Results from the MINOS+ Experiment

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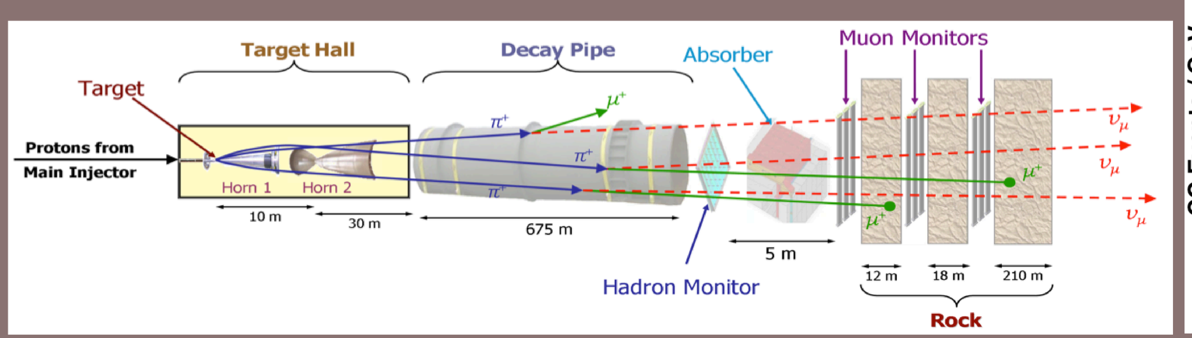
The MINOS+ Experiment in the NuMI Beam

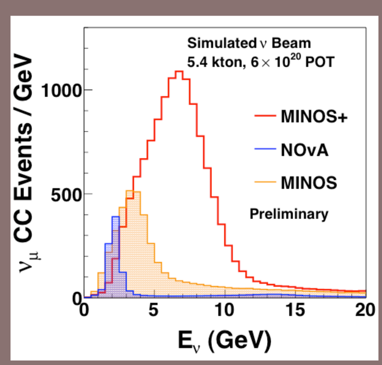
The NuMI Beam [1]:

- 120 GeV protons from the Main Injector impact on a graphite target
- Two magnetic horns focus secondary hadrons which decay into neutrinos in the decay pipe
- The absorber and the subsequent rock absorb the remaining hadrons but neutrinos travel towards the detectors

The MINOS+ Experiment [2]:

- MINOS+ was the continuation of the on-axis 735km baseline MINOS experiment and took data from 2013-2016 seeing a medium energy (ME) beam; MINOS+ saw large statistics on-axis NuMI Beam
- MINOS took data in a low energy configuration from 2005-2012
- MINOS(+) used a Near Detector (ND) at Fermilab and a Far Detector (FD) in the Soudan Mine in Minnesota, baseline 730km
- The ND detected the neutrinos before oscillations, and the FD after oscillations



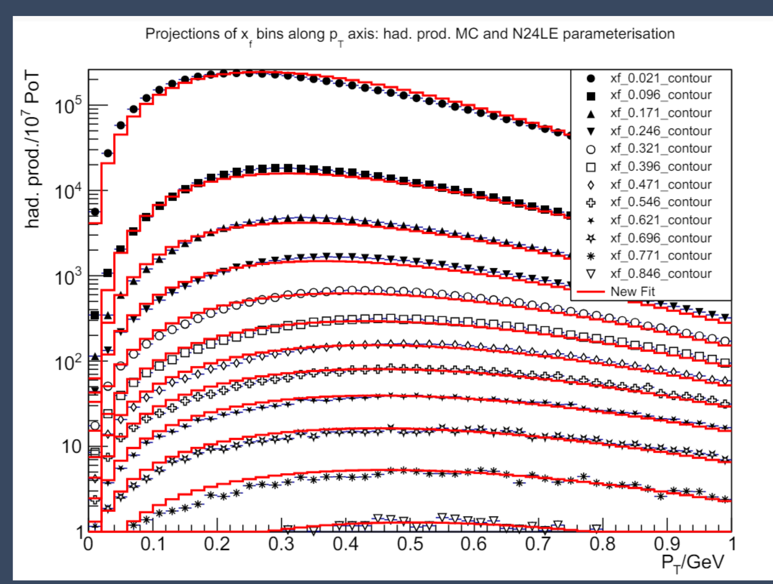


NuMI Beam Fits

Hadron Production Parametrisation:

