numu and nue CC inclusive cross-sections using ND280

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NuInt14 – 19 May 2014

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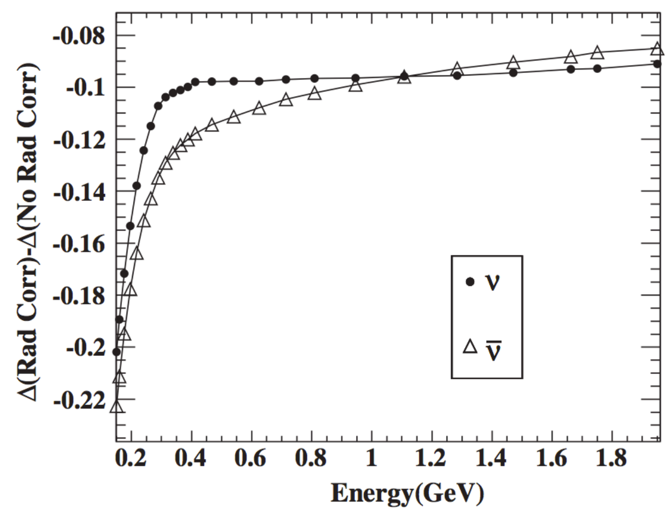
Why electron neutrinos?

- CC ν_e interactions are signal and largest background in $\nu_\mu \rightarrow \nu_e$ appearance measurements
- Understanding differences between ν_μ and ν_e cross-sections is critical for reducing systematics in future LBL experiments
- Theoretical differences need to be constrained with data!

Category	Events
CC ν_e signal	17.3
CC ν_e background	3.2
Other background	1.1

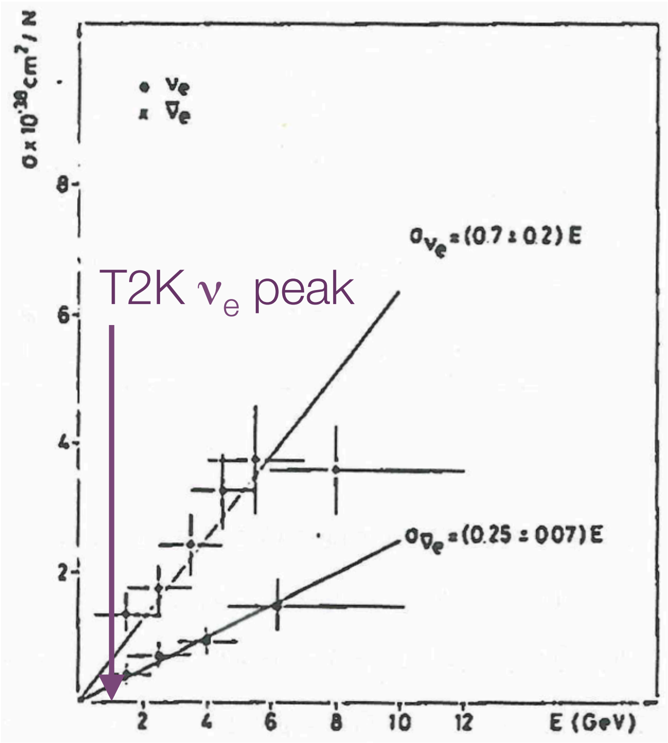
T2K MC prediction for $\sin^2(2\theta_{13}) = 0.1$
arXiv:1311.4750



Example change in fractional difference between ν_e and ν_μ CCQE x-secs, Day and McFarland, arXiv:1206.6745

Goal of this analysis

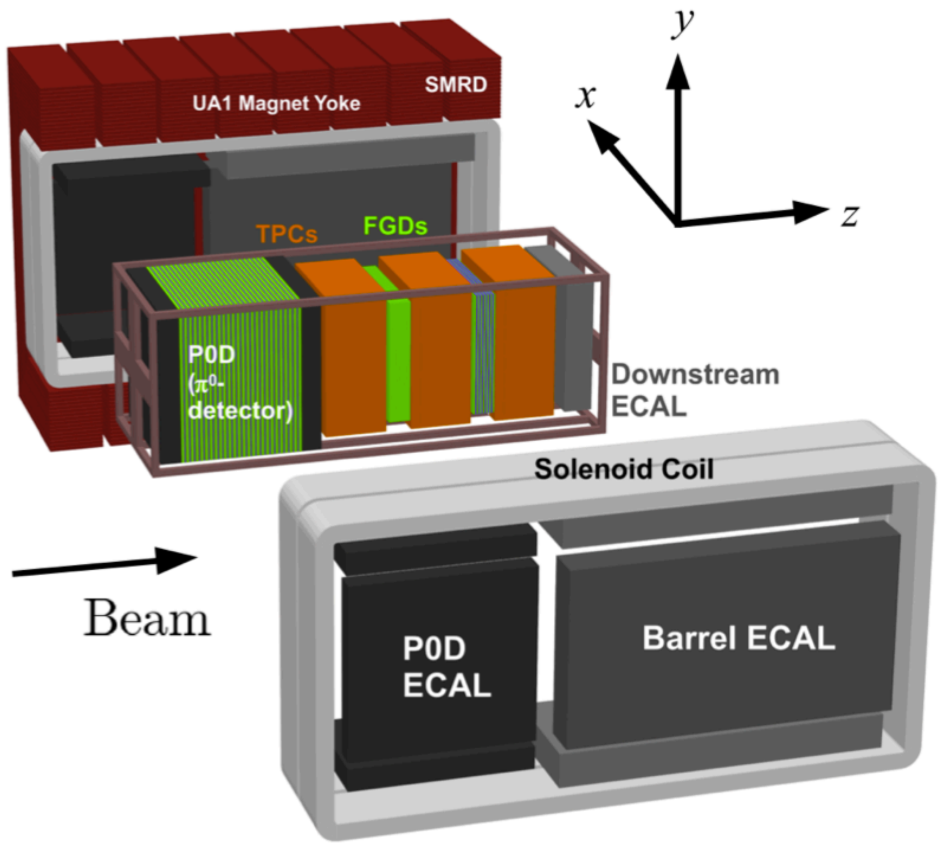
- Gargamelle published ν_e and anti-ν_e CC inclusive cross-section in 1978
- This analysis measures ν_e CC inclusive cross-section on carbon
  - Differential as a function of
    - Electron momentum
    - Electron angle
    - Q^2 of interaction
  - Total flux-averaged cross-section



