Neutrino / anti-neutrino separation

with a non-magnetized detector

Studies in wrong-sign identification

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10/6/12

Outline

1. MiniBooNE and wrong-sign contamination in the Booster Neutrino Beam (BNB)
2. Three measurements of ν_μ flux in BNB $\bar{\nu}_\mu$ beam
3. Future utility of these techniques

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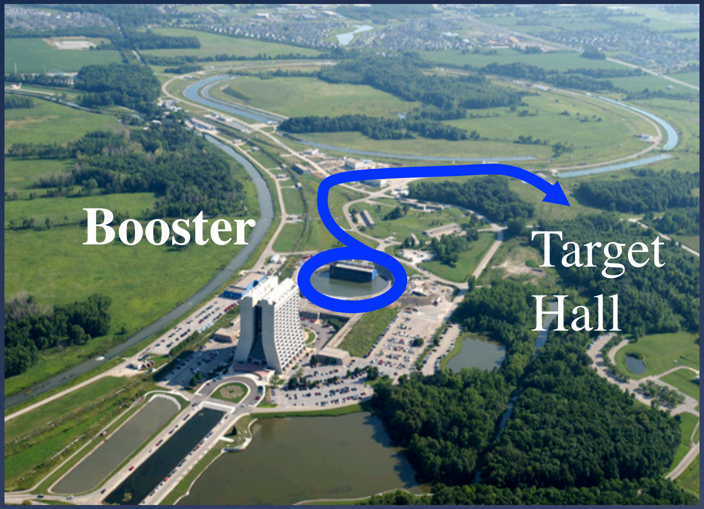
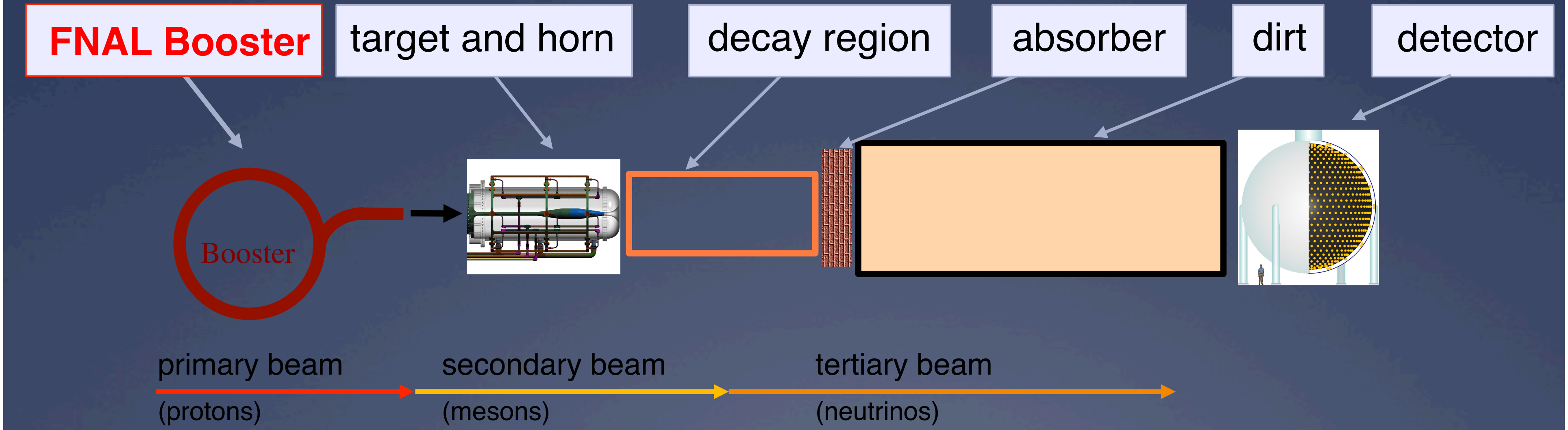
Booster Neutrino Beam



8.9 GeV/c momentum protons extracted from Booster, incident on a Beryllium target



FNAL Booster

target and horn

decay region

absorber

dirt

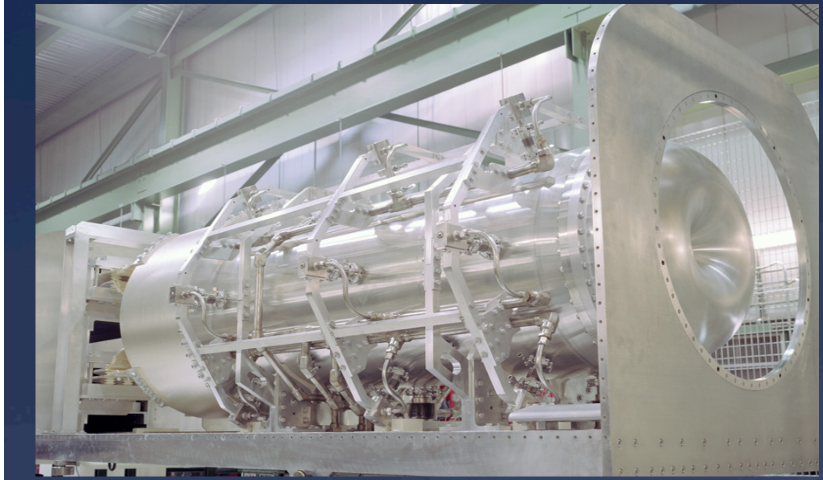
detector

primary beam (protons)

secondary beam (mesons)

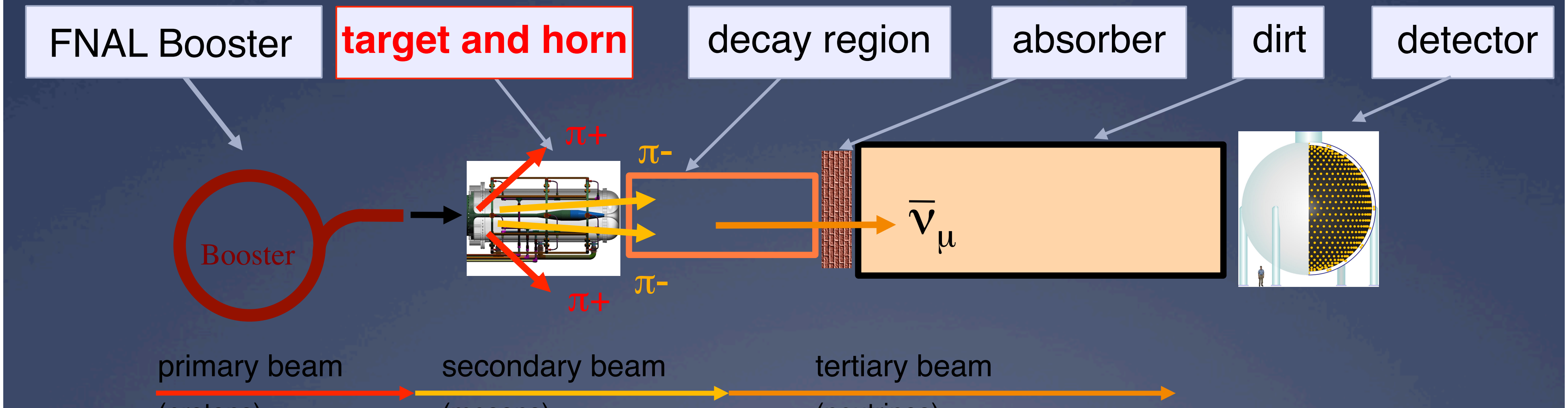
tertiary beam (neutrinos)

Booster Neutrino Beam



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

(“neutrino” vs “anti-neutrino” mode)



