Separating ν and anti-ν components with non-magnetized detectors

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New Perspectives 2012

Outline

1. Booster Neutrino Beam (BNB)
2. Three measurements of ν_μ flux in BNB $\bar{\nu}_\mu$ beam
3. Community interest, conclusions

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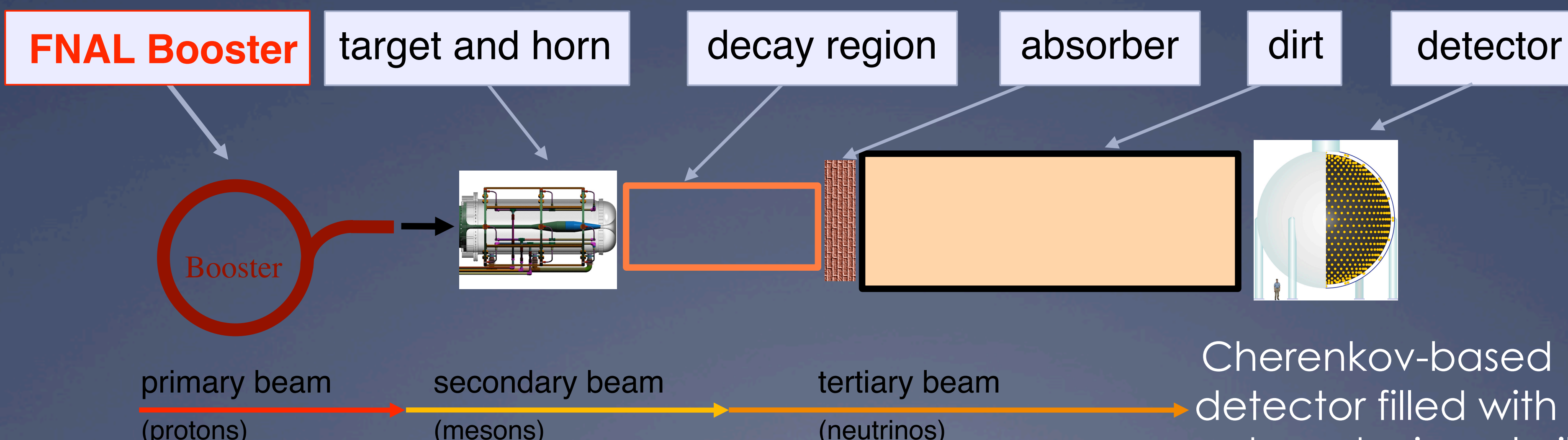
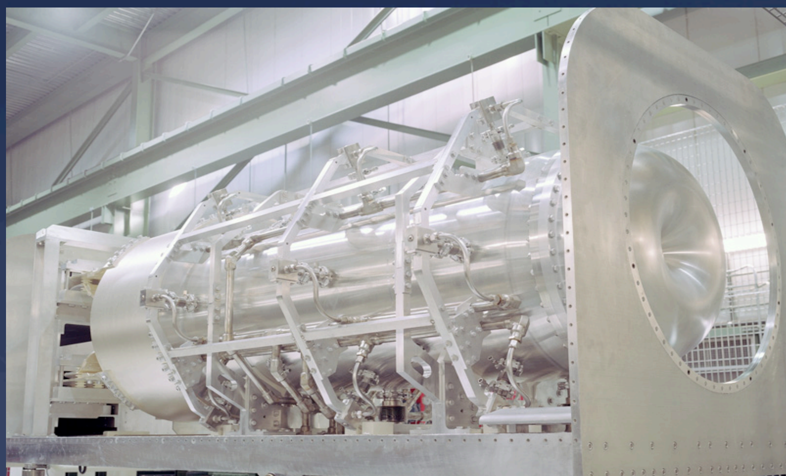
Booster Neutrino Beam

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



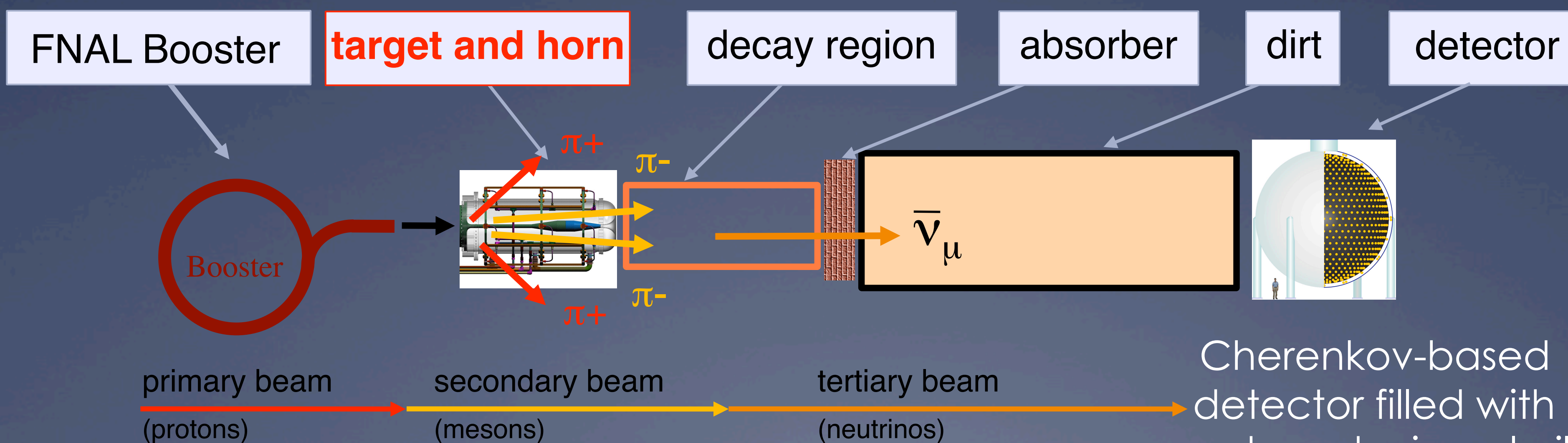
Cherenkov-based detector filled with undoped mineral oil

