Constraining the NuMI Flux

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Fermilab

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With thanks to:

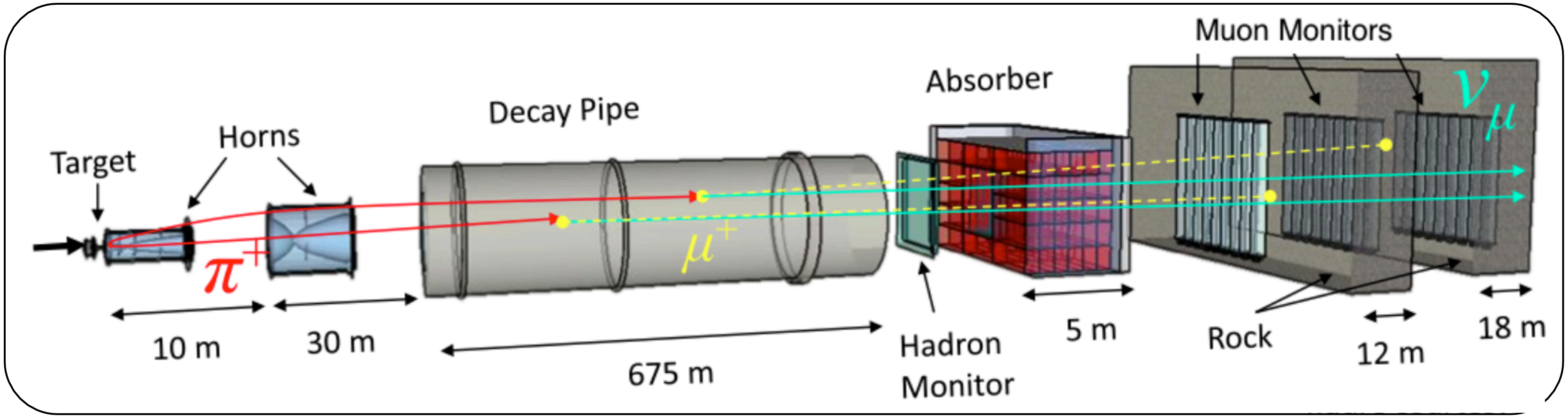
Bob Zwaska, Jeff Nelson, Anne Norrick, Leo Aliaga, Mike Kordosky

Outline

- Introduction to NuMI Beamline
- From Indirect to Direct Constraints
  – Monte Carlo Predictions
  – Hadron Production Constraints
  – In Situ Muon Flux Constraints
  – Neutrino Flux Measurements
    - Neutrino-electron Scattering
    - "Low-Nu" technique
  – Alternate Beam Configuration Data
- Scorecard

The best way to constrain?

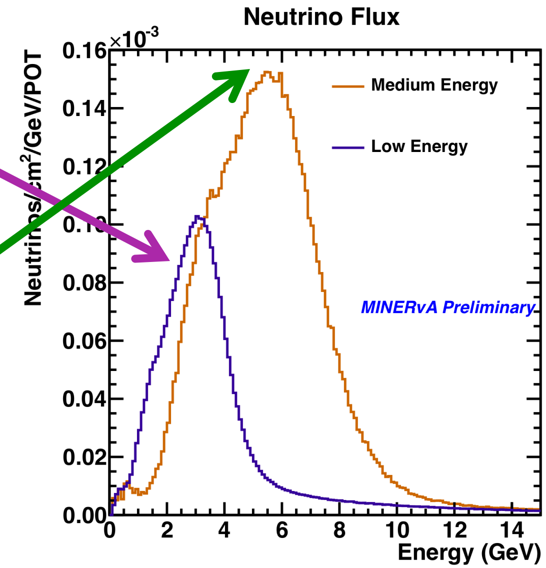
Simplifying the problem…

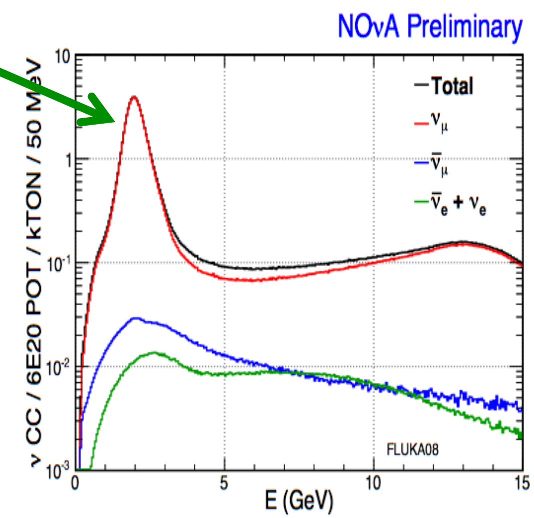


- Protons strike target, make pions and kaons
  - Need to understand hadron production for 120GeV protons on 2 interaction lengths of graphite
- Pions and kaons focused by magnetic horn
  - Need to understand and simulate focusing elements
- Pions and kaons decay in beamline
  - Those pions and kaons often reinteract in the beamline, need to understand tertiary production (production on Al, etc.)

Fluxes in NuMI Beamline

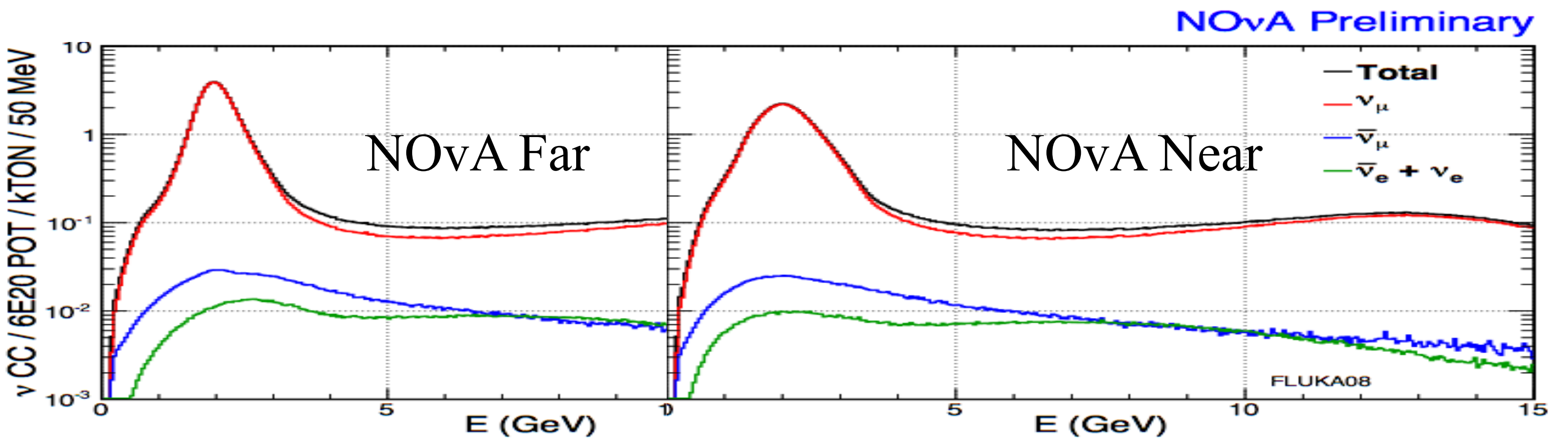
- Low Energy Run
  - 2005 through 2012
  - Neutrinos and Antineutrinos both
  - 95cm graphite target
  - “Moveable” target
  - 12×10^{20} protons on target
- Medium Energy Run
  - September 2013 and beyond
  - Neutrinos and Antineutrinos planned
  - 95cm graphite target
  - Non-moveable target
  - *2×10^{20} protons on target and counting…*



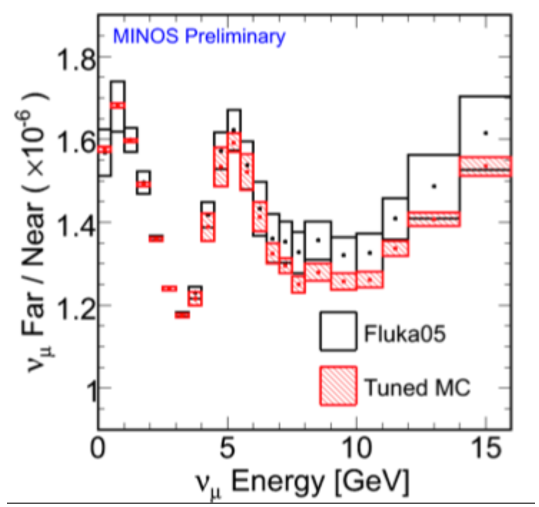


Near Flux, Far Flux

- Two-detector experiment mantra: “ Φ and σ uncertainties cancel…”
- Far and Near Fluxes are not identical, even without oscillations



- Experiments measure flux x resolution x σ…
- near and far fluxes change because of oscillations
- This is why we need good cross section experiments!

