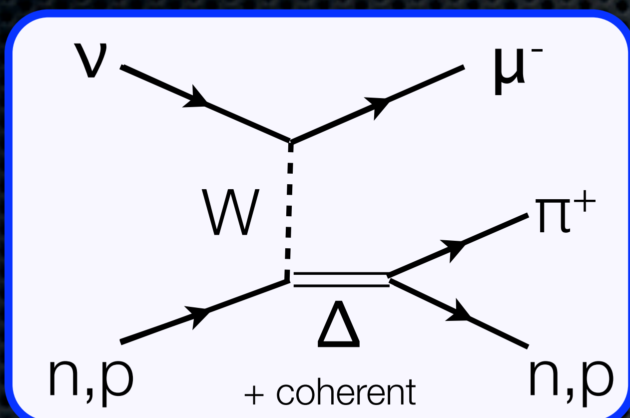
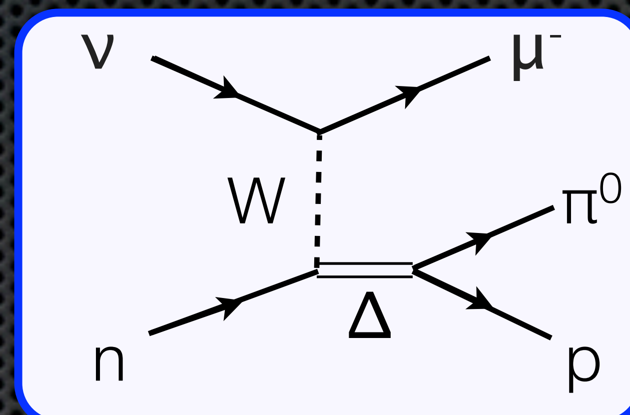
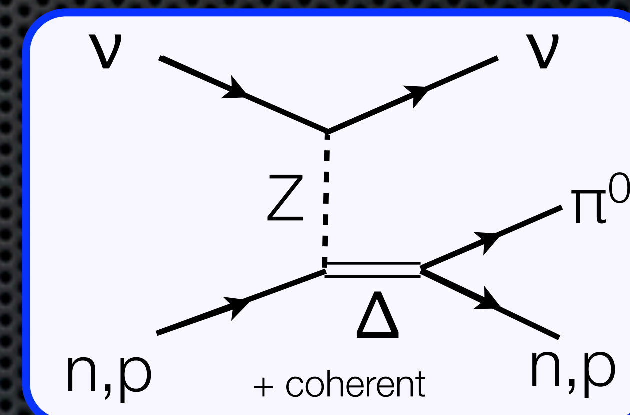
Measurements of Single-Pion Production at MiniBooNE







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2011.03.08

BooNE
BOOSTER NEUTRINO EXPERIMENT

UNIVERSITY OF COLORADO
LET YOUR LIGHT SHINE
1876

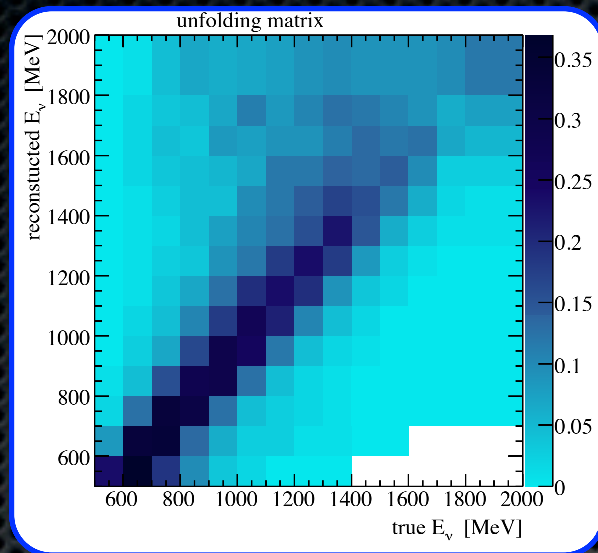
Outline

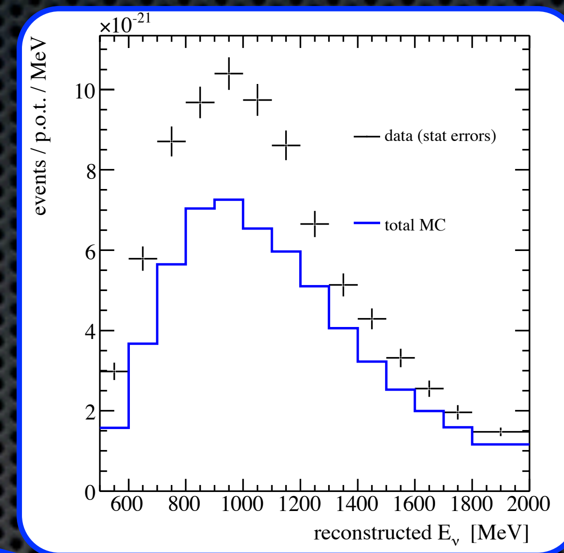
- Measuring cross sections.
- Predicted neutrino flux.
- Event reconstruction at MiniBooNE.
- $NC\pi^0$ cross sections.
- $CC\pi^+$ cross sections.
- $CC\pi^0$ cross sections.
- Comparisons.
- Conclusions.

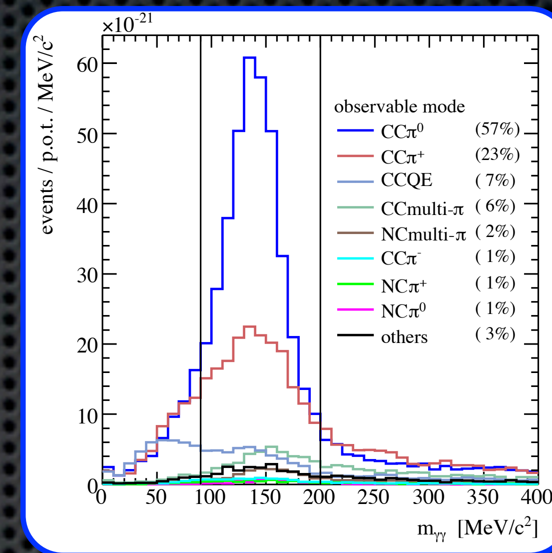
interior of the MiniBooNE main tank

Measuring cross sections

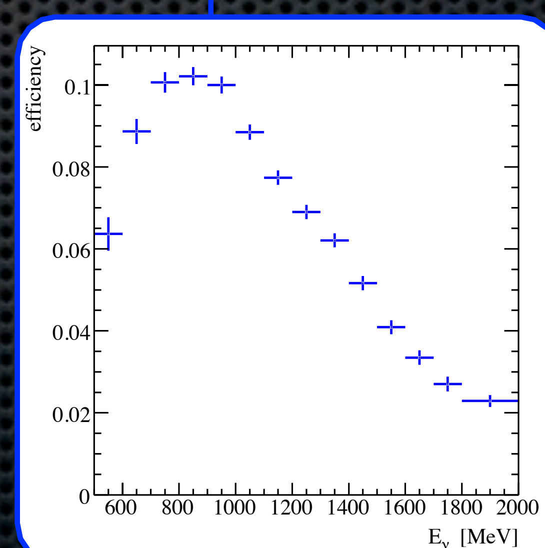
- N_j = Event rate
- B_j = Background prediction/ measurement
- U_{ij} = Unfolding detector response
- ε_i = cut efficiency
- Φ_i = neutrino flux
- N_{targs} = number of targets
- Δx_i = variable's bin width

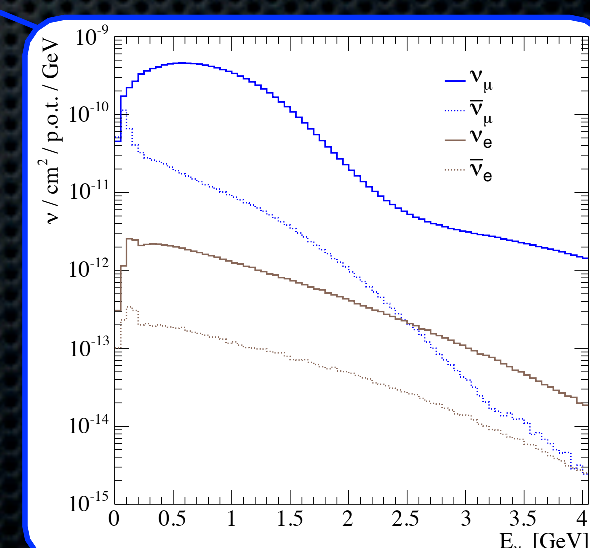






$$\left.\frac{\partial\sigma}{\partial x}\right|_i = \frac{\sum_j^{\text{bins}} U_{ij}\left(N_j - B_j\right)}{\varepsilon_i \phi_i N_{targs} \Delta x_i}$$

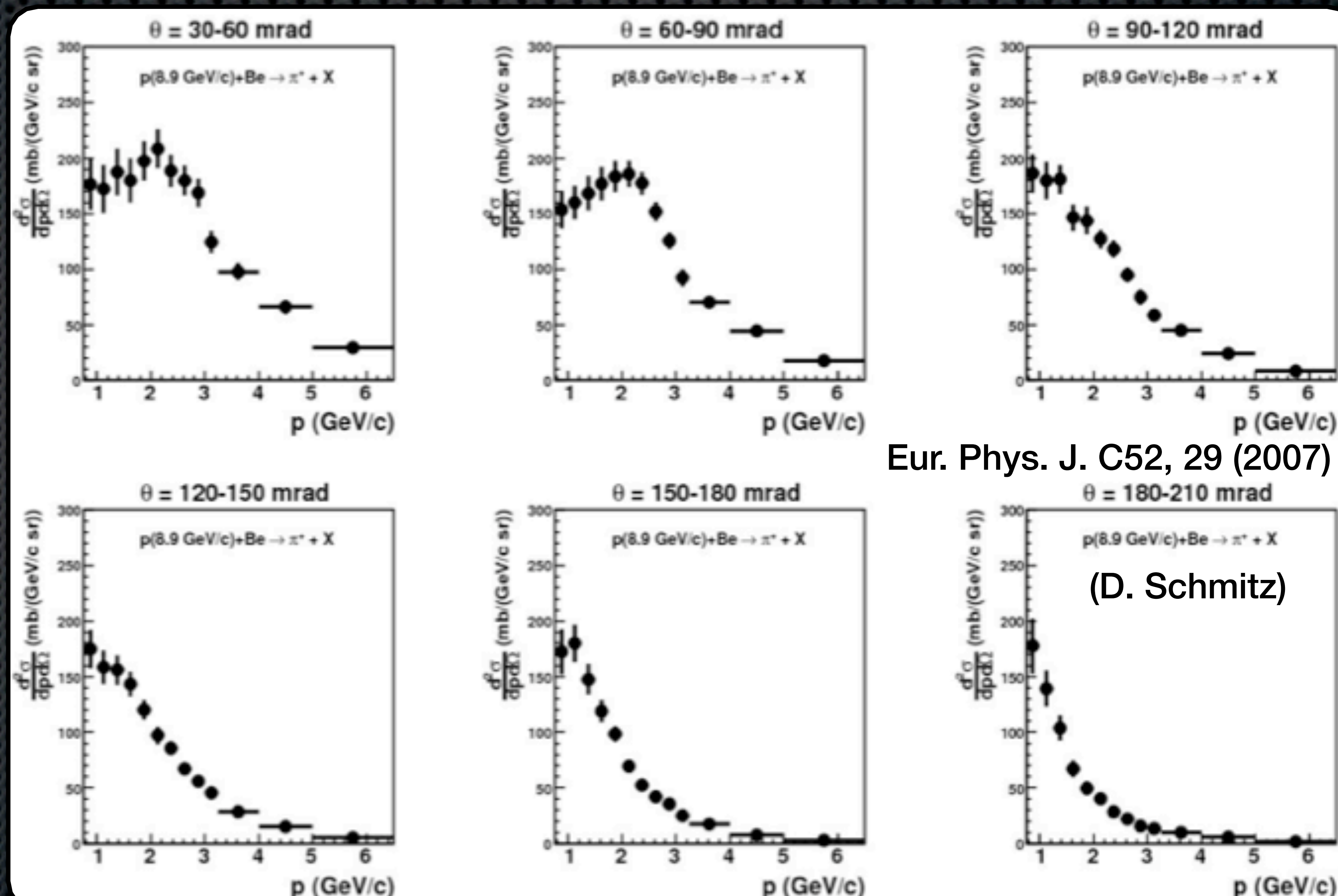




Predicting the flux

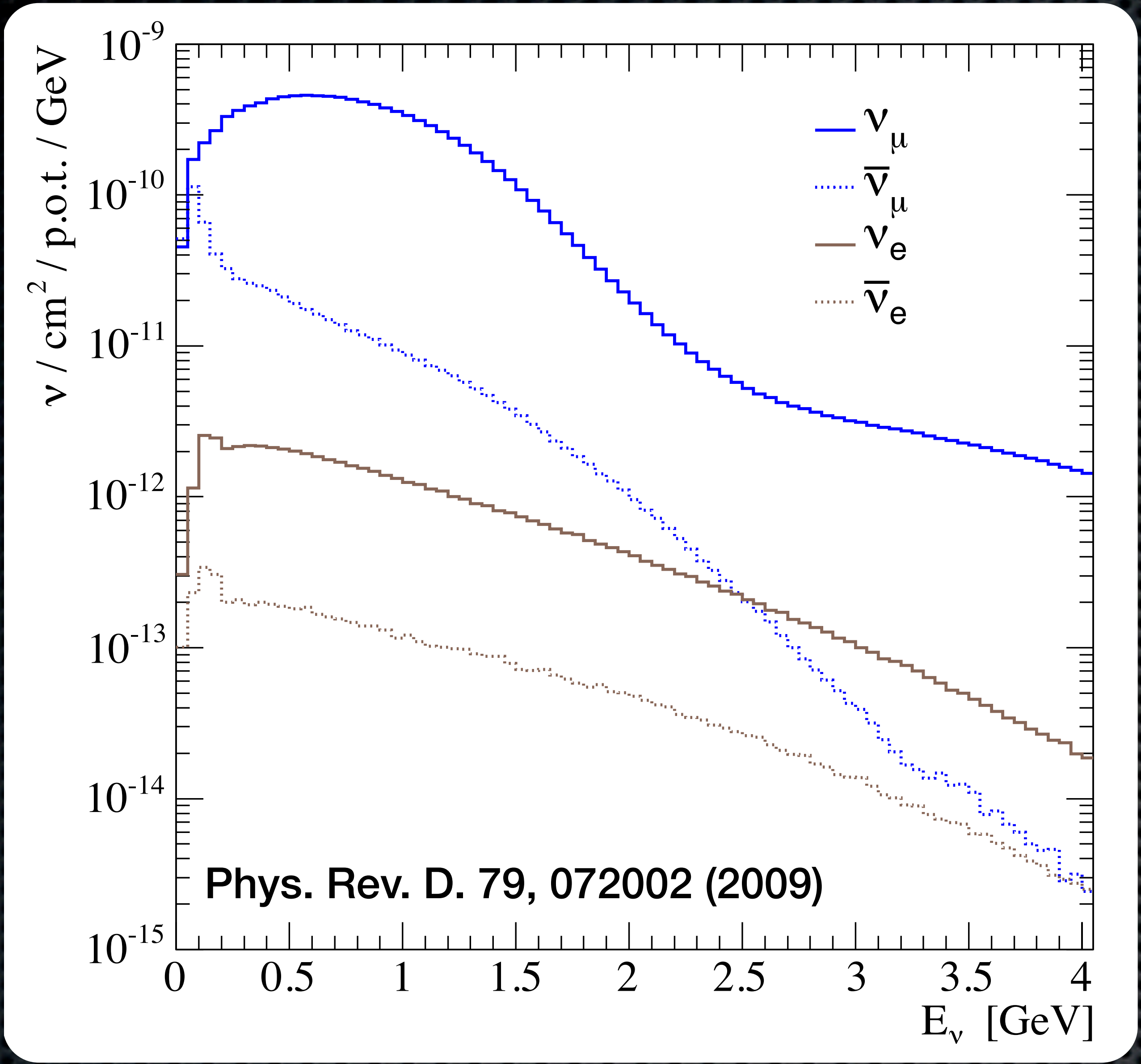
$$\left.\frac{\partial\sigma}{\partial x}\right|_i = \frac{\sum_{j}^{\text{bins}} U_{ij}\left(N_j - B_j\right)}{\varepsilon_i \phi_i N_{targs} \Delta x_i}$$

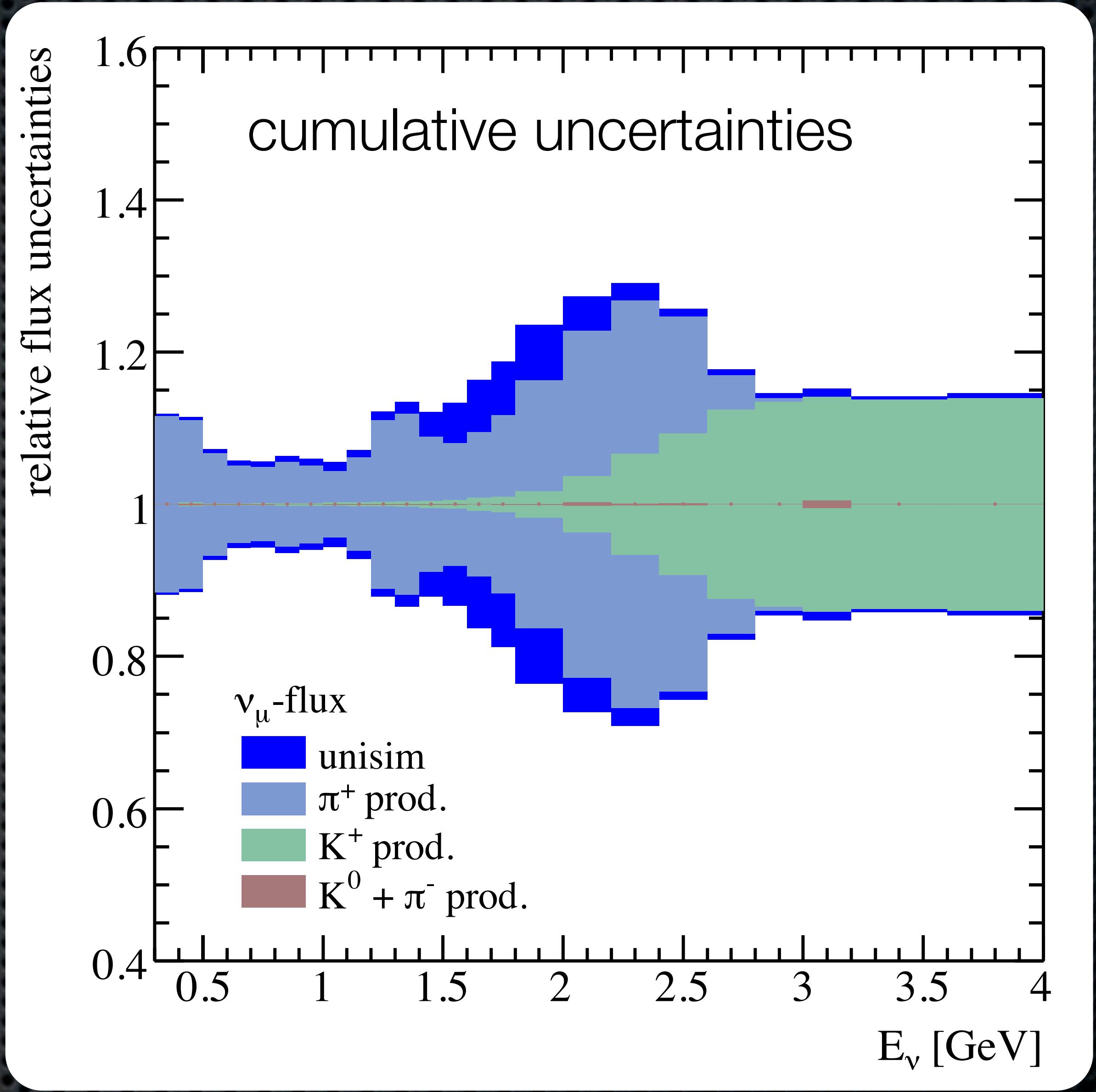
- The HARP experiment at CERN measured meson production off a replica MiniBooNE target.
- HARP covers 80% of the phase space of pions that produce neutrinos that hit the detector.
- Gives a 7% uncertainty.



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

ν_μ flux

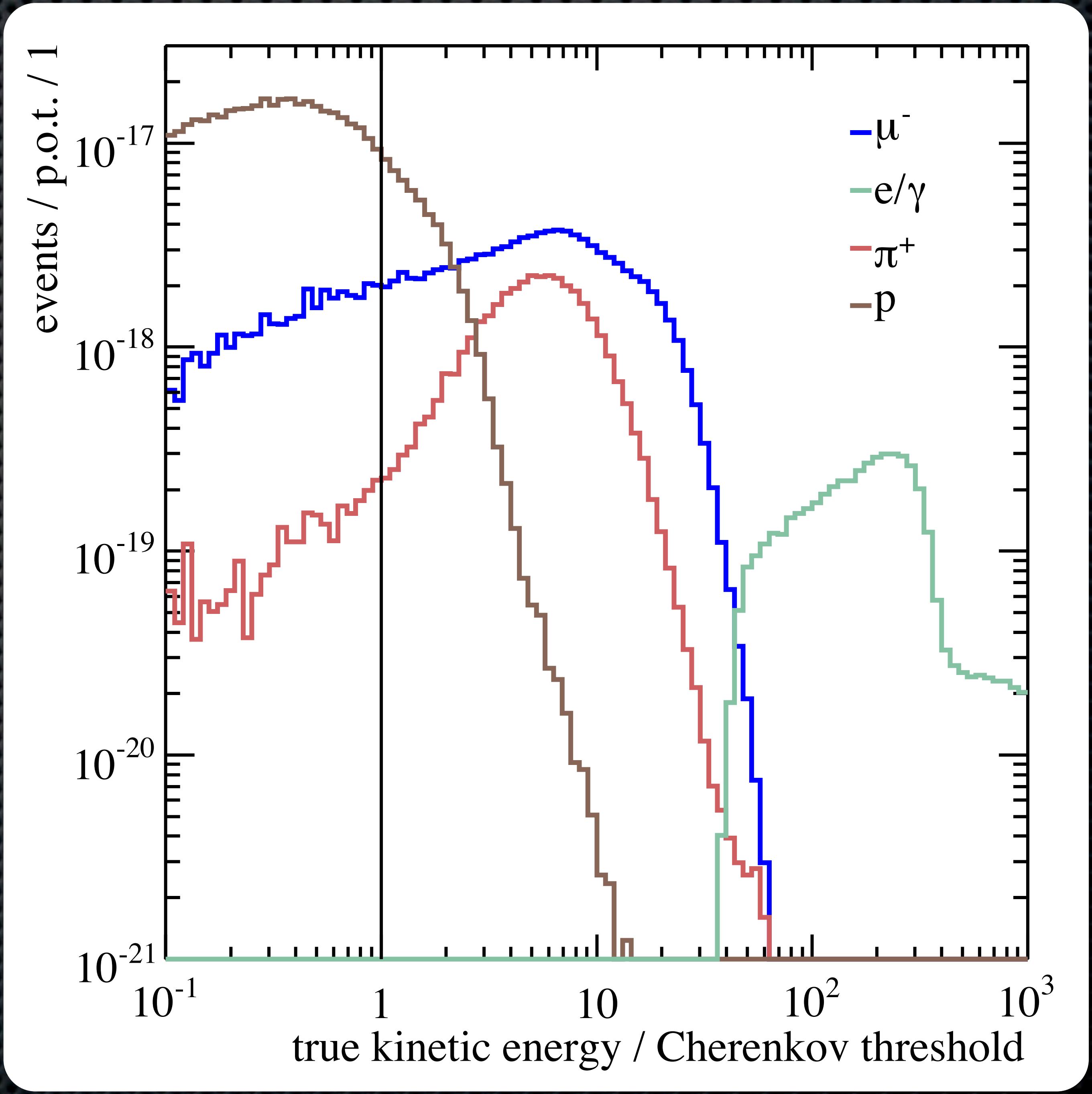




- Low-energy region is dominated heavily by ν_μ from π^+ decay; high-energy region dominated by ν_μ from kaon decays.

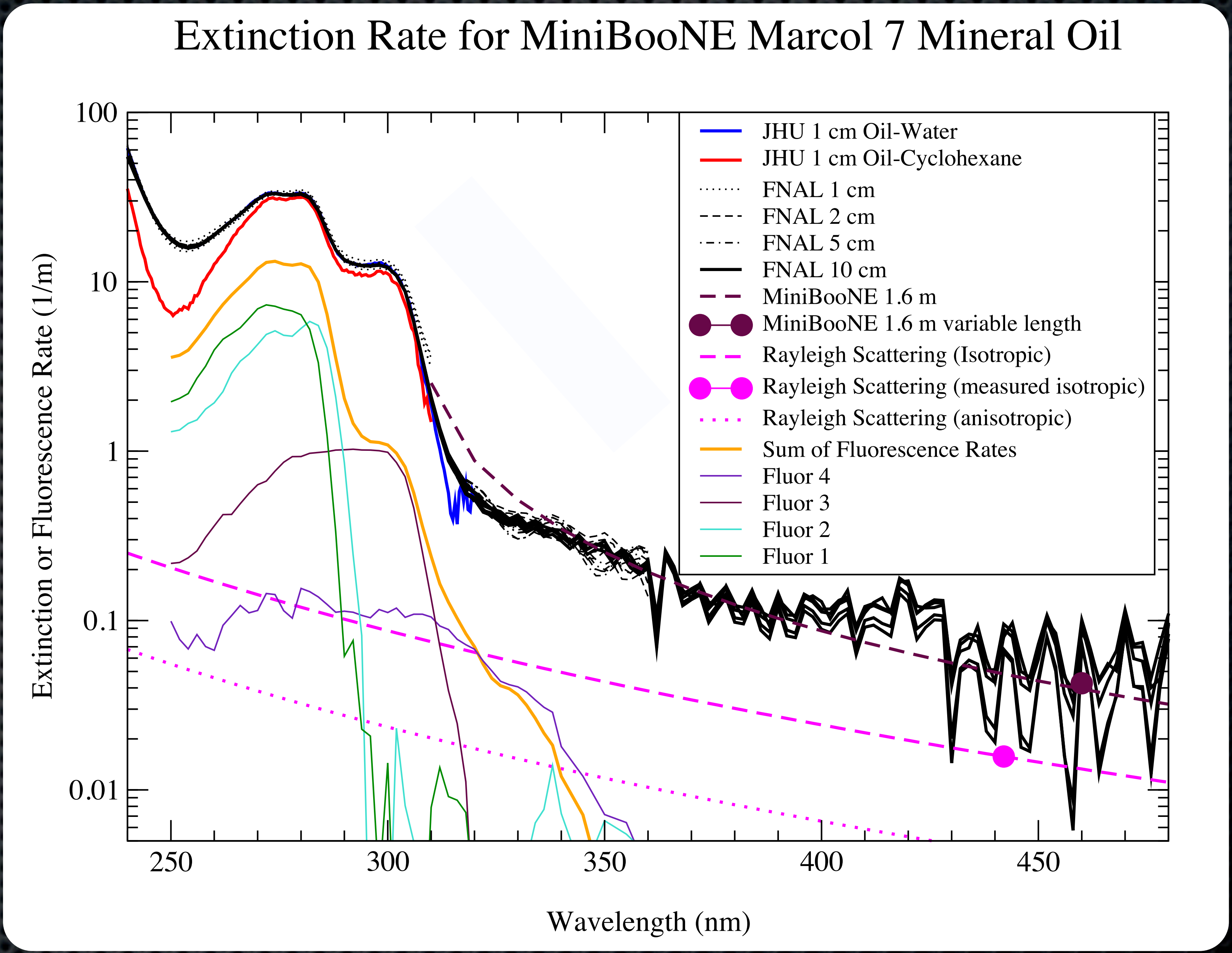
Čerenkov thresholds

- MiniBooNE primarily detects particles via their Čerenkov radiation.
- All e/γ are above threshold.
- Most μ^- and π^+ are above threshold.
- Most protons are below threshold.
- Particles are classified by the topology of their Čerenkov profiles.



