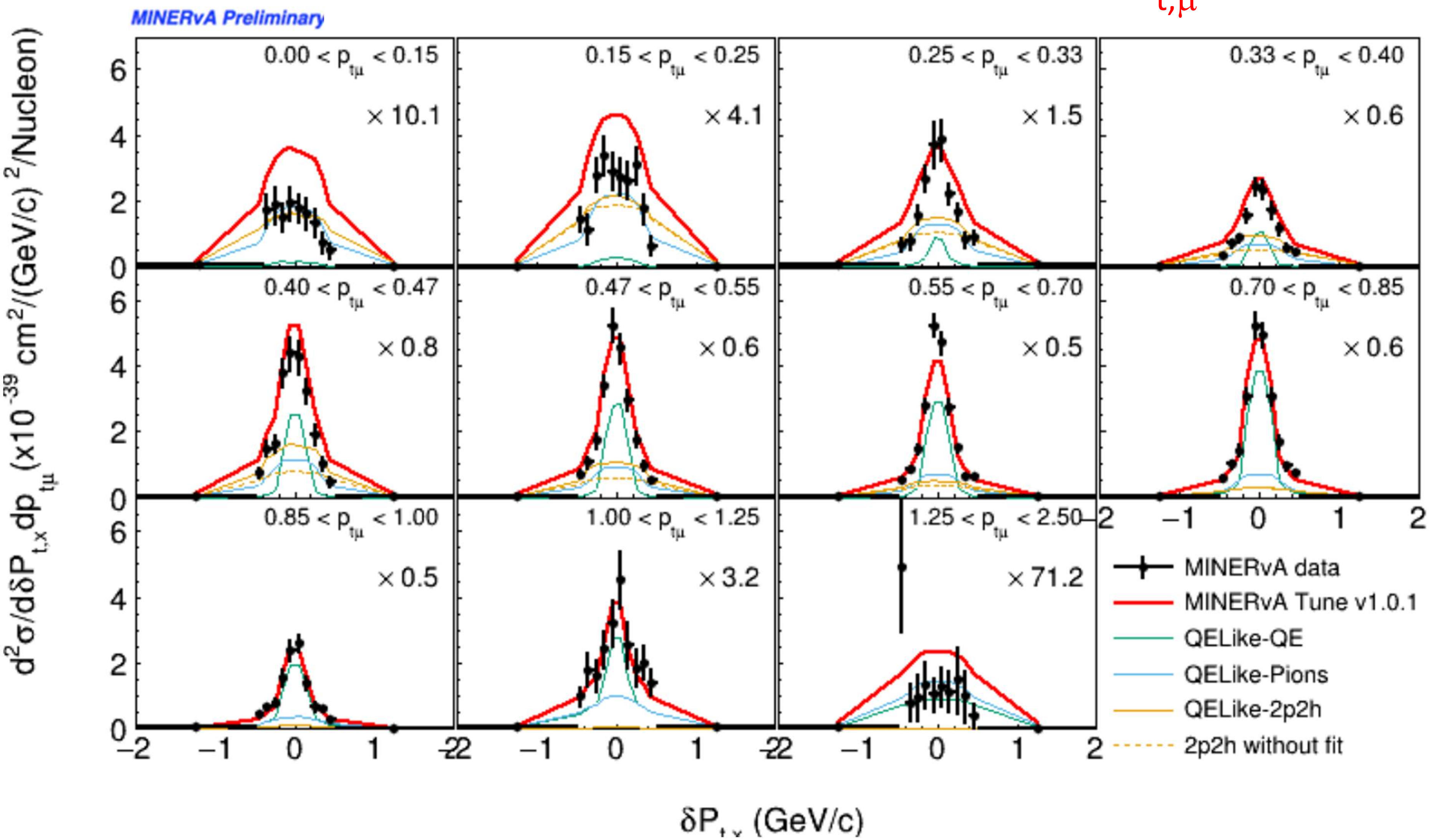
$\delta_{pt,x}$



MINERvA Preliminary
0.00 < p_tμ < 0.15
×10.1
0.15 < p_tμ < 0.25
×4.1
0.25 < p_tμ < 0.33
×1.5
0.33 < p_tμ < 0.40
×0.6
0.40 < p_tμ < 0.47
×0.8
0.47 < p_tμ < 0.55
×0.6
0.55 < p_tμ < 0.70
×0.5
0.70 < p_tμ < 0.85
×0.6
0.85 < p_tμ < 1.00
×0.5
1.00 < p_tμ < 1.25
×3.2
1.25 < p_tμ < 2.50
×71.2
MINERvA data
MINERvA Tune v1.0.1
QELike-QE
QELike-Pions
QELike-2p2h
2p2h without fit
d²σ/dδP_t,x dp_tμ (x10⁻³⁹ cm²/(GeV/c)²/Nucleon)
δP_t,x (GeV/c)