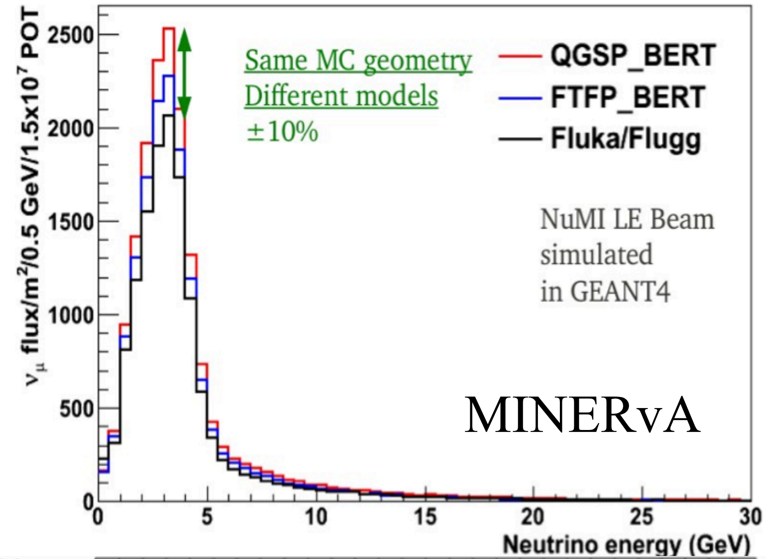


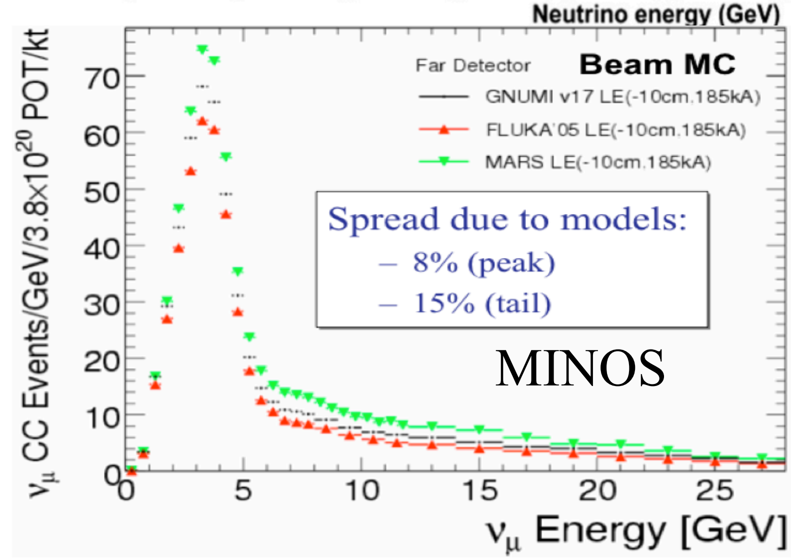
MINOS,
LE Beam

MONTE-CARLO ONLY CONSTRAINTS OF FLUX

Hadron Production Simulations

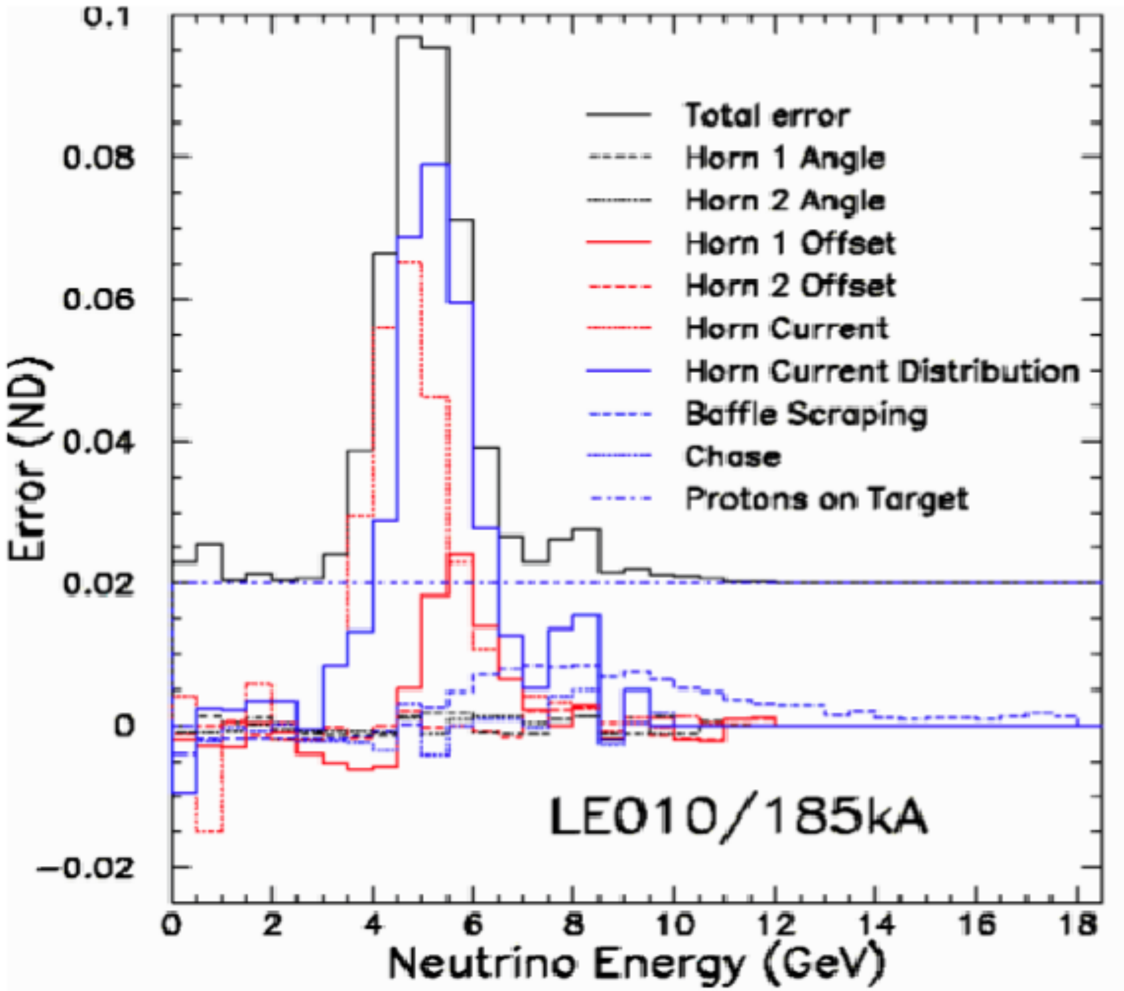
- GEANT-4 Based Model
  - Used by MINERvA
  - Different hadron production models inside GEANT:
    - FTFP, QGSP, BERTini models
- FLUKA
  - Used by MINOS and MINOS+
  - FLUKA08, transitioning to FLUKA11 *[www.fluka.org]*
  - Geometry defined through GEANT framework
- Different Hadron Production & Cascade Models provide early estimates for flux uncertainties





Flux Uncertainties from Beam Focusing

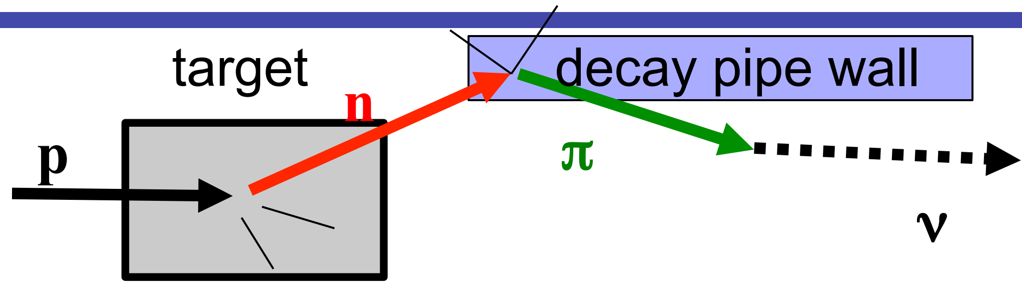
- Different uncertainties in beamline geometry and parameters produce different possible changes in expected spectrum
- Focusing errors tend to be on high side of focusing peak
- Overall level also uncertain: proton counting not trivial



Ref: Z. Pavlovich, PhD thesis, UT Austin 2008

HADRON PRODUCTION DATA

Incorporating Hadron Production Data



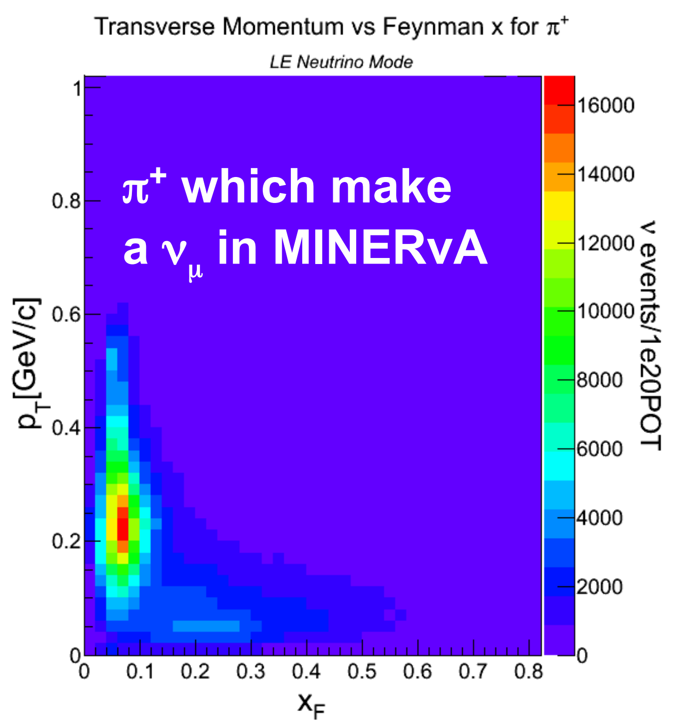
- Cascade leading to ν is tabulated at generation. Save kinematics & material
- In analysis, interactions reweighted as σ(data)/σ (MC)
- Includes correction for beam attenuation in the target.

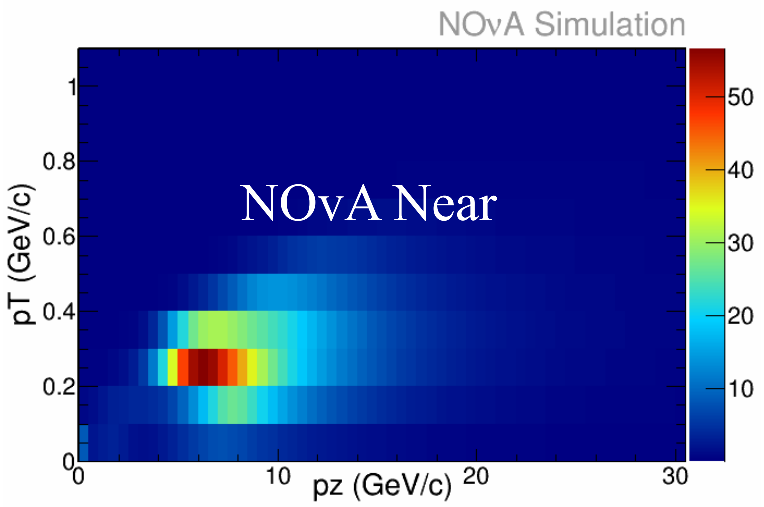
Datasets Used by MINERvA:

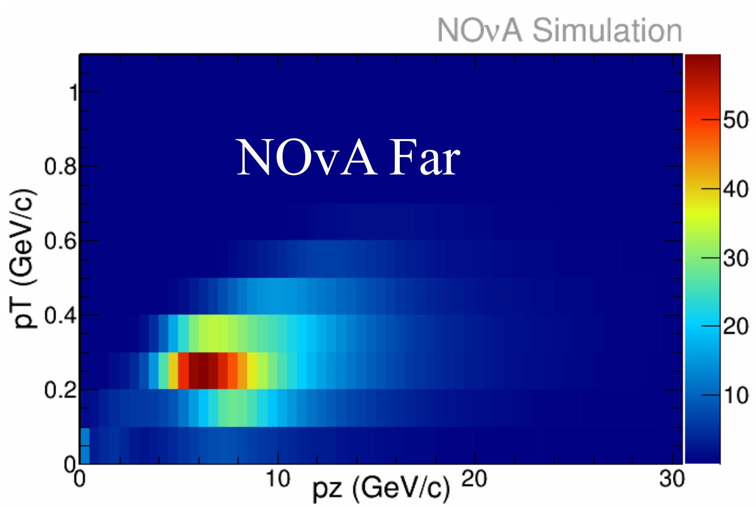
- NA49 pC @ 158 GeV
  - $\pi^{\pm}$ production for xF < 0.5 *[Eur.Phys.J. C49 (2007) 897]*
  - $K^{\pm}$ production for xF < 0.2 *[G. Tinti Ph.D. thesis]*
  - π production for xF<0.9 [*Eur.Phys.J. C73 (2013) 2364]*
- MIPP pC @120 GeV *[A. Lebedev Ph.D. thesis]*
  - K/π ratio + NA49 extends kaon coverage to xF<0.5
- Weights applied for 12 < $p_{incident}$ <120 GeV.
  - Data cross-section scaled using FLUKA
  - Checked by comparing to NA61 pC → $\pi^{\pm}$ X at 31 GeV/c *[Phys.Rev. C84 (2011)034604]*
- Interactions on Al, Fe, He and Air treated as if on C

Which pions matter?