Optical Model

- The primary sources of light are propagated through the tank until detection by a PMT.
- Primary light sources:
    - Čerenkov
    - Scintillation
- Secondary effects:
    - Rayleigh scattering
    - Raman scattering
    - Fluorescence

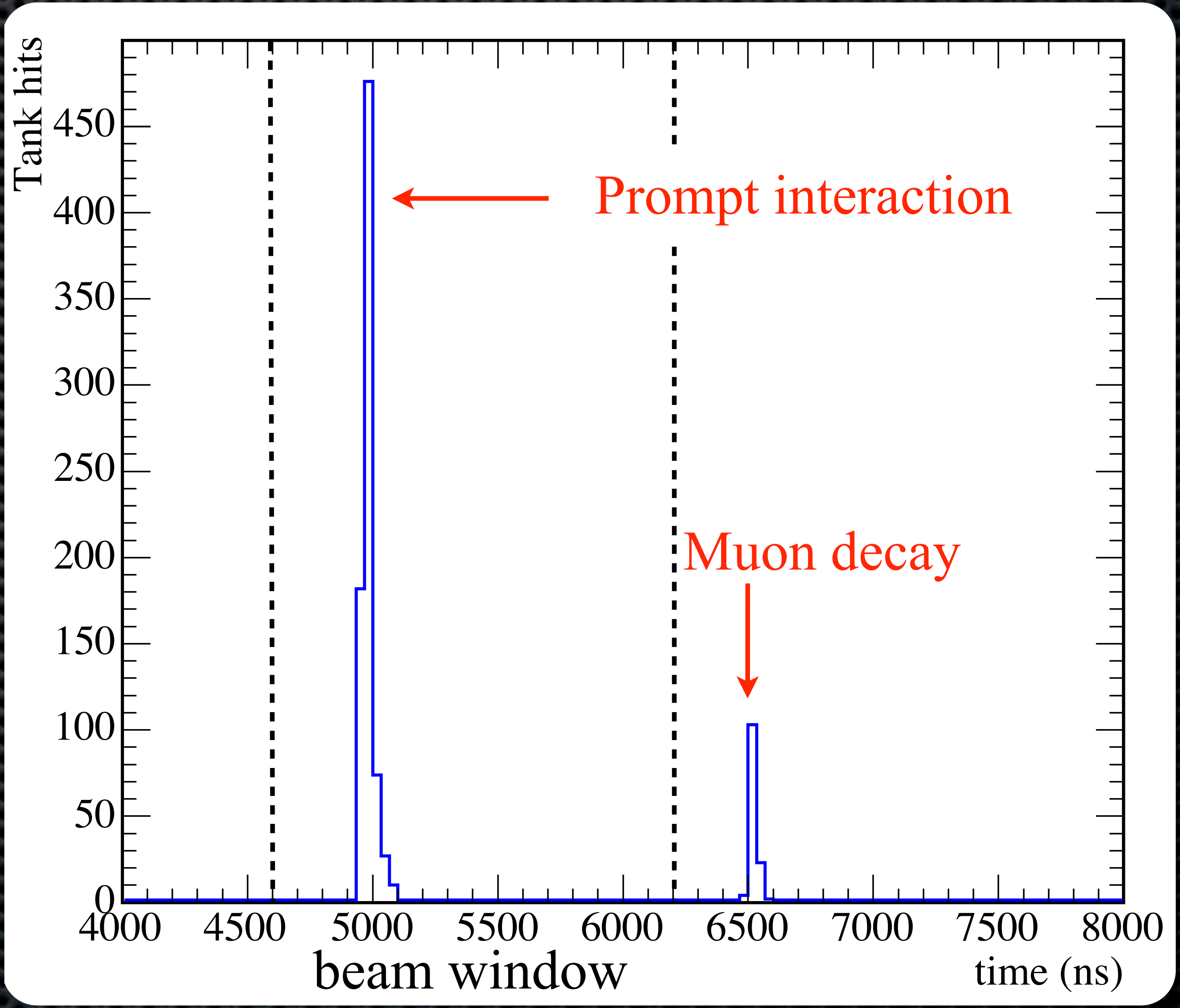


MiniBooNE “subevents”

- A subevent is a cluster of PMT hits within a short amount of time.
- The first subevent is the prompt neutrino interaction.
- All subsequent subevents are electrons from stopped muon decays.

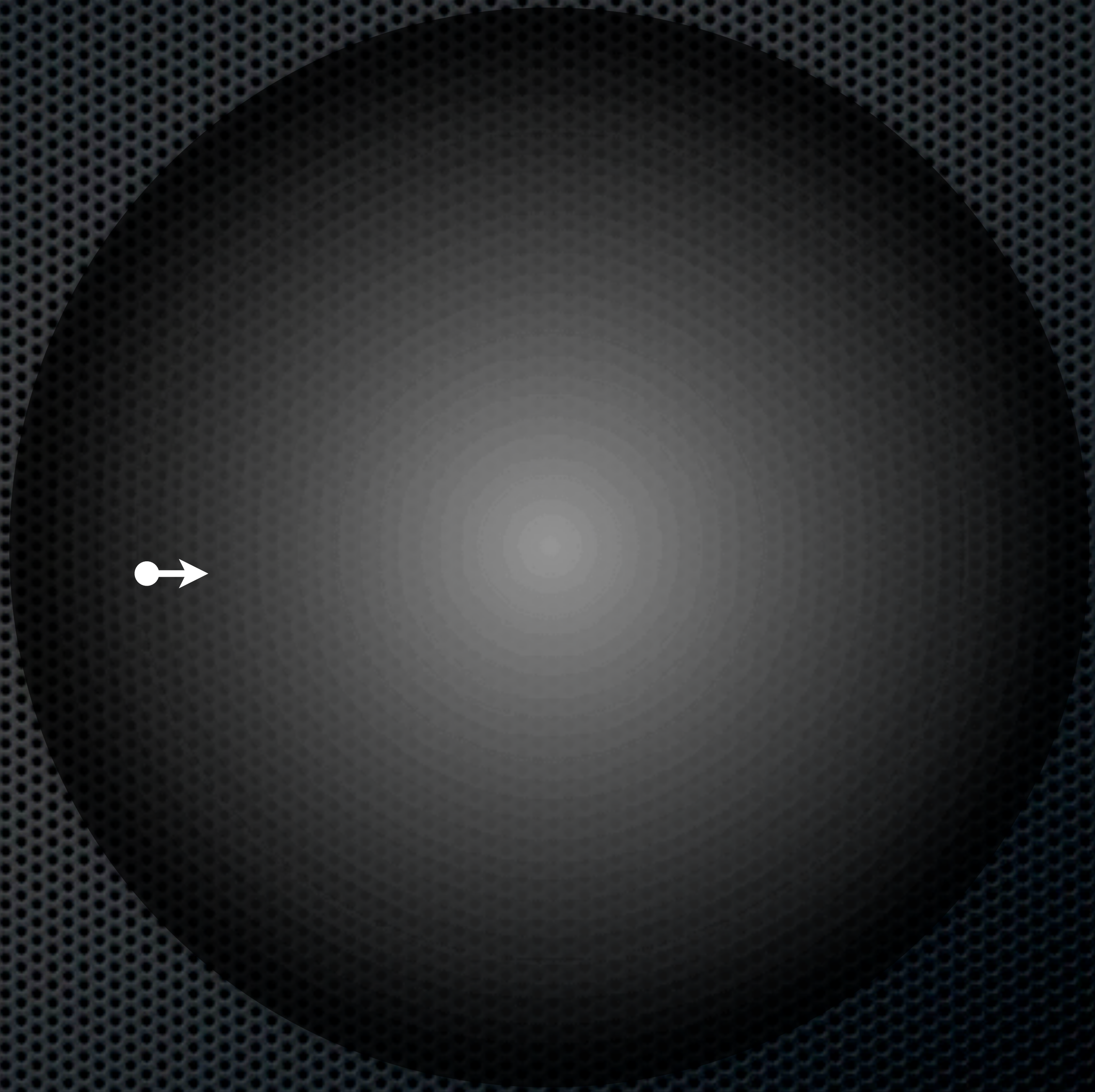
Mode	$NC\pi^0$	$CC\pi^0$	$CC\pi^+$
μ decays	0	1	2
subevents	1	2	3

A single neutrino event

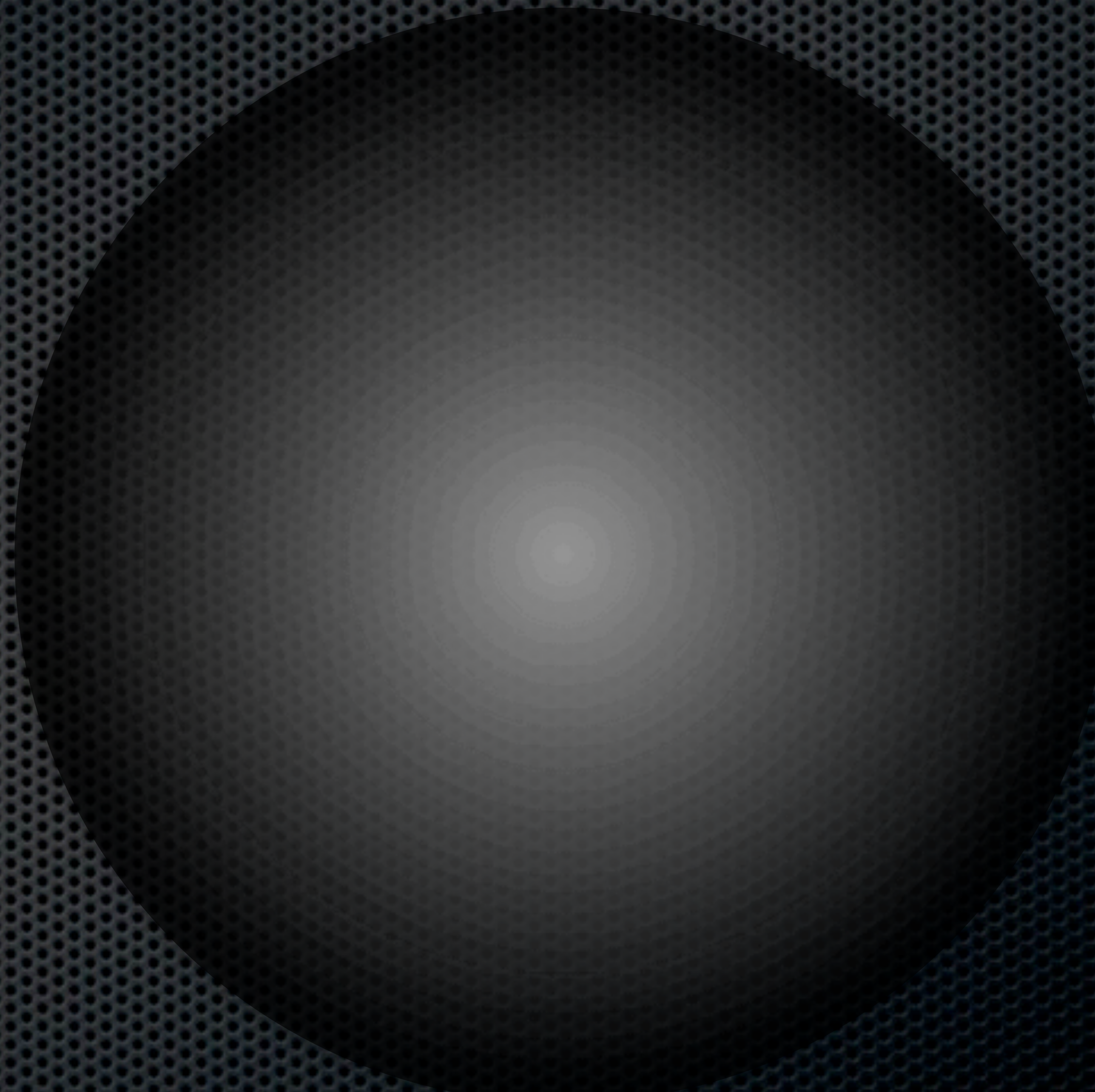


Muons in the tank

- Muons continuously lose energy until they stop.
- The decay-at-rest electron is above threshold and travels a short distance in a random direction.



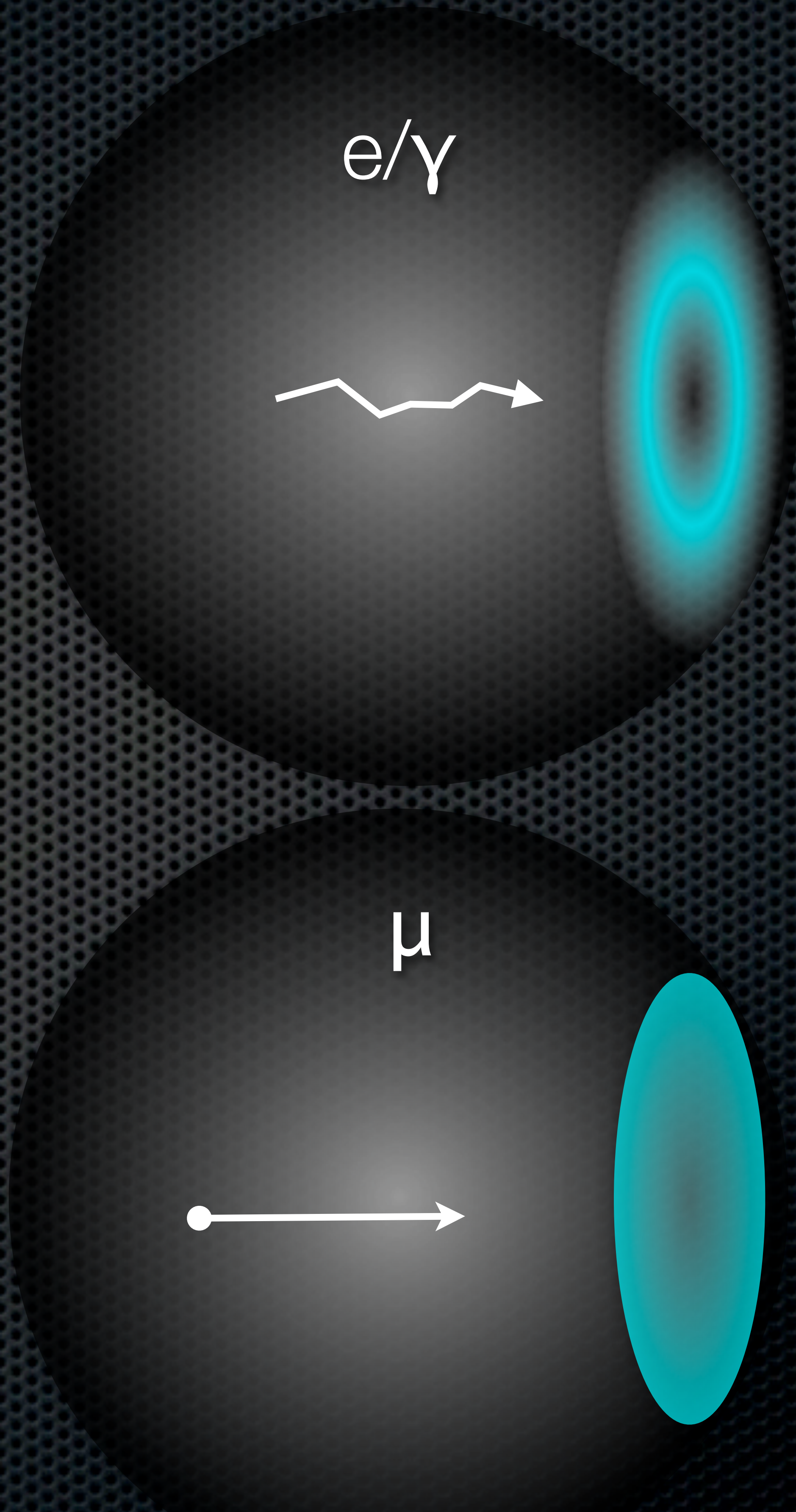
Muons in the tank



- Muons continuously lose energy until they stop.
- The decay-at-rest electron is above threshold and travels a short distance in a random direction.

Single-particle fitting

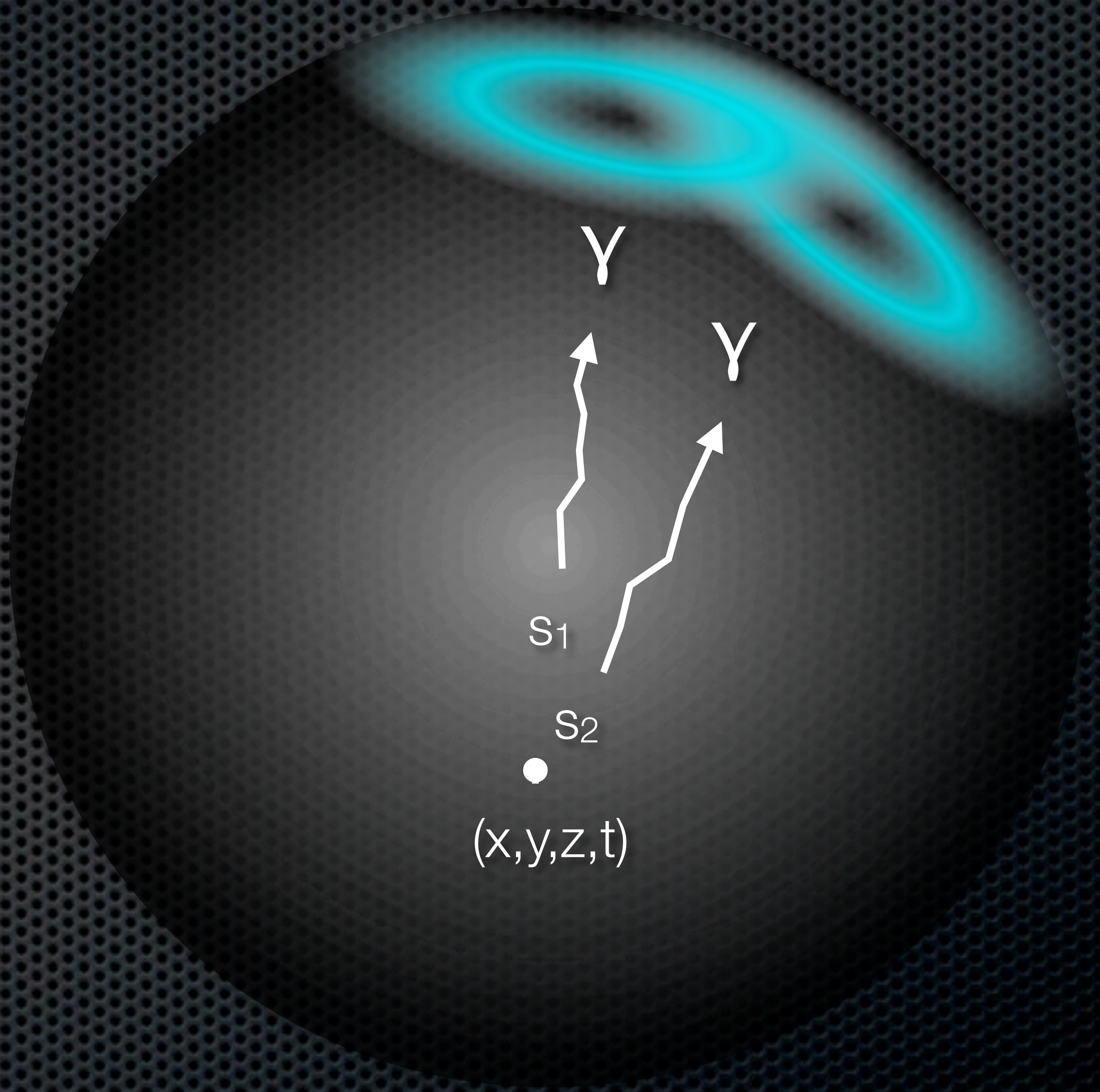
- A maximum-likelihood fit is performed to both identify the particle and its kinematics.
- Each particle track is parametrized by 7 quantities:
  - Event vertex: (x,y,z,t)
  - Kinetic energy: (E)
  - Direction: (θ,φ)
- Each particle type has a different predicted light profile.
  - Separate PDFs are combined for the Čerenkov and scintillation portions.
- The product of the PDFs for each PMT forms the likelihood.



R.B. Patterson et al., Nucl. Instrum. Meth. A608, 206 (2009)

CCπ^0 fitting

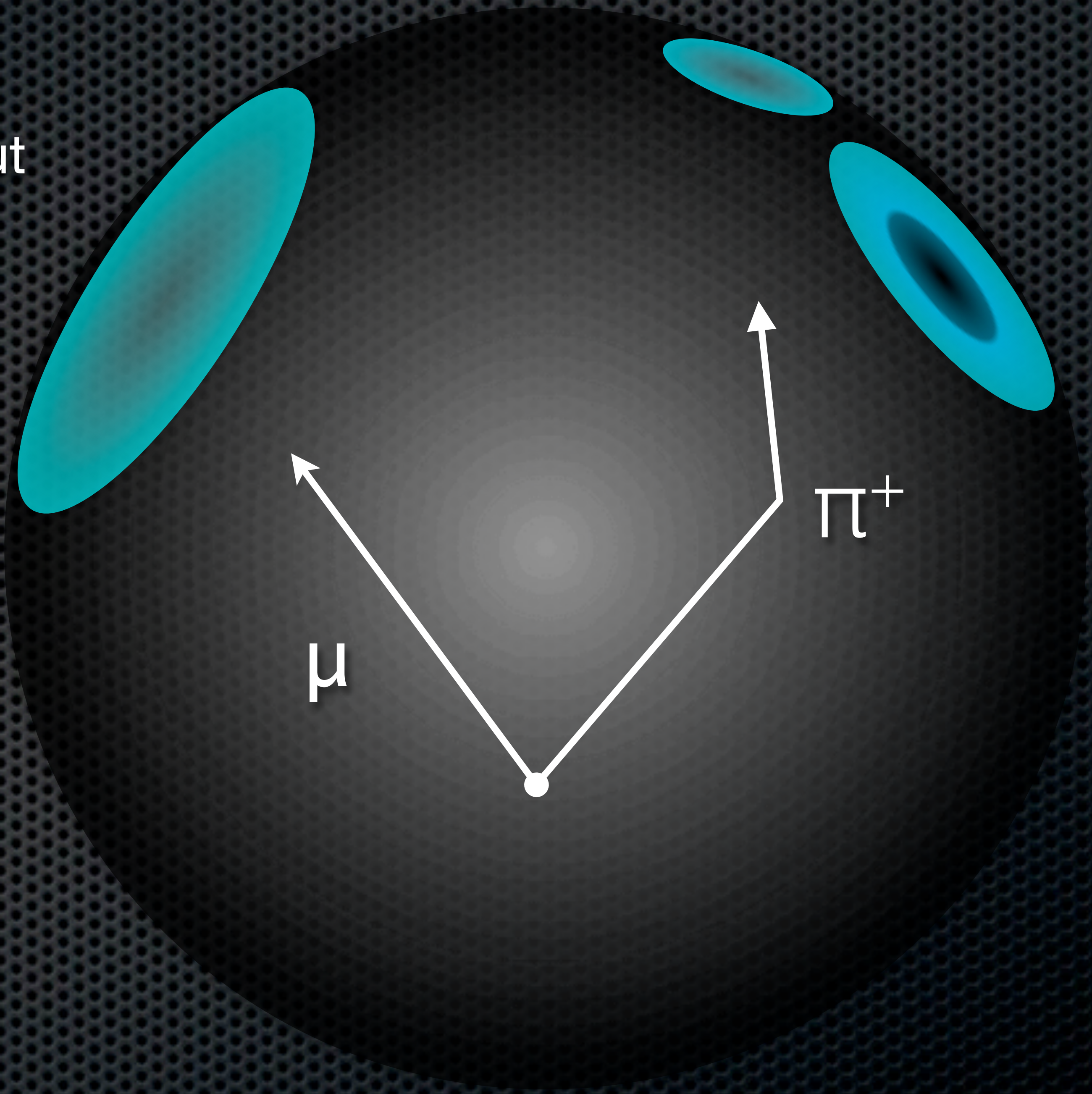
- For π^0 tracks, we have 12 parameters to fit:
  - Event vertex: (x,y,z,t)
  - 1st photon: (E,θ,φ,s)
  - 2nd photon: (E,θ,φ,s)
- The vertex is disjointed because of the photon conversion length (67cm) in mineral oil.
- The Čerenkov profiles are time sorted and weighted by the bayesian probability that that track triggered that tube first.
- The scintillation profiles are averaged.



- A constrained mass fit is also performed which is used to determine the kinematics.

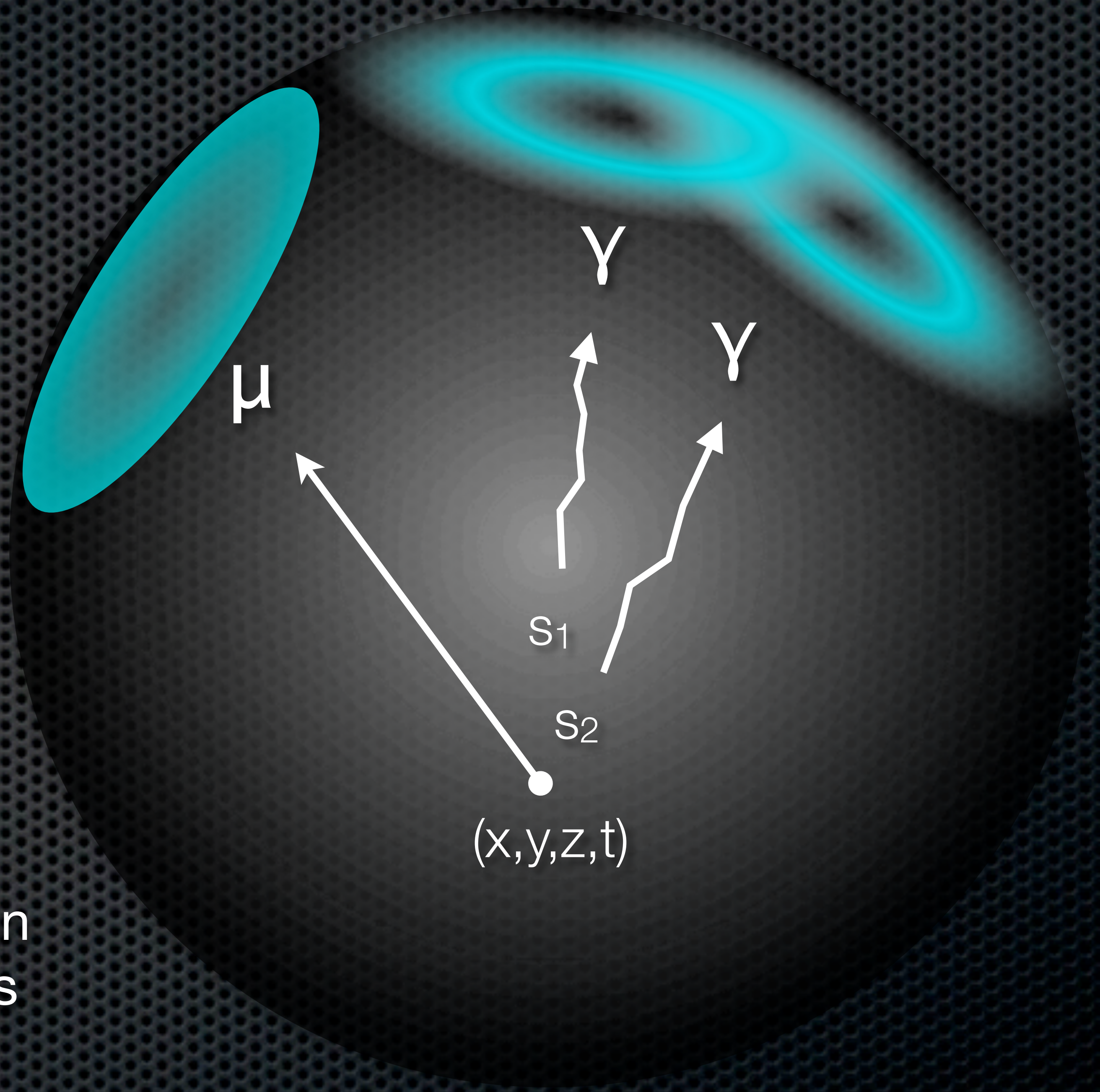
CCπ^+ fitting

- π^+ particles are similar to muons but occasionally have a hard hadronic scatter.
- For three tracks, we have 13 parameters to fit:
  - Event vertex: (x,y,z,t)
  - Muon: (E,θ,φ)
  - Upstream π^+: (E,θ,φ)
  - Downstream: $(\Delta E_{kink},\theta,\varphi)$



$CC\pi^0$ fitting

- For three tracks, we have 15 parameters to fit:
  - Event vertex: (x,y,z,t)
  - Muon: (E,θ,φ)
  - 1st photon: (E,θ,φ,s)
  - 2nd photon: (E,θ,φ,s)
- No mass constraint is ever used in the $CC\pi^0$ fit as the muon provides an accurate vertex.



