$\bar{\nu}_\mu$ CCQE at MiniBooNE

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NuInt '11
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Outline

1. Booster Neutrino Beam
2. CCQE events in MiniBooNE
3. MiniBooNE ν_μ CCQE result review
4. ν_μ flux in $\bar{\nu}_\mu$ beam measurements
5. RFG model comparisons to $\bar{\nu}_\mu$ CCQE data
6. Future BooNE CCQE measurements, conclusions

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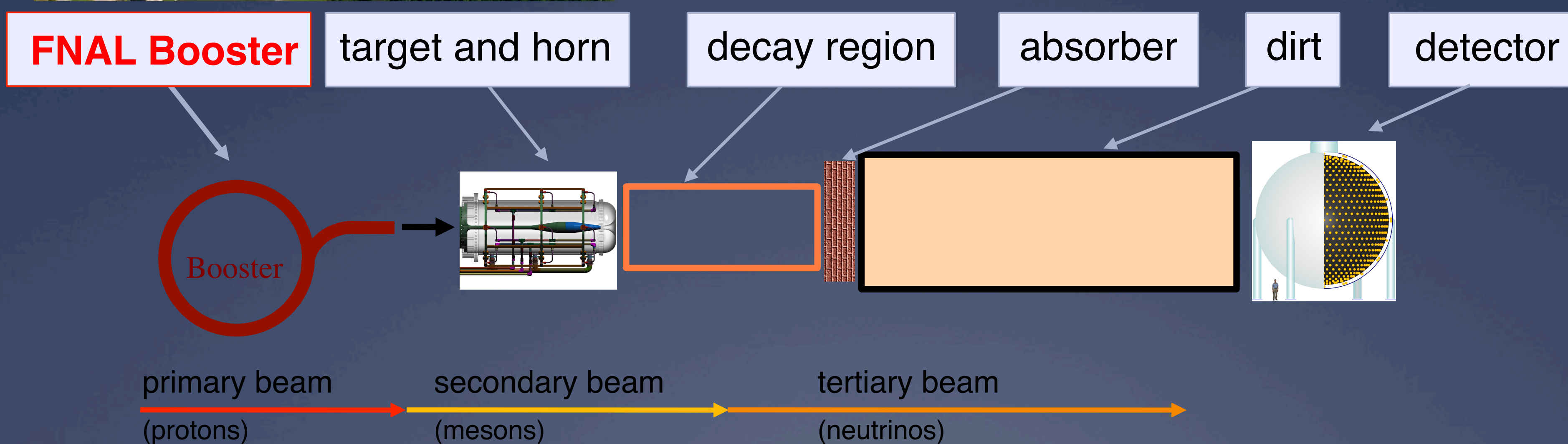
Booster Neutrino Beam

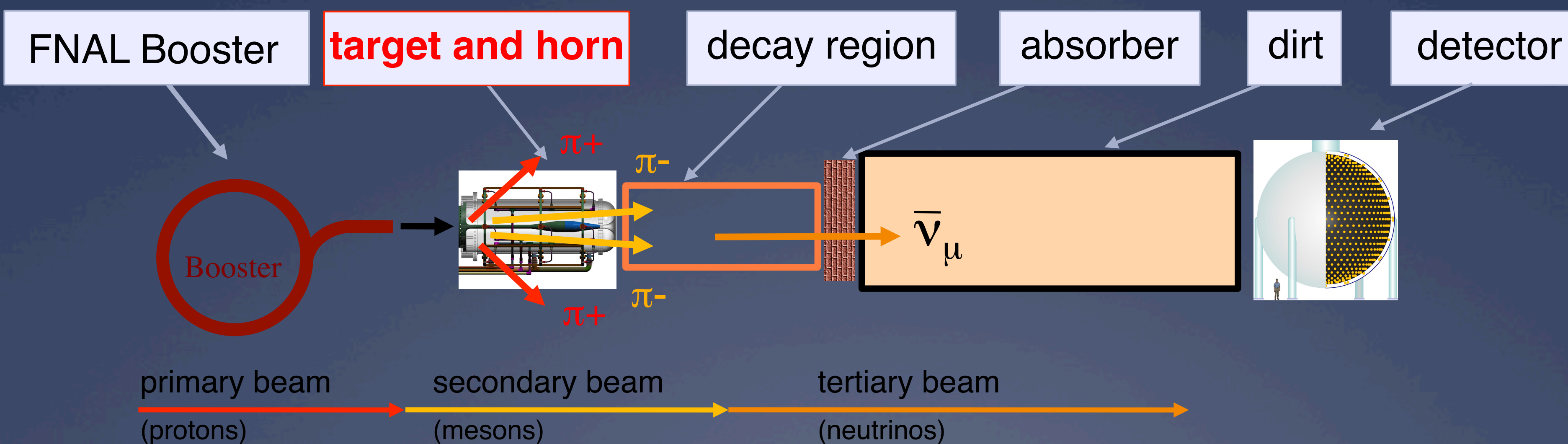
8.9 GeV/c momentum protons extracted from Booster, steered toward a Beryllium target in bunches of 5×10^{12} at a maximum rate of 5 Hz



Booster Neutrino Beam

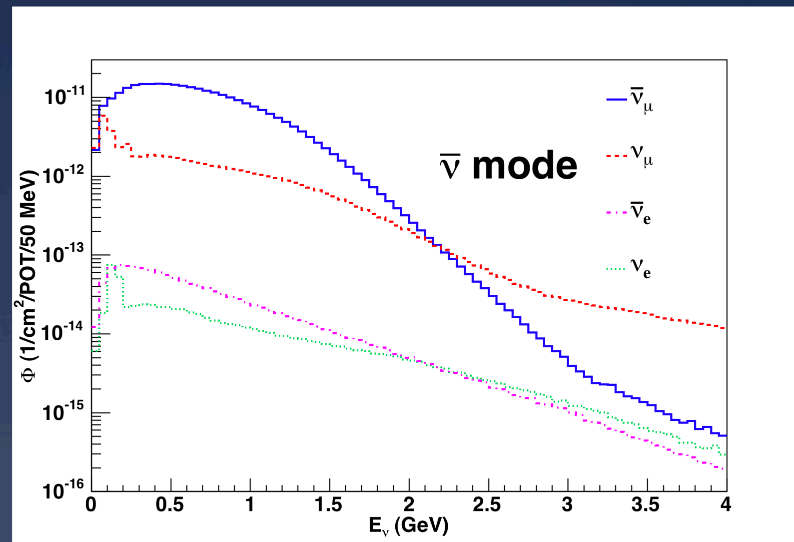
Magnetic horn with reversible polarity focuses either neutrino or anti-neutrino parent mesons

("neutrino" vs "anti-neutrino" mode)

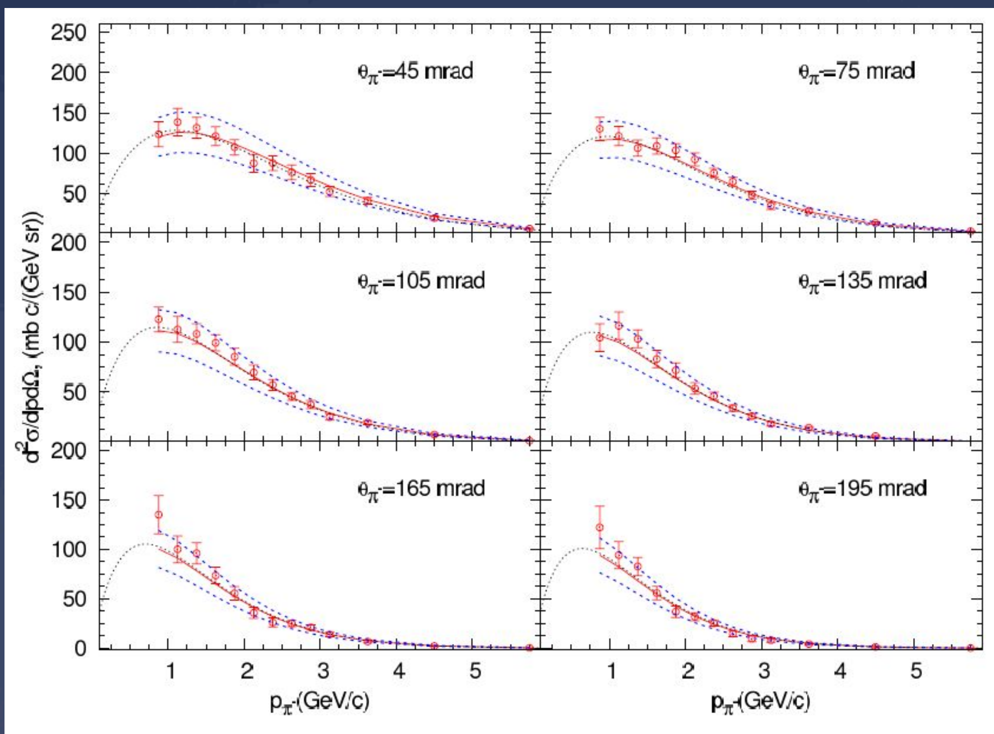


MiniBooNE Flux

- Flux prediction based exclusively on external data - no *in situ* tuning



MiniBooNE collaboration,
Phys. Rev. D79, 072002 (2009)



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

- Dedicated pion production data taken by HARP experiment to predict neutrino flux at MiniBooNE
- A spline fit to these data brings flux uncertainty to ~9% for pions produced in HARP-covered phase space

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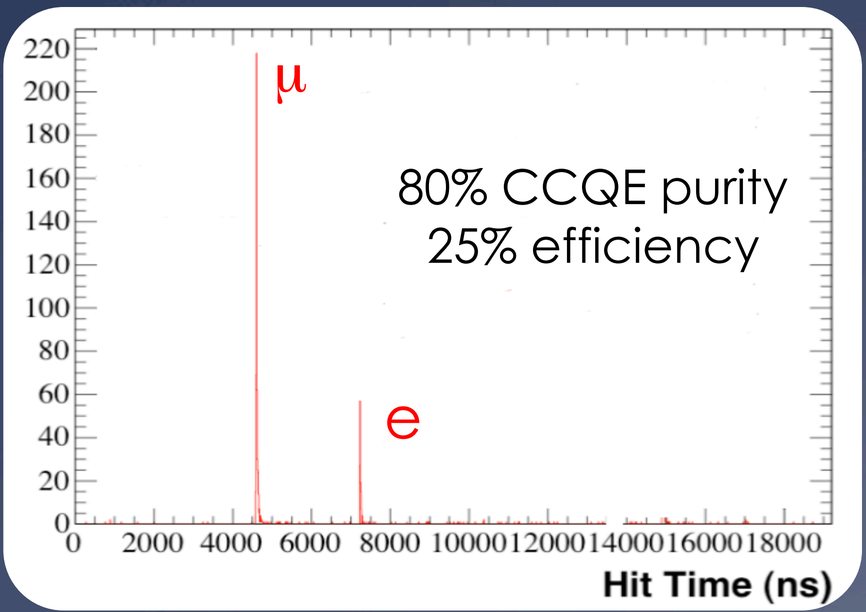
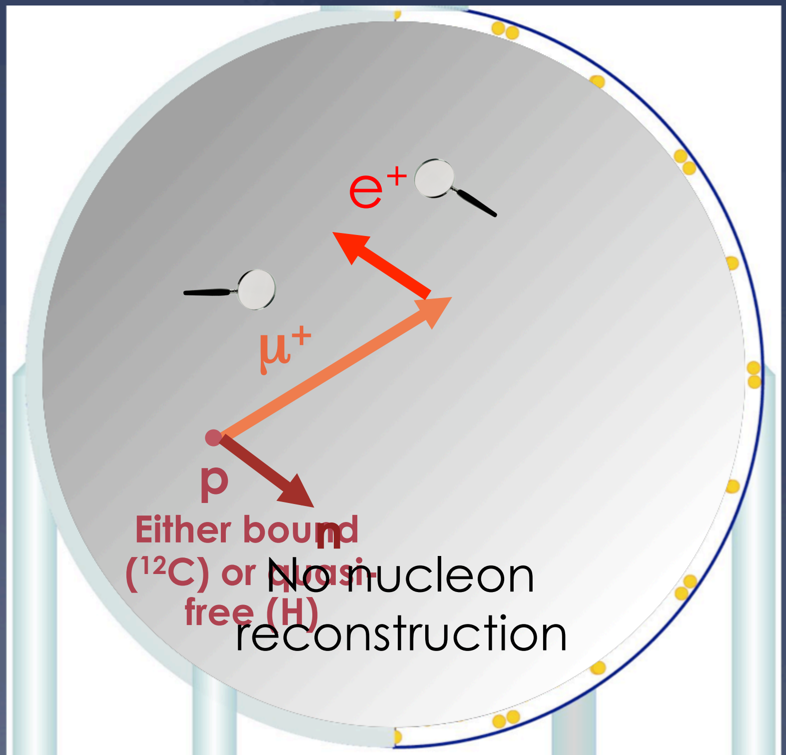
CCQE Events in MiniBooNE

CCQE is the most prevalent interaction at MiniBooNE's energy range, accounting for ~40% of all events.

MiniBooNE: spherical Cherenkov detector, filled with 800 tons of undoped mineral oil (CH_2)



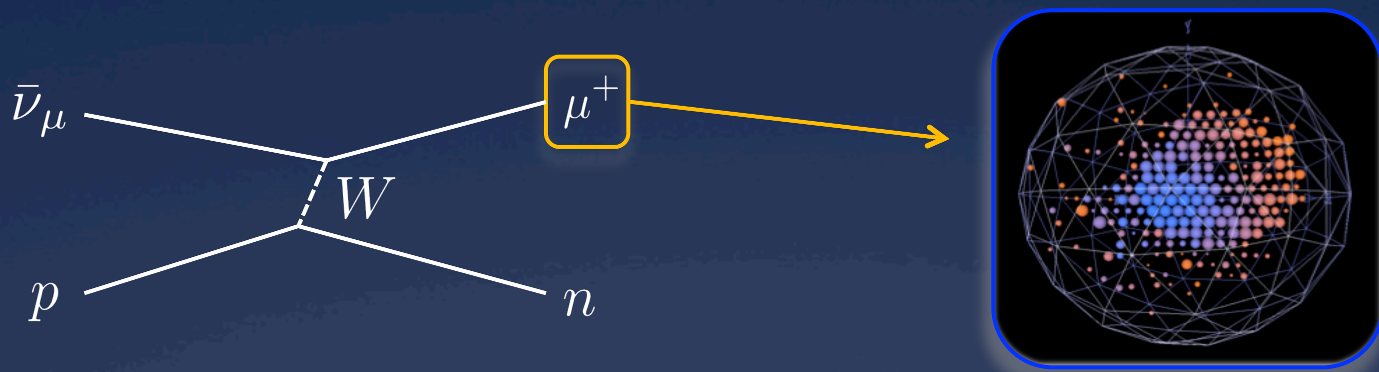


CCQE Events in MiniBooNE

- MiniBooNE nuclear simulation: Relativistic Fermi Gas (RFG) model Nucl. Phys. B43 (1972) 605
  - Models nucleons as independent, quasi-free particles bound by a constant E_B
  - All struck (outgoing) nucleons subject to Pauli blocking, enforced by a global Fermi momentum
  - Dipole axial form factor, $F_A(Q^2) = 1.267(1 - Q^2/M_A{}^2)^{-2}$
  - Non-dipole vector form factor

    Bodek *et al*,. arxiv:hep-ex/0308005

CCQE Events in MiniBooNE



Only the muon from the primary interaction is observed, but we can reconstruct incident anti-neutrino energy and momentum transfer based on muon kinematics

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Under the assumption of a target proton at rest,
(θ_μ: muon angle wrt neutrino beam)

$$E_{\bar{\nu}}^{\mathrm{QE}} = \frac{2(M_p - E_B)E_\mu - (E_B^2 - 2M_pE_B + m_\mu^2 + \Delta M^2)}{2[(M_p - E_B) - E_\mu + p_\mu \cos\theta_\mu]}$$

$$Q^2_{\mathrm{QE}} = 2E_{\bar{\nu}}^{QE}(p_\mu \cos\theta_\mu - E_\mu) + m_\mu^2$$

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MiniBooNE ν_μ CCQE Review

* First presented NuInt09, T. Katori
  Phys. Rev. **D81**, 092005 (2010)

* Measurements:
  * $d\sigma/dQ^2$
  * $\sigma(E_\nu)$
  * $d^2\sigma/dT_\mu\, d\cos\theta_\mu$

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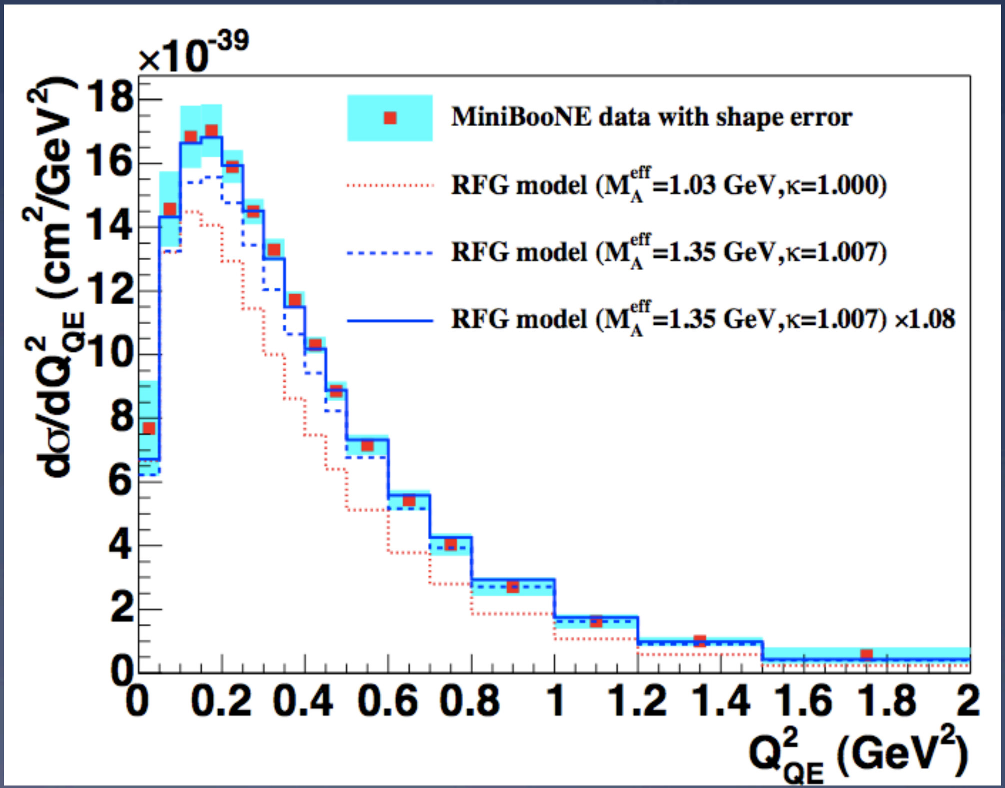
- Measurements:
  - $d\sigma/dQ^2$

