MiniBooNE Cross Section Measurements

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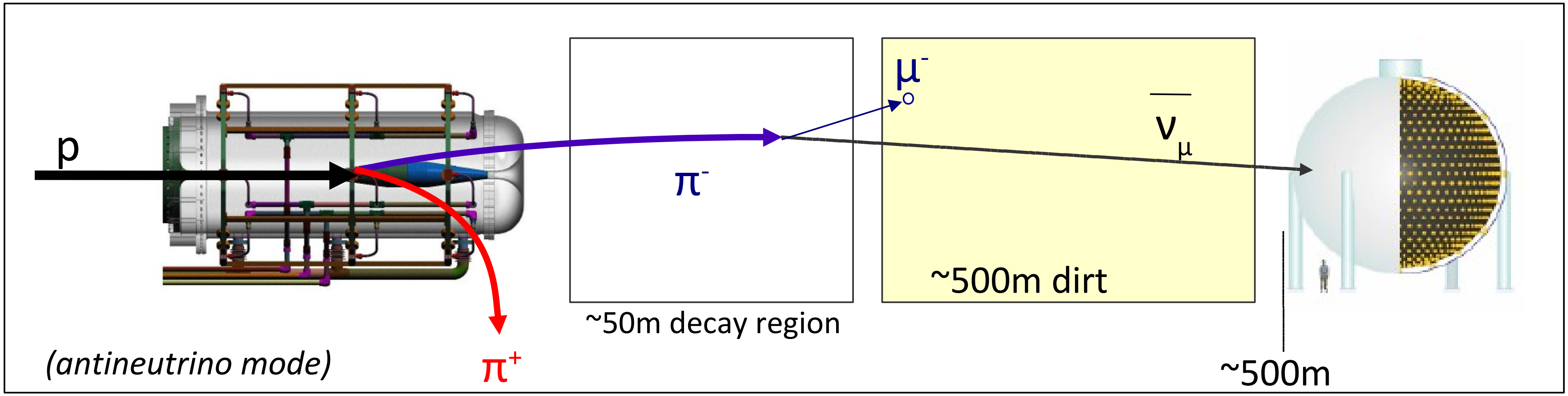
Outline

- Booster Neutrino Beamline & MiniBooNE detector
- Cross section measurements with MiniBooNE
- New results
  - Anti neutrino CCQE (J. Grange)
- Forthcoming results
  - NC Elastic (R. Dharmapalan)
  - CC inclusive (M. Tzanov)
- Conclusion

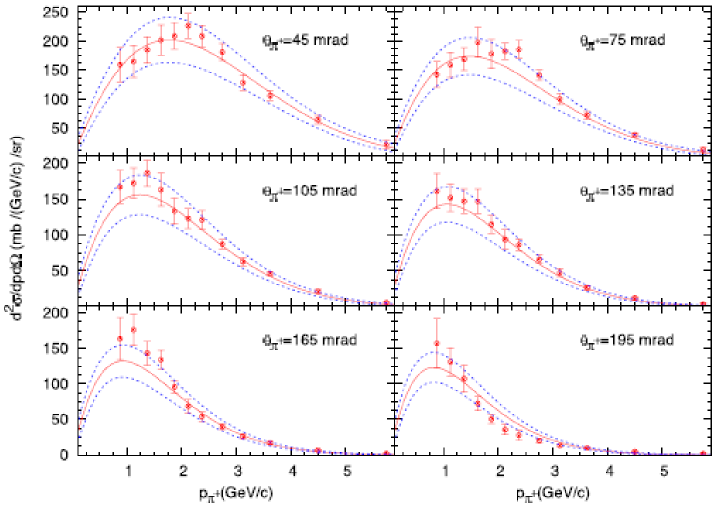
Booster Neutrino Beam

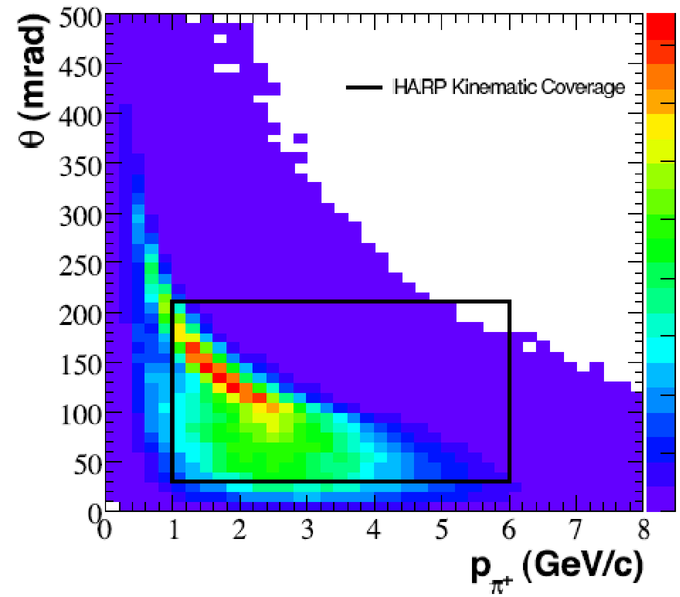


- Designed to study LSND anomaly - similar L/E as LSND
  - MiniBooNE ~500m/~500MeV
  - LSND ~30m/~30MeV
- Horn focused neutrino beam (p+Be)
  - Horn polarity → neutrino or anti-neutrino mode
- Mineral oil Cherenkov detector

Hadron production in BNB target

- Major uncertainty in the neutrino flux prediction due to pion production in p+Be interactions
- Need to know neutrino flux for precise cross section measurements
- Used external pi+ & pi- production data (HARP, BNL E910)
- HARP measured production on Be target using 8.9GeV protons
- Covers phase space contributing to 78% of neutrino flux from pi+ (76% from pi- in antineutrino mode)
- Overall 9% flux uncertainty – dominant error in cross section measurement





HARP collaboration, Eur. Phys. J. C52 29 (2007)

