Updates to the fiTQun Event Reconstruction and Interface to WCsim

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for Team fiTQun

Hyper-Kamiokande Workshop #3

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fiTQun Review

- Reminder: fiTQun is a maximum likelihood fitter
  - Likelihood function defined with PMT charge and time:

$$L(\mathbf{x}) = \prod_{i}^{\text{unhit}} P(i\text{unhit}|\mathbf{x}) \prod_{i}^{\text{hit}} P(i\text{hit}|\mathbf{x}) f_q(q_i|\mathbf{x}) f_t(t_i|\mathbf{x})$$

Unhit probability | Hit probability | Charge likelihood | Time likelihood

  - Track parameters ($\mathbf{x}$) varied simultaneously to maximize the likelihood
- Please refer to previous workshops for more details on the algorithm and progress:
  1. http://indico.ipmu.jp/indico/getFile.py/access?contribId=35&sessionId=9&resId=0&materialId=slides&confId=7
  2. http://indico.ipmu.jp/indico/getFile.py/access?contribId=20&sessionId=10&resId=0&materialId=slides&confId=10

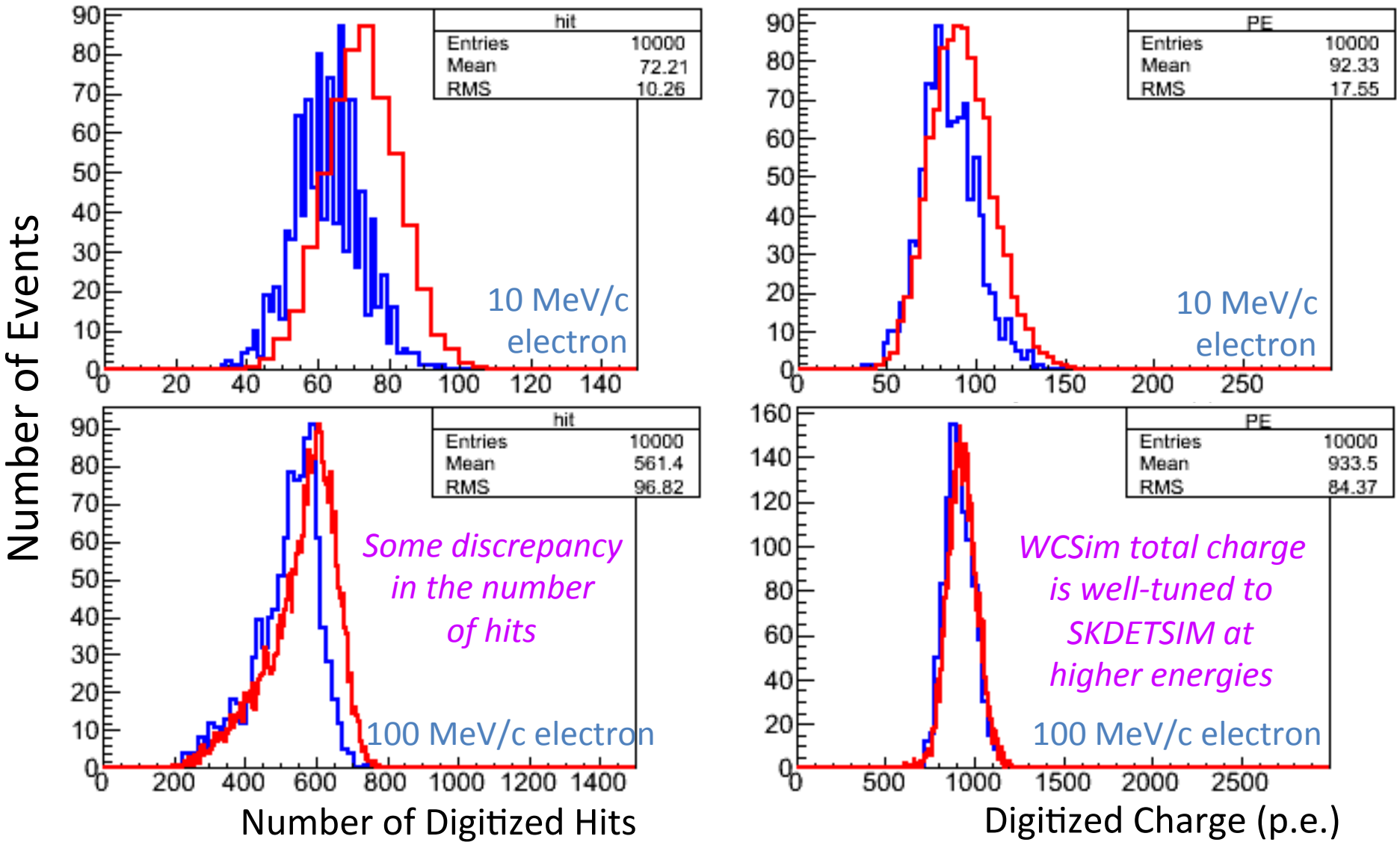
fiTQun-WCSim Interface

Blair Jamieson
(U. Winnipeg)

- Implementation is mostly complete
  - fiTQun can be compiled with no dependence on SK internal libraries nor CERNLIB
  - Geometry read directly from WCSim file
  - Hit and time information structure has been generalized from SKDETSIM to also read from WCSim format file
- Some quick studies performed so far:
  - Limited checks of vertex and momentum reconstruction in SK mode

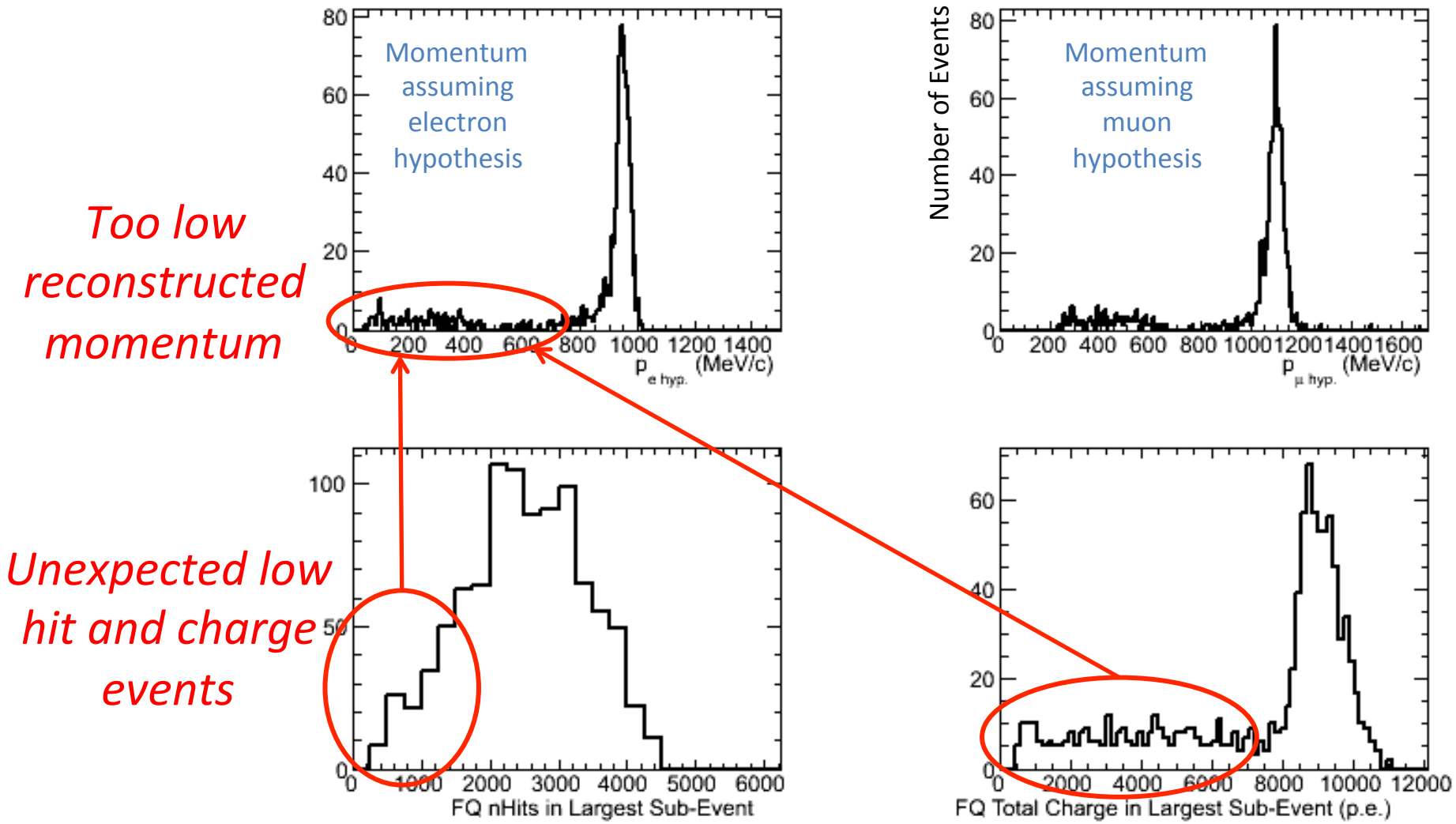
Hit and Charge Information

Legend: SKDETSIM, WCSim (1st fiTQun sub-event)



Momentum Reconstruction

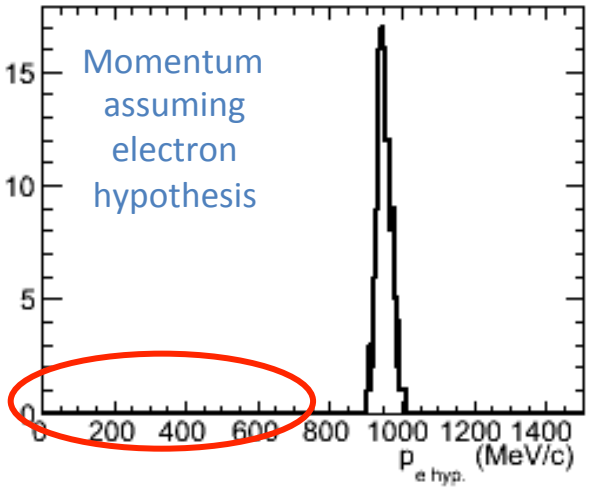
- 1 GeV/c electron, random position and direction:

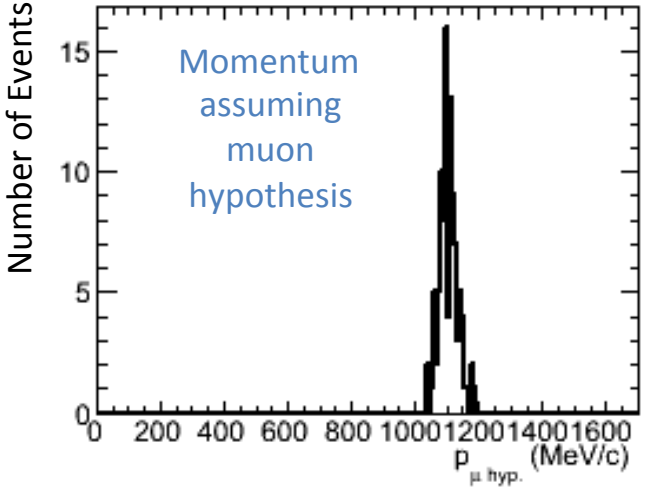


Momentum Reconstruction

- Reject events with >1 identified sub-event

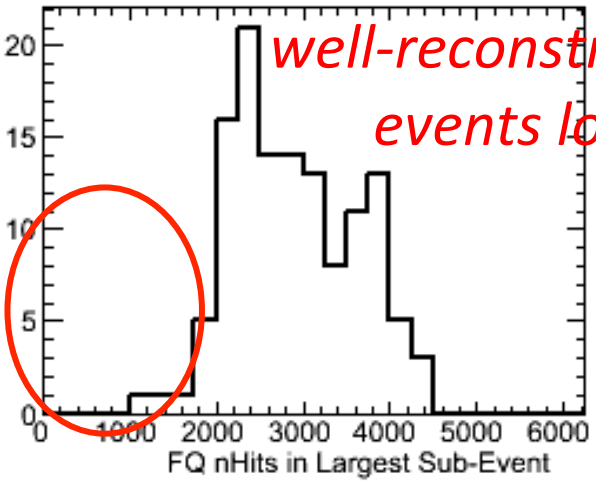
Population of mis-recon-structed events removed