Observables and inferables for single-pion

- Observables:
  - Lepton/photon/charged-pion four-momentum.
  - Neutral-pion kinematics: $p_{\pi^0} = p_{\gamma 1} + p_{\gamma 2}$
- Inferables:
  - Neutrino energy:
    X = sum of all measured particles
    m_p -> m_n for $CC\pi^+$

    $$E_\nu = \frac{m_p^2 - m_n^2 - m_X^2 + 2m_n E_X}{2\left(m_n - E_X + |p_X| \cos\theta_{\nu X}\right)}$$
  - Four-momentum transfer: $Q^2 = -(p_\nu - p_\mu)^2$
  - Resonance kinematics: $p_N = p_\nu - p_\mu + m_n$
- Assuming a stationary nucleon target, a nucleon recoil, and that the neutrino is traveling in the beam direction.

MC cross-section model NUANCE

- CCQE: Nucleons modeled as a relativistic fermi gas (RFG). Flat momentum distribution until a cutoff (fermi momentum).
  - Dipole form factor: **M_A = 1.03 GeV**

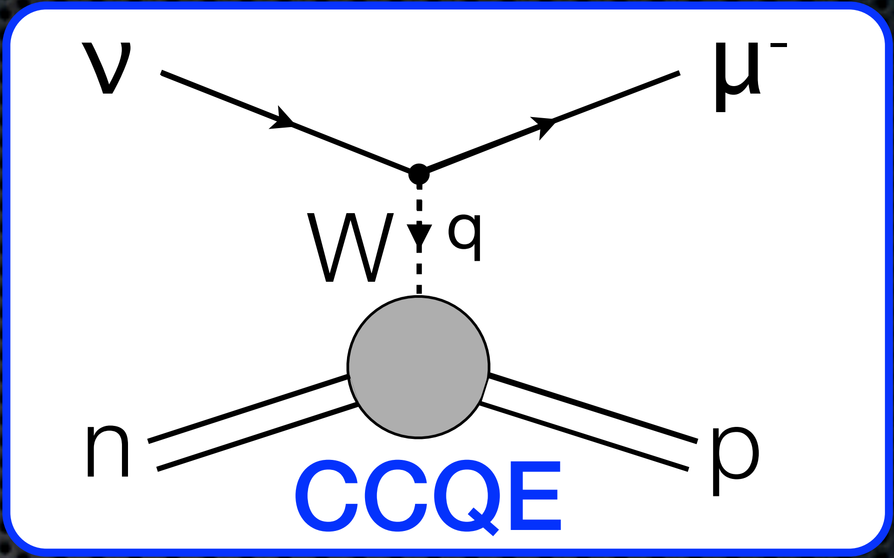
    Smith/Moniz: Nucl. Phys. B43, 605 (1972)

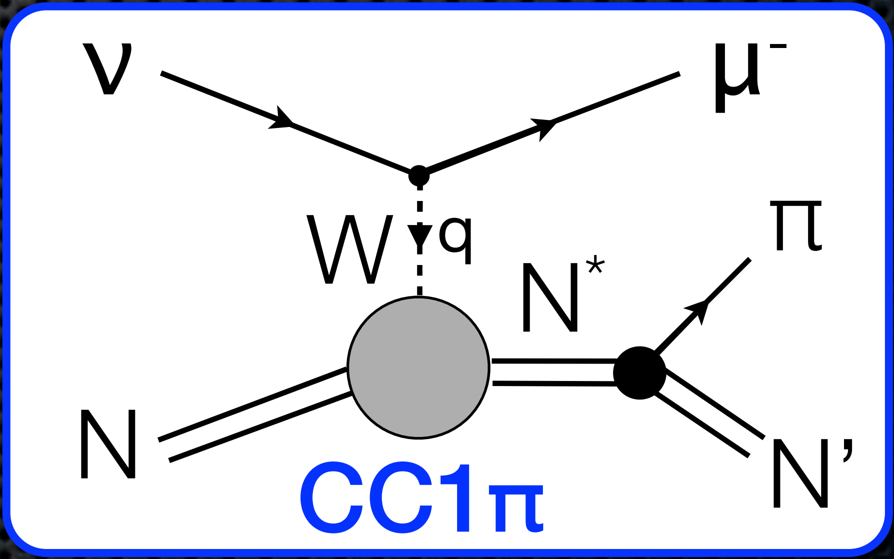
- (NC)CC1π: Relativistic quark model with the inclusion of 18 baryon resonance below 2 GeV.
  - Dipole form factor: **M_A = 1.1GeV**

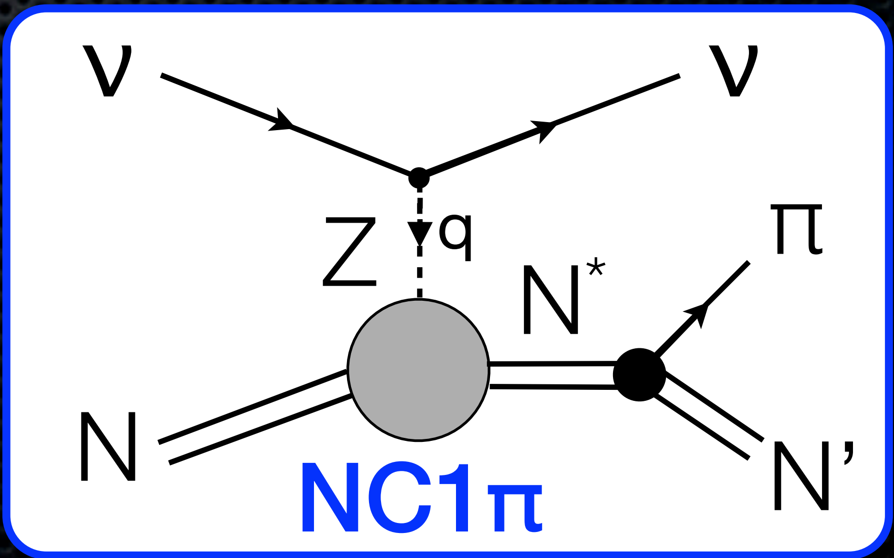
    Rein/Seghal: Annals of Physics, 133, 79 (1981)

$$F_A(Q^2) = \frac{F_A(0)}{(1 + Q^2/M_A^2)^2}$$

- FSI model includes nucleon resonance interactions with the spectator nucleons and pion interactions.
- MC model does not affect the measurements much.



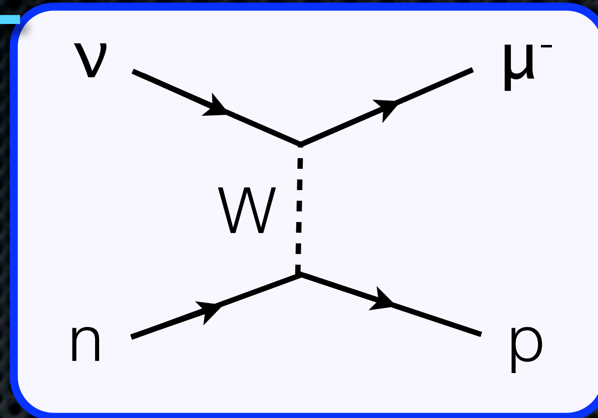


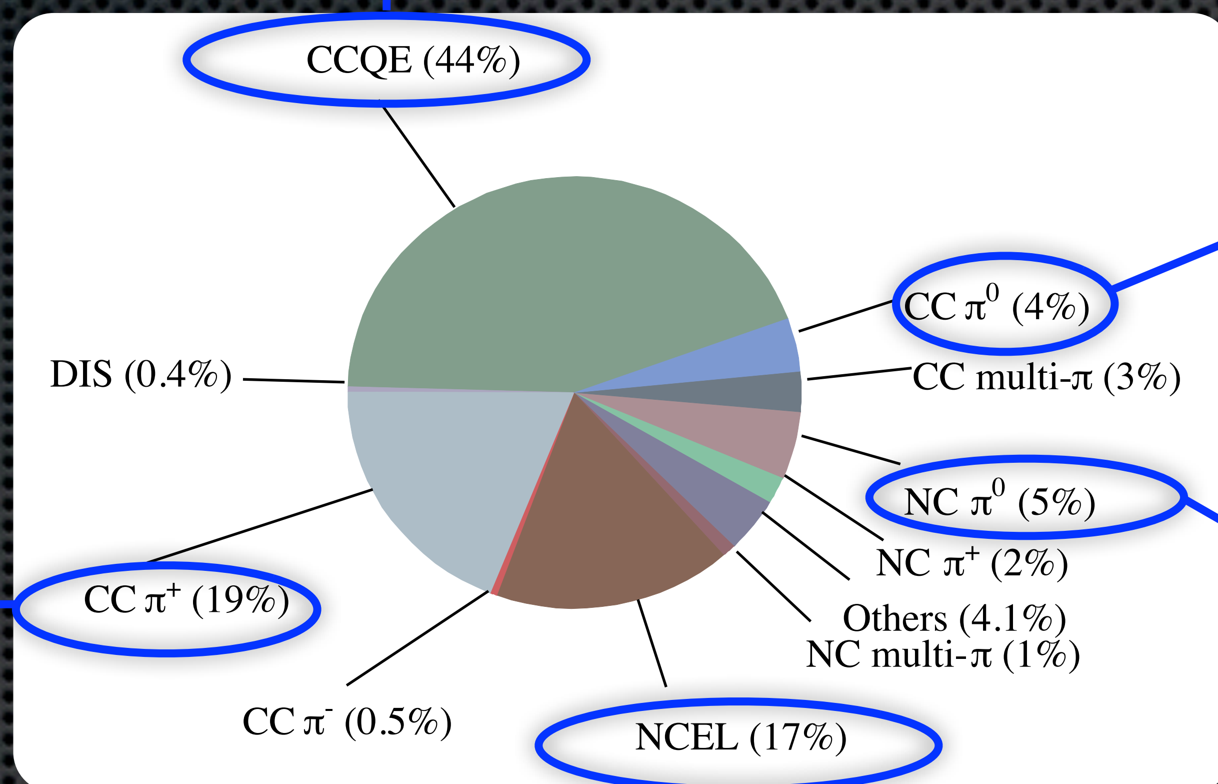


Predicted Event rates

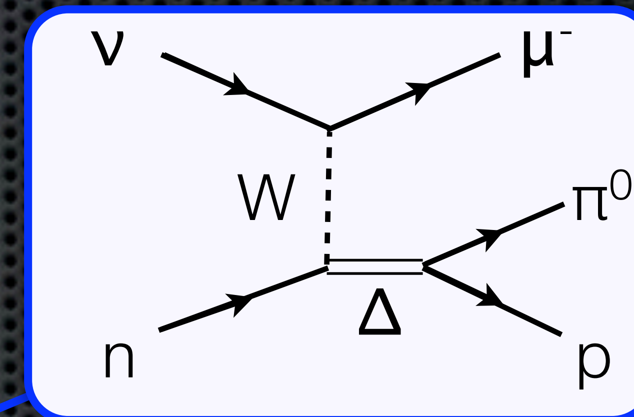
- A total of 6.3x10[20] p.o.t. equates to ~1,000,000 total neutrino interactions.
- MiniBooNE has measured 5 modes in detail.

CCQE

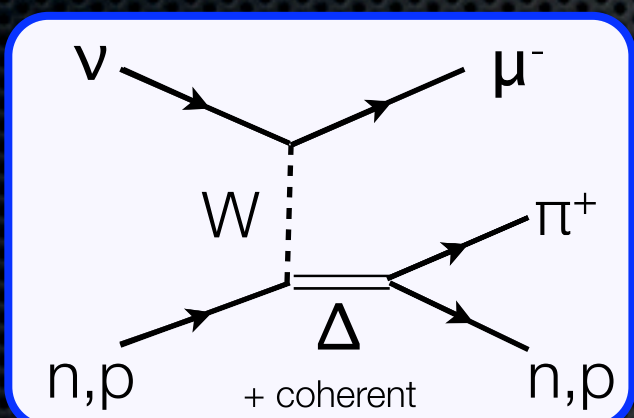


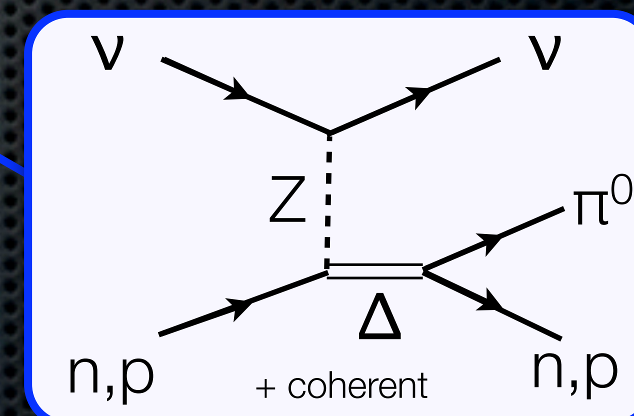


CCπ⁰

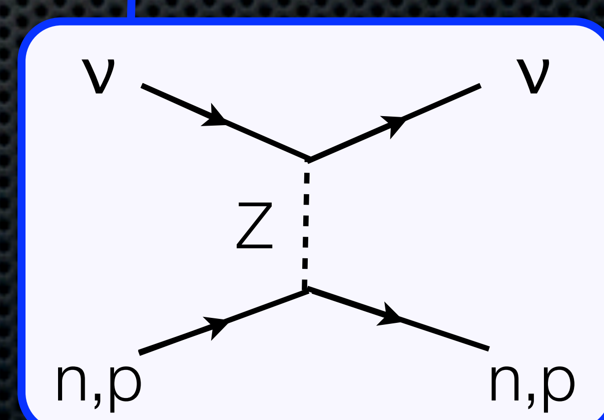


CCπ⁺





NCπ⁰

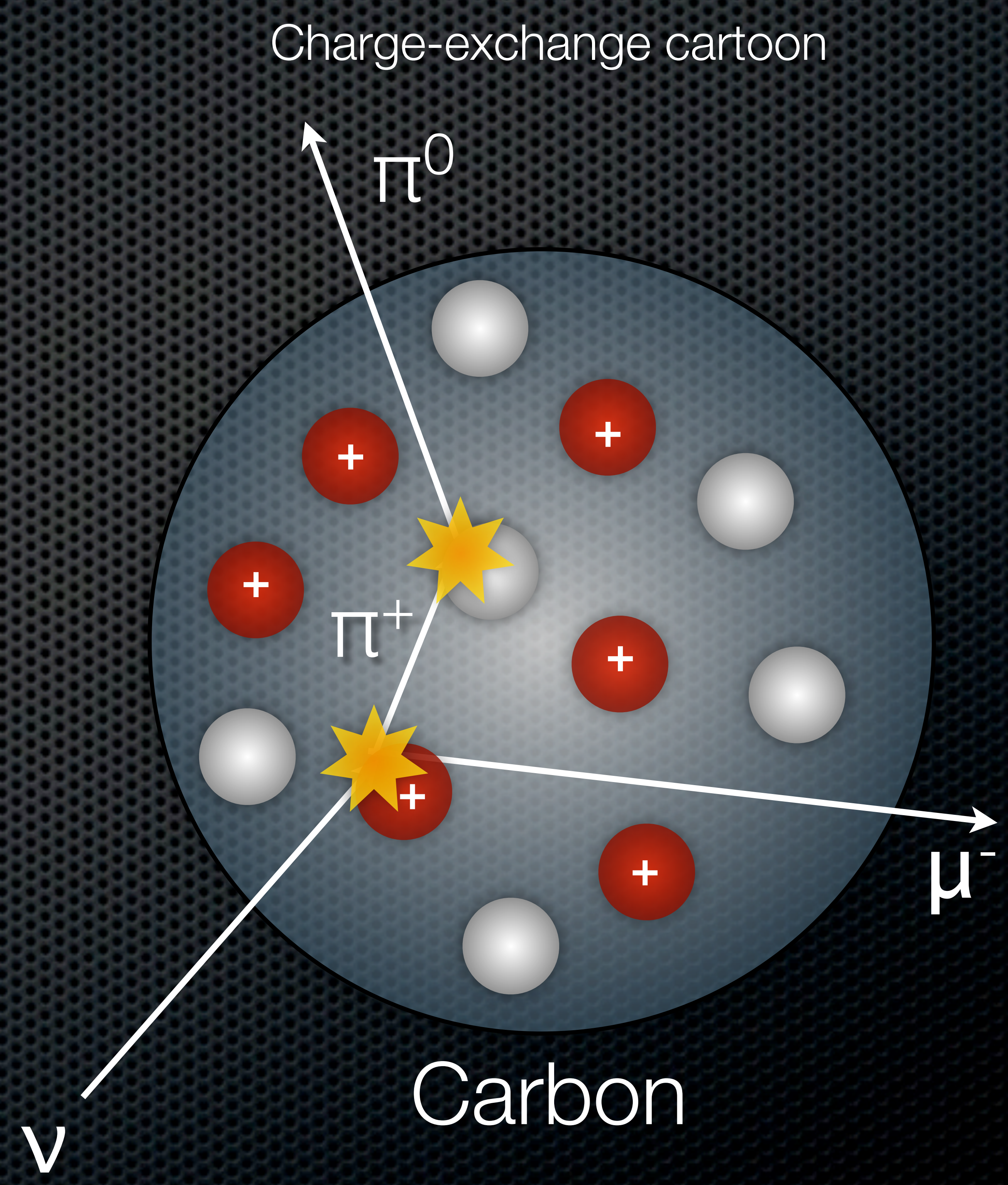


NCEL

- These 5 modes comprise 89% of the total rate and 96% of the CC modes.

Final-state interaction effects

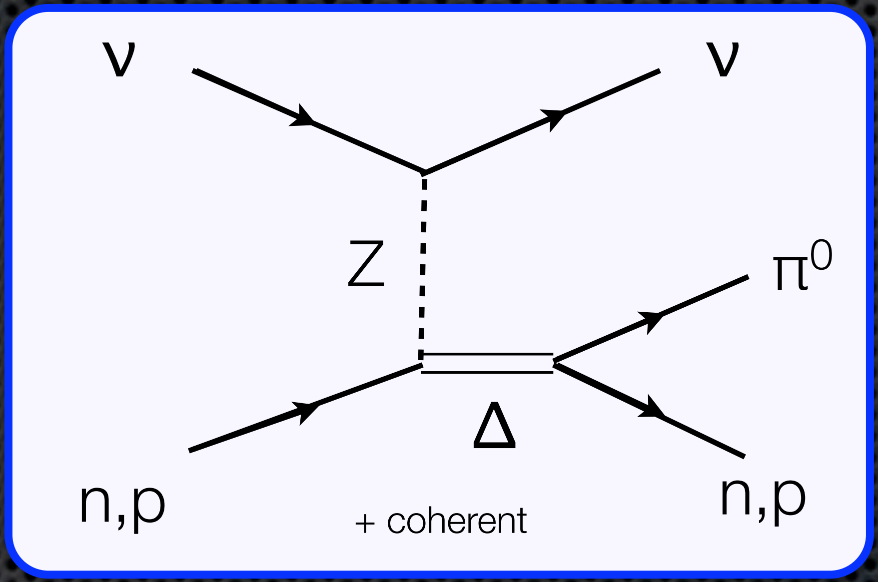
- The particles that "exit" the target nucleus are not necessarily the final-state particles from the initial neutrino-nucleon interaction.
- True CCπ^+ can look like CCQE (π^+ absorption) or like CCπ^0 (charge exchange).
- As experimentalists all we can "see" is what came out of the nucleus. These are called observable events.
- Generally, the original nucleus breaks up.
  - The nuclear debris is typically unobserved in a Čerenkov-style detector.
- Not corrected out!



Event selection cuts

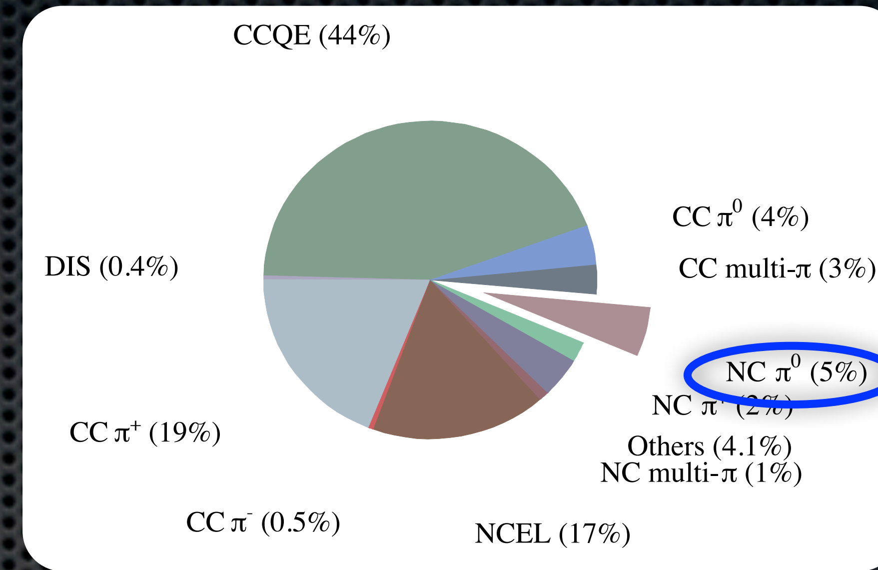
- Simple cuts on basic quantities help classify events into different categories.
- Beam time window cut on first SE: $4600\ \mathrm{ns} < \langle T \rangle < 6200\ \mathrm{ns}$
- Subevents cut: (1 for NCπ^0, 2 for CCπ^0, and 3 for CCπ^+)
- PMT hits cuts:
  - Veto hits < 6 for all subevents.
  - Tank hits $> 200(175)$ for first subevent (175 is for CCπ^+).
  - Tank hits < 200 for subevents 2 & 3.
- Each also uses slightly different fiducial cuts (efficiency corrected in the cross sections).