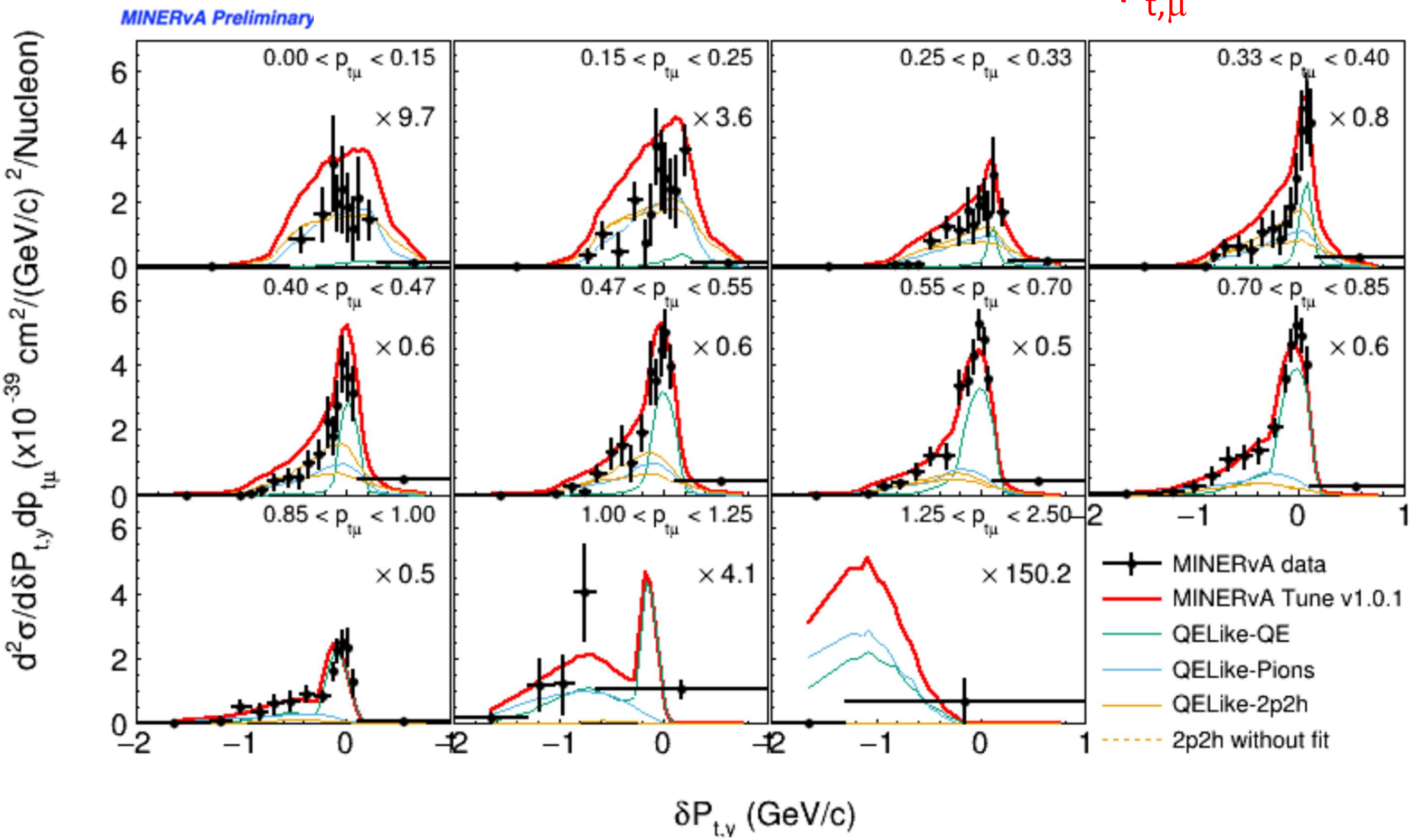
$\delta_{pt,x}$

Question: What is the peak position, width, and symmetry as a function of $P_{t,\mu}$

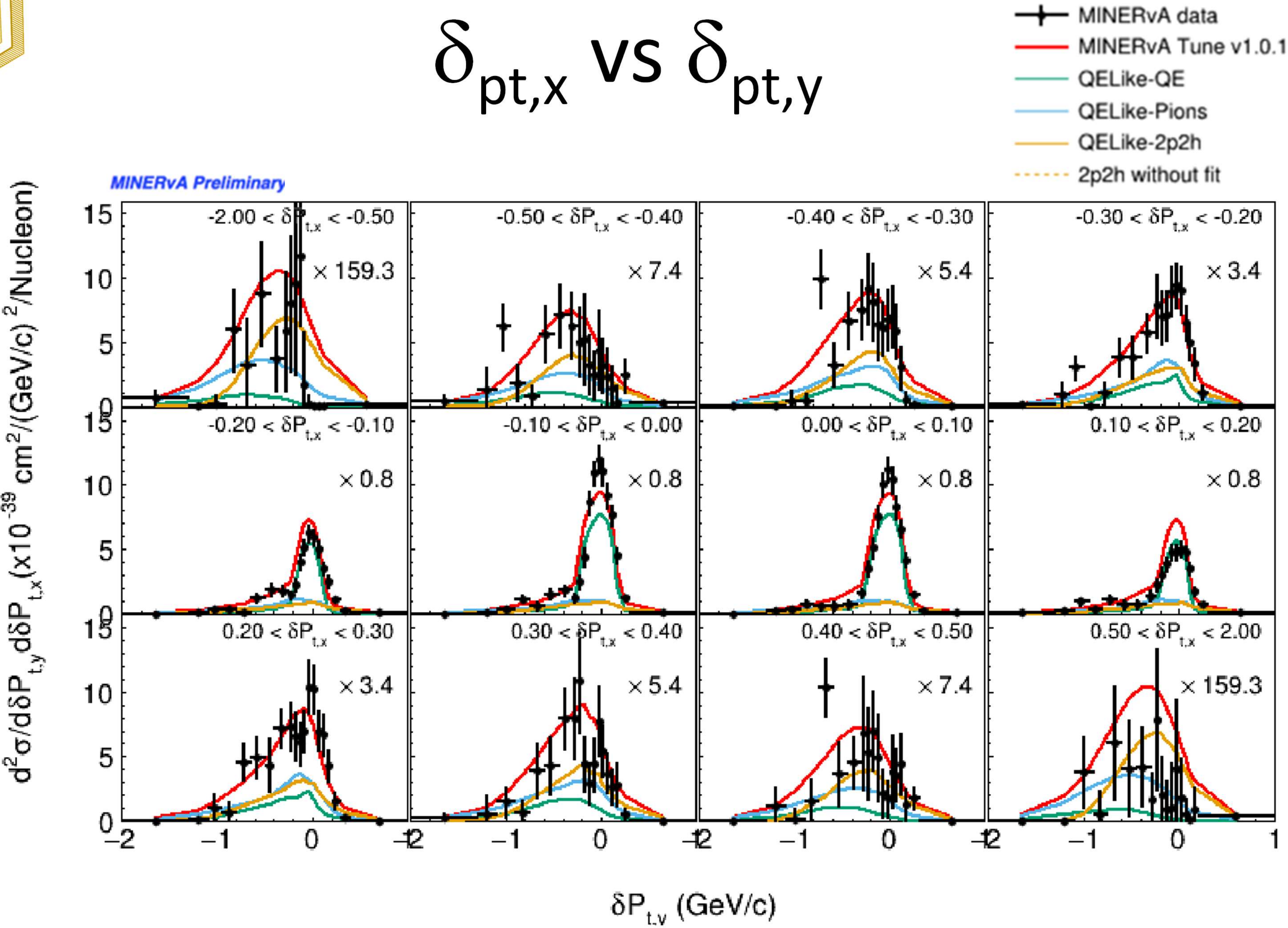


$\delta_{pt,y}$

Question: What is the peak position, width, and symmetry as a function of $P_{t,\mu}$