FNAL Booster

target and horn

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primary beam
(protons)

secondary beam
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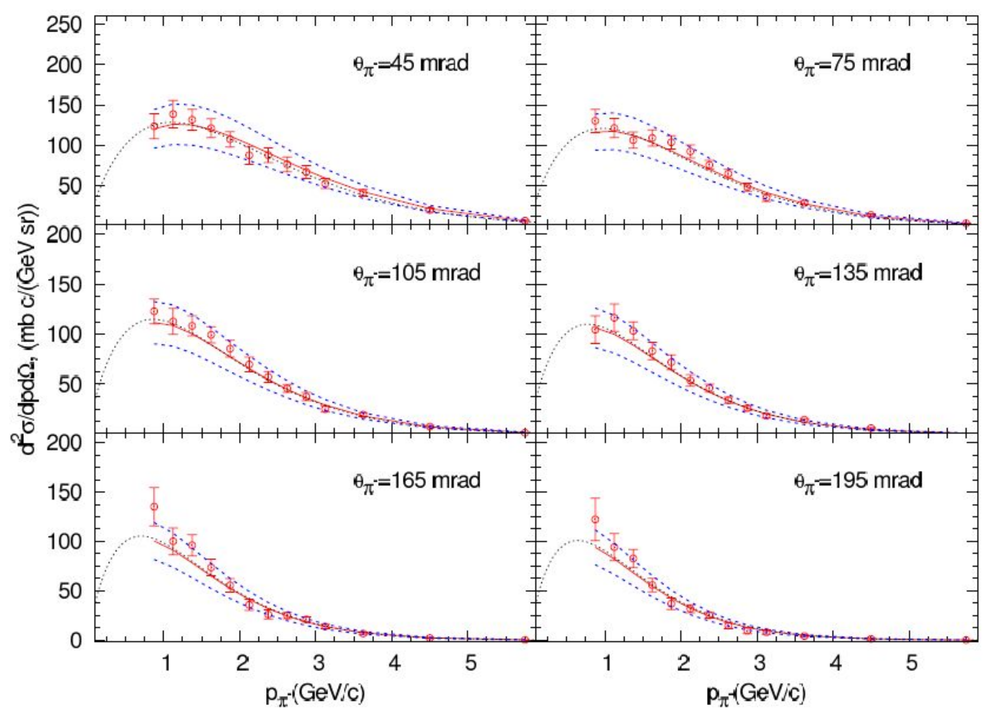
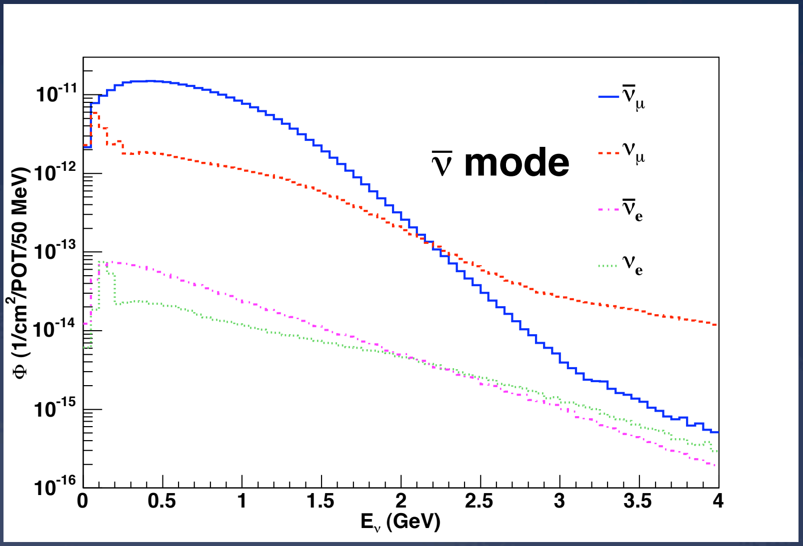
tertiary beam
(neutrinos)

MiniBooNE Flux

- Uses dedicated hadroproduction data from HARP



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

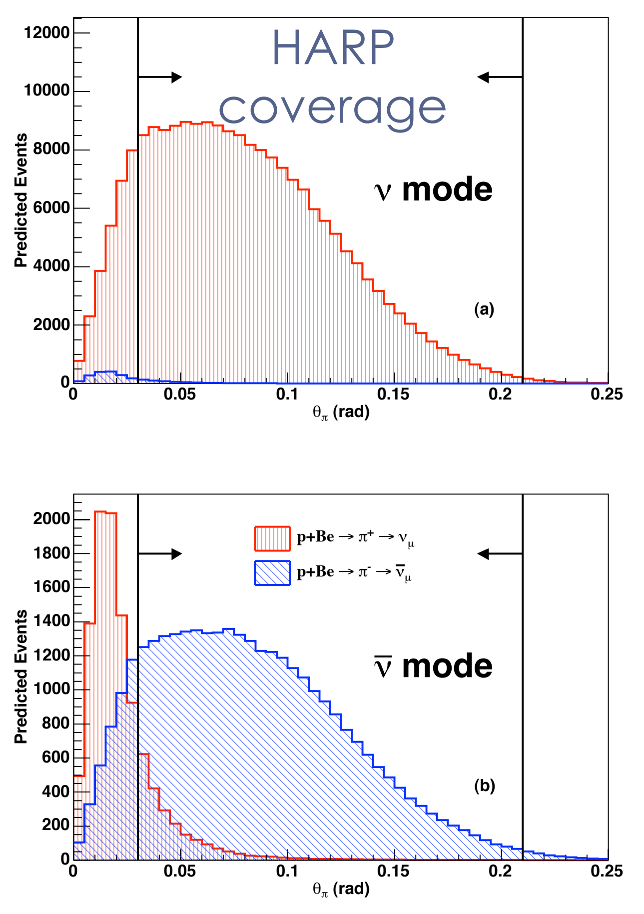


MiniBooNE collaboration,
Phys. Rev. D79, 072002 (2009)

- A spline fit to these data brings flux uncertainty to ~9%

MiniBooNE Flux

- ~9% errors only true for "right sign" events
- Due to large proton background, pion production below 30 mrad not reported
- Another benefit of off-axis beams (Nova, T2K, etc.)

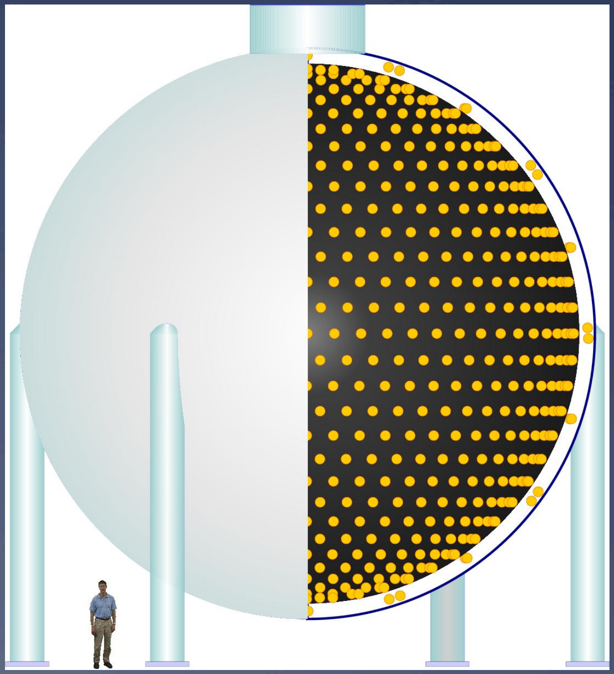


This motivates a dedicated study of ν_μ content of the beam

MiniBooNE detector

- 6.1m radius sphere houses 800 tons of pure mineral oil.
- 1520 Photo Multiplier Tubes uniformly dispersed in 2 regions of tank (240 veto, 1280 inner tank)
- Cherenkov detector: best at measuring lepton kinematics
- No B-field!

