Measuring nuclear effects in pionic semi-exclusive final states using the MINERvA Detector

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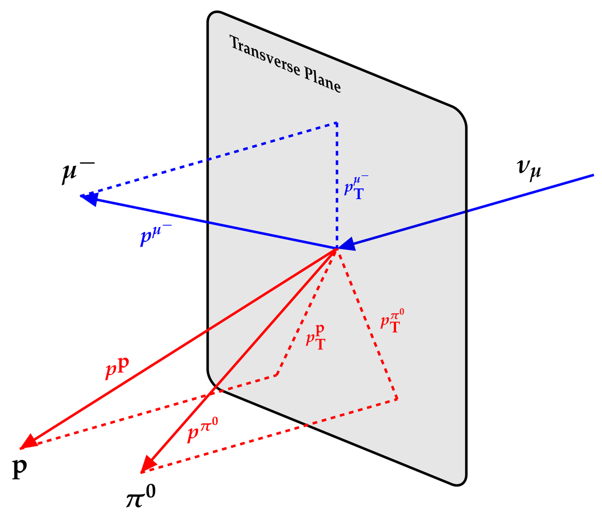
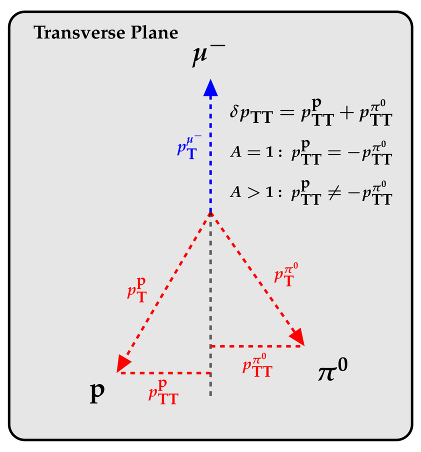
Introduction

- Nuclear effects are currently one of the dominant sources of systematic uncertainty in oscillation measurements [1,2].
  - Signal and background selection efficiencies.
  - Reconstructed neutrino energy spectra.
- Measuring final states with exactly one μ^-, and at least one π^0 and p.
  - Will aid in reducing such uncertainties in Multi-GeV oscillation experiments [3,4].
  - This work is an extension to the analysis on the 'delta rich' sample in [5].
- Nuclear dynamics probed by double transverse momentum (δp_{TT}) — a kinematic imbalance of the hadronic final state [6].