Using the RFG nuclear model, the axial mass M_A and an empirical Pauli blocking scale was extracted from a shape-only fit to data



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* Measurements:
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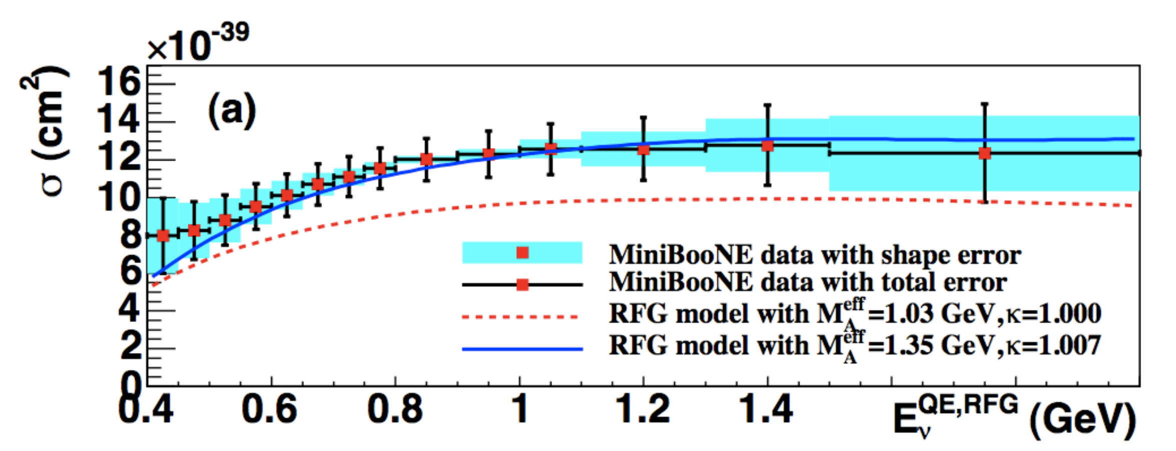
  * $\sigma(E_\nu)$

More interesting, ν_μ CCQE σ > 30% higher than expected!



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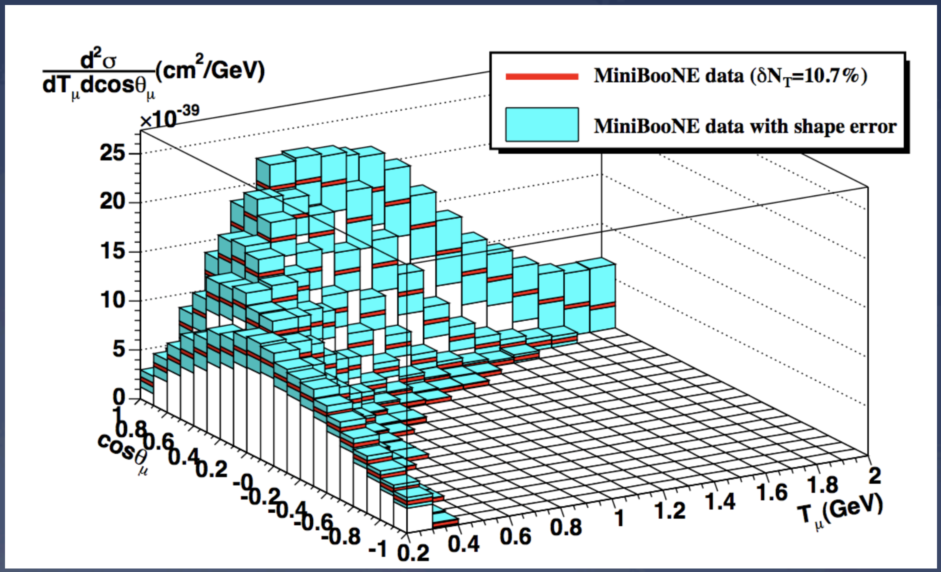

* Primary result - extraction based on observables only
  * Independent of interaction model assumptions

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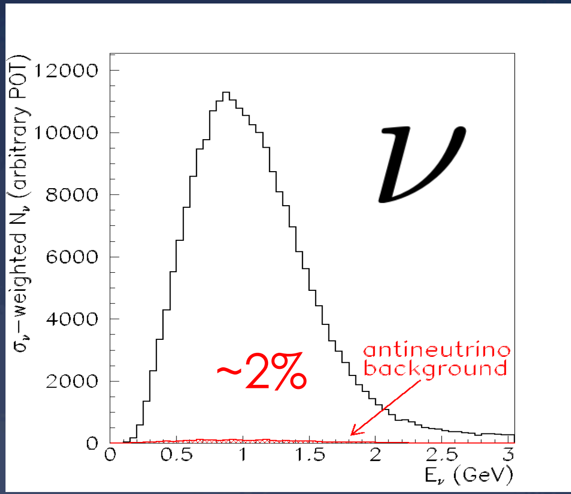
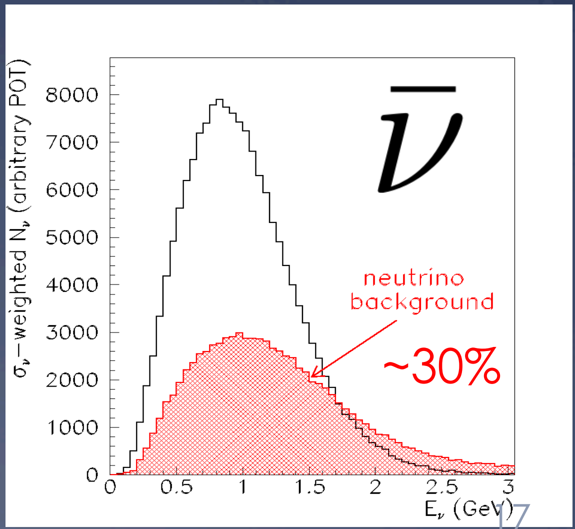
Wrong-sign Background

G. P. Zeller

* "Wrong signs": anti-neutrinos in the neutrino beam and vice versa
* MiniBooNE detector unmagnetized, cannot separate contributions based on CC interactions
* Wrong-sign background far more serious in anti-neutrino mode due to both flux and cross section effects



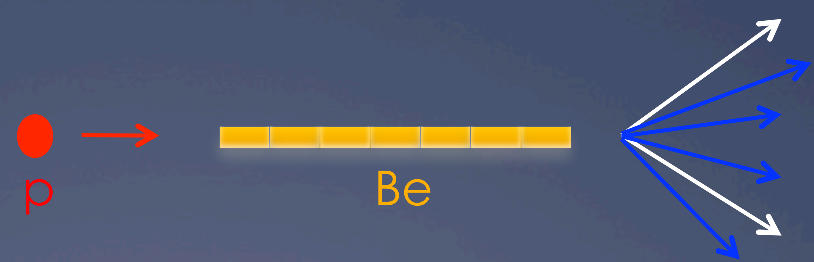


Wrong-sign Background

* Cross section: at MiniBooNE energies (E_ν~1 GeV), neutrino cross section ~ 3x higher than anti-neutrino

$$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 |V_{ud}|^2}{8\pi E_\nu^2}\left[A\left(Q^2\right) \boxed{\pm} B\left(Q^2\right)\left(\frac{s-u}{M^2}\right) + C\left(Q^2\right)\left(\frac{s-u}{M^2}\right)^2\right]$$

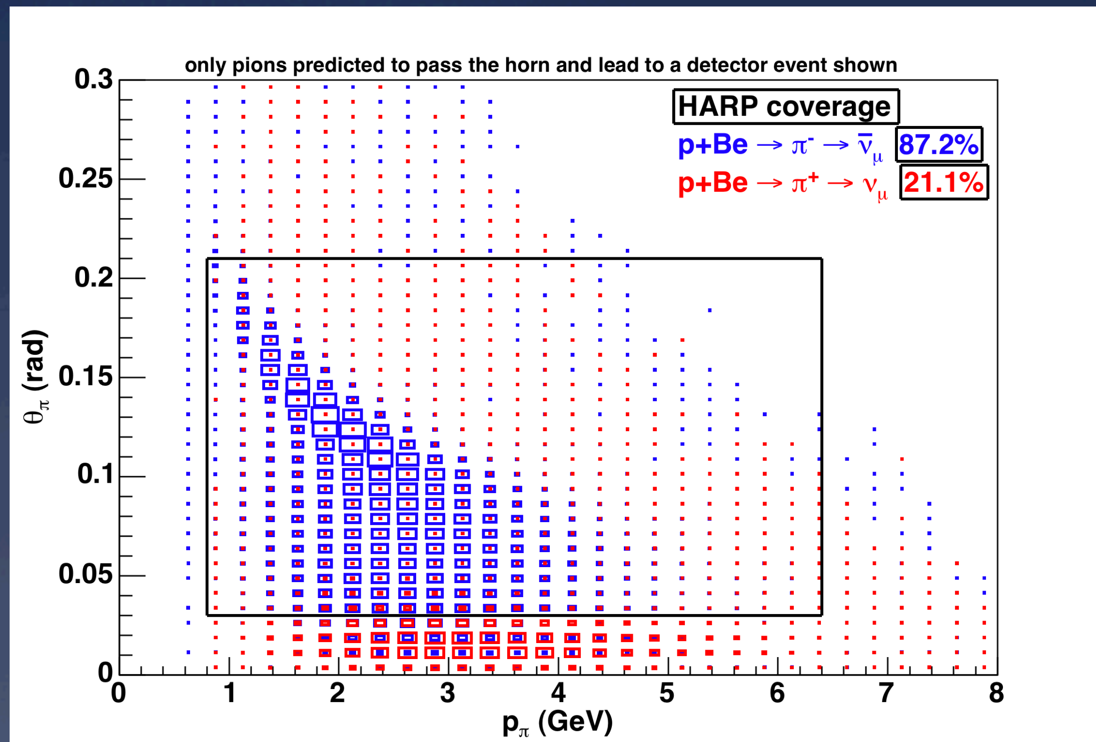
* Flux: leading particle effect creates ~ 2x as many π+ as π-



π+ π−

How wrong signs contribute to flux

- Wrong-sign pions escape magnetic deflection and contribute to the anti-neutrino beam via low angle production



- In anti-neutrino mode low-angle production is a *crucial* flux region and we do not have a reliable prediction

This motivates a dedicated study of ν_μ content of the beam

Wrong-sign measurements

* Three independent and complementary measurements of the wrong-sign background:

    1. Fitting the angular distribution of the CCQE sample for the neutrino and anti-neutrino content
    2. Comparing predicted to observed event rates in the $CC\pi^+$ sample
    3. Measuring how often muon decay electrons are produced (exploits μ^- nuclear capture)

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First measurement of the ν_μ content of a $\bar{\nu}_\mu$ beam using a non-magnetized detector.
arxiv:1102.1964

Wrong-sign measurements

* General strategy: isolate samples sensitive to the ν_μ beam content, apply the measured cross sections from neutrino mode (CCQE, CCπ^+)
  * *Crucial* application of BooNE-measured ν_μ σ's

* The level of data-simulation agreement then reflects the accuracy of the ν_μ flux prediction

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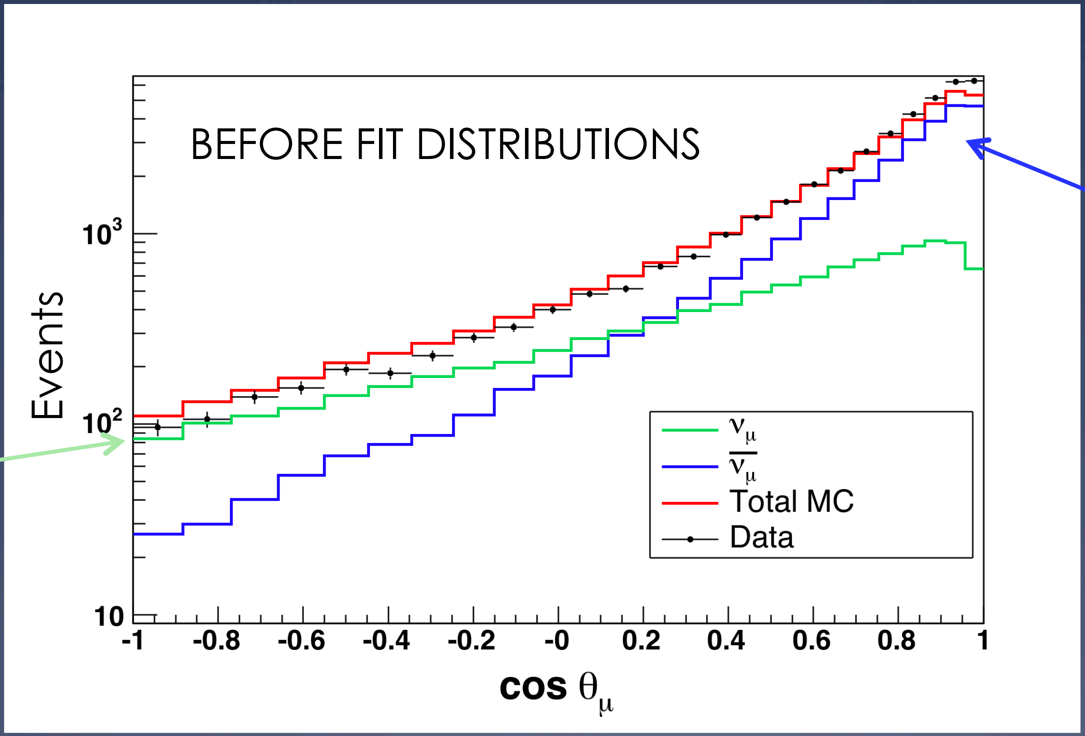
Fitting the outgoing muon angular distribution

* In the RFG, due to the interference term the CCQE $\nu_\mu\,\sigma >> \overline{\nu}_\mu\,\sigma$ for backward-going μ

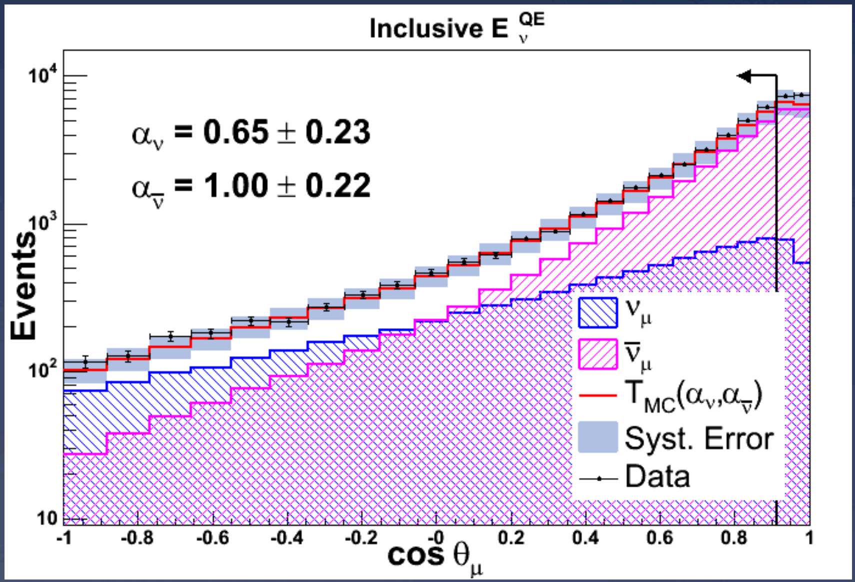


Scale the $\overline{\nu}_\mu$ template by "$\alpha_{\overline{\nu}}$"

Scale the ν_μ template by "α_ν"

Fitting the outgoing muon angular distribution

- Results indicate the ν_μ flux is over-predicted by ~30%
- Fit also performed in bins of reconstructed energy; consistent results indicate flux spectrum shape is well modeled



$E_{\bar{\nu}}^{QE}$(MeV)	α_ν	$\alpha_{\bar{\nu}}$
< 600	0.65 ± 0.22	0.98 ± 0.18
600 - 900	0.61 ± 0.20	1.05 ± 0.19
> 900	0.64 ± 0.20	1.18 ± 0.21
Inclusive	0.65 ± 0.23	1.00 ± 0.22