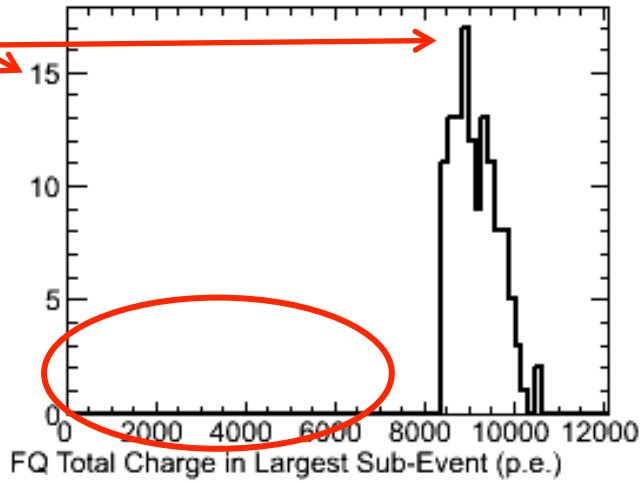




But too many well-reconstructed events lost

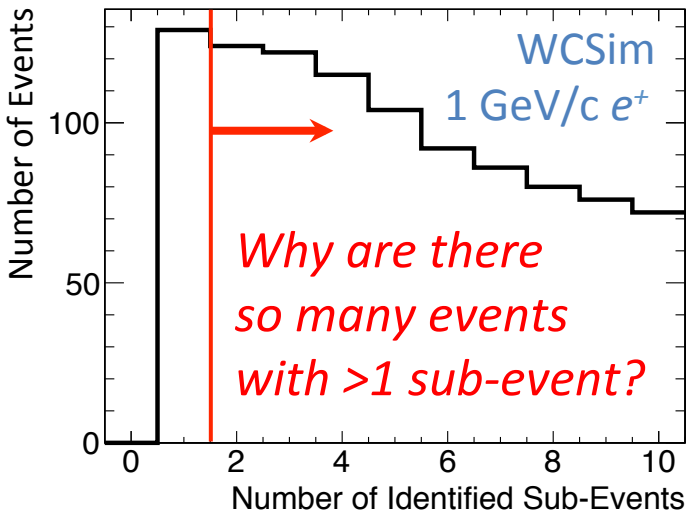
Low hit events removed



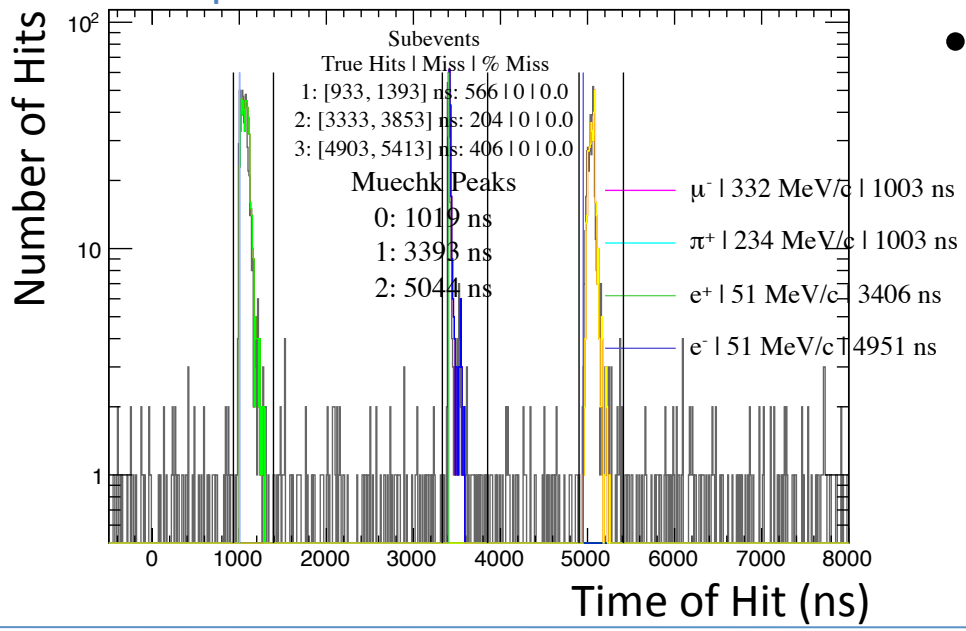


Sub-Event Builder Issue

- Recall: *fiTQun* uses a hit-time clustering algorithm (*spliTChan*) and a peak-finding algorithm to separate sub-events (e.g. decay-e)
  - Tuned to SKDETSIM *SK4* noise + electronics model



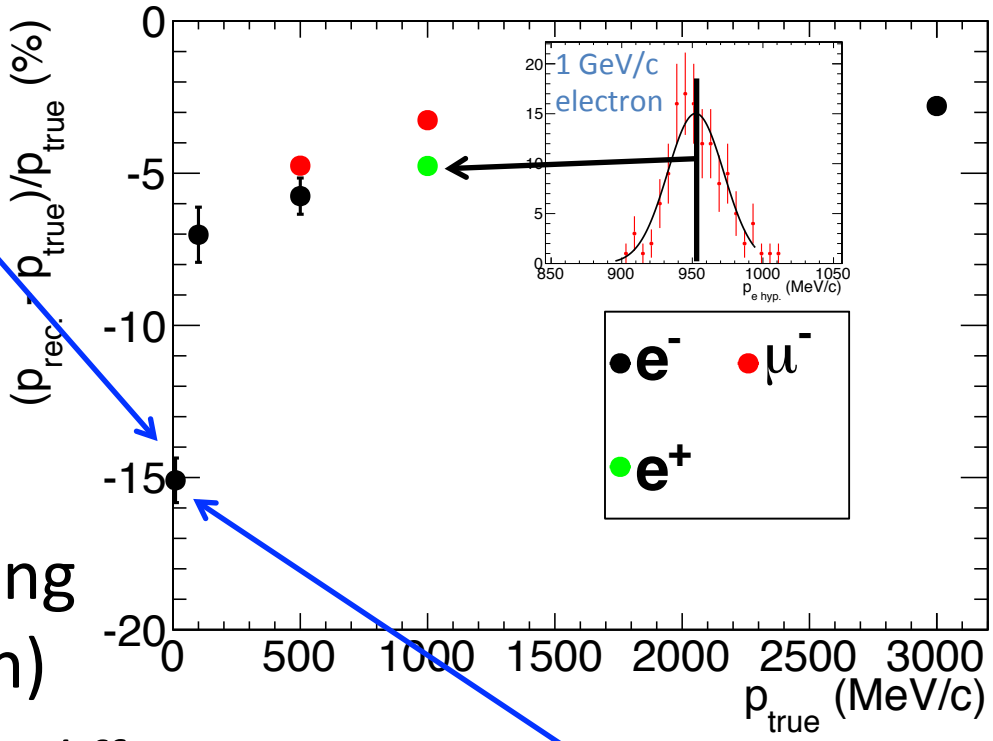
Example ν Interaction in SKDETSIM

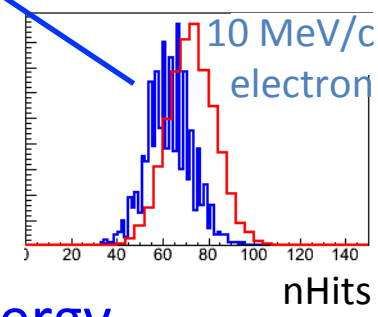


- WCSim using SK1 electronics model with *no noise*
  - spliTChan incorrectly dividing the hits
  - ➢ *Need to understand noise model and electronics, and develop a more generic sub-event builder*

Momentum Reconstruction Bias

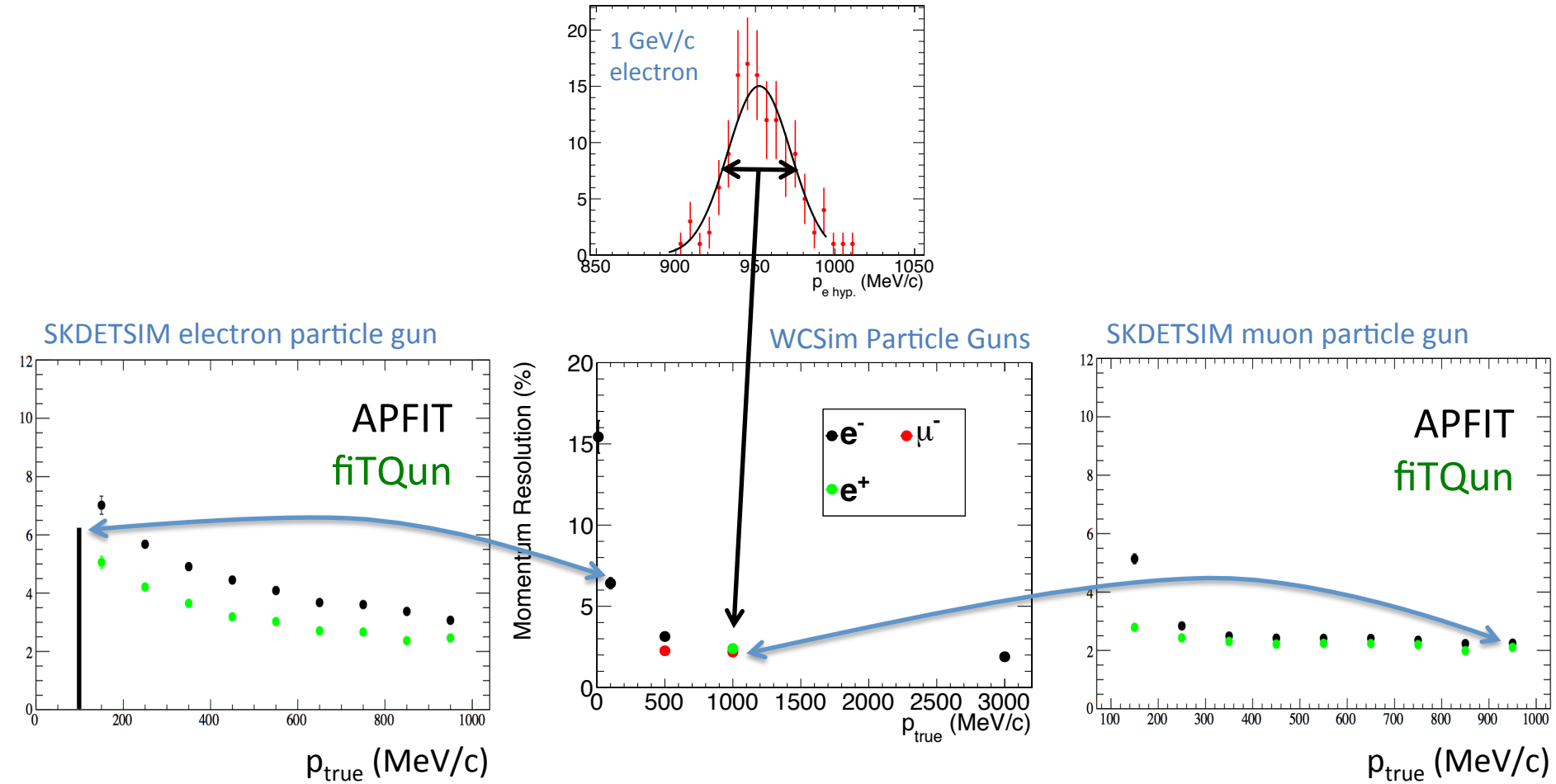
- Various momenta simulated and reconstructed for $\mu^{\pm}$ and $e^{\pm}$
- *Bias becomes worse towards low energy*
  - Maybe related to the sub-event builder issue
  - But can also be something else (under investigation)
    - *fiTQun is very sensitive to differences in modeling and tuning*
    - *Single p.e. distributions, digitization model, etc.*
    - Recall: Discrepancy in the number of hits, which becomes more important than charge at low energy