Nucl. Instr. Meth. A599, 28 (2009)



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2. Three measurements of ν_μ flux in BNB $\bar{\nu}_\mu$ beam
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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

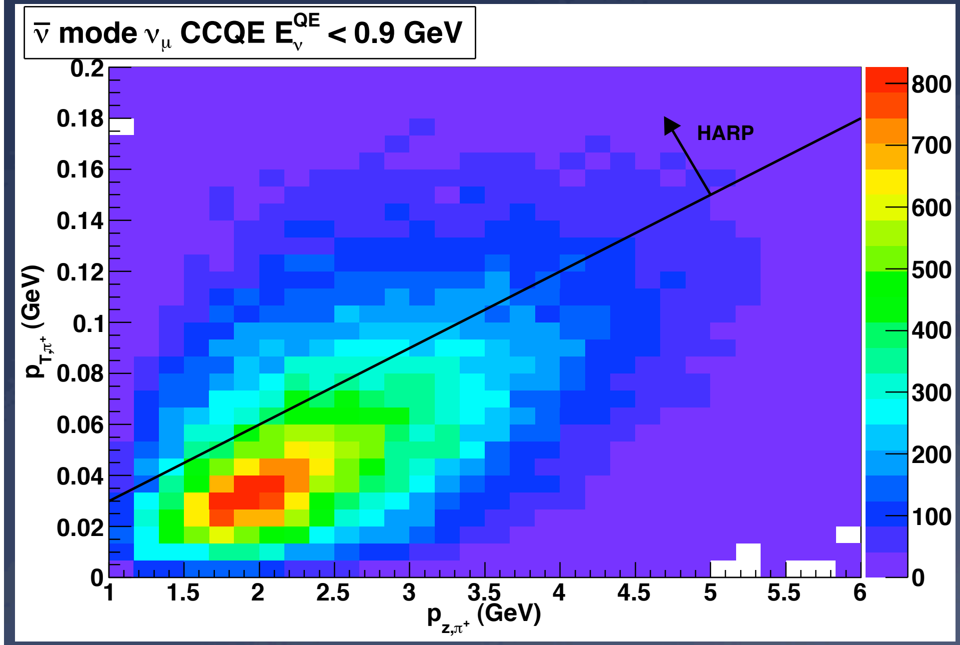
$$\frac{\mathrm{Rate}^{\mathrm{data}}}{\mathrm{Rate}^{\mathrm{sim}}} = \frac{\Phi^{\mathrm{true}} \times \sigma^{\mathrm{meas}}}{\Phi^{\mathrm{sim}} \times \sigma^{\mathrm{meas}}} = \frac{\Phi^{\mathrm{true}}}{\Phi^{\mathrm{sim}}}$$

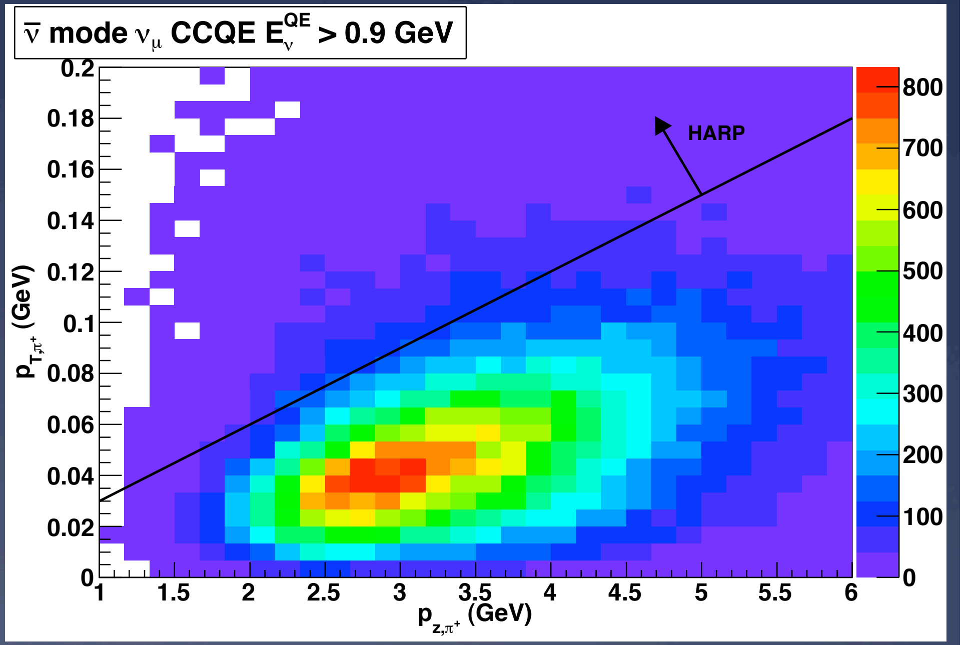
- The level of data-simulation agreement then reflects the accuracy of the ν_μ flux prediction

- Of course, if you're just interested in subtracting the bkg wrong-signs, don't need the true σ

Wrong-sign measurements

- Important to bin in E_ν as finely as possible to check ν_μ spectrum





- Different energies have different relative HARP coverage too - might expect flux accuracy to be $f(E_\nu)$

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)

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in draft

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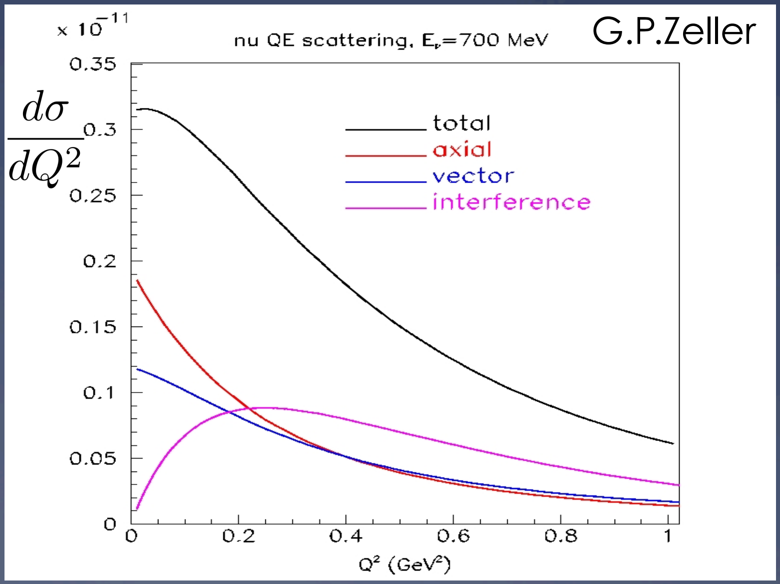
Fitting the outgoing muon angular distribution

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

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

- The divergence is more pronounced at higher Q², which is strongly correlated with backward scattering muons

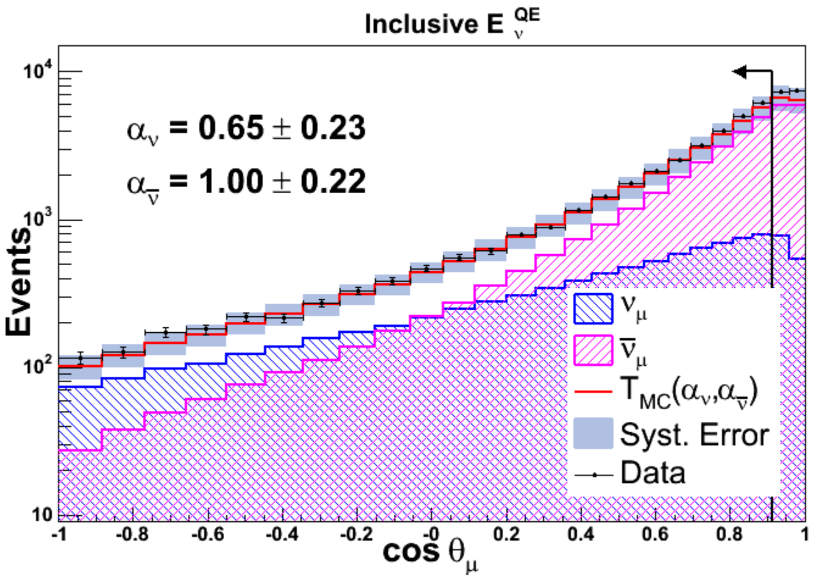


G.P.Zeller

Fitting the outgoing muon angular distribution

- Results indicate the ν_μ flux is over-predicted by ~30%

- Exclusive reconstructed E results: consistency indicate spectrum shape is well modeled