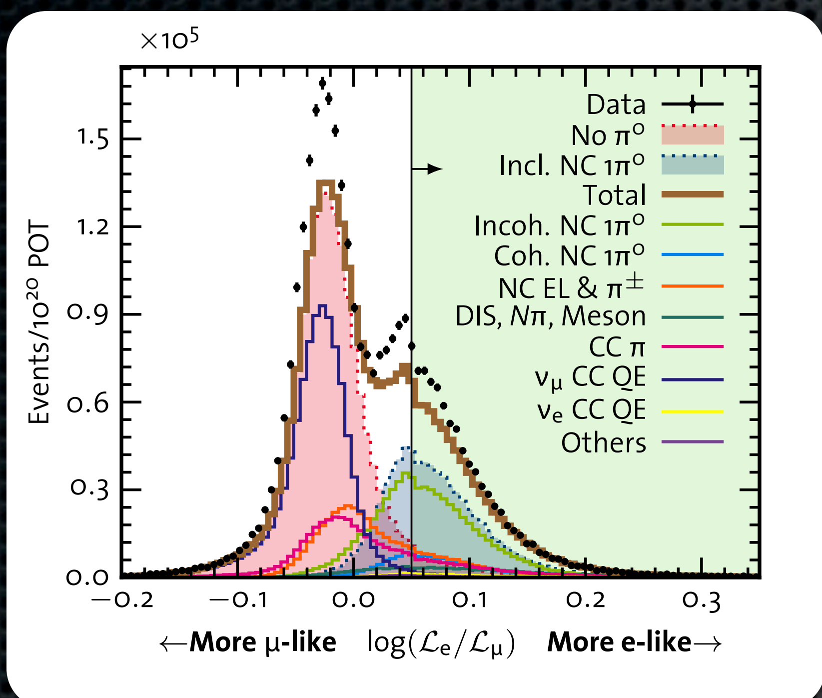
Observable NCπ^0 differential cross sections

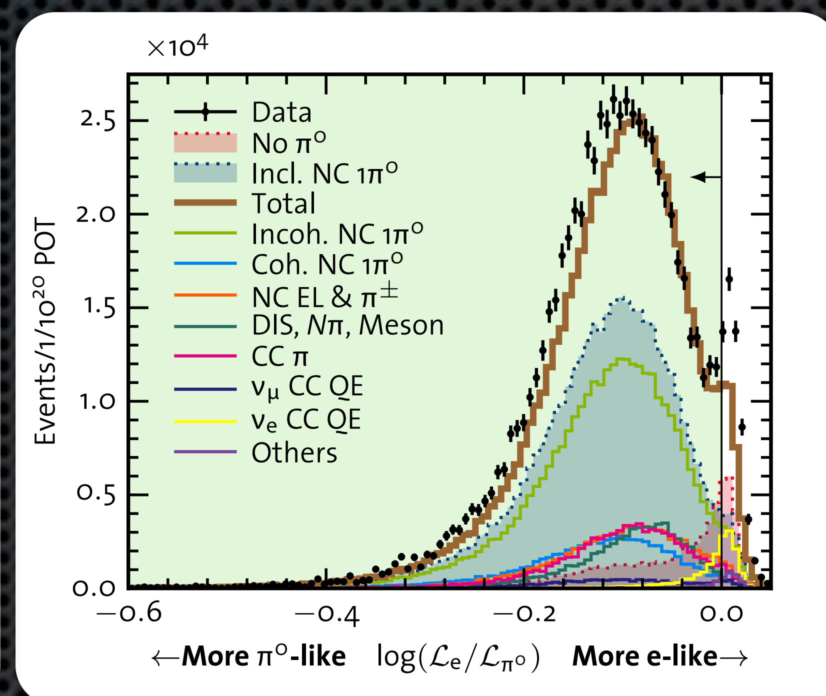


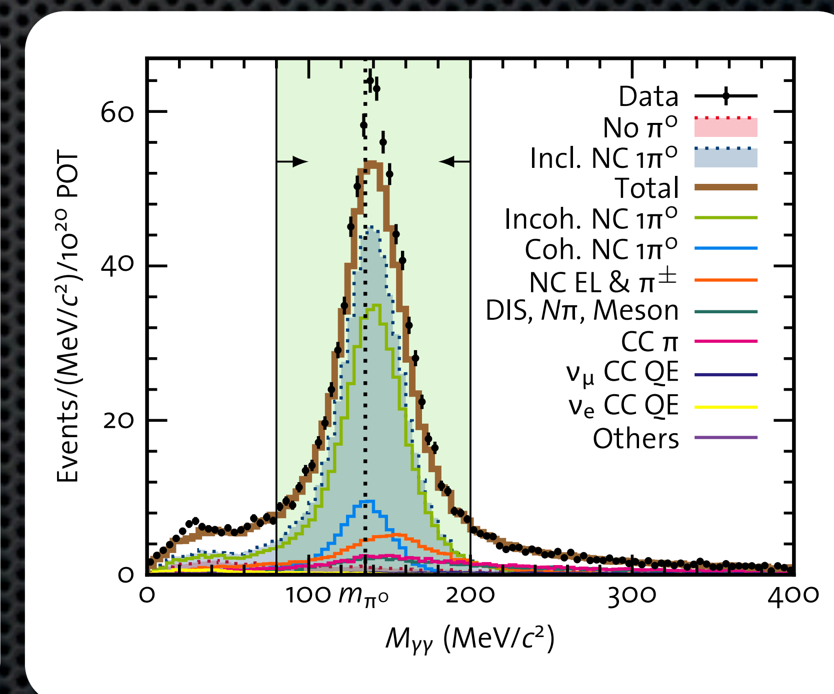
- Previously presented by C. Anderson at NUINT09.
- A.A. Aguilar-Arevalo et al., Phys. Rev. D81, 013005 (2010)

NCπ^0 selection cuts





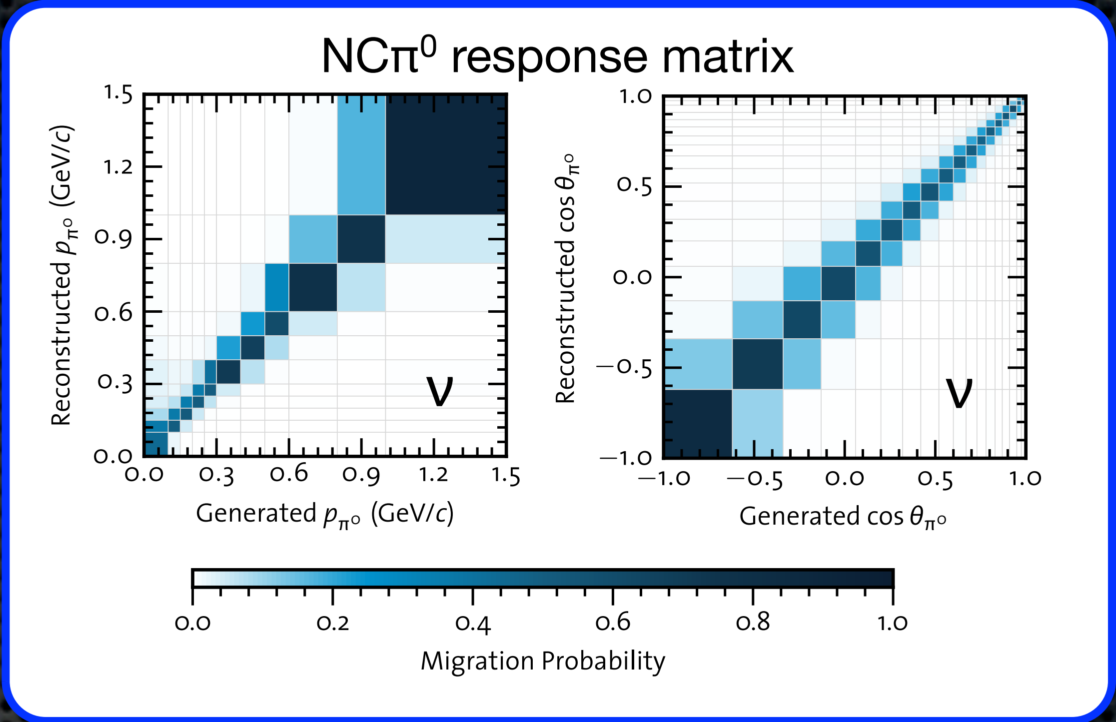




- Likelihood cuts are optimized to reject backgrounds (constrained mass fit).
- Mass cut is from the unconstrained fit.
- A total of 21375 candidate events with 75% purity and 36% efficiency.

Unfolding

- Attempts to correct out detector response and reconstruction assumptions to help remove the dependance of the measurement on the experiment.
- The methods explored in the NCπ^0 analysis:
  - None.
  - Inverse response matrix (not used).
  - Tikhonov Regularization (smooth the Inverse response matrix).
  - Bayesian unsmearing.
- Both CCπ^+ and CCπ^0 use the Bayesian method exclusively.



Inverse: Normalize out the true distribution; Invert.

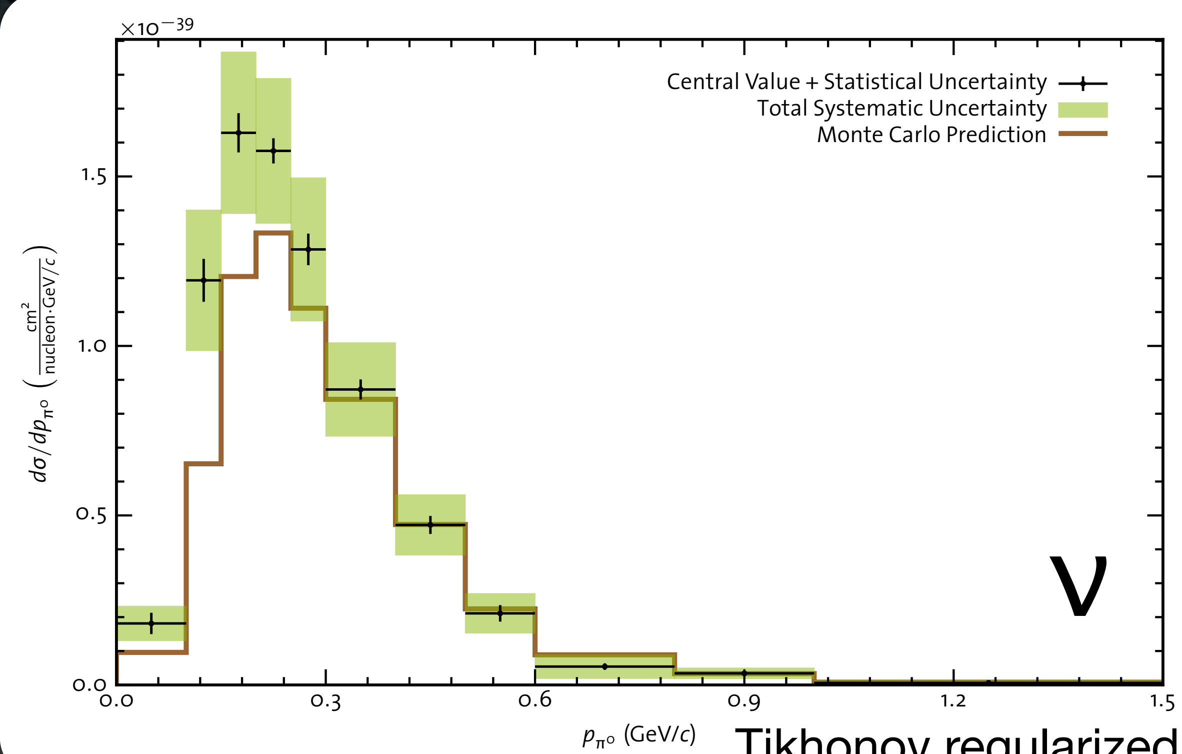
$$R_{ij}^{-1} = \left[\frac{P(t_j|r_i)P(r_i)}{\Sigma P(t_j|r_n)P(r_n)} \right]^{-1}$$

Bayesian: Normalize out the reconstructed distribution.

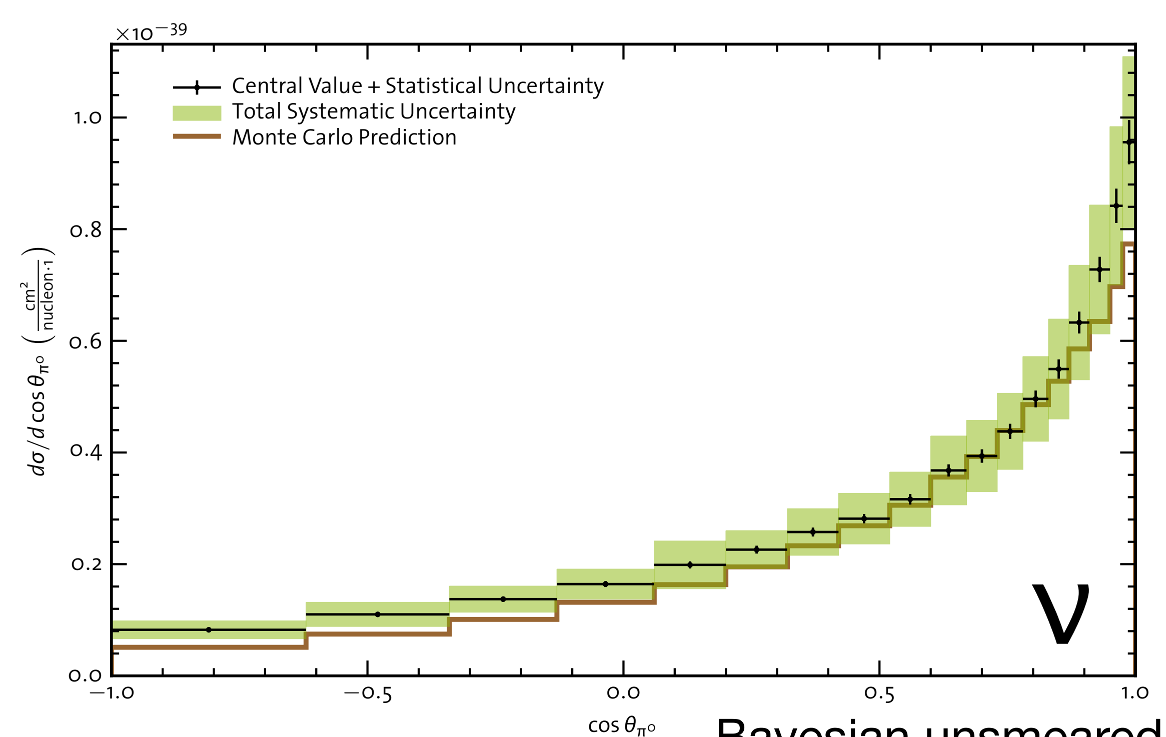
$$U_{ij} = P(t_i|r_j) = \frac{P(r_j|t_i)\,P(t_i)}{\Sigma\,P(r_j|t_n)\,P(t_n)}$$

NCπ^0 cross sections

A.A. Aguilar-Arevalo et al.,Phys. Rev. D81, 013005 (2010)



Tikhonov regularized

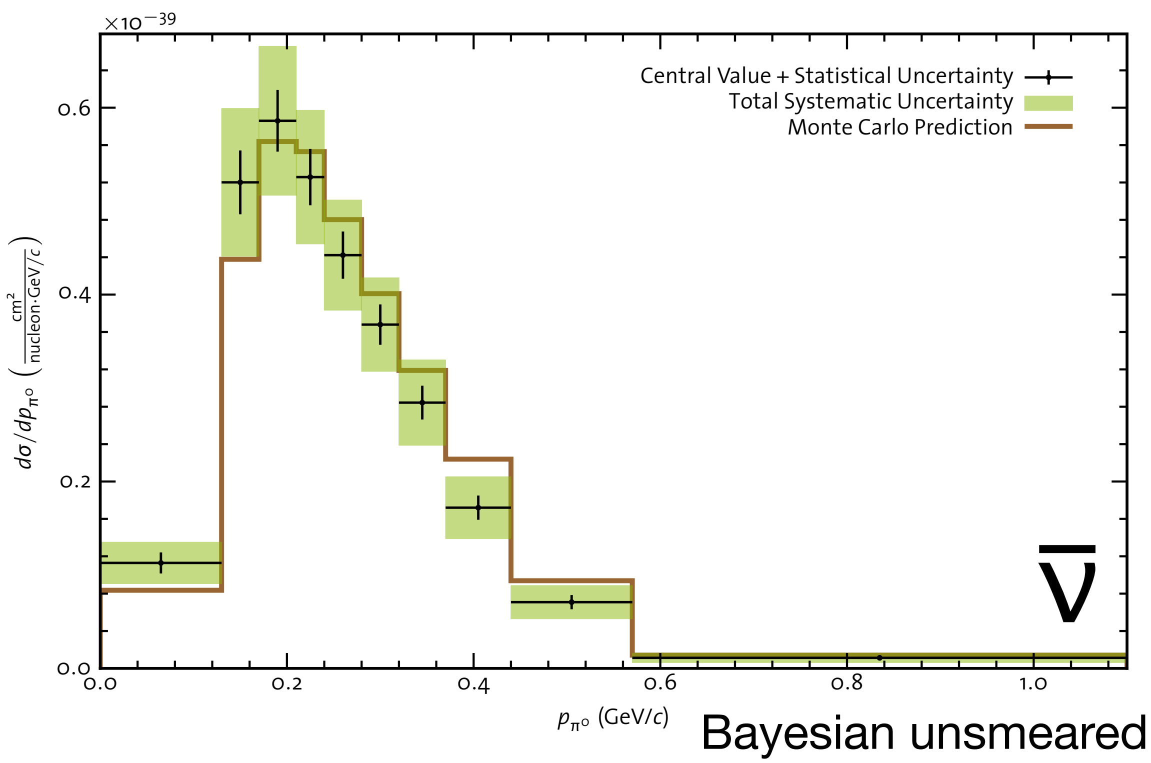


Bayesian unsmeared

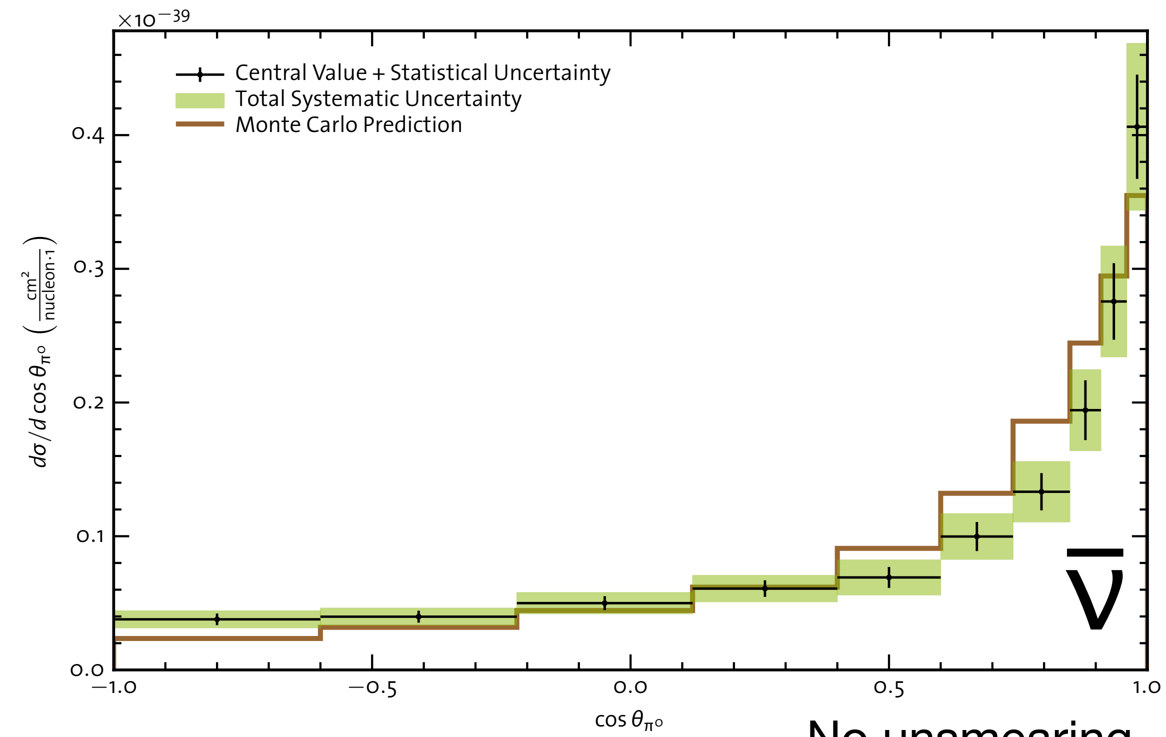
- Full reconstruction of both photons allows for the measurement of the π^0 kinematics.
- NUANCE normalization prediction is low compared with the measurements.
- 15.9% total uncertainty.
  - ~11% from π$^+$ production in the beam.
  - ~8% from neutrino cross-section model.

NCπ^0 anti-neutrino cross sections

- NUANCE normalization roughly matches the measurements.

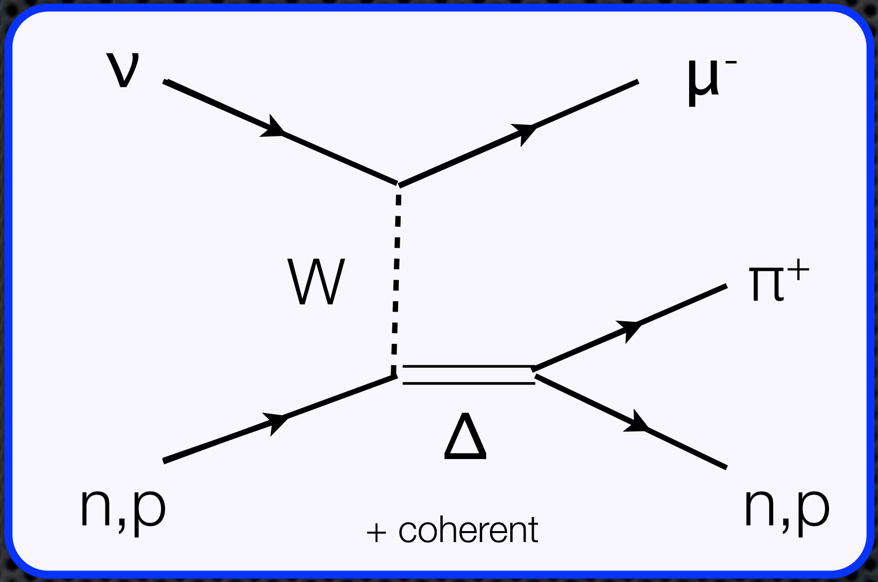


Bayesian unsmeared



No unsmearing

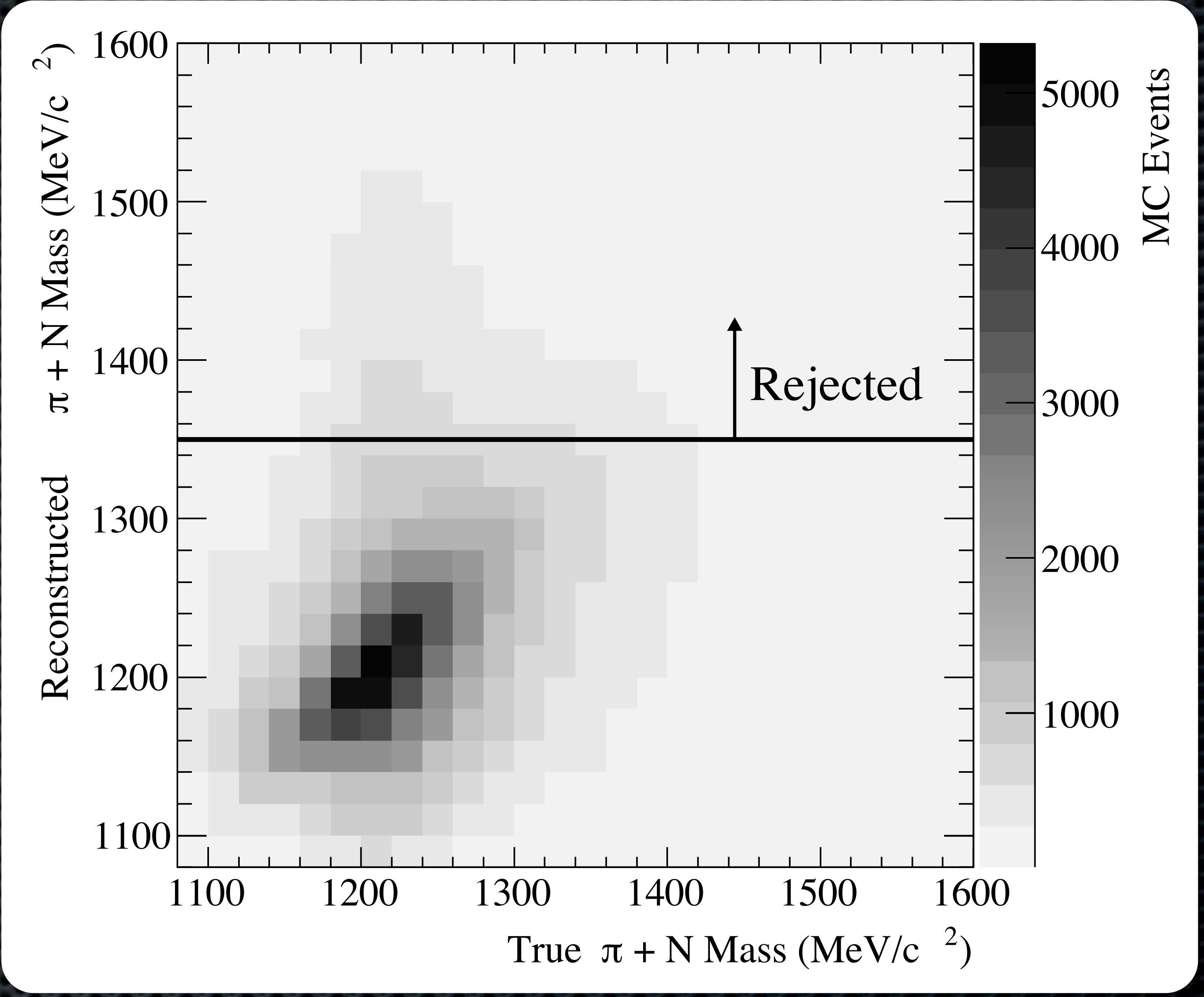
Observable CCπ^+ cross-sections



- Previously presented by M. Wilking at NUINT09.
- arXiv:1011.3572 accepted by PRD.

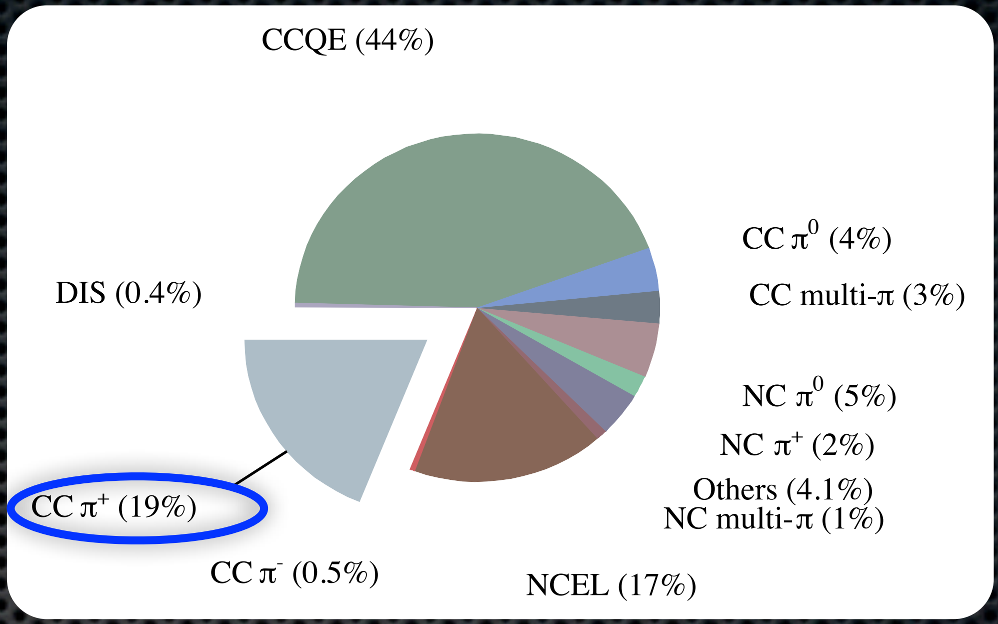
CCπ$^+$ selection cuts

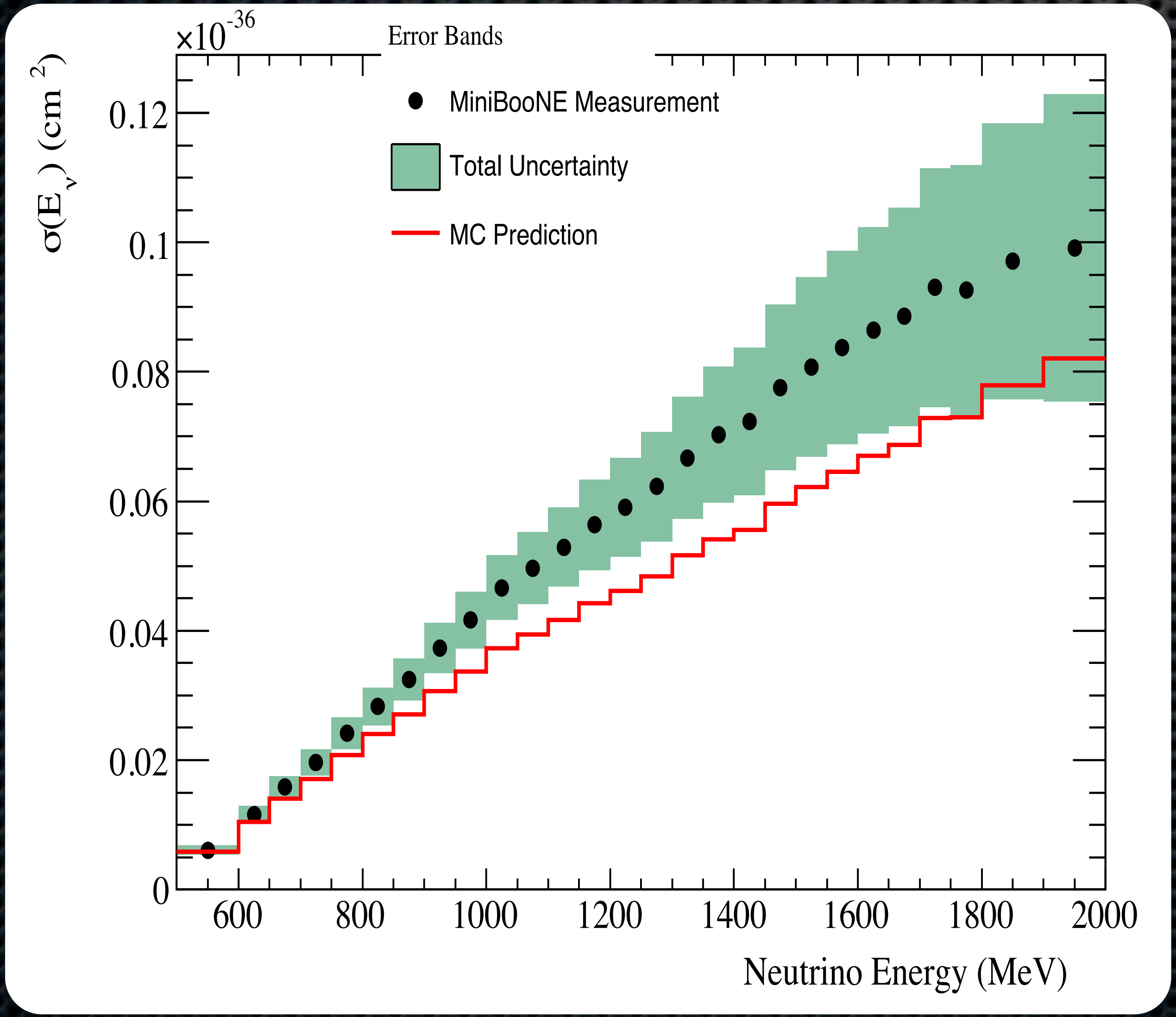
- 3 subevent sample is already mostly pure CCπ$^+$.
- Hadronic-system mass cut:
  - Rejects misreconstructed events and some more backgrounds.
- A total of 48,322 candidate events with an efficiency of 12.7% and a purity of 90.0%.
  - Purest measured mode in MiniBooNE.