Kinematic Constraints

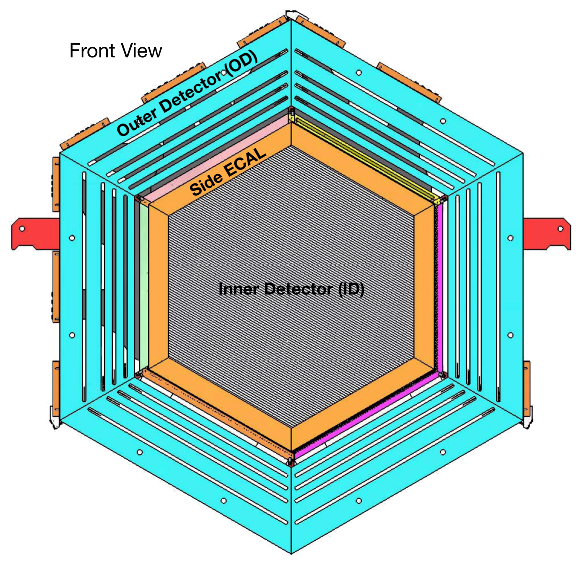
$1.5 < E_\mu\ (\mathrm{GeV}) < 20.0$

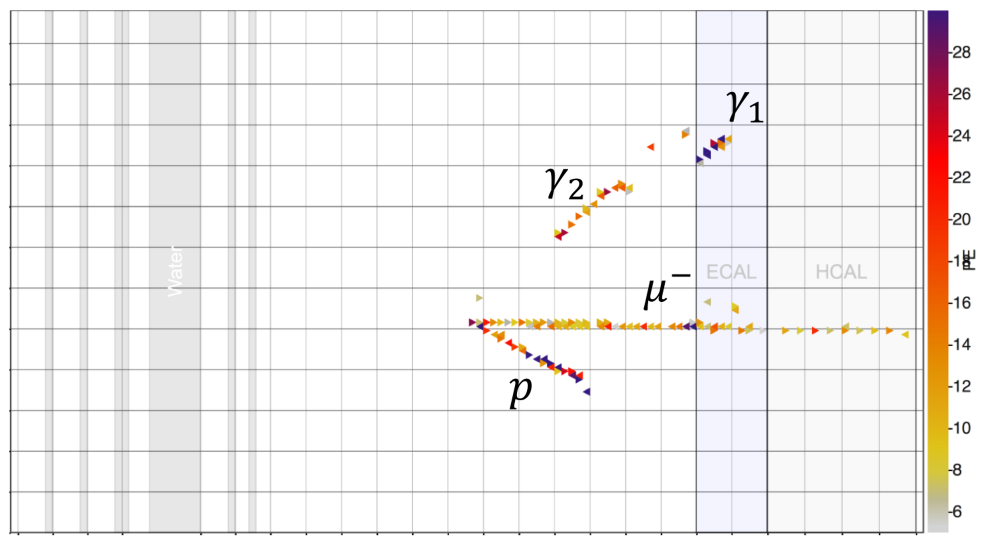
$p_p > 450\ (\mathrm{MeV}/c)$

$60 < m_{\gamma\gamma}\ (MeV) < 200$

$\theta_\mu < 25°$

The MINERvA Detector

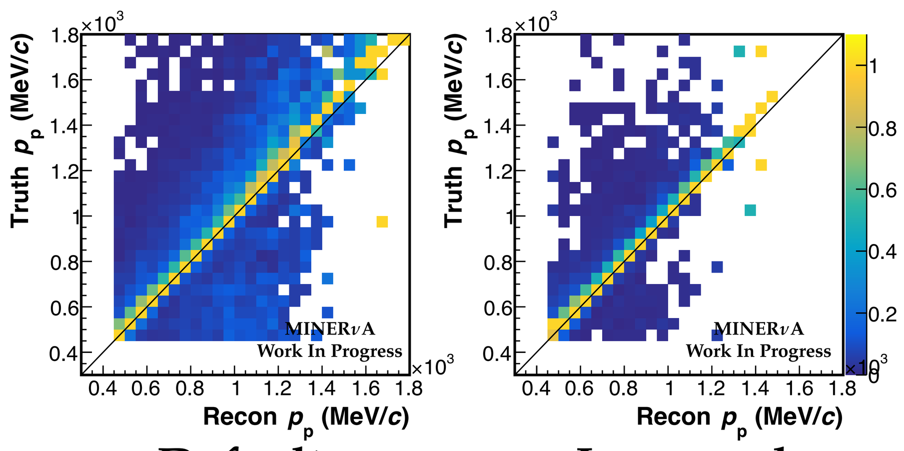




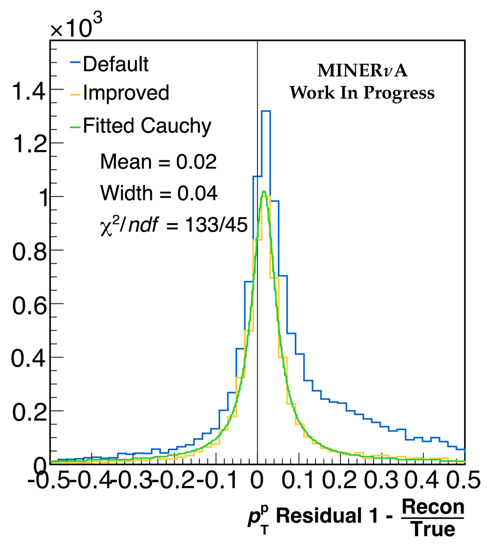
- Situated on-axis in NuMI Beam.
  - Analysis studies low energy dataset peaked at 3.5 GeV.
- Active tracker capable of reconstructing low energy (T = 110 MeV) tracks
  - Precise directionality (within 3 mm),
  - Particle identification and momentum provided by dE/dx profiling.
- MINOS near detector measures charge and momentum of forward going muons.
- ECAL and HCAL aids in full event containment.