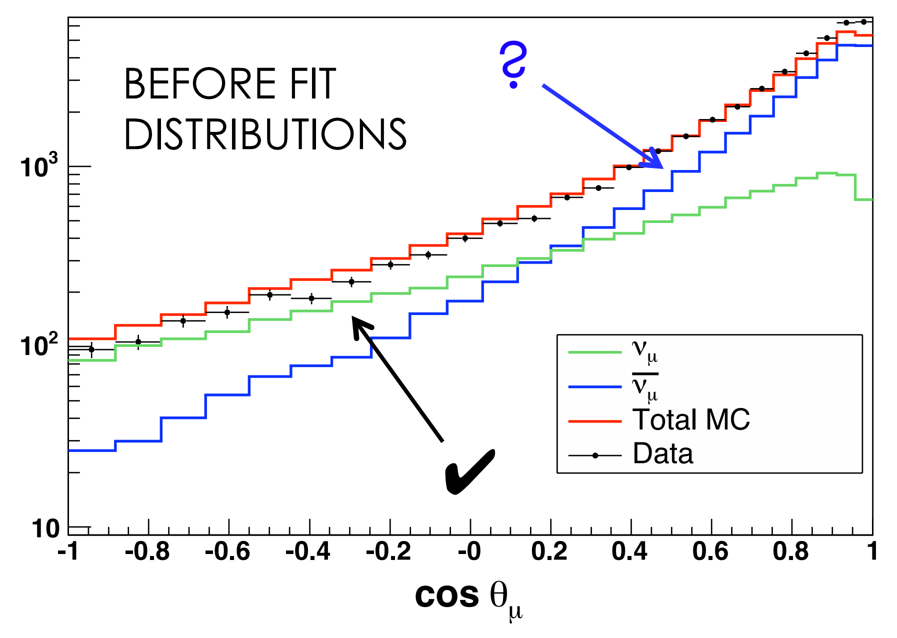


$E_{\bar{\nu}}^{QE}$ (MeV)	ν_μ scale	anti-ν_μ scale
< 600	0.65 ± 0.22	0.98 ± 0.18
600 - 900	0.61 ± 0.20	1.05 ± 0.19
> 900	0.64 ± 0.20	1.18 ± 0.21
Inclusive	0.65 ± 0.23	1.00 ± 0.22

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

- Many exp't and theory improvements recently, σ knowledge will improve and this technique could be very powerful



Wrong-sign measurements

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

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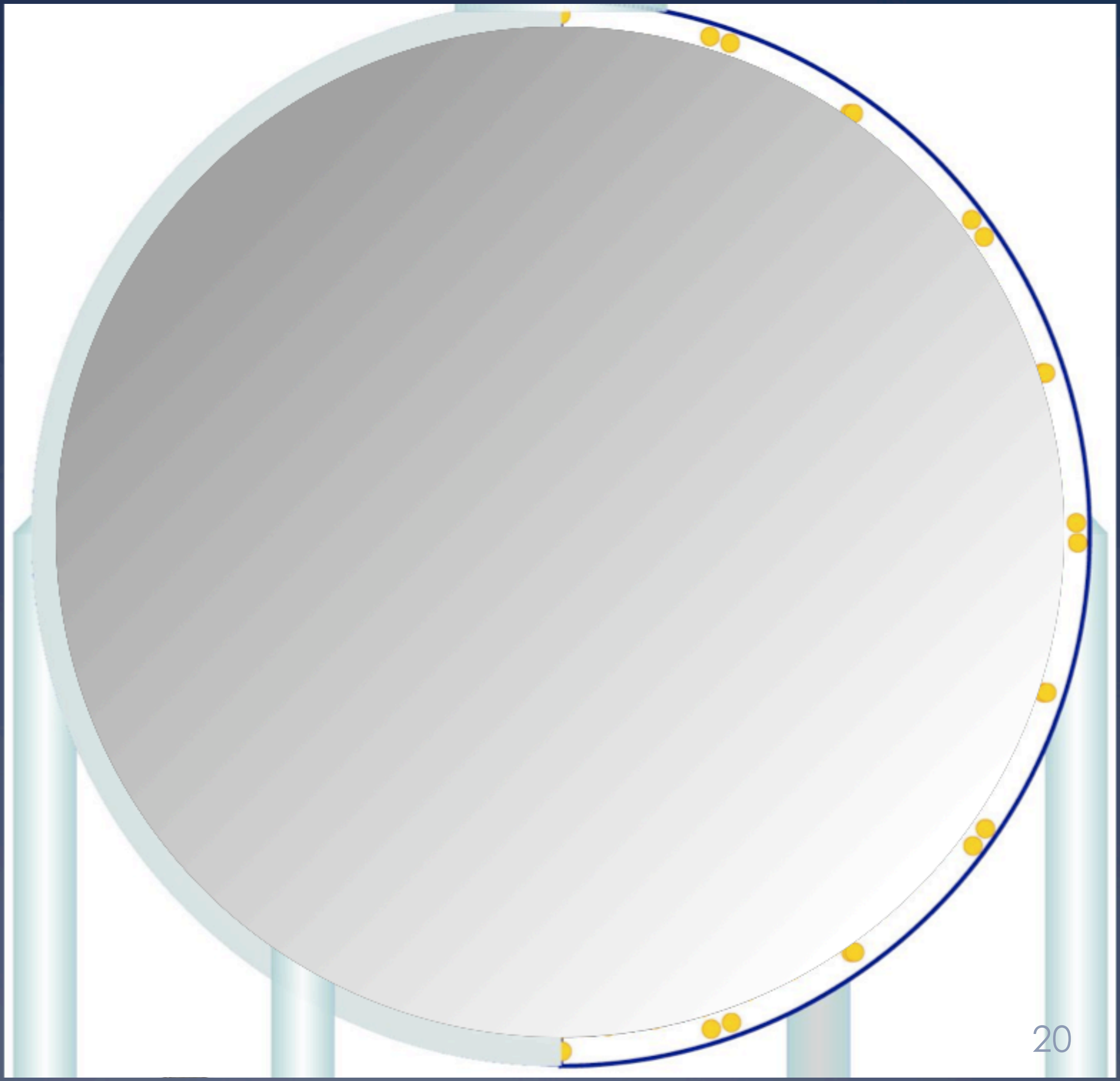
CCπ^+ sample formation

$$\nu_\mu + N \rightarrow \mu^- + \pi^+ + N$$



CCπ⁺ sample formation

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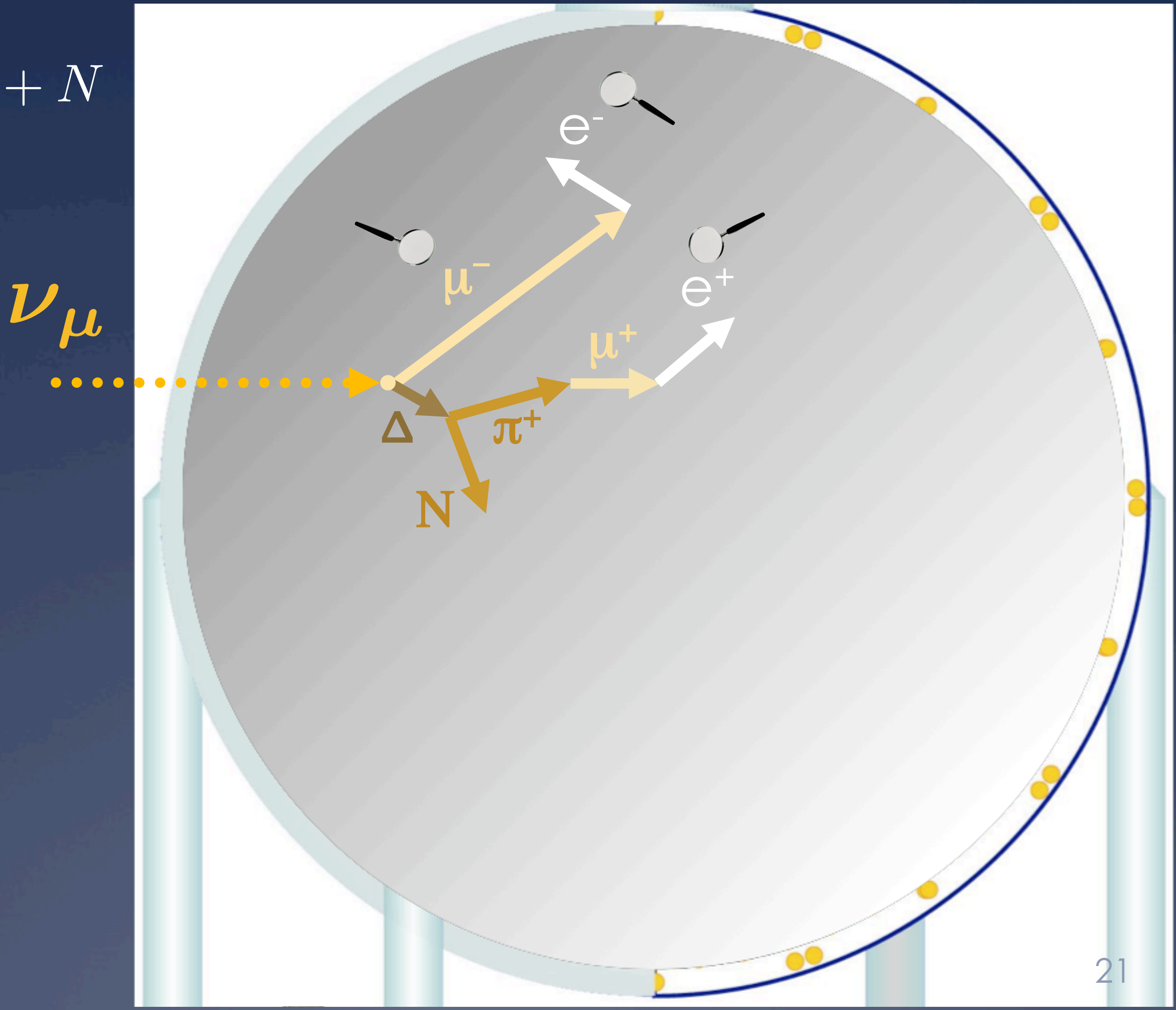