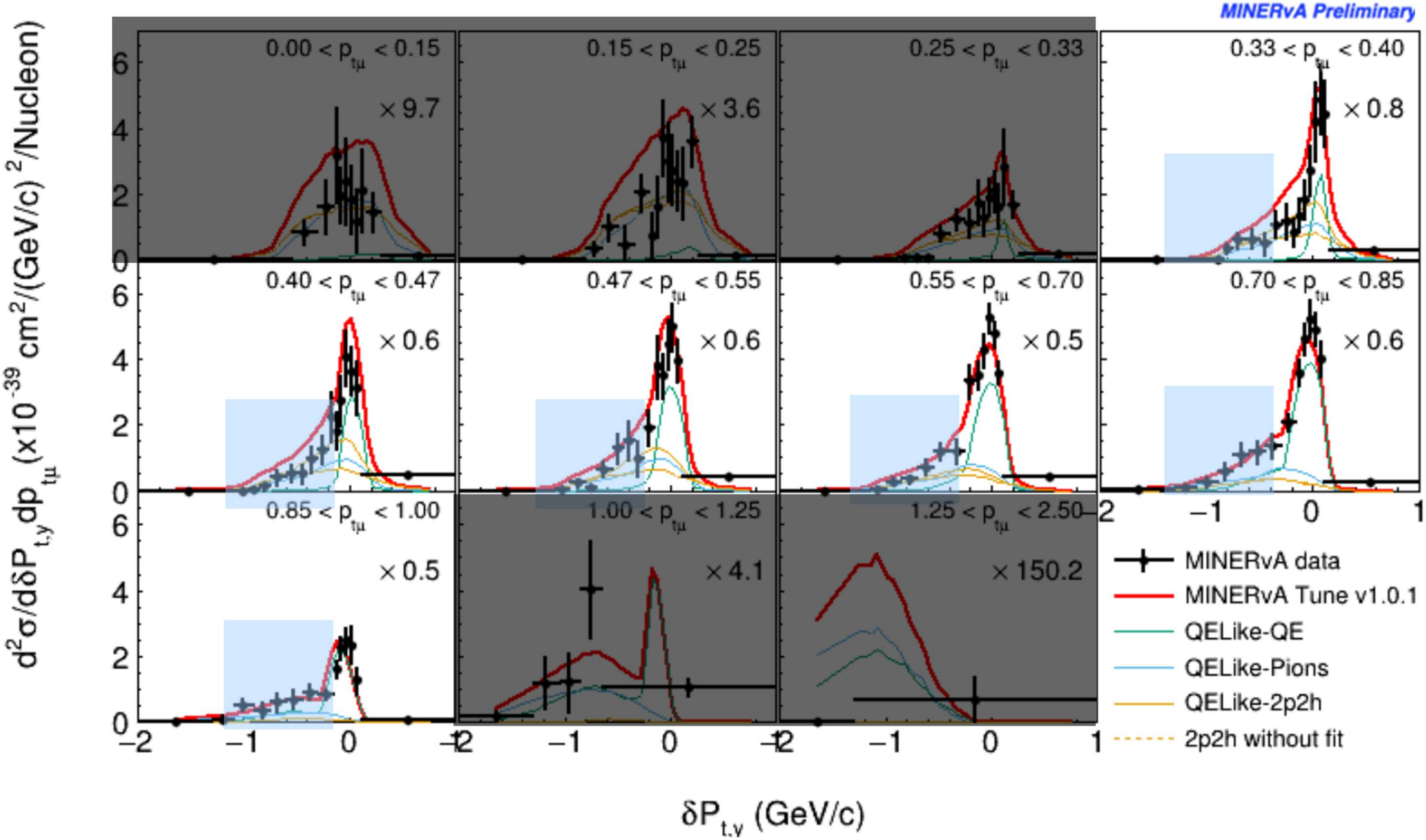
$\delta_{pt,x}$ vs $\delta_{pt,y}$



Can we do more?

- A lot of the metrics are QE centric with a non-QE "background"
- Using the data and extrapolating using the model we can constrain this "background"
- Extract a scale factor per $P_{t,\mu}$ bin
  - Can apply to other results for cross checks and extracting QE-only results

Constraining Non-QE
Use $\delta_{pt,y}$ tail to constrain



Scale factor PER $P_{t,\mu}$ bin

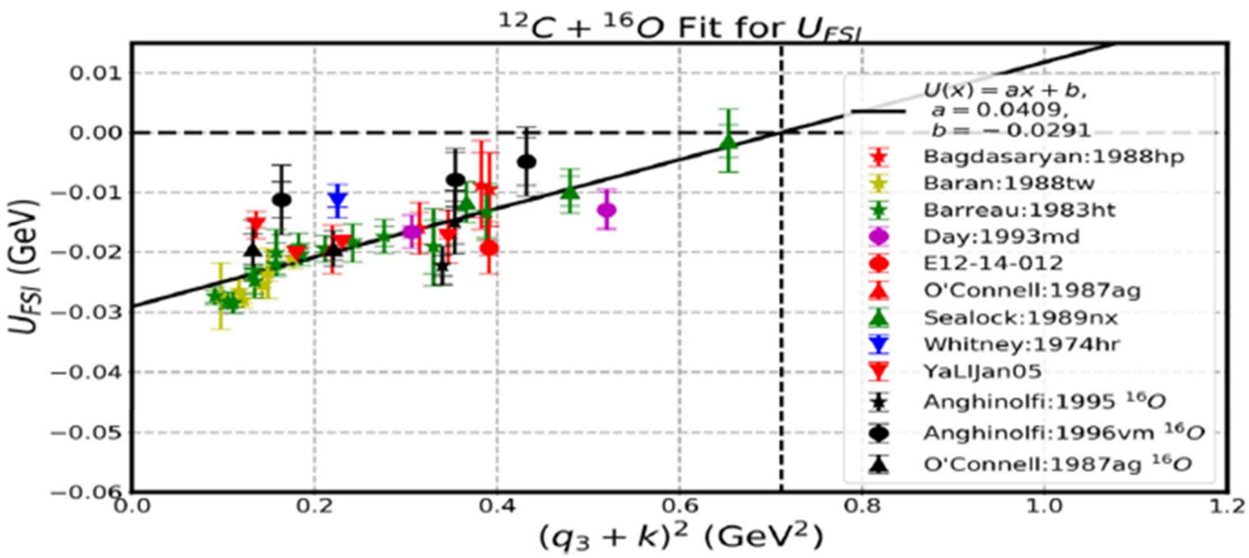
More?

- Using a formalism from *Eur.Phys.J.C* 79 (2019) 4, 293 from Arie Bodek and Tejin Cai explore shifting the proton-muon system by energies related to the Coulomb potential, U_{fsi}, and binding energy

TABLE I. Calculated energy corrections to the final state leptons and hadrons from the GENIE generator for QE neutrino scattering on ^{12}C, $\Delta^{C}_{GENIE} = 25$ MeV, $E_x = 10.1$ MeV. Other interaction channels are not altered.