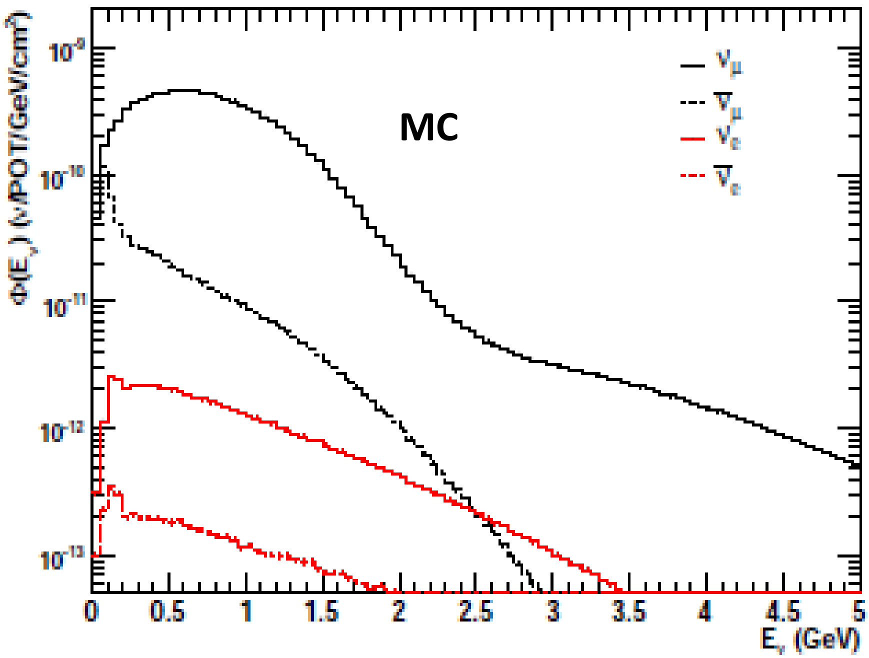
Predicted flux

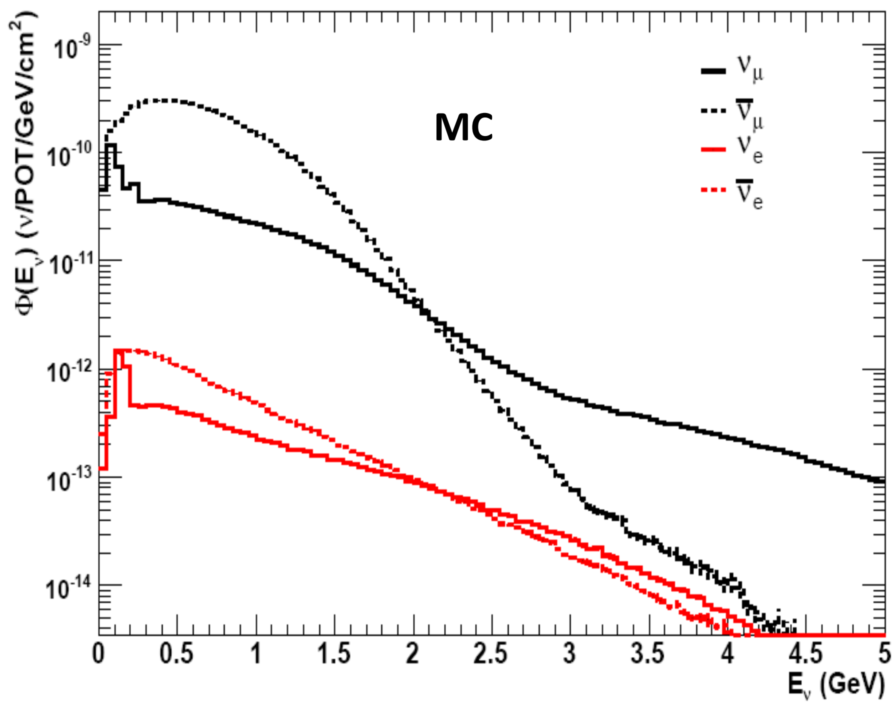
Neutrino mode

ν_μ	93.6%
$\bar{\nu}_\mu$	5.8%
$\nu_e + \bar{\nu}_e$	0.6%

Anti-neutrino mode

ν_μ	15.7%
$\bar{\nu}_\mu$	83.7%
$\nu_e + \bar{\nu}_e$	0.6%





Phys. Rev. D79, 072002 (2009)

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Wrong signs

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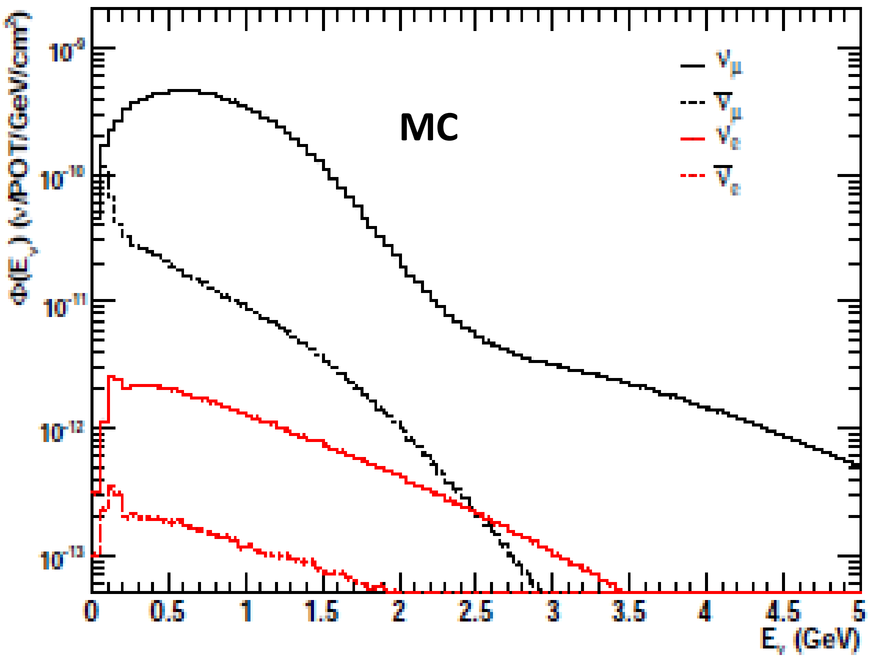
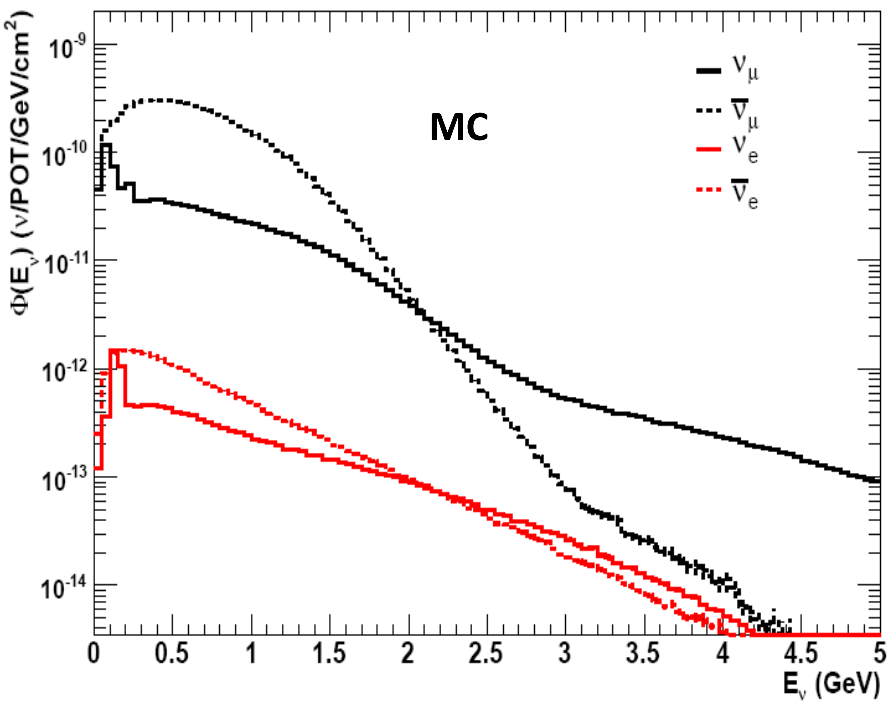
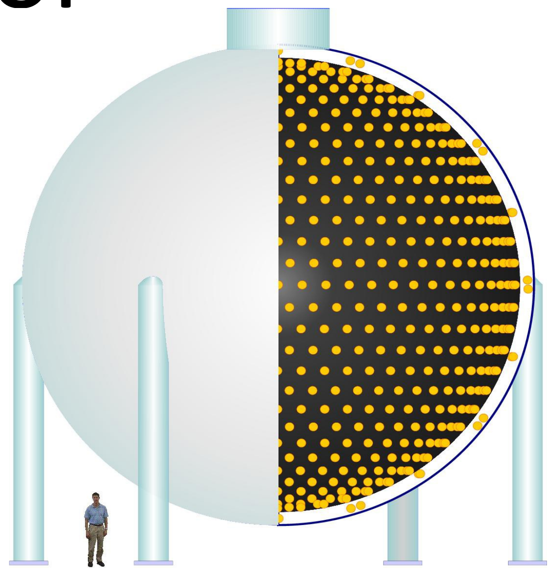