Booster Neutrino Beam



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

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



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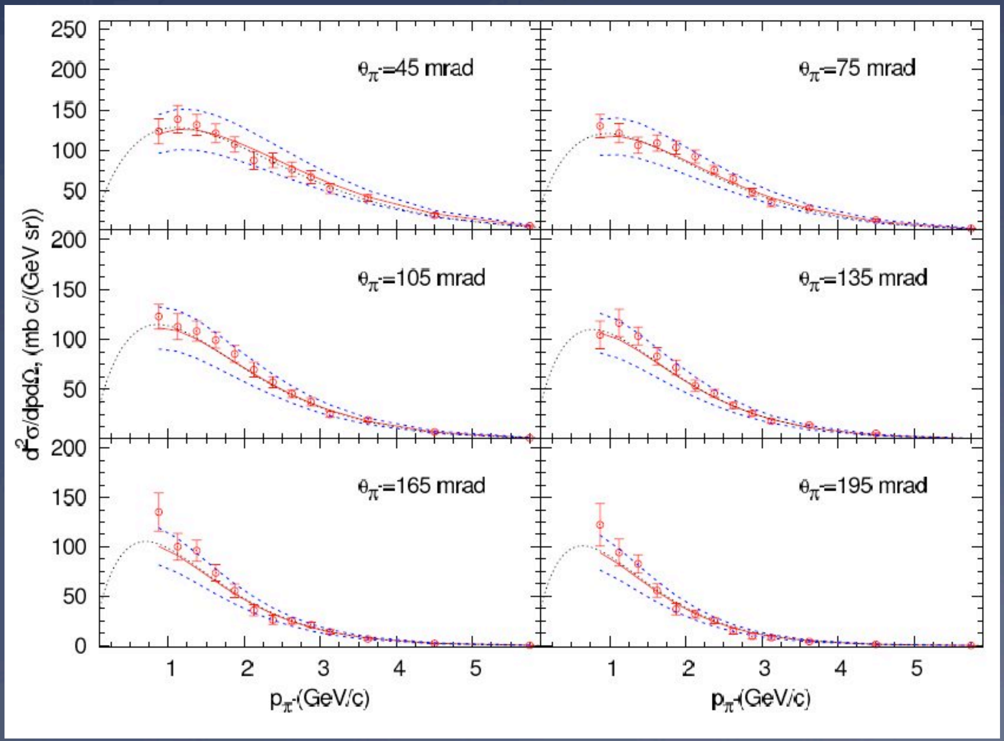
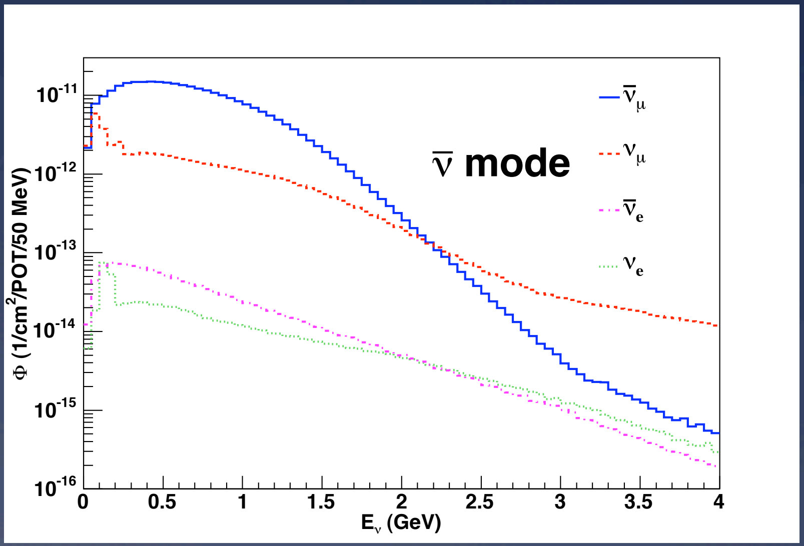
MiniBooNE Flux

