MINOS+ and the NuMI Beam

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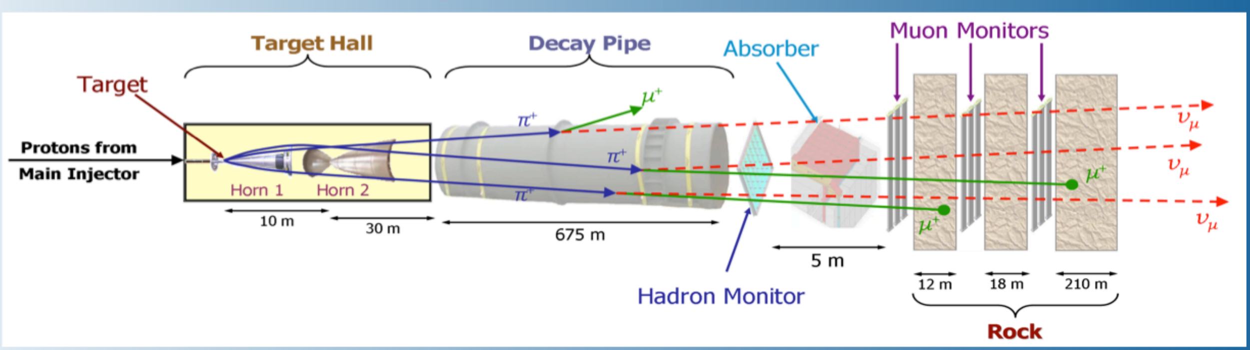
on behalf of the MINOS+ Collaboration

1. The MINOS+ Experiment in the NuMI Beam

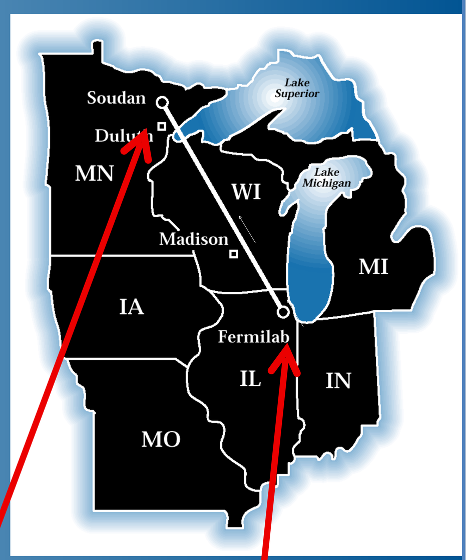


The NuMI Beam [1]:

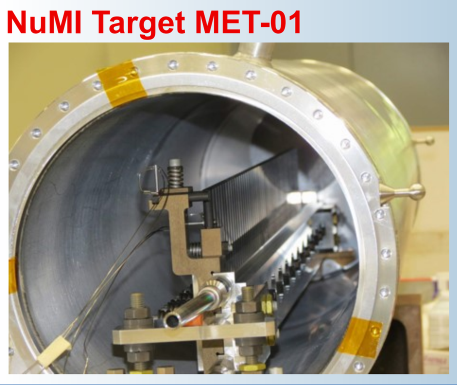
- 120 GeV protons from the Main Injector impact on a graphite target
- The resulting hadrons are focused by two magnetic horns and decay into neutrinos and other particles in the decay pipe
- The absorber and the subsequent rock absorb the latter, leaving only the neutrinos to travel towards the detectors

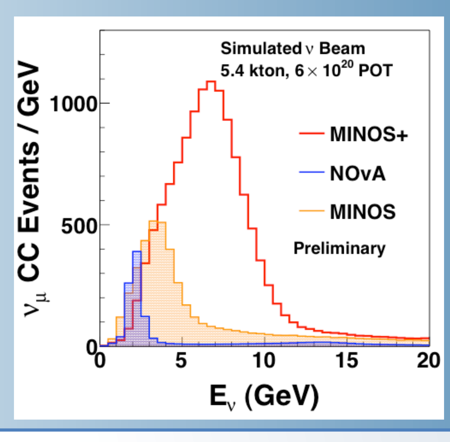
The MINOS+ Experiment:

- 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 a large statistics on-axis NuMI Beam
- MINOS+ used a Near Detector (ND) at Fermilab and a Far Detector (FD) in the Soudan Mine in Minnesota
- The ND detected the neutrinos before oscillations, and the FD after oscillations