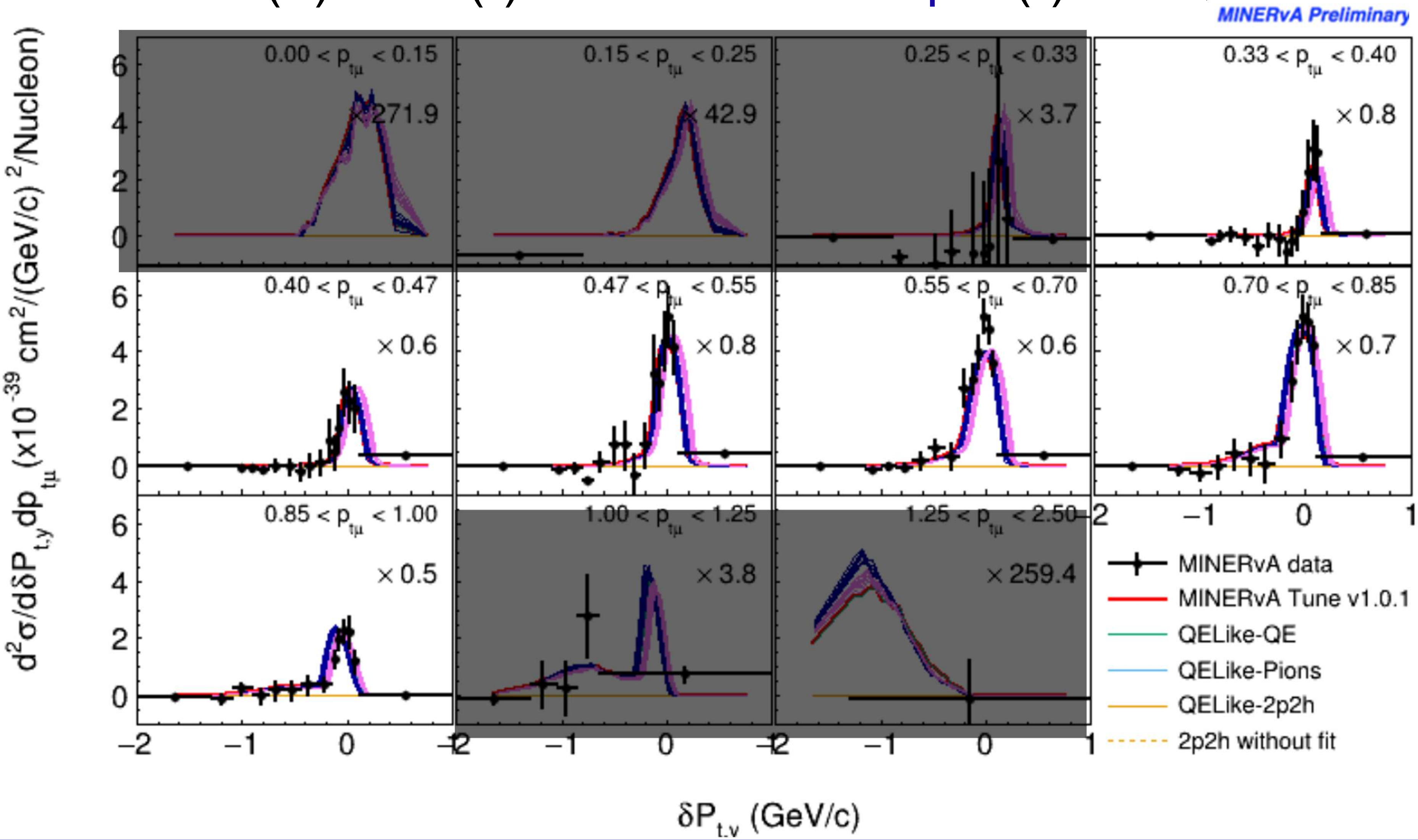
Correction	$E^P = E^P_{GENIE} + \delta^P$ δ^P(MeV)	$E^\mu = E^\mu_{GENIE} + \delta^\mu$ δ^μ(MeV)	GENIE baseline shift, $\langle\delta^\mu\rangle, \langle\delta^\mu\rangle$ (MeV)	QE baseline shift $\langle\delta p_{Ty}\rangle$(MeV/$c$)
0: Default (no corrections)	0	0	0,0	0
1: U_{opt} only (w/ E_x&Δ^C_{GENIE})	$\Delta^C_{GENIE} - \lvert U_{opt}\rvert$	$\lvert U_{opt}\rvert - E_x$	22.7, −7.8	29.4
2: U_{opt} and V_{eff} (w/ E_x&Δ^C_{GENIE})	$\Delta^C_{GENIE} - \lvert U_{opt}\rvert + \lvert V^P_{eff}\rvert$	$\lvert U_{opt}\rvert - E_x - \lvert V_{eff}\rvert$	25.8, −10.9	33.9

Fig. 17 Extracted values of U_{FSI} versus $(q_3 + k)^2$ for 33 Carbon ($^{12}_{6}$C) and 8 Oxygen ($^{16}_{8}$O) spectra



Post constraint – two shifts as example

Pink (+) to δ^p (-) to δ^μ Purple (-) to δ^p (+) to δ^μ



Scan over parameters and find optimal solutions globally and as a function of $P_{t,\mu}$

Pros/Cons of Cross Section and Reconstructed Spaces

Cross Section Space

- Pros
  - Models live in this space – easy to apply
- Cons
  - Result depends on efficiency correction and unfolding of Non-QE models