Gargamelle ν_e and anti-ν_e CC inclusive measurements, Nucl. Phys. B 133, 1978

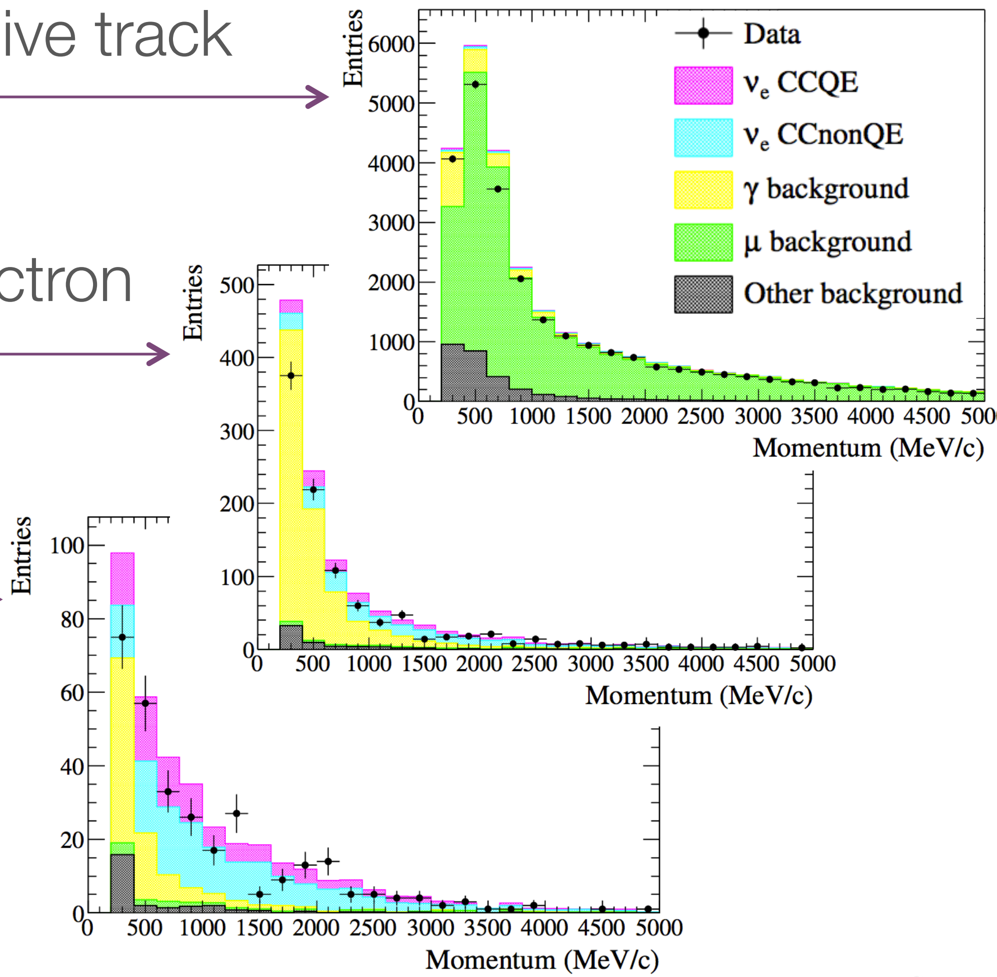
Event selection

- Analysis uses T2K off-axis near detector – ND280
  - FGDs – active targets (plastic scintillator) 2 x 2 x 0.3 m^3
  - TPCs – give excellent momentum resolution and particle identification (PID)
  - ECals – help with PID
- Use all good data from 2010–2013: 5.9e20 POT
- Signal events are CC ν_e interactions in upstream FGD



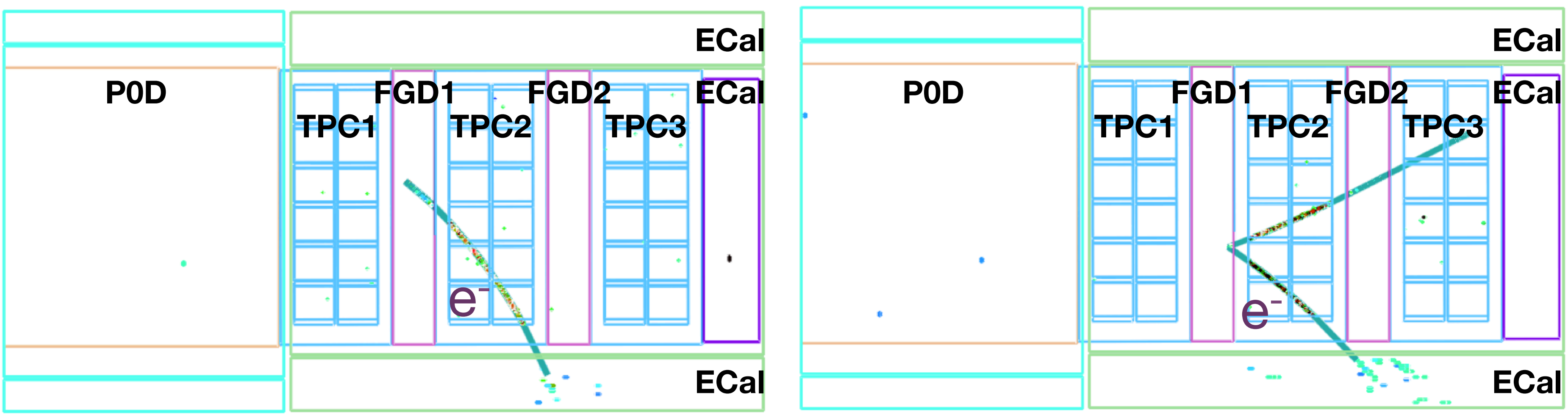
Event selection

- Highest momentum negative track starts in FGD1
- PID is compatible with electron (using TPCs and ECals)
- Reduce background from $\gamma \rightarrow e^+e^-$ conversions
  - Veto on activity upstream of FGD1
  - No e^+ near the e^-