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



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

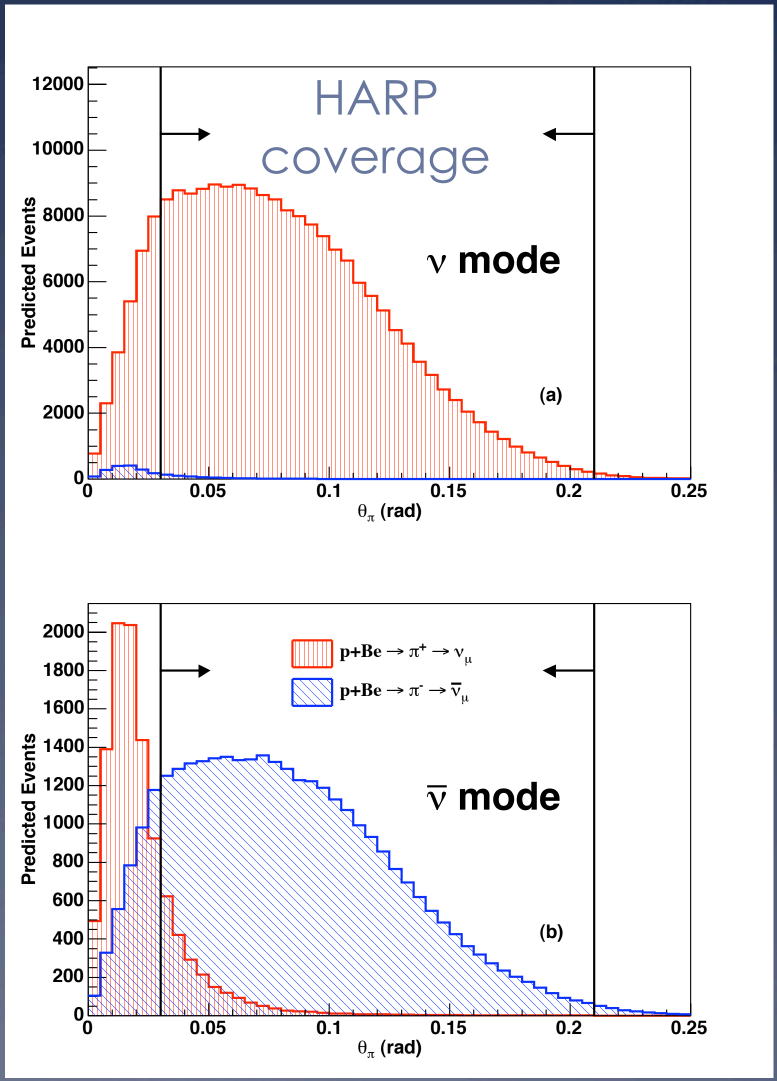


MiniBooNE collaboration,
Phys. Rev. D79, 072002 (2009)

* 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%

MiniBooNE Flux

* ~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 (top plot), severe complication for anti-neutrino mode (bottom)



MiniBooNE Flux

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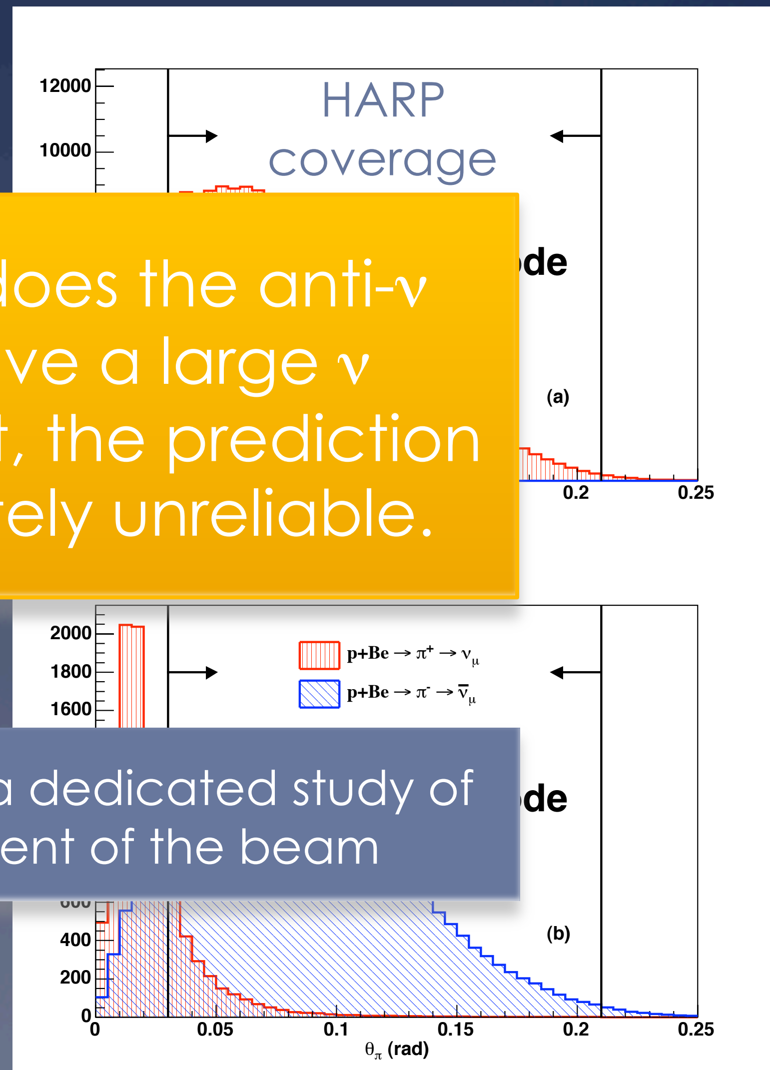

Not only does the anti-ν data have a large ν component, the prediction is completely unreliable.