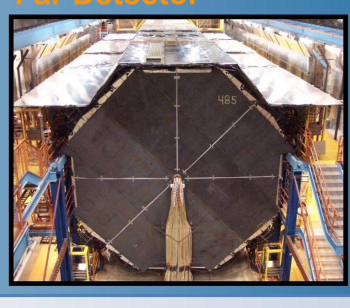


NuMI Target MET-01



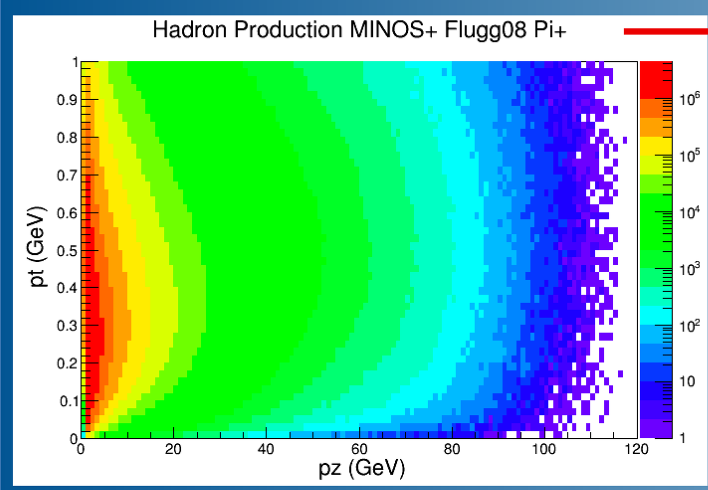


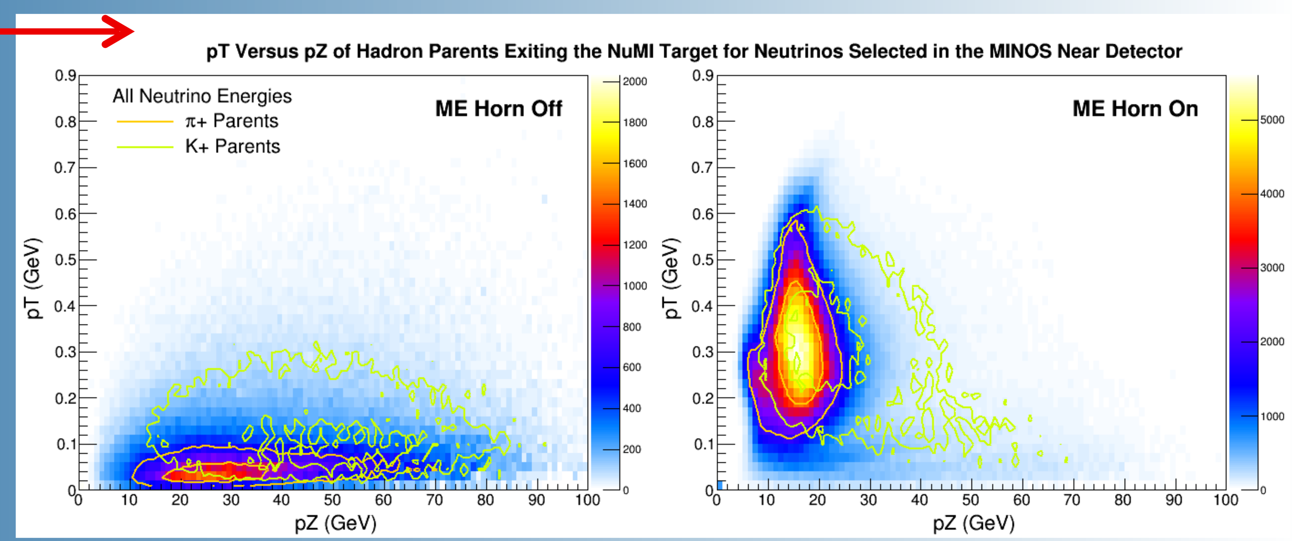
Far Detector



Near Detector

2. Hadron Production Phase-Space and Horn Off Data



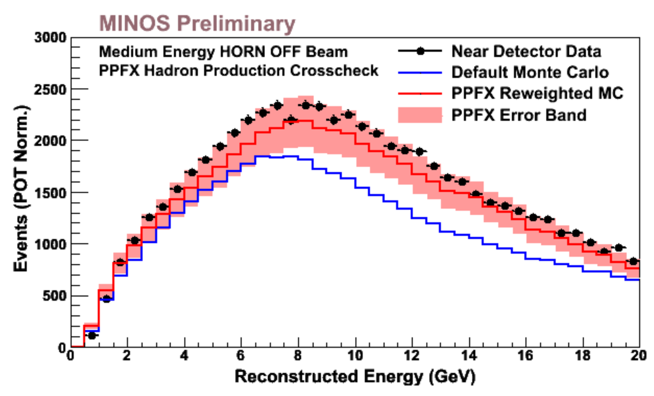


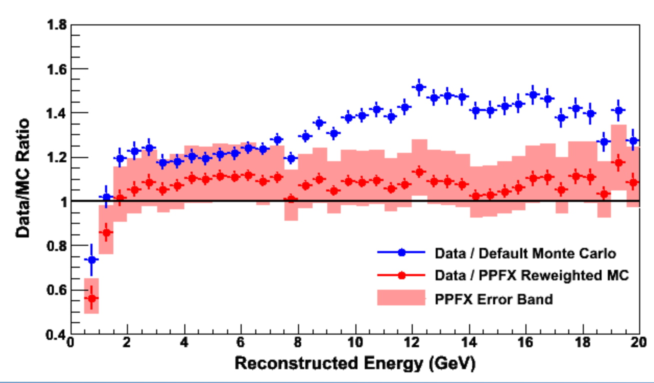
The Flux Simulation

- MINOS+ uses FLUKA08 [2] Monte Carlo (MC) to simulate the NuMI beam flux
- Neutrino flux in MINOS+ comes mainly from positive pions, with some positive kaons at higher reconstructed energies
- When the horn current is off, neutrinos seen in the MINOS+ ND mostly come from hadron parents that had a low p_T