Sample event displays

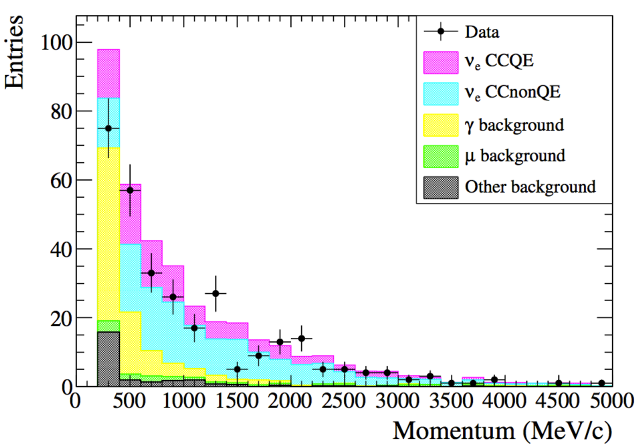
- Two events passing the ν_e event selection

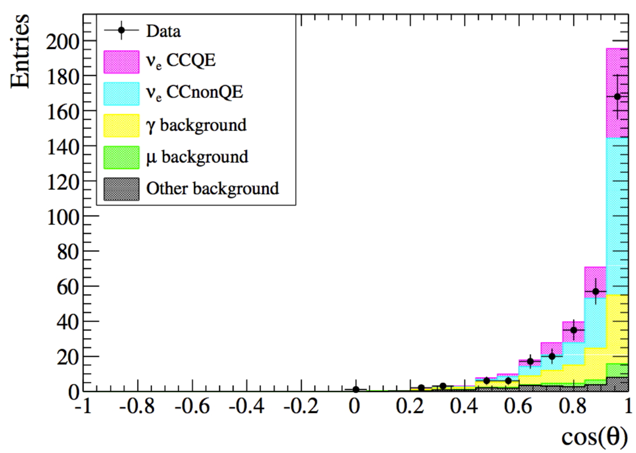


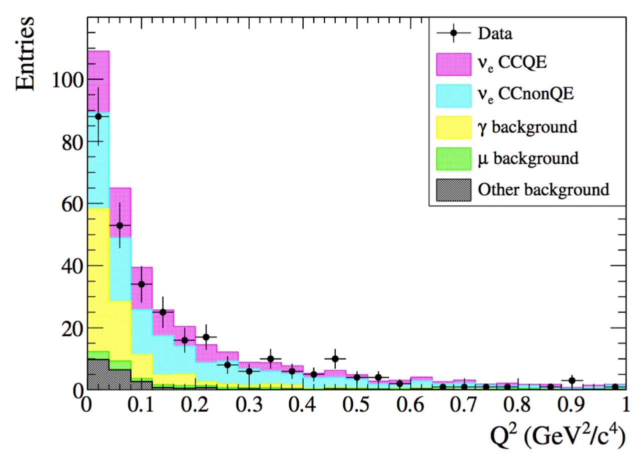
Event properties

- Sample is 65% pure CC ν_e interactions
- Not uniform acceptance!
- Large background from $\gamma \rightarrow e^+e^-$ conversions

Category	Fraction (%)	Expected #
ν_e CCQE	25.2	95.0
ν_e CCnonQE	39.8	150.0
γ background	23.8	89.8
μ background	4.1	15.5
Other background	7.1	26.8

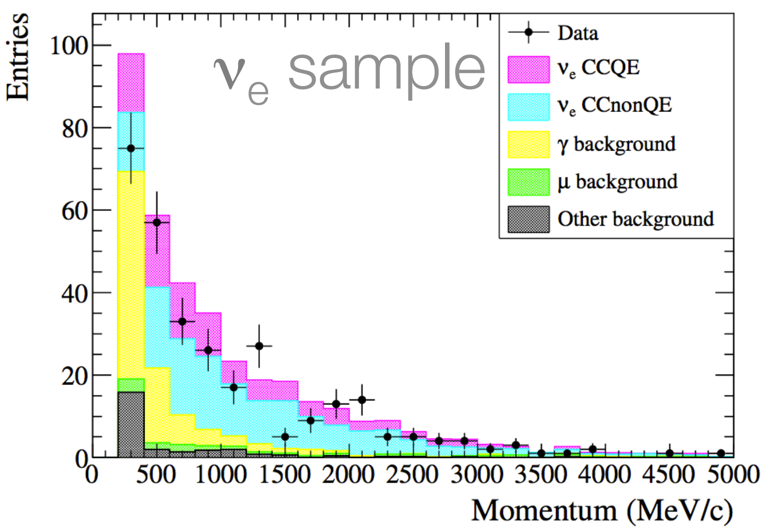


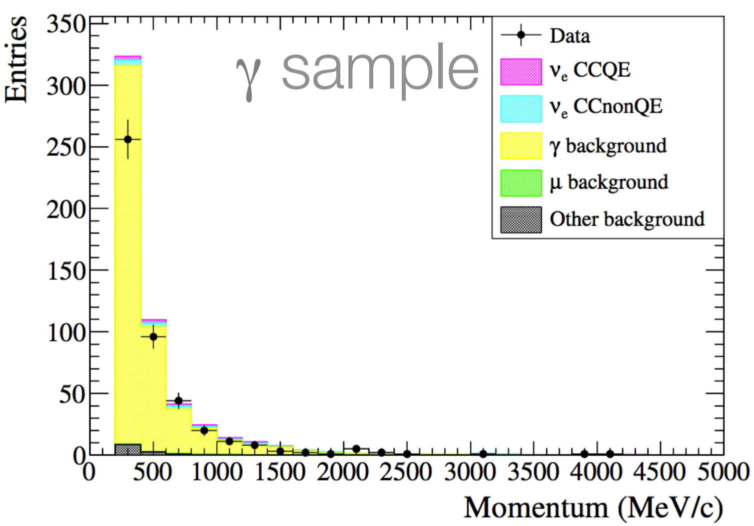




Gamma background

- 24% of events in ν_e sample are from $\gamma \rightarrow e^+e^-$ conversions
- Select a sample of e^+e^- pairs starting in FGD1 to constrain this background
- Sample is 95% pure in γ pair conversions





Bayesian unfolding method

- Use MC to create smearing matrix linking reconstructed and true variables – this gives P(RecoBin|TrueBin)
- Uses Bayes' theorem to find P(TrueBin|RecoBin), and unfold data to the **true distribution estimate**
- t_k is true bin; r_j is reco bin; m is iteration (but we only do 1)

