K^+ production by neutrinos at MINERvA

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University of Rochester
Fermilab Wine and Cheese
5 February, 2016

The big picture

- Motivation for studying K^+ production by neutrinos
- Identifying K^+ in MINERvA
- Differential cross section measurements:
  - Charged-current K^+ production
  - Neutral-current K^+ production
- Search for charged-current coherent K^+ production

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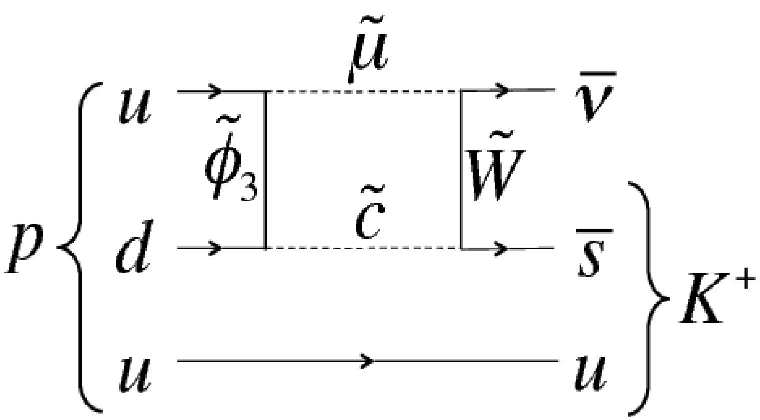
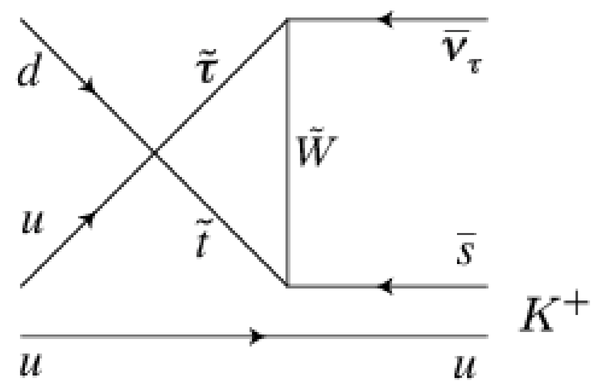
Why study K^+ production?

- K^+ production by atmospheric neutrinos, especially by the neutral current, is a background in searches for the proton decay $p \rightarrow K^+\nu$



Abe, K. et al. arXiv:1109.3262



Hewett, J.L. et al. arXiv:1401.6077 [hep-ex]
FERMILAB-CONF-14-019-CH02

Why study K^+ production?

- K^+ production by atmospheric neutrinos, especially by the neutral current, is a background in searches for the proton decay $p \to K^+\nu$
- K^+ production complements measurements of π^+ production as a probe of hadron interactions inside the nucleus

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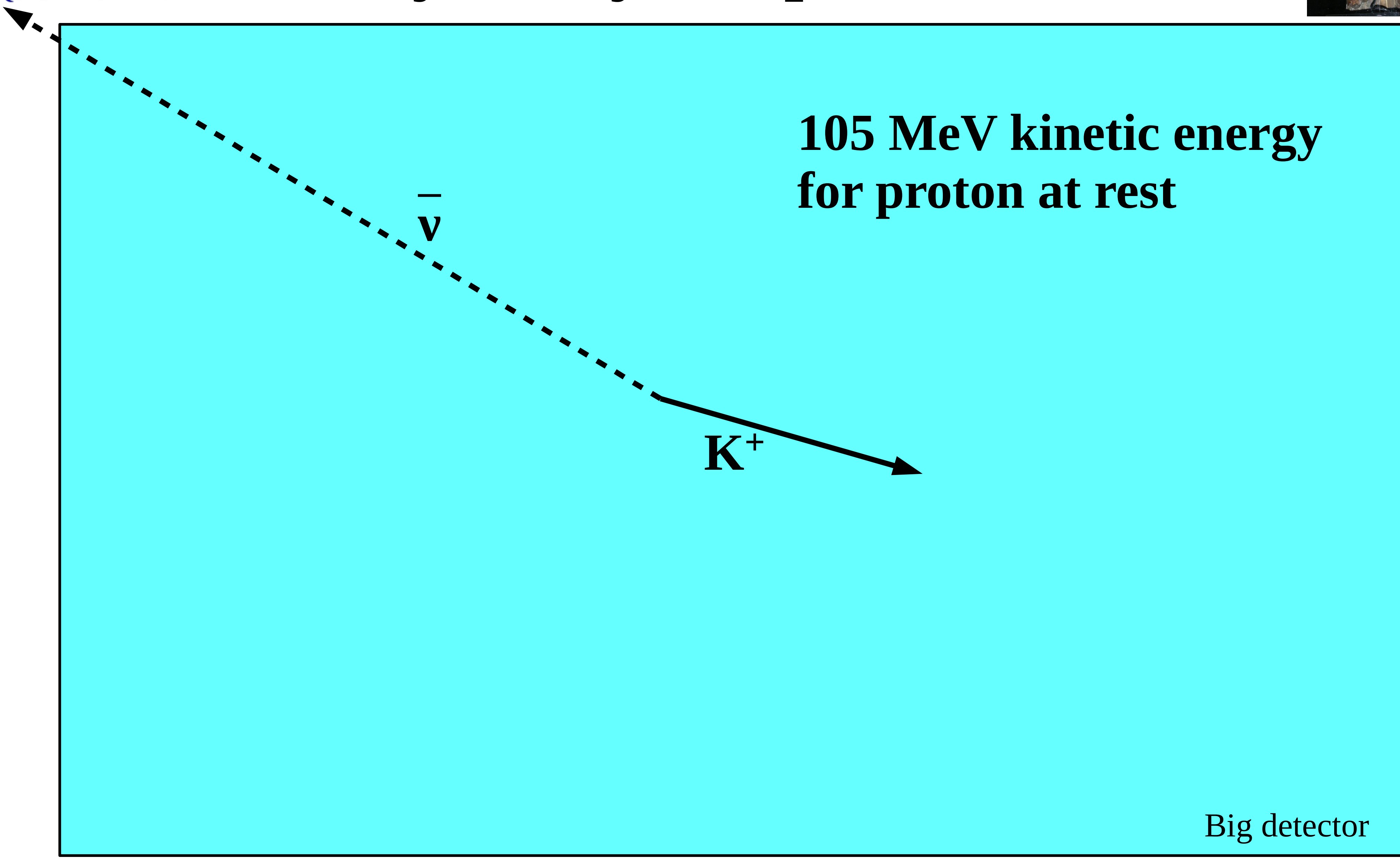

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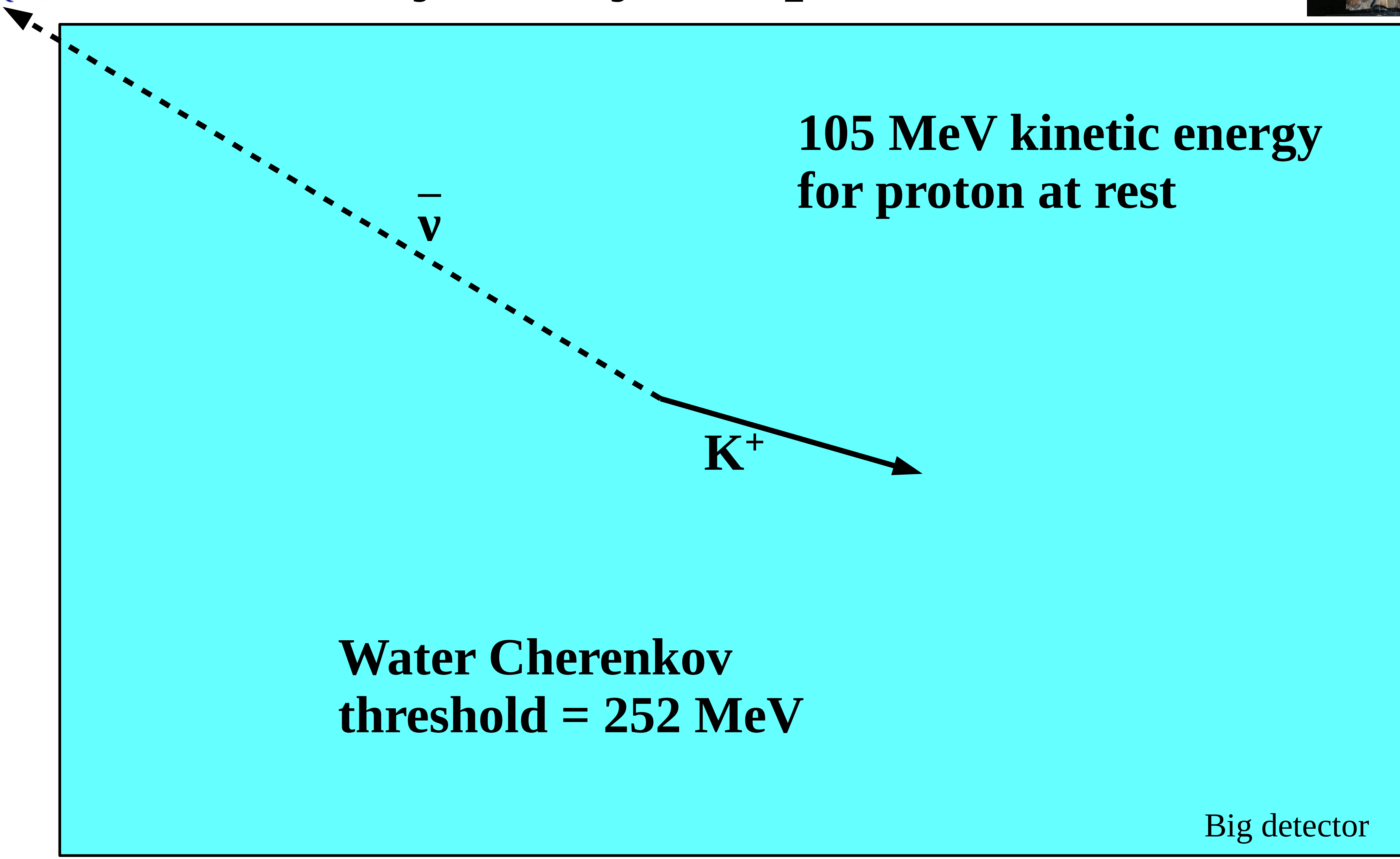

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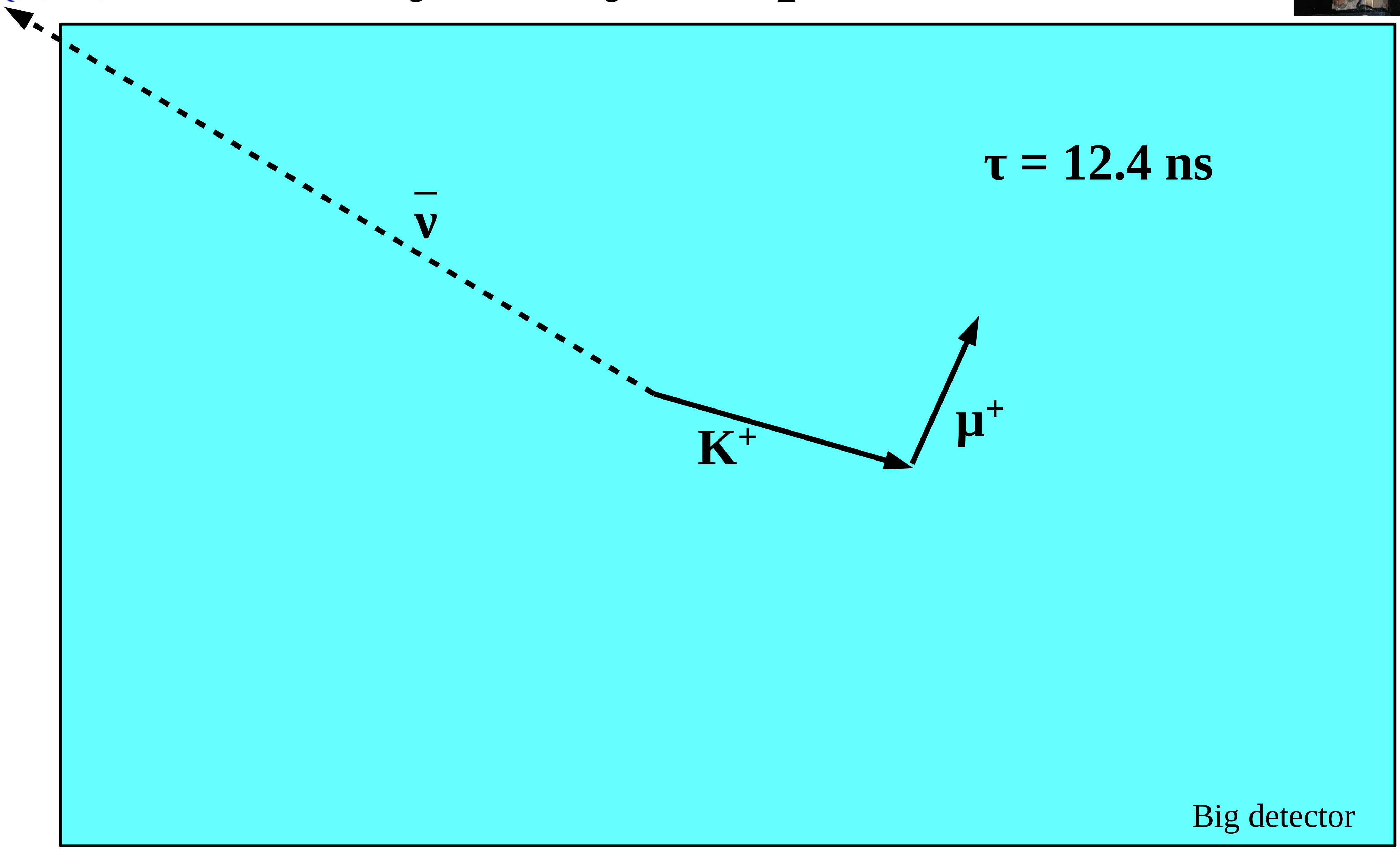

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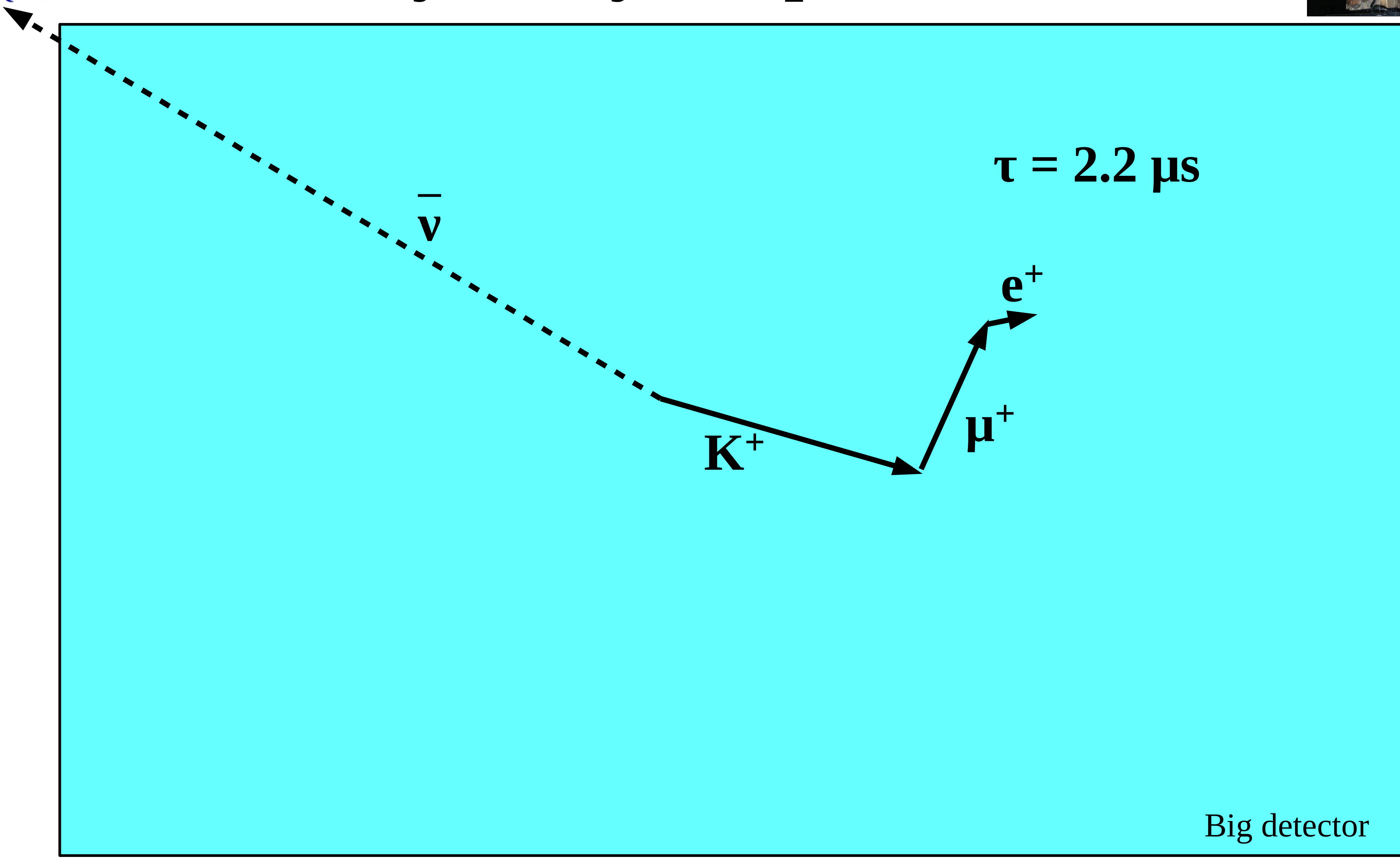

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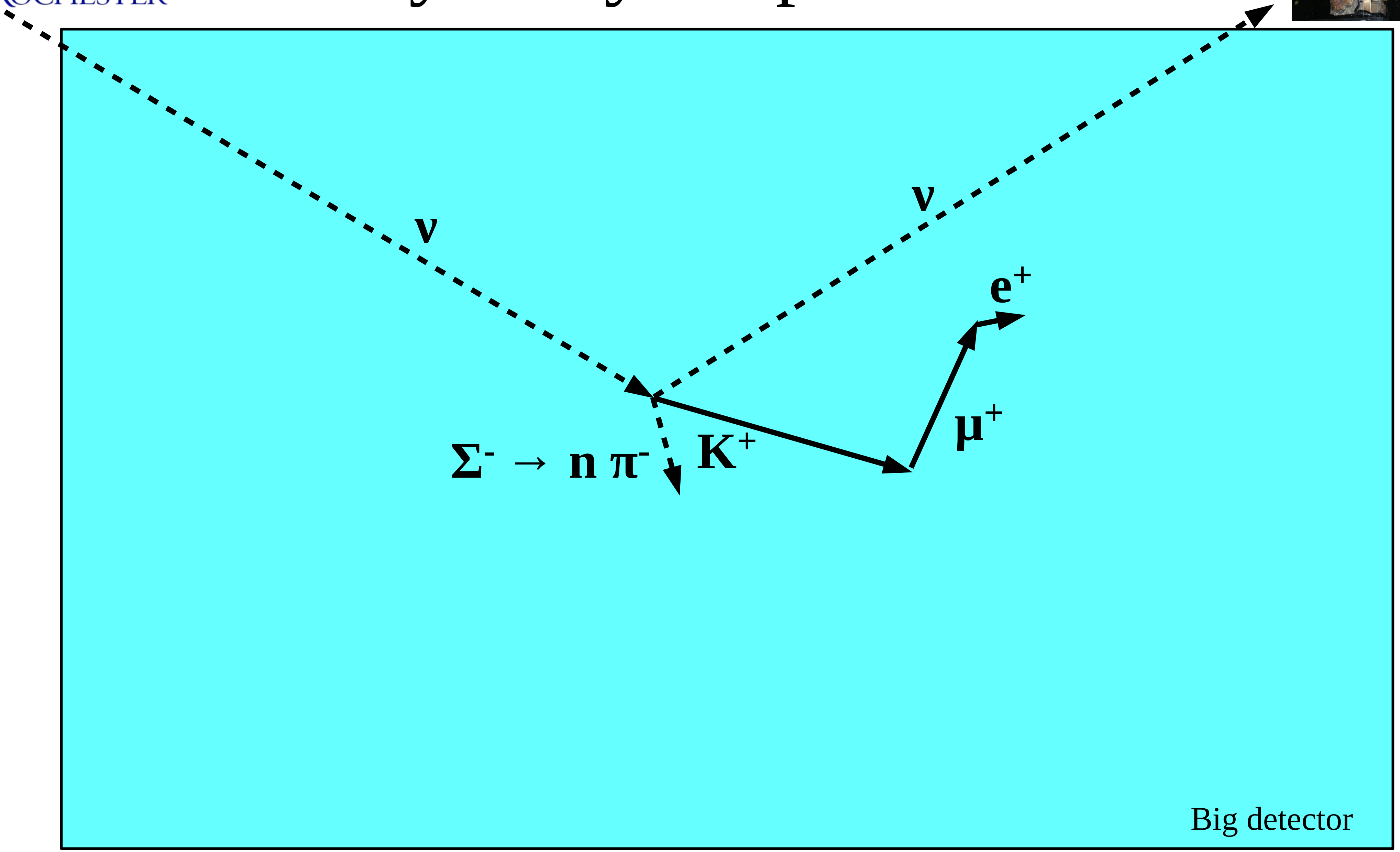
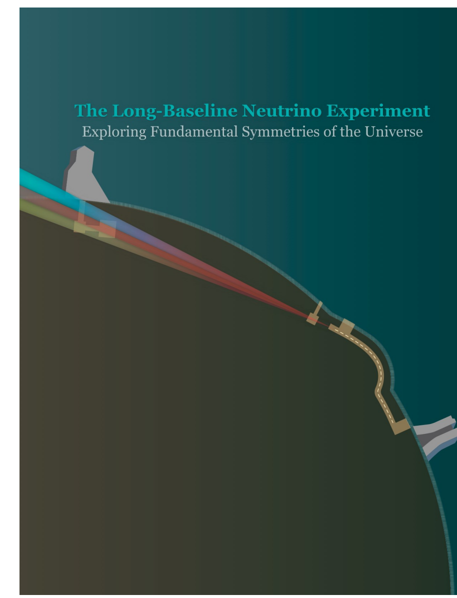


DUNE background prediction

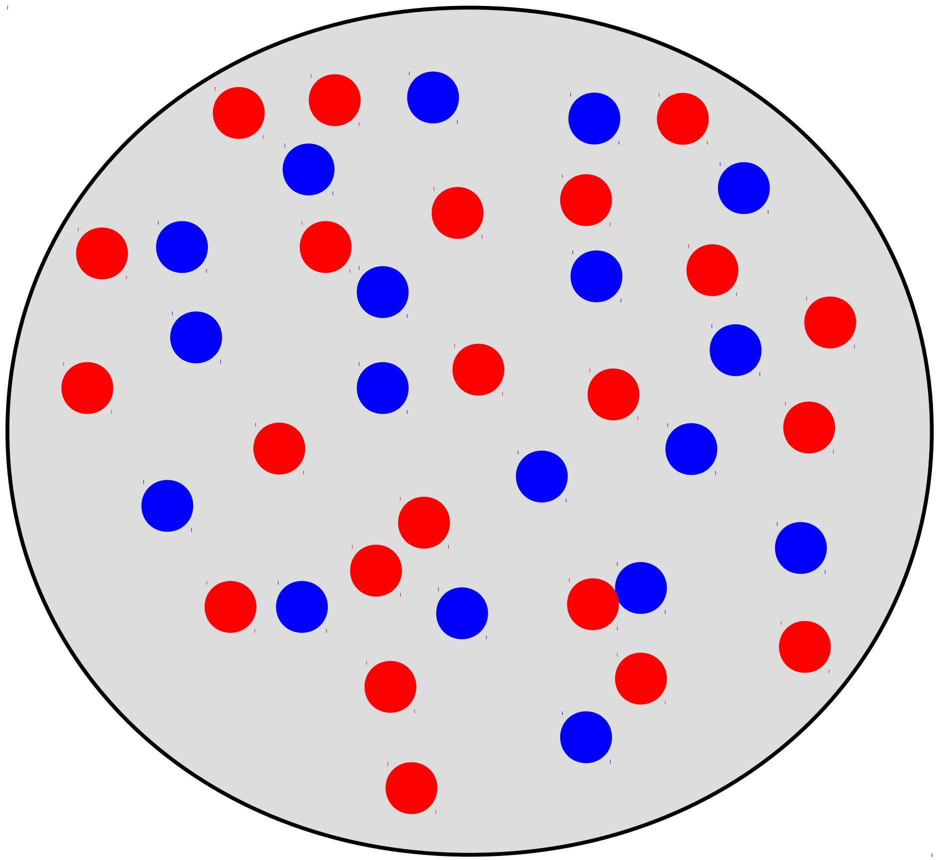
1 event per Mton-year JHEP **0704** 041 (2007)

“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?”



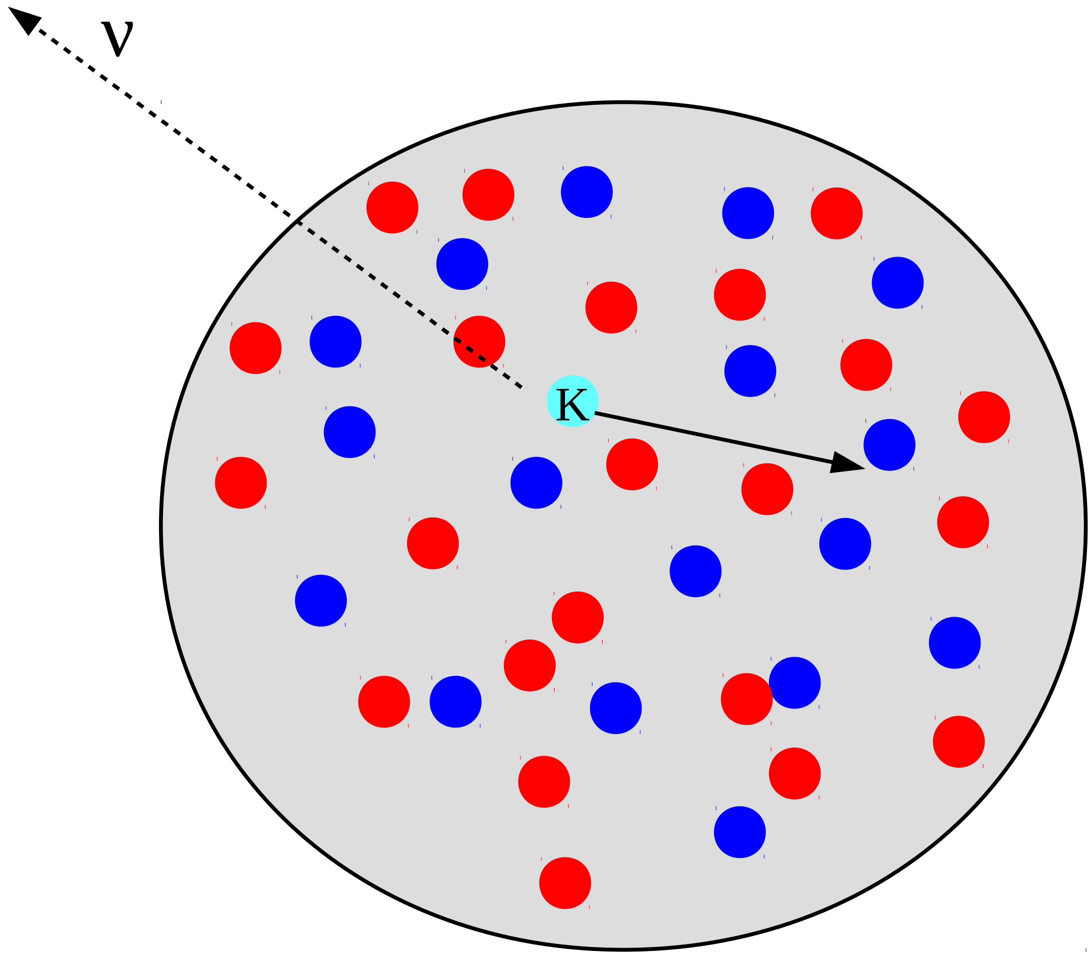
Zoom in on the nucleus

A proton is about to decay!



Argon nucleus
not to scale

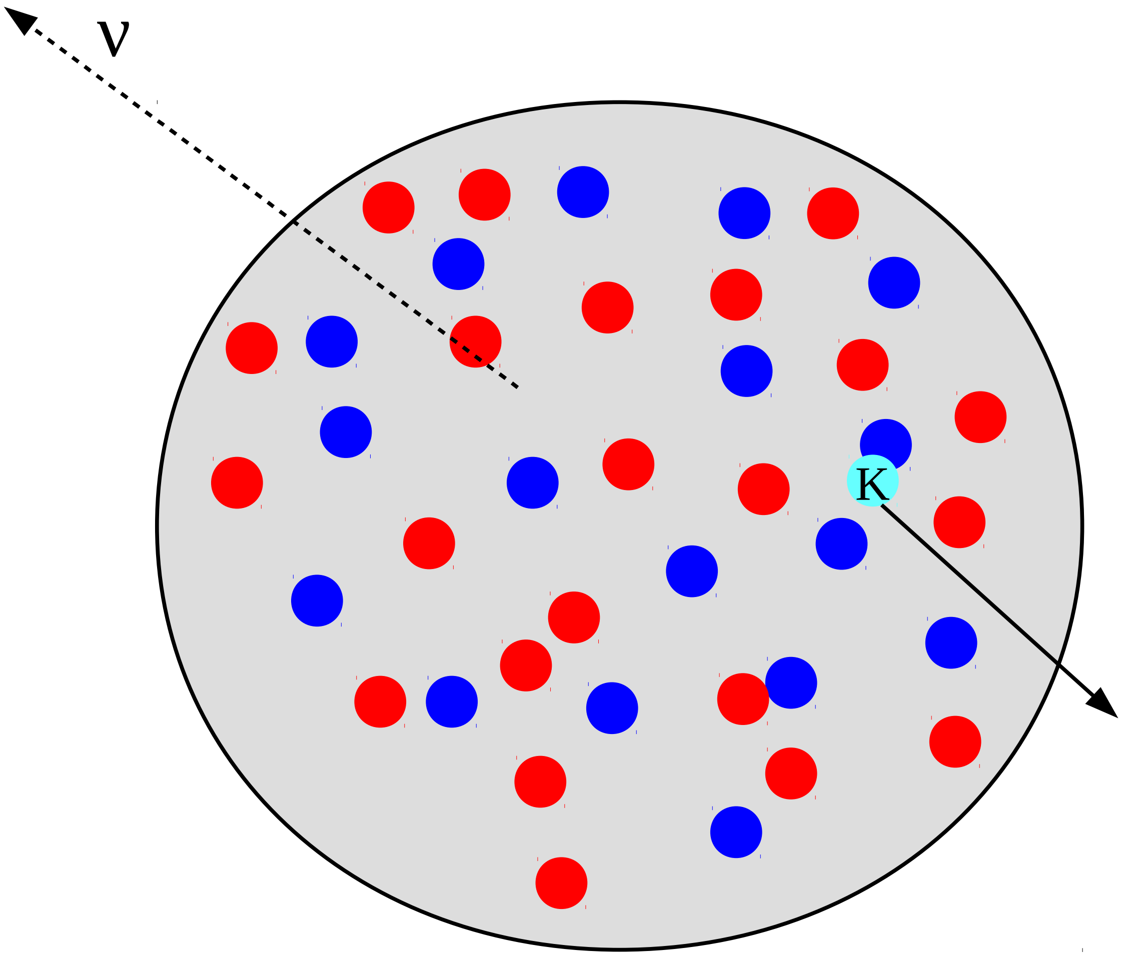
Zoom in on the nucleus



The kaon must get out of the nucleus, and may undergo final-state interactions (FSI)

Argon nucleus
not to scale

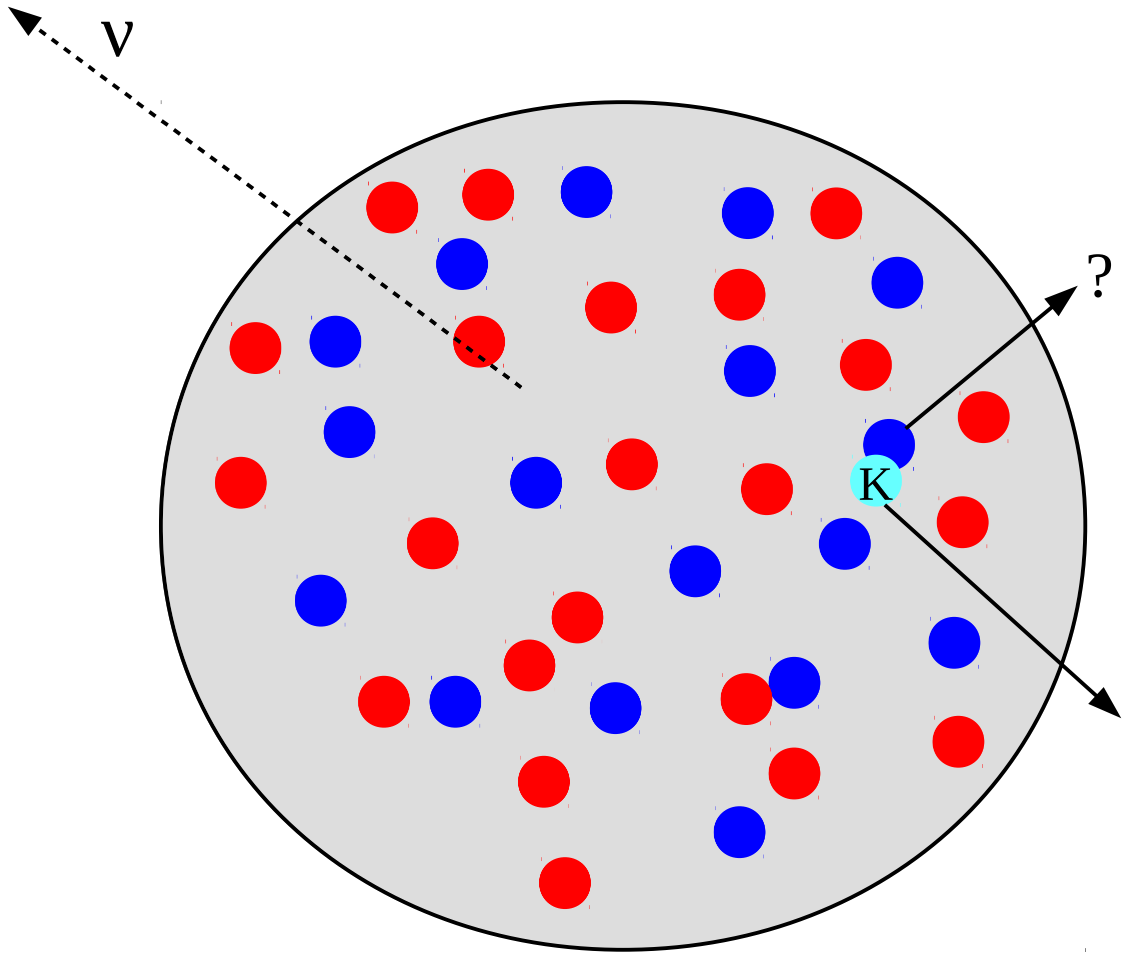
Zoom in on the nucleus



Momentum spectrum is smeared by FSI

Argon nucleus
not to scale

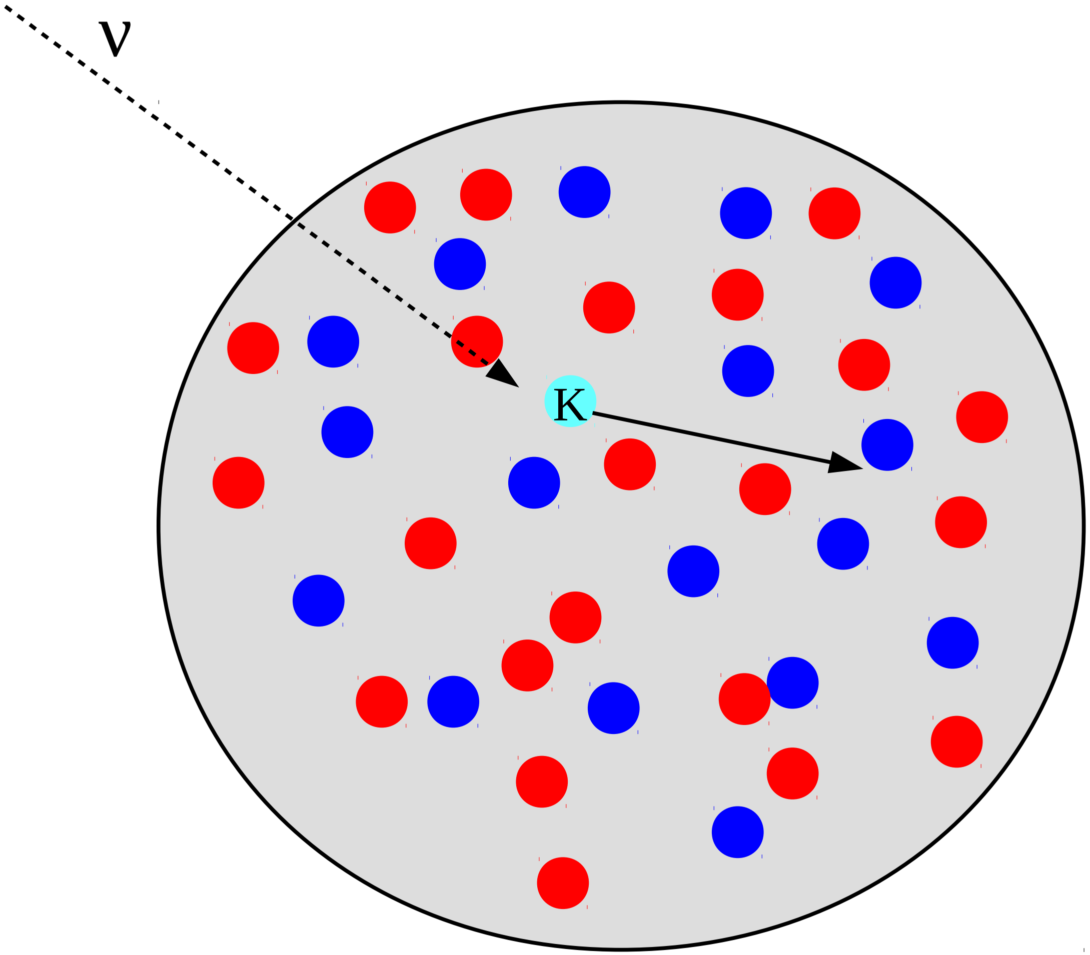
Zoom in on the nucleus



And other nucleons could be knocked out

Argon nucleus
not to scale

We can study this with neutrinos

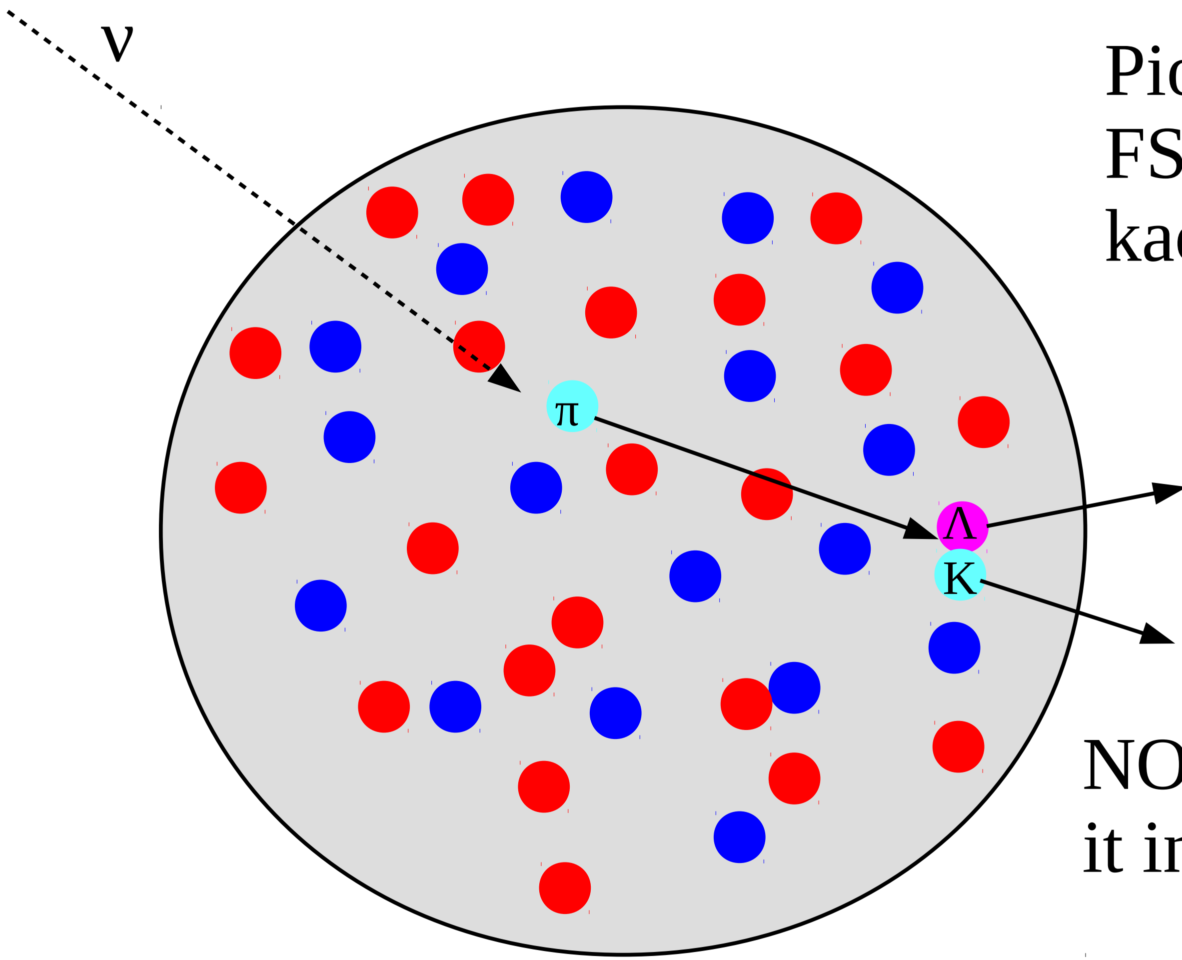


FSI affects kaons produced in neutrino reactions

Does our nuclear model (kaon spectrum) agree with the data?

Argon nucleus
not to scale

Kaon production via FSI



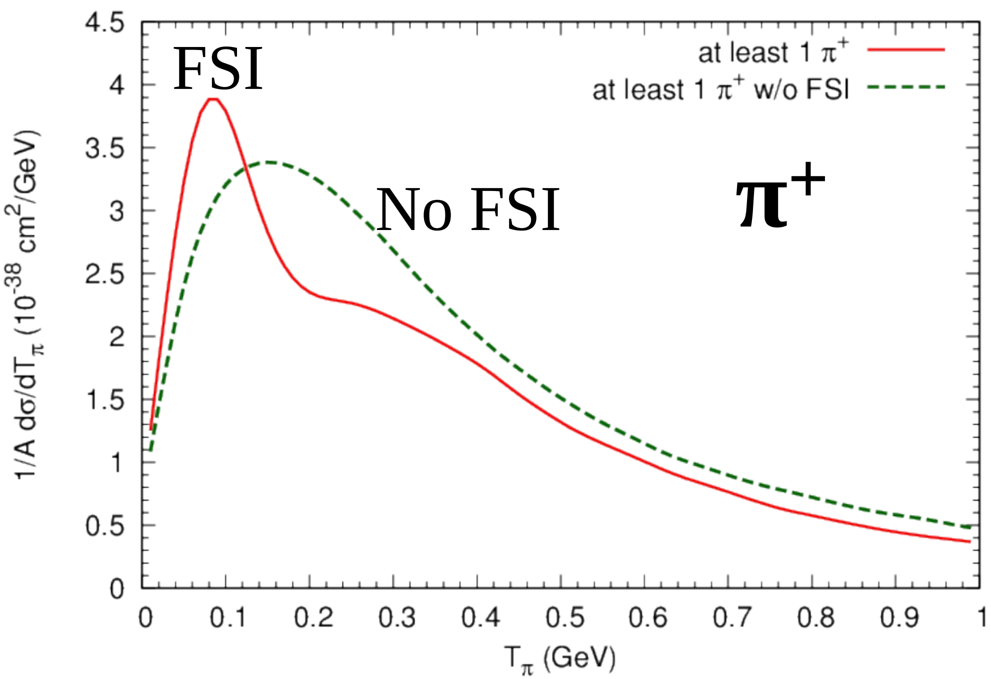
Pion production + FSI can produce kaons

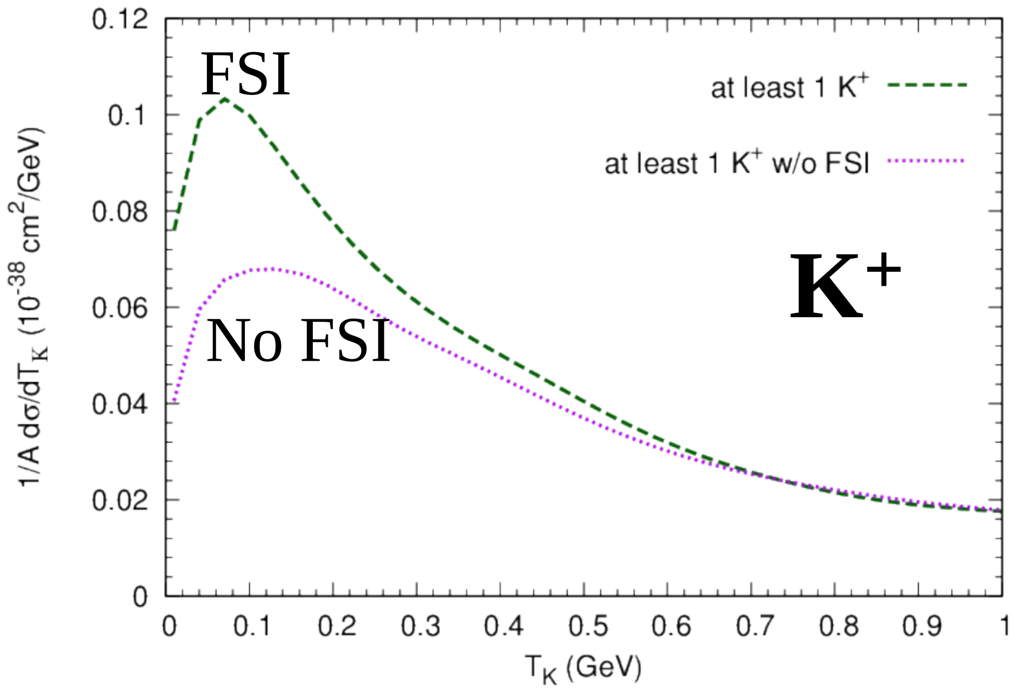
NOT in GENIE...is it in the data?

Argon nucleus
not to scale

Pion and kaon production as probes of FSI

ν_μ CC GiBUU event generator predictions, MINERvA LE flux, carbon target

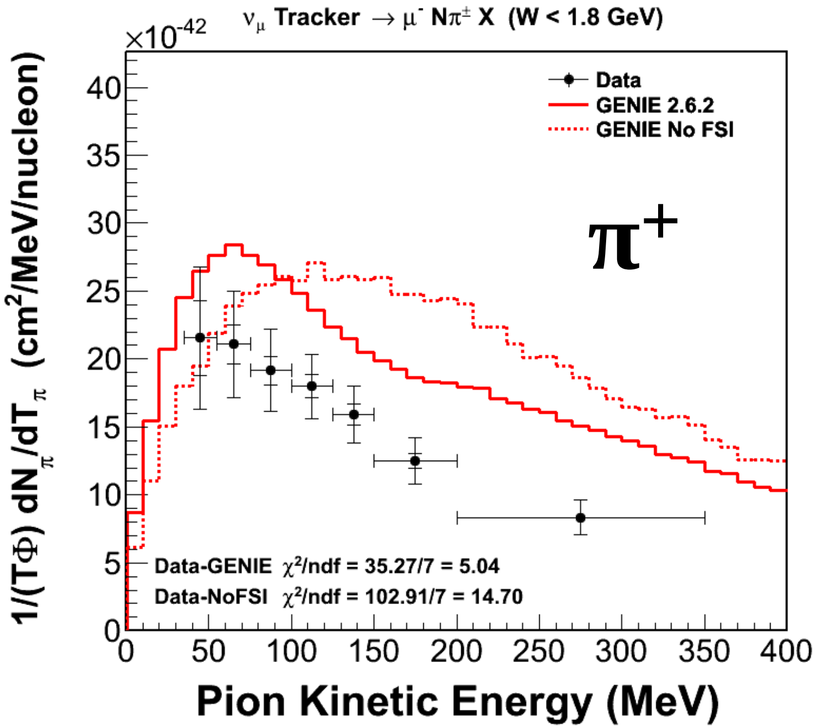




Mosel, Lalakulich, Gallmeister, Phys. Rev. D 89, 093003

Pion and kaon production as probes of FSI

ν_μ CC MINERvA data



Phys. Rev. D 92, 092008 (2015)
Wine & Cheese 7 February 2014

K^+

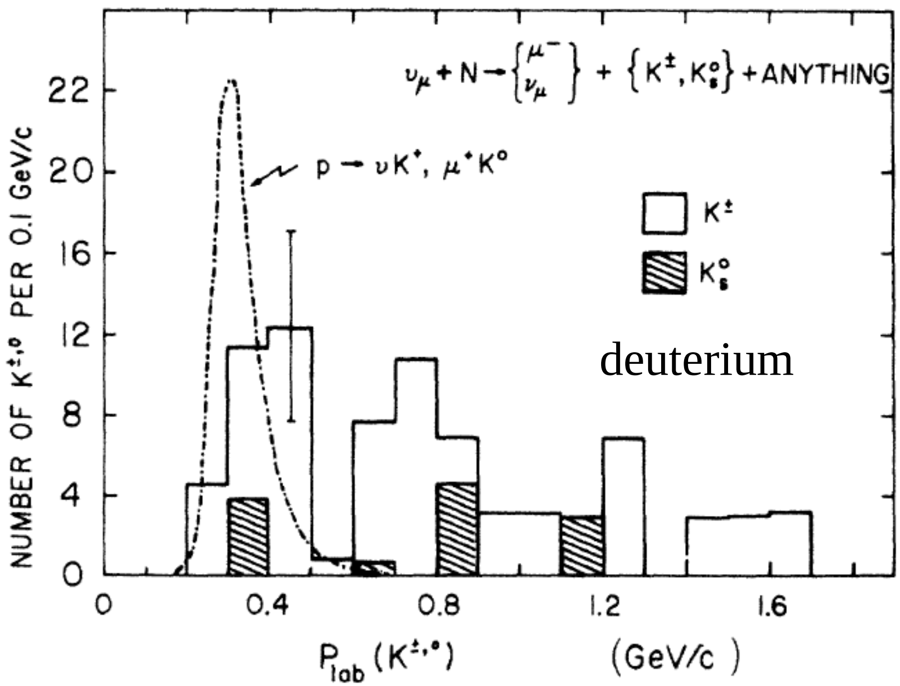
Today!

What can MINERvA do?