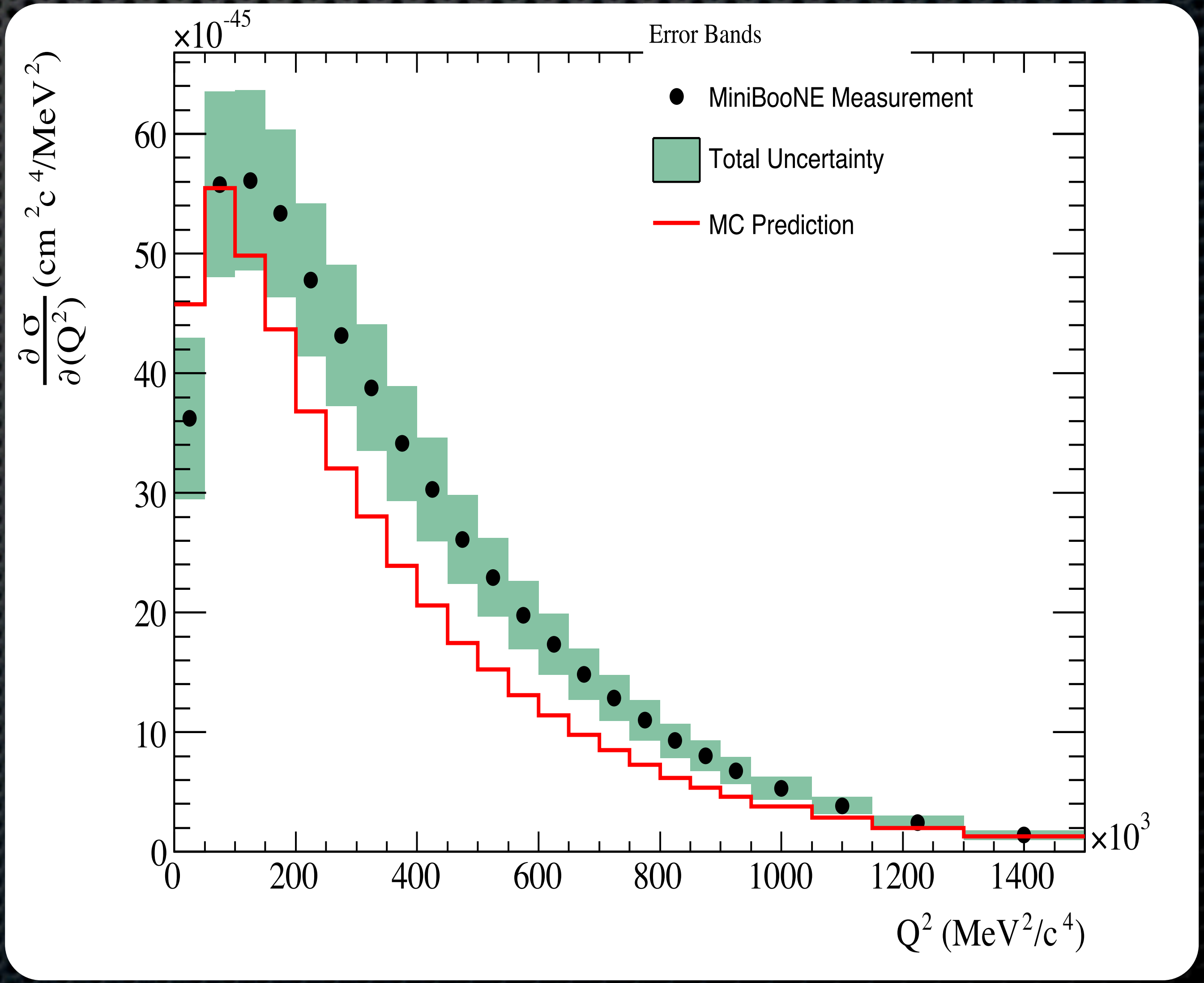


Observable CCπ+ cross sections

- NUANCE prediction is low compared with the measurements.
- Data shows a low-Q^2 suppression.

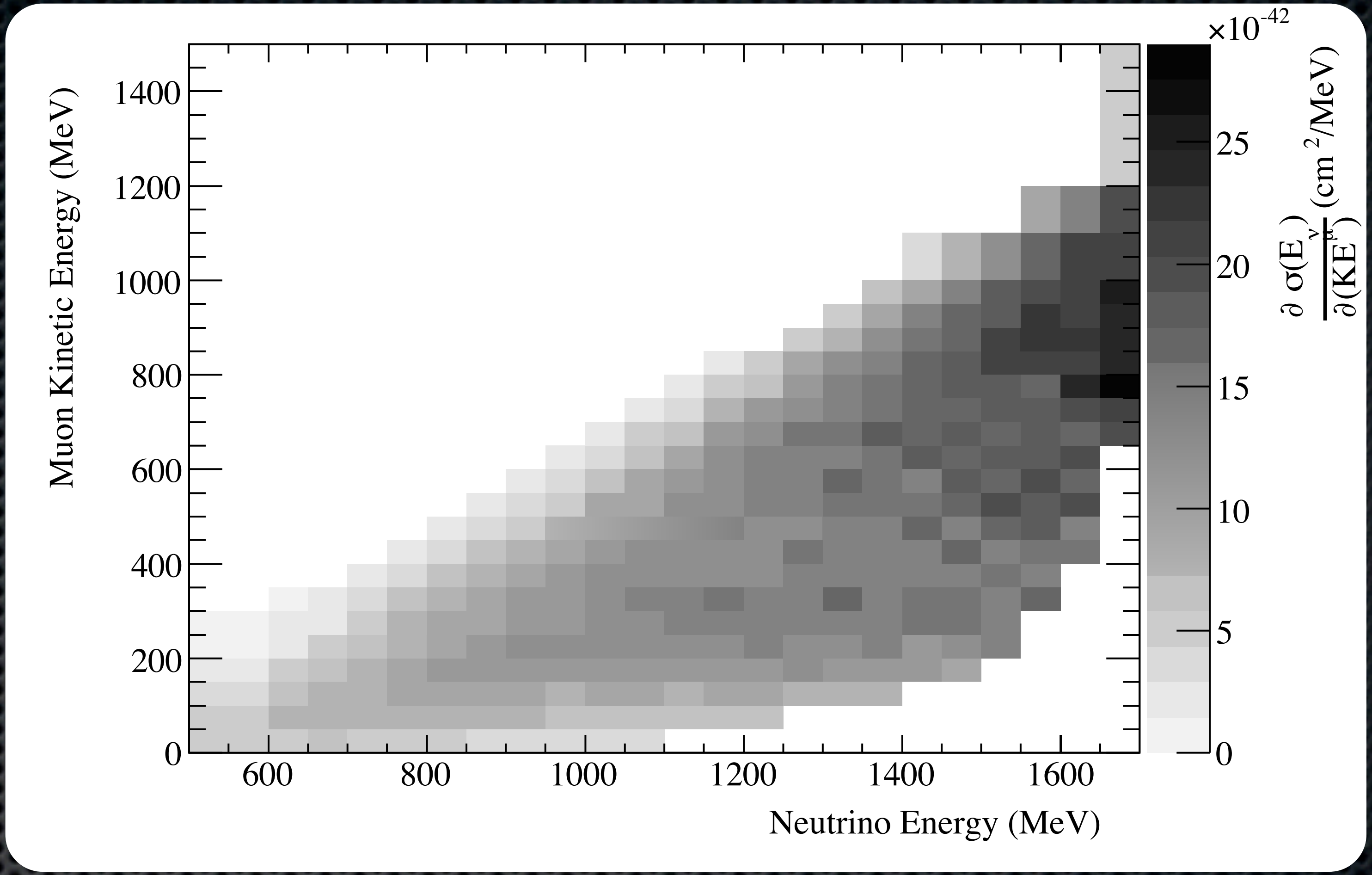


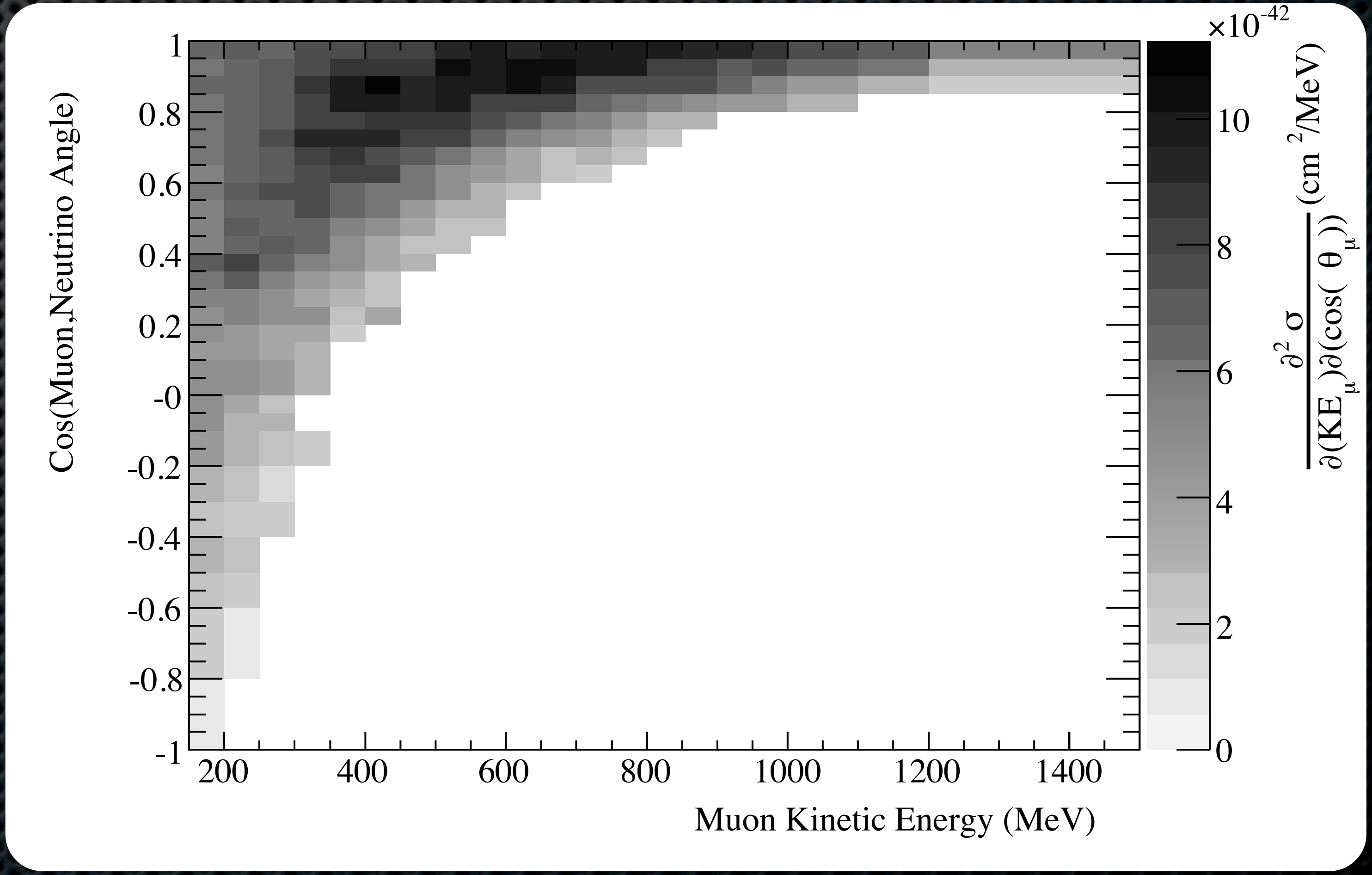




Muon differential cross sections

- Single-differential cross-section measurements are presented as a function of neutrino energy to remove the flux dependance.
- First ever double-differential cross sections in angle and energy!





Pion differential cross sections

- Pion observables are also measured.
- A total of 8 cross-section measurements are available:

$\sigma(E_\nu)$

$d\sigma(E_\nu)/dQ^2$

$d\sigma(E_\nu)/dT_\mu$

$d\sigma(E_\nu)/d\cos\theta_\mu$

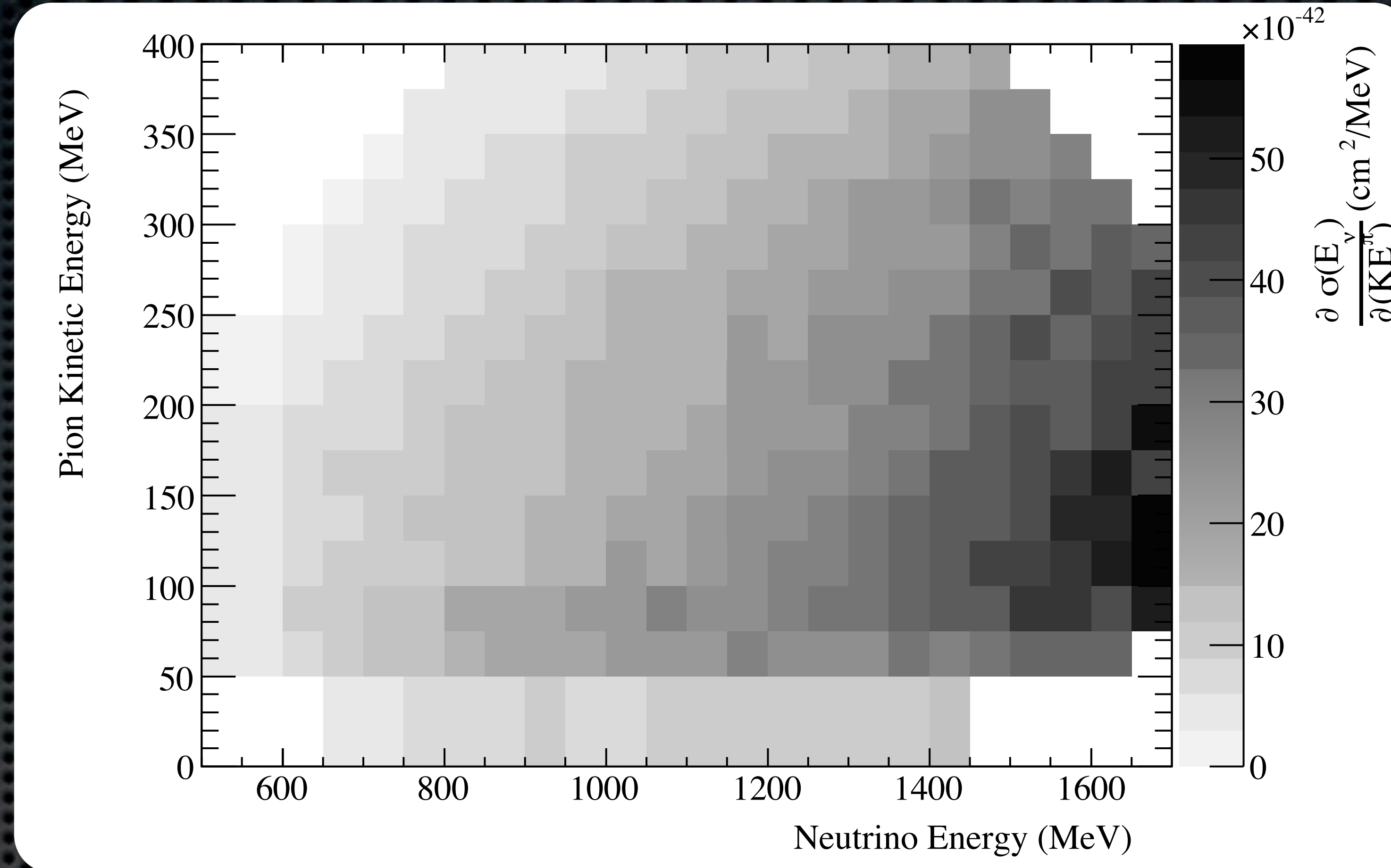
$d\sigma(E_\nu)/dp_\pi$

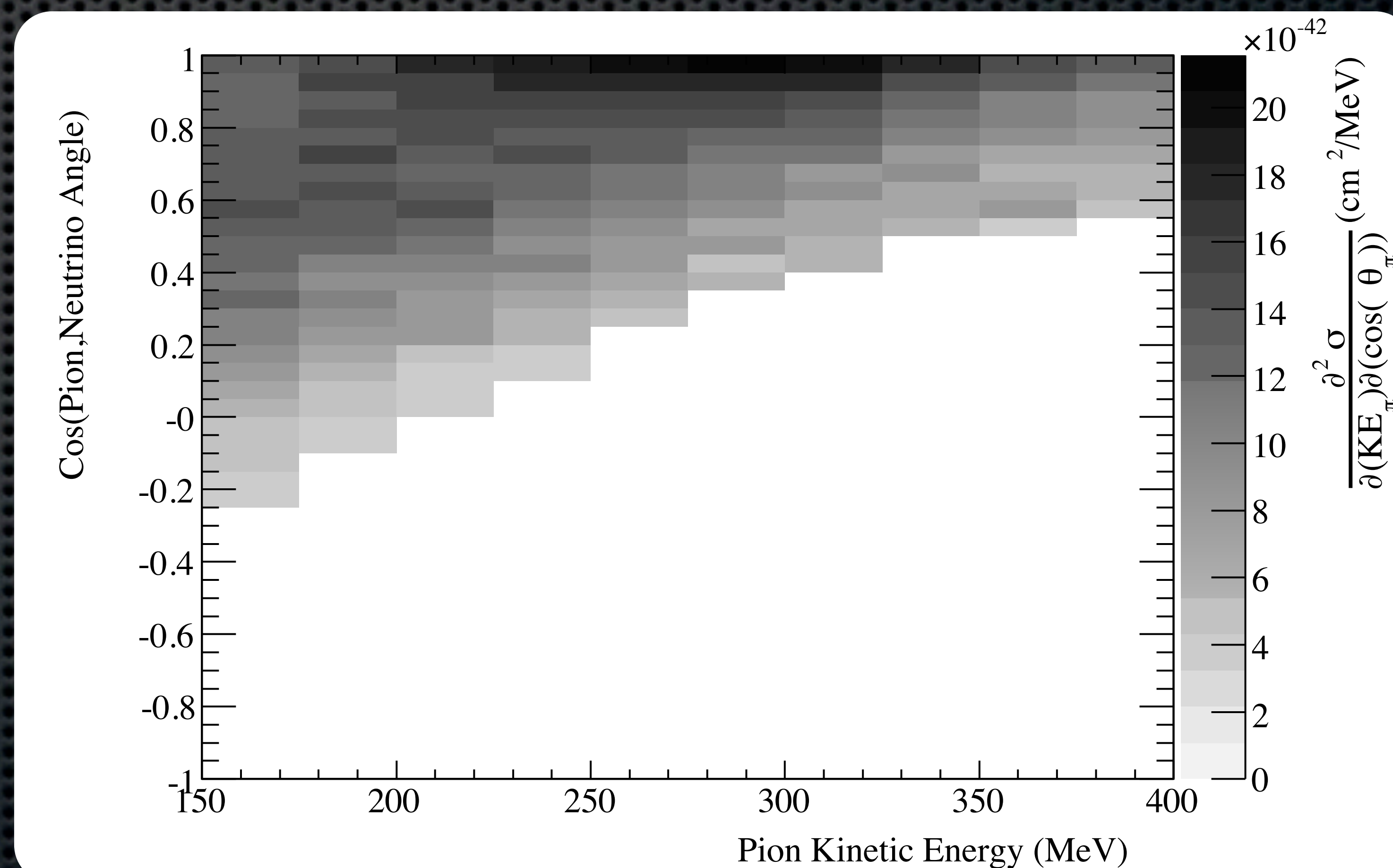
$d\sigma(E_\nu)/d\cos\theta_\pi$

$d^2\sigma/dT_\mu d\cos\theta_\mu$

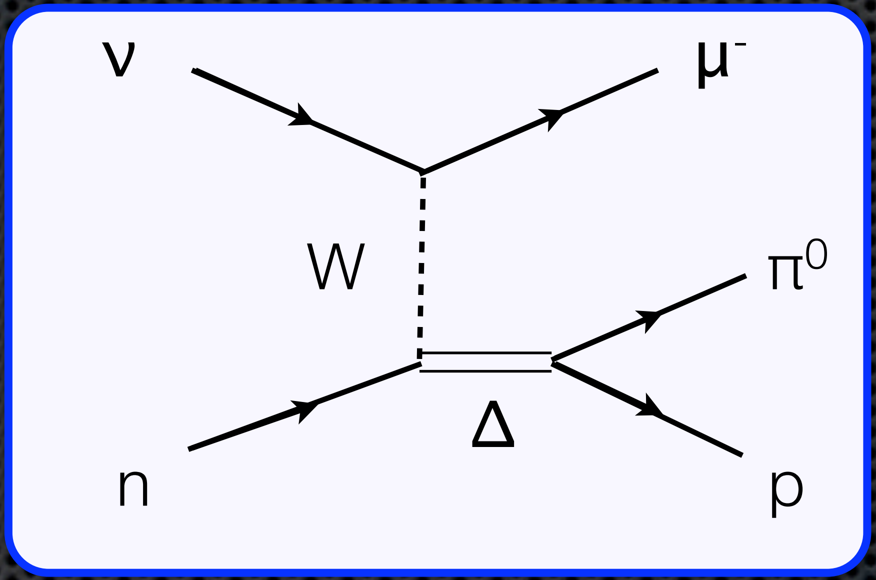
$d^2\sigma/dT_\pi d\cos\theta_\pi$

least model dependent! (this note covers the last six measurements)





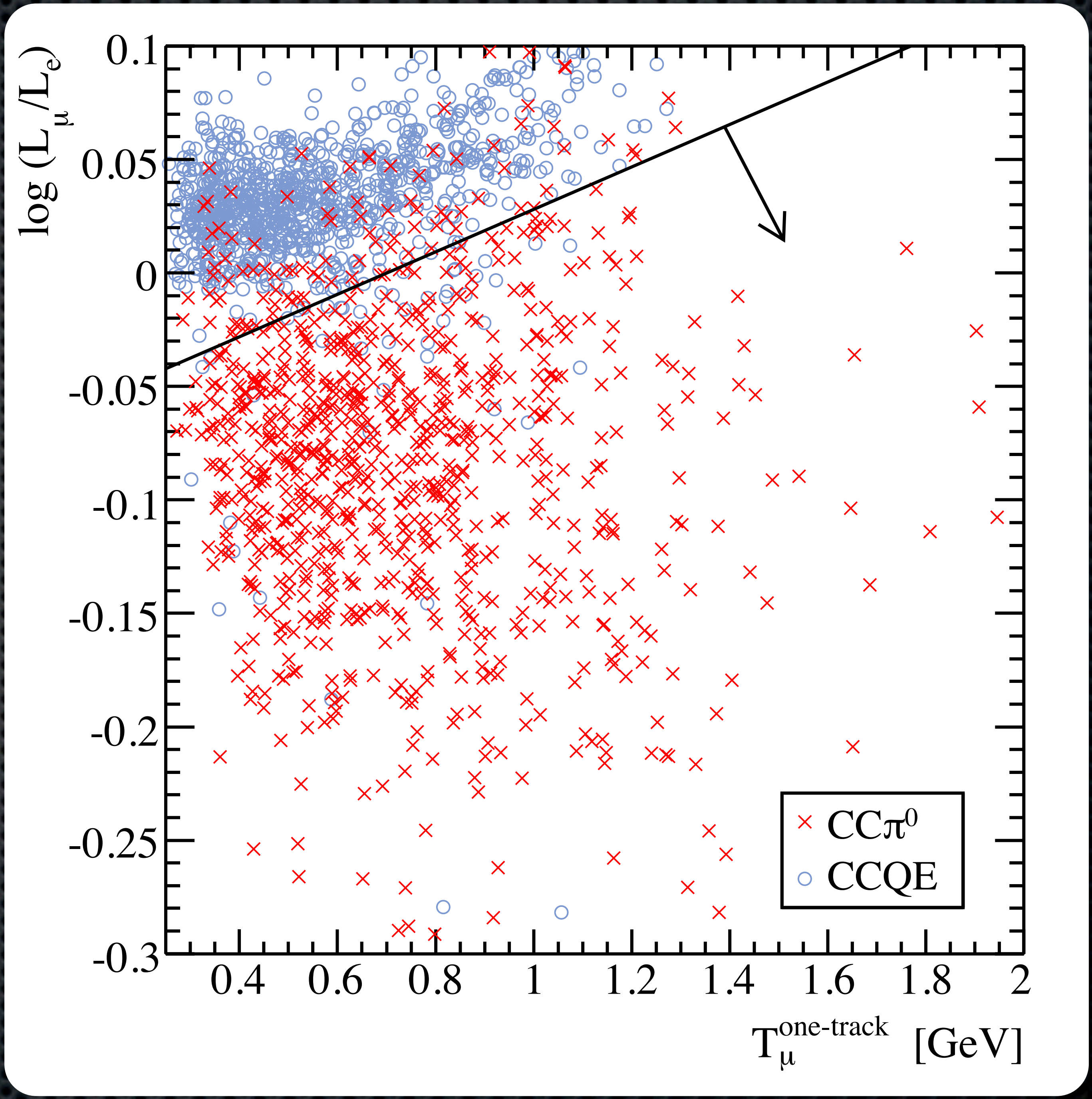
Observable CCπ^0 cross-sections



- The event reconstruction was previously presented by R. Nelson at NUINT09.
- arXiv:1010.3264 accepted by PRD.