MC smearing matrix

MC prior

$$P_m(t_k|r_j) = \frac{P(r_j|t_k)P_m(t_k)}{\sum_{\alpha=1}^{n_t} P(r_j|t_\alpha)P_m(t_\alpha)}$$

$$N_{t_k}^{m+1} = \frac{1}{\epsilon_{t_k}} \sum_{j=1}^{n_r} P_m(t_k|r_j)(N_{r_j}^{\mathrm{meas}} - B_{r_j})$$

Estimate in true bin

Efficiency

Data in reco bin

MC bkg in reco bin

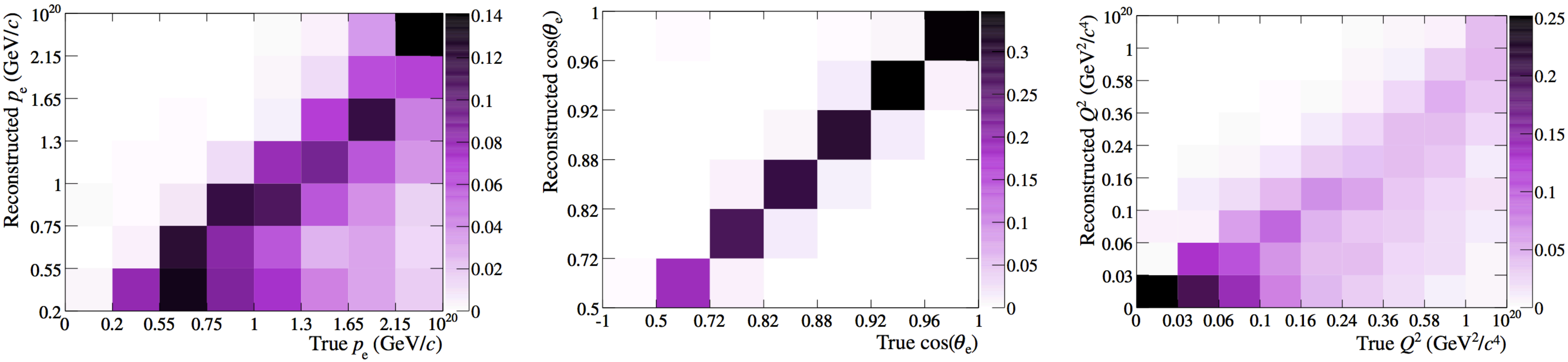
$$P_m(t_k|r_j) = \frac{P(r_j|t_k)P_m(t_k)}{\sum_{\alpha=1}^{n_t} P(r_j|t_\alpha)P_m(t_\alpha)} \qquad N_{t_k}^{m+1} = \frac{1}{\epsilon_{t_k}} \sum_{j=1}^{n_r} P_m(t_k|r_j)(N_{r_j}^{\text{meas}} - B_{r_j})$$

Monte Carlo inputs

- Flux simulated using FLUKA2008, then tuned based on NA61 hadron production data
- NEUT version 5.1.4.2, then tuned based on MiniBooNE CC1π data
- GEANT-based MC to model ND280 detector response
- Background is constrained using data – see later in talk
- Signal efficiencies and priors completely depend on MC
  - Introduces dependency on MC model used
  - Studies show the effect is small

$$P_m(t_k|r_j) = \frac{P(r_j|t_k)P_m(t_k)}{\sum_{\alpha=1}^{n_t} P(r_j|t_\alpha)P_m(t_\alpha)} \qquad N_{t_k}^{m+1} = \frac{1}{\epsilon_{t_k}} \sum_{j=1}^{n_r} P_m(t_k|r_j)(N_{r_j}^{\text{meas}} - B_{r_j})$$

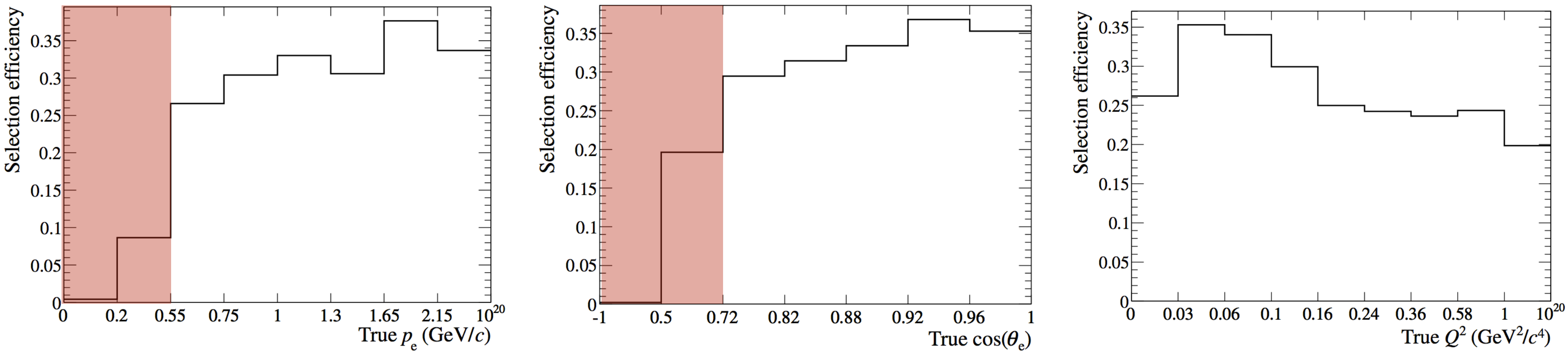
Smearing matrices



- Significant smearing in momentum (and Q^2) due to bremsstrahlung
  - TPC information dominates the momentum estimate
  - If photon is emitted in FGD1 (before electron reaches TPC), TPC measures the "wrong" (lower) momentum

$$P_m(t_k|r_j) = \frac{P(r_j|t_k)P_m(t_k)}{\sum_{\alpha=1}^{n_t} P(r_j|t_\alpha)P_m(t_\alpha)} \qquad N_{t_k}^{m+1} = \boxed{\frac{1}{\epsilon_{t_k}}} \sum_{j=1}^{n_r} P_m(t_k|r_j)(N_{r_j}^{\text{meas}} - B_{r_j})$$

Efficiency



- Low selection efficiency at low momentum and high/backwards angles
- Relies on the MC model to unfold into these "unseen" regions
- Introduces more model-dependency to the result