- When the horn current is on (normal beam operation), the selected neutrinos come from a wider p_T phase space as the neutrino parents are focused by the horns

The Horn Off Data:

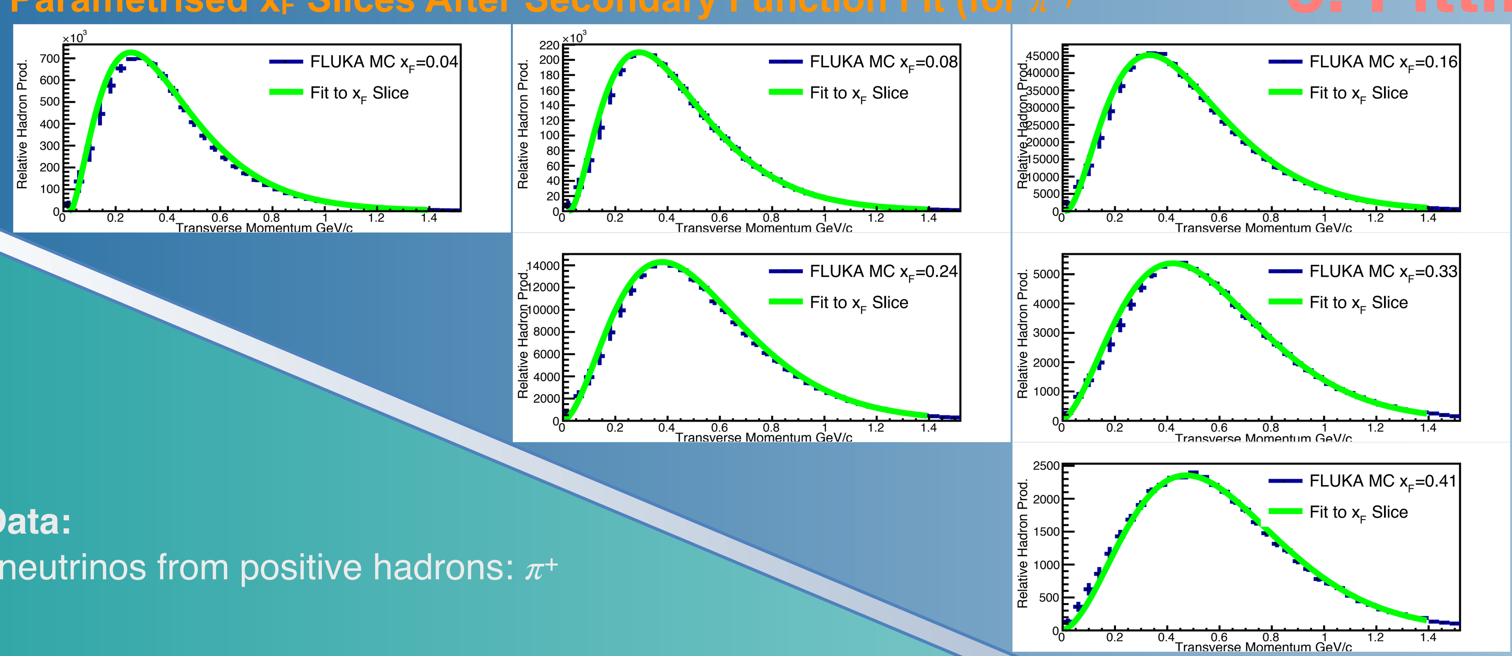
- The horn off data sample provides a unique opportunity to disentangle hadron production from focusing effects
- It allows the checking of a priori hadron production flux calculations, for example PPFX [3], which uses mostly thin-target hadron production data to derive flux predictions
- For the MINOS+ horn off sample, PPFX helps with the Data / Monte Carlo agreement below 20GeV (validated region for PPFX)