$$\frac{d^2N}{dx dp_T} = [Bp_T + Cp_T^2]\, e^{-Dp_T^E}$$

$$x_F = \frac{p_Z}{120}$$



- NuMI beam flux (G4NuMI) shows disagreement between data and MC at peak for NuMI neutrino experiments
- Hadron production and horn focusing effects are fit to MINOS ND Data
- **Stage 1: Parametrise hadron production in flux MC (G4NuMI) (improvements over [3])**
  - Flux : quadratic and new exponential term improve prediction for pT range 0 < pT < 1.4 GeV/c
  - Parametrisation of secondary functions (B, C, D, E) uses an empirical approach to describe flux MC
  - Both LE and ME MC treated separately

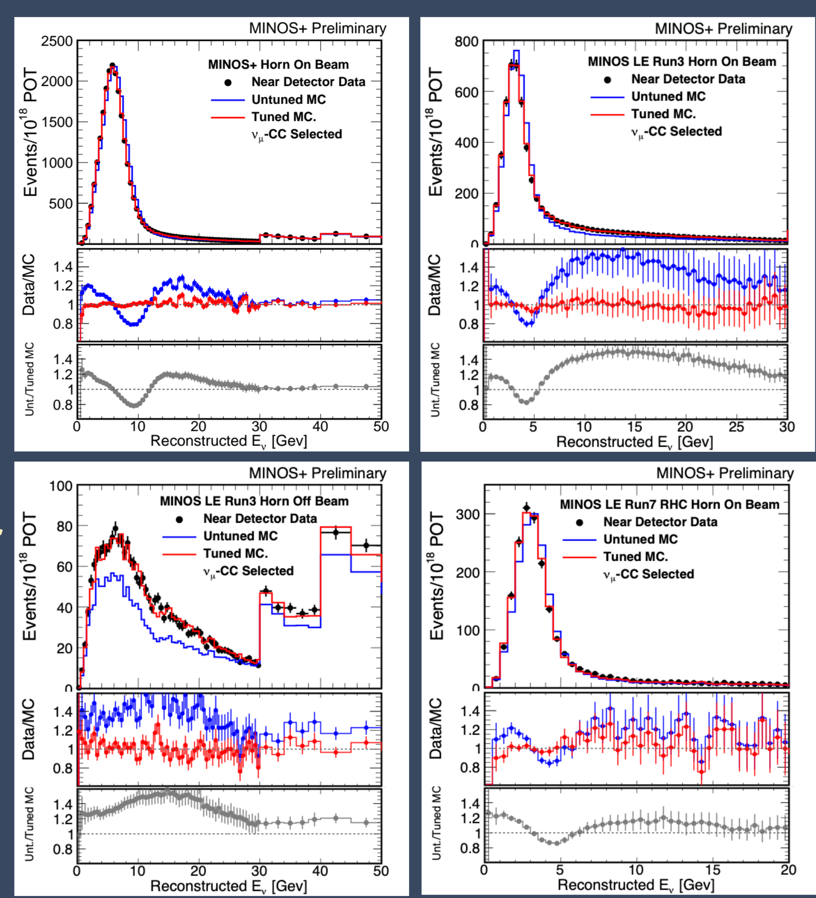
<- hadron prod parametrisation π+
-> hadron prod weights from ND fit