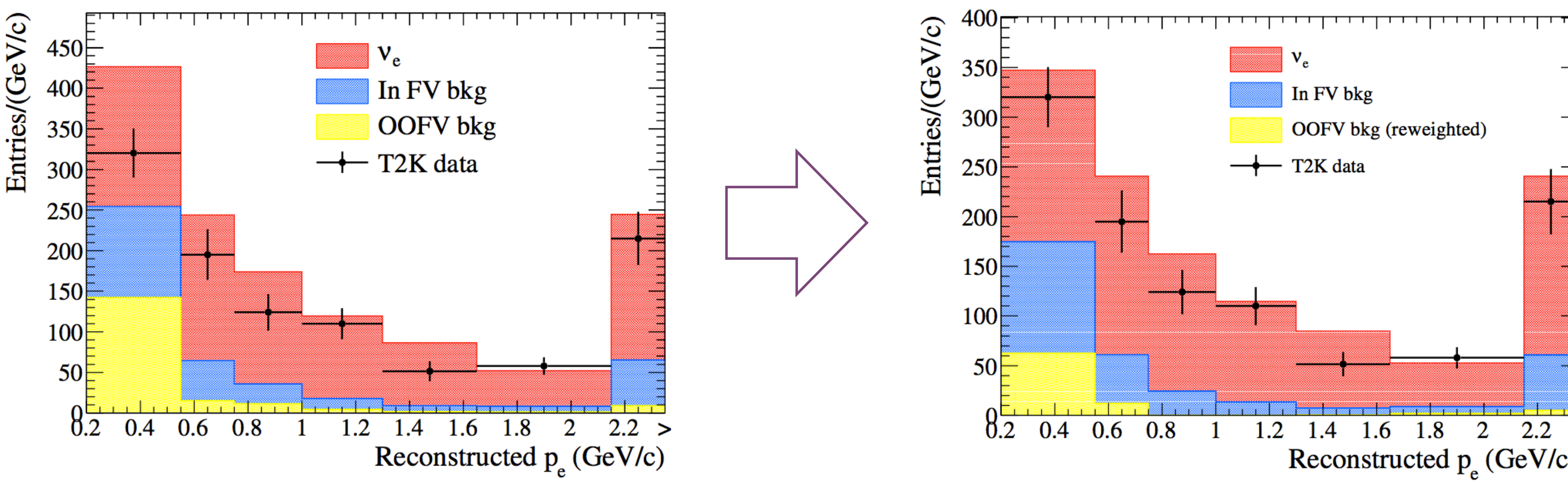
Reduced phase-space

- Can reduce model-dependency by only looking at regions with good efficiency
  - Reconstructed momentum > 550 MeV/c
  - Reconstructed cos(θ) > 0.72
- Only events passing BOTH these criteria are considered in the "reduced phase-space" analysis
  - No attempt is made to unfold into the "unseen" regions
- Results for both the full and reduced phase-spaces will be presented

$$P_m(t_k|r_j) = \frac{P(r_j|t_k)P_m(t_k)}{\sum_{\alpha=1}^{n_t} P(r_j|t_\alpha)P_m(t_\alpha)} \qquad N_{t_k}^{m+1} = \frac{1}{\epsilon_{t_k}} \sum_{j=1}^{n_r} P_m(t_k|r_j)(N_{r_j}^{\text{meas}} - B_{r_j})$$

Background subtraction

- Use the γ sample to constrain part of the background
- Events where the neutrino interacts Outside Of the Fiducial Volume (OOFV) are least well understood
- Use γ sample to re-weight OOFV events in ν_e sample