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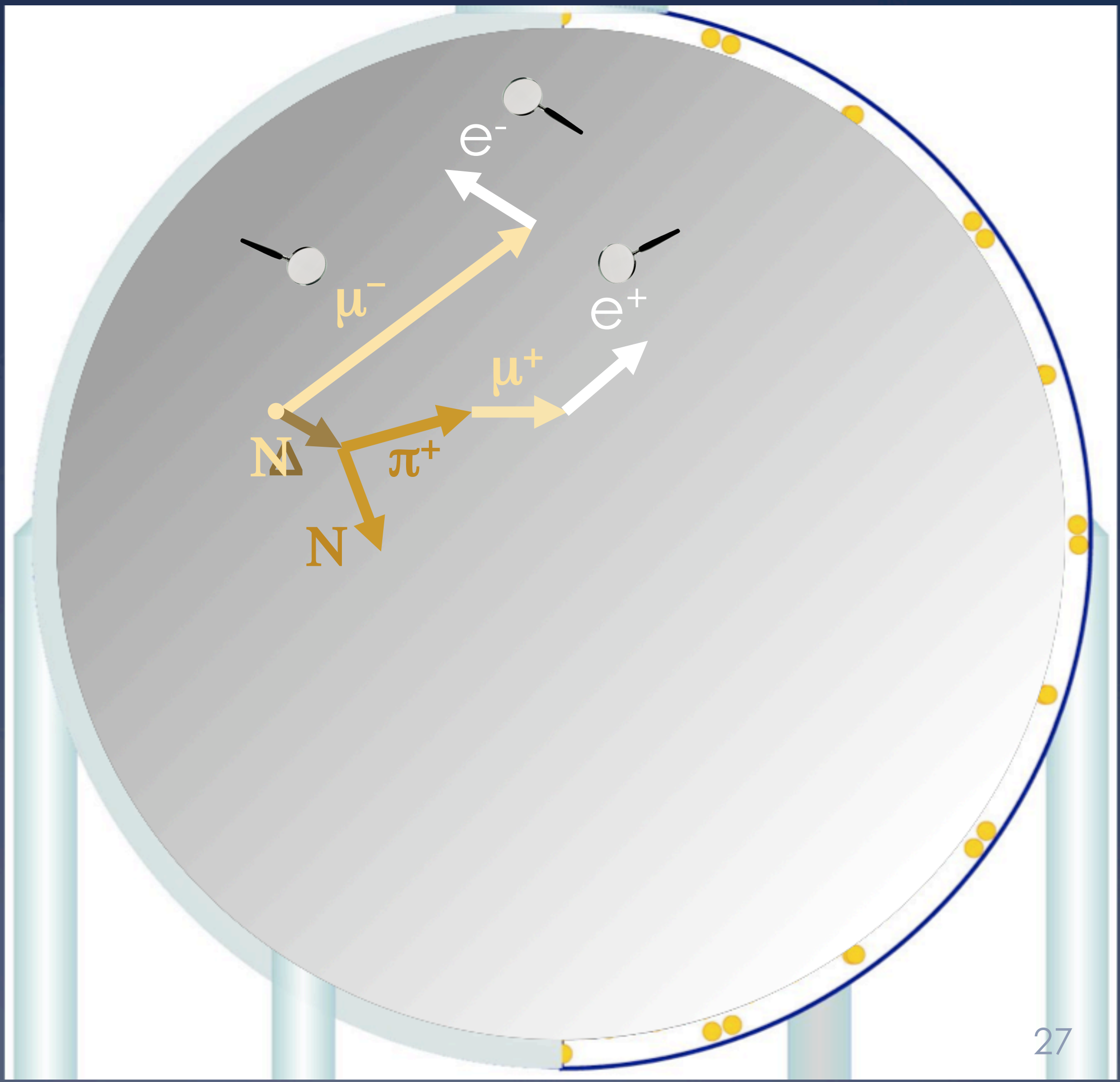
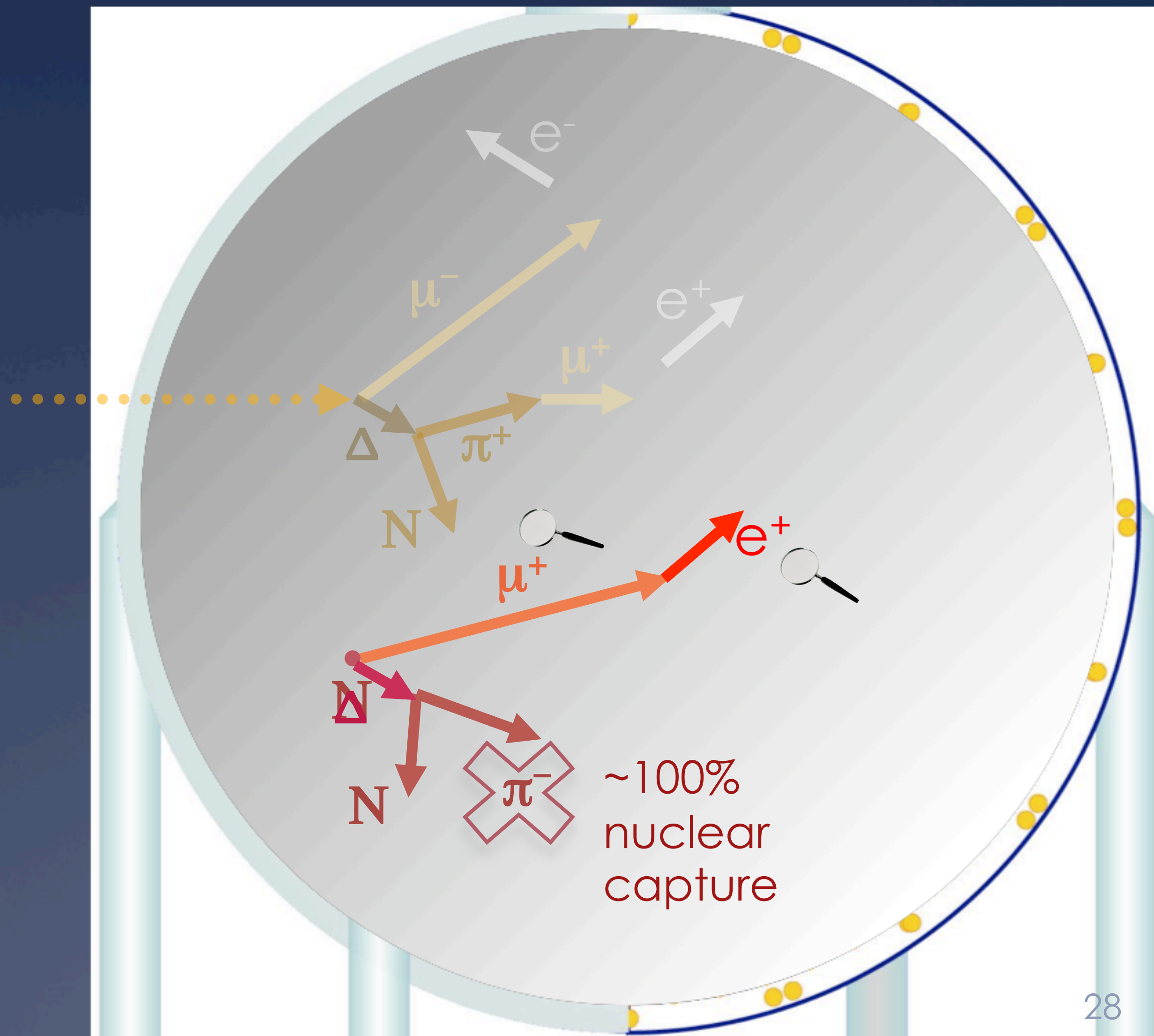
CCπ^+ sample formation

* The neutrino induced resonance channel leads to three leptons above Cherenkov threshold
  1. Primary muon
  2. Decay electron
  3. Decay positron



CCπ+ sample formation



* Due to nuclear π⁻ capture, the corresponding anti-neutrino interaction has only two:
  1. Primary muon
  2. Decay positron

$CC\pi^+$ ν_μ flux measurement

- With the simple requirement of two decay electrons subsequent to the primary muon, we isolate a sample that is ~80% neutrino-induced.
- Data/simulation ratios in bins of reconstructed energy indicate the neutrino flux is over-predicted in normalization, while the spectrum shape is consistent with the prediction

E_ν^Δ (MeV)	ν_μ Φ scale "α_ν"
600 - 700	0.65 ± 0.10
700 - 800	0.79 ± 0.10
800 - 900	0.81 ± 0.10
900 - 1000	0.88 ± 0.11
1000 - 1200	0.74 ± 0.10
1200 - 2400	0.73 ± 0.15
Inclusive	0.76 ± 0.11

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Model-independent measurement, employed by both CCQE, NCE anti-neutrino analyses

Wrong-sign measurements

* Three independent and complementary measurements of the wrong-sign background:

1. Fitting the angular distribution of the CCQE sample for the neutrino and anti-neutrino content
2. Comparing predicted to observed event rates in the $CC\pi^+$ sample
3. Measuring how often muon decay electrons are produced (exploits μ^- nuclear capture)

μ^- capture measurement

- We isolate a > 90% CC sample for both μ-only and μ+e samples
- CC events typically observe both μ+e - two reasons why we may not observe the decay electron:
  1. Decay electron detection efficiency
  2. μ^- nuclear capture (ν_μ CC events only)

μ^- capture measurement

* By requiring $(\mu\text{-only}/\mu+e)^{data} = (\mu\text{-only}/\mu+e)^{MC}$ and normalization to agree in the μ+e sample we can calculate a ν_μ flux scale α_ν and a rate scale $\alpha_{\bar{\nu}}$

$$\frac{\mu}{\mu + e}^{\mathrm{data}} = \left(\frac{\alpha_\nu \, \nu^\mu + \alpha_{\bar{\nu}} \, \bar{\nu}^\mu}{\alpha_\nu \, \nu^{\mu+e} + \alpha_{\bar{\nu}} \, \bar{\nu}^{\mu+e}} \right)^{\mathrm{MC}}$$

Predicted neutrino content in the μ+e sample, for example

μ^- capture measurement

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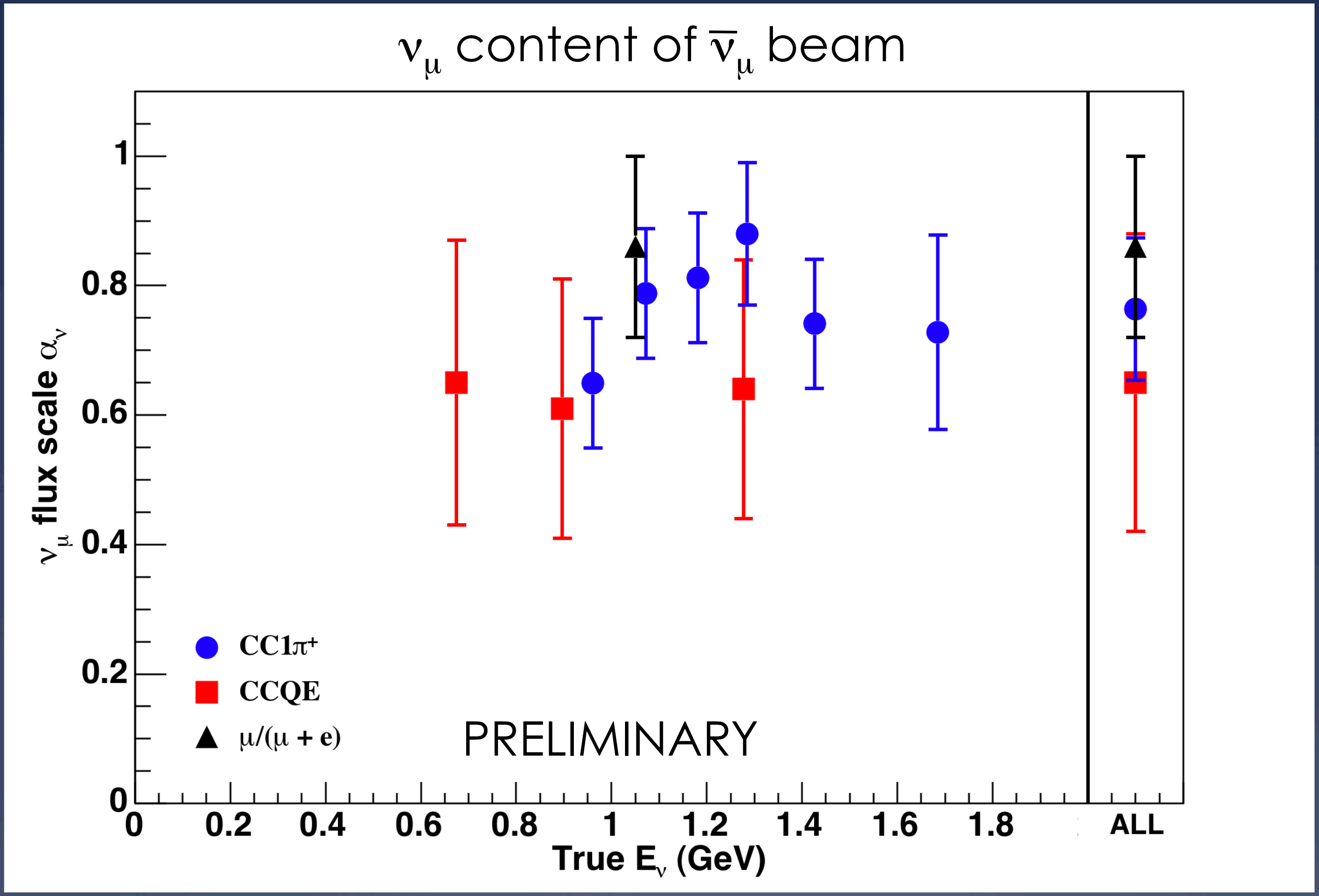
Results:

$$\alpha_\nu = 0.86 \pm 0.14$$

$$\alpha_{\bar{\nu}} = 1.09 \pm 0.23$$

PRELIMINARY

Neutrino flux measurement summary



* Discrepancy with prediction appears to be in normalization only - flux shape is well modeled

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RFG model comparisons

* Will show **bkg-subtracted data**
  * Purity: 64%.
  * Data not corrected for reconstruction biases

Contribution	%
$\bar{\nu}_\mu$ CCQE	64
ν_μ CCQE	14
CCπ-	14
CCπ+	4
Other	4

CONSTRAINED (ν_μ CCQE, CCπ+)

PARTIALLY CONSTRAINED (CCπ-)

RFG model comparisons

* Will compare data to **absolutely-normalized** simulation under two CCQE model hypotheses:

↪ "M_A^H": axial mass for hydrogen scattering, "M_A^C": carbon

1. $M_A^C = 1.35$ GeV, $\kappa = 1.007$, $M_A^H = 1.02$ GeV
2. $M_A^C = M_A^H = 1.02$ GeV $\kappa = 1.000$

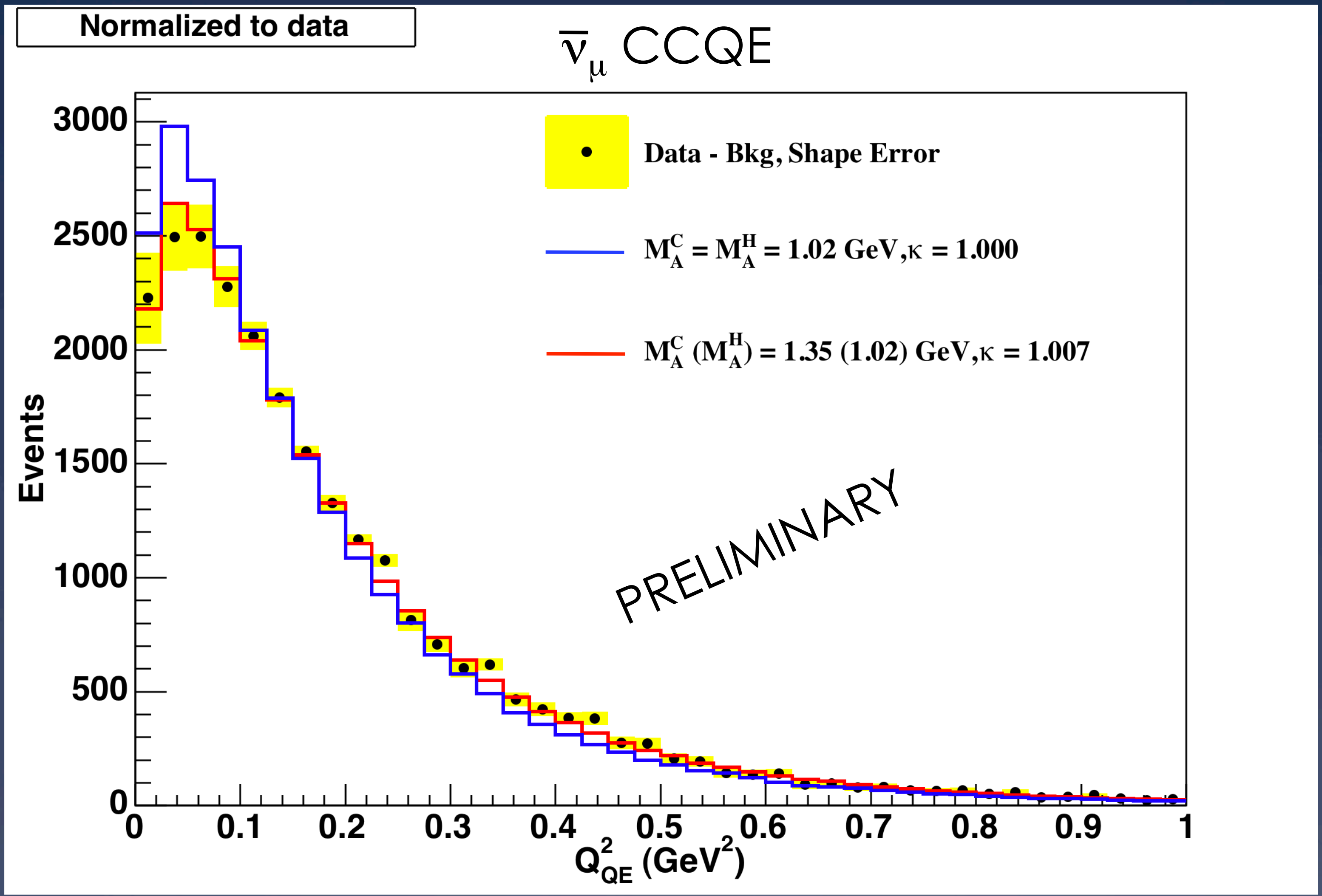
$M_A = 1.35$ GeV, $\kappa = 1.007$ consistent with BooNE ν_μ data [1]