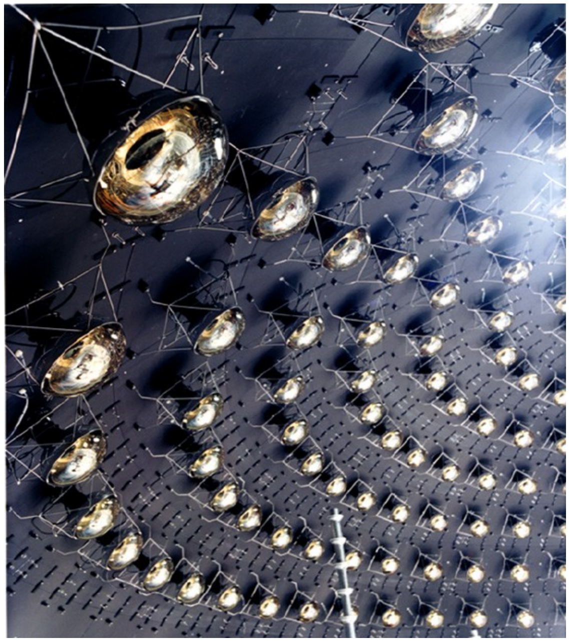


Phys. Rev. D79, 072002 (2009)

MiniBooNE Detector

- 6.1m radius sphere filled with 800t of pure mineral oil – interactions on CH_2
- 1280 PMTs inner region and 240 PMTs in outer veto region
- 10% photo cathode coverage
- 4pi detector – covers entire angular space
- Event reconstruction primarily based on Cherenkov light – best at reconstructing leptons
- Timing and topology
- Scintillation light enables measurement of NC elastic events



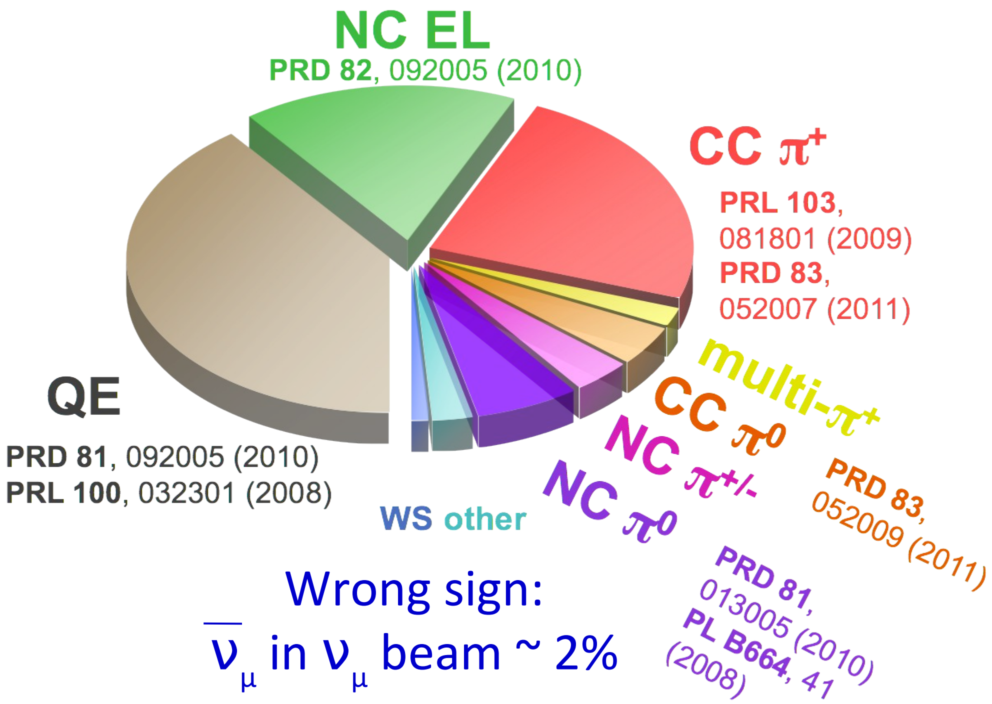


Nucl. Instr. Meth. A599, 29 (2009)