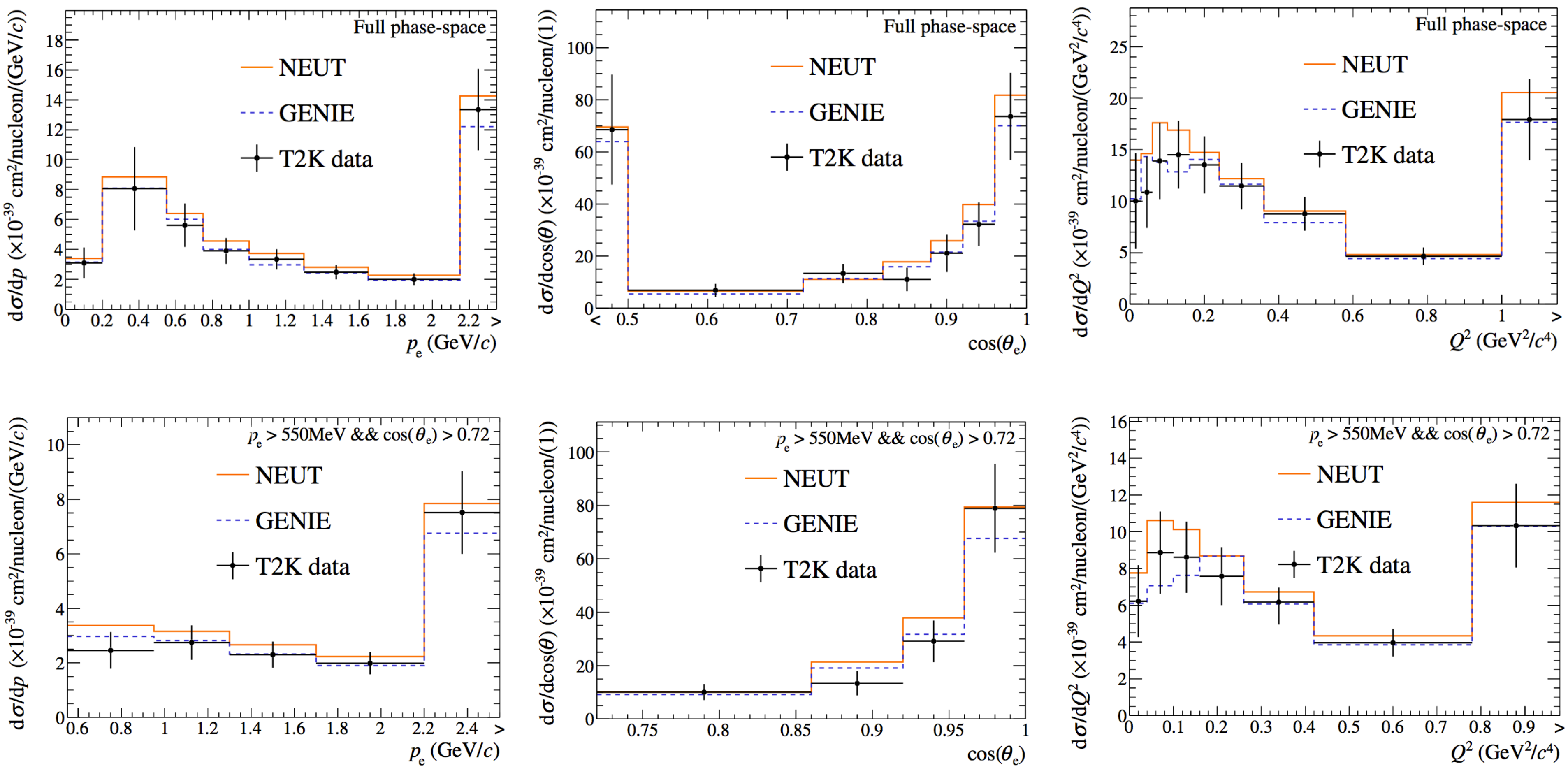
Uncertainties

- Uncertainties calculated using covariance matrix method
- Create separate covariance matrices for
  - Data statistics
  - MC statistics
  - Detector
  - Flux and cross-section
  - Background subtraction technique
- 1000 throws for each, affecting both ν_e and γ samples

Uncertainties

- Detector systematics
  - TPC, FGD, ECal and external systematics
  - Computed using special samples (cosmic rays, through-going muons, electrons entering the ECal etc)
- Flux systematics
  - Based on beam measurements, NA61 data and other external hadron production data
- Cross-section systematics
  - Common systematics for all analyses in T2K
  - Based on external data and theoretical motivations
- See arXiv:1403.2552 for full details of all these

Differential cross-section results

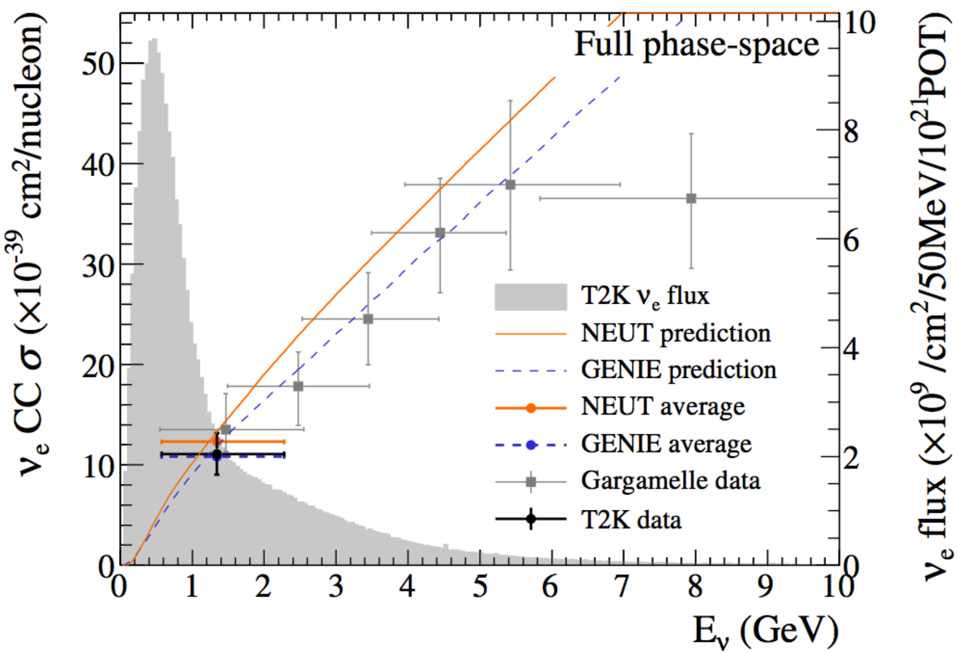


(NEUT v5.1.4.2; GENIE v2.6.4)

Total cross-section result

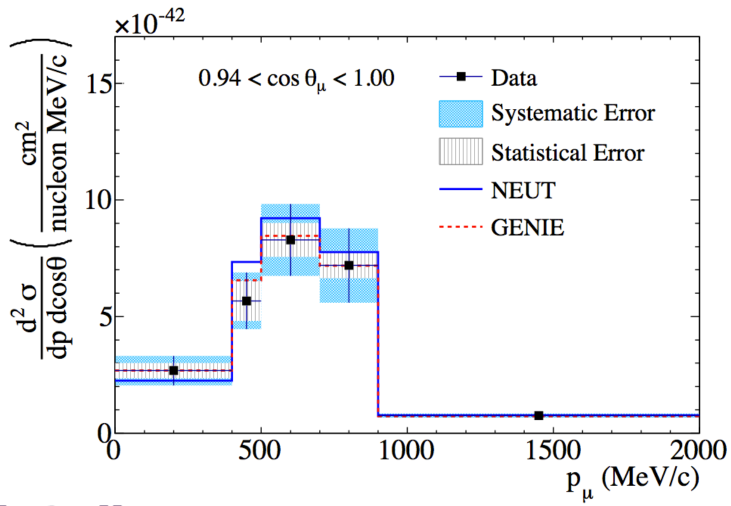
- Good agreement with both NEUT and GENIE, given current uncertainties
- Largest uncertainties are
  - Flux (12.9%)
  - Statistics (8.7%)
  - Detector (8.4%)

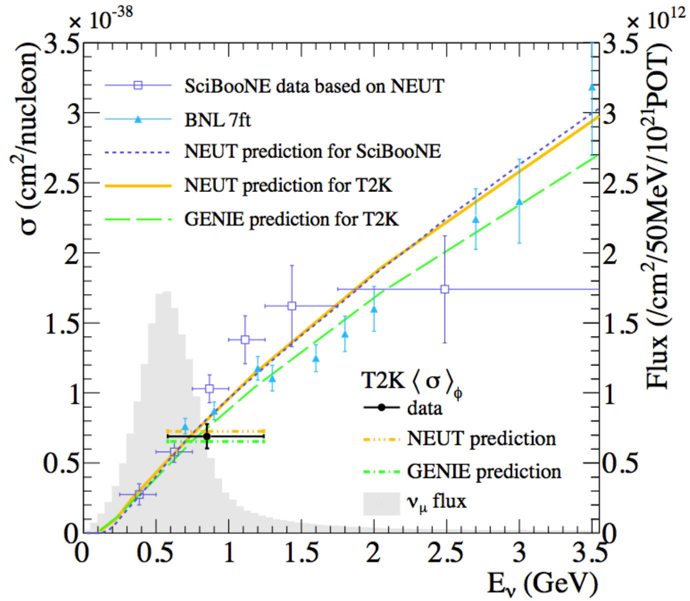
Model/result	σ (x10^{-38} cm^2/nucleon)
NEUT nominal	1.23
GENIE nominal	1.08
T2K data	1.11 ± 0.20