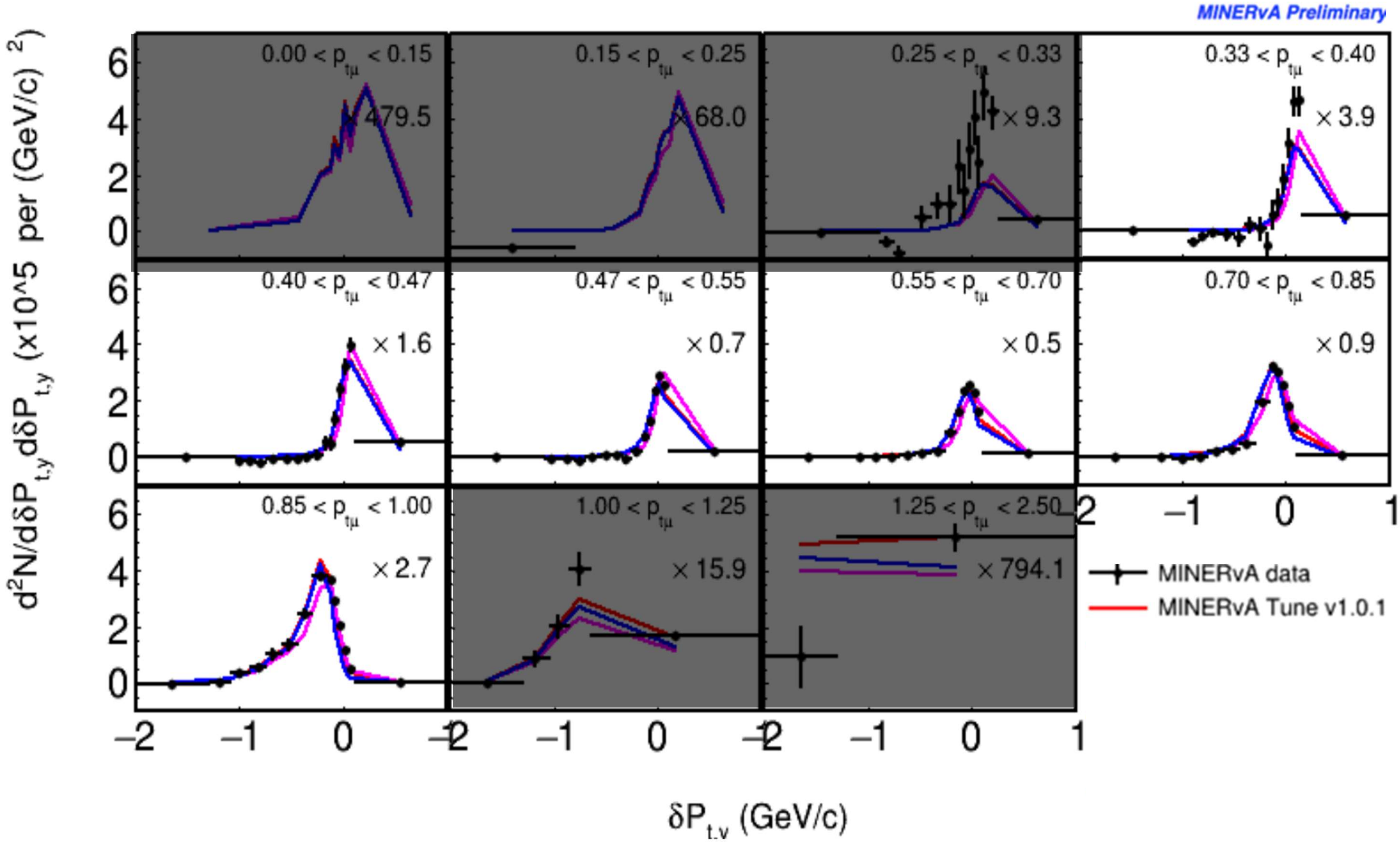
Reconstructed Space

- Pros
  - Data driven shapes with little MC influence
  - Post subtraction – depend on modeling of single process
- Cons
  - Requires forward folding (smear) model through a detector model
  - Harder to work back to the model

Should explore both. Qualitatively they should agree if the pieces are correct

Reconstructed Space

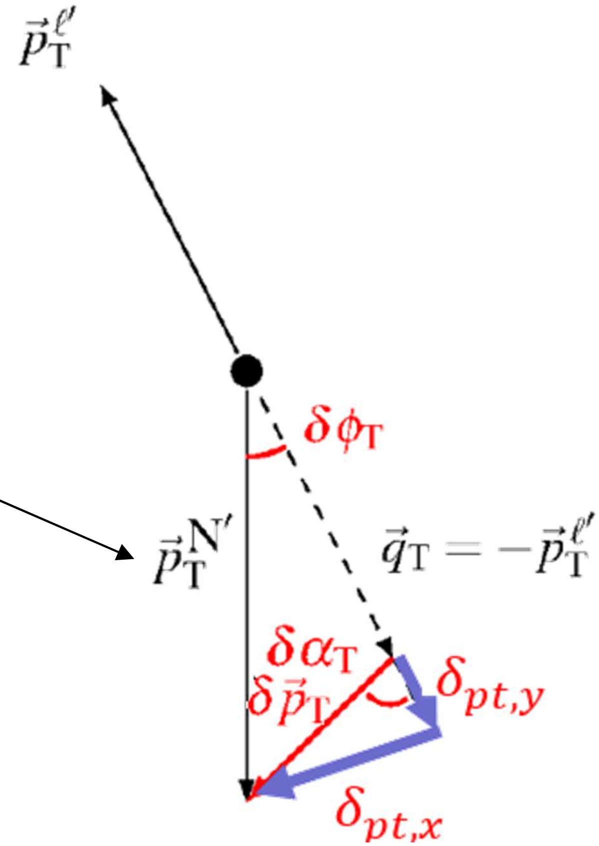
Pink (+) to δ^p (-) to δ^μ Purple (-) to δ^p (+) to δ^μ



k_x

- By subtracting Non-QE but QE-Like events we can access struck nucleon momentum components

Use struck nucleon momentum rather than post-FSI proton

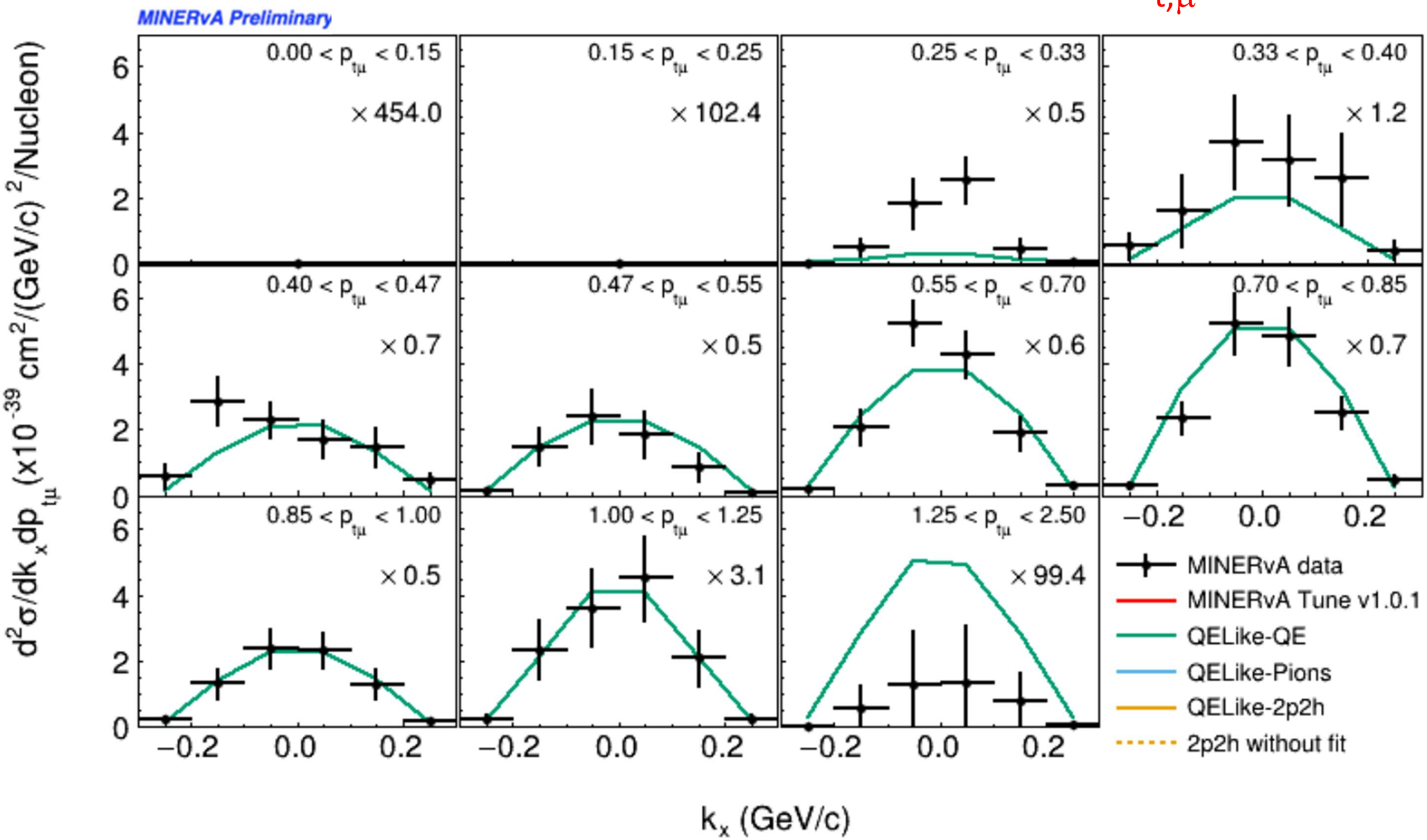


k_x

- Modify standard TKI selection to cut on $|d_{p,tx}>0.3\ \text{GeV}|$
  - Kx in the +/- 0.3 GeV region is the primary QE peak
  - Including beyond introduces strong negative bins when subtracting QELike non-qe
    - Problem for unfolding!
  - Redo $\delta_{pt,y}$ tail fit for modified selection

k_x

Question: What is the peak position, width, and symmetry as a function of $P_{t,\mu}$



Approval

Looking to the future

- Publication writing in progress
- More work to be done with additional two and three dimensional combinations for TKI results
- Efforts to use a higher statistic <3GeV> sample?
  - More dimensions? Compare between datasets?