Neutrino mode cross sections

- Collected data corresponding to 6.5×10^{20} POT
- ~1000000 interactions in fiducial volume
- MiniBooNE has published ~90% of the total neutrino mode rate

Event rates

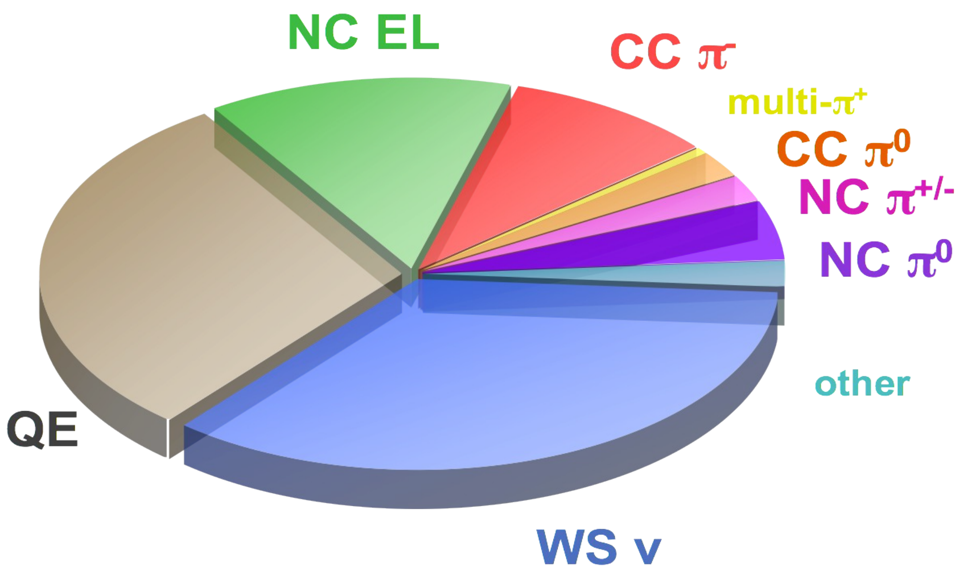


Wrong sign: $\bar{\nu}_\mu$ in ν_μ beam ~ 2%

Anti neutrino mode cross sections

- Collected data corresponding to more than 10^{21} POT
- Unprecedented $\bar{\nu}$ statistics
- Large background from wrong-sign ν_μ
  - has been addressed

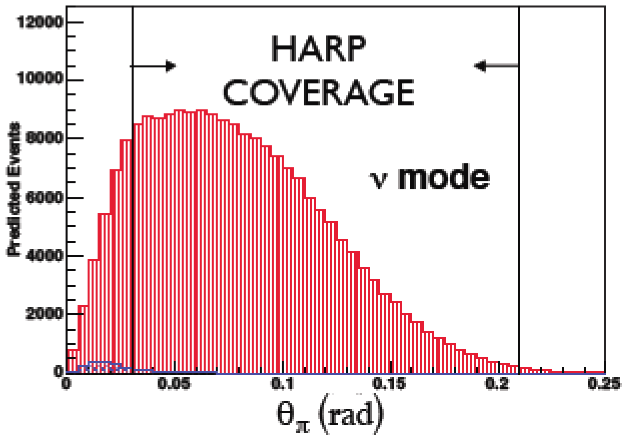
Event rates

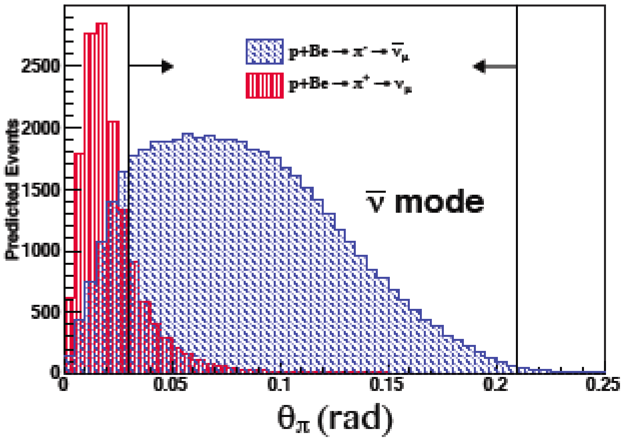


Wrong sign:
ν_μ in $\bar{\nu}_\mu$ beam ~ 40%!

Wrong sign background

- Pion parents contributing to wrong sign flux in antineutrino mode not covered by HARP measurement
- Have to measure this background
- No magnetic field to distinguish μ^+ vs μ^-

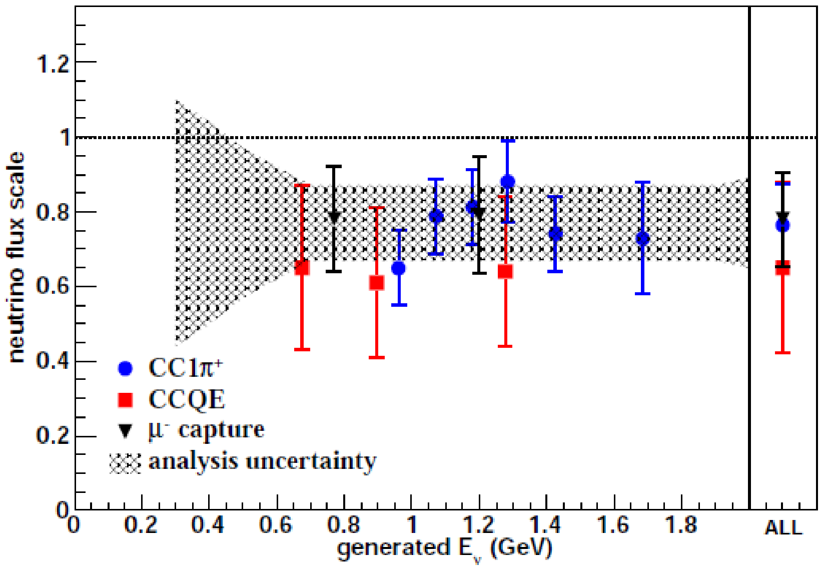




WS background (cont'd)

- Three methods yield consistent results
  - CC1pi$^+$ - direct rate measurement of wrong signs
  - μ^- capture – due to nuclear capture ν_μ CC events less likely to produce decay electrons compared to $\bar{\nu}_\mu$
  - CCQE – angular distribution (not actually used since it depends on $\bar{\nu}_\mu$ cross section)