- Measure K^+ production cross sections on CH
- Benchmark Monte Carlo generators
- Measure kaon spectrum sensitive to FSI

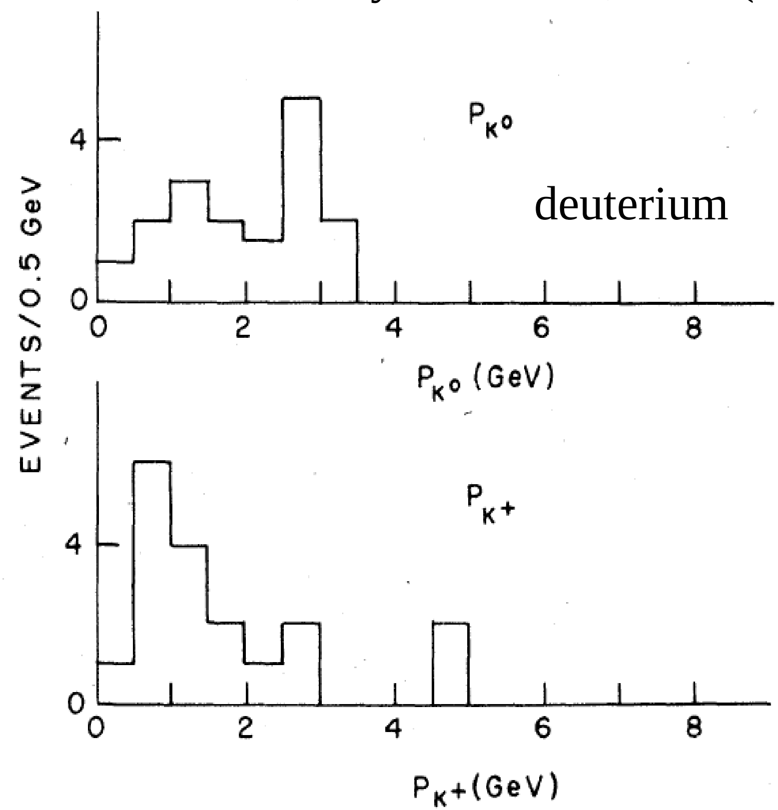
Existing K^+ neutrino data

W. A. Mann et al., Phys.Rev. D34, 2545 (1986)



ANL 12' bubble chamber

N. J. Baker et al., Phys.Rev. D24, 2779 (1981)



BNL 7' bubble chamber

Also Gargamelle: Physics Letters B 73 4-5 (1978)

Types of reactions

- “Associated production”, “ΔS = 0”: pairs of strange particles in final state
  - $\nu_\mu\, n \rightarrow \mu^- K^+ \Lambda$
  - $\nu_\mu\, n \rightarrow \mu^- K^+ K^- p$
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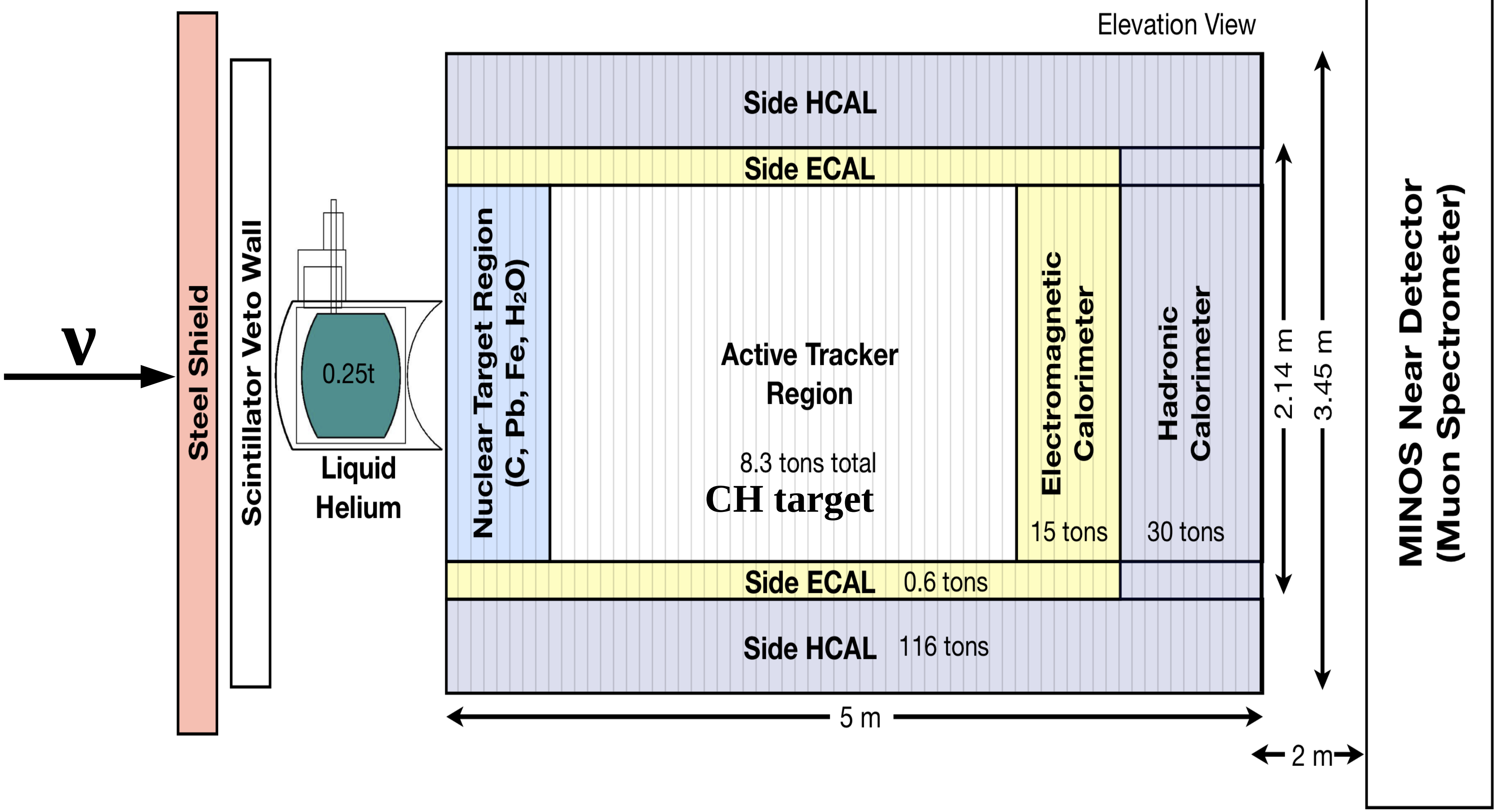
- "Single kaon production", "ΔS = 1": Cabibbo-suppressed, single kaon final state
  - $\nu_\mu\ N \rightarrow \mu^-\ K^+\ N$
- "Coherent kaon production": nucleus remains in ground state
  - $\nu_\mu\ A \rightarrow \mu^-\ K^+\ A$

Meet the generator

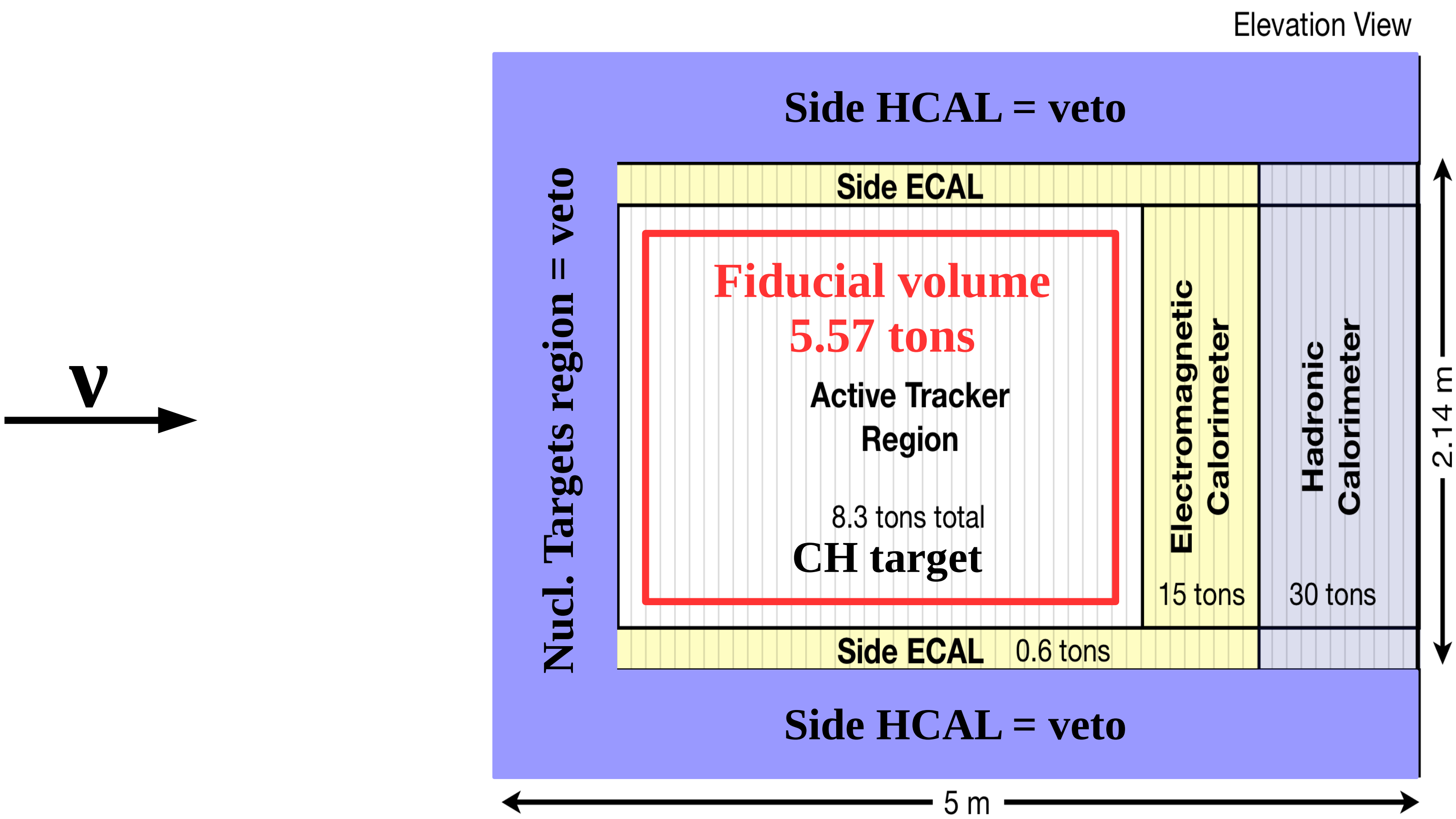
- GENIE version 2.8.4
  - Also used by NOvA, DUNE, MicroBooNE, others
- Kaons are generated in the hadronization model:
  - KNO for $1.7 < W / \text{GeV} < 2.3$
  - AGKY for $2.3 < W / \text{GeV} < 3.0$
  - PYTHIA for $W > 3$ GeV
- Rate of strange production is tuned to Λ and K^0_S data on deuterium from BEBC and FNAL 15' bubble chambers
- Single kaon production not in default model, but introduced in 2.10 based on Alam et al. Phys.Rev. **D**82 033001 (2010)
- No coherent K^+ production

The MINERvA detector



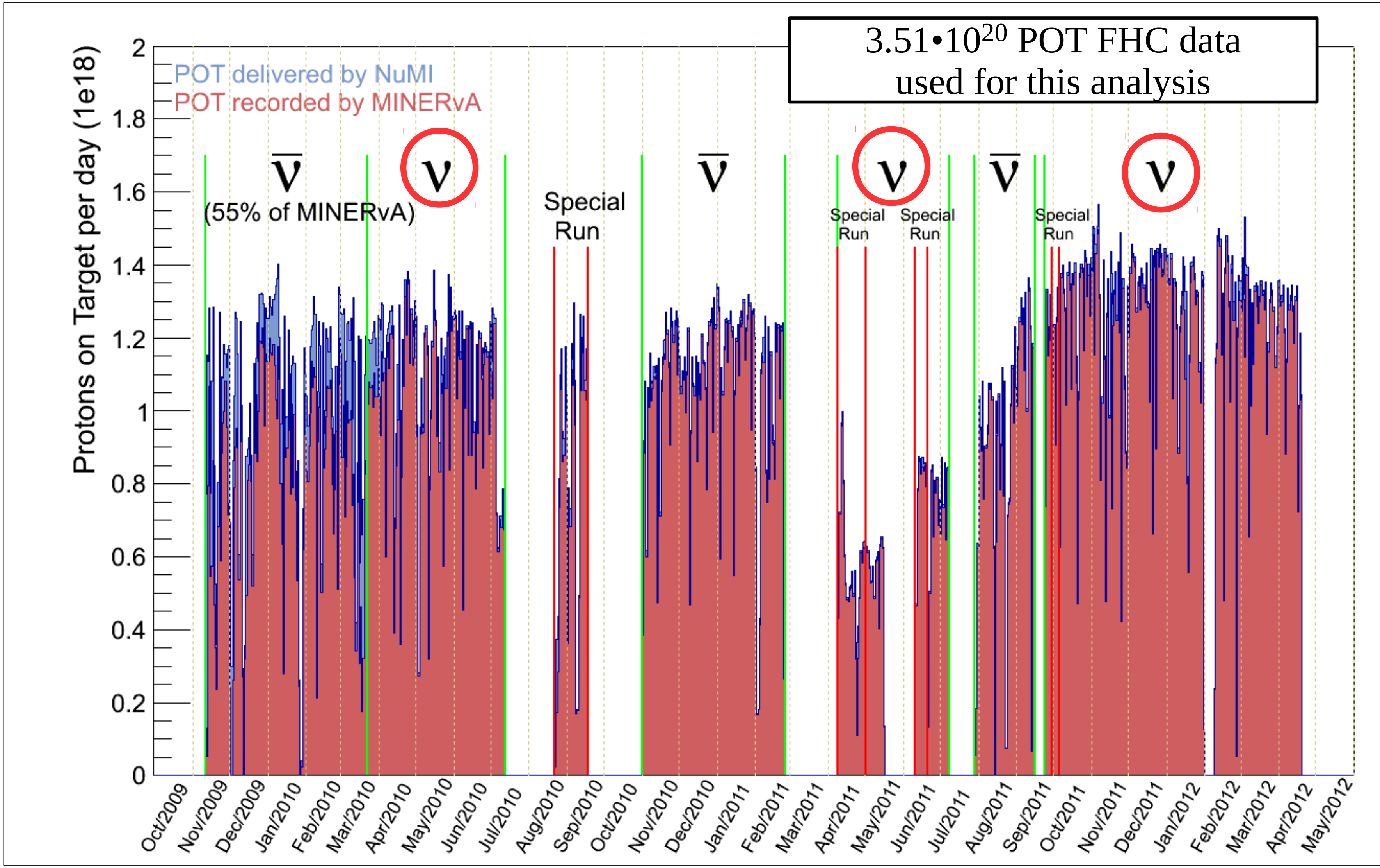
Nucl. Inst. and Meth. A743 (2014) 130
arXiv:1305.5199

The MINERvA detector for this analysis



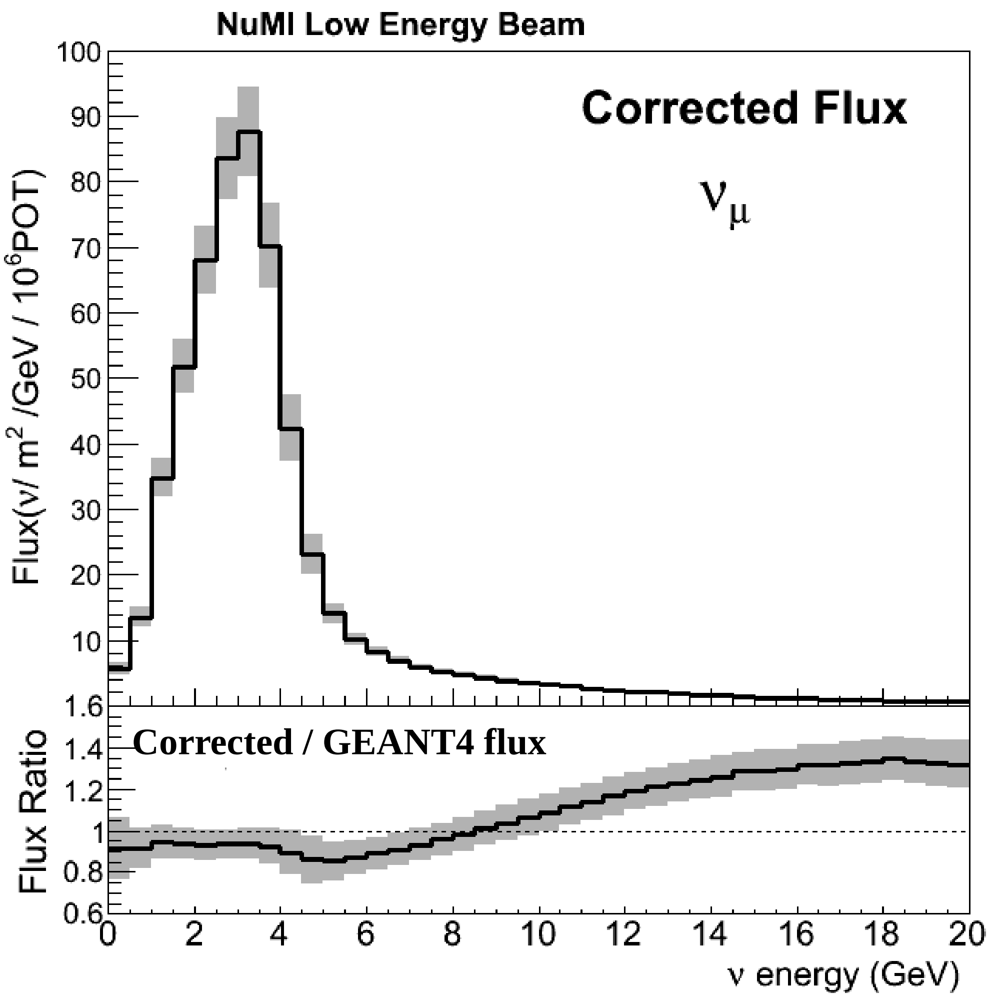
Nucl. Inst. and Meth. A743 (2014) 130
arXiv:1305.5199

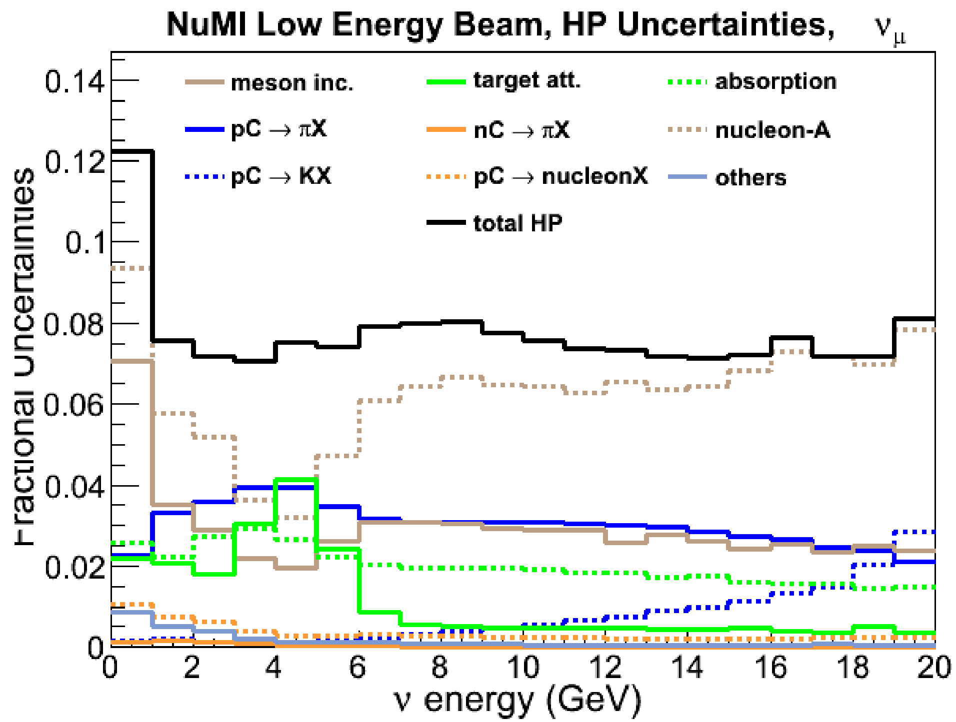
Thank you for the beam!



Neutrino flux

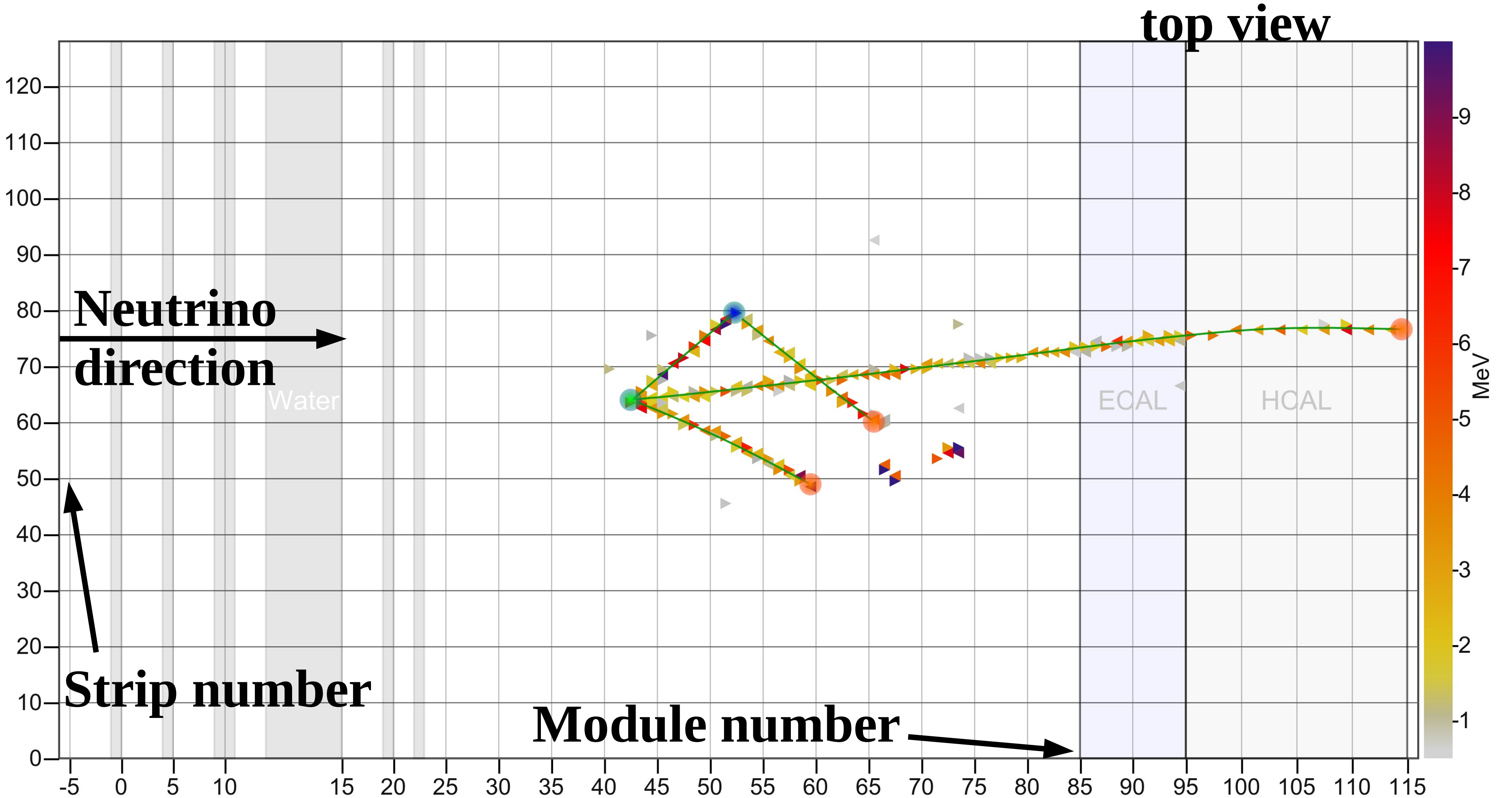
Leo Aliaga Wine & Cheese, 18 December 2015





NuMI “low energy” beam tune, ~3.5 GeV peak energy, with ~8% uncertainty dominated by hadron production

Kaon candidate event display



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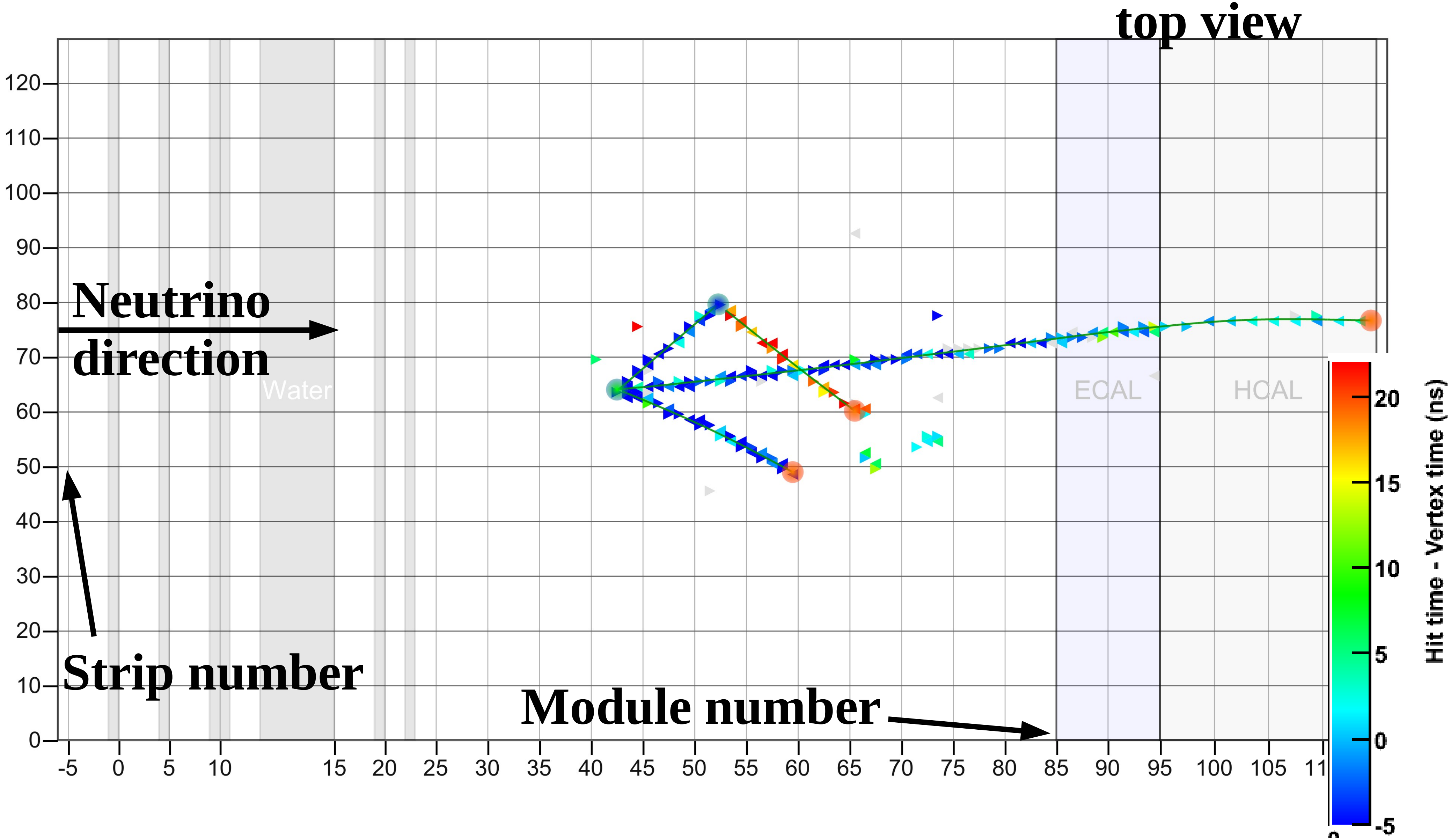
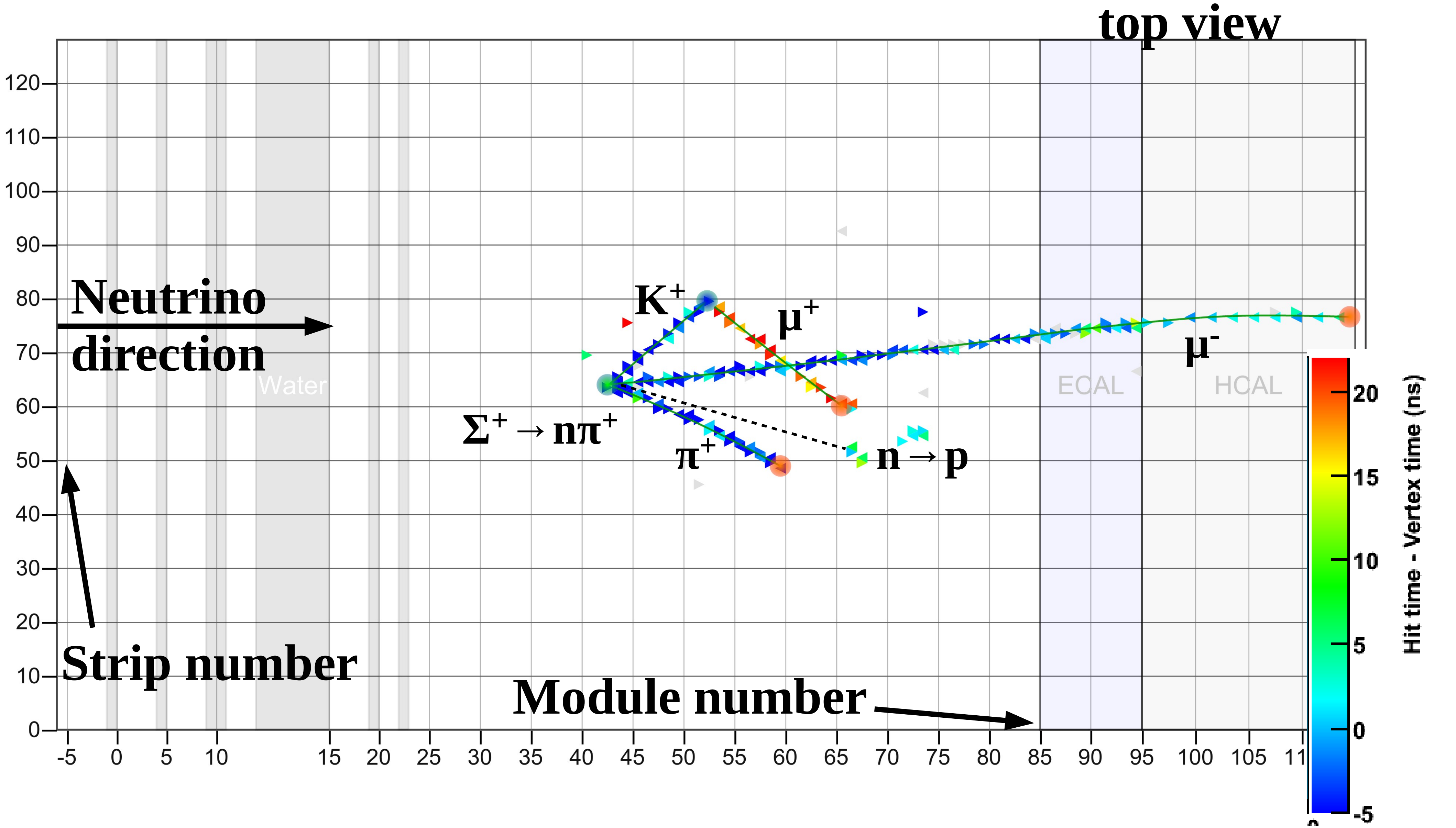
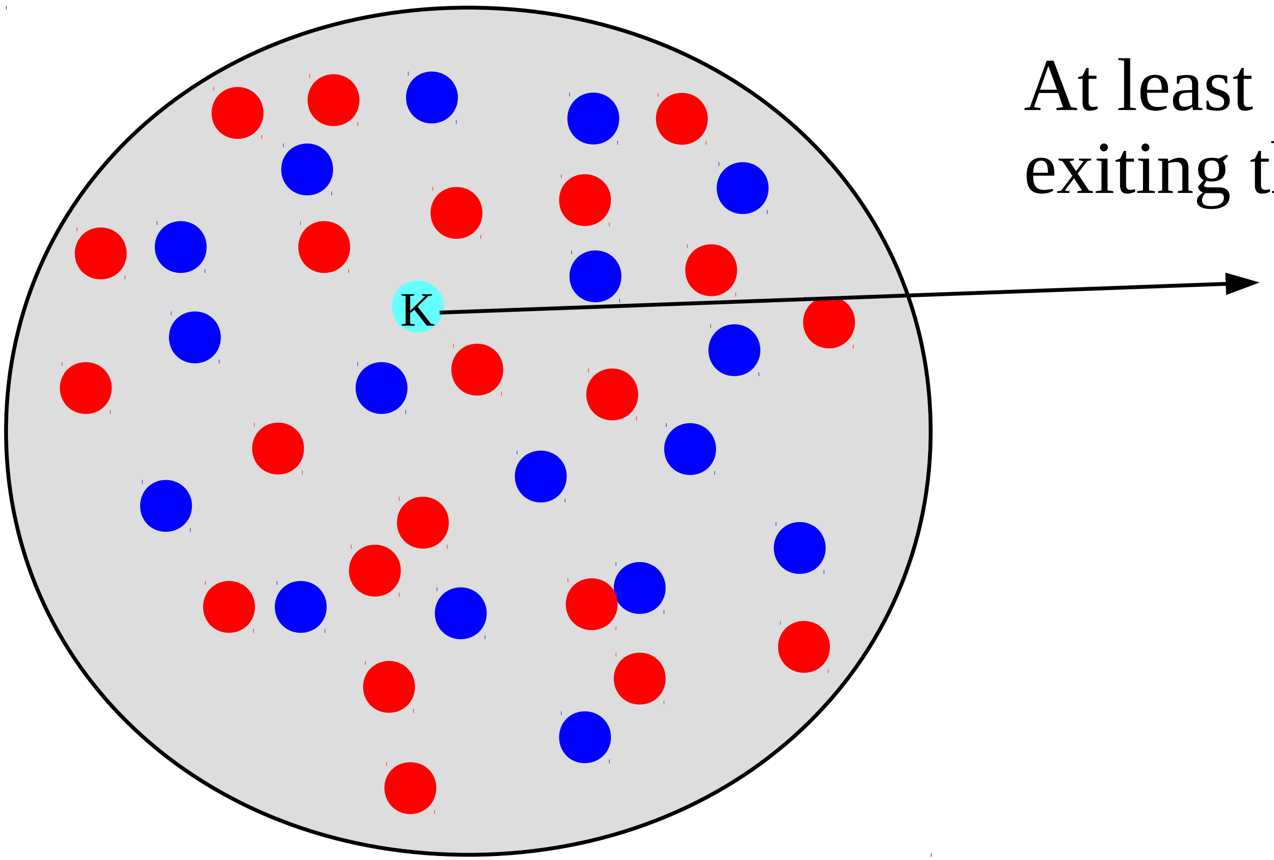


My guess: $\nu_\mu p \rightarrow \mu^- K^+ \Sigma^+$

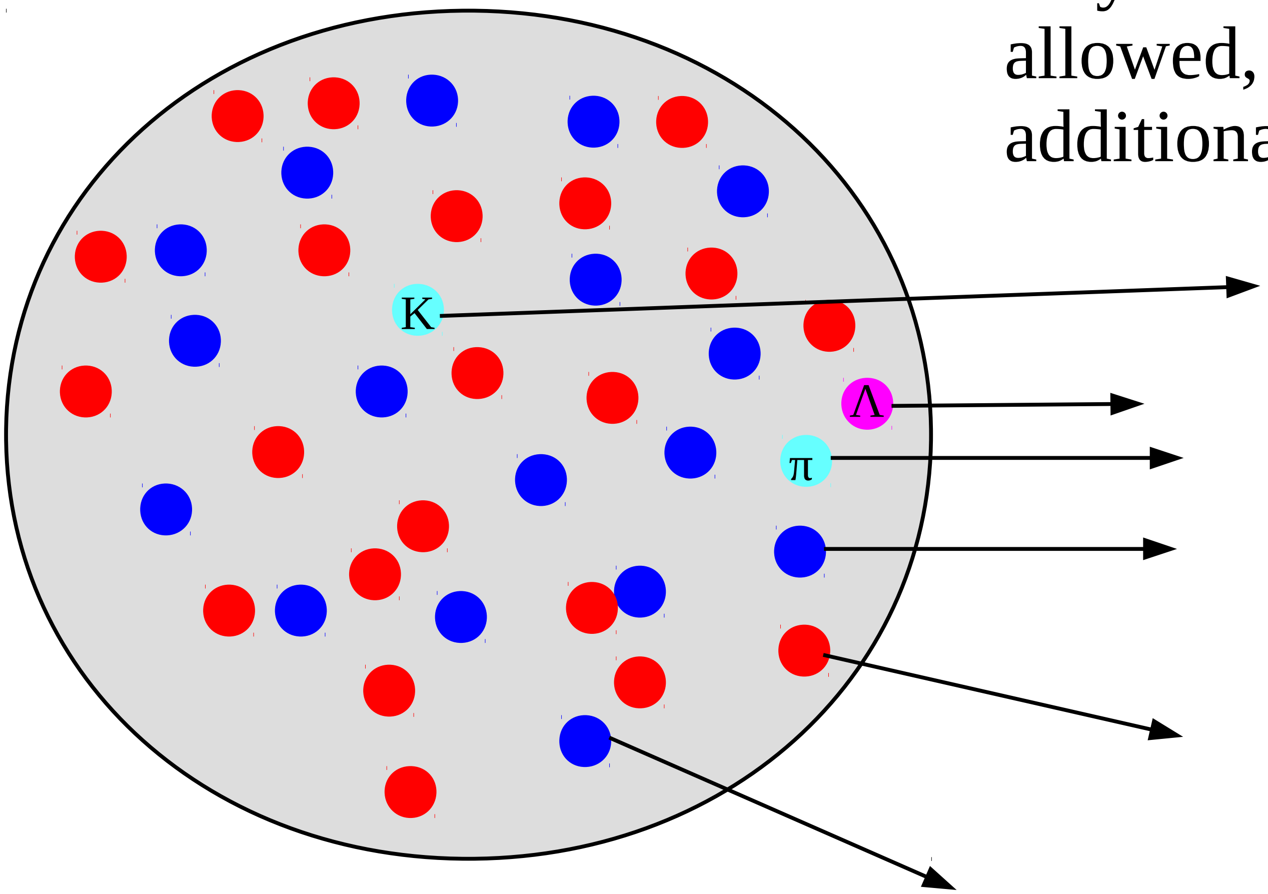


Signal definition



At least one K^+ exiting the nucleus

Signal definition

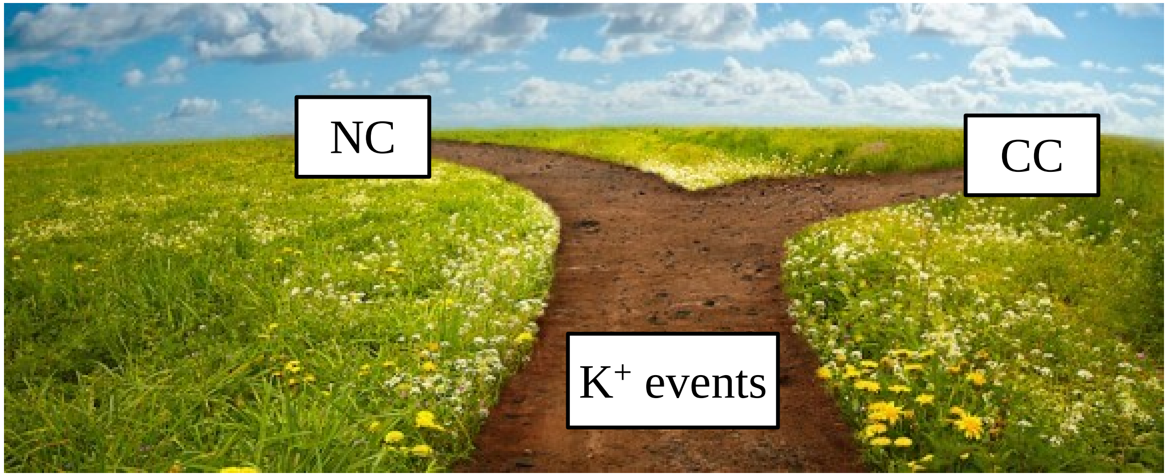


Any other particles are allowed, including additional kaons

CC and NC sample definitions

For CC analysis, require μ^- in the final state

For NC analysis, require zero charged leptons at neutrino interaction vertex



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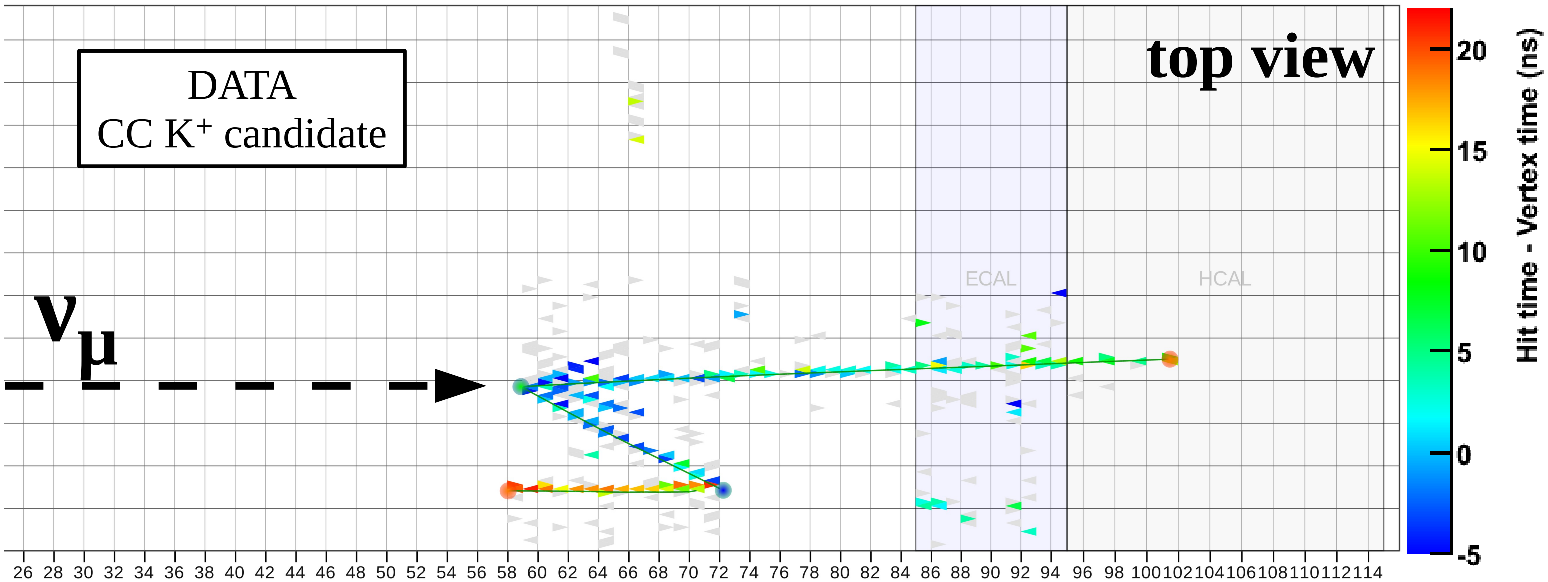
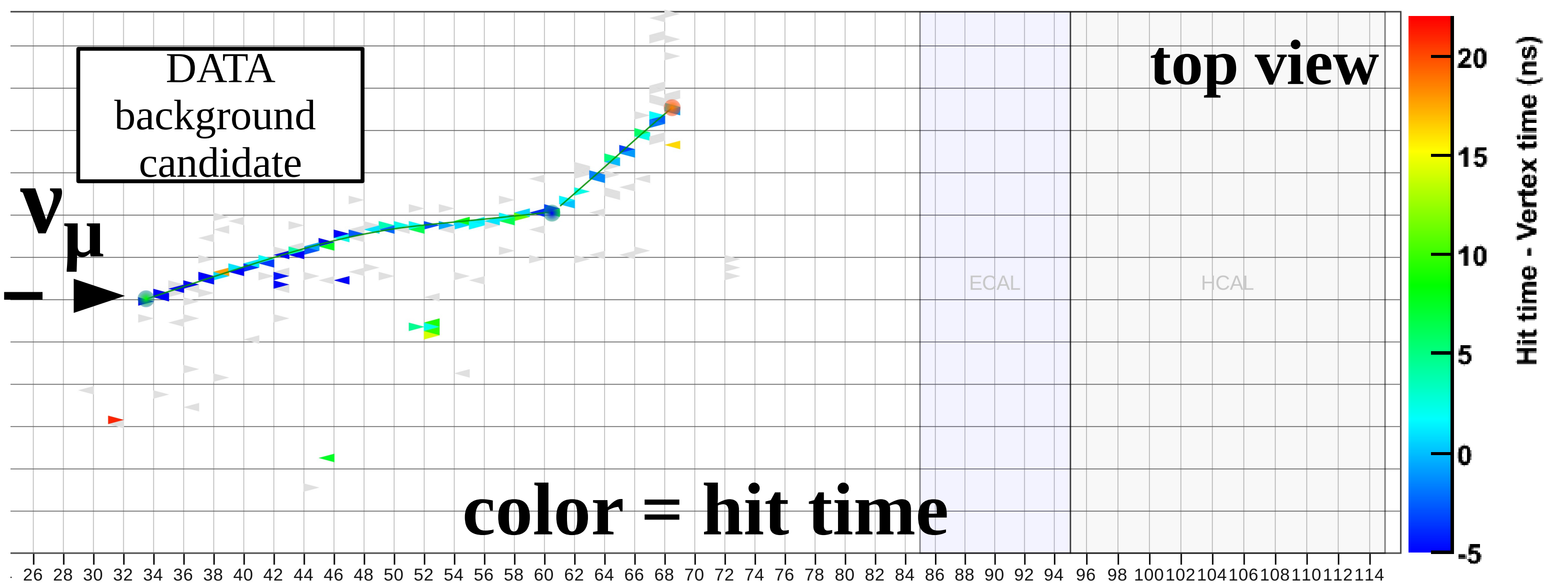
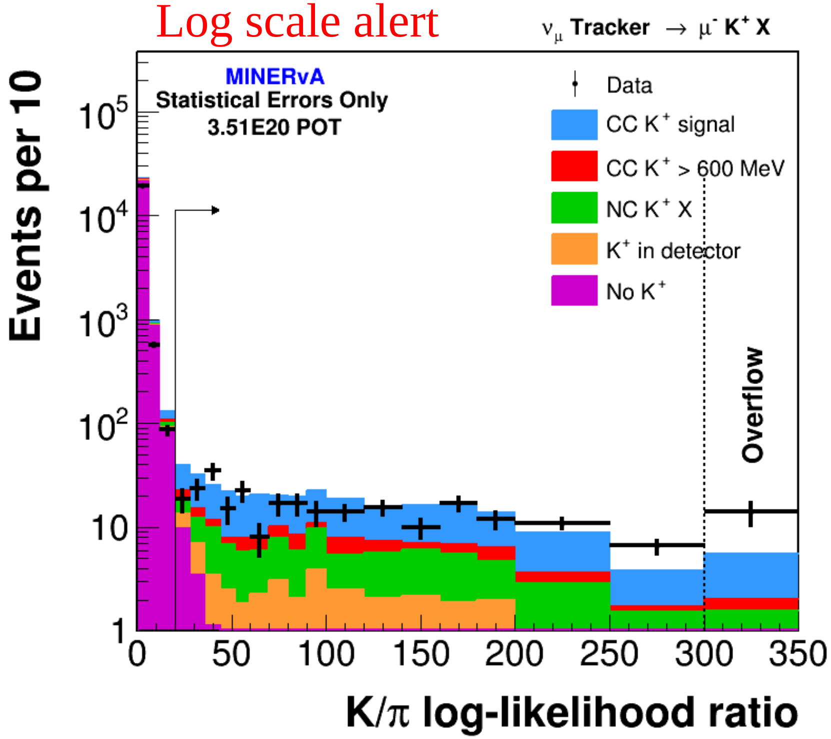
Identifying K^+ by timing

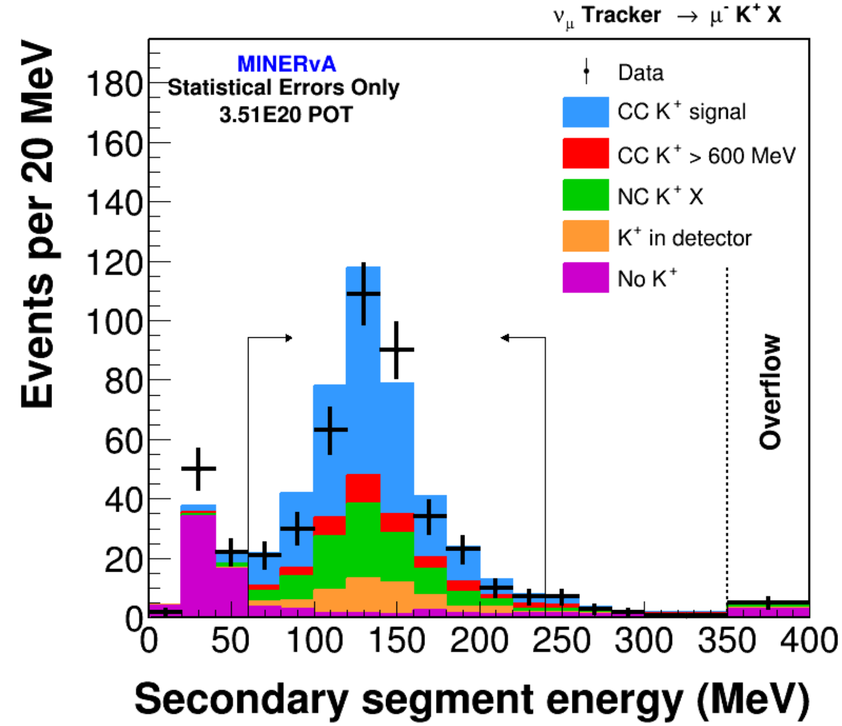




Kinked track selection

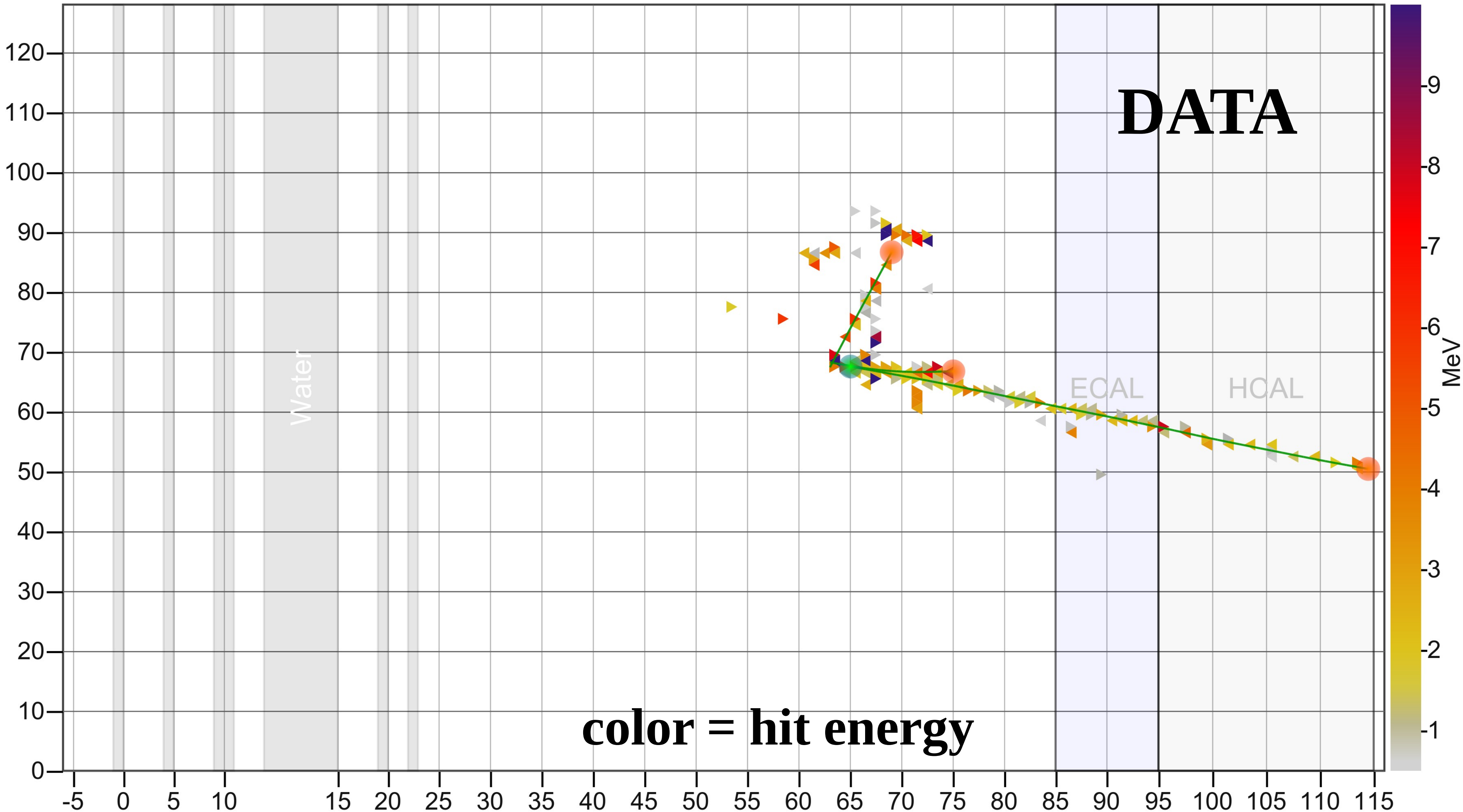
Log scale alert



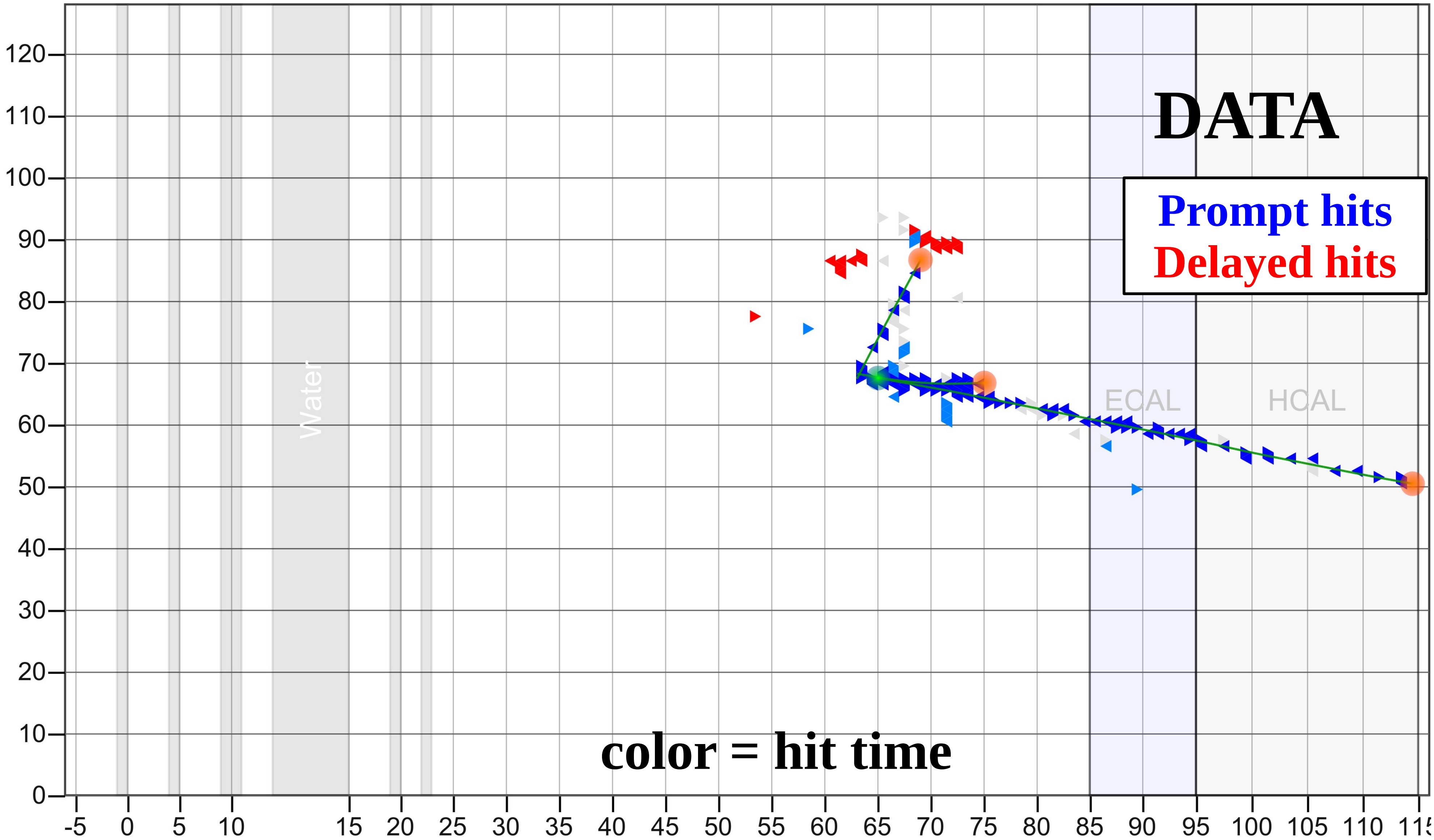


- Fit timing profile with two hypotheses, cut on log-likelihood ratio to select kaon-like events
- All from $K^+ \rightarrow \mu^+ \nu$ decays, muon is monoenergetic

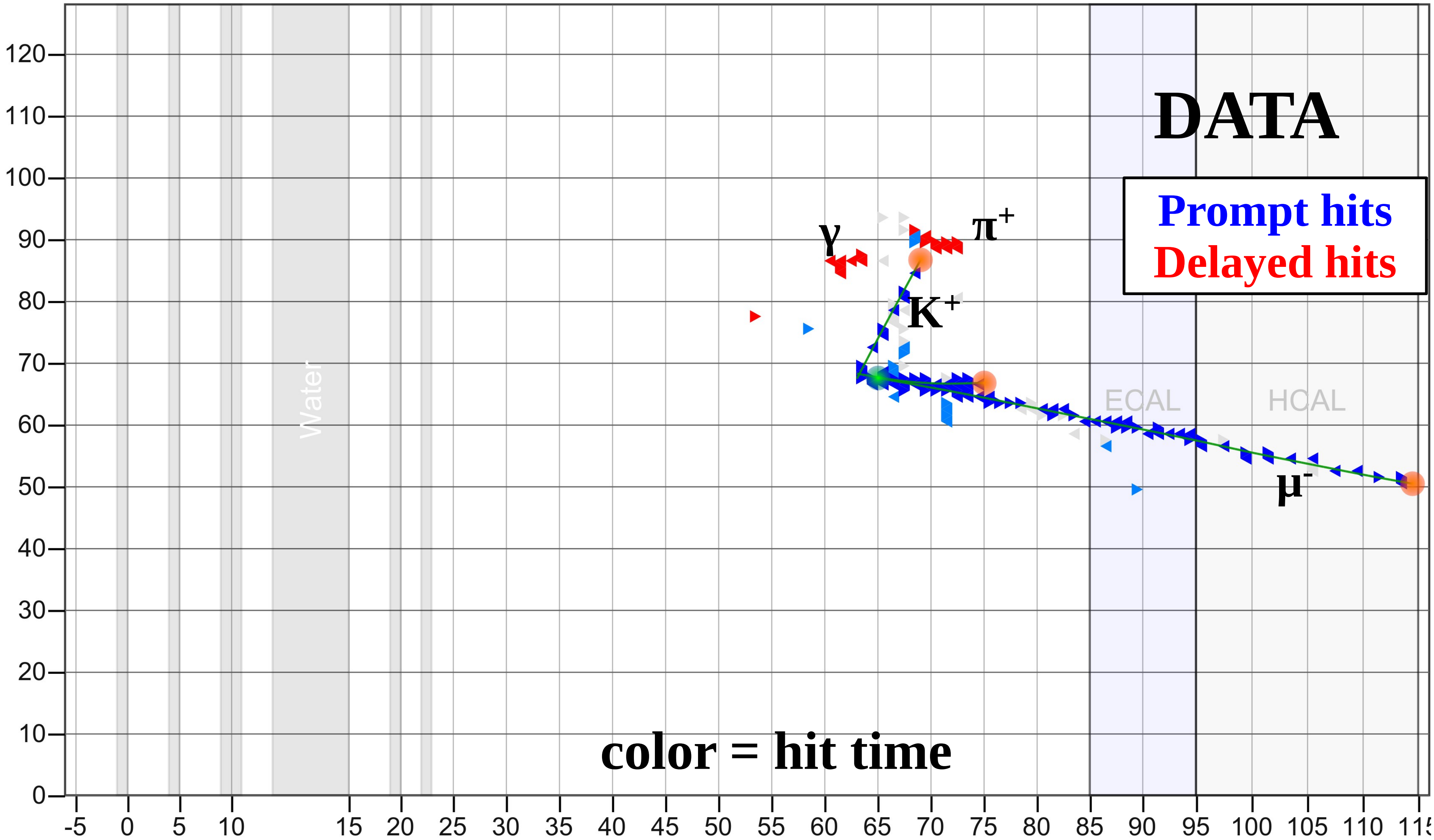
Reconstructing events without kinked tracks



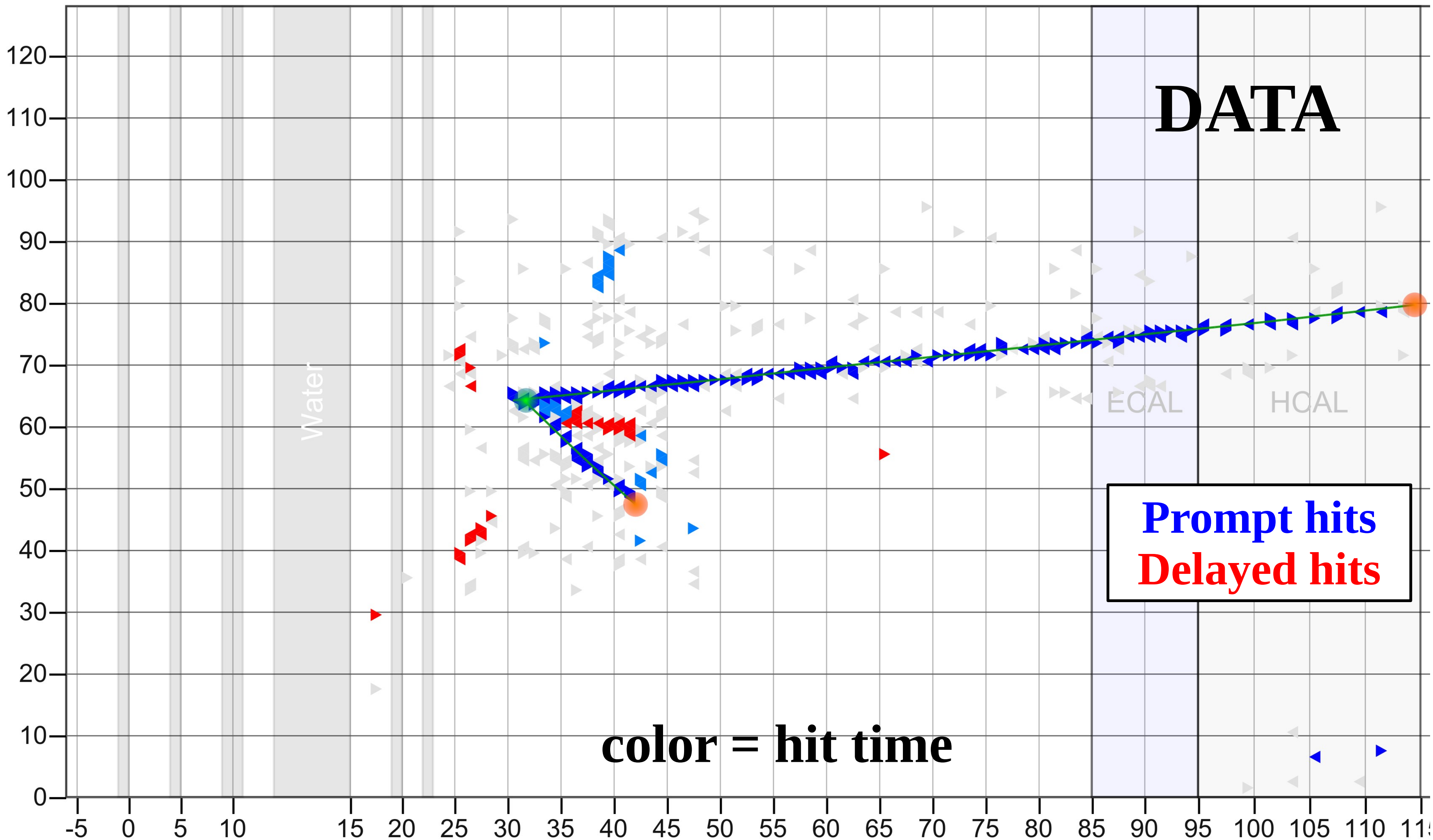
Hits are grouped into narrow bunches in time: “time slivers”



My guess


DATA
Prompt hits
Delayed hits
γ
π+
K+
μ-
ECAL
HCAL
Water
color = hit time
120
110
100
90
80
70
60
50
40
30
20
10
0
-5 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115