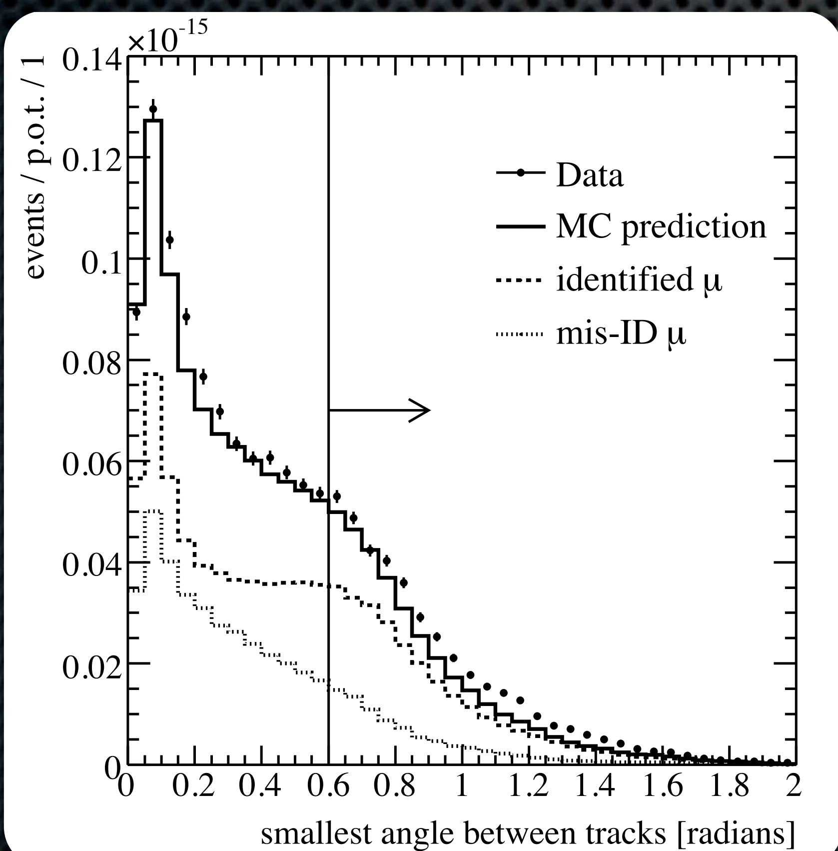
Pre-filtering before the fit

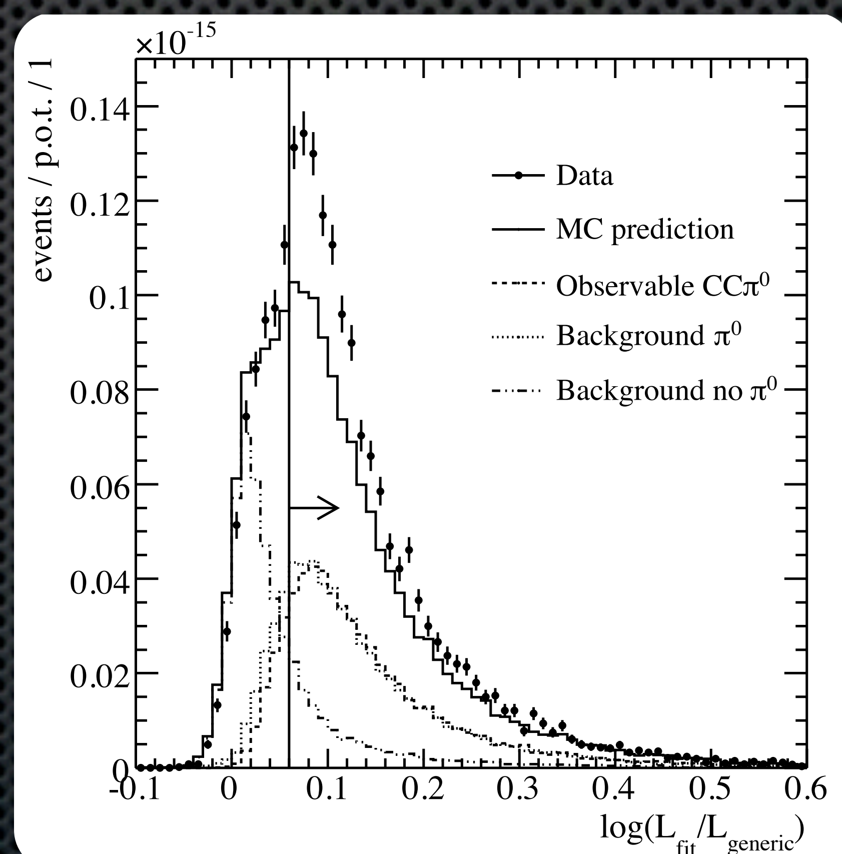
- Since CCQE is also in the 2 subevent sample, the sample needs to be reduced to something more manageable before the fitter is run.
  - CCQE is ~70% of the 2SE sample.
  - $CC\pi^0$ is only 6%.
- A one-track likelihood ratio cut vs one-track energy reduces CCQE events by 98% while keeping 86% of $CC\pi^0$ events.

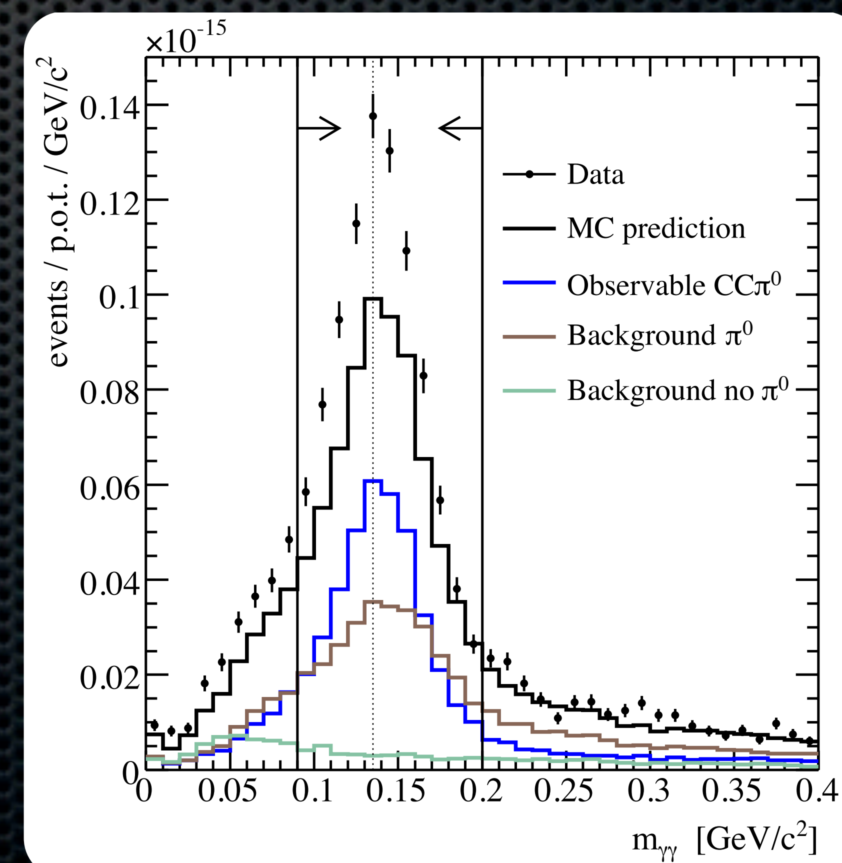


$CC\pi^0$ selection cuts

- A fit likelihood after particle ID vs the fit before particle ID cut removes most of the events without π^0 anywhere in the event.
- Cutting on the smallest angle between tracks removes mis-reconstructions.
- Cutting on the reconstructed π^0 mass reduces backgrounds and selects good events.
- A total of 5810 candidate events with 57% purity and 6.4% purity pass cuts.

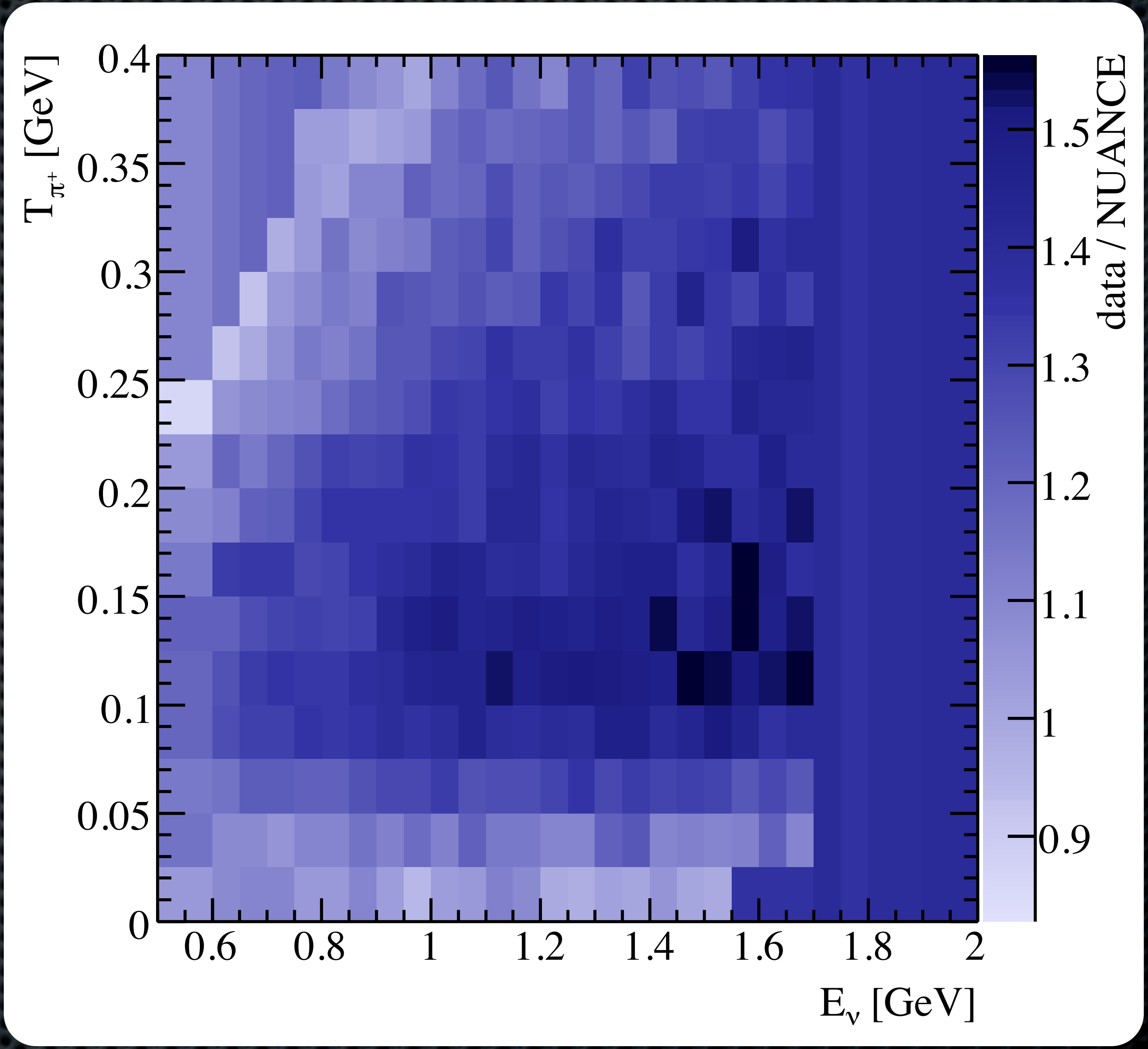






$CC\pi^+$ data constraint

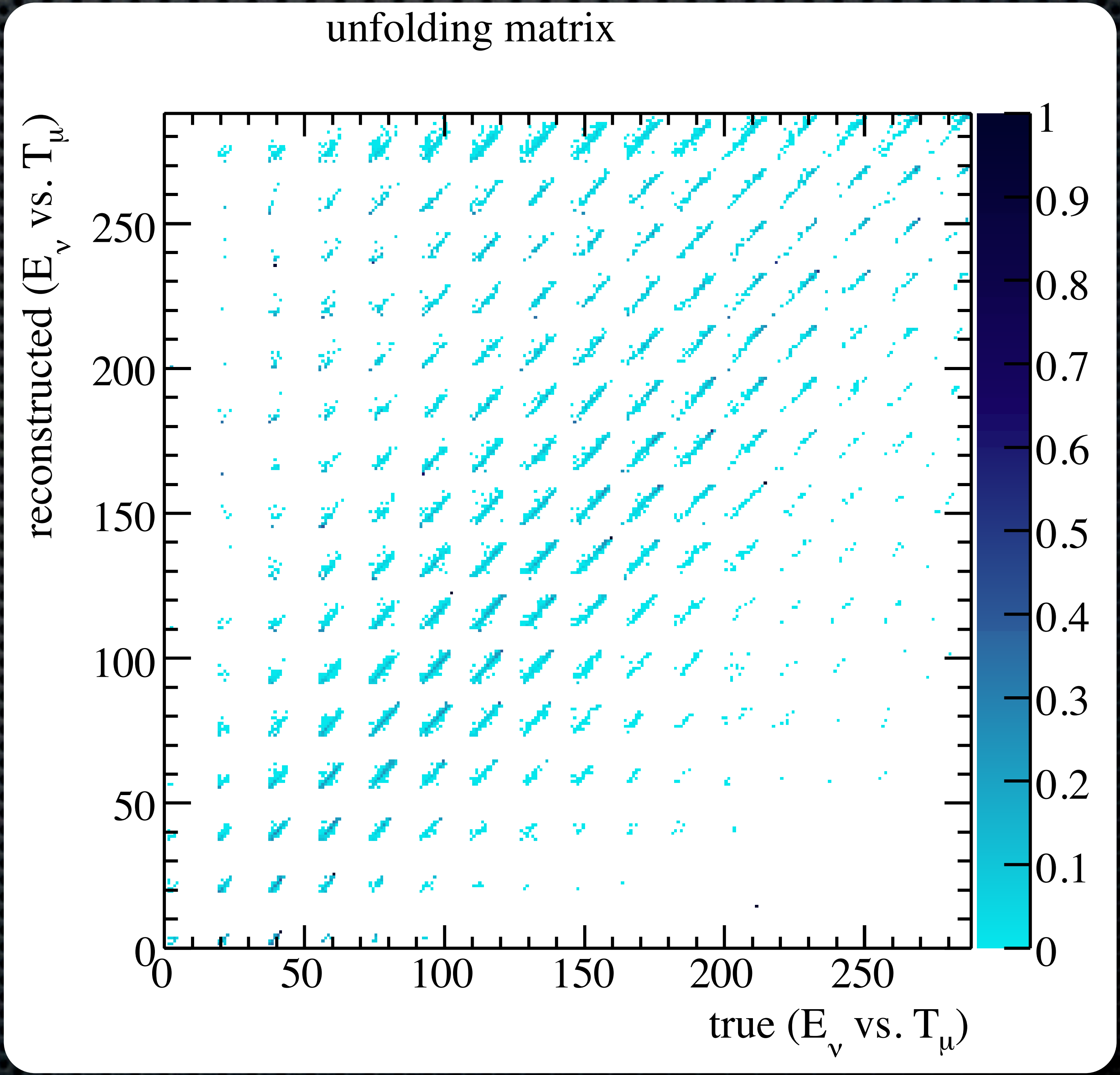
- The scheme to re-weight these events involves two of the measured cross-section measurements:
  - $\sigma(E_\nu)$, $d\sigma(E_\nu)/dKE_\pi$
- The ratio of Data/MC defines the re-weighting and is a function of KE_π and E_ν.
- Any place that the differential cross-section left unreported values we use the total cross-section.
- This re-weighting is applied to all observable $CC\pi^+$ events that make it into this sample.
- This places the uncertainty on $CC\pi^+$ production on our own measurements.



Differential cross-section unfolding

$$U_{ij} = P(t_i | r_j) = \frac{P(r_j | t_i)\, P(t_i)}{\Sigma P(r_j | t_n)\, P(t_n)}$$

- Bayesian-style unfolding is used.
- Rates are unfolded in two dimensions simultaneously.
- Each variable is unfolded simultaneously with neutrino energy.
  - Allows us to restrict the flux to the same region as the total cross-section measurement.
- Matrix is 4D so ignore this projection.

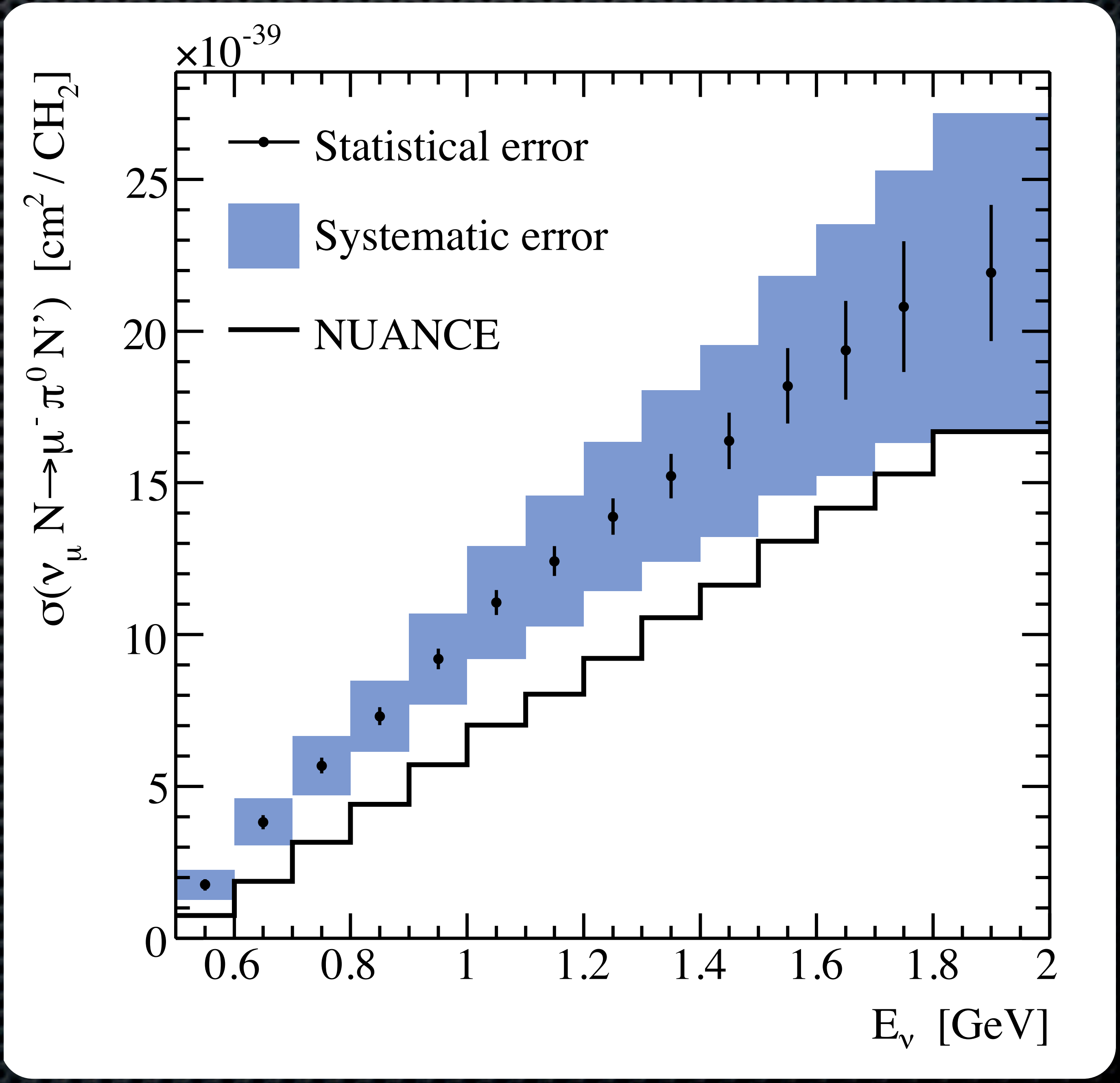


Observable CCπ^0 total cross section

$$\sigma(E_\nu)_i = \frac{\sum_j^{bins} U_{ij}\left(N_j - B_j\right)}{\varepsilon_i \, \Phi_i \, N_{targs}}$$

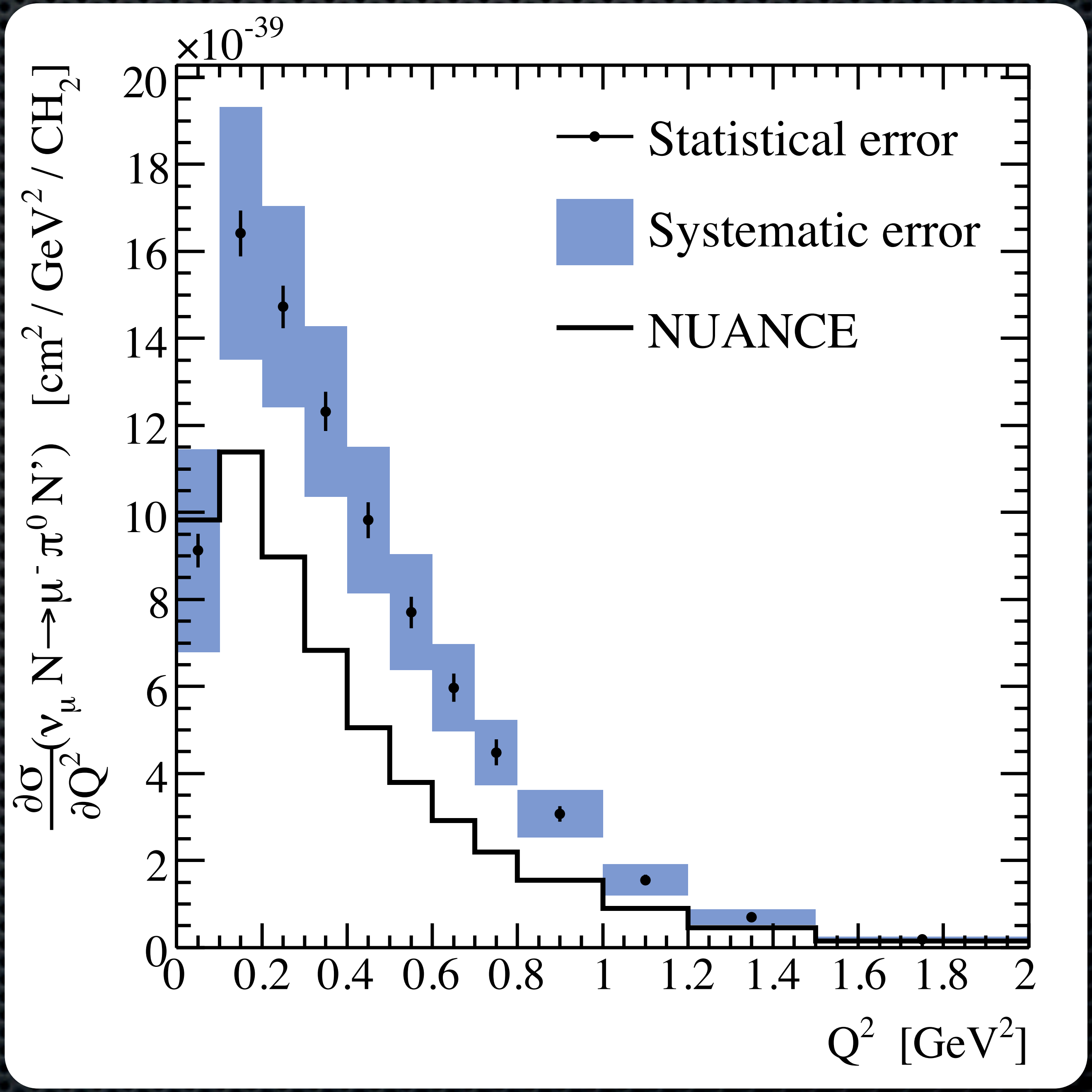
- NUANCE prediction is significantly below measurement.

Error	Fraction
Statistical	3.3%
$\pi^+ \rightarrow \pi^0$ and π^+ absorption in oil	12.9%
Horn variations	7.5%
Beam π^+	7.3%
ν background cross sections	5.8%
Discriminator threshold	5.7%
Optical Model	2.8%
QT correlation	1.1%
Beam K^+	0.9%
CCπ^+ production	0.5%
Beam π^-	0.3%
Hadronic	0.2%
Beam K^0	0.03%
Total Systematic Error	18.7%



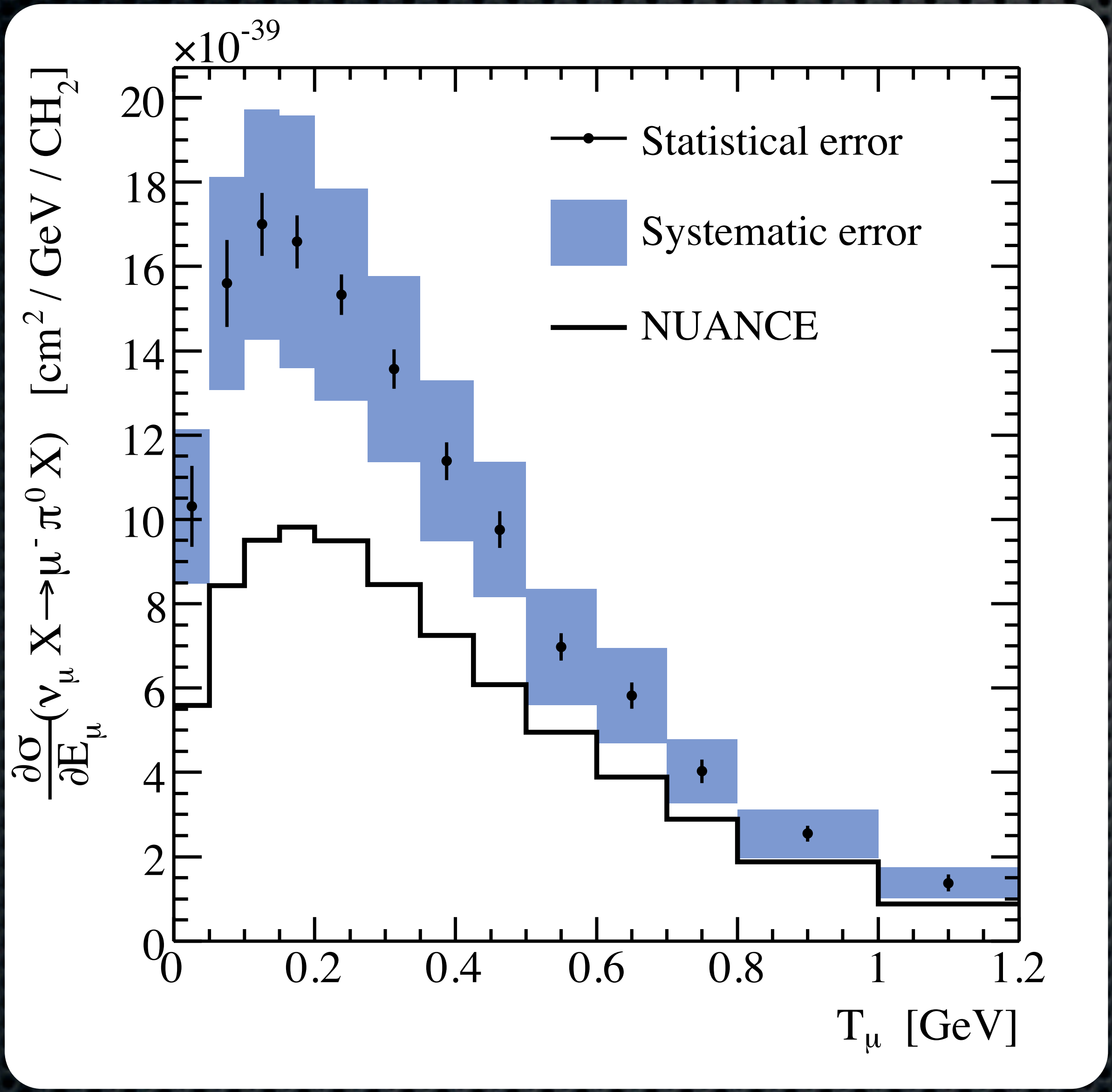
Observable CCπ^0 differential cross section in Q^2

- Low-Q^2 suppression.
- Previous measurements are inclusive of other single pion modes.
- First time this has ever been measured off a nuclear target.
- Neutrino flux is restricted between 0.5 and 2.0 GeV.