- Predicted ν_μ flux in antineutrino mode constrained to better than 15% - not a dominant uncertainty anymore

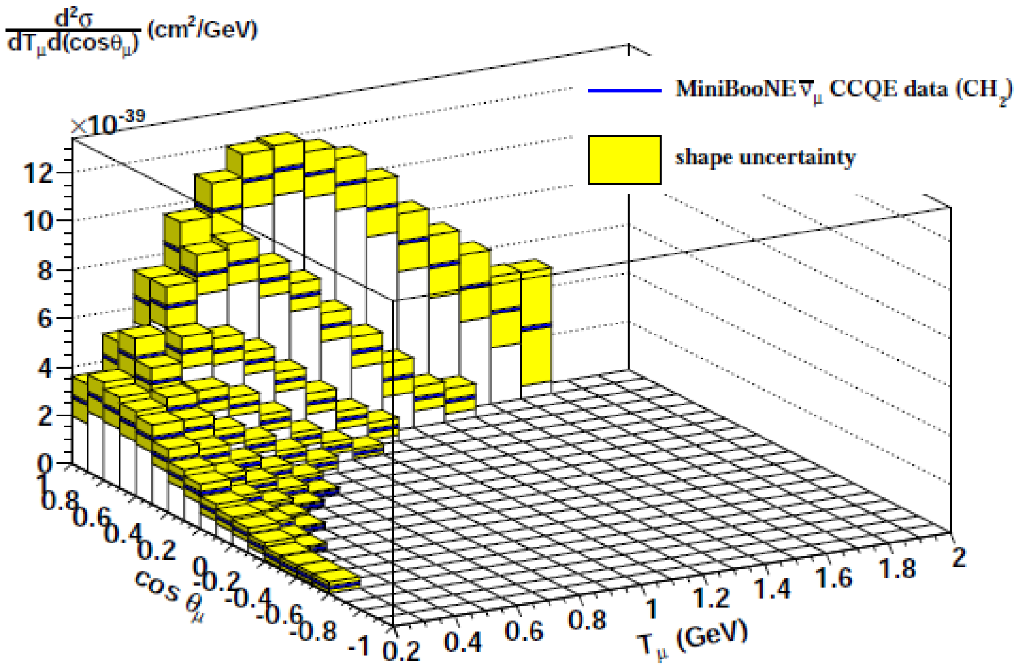


Phys. Rev. D84, 072005 (2011)

CCQE results

- 71k $\bar{\nu}_\mu$ CCQE candidates (30% efficiency/60% purity)
- Largest background from wrong signs (measured)
- Main result is the double differential on CH_2 - least model-dependent measurement possible with MiniBooNE data
- Many other cross sections available in the paper (hydrogen subtracted CCQE, Total $\sigma(E_\nu)$, ...)

Uncertainty type	Normalization uncertainty (%)
$\bar{\nu}_\mu$ flux	9.6
Detector	3.9
Unfolding	0.5
Statistics	0.8
ν_μ background	3.9
$CC1\pi^-$ background	4.0
All backgrounds	6.4
Total	13.0



Phys. Rev. D88, 032001 (2013)

Bit of history

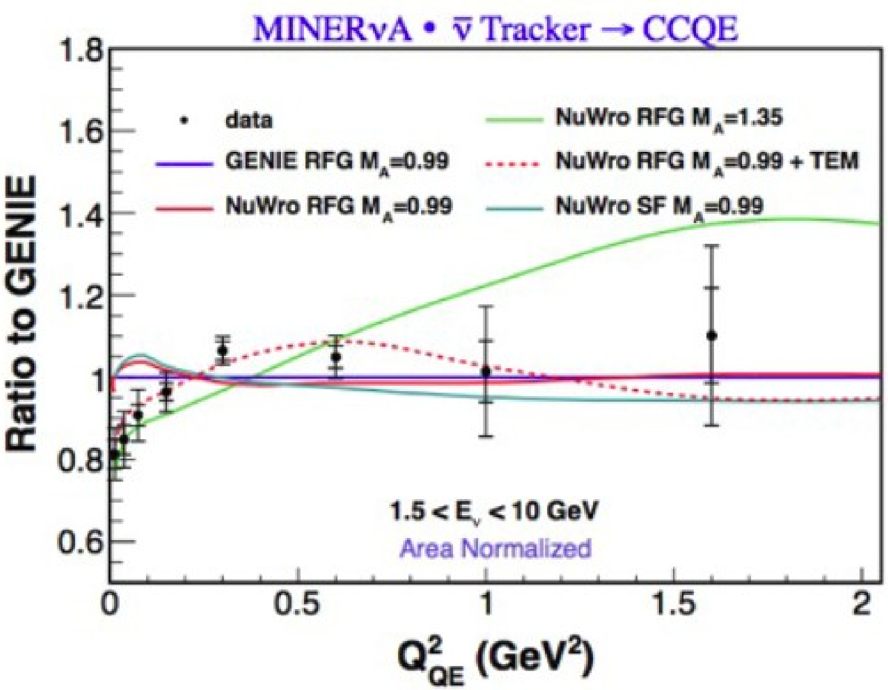
- In the early days saw discrepancy between neutrino data & prediction (Relativistic Fermi Gas (RFG) +M_A=1.0GeV)
- No model at the time, so tuned M_A for oscillation analysis
- Good fit with M_A=1.35GeV, however suspected this is just effective parameter covering for nuclear effects
  - Published double differential $\sigma(T_\mu, \theta_\mu)$
  - independent of interaction assumptions (unlike total cross section $\sigma(E_\nu)$)

Why M_A worked well for MiniBooNE?