Reconstructing events with K^+ below tracking threshold



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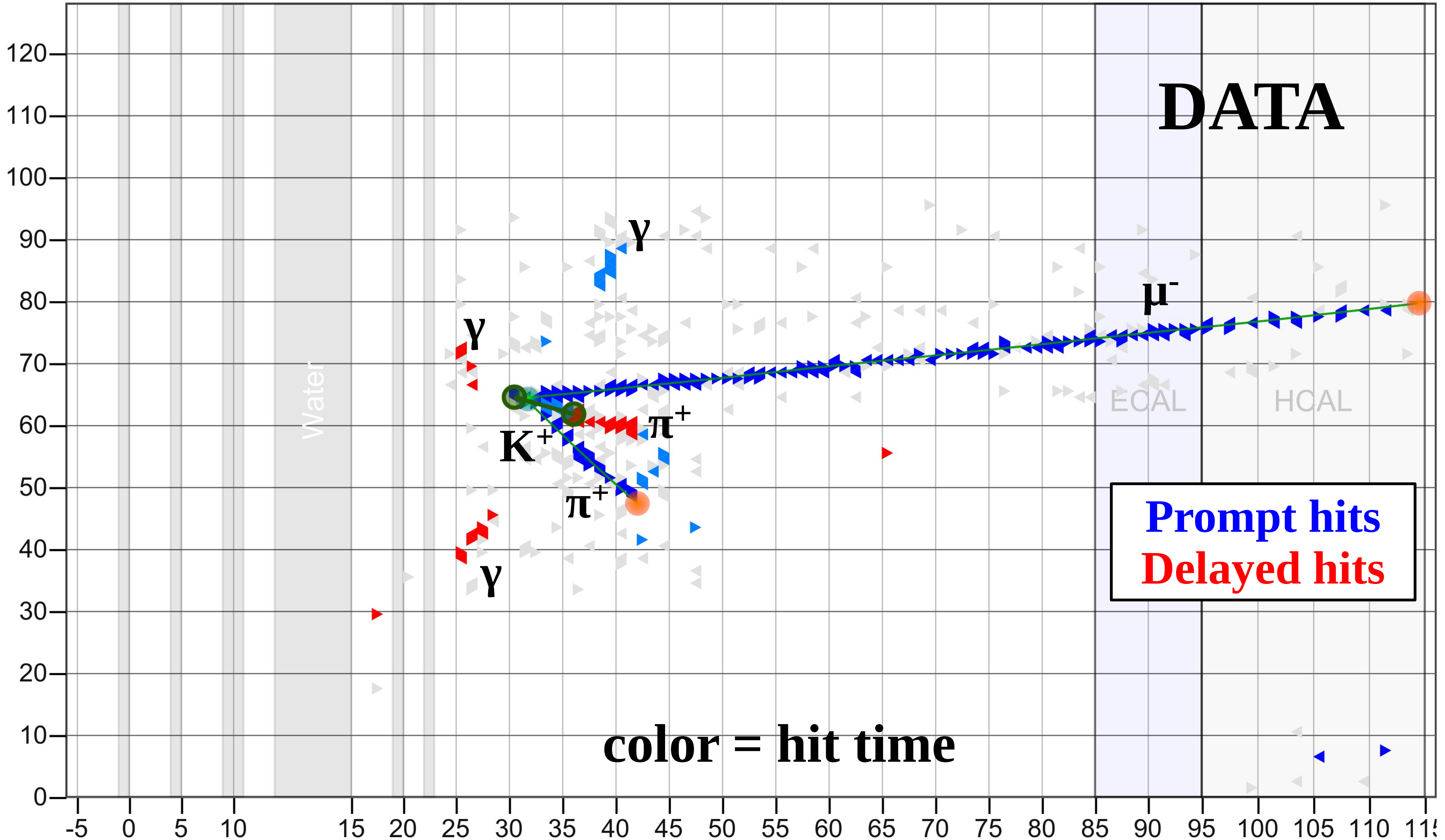
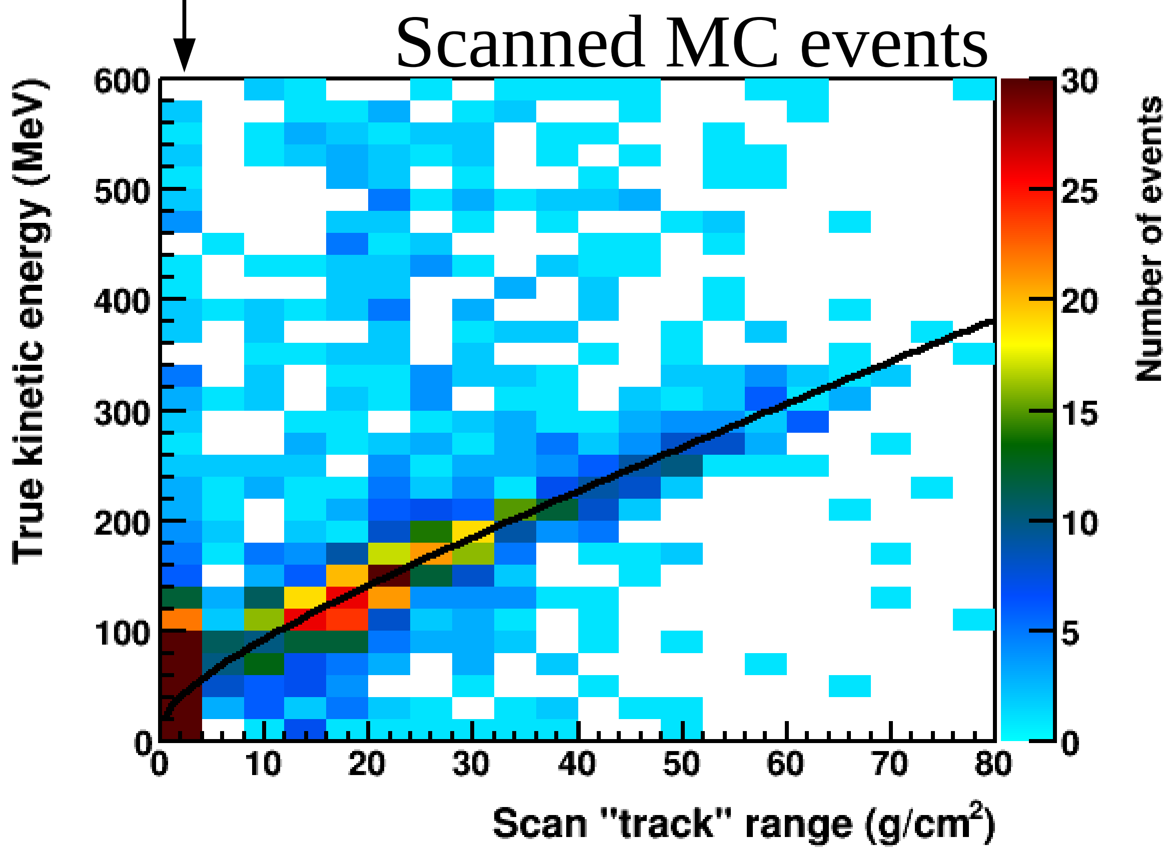
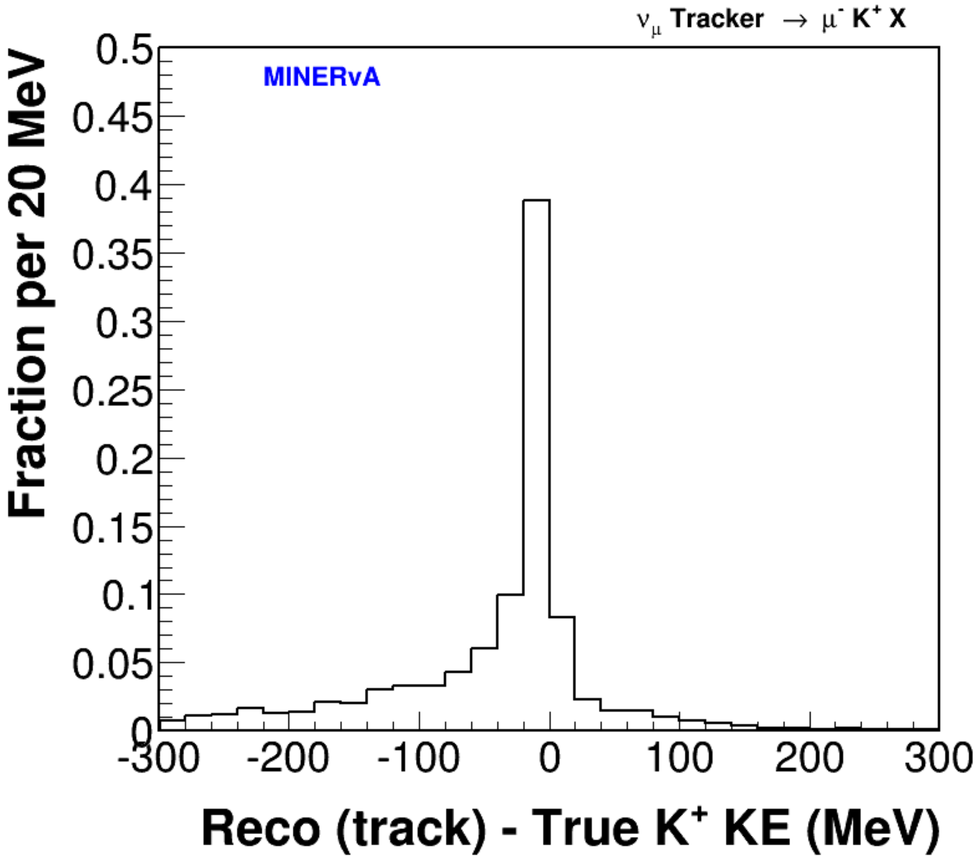


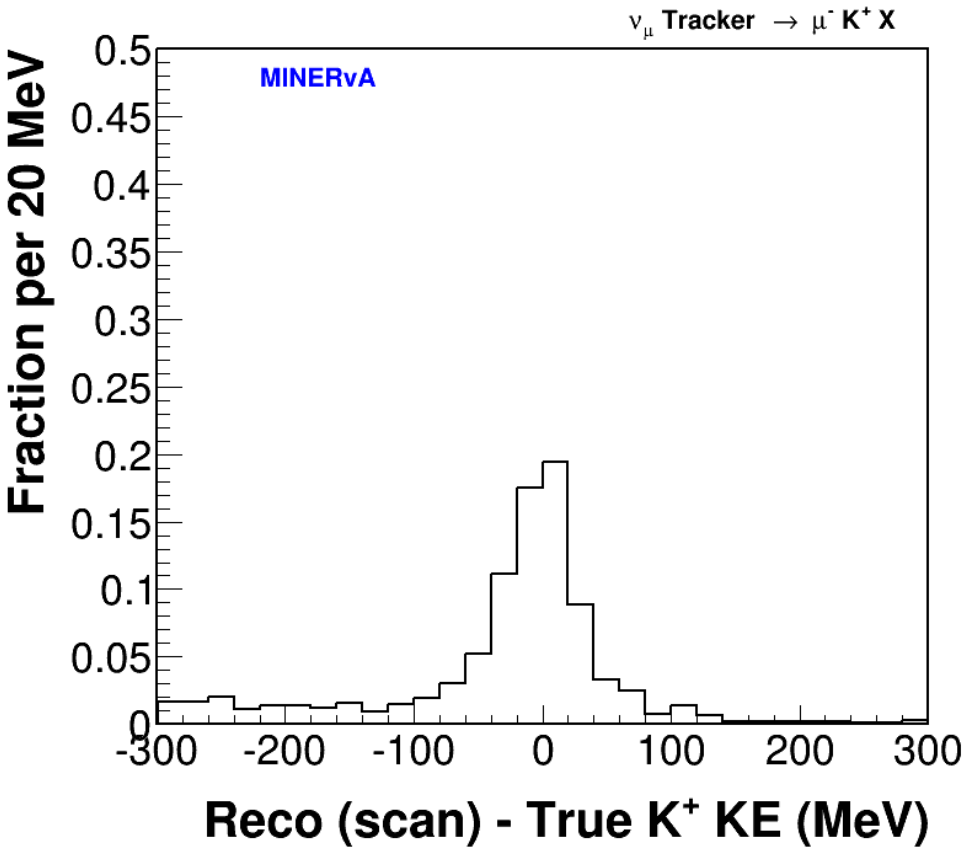
Use MC to convert range to kaon kinetic energy

Too short to make a "User track"

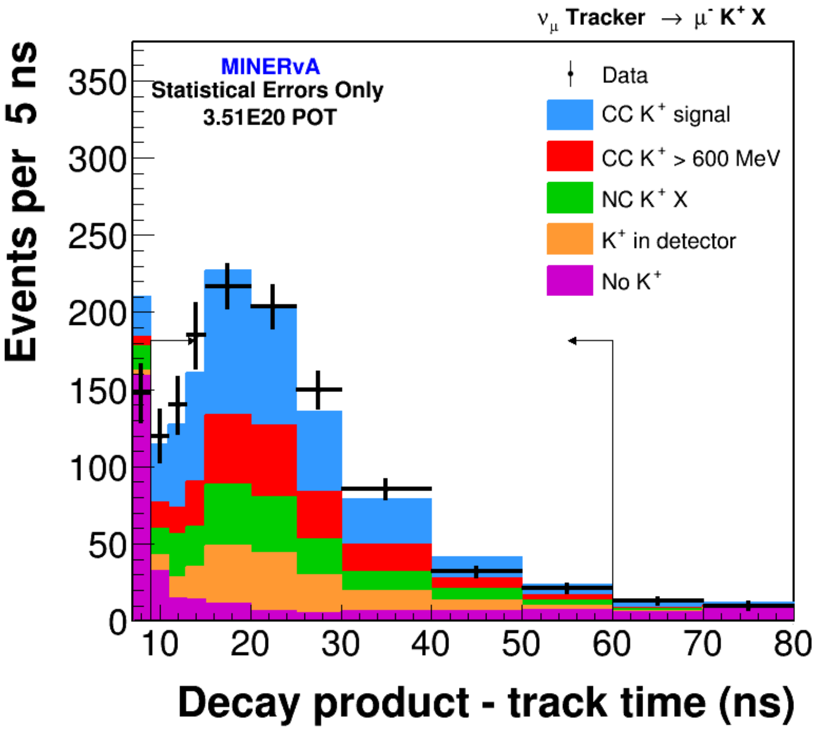


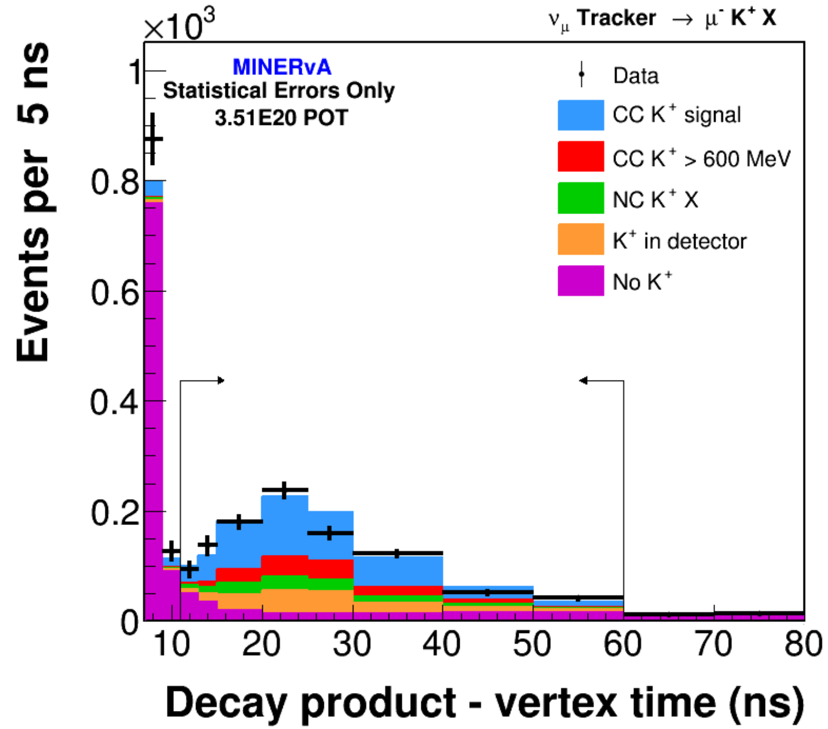
Kaon kinetic energy residuals





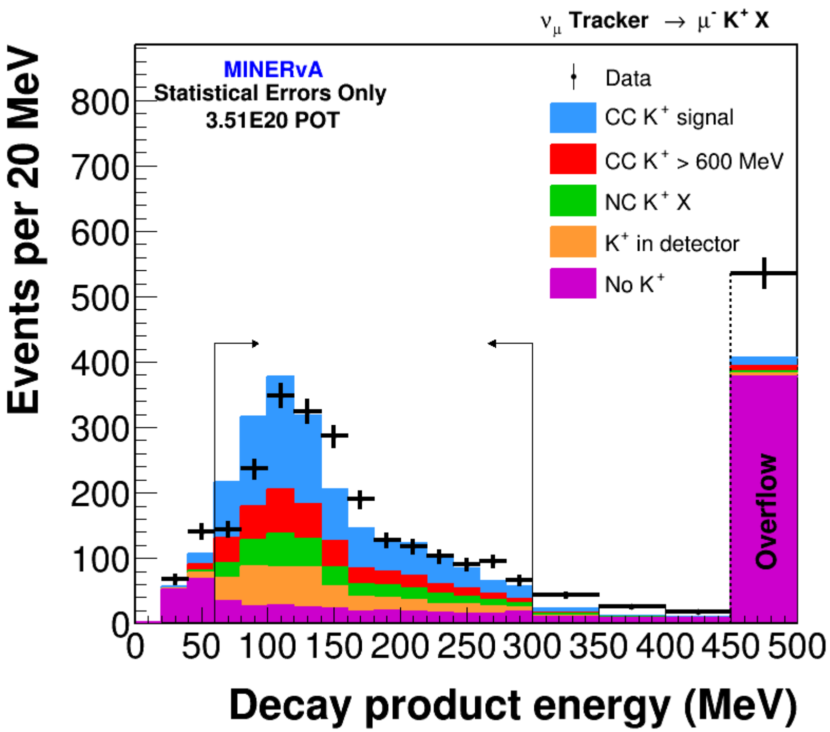
Time difference to decay

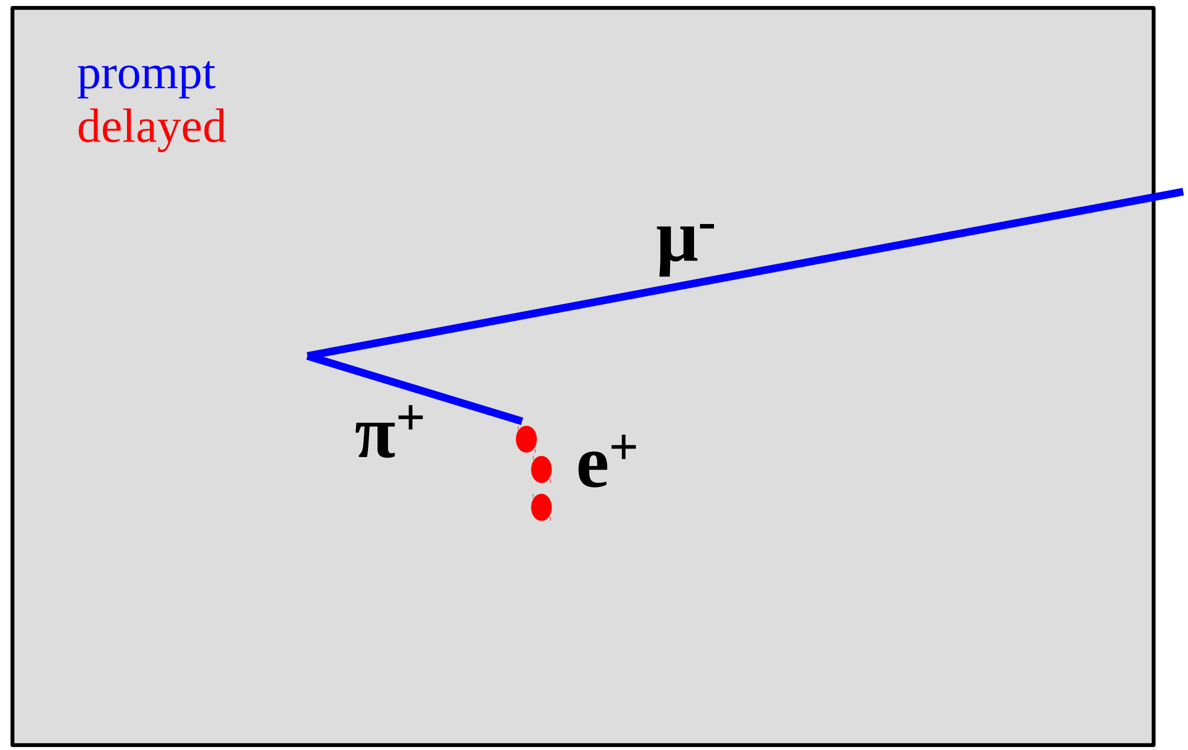




- Suppressing an enormous number of background events below 7 ns time gap

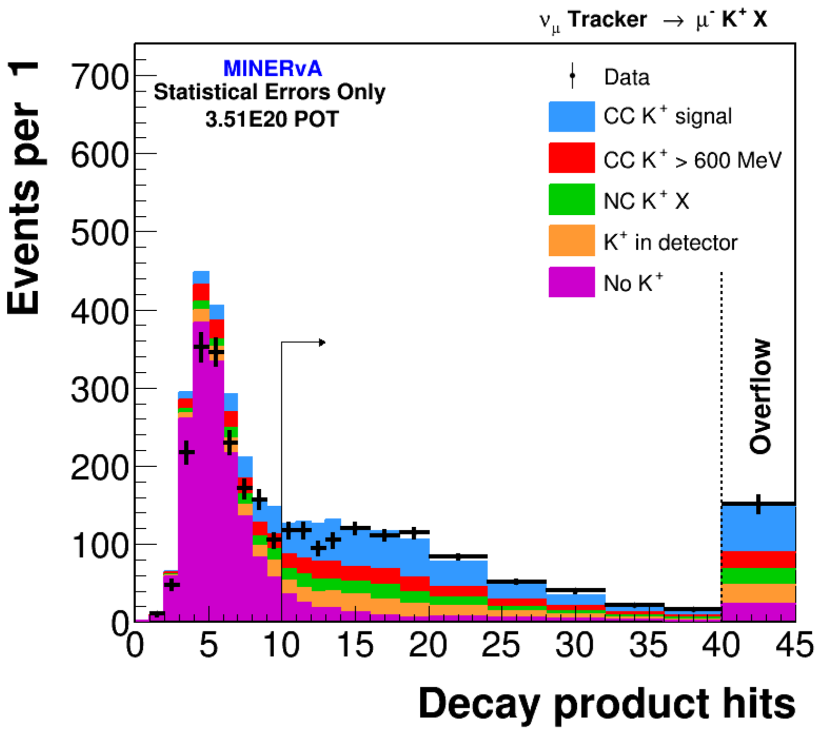
Decay candidate energy

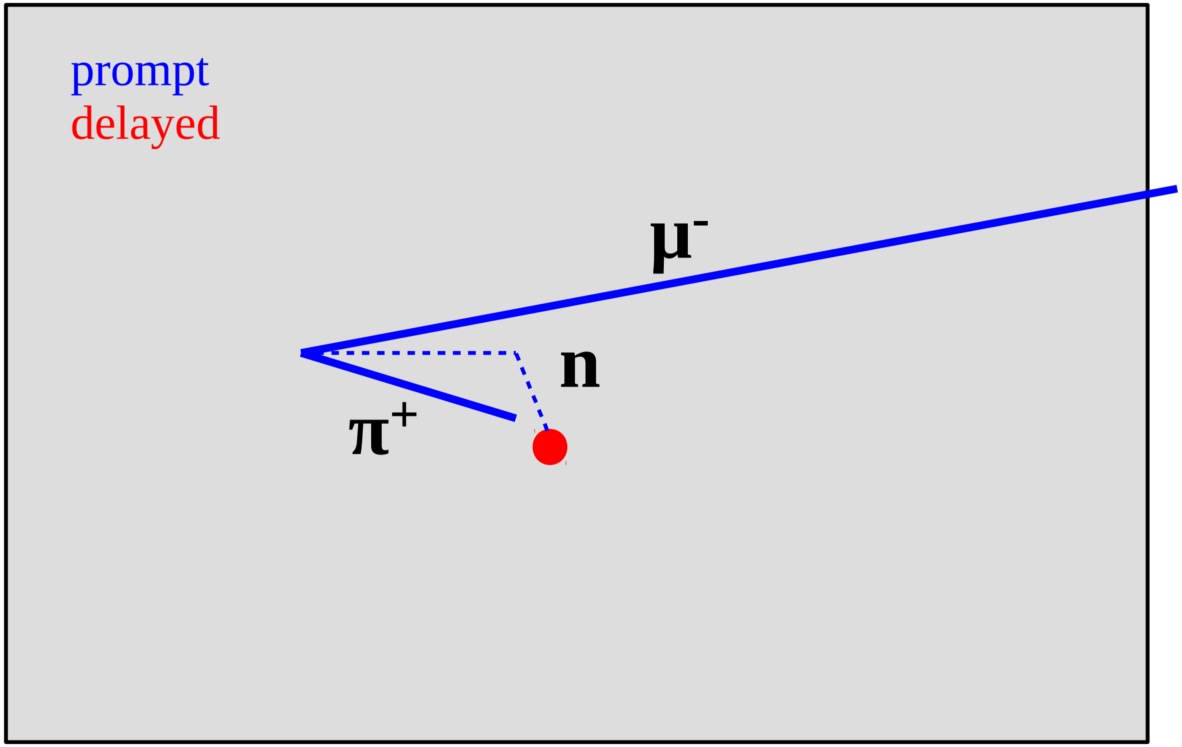




- Require energy to be consistent with $K^+ \rightarrow \mu^+ \nu$ or $K^+ \rightarrow \pi^+ \pi^0$

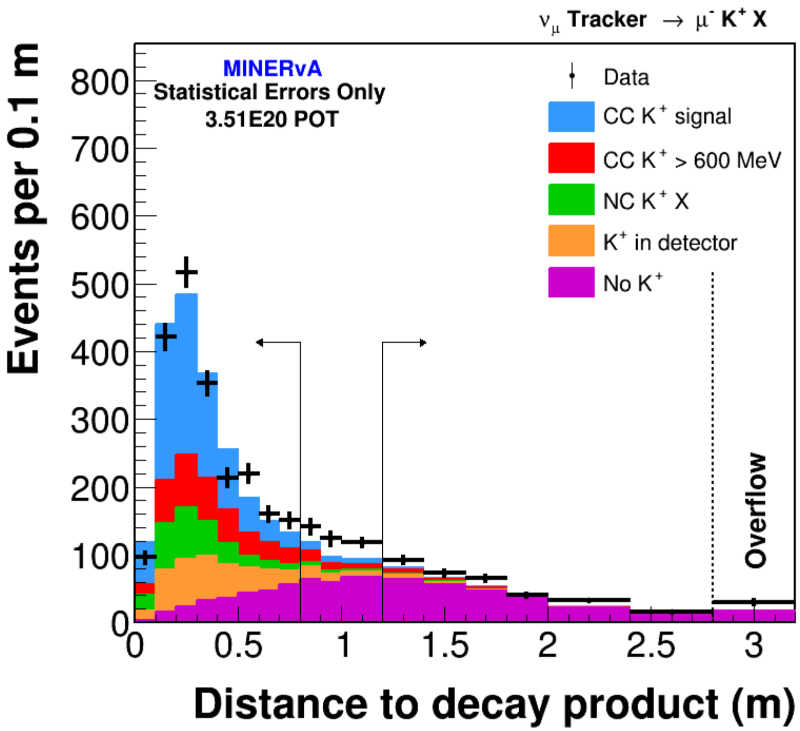
Decay number of hits

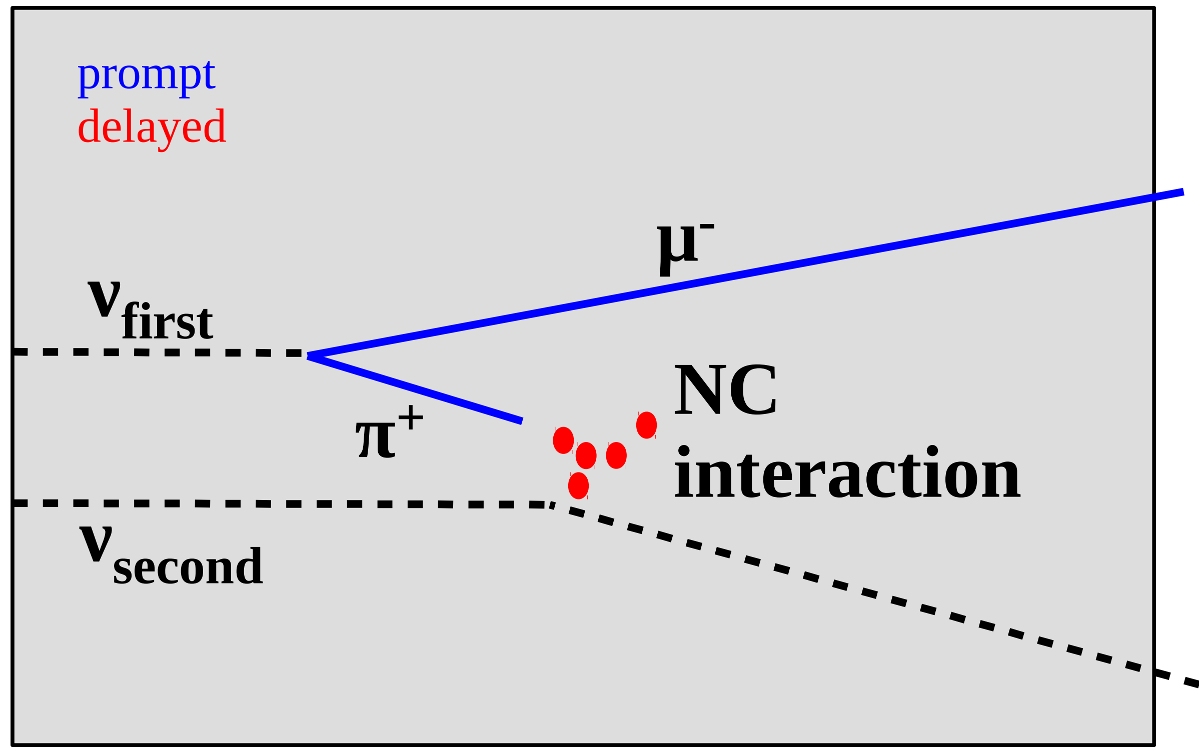




- Require at least 10 energy deposits (hits); neutron interaction will typically produce fewer

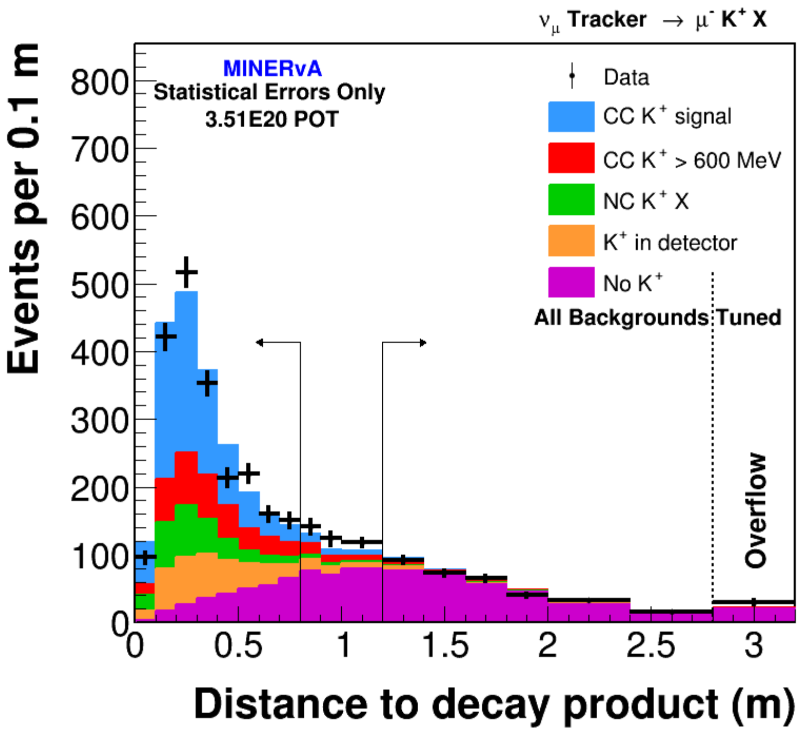
Distance to decay product

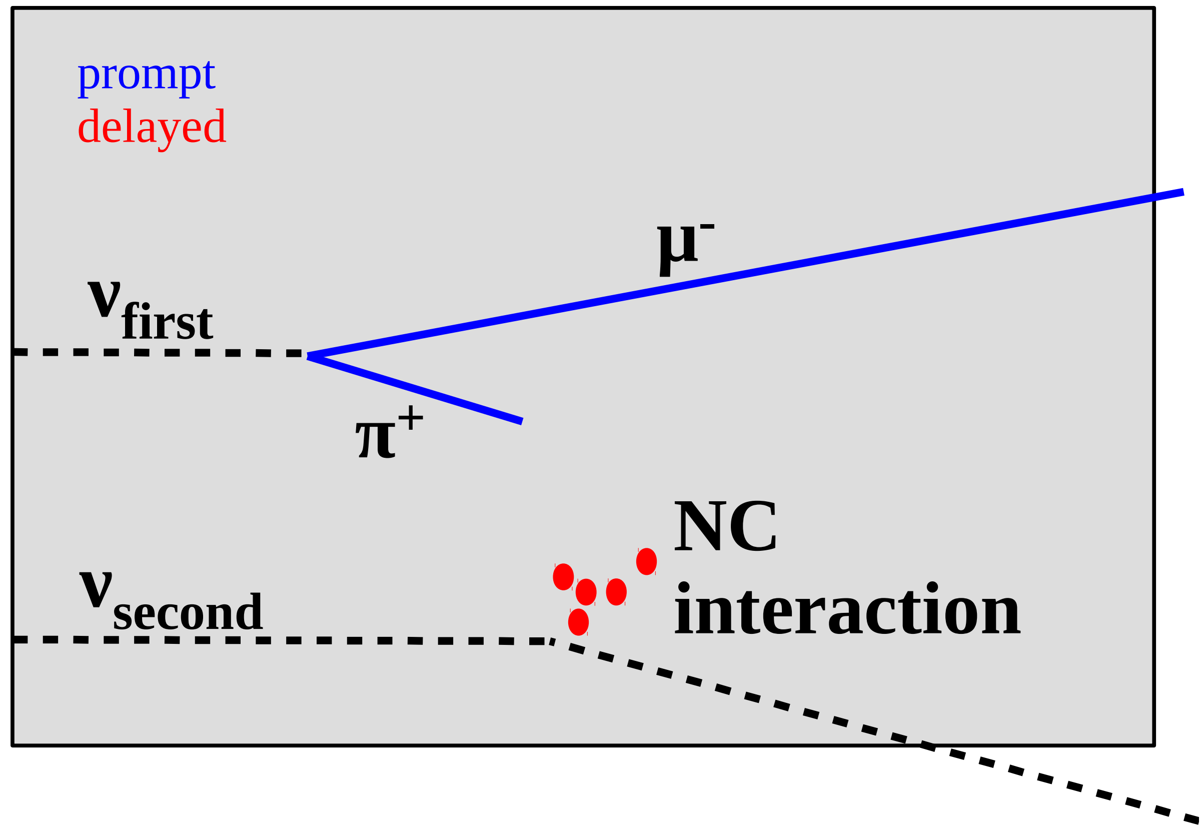




- Require decay product candidate to be spatially near the kaon track candidate

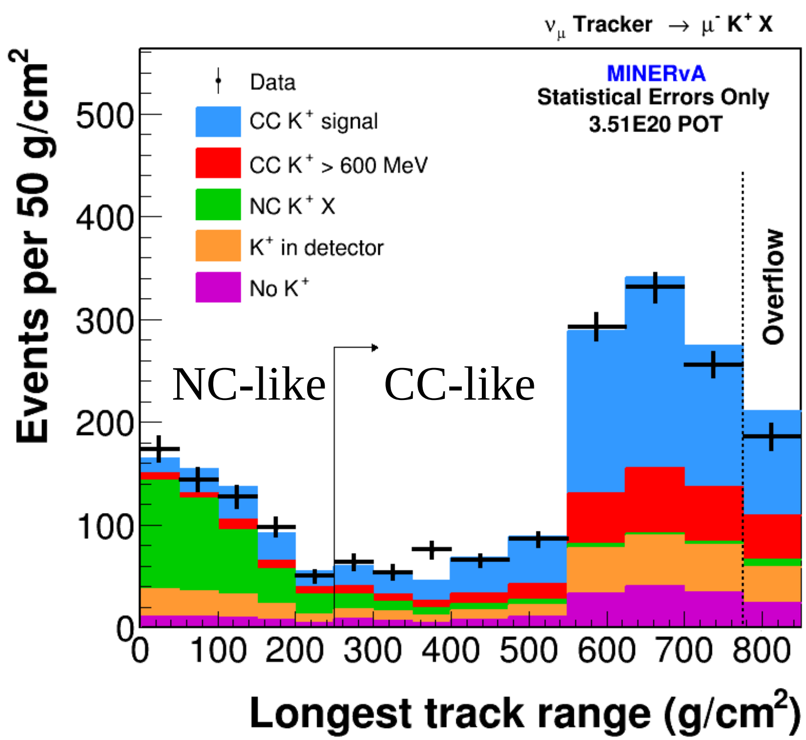
Tune the pile-up background

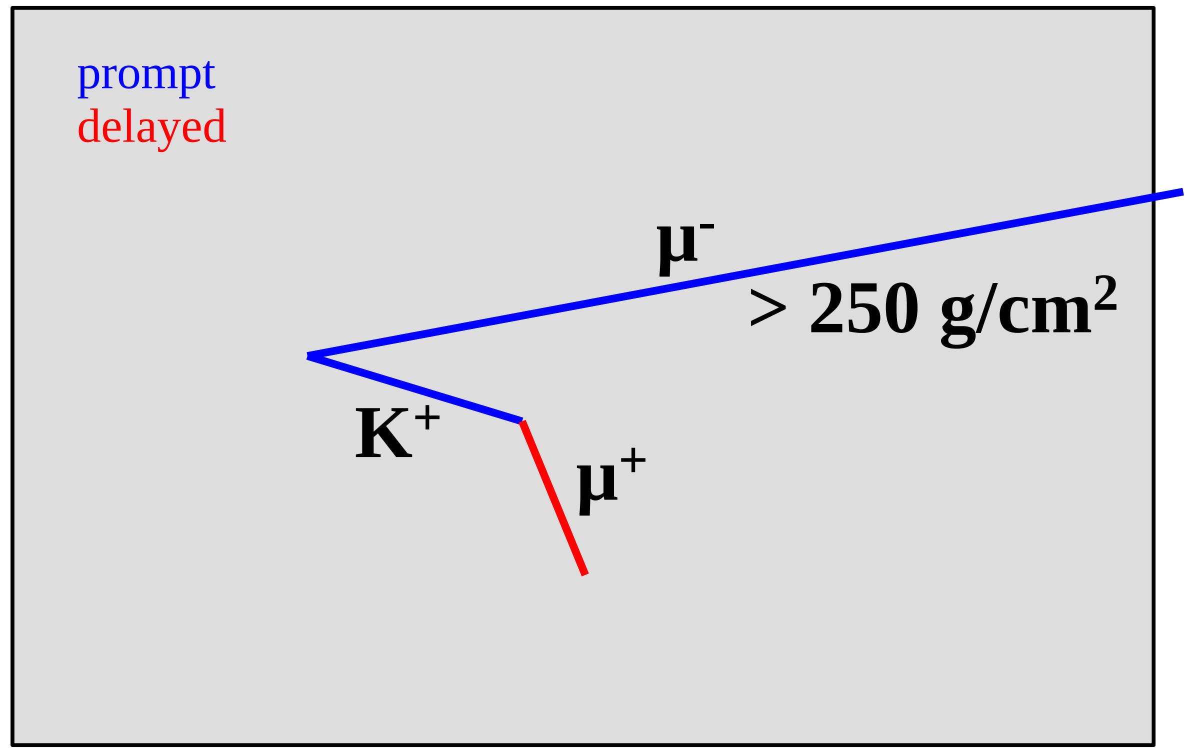




- Use events where the late activity is far from the kaon candidate to measure the pile-up background in data

CC/NC separation

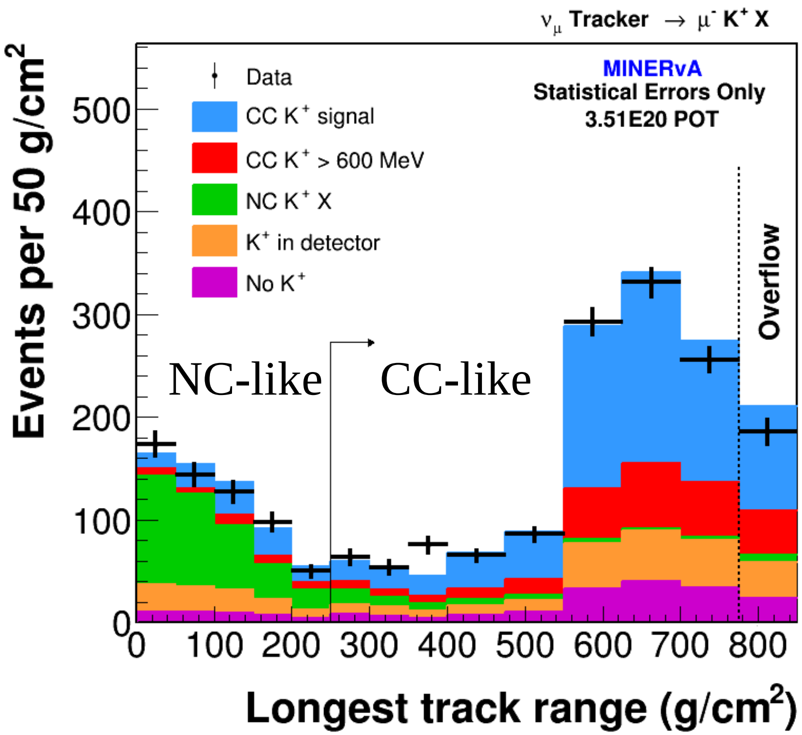


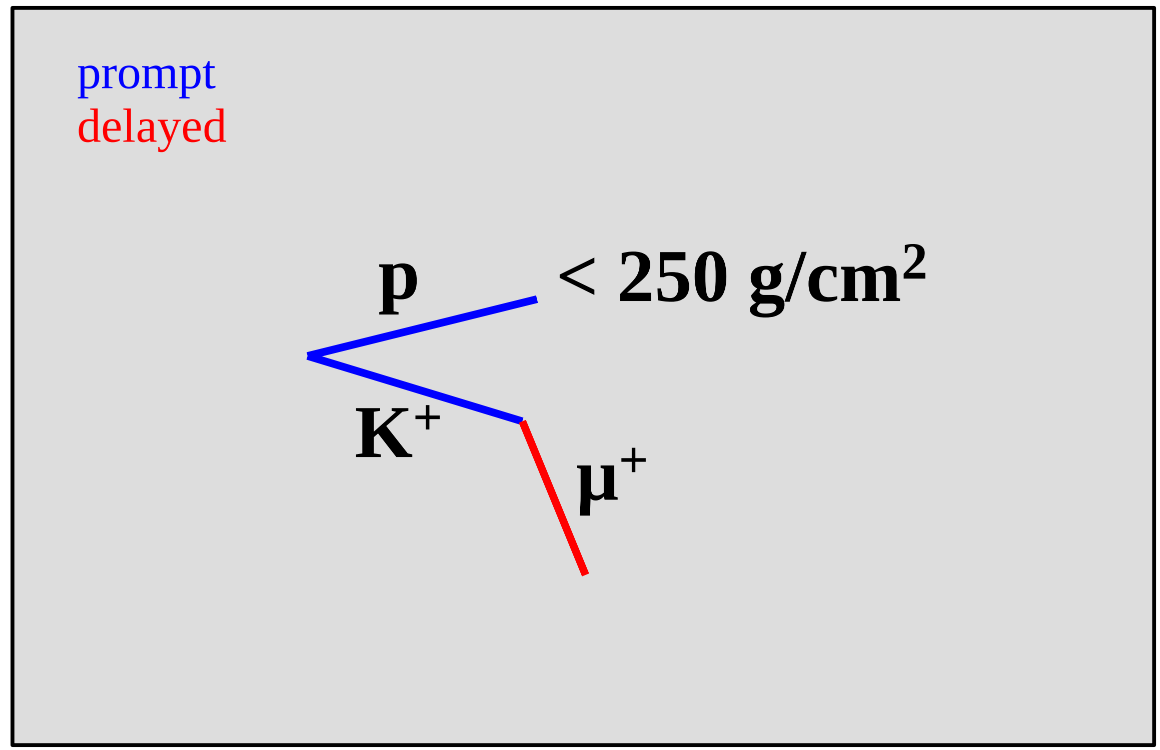


- For CC event, require a track to travel > 250 g/cm^2

UNIVERSITY of ROCHESTER

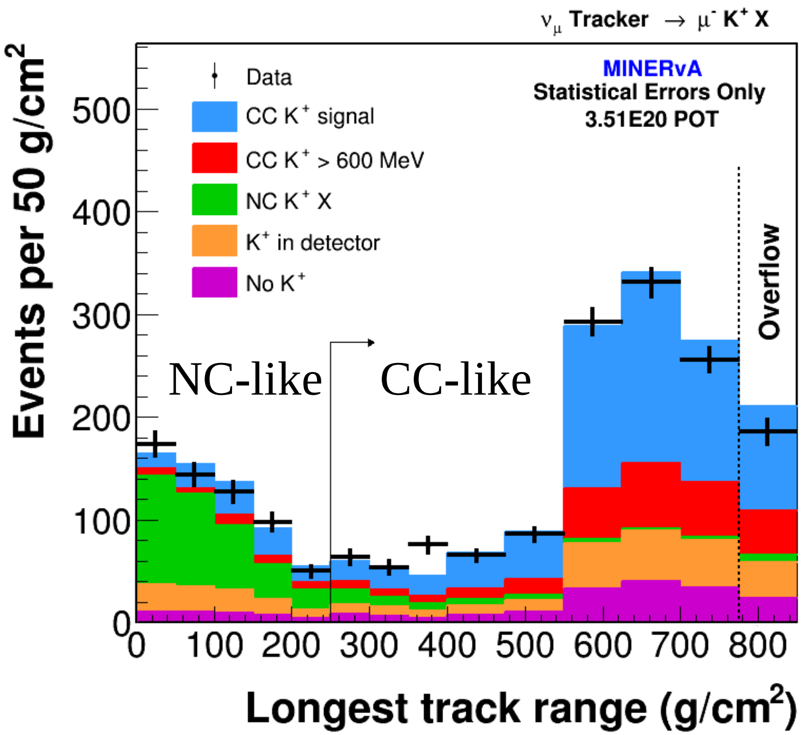
CC/NC separation

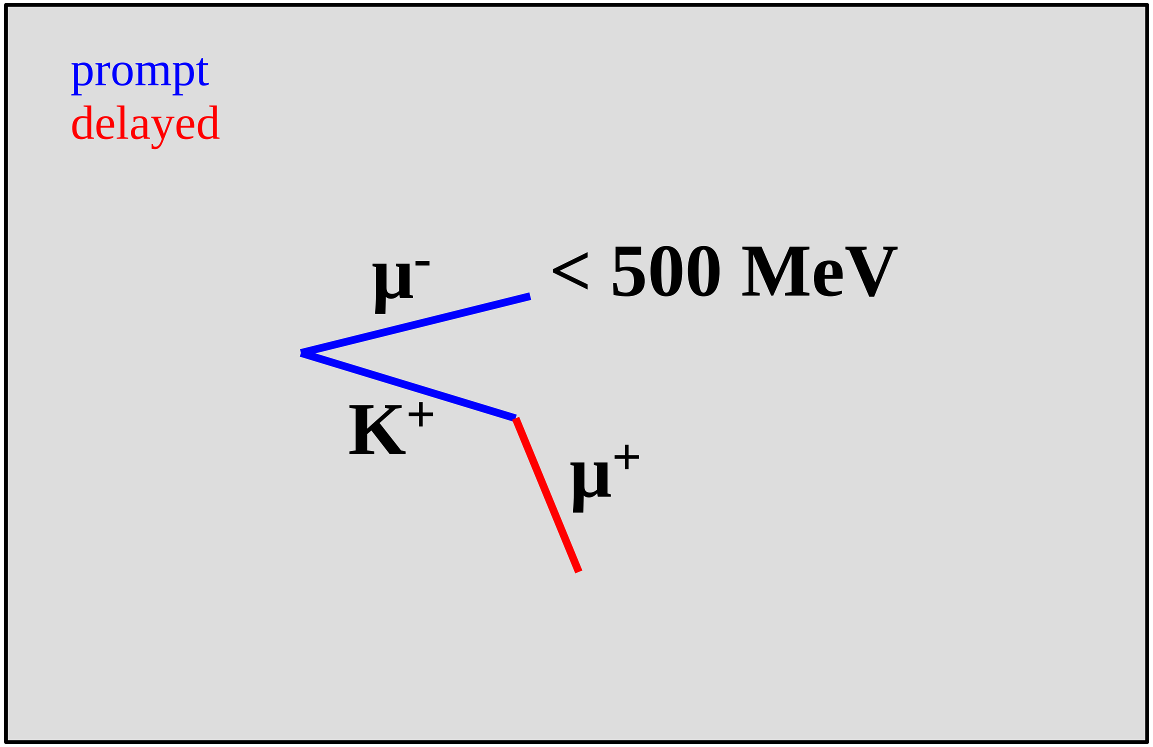




- Cut corresponds to ~3.1 nuclear interaction lengths
- Back of F.V. through calorimeters ~550 g/cm^2

CC/NC separation





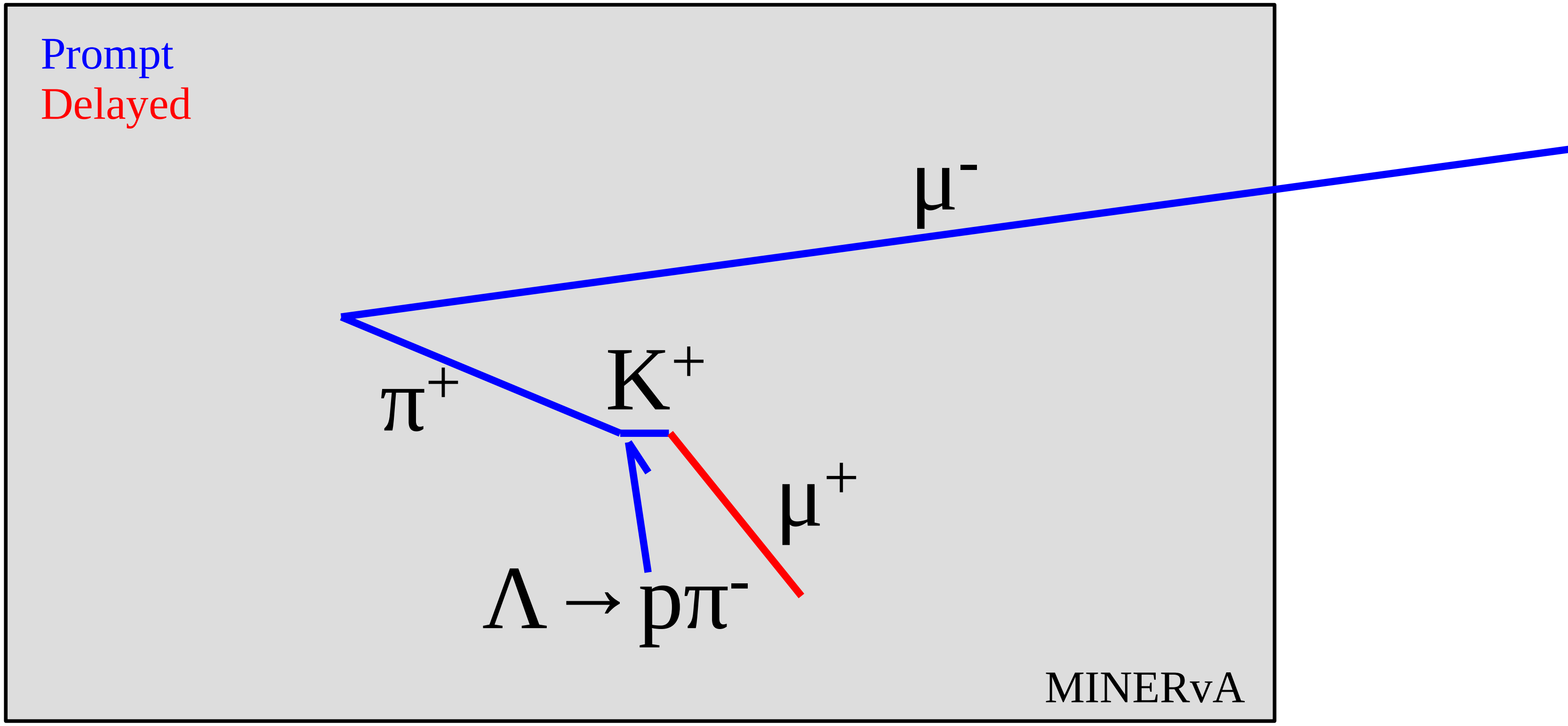
- Implicit cut on muon energy > 500 MeV for CC analysis
- Muon/pion separation at these energies is poor

We have come to a fork in the road

Now we have selected events with K^+

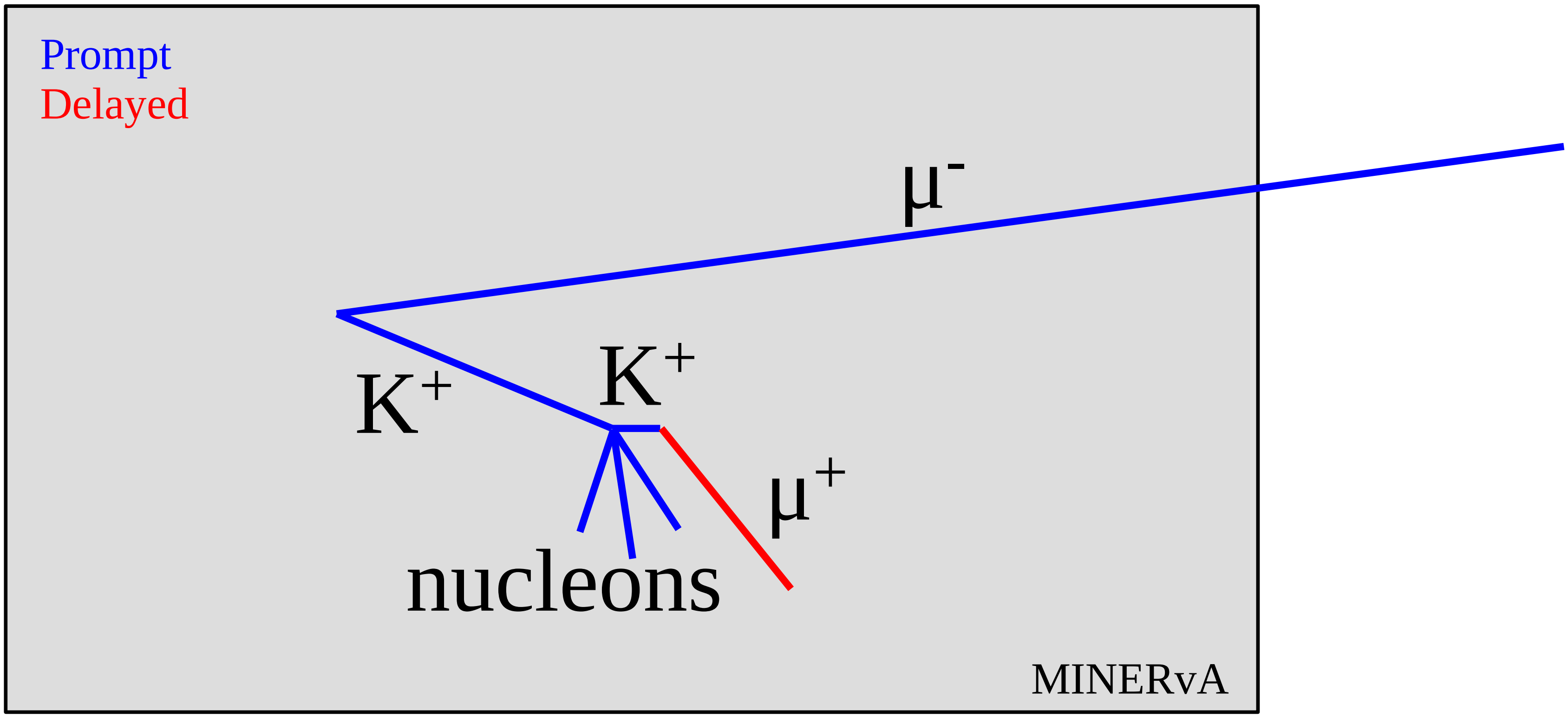
Cross section extraction is qualitatively similar for CC and NC analyses:
We will follow the CC "path"

Troublesome event #1



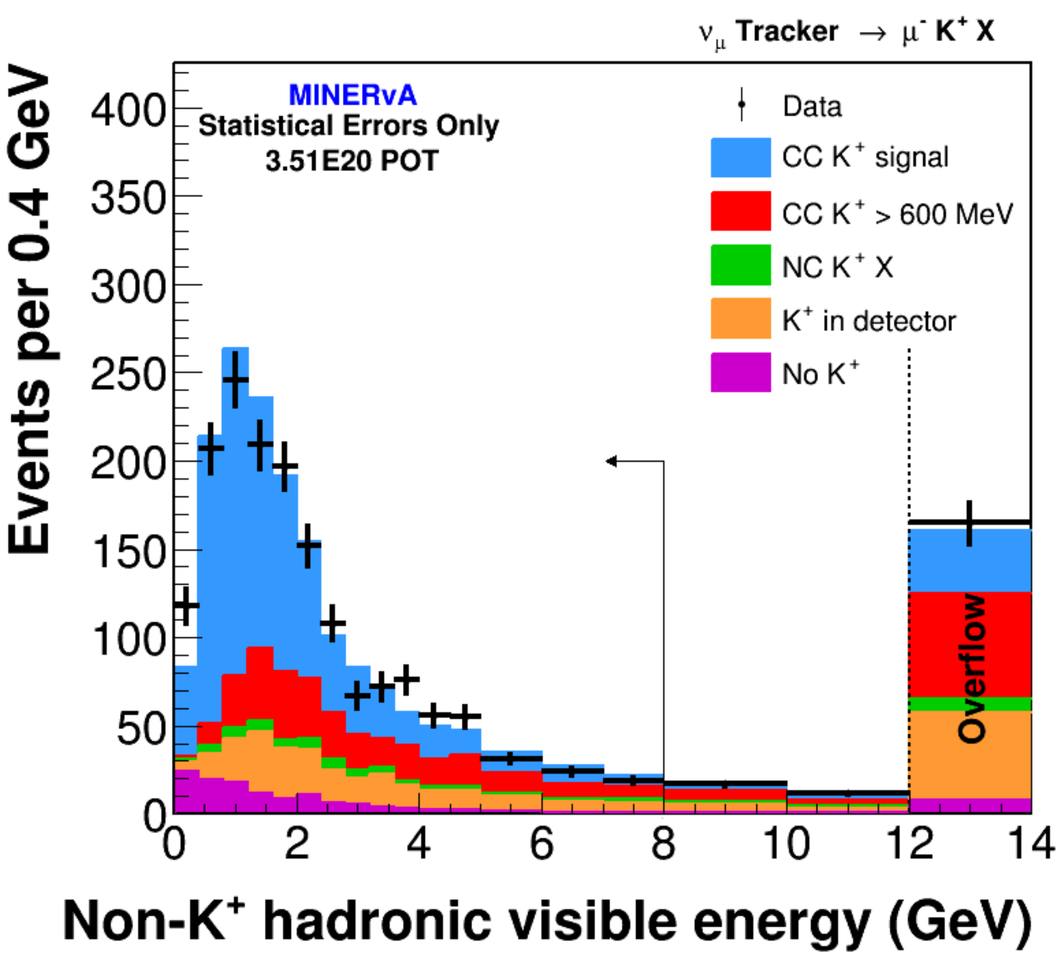
- Pion interactions that produce kaons inside the detector, but outside the target nucleus, are a background