- NOvA Near and Far Detectors: peak flux at about x_F=0.05-0.07 (6-8GeV)
- MINERvA and MINOS ND, Low Energy beam: peak at x_F=0.06







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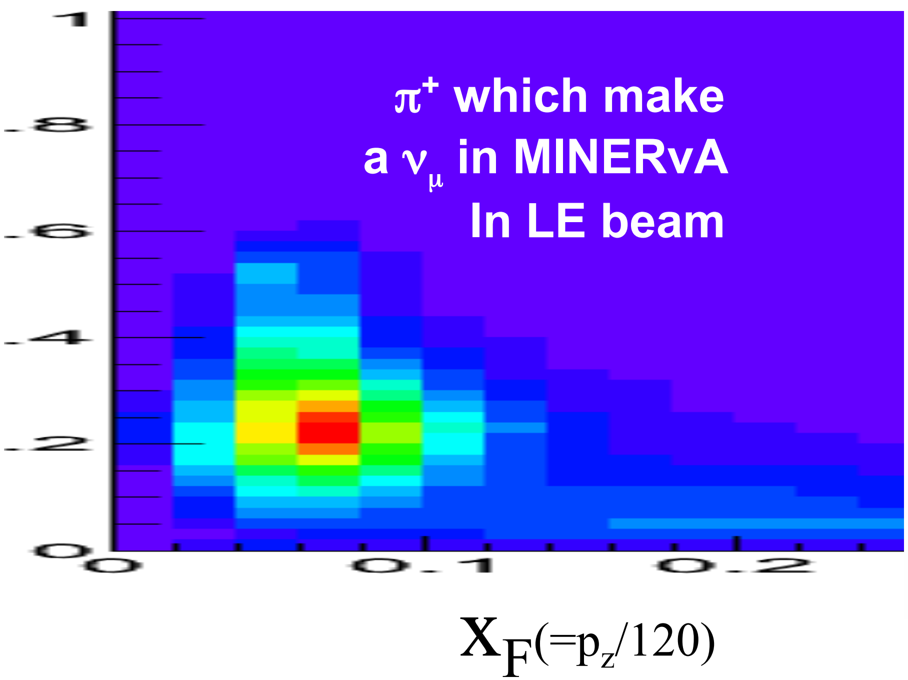
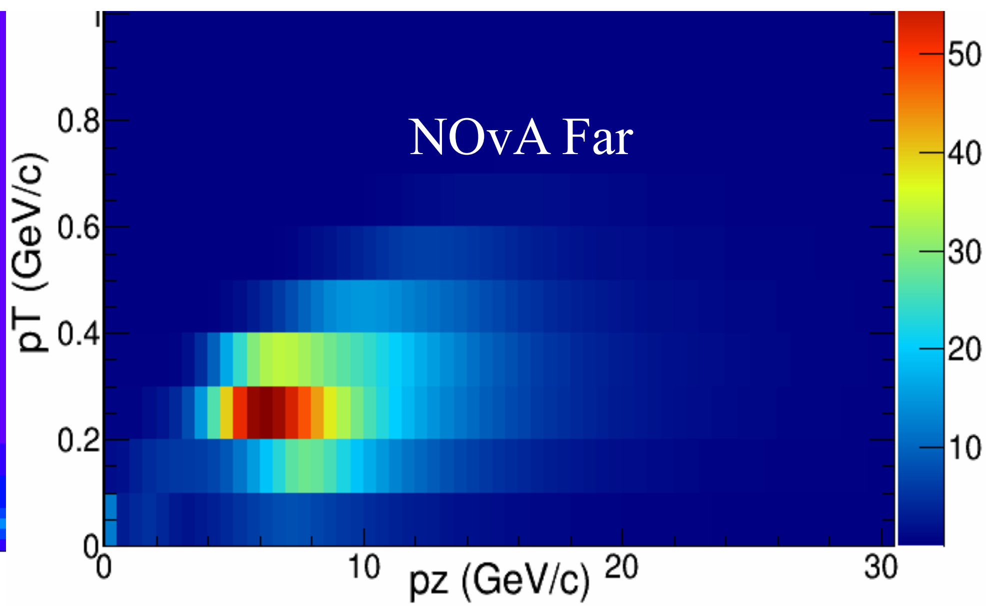
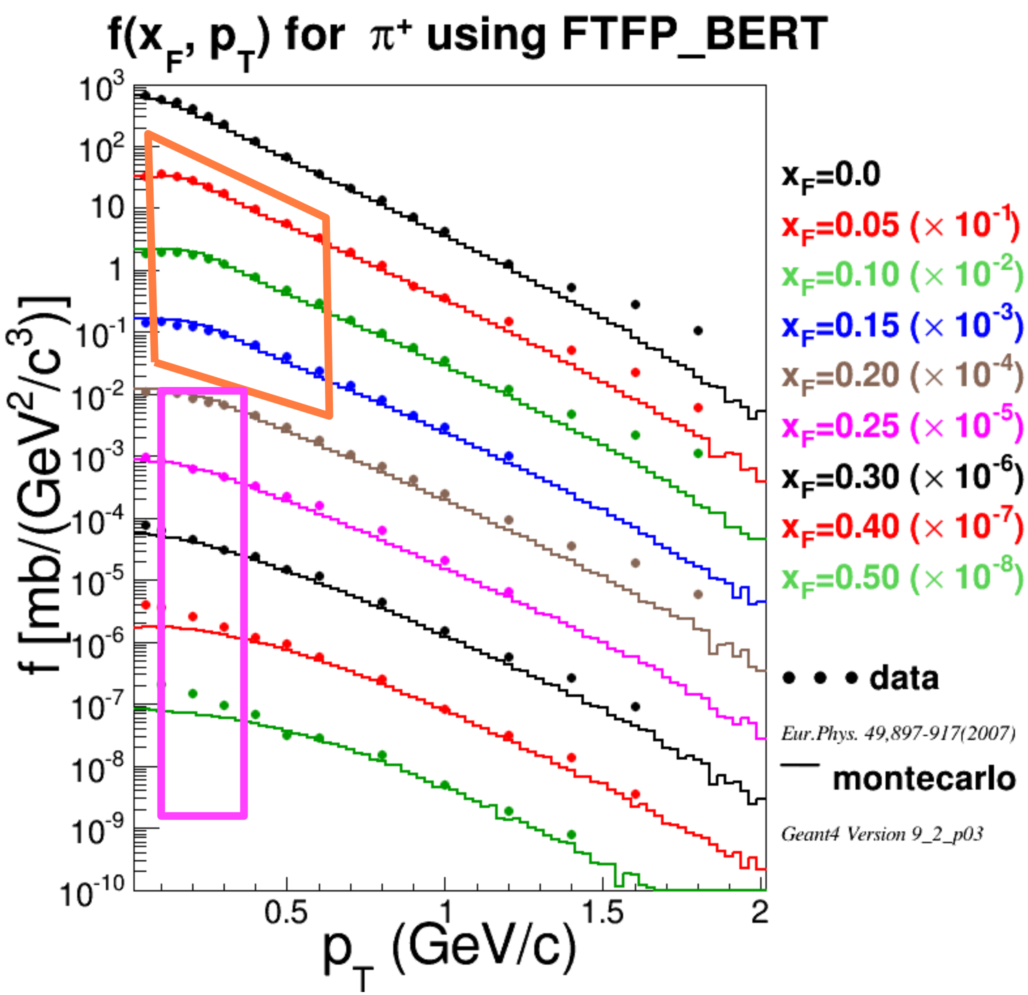
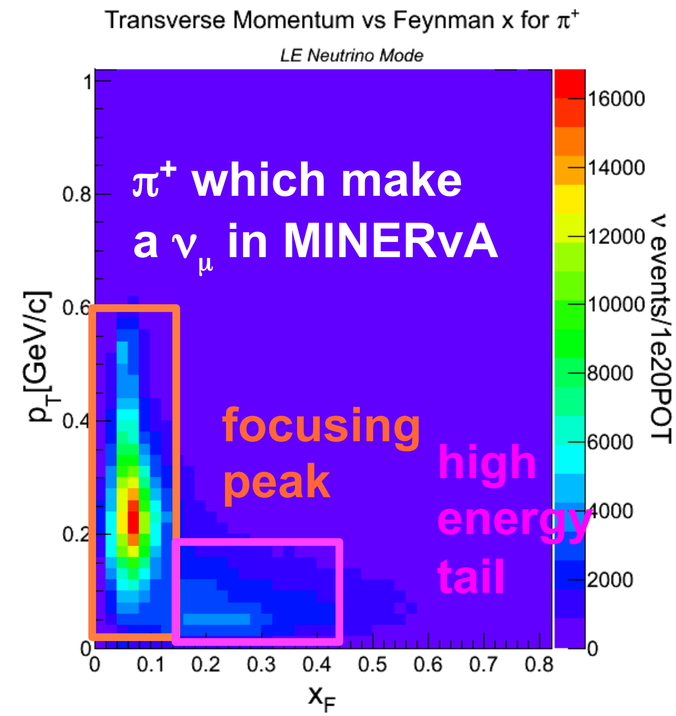




NA49 for pC->π^+X

$f(x_F,p_T) = E\, d^3s/dp^3$ = invariant production cross-section





Uncertainties
7.5% systematic
2-10% statistical

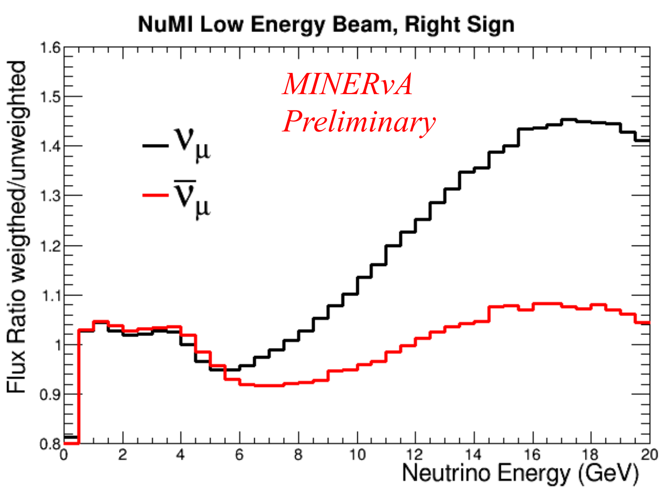
Reweighting Summary

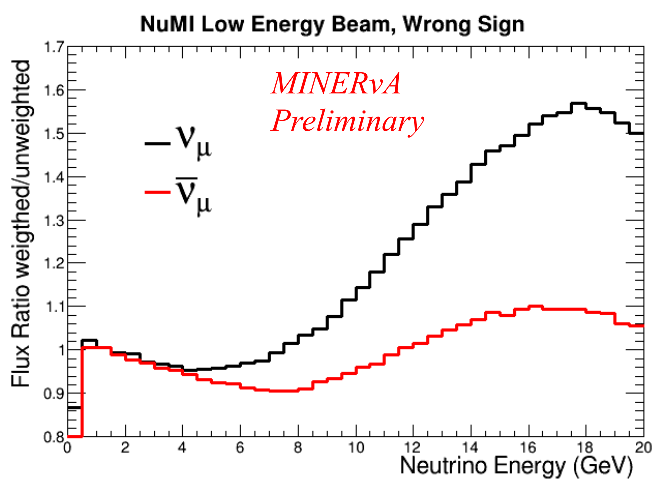
- What MINERvA does reweight:

neutrino energy	average # interactions / event	% interactions reweighted
3-4 GeV	1.362	75.18%
15-16 GeV	1.303	71.93%
30-31 GeV	1.30	64.0%
0-30 GeV	1.463	69.62%