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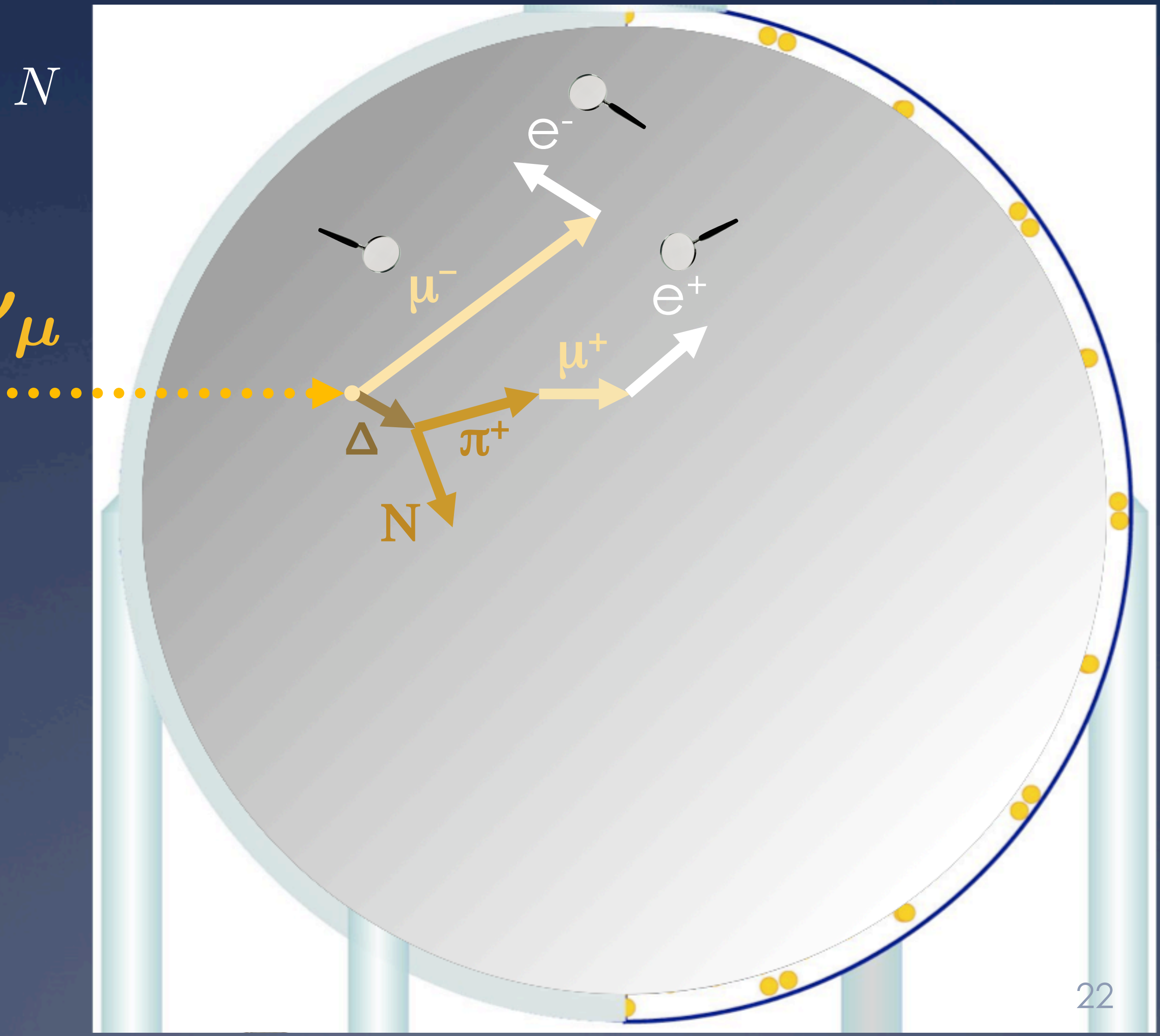
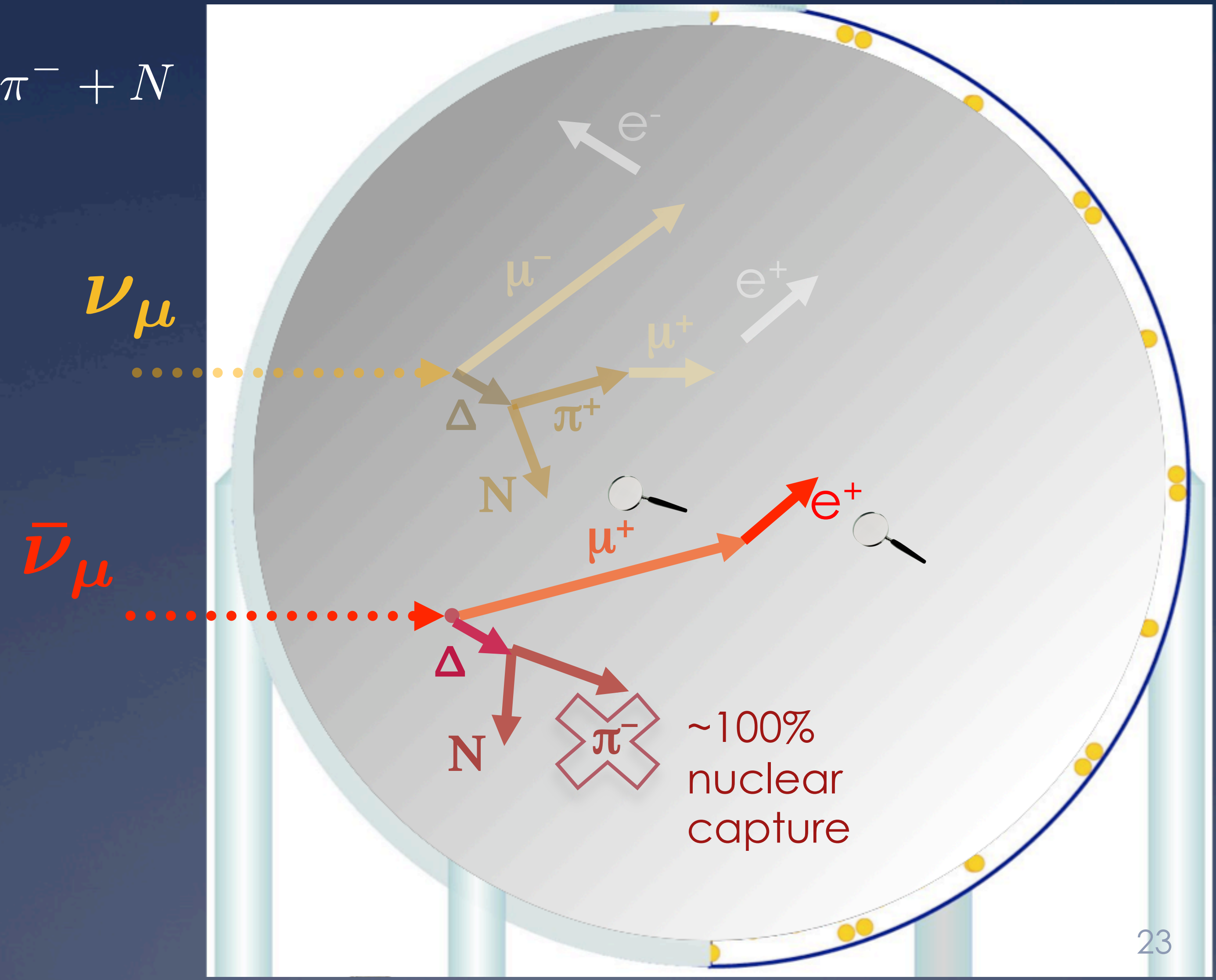