Reconstruction Improvements

Proton

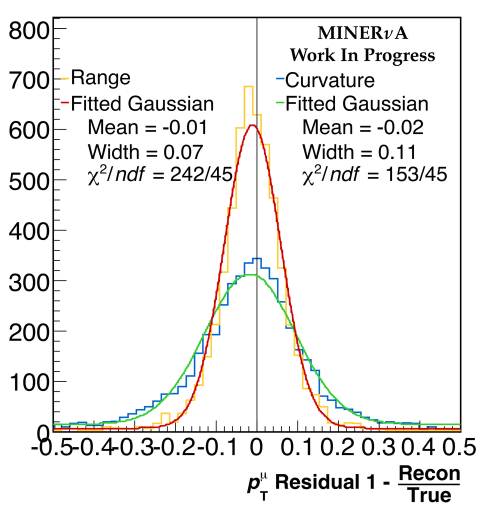


Default Improved

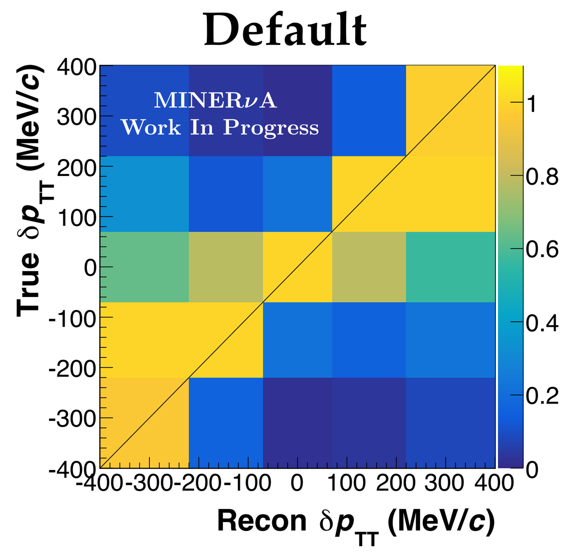


- Inelastic scattering ($pA \to nA'$) results in ill-measured range.
- Leads to incorrect momentum reconstruction.
- Such events can be removed by considering energy at tracks last six measurement nodes.

