K^+ production in MINERvA and GENIE

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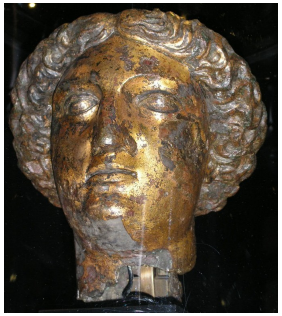
21 December, 2015

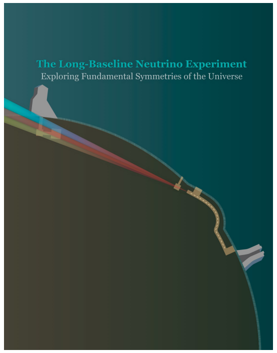


ν-induced K^+ background

- Super-K: 8.4% efficient with 1.11 bkg/Mton-yr
  - Phys. Rev. D 90, 072005 (2014)
- LArTPC: 97% efficient with 1 bkg/Mton-yr
  - JHEP **0704** 041 (2007)

"It is natural to ask to what extent simulations are capable of providing reliable estimates for such rare processes. What if the actual rate for single-kaon atmospheric-neutrino events is higher by a factor of ten or more? Is that even conceivable?"

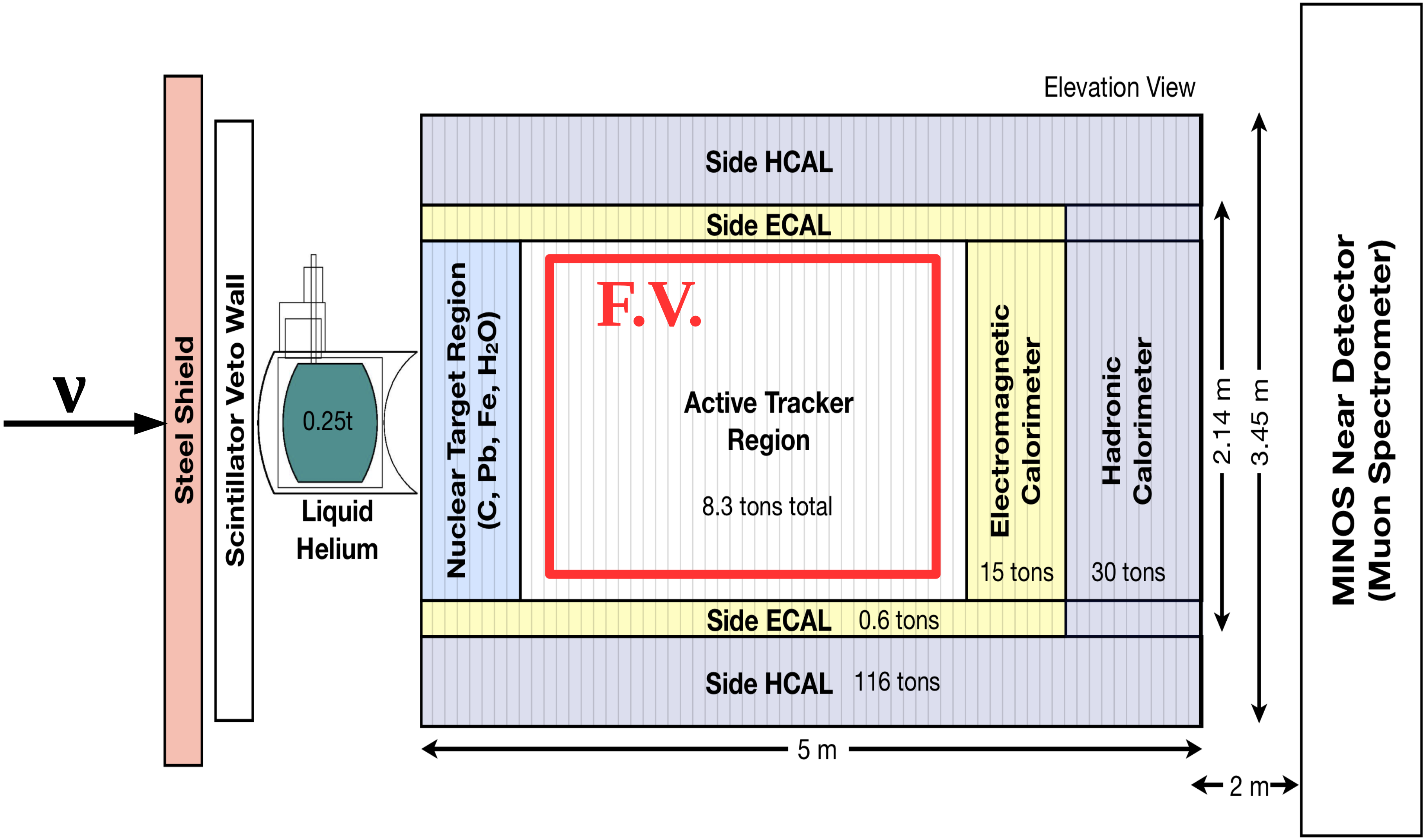
-DUNE/LBNE science document, Chapter 5



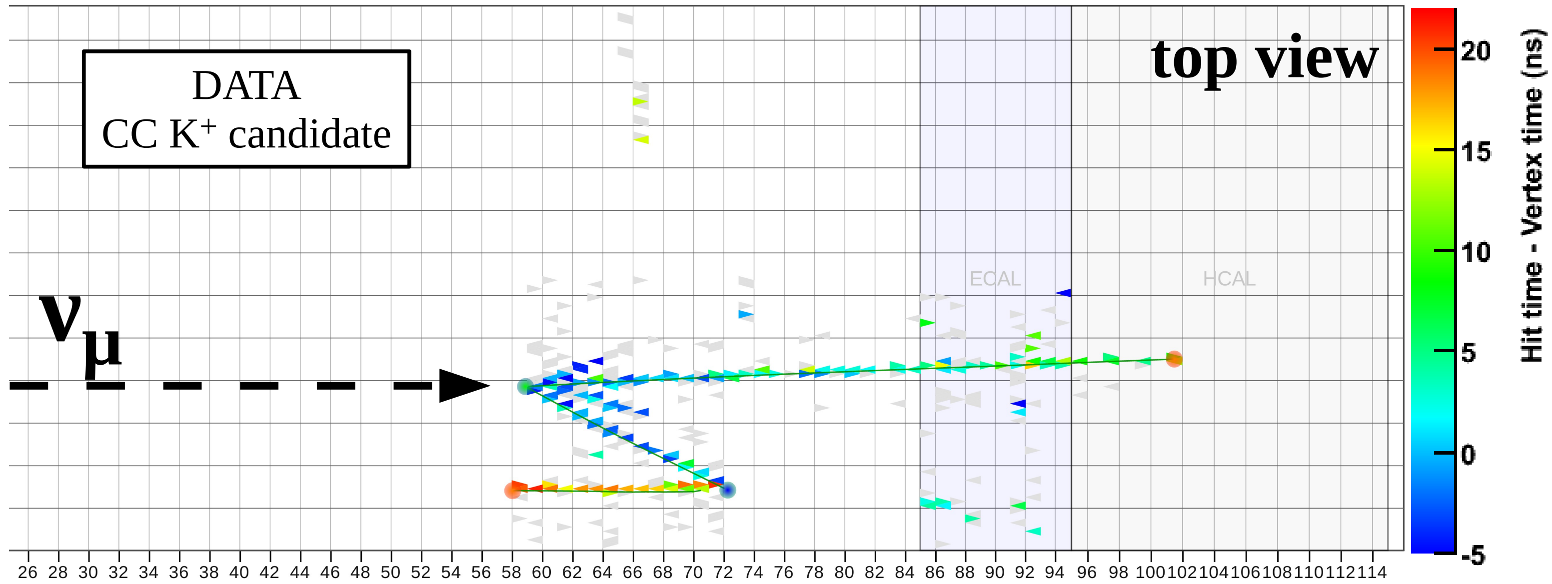
What can MINERvA do?

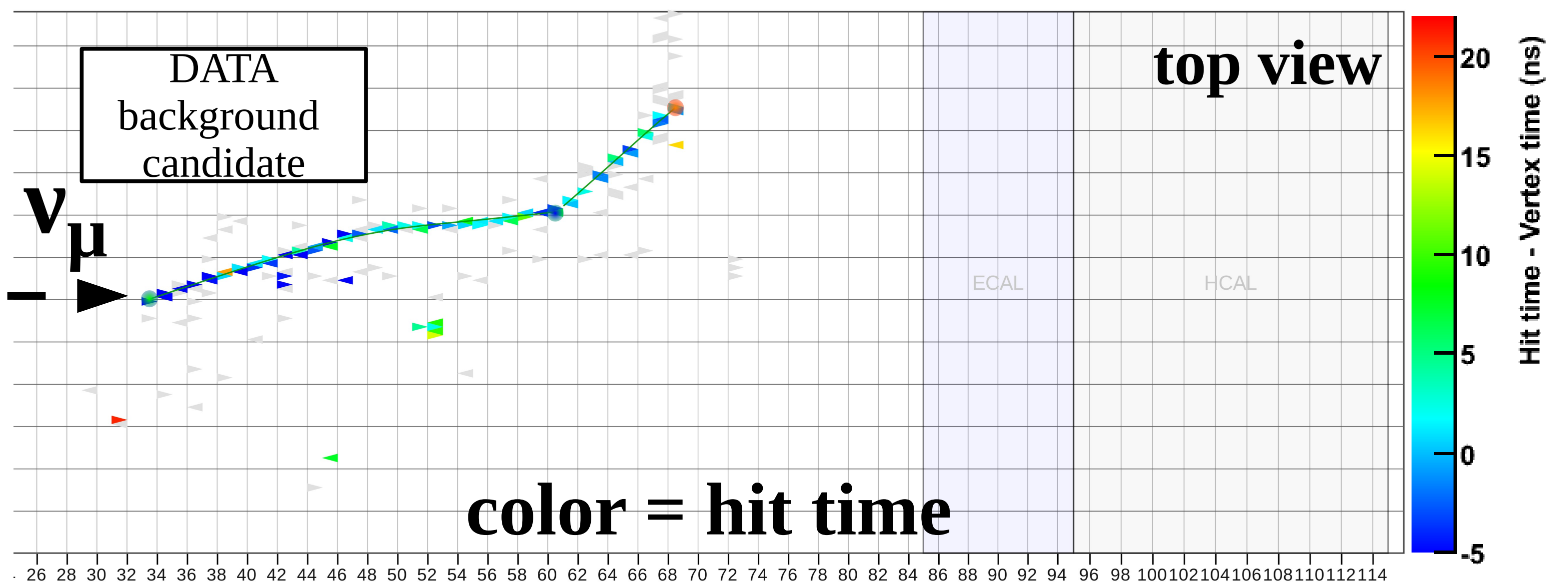
- MINERvA will publish cross sections for neutral-current K^+ production at $E_\nu \sim 3$ GeV
- Both kaon energy and total hadronic energy to look for "kaon plus nothing" NC final state
- Benchmark your favorite Monte Carlo, increase confidence in $p \rightarrow K\nu$ background prediction