This motivates a dedicated study of the ν_μ content of the beam

1. Booster Neutrino Beam (BNB)
2. Three measurements of ν_μ flux in BNB $\bar{\nu}_\mu$ beam
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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.
Phys. Rev. D81: 072005 (2011)

Wrong-sign measurements

- General strategy: isolate samples sensitive to the ν_μ beam content, apply the measured cross sections from neutrino mode (CCQE, $CC\pi^+$)
  - *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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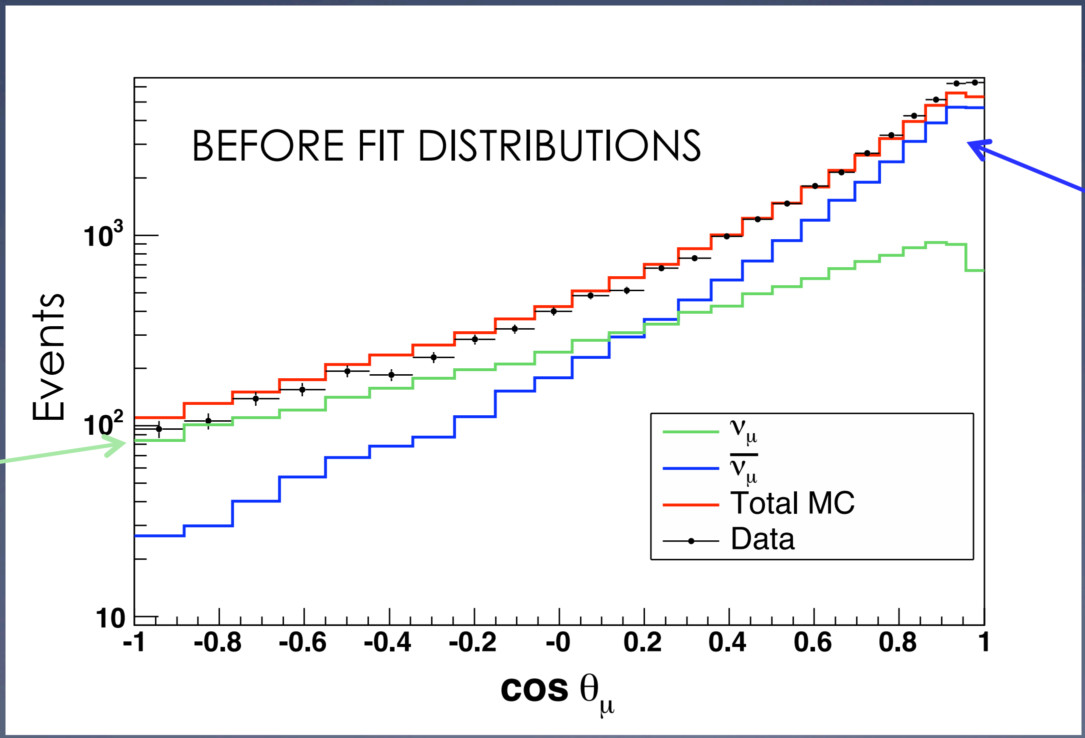
Fitting the outgoing muon angular distribution

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

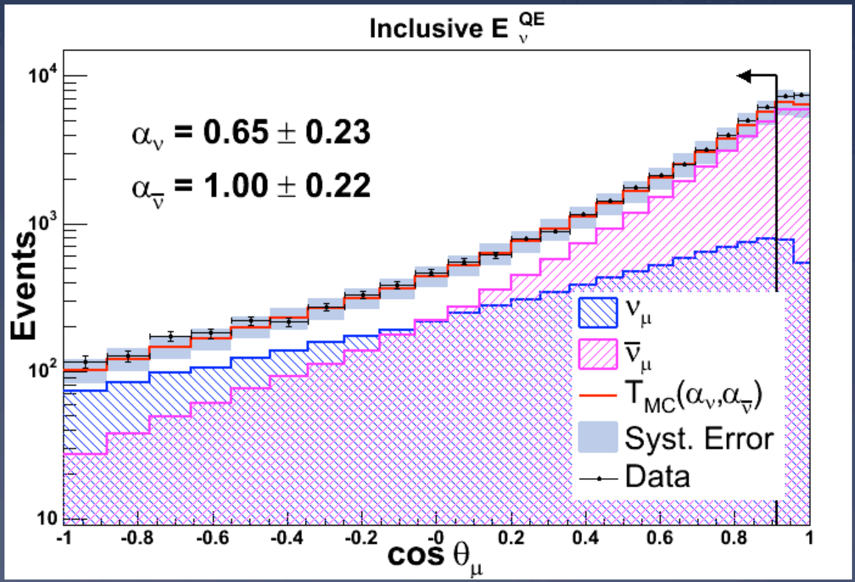


Scale the $\overline{\nu}_\mu$ template by "$\alpha_{\overline{\nu}}$"

Scale the ν_μ template by "α_ν"

Fitting the outgoing muon angular distribution

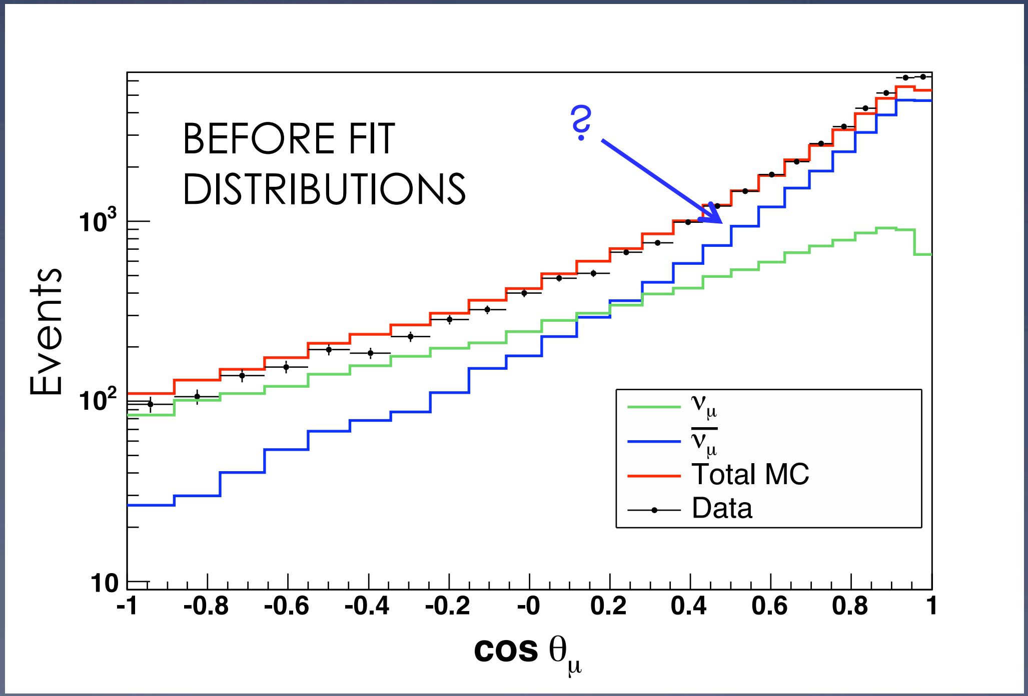
- Results indicate the ν_μ flux is over-predicted by ~30%
- Fit also performed in bins of reconstructed energy; consistent results indicate flux spectrum shape is well modeled