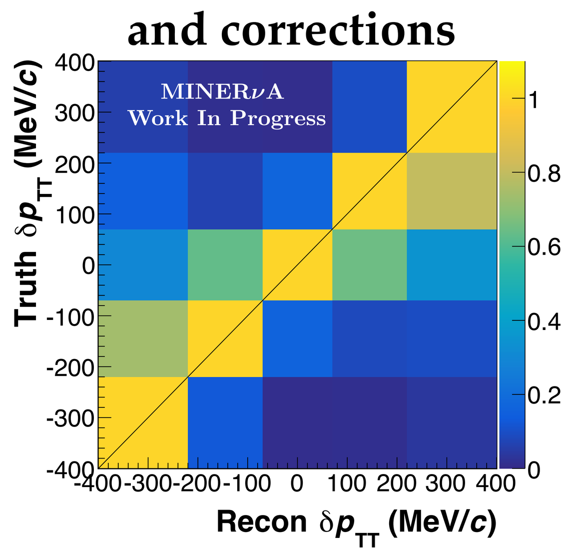
Muon



Default



Kinematic improvements and corrections

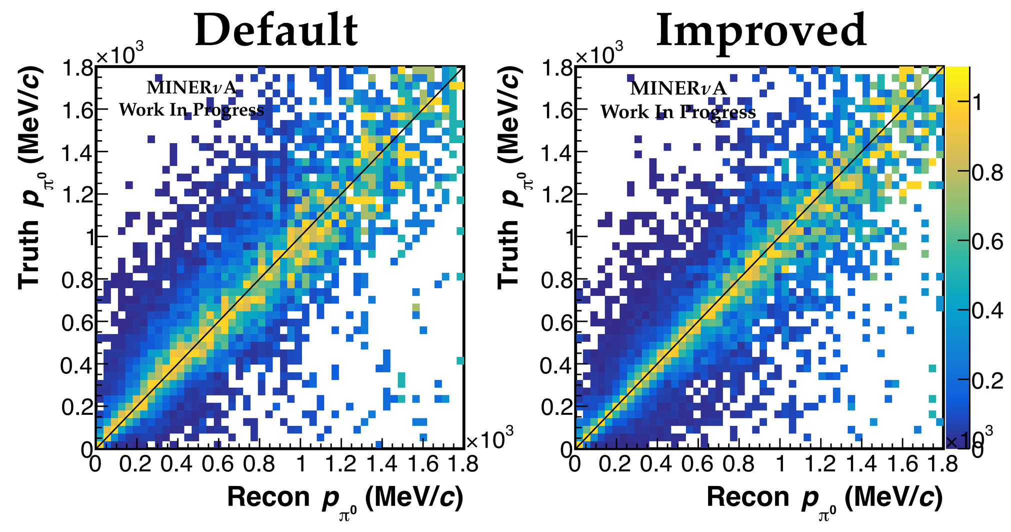


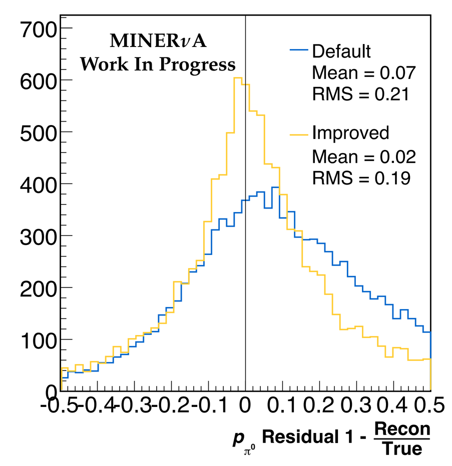
Pion

- Neutral pions identified via dominant decay ($\pi^0 \to \gamma\gamma$).
- Kinematics determined using photons energy and direction
  - Momentum limited by photons calorimetric reconstruction,
  - Angular resolution is good.
- Use precise angular determination to improve calorimetric estimates by fitting $m^2 = 2E_1E_2(1-\cos\theta_{12})$ using a penalty term

$$\chi^2_{\mathrm{pen}} = \frac{(E_1 - E_1^{meas})^2}{\sigma^2_{E_1}} + \frac{(E_2 - E_2^{meas})^2}{\sigma^2_{E_2}}.$$