Our detector



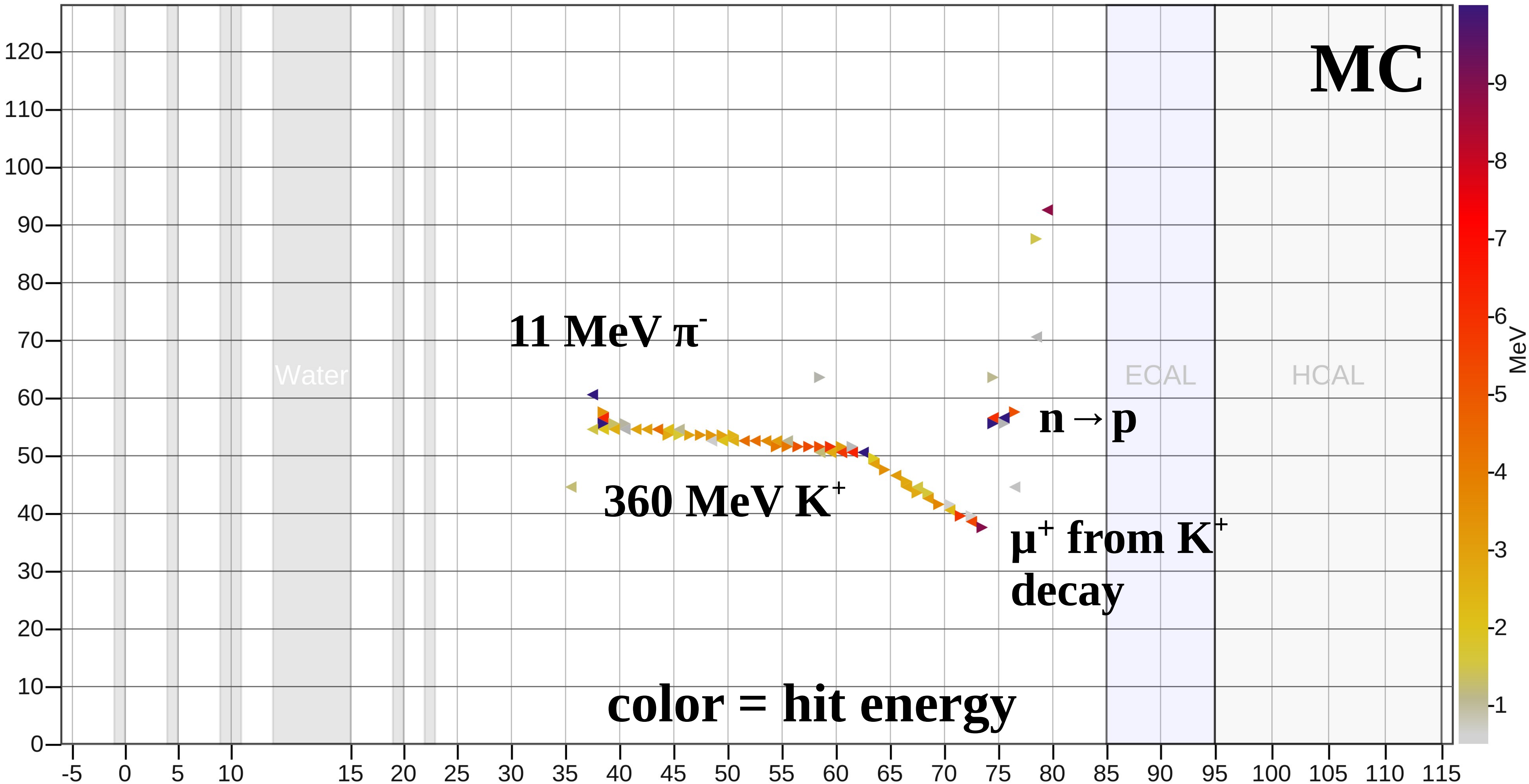
Identifying kaons by timing



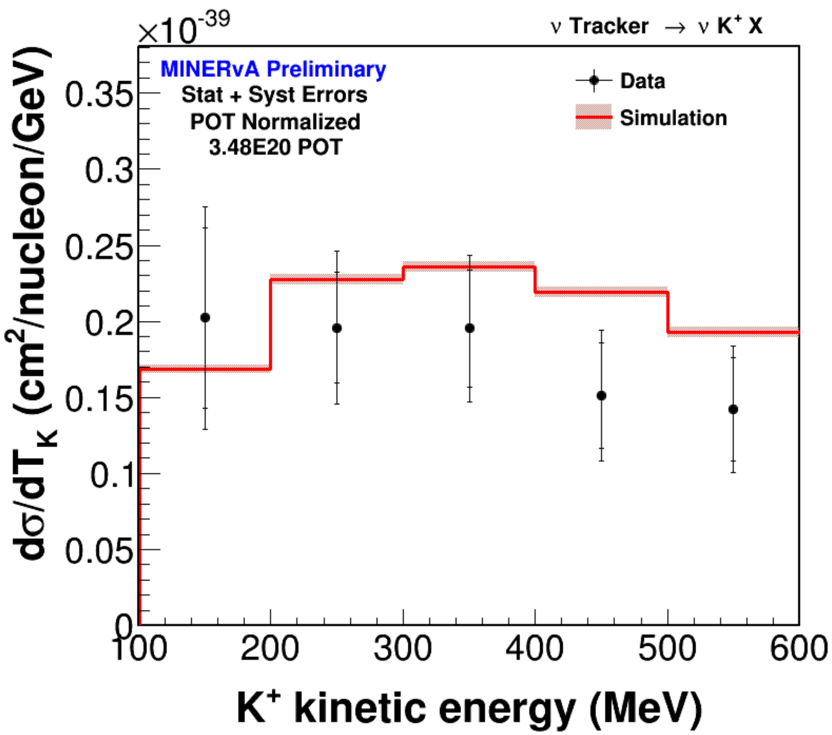


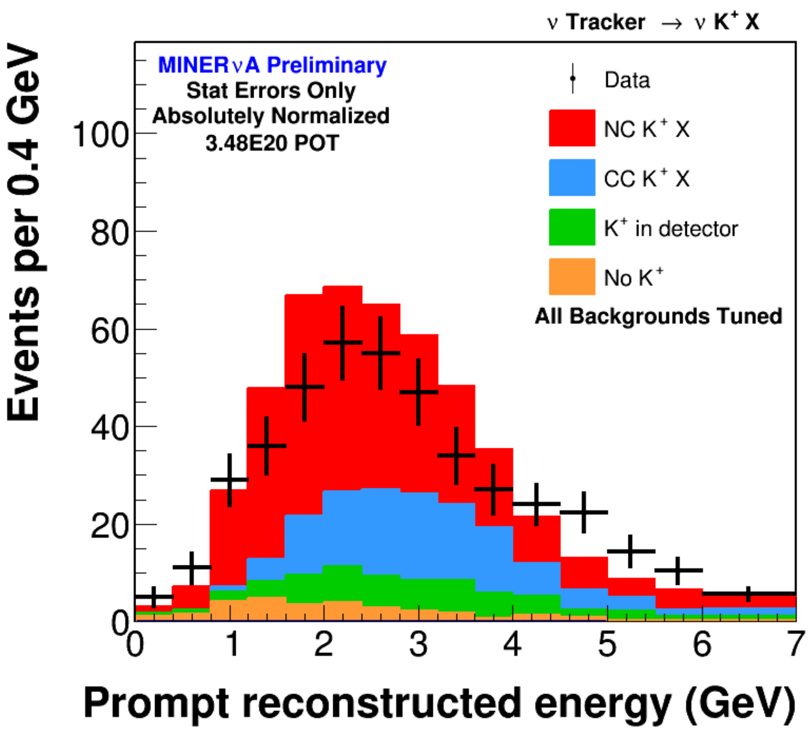
Example “K + nothing” event

$\nu\, n \rightarrow \nu\, K^+ \Sigma^-$



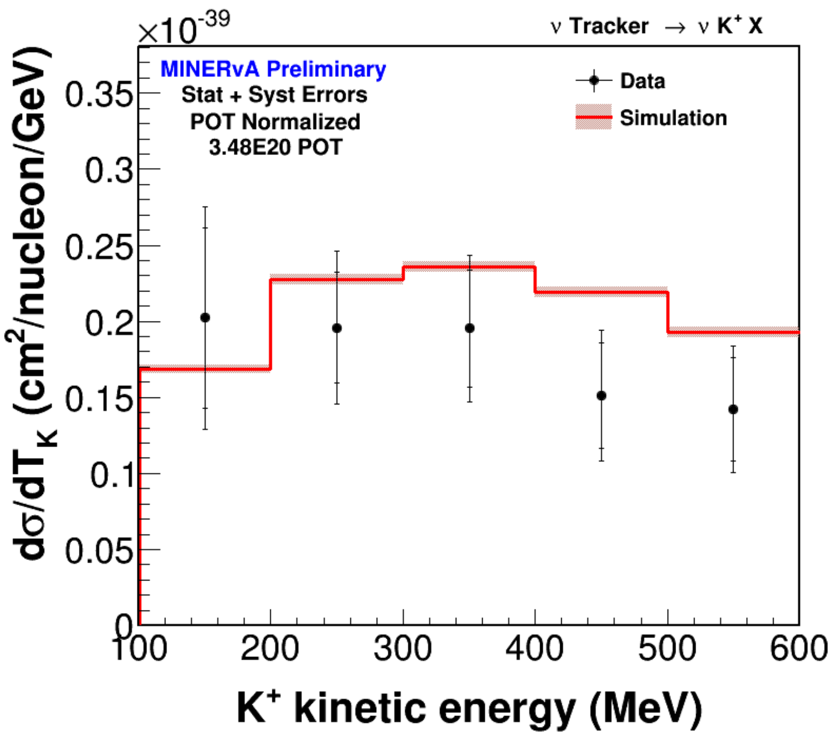
Preliminary results

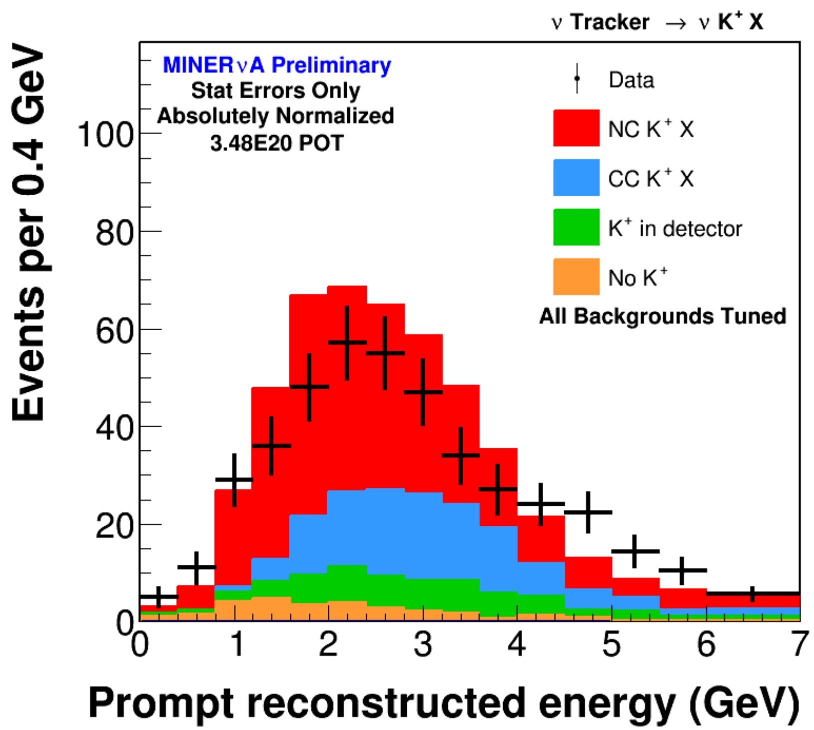




- GENIE rate of NC K^+ agrees with MINERvA data
- Hadronic energy distribution broadly agrees

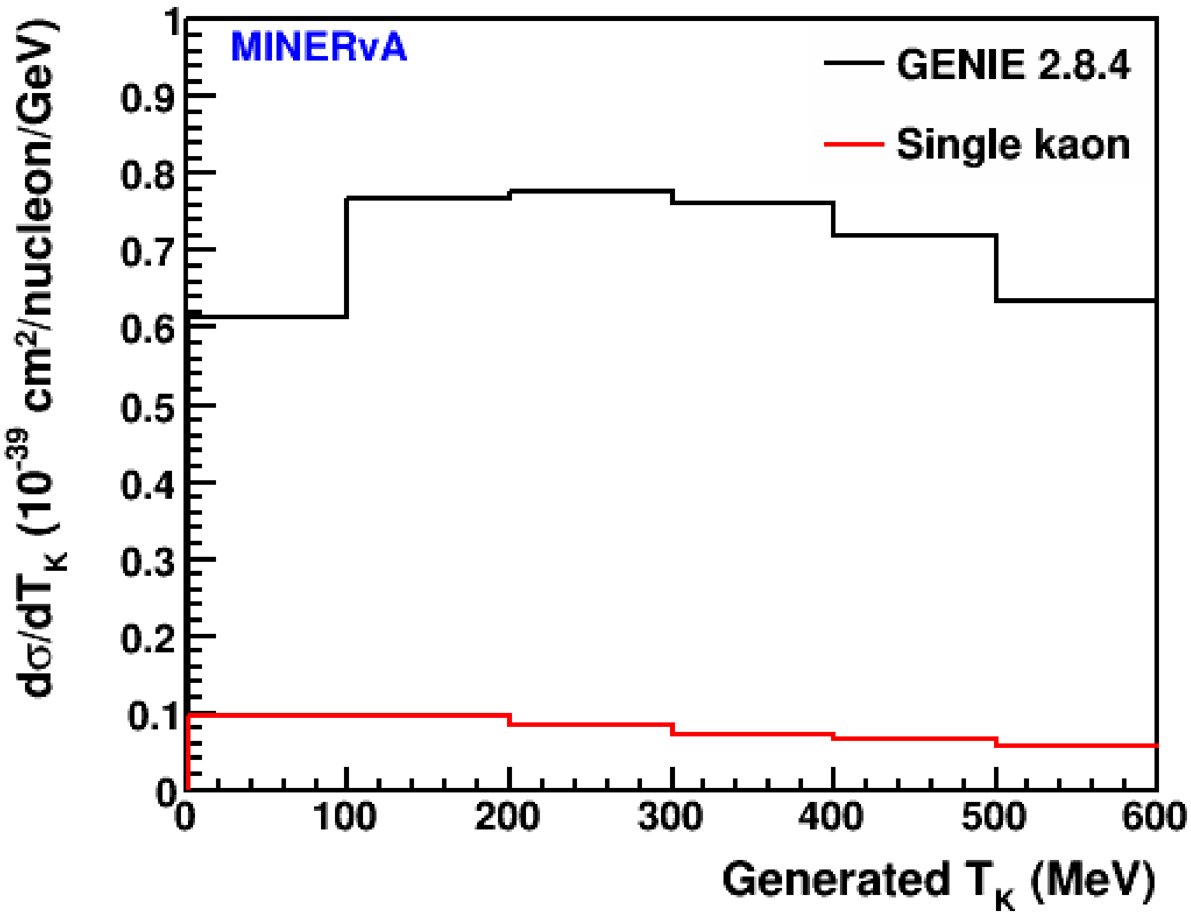
Updates





- Final results (February 2016) will have updated flux, plus a few analysis improvements
- Turn the "prompt reconstructed energy" into a cross section vs. ν - E_K

Single kaon production

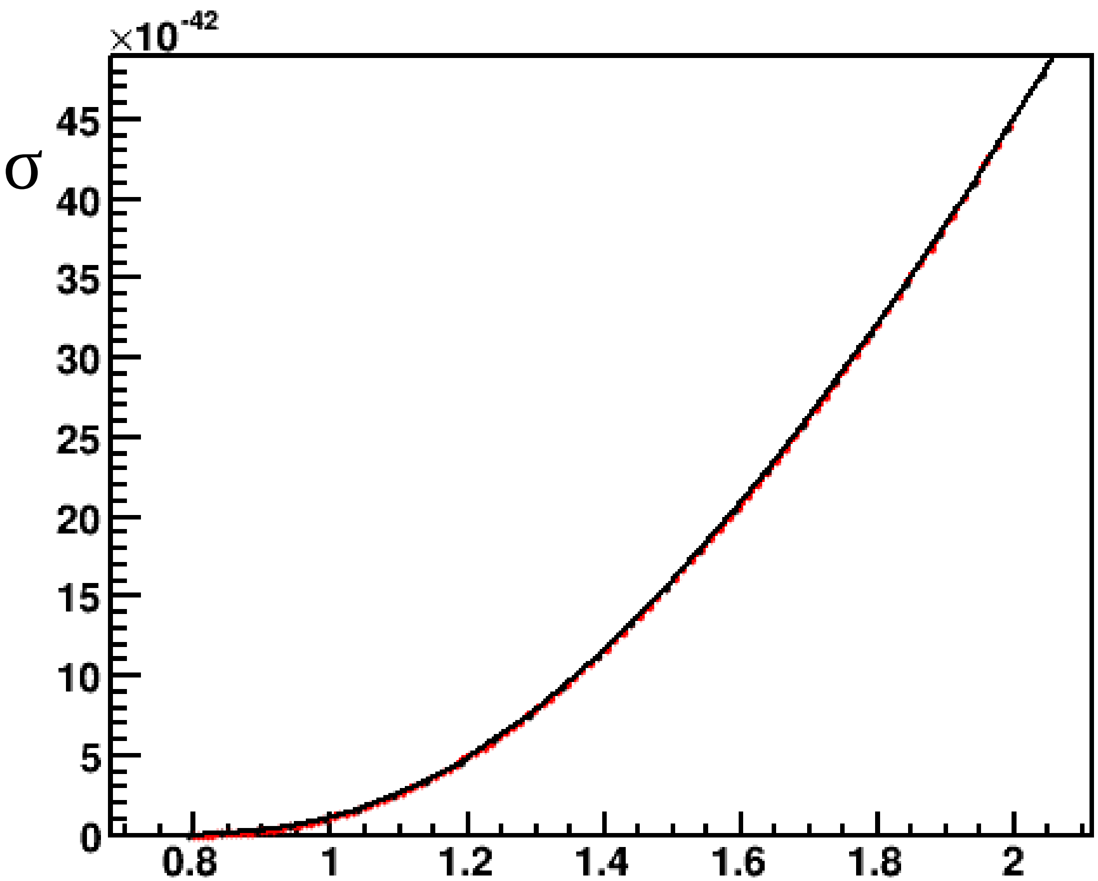


Cabibbo-suppressed process, $\nu\, N \rightarrow \mu^- K^+ N$

For MINERvA LE flux (~3 GeV), it's < 10% of the total CC K^+ cross section

Dominant mode for neutrino energy < 1.5 GeV

Total cross section

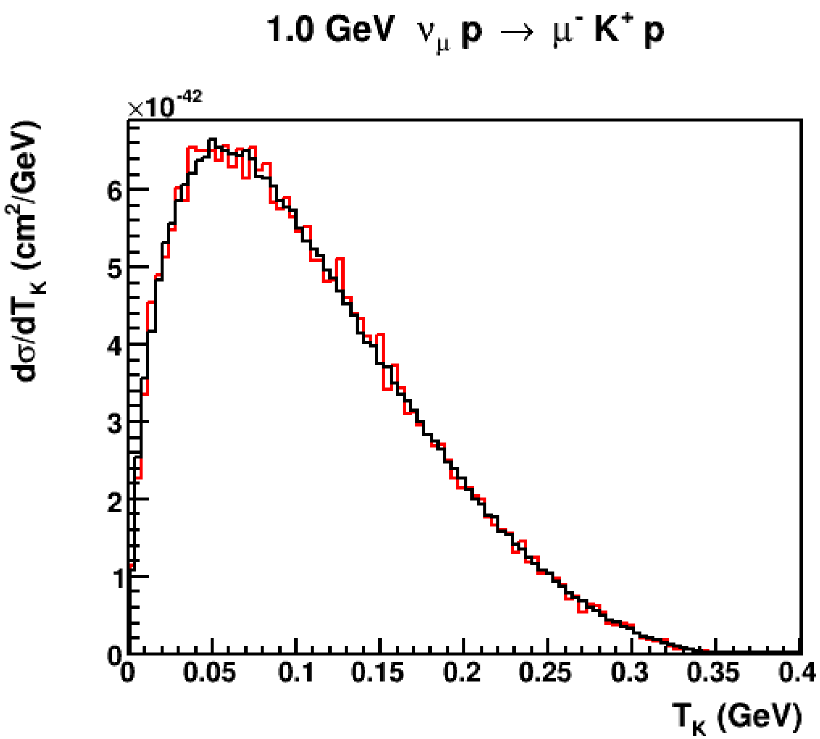


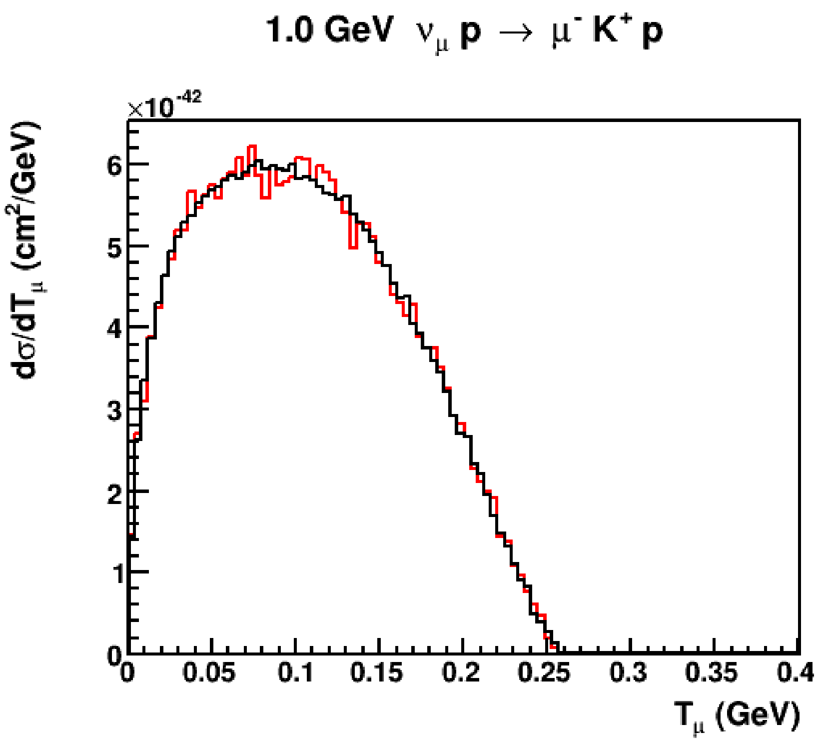
Neutrino energy (GeV)

Theorists trust the model for neutrino energy < 2 GeV

Predicts full 3-particle final state, kinematics are unrealistic at high W

Kaon and muon kinematics





- At 1 GeV neutrino energy, about half the cross section is muons below water Cherenkov threshold

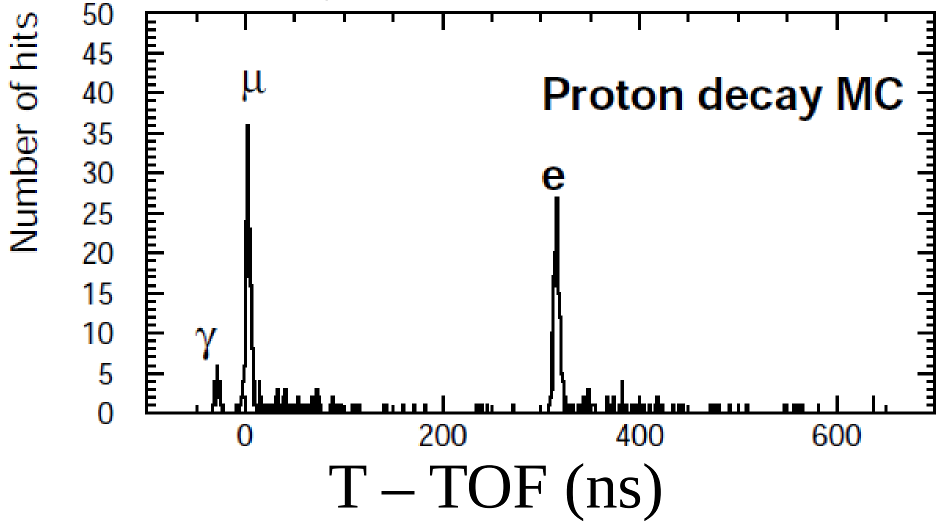
Result release schedule

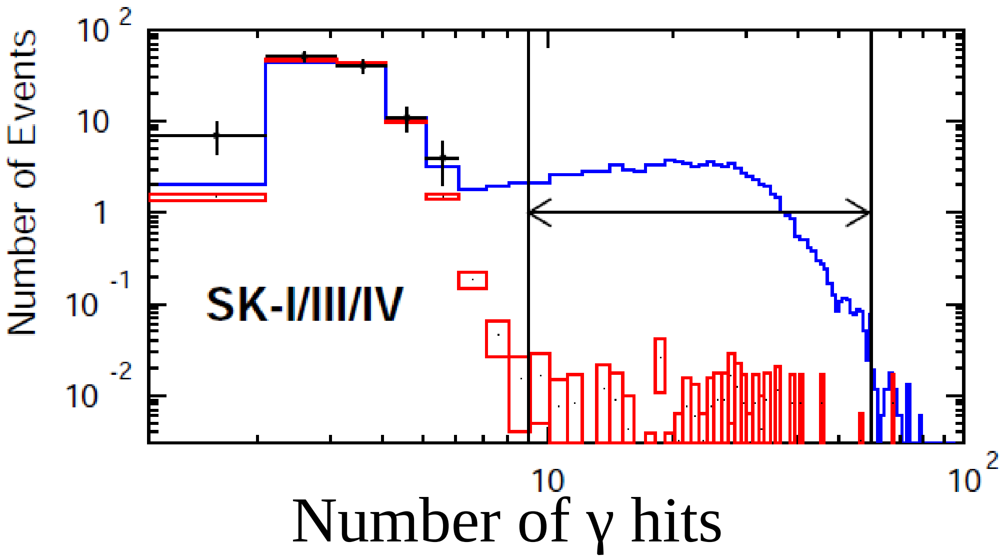
- FNAL wine & cheese seminar February 5 (CC & NC kaon production)
- Papers shortly thereafter