The other flavour

- Double differential ν_μ CC inclusive cross-section published last year in PRD (arXiv:1302.4908)
- Agreed with both NEUT and GENIE
- ND280 are currently focussing on exclusive channels, so no ν_μ inclusive update this year





Summary

- Theoretical differences are expected between ν_μ and ν_e cross-sections
- Constraining these with data is critical to reducing systematic uncertainties, as LBL experiments search for CP violation
- ND280 has measured the ν_e CC inclusive cross-section on carbon
- Results in good agreement with both NEUT and GENIE

Backups

Uncertainties (%)

Total uncertainty in each Q^2 bin

Q^2 (GeV^2/c^4)	Data stat.	MC stat.	Detector	Flux	X-sec	OOFV	Total
0.00–0.03	30.8	8.9	19.6	17.6	18.9	8.2	46.3
0.03–0.06	19.7	6.9	13.6	15.1	11.3	6.3	31.9
0.06–0.10	15.3	5.3	11.6	14.2	9.7	4.9	26.7
0.10–0.16	12.4	4.6	9.4	13.3	7.5	3.8	22.6
0.16–0.24	10.0	4.1	7.9	12.6	8.2	2.5	20.4
0.24–0.36	9.1	3.7	8.0	12.6	8.1	2.3	19.6
0.36–0.58	8.6	3.2	7.7	12.5	6.4	1.7	18.6
0.58–1.00	9.1	3.3	7.6	12.5	4.9	1.4	18.2
> 1.00	11.7	4.0	8.9	13.2	7.9	1.6	21.9
Total	8.7	2.3	8.4	12.9	5.3	2.1	18.7

Uncertainty on total CCinc x-sec for each systematic

Total uncertainty on total CCinc x-sec

Statistical uncertainty

- Data statistics
  - Poisson vary contents of each bin in nue and gamma samples
- MC statistics
  - Separately vary the nue, gamma and other components of the nue and gamma samples

Detector systematics

- Use data to constrain all systematics

Events outside ND280
Entering the selection
Pile-up affecting veto cuts

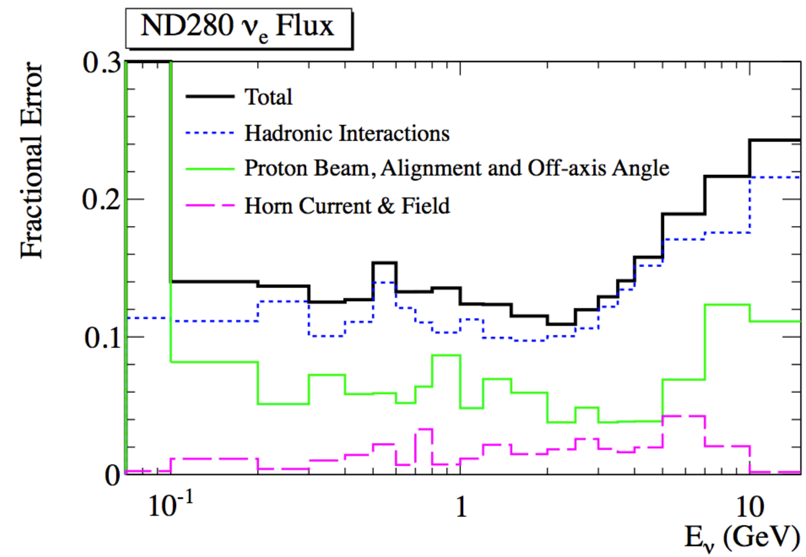
TPCs
B-field distortion
Charge confusion
Momentum resolution
Cluster efficiency
Track efficiency
PID (e, mu/pi, p)

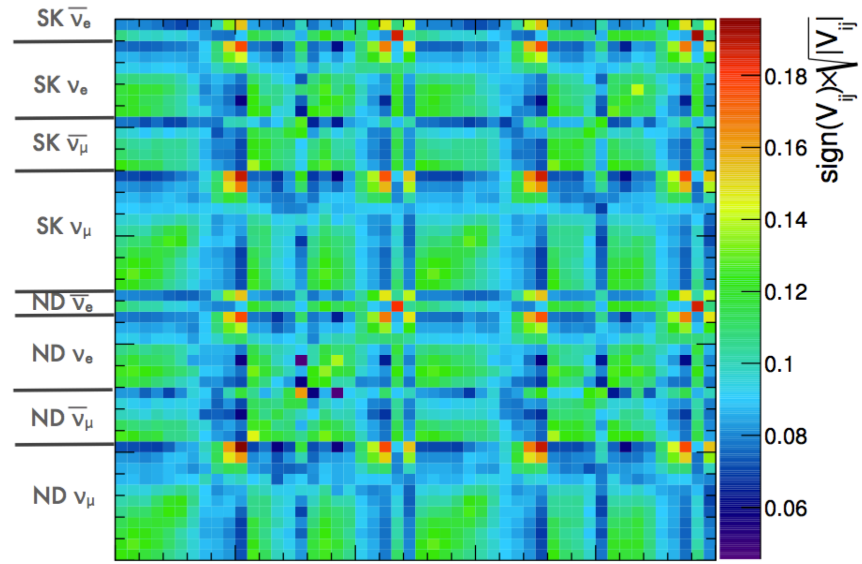
FGDs
Mass
Track efficiency
Michel electron efficiency
TPC-FGD matching
Pion secondary interactions