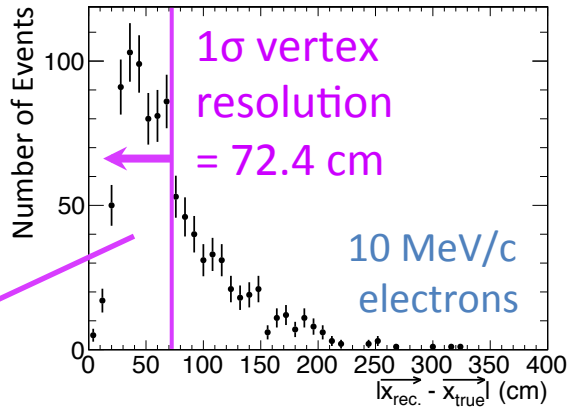
Momentum Resolution

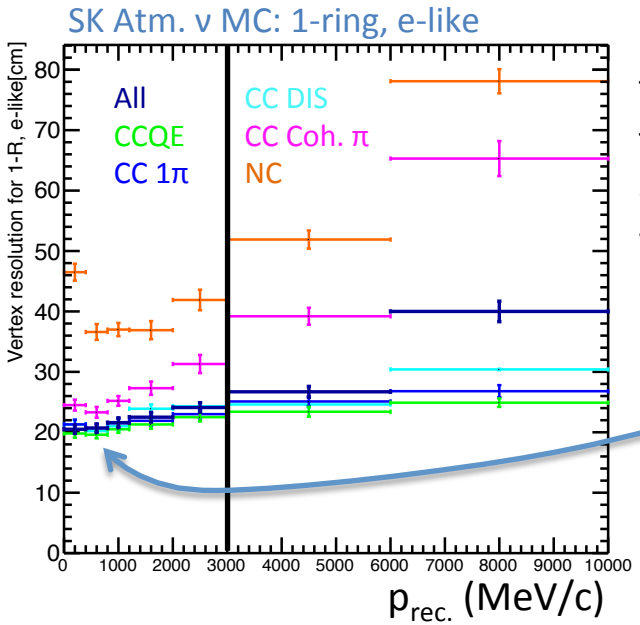
- *Momentum resolution seems to agree between SKDETSIM and WCSim particle guns*

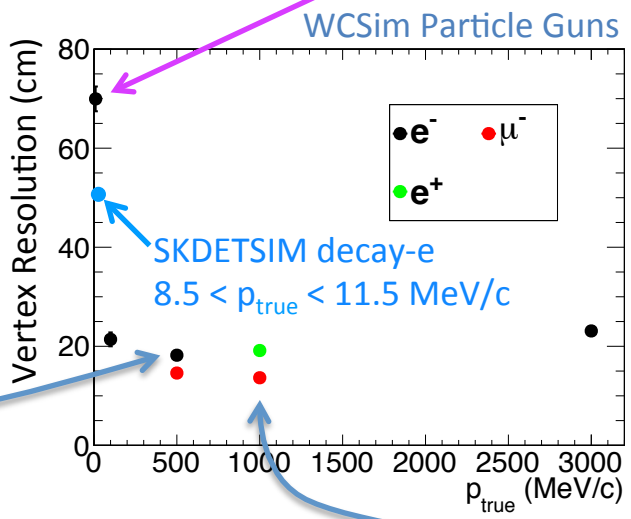


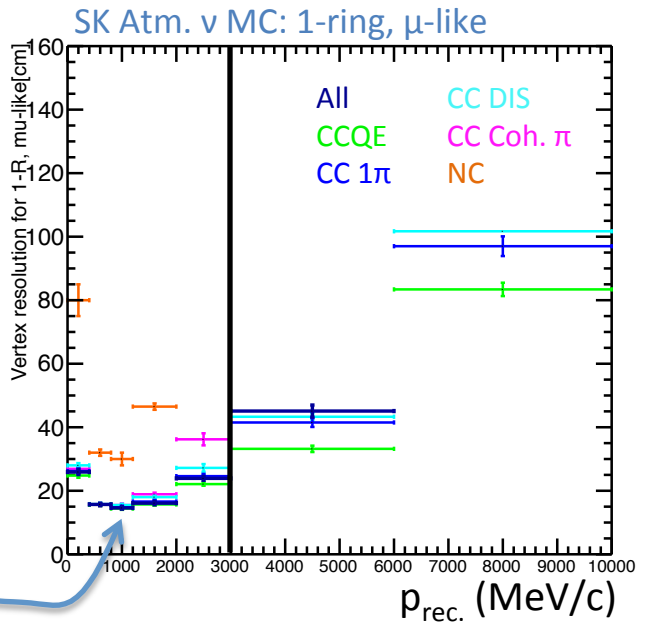
Vertex Resolution

- *Vertex reconstruction for high energy events seems to be OK*
- Some discrepancy to SKDETSIM below 100 MeV/c









Summary of fiTQun-WCSim Interface

- *fiTQun is running on WCSim output!*
- Still some *issues observed*
  - *Sub-event* builder has some issues with WCSim output
  - Reconstructed momentum biases
- Investigation and additional validation underway
  - Not yet ready for detailed physics analyses
- Some more things to do:
  - Clean up the ROOT ntuple output and combine with WCSim ntuple
  - Develop more generic sub-event building algorithm
  - Optimize PMT angular acceptance, light attenuation and yield parameters to match that of WCSim
  - Capability to scale in size the current (cylindrical) scattering table
  - Generalize light scattering table for non-cylindrical geometry

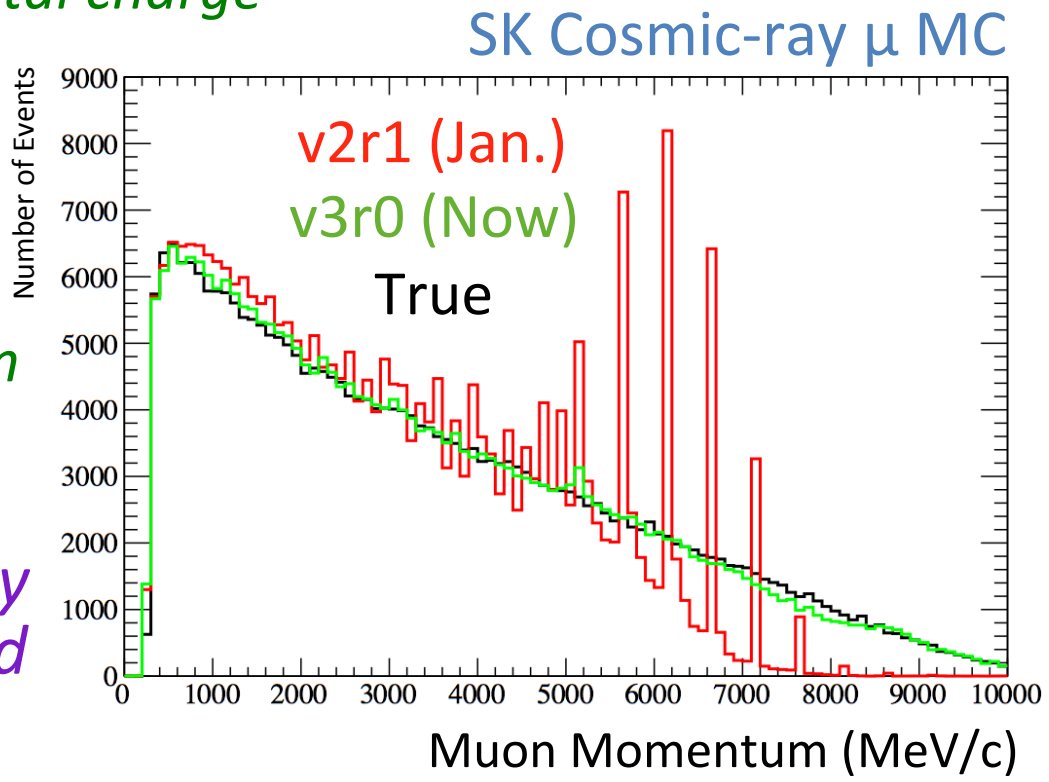
ALGORITHM UPDATES

Current features (New since Jan.)

- Subevent algorithm - Count and fit decay electrons
  - Peak finder, time clustering
  - In-gate decay charge masking & fitting
- Time dependent SK PMT gain correction
- One ring fit (e, μ, π^+, p, K^+)
  - Improved high (> 3 GeV/c) momentum reconstruction
  - Reduced π^+ fit failures by improving momentum seed
- π^0 fit
  - Vertex seed correction
- 2/3/4-ring fits with all possible combinations of e and π^+ rings

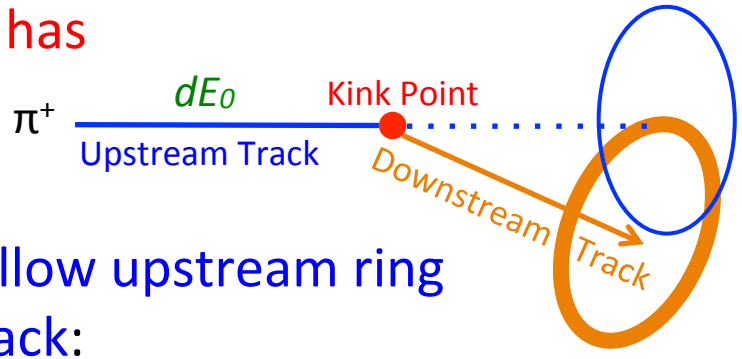
Improved Momentum Reconstruction

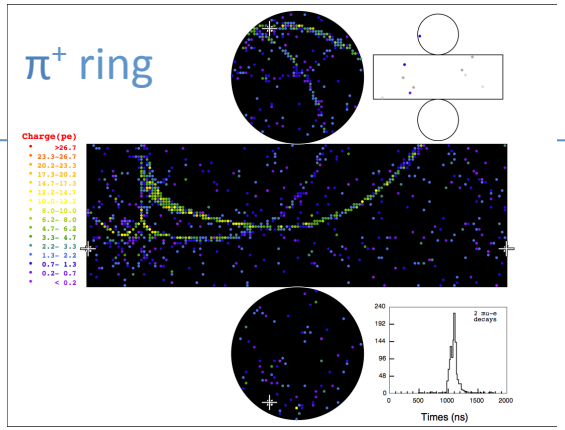
- Previous effort focused on tuning fiTQun around T2K peak energy (< 1 GeV)
- At high energy (> ~2 GeV), reconstructed muon or π^+ momentum had large negative bias
  - *Tentatively apply bias correction with stronger constraint on total charge*
- Momentum spectrum had spikes due to the roughness of the likelihood surface
  - *Apply spline interpolation of the likelihood*
- *Important for high energy atmospheric neutrino and cosmic ray analyses*