- What MINERvA does not reweight:

produced particle	**Uncon-strained**	**all**
p	0.108	0.236
$\pi^{\pm}$	0.015	0.877
$K^{\pm}$	0.002	0.031
K_S K_L	0.028	0.028
n	0.049	0.049

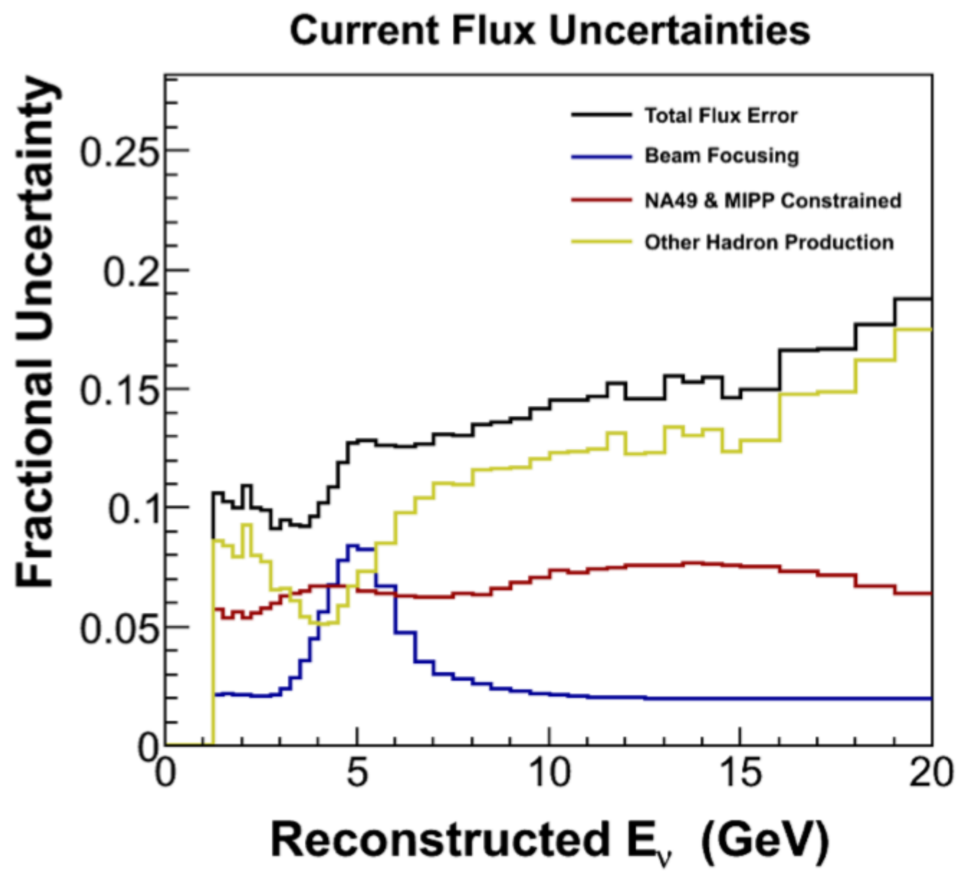




Current Status of Flux Uncertainties

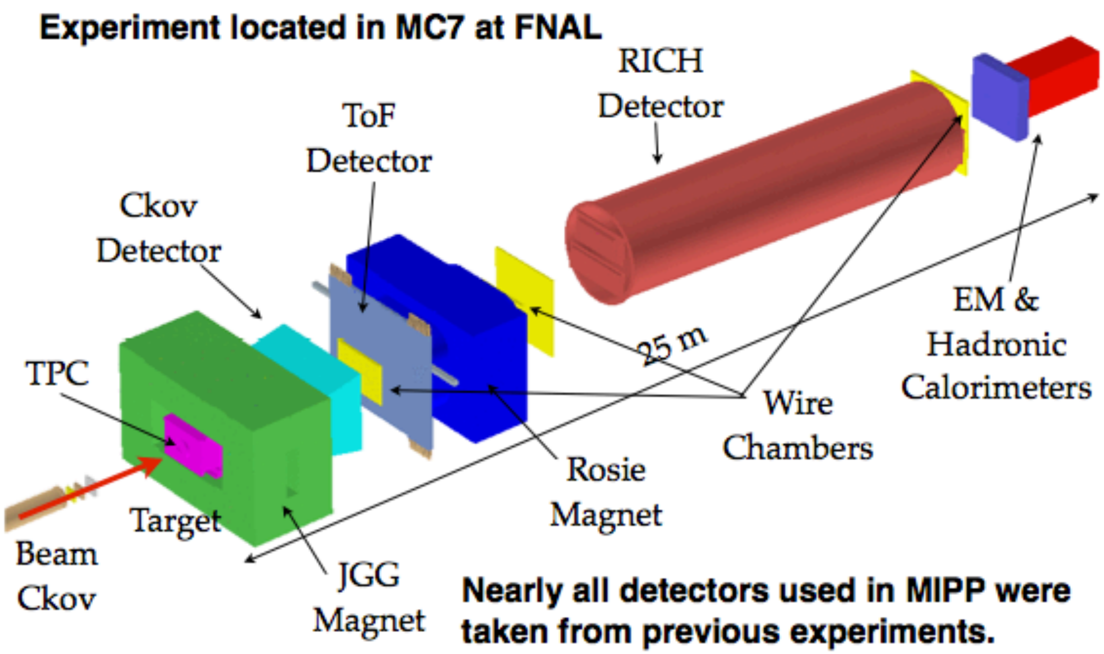
- Current uncertainties based on NA49 and model comparisons where no data exist
- More measurements (esp. MIPP thick target measurements) should help
- This implies that all hadron production measurements give consistent predictions

- ***Enter MIPP…***



MIPP π/K ratio only

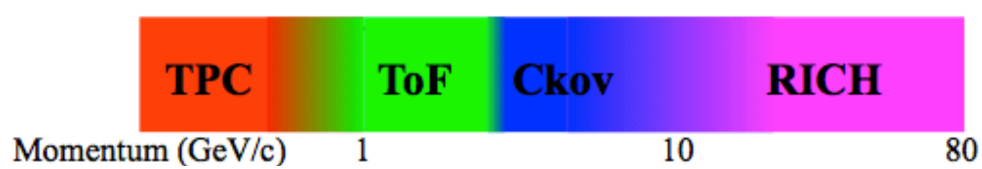
MIPP for pC$\rightarrow\pi^+X$



- Goal: collect comprehensive hadron production cross-section data set with particle id using various beams and targets (thick and thin).
- These data may then be used to tune / validate MC event generators.

- Full acceptance spectrometer
  - Two analysis magnets deflect in opposite directions
  - TPC + 4 Drift Chambers + 2 PWCs

- Designed for excellent particle ID (PID) separation (2-3σ)