$M_A = 1.02$ GeV consistent with light target data [2]

[1] MiniBooNE, Phys. Rev. **D81**, 092005 (2010)

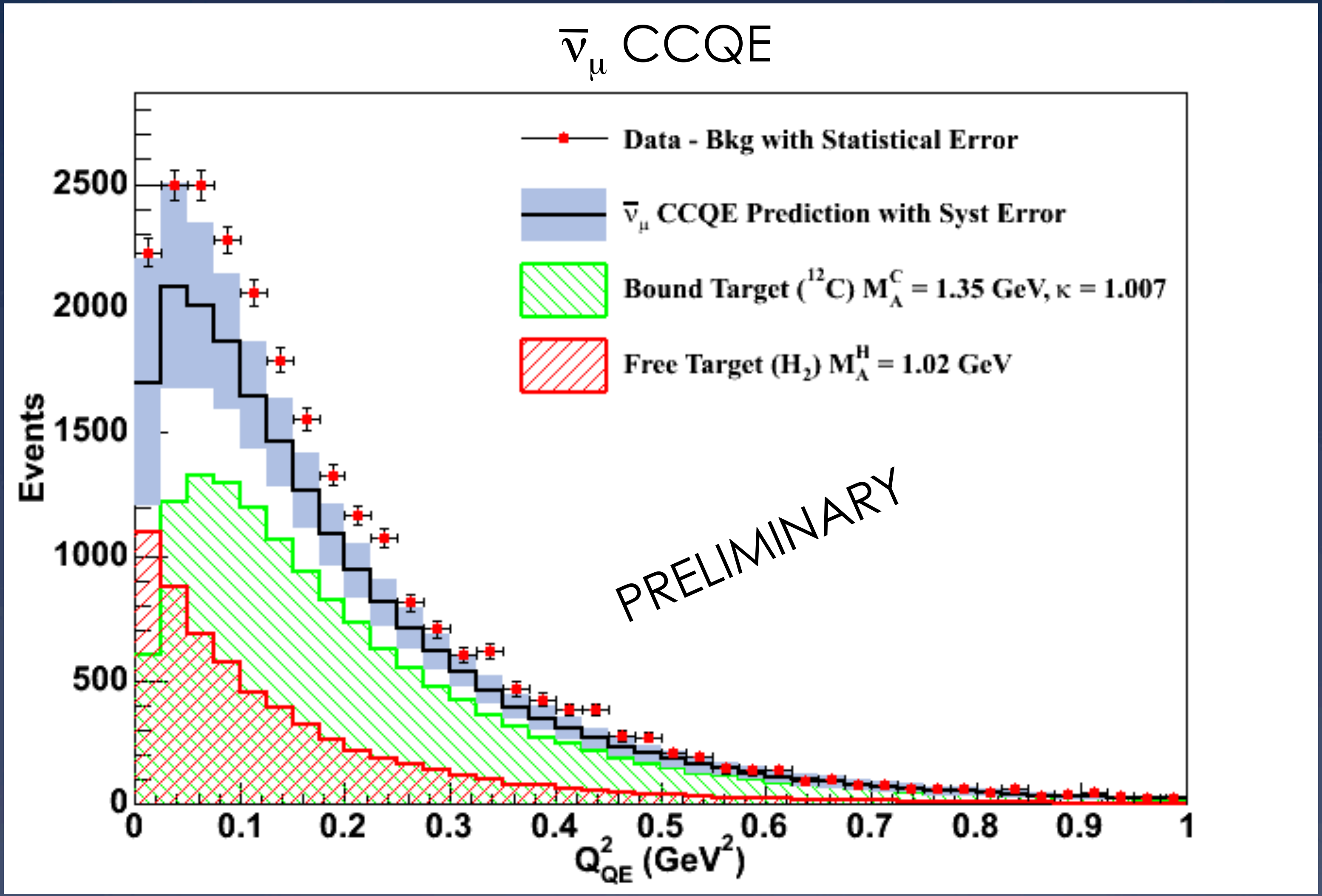
[2] Bodek *et al*,. arxiv:hep-ex/0308005

Q^2_{QE}: shape comparison to data



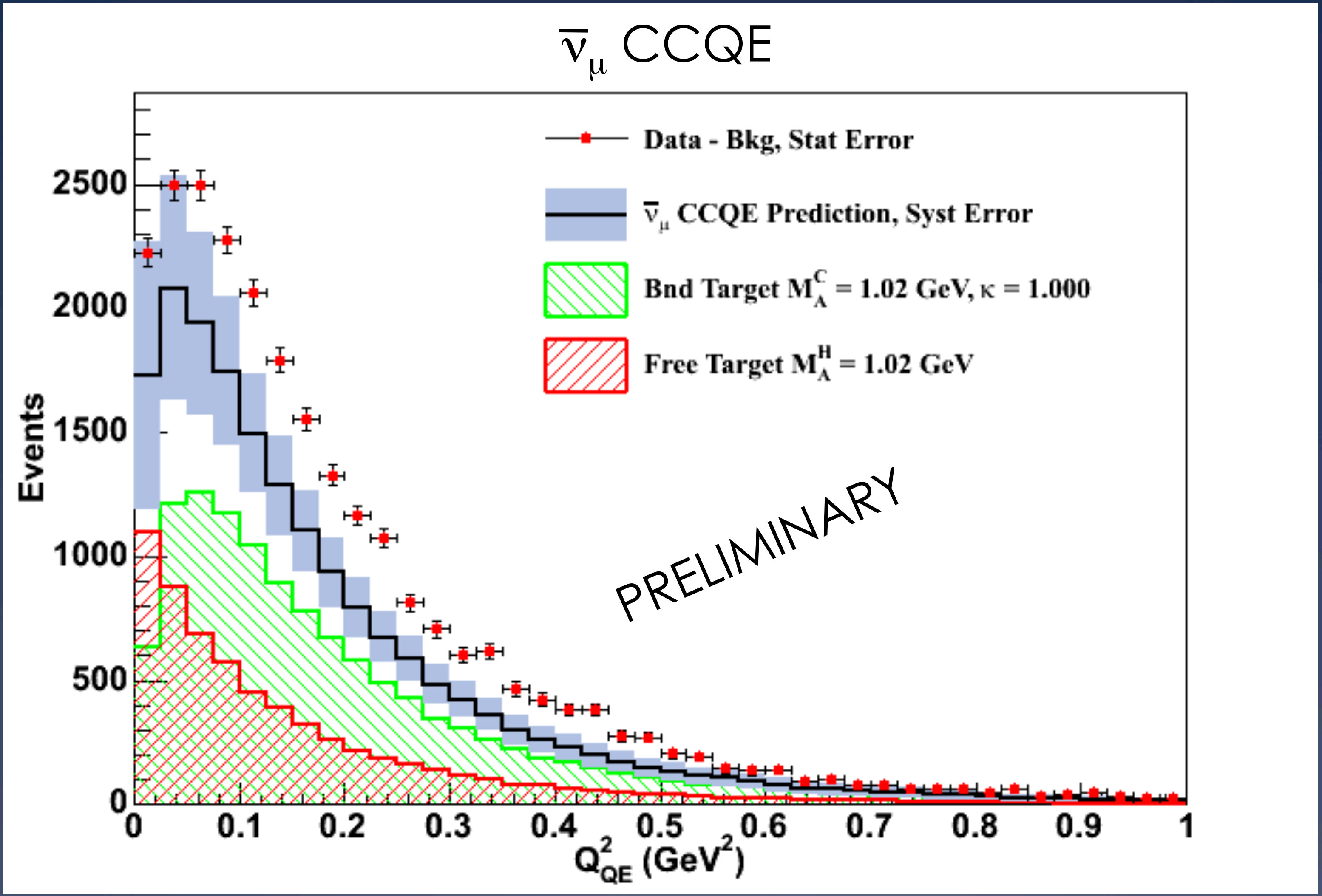
M_A = 1.02 GeV, κ = 1 inconsistent with data shape

Q^2_{QE}: absolute comparison with



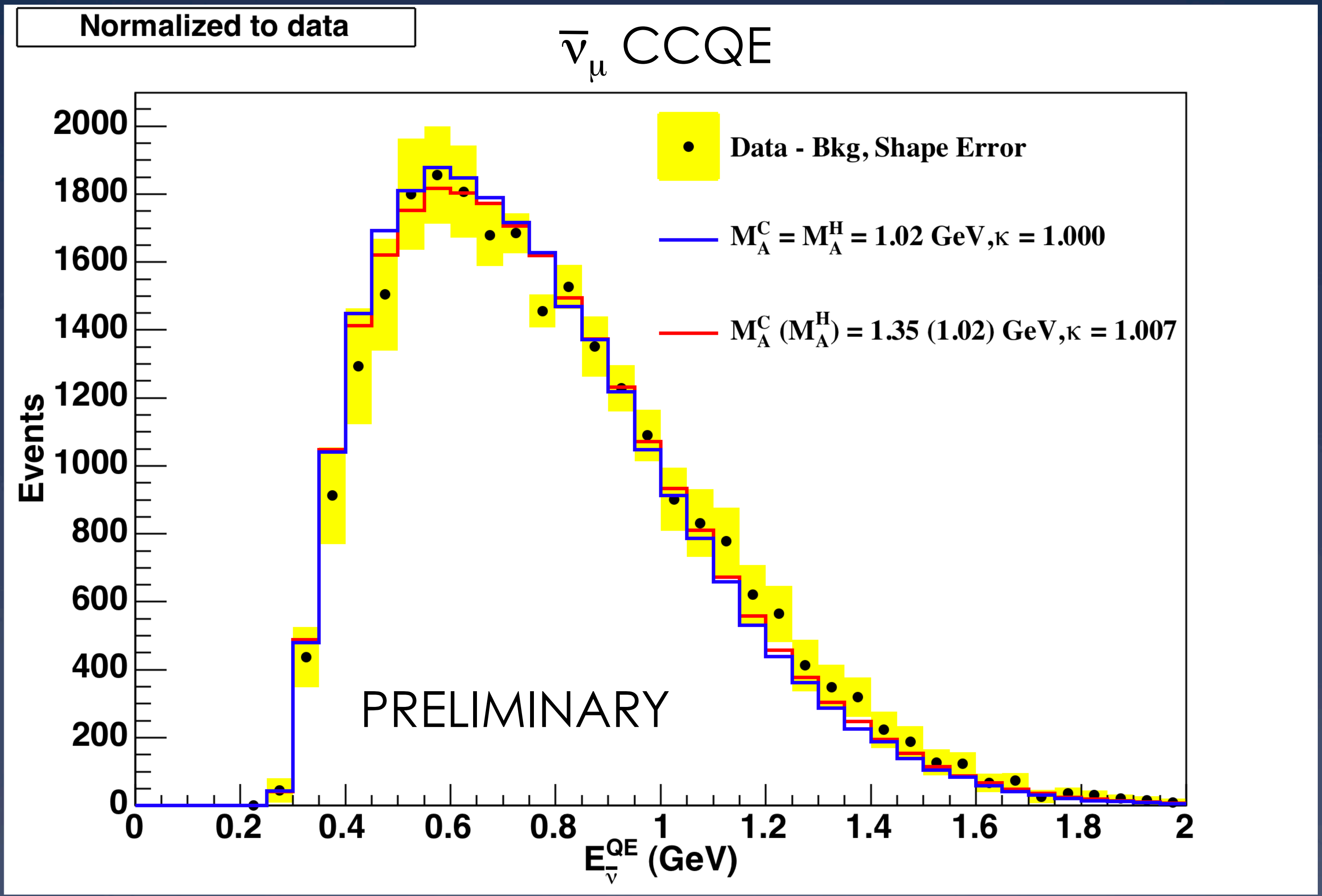
data/MC integrated ratio: 1.21 ± 0.12

Q^2_{QE}: absolute comparison with



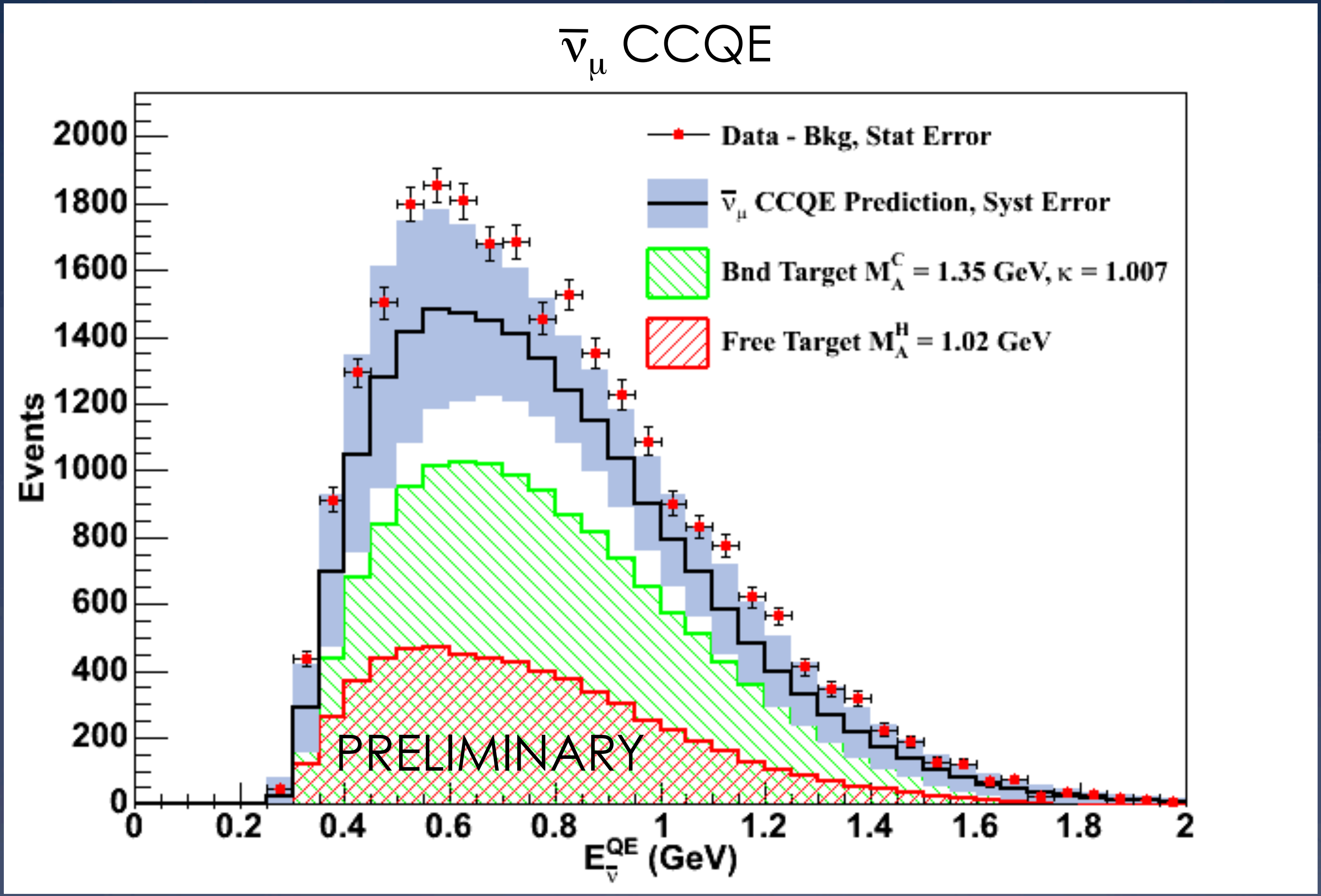
data/MC integrated ratio: 1.39 ± 0.14

$E_{\bar{\nu}}^{QE}$: shape comparison to data



$E_{\bar{\nu}}^{QE}$ shape insensitive to CCQE model parameters

E_ν^{QE}: absolute comparison with



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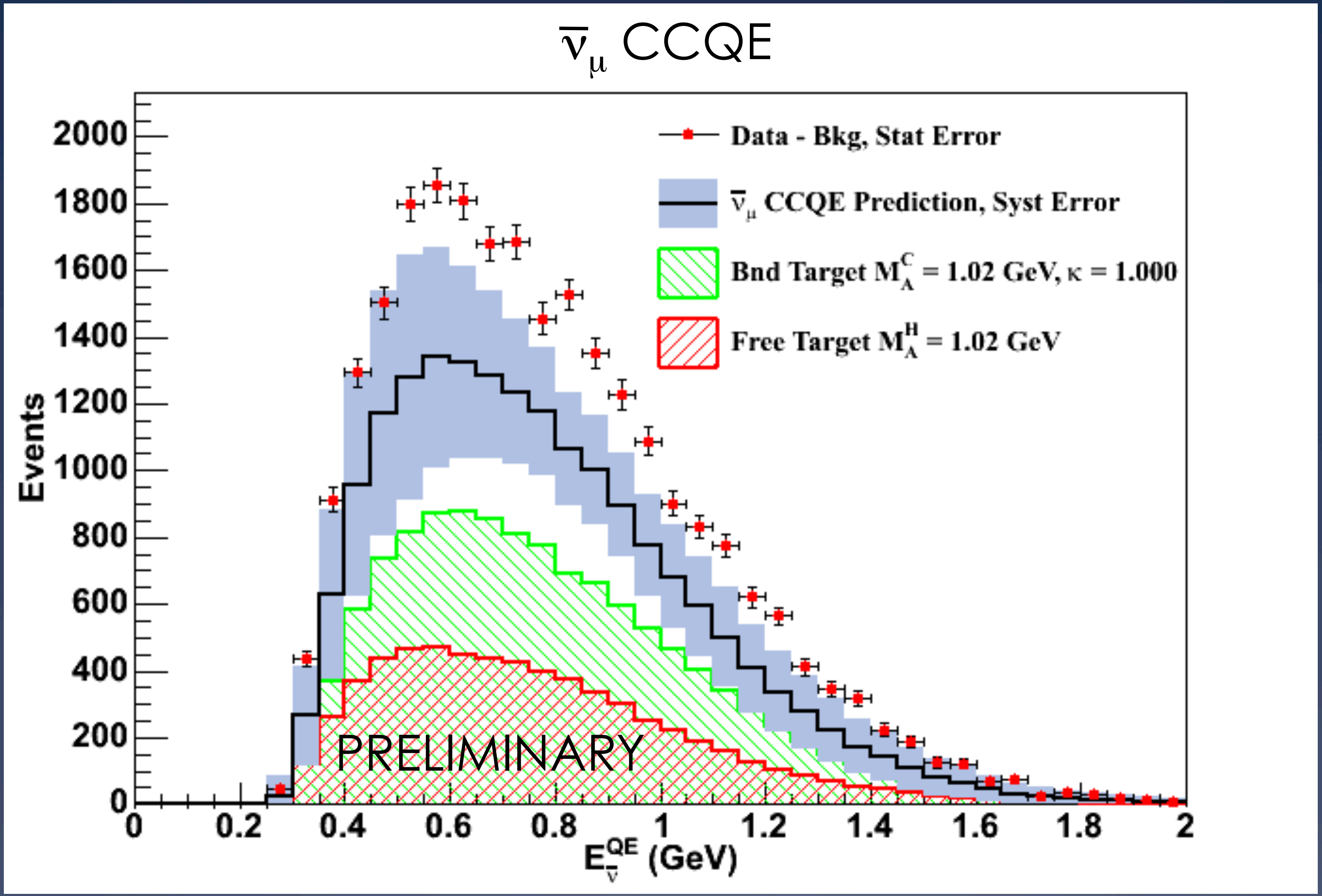