Backup slides

$p \rightarrow K^+\nu$ at Super-K

Phys. Rev. D 90, 072005 (2014)





K^+ is below threshold

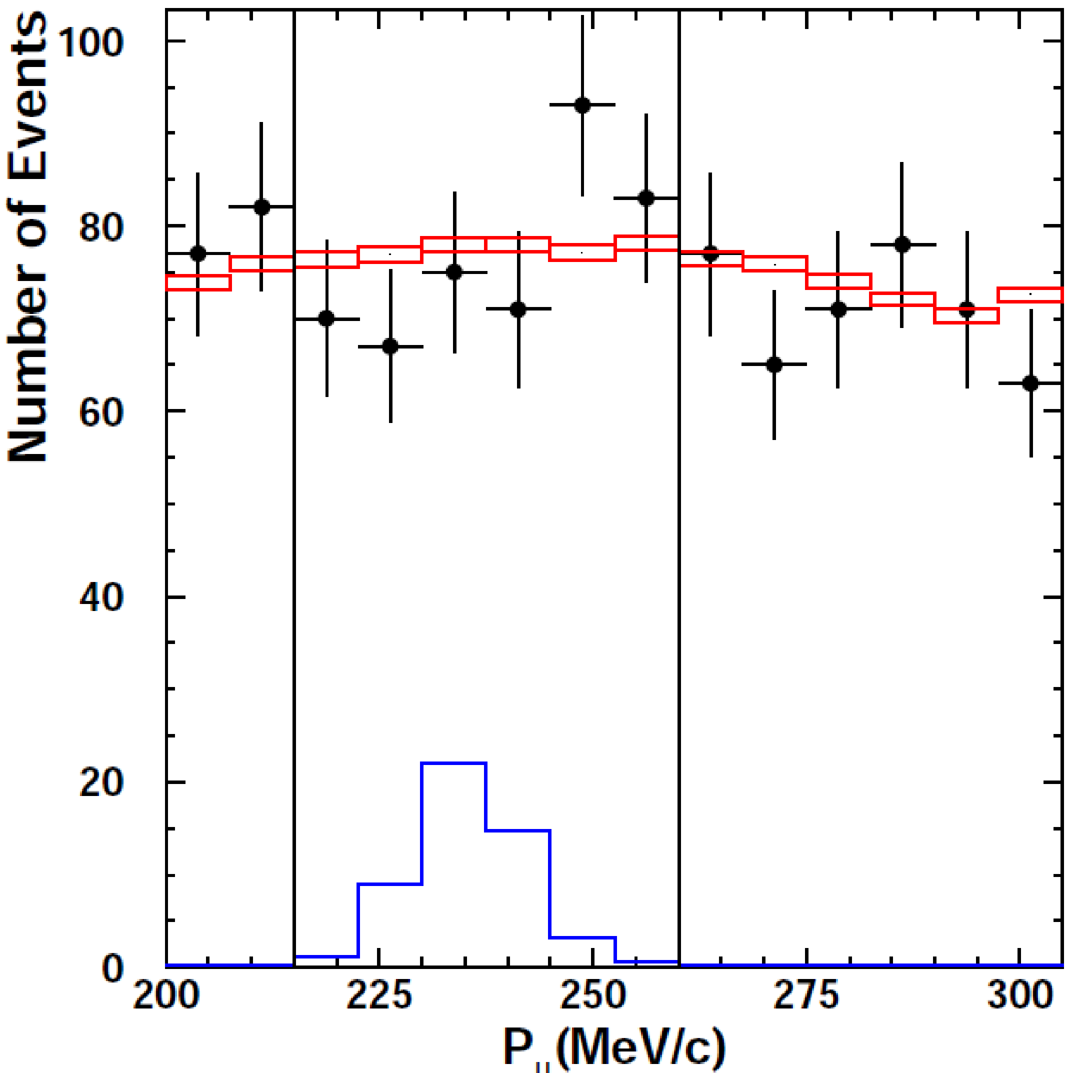
Require prompt γ from ^{15}N de-excitation, delayed decay products from $K \rightarrow \mu \rightarrow e$

$\nu\, p \rightarrow \nu\, K^+ \Lambda$ gives exactly the same signature – an irreducible background

Expect ~3 of these in 5 years of Hyper-K

$p \rightarrow K^+\nu$ at Super-K

Phys. Rev. D 90, 072005 (2014)



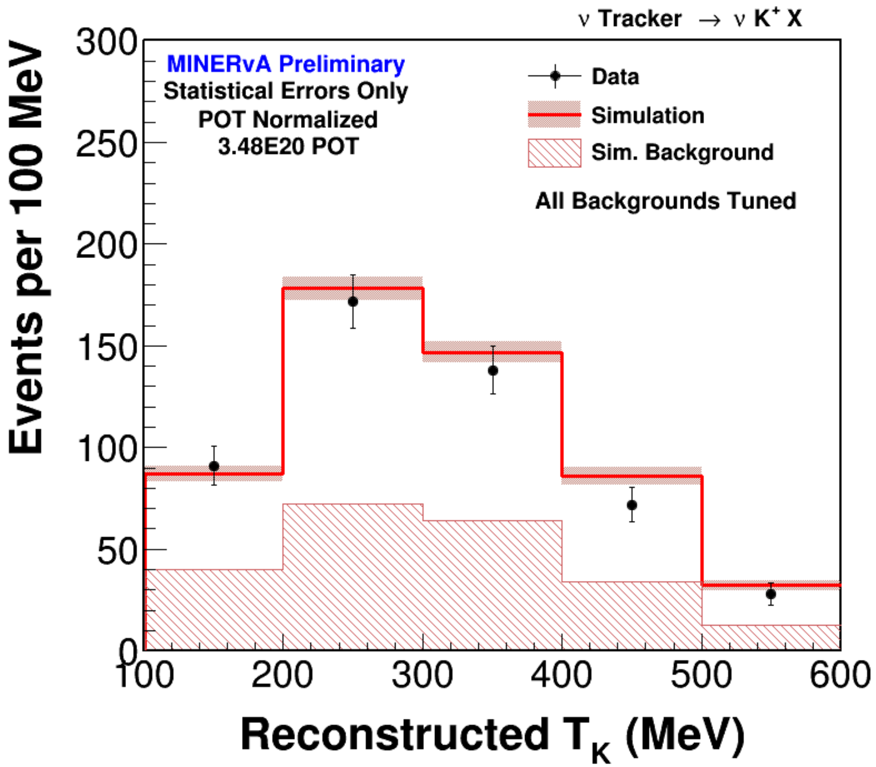
1 μ-like ring + 1 decay electron

Dominant background from $\nu_\mu\, n \rightarrow \mu^-\, p$

Also a background with the same shape as the signal from $\nu\, p \rightarrow \nu\, K^+\, \Lambda$ and other similar processes

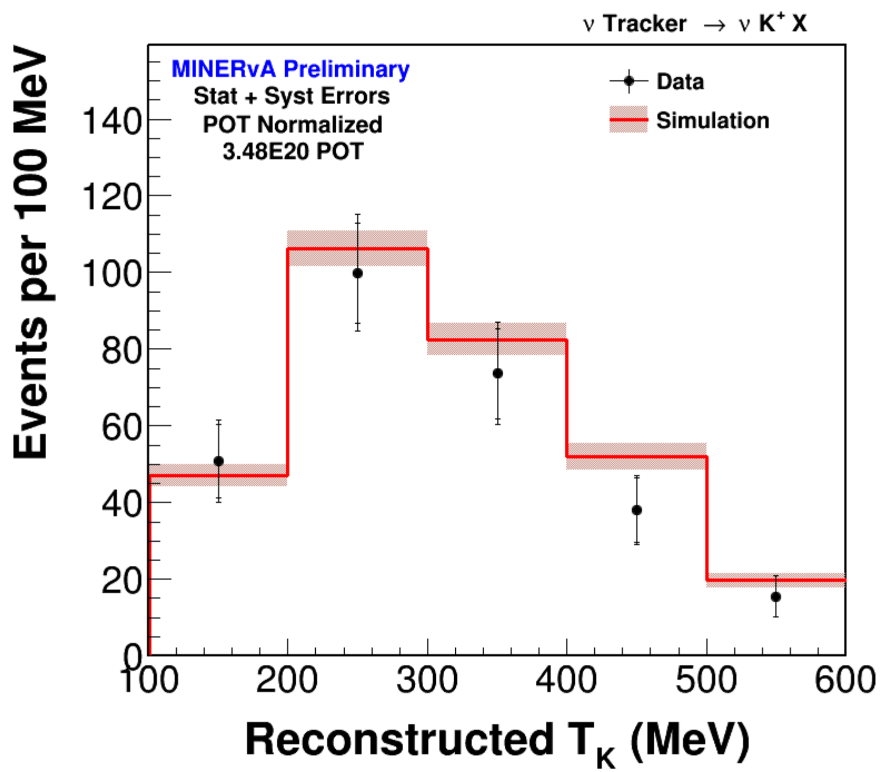
Toward a cross section: reconstructed events

$$\left(\frac{d\sigma}{d\xi}\right)_i = \frac{1}{\Phi} \times \frac{1}{T_n} \times \frac{1}{(\Delta\xi)_i} \times \frac{\sum_j U_{ij}\left(N_j^{obs} - N_j^{bknd}\right)}{\epsilon_i}$$



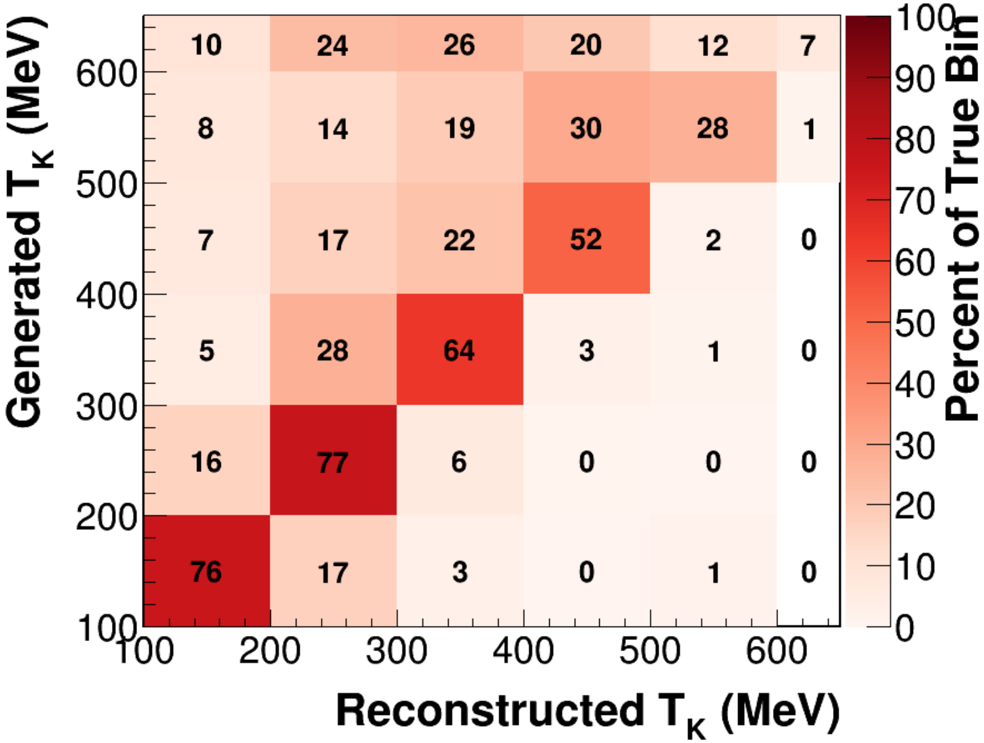
Toward a cross section: background subtraction

$$\left(\frac{d\sigma}{d\xi}\right)_i = \frac{1}{\Phi} \times \frac{1}{T_n} \times \frac{1}{(\Delta\xi)_i} \times \frac{\sum_j U_{ij}\left(N_j^{obs} - N_j^{bknd}\right)}{\epsilon_i}$$



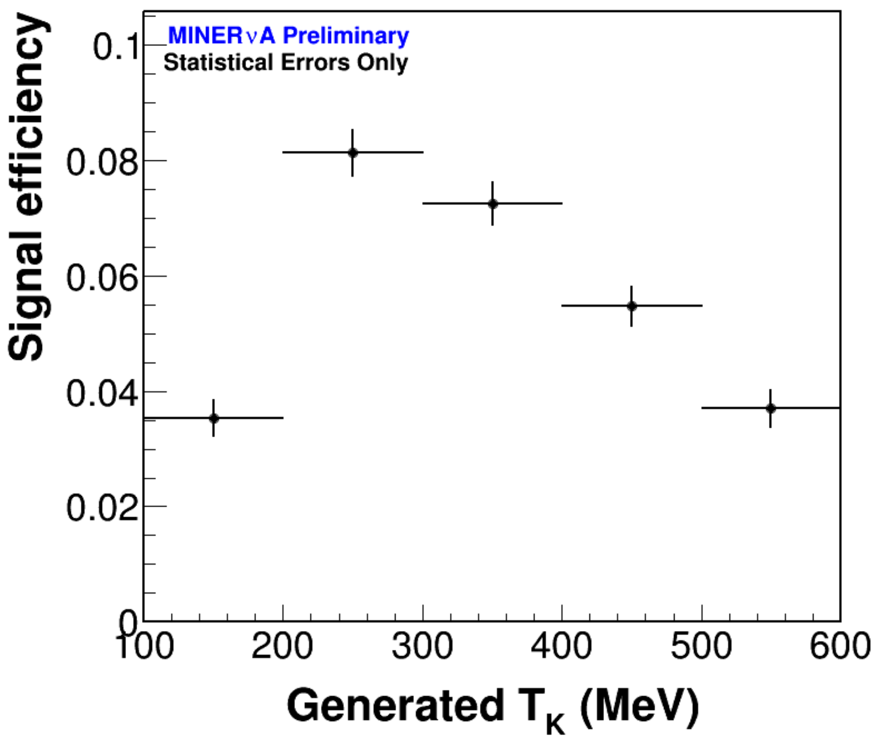
Toward a cross section: unsmearing matrix

$$\left(\frac{d\sigma}{d\xi}\right)_i = \frac{1}{\Phi}\times\frac{1}{T_n}\times\frac{1}{(\Delta\xi)_i}\times\frac{\sum_j U_{ij}\left(N_j^{obs}-N_j^{bknd}\right)}{\epsilon_i}$$



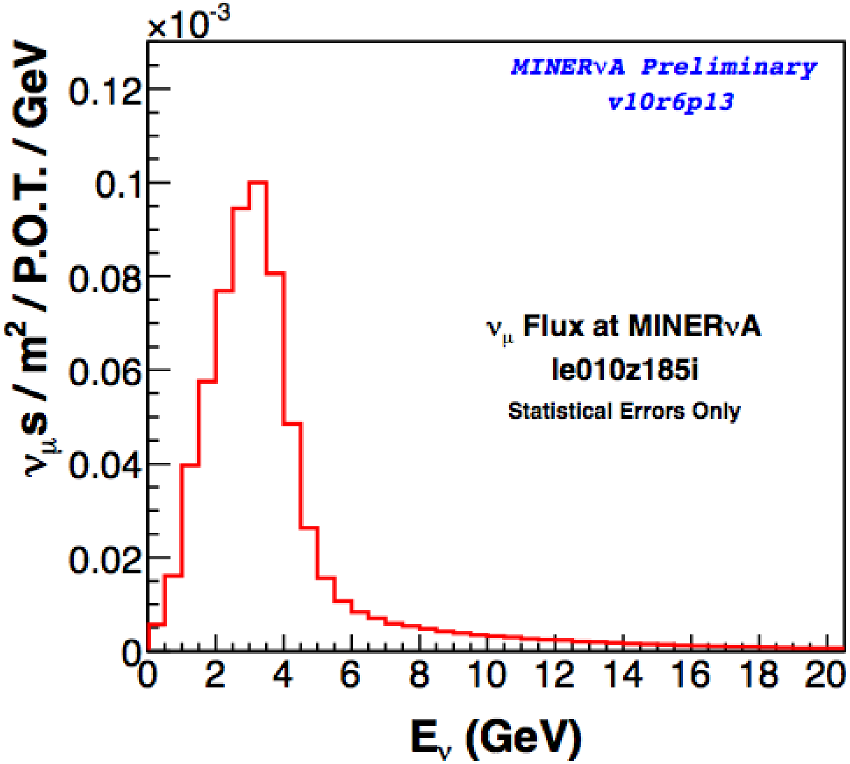
Toward a cross section: efficiency correction

$$\left(\frac{d\sigma}{d\xi}\right)_i = \frac{1}{\Phi} \times \frac{1}{T_n} \times \frac{1}{(\Delta\xi)_i} \times \frac{\sum_j U_{ij}\left(N_j^{obs} - N_j^{bknd}\right)}{\epsilon_i}$$