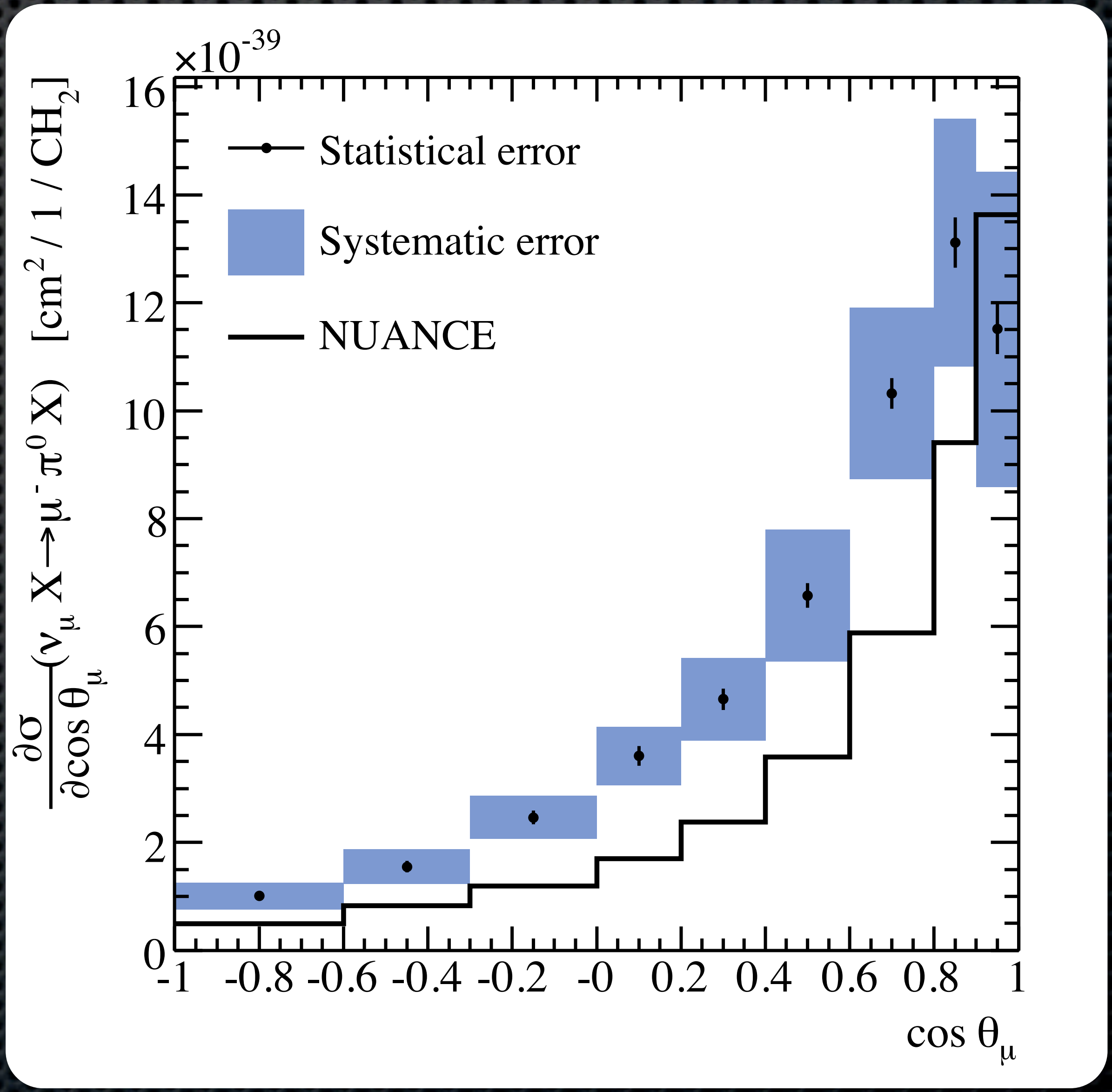


Observable CCπ^0 cross section differential in μ kinematics

- First measurements ever.
- Energy shows overall enhancement, and is not expected to be affected by FSI.
- Forward angle dip is correlated to low-Q^2 suppression. Also seen in CCQE.



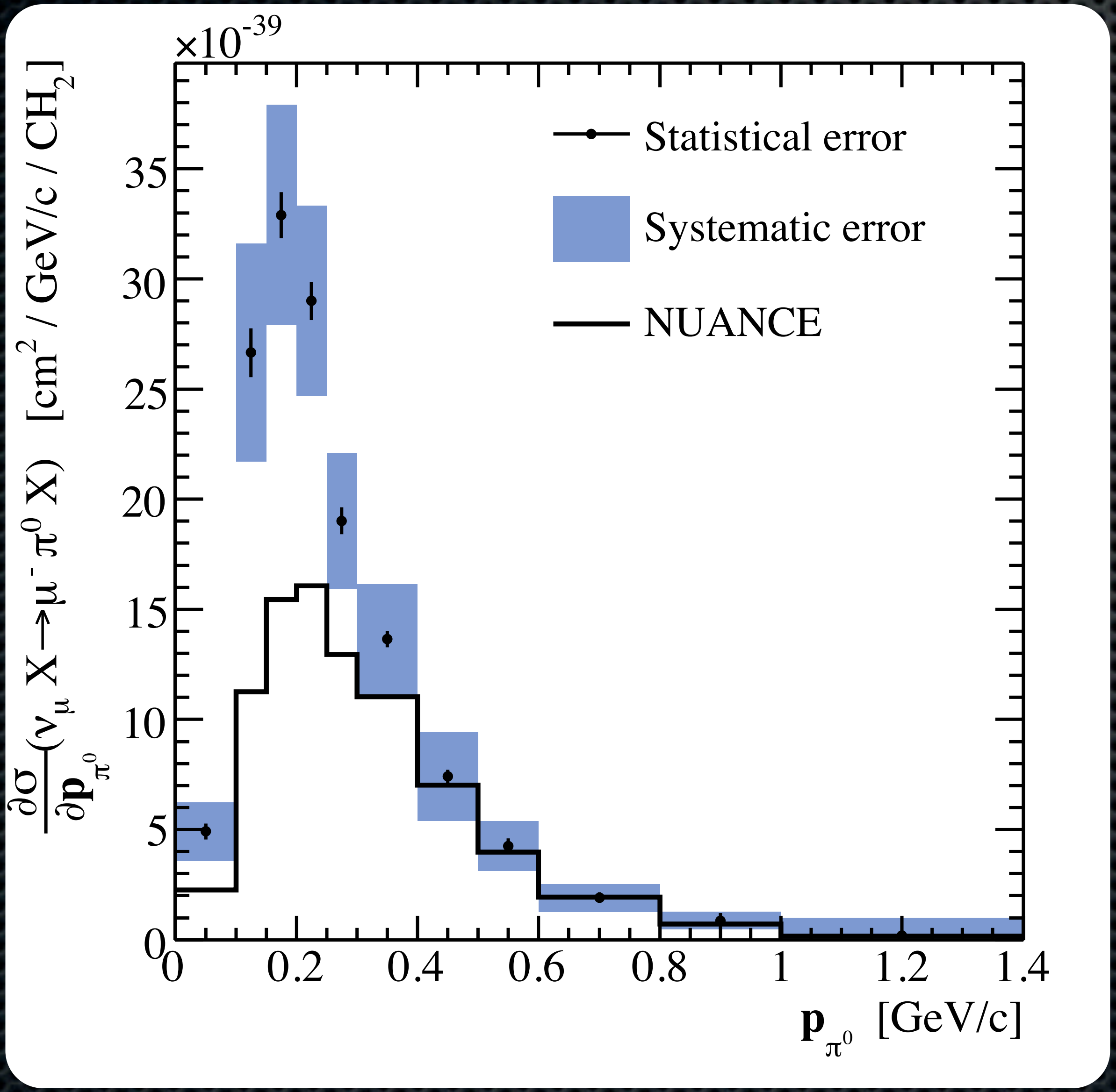
7.4% resolution



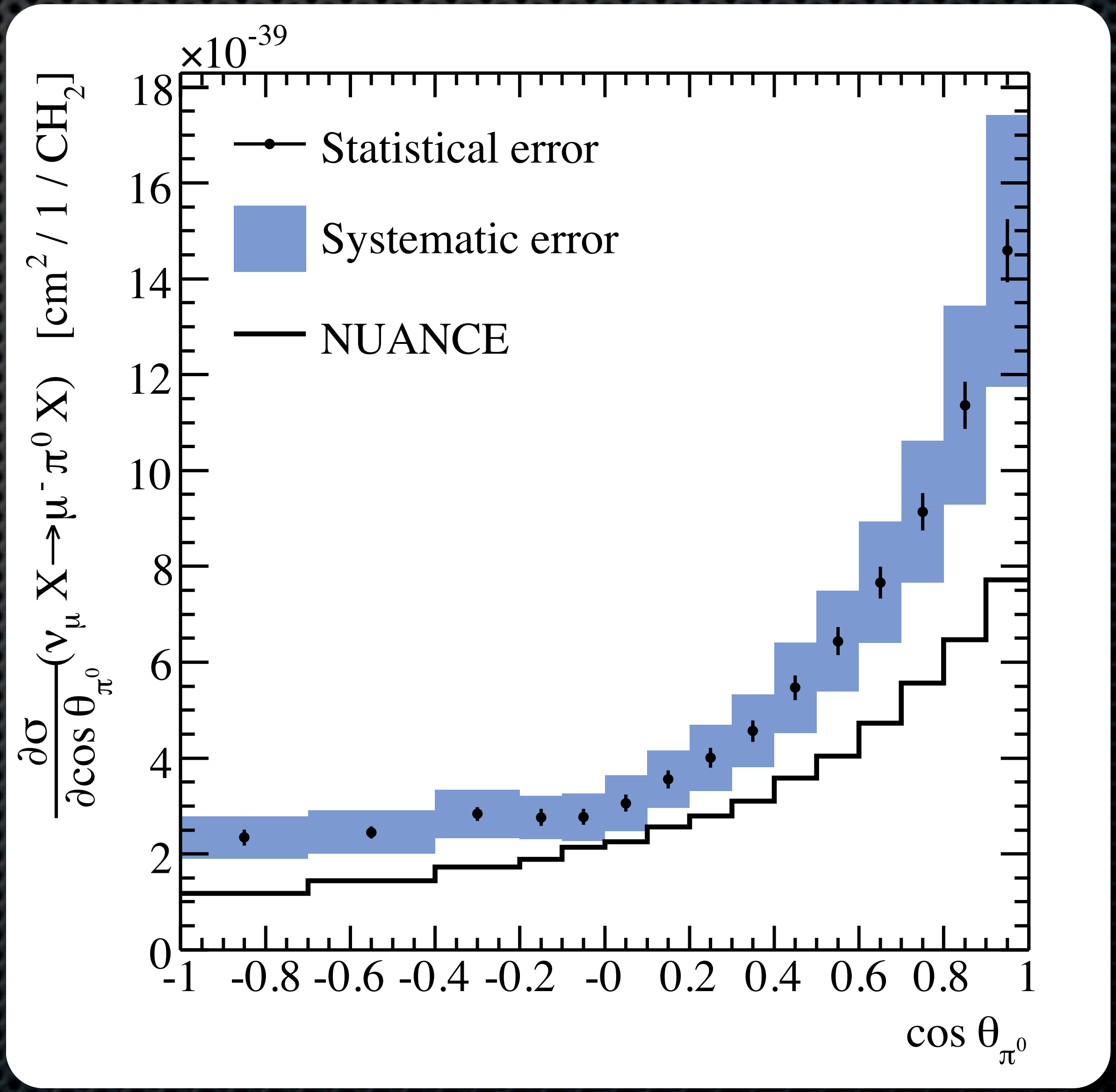
2° resolution

Observable CCπ^0 cross section differential in π^0 kinematics

- First measurements.
- Momentum is sensitive FSI.
- The forward direction enhancement is also observed in the NCπ^0 cross section.



12.5% resolution



7.8° resolution

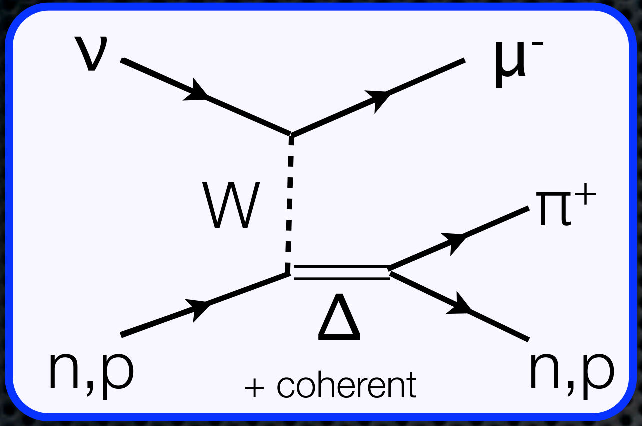
Flux-averaged total observable CCπ^0 cross section

- Cross check on the various measurements.
- The flux-averaged total cross section is calculable from each measurement.
  - $\langle E_\nu \rangle_\Phi$ = 0.965 GeV
- They agree to within 6%.
- A simple average is calculated assuming 100% correlated uncertainties.

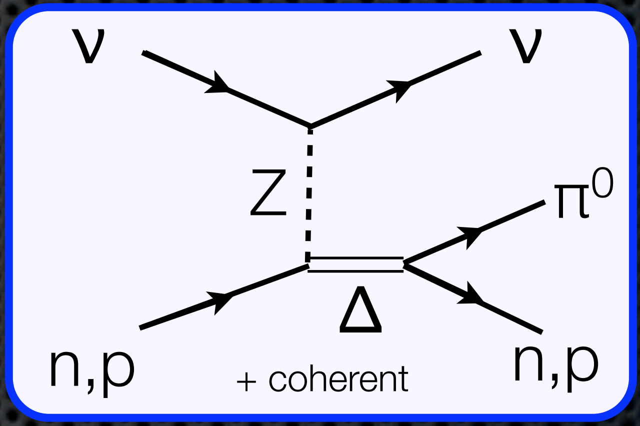
Measurement	$\langle\sigma\rangle_\Phi$ [10^{-39} cm^2]
σ	9.1±1.4
$d\sigma/dQ^2$	9.3±1.6
$d\sigma/dE_\mu$	9.2±1.5
$d\sigma/d\cos\theta_\mu$	9.1±1.5
$d\sigma/dp_\pi$	9.0±1.5
$d\sigma/d\cos\theta_\pi$	9.5±1.6
Average	9.2±1.5

Single-pion comparisons

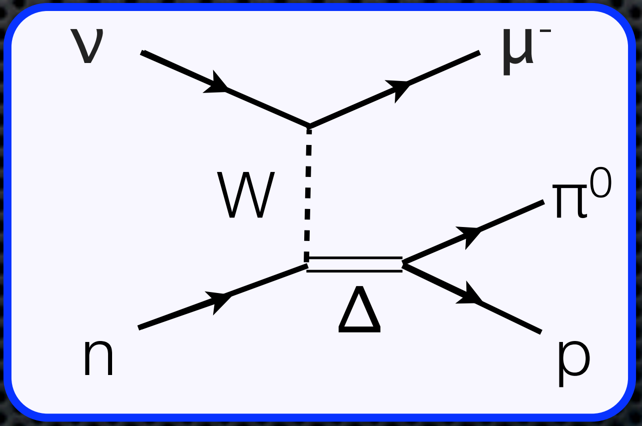
$CC\pi^+$



$NC\pi^0$



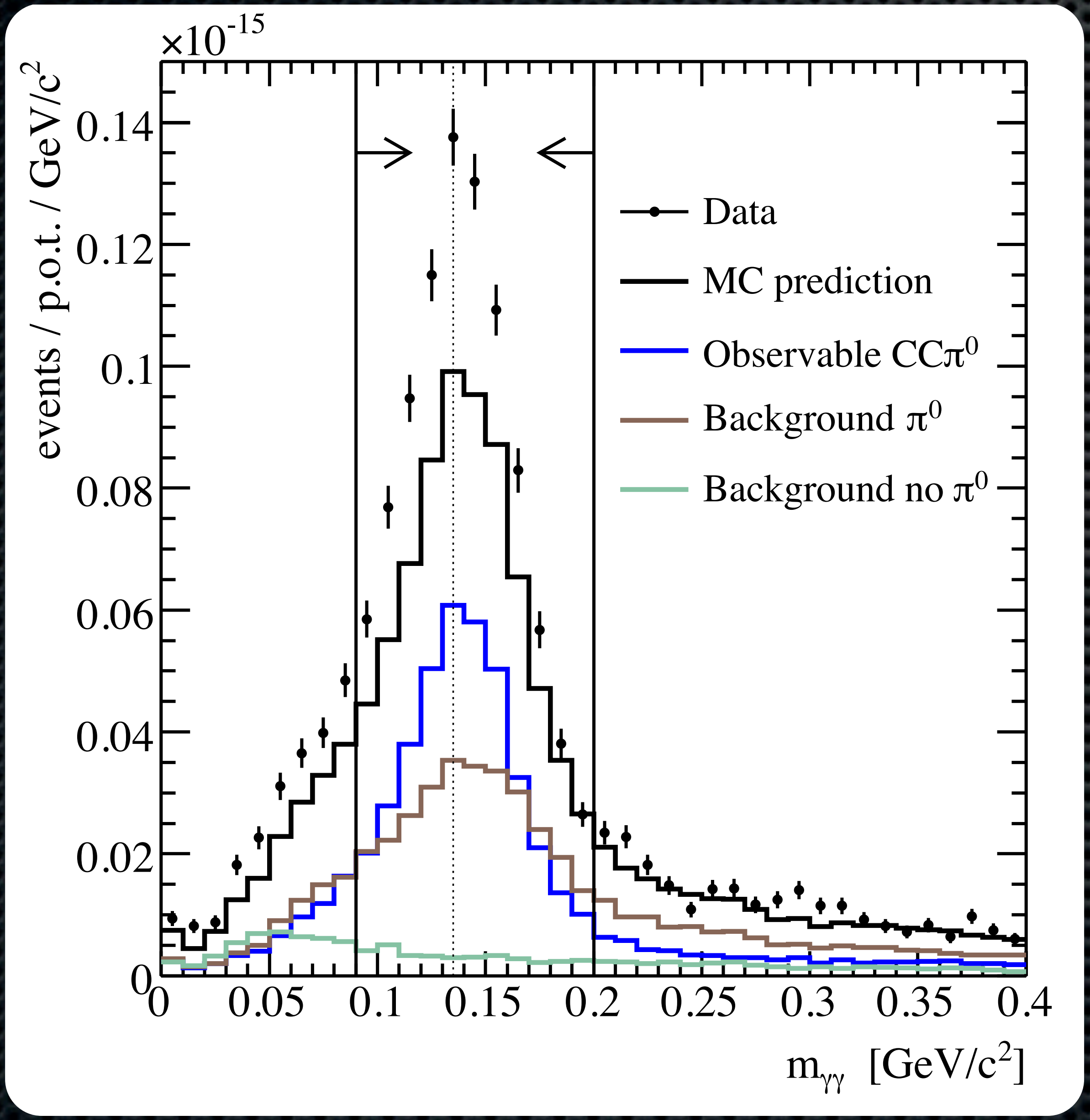
$CC\pi^0$



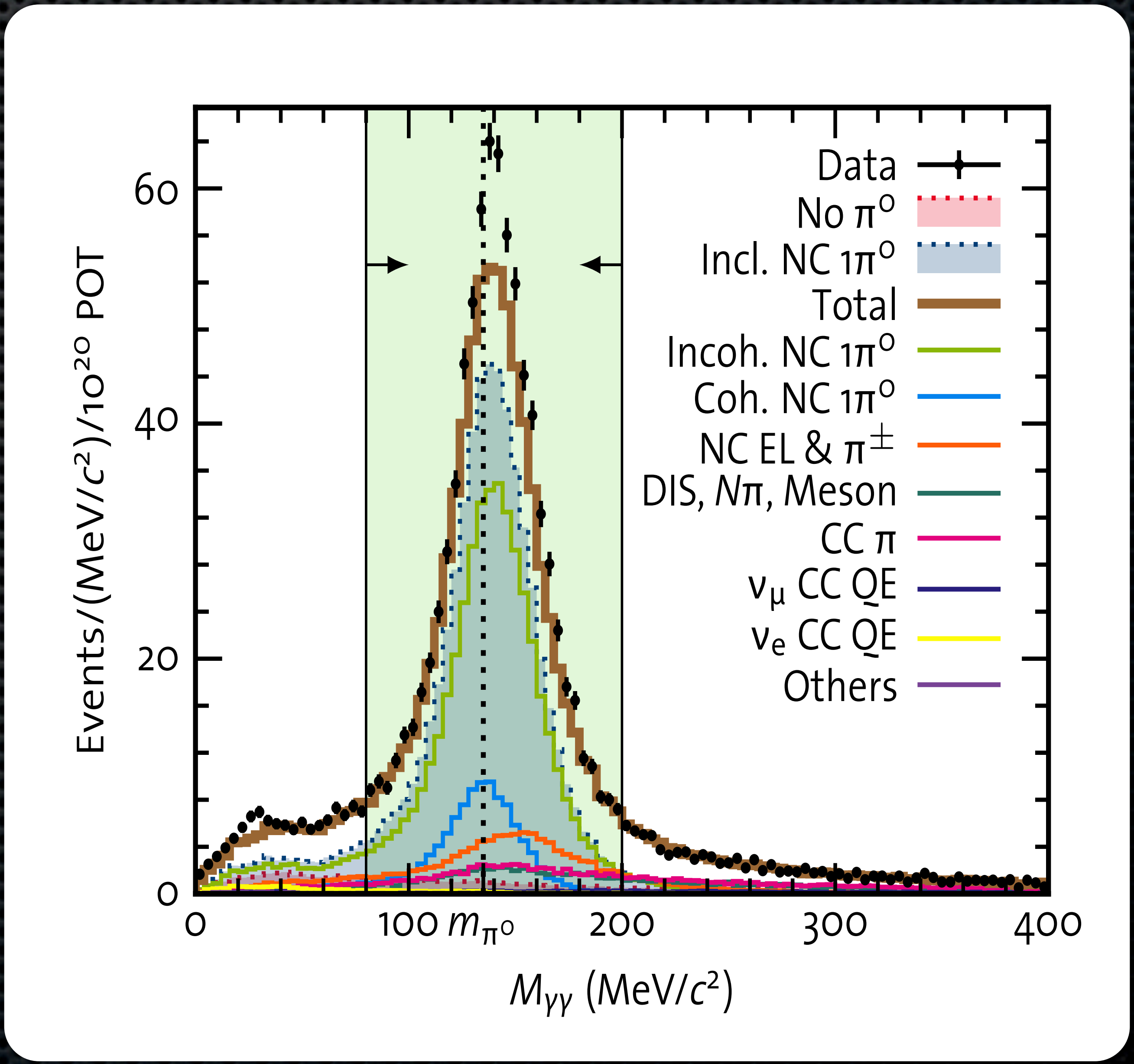
Reconstructed π^0 mass

- Both analyses peak at the known π^0 mass.