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Future $\overline{\nu}_\mu$ CCQE measurements

* Absolute and differential cross section measurements, including the model-independent double differential cross section

$$\sigma(E_{\overline{\nu}})$$

$$d\sigma/dQ^2$$

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

Future $\bar{\nu}_\mu$ CCQE measurements

* Absolute and differential cross section measurements, including the model-independent double differential cross section

$$\sigma(E_{\bar{\nu}})$$

$$d\sigma/dQ^2 \rightarrow \frac{d\sigma}{dQ^2}^{\nu} - \frac{d\sigma}{dQ^2}^{\bar{\nu}} \propto F_A$$

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

Taking the difference between ν_μ and $\bar{\nu}_\mu$ data in the Q^2 distribution gives direct sensitivity to the axial form factor

Conclusions

- Though MiniBooNE is unmagnetized, a model-independent statistical technique measures the ν_μ content in the $\overline{\nu}_\mu$ beam to ~15% uncertainty
- Shape comparisons to data show consistency with RFG model parameters extracted from BooNE ν_μ data, while M_A = 1.02 GeV remains inconsistent with BooNE data.
- Normalization discrepancy ([data-bkg]/prediction):
  - **1.21 ± 0.12** for M_A^C = 1.35 GeV, κ = 1.007 M_A^H = 1.02 GeV
  - 1.39 ± 0.14 for M_A^C = M_A^H = 1.02 GeV κ = 1.000
  - ν_μ CCQE data: **1.05 ± 0.08** for M_A = 1.35 GeV, κ = 1.007

PRELIMINARY

Conclusions

- MiniBooNE will soon publish absolute and differential $\bar{\nu}_\mu$ CCQE cross sections, will also use ν_μ CCQE measurement to measure interference term in Q^2 and E_ν

More from MiniBooNE today

- For new results in the MiniBooNE anti-neutrino NCE channel please see the next talk by R Dharmaplan
- For a comprehensive review of MiniBooNE single pion production see R Nelson's talk this afternoon

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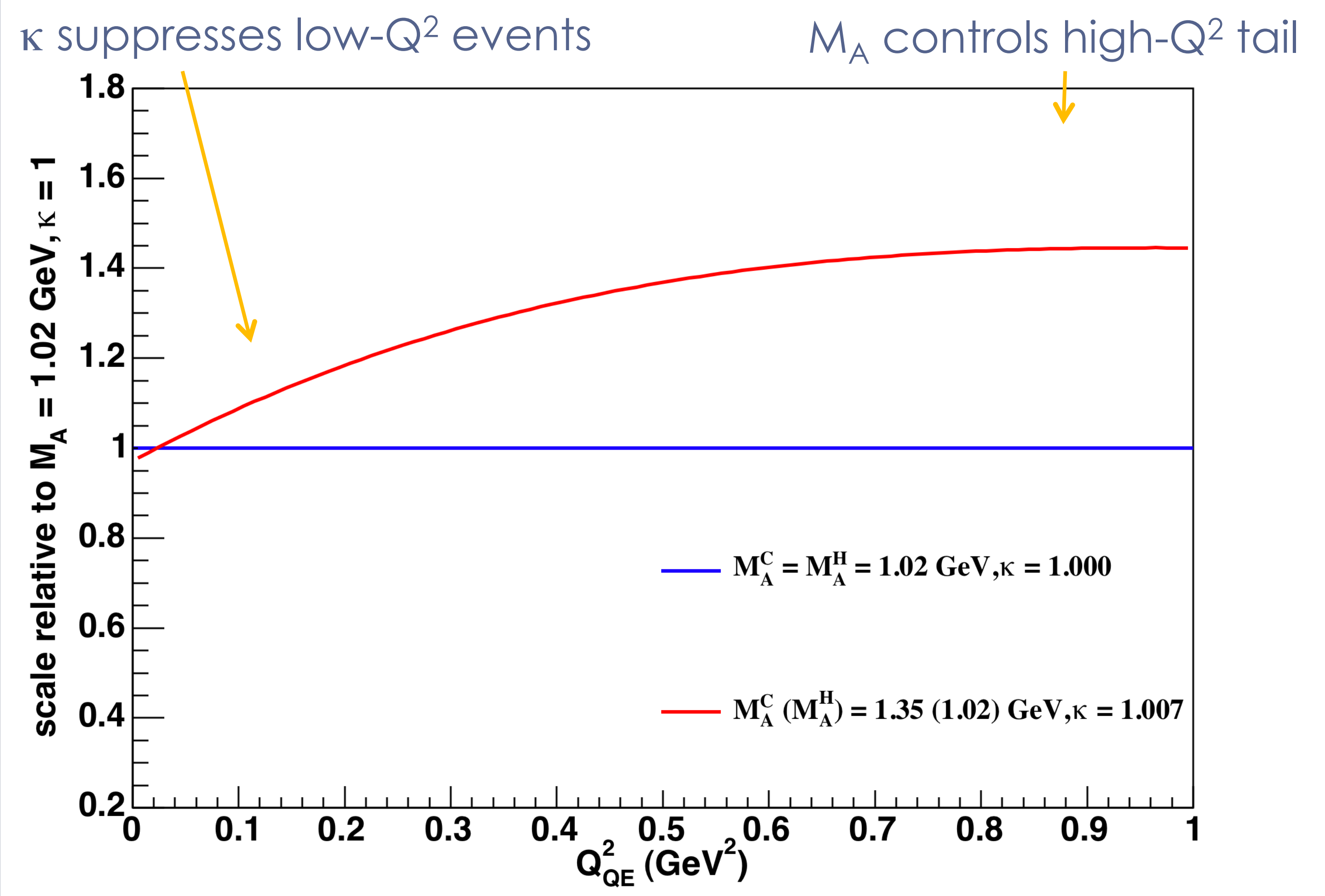
Thanks for your attention!

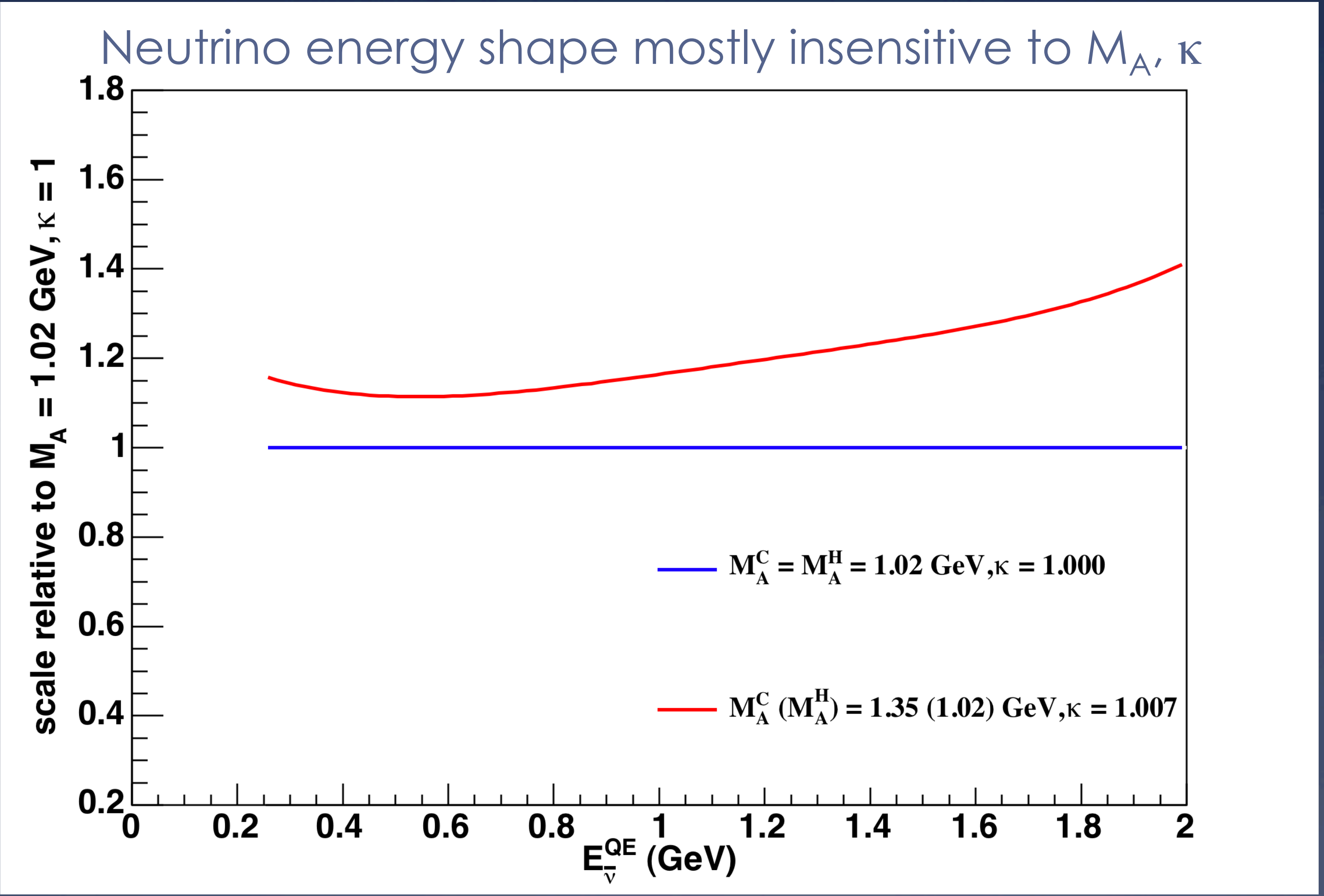
backup

RFG model comparisons: Q^2 shape



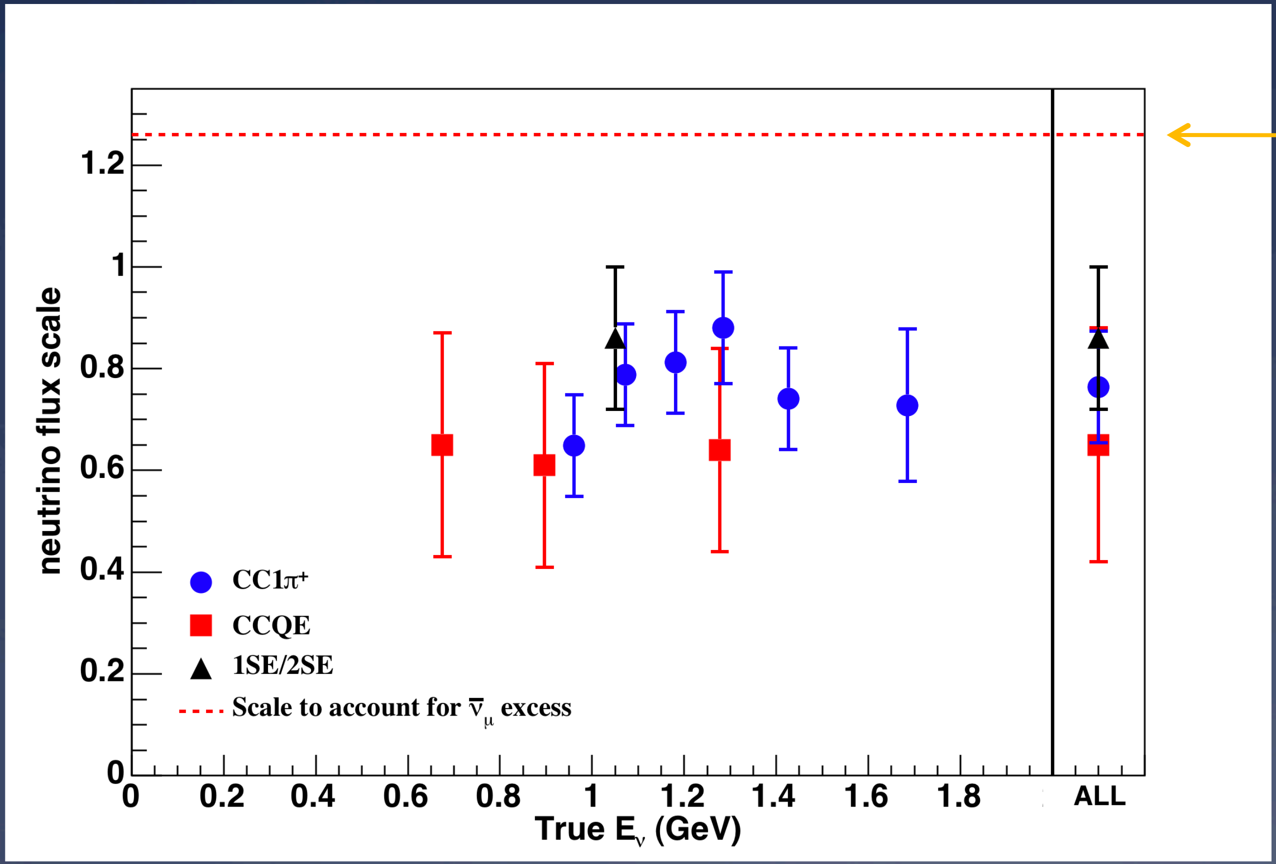
$$Q^2_{\mathrm{QE}} = 2E^{QE}_{\bar{\nu}}(p_\mu \cos\theta_\mu - E_\mu) + m^2_\mu$$

RFG model comparisons: $E_{\bar{\nu}}^{QE}$ shape



$$E_{\bar{\nu}}^{QE} = \frac{2(M_p - E_B)E_\mu - (E_B^2 - 2M_pE_B + m_\mu^2 + \Delta M^2)}{2[(M_p - E_B) - E_\mu + p_\mu \cos\theta_\mu]}$$

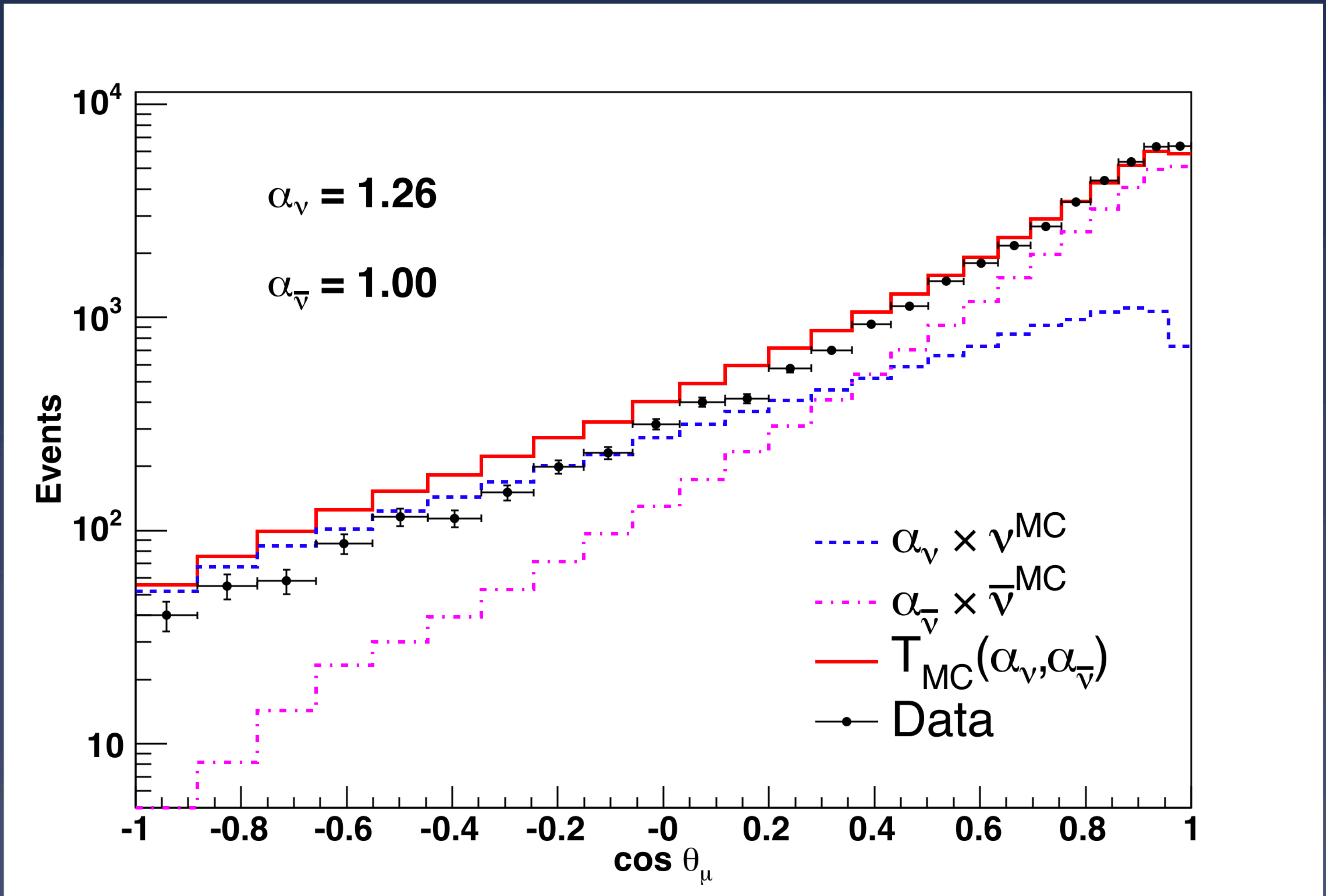
How wrong would the ν_μ Φ measurement have to be to account for observed enhancement?