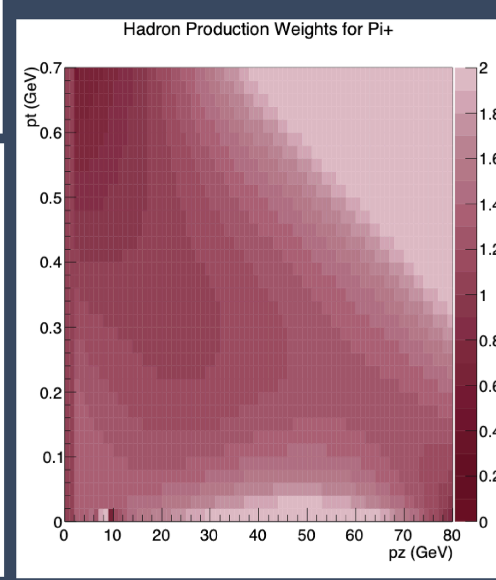
$$B'(x_F) = (p_0 + p_1 x_F)B(x_F)$$
$$C'(x_F) = (p_2 + p_3 x_F)C(x_F)$$
$$D'(x_F) = (p_4 + p_5 x_F)D(x_F)$$
$$E'(x_F) = (p_6 + p_7 x_F)E(x_F)$$

$$W(p_T, x_F) = \frac{[B' p_T + C' p_T^2] exp(-D' p_T^{E'})}{[B p_T + C p_T^2] exp(-D p_T^{E})}$$

Stage 2: Fit to Near Detector Data:

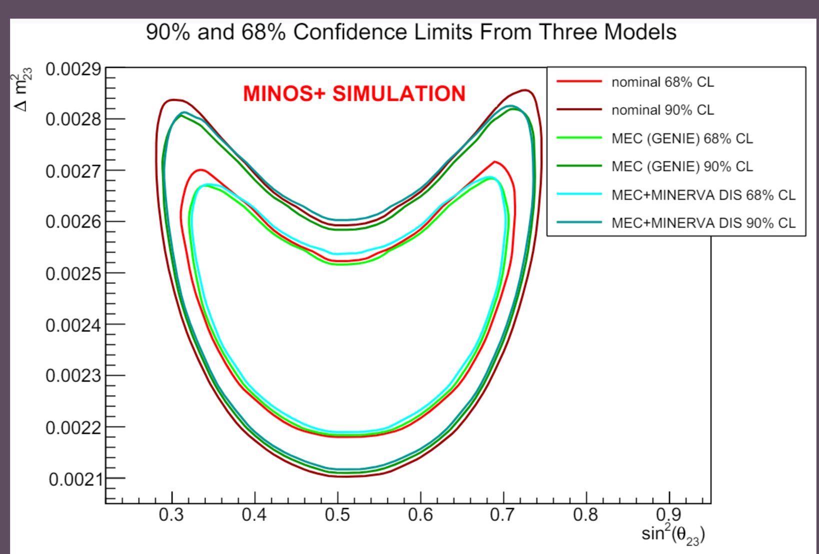
- Hadron prod is fit together with horn focusing parameters
- Horn current scale prefers -10kA.
  - Higher than 4kA error on horn current, assumed to account for any focusing effects
- 10kA consistently seen both for the low energy beam (2005-2012) and the medium energy beam (2012-2016)
- New beam fit for both LE Horn On, Forward and Reverse Horn Current





New MINOS+ Analysis

- Effect of MEC studied and shown to be negligible
- Effect of beam weighting studied on fake data sample
- Many universes analysis of systematic/statistical effects and their impact on fit result
- Covariance matrix for systematics