Troublesome event #2



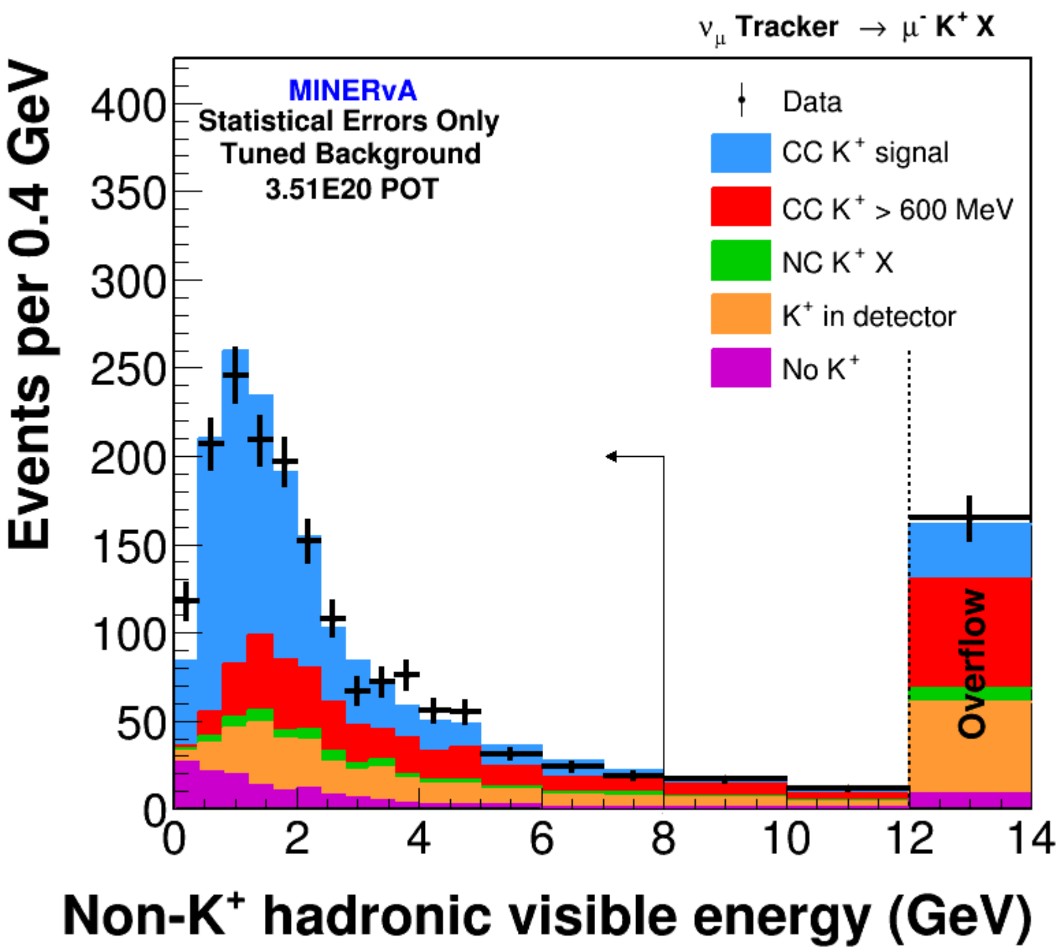
- High-energy kaons (KE > 0.6 GeV) that interact in the detector have badly misreconstructed energies

Constraining high-energy kaons and π→K in detector events



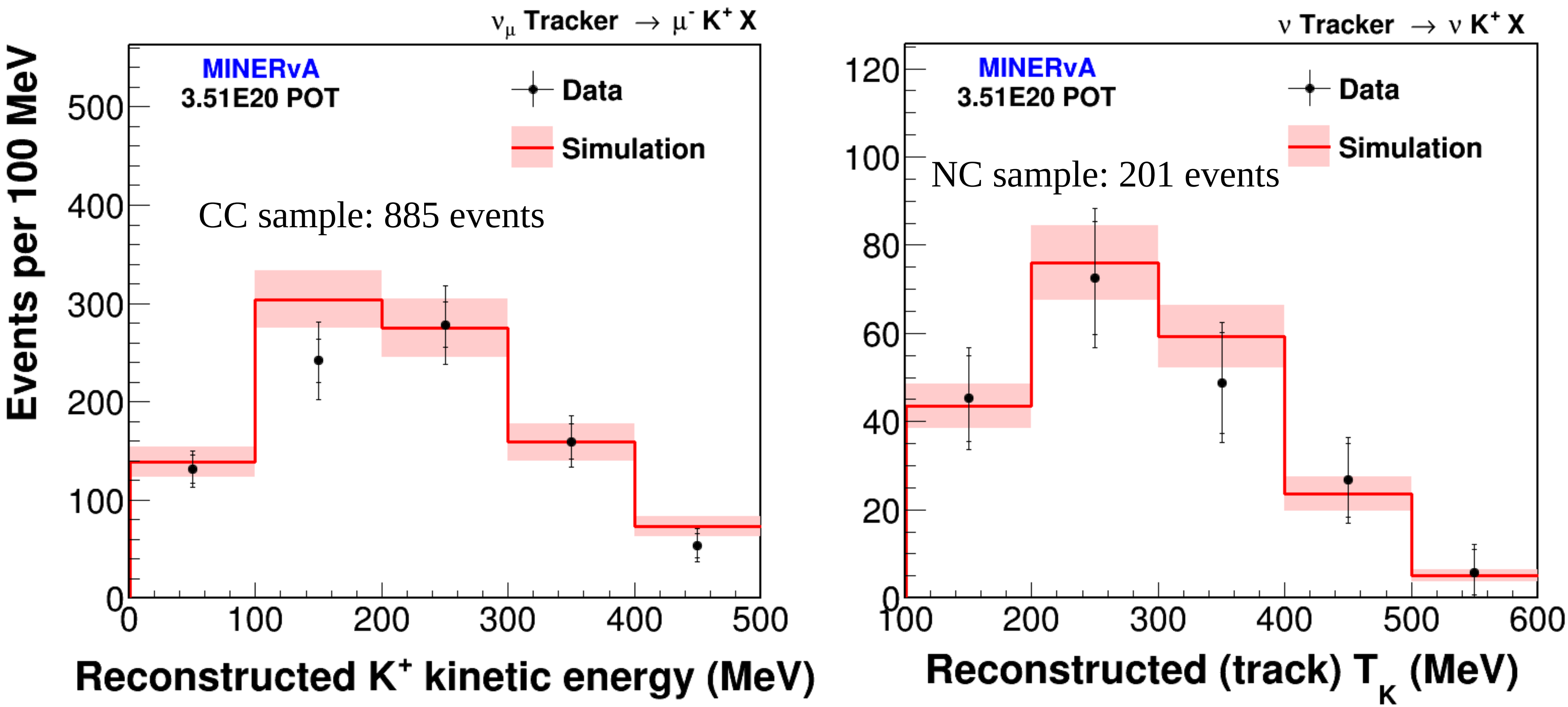
- Events with interactions have high visible energy in the detector
- Use sideband of very high hadronic visible energy

Tune the background



- Constrain the high-energy kaons, and kaons from pion interactions together

Sample sizes after background subtraction



The big picture

- Motivation for studying K^+ production by neutrinos
- Identifying K^+ in MINERvA
- Differential cross section measurements:
  - Charged-current K^+ production
  - Neutral-current K^+ production
- Search for charged-current coherent K^+ production

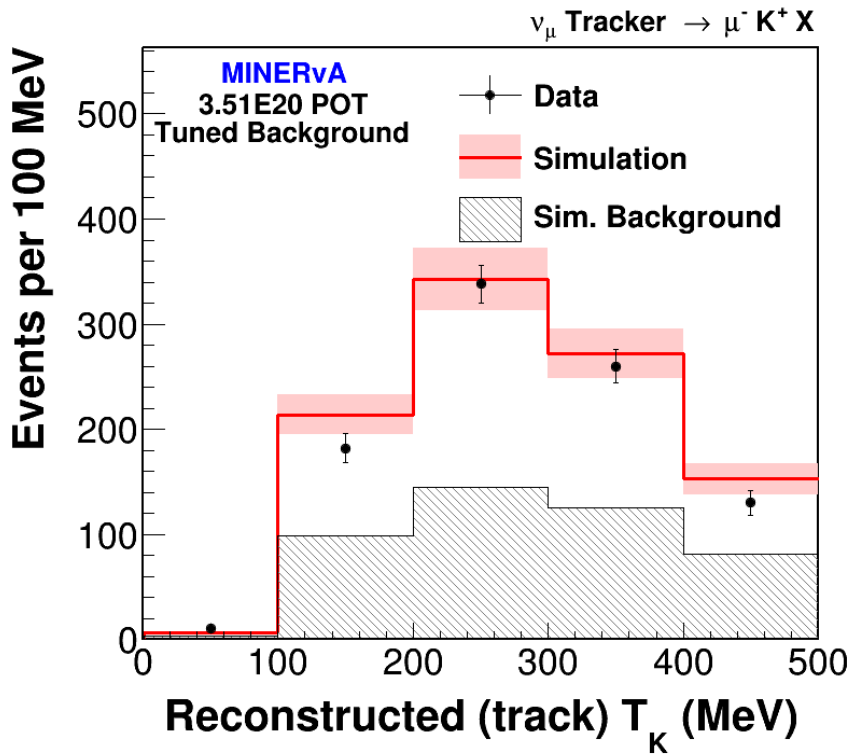
Extracting a cross section

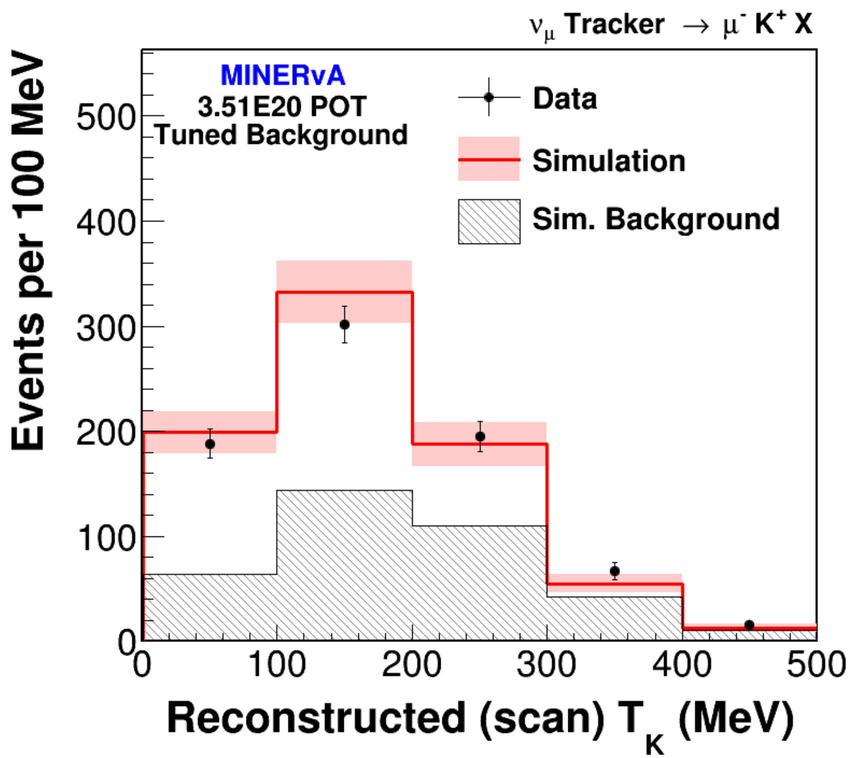
$$\left(\frac{d\sigma}{d\xi}\right)_i = \frac{1}{\Phi} \times \frac{1}{T_n} \times \frac{1}{(\Delta\xi)_i} \times \frac{\sum_j U_{ij}\left(N_j^{obs} - N_j^{bknd}\right)}{\epsilon_i}$$

- differential cross section in true bin *i*
- integrated flux
- number of targets
- bin width
- unsmearing matrix
- observed events in reconstructed bin j
- predicted background
- efficiency

Extracting a cross section

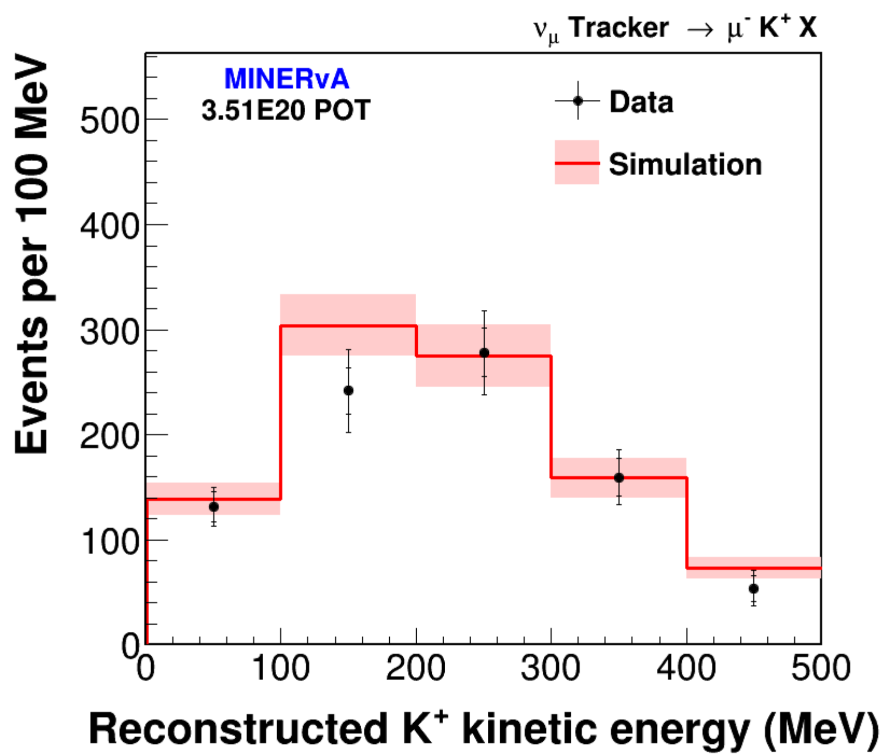
$$\left(\frac{d\sigma}{d\xi}\right)_i = \frac{1}{\Phi} \times \frac{1}{T_n} \times \frac{1}{(\Delta\xi)_i} \times \frac{\sum_j U_{ij}\left(N_j^{obs} - N_j^{bknd}\right)}{\epsilon_i}$$





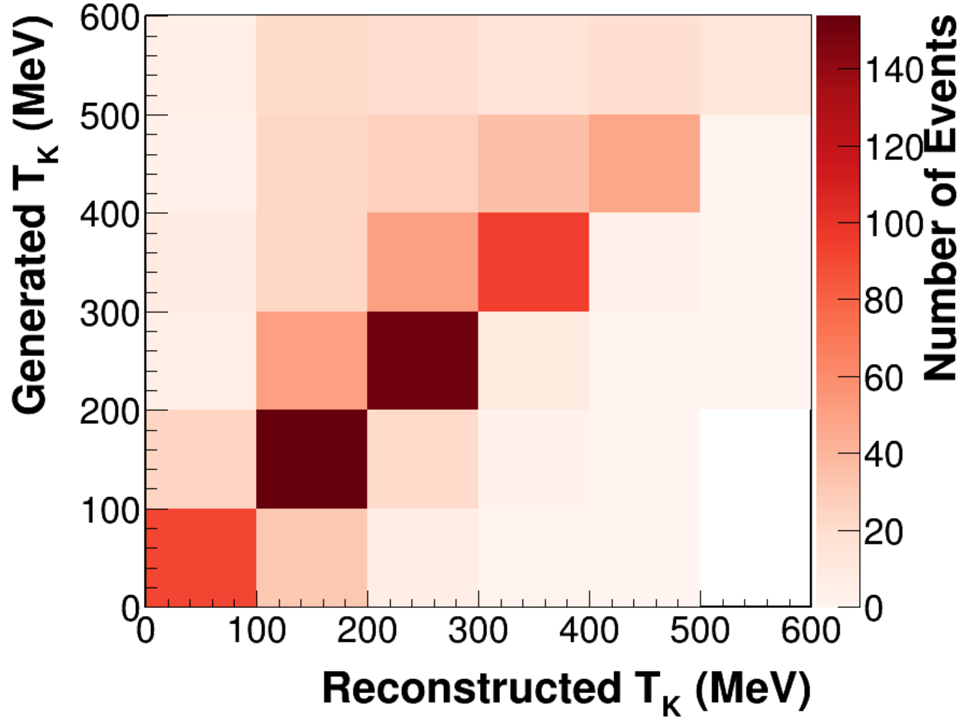
Extracting a cross section

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



Extracting a cross section

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



Extracting a cross section

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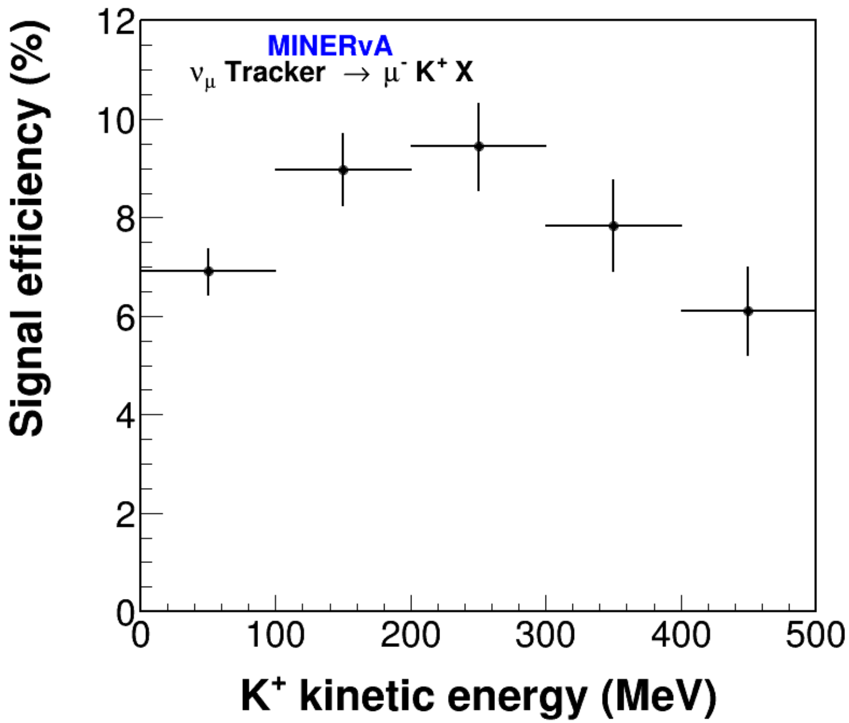
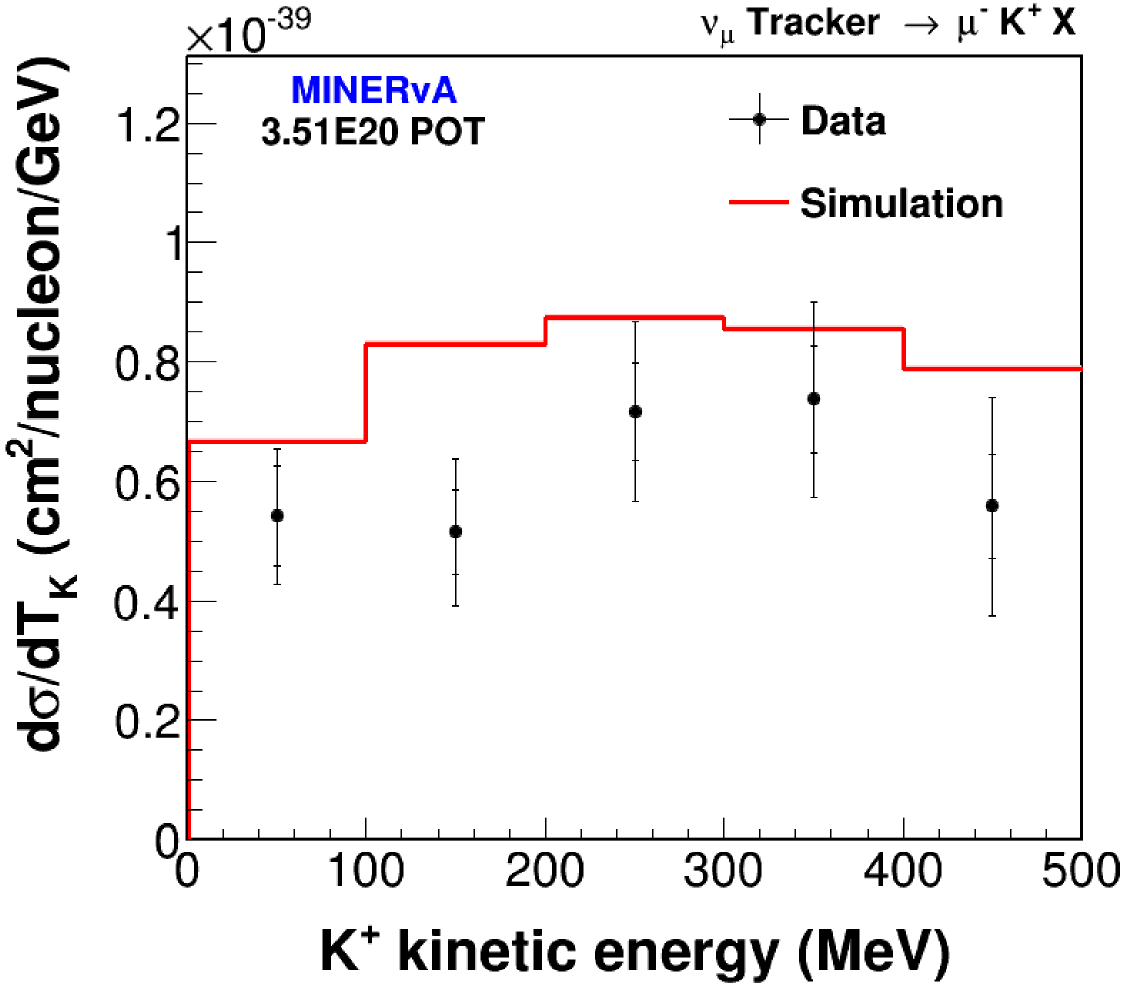
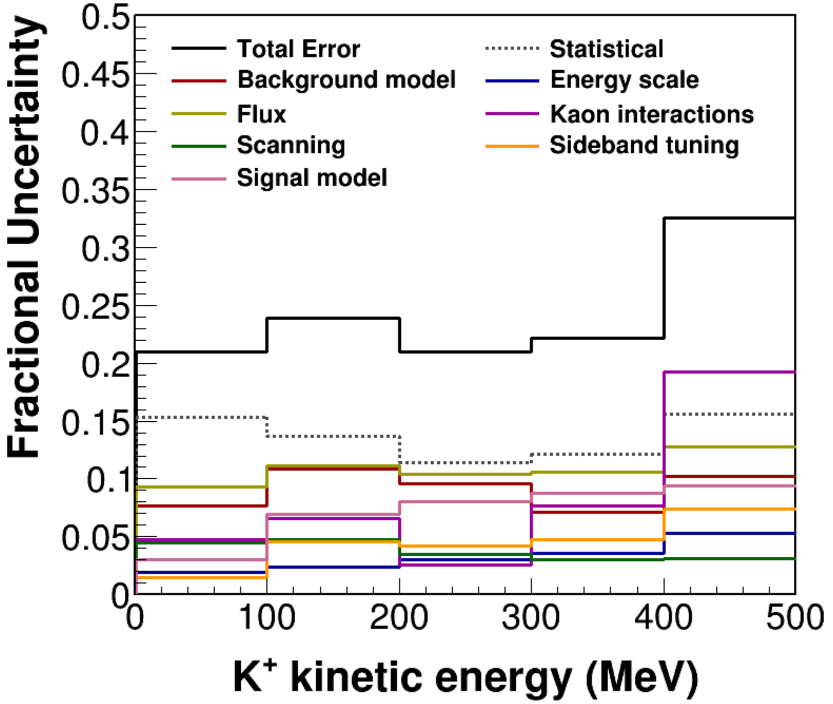
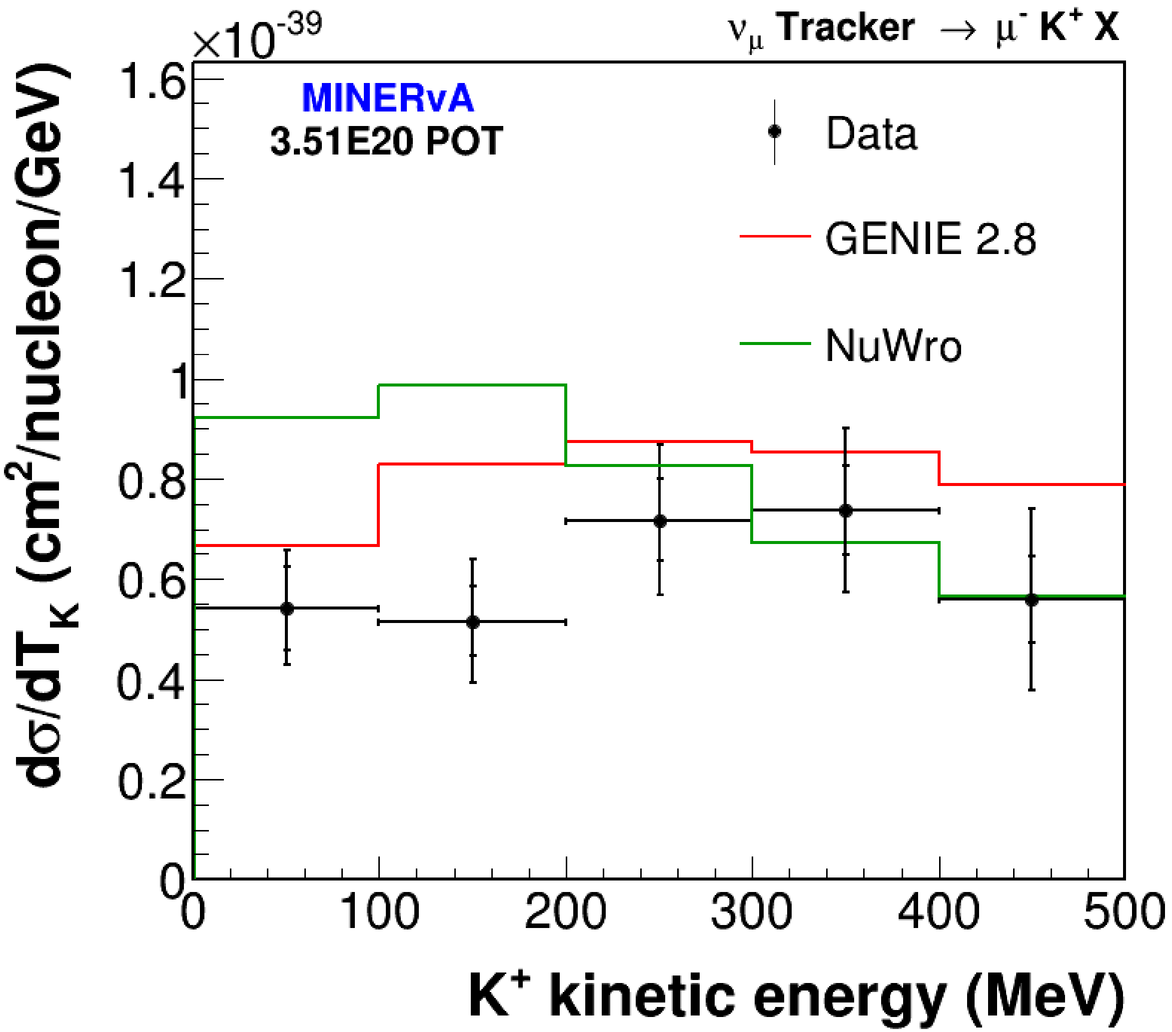


Cross section: good agreement with GENIE





Data disfavors NuWro



- Kaons in NuWro come only from hadronization (PYTHIA)
- Shape is inconsistent with NuWro at low energy

Go back to the fork

NC cross section extraction is qualitatively similar

Skip to the results instead

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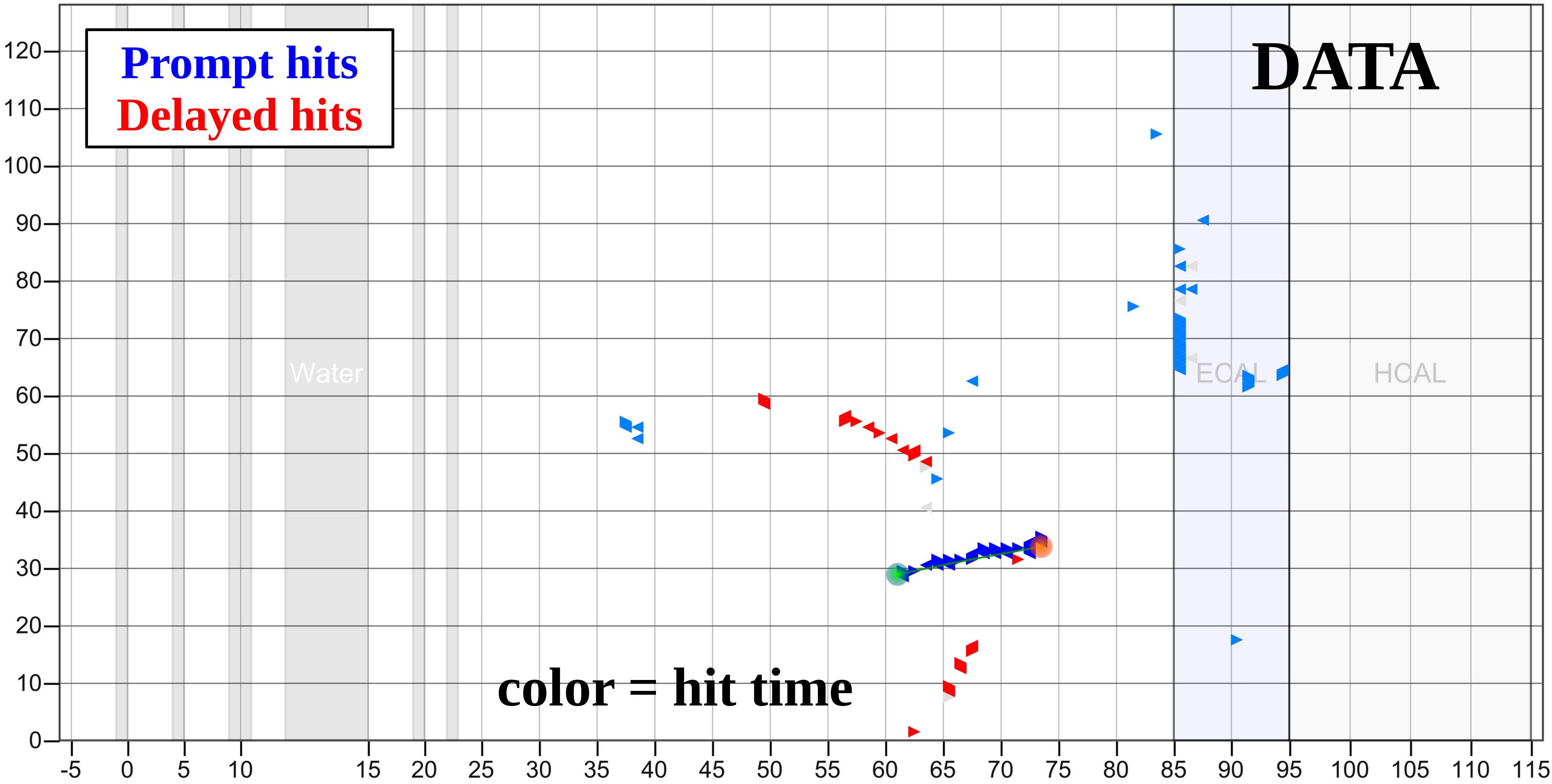
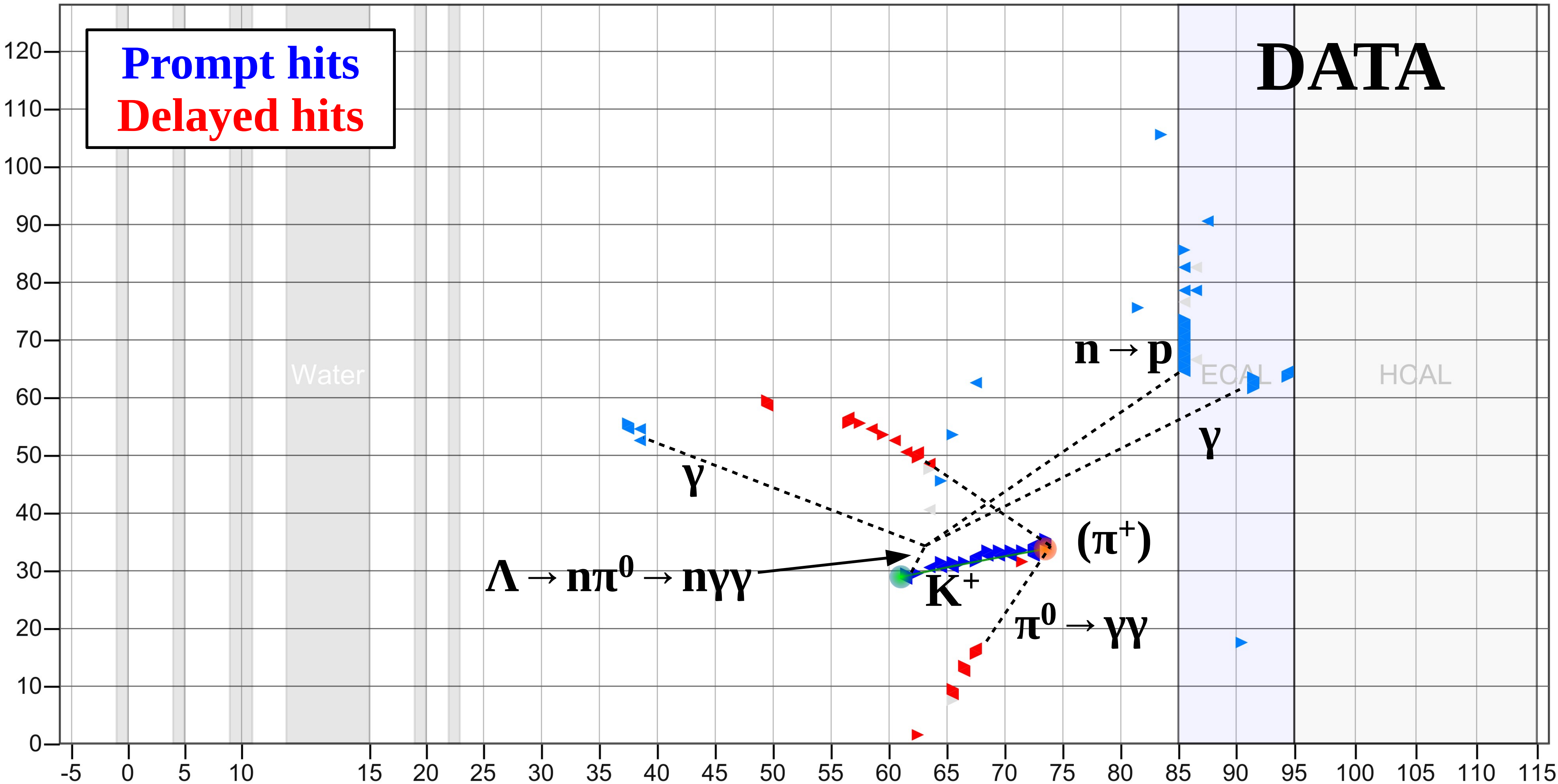
Neutral current event

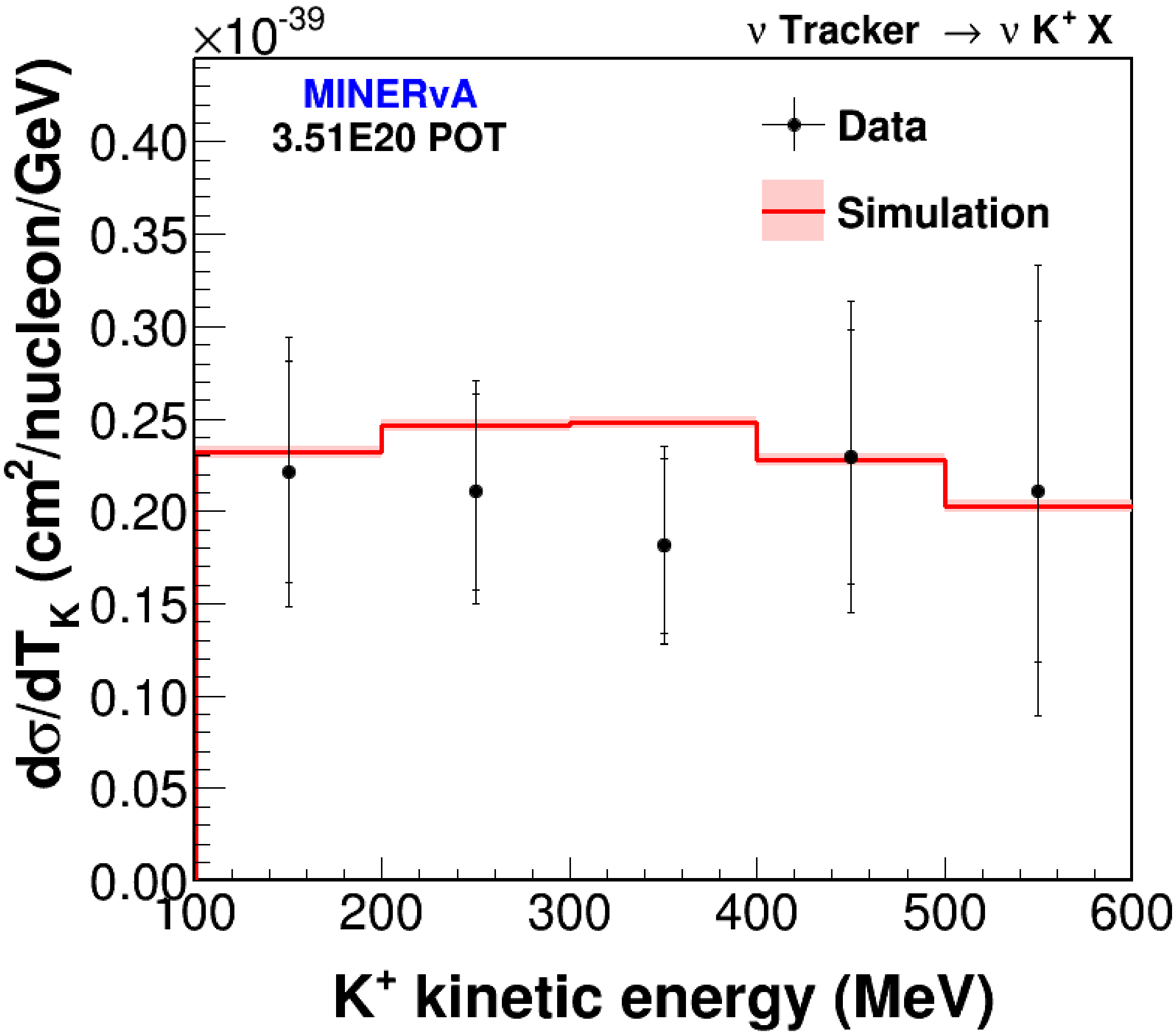


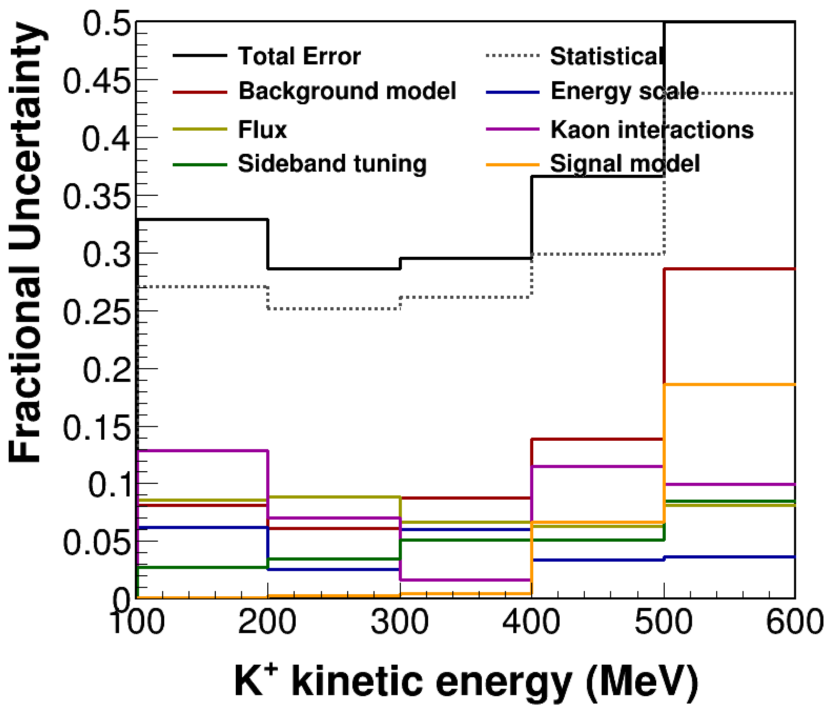
My guess



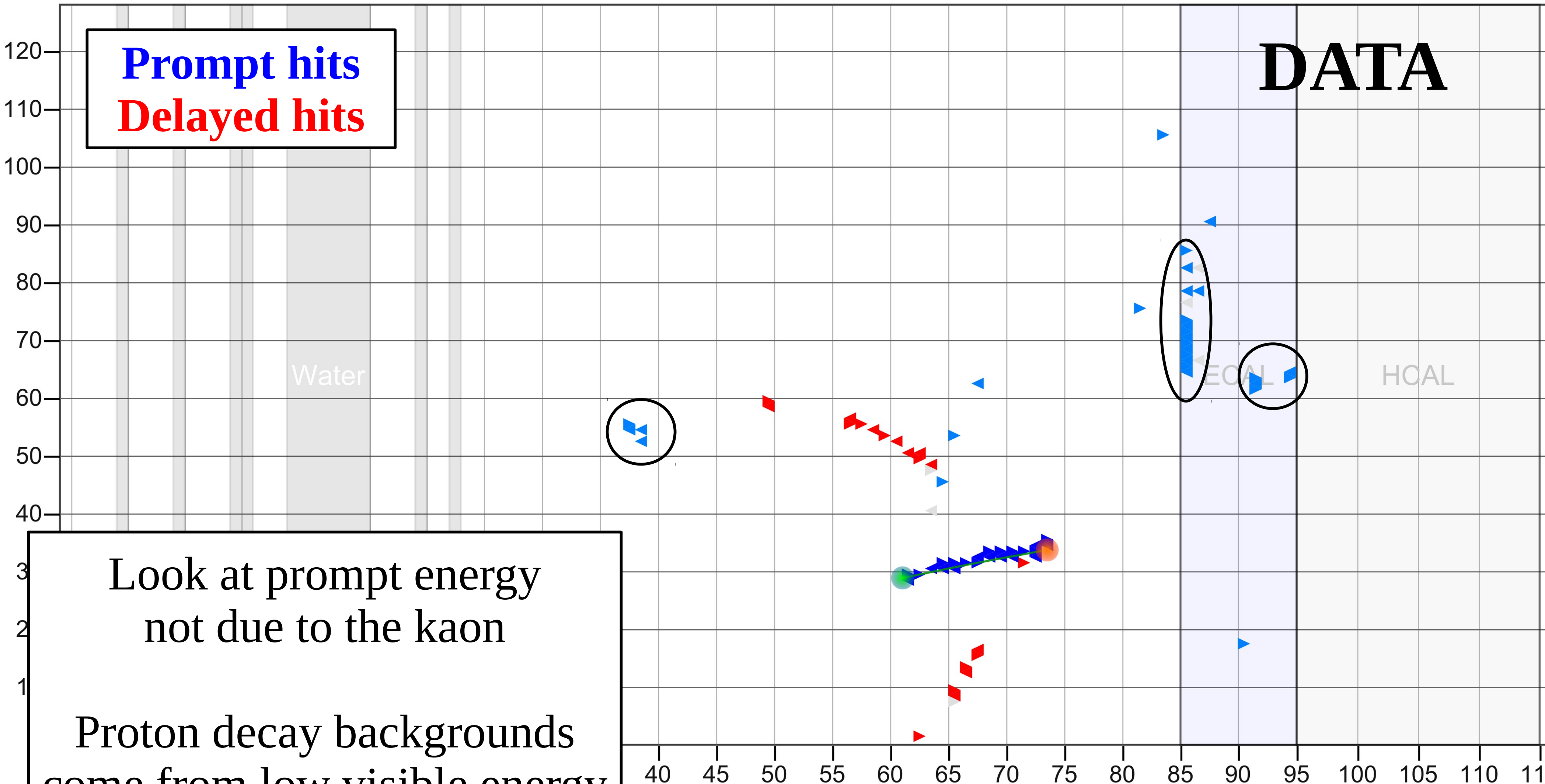
Prompt hits
Delayed hits
DATA
Water
ECAL
HCAL
n → p
γ
γ
(π+)
Λ → nπ0 → nγγ
K+
π0 → γγ

Cross section: good agreement with GENIE





Additional measurement: non-kaon visible energy



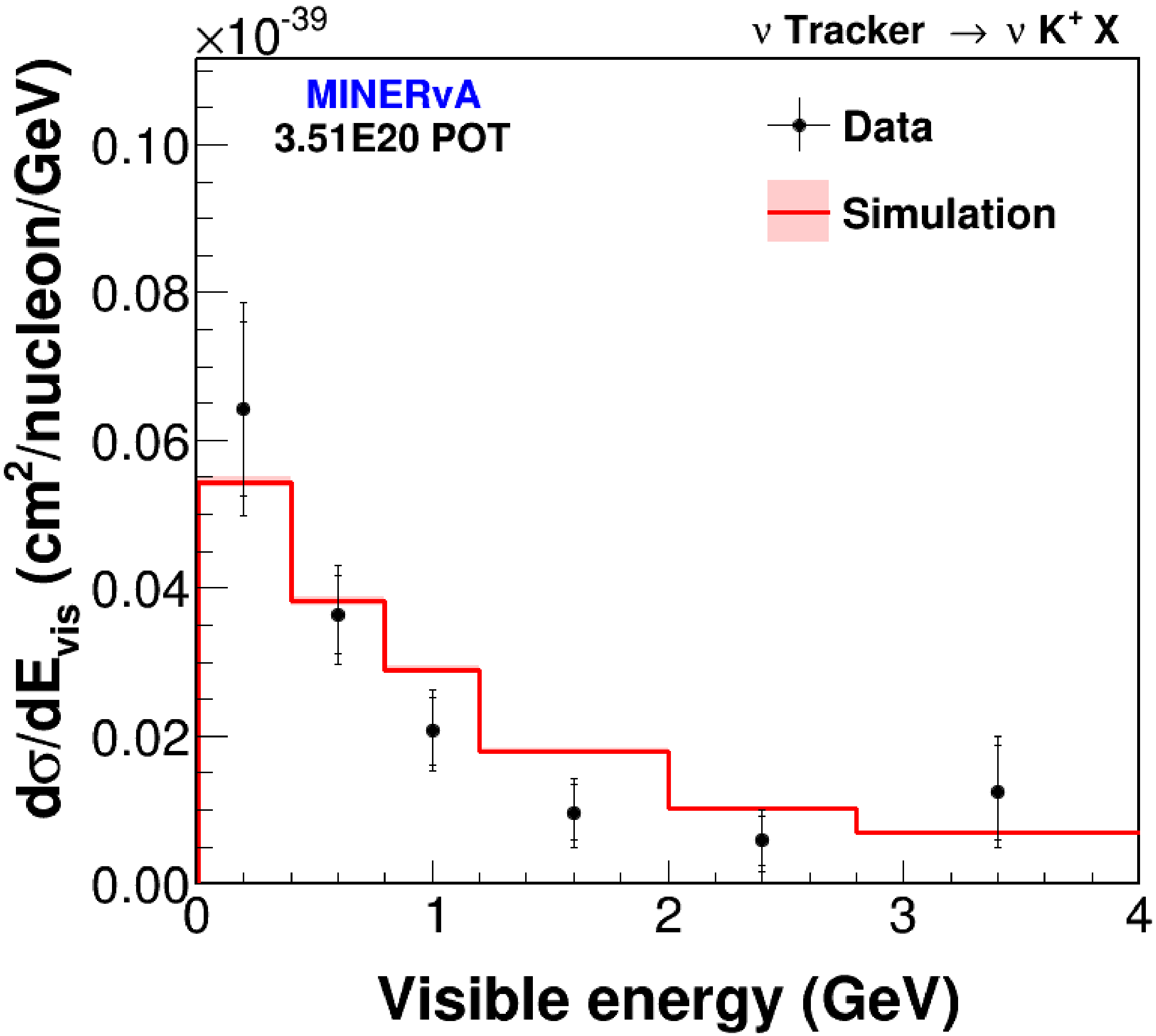
Look at prompt energy not due to the kaon

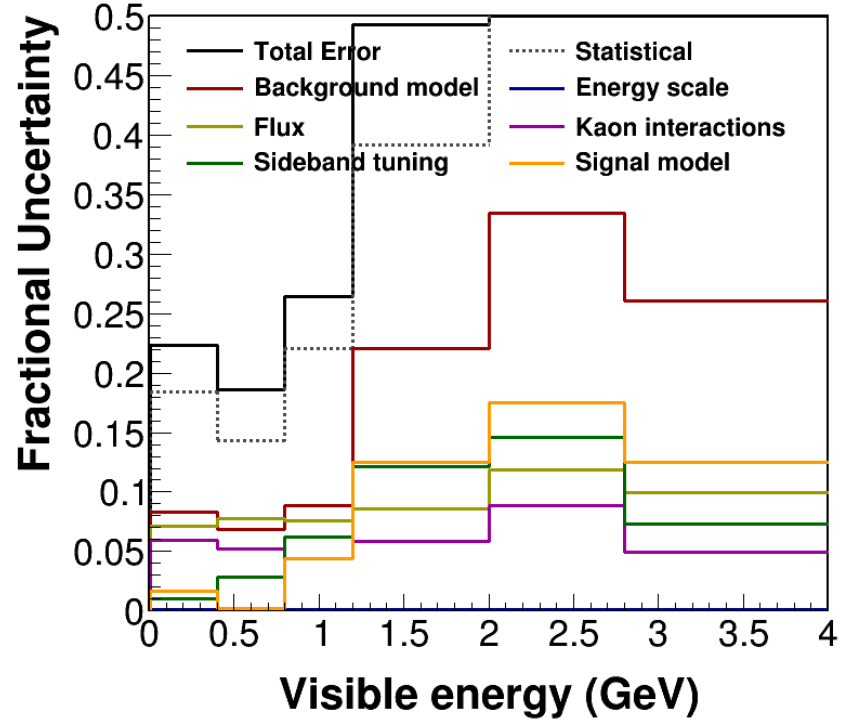
Proton decay backgrounds come from low visible energy

Defining a model-independent proxy for "visible energy"

- Total non-kaon hadron energy is $\nu - E_K$
- But detector response to neutrons, protons, pions is very different – we don't want to rely on a Monte Carlo to tell us how the energy is distributed
- Define "true visible energy":
  - Kinetic energy of p, $\pi^{\pm}$, K^{-}
  - Total energy of π^{0}, K^{0}
  - Include prompt decay products of strange baryons Λ, Σ

Visible energy cross section





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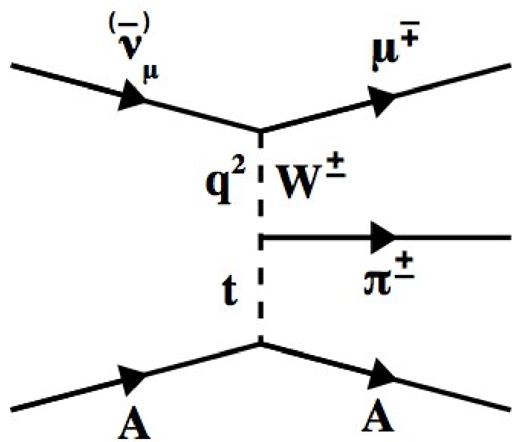
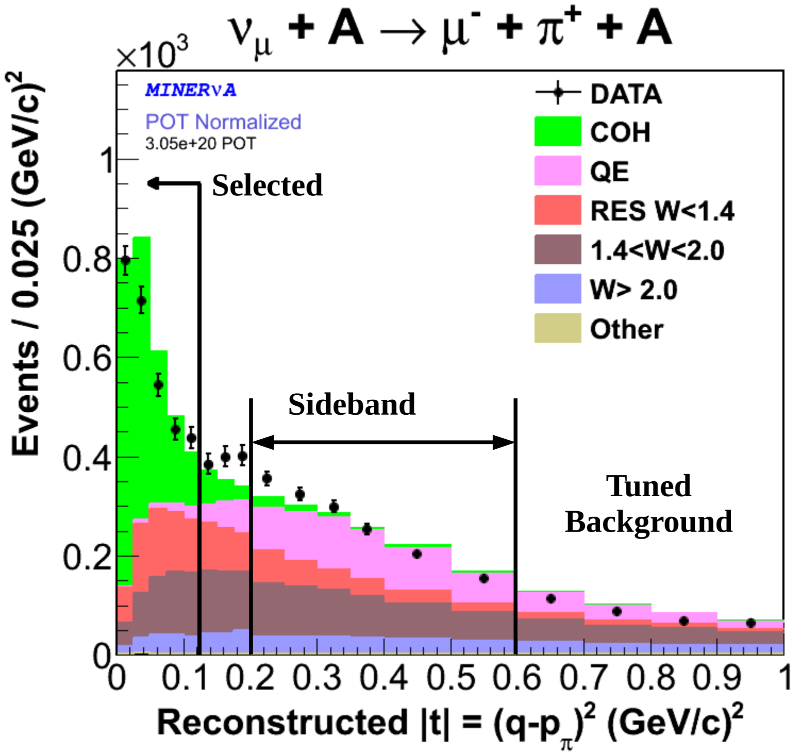
Coherent meson production

Phys. Rev. Lett. 113, 261802 (2014)

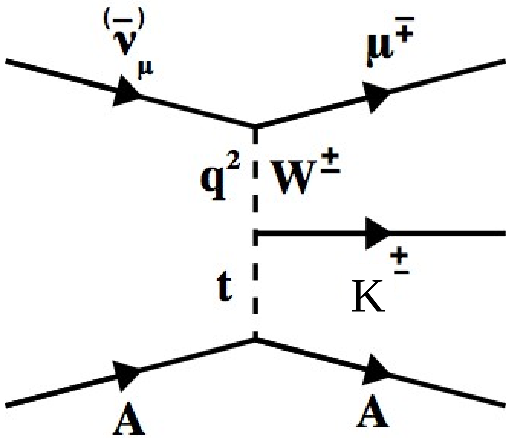


$$t = |q - p_\pi|^2$$



- Neutrino interacts with entire nucleus, which remains in its ground state
- Characterized by small four-momentum transfer to nucleus

Coherent kaon production?