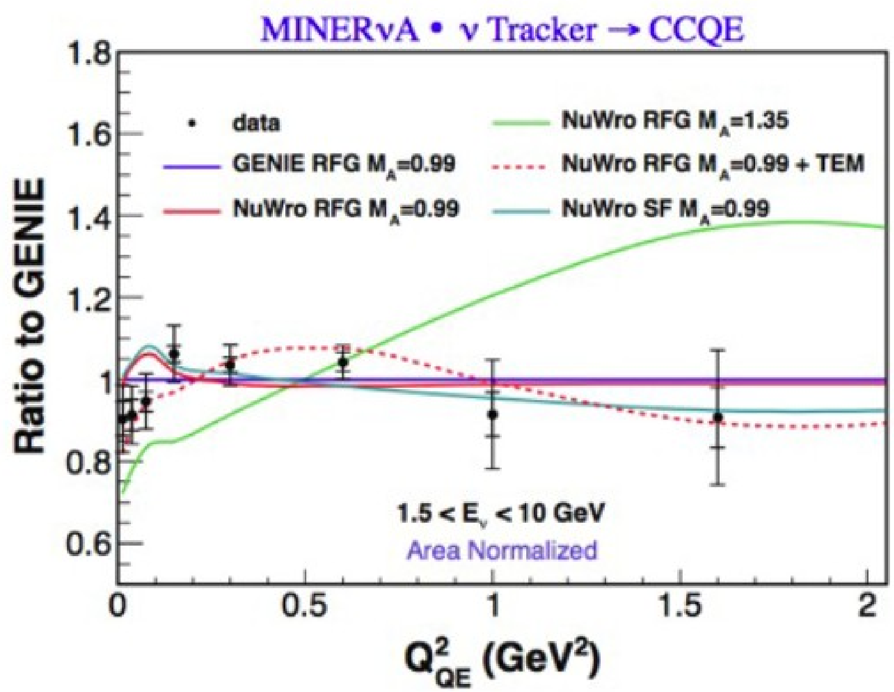
- Recent Minerva results prefer strongly M_A=1GeV+Tranverse Enhancement Model (TEM) over RFG+M_A=1.35GeV

See talks by:
Chris Marshal (Tuesday WG2 10:30)
David Schmitz (Friday Plenary 10 8:30)

Phys. Rev. Lett. 111, 022501 (2013)

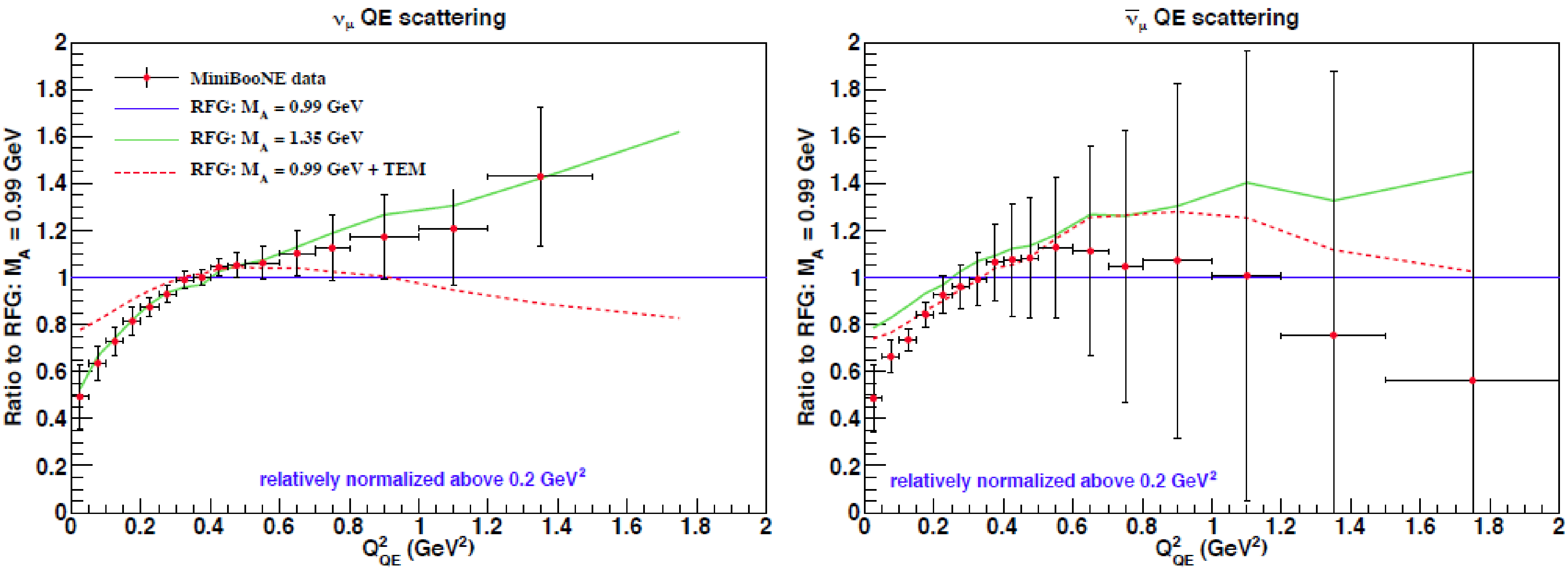


Phys. Rev. Lett. 111, 022502 (2013)



Why M_A worked well for MiniBooNE?

- Recent Minerva results prefer strongly M_A=1GeV+Tranverse Enhancement Model (TEM) over RFG+M_A=1.35GeV
- At BNB energies two models degenerate (above Q^2>0.2GeV^2)



Forthcoming cross sections

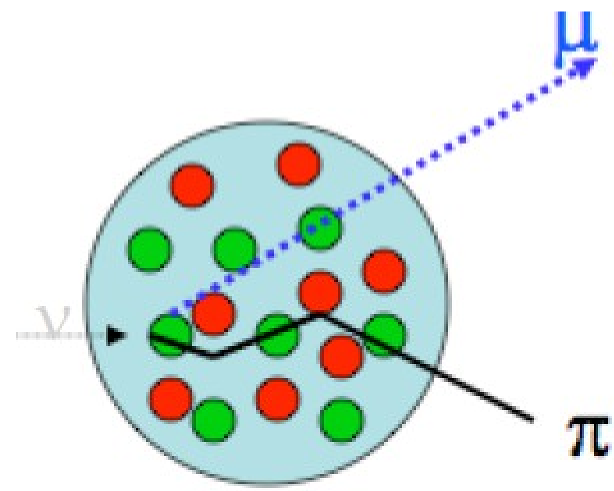
- CC inclusive
- NC elastic

CC inclusive

- Very important to measure inclusive cross section as well as exclusive channels to build models
- Can’t just add CCQE, CCpi+ and CCpi0, complicated correlated systematics
  - Each channel is a background for the others through FSI model