- Three observable leptons
  1. Primary muon
  2. Decay electron
  3. Decay positron

CCπ^+ sample formation

$$\bar{\nu}_\mu + N \rightarrow \mu^+ + \pi^- + N$$



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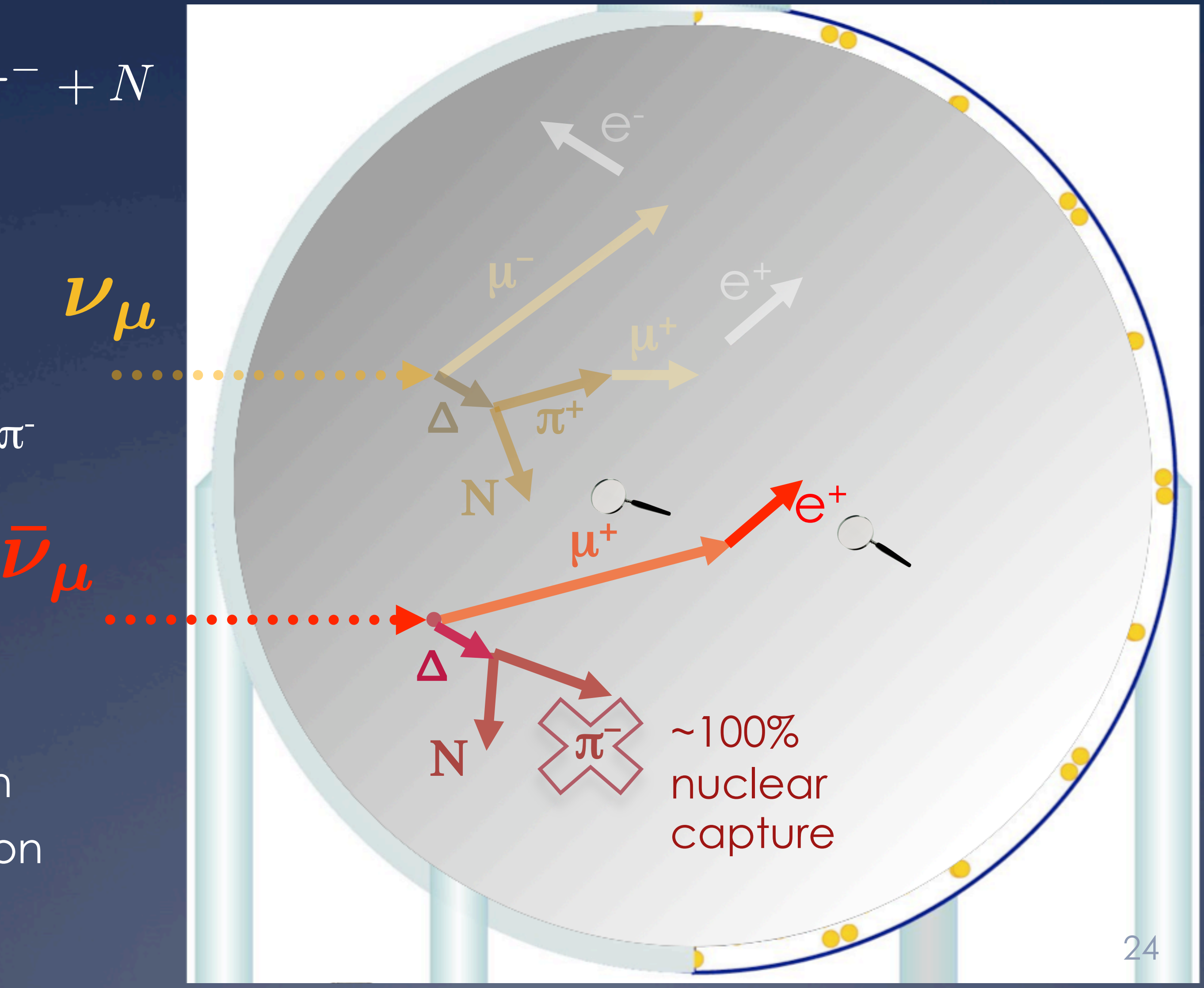

- Due to nuclear π^- capture, the corresponding anti-neutrino interaction has only two:
  1. Primary muon
  2. Decay positron

CCπ^+ ν_μ flux measurement

- Require two decay electrons after the primary muon, get a sample that is ~80% ν-induced.

- Data/simulation ratios in bins of reconstructed energy indicate the neutrino flux is over-predicted in normalization, while the simulated spectrum looks fine

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

CCπ+ σ measurement:
Phys. Rev. D83, 052007 (2011)

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 CCπ^+ sample
  3. Measuring how often muon decay electrons are produced (exploits μ^- nuclear capture)

μ^- capture measurement

- Due to μ^- nuclear capture (~8% in min. oil), fewer ν-induced CC events lead to a decay electron. By adjusting the ν and anti-ν predictions, find a ν flux factor α_ν and anti-ν rate scale $\alpha_{\bar{\nu}}$