3. Fitting the NuMI Beam Flux - Parametrisation

Parametrised x_F Slices After Secondary Function Fit (for π^+)



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

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

The NuMI Beam Flux is Fit in 2 Stages:

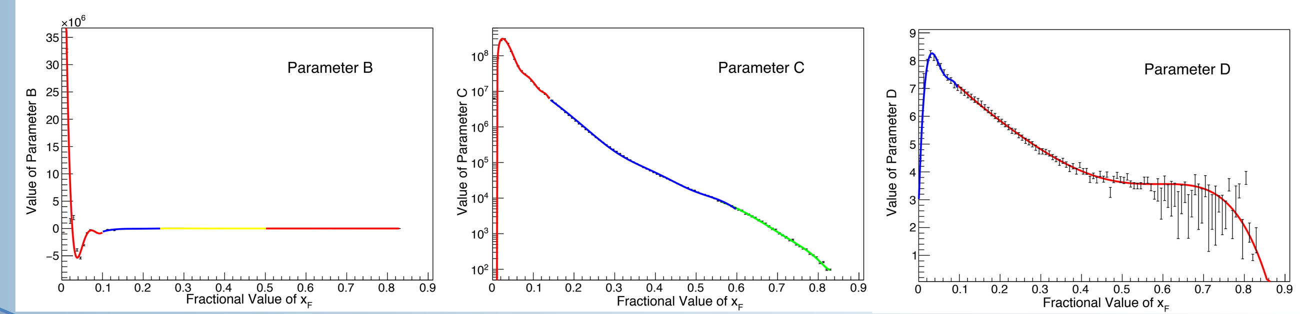
1. Parametrise the MC hadron production for pions (positive and negative)
2. Fit the ND data with weights constructed from the parametrised hadron production

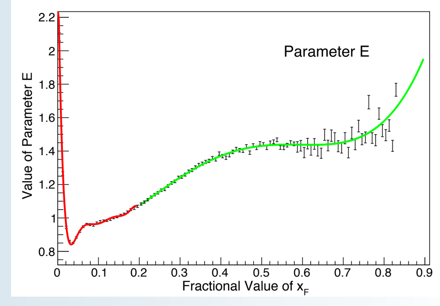
Stage 1: Parametrise the Hadron Production in the Flux MC

- Innovations (compared to previous work [4]):
- Flux rate equation has evolved form; quadratic term and variation of exponential term allow the parametrisation to work well for the entire p_T range $0 < p_T < 1.4$ GeV/c

$$\frac{d^2N}{dx_F dp_T} = [B p_T + C p_T^2] e^{-D p_T^E} \qquad x_F = \frac{p_Z}{120}$$