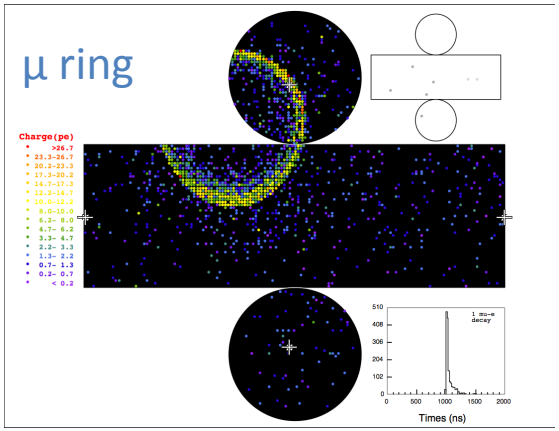


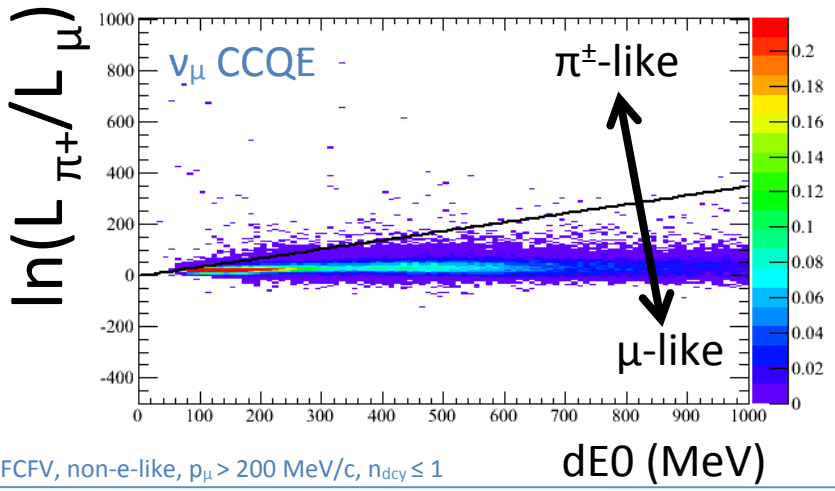
Fitting Hadrons

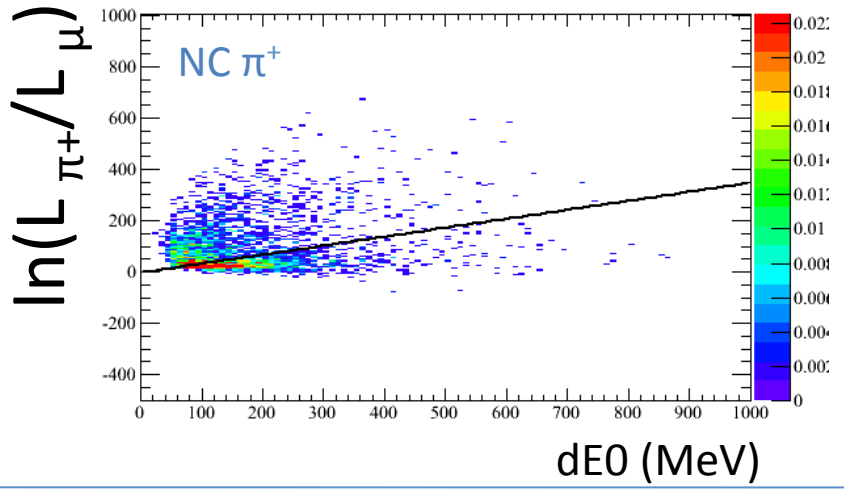
- Hadron track often has a kink due to interactions with nuclei
- Produces sharp, hollow upstream ring
- Fit the upstream track:
  - Additional parameter *dE0*: energy lost before the kink
  - Characterizes the thickness of the ring
- μ/π⁺ separation seen in the likelihood ratio with the 1-ring μ fit:







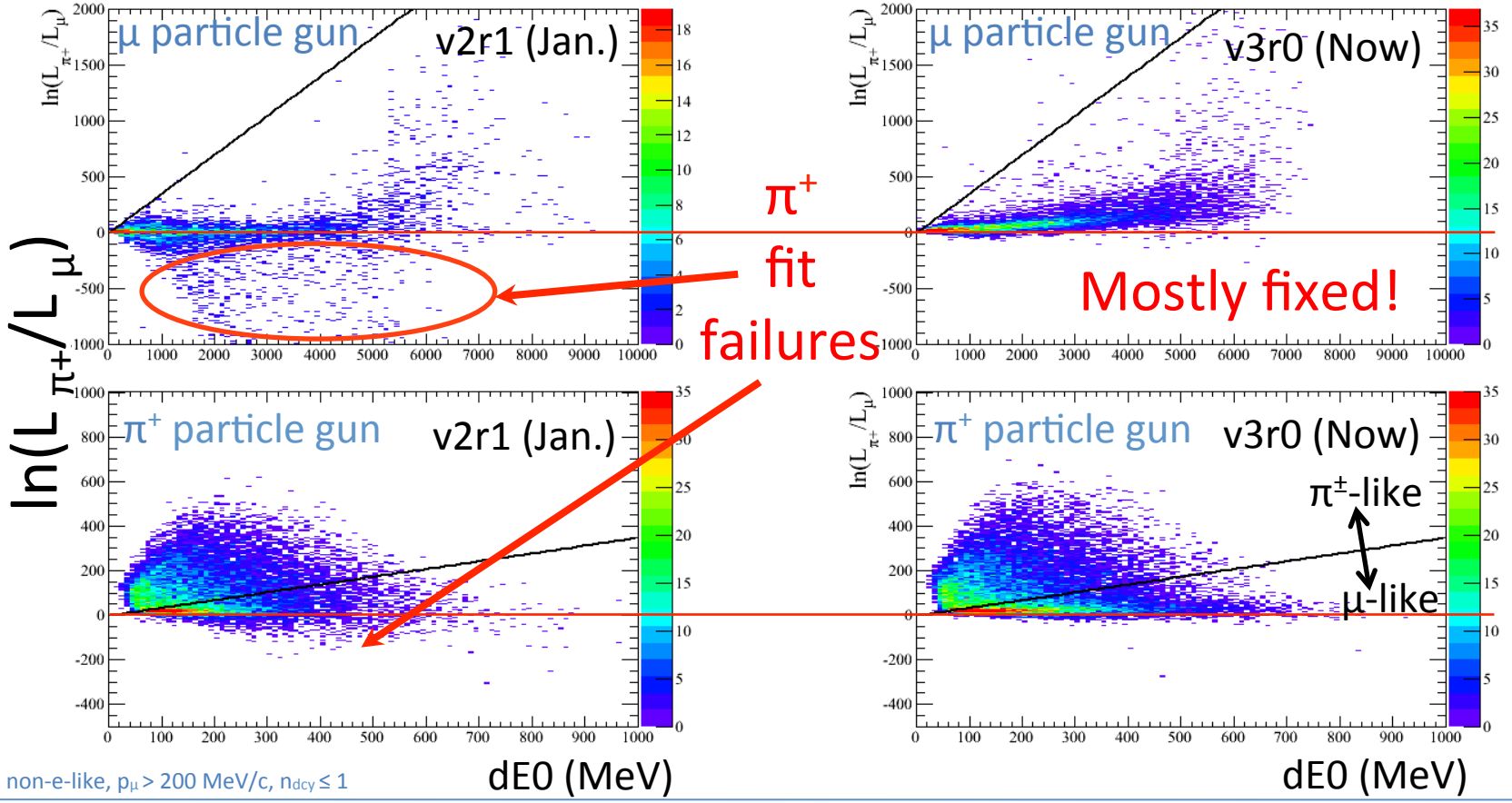




Cuts: FCFV, non-e-like, $p_\mu > 200$ MeV/c, $n_{dcy} \leq 1$

π^+ Fitter Improvement

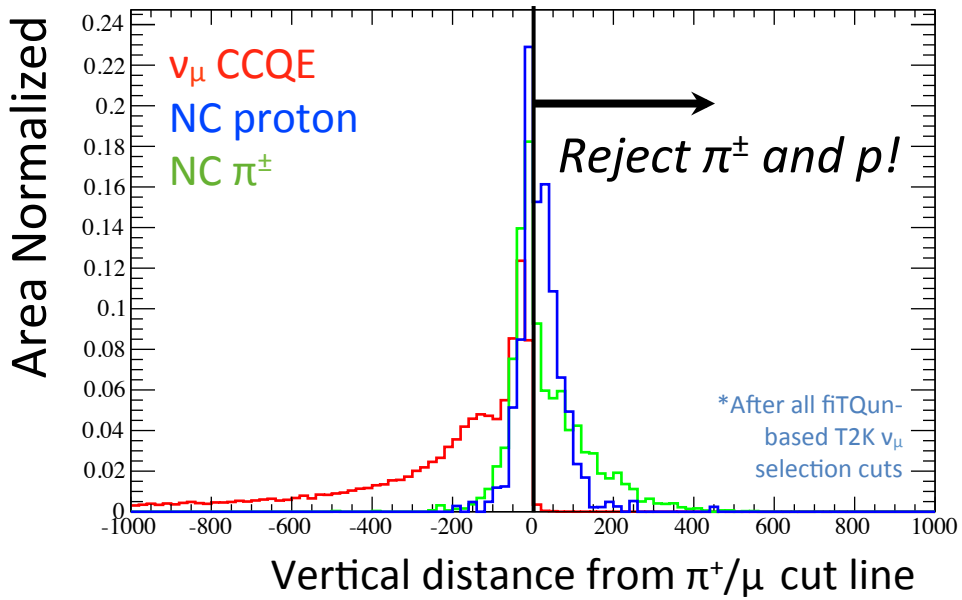
- Previously, momentum seed for π^+ fitter was $p_\mu/(M_\mu/M_{\pi+})$
- *Now perform momentum scan to find seed*

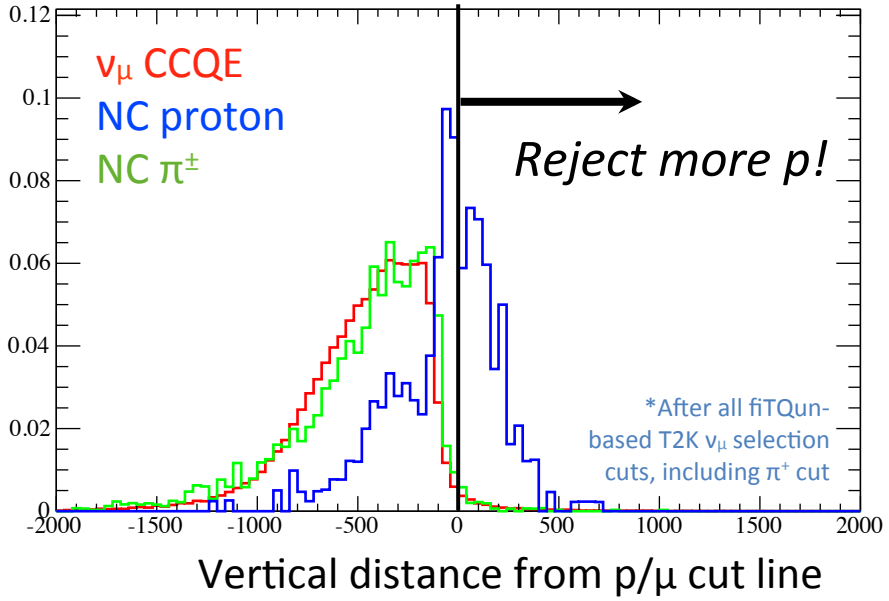


Cuts: FCFV, non-e-like, $p_\mu > 200$ MeV/c, $n_{dcy} \leq 1$

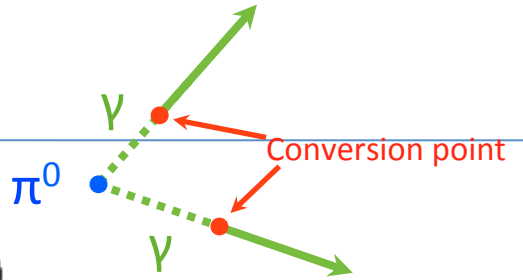
More Hadron Hypotheses!