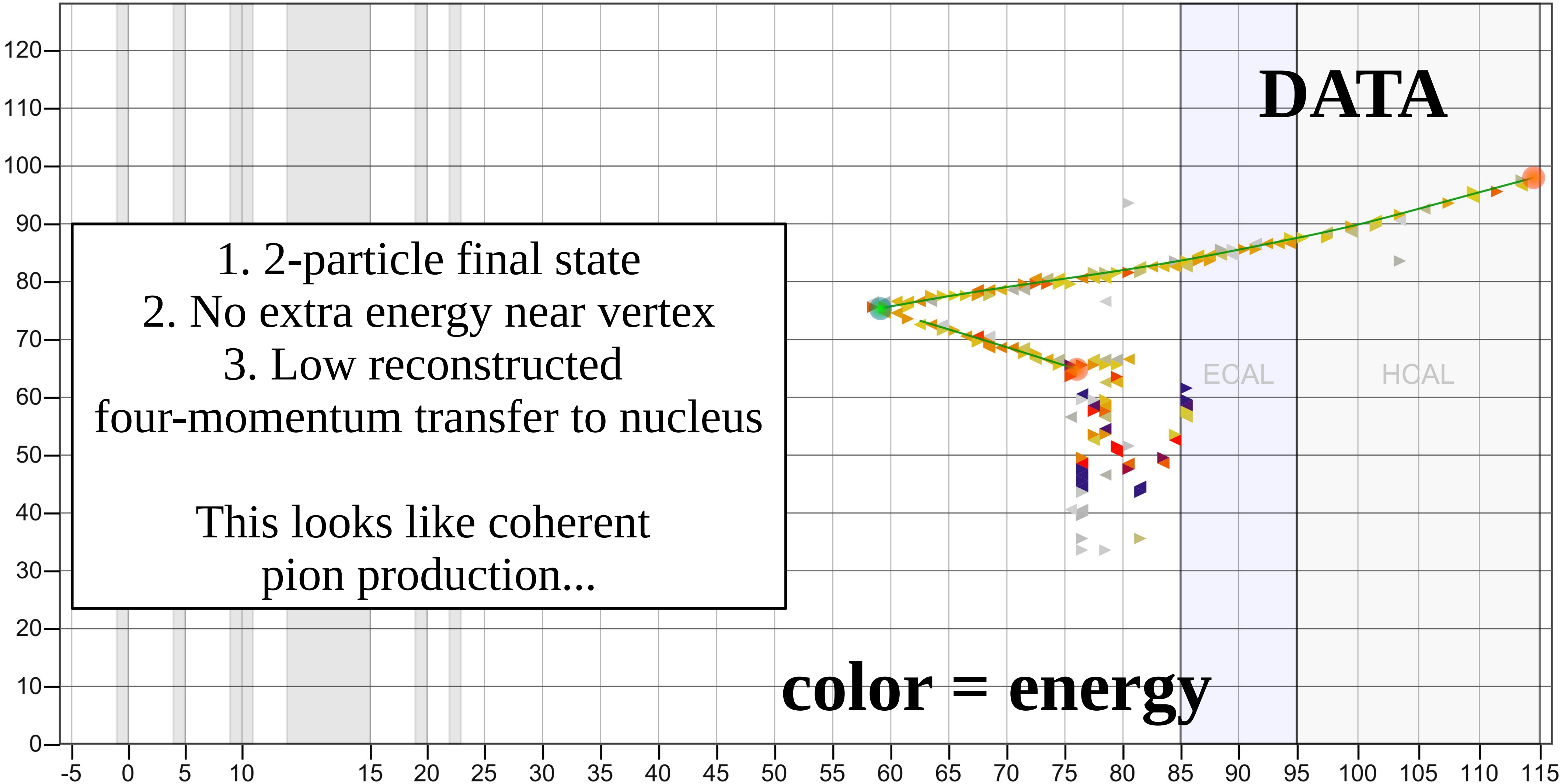


$$\mathbf{t = |q - p_K|^2}$$

Expect factor of ~20 Cabibbo suppression, plus additional factor of ~4 phase space suppression due to heavier final state

- Never been observed experimentally
- Theoretical prediction from L. Alvarez-Ruso et al., Phys. Rev. **C** 87, 015503

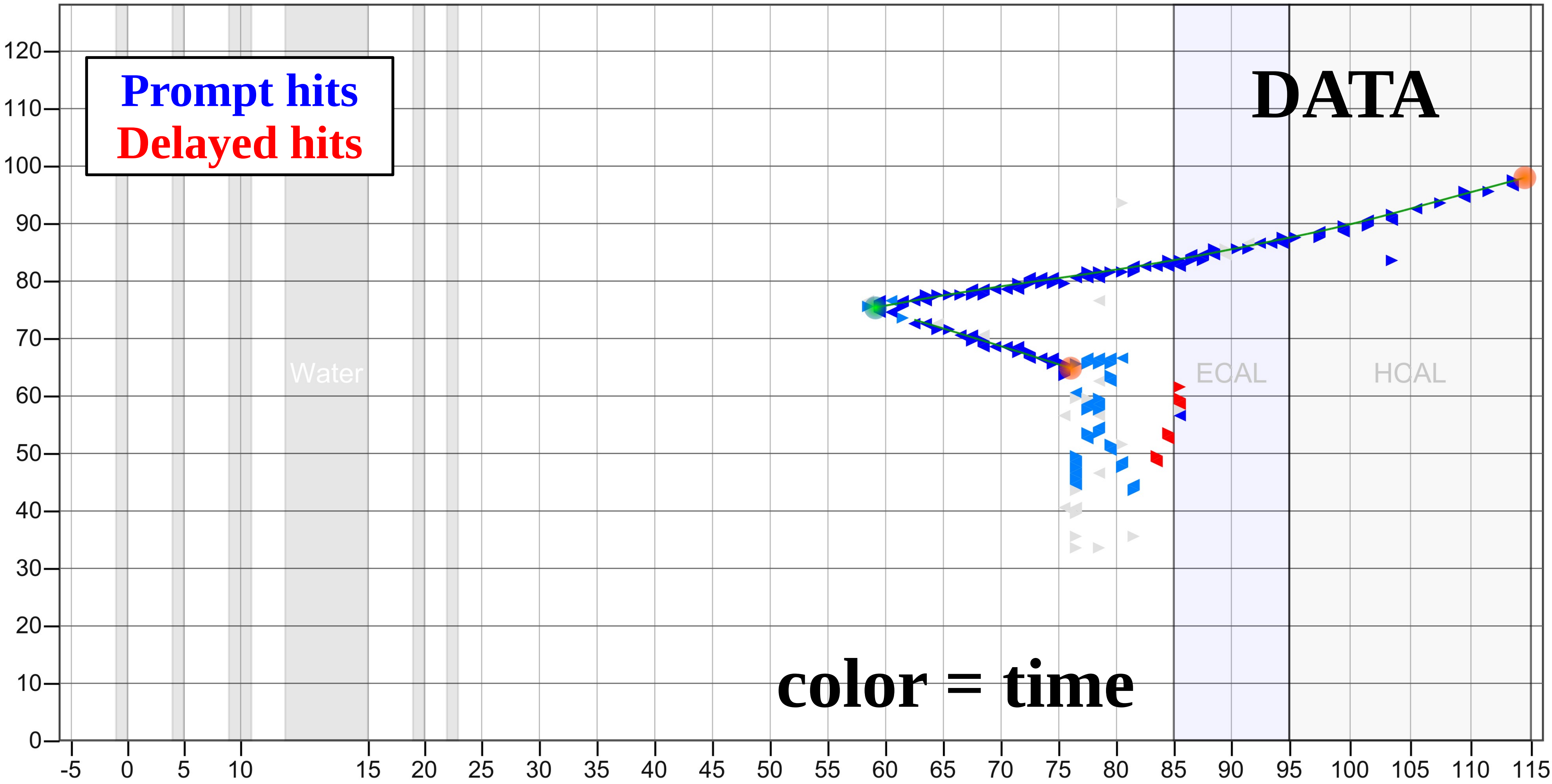
Coherent kaon production?



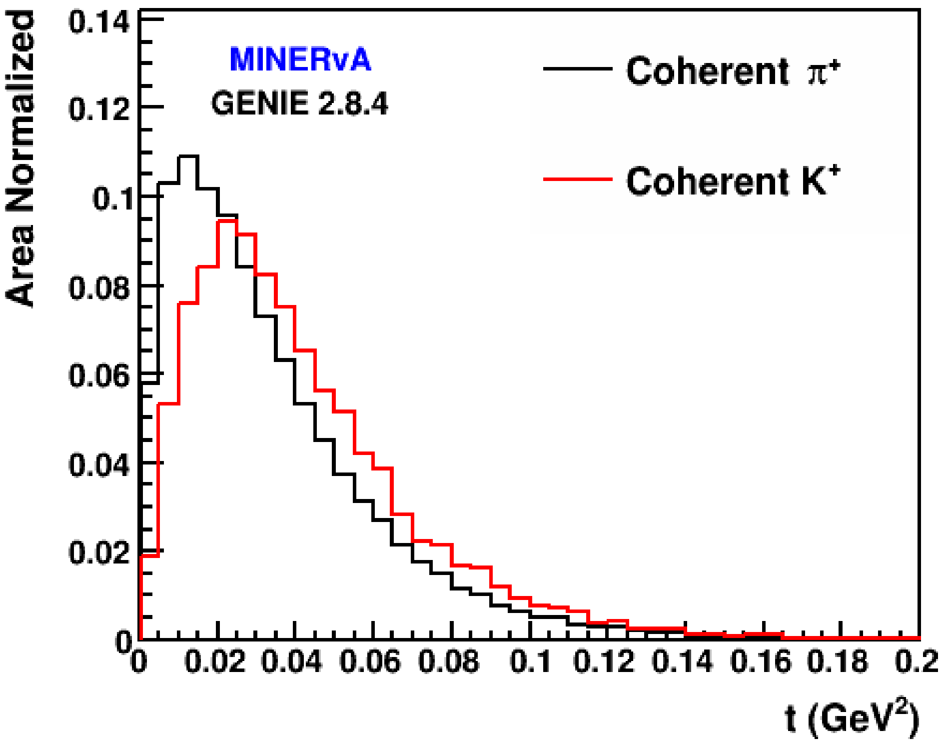
1. 2-particle final state
2. No extra energy near vertex
3. Low reconstructed four-momentum transfer to nucleus

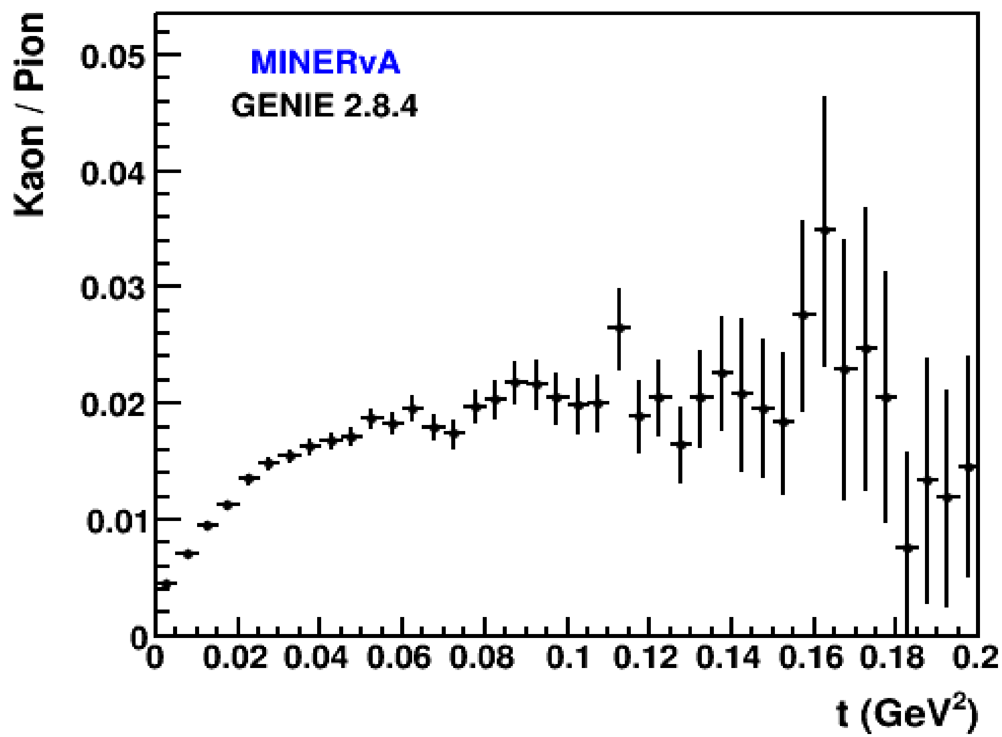
This looks like coherent pion production...

Coherent kaon production?



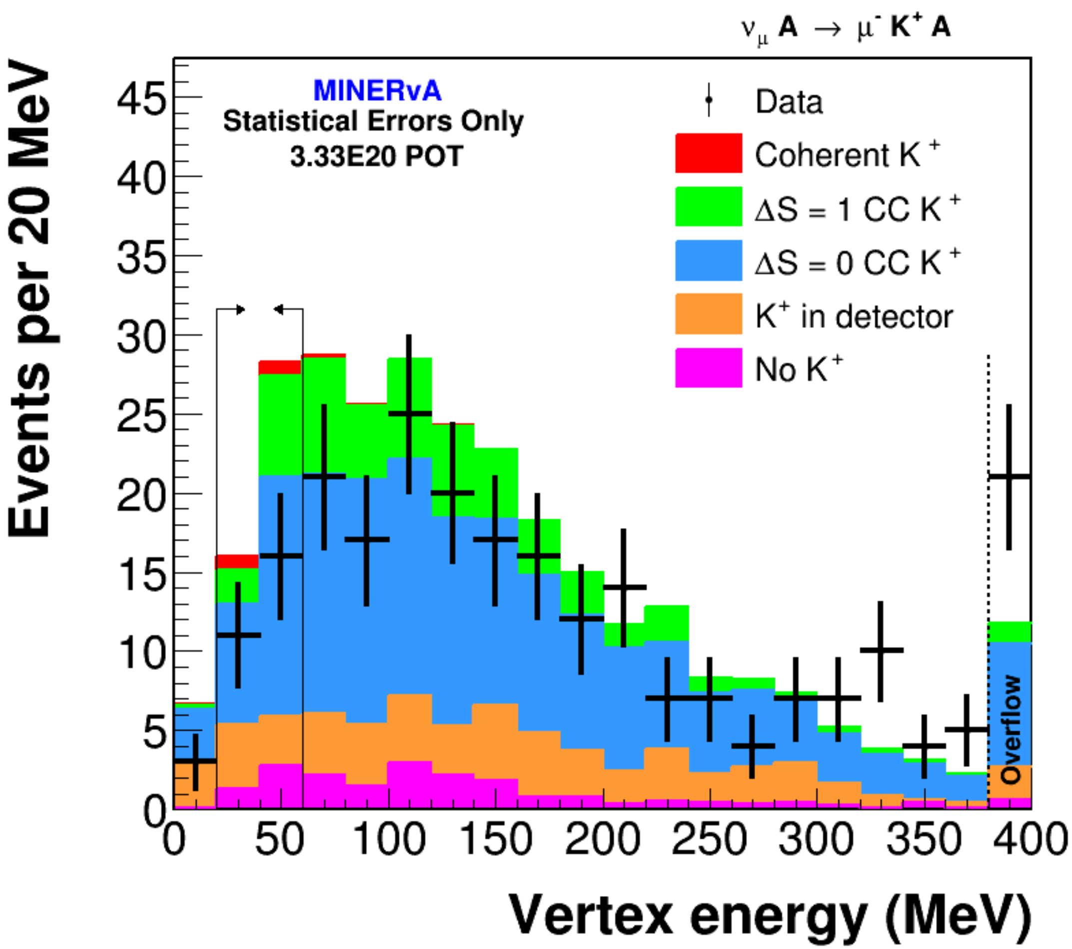
Coherent signal simulation





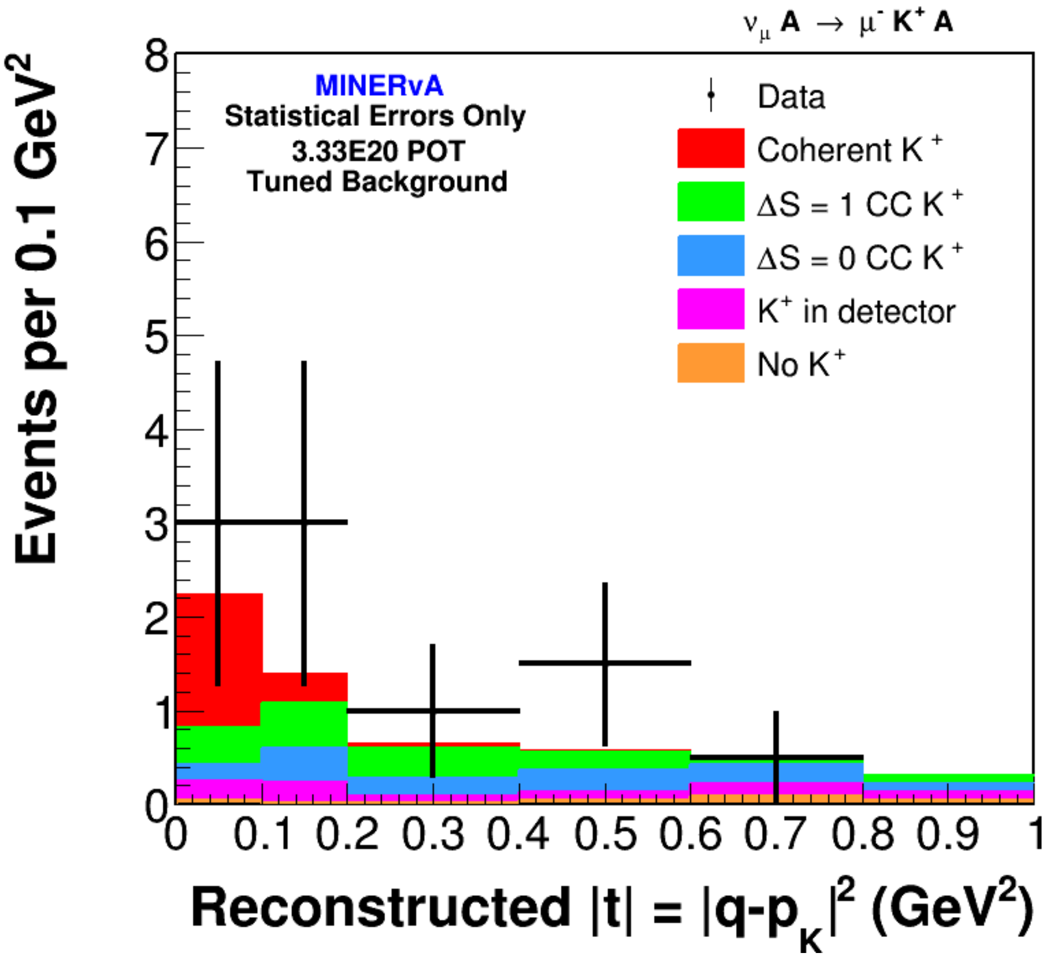
- Take coherent π^+ events from GENIE 2.8, and replace the π^+ with a K^+
- Assumes π-A and K-A elastic cross sections are equal
- MC only used for shape of reconstructed t

Energy ~10cm around vertex



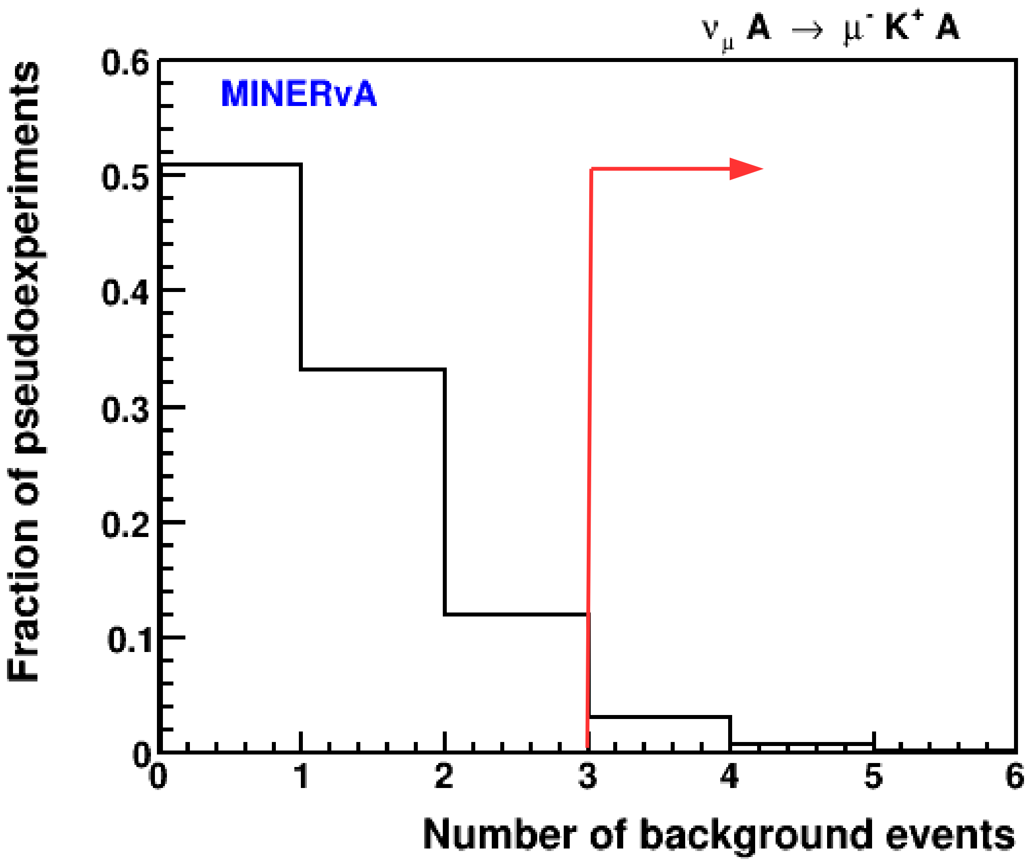
- Require two tracks, with vertex energy between 20 and 60 MeV
- Red is coherent signal MC

Reconstruct t from muon and kaon 4-vectors



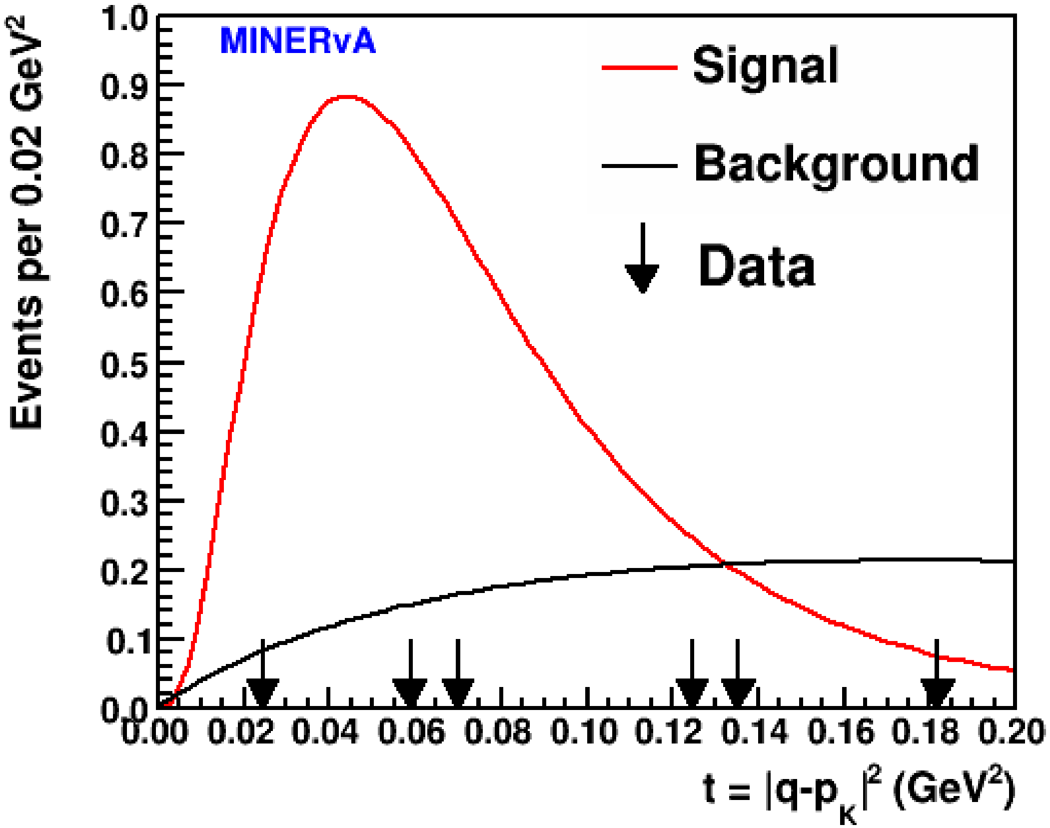
- Cut on vertex energy, no isolated showers from π^0
- Tune background to sideband region
- Event counting analysis: signal region $t < 0.1$ was chosen blind
- Spectral analysis: use $t < 0.2$

Event counting analysis: Reject null hypothesis at 96%



- Probability to observe 3 or more background events is 3.9%

Spectral analysis



For background and signal PDFs B and S,

$$\mathcal{L}(\mu) = \prod_{data\ i} (\mathtt{B}(t_i) + \mathtt{S}_\mu(t_i))$$

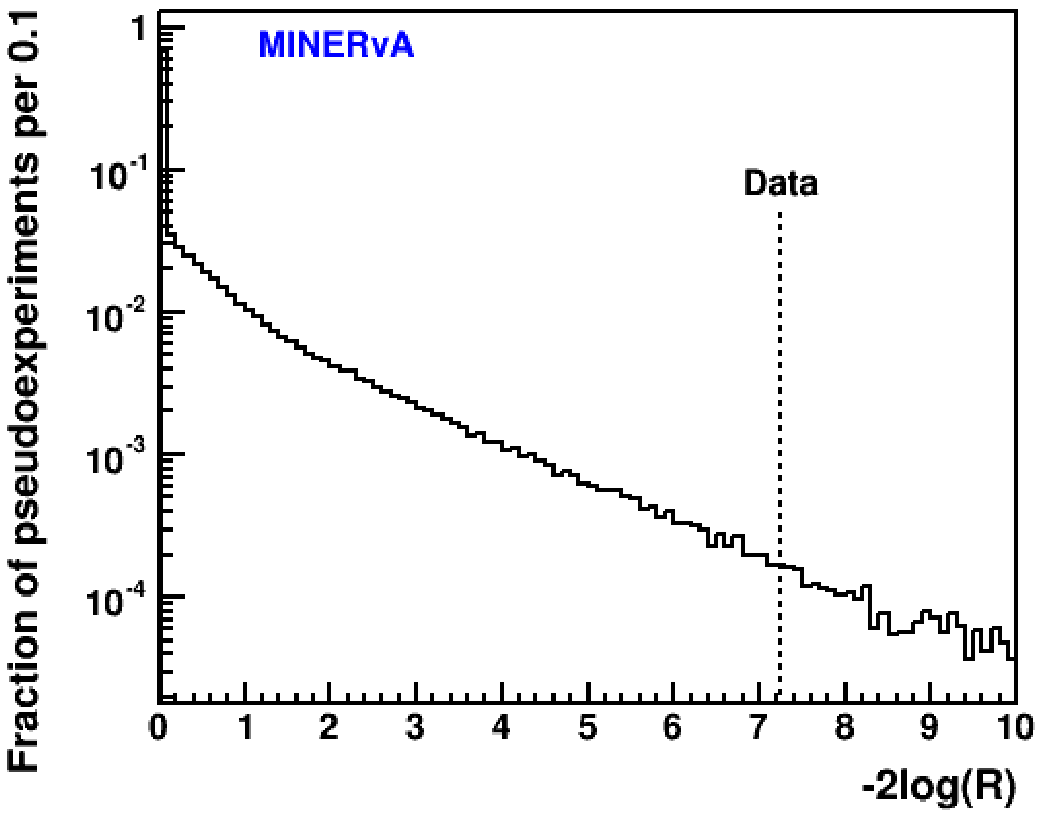
where μ is the integrated number of signal events:

$$\int_0^{0.2} \mathtt{S}_\mu(t)dt = \mu$$

R is the likelihood ratio of the null hypothesis (μ = 0) to the best-fit value of μ

$$R = \frac{\mathcal{L}(0)}{\mathcal{L}(\mu_{best})}$$

Spectral analysis



- μ_{best} in data is 4.0
- $-2\log(R) = 7.24$
- In background-only pseudoexperiments, the probability to observe $-2\log(R) > 7.24$ is 0.3%
- 3σ observation of coherent K^+ signal in spectral analysis

Summary

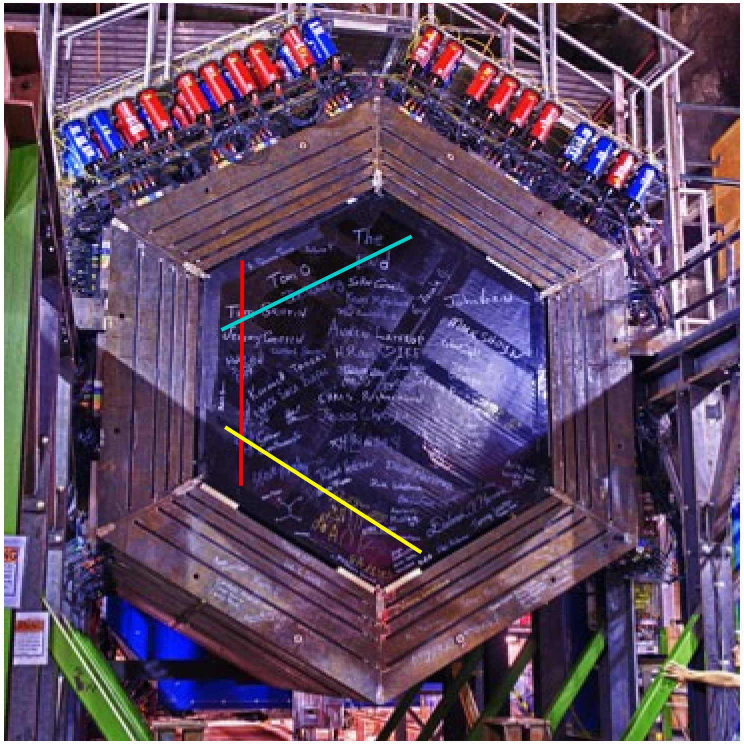
- MINERvA has made the best measurement to date of charged-current and neutral-current K^+ production by neutrinos
- Probed FSI by studying kaon spectrum
- Looked for “kaon plus nothing” neutral current events that could fake proton decay signal
- Observed charged-current coherent K^+ production at 3σ
- GENIE cross section + nuclear model does a good job of reproducing the data – great news for DUNE & Hyper-K nucleon decay searches

Thank you

The MINERvA collaboration in Duluth, Minnesota, 2014

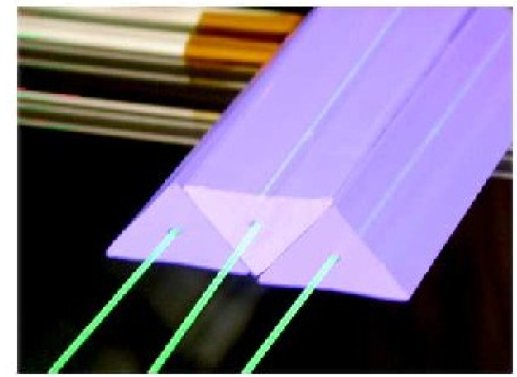
Backups

The MINERvA detector



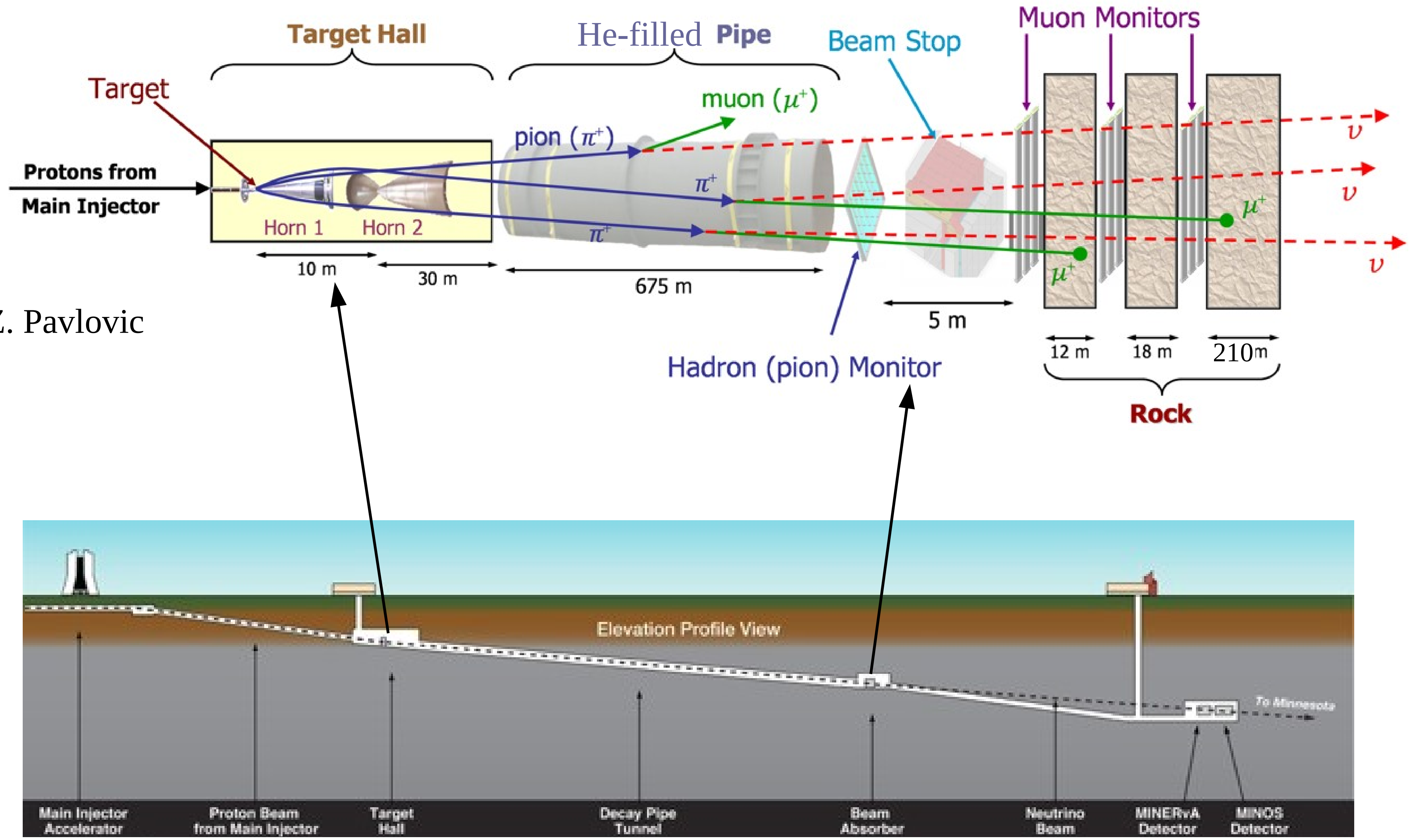
Plane views:
1. Vertical bars
2. +60°
3. –60°

208 active planes × 127 scintillator bars



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

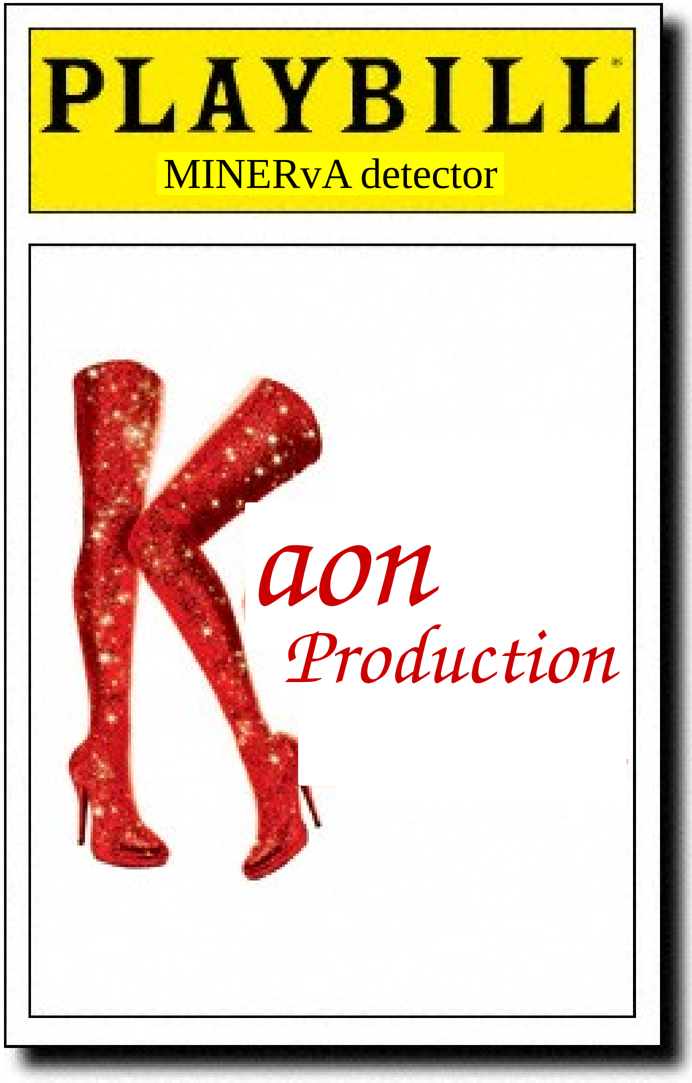
NuMI beamline



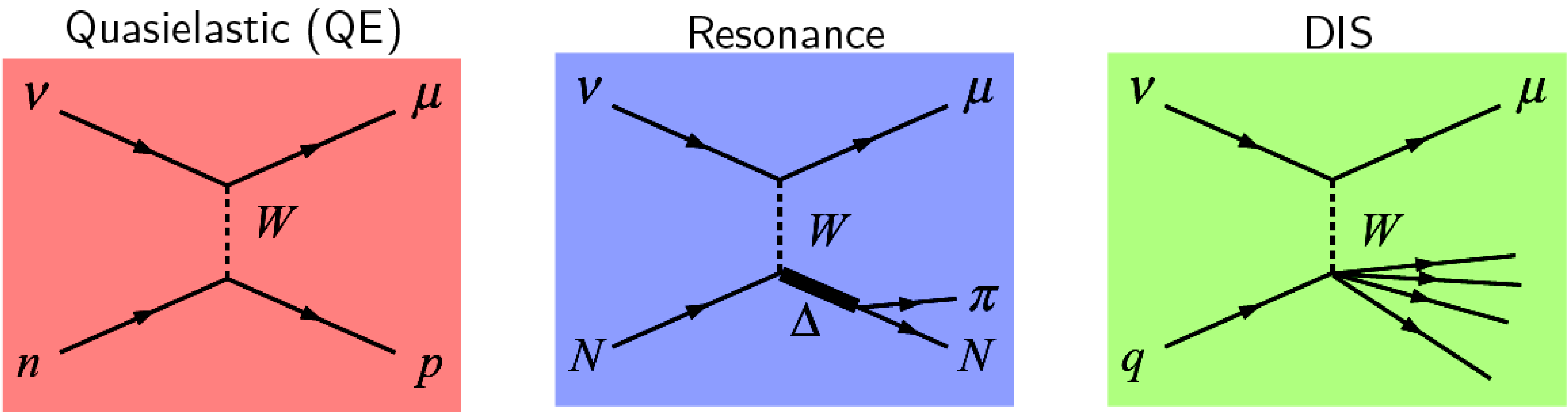
Z. Pavlovic

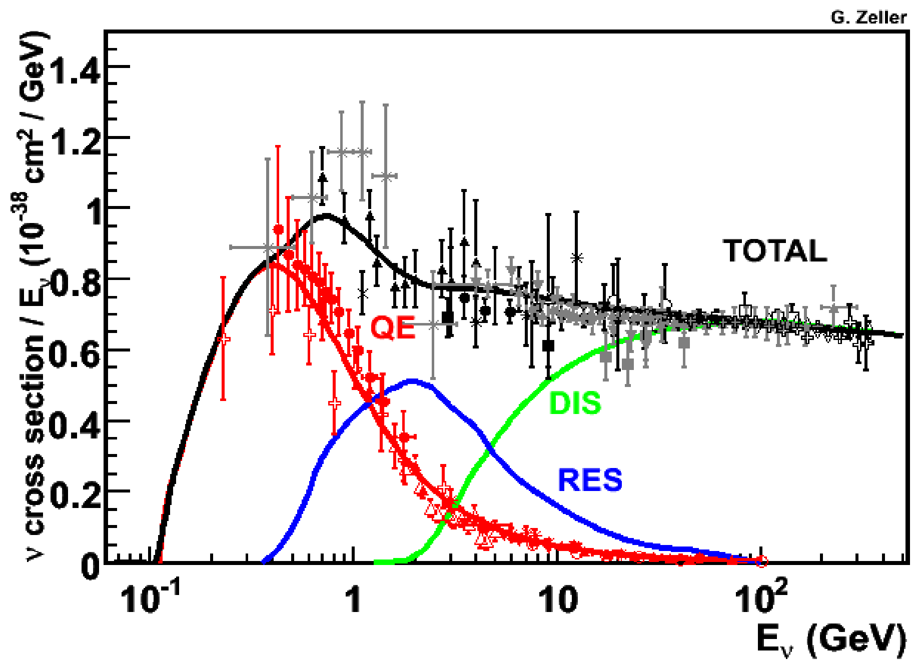
Meet the cast

- K^+ ($u\bar{s}$), 494 MeV, τ = 12.4 ns
  - $K^+ \rightarrow \mu^+ \nu$ (64%)
  - $K^+ \rightarrow \pi^+ \pi^0$ (20%)
- Λ (uds), 1115 MeV, τ = 0.3 ns
- $\Sigma^\pm$ (uus/dds), ~1190 MeV, τ ~ 0.1 ns
- K^0 ($d\bar{s}$), 498 MeV, either decays promptly, absorbs, or charge exchanges to K^+



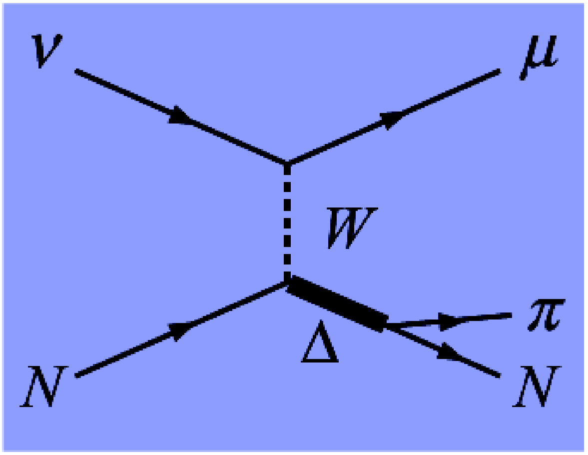
GENIE 2.8.4 MC simulation





Resonance production of kaons

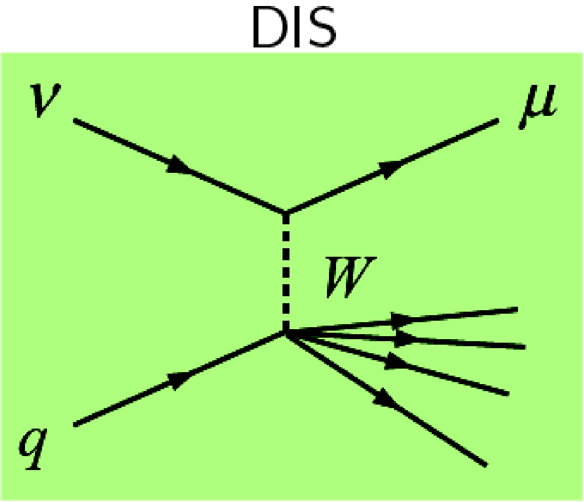
Resonance



"Associated production" of K + strange baryon (Λ, Σ) from the decay of high-mass baryon resonances

In GENIE, individual resonances are simulated up to hadronic invariant mass W = 1.7 GeV, which is barely above the KΛ threshold of ~1.6 GeV, so very few kaons come from resonance decays in GENIE

Kaons from hadronization

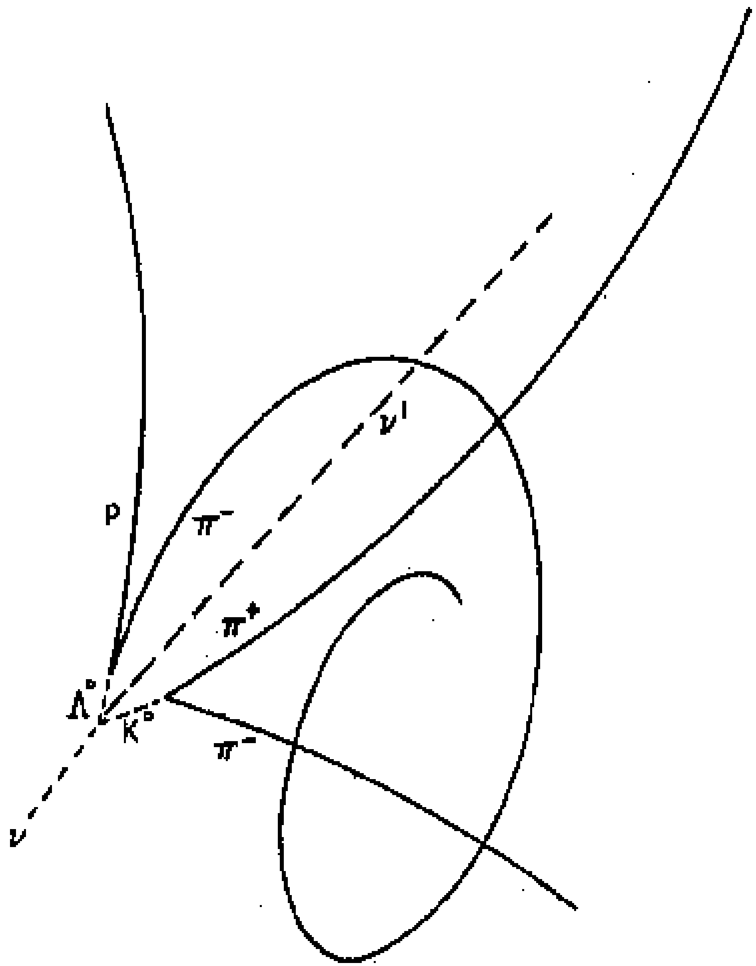


In DIS, it is possible to get $s\bar{s}$ pairs in hadronization, which results in KK, KΛ or KΣ pairs

GENIE uses KNO parameterization for 1.7 < W < 2.3 GeV, the “AGKY” model for 2.3 < W < 3.0, and PYTHIA for W > 3.0

Tuned to Λ and K^0 bubble chamber data vs. W

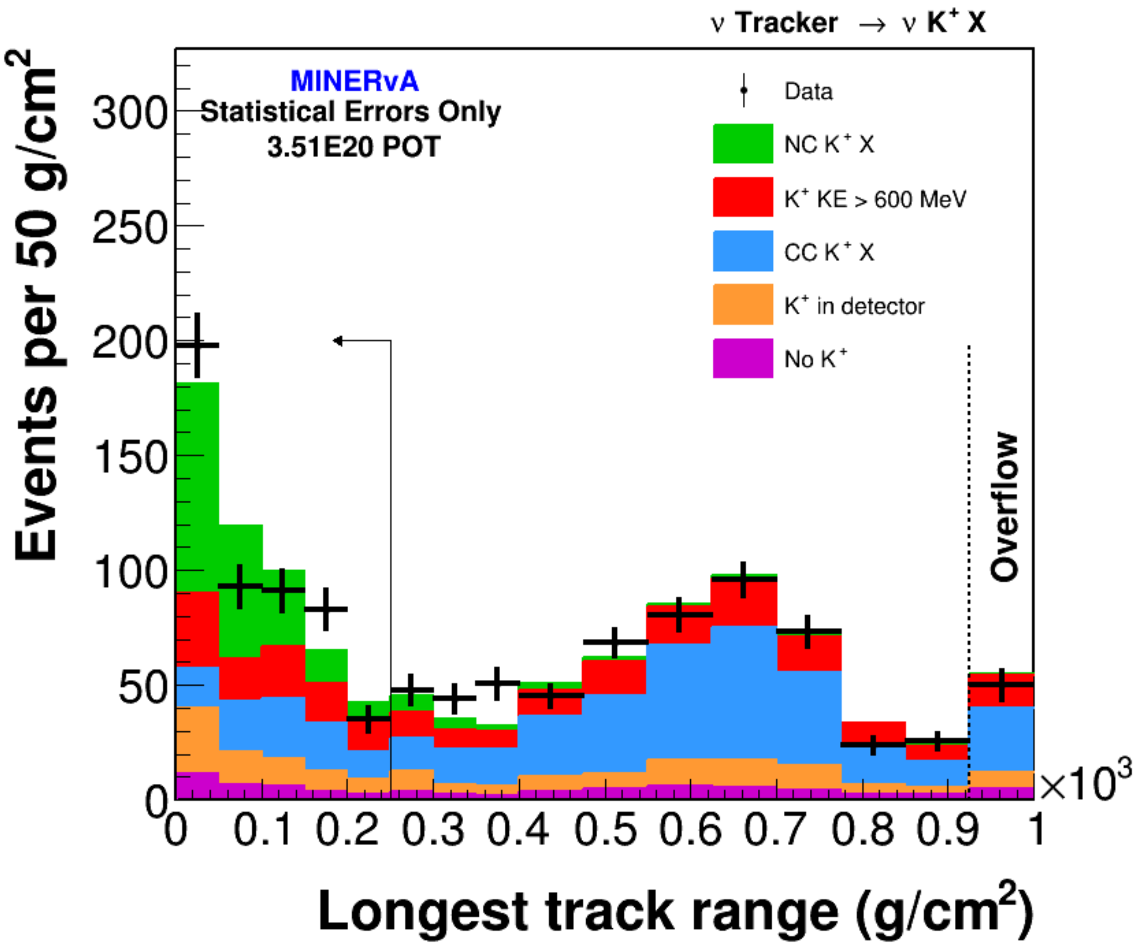
Kaons in bubble chambers



ANL 12' $K^0\Lambda$ event

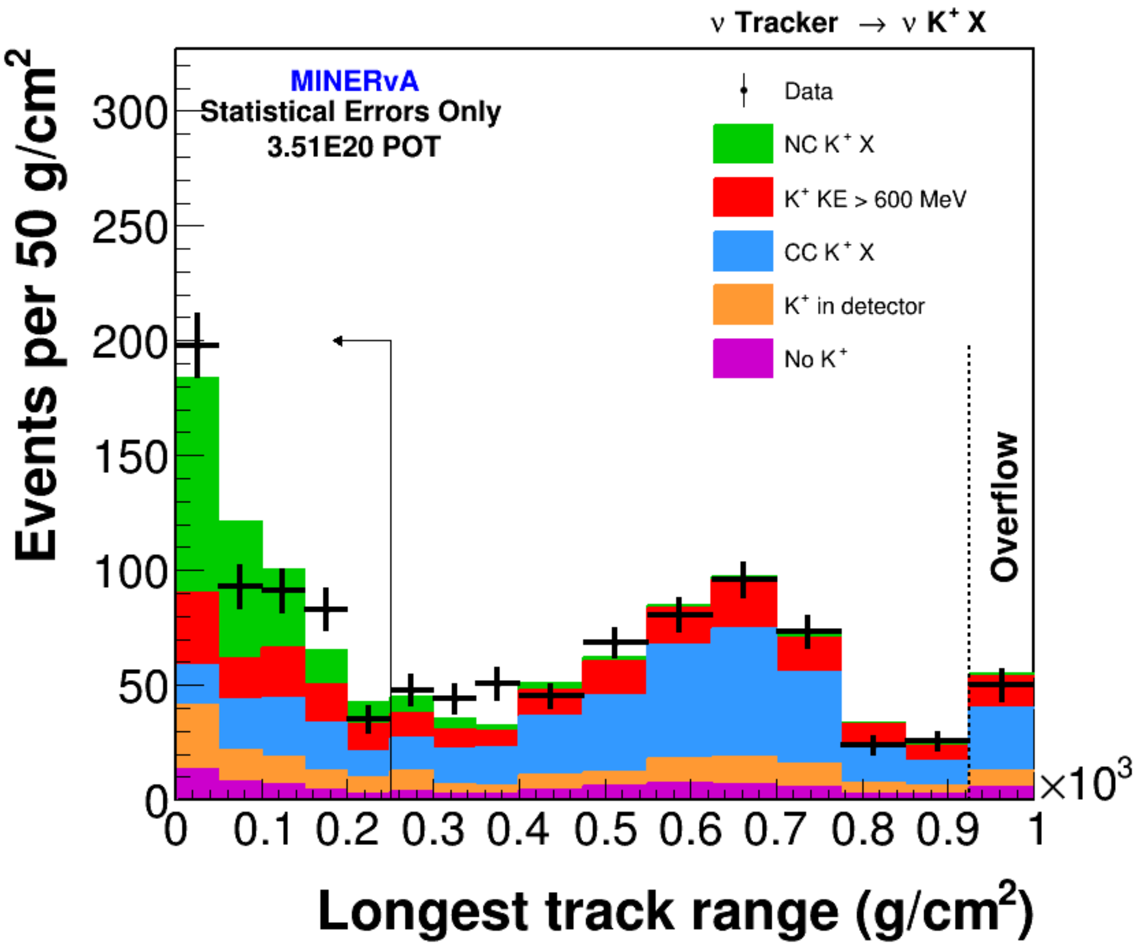
- Bubble chambers are fantastic detectors for $\Lambda \rightarrow p\pi^-$ and $K^0 \rightarrow \pi^+\pi^-$ from the "double V"
- K^+ are much harder
  - Ionization pattern can be ambiguous between π/K/p
  - Can reconstruct decay if the kaon stops in detector
  - Can infer from presence of Λ

Longest track range (NC)



- Additional cut: reject MINOS-matched tracks
- Use CC-like region as a sideband
- Rejecting MINOS tracks reduces the amount of extrapolation from low-y to high-y events

Tune the background



- Scale the non-pile-up backgrounds by 0.96
- Because you scale multiple backgrounds simultaneously, uncertainties arise when the composition is different in signal and sideband region

Extracting a cross section: NC

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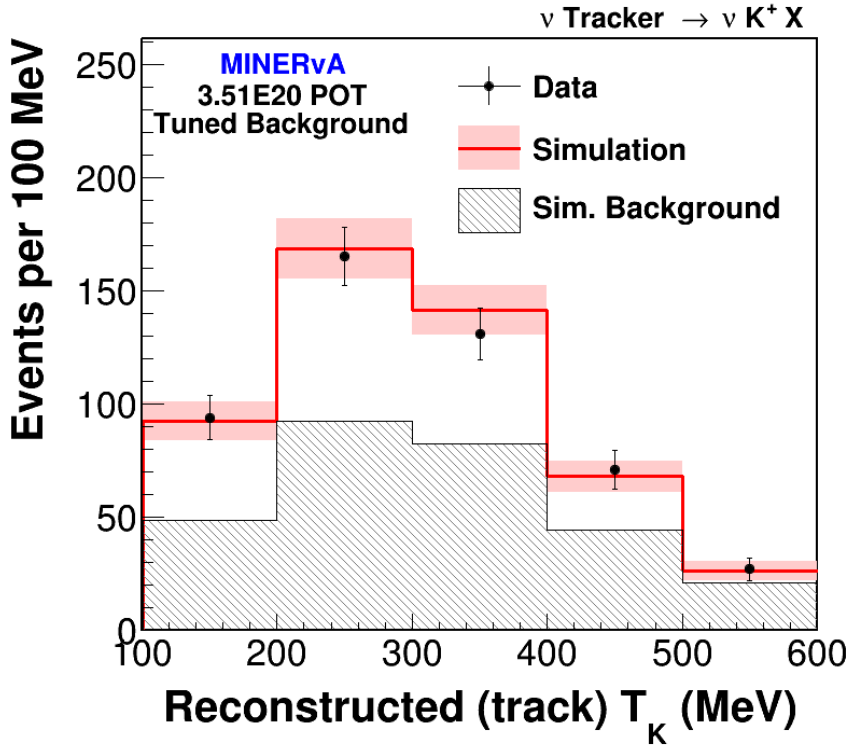

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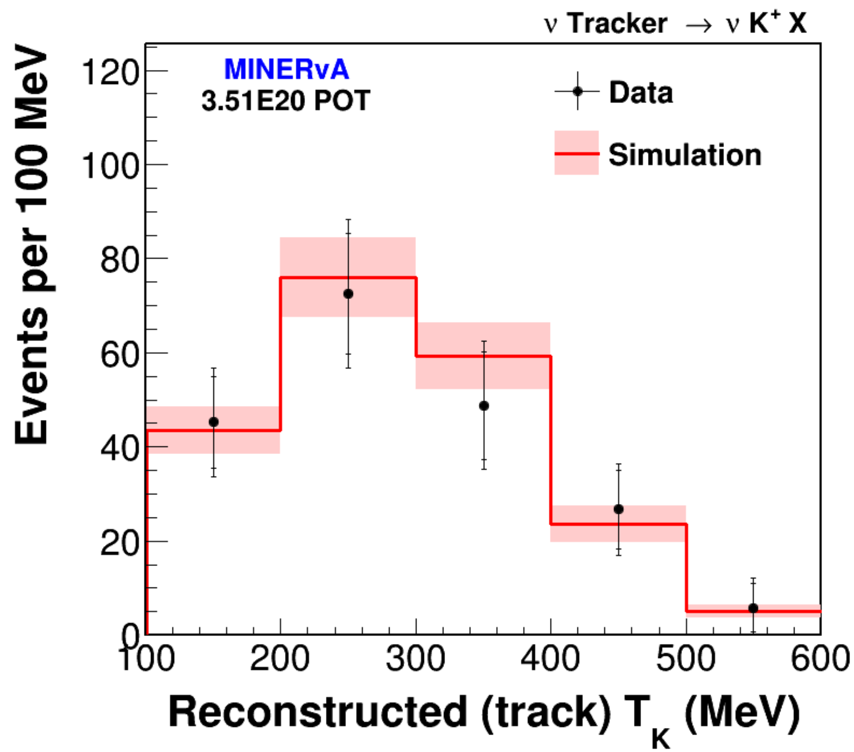

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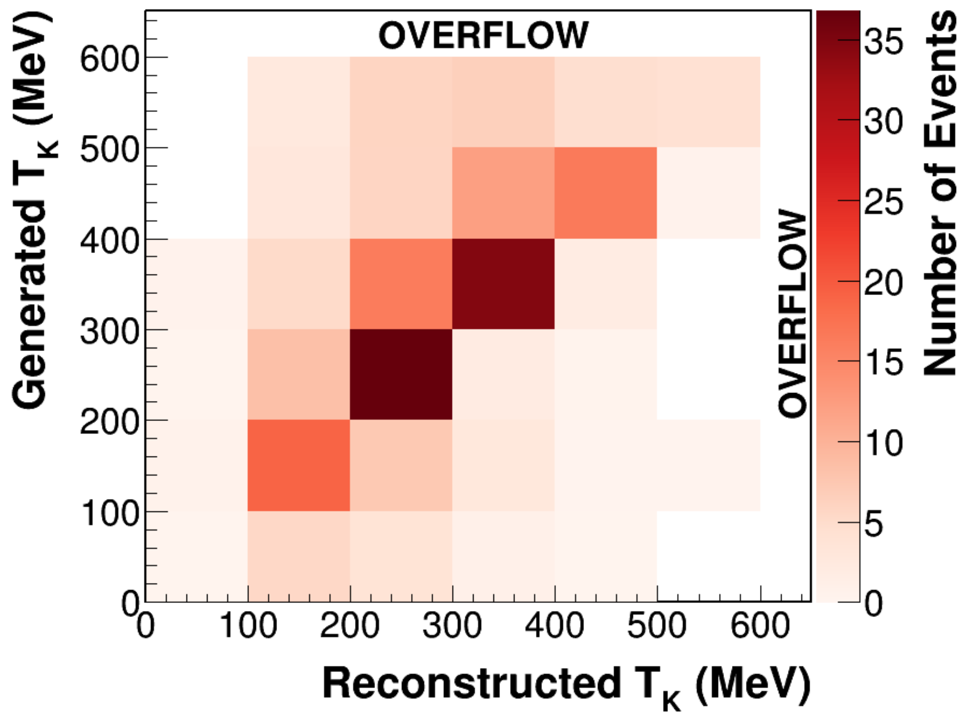

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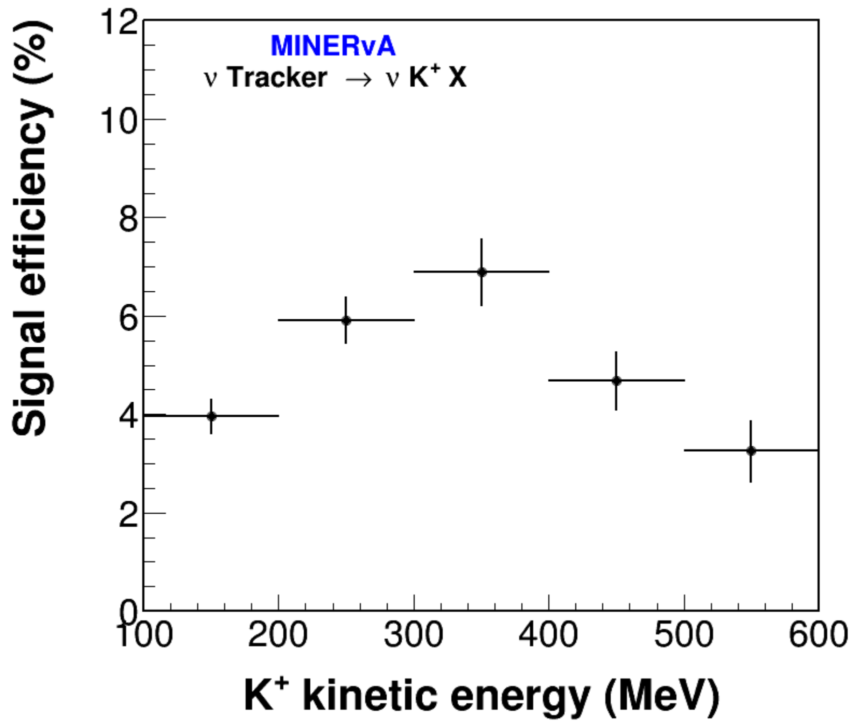
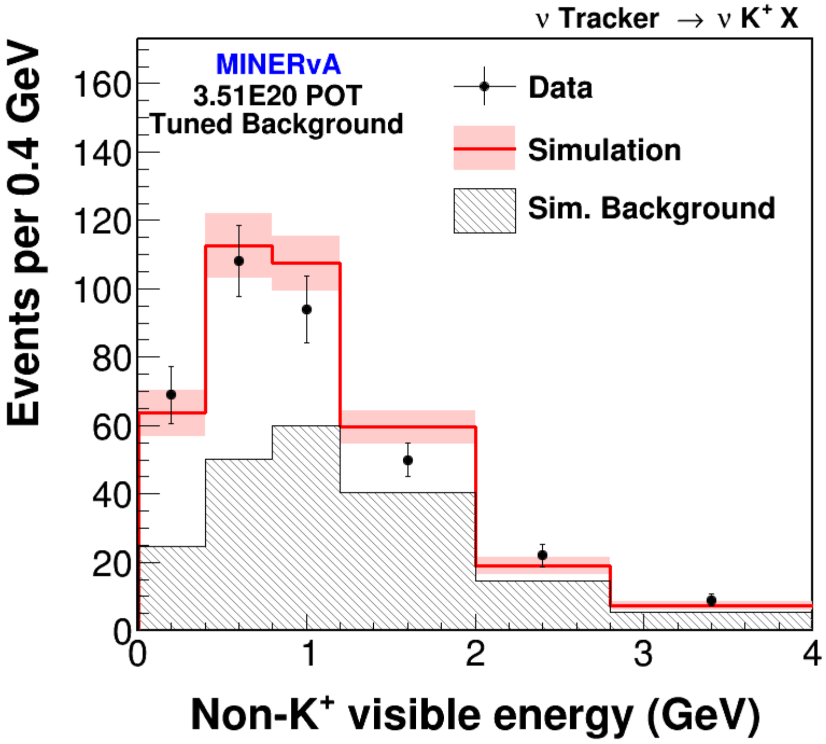