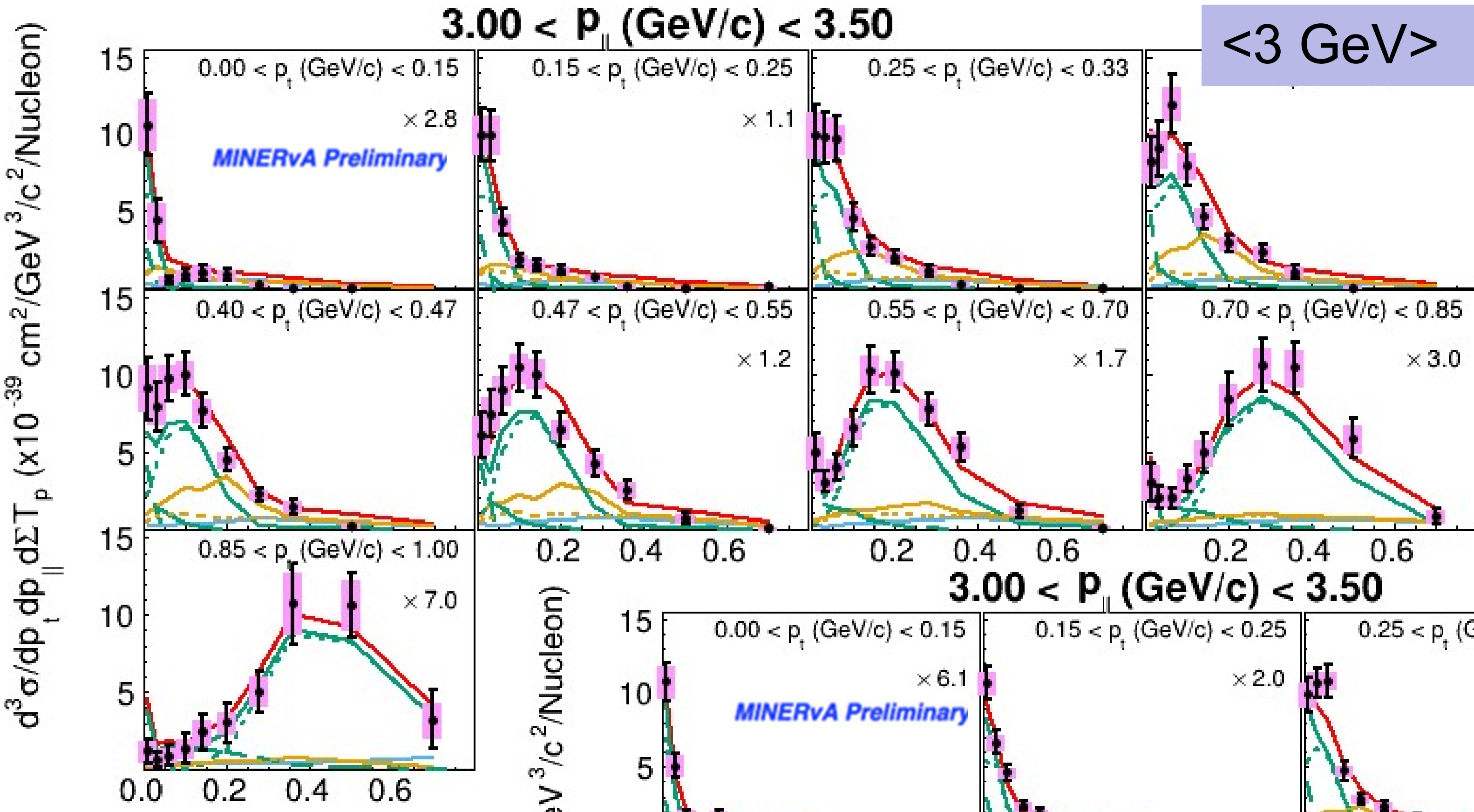
Conclusions

- *New* triple differential result using both datasets are coming soon – similar MC-Data differences as seen in *Phys.Rev.Lett.* 129 (2022) 2, 021803 with additional energy dependent comparisons
- *New* double differential TKI results comparing $P_{t,\mu}$ against a variety of variables
- *New* using $\delta_{pt,y}$ to constrain non-QE but QE-Like events a pure QE sample is extracted
- *New* direct probe of k_x of the struck nucleon