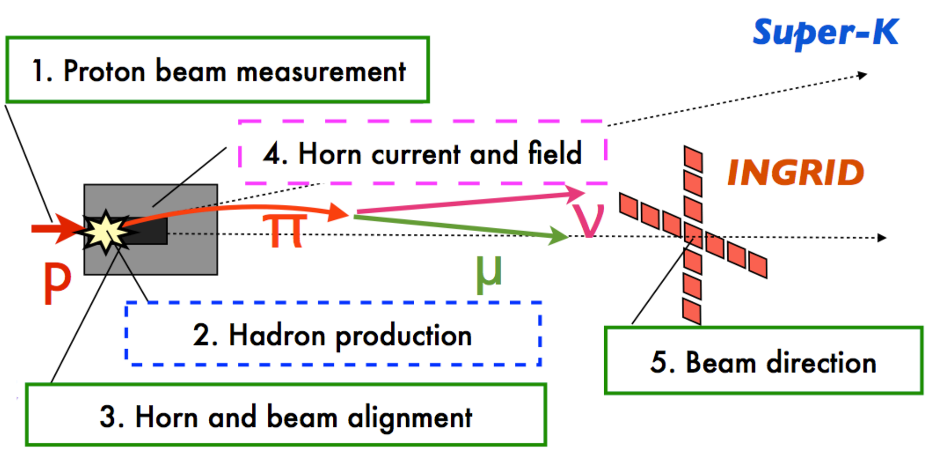
ECals
PID
Energy resolution
Energy scale
TPC-ECal matching

Flux systematics

- Consider 5 sources of uncertainty
- Compute covariance matrix for near-far extrapolation, but only use ND280 part for this analysis







X-sec model

- CCQE: Llewellyn-Smith with Smith-Moniz Fermi gas model for nucleus
- CC1π: Rein-Sehgal resonance model
- DIS and CCnπ: GRV98 PDF with Bodek-Yang correction
- FSI: Cascade model (track secondary particles until they exit nucleus)

X-sec systematics

Pion scattering data
Electron scattering data
MiniBooNE
MiniBooNE / NOMAD
K2K / SciBooNE
Other

Parameter	Nominal value	Uncertainty	Category
F_1^{Inel}	0.00	0.41	FSI
F_2^{Inel}	0.00	0.34	FSI
F^{Prod}	0.00	0.57	FSI
F^{Abs}	0.00	0.28	FSI
F_1^{CX}	0.00	0.50	FSI
F_2^{CX}	0.00	0.41	FSI
M_A^{QE} (GeV/c^2)	1.21	0.45	CCQE
M_A^{RES} (GeV/c^2)	1.41	0.11	Pion production
$x^{\mathrm{CC\ other}}$ (GeV)	0.00	0.40	Pion production
x^{SF}	0.00	1.00	Nuclear
E_B (MeV)	25.00	9.00	Nuclear
p_F (MeV/c)	217.00	30.00	Nuclear
$x^{\pi\text{-less}}$	0.20	0.20	Pion production
x_1^{QE}	1.00	0.11	CCQE
x_2^{QE}	1.00	0.30	CCQE
x_3^{QE}	1.00	0.30	CCQE
$x_1^{\mathrm{CC1}\pi}$	1.15	0.43	Pion production
$x_2^{\mathrm{CC1}\pi}$	1.00	0.40	Pion production
$x^{\mathrm{CC\ coh.}}$	1.00	1.00	Pion production
$x^{\mathrm{NC\ other}}$	1.00	0.30	Pion production
$x^{\mathrm{NC1}\pi^0}$	0.96	0.43	Pion production

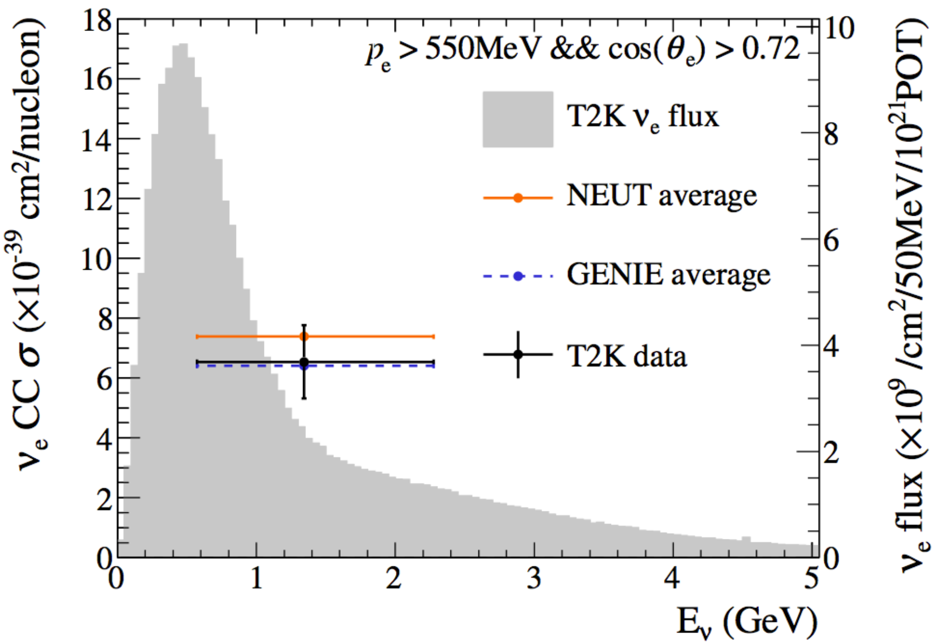
OOFV systematic

- Exact source of lower OOFV background is not fully understood
- To be conservative, want to enlarge the systematic beyond just the statistics of the gamma sample
- Treat the data/MC difference as a 3σ uncertainty

Restricted phase-space

- Good agreement with both NEUT and GENIE
- Note that the full T2K flux is used in the flux-averaging, including the low-energy part that doesn't create electrons with p > 550 MeV

Model/result	σ ($\times 10^{-39}$ cm^2/nucleon)
NEUT nominal	7.38
GENIE nominal	6.41
T2K data	6.54 ± 1.22



A second slide about numu

- ν_μ flux is lower energy than ν_e flux – comparison between results is not trivial!
- ν_μ mean energy is 0.85 GeV

Model/result	σ (x10^{-39} cm^2/nucleon)
NEUT nominal	7.27
GENIE nominal	6.54
T2K data	6.91 ± 0.13 (stat) ± 0.84 (syst)

- ν_e mean energy is 1.34 GeV

Model/result	σ (x10^{-38} cm^2/nucleon)
NEUT nominal	1.23
GENIE nominal	1.08
T2K data	1.11 ± 0.10 (stat) ± 0.18 (syst)