MINOS+ $\sin^2(\theta_{23})$ Result

New MINOS+ results on muon neutrino disappearance

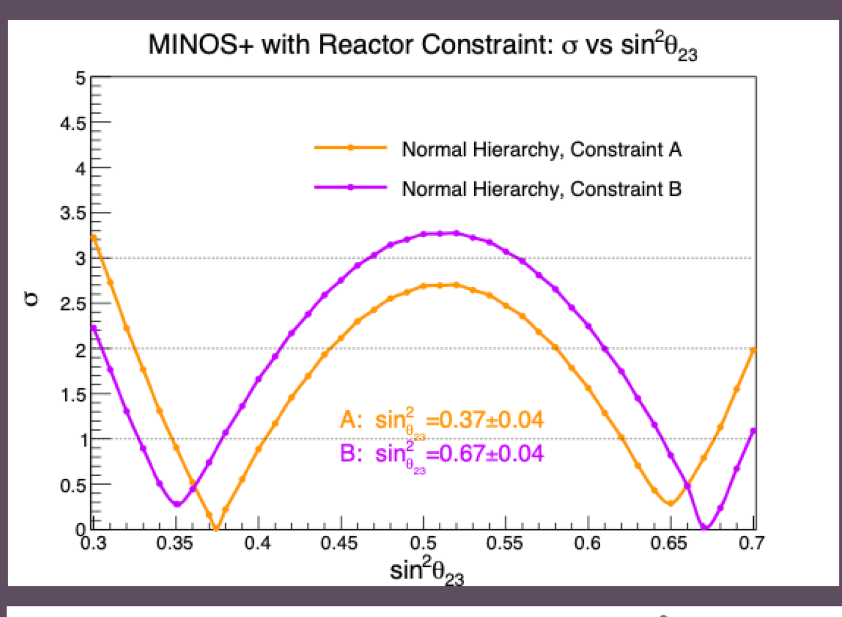
Incorporate Δm^2_{32} value constrained by Daya Bay [4,5] and RENO [6,7] and independent of θ_{23} which is measured by MINOS+

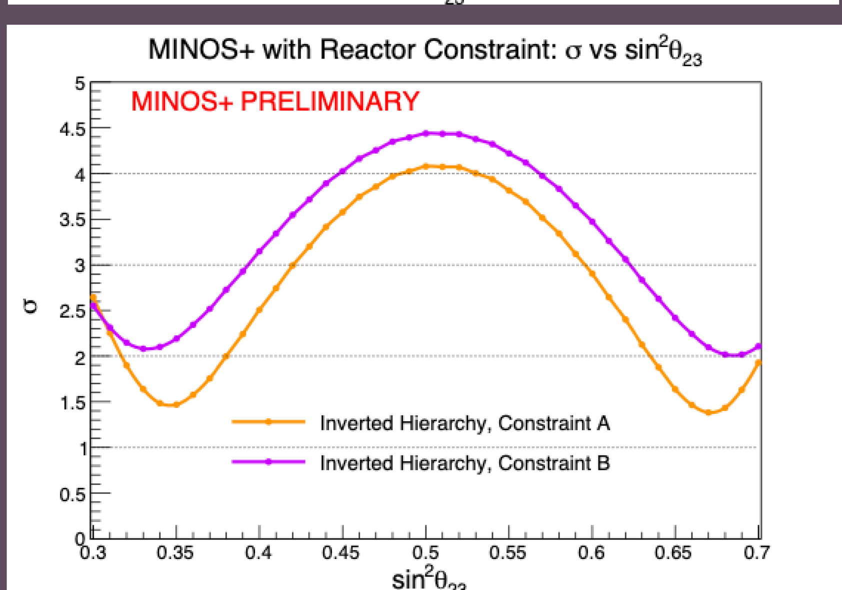
Constraint A uses the Daya Bay result from [4]

$$\Delta m^2_{32} = 2.51\times10^{-3} \pm 0.05 eV^2$$
$$\Delta m^2_{32} = -2.61\times10^{-3} \pm 0.05 eV^2$$

Constraint B uses [5]. A weighted average is calcuated in combination with RENO [7].

$$\Delta m^2_{32} = 2.70\times10^{-3} \pm 0.09 eV^2$$
$$\Delta m^2_{32} = -2.80\times10^{-3} \pm 0.09 eV^2$$





With new DB constraint (B), maximal mixing excluded at > 3σ
Inverted Hierarchy disfavoured at 2 σ
With constraint A, respective numbers are 2.7σ and 1.5σ

Best Fit Values

Constraint A:

$$\sin^2\theta_{23} = 0.37 \pm 0.04$$
$$\Delta m^2_{32} = 2.50\times10^{-3} \pm 0.06 eV^2$$

Constraint B:

$$\sin^2\theta_{23} = 0.67 \pm 0.04$$
$$\Delta m^2_{32} = 2.60\times10^{-3} \pm 0.10 eV^2$$