$E_{\bar{\nu}}^{QE}$(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

Model dependence

- Though the ν_μ CCQE scattering template is known (from our measurement), the result is correlated to the (unknown) anti-ν_μ distribution and therefore biased
- In the future, thanks to current expt's, σ's will be much better known and this technique could be very powerful



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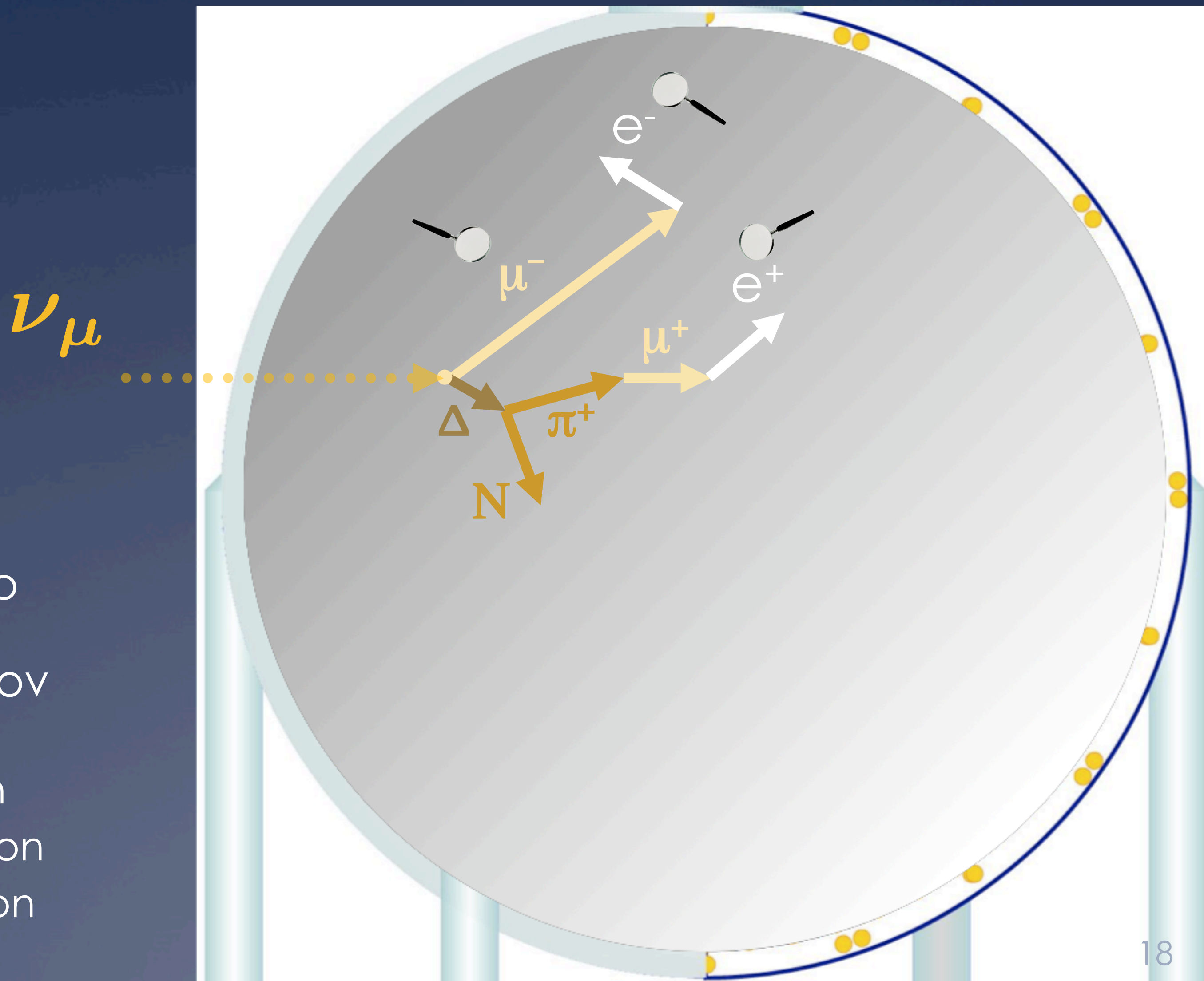
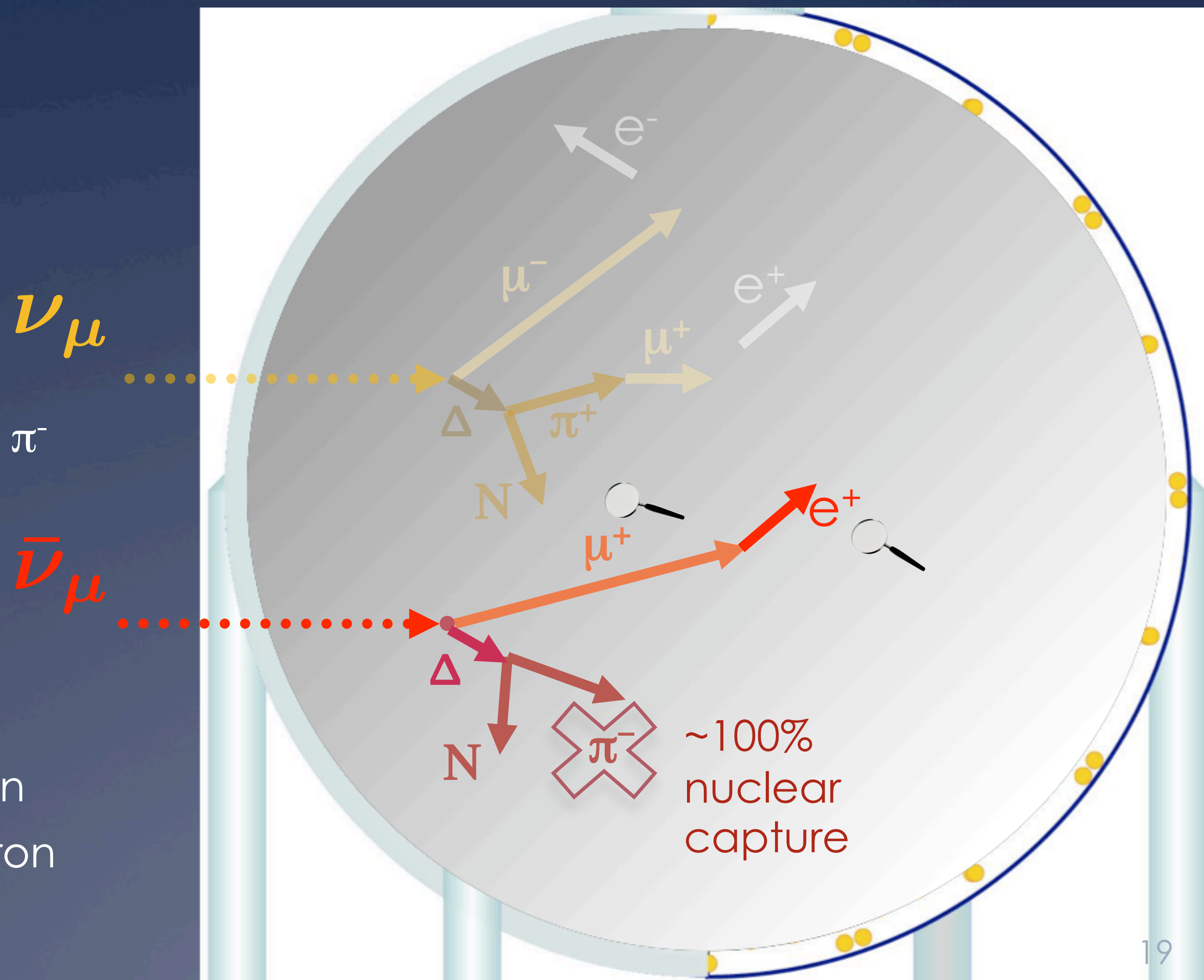
CCπ$^+$ sample formation