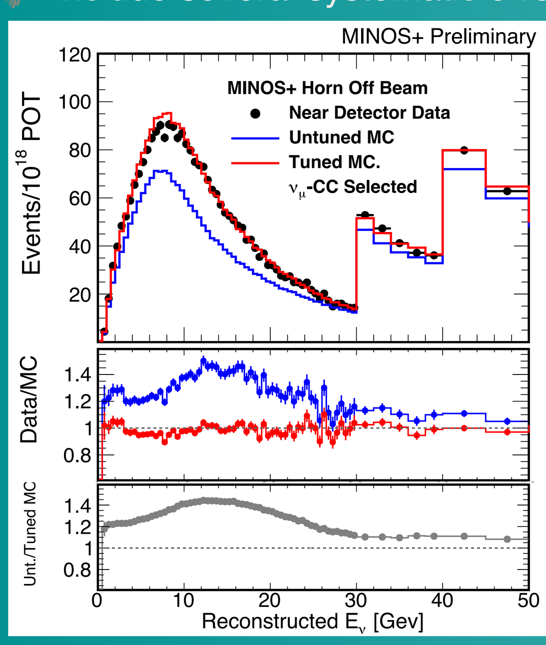
- The parametrisation of the secondary functions (B, C, D, E) uses an empirical parametrisation of flux MC to describe the latter as well as possible (shown for π^+)

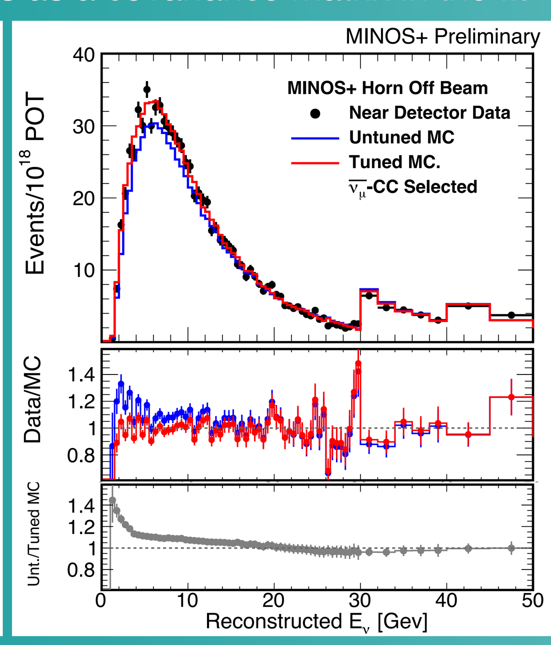


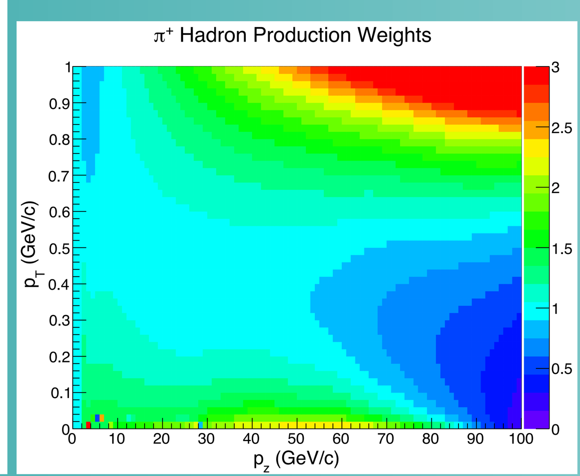


Stage 2: Fit the Near Detector Horn Off Data:

- First fit the hadron production for muon neutrinos from positive hadrons: π^+ (K^+ using the same weights as π^+)
- Then fix the π^+ parameters and fit anti-neutrino negative hadron parents
- Include several systematic errors as a covariance matrix in the fit







Other Fit Details:

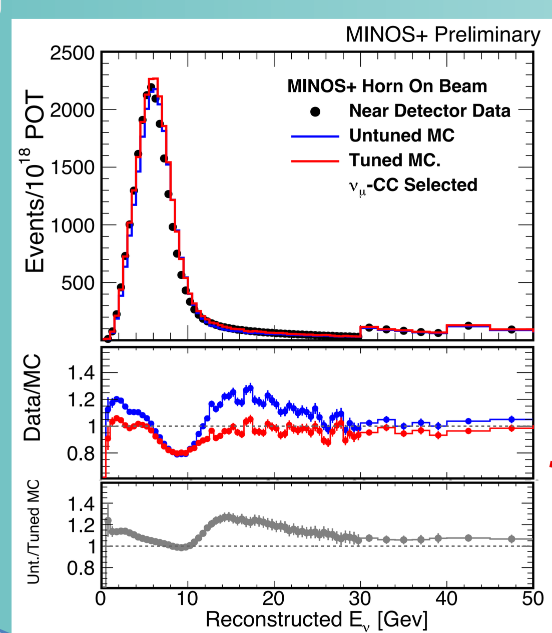
- Mean p_T penalty term
- Rate change penalty in horn on p_T-p_Z region to anchor the fit. Combined with the new parametrisation, it allows the horn off data to fit out hadron production data/MC differences in both the horn off and the horn on samples
- When the parent exiting the target is a proton, use the hadron production weight corresponding to the direct neutrino parent

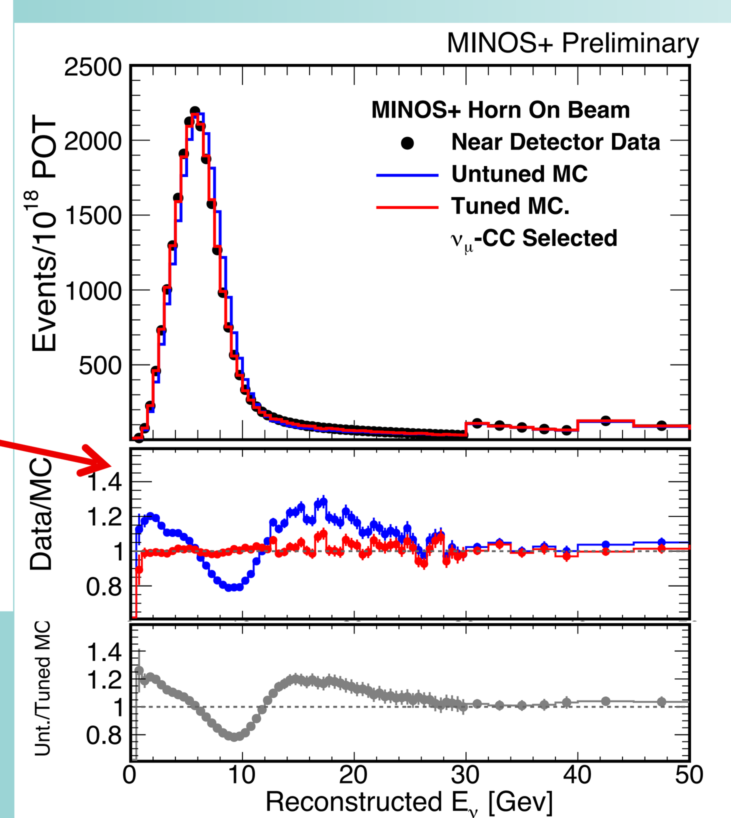
4. Fitting the NuMI Beam Hadron Production - Fit to Horn Off Data

Applying the Hadron Production Results to Horn On MC:

- After the hadron production horn off fit, we can apply the resulting weights to the horn on MC and compare to the horn on Data
- This improves the horn on agreement everywhere except at the falling edge of the peak, a region particularly susceptible to horn focusing effects