Systematic Error Covariance

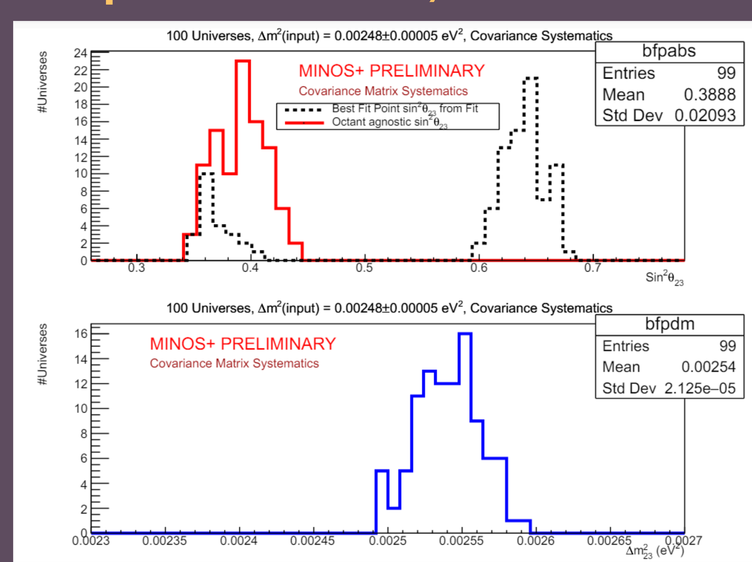
Covariance matrix built for 4 dominant systematic errors
Replaces penalty term extrapolation approach from previous analyses
Shown to be robust in universe studies

The example shown here (right) has the parameters:

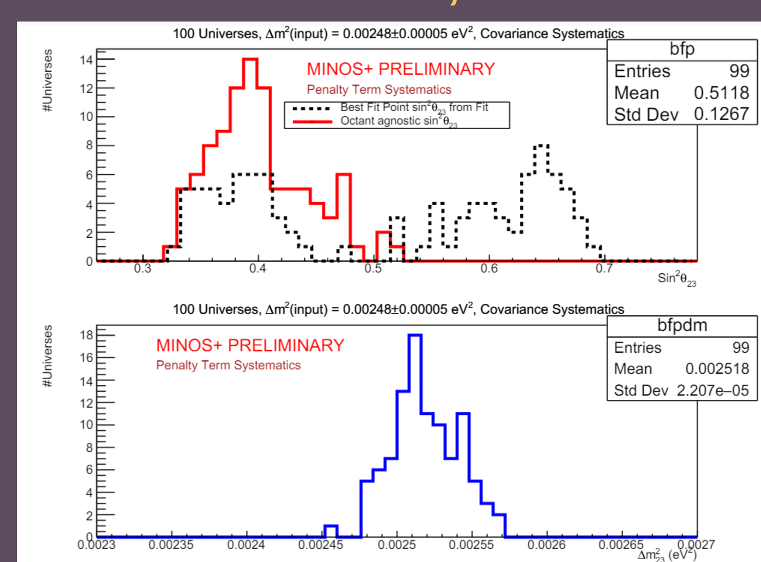
Δm^2_{32} = 0.00248

sin (θ_{23}) = 0.38

Separate runs fit, DstBaseline

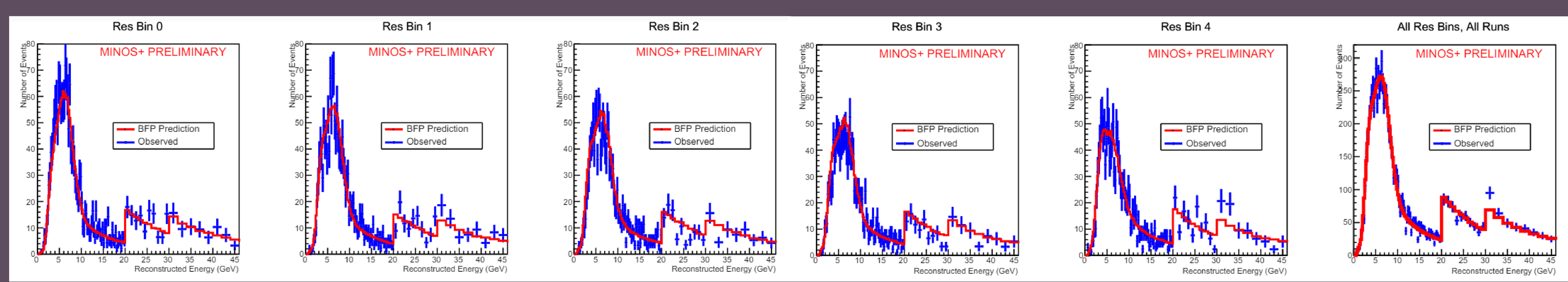


Combined runs fit, DstBaseline



Resolution bins

Resolution binning has been implemented for the ME beam samples. Previously this was only done for the LE beam samples. This adds additional sensitivity to the analysis of 2.5×10^{21} POT

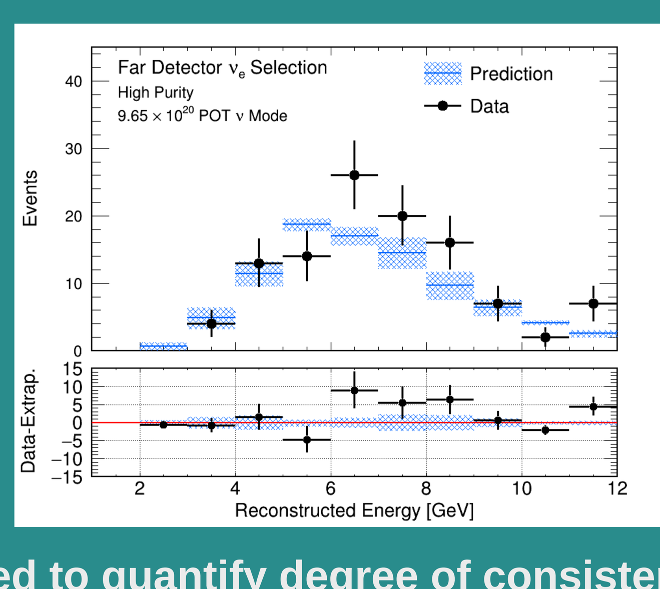


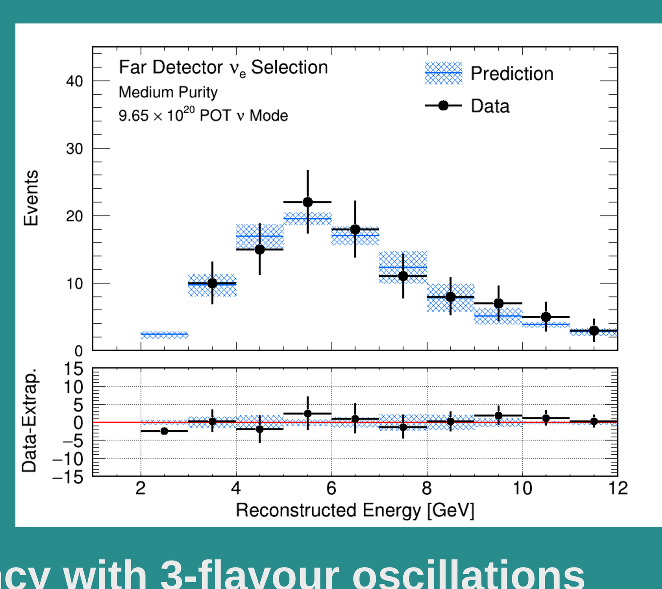
High Energy ν_e Appearance Analysis

The world's low-energy, long-baseline ν_e appearance data is consistent with 3-flavour model.

High energy (6 < E_ν < 12 GeV), long baseline ν_e appearance is largely unconstrained. HE configuration of MINOS+ probes anomalous ν_e appearance in the Far detector.

- Using extrapolation, we compare best fit world parameters to MINOS+ predictions
- Medium-purity sample (right) agrees with 3-flavour model across all energies
- No clear discrepency with expectation in the High-purity sample (left) at higher energy
- PISCES framework [9] to be used to quantify degree of consistency with 3-flavour oscillations





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