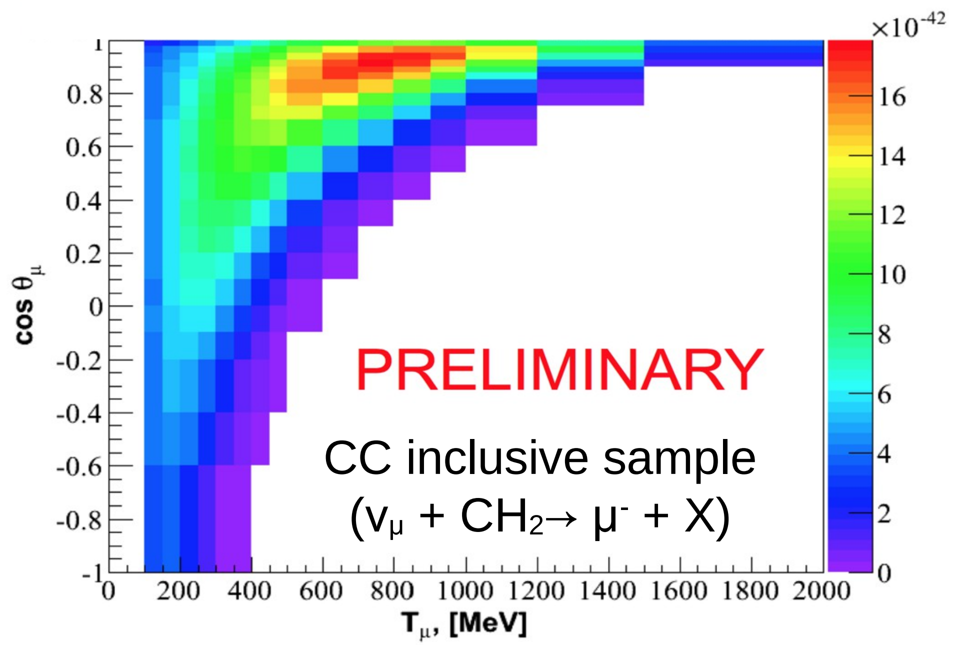
New reconstruction

- Developed for CC inclusive measurement
- Muon kinematics from 2-track likelihood fit; second fitted track absorbs the bias due to second most prominent ring
- Significant improvement of muon kinetic energy – resolution is about 5% (angle resolution as before better than 1deg)



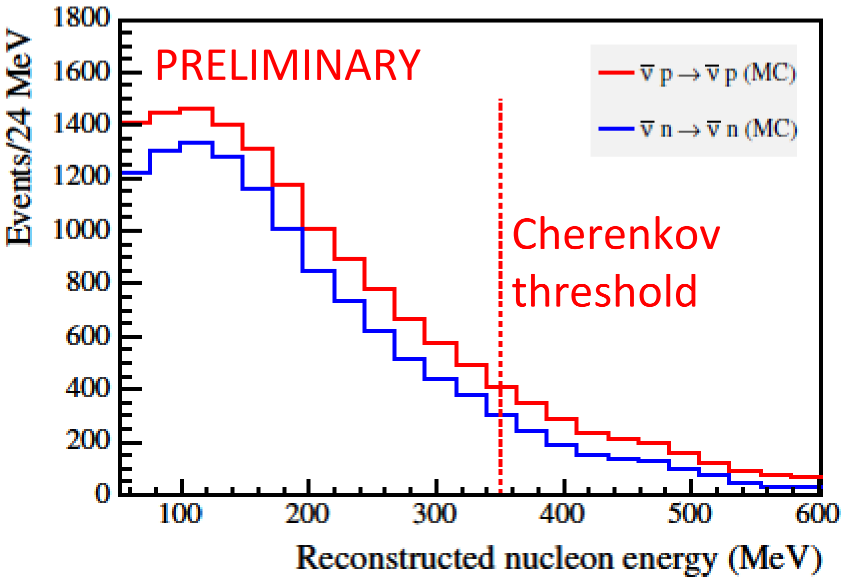
CC inclusive results

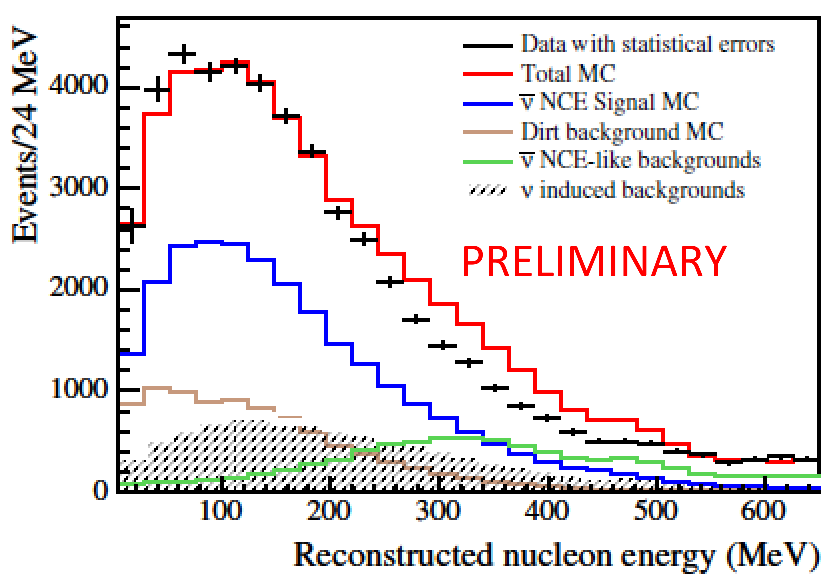
- Selected 344k events with 96% purity
- Coming soon $d\sigma/dT_{\mu}d(\cos\theta_{\mu})$, and a whole suite of other cross sections
- Full lepton reconstruction without any assumptions about nuclear target, no dependence on FSI



NC elastic

- Use scintillation light from mineral oil
- Measure n & p NC elastic interactions – some separation above Cherenkov threshold (350 MeV)
- 61k event candidates (32% efficiency, 40% purity)