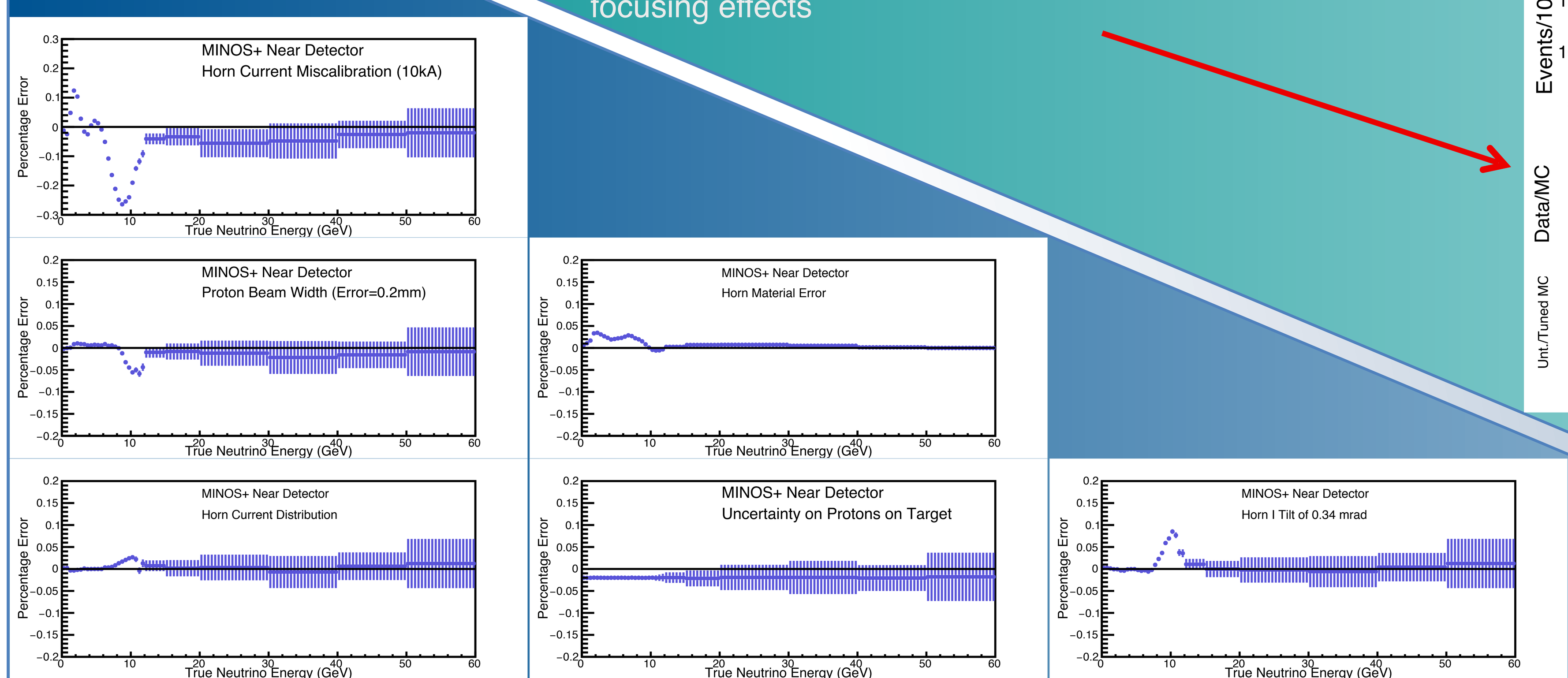
5. Fitting Focusing - Fit to Horn On Data





Focusing Fitting:

- The remaining Data/MC difference can be fitted out using two effective focusing parameters
- This is because many of the considered focusing errors are strongly correlated with each other
- For the fit we used horn material to account for effects such as thickness of inner horn conductor and water cooling of the horn
- We also used horn current mis-calibration which favours a value of 10kA to account for any unknown focusing effects
- After the focusing fit we are able to achieve good data/MC agreement in horn on beam



Flux Errors:

- While only two effective focusing parameters are needed to fit the data/MC differences, we model a number of systematic errors to include in the analysis (some examples are shown here)
- Those errors are calculated for the full true neutrino energy space up to 120GeV
- We also derive a hadron production error band by simulating thousands of alternative flux universes utilising the hadron production parameter error matrix resulting from the horn off data fit

Conclusions:

- **Horn off data can be a very powerful sample that can be used to derive hadron production weights for both the horn on and horn off p_T-p_Z phase space, away from any other focusing mis-modelling effects**
- **The results show evidence that there are focusing effects that are at present not well understood**
- **In a standard muon neutrino disappearance analysis we can correct for such effects due to the power of having two detectors**

6. Focusing Errors and Conclusions

[1] P. Adamson et al., NIM A, Vol. 806, 279-306 (2016)
[2] T.T. Böhlen et al., Nuclear Data Sheets Vol. 120, 211-214 (2014); A. Ferrari, P.R. Sala, A. Fasso`, and J. Ranft, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773
[3] L. Aliaga et al. (MINERvA), Phys. Rev. D 94, 092005 (2016), [Addendum: Phys. Rev. D 95, 039903 (2017)]
[4] P. Adamson et al. (MINOS), Phys. Rev. D 77, 072002 (2008)