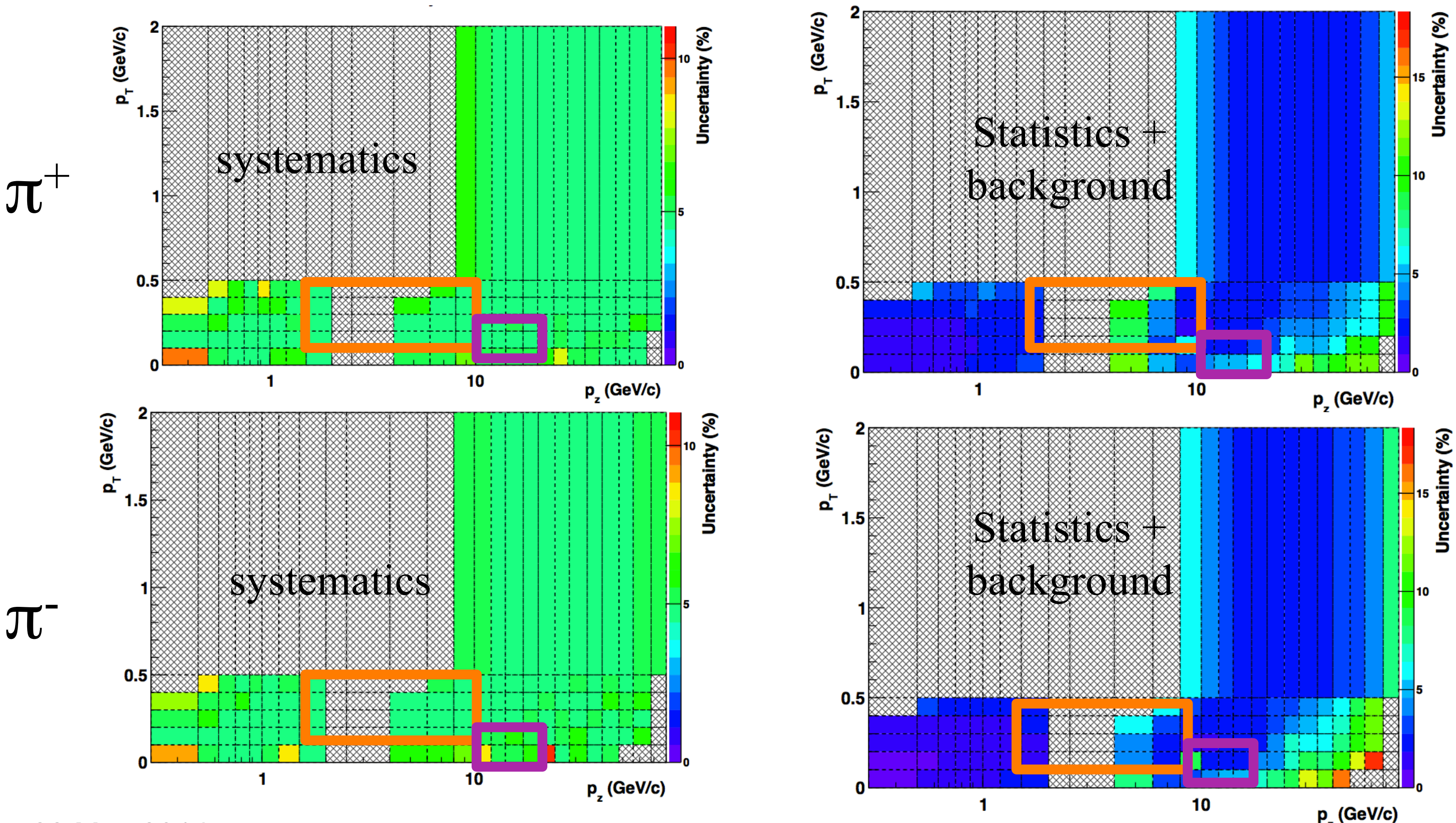
J. Paley, FNAL JETP seminar 4/8/14

MIPP Sensitivity

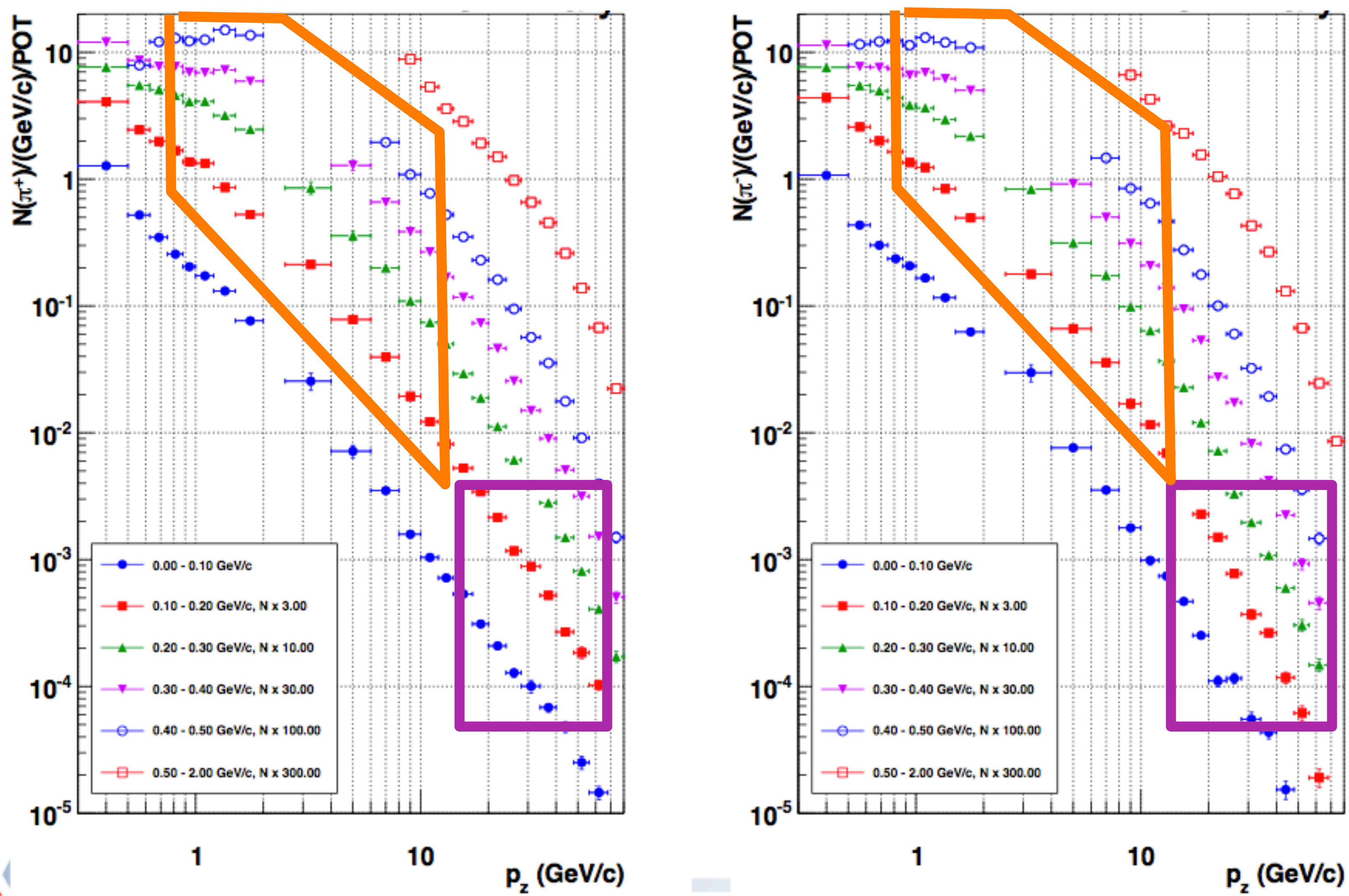
NuMI Low energy Focusing peak

NuMI Low energy “high energy tail”

- Statistical: mostly a few % Systematic: 5-7%



MIPP Results and NuMI Acceptance

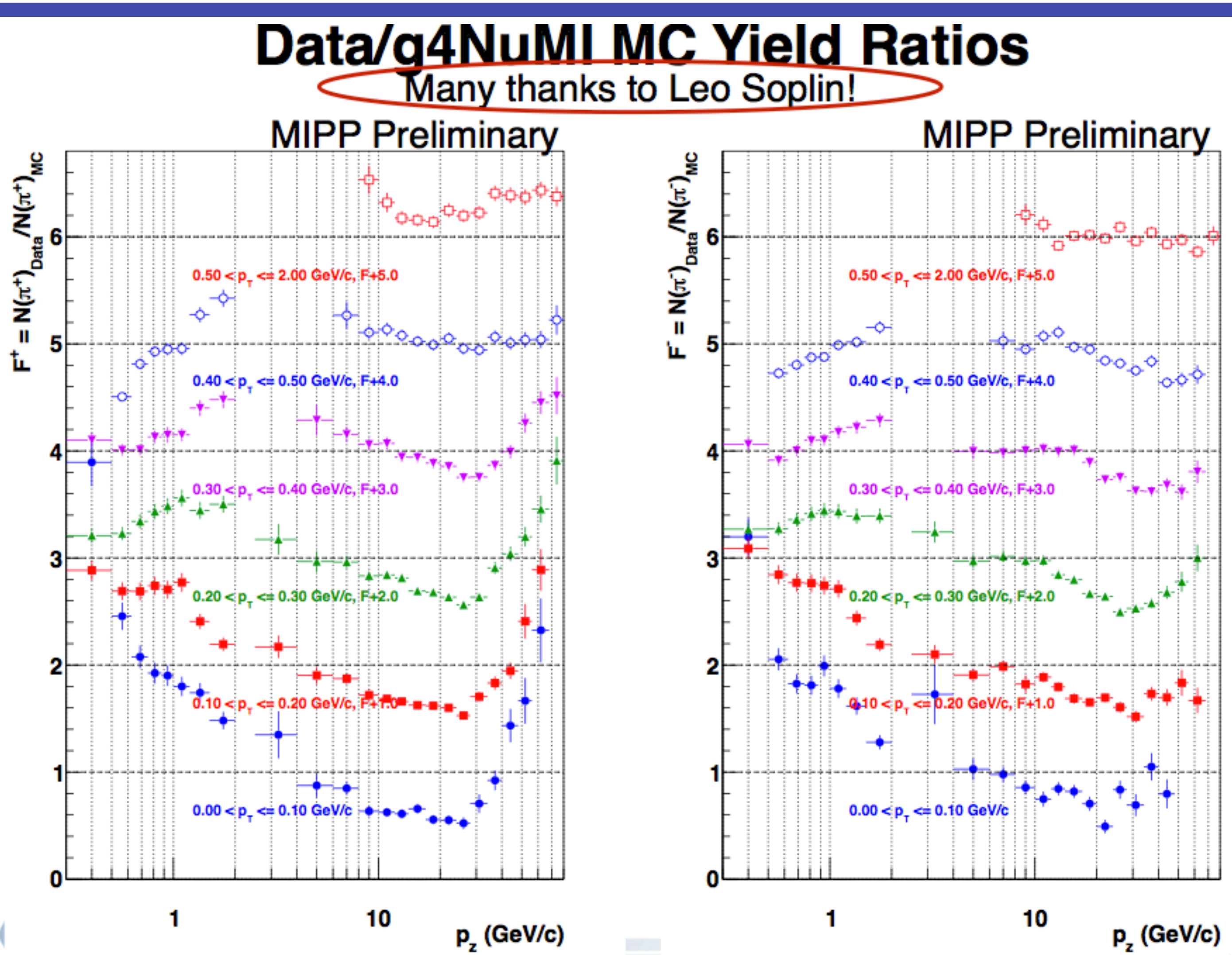


NuMI Low energy Focusing peak

NuMI Low energy "high energy tail"

Ref: J.M.Paley, M.D.Messier, R.Raja et al, arXiv: 1404.5882

MIPP comparison to GEANT4



NA61 measurements of NuMI Target

- Will hear much about NA61 from Alicia Marino
- Work underway to get NuMI target in this hadron production experiment also
- Potential Advantages of NA61 data set over NA49 or MIPP data:
  - Will be able to tie thin and thick target together in same experimental apparatus (lower systematics on measuring effects of tertiary interactions)
  - Improved kinematic coverage

IN SITU MUON FLUX CONSTRAINTS: SEE ALYSIA MARINO’S TALK

IN SITU NEUTRINO FLUX CONSTRAINTS

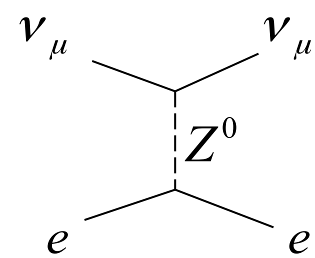
NEUTRINO-ELECTRON SCATTERS
“LOW NU” FLUX

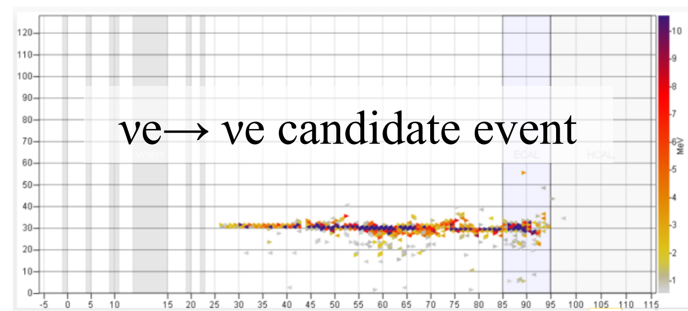
Constraint on Total Flux

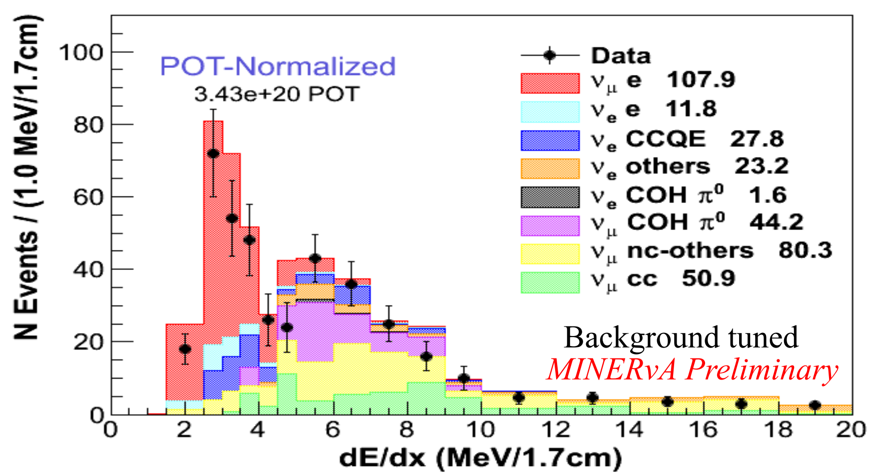
- Neutrino-electron scattering provides theoretically clean measure of total flux
- Signal at MINERvA relatively easy: single electron moving in beam direction
- Catch: process is 1/2000th the size of neutrino-nucleon scattering
- Need good angular resolution and electron ID
- Use dE/dx at beginning of track candidate to isolate electrons from photons