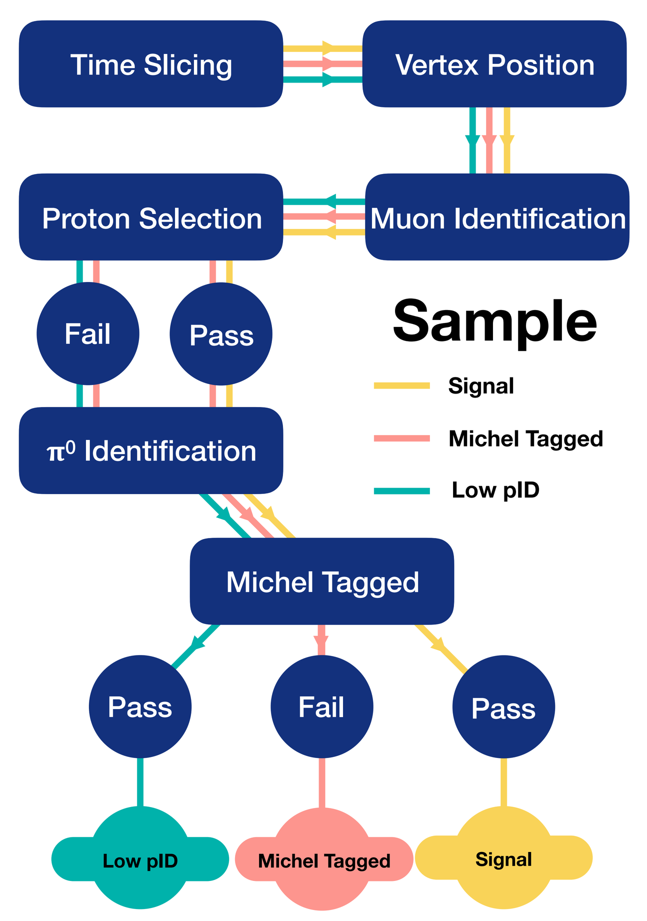
Default Improved

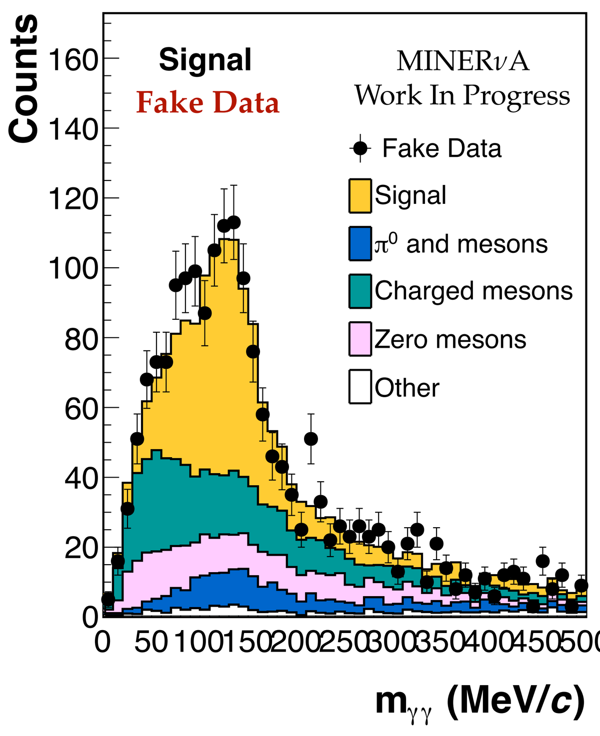


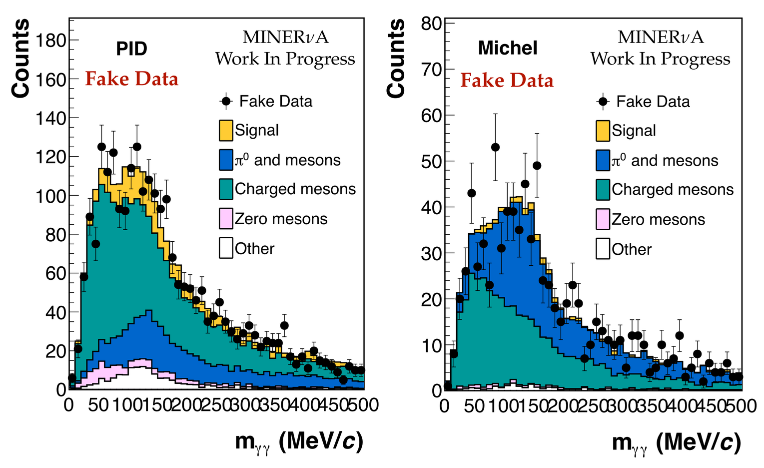


Corrections made to final state kinematics where any reconstruction bias remains — these are determined analytically.