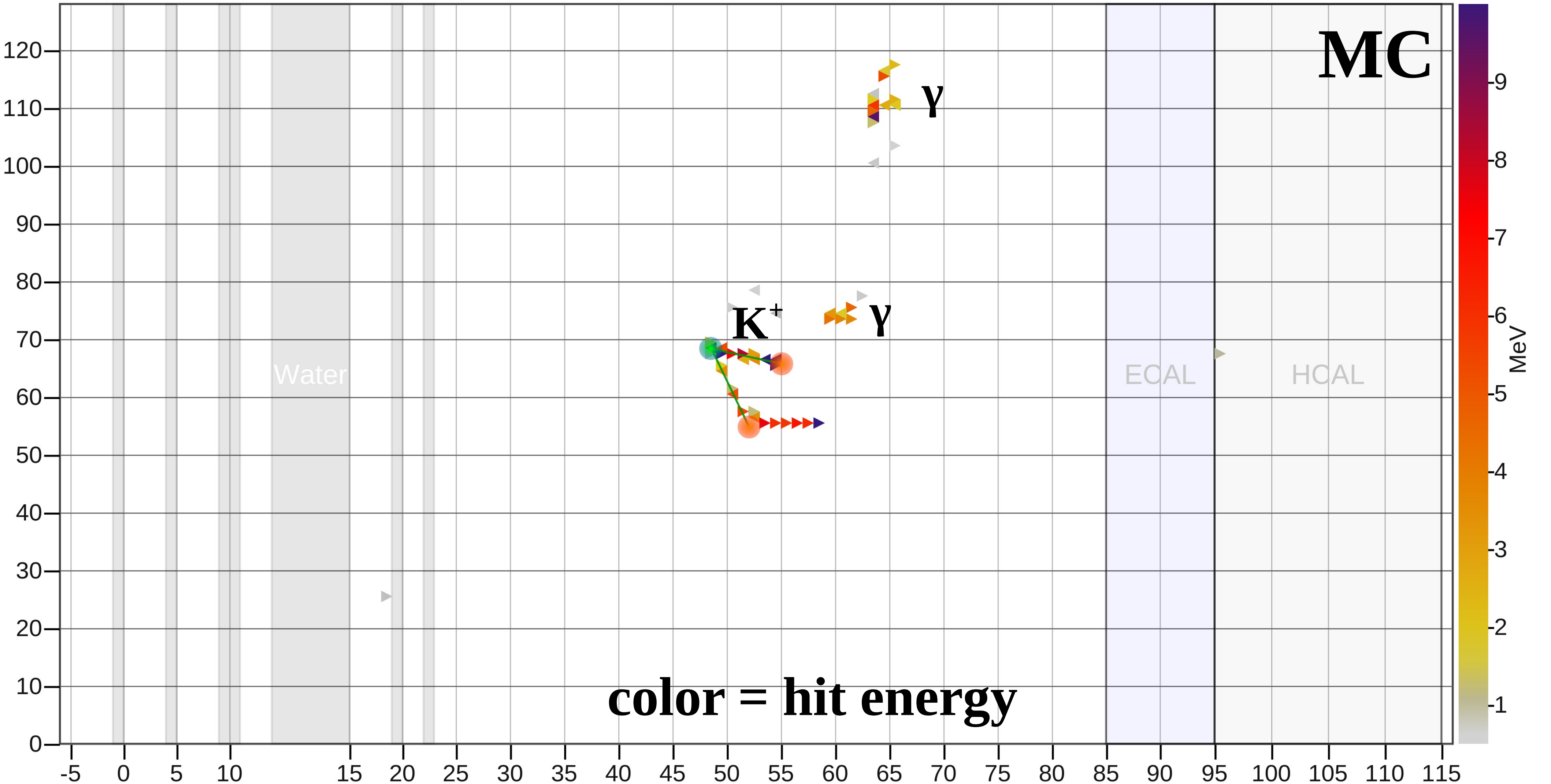


Toward a cross section: dividing by the flux

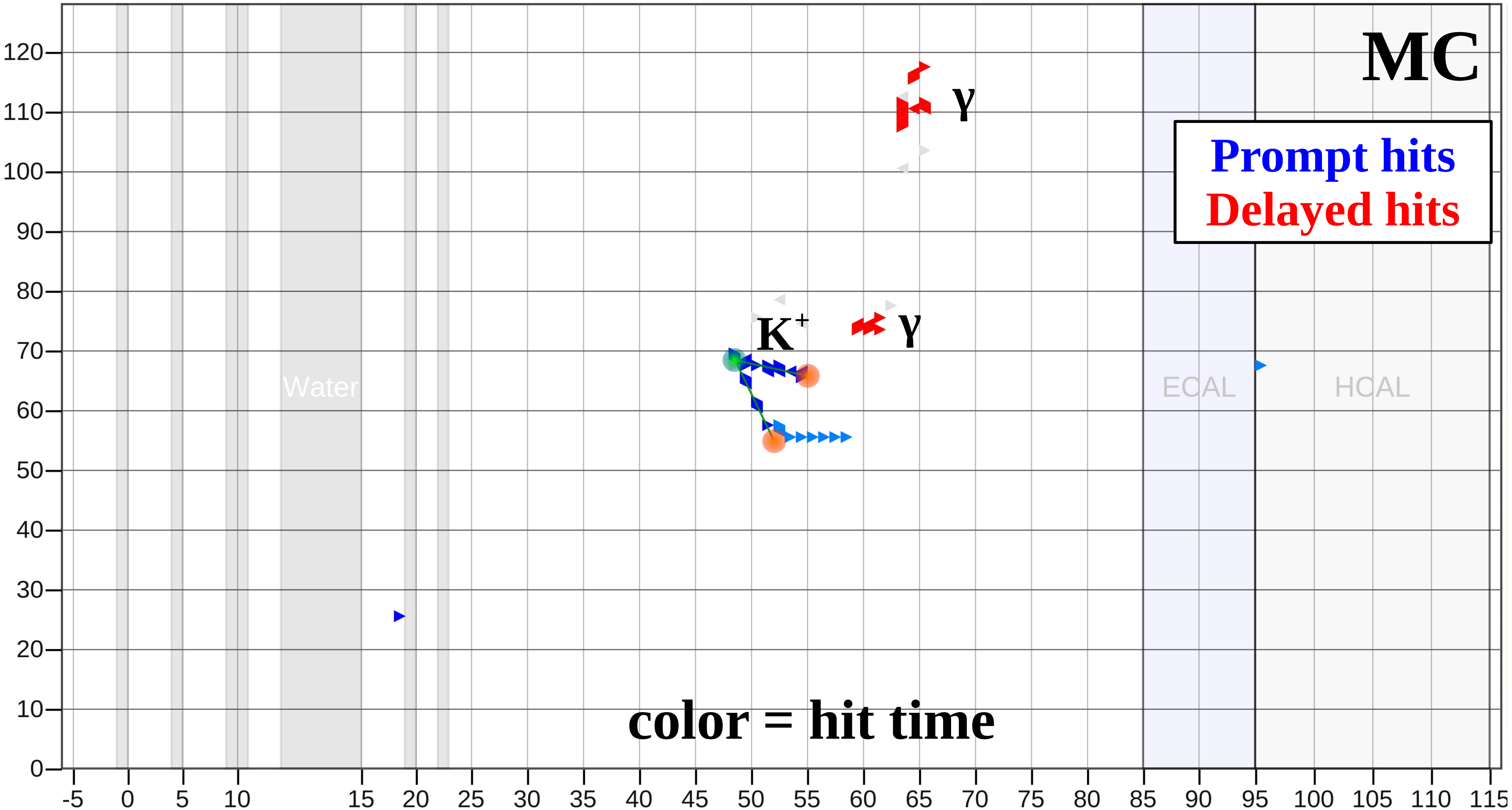
$$\left(\frac{d\sigma}{d\xi}\right)_i = \frac{1}{\Phi} \times \frac{1}{T_n} \times \frac{1}{(\Delta\xi)_i} \times \frac{\sum_j U_{ij}\left(N_j^{obs} - N_j^{bknd}\right)}{\epsilon_i}$$



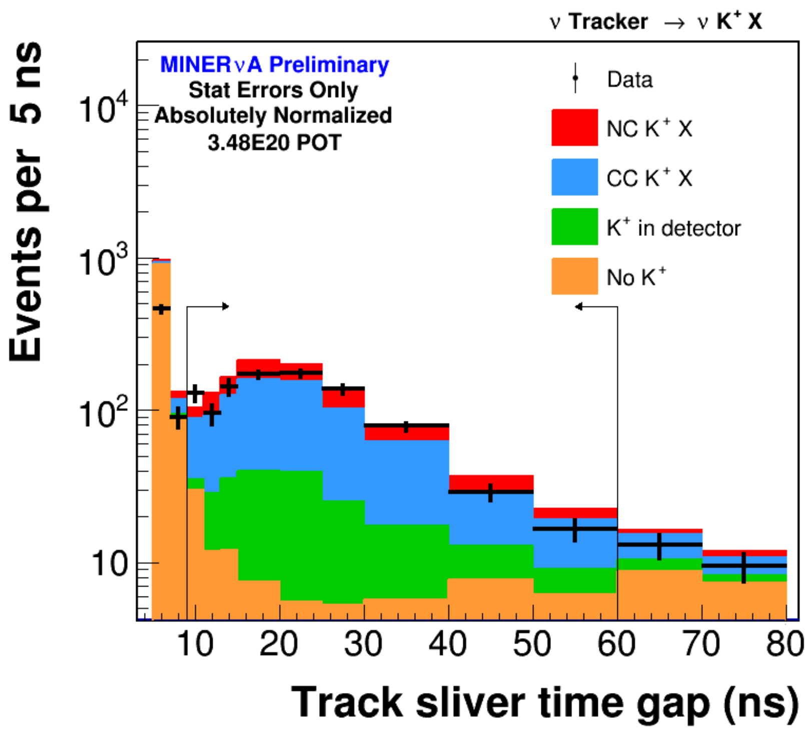
Reconstructing events without kinked tracks

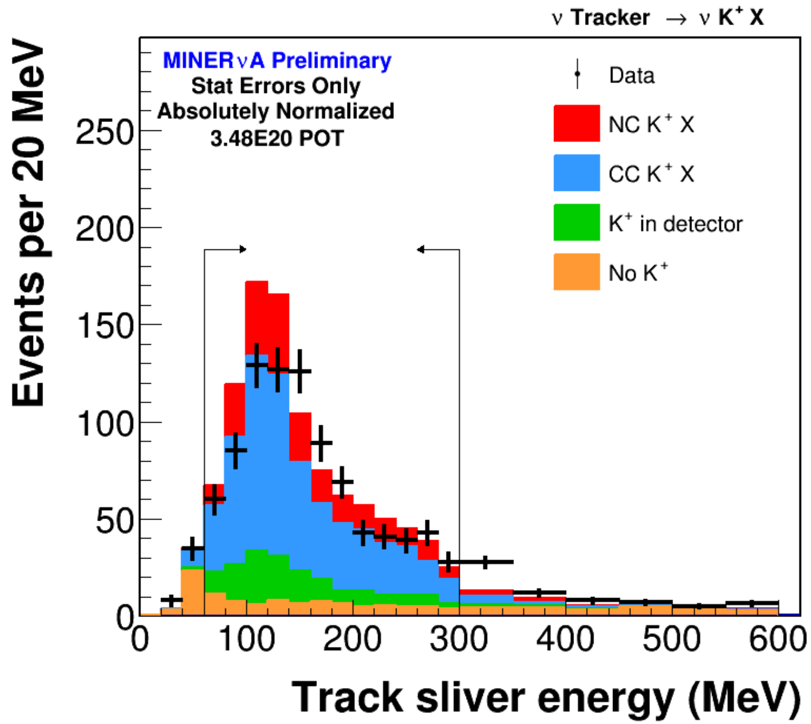


Hits are grouped into narrow bunches in time: “time slivers”



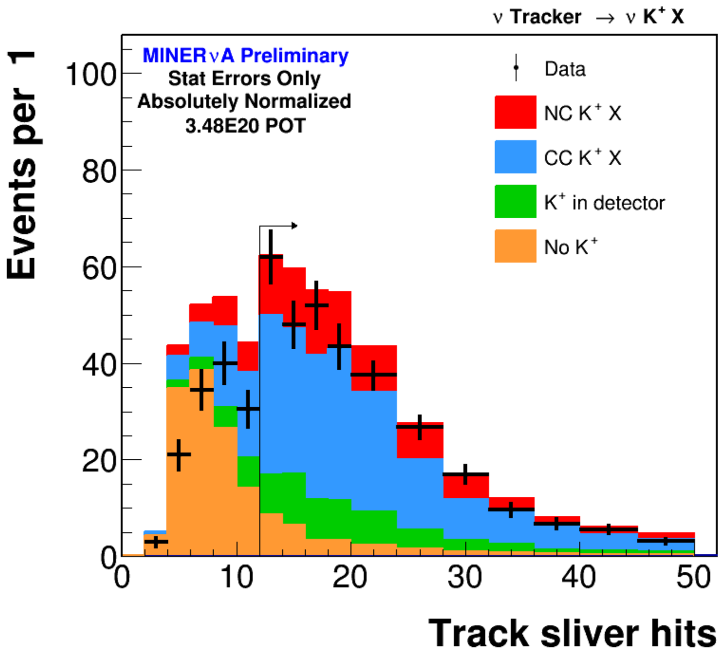
Selecting time sliver events

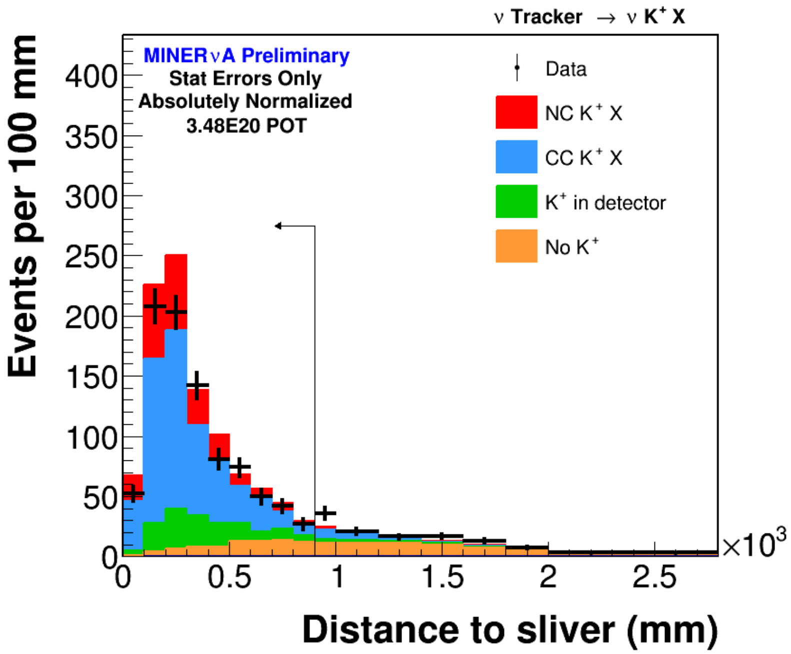




- Interacting pions have small time gap
- Accidental pile-up events can have large energy

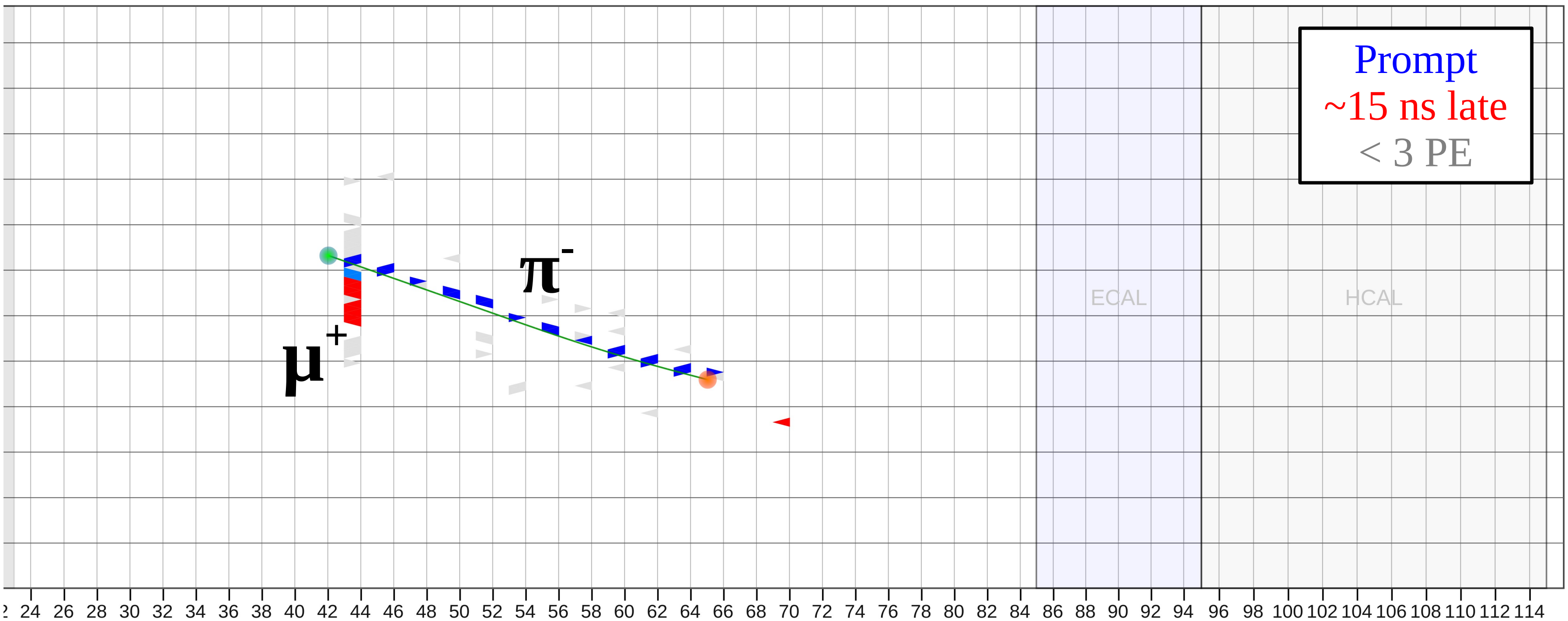
Additional time sliver cuts





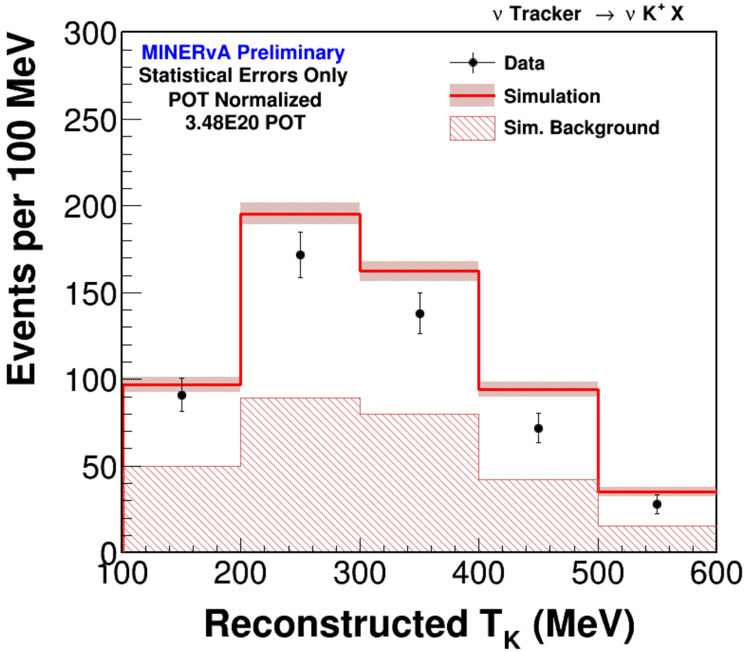
- Reject neutrons with number of hits cut
- Reject pile-up with distance cut