* 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
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

Wrong-sign measurements

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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. Michel electron detection efficiency
  2. μ^- nuclear capture (ν_μ CC events only)

μ^- capture measurement

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

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

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

μ^- capture measurement

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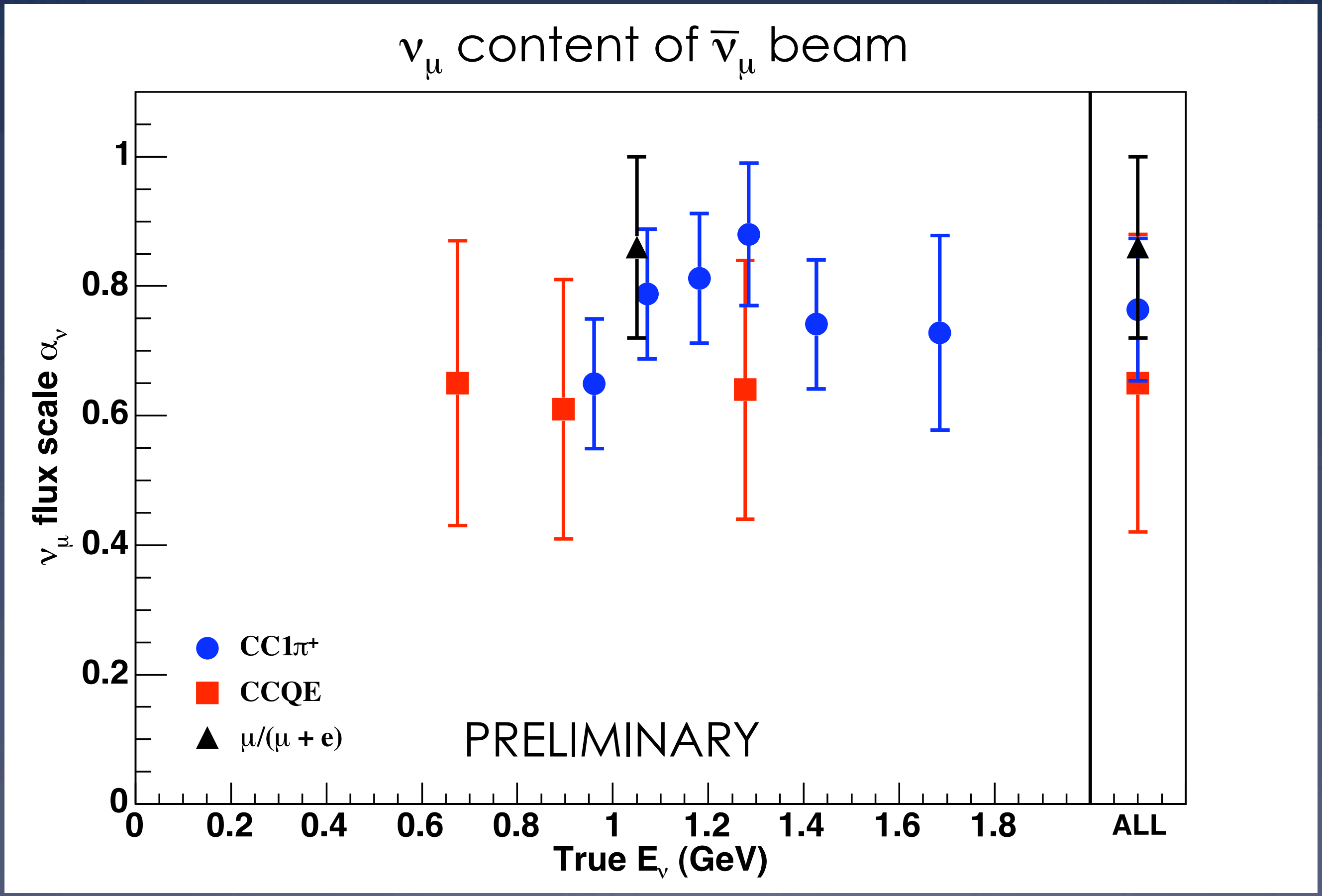
Results:

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

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

PRELIMINARY

Neutrino flux measurement summary



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

Strategy revisited

- General strategy: isolate samples sensitive to the ν_μ beam content, apply the measured cross sections from neutrino mode (CCQE, $CC\pi^+$)
  - *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

Strategy revisited

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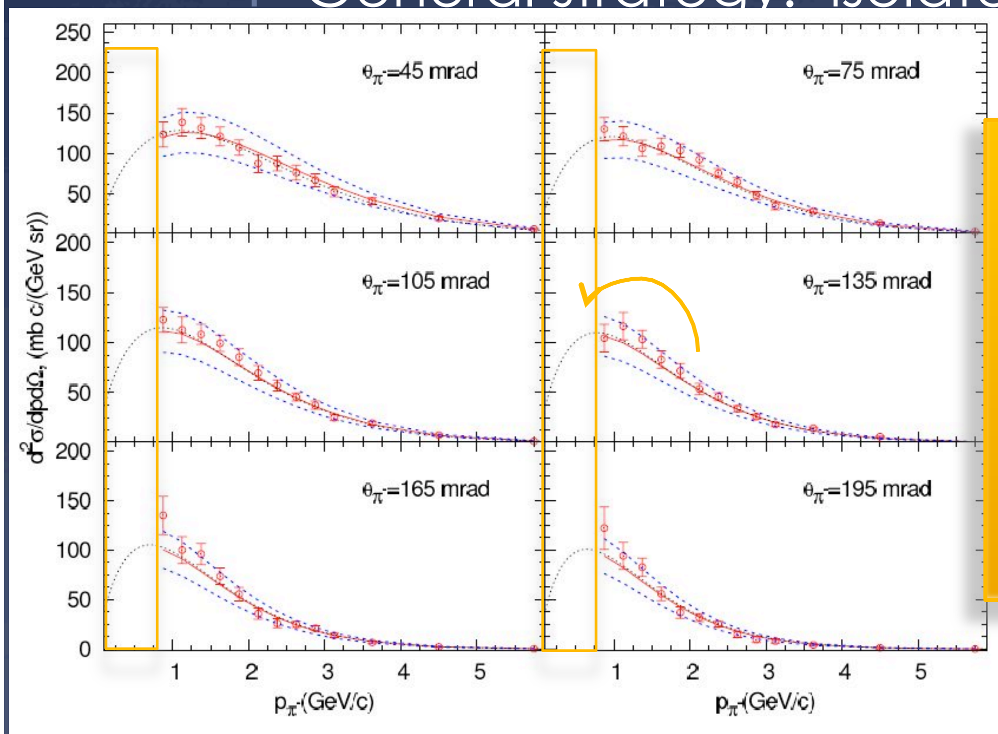

Takes hadro-production data, uses it to place similar errors on the flux region *not measured!*

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Who else cares?