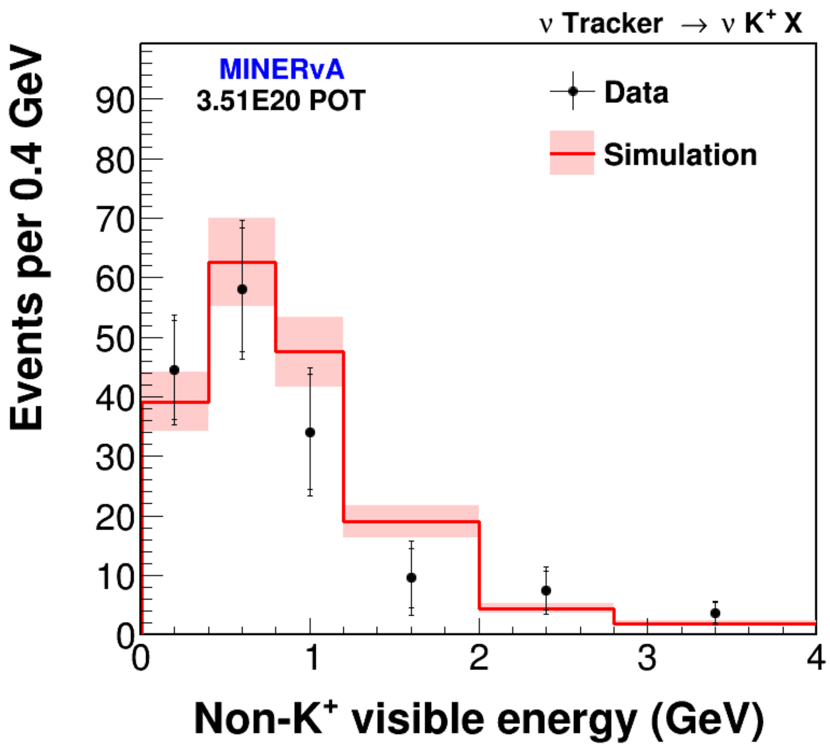
Extracting a cross section: NC

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



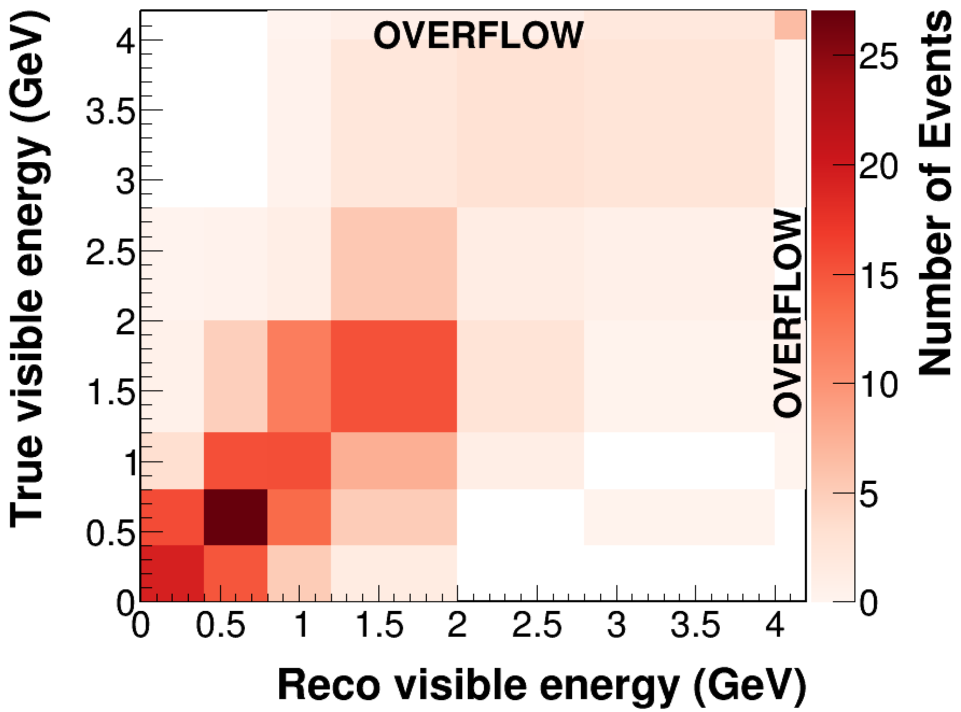
Extracting a cross section: NC

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



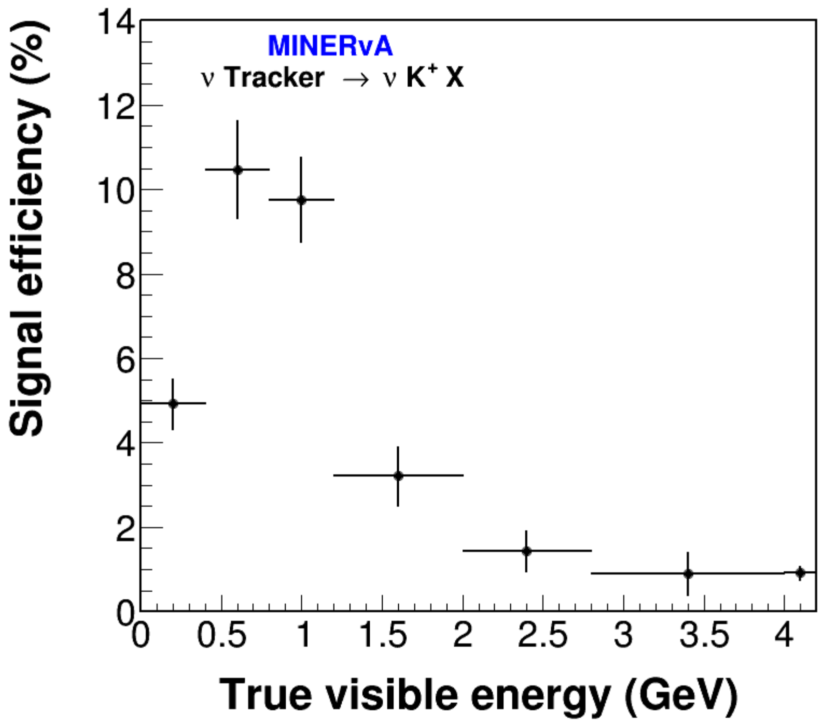
Extracting a cross section: NC

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

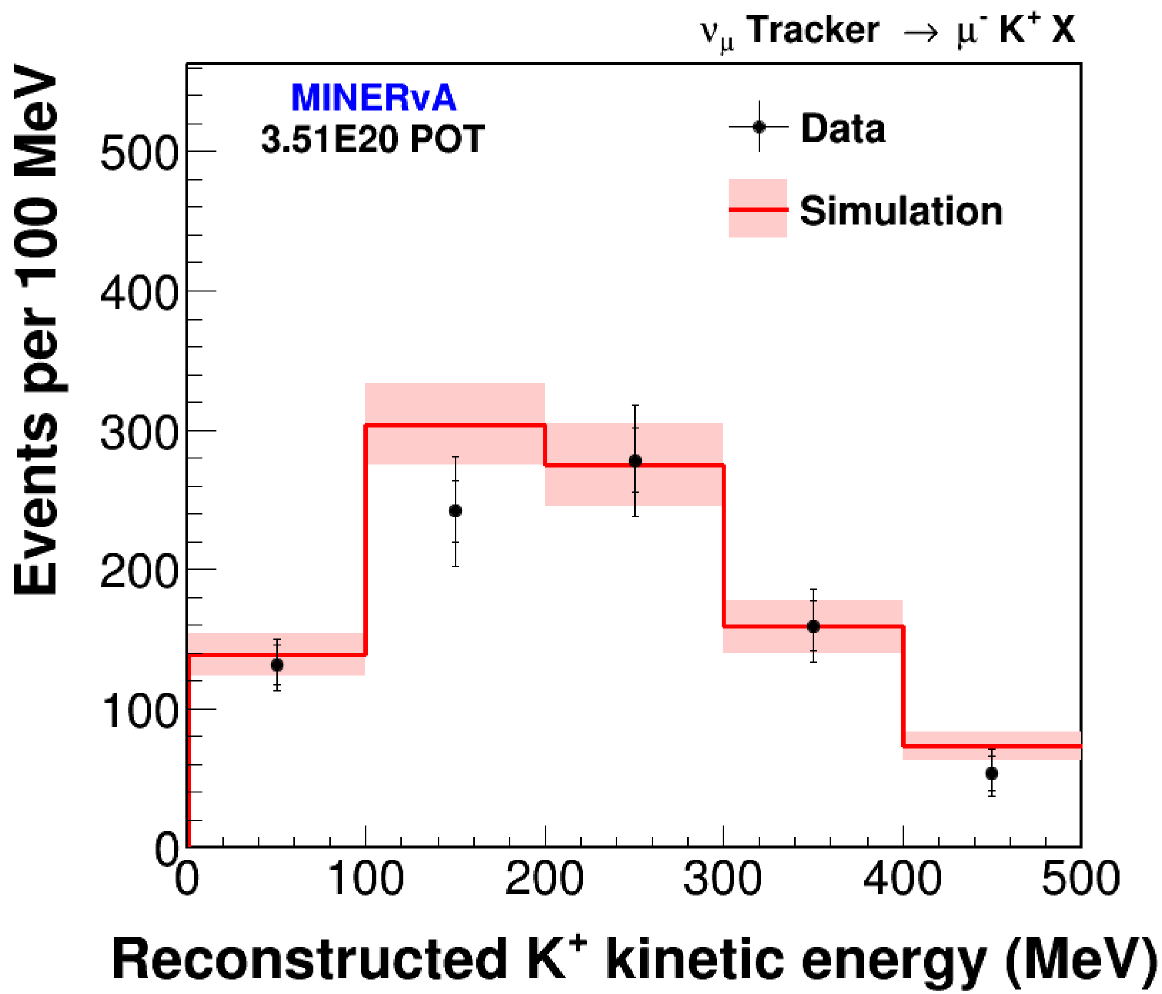


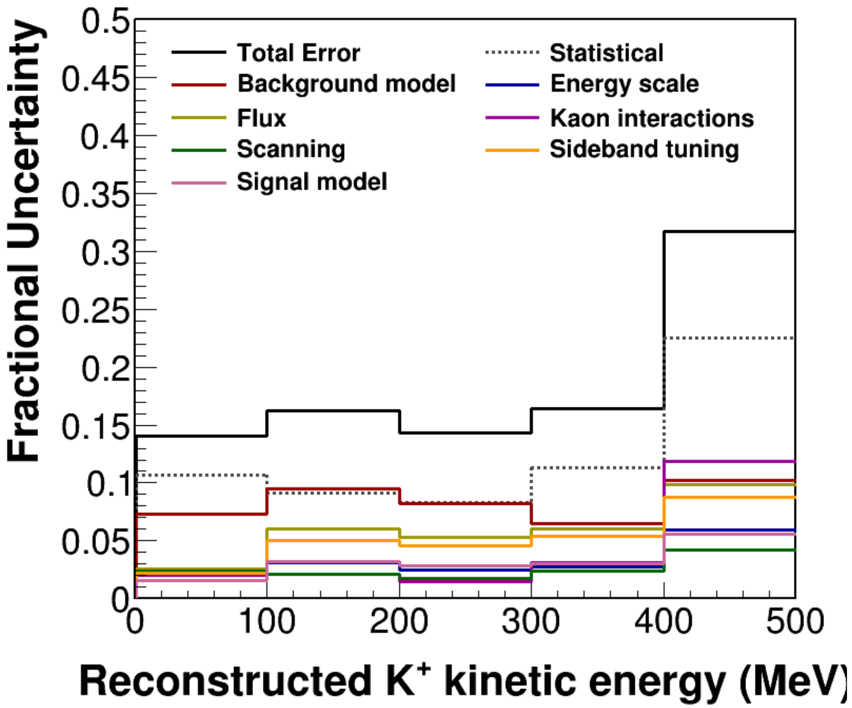
Extracting a cross section: NC

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

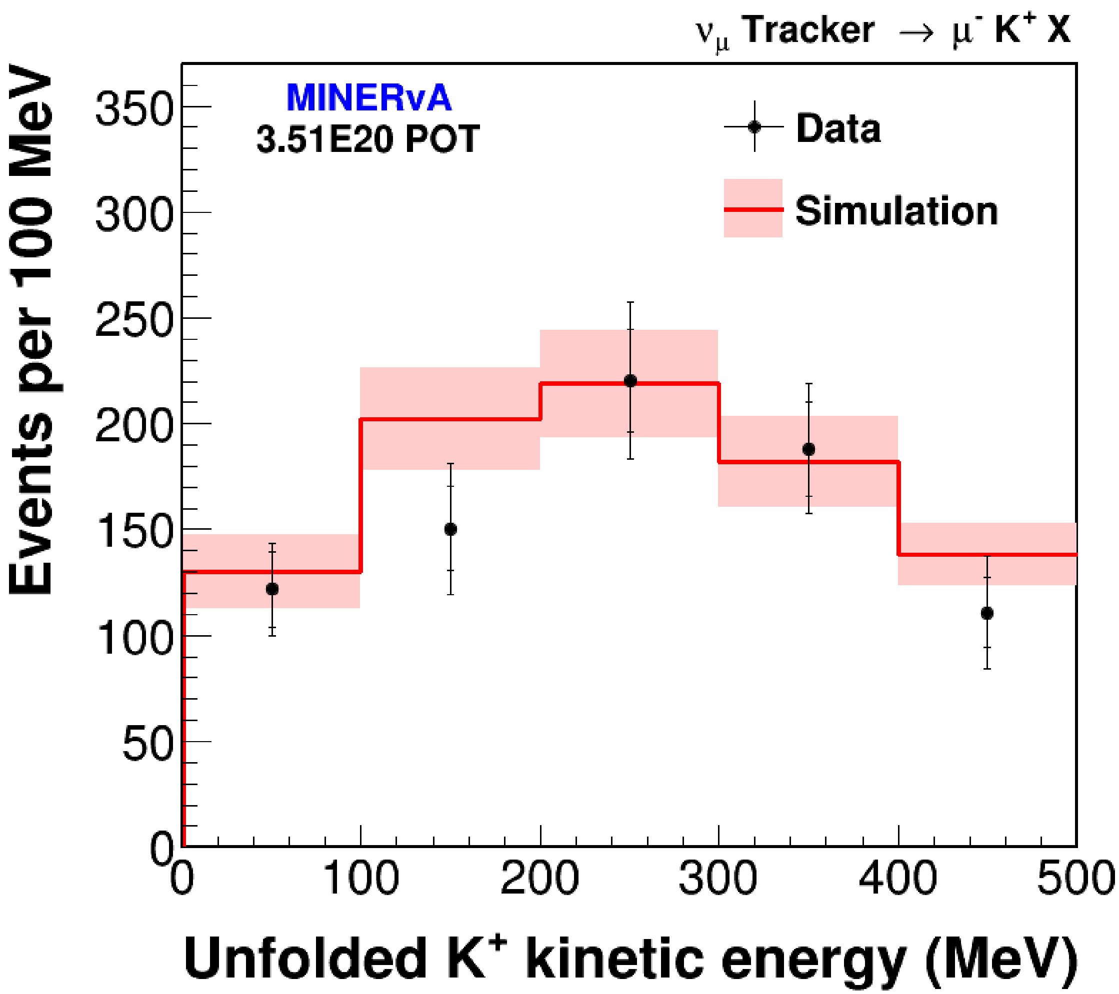


CC background-subtracted

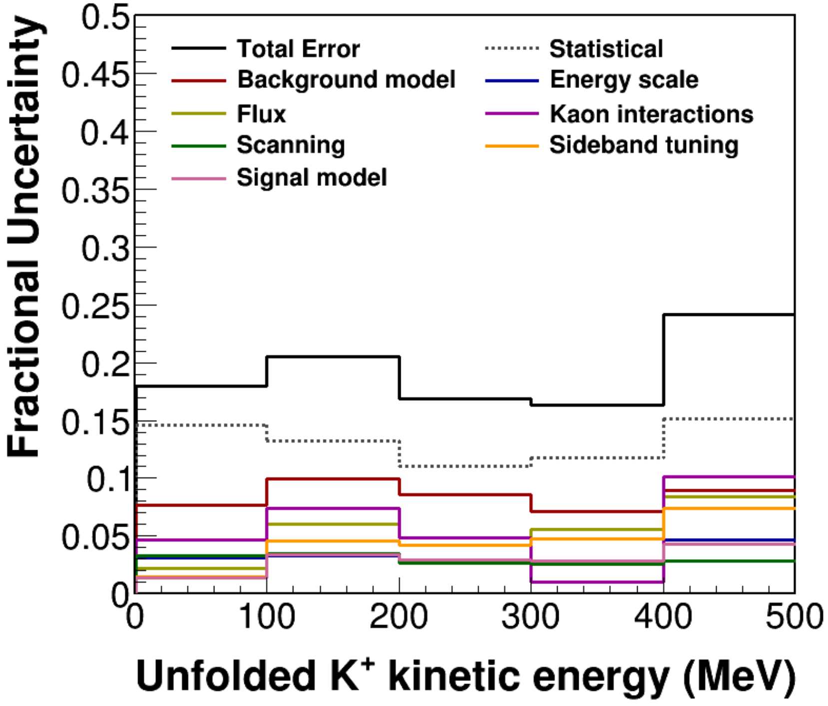




CC unfolded

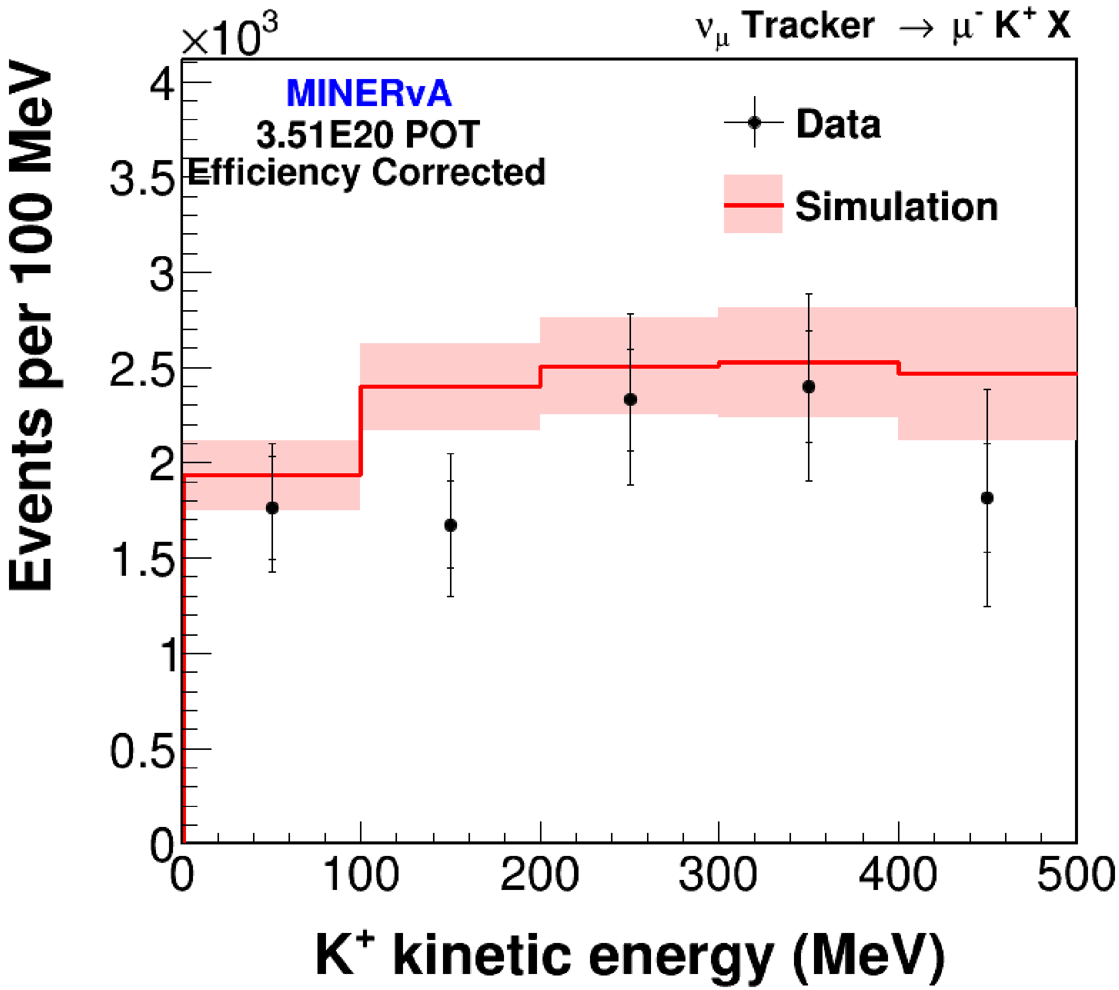


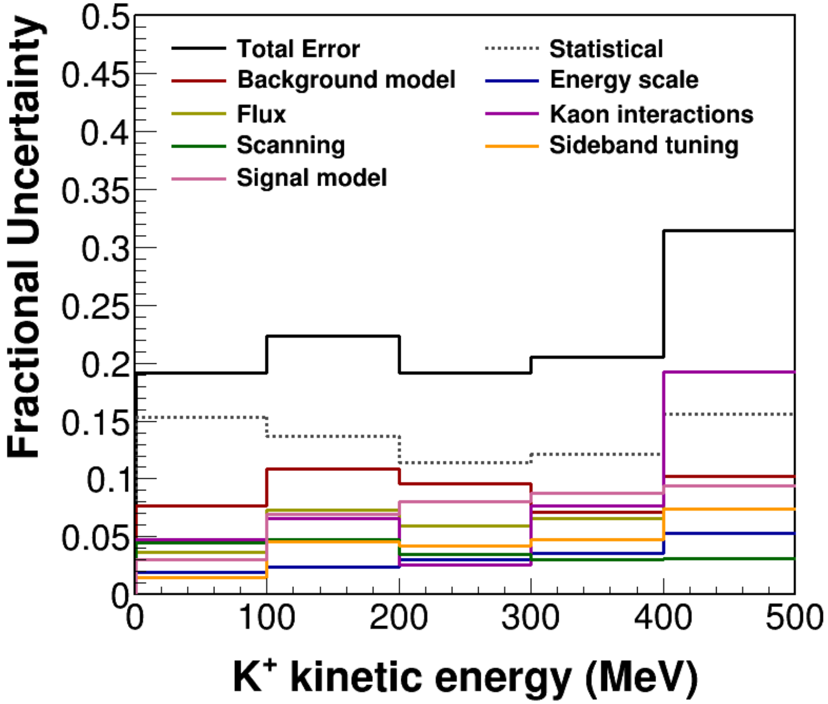
ν_μ Tracker $\rightarrow \mu^- K^+ X$
MINERvA
3.51E20 POT
Data
Simulation
Events per 100 MeV
Unfolded K+ kinetic energy (MeV)



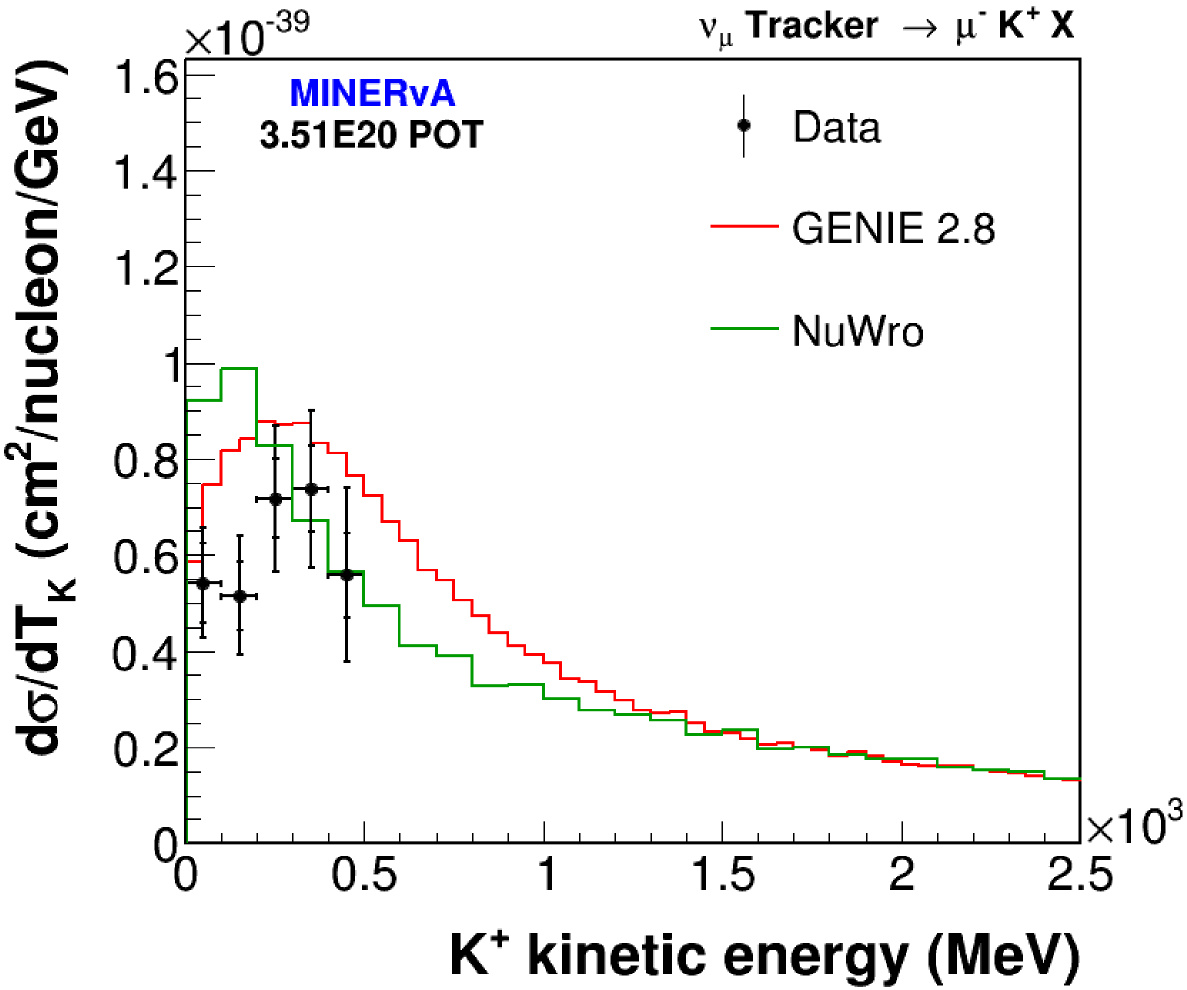
Total Error
Statistical
Background model
Energy scale
Flux
Kaon interactions
Scanning
Sideband tuning
Signal model
Fractional Uncertainty
Unfolded K+ kinetic energy (MeV)

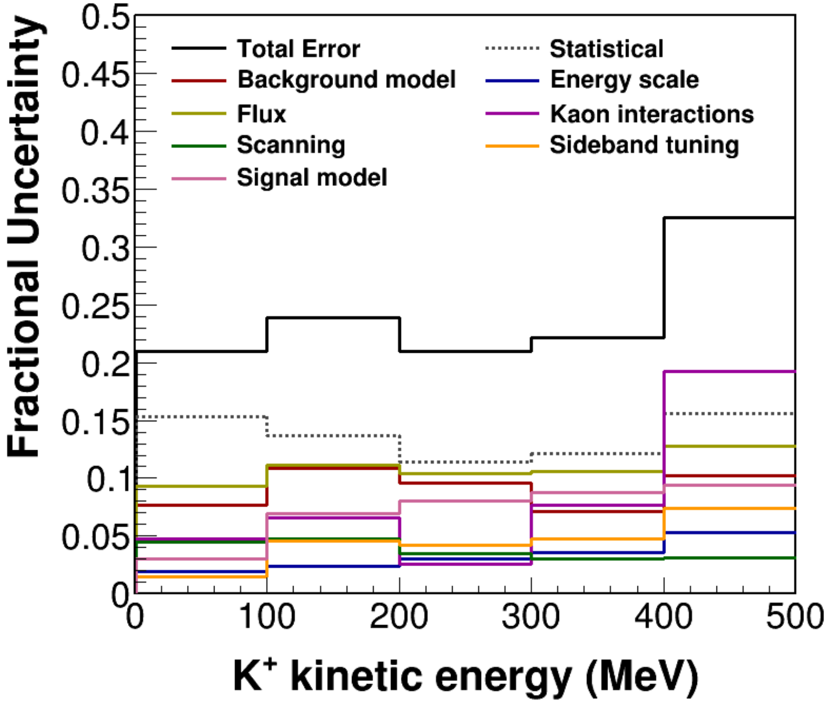
CC efficiency-corrected



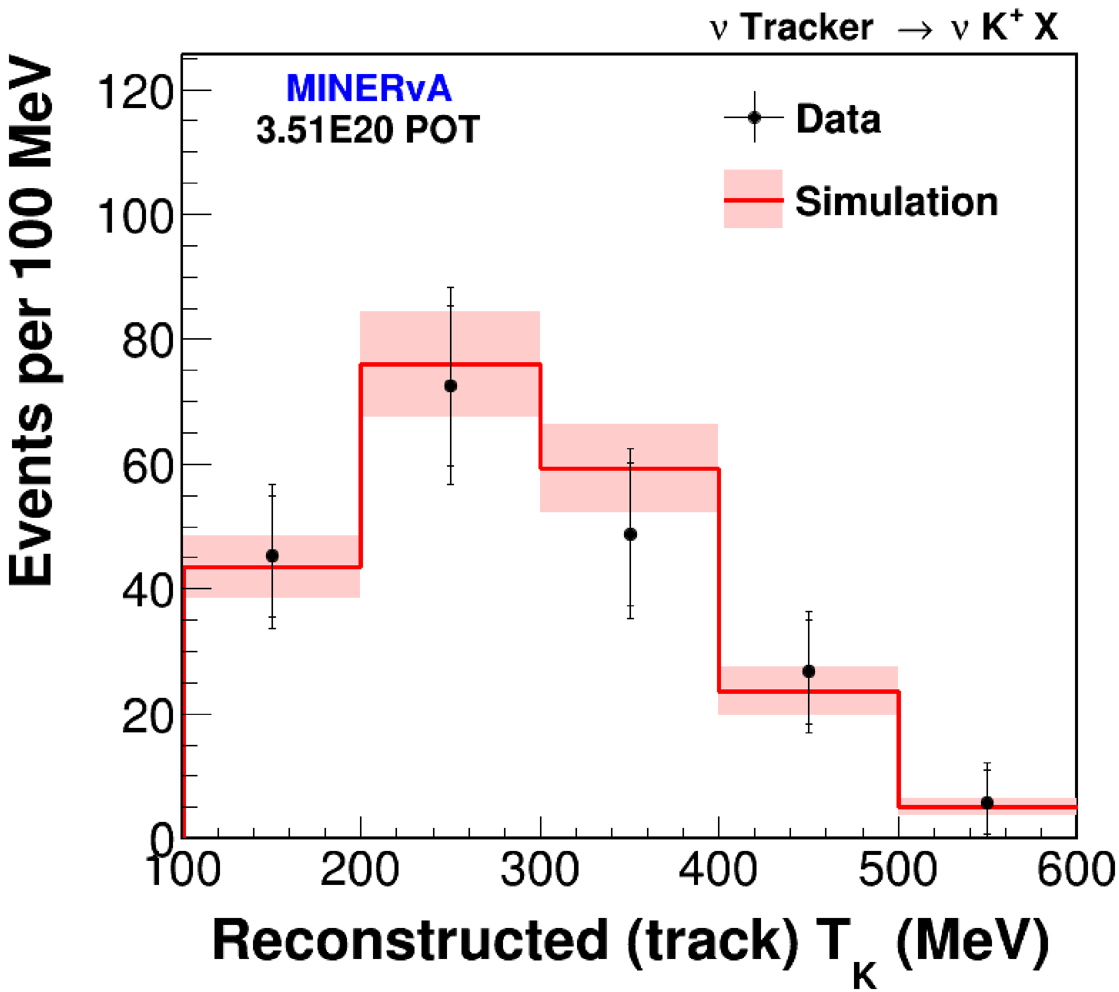


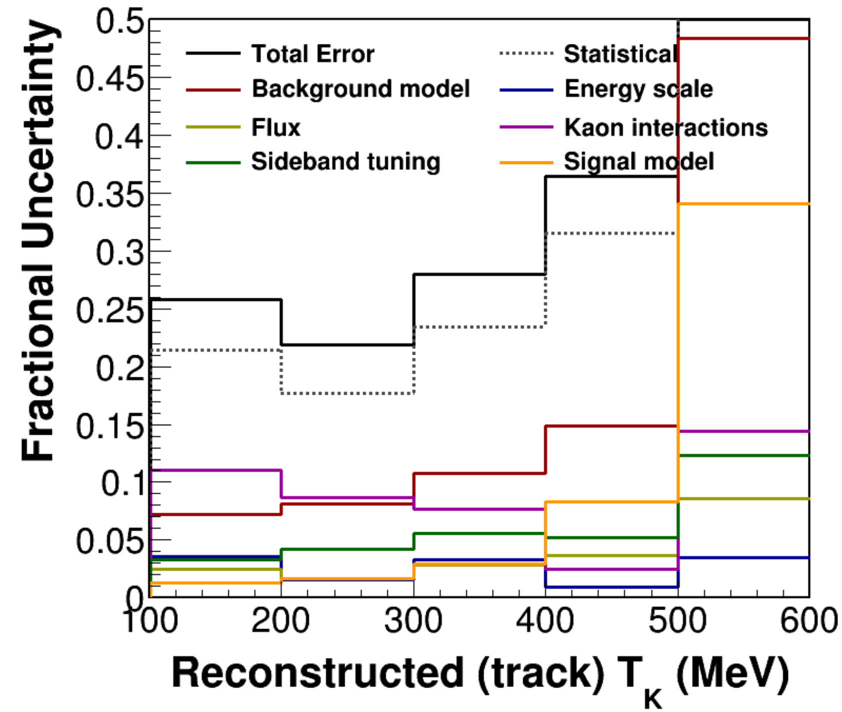
CC XS: zoomed out



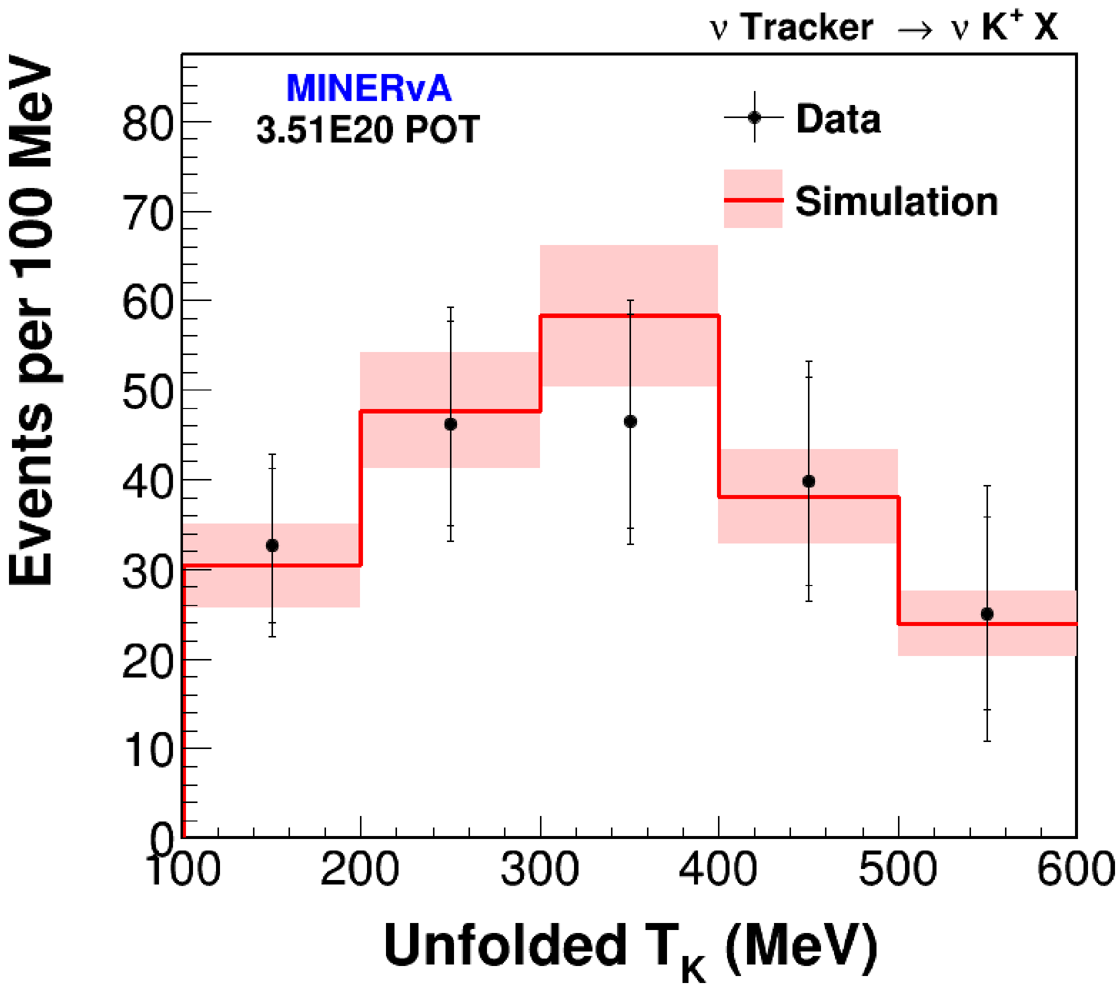


NC background-subtracted

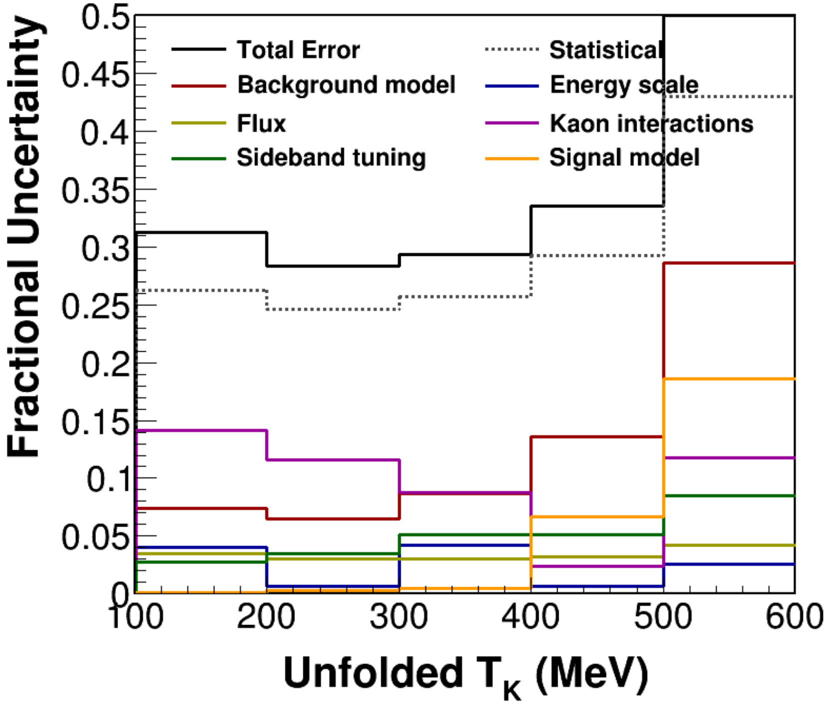




NC unfolded

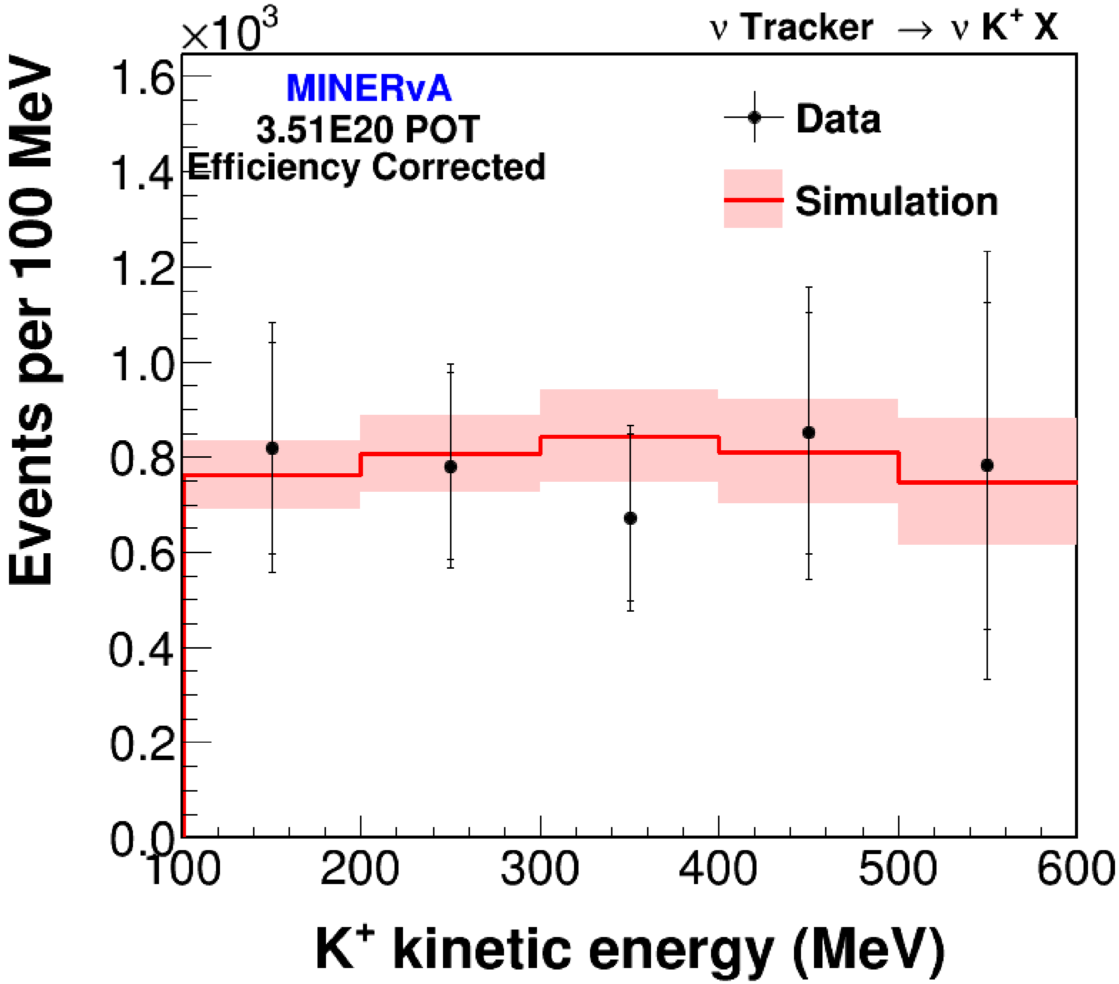


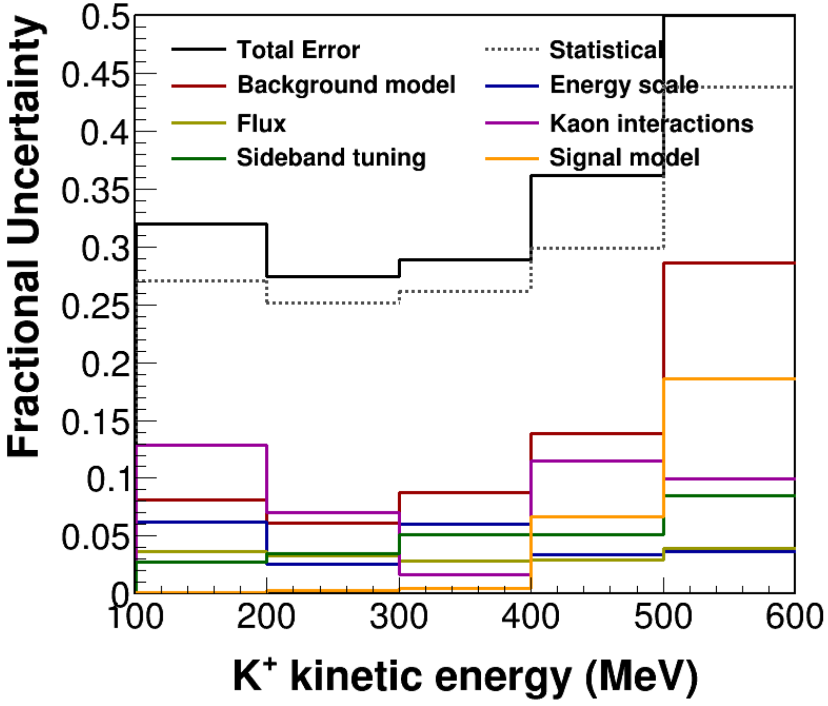
ν Tracker → ν K⁺ X
MINERvA
3.51E20 POT
Data
Simulation
Events per 100 MeV
Unfolded T_K (MeV)



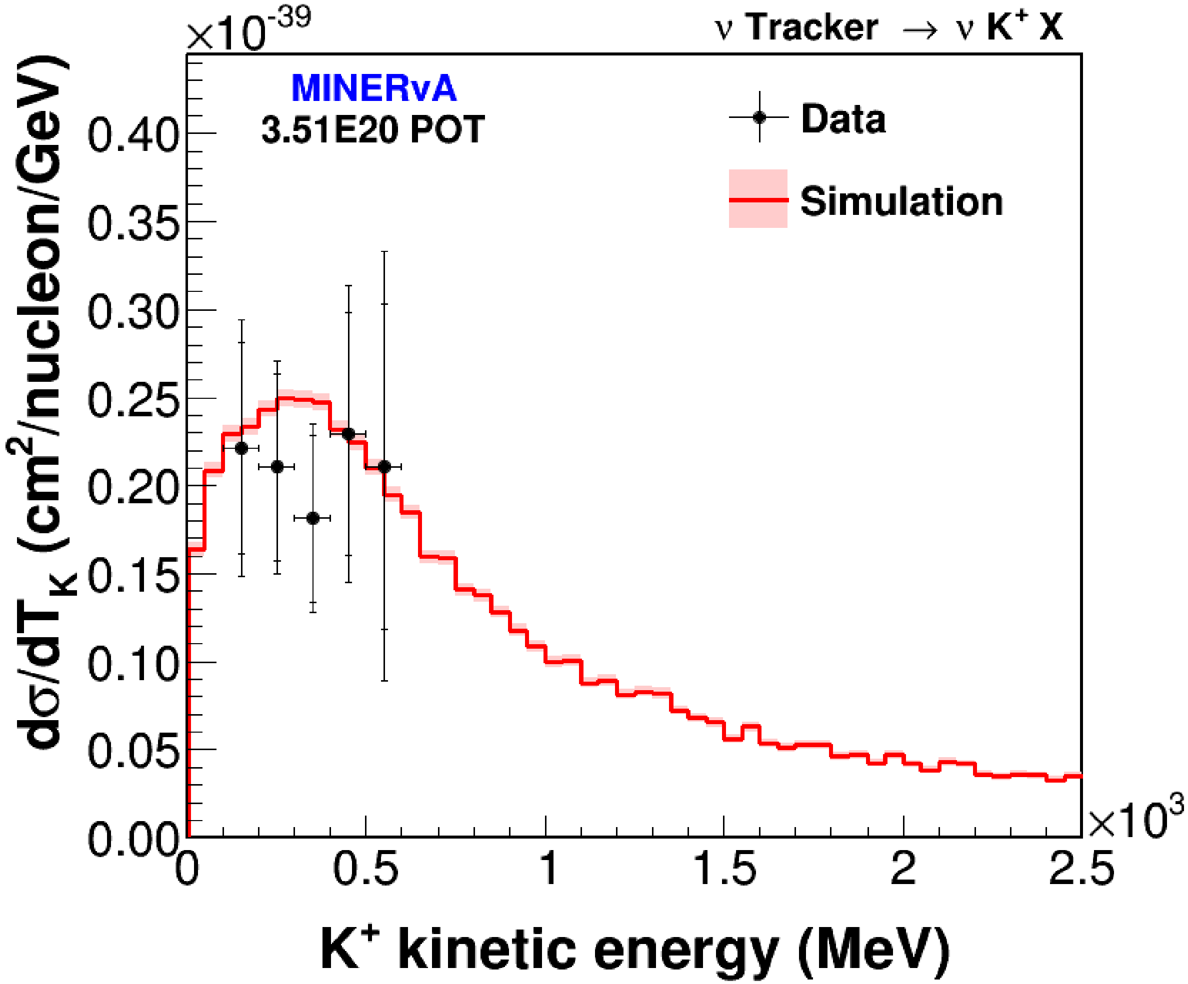
Total Error
Statistical
Background model
Energy scale
Flux
Kaon interactions
Sideband tuning
Signal model
Fractional Uncertainty
Unfolded T_K (MeV)