- *Proton* and *charged kaon* hypotheses implemented similarly to the π^+ hypothesis
  - *Relying on hadronic interactions and differences in Čerenkov profiles*
- Many useful possibilities for these hadron fitters:
  - Reconstruction of CC 2-track events for neutrino oscillation signal
    - 2-track CCQE (lepton + p), CCπ^+ (lepton + π^+)
  - Background rejection and signal reconstruction for proton decay
  - More NC rejection for ν_μ CCQE analyses:



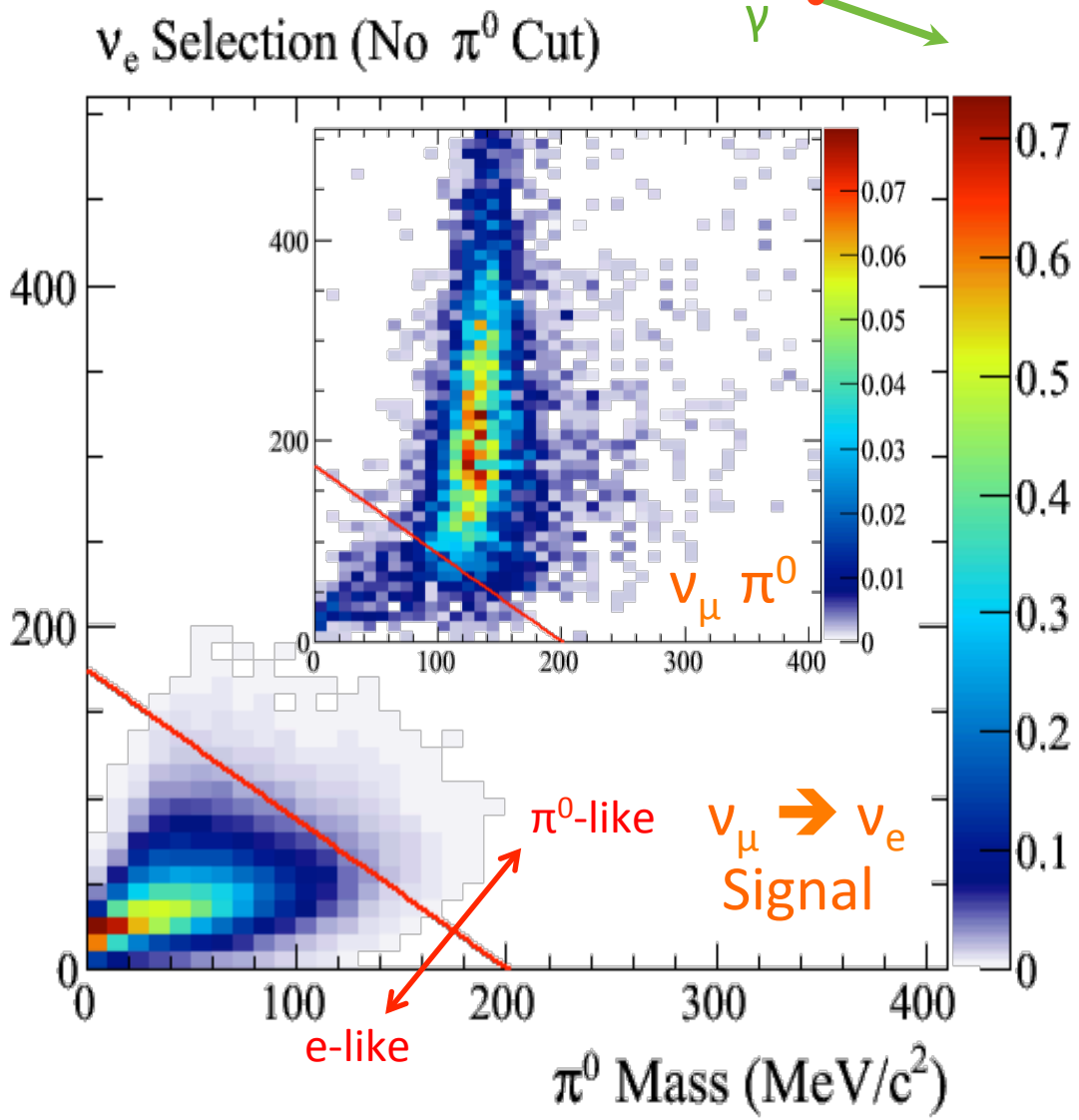


π^0 Fitter



- Recall: Dedicated π^0 fitter
  - Fit the two decay γ rings, considering conversion length
  - Able to find low energy γ ring well

- *Now used for π^0 rejection in official T2K analysis*
  - π^0 background reduced to < 1/3 compared to previous ν_e selection

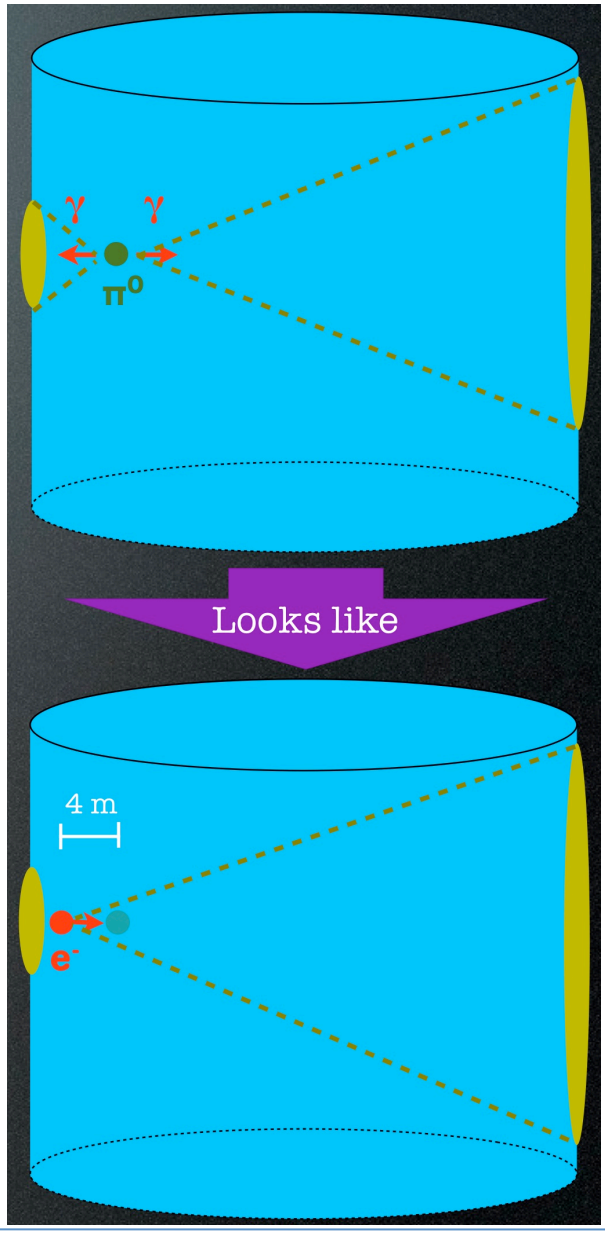


π^0 Vertex Seeding Correction

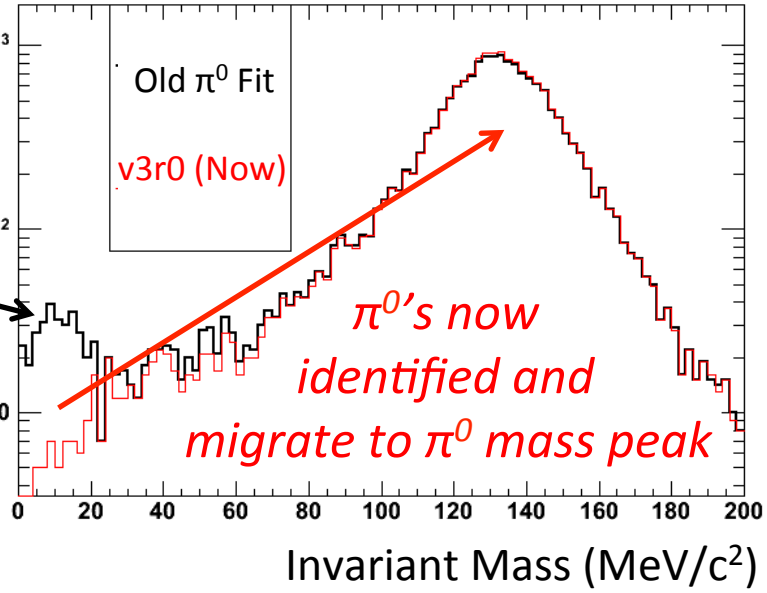
- Special topology where the true π^0 vertex is near the wall and decay is back-to-back
- The 1-ring fit pulls the vertex back to account for the backward ring with scattered light

➢ *Bad vertex seed ➔ bad π^0 fit*

- *Fix: Correct the vertex seed prior to π^0 fit*



Misreconstructed π^0's become background in ν_e analysis



Summary

- WCSim output interfaced to fiTQun
  - Still some issues under investigation prior to use in detailed physics analyses
  - But once fixed, we expect good performance
- Several improvements and corrections to the core of fiTQun
- More hadron hypothesis
  - Which can be used to build more multi-ring hypothesis
- Several validation checks with SK control samples
- Heavy development ongoing in fitter improvements and analysis within SK

Acknowledgements (Team fiTQun)

- University of British Columbia
  - Sophie Berkman, Hirohisa Tanaka, Shimpei Tobayama
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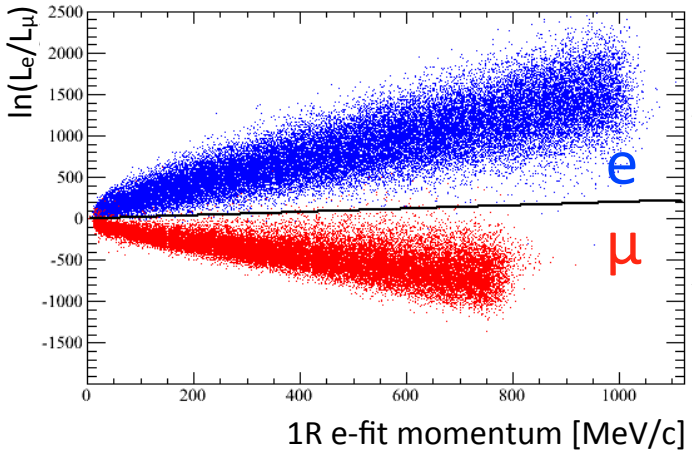
  - Stephen Coleman, Andrew Missert, Eric Zimmerman
- TRIUMF
  - Michael Wilking
- University of Winnipeg
  - Blair Jamieson

APPENDIX

PID/Number of Rings

- Distinguish between different event topologies by making a cut on the best-fit likelihood ratio:
  - e.g. One-ring e/μ separation by cutting on the likelihood ratio of 1R-e and 1R-μ hypotheses



*Sample: particle gun e/μ p<1GeV/c

ID as electron

ID as muon

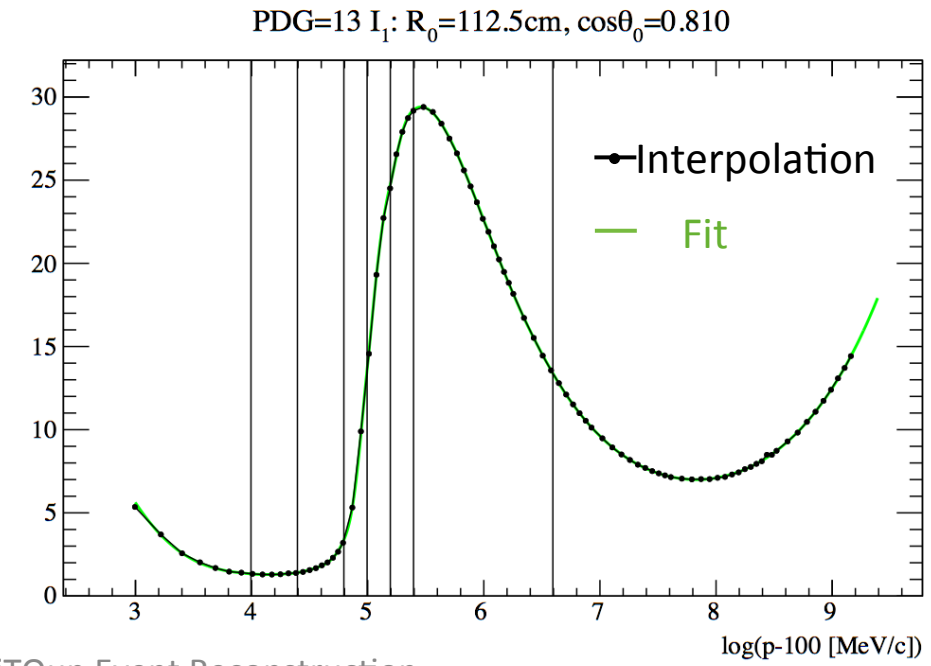
- Separation of e/π^0, μ/π^+, and number of ring determination are done in a similar manner