CCπ^0

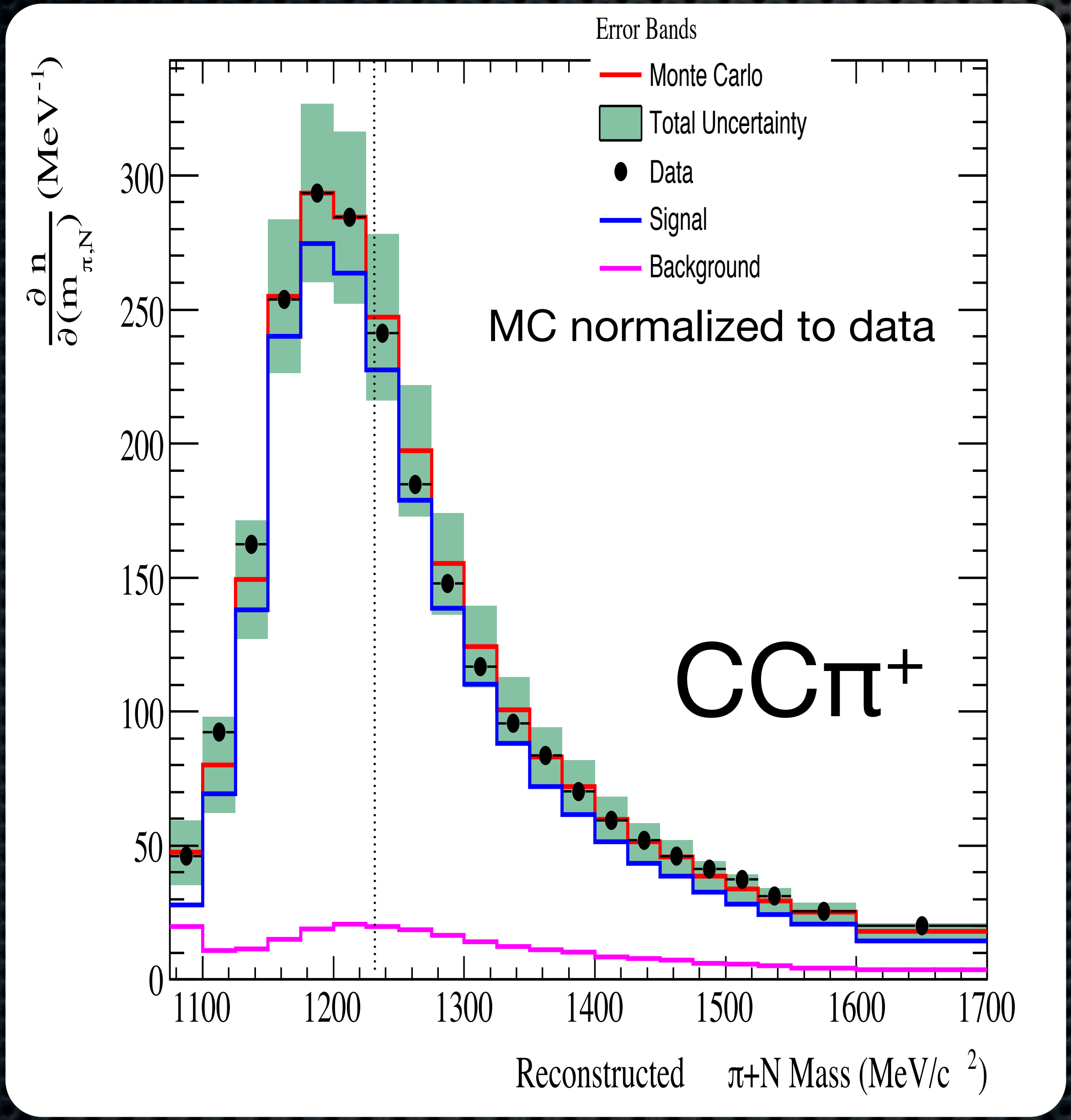


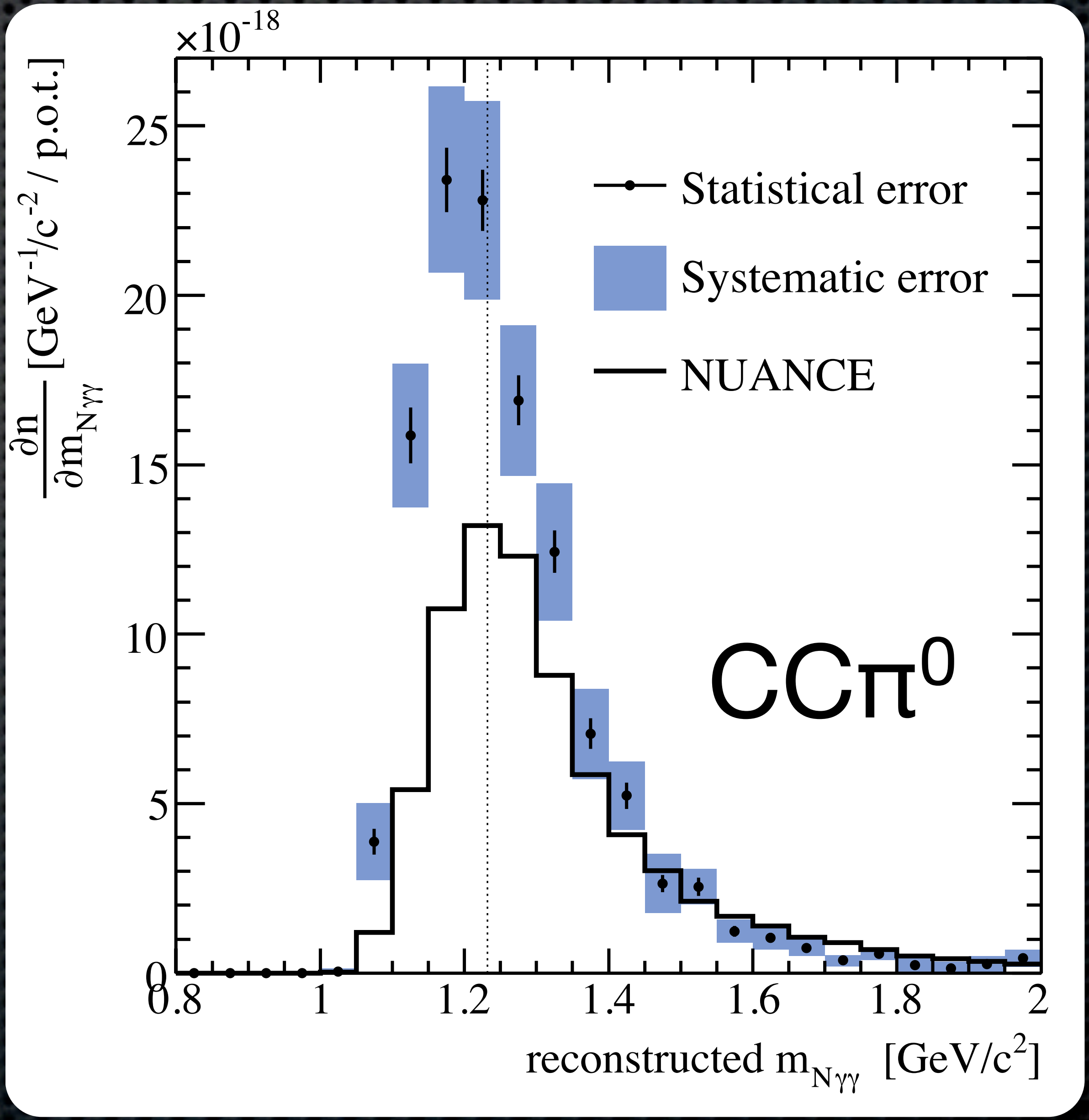
NCπ^0



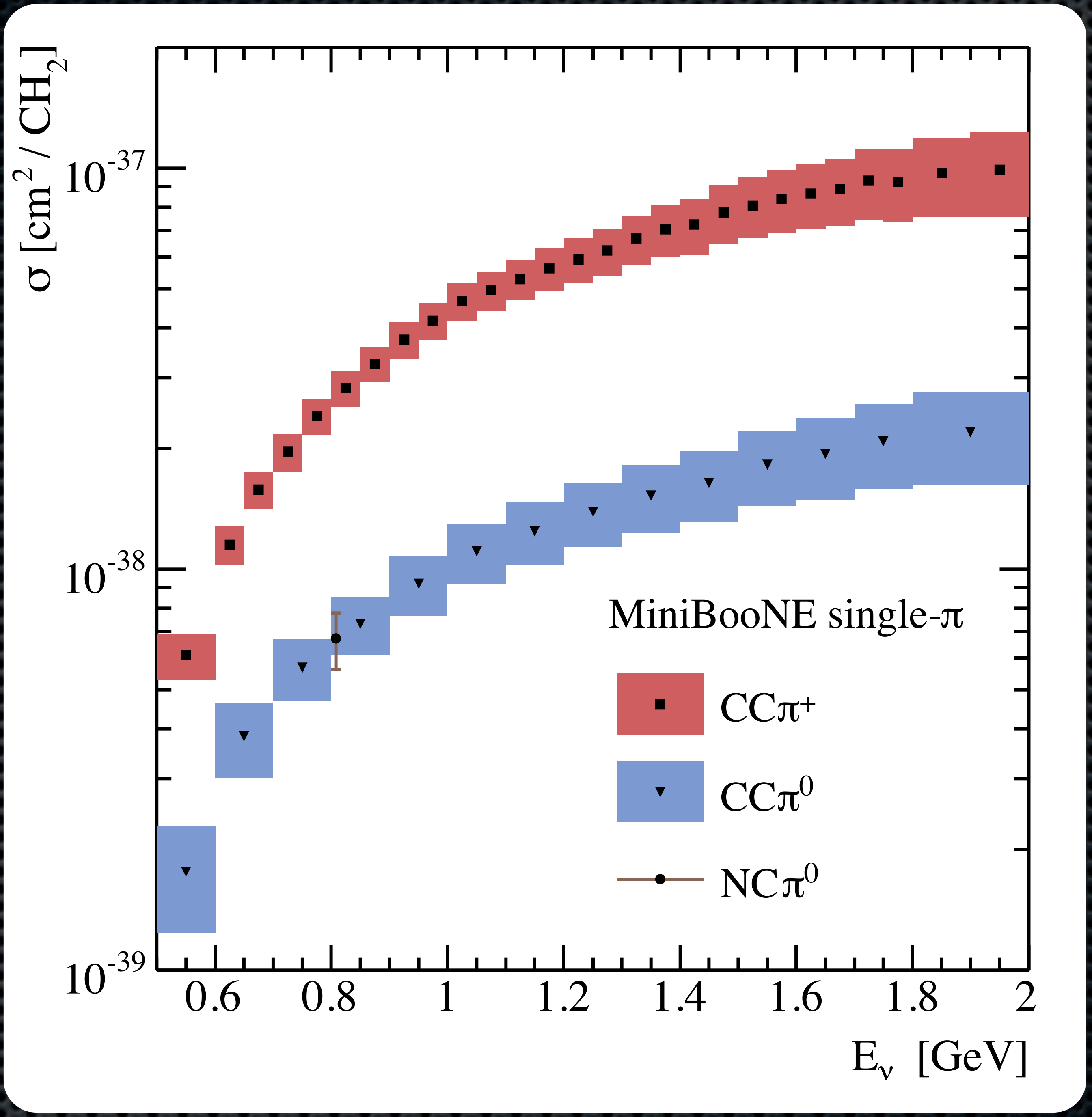
Reconstructed baryon resonance mass

- Both analyses show a slightly lower Δ mass than expected.
- Most likely due to nuclear effects.





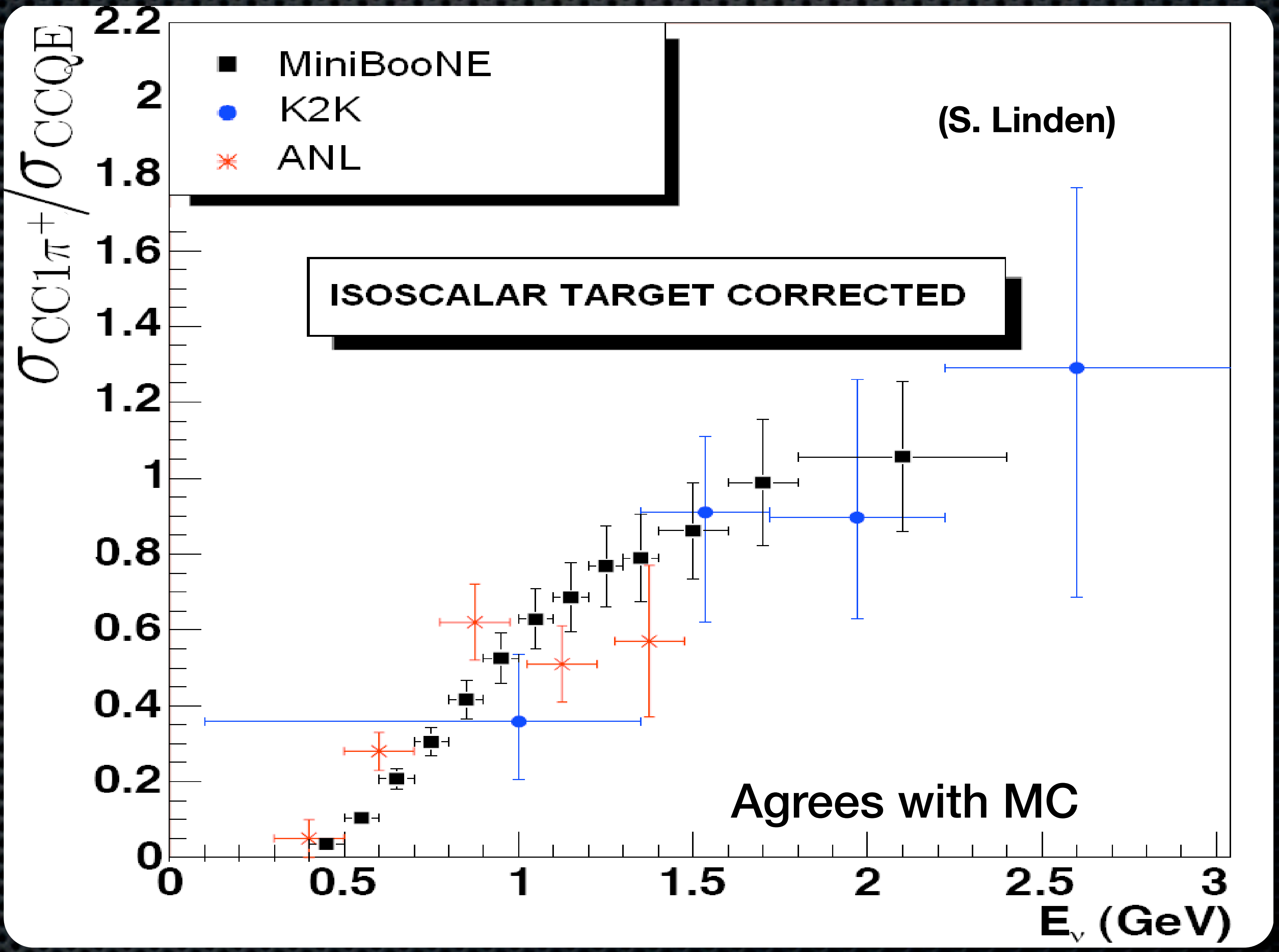
Single-pion total cross sections



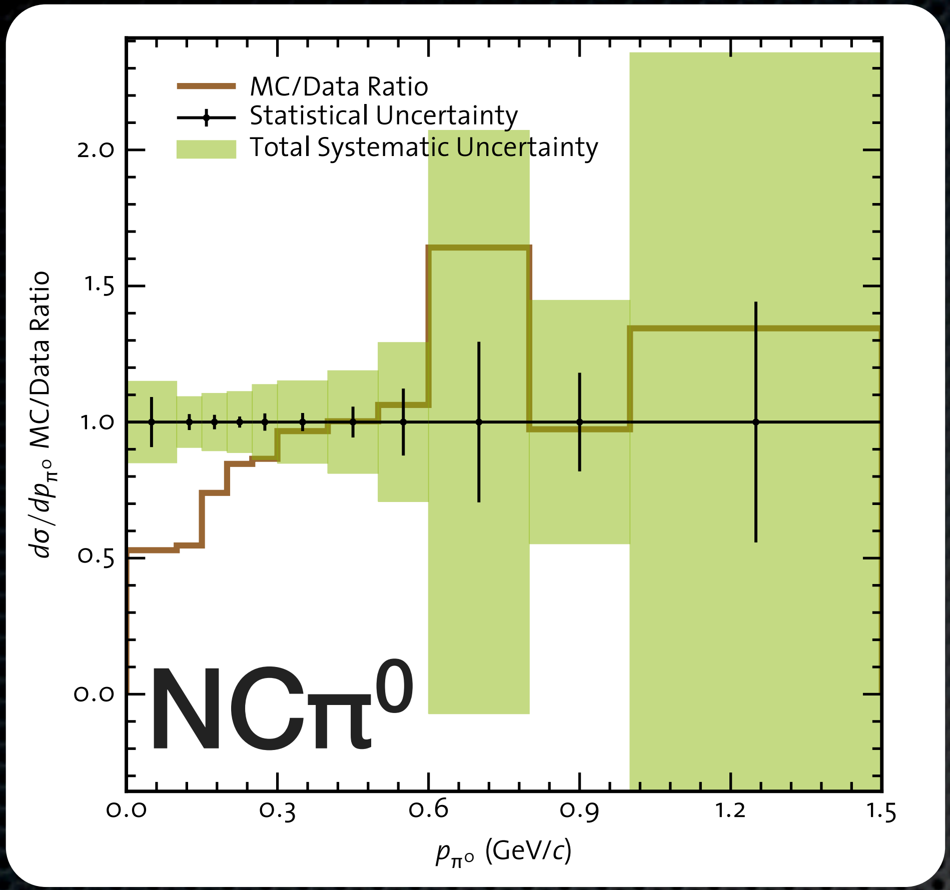
- Measurements are on a CH_2 target.

CCπ⁺/CCQE ratio analysis

- Independent analysis.
- Uses the CCQE reconstruction assuming a Δ for CCπ⁺ events to reconstruct the neutrino energy.

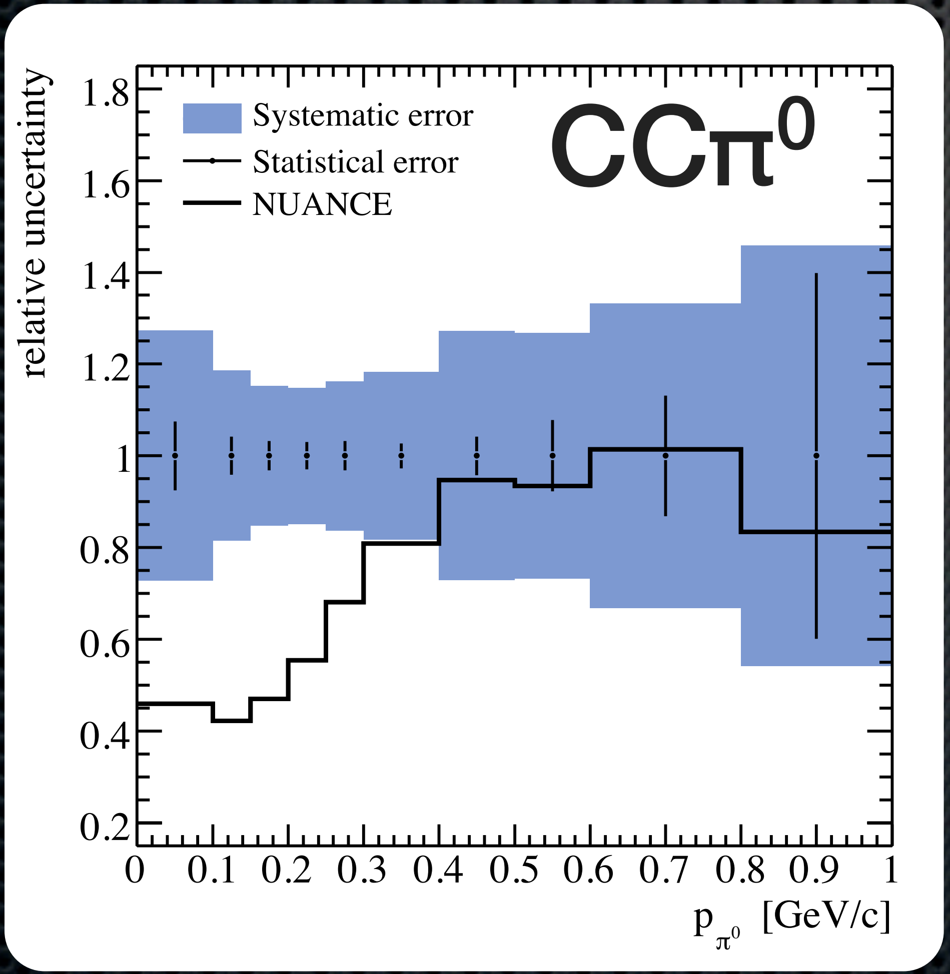


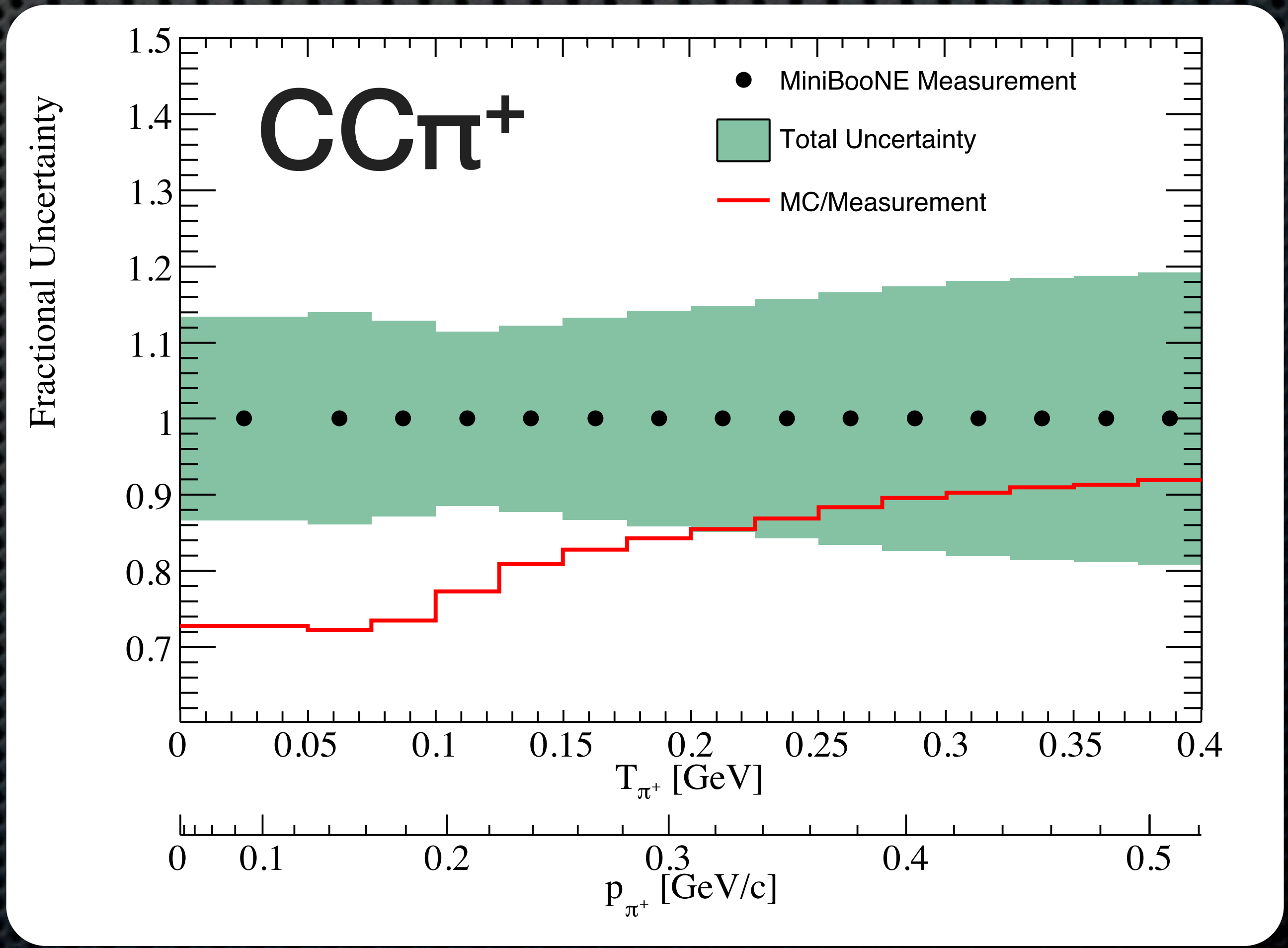
Phys. Rev. Lett. 103, 081801 (2009)



Pion momentum

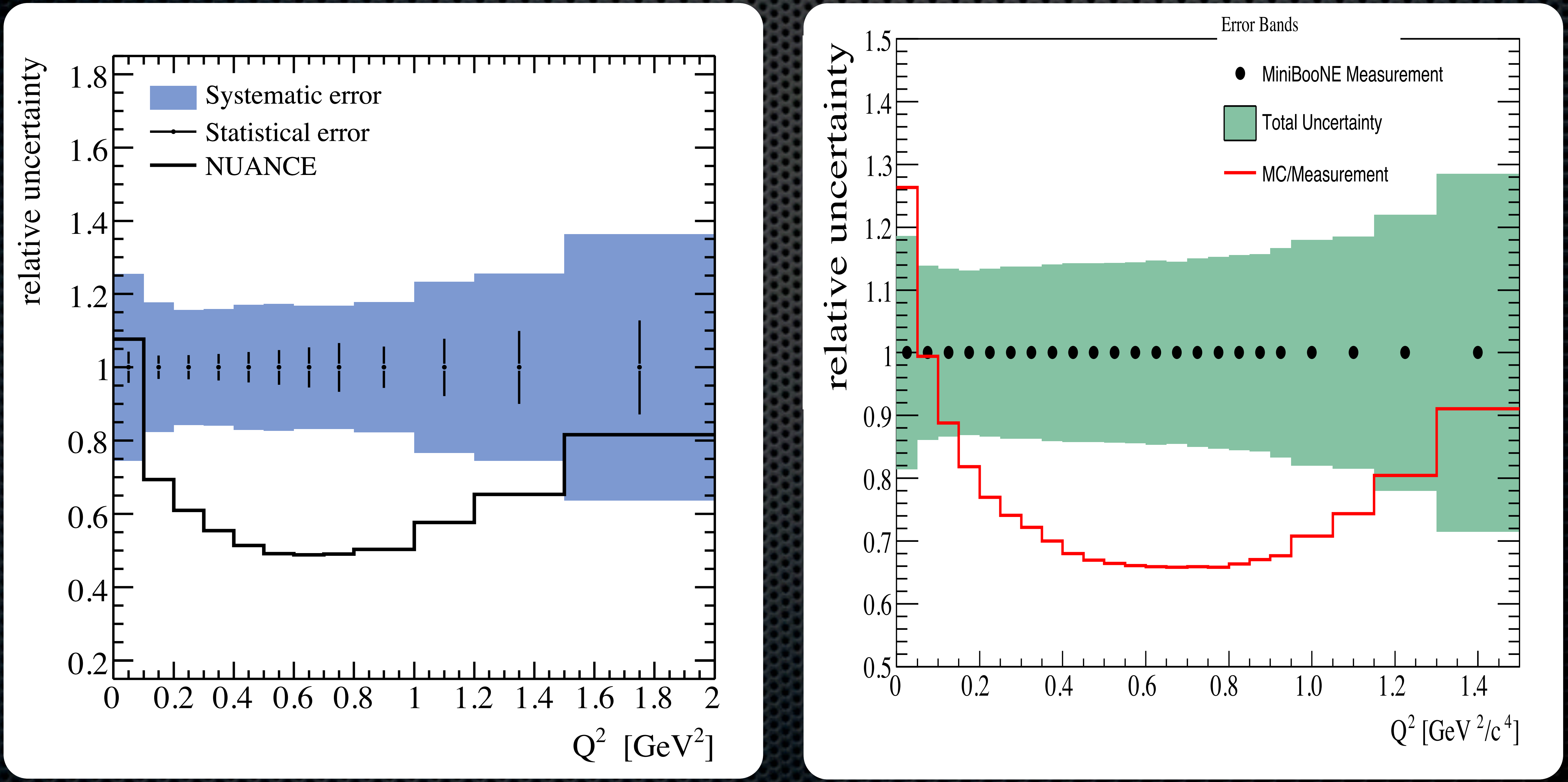
- Prediction is 50%(25%) low and flat below 0.2 GeV/c for $\pi^0(\pi^+)$.
- Approaches the data at 0.5 GeV/c.
- Matches data above 0.5 GeV/c, though stats are low.
- Most sensitive to pion FSI.





CC single-pion Q^2

- Both analyses show a low-Q^2 suppression compared with prediction.
- Most sensitive to form factors and nuclear effects.

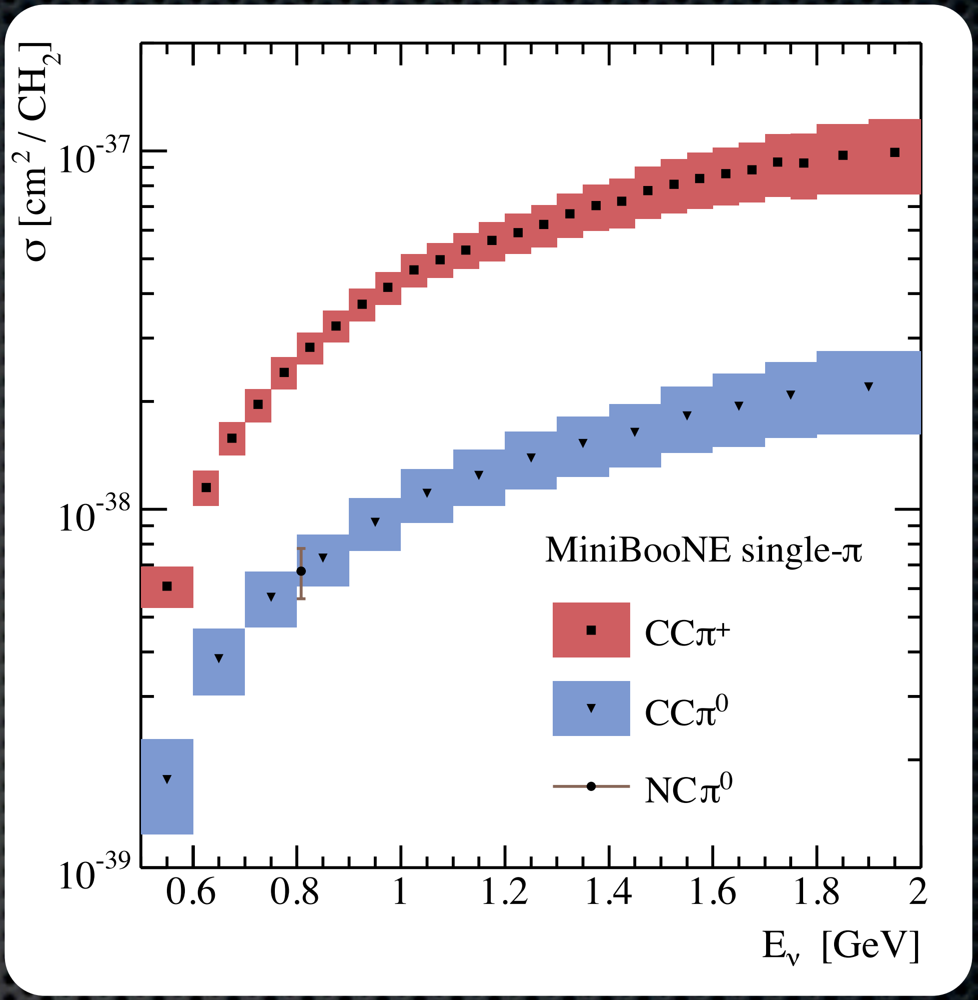


Single-pion cross-section measurements

- A total of 16 measurements!
- ✳ = presented as a function of neutrino energy.
- Least model dependent results!

Measurement\Mode	$NC\pi^0$	$CC\pi^0$	$CC\pi^+$
$\sigma(E_\nu)$		✓	✓
$d\sigma/dQ^2$		✓	✓✳
$d\sigma/dp_\pi$	✓	✓	✓✳
$d\sigma/d\cos\theta_\pi$	✓	✓	✓✳
$d\sigma/dT_\mu$		✓	✓✳
$d\sigma/d\cos\theta_\mu$		✓	✓✳
$d^2\sigma/dT_\mu d\cos\theta_\mu$			✓
$d^2\sigma/dT_\pi d\cos\theta_\pi$			✓

Conclusions



- Through the use of custom event fitters MiniBooNE has measured 3 single-pions in great detail.
- Many final-state (after nucleus) particle kinematics have been measured for the first time (at these energies).
  - These cross sections are as model independent as can be produced.
- Many similarities exist between the modes:
  - All measurements are higher than the NUANCE predictions.
  - All pion momenta are under-predicted at low momentum.
  - Both CC modes show a low-Q^2 suppression.