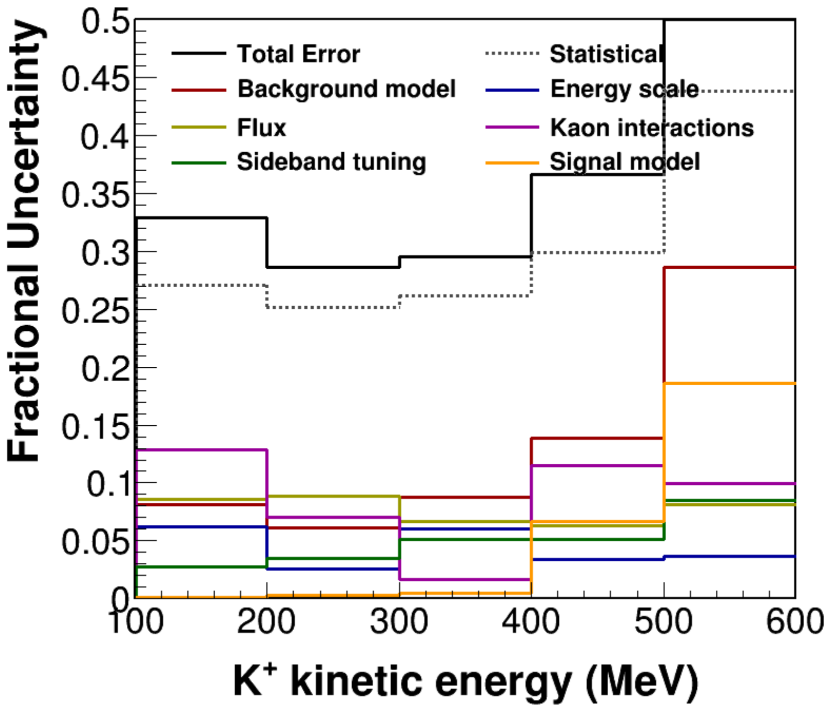
NC efficiency-corrected



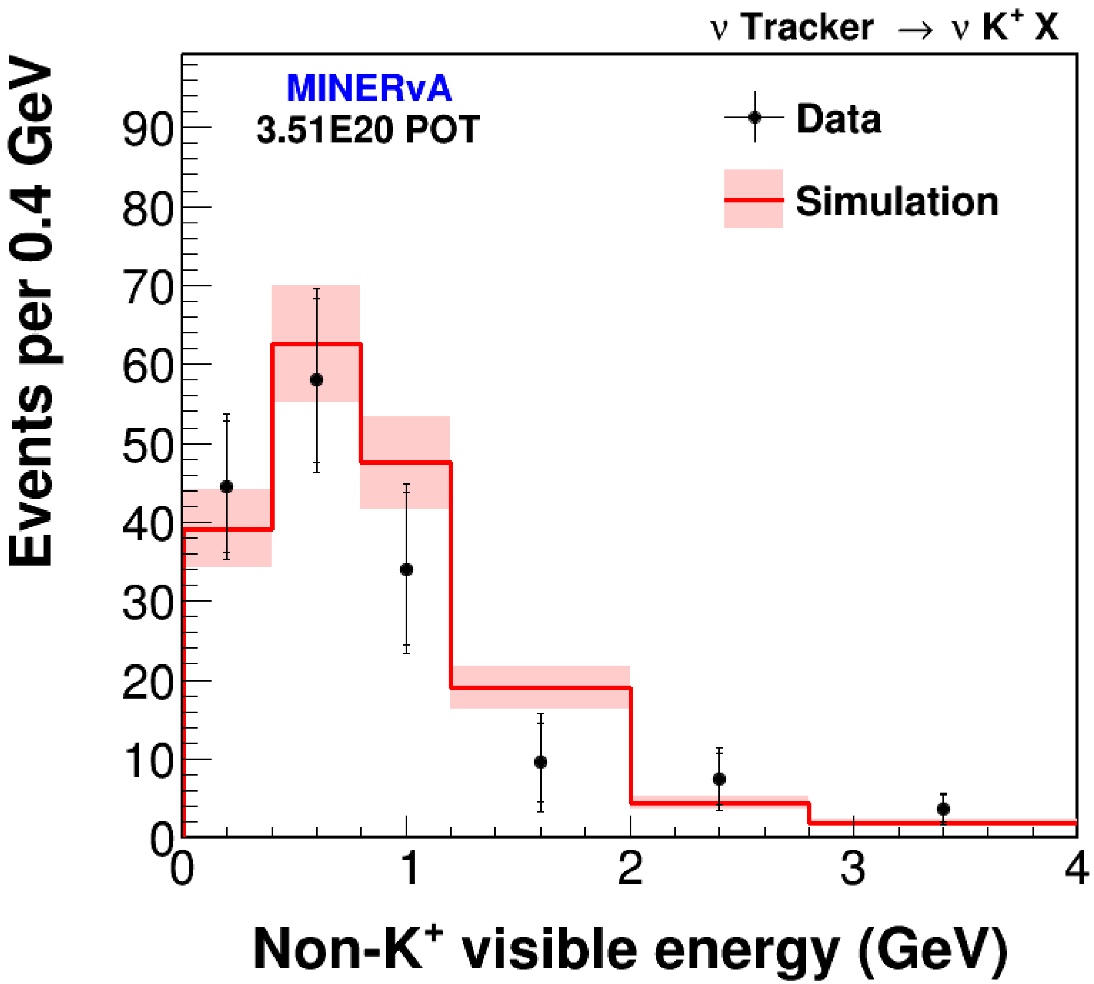


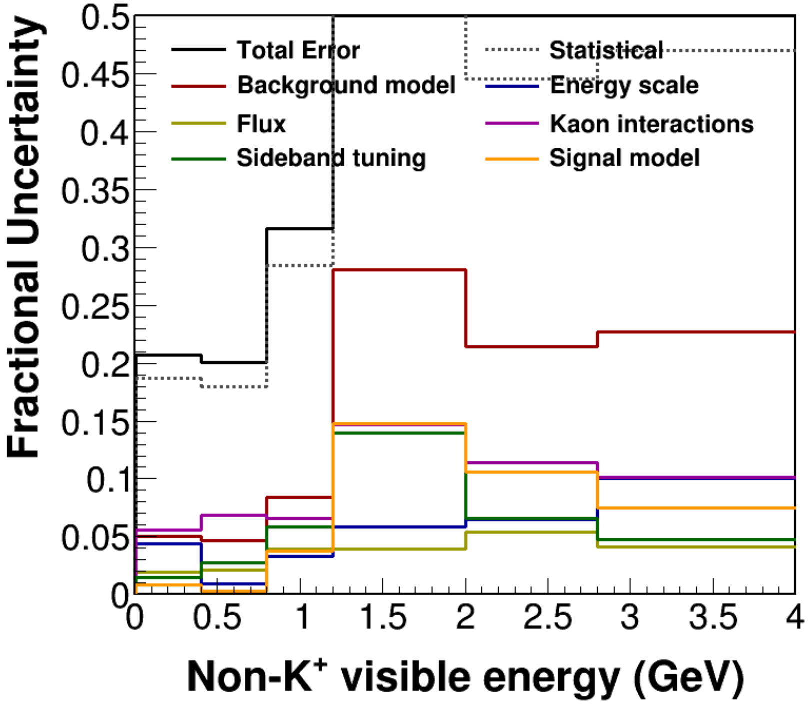
NC XS: zoomed out



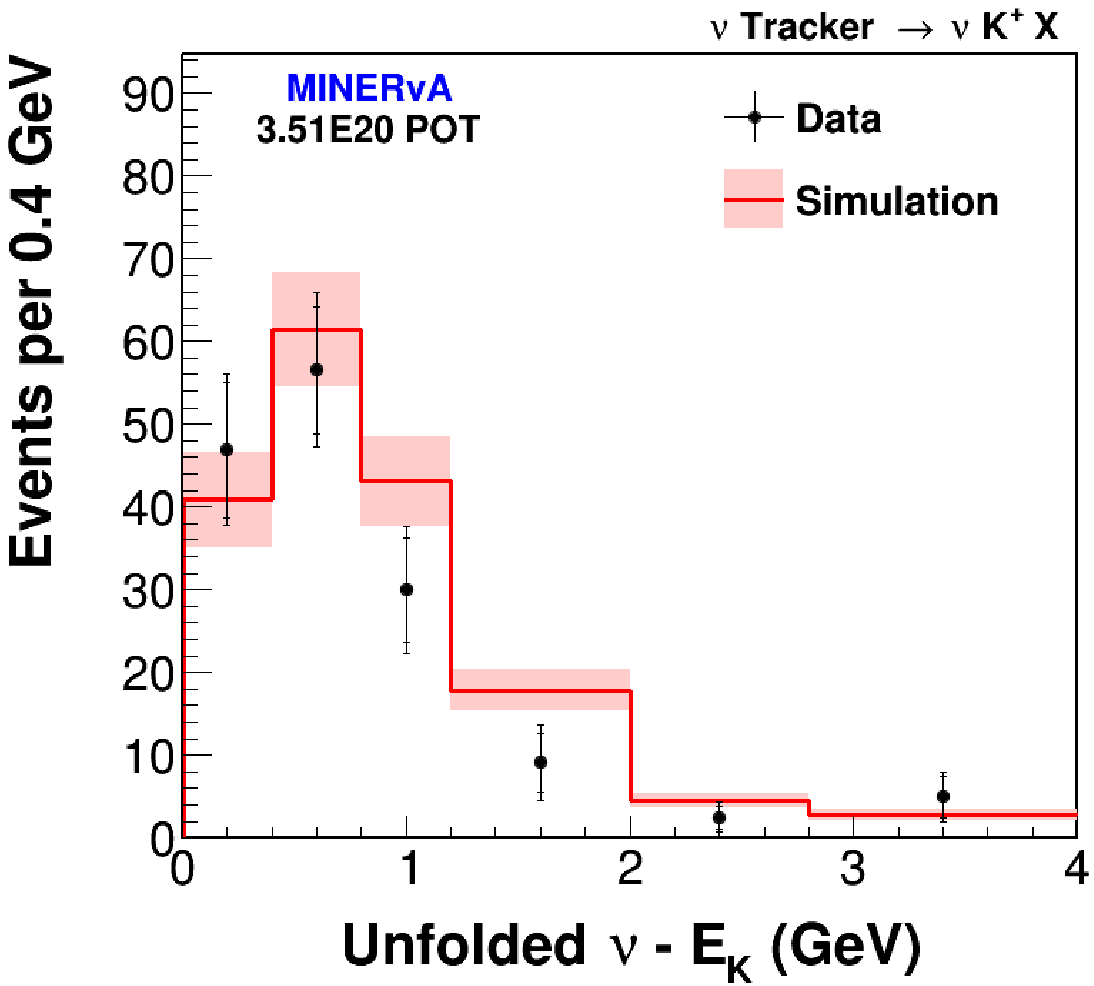


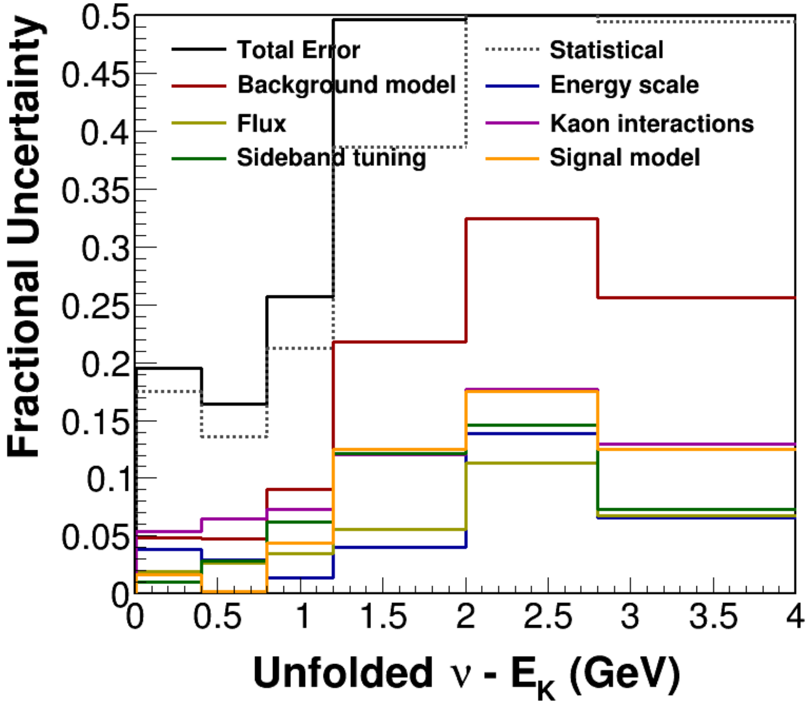
NC visible energy background-subtracted



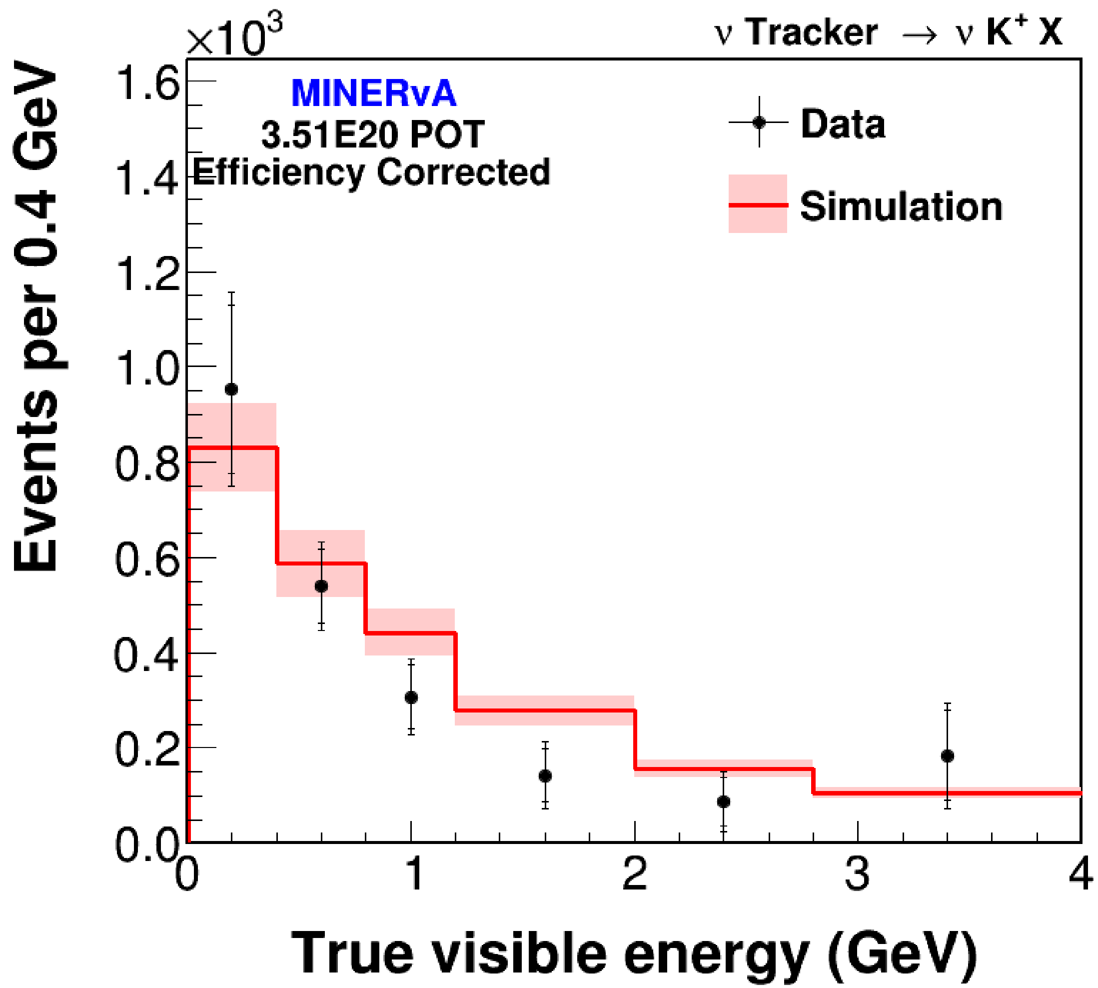


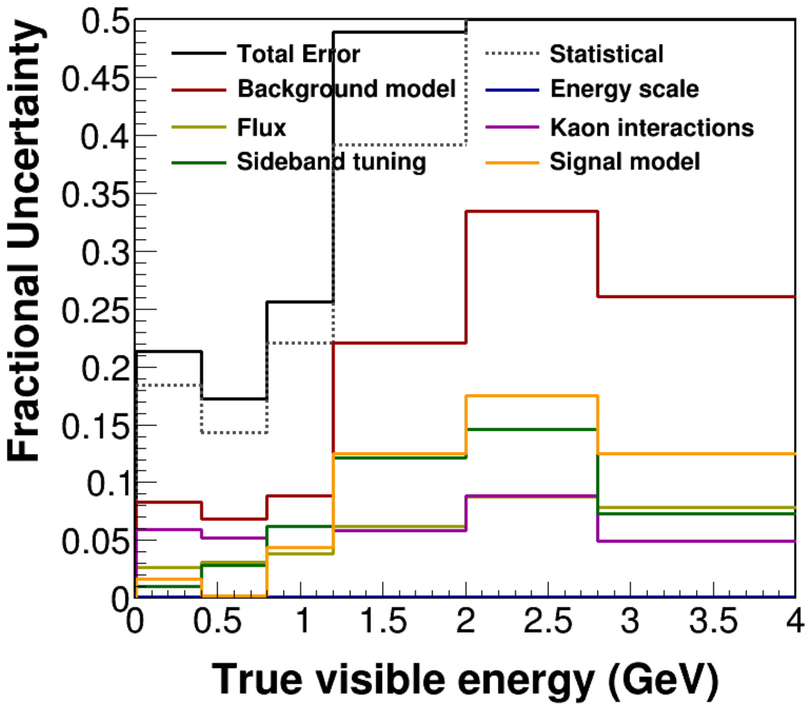
NC visible energy unfolded



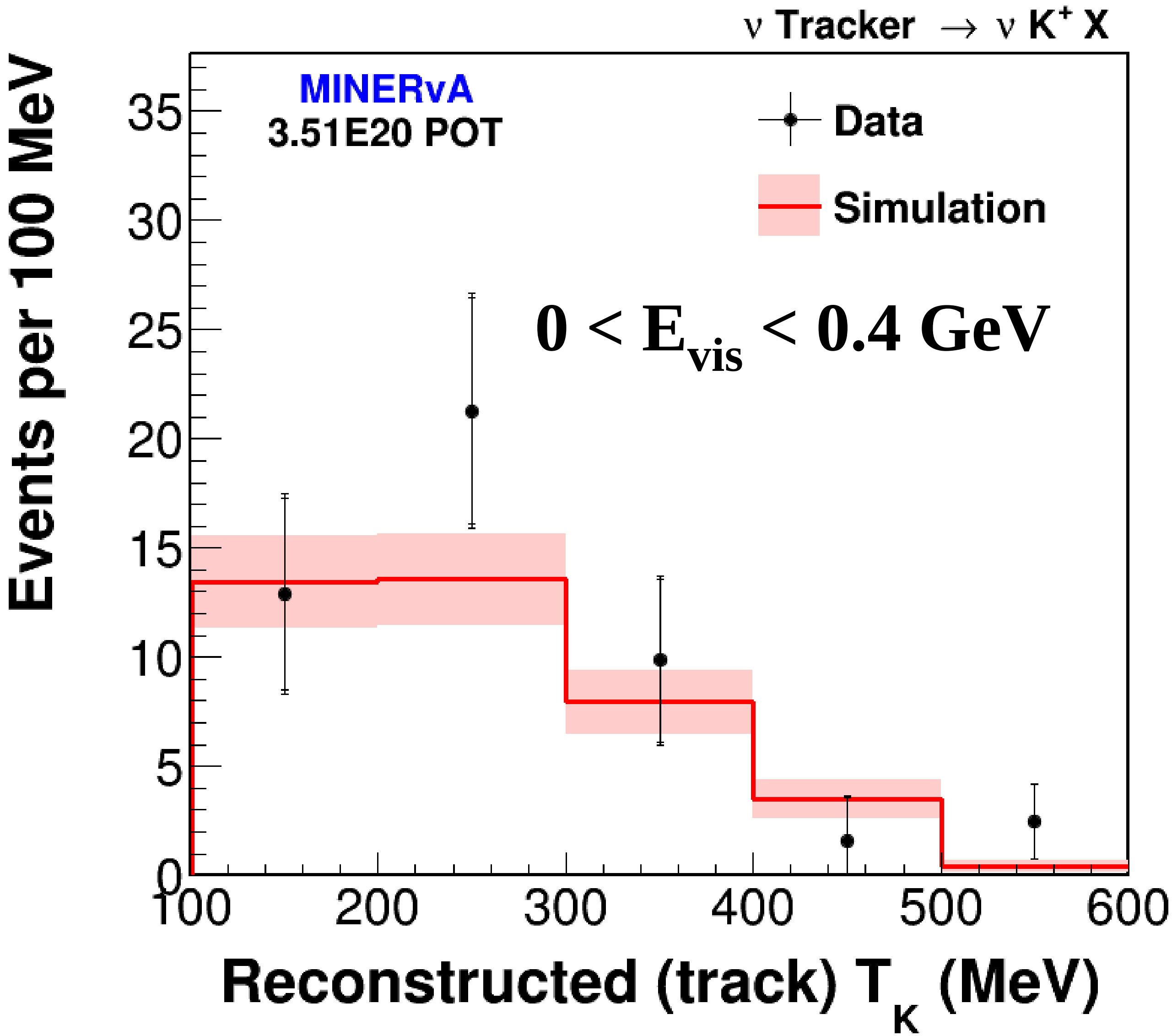


NC visible energy unfolded

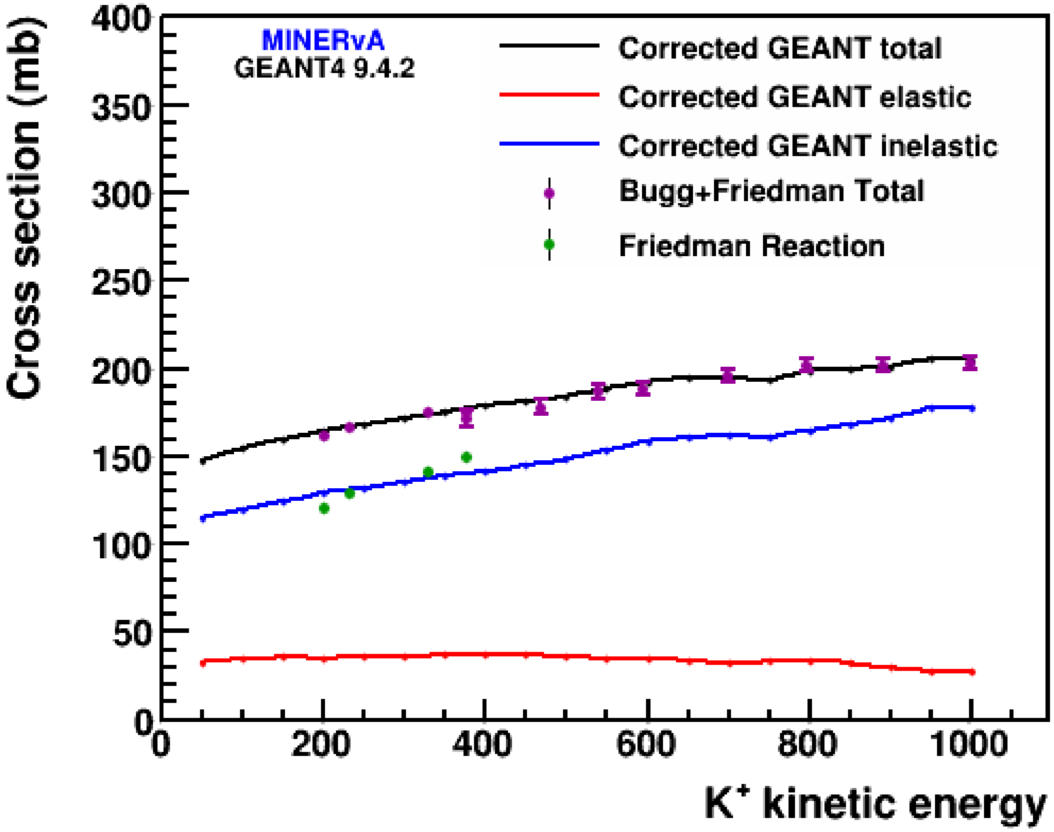




NC kinetic energy in lowest visible energy bin only



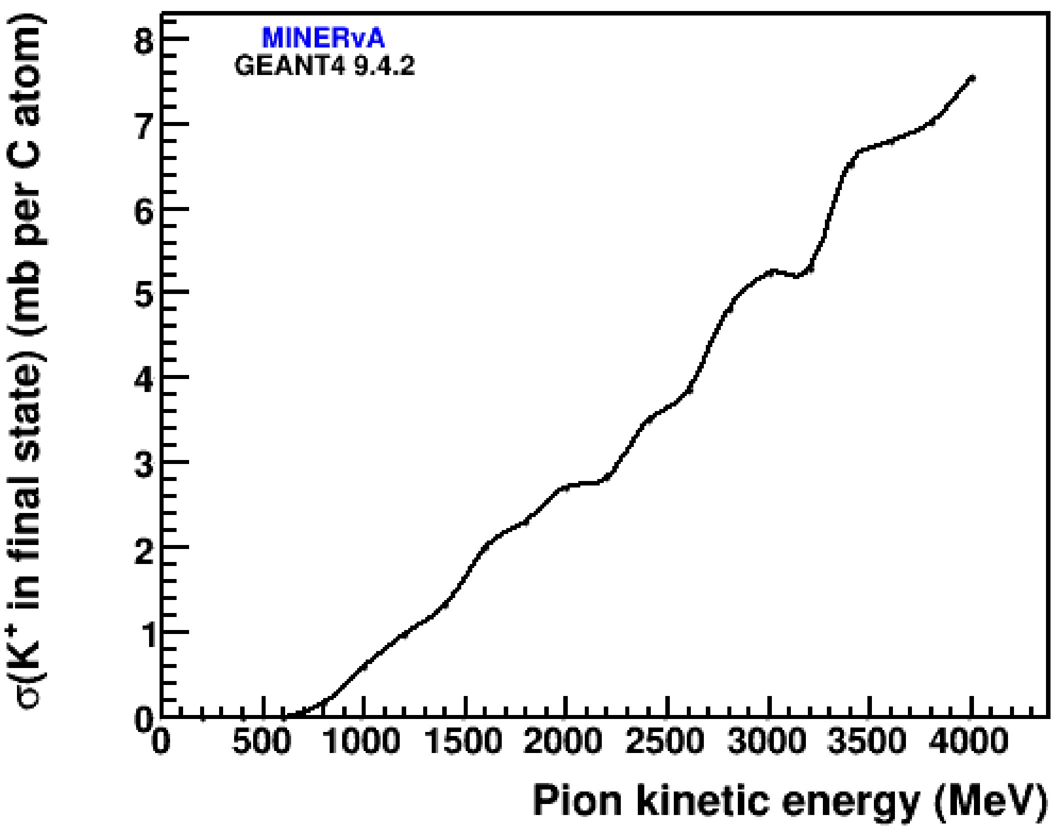
Kaon-carbon interactions



Force agreement between GEANT4 (old version) and external data by reweighting events based in interaction fate

Take ±10% uncertainty on inelastic cross section, which covers disagreement conservatively

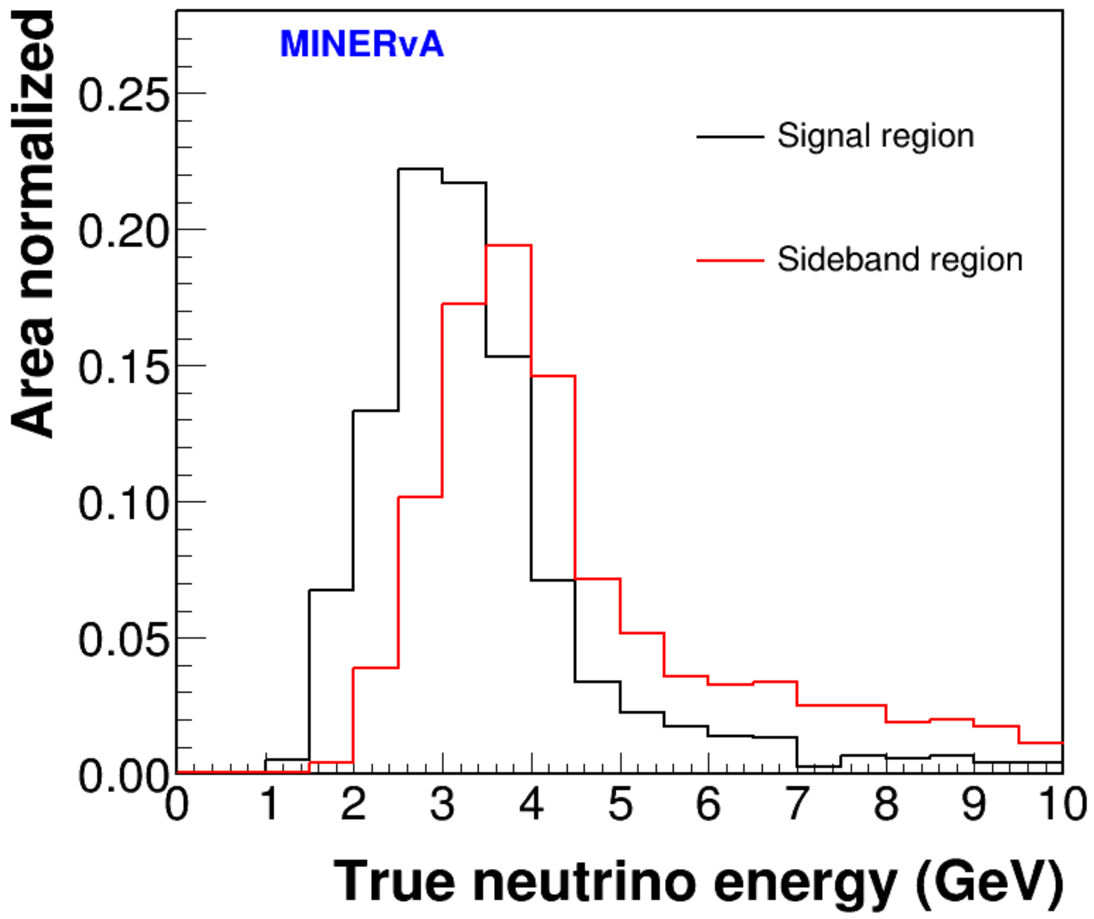
$\pi^+C \rightarrow K^+X$ cross section



Force agreement between GEANT4 (old version) and external data by reweighting events based in interaction fate

Take ±10% uncertainty on inelastic cross section, which covers disagreement conservatively

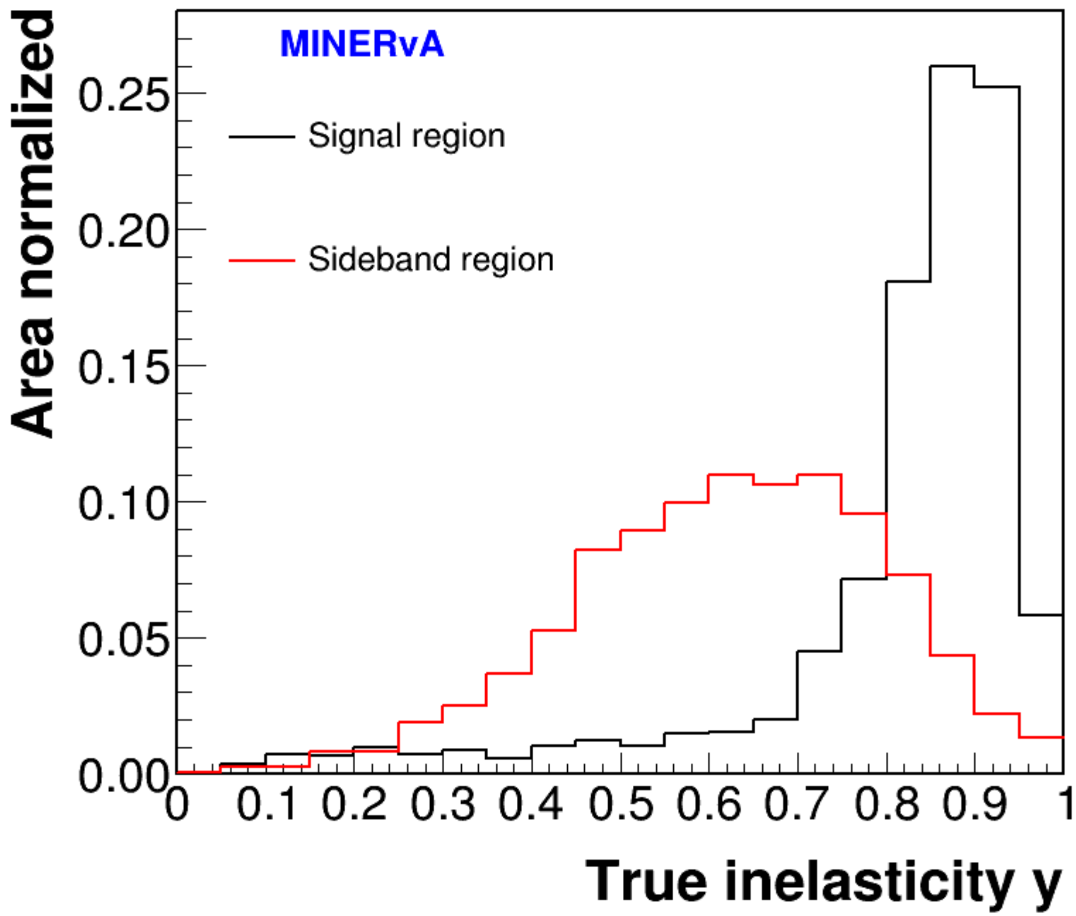
NC sideband constraint on CC events: neutrino energy



Flux error enters because signal region is low-energy muons, which tend to come from lower-energy neutrinos

Sideband region includes flux tail, where uncertainties are generally larger

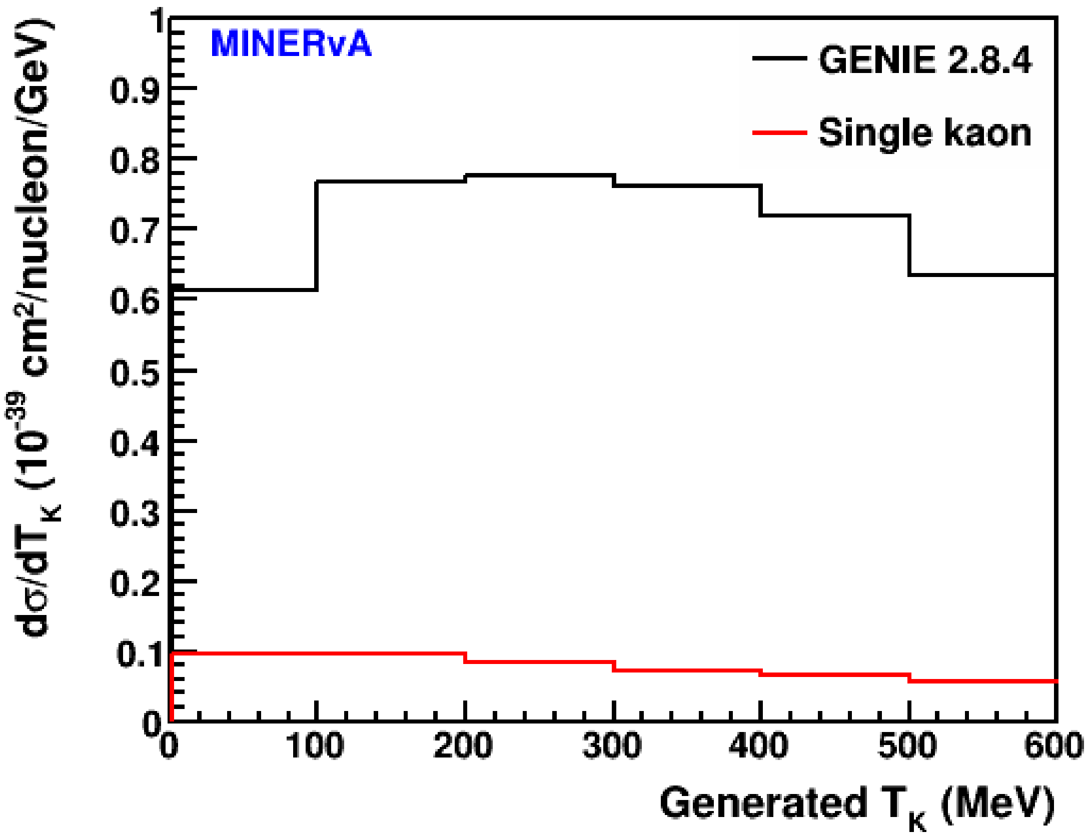
NC sideband constraint on CC events: y distribution



Signal region is very high y because muon energy is small (< 500 MeV)

Sideband region is all muons > 500 MeV, which is lower inelasticity, but we exclude very low y events from the sideband to reduce the extrapolation

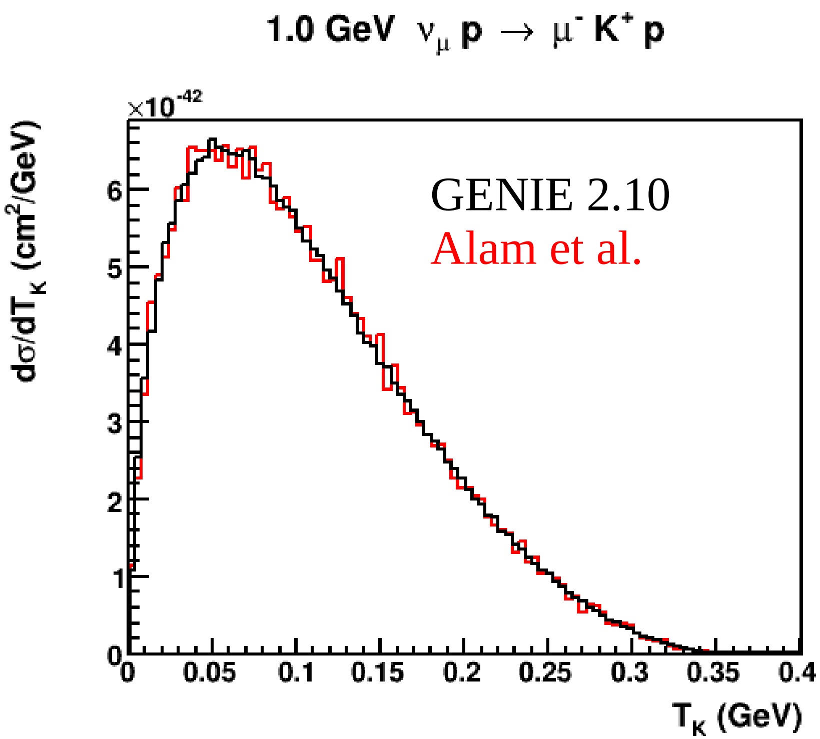
Single kaon production



~10% of total cross section for MINERvA flux, according to this one model

Combine SK and nominal samples by fixing cross section as a function of W

Single kaon production



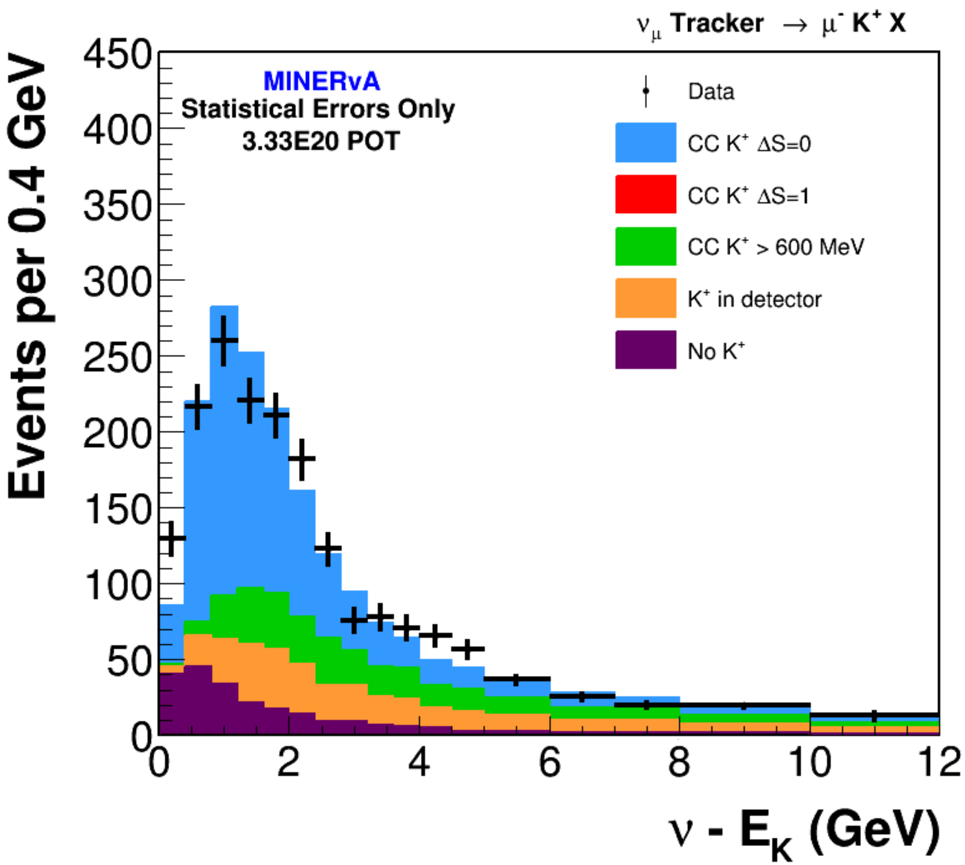
Cabibbo-suppressed channel $\nu_\mu N \rightarrow \mu^- K^+ N$ is not in GENIE 2.8

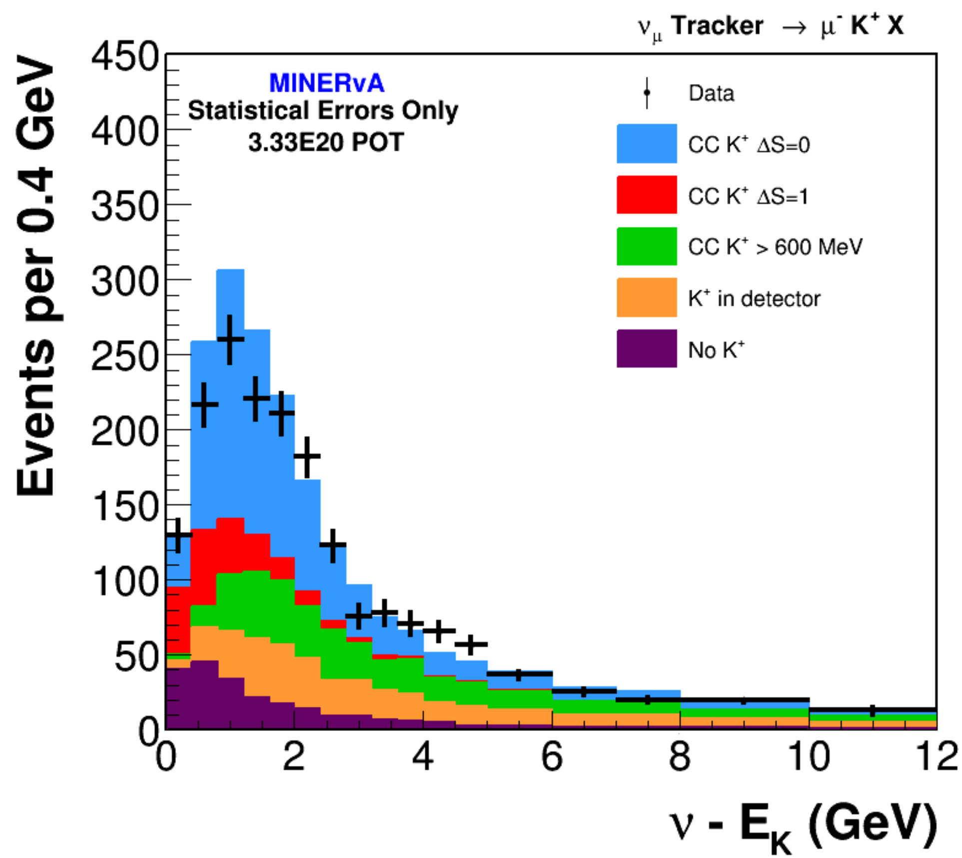
Potentially important, if acceptance is different for these events

Implemented based on Alam et al. Phys.Rev. **D**82 033001 (2010), and in GENIE 2.10

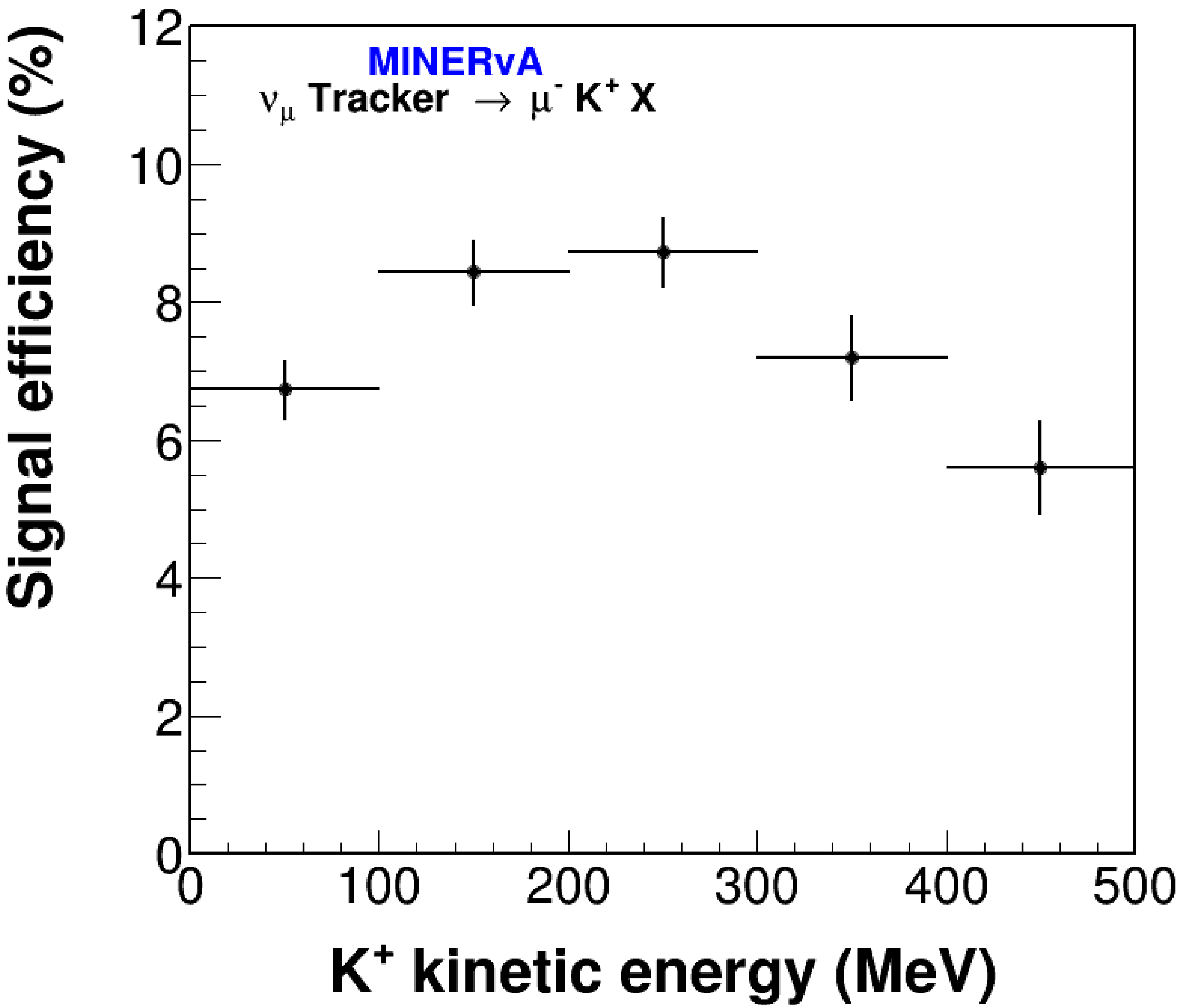
Used to implement a correction in this analysis

SK hadronic energy distribution

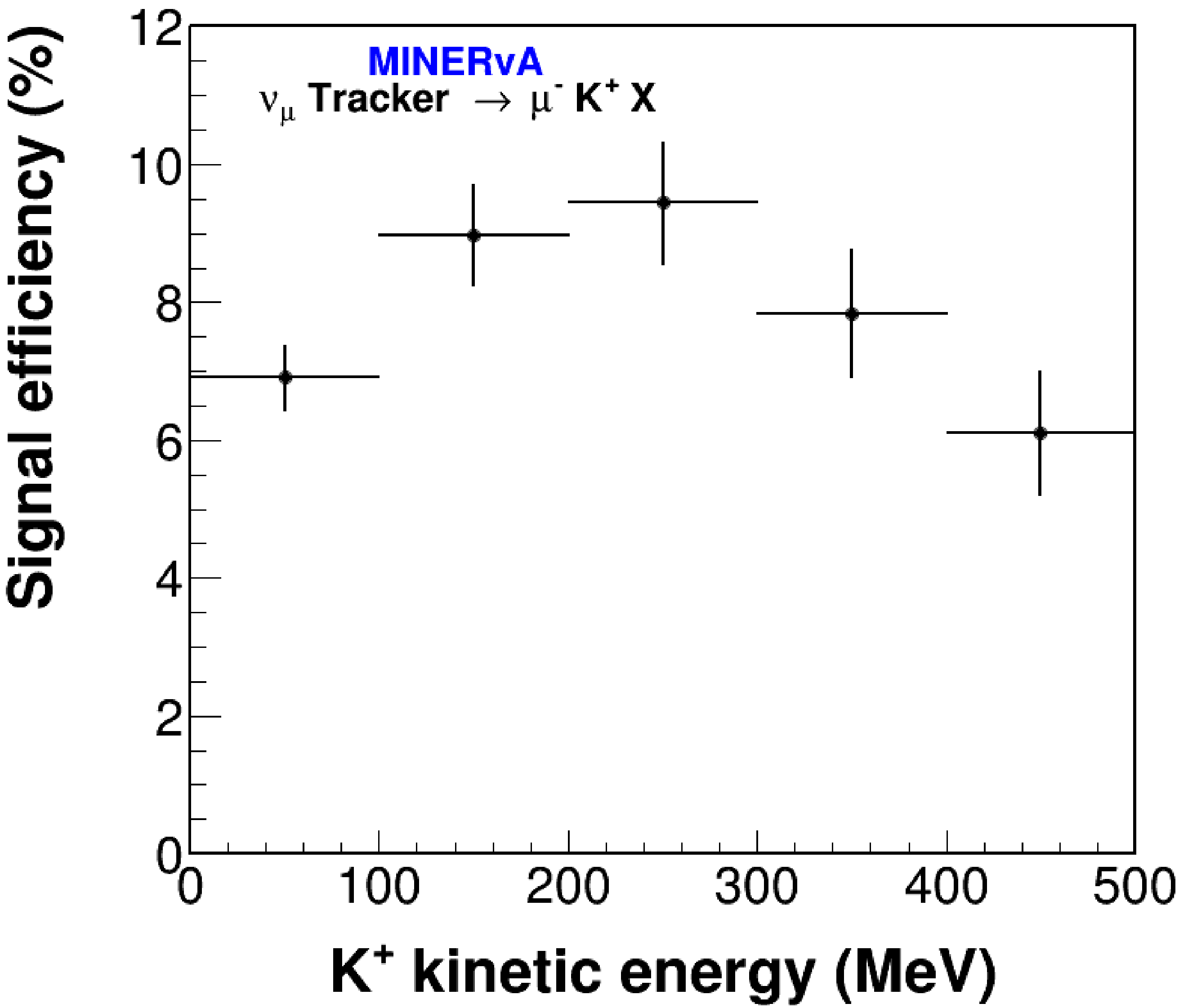




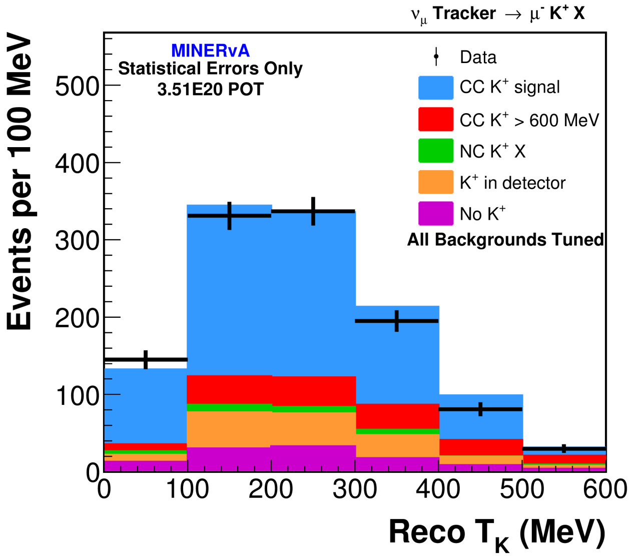
Nominal efficiency

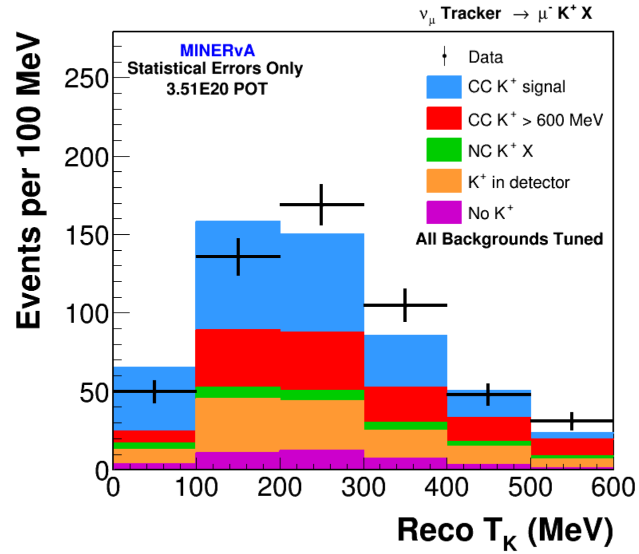


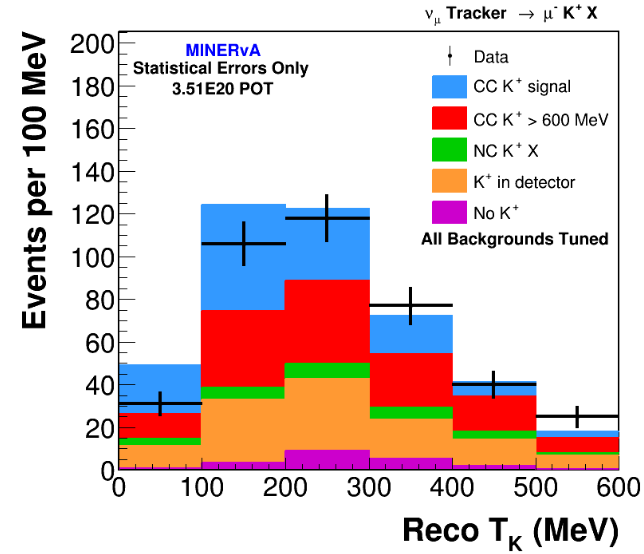
Corrected efficiency

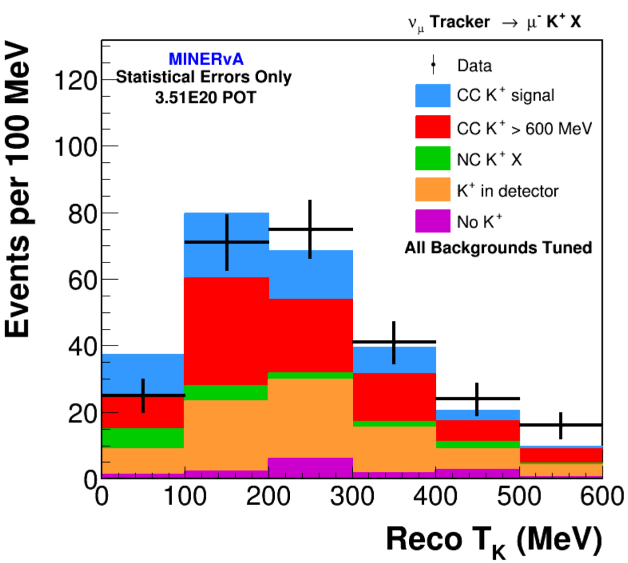


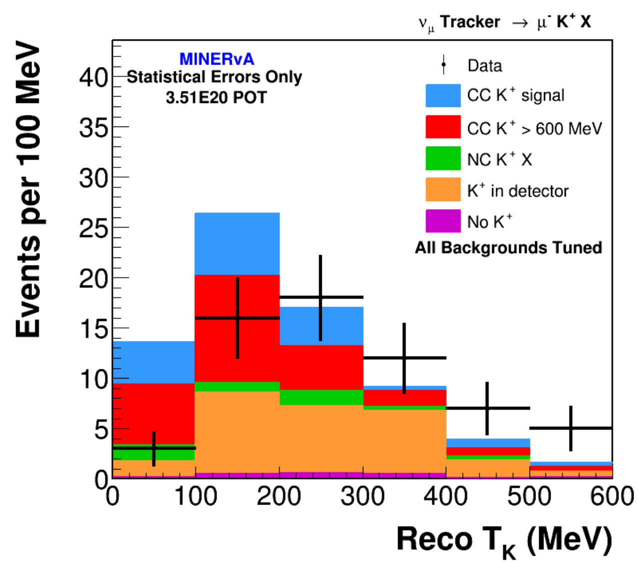
Kaon kinetic energy vs. E_{vis}







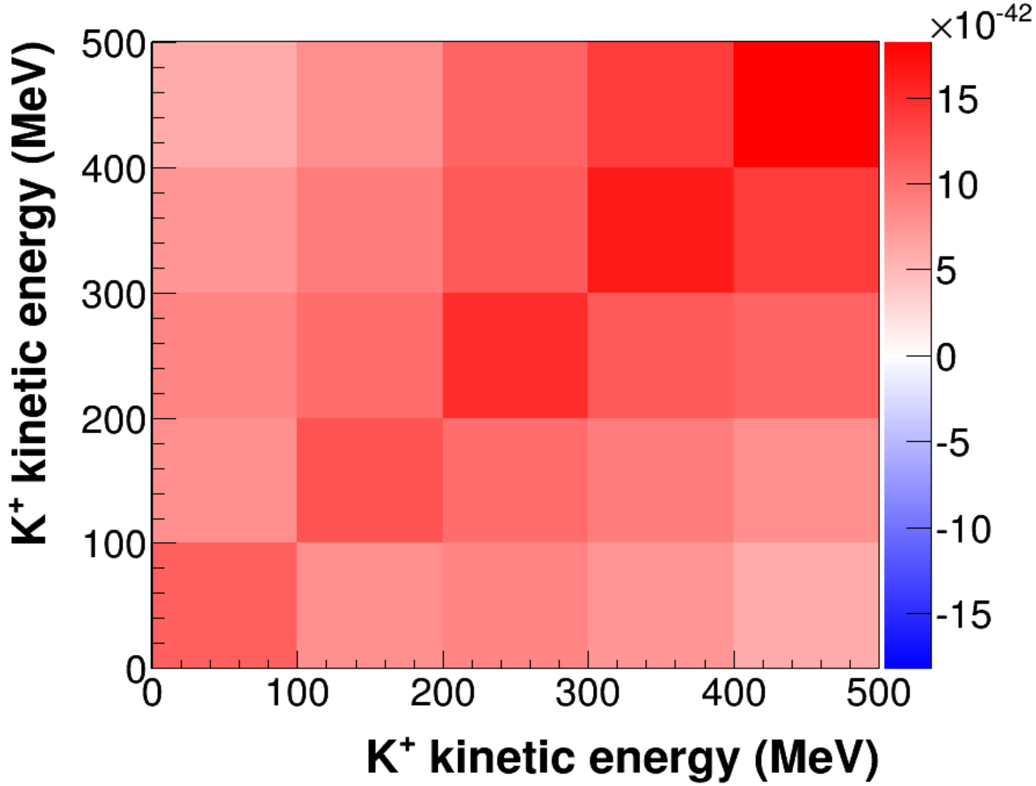


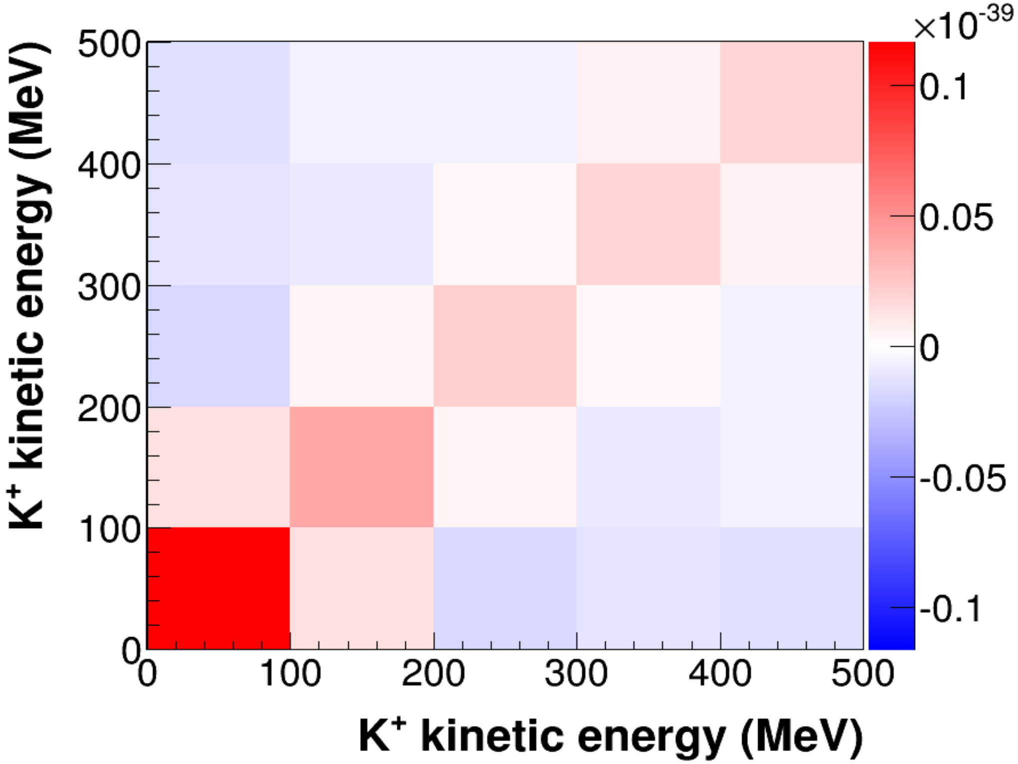


Reconstructed kinetic energy in slices of hadronic visible energy

In reading order:
$0 < E_{vis}$ / GeV < 2
$2 < E_{vis}$ / GeV < 4
$4 < E_{vis}$ / GeV < 8
$8 < E_{vis}$ / GeV < 20
$20 < E_{vis}$ / GeV

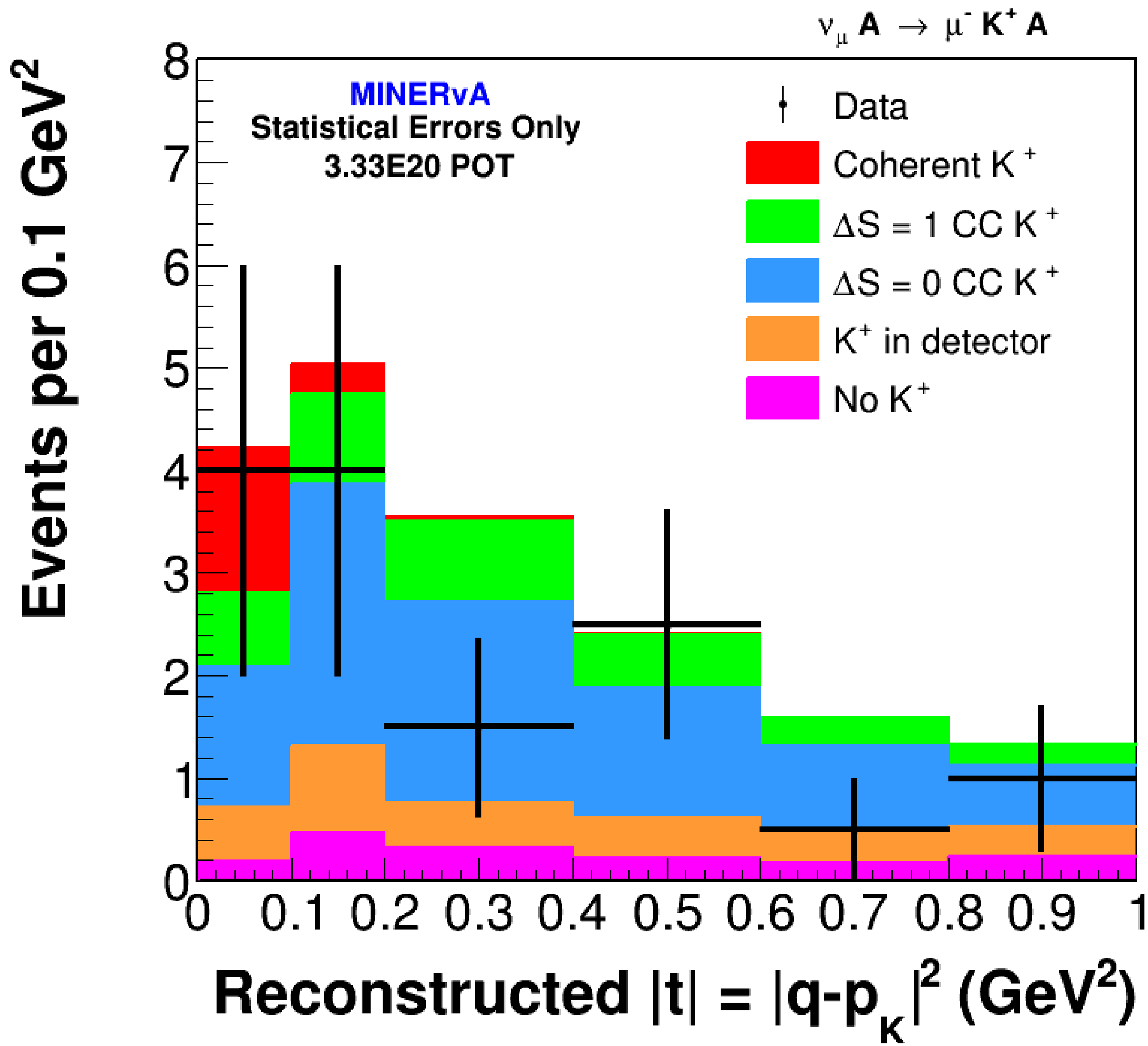
Covariance matrices: CC



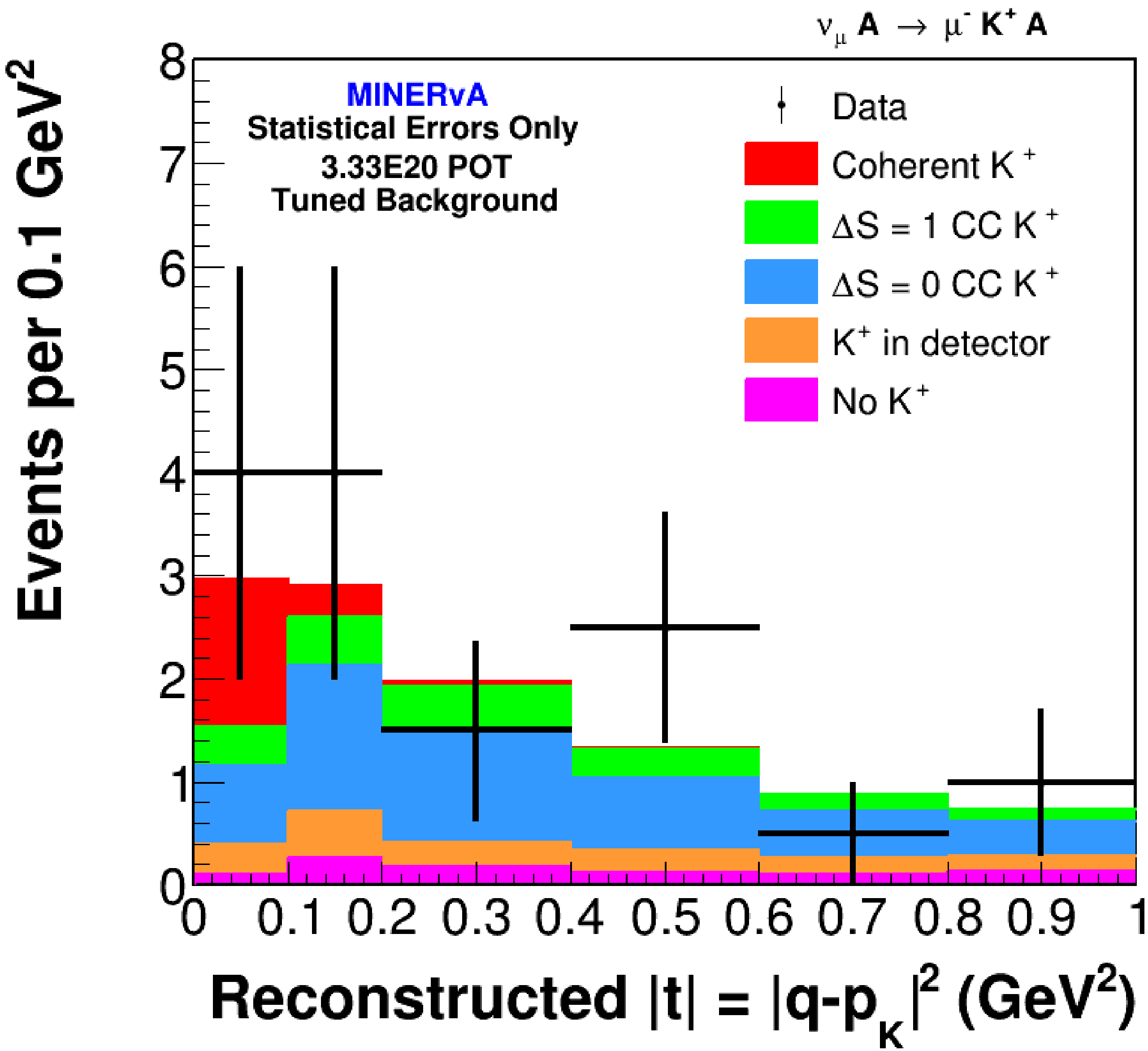


Systematic uncertainties only (left), statistical uncertainty only, which enters via the unfolding procedure