Smoothing the Profiles

- v2: Cherenkov and time likelihood profiles were generated at coarsely binned discrete momentum values
- The fitter linearly interpolates the profiles in momentum, and was caught at local minima of the likelihood surface
- v3: Fit & smooth the the profiles in terms of momentum↓

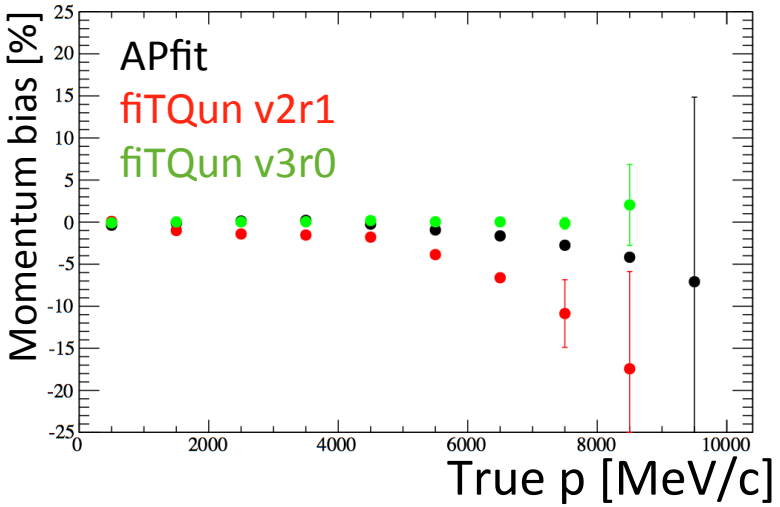
e.g.) One bin of muon Cherenkov profile →

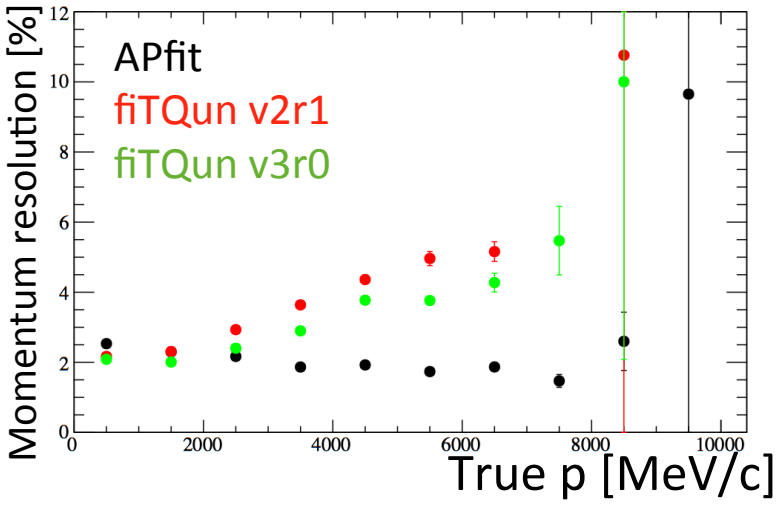
(similar procedure for the time likelihood)



Momentum Bias & Resolution

*Muon particle gun <10GeV/c, FC, true FV, 1-ring

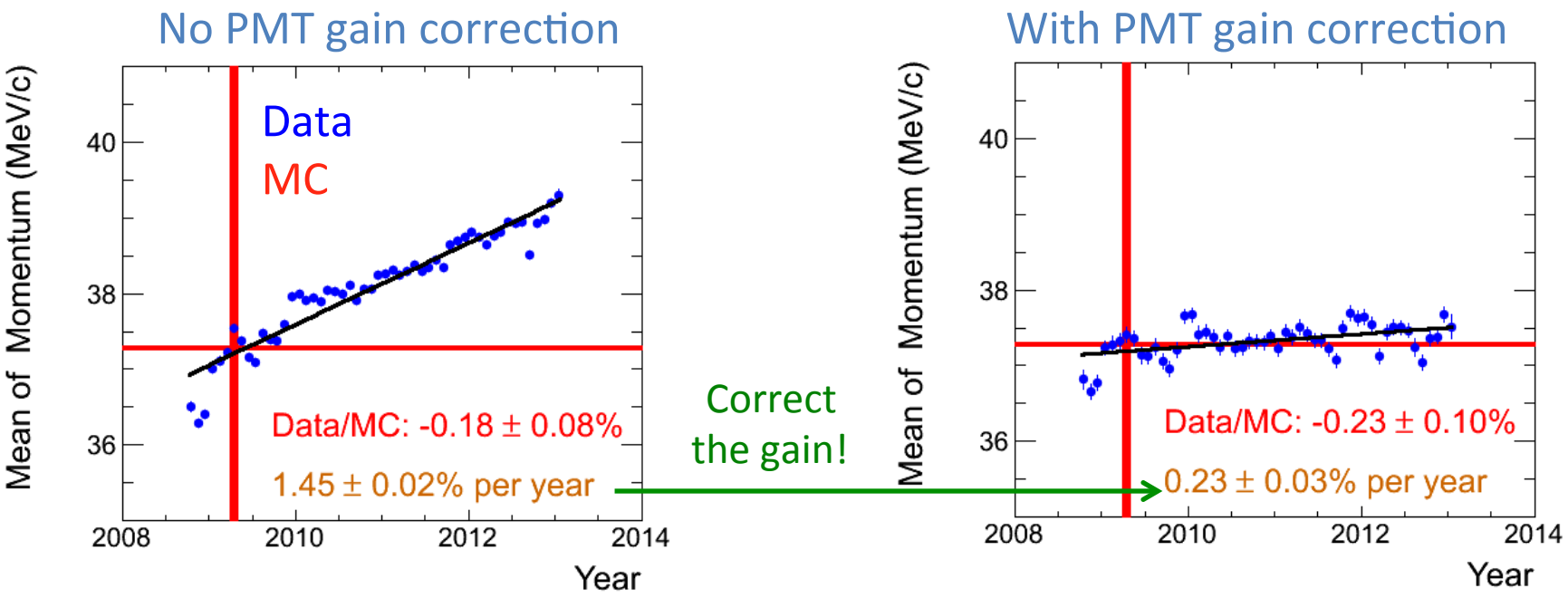




- Muon momentum bias and resolution get worse at very high momentum
- Approximations that are used for charge & time likelihood calculation get worse as particle track gets longer
- In order to fundamentally improve momentum resolution/bias, we need to develop a new method of approximating likelihood calculations
- v3: As a tentative solution, introduced ad-hoc bias correction, and put stronger constraint on total charge to improve resolution

Time Dependent PMT Gain Correction

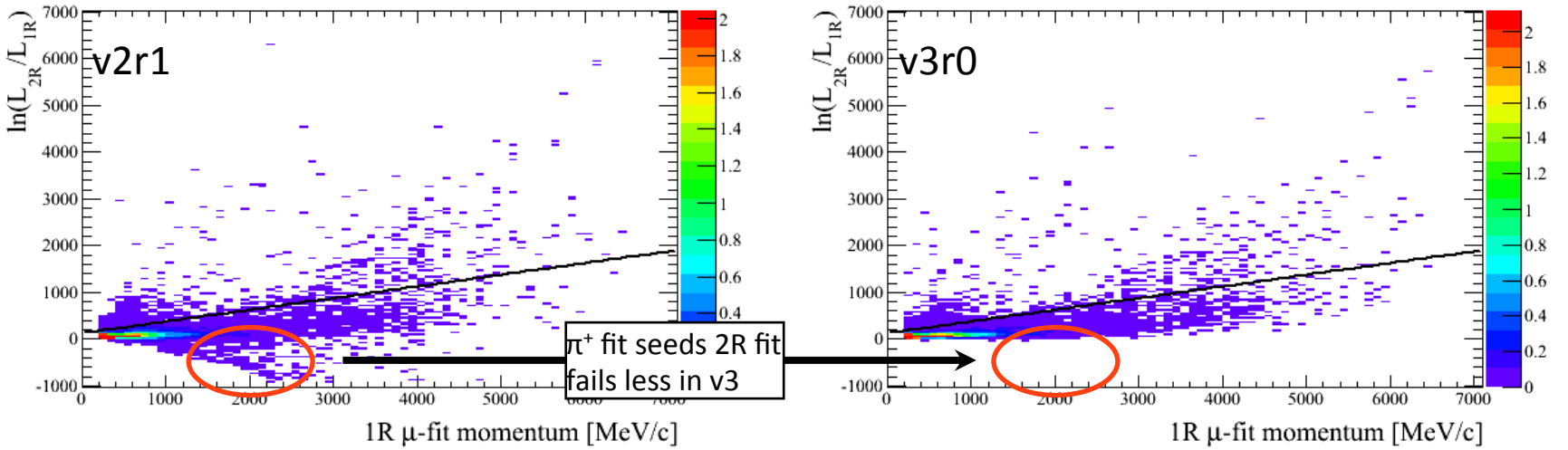
- Correct PMT gain increase based on dark noise charge measurements
- *Time dependence of reconstructed momentum is mostly removed*
  - Decay-e data from stopping cosmic muons in SK shown



2R/1R Likelihood Ratio

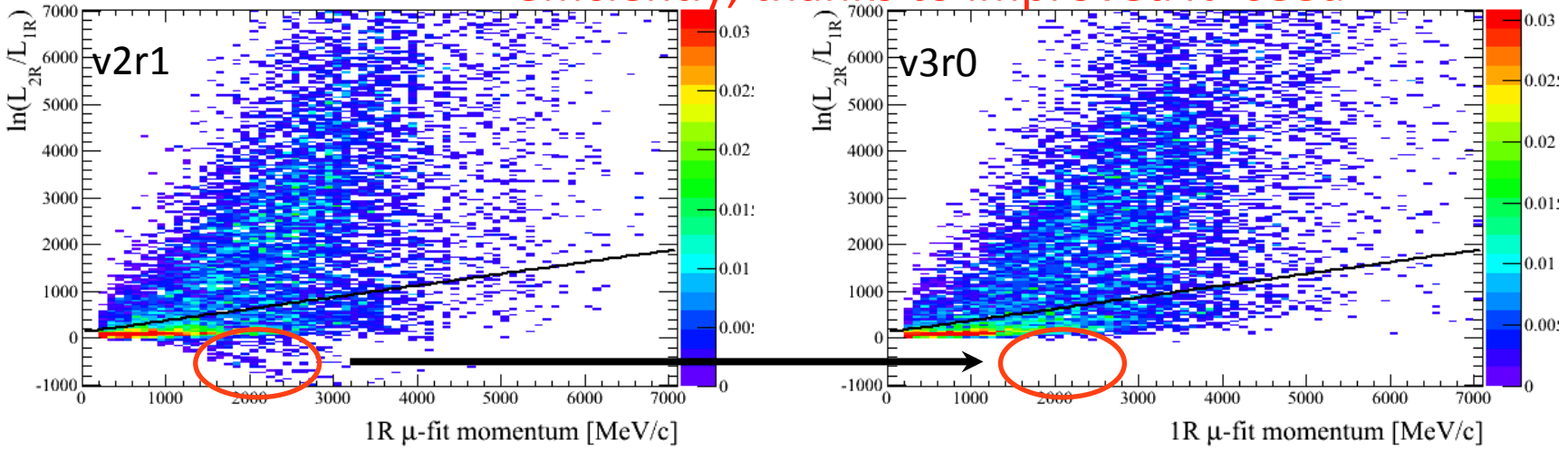
*T2K ν_μ, fiTQun FCFV, non-e-like, p_μ>200MeV/c, n_{dcy}<=1