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$$





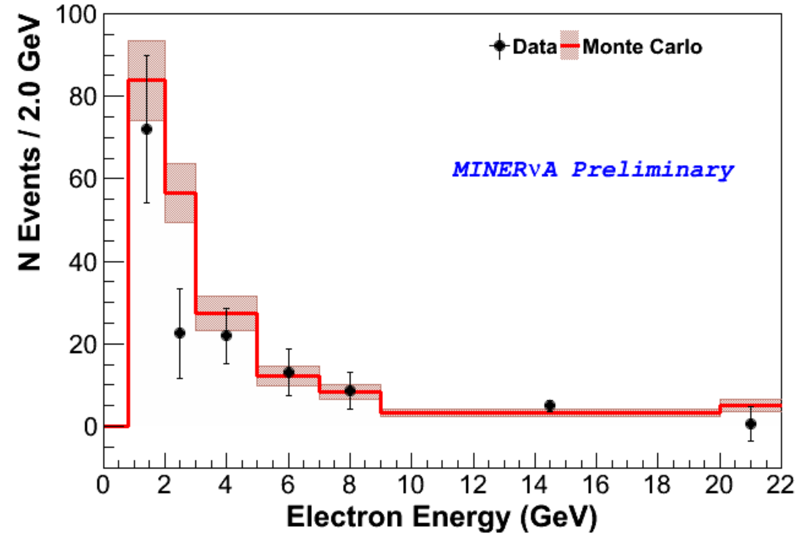


Neutrino-Electron Scattering Low and Medium Energy Beam

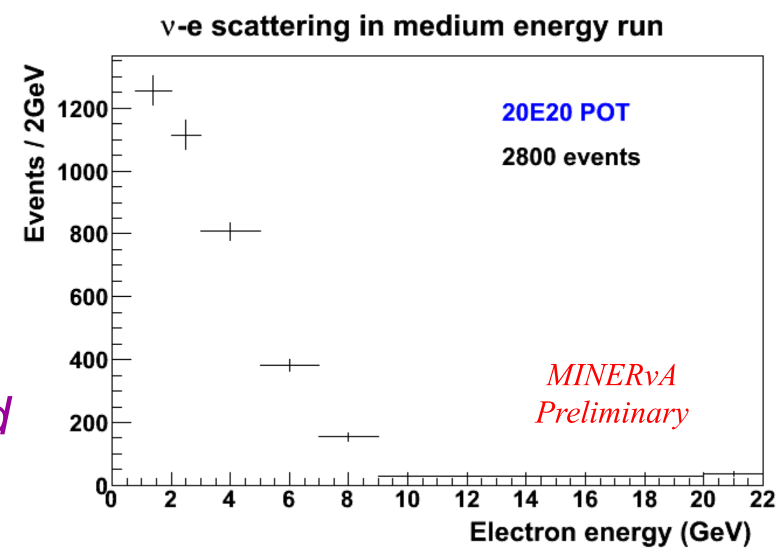
- Low Energy result:
  - ν-e scattering events after background subtraction and efficiency correction:

123.8 ± 17.0 (stat) ± 9.1 (sys)
total uncertainty: 15%

  - Prediction from Simulation: 147.5 ± 22.9 (flux)
    - Flux uncertainty: 15.5%



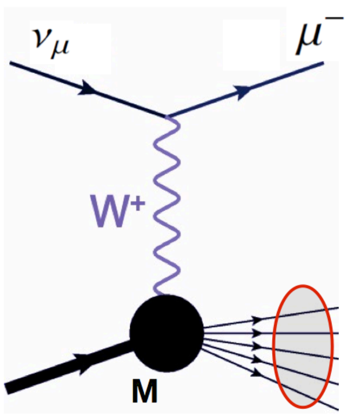
- Medium Energy Projection:
  - Expect statistical uncertainty of ~2%
  - Systematic uncertainty on this measurement is now 7% → 5% “easily”



- *Could become the most well-constrained flux in history of neutrino beams*

Low-ν flux Technique: another standard candle

- Use Charged Current Events:



Differential cross section can be expressed as:

$$\frac{d\sigma}{d\nu} = A\left(1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{2E^2}\right)$$

ν : energy transferred to the hadronic system

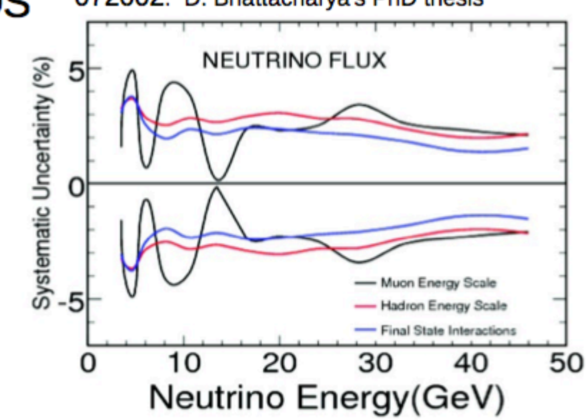
E : neutrino energy

A, B, and C: integrals over structure functions (on target material!)

Normalize to high energy inclusive cross section

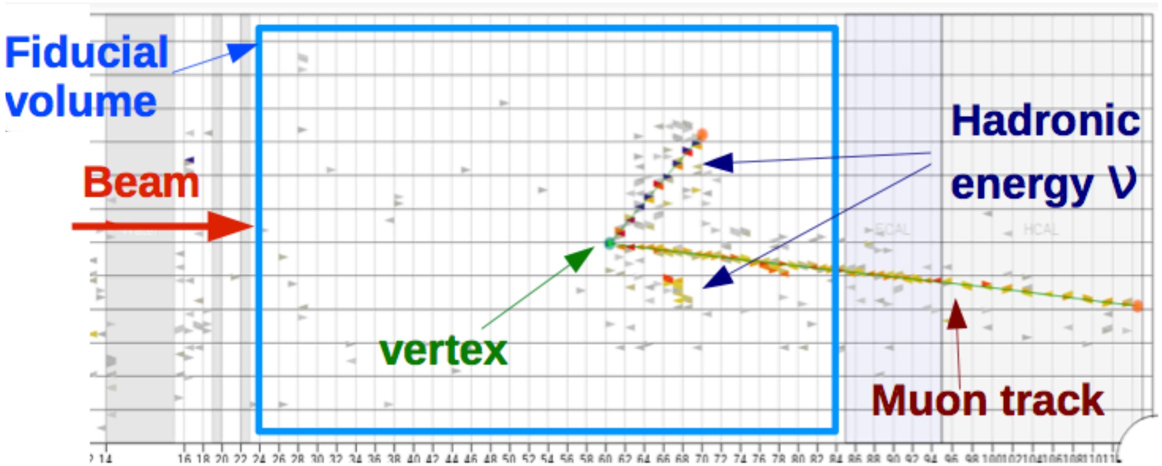
- Previous measurement from MINOS
  - Neutrino: 3~50 GeV
  - Flux uncertainty: 5%~8%
    - Dominated by systematic uncertainties at low energy
    - Dominated by statistical uncertainty at higher energies

MINOS Collaboration, Phys. Rev. D 81, 072002. D. Bhattacharya's PhD thesis



L. Ren, APS 2014

Low-ν flux Technique, II

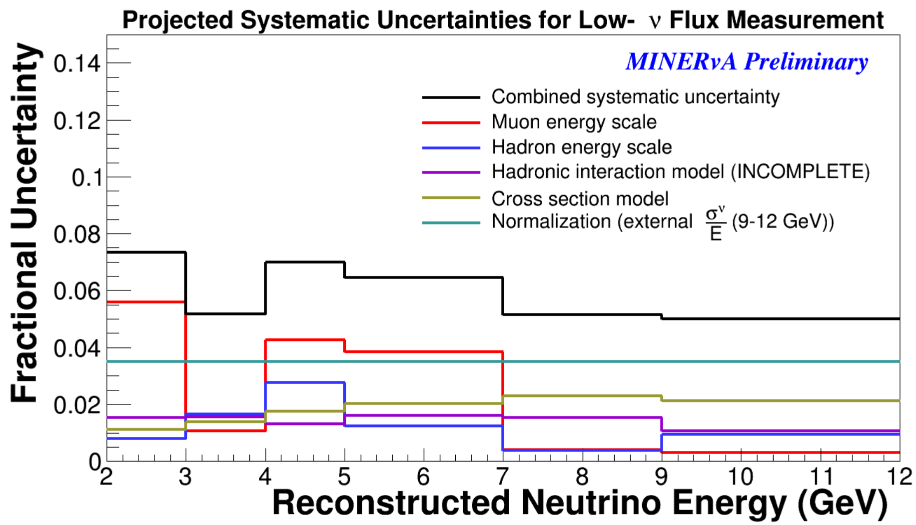


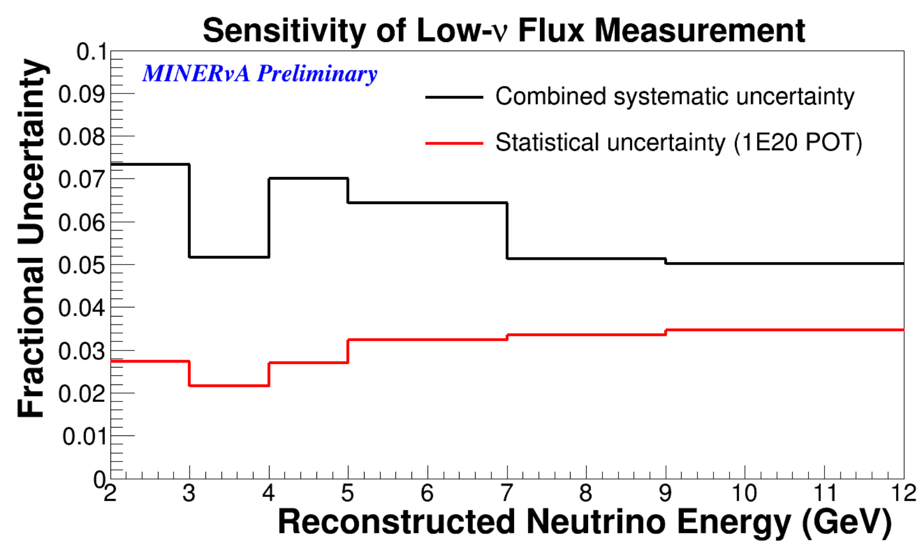
- MINERvA plan for low-ν analysis:
  - Take advantage of totally active detector technology, lower ν cuts
  - Will run this analysis on neutrino and antineutrino beams
  - Can also use this technique on rui with modified beam configurations
  - Normalize to NOMAD σ_{tot} from 9-12GeV on Carbon (±3.6%)

- Inclusive sample:
  - Vertex within fiducial volume
  - MINOS-matched track with negative charge
- Flux sample:
  - 2<E<3 GeV, **ν <0.3 GeV**
  - 3<E<7 GeV, **ν <0.5 GeV**
  - 7<E<12 GeV, **ν <1 GeV**

Expected Uncertainties in MINERvA low-ν Analysis

- Detector Energy scales
  - Muon energy (range and curvature both have associated uncertainties)
  - Hadron energy response of detector
- GENIE Cross Section Model
  - Comes in for corrections vs ν in extrapolation from high energy
  - Also comes in because of detector modeling: muons need to be accepted in MINOS near detector
  - Some FSI uncertainties not yet incorporated here
- GEANT4 Detector response model
  - Have to consider uncertainties in pion, neutron interaction cross section, formation zone effects, etc.