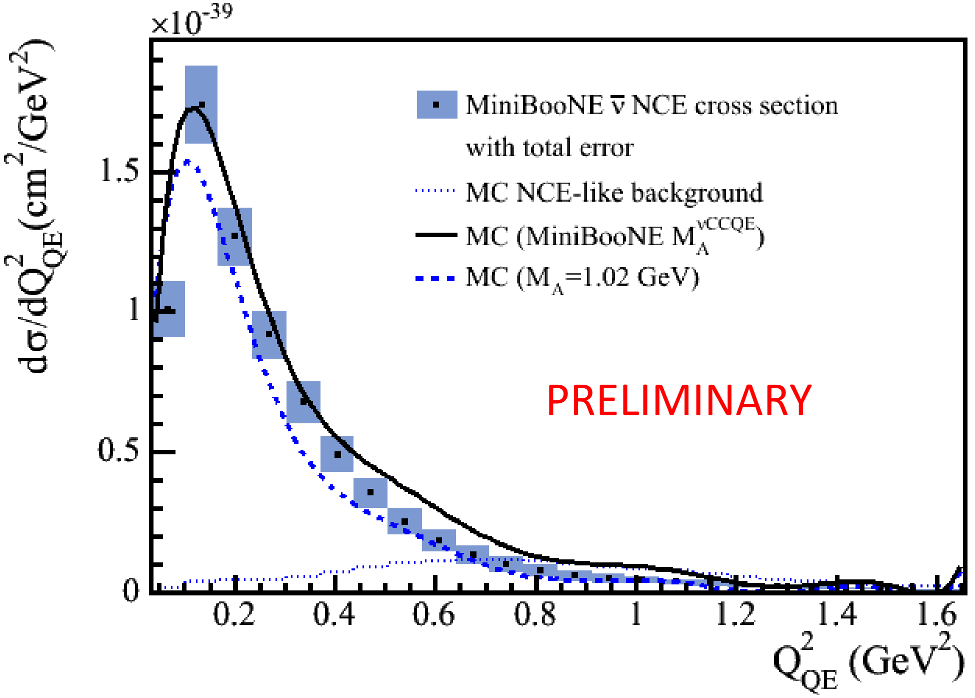




NC results

- Main result is $d\sigma/dQ^2$
- Normalization agrees well with MC prediction (tuned to ν_μ CCQE data)
- Q^2 calculated using nucleon energy assuming interaction with an independent, at-rest target – complementary to CCQE

Error source	Normalization uncertainty (%)
anti-ν flux	6
Backgrounds	6
Detector	15
Unfolding	7
Total (includes correlations)	**21**



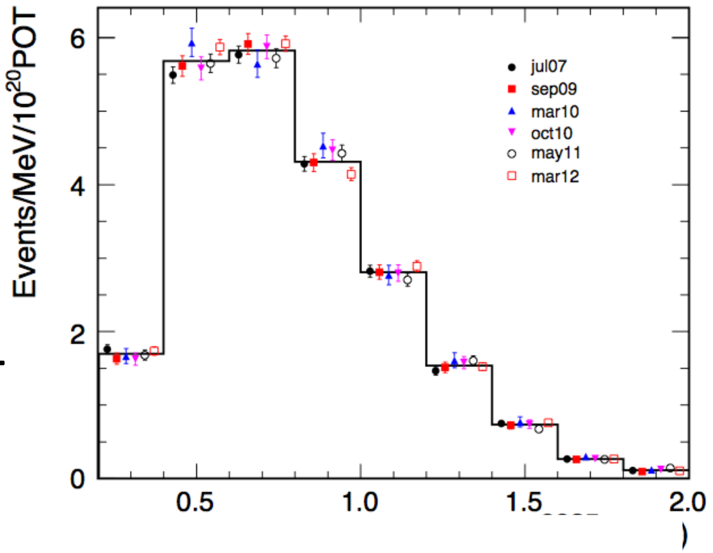
Conclusion

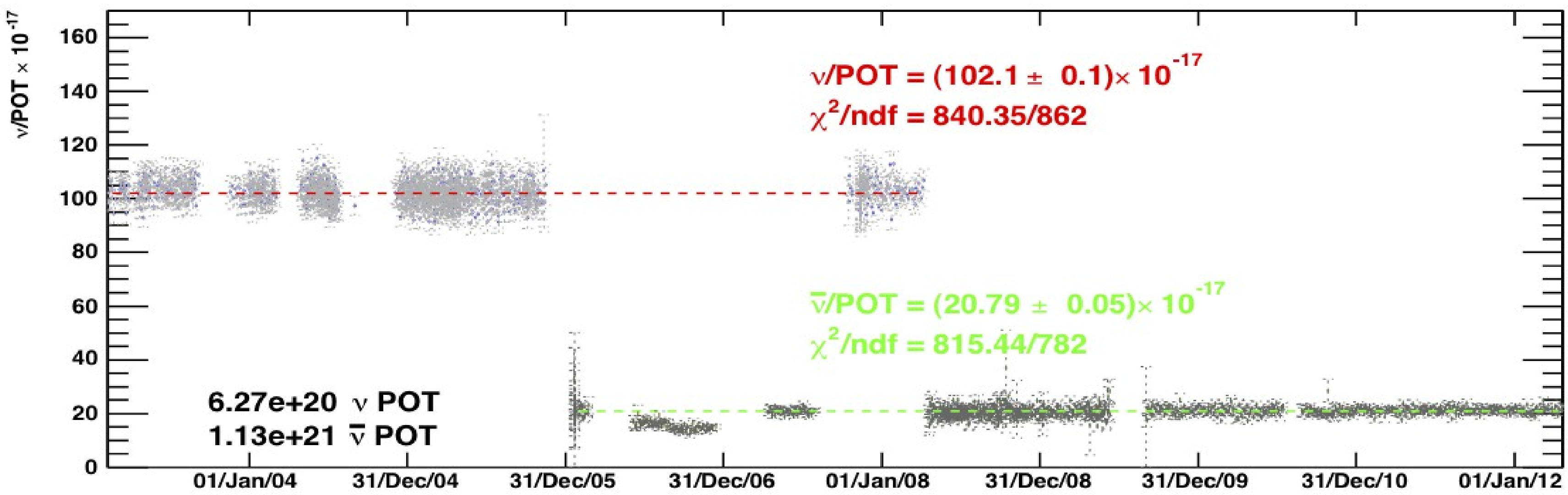
- 10 years of MiniBooNE running (2002-2012)
- Extremely stable:
  - Neutrino rate/POT at 2% level
  - Energy scale stable within 1%
  - 6.5e20 POT in neutrino and 11.3e20 POT in antineutrino mode
- MiniBooNE measured cross sections for 90% of events in neutrino mode and 83% in antineutrino mode (when new antineutrino CCQE cross sections & NC elastic are included)
- Coming soon CC inclusive and antineutrino NC elastic cross sections
- Important measurements to fully understand the cross sections and nuclear models

Backup

10 years of running

- Detector and beam extremely stable
- Neutrino/POT within 2%
- Detector calibration stable at 1% level
- 6.5e20 POT in neutrino and 11.3e20 POT in antineutrino mode





Transverse Enhancement Model

- Empirical model which modifies the magnetic form factors of bound nucleons to reproduce an enhancement in the transverse cross-section observed in electron-nucleus scattering attributed to the presence of meson exchange currents (MEC) in the nucleus
- Eur. Phys. J. C 71, 1726 (2011)