Prediction * 1.26, 4.5σ from CCπ+ measurement

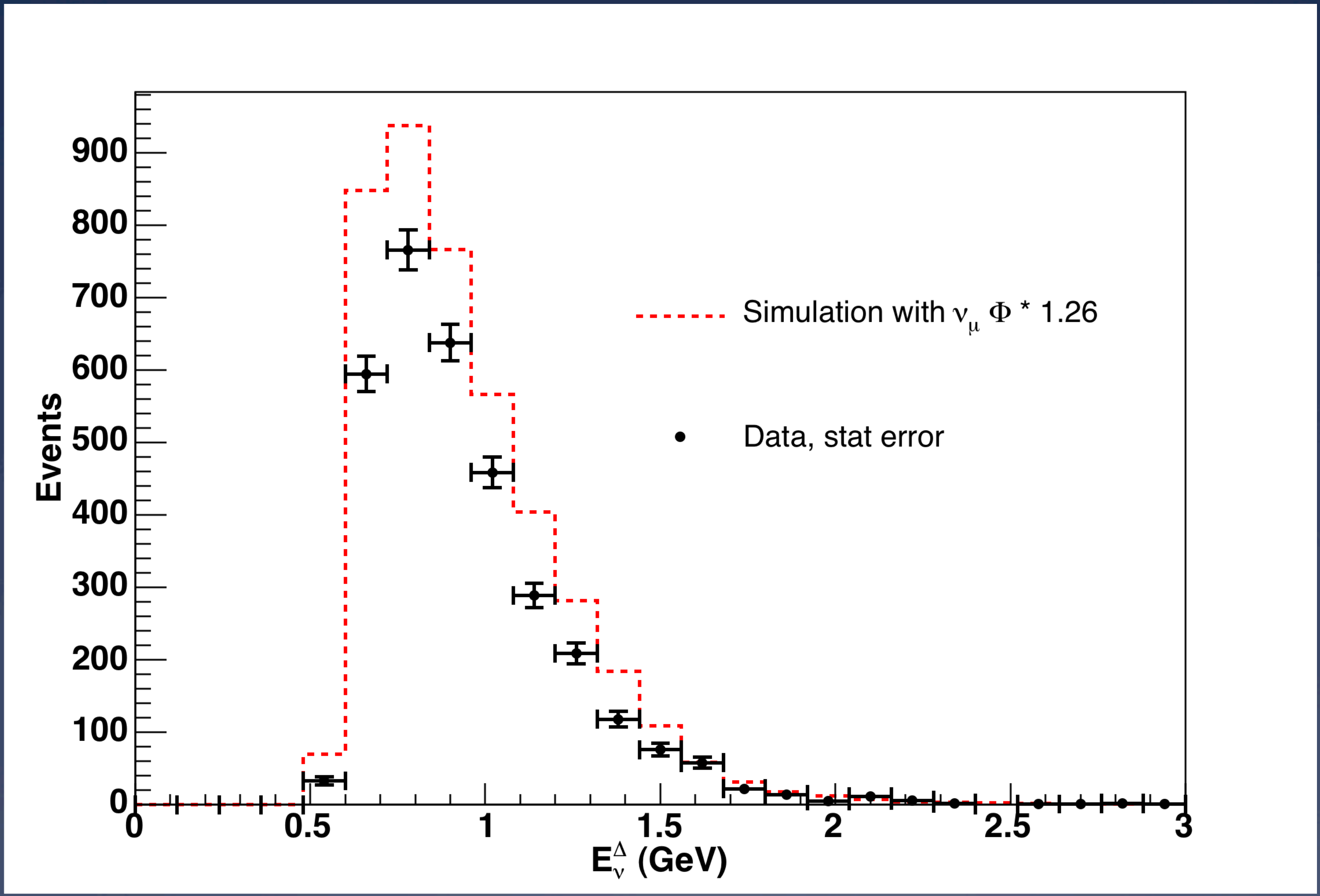
Comparing to "#1": M_A^C (M_A^H) = 1.35 (1.02) GeV, κ = 1.007

How wrong would the ν_μ Φ measurement have to be to account for observed enhancement?



μ scattering angle shape mismatched with ν_μ Φ * 1.26

How wrong would the ν_μ Φ measurement have to be to account for observed enhancement?



CCπ^+ sample severely over-predicted

Wrong-sign Flux Prediction

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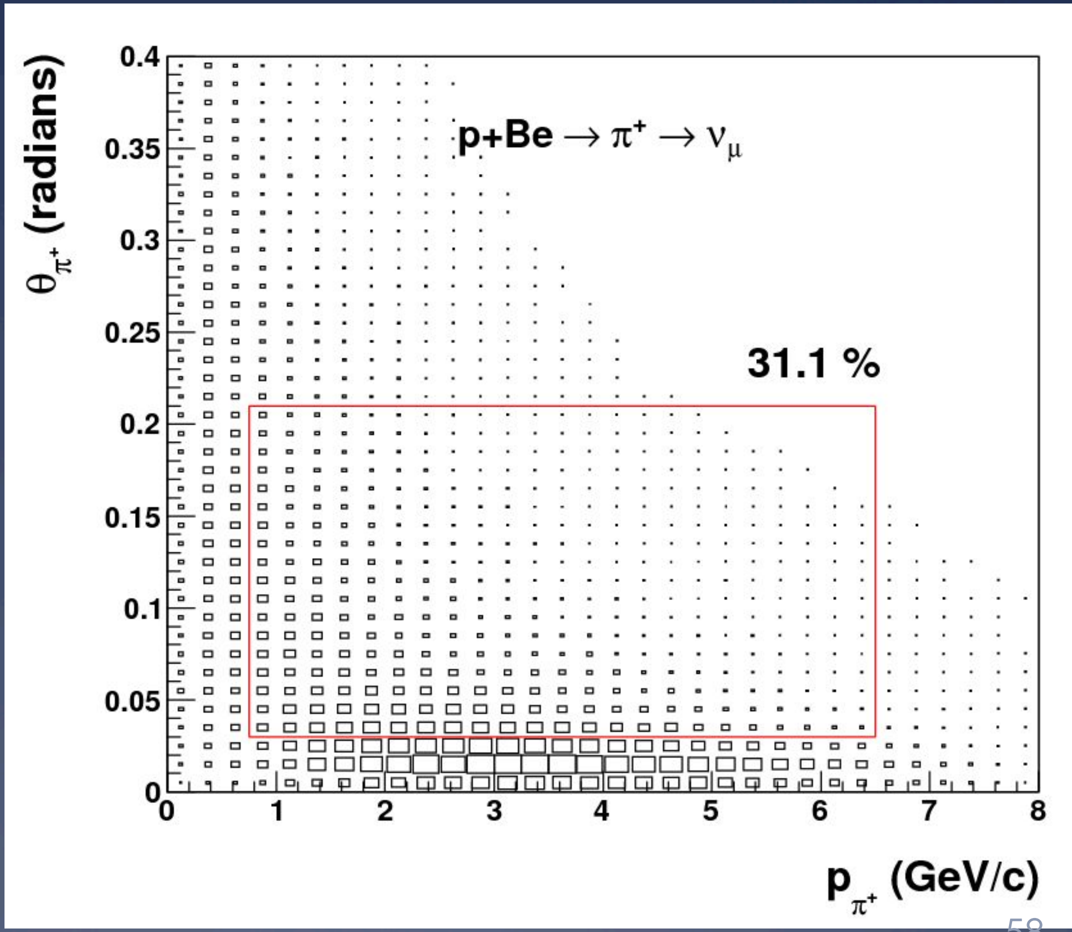
- Not cross-section weighted



How Wrong Signs Contribute to Flux

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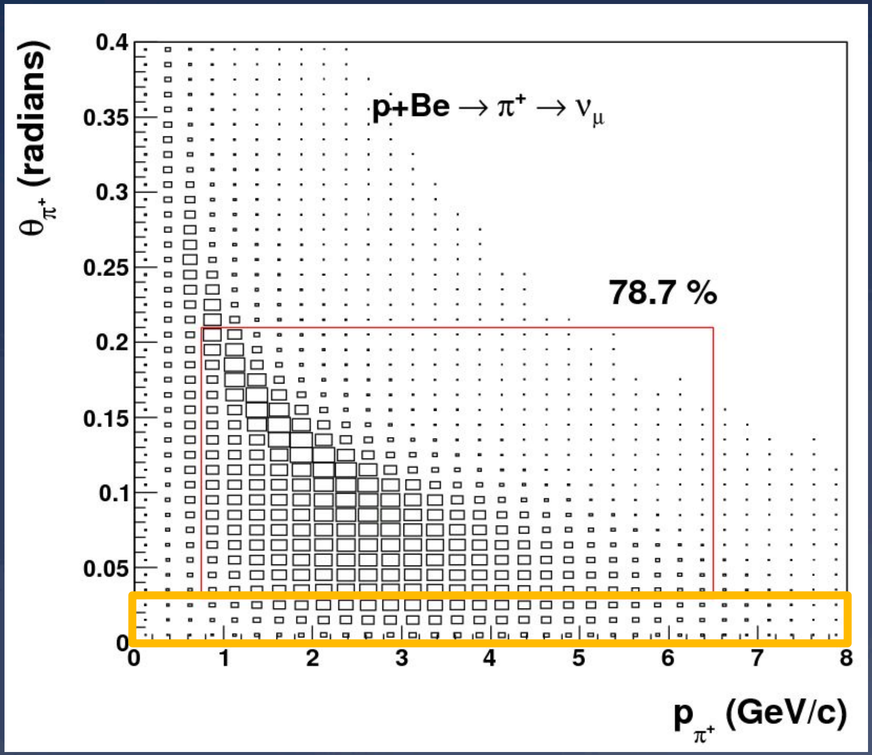
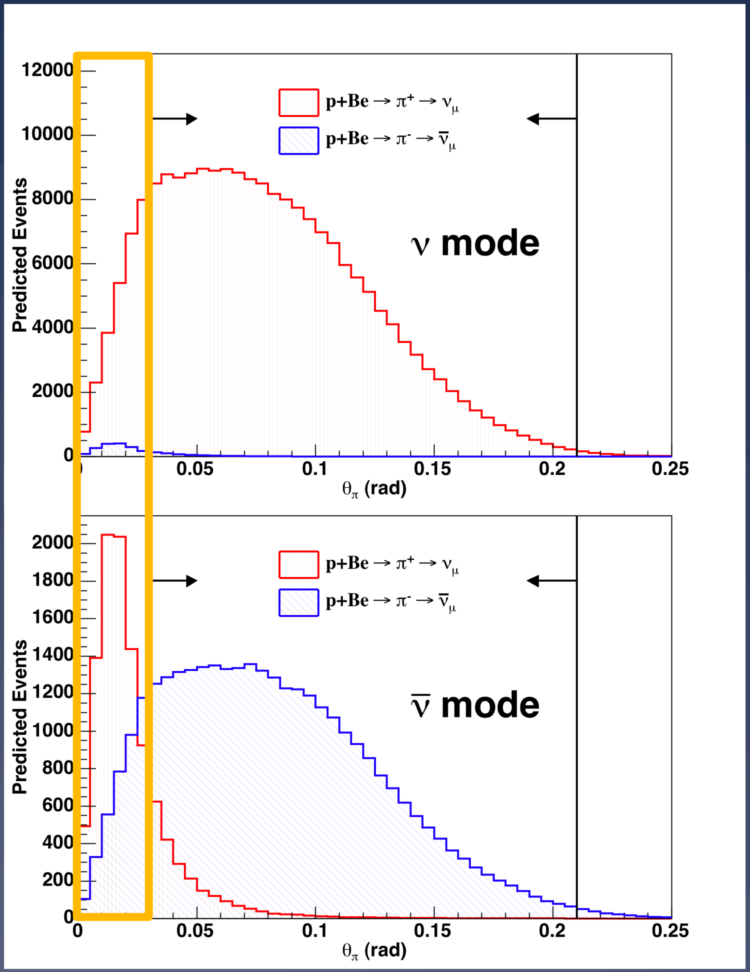
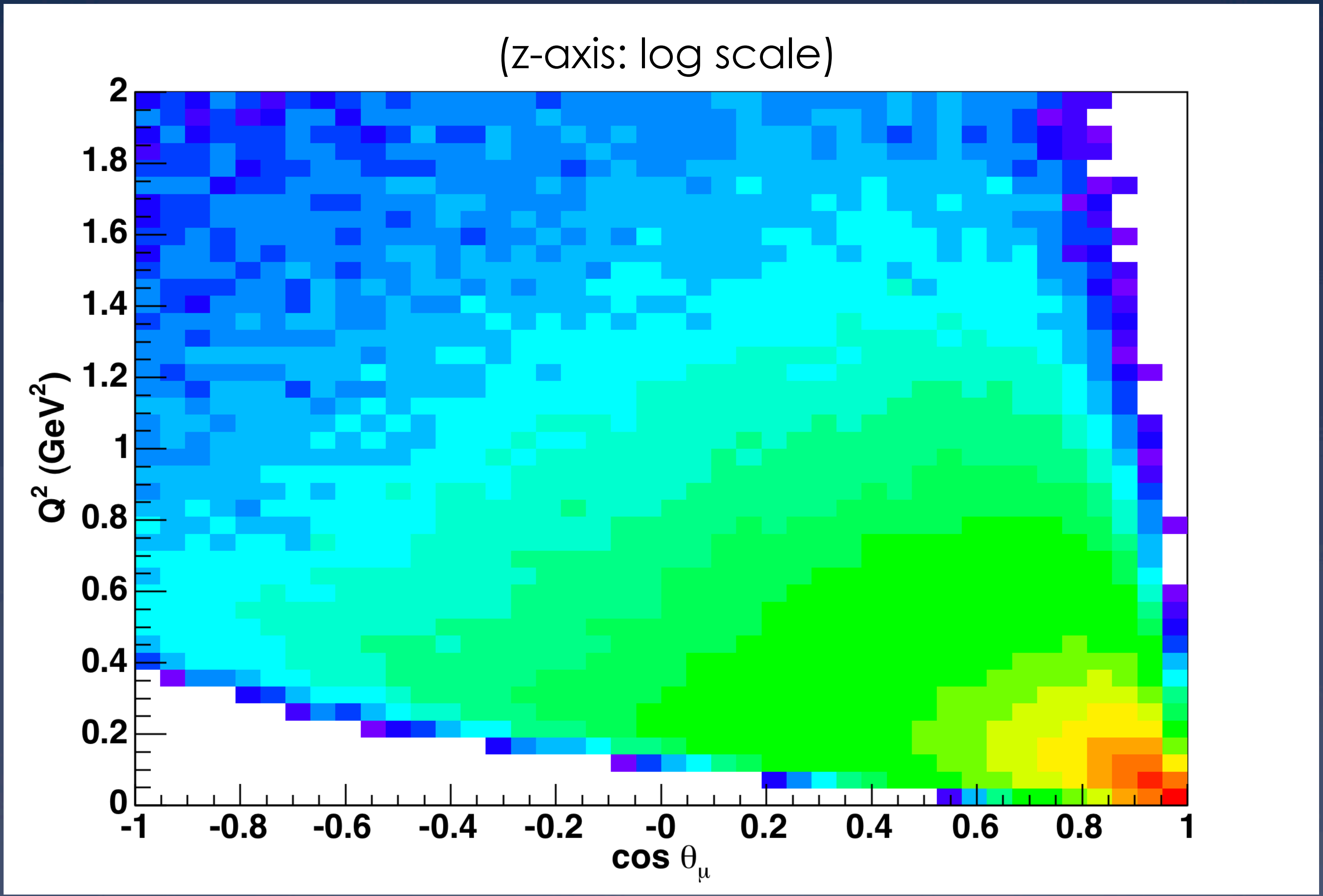