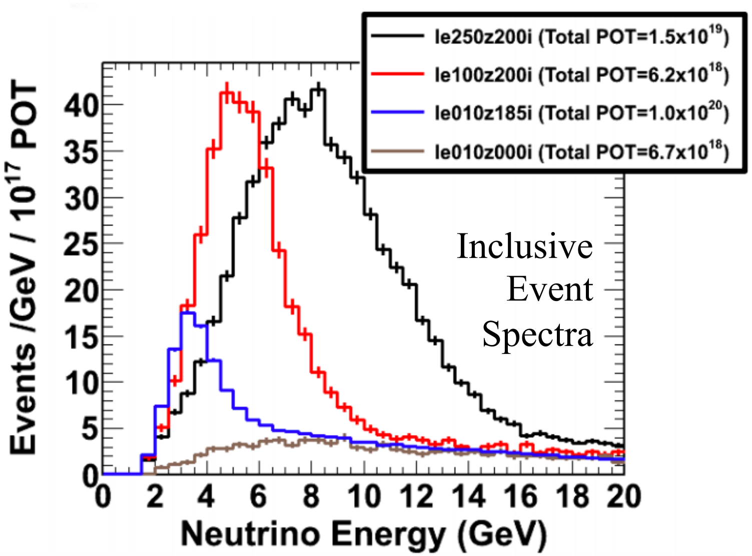


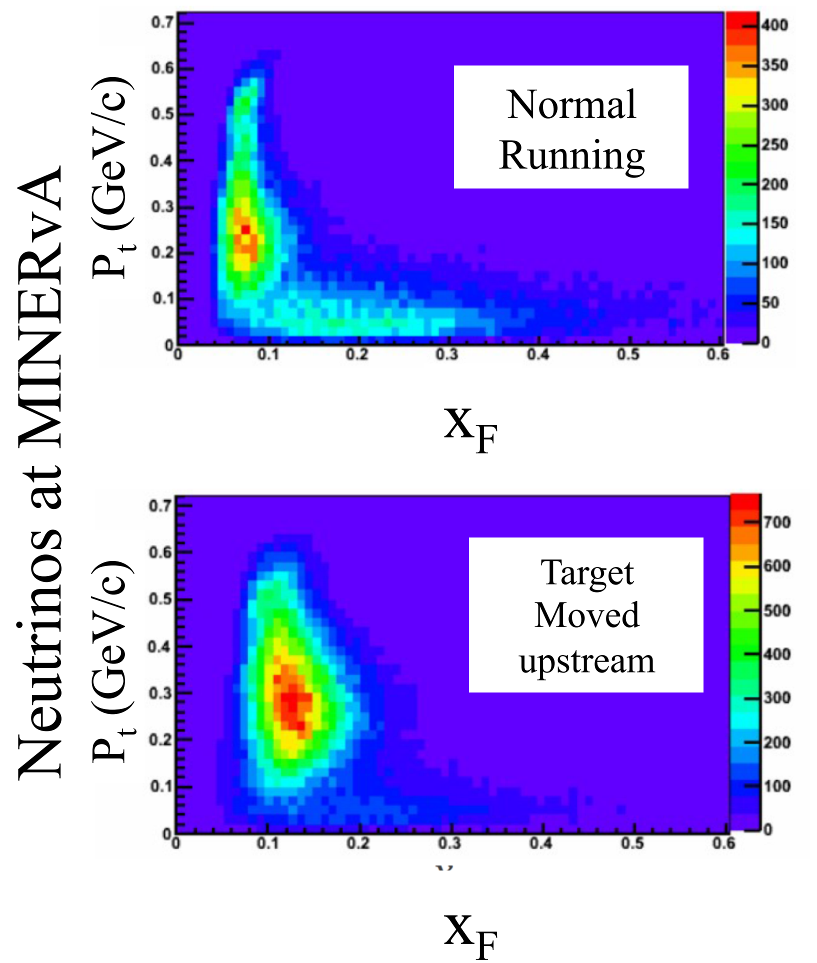


“SPECIAL RUNS” FOR FLUX DETERMINATION

Getting to Neutrino Energy Spectrum: Special Runs to Understand Flux

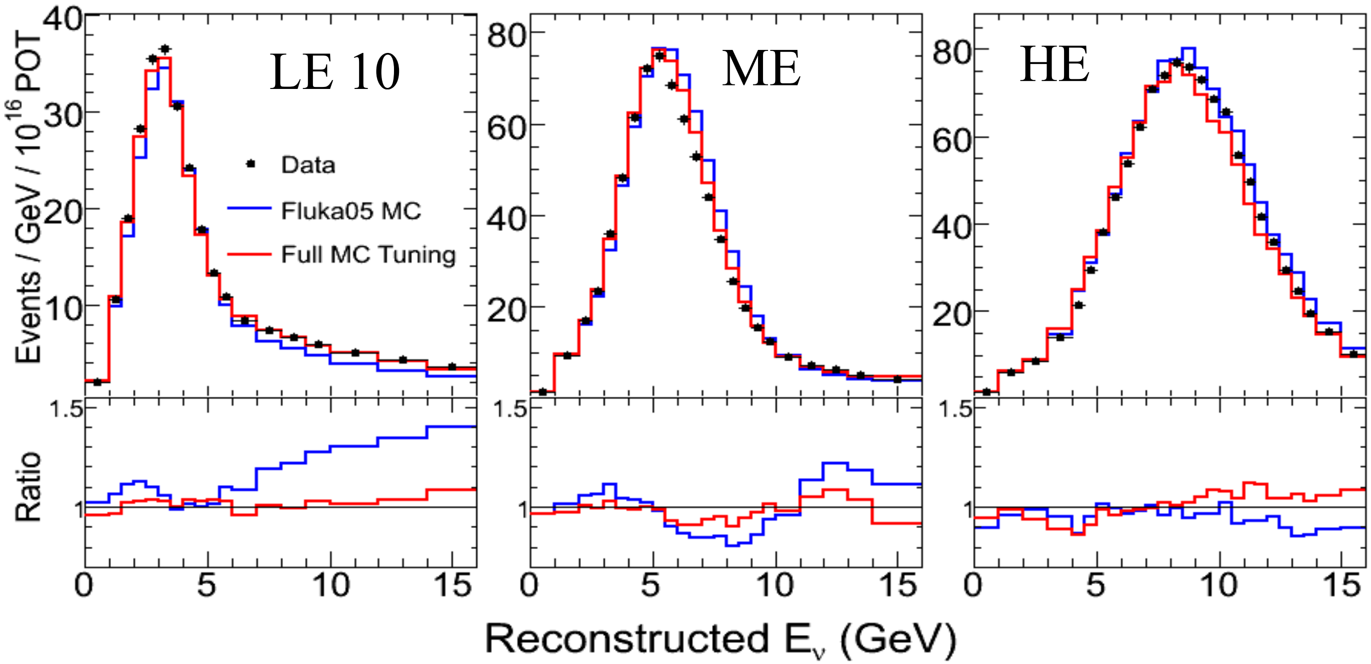
- By changing target position with same focusing elements, can disentangle focusing uncertainties from hadron production uncertainties
  - Different geometry focuses different parts of xF p_T space
  - MINERvA is doing this by using low ν events

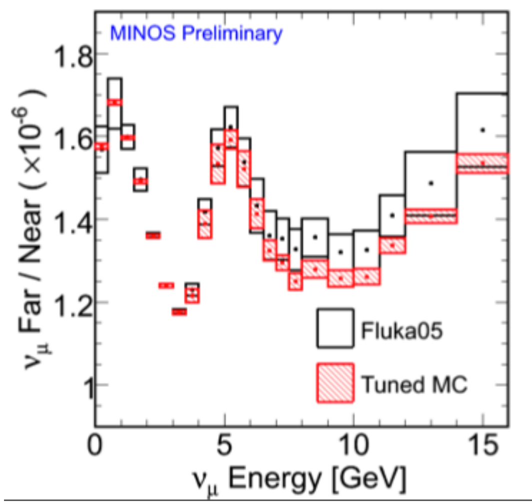




Pion Phase Space

MINOS Special Run Experience





- Big change in high energy “tail” of LE flux (recall “15% model differences”)
- Remaining data/MC discrepancies ~5-10% level
- This is the “SKZP flux” that Argoneut uses

Phys. Rev. D76 (2007) 072005

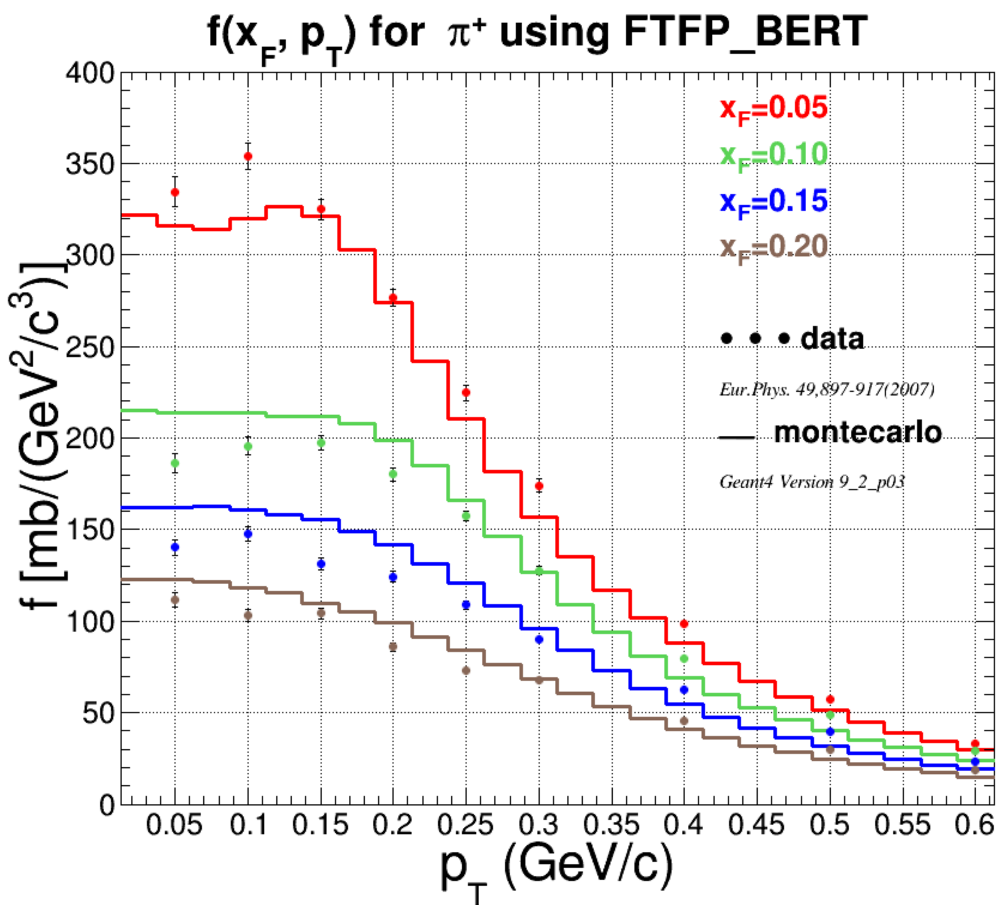
Conclusions

- Many different ways to constrain the NuMI Flux — (Uncertainties)
  - Hadron Cascade model comparisons — 15%
  - External Measurements
    - Thin target, various proton energies — 10%
    - Thick target, 120GeV proton energies — 6-7%
  - In Situ Techniques
    - Secondary Muon Fluxes — 15-30%
    - Neutrino-electron events (integrated energy-weighted flux) — 15% (LE)→ 5 (ME)%
    - Low-nu flux measurements — 7-8%
  - Tests with modified beamline geometries
    - Moving target relative to horn — <7%
    - Turning off the horn…
- Getting to 5% flux uncertainty will be a challenge, may be achievable with all these methods working together