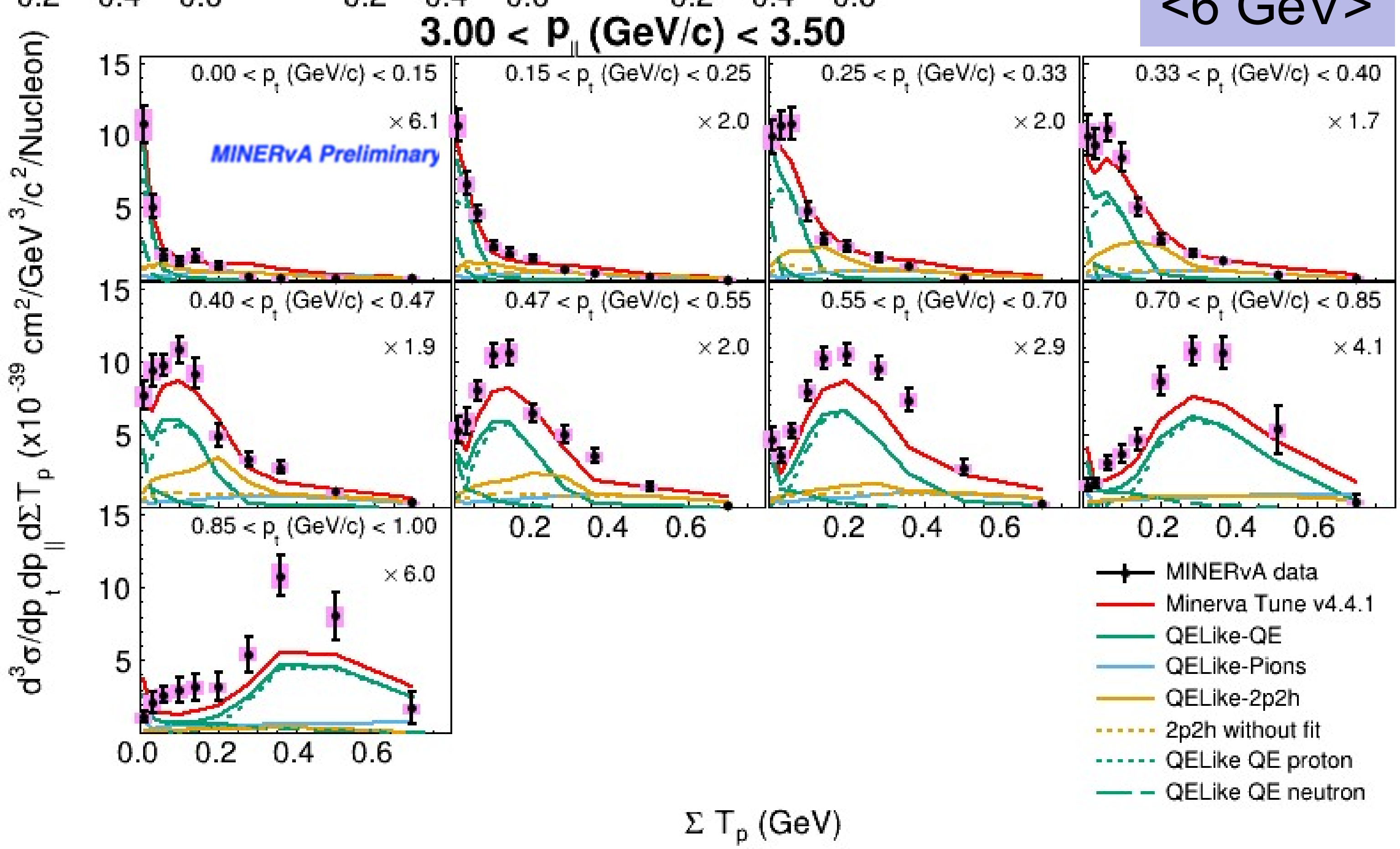
Backups

Single $P_{||}$ Slice

<3 GeV>

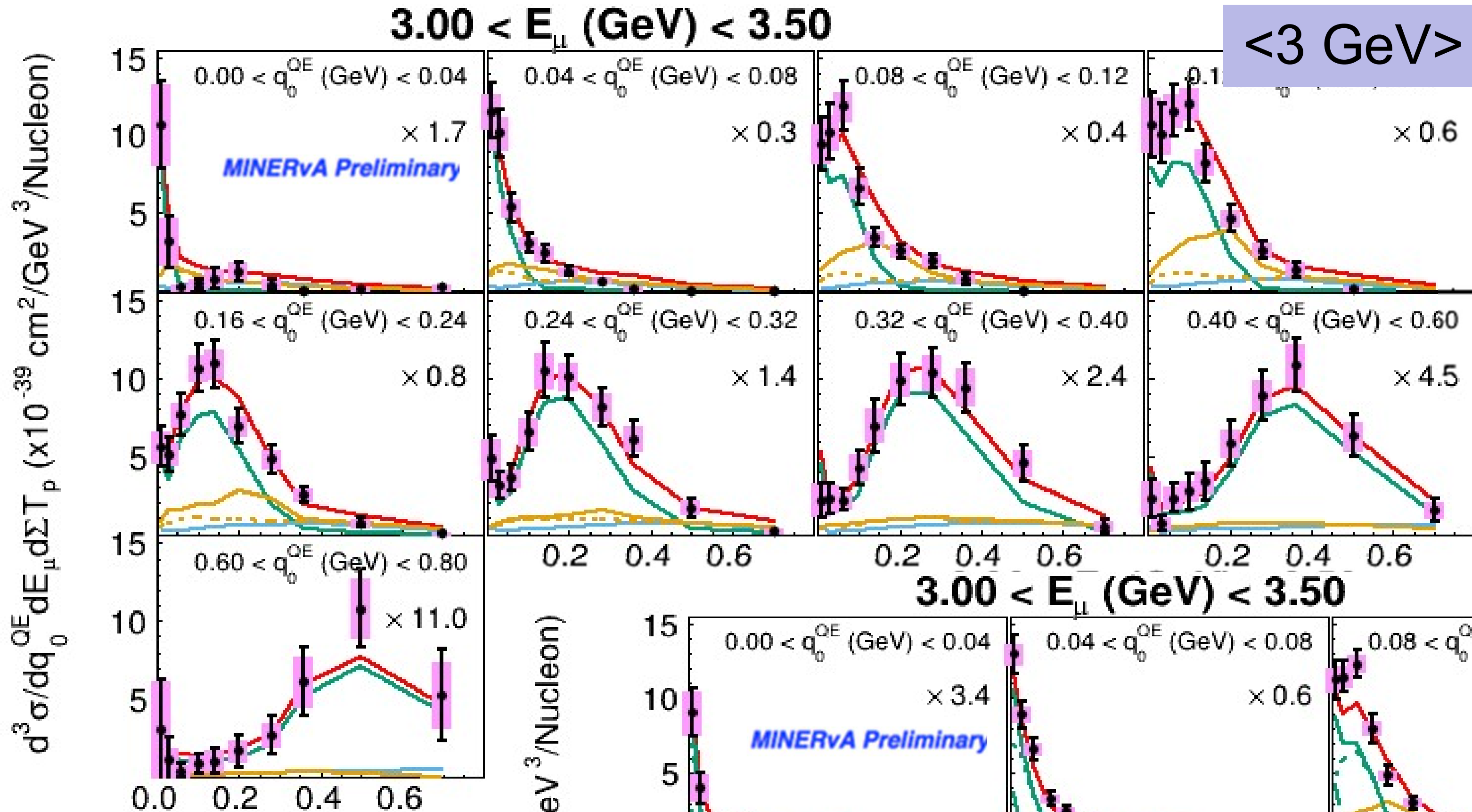


<6 GeV>

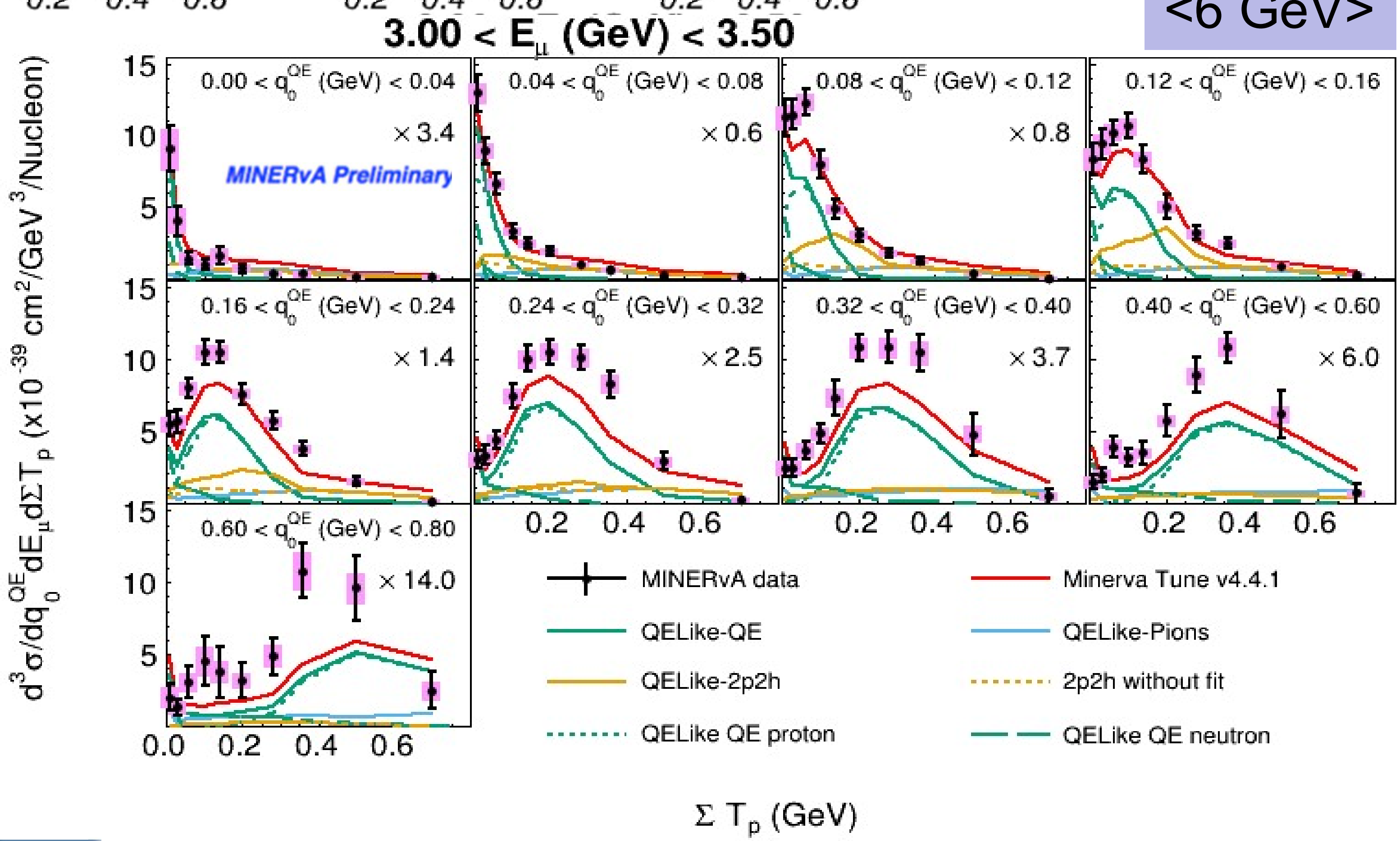