* Anyone using anti-ν beams without B-fields!
  * Noνa
  * T2K far detector
* LBNE: yesterday we heard "preferred reconfiguration" is FD at Homestake without near detector. If no B-field, μ^- capture technique could be very powerful in WS discrimination (argon: ~75% capture, carbon: ~8%!)
  * almost event-by-event discrimination without B-field
* Minerνa: can get powerful stat increases if use μ's stopped in main detector

Conclusions

* Though MiniBooNE is unmagnetized, model-independent statistical techniques measure the ν_μ content in the $\bar{\nu}_\mu$ beam to ~15% uncertainty
* This is the first demonstration of a set of techniques that could well be used in the near future for CP-violation, mass hierarchy and σ measurements

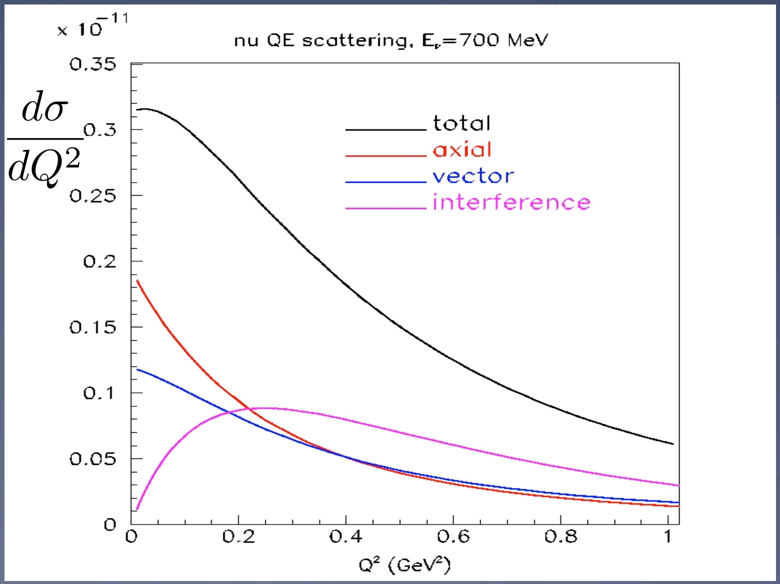
backup

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

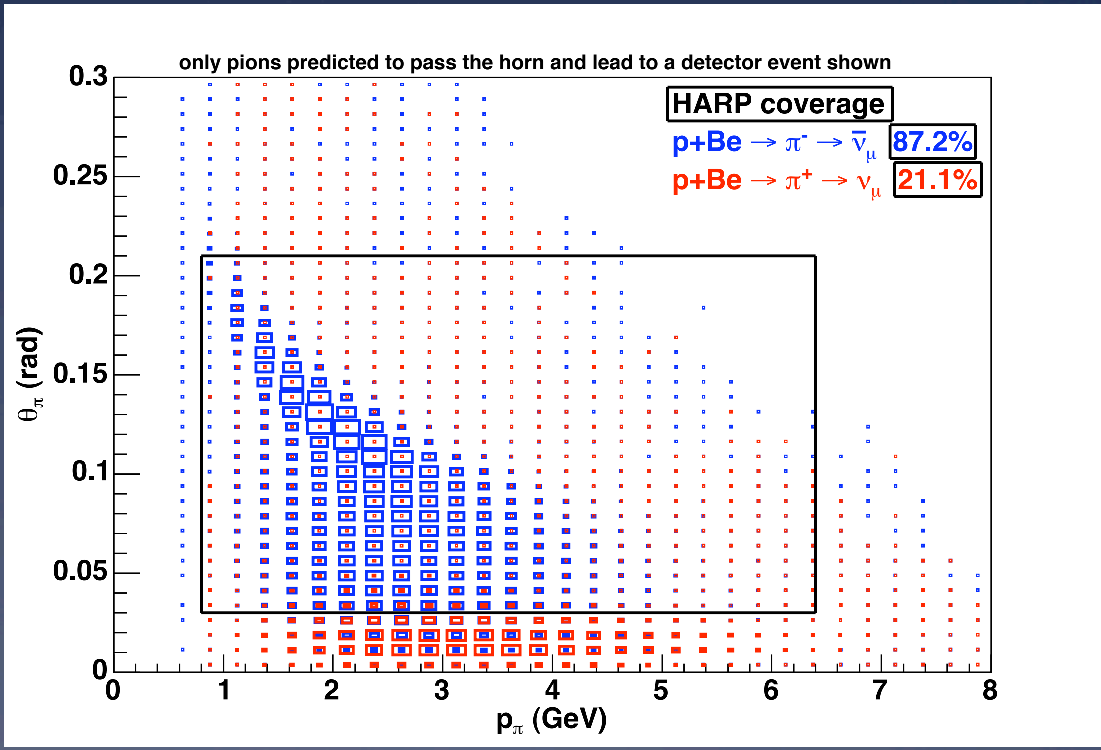
$$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 |V_{ud}|^2}{8\pi E_\nu^2}\left[A\left(Q^2\right) \pm B\left(Q^2\right)\left(\frac{s-u}{M^2}\right) + C\left(Q^2\right)\left(\frac{s-u}{M^2}\right)^2\right]$$

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



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

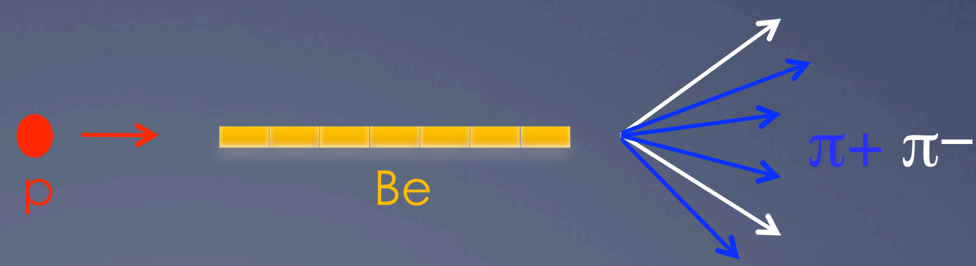
This motivates a dedicated study of ν_μ content of the beam

Why so different?

- 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-



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