ν_μ CCQE



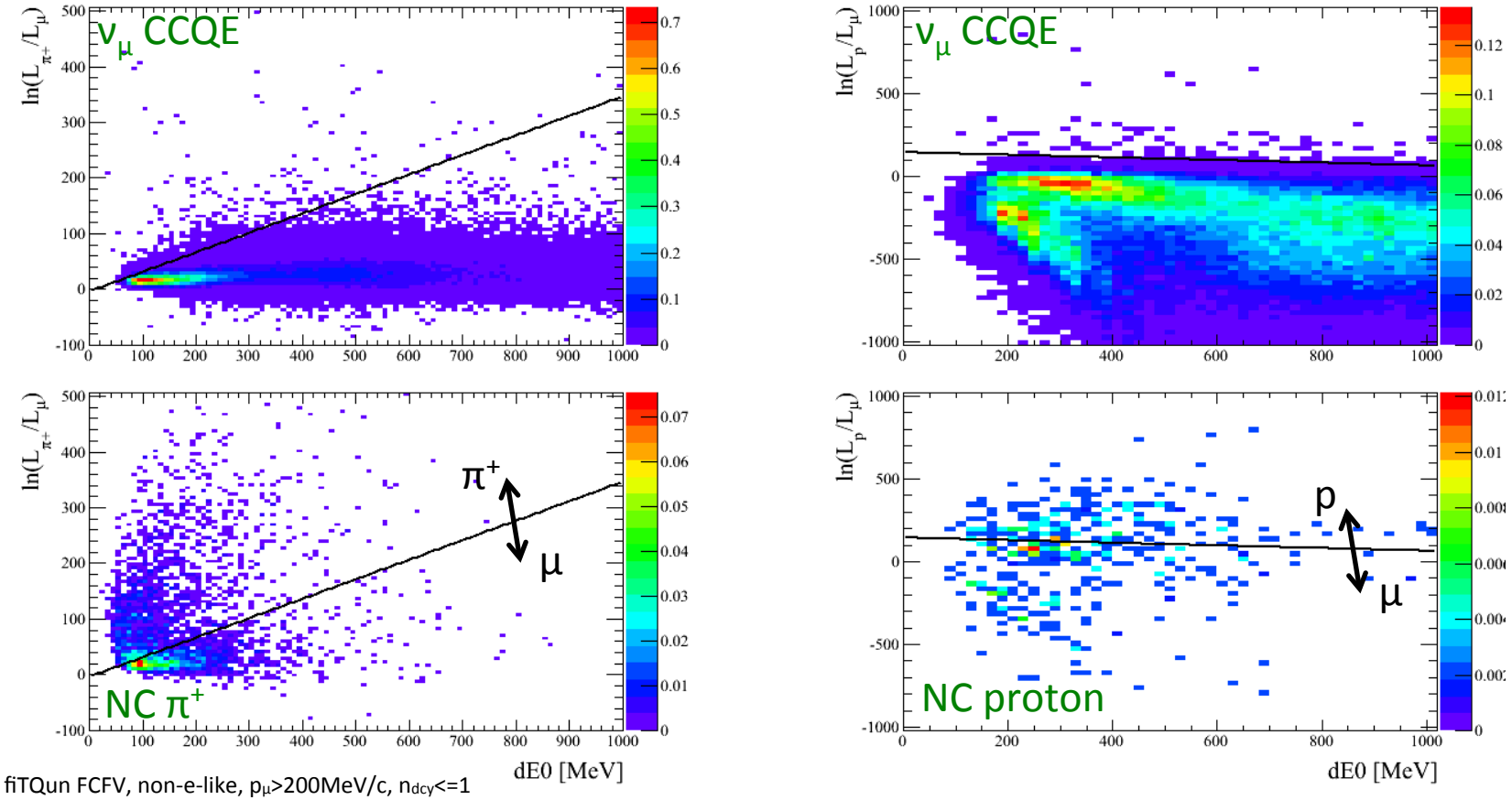
ν_μ CC non-QE

v3 reconstructs multi-ring events more efficiently, thanks to improved π^+ seed



NC π^+ and Proton Rejection

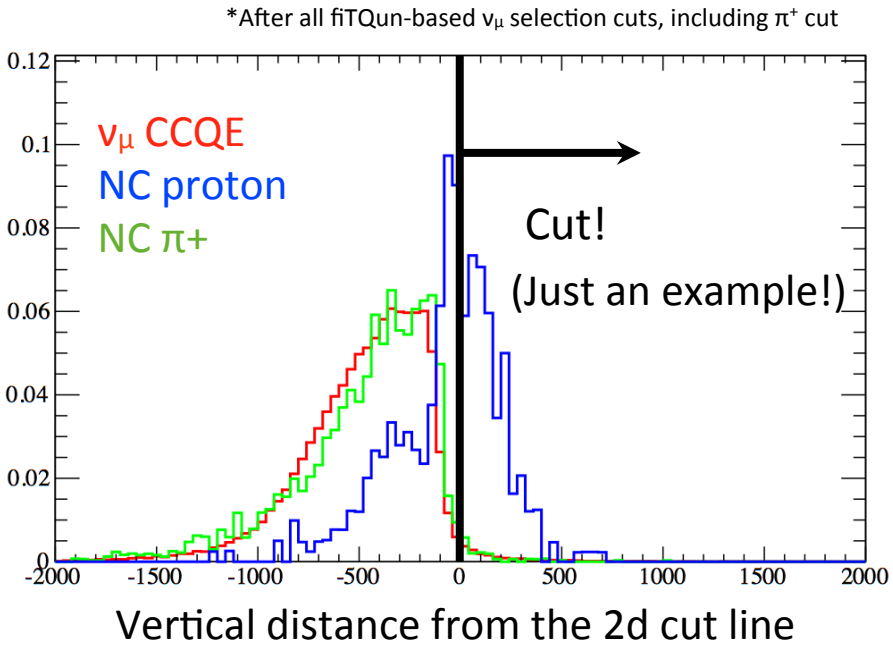
- Apply standard SK ν_μ selection
- Apply π^+ selection cut (left)
- Then apply proton selection cut (right)



Cuts applied: fiTQun FCFV, non-e-like, p_μ>200MeV/c, n_{dcy}<=1

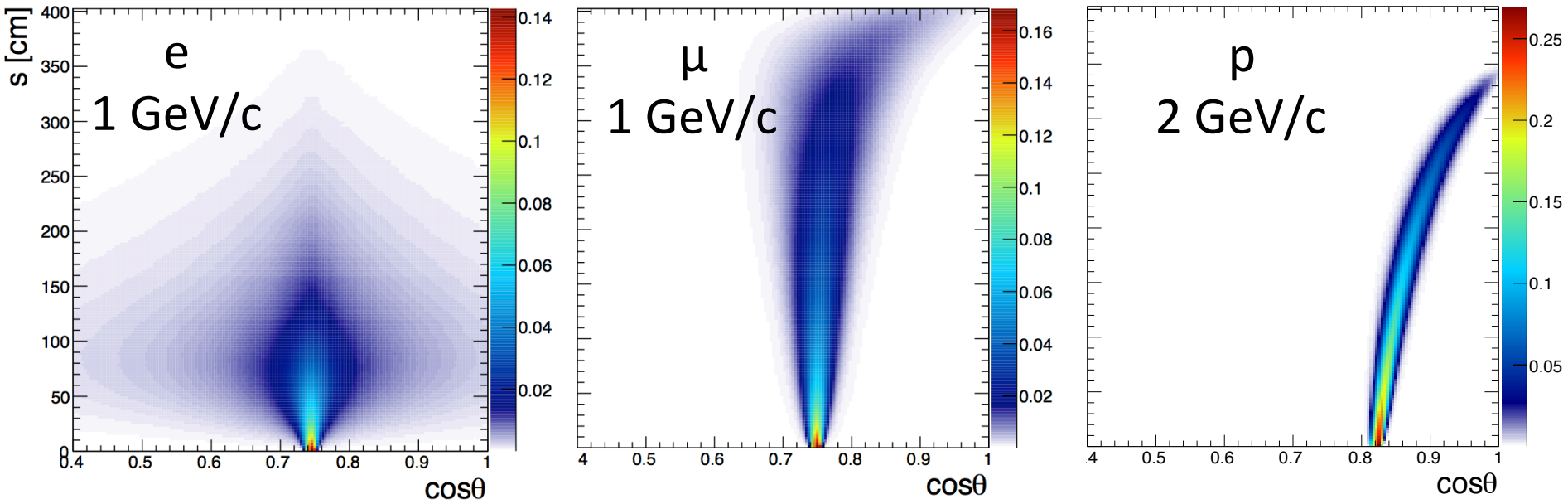
π^+ and Proton Cut

- We can further reduce NC proton by cutting on the proton/μ fit likelihood ratio
- Reduction rate compared to standard APfit selection:
  - NC proton: 80%
    - 72% with π^+ cut only
  - NC total: 60%
    - 58% with π^+ cut only
  - Signal ν_μ CCQE:2.1%
    - 2.1% with π^+ cut only