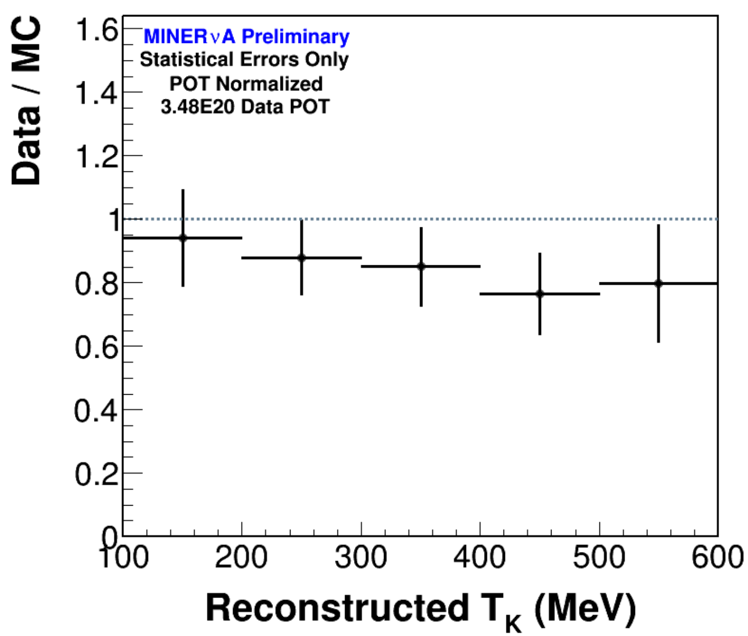
Vertex time sliver example



- π^- from Σ^- decay is tracked
- 68 MeV K^+ is too short to see, but its decay μ^+ is observed near the vertex 15 ns late

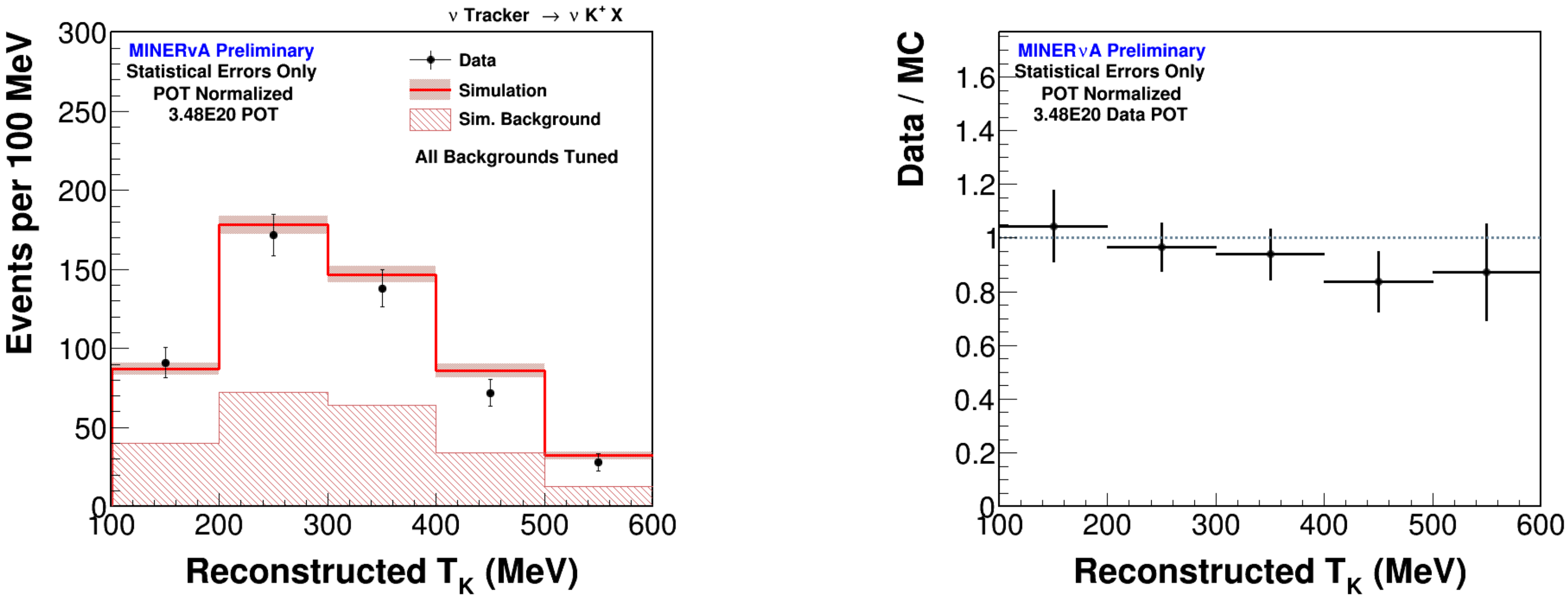
Raw kinetic energy distribution





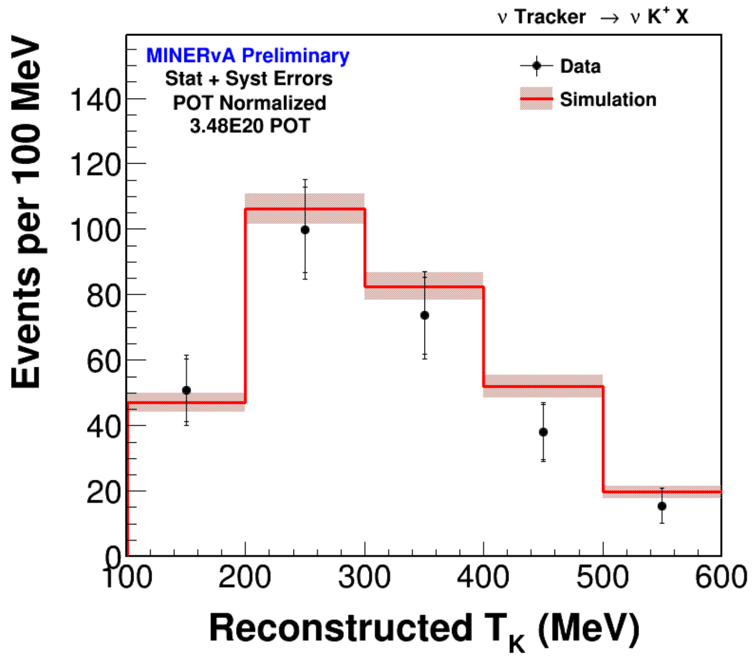
- Raw background prediction

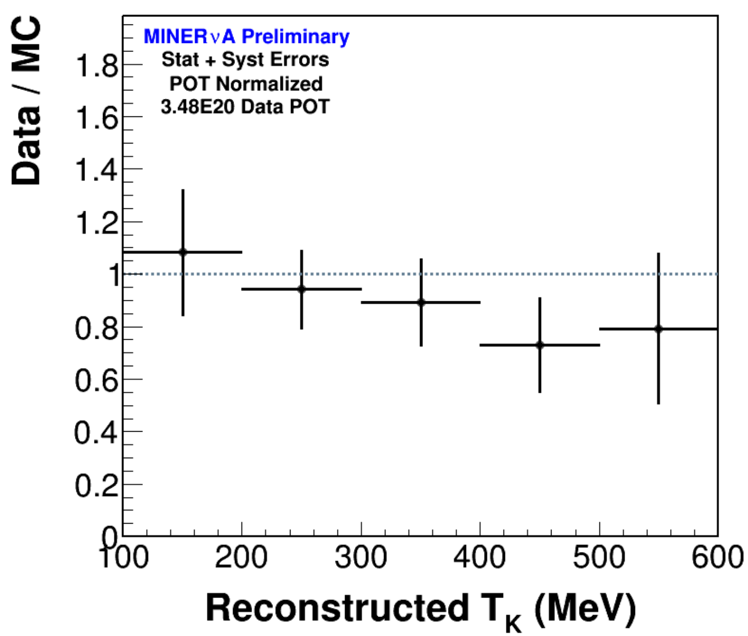
Tuned kinetic energy distribution



- Background prediction scaled by 0.81 based on longest track range sideband fit

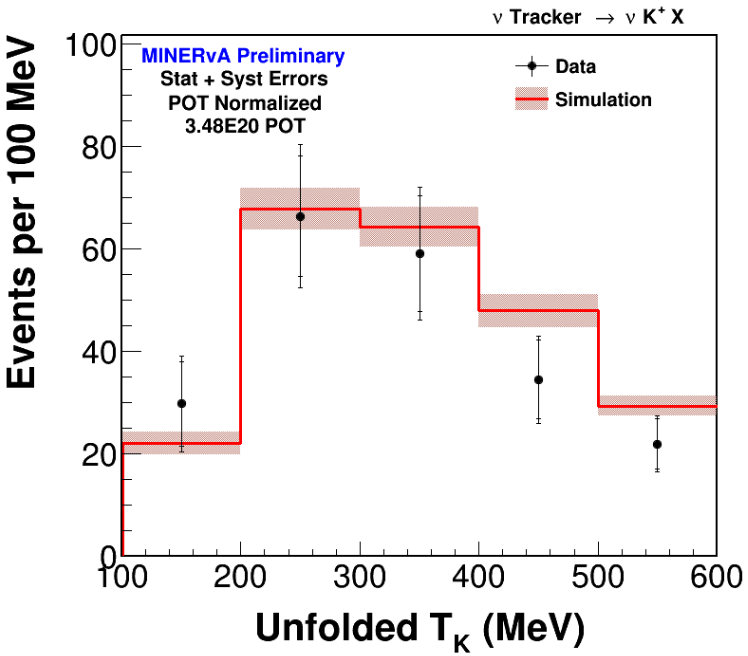
Background subtracted

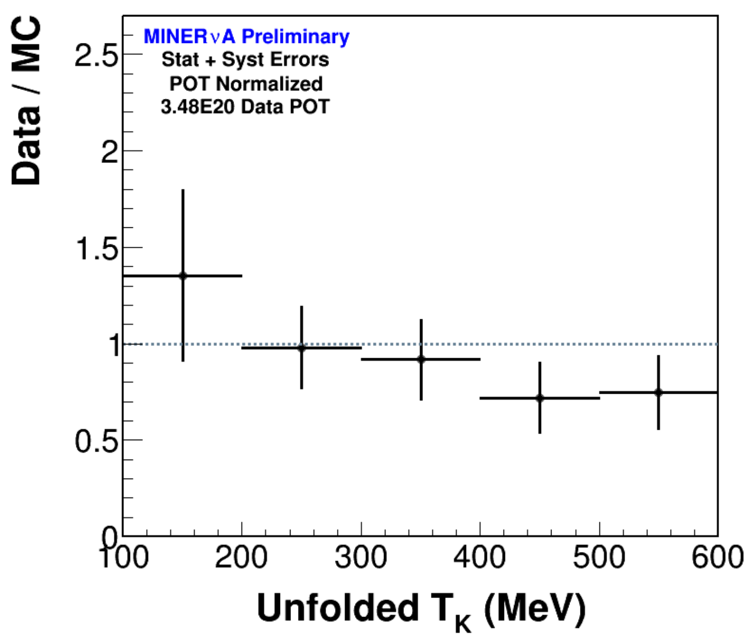




- Tuned background subtracted

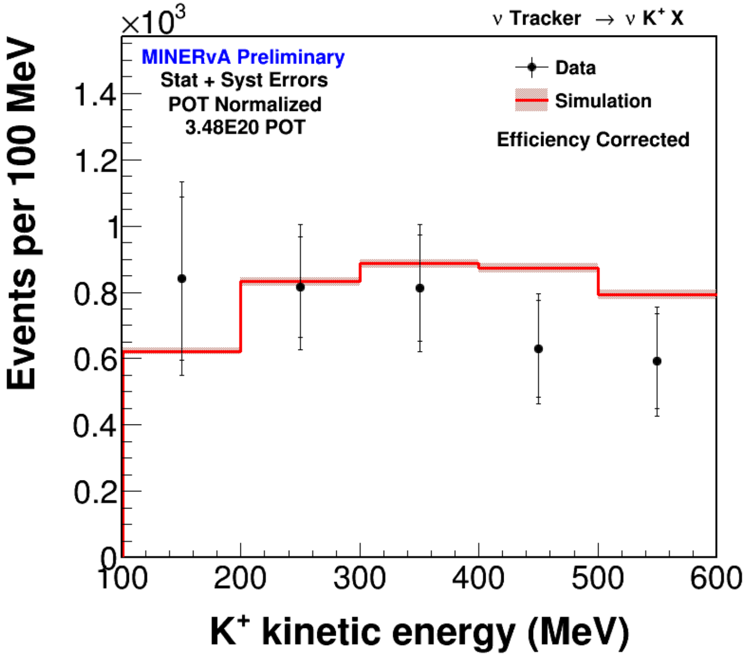
Unfolded distribution

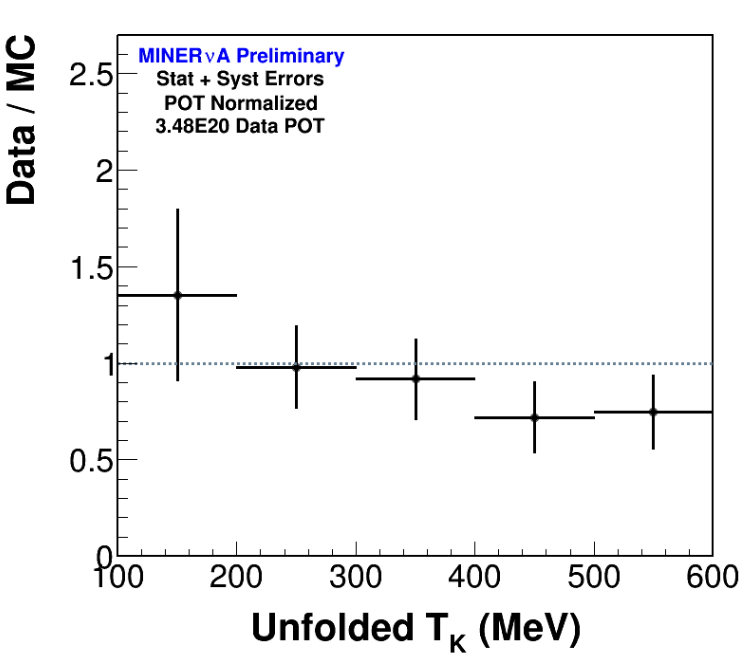




- Reconstructed kinetic energy is unfolded to true kinetic energy

Efficiency corrected

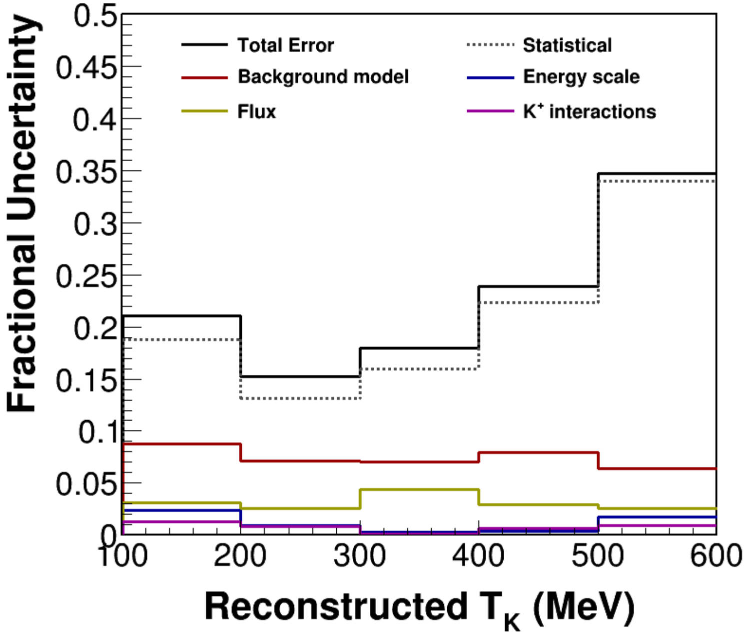




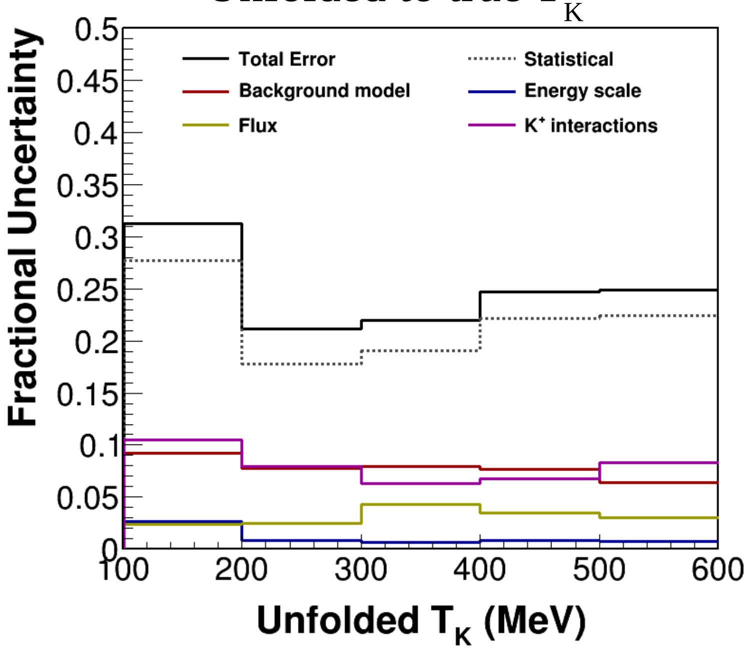
- Divide by efficiency

Uncertainties (1)