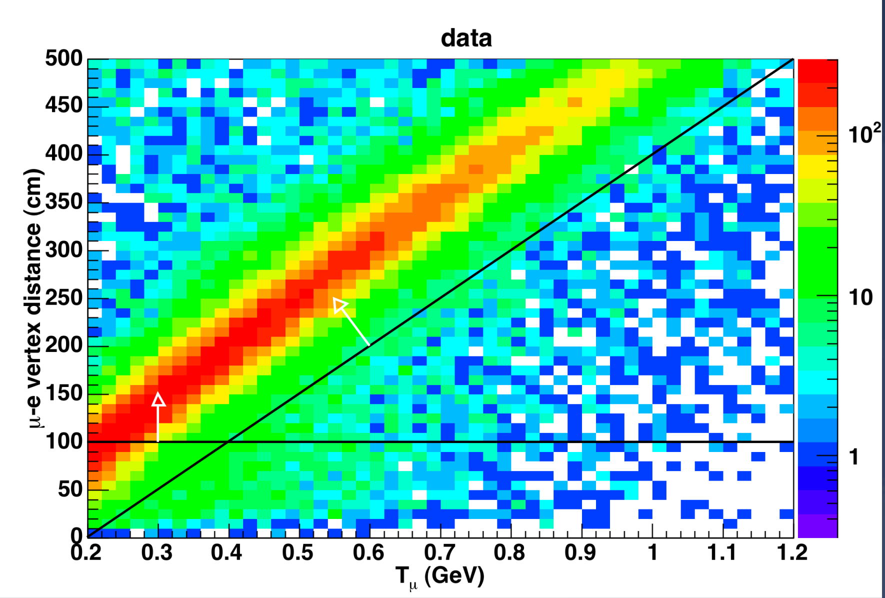
- Same low angle region not covered by HARP the most important for ν_μ contamination

Q^2 - muon angle correlation



CCQE Selection

1. Two subevents
2. Veto hits < 6, both subevents
3. Vertex, 1st subevent < 500cm from tank center (fiducial volume)
4. 1st subevent:
   4.4 < cluster time (μs) < 6.4
5. 1st subevent: T_μ > 200 MeV
6. μ range > (500 * T_μ - 100) cm
   μ range > 100 cm.
7. 1st subevent ln (μ/e) > 0
8. cos θ_μ > 0



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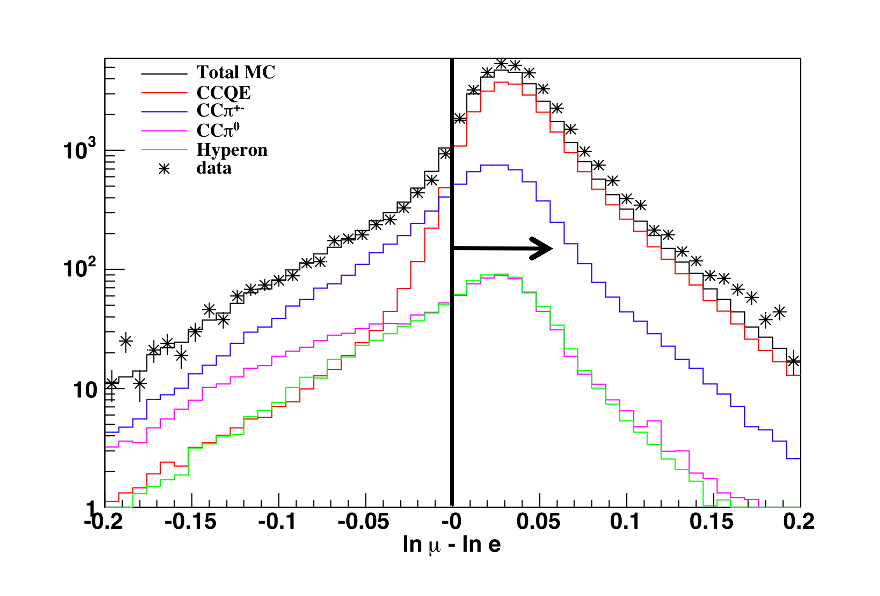

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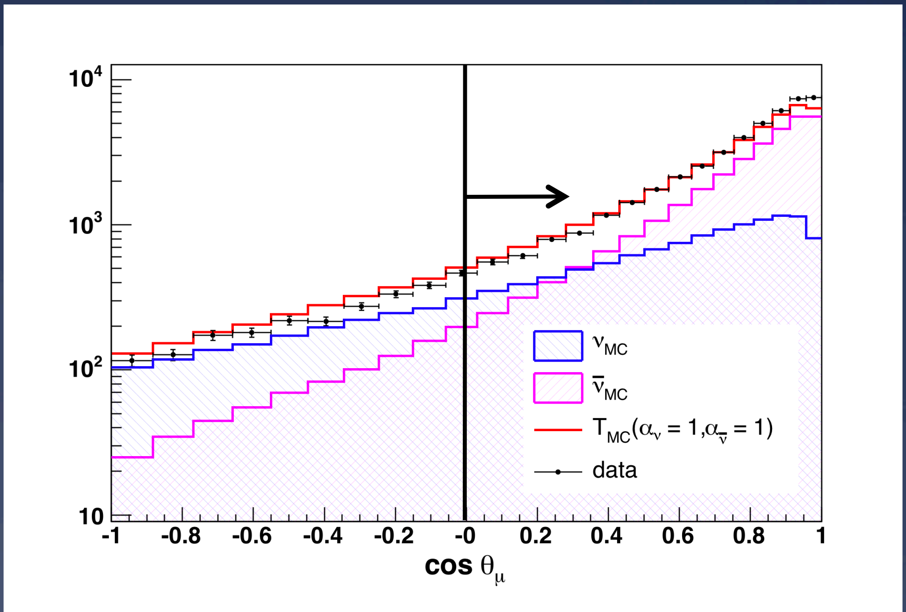
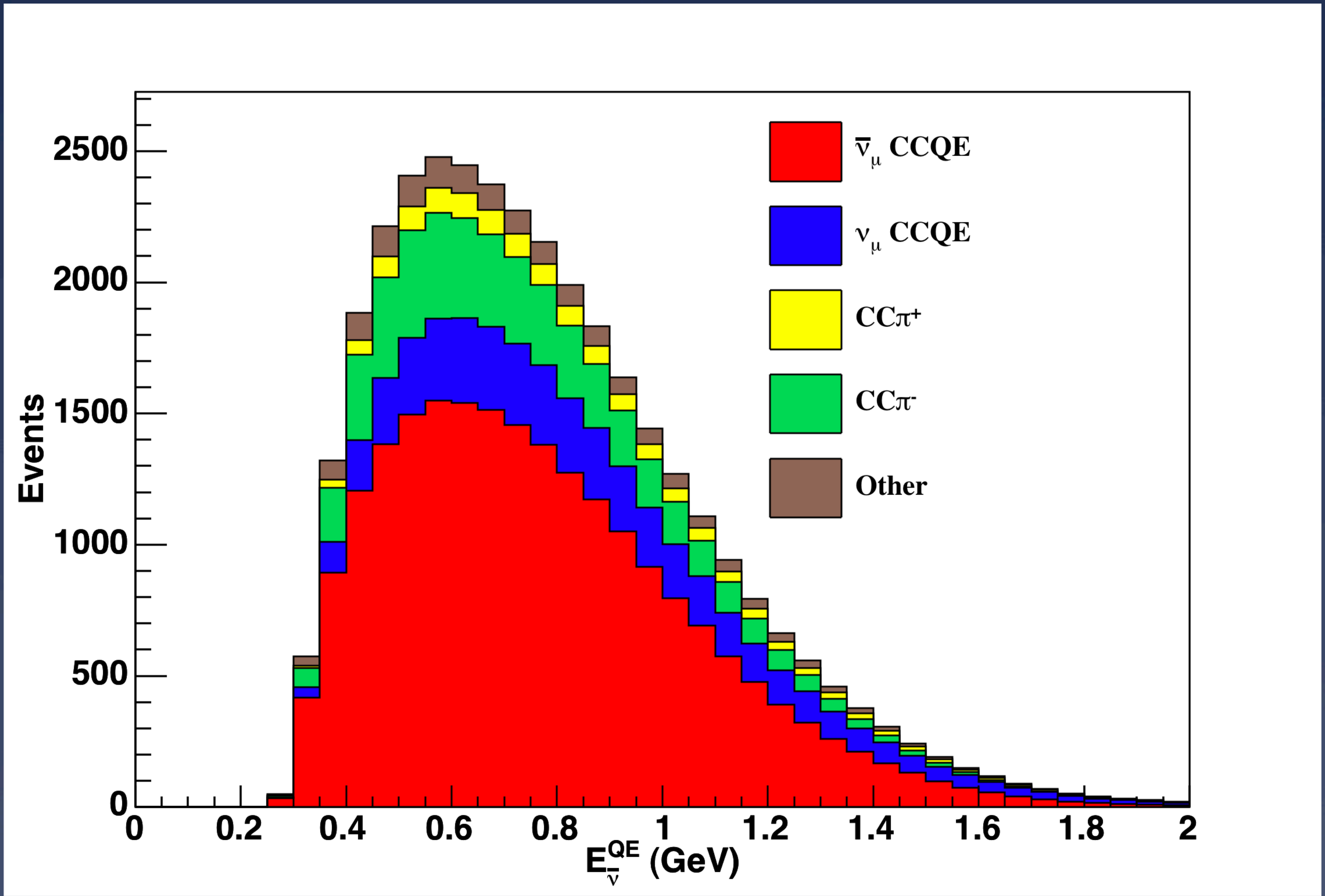
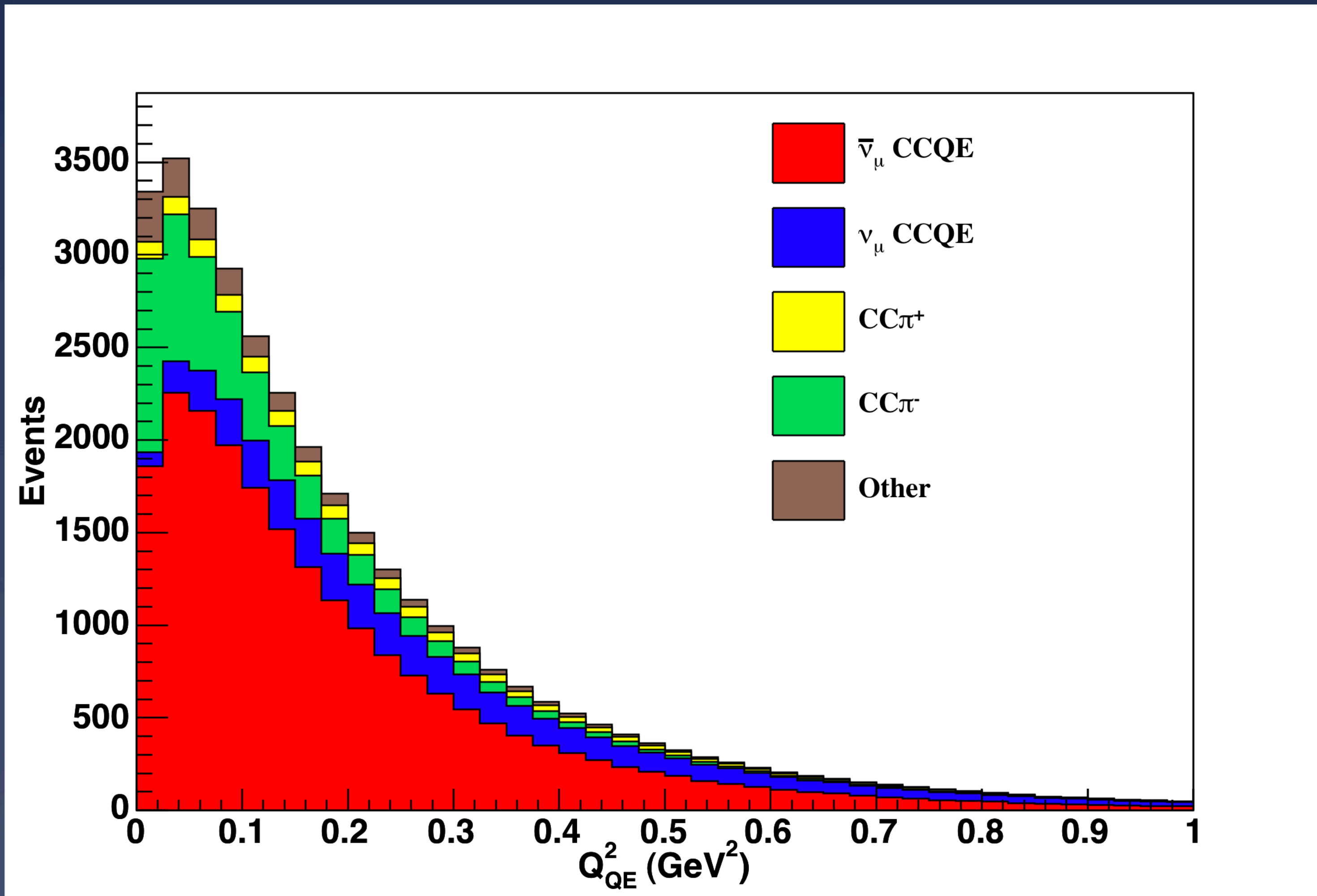