Single E_μ Slice

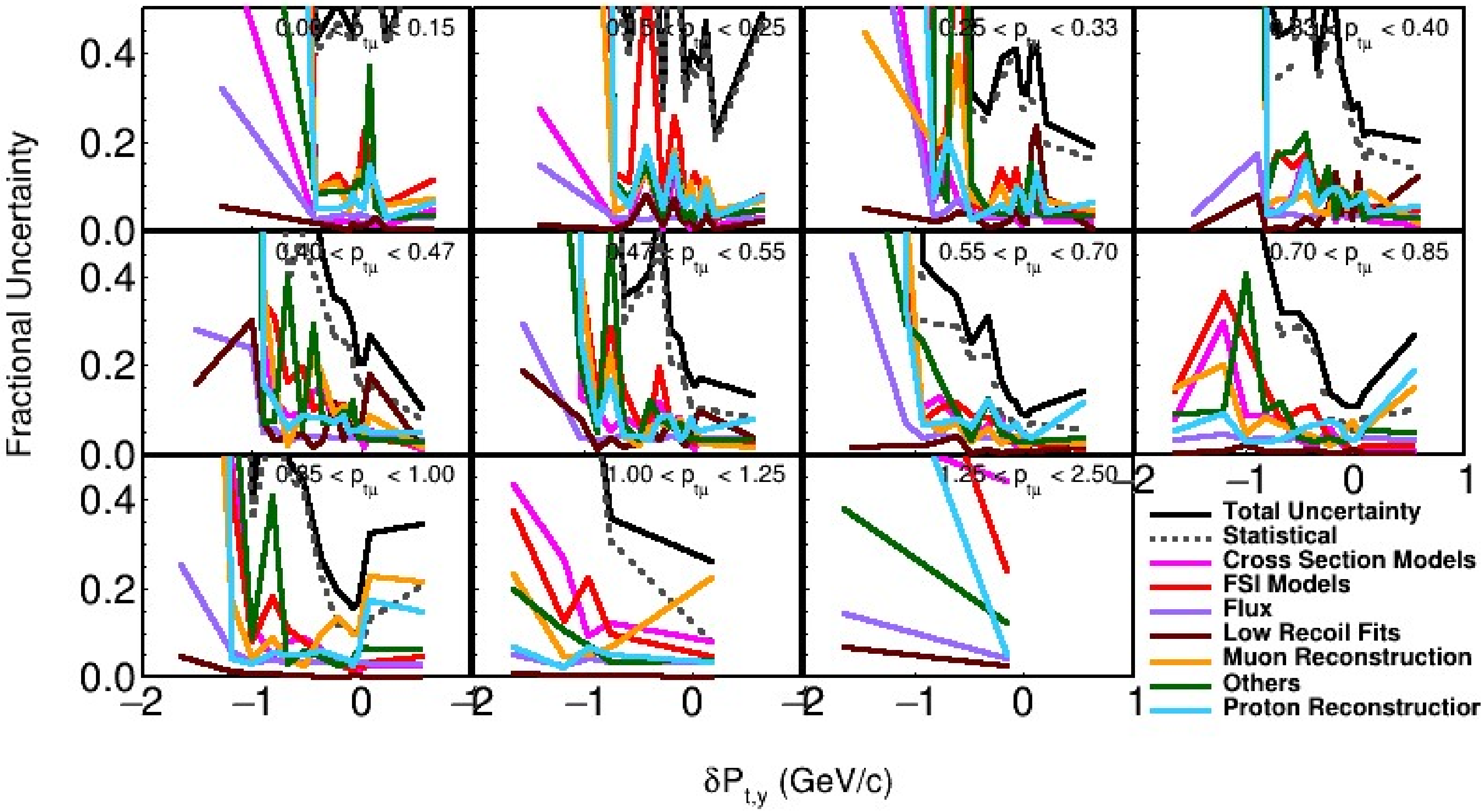
<3 GeV>



<6 GeV>



Uncertainty $\delta_{pt,y}$



Uncertainty $\delta_{pt,x}$