Background-subtracted reconstructed T_K

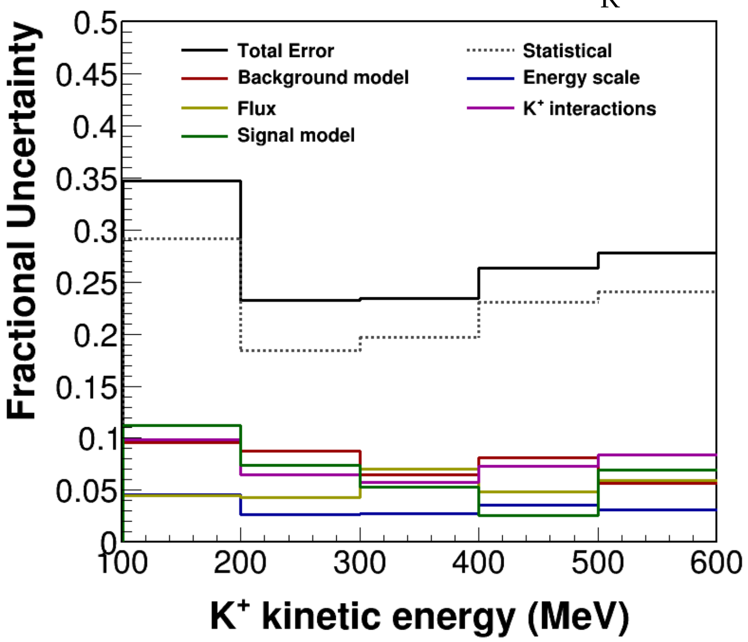


Unfolded to true T_K

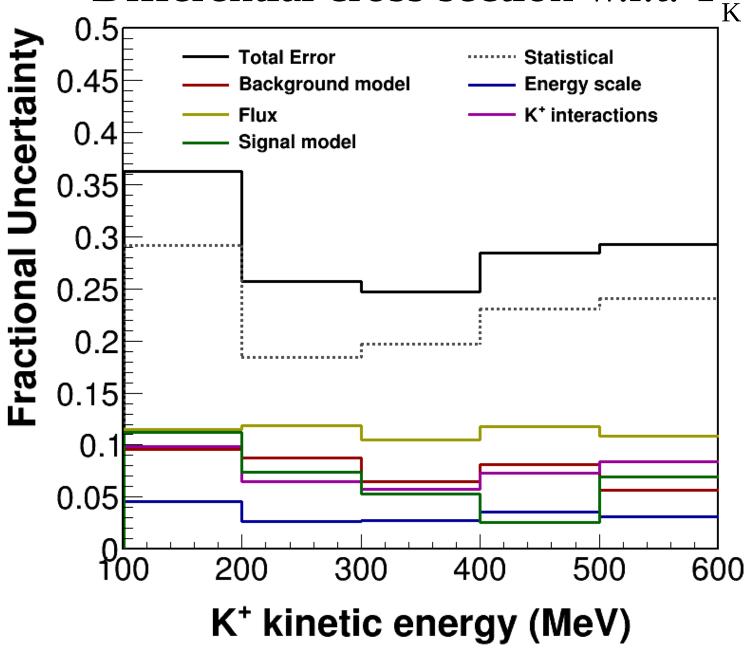


Uncertainties (2)

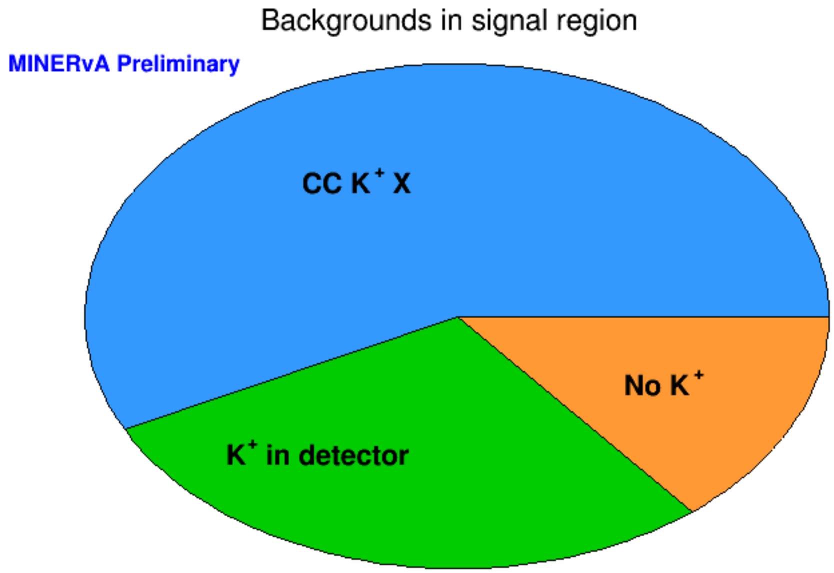
Efficiency-corrected T_K

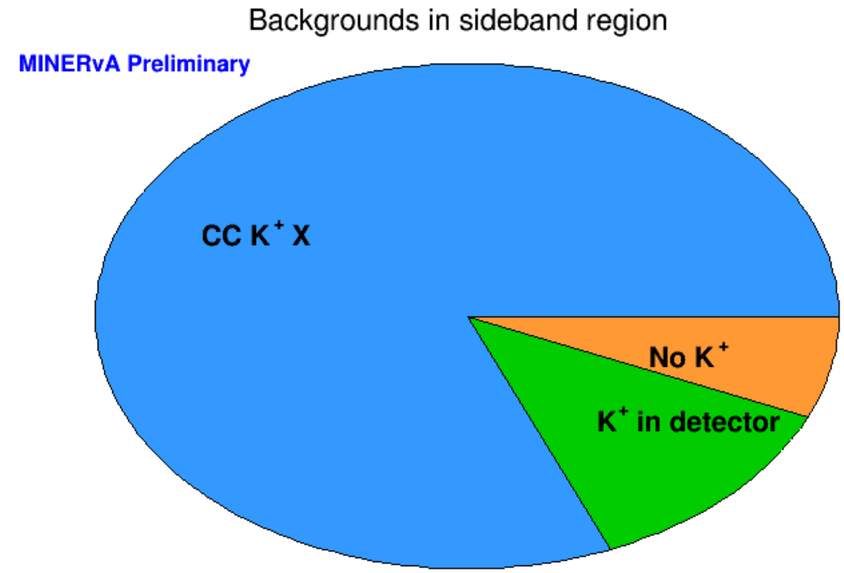


Differential cross section w.r.t. T_K



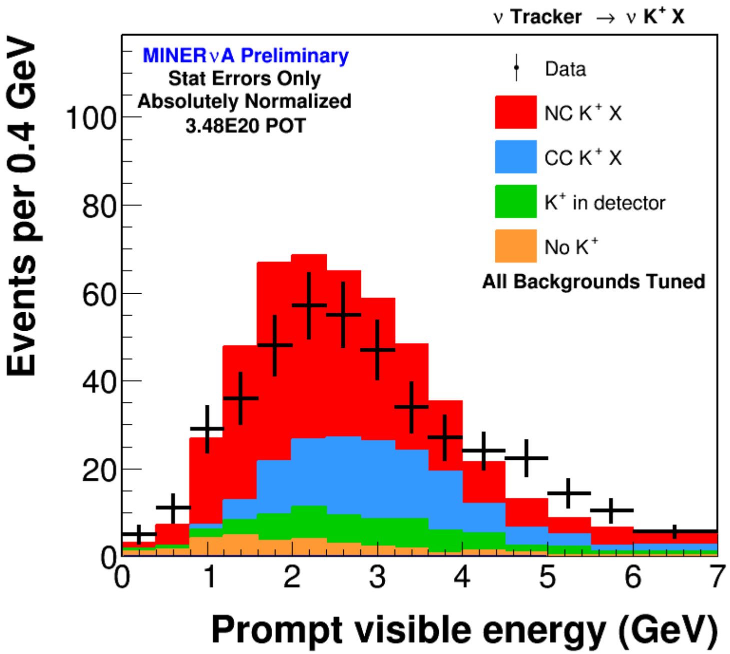
Background composition in signal and sideband regions

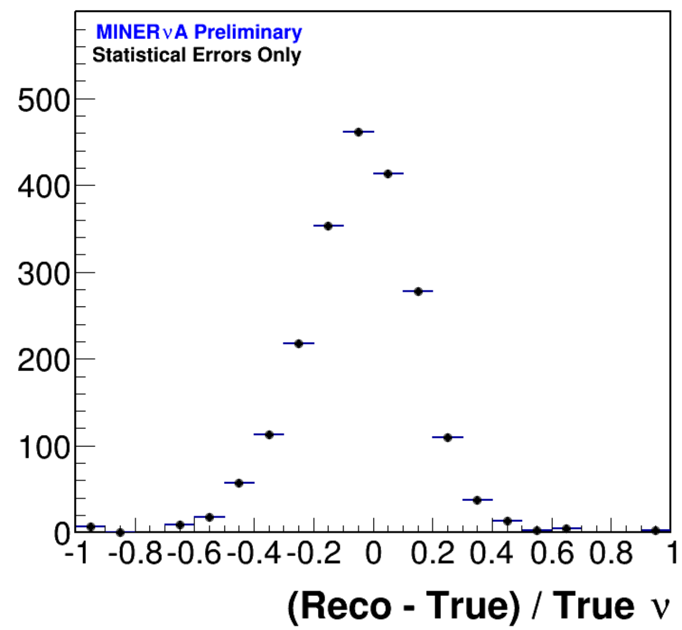




- Green and gold backgrounds in sideband region are ~100% CC; in signal region they are about 70% NC

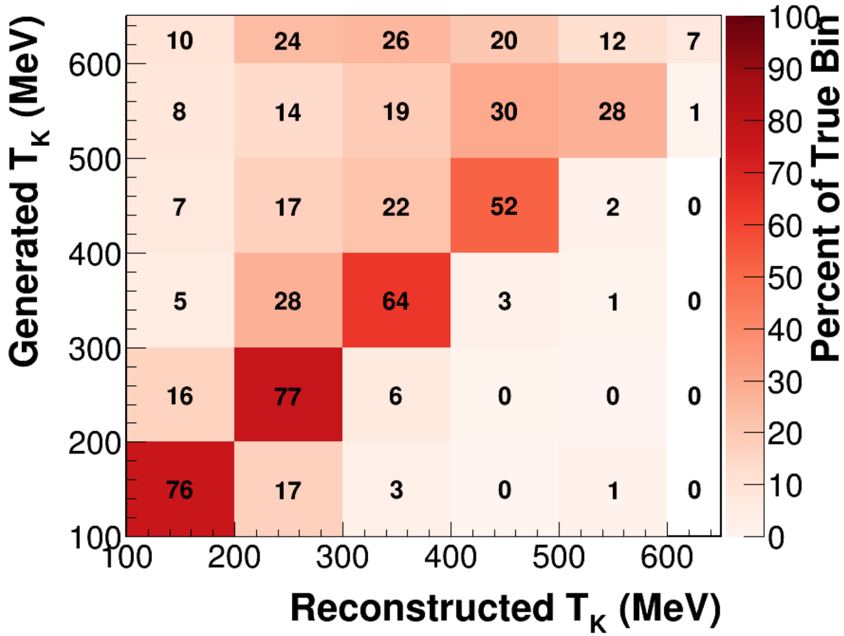
ν resolution

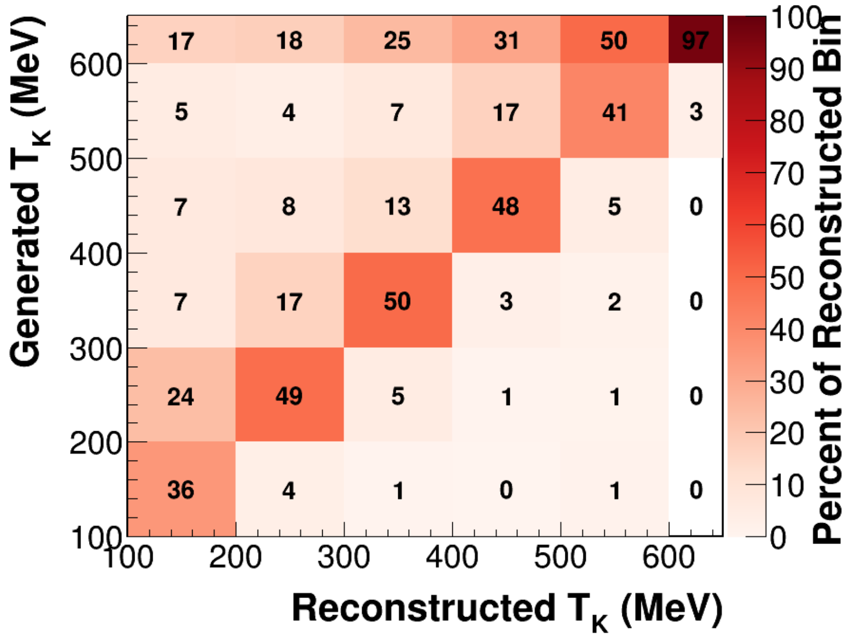




- Work in progress on a better estimator of $\nu - E_K$ for final result

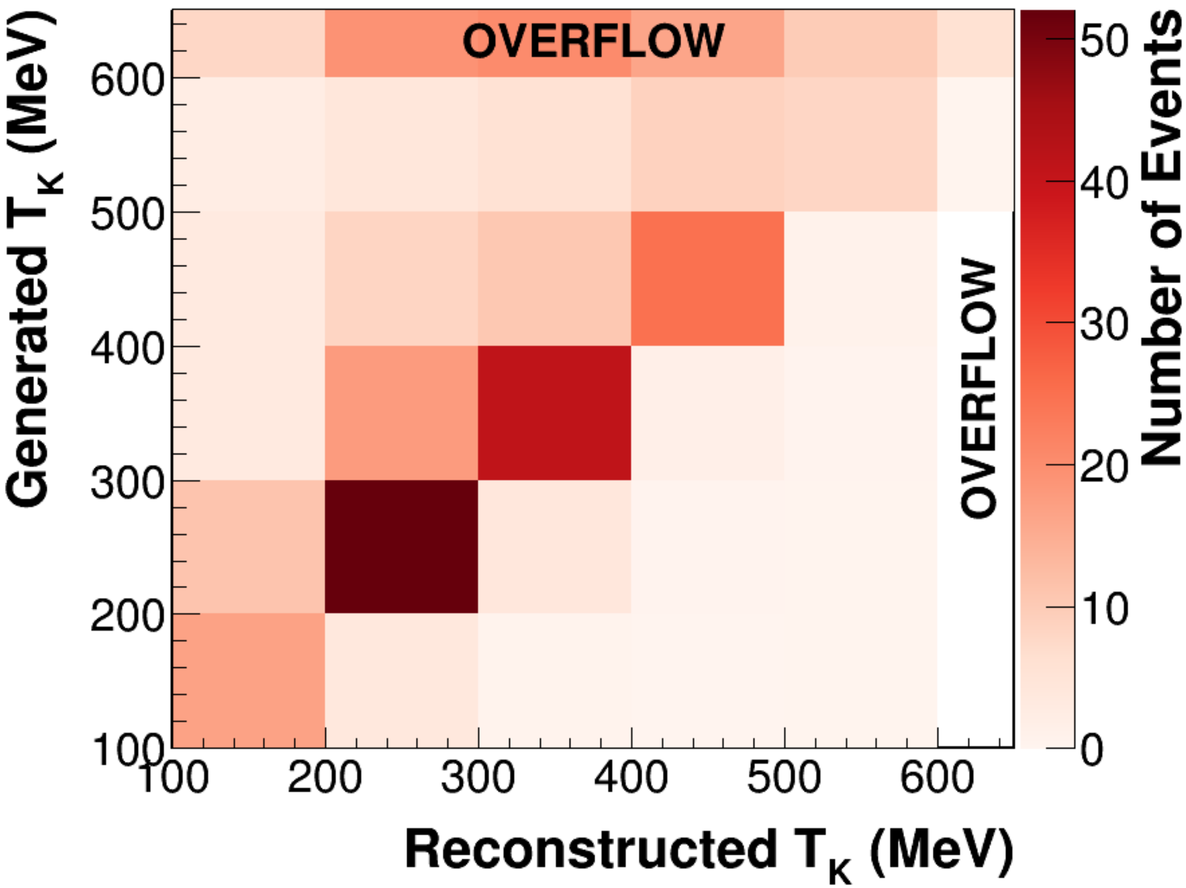
Smearing matrices



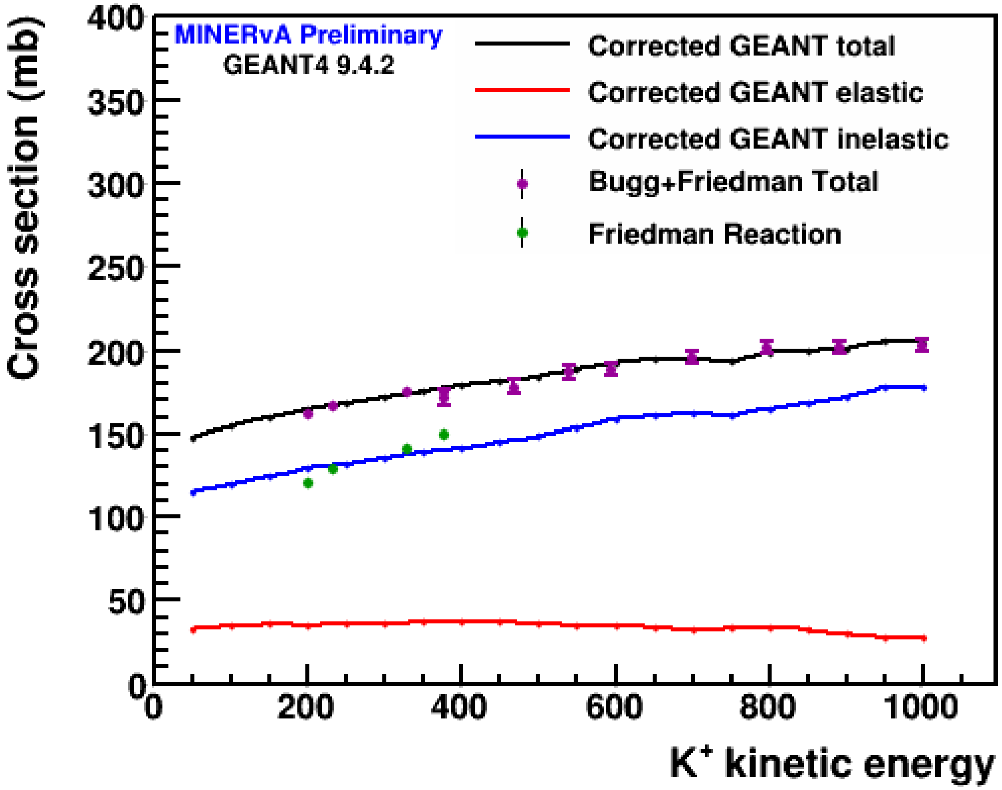


- Row normalized (left)
- Column nomralized (right)