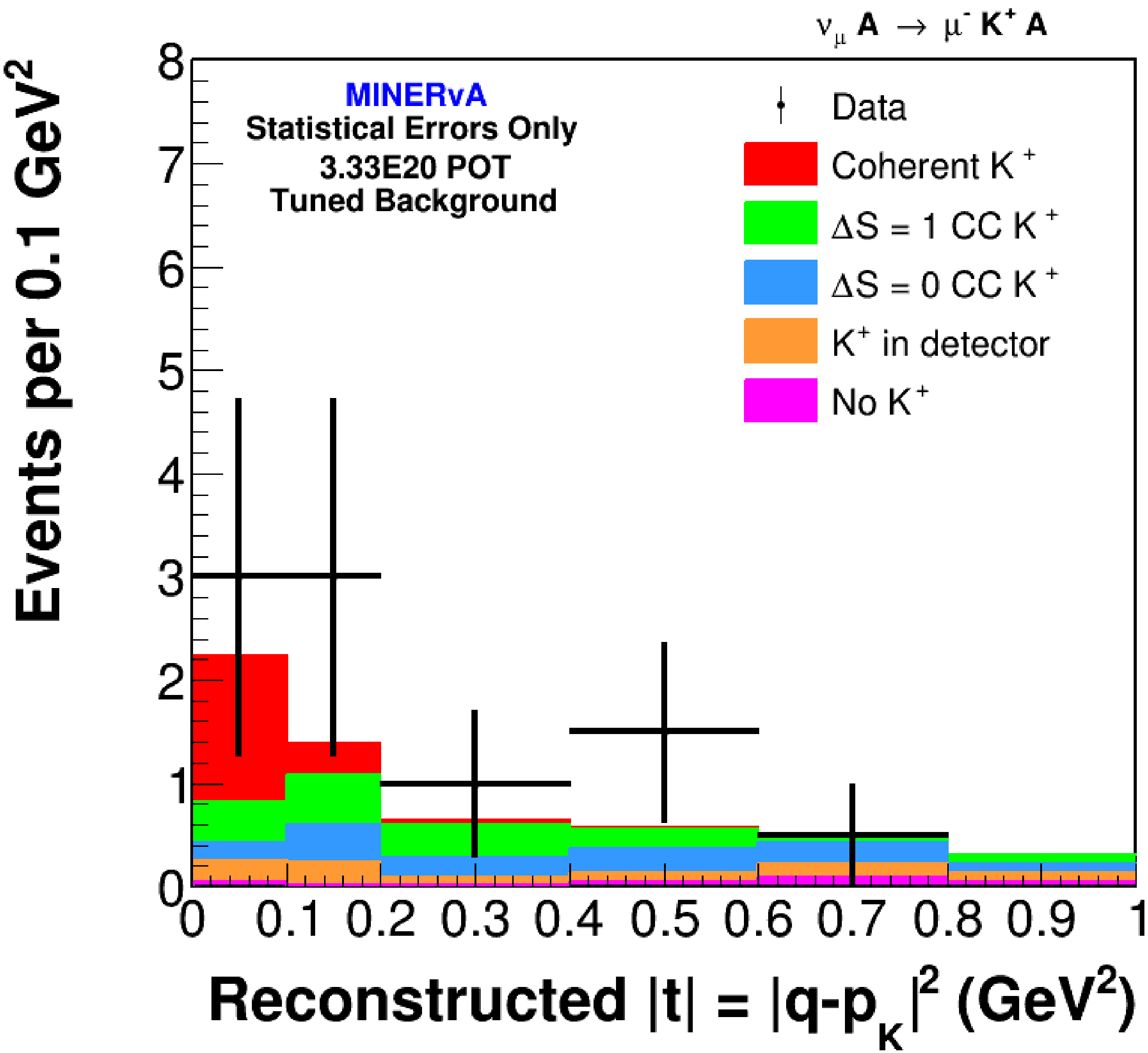
Coherent t raw background



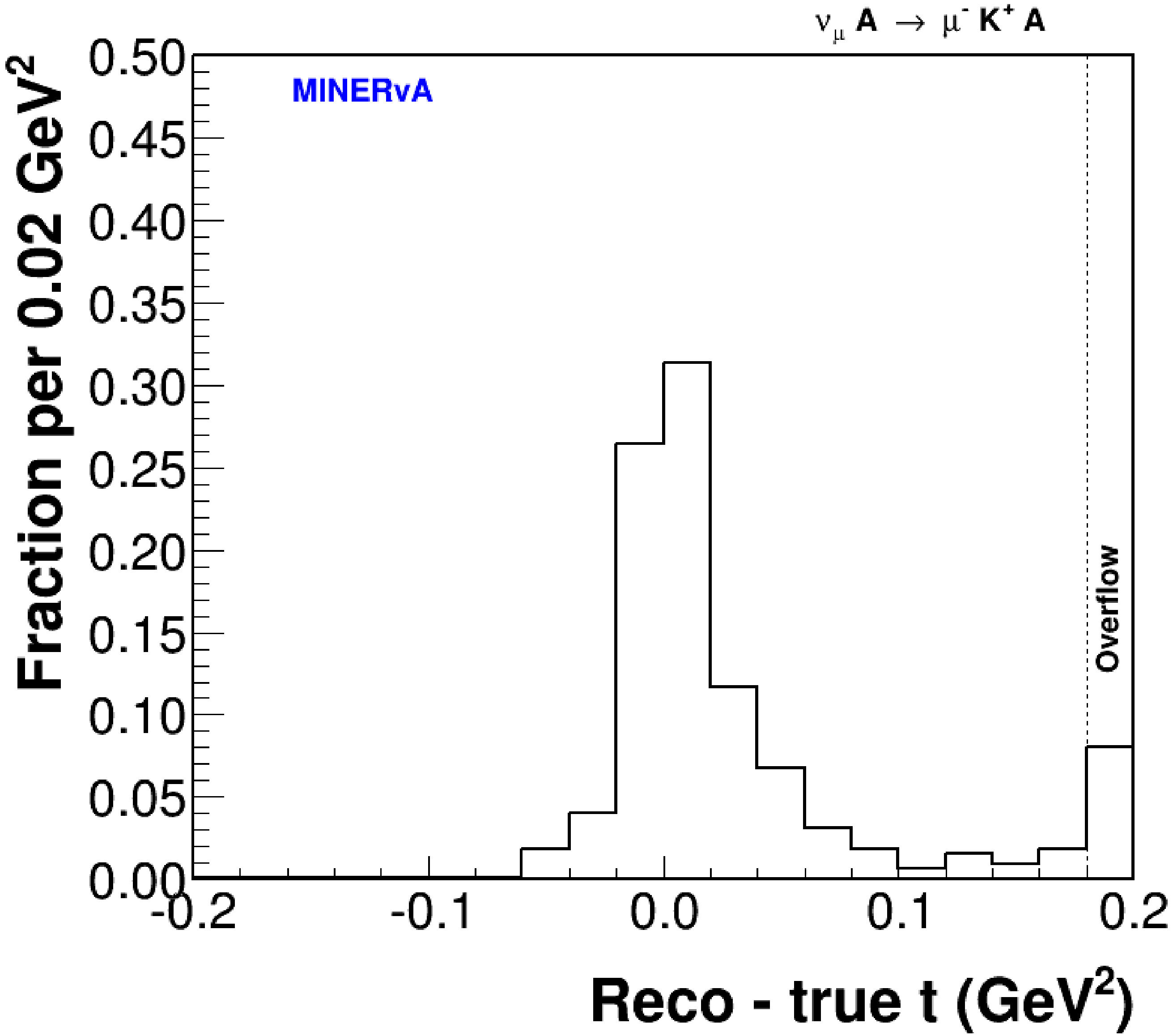
Coherent t tuned background



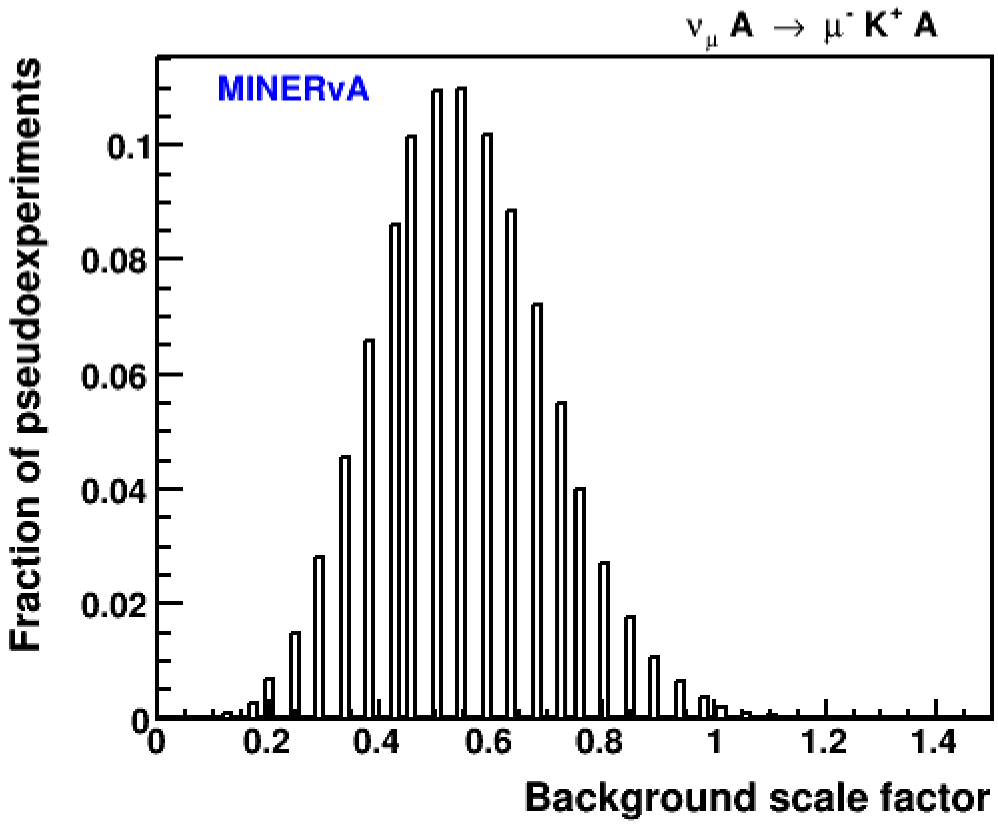
Coherent t tuned background after π^0 rejection scan

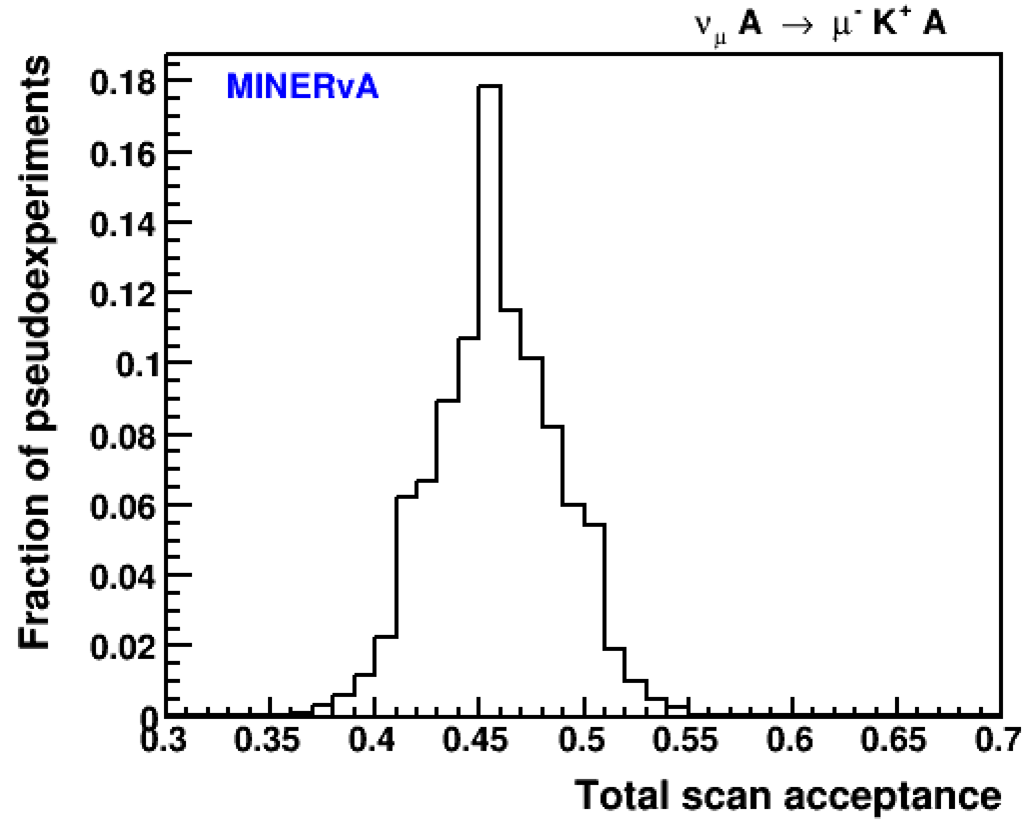


Coherent t residual



Coherent background prediction

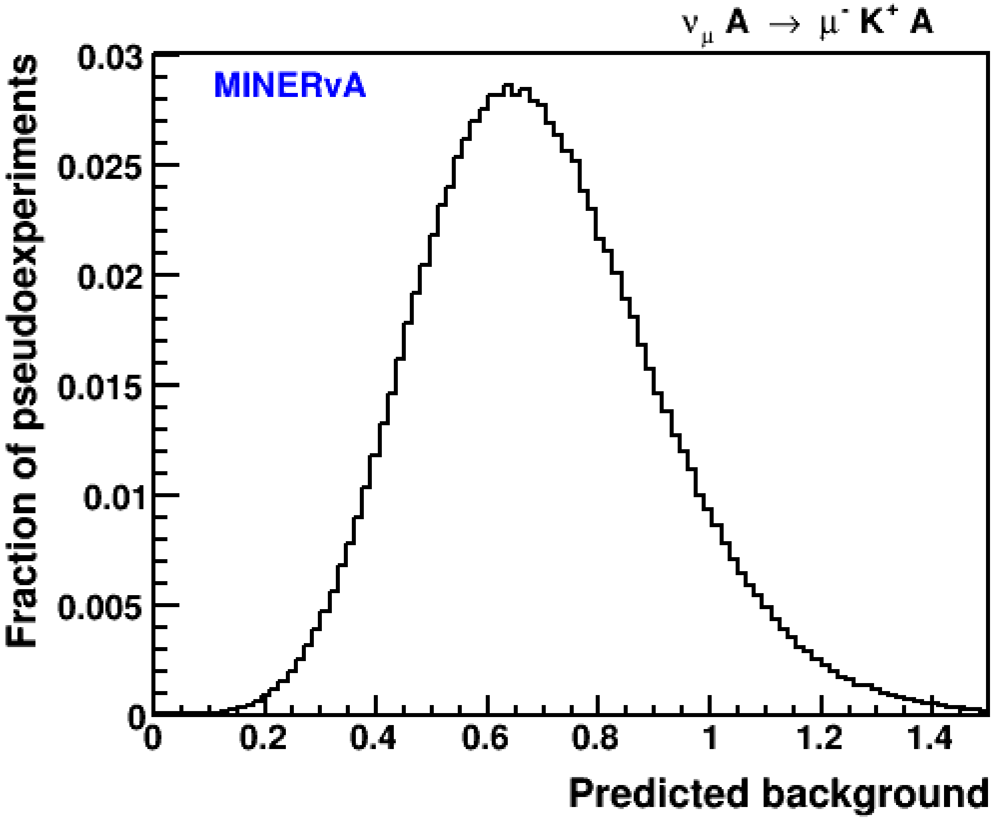




Left: scale factor for background based on sideband constraint

Right: Background acceptance in the π^0 rejection scan

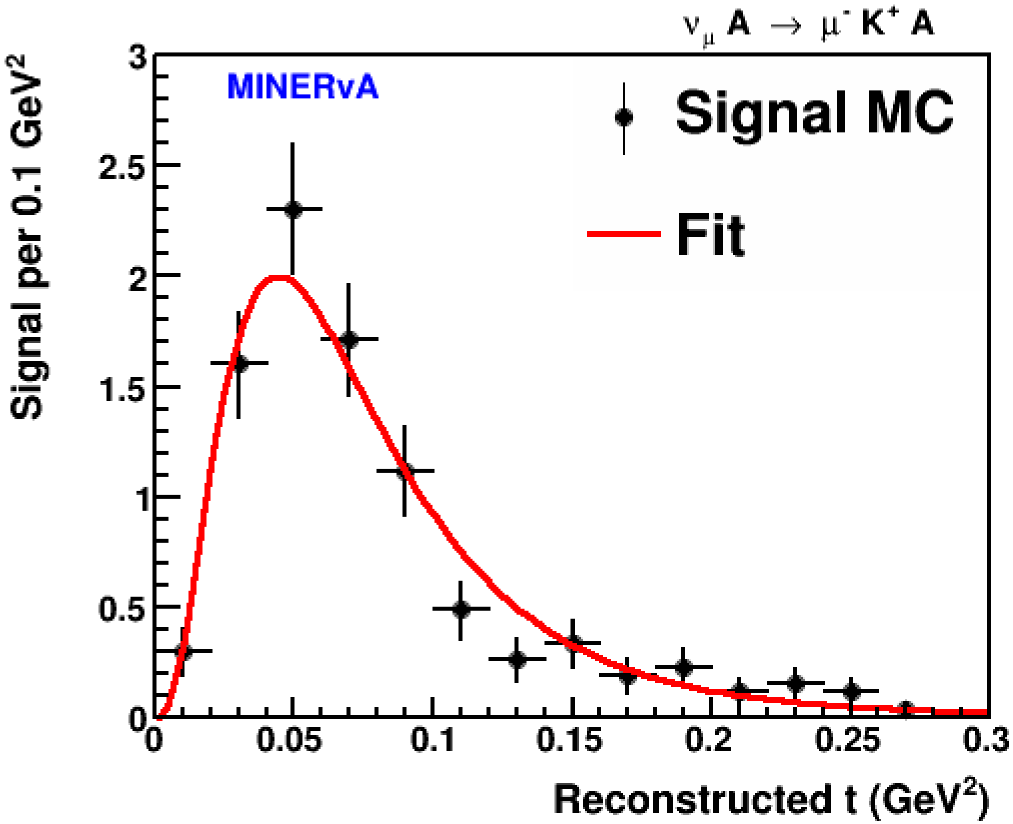
Coherent background prediction

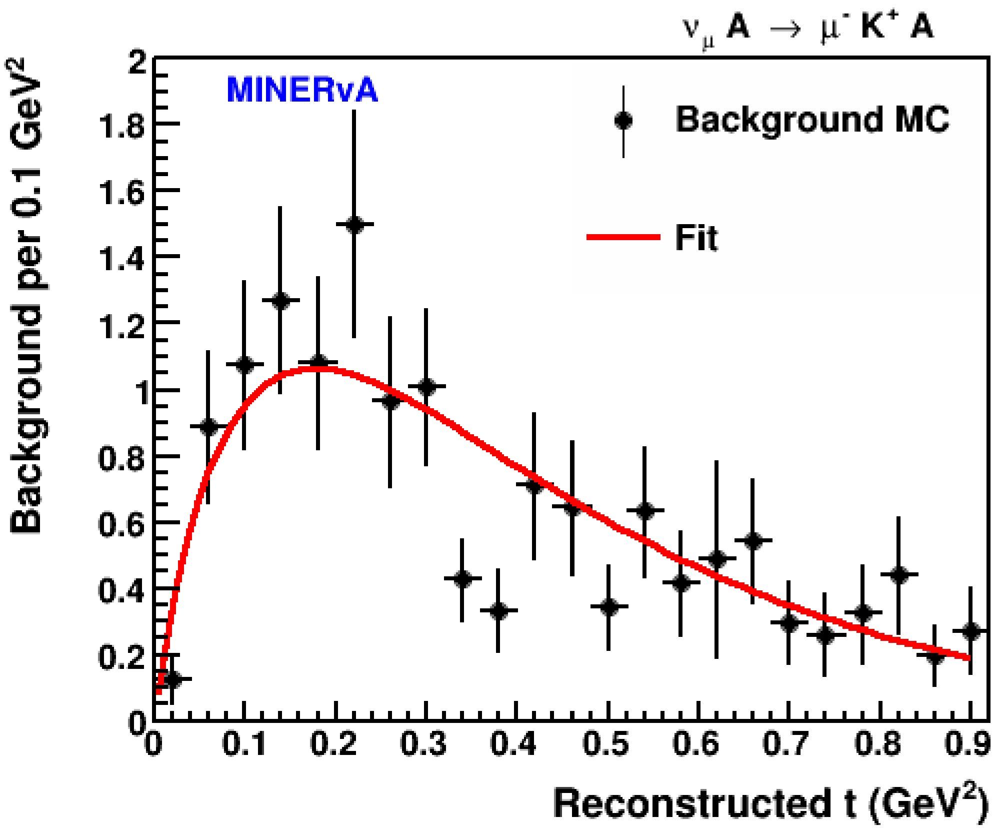


In each pseudoexperiment, scale the nominal background by randomly taking a number from each of the plots on the previous slide and multiplying them together

This plot is the mean number of background events – "observed" background in a pseudoexperiment is a Poisson random number taken from a distribution with this mean

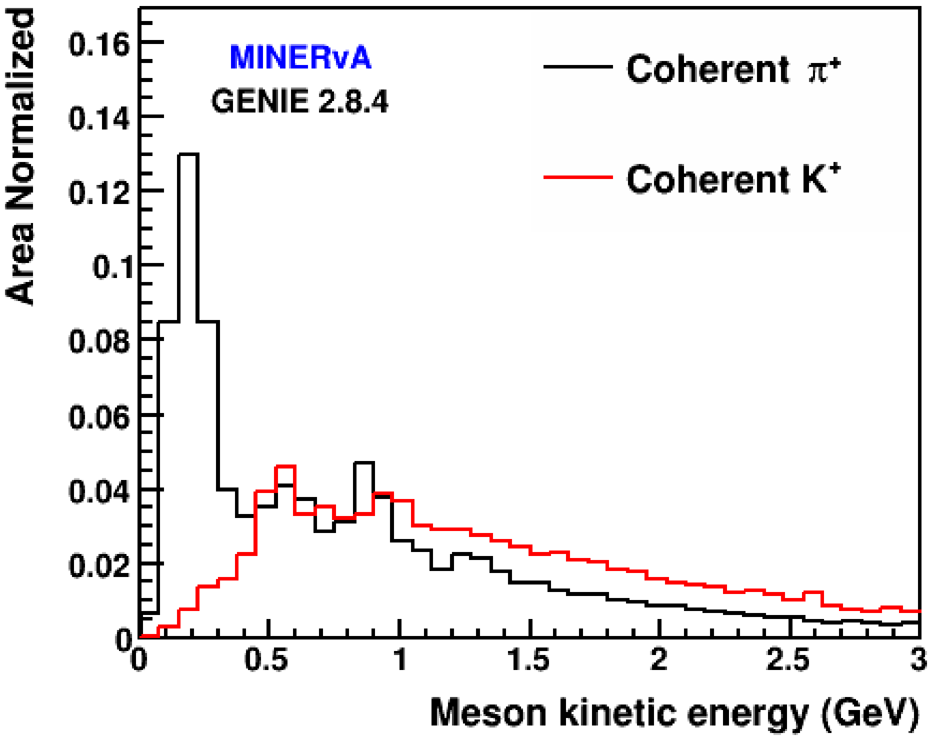
Signal and background templates

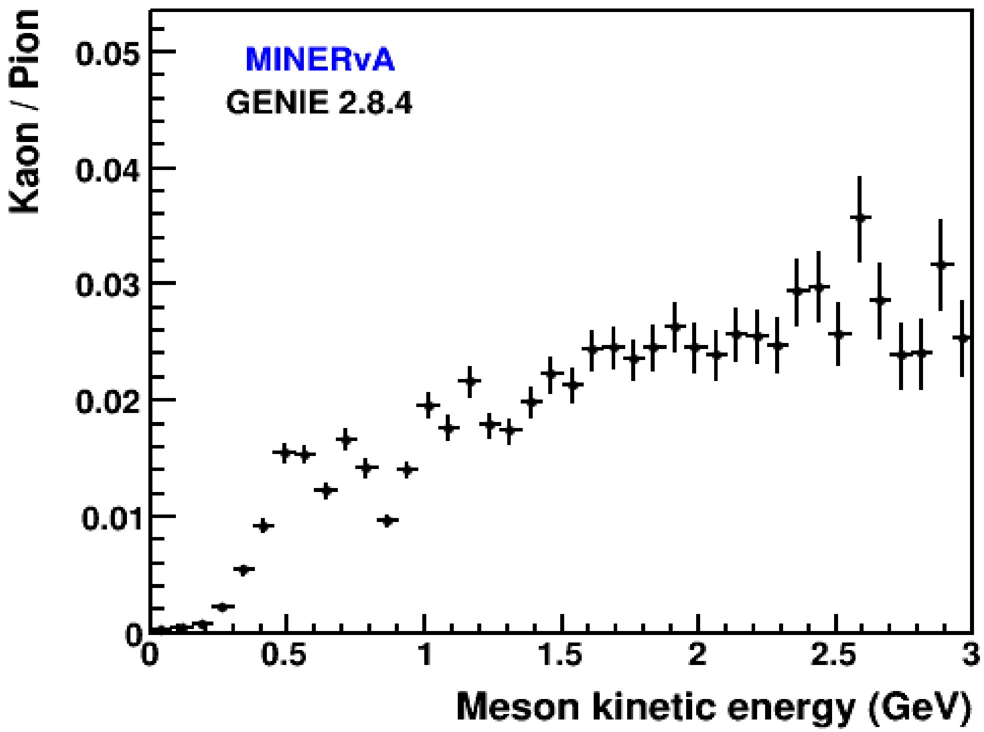




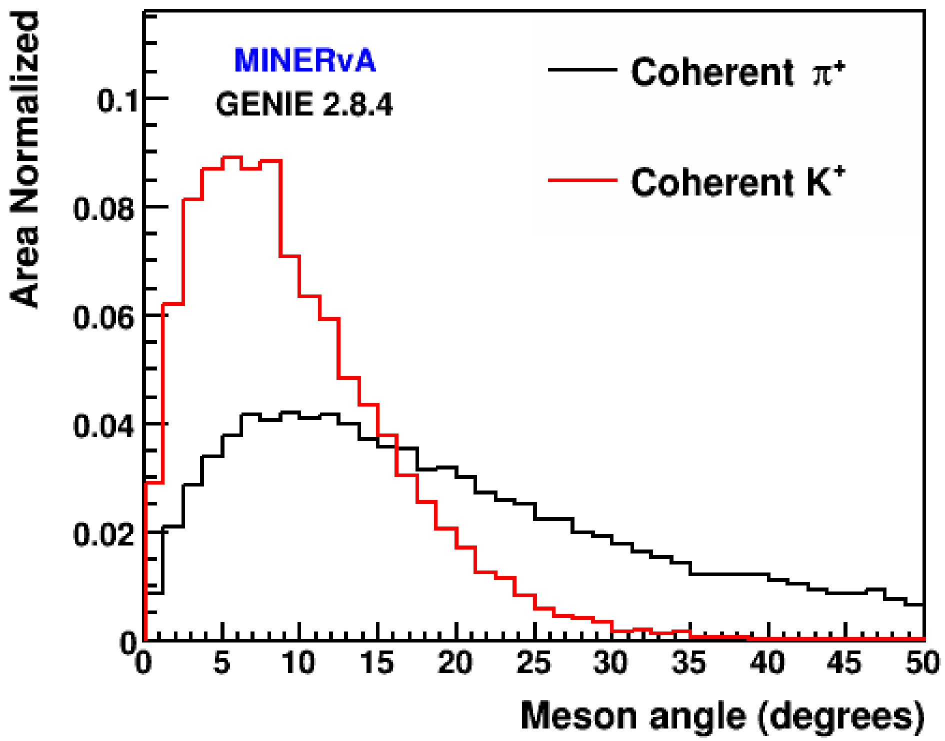
Use fits to the signal and background MC to perform an unbinned likelihood fit on the data

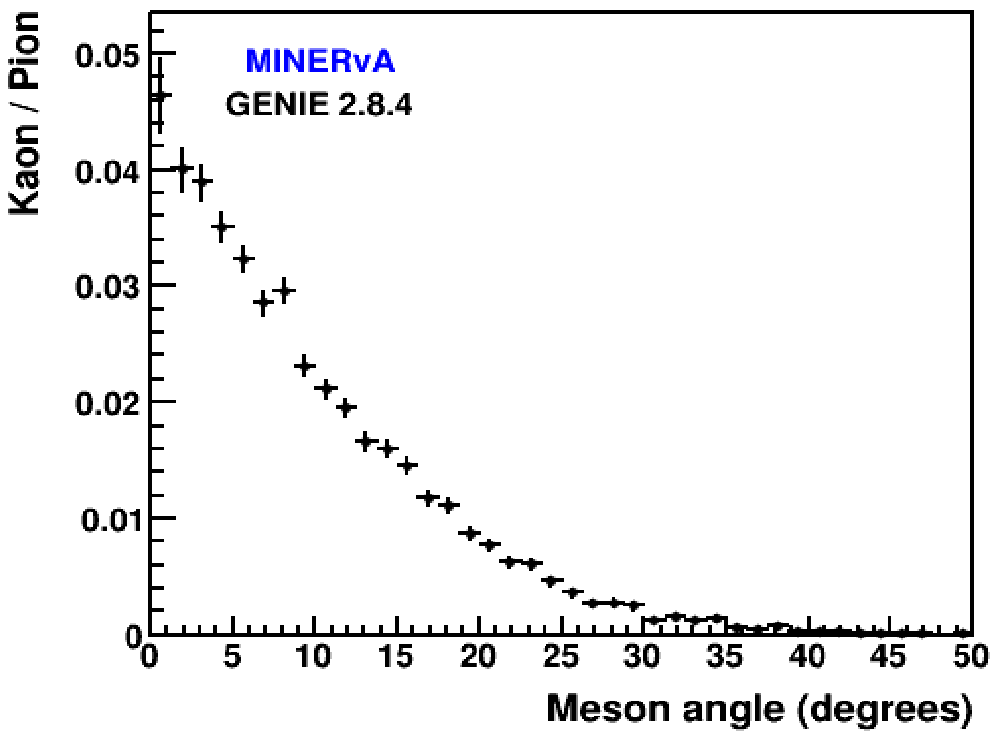
Coherent signal model: KE



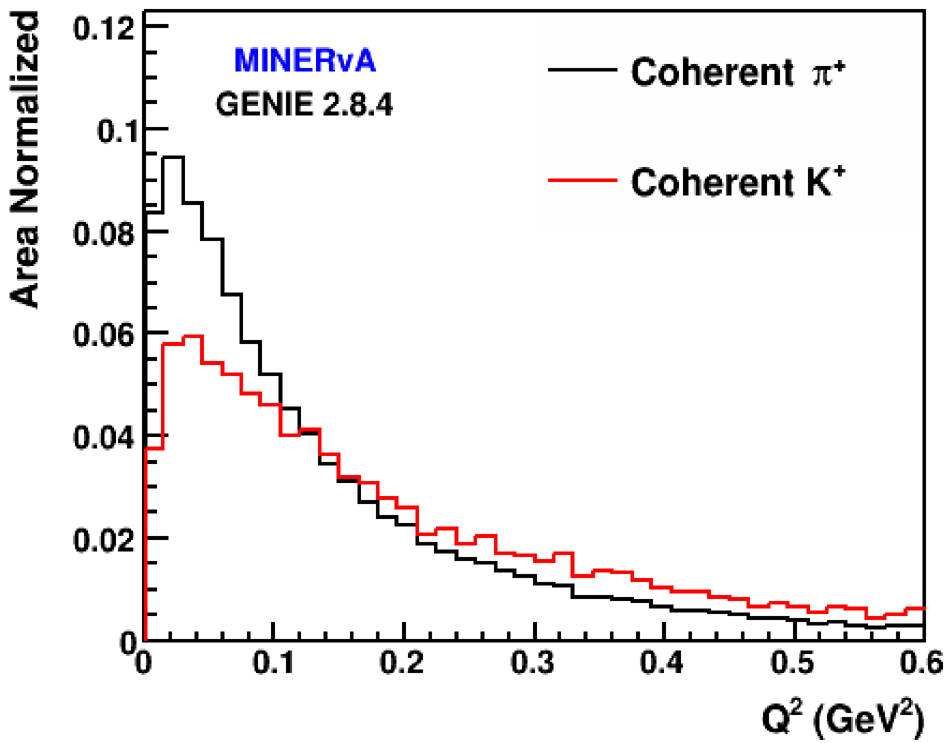


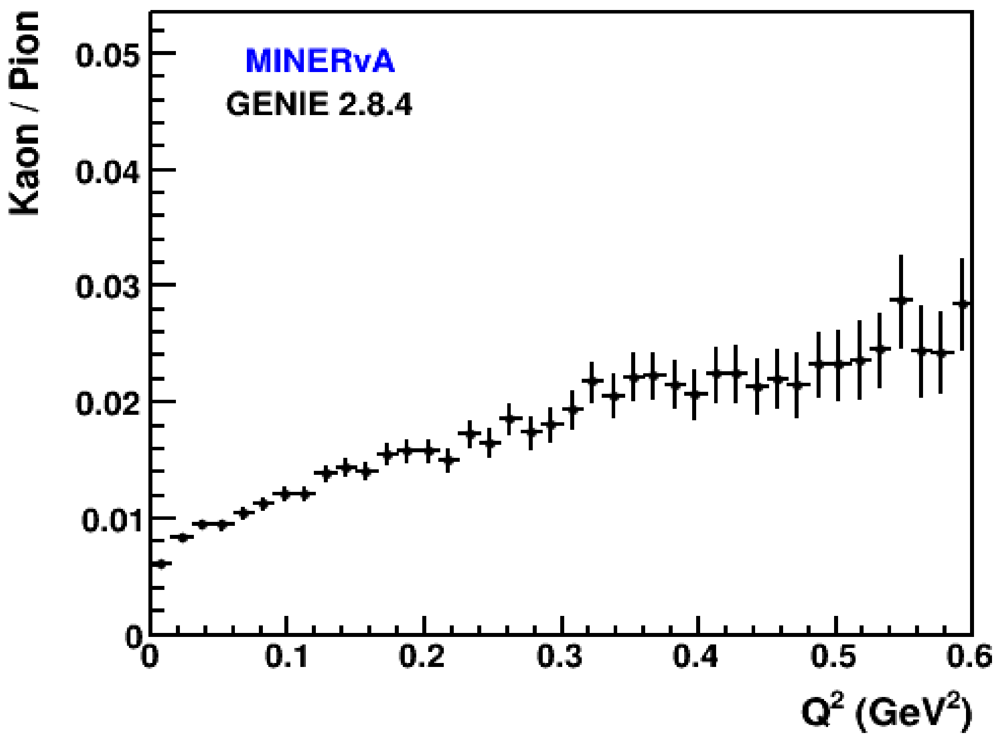
Coherent signal model: theta



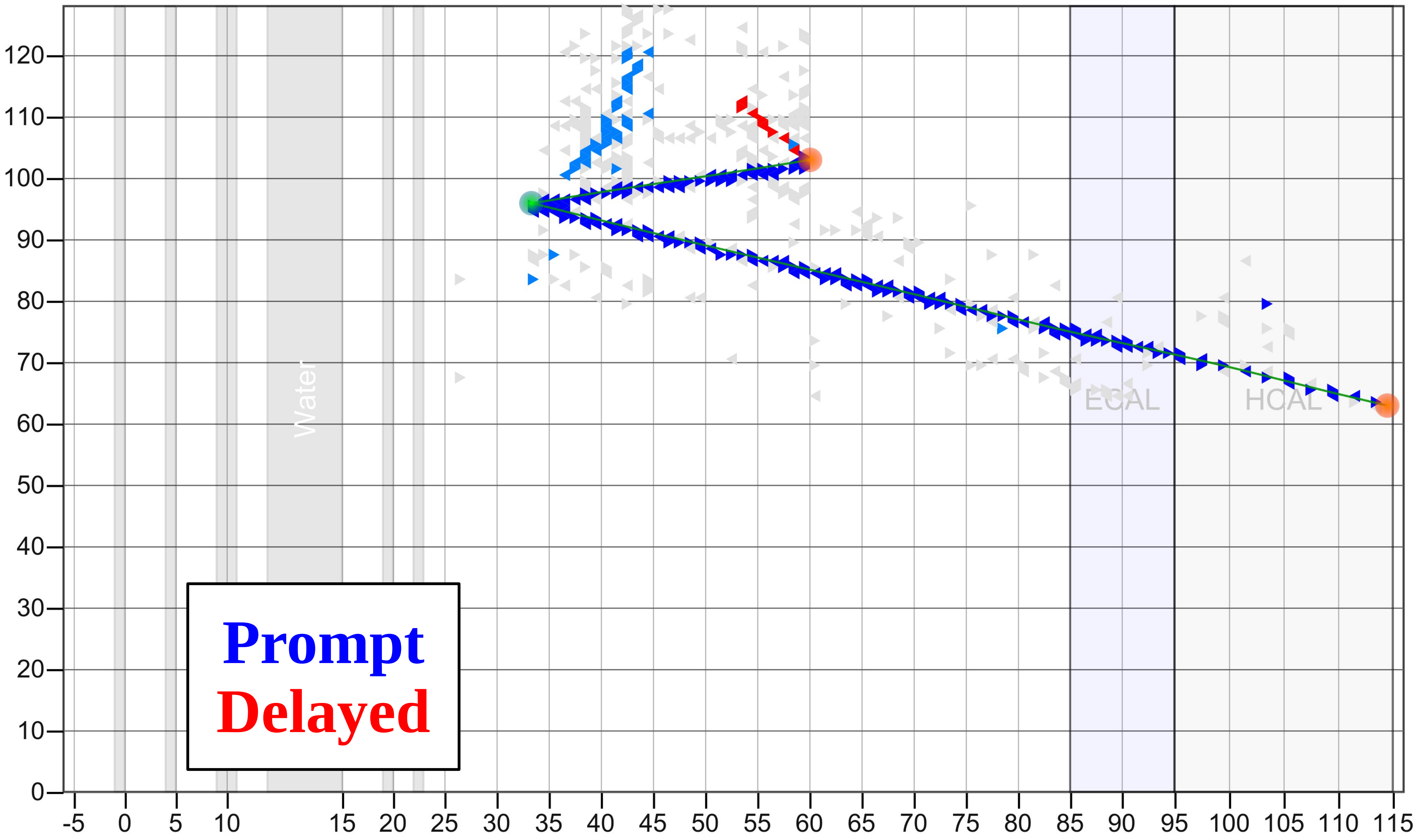


Coherent signal model: Q^2

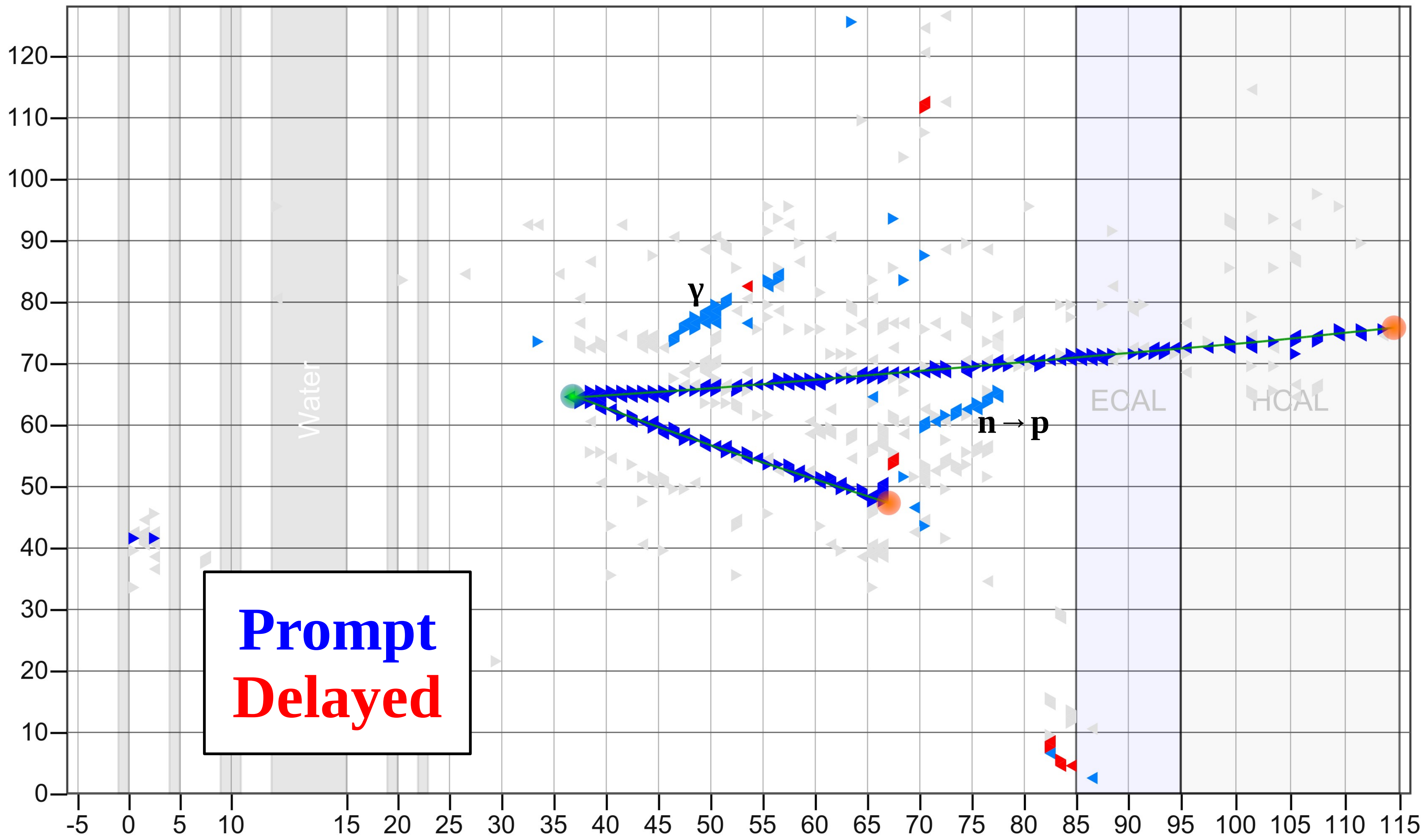




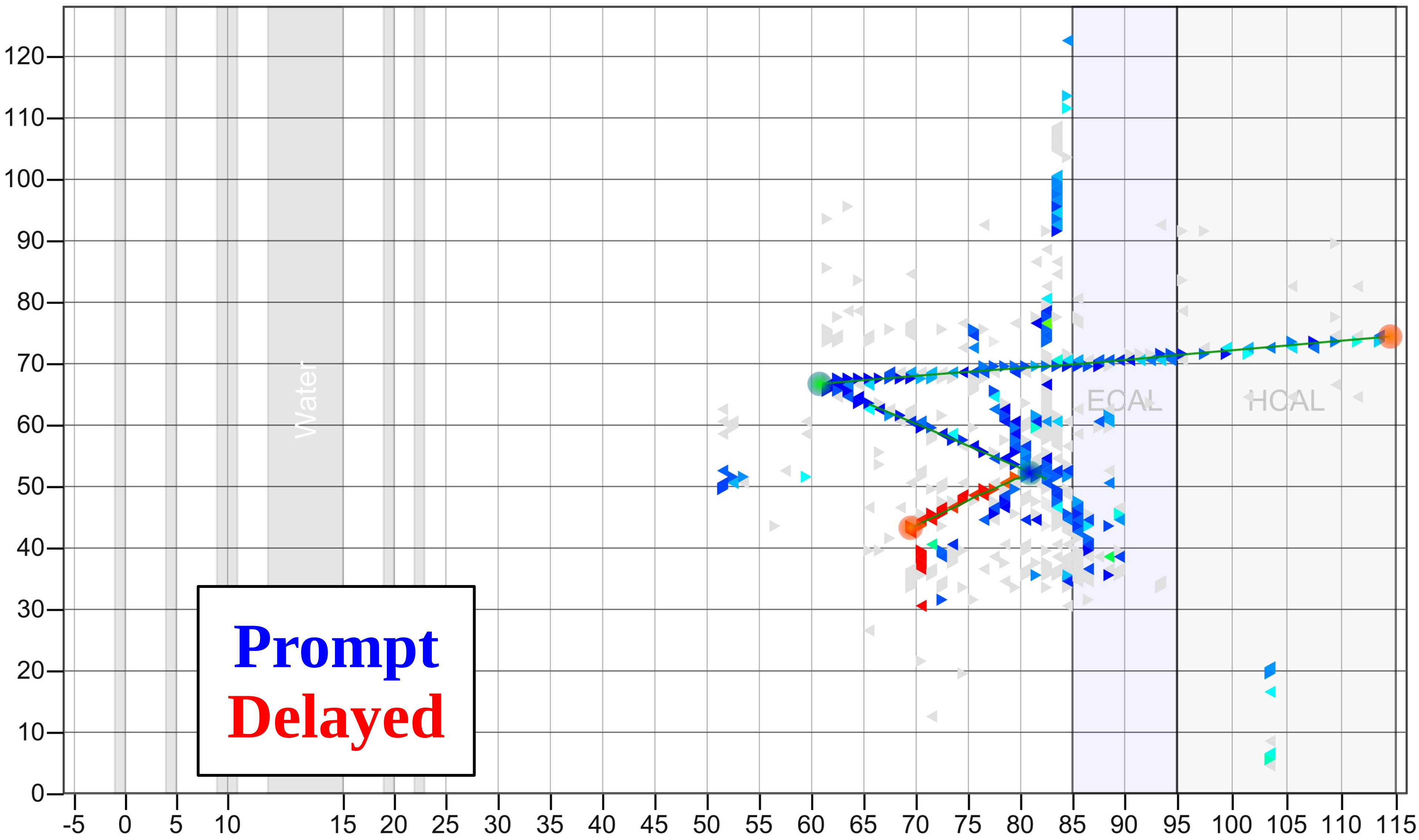
π^0 scan: reject #1



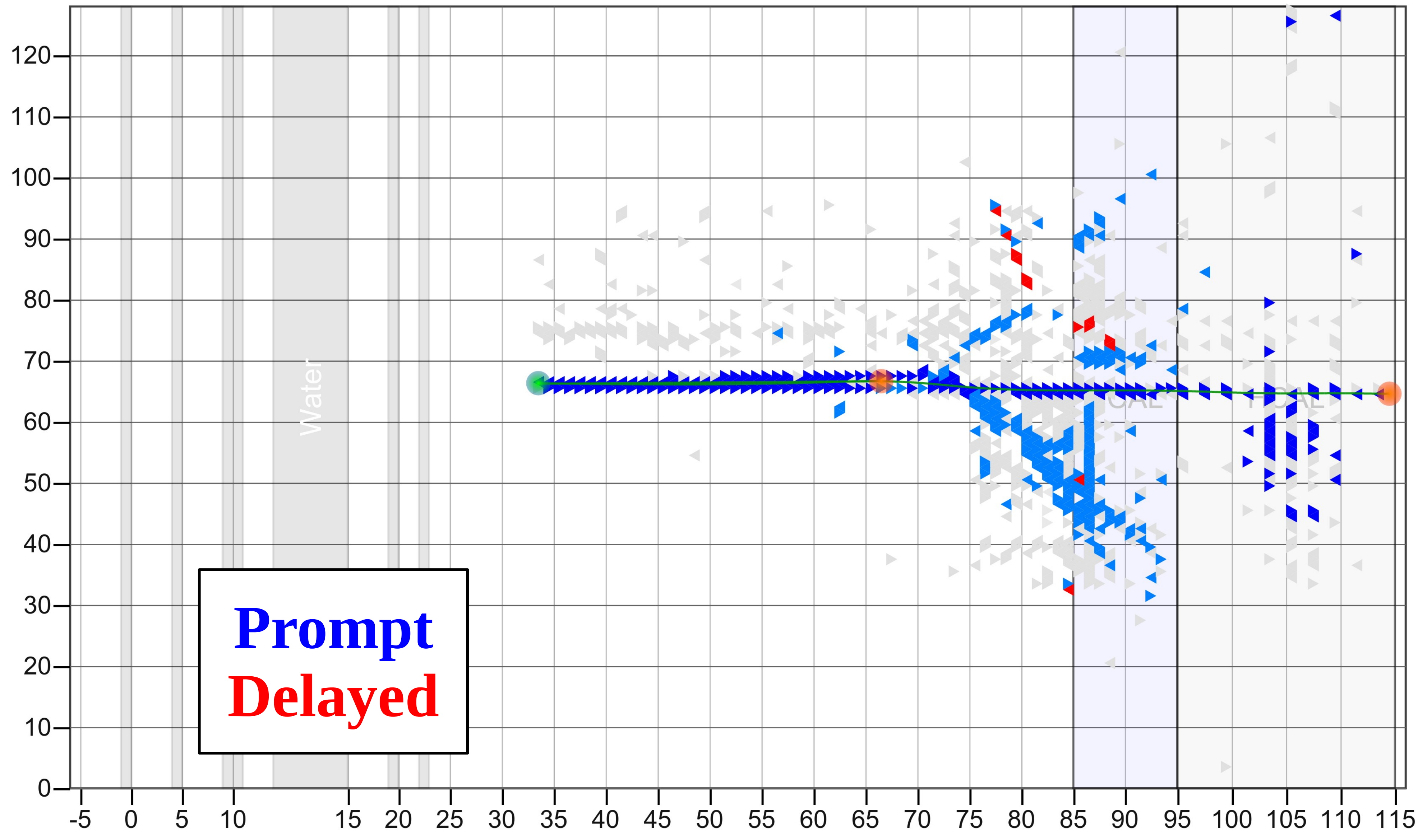
π^0 scan: reject #2



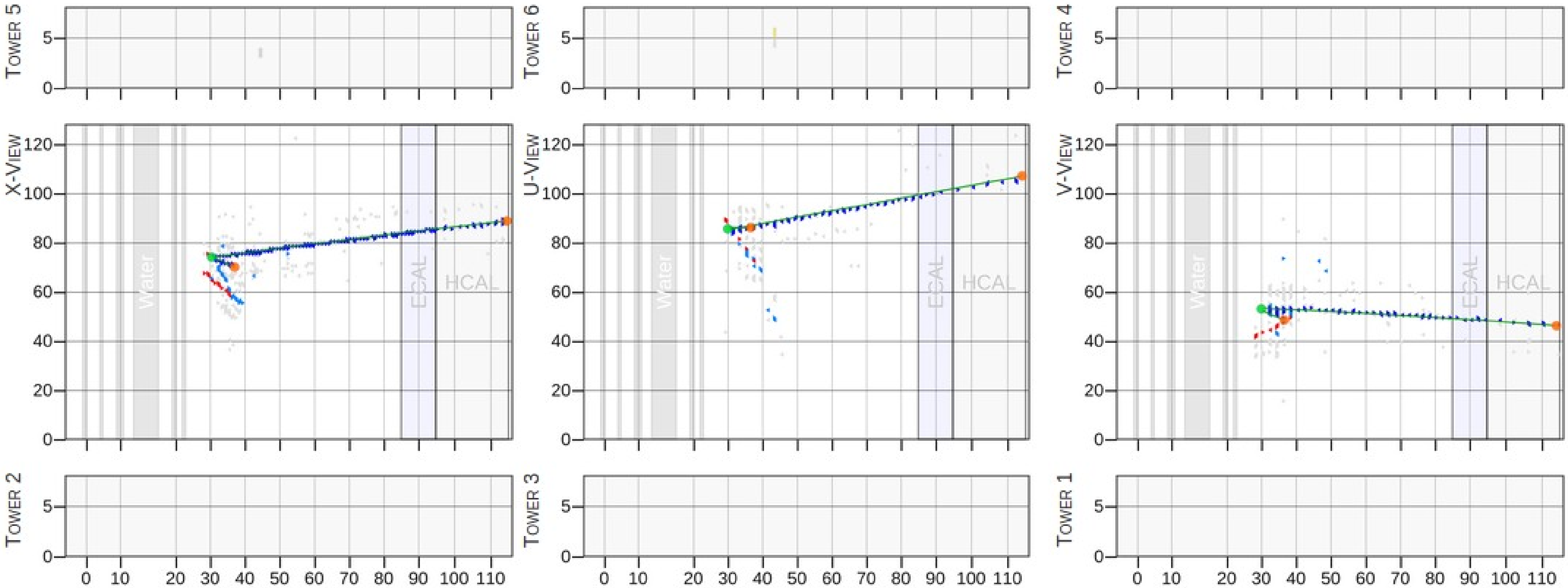
π^0 scan: keeper #1



π^0 scan: keeper #2

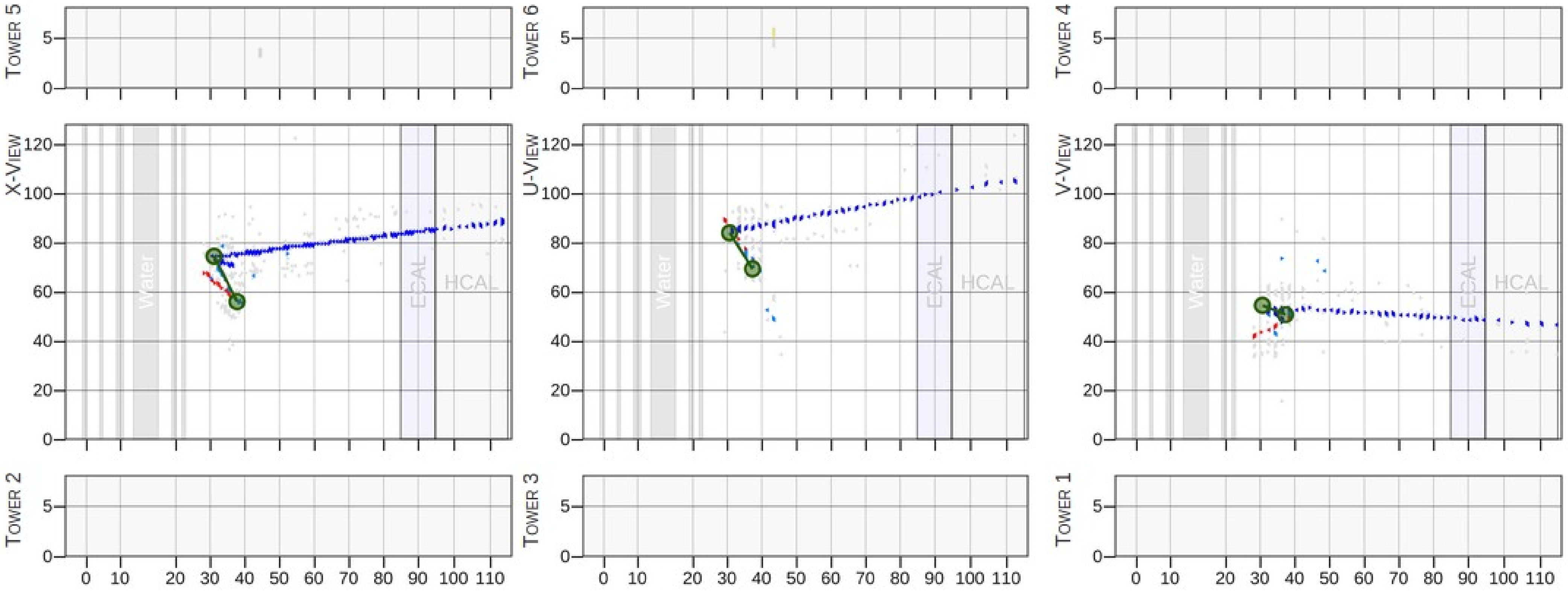


Including low-energy kaons



μ^- K^+ Λ final state, π^- from Λ decay is tracked, but K^+ is not

Scan for the range



In U view, decay μ^+ overlaps the vertex, but a human with some training can make an excellent range measurement