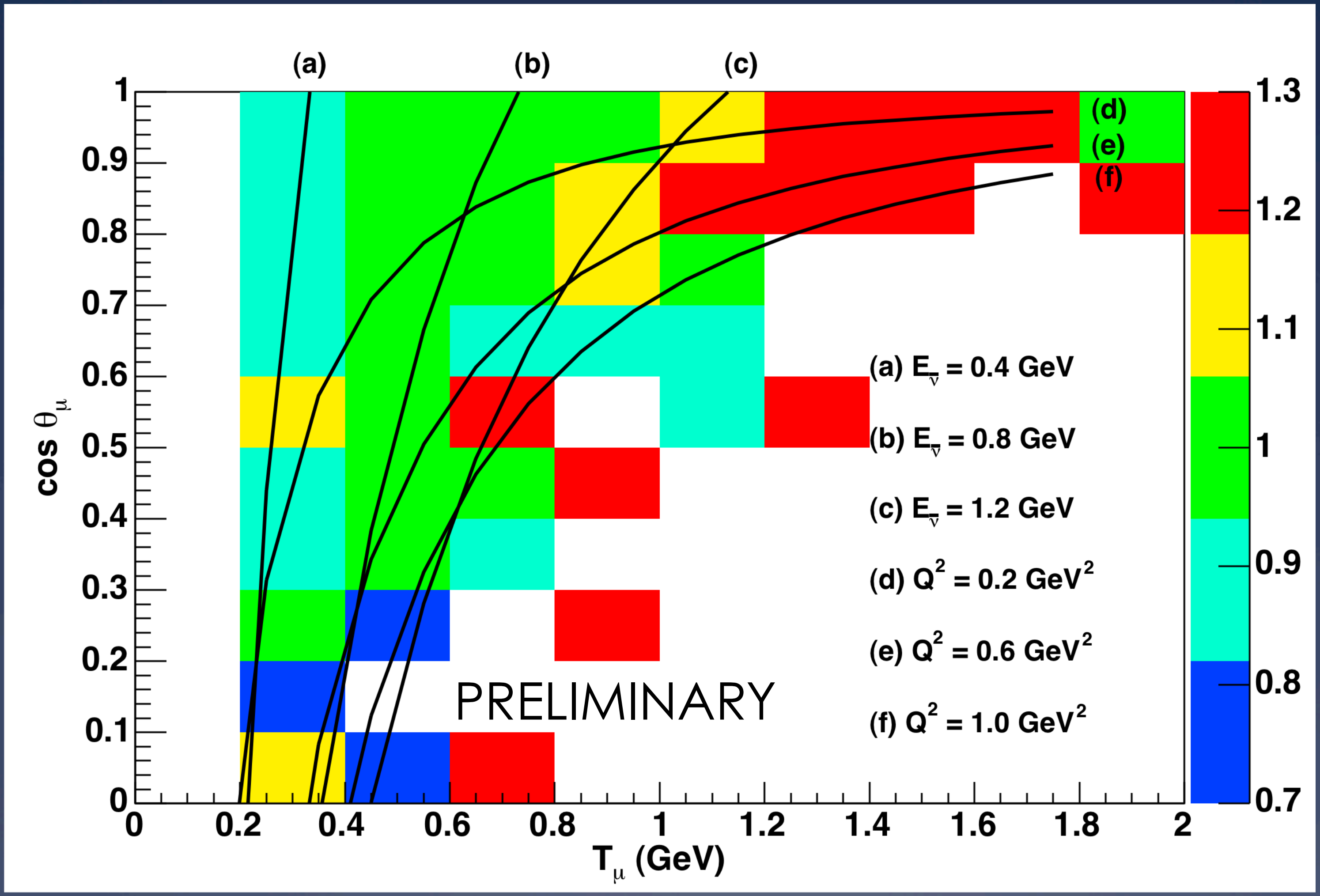
Event composition in E_ν^{QE}



Event composition in Q^2_{QE}

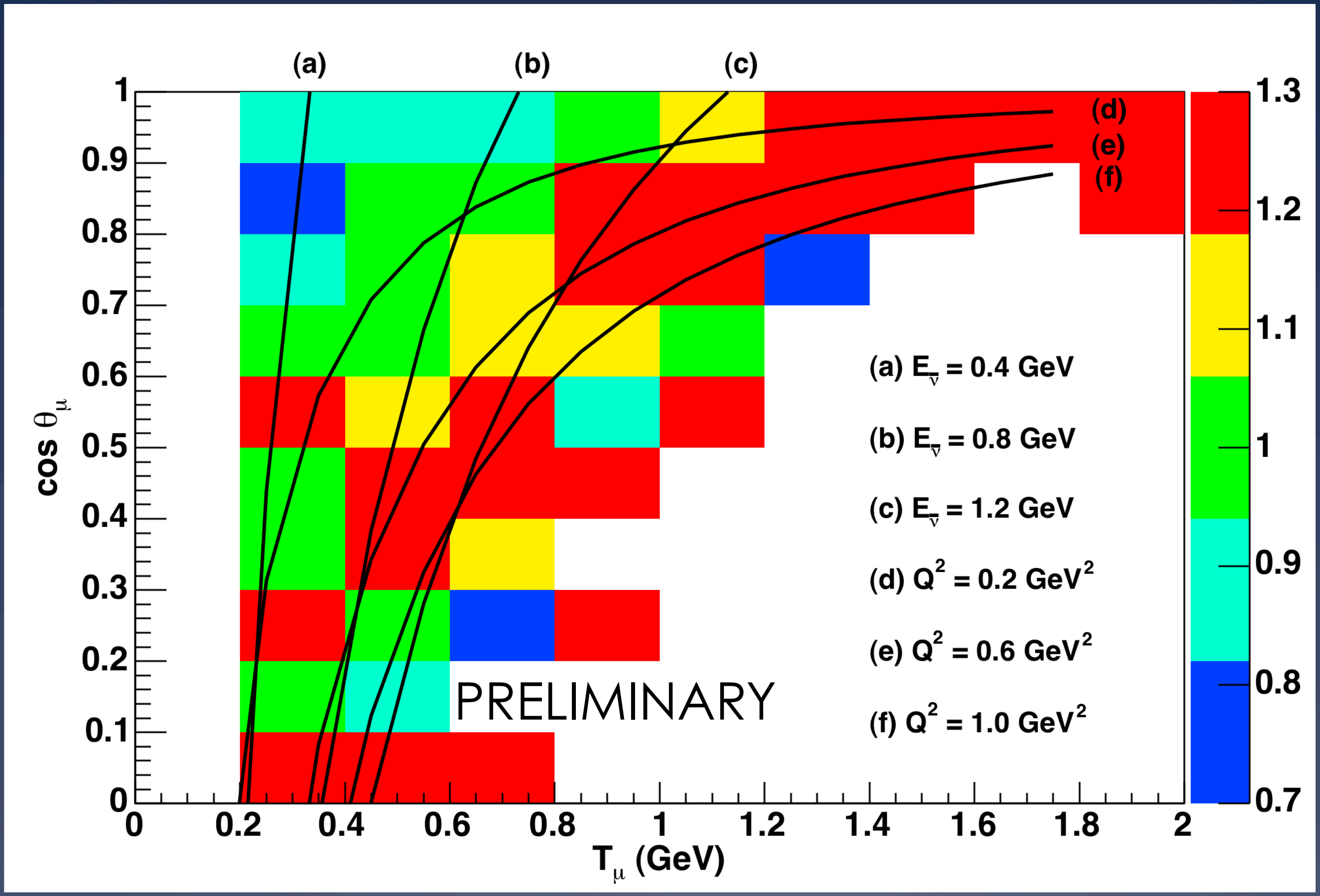


Two dimensional muon kinematics - data/MC ratio, "#1" M_A^C = 1.35 GeV, M_A^H = 1.02 GeV, κ = 1.007



SHAPE COMPARISON

Two dimensional muon kinematics - data/MC ratio, "#2"
$M_A^C = M_A^H = 1.02$ GeV, $\kappa = 1.000$

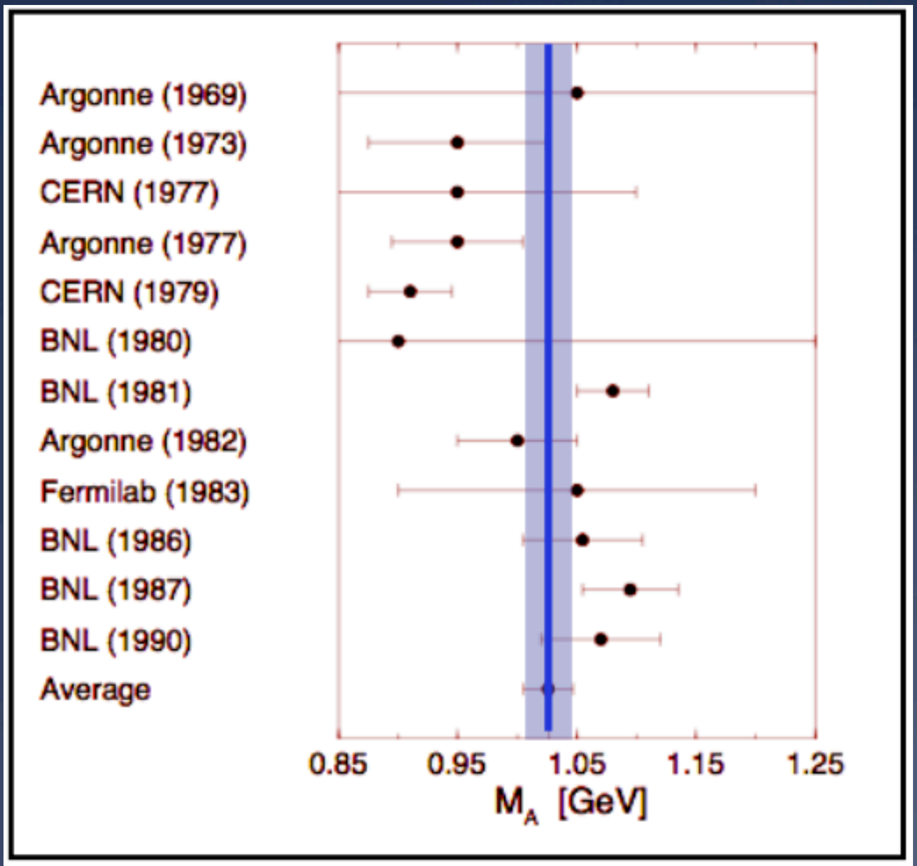


SHAPE COMPARISON

Background simulation

* Sample is ~65% pure $\bar{\nu}_\mu$ CCQE.
* Of the remaining 35%, 30% are corrected based on MiniBooNE measurements
  * ν_μ flux corrected by CCπ+-based measurement
  * Observed ν_μ CCQE cross section implemented
  * All CCπ bkg events corrected based on kinematic measurements

MiniBooNE ν_μ CCQE Review



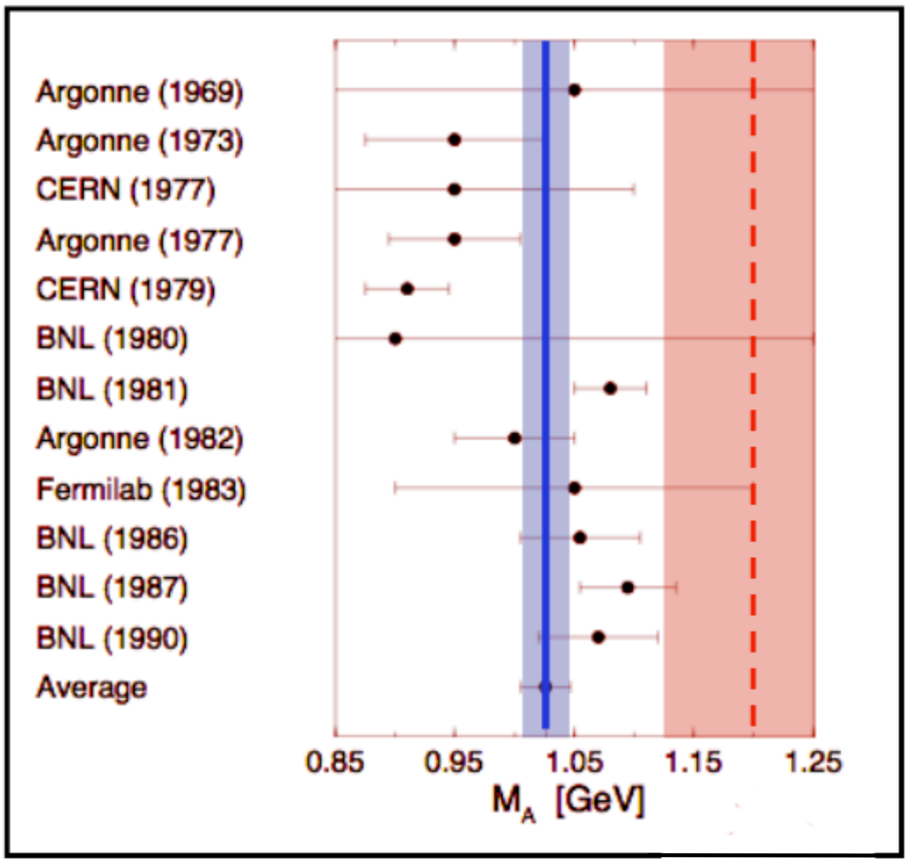
- M_A = 1.35 GeV comes in conflict with the previous M_A measurements taken on mostly light nuclear targets

Previous world average:

$M_A = 1.02 \pm 0.01$ GeV

J. Phys.: Conf. Ser. **110** 082004 (2008)

MiniBooNE ν_μ CCQE Review



- However, other recent experiments have observed a larger axial mass as well

Source	Measured M_A (GeV)
K2K SciFi	1.20 ± 0.12
K2K SciBar	1.14 ± 0.11
MINOS	1.26 ± 0.17
NOMAD	1.07 ± 0.07
MiniBooNE	1.35 ± 0.17

- Notable NOMAD measurement on a carbon nuclear target consistent with M_A = 1.02 GeV
- Crucial to recognize model dependence in interpretations: e.g. NOMAD makes some requirement of 1 μ, 1 p in FS; MiniBooNE makes no outgoing nucleon requirement

Fitting the Outgoing Muon Angular Distribution

* We form a linear combination of the neutrino and anti-neutrino content to compare with CCQE data:

$$T_{MC}(\alpha_\nu, \alpha_{\bar{\nu}}) \equiv \alpha_\nu \, \nu^{MC} + \alpha_{\bar{\nu}} \, \bar{\nu}^{MC}$$

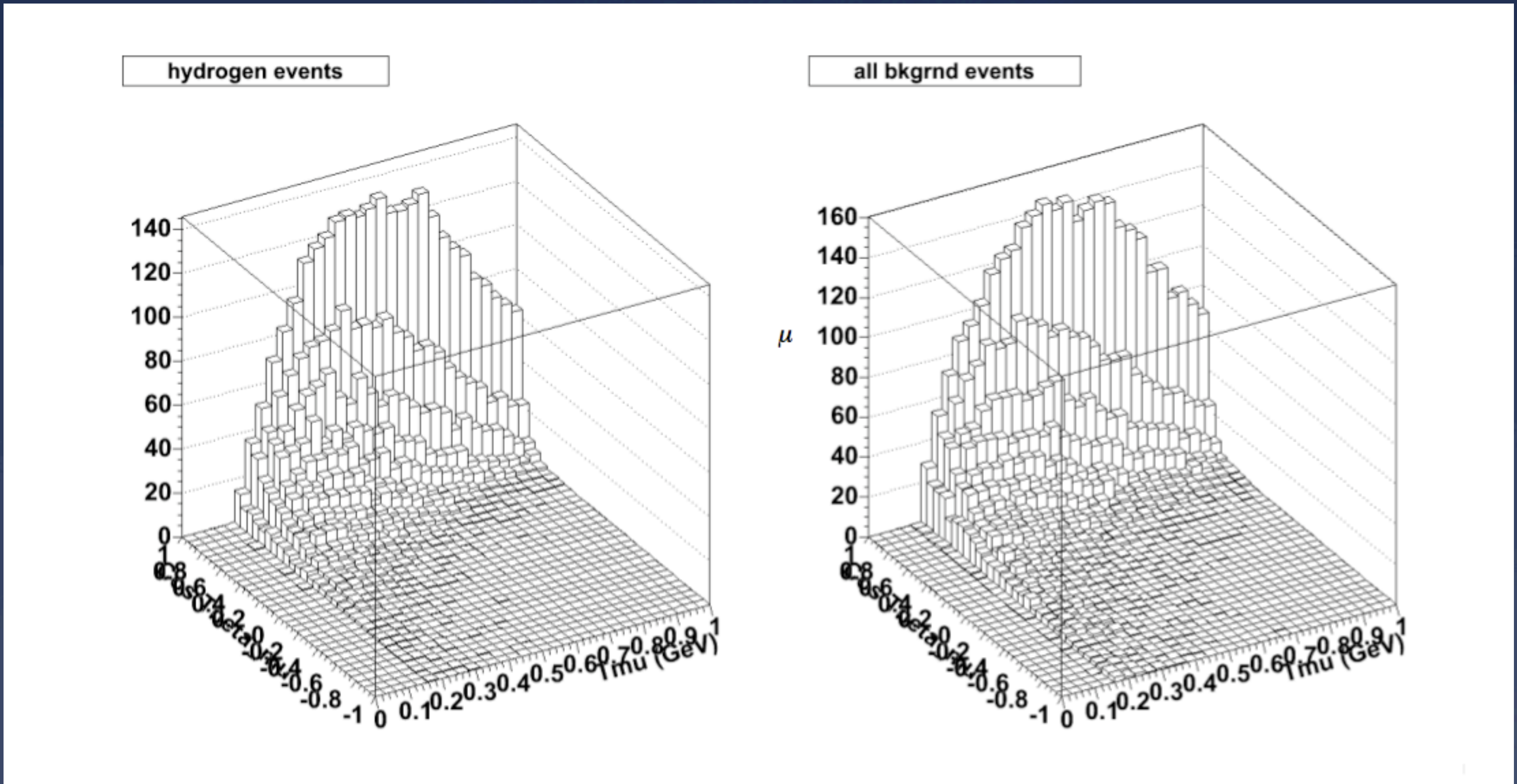
Rate scales to be extracted from data

All predicted neutrino, anti-neutrino events

* And minimize χ^2:

$$\chi^2 = \sum_{i,j} \left(T_{MC}(\alpha_\nu, \alpha_{\bar{\nu}})_i - d_i\right) M_{ij}^{-1} \left(T_{MC}(\alpha_\nu, \alpha_{\bar{\nu}})_j - d_j\right)$$

Can we separate H_2 content?

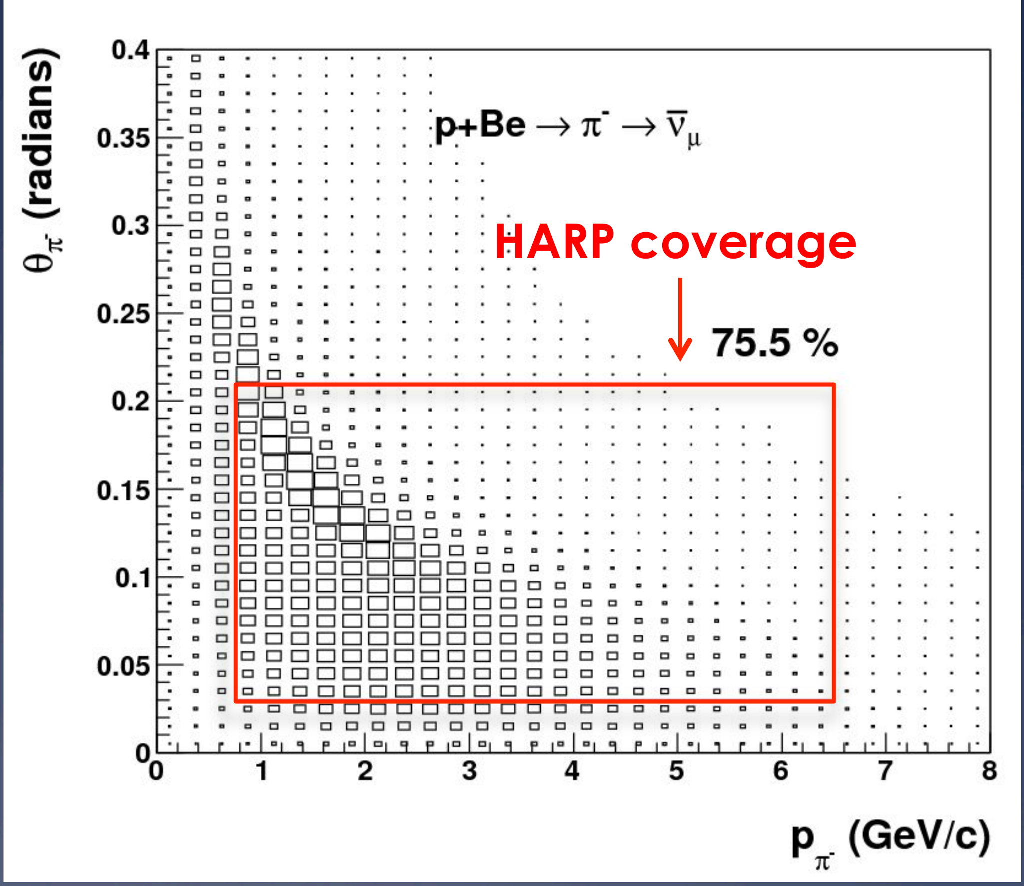


Even in Tμ - cos θ_μ space, H_2 content completely degenerate with CCπ bkgs

MiniBooNE Flux

D Schmitz

- ~9% errors only true for pions produced in HARP-covered phase space
- Due to large proton background, pion production below 30 mrad not reported
- While not a serious issue for neutrino mode, we'll see later this is the dominant production region for a critical background to the anti-neutrino analyses



π- phase space contributions to anti-neutrino mode flux

Fitting the outgoing muon angular distribution

* Neutrino vs anti-neutrino CCQE cross sections differ exclusively by an interference term that changes sign between the two

$$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 |V_{ud}|^2}{8\pi E_\nu^2} \left[A\left(Q^2\right) \pm B\left(Q^2\right)\left(\frac{s-u}{M^2}\right) + C\left(Q^2\right)\left(\frac{s-u}{M^2}\right)^2 \right]$$

* The divergence is more pronounced at higher Q^2, which is strongly correlated with backward scattering muons