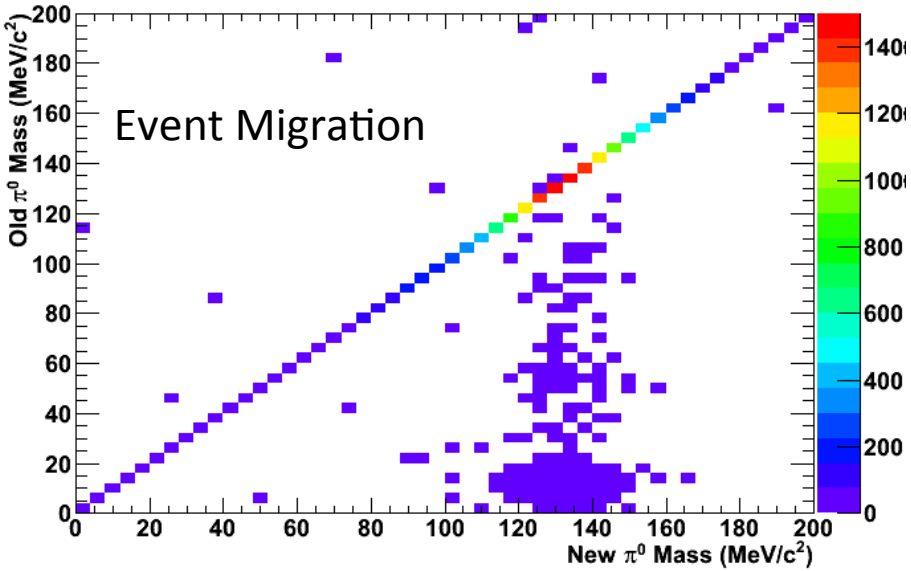
Cherenkov Profiles

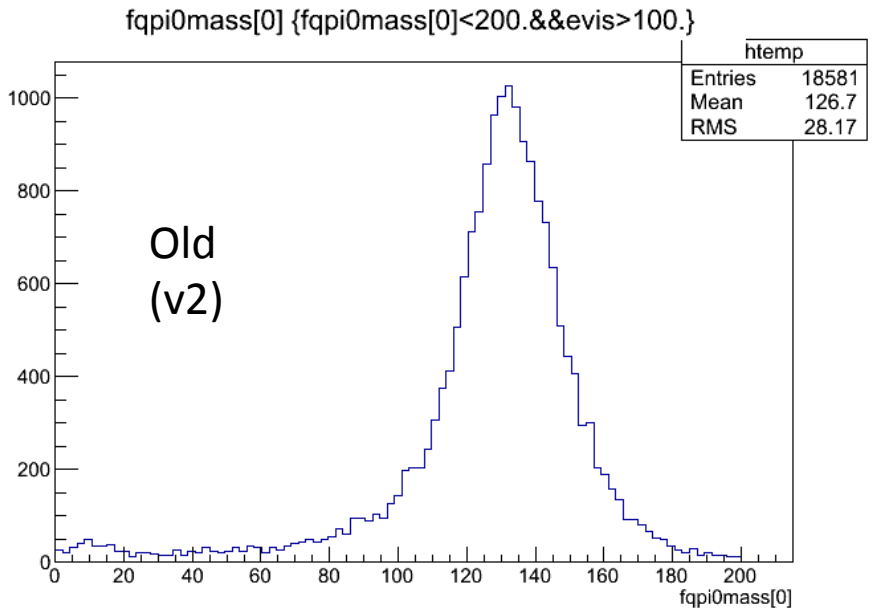
- Provide additional PID discrimination

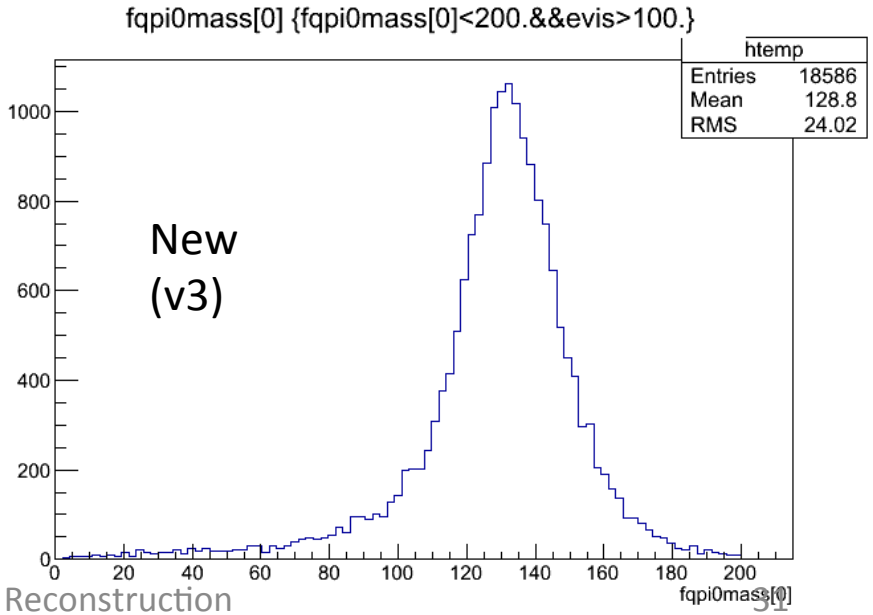


π^0 Fit Performance in v3

- The bump at low π^0 mass has been removed
- All of these events have migrated to the correct π^0 mass

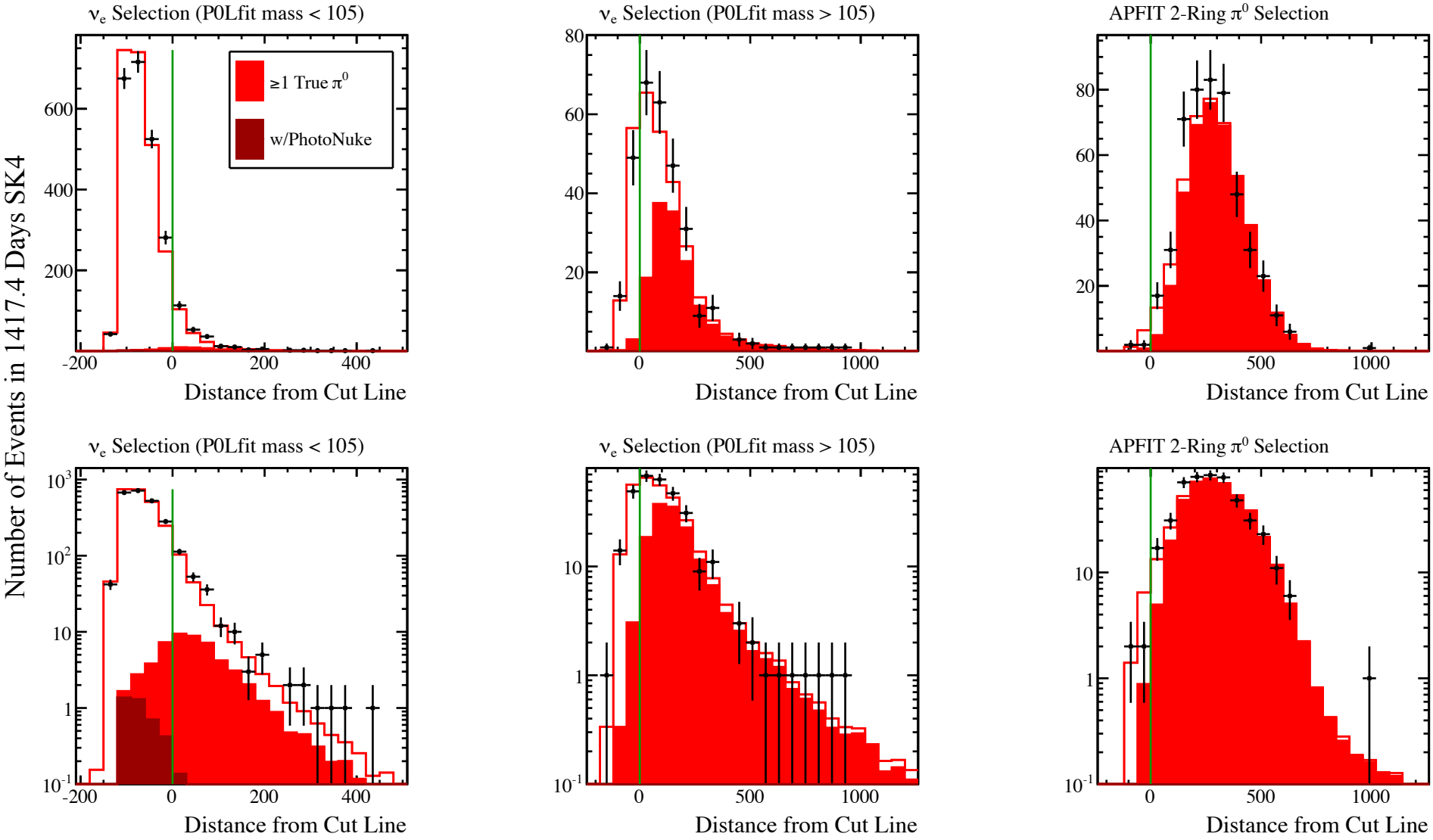






π^0 Cut in SK Atmospheric Data

- T2K π^0 cut rejection applied to atmospherics

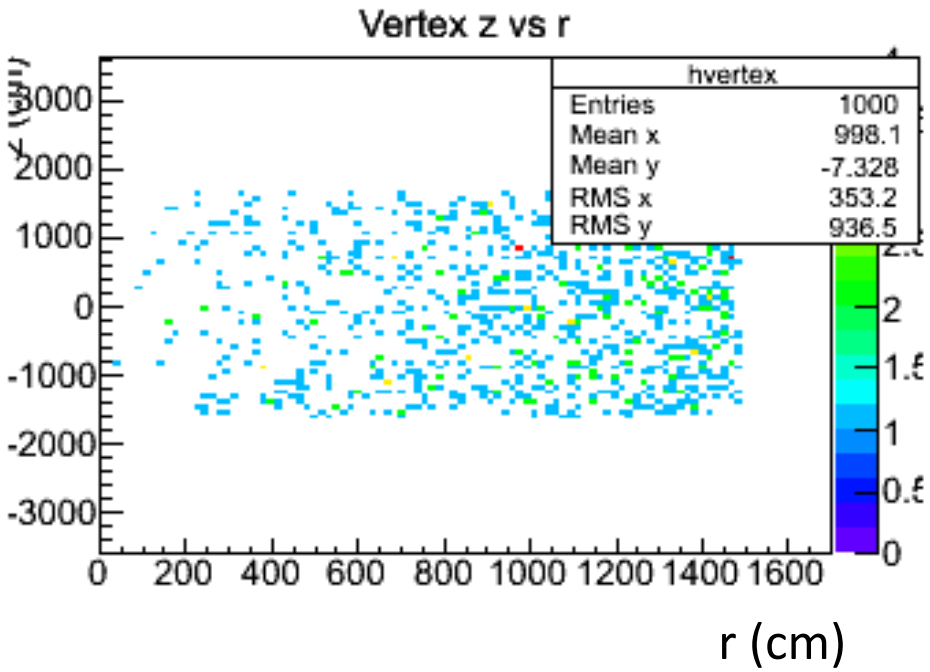


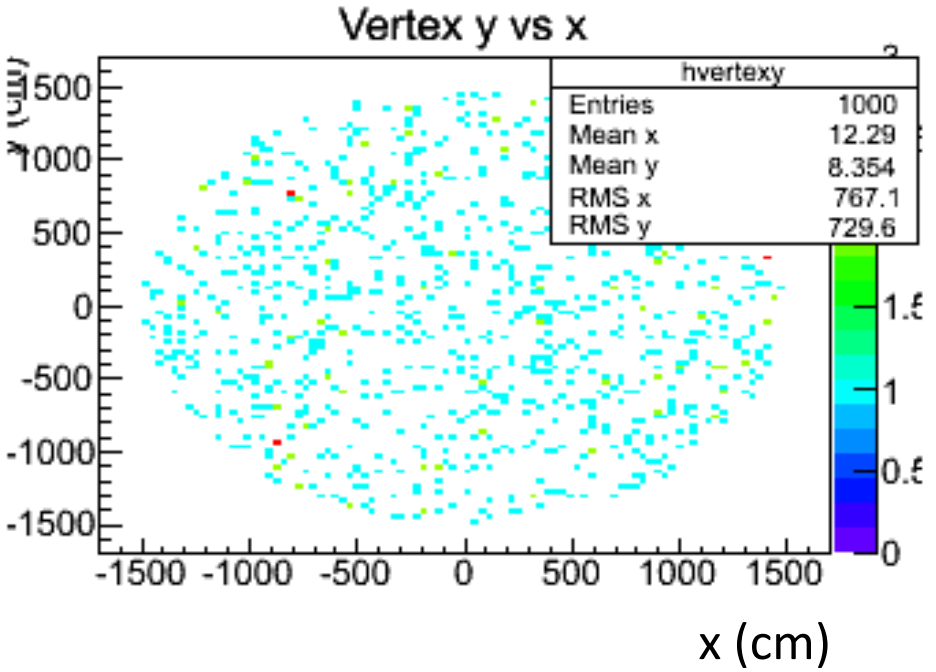
POLfit/fiTQun comparison

	POLfit	fiTQun π^0 fit
# of fit parameters	3	12
- Vertex	fixed at 1-ring vertex (0)	float (3)
- γ conversion length	fixed (0)	float, for both rings (2)
- γ direction: 1st/2nd	fixed/float (2)	float/float (4)
- γ energy: 1st/2nd	fixed/float (1)	float/float(2)
- Time information	Not used (0)	Used & fit (1)
Indirect light calculation	Rayleigh-like scattering No reflection	Based on template generated from MC w/ scattering & reflections

WCSim Generated Vertices

- For momentum reconstruction study, vertices generated within the ID





π^0 Fitter

- Also simulated π^0 particle gun at 2 momenta
- Reconstructed π^0 mass is also negatively biased
  - *Probably related to previous issues observed*