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

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

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

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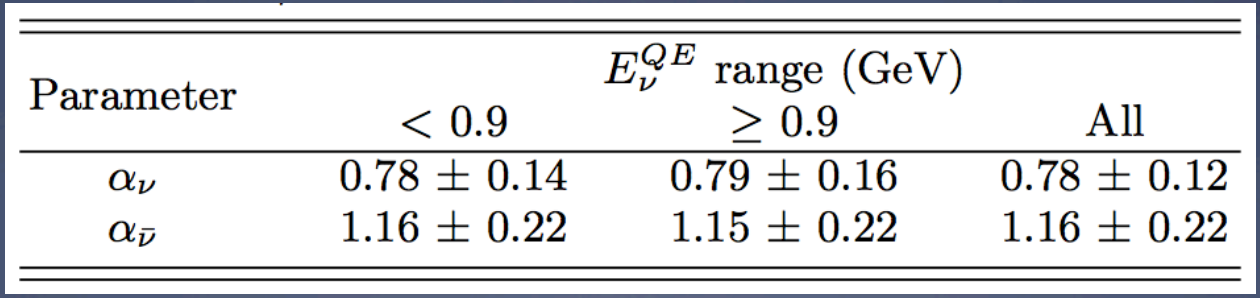
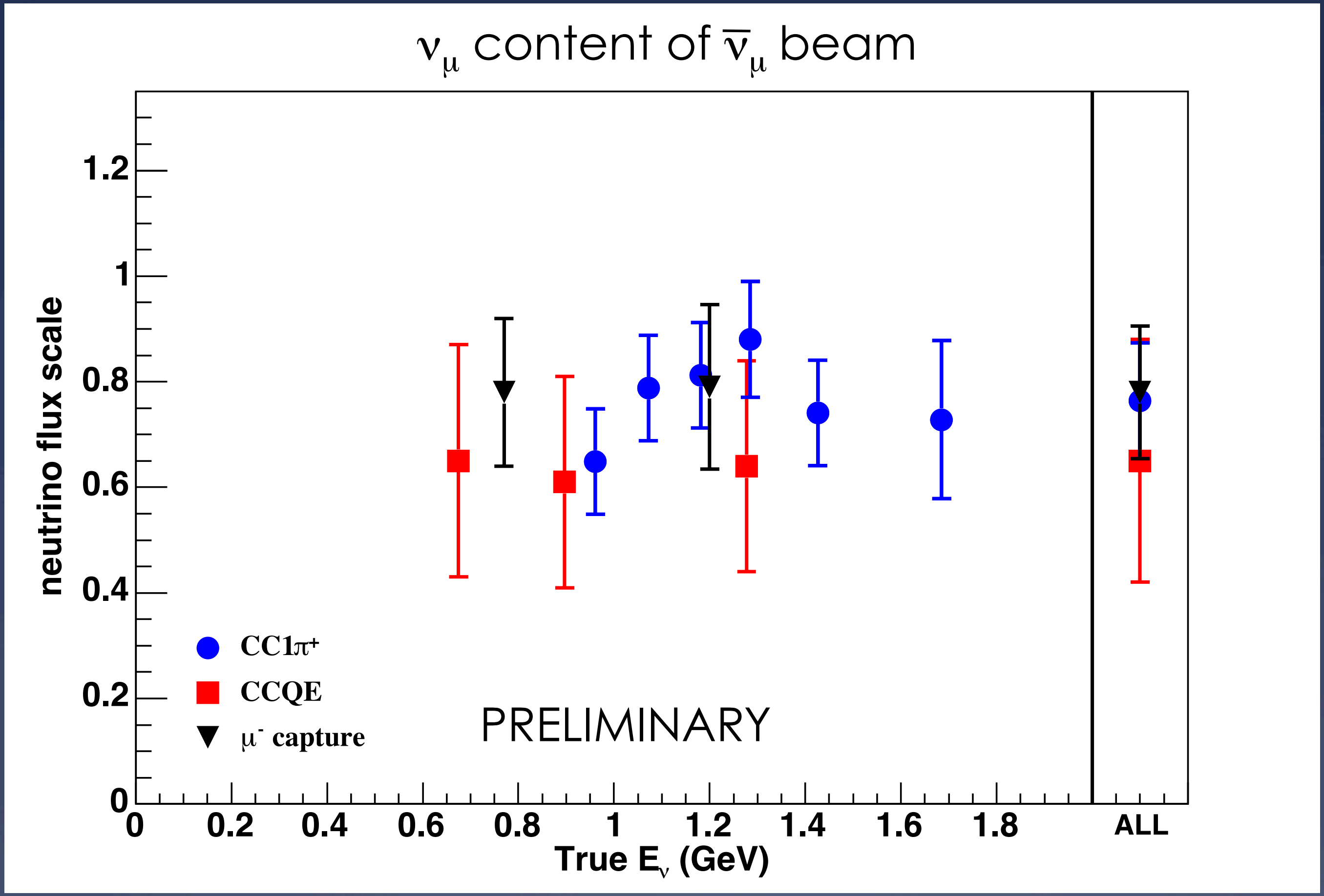
Results:

PRELIMINARY



Parameter	E_ν^{QE} range (GeV)		
	< 0.9	≥ 0.9	All
α_ν	0.78 ± 0.14	0.79 ± 0.16	0.78 ± 0.12
$\alpha_{\bar{\nu}}$	1.16 ± 0.22	1.15 ± 0.22	1.16 ± 0.22

Neutrino flux measurement summary

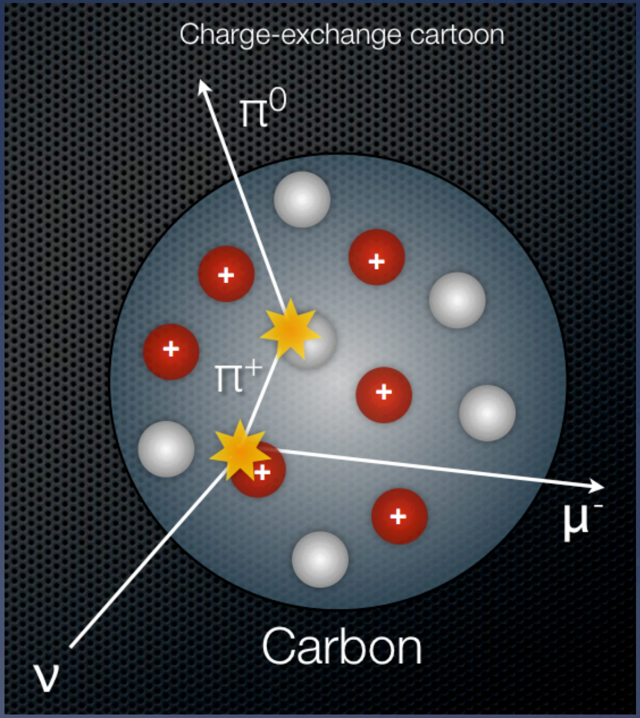


- Discrepancy with prediction appears to be in normalization only - flux shape is well modeled. 13% error on final measurement

Using your own σ measurements

- Most detector errors cancel by correcting anti-ν mode MC for σ's observed in the ν exposure
- Similar to two-detector osc experiments, but instead of 1 beam + 2 detectors, we use 2 beams + 1 detector
- Φ uncertainty dominated by ν-mode Φ knowledge and stats

R. Nelson



Φ measurement insensitive to FSI!

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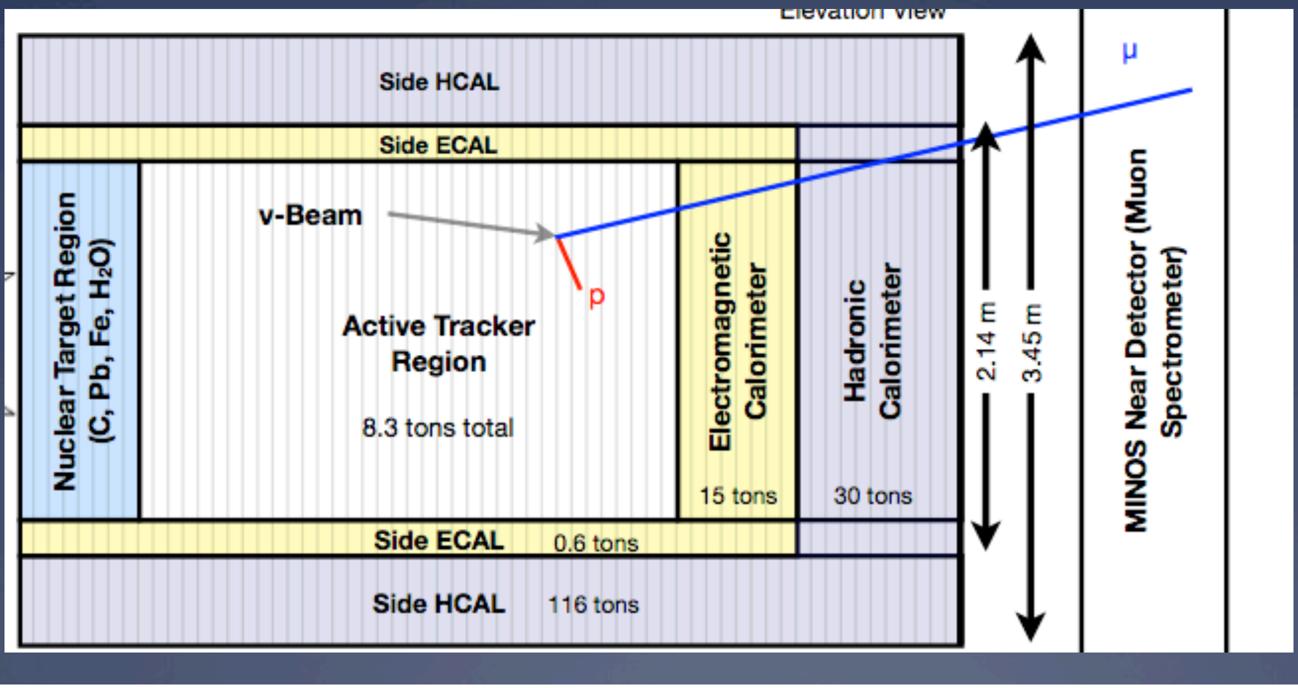
2. Three measurements of ν_μ flux in BNB $\bar{\nu}_\mu$ beam

