MINOS: Unpacking the NuMI Beam Simulation Using the Near Detector

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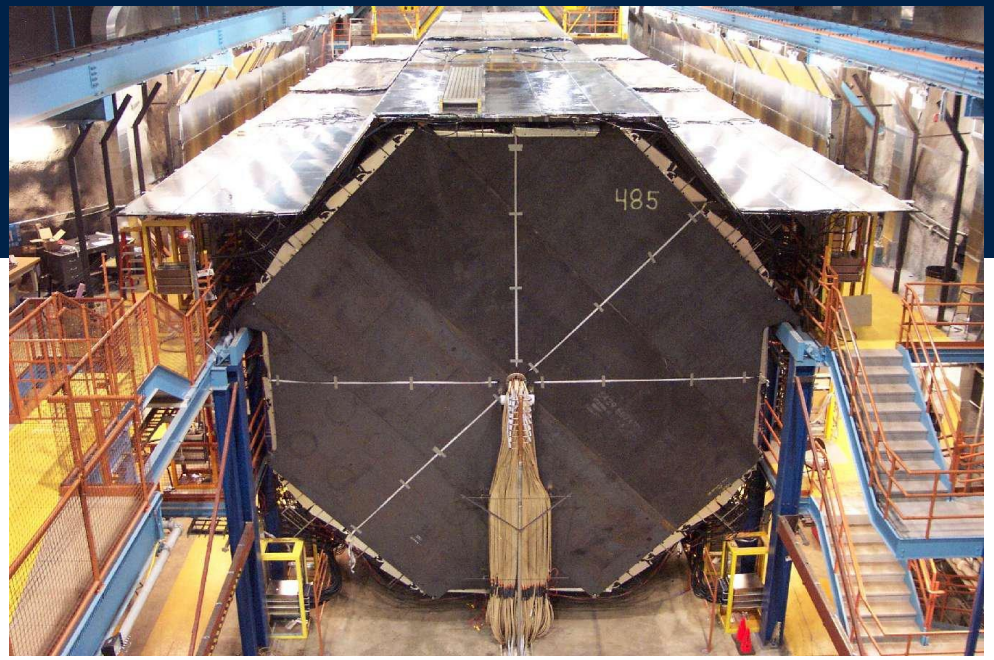
Background: Gustave Doré

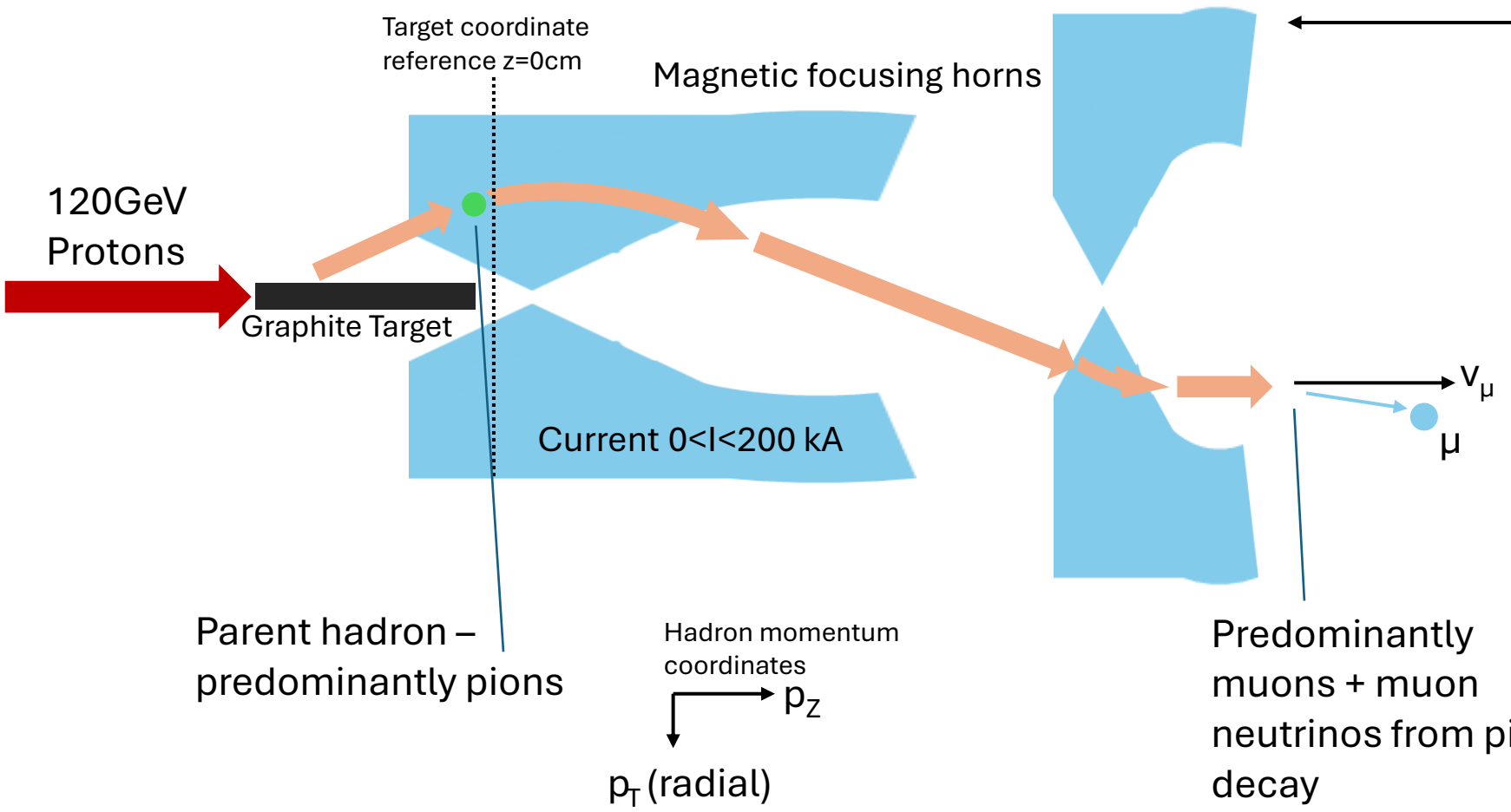
MINOS detector

- Long baseline 735km neutrino oscillation experiment
- Looked for disappearance of ν_μ at far detector to measure oscillation parameters
- Active from 2005 to 2016 and in its day made the most precise Δm^2_{32} and $\sin^2\theta_{23}$ measurements



NuMI Beam

Hadron Production **Focusing/optics** **Detection**

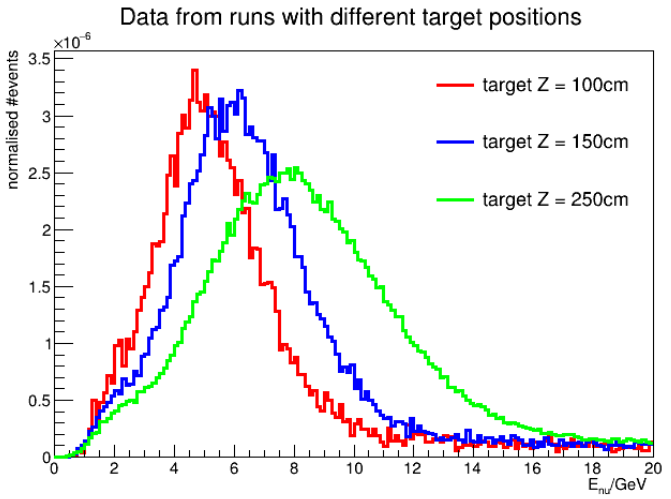


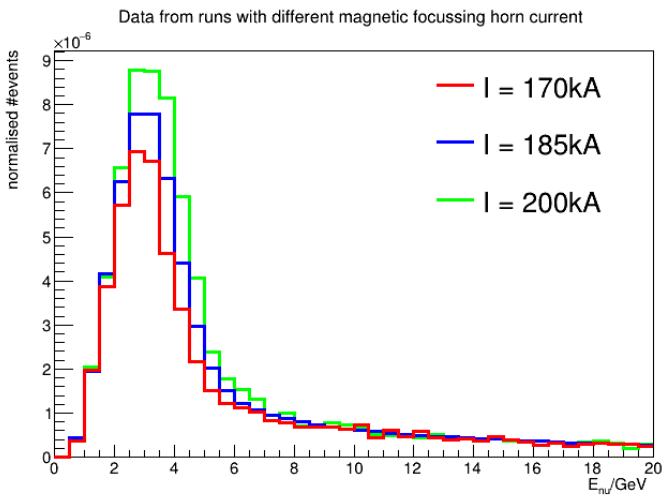
MINOS Near Detector

Calorimetry + charge measurement

Why are we still interested in MINOS

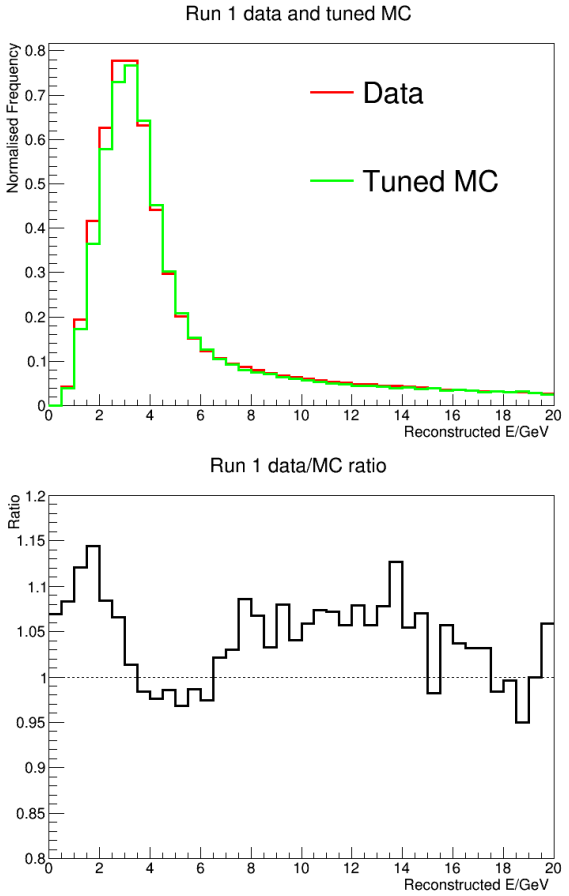
- MINOS took lots of data in many different beam configurations, providing neutrino energy spectra for a range of conditions
- Near Detector data allows us to make inferences about the NuMI beam simulation, which is relevant to contemporary experiments' beam design





Simulation of the NuMI beam

- MC model of the ND energy spectrum using the G4NuMI-FLUGG simulation have imperfect agreement with the data
- A study identified that a major source of error was the hadron production in the NuMI target due to disagreement of up to 30% across different theoretical models

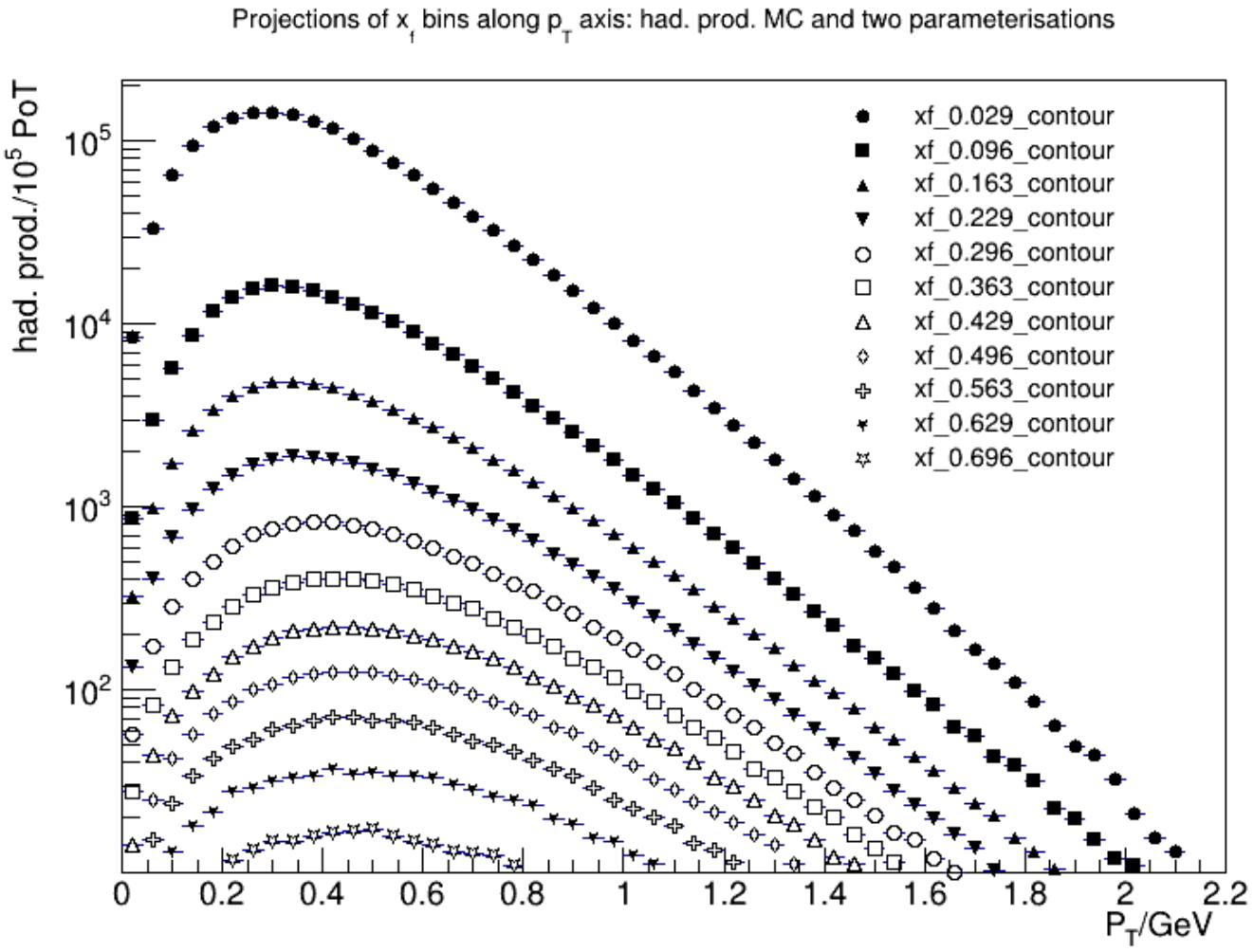


Model	$\langle p_T \rangle$ (GeV/c)
Fluka 2001[23]	0.43
Fluka 2005[23]	0.36
MARS-v.15[17]	0.38
Malensek[22]	0.50
Geant/Fluka[19]	0.37
Sanford-Wang[20]	0.42
CKP[21]	0.44

Mean transverse momenta of π^+ from a graphite target struck by 120GeV protons, as calculated by several interaction Monte Carlo's. Taken from [1]

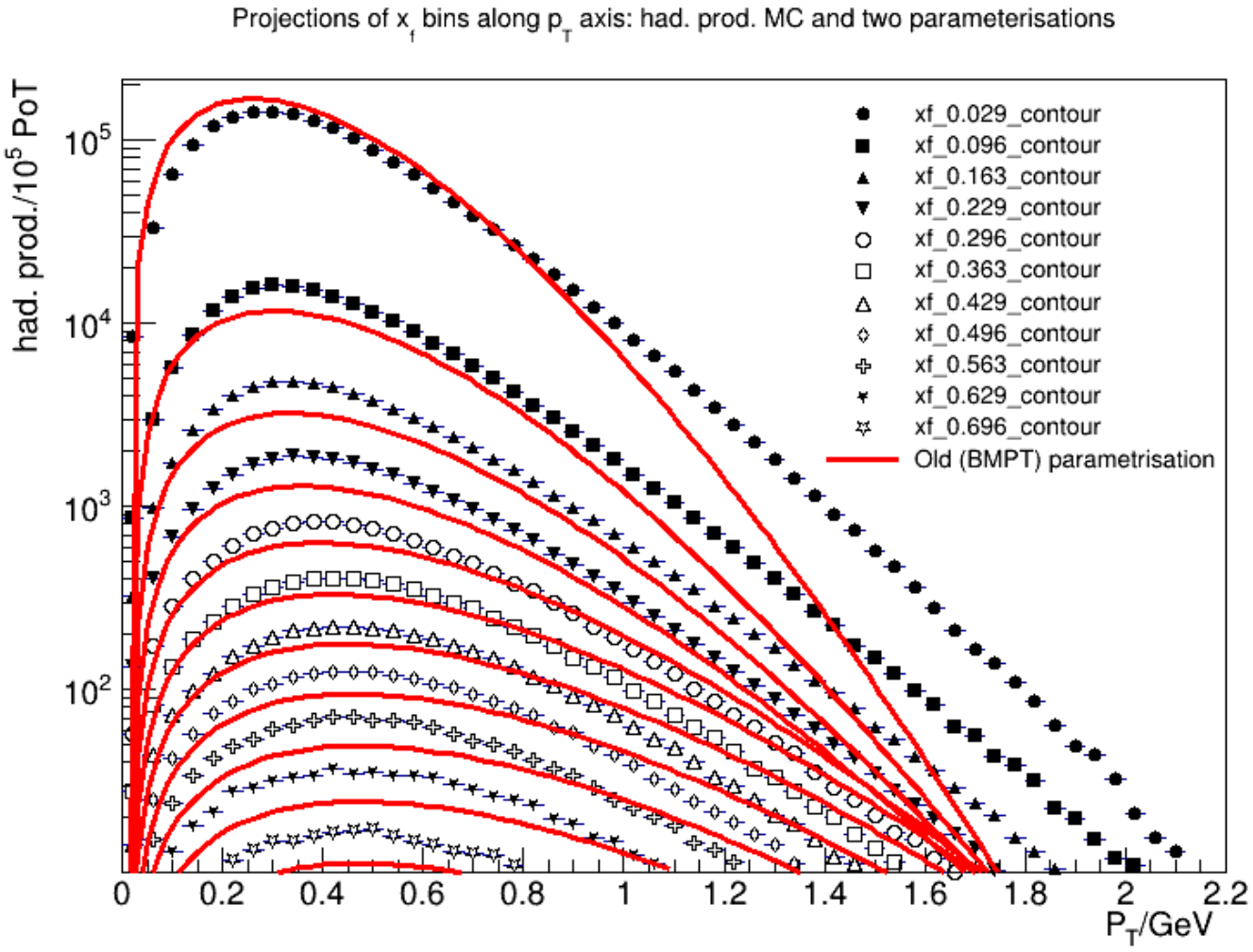
[1] S. Kopp, Z. Pavlovic, P. Vahle and R. Ospanov, Constraining the Beam Neutrino MC Flux Using the MINOS ND Data, MINOS Doc-DB #2965.

Hadron Production



- FLUGG prediction for hadron production momentum
- Reweight this by fitting to data
- Requires good parametrization

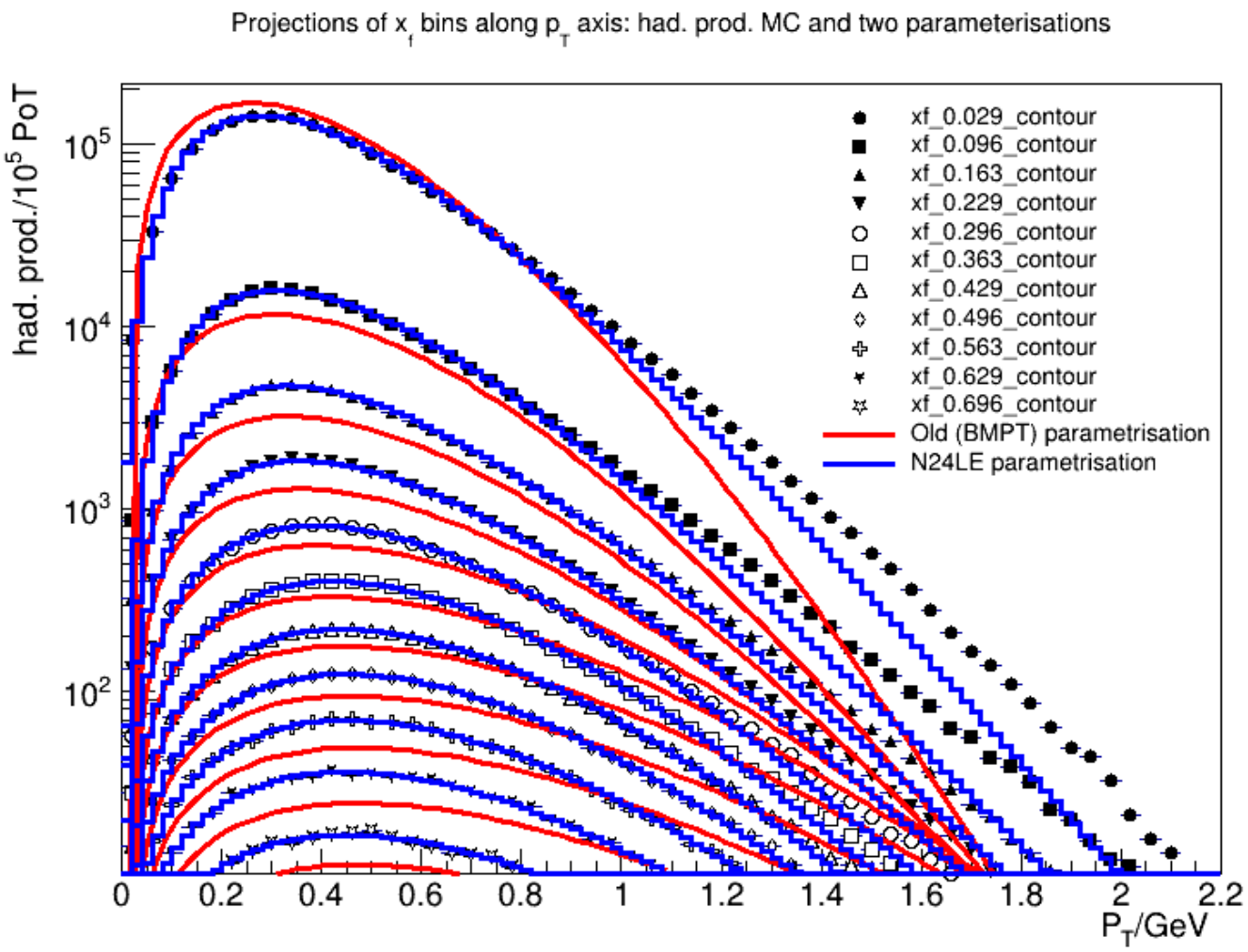
Hadron Production



$$\frac{d^2N}{dx_F dp_T} = [A(x_F) + B(x_F)p_T]exp(-C(x_F)p_T^{\frac{2}{3}})$$

- Earlier attempt –standard BMPT parametrization
- Combines theoretical and empirical terms
- Fit to the different MC x_F bands but imperfect model

Hadron Production



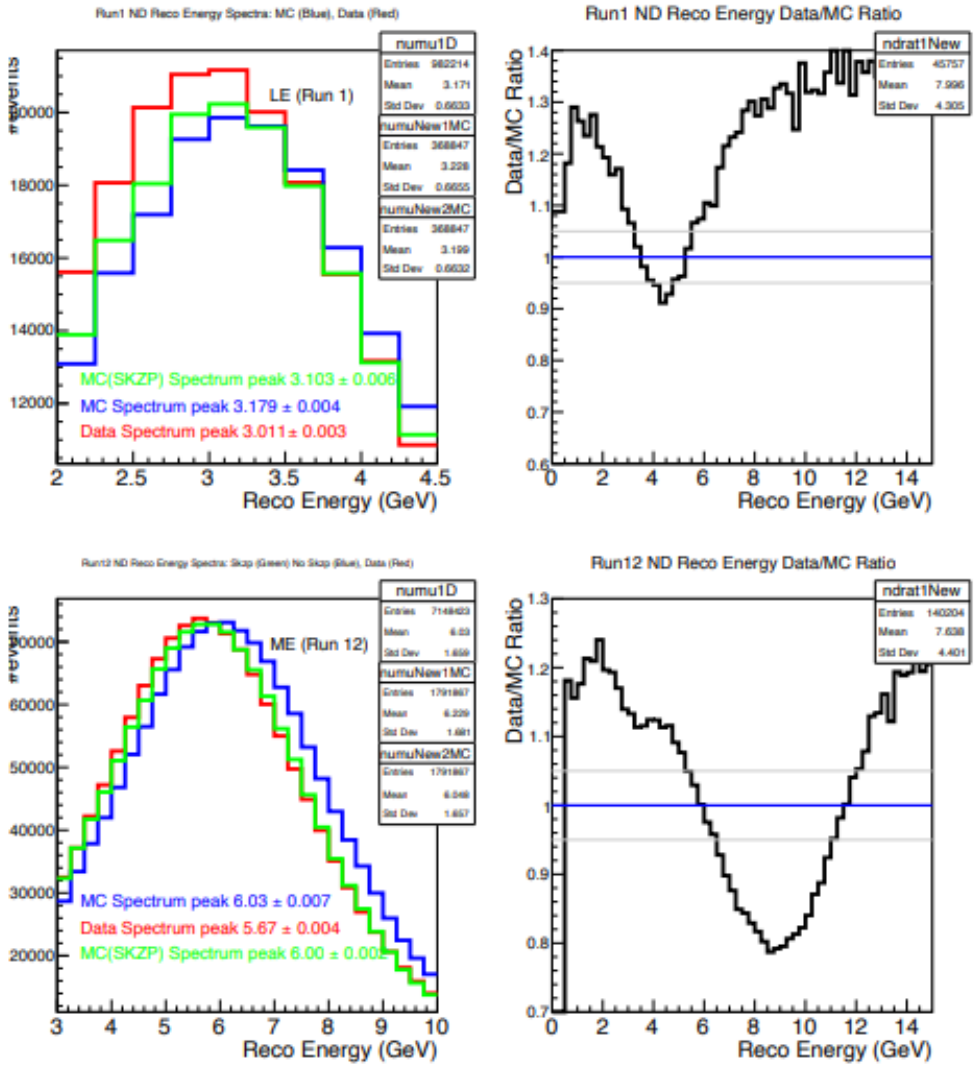
$$\frac{d^2N}{dx_F dpT} = \left(B(x_F)p_T + C(x_F)p_T^2\right)e^{-D(x_F)p_T^{E(x_F)}}$$

$$e.g.\ B = \sum_i b_i x_F^i \qquad x_F = \frac{p_Z}{120}$$

- New N24LE parametrization
- BCDE parameters are polynomials in x_F
- Empirical approach in different regions of p_T

- BCDE are then parameters in fit to data

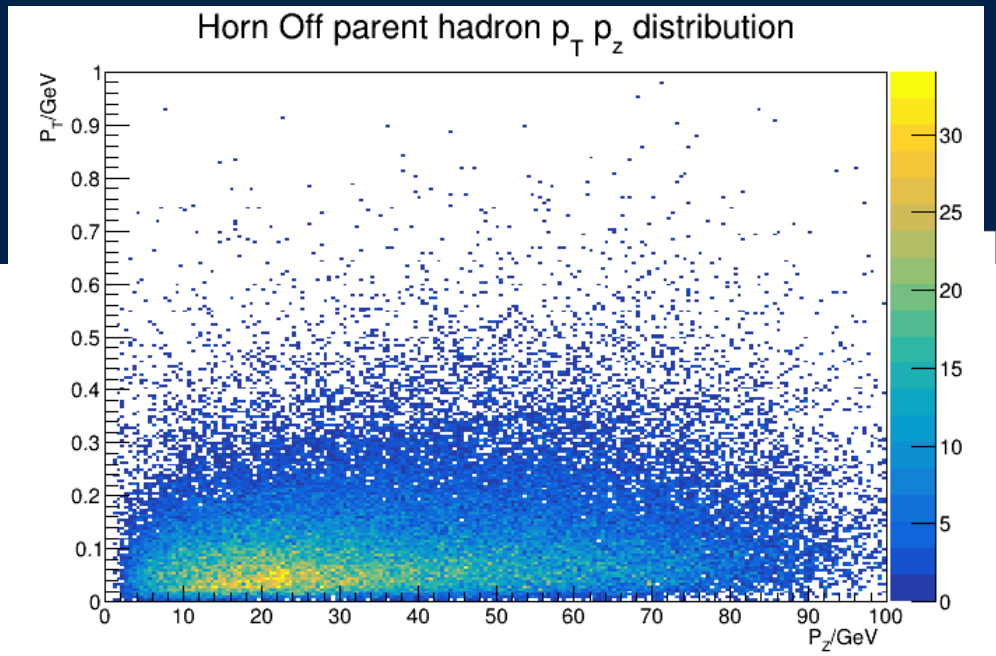
Focusing Parameter

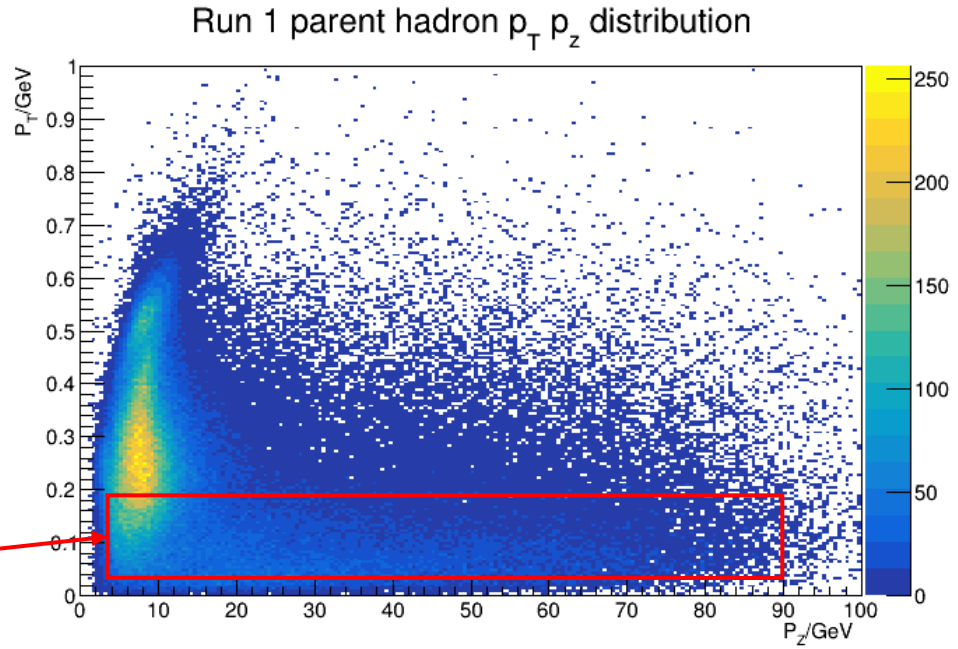


- LE (top) and ME (bottom) energy peak mismatch between MC and data
- This was considered to be due to the simulation of the focusing
- Horn Current Miscalibration parameter was used to correct peak
- Preferred horn current correction is so large (~10kA) that it is labelled an **effective parameter** incorporating all beam optics

The Horn Off sample

- Runs with no current through the magnetic focusing horns
- Low stats, but virtually unaffected by beam systematics
- They can be used to constrain hadron production parameters
- Useful to fit with horn on runs, as all samples contain ‘horn-off-type’ events





Region of high p_Z low p_T ‘horn off type’ events, largely unaffected by magnetic focussing

Effective parameters for ND

- There is also unknown physics in the ND
- Normalization based on neutrino interaction is introduced to pick up ND effects

QE

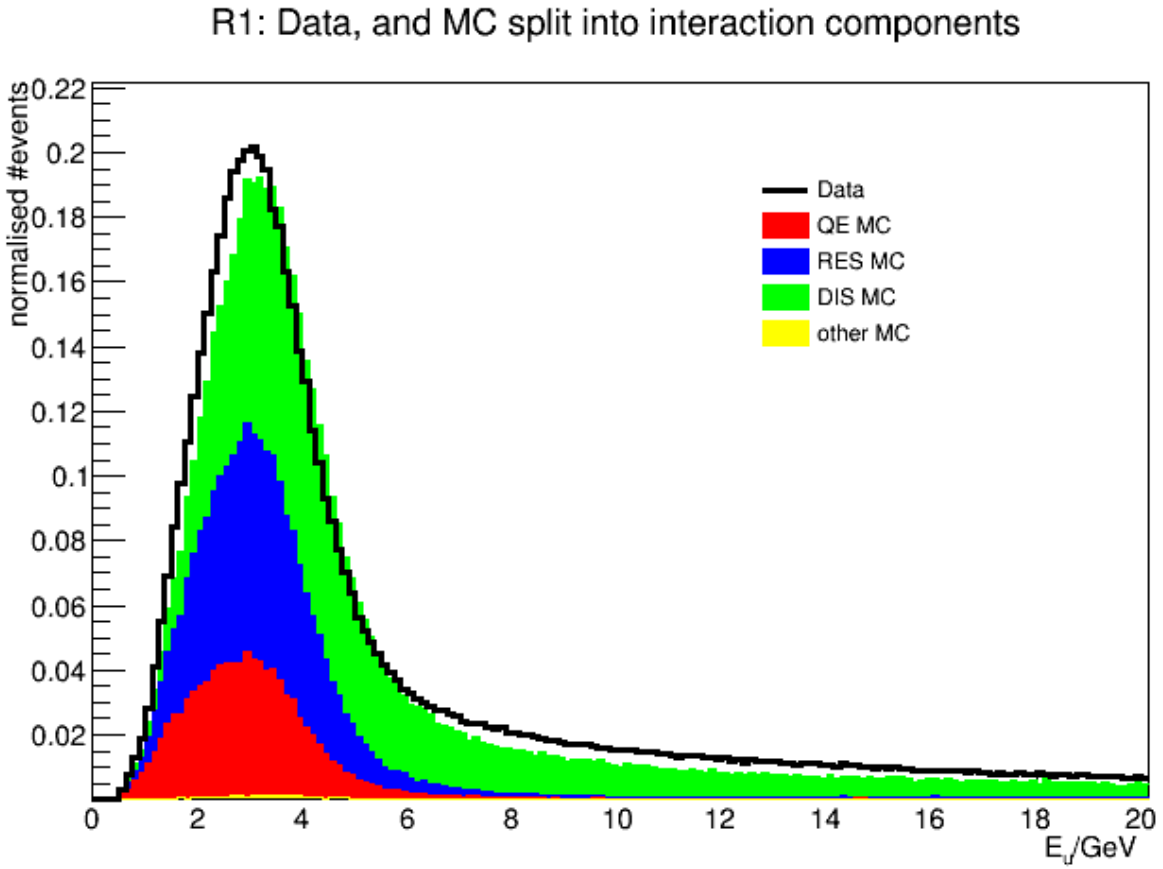
$\nu_\mu + n \rightarrow \mu^- + p$

Resonance

$\nu_\mu + p \rightarrow \mu^- + \Delta^{++} \rightarrow \mu^- + p + \pi^+$

DIS

$\nu_\mu + N \rightarrow \mu^- + hadronic\ shower$

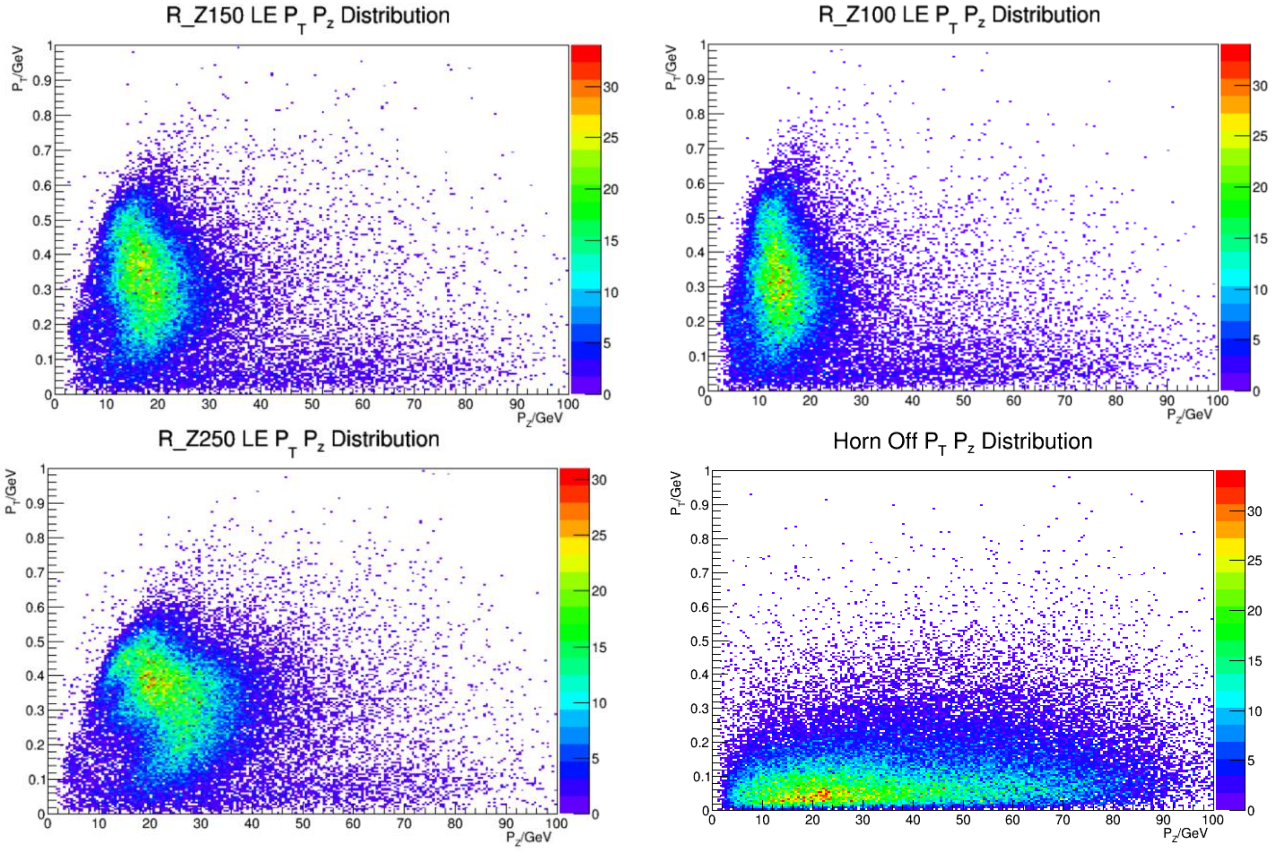


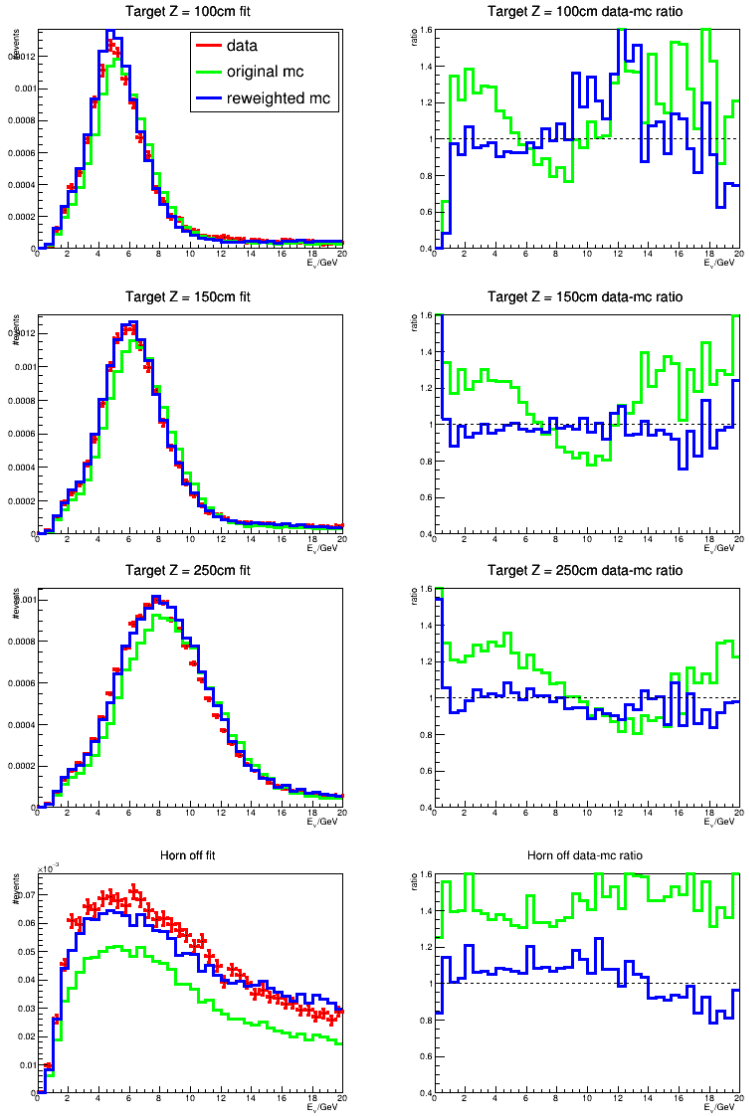
Extracting information from the fits

Target Parameters	Focusing Parameters	ND Parameters
• Hadron Production • Target Decay • Target Position • Intensity	• Focusing Horn Current • Decay pipe atmosphere	• Interaction Effects

Fit Results

- Fit with different target position samples + horn off to cover wide range of p_T p_Z space and constrain focusing systematics, obtaining ND parameters

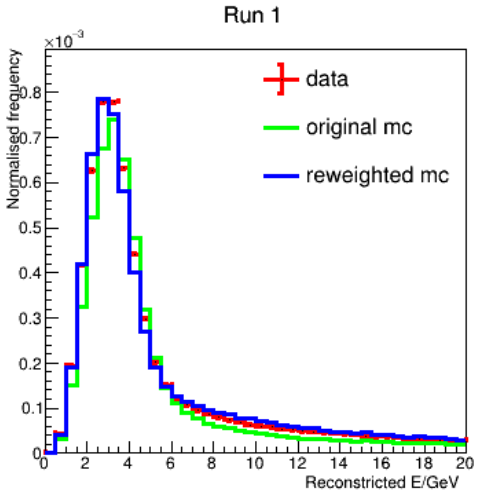


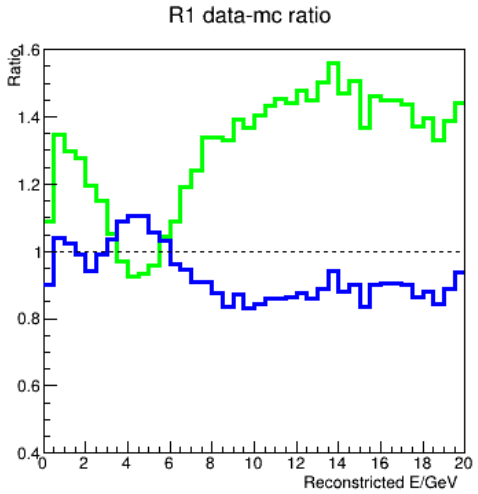


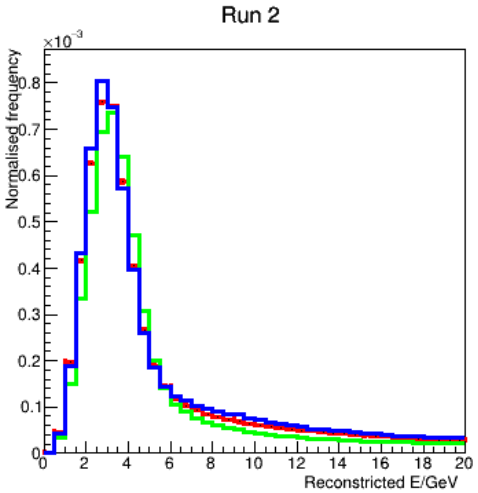
MINOS preliminary

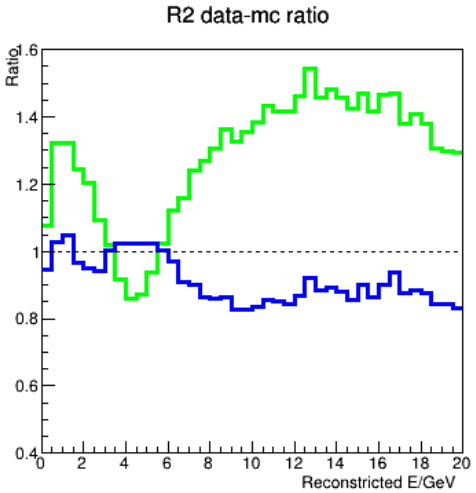
Applying parameters to other samples

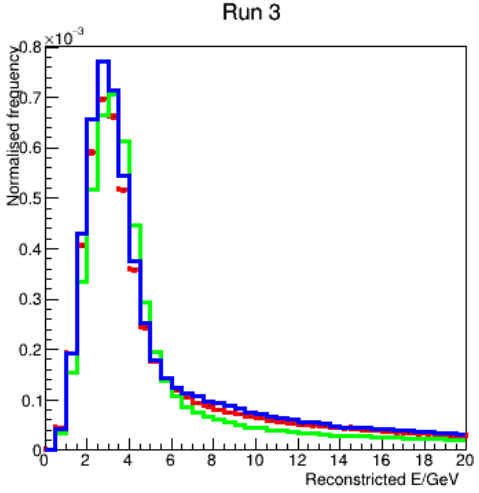
- Parameters found in previous fit used to reweight different MC, results in moderately improved fit to data

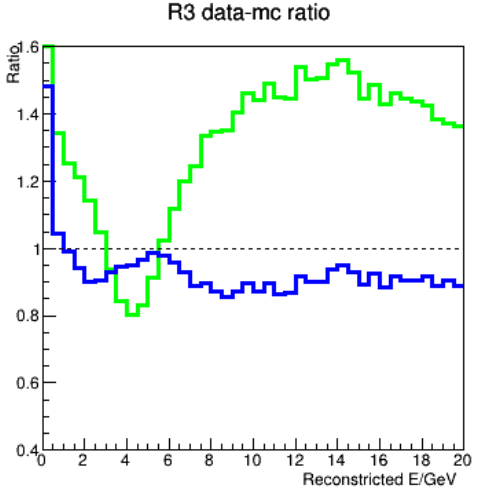








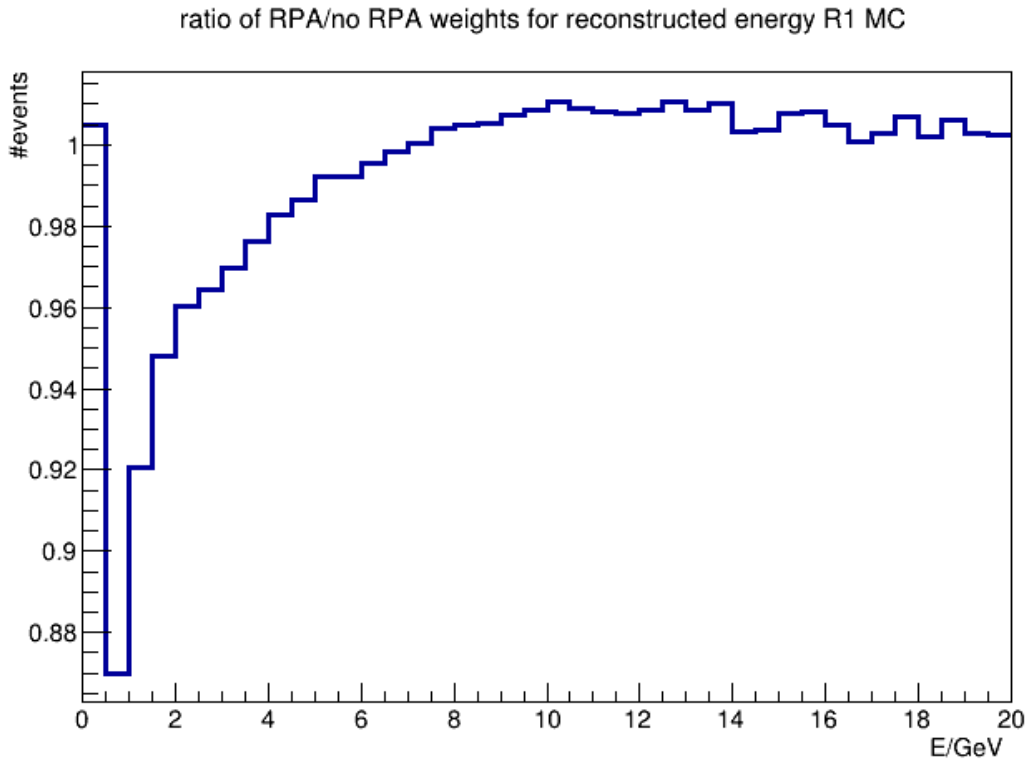




R2&3 target decay accounted for

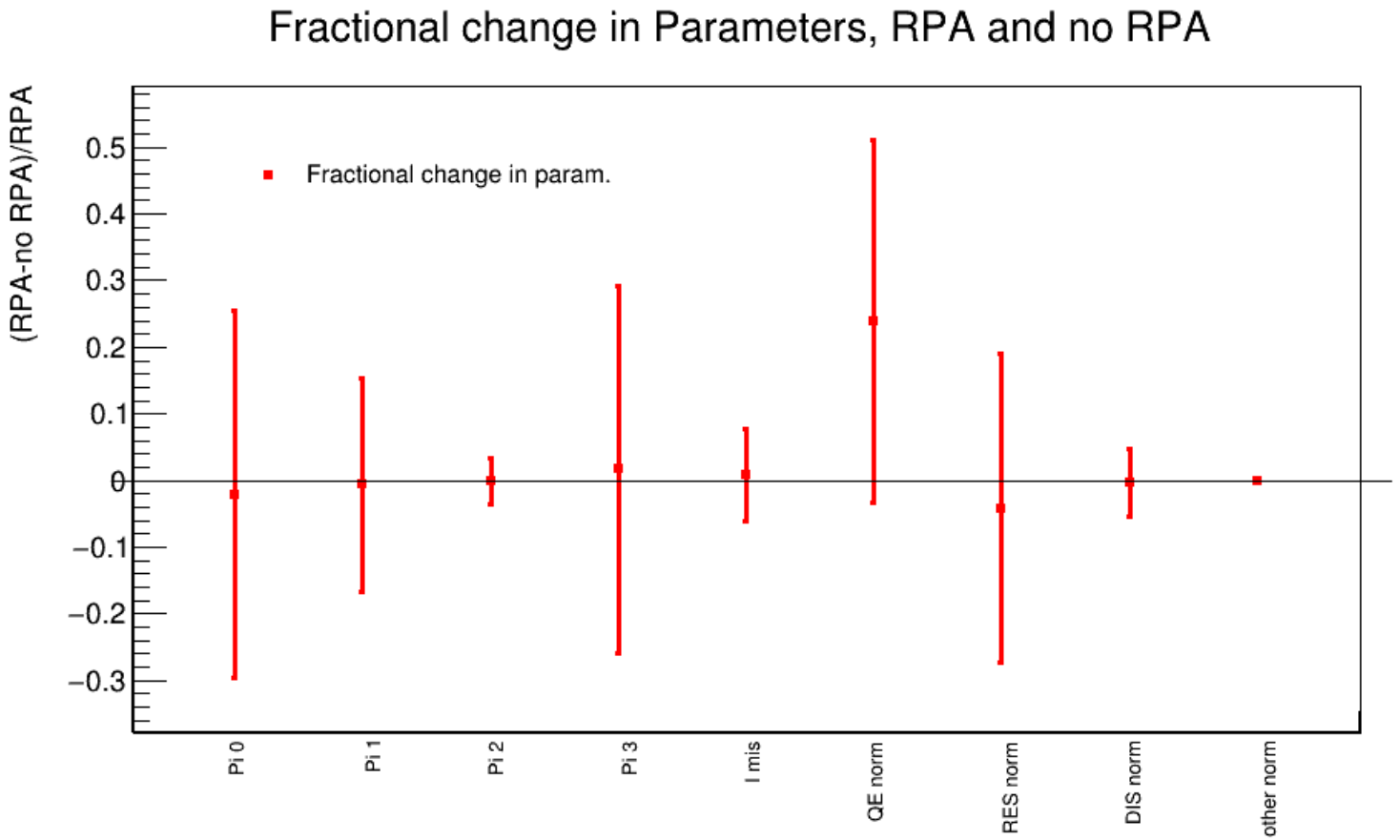
Testing the ND physics model

- Random Phase Approximation (RPA) weights are used in the simulation
- This models the effect of complex inter-nucleon interactions in atoms on the neutrino cross section in the Near Detector
- The overall effect of the change in potential is a suppression of quasi-elastic type neutrino interactions at low energy [3]



[3] Deka P, Singh J, Sarma N, Bora K. Uncertainties in the oscillation parameters measurement due to multi-nucleon effects at NOvA experiment. Nuclear Physics B. 2022 Oct 1;983:115903.

Parameter reaction to RPA weights



Summary

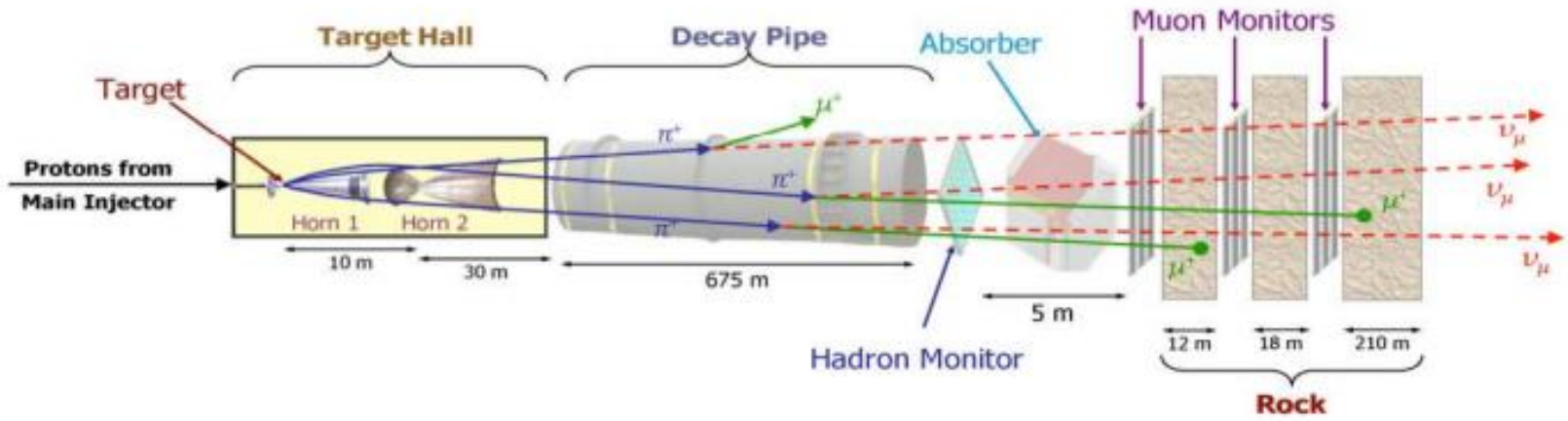
- We are trying to improve understanding the components of the NuMI beam simulation, due to its relevance in contemporary neutrino beams
- Improved hadron production momentum parametrisation
- Use effective parameters to separate Target, Focussing, and detector interaction effects during fit to data
- Parameter results shown to improve the MC of other MINOS run configurations
- Can hopefully be used to inform beam design + simulation

Invite Questions

Backup

Beam systematics

- Also incorporate effects associated with other beam components
- Some are fixed based on surveys – Target Z position
- Others are free parameters in the fit – Horn Current Miscalibration, target decay



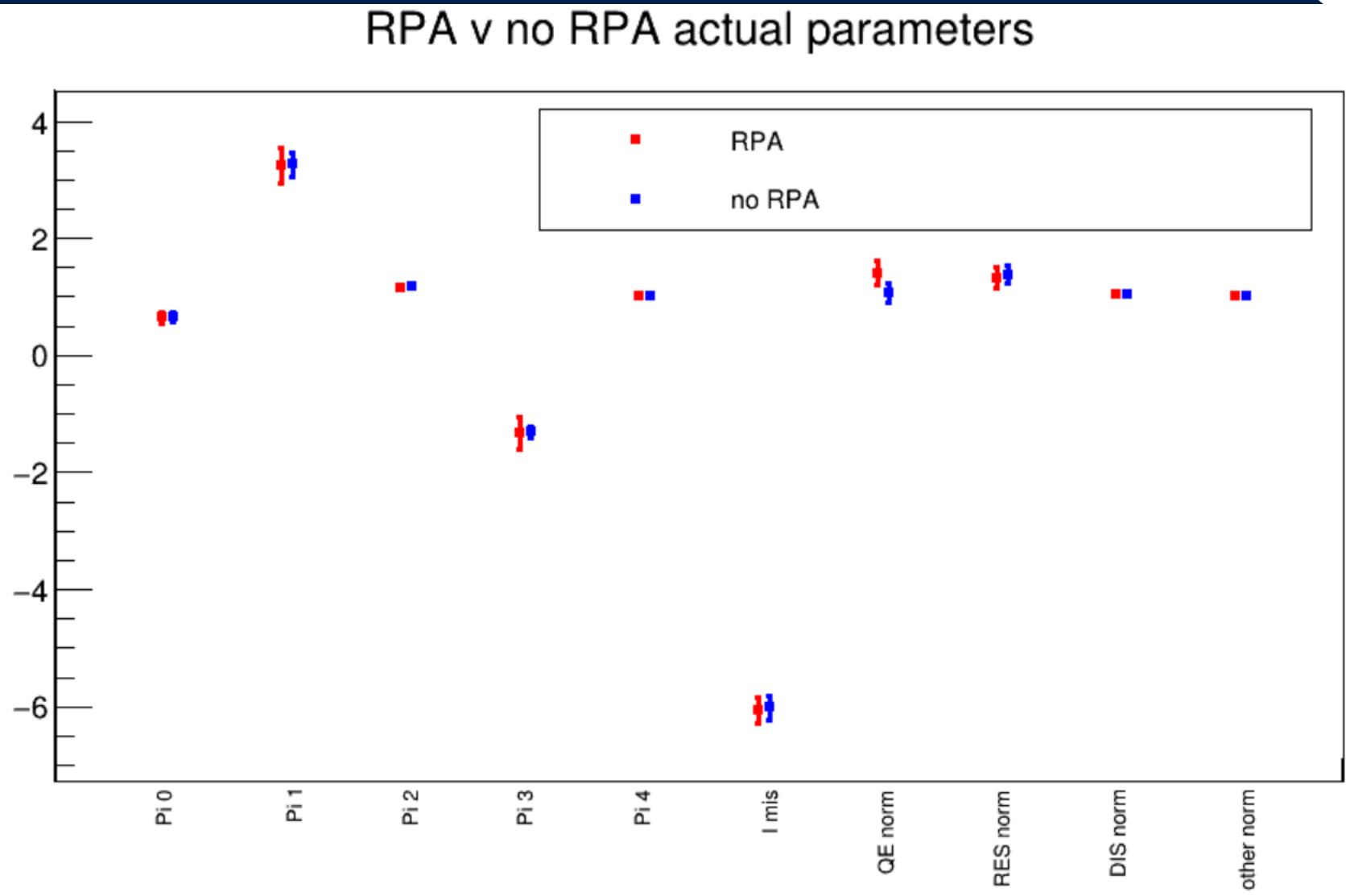
Schematic of the NuMI beam, reproduced from [2]

[2] P. Adamson et al., "The NuMI Neutrino Beam," Nucl. Instrum. Meth., vol. A806, pp. 279–306, 2016.

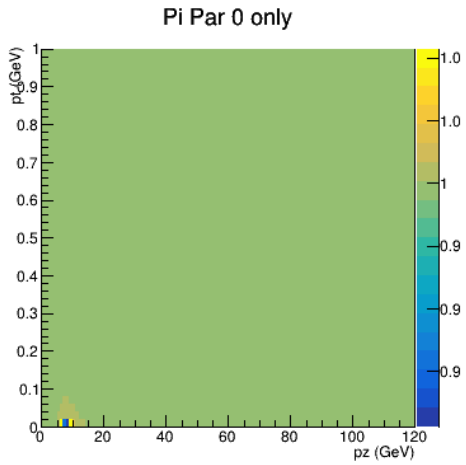
Parameters RPA v no RPA

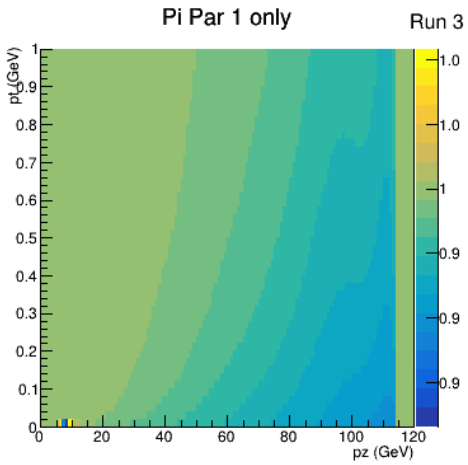
	RPA	No RPA
Pi 0 :	0.649422 +/- 0.092940	0.663331 +/- 0.086148
Pi 1 :	3.237669 +/- 0.303910	3.258092 +/- 0.213383
Pi 2 :	1.163347 +/- 0.028383	1.164678 +/- 0.013039
Pi 3 :	-1.335198 +/- 0.279268	-1.312645 +/- 0.088701
I mis :	-6.062433 +/- 0.215879	-6.017456 +/- 0.205155
QE norm :	1.401484 +/- 0.208088	1.065699 +/- 0.170377
RES norm :	1.327494 +/- 0.168526	1.383580 +/- 0.139345
DIS norm :	1.038960 +/- 0.035984	1.042975 +/- 0.016188
other norm :	1.000000 +/- 0.000000	1.000000 +/- 0.000000

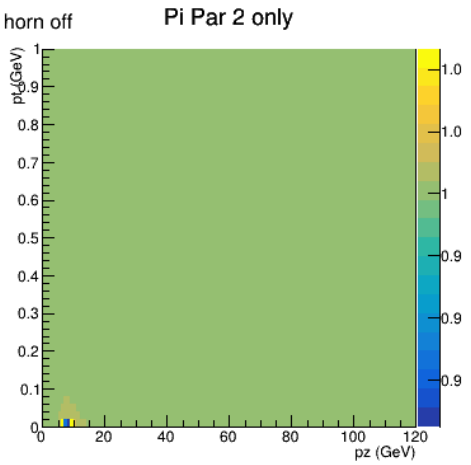
Parameters RPA v no RPA

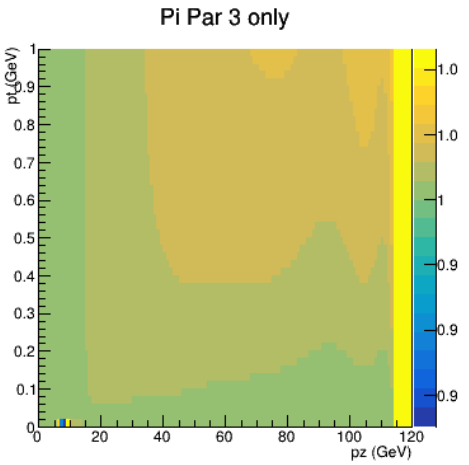


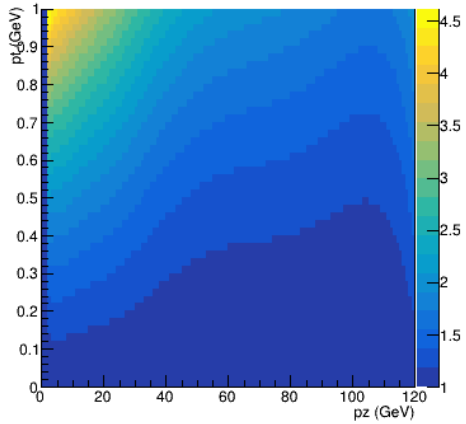
Run 3 + le horn off

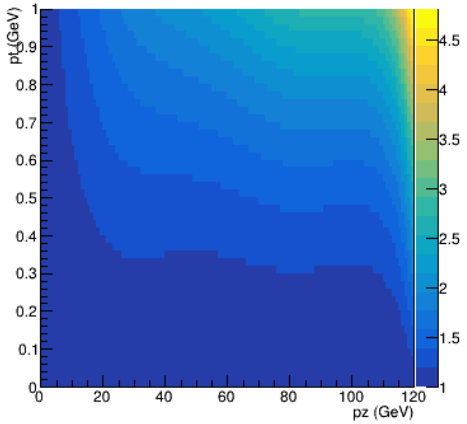


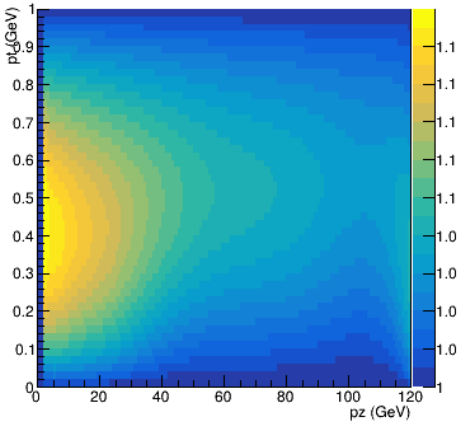


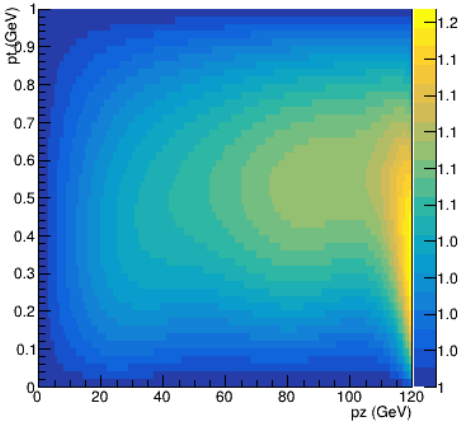




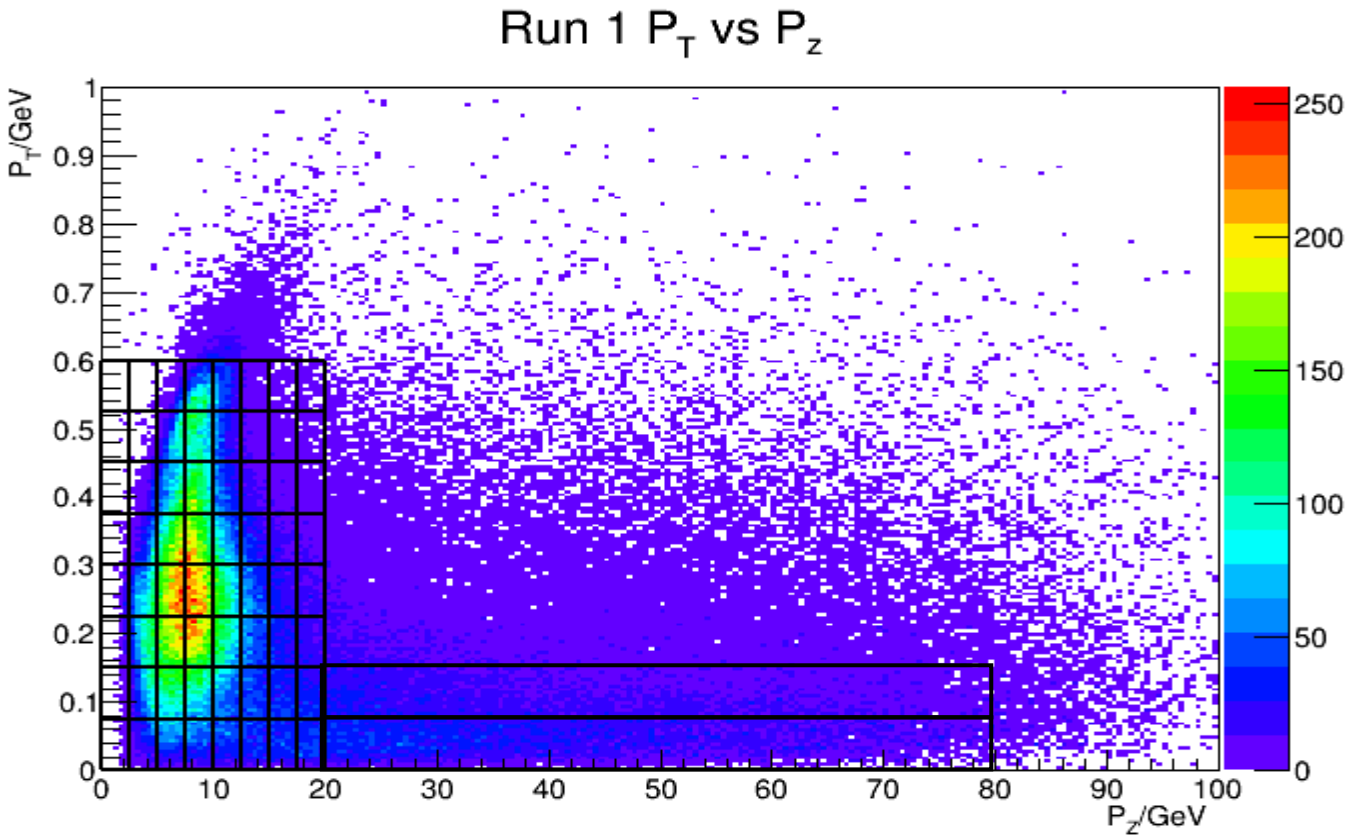






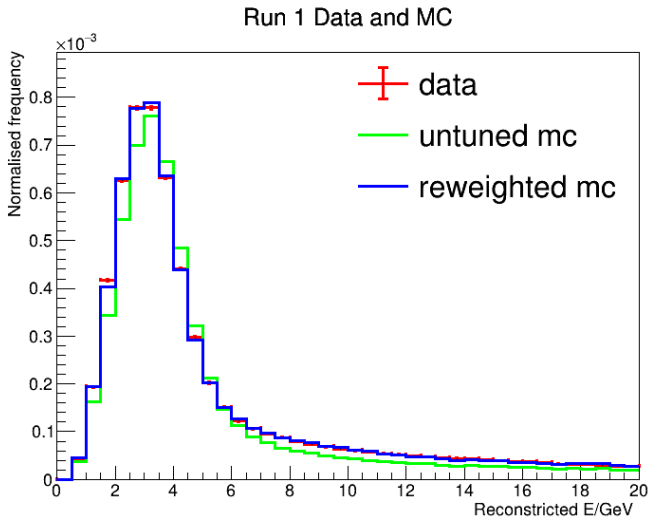


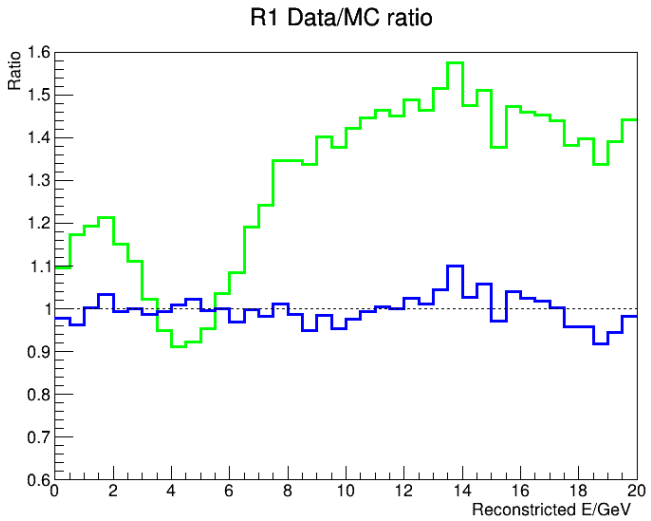
Pt Pz binning scheme

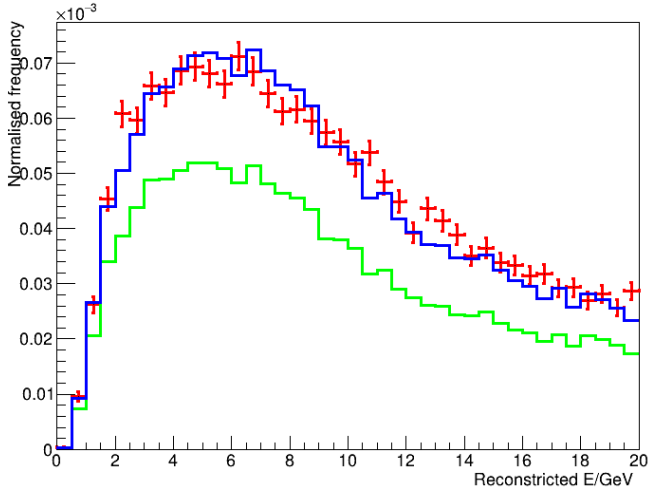


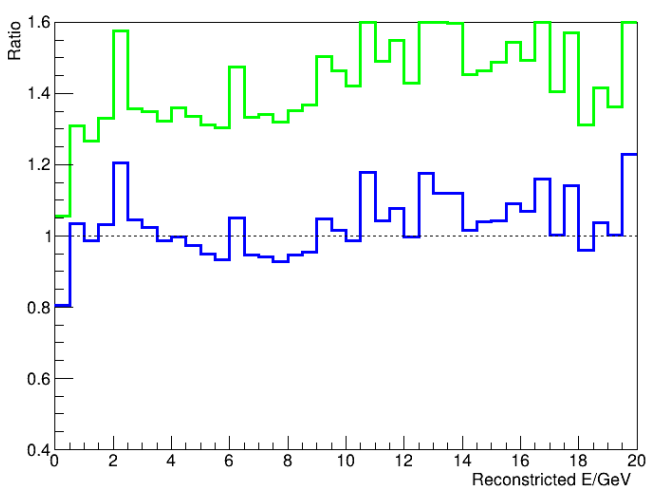
Typical Fit to data

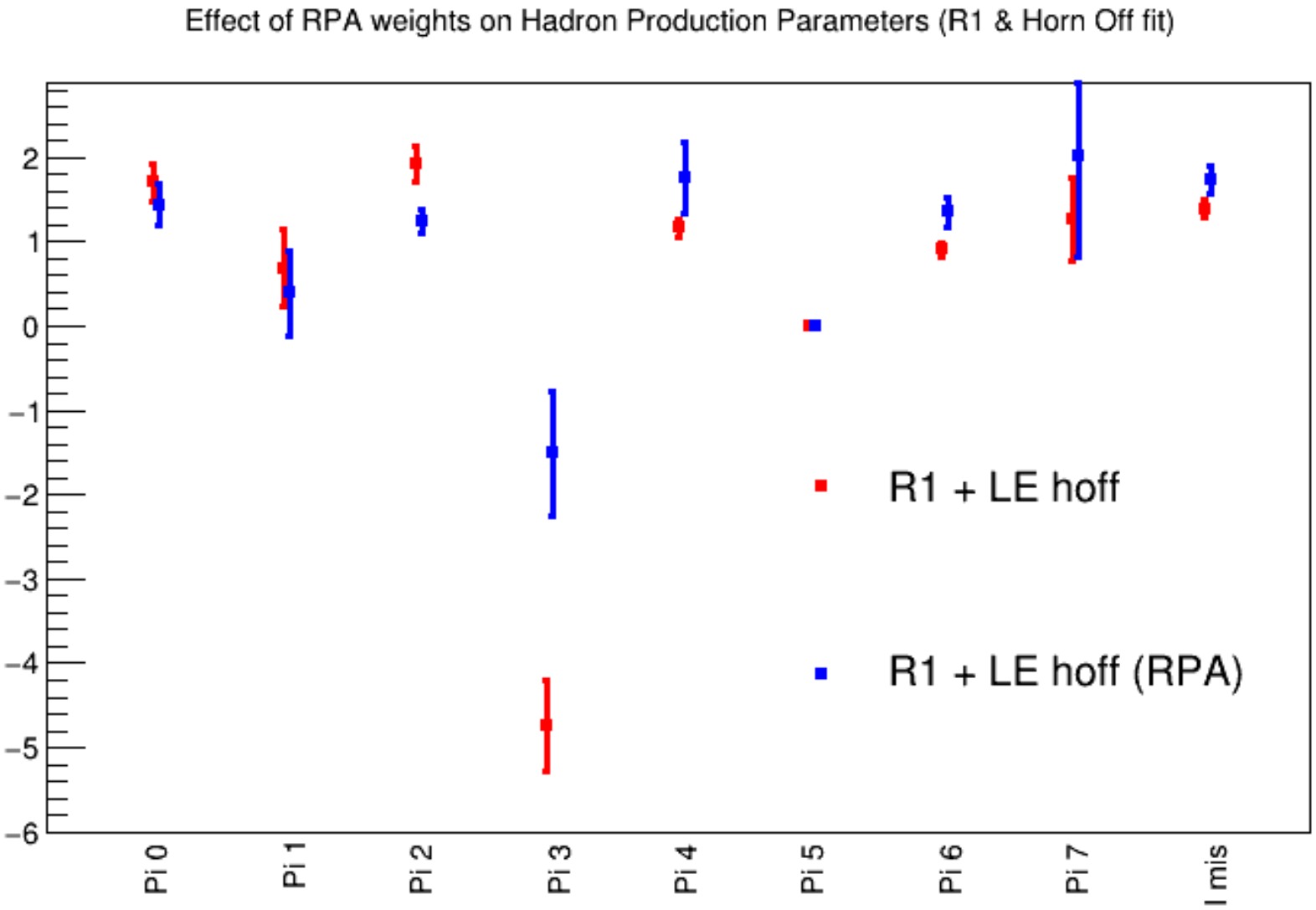
- Results of a joint MC fit to the data with Run 1 and horn off samples
- 8 hadron production parameters + 1 focusing parameter
- Minuit is used to fit MC to data using parameters





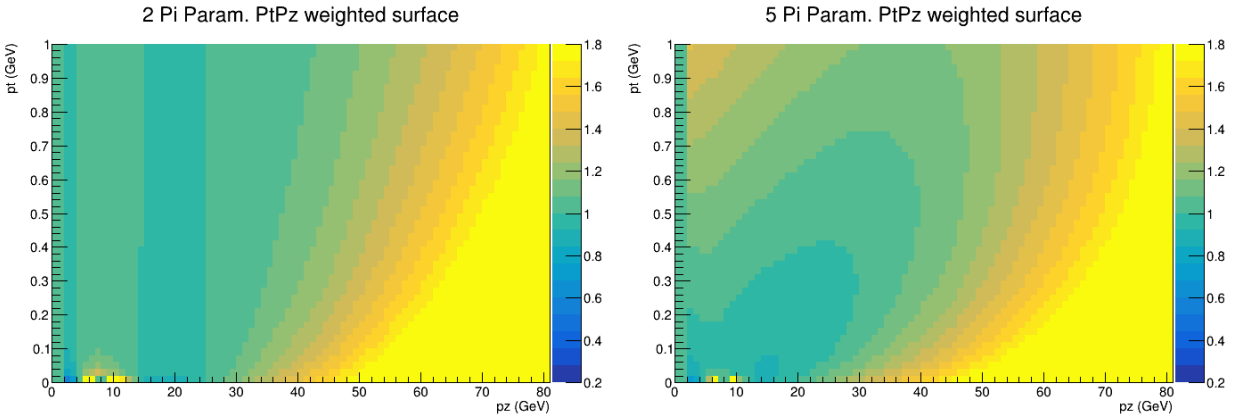


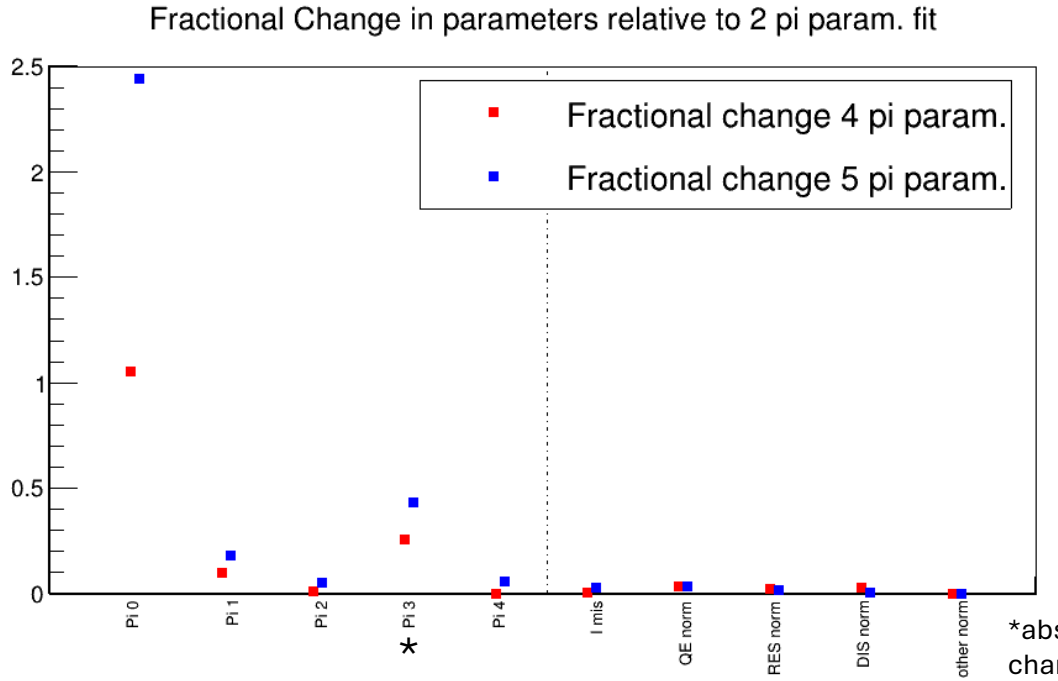



Effect of RPA weights on Hadron Production Parameters (R1 & Horn Off fit)
2
1
0
−1
−2
−3
−4
−5
−6
Pi 0
Pi 1
Pi 2
Pi 3
Pi 4
Pi 5
Pi 6
Pi 7
I mis
R1 + LE hoff
R1 + LE hoff (RPA)

Fit Results

- Normalisations of interaction types do not vary hugely as hadron production parameters are introduced, altering target weightings





*absolute change