Unnormalized smearing matrix



Correcting GEANT4 XS

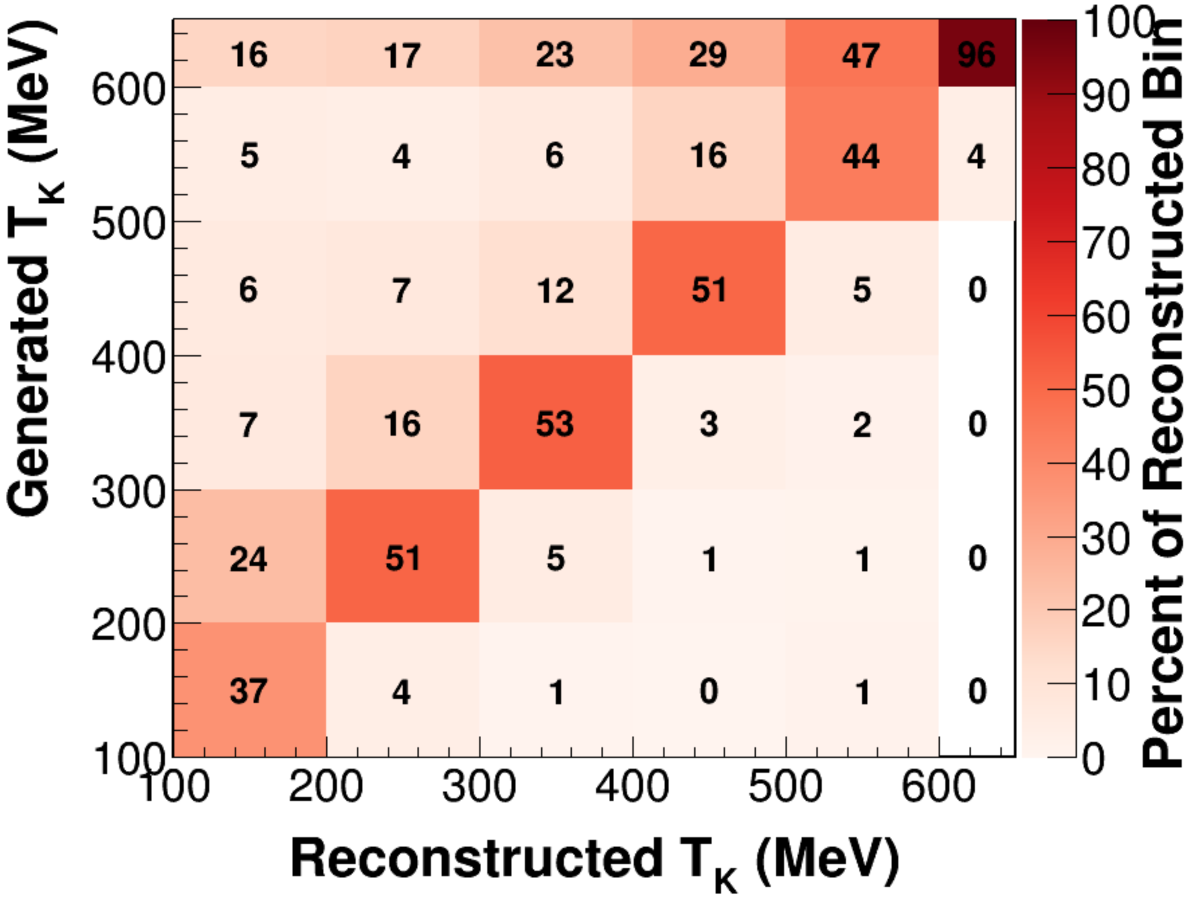


Events are reweighted based on interaction fate to force agreement between GEANT4 simulation and external data

Inelastic XS is increased ~40% relative to out-of-the-box GEANT prediction

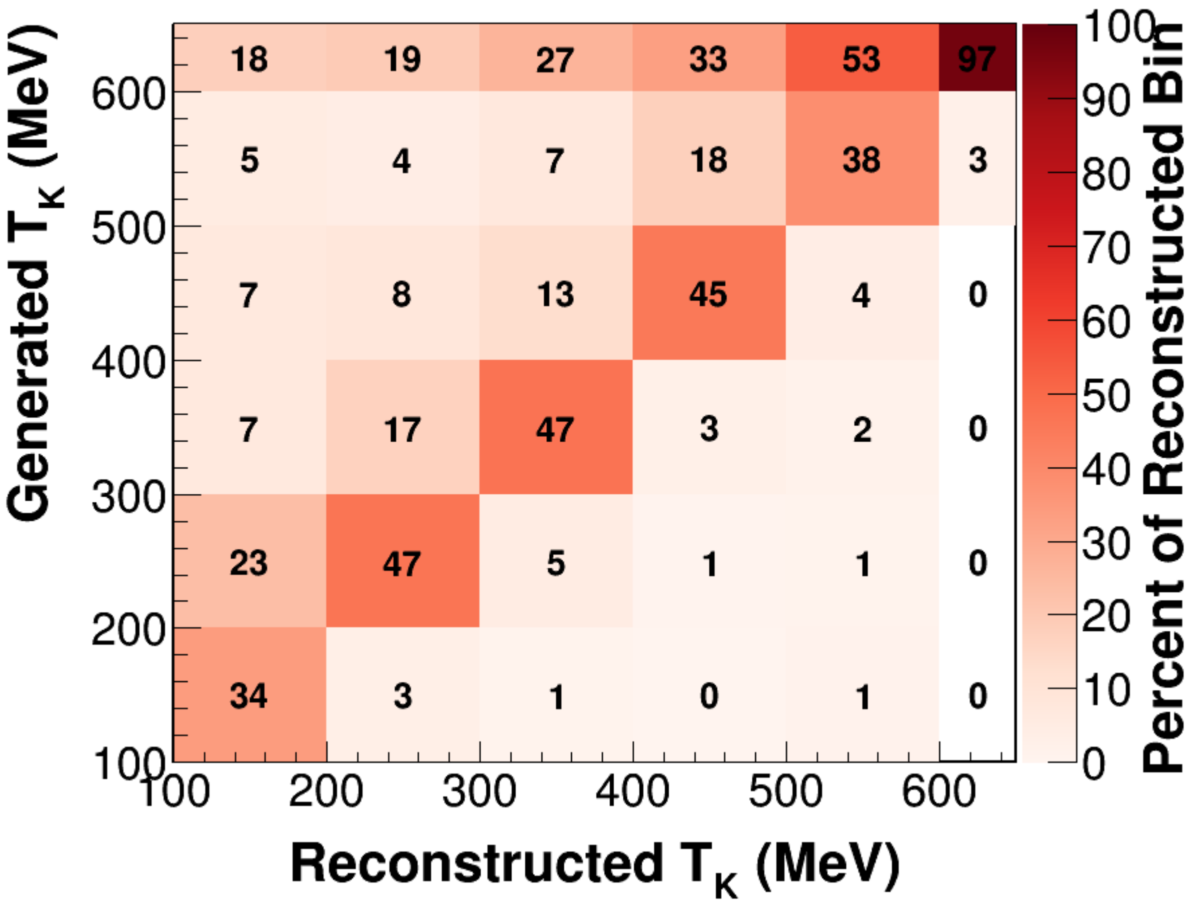
Phys.Rev. 168, 1466-1475 (1968)
Phys. Rev. C 55, 1304 (1997)

Inelastic XS – 10%



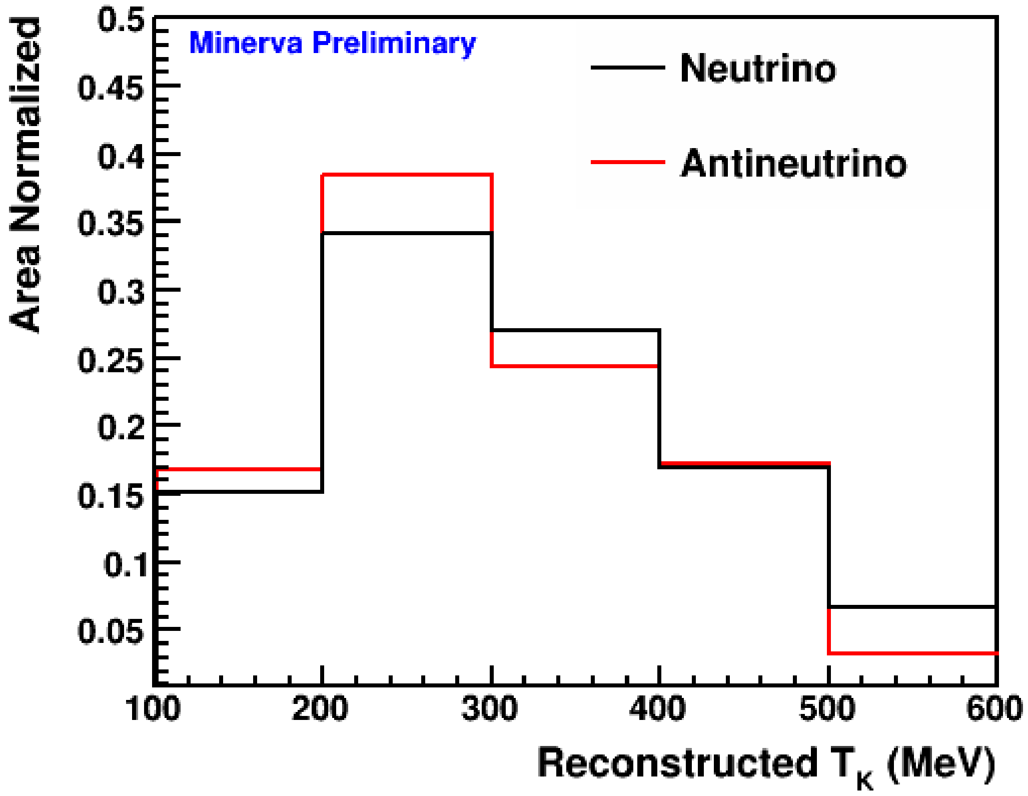
Reduces the amount of migration from high true KE to low reconstructed KE

Inelastic XS + 10%



Reduces the amount of migration from high true KE to low reconstructed KE

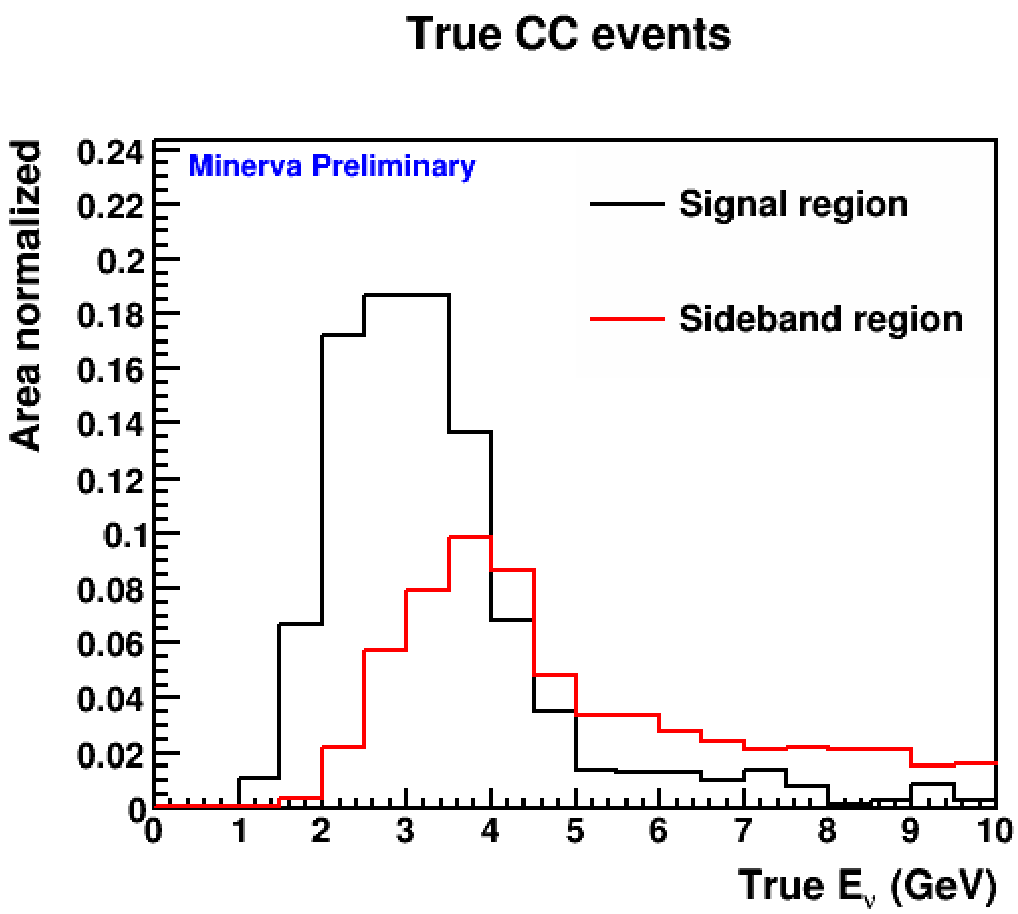
Antineutrino-induced events



89% of the integrated flux and 92% of the accepted events are from neutrinos

The cross section we measure is a combined neutrino-antineutrino result

Signal & sideband flux

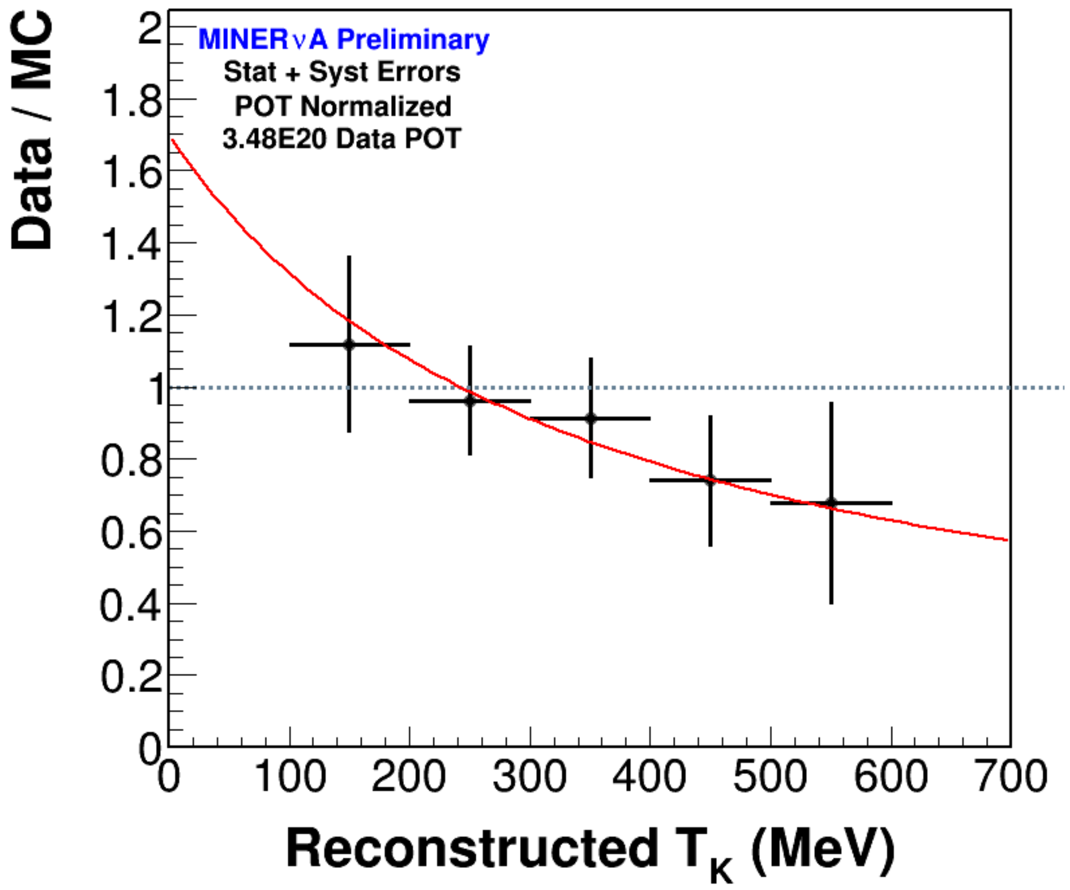


True CC events in signal region have low muon energy

Because of this, CC backgrounds in the signal region are preferentially lower neutrino energy

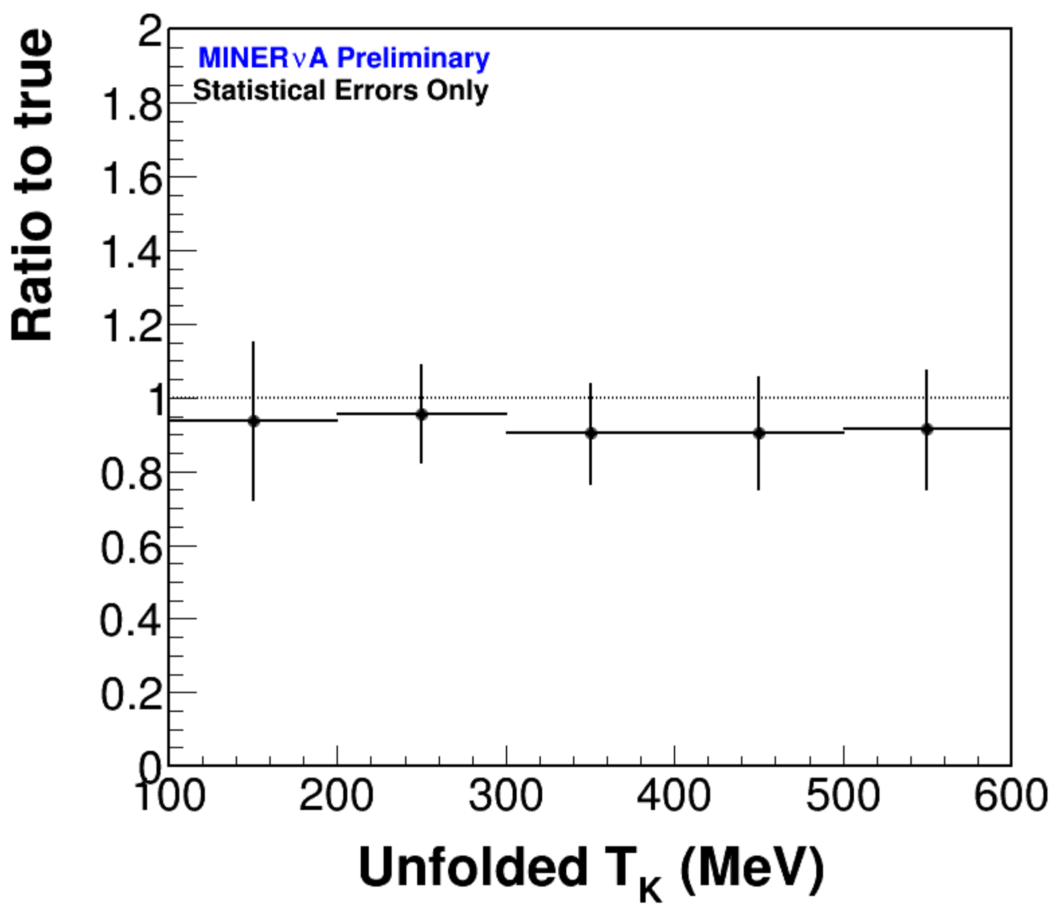
Higher neutrino energy events are from high y