3. Future utility of these techniques

Current expts

- Nova
  - if run anti-ν mode
- Minerva: can get powerful statistical increases, more kinematic coverage (via μ angle) if use μ's stopped in main detector

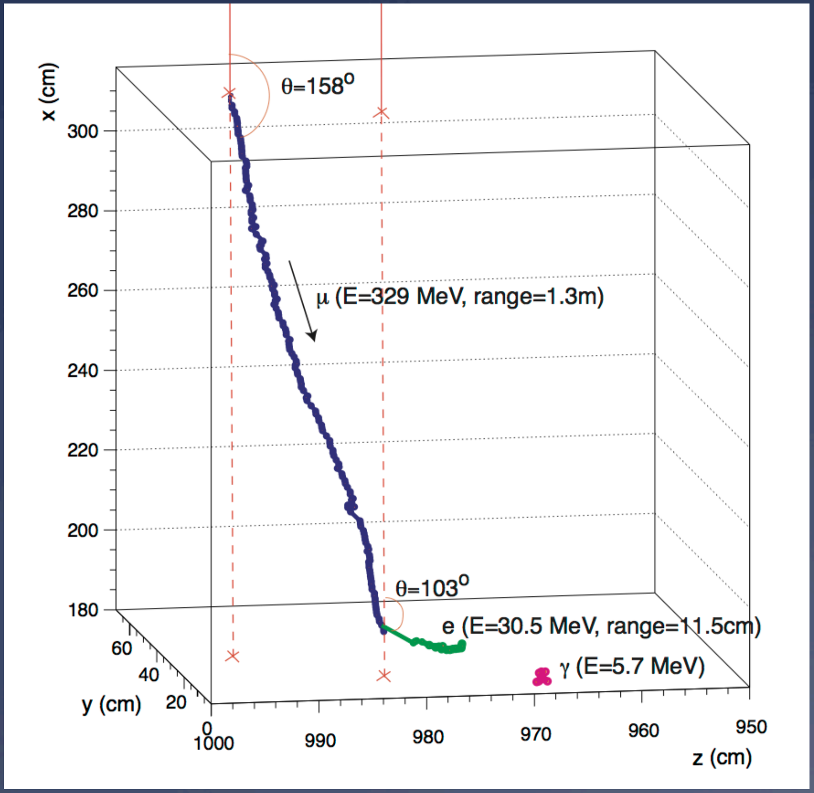


Future expts: LAr

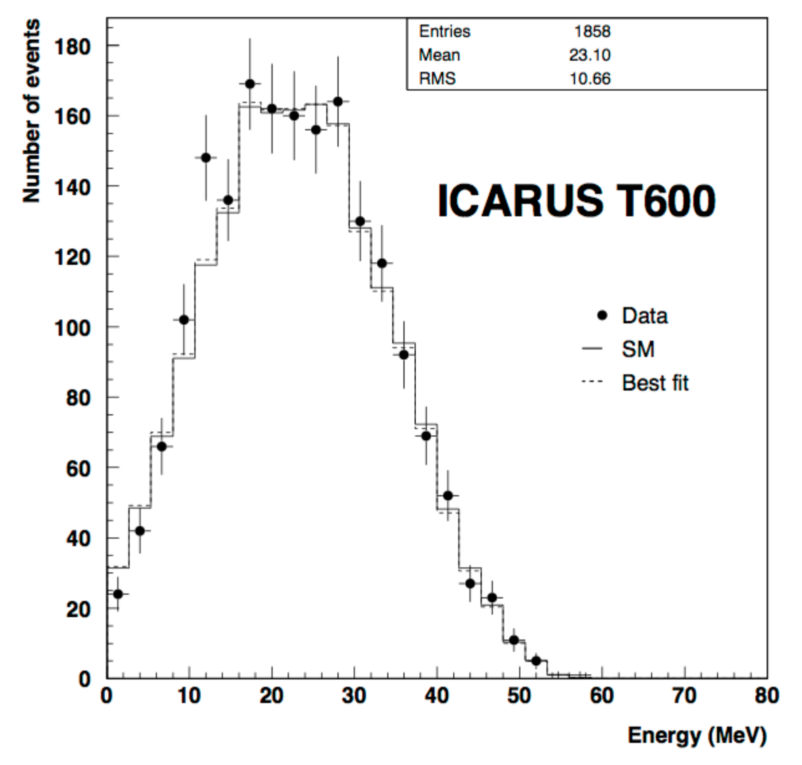
- LBNE: first phase will be single LAr detector on Homestake surface.
- If no B-field, μ^- capture technique could be very powerful in wrong-sign discrimination w/o ND
  - 8% μ^- capture in carbon gives enough statistical power to separate ν from anti-ν in energy bins, argon has ~75% Phys Rev C 35, 2212 (1987)
  - almost event-by-event discrimination without B-field!
- Could use π^+ as well: CC1π^+ exclusively ν-induced, in general most π^+ due to ν processes

Future expts: LAr

- ICARUS has demonstrated Michels can be reconstructed well in argon Eur Phys J C33, 233 (2004)



single event



spectrum

Other handles

- Fit μ lifetime to combination ν + anti-ν templates
  - different way of using μ capture

- Nuclear recoil - for CCQE, expect outgoing p for ν_μ, outgoing n for anti-ν_μ events. Be careful!
  - meson exchange currents predict combo. of p+n ejection in both cases (open question)
  - final state interactions
  - proton detection modeling
  - very active field in both exp't and theory - we ought to be better informed soon

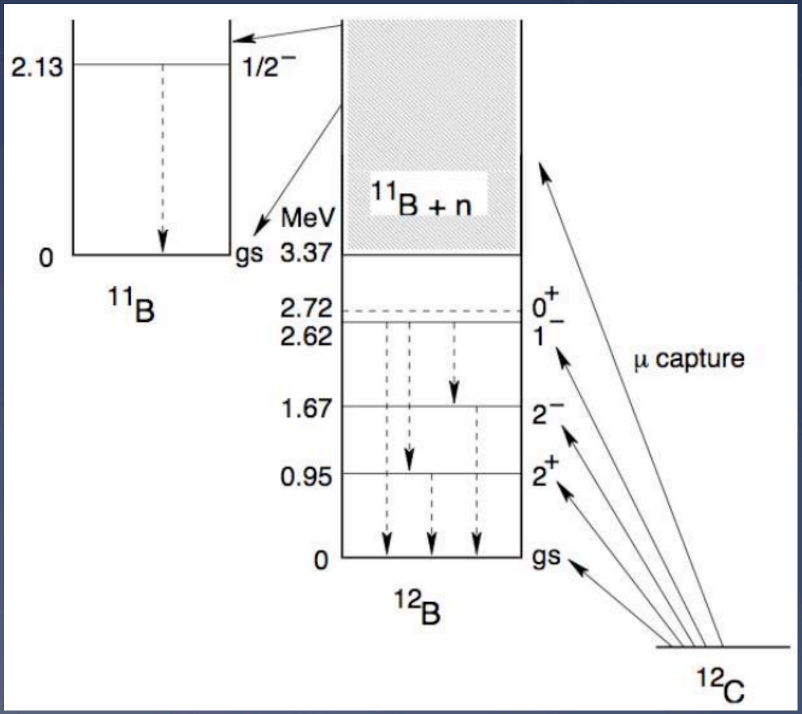
Summary

- Though MiniBooNE is unmagnetized, minimally model-dependent statistical techniques measure the ν_μ content in the $\bar{\nu}_\mu$ beam to ~13% uncertainty
- This is the first demonstration of a set of techniques that could used to inform technology decisions and facilitate next-generation oscillation measurements

backup

μ^- capture measurement

- ~8% of stopped μ^- captures on ^{12}C, but