Selection and Sidebands







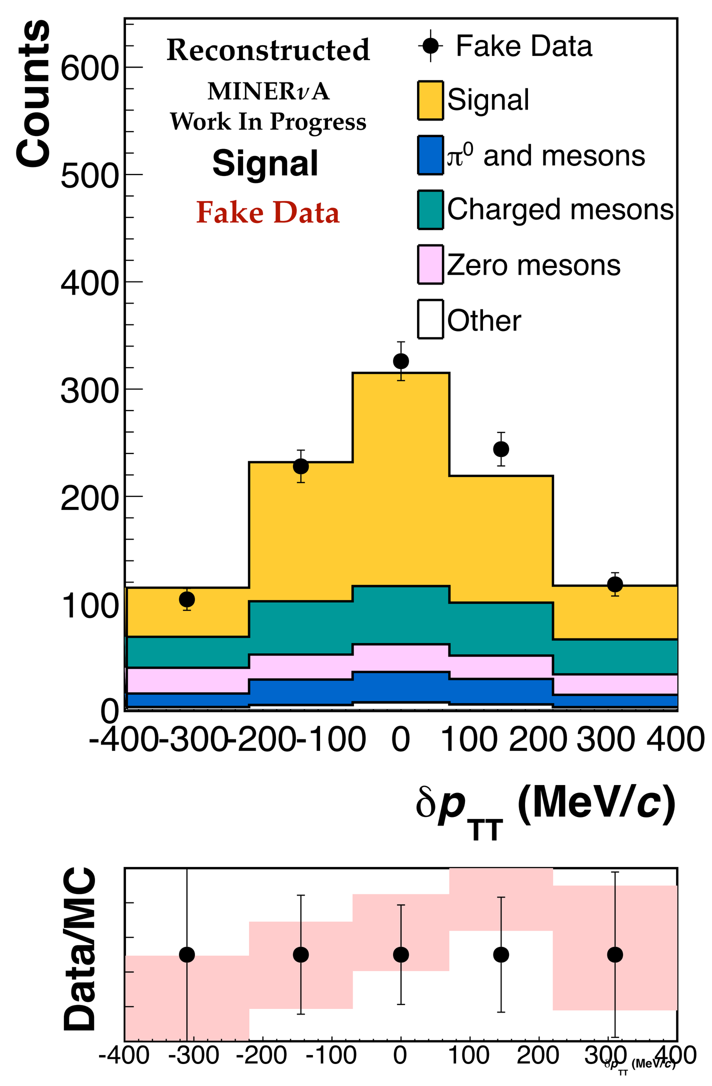
- Dominant backgrounds are constrained using four sidebands
  - Low/High invariant mass,
  - Michel Tagged Events,
  - Low proton score sample.
- χ^2 fit to determine respective background normalisations.

Signal Extraction

Apply d'Agostini Unfolding in order to remove detector response

$$\frac{d\sigma}{d(\delta p_{TT})_i} = \frac{1}{T\Phi\Delta_i\,(\delta p_{TT})\,\varepsilon_i}\sum_j U_{ij}\left(N_j^{\mathrm{Data}} - N_j^{\mathrm{Bkg}}\right)$$

- Reliable signal extraction relies in understanding the un-smearing procedure.
- Determine optimal regularisation strength such that the signal extraction method has minimal model dependence.
- Using Fake Data (statistically equivalent to NuMI low energy dataset) want to determine regularisation strength by considering unfolding to
  - Nominal Monte Carlos (MC) model,
  - Warped Fake data — Vary underlying true distribution and propagate through to reconstructed.
- Use statistically fluctuated data for each study when assessing unfolding procedure.



[1] K. Abe *et al.* (T2K), Phys. Rev. **D97** 012001 (2018), [2] P. Adamson (NOvA), Phys. Rev. Lett. 118 (2017) no.15, 151802, [3] NOvA Technical Design Report, FERMILAB-DESIGN-2007-01, [4] R. Acciarri et al. (DUNE Collaboration), arXiv:1512.06148, [5] O. Altinok (MINERvA), Phys. Rev. **D96**, 072003 (2017), [6] X.-G. Lu, D. Coplowe, R. Shah, G. Barr, D. Wark, and A. Weber, Phys. Rev. **D92**, no. 5, 051302 (2015)