Unfolding bias test



Warp the MC by this function, which represents the data/MC disagreement in reconstructed kinetic energy before unfolding

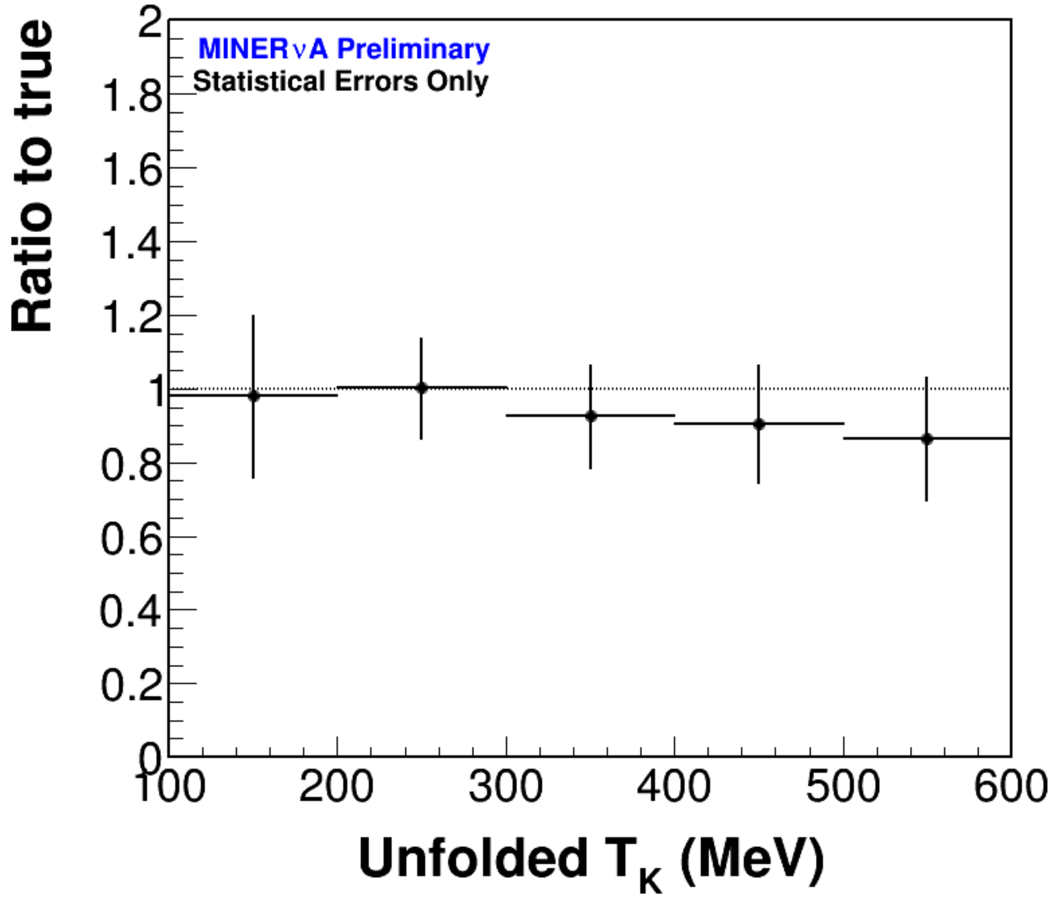
Unfolded warped MC



Unfolded using Bayesian method with three iterations

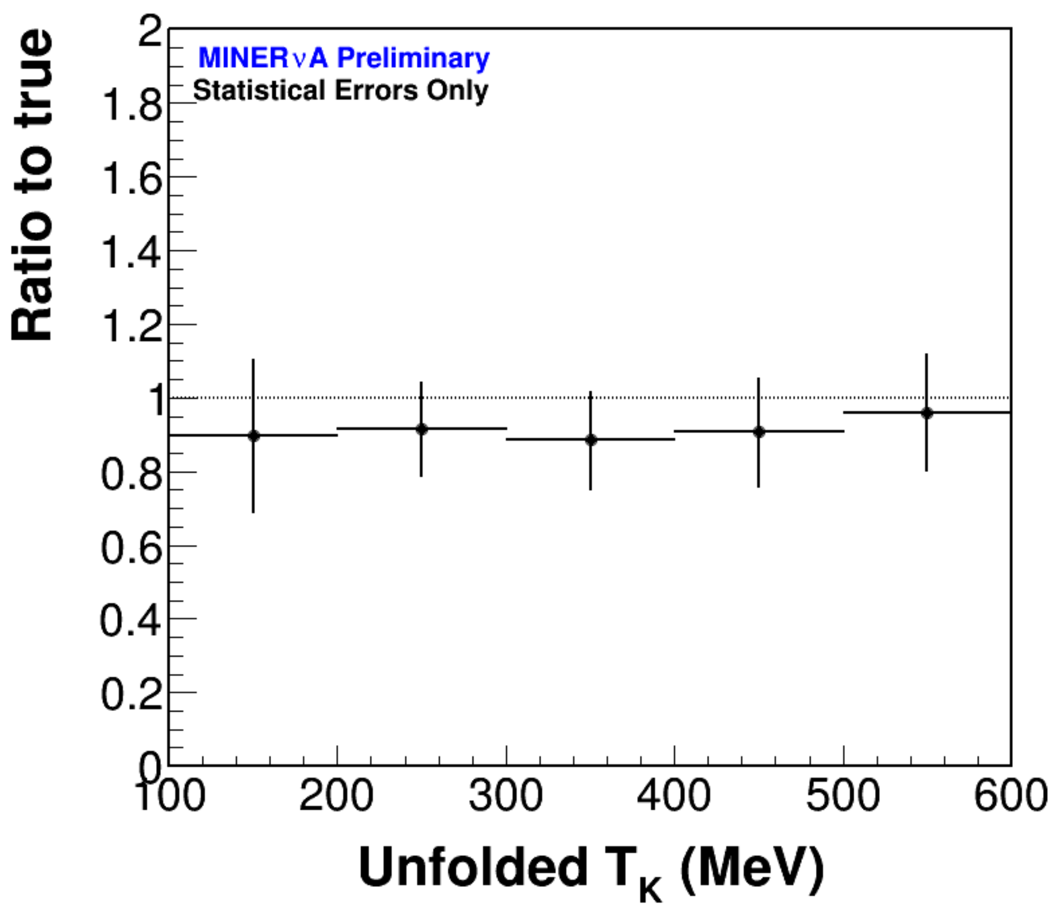
30% of the post-unfolding stat error is added to account for bias, fully correlated in the bins we report

Unfolded with -10% matrix



Not a significant effect

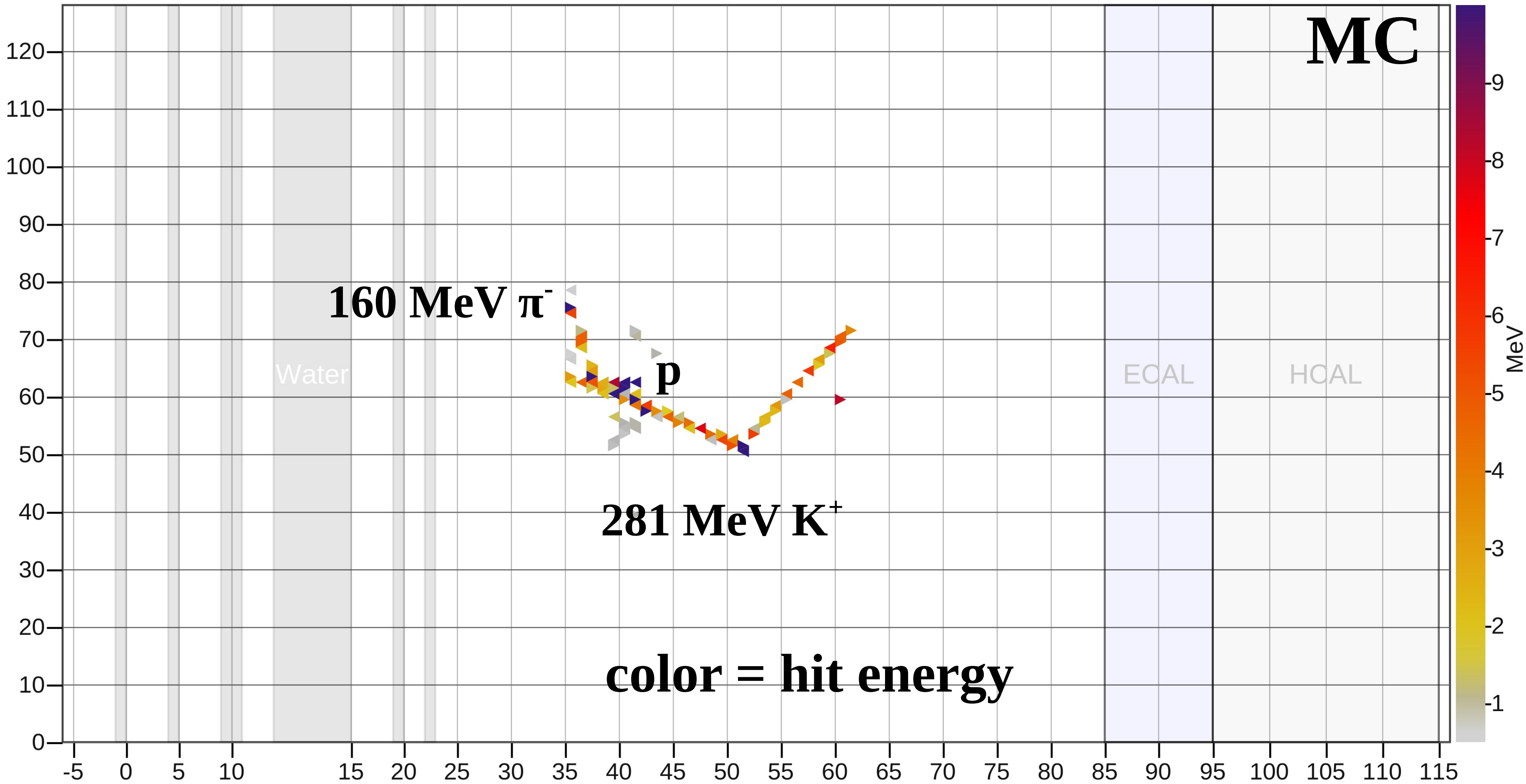
Unfolded with +10% matrix



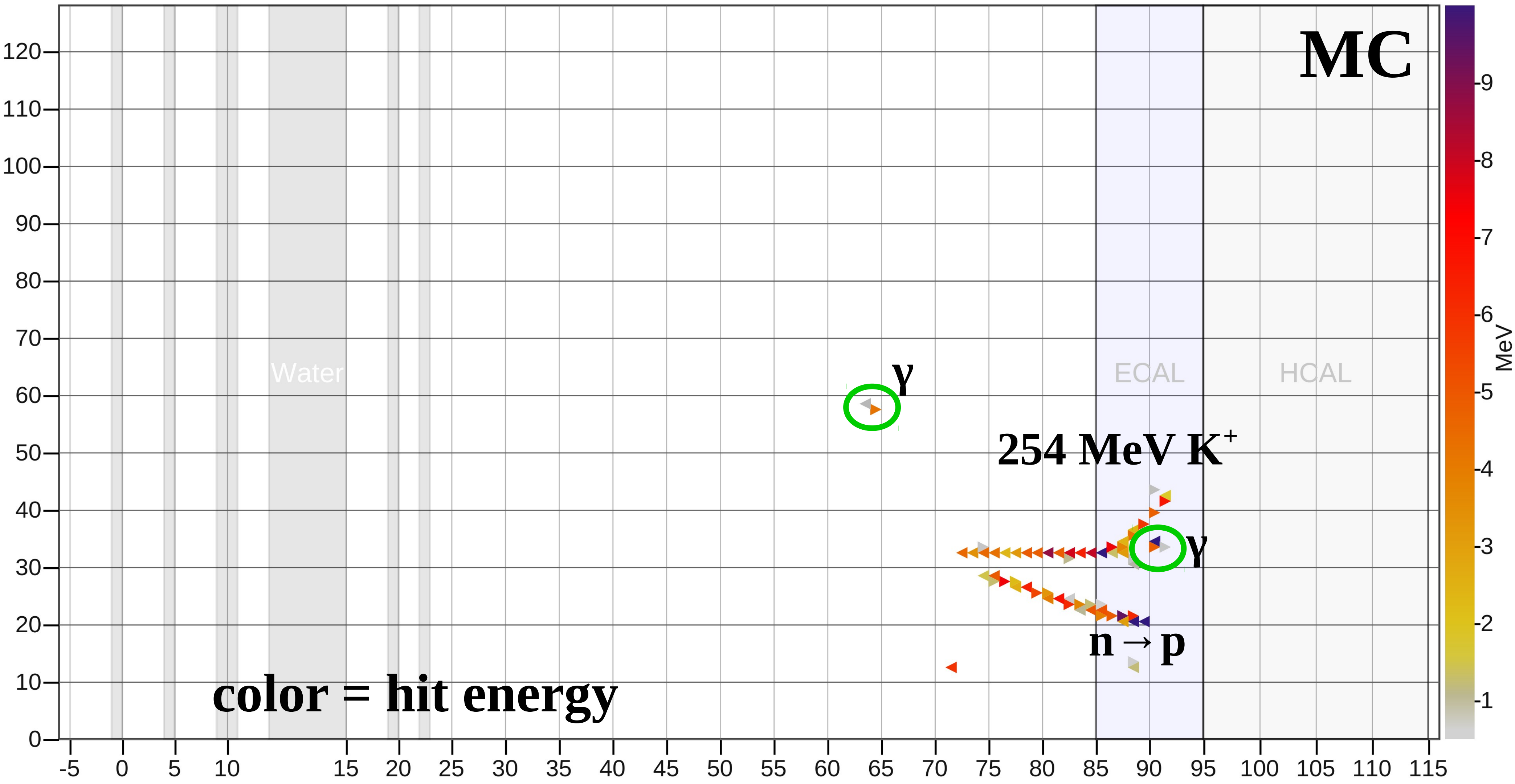
Again, not a significant effect

The unfolding bias is not dependent on the inelastic cross section in the MC

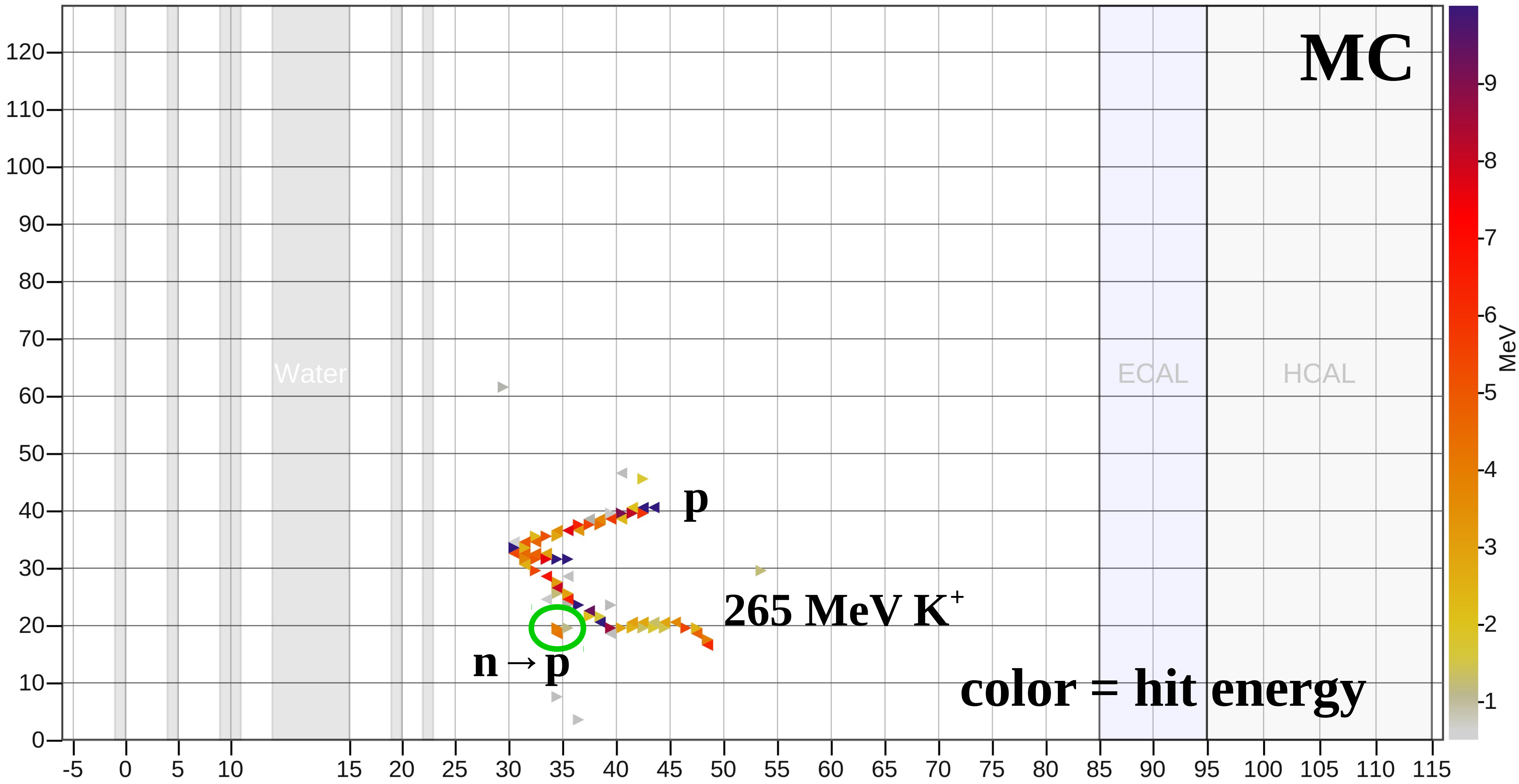
Interacting pions and protons



n/π^0 separation I



n/π^0 separation II



π^0 produced in detector