BACKUP SLIDES

Reweighting for Hadron Production

- Closeup around the focusing peak: differences <10%

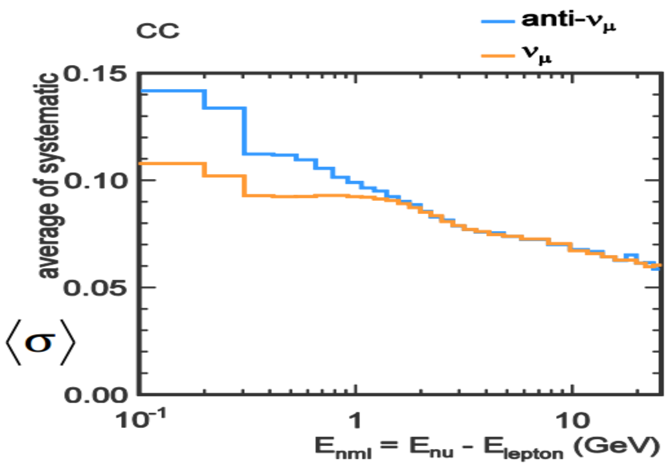


MINERvA low-ν Systematic Uncertainties

- Muon Energy Scale

Error Source	Error
MINOS Range	2.%
MINOS Curvature ($p_\mu < 1GeV$)	2.5%
MINOS Curvature ($p_\mu > 1GeV$)	0.6%
MINERvA $\frac{dE}{dx}$ (scintillator)	30 MeV
MINERvA $\frac{dE}{dx}$ (C, Fe, Pb)	40 MeV
MINERvA mass (scintillator)	11 MeV
MINERvA mass (C, Fe, Pb)	17 MeV

- Hadron Energy Scale



- Subset of GENIE Systematic Variations

process	GENIE Knob name	parameter in option file	default value	1 sigma
QEL	MaCCQE	QEL-Ma	0.990	+25%, -15%
	VecFFCCQEShape	ElasticFormFactorsModel	BBA05ELFormFactorsModel	DipoleELFormFactorsModel
RES	MaRES	RES-Ma	1.120	+/-20%
	MvRES	RES-Mv	0.840	+/-10%
DIS	Rvp1pi	DIS-HMultWgt-vp-CC-m2 DIS-HMultWgt-vp-NC-m2	0.1 0.1	+/-50%
	Rvn1pi	DIS-HMultWgt-vn-CC-m2 DIS-HMultWgt-vn-NC-m2	0.3 0.3	+/-50%
	Rvp2pi	DIS-HMultWgt-vp-CC-m3 DIS-HMultWgt-vp-NC-m3	1. 1.	+/-50%
	Rvn2pi	DIS-HMultWgt-vn-CC-m3 DIS-HMultWgt-vn-NC-m3	1. 1.	+/-50%

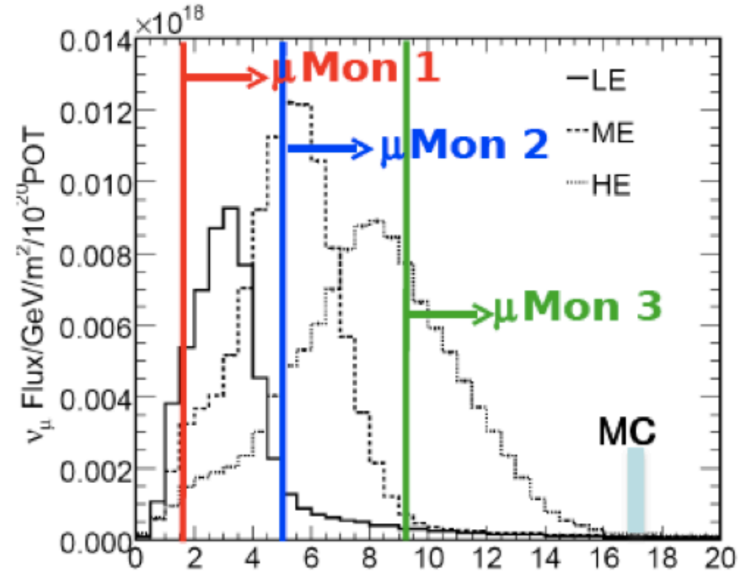
MINERvA low-ν Systematic Uncertainties, II

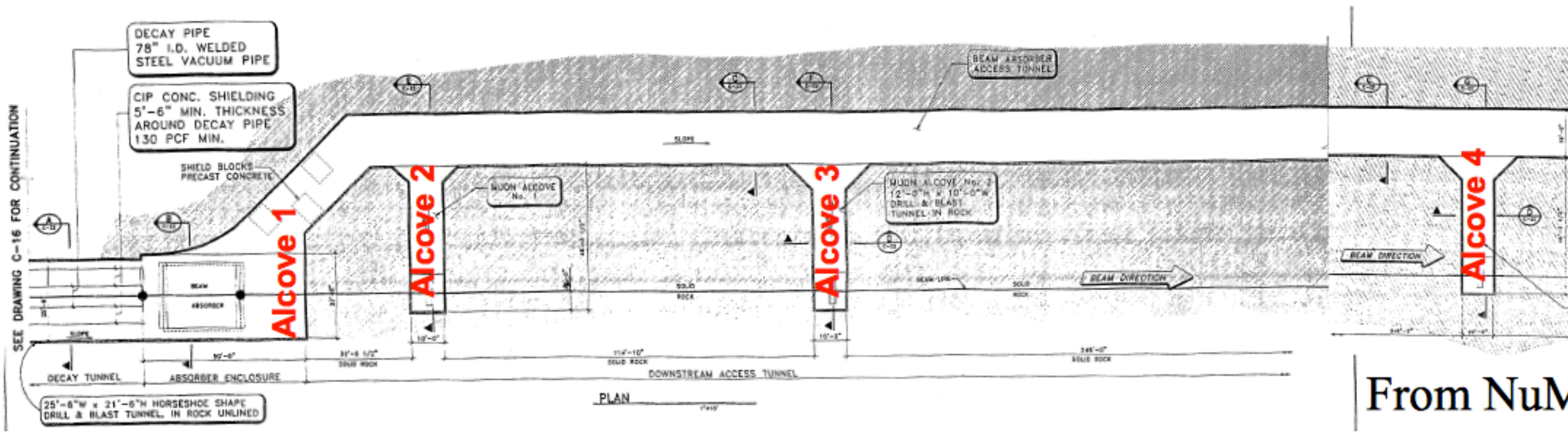
- Other GENIE variations

GENIE Knob name	Description	1 σ
MFP_pi	mean free path for pions	$\pm 20\%$
MFP_N	mean free path for nucleons	$\pm 20\%$
FrAbs_pi	pion fates - absorption	$\pm 30\%$
FrCEx_pi	pion fates - charge exchange	$\pm 50\%$
FrElas_pi	pion fates - elastic	$\pm 10\%$
FrInel_pi	pion fates - inelastic	$\pm 40\%$
FrPiProd_pi	pion fates - pion production	$\pm 20\%$
FrCex_N	nucleon fates - pion charge exchange	$\pm 50\%$
FrElas_N	nucleon fates - elastic	$\pm 30\%$
FrInel_N	nucleon fates - inelastic	$\pm 40\%$
FrAbs_N	nucleon fates - absorption	$\pm 20\%$
FrPiProd_N	nucleon fates - pion production	$\pm 20\%$
AGKYxF1pi	AGKY hadronization model x_F	$\pm 20\%$
Theta_Delta2Npi	Δ decay angular distribution	on/off
RDecBR1gamma	Res decay branching ratio to gamma	$\pm 50\%$

Muon Monitors in NuMI

- The NuMi Beam Line has four ionization chambers that perform an integral flux measurement and differentiate it using different thresholds imposed by :
  - The spatial disposition of the monitors and their materials in between -> Thus constraining the energy spectrum of muons.
    - 1: $E_{\mu,\pi}$ 4.2 GeV (E_ν 1.8 GeV)
    - 2: $E_{\mu,\pi}$ 11 GeV (E_ν 4.7 GeV)
    - 3: $E_{\mu,\pi}$ 21 GeV (E_ν 9 GeV)
    - 4: $E_{\mu,\pi}$ 39.7 GeV (E_ν 17 GeV)
  - The variable configurations of horn current and target position -> Thus constraining parent hadrons (xf,pt).



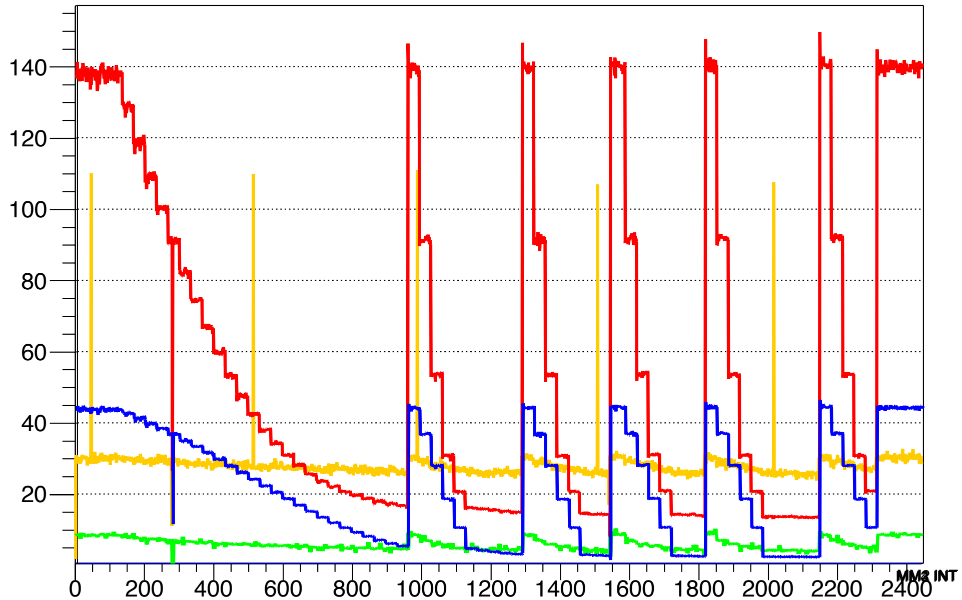


From NuMI TDR

Horn Current Scans

- By changing the horn current and taking a few spills, we can sweep through the pt pz phase space for pions

Integrated current for MM1, MM2, MM3 and MM4



M-J. Bustamante-Rosell, 4/14/14 AEM talk

- Analysis in progress
- Data exists for LE beam also, several target positions
- Based on *L. Loiacono, "Measurement of the Muon Neutrino Inclusive Charged Current Cross Section on Iron Using the MINOS Detector," PhD Thesis, UT Austin 2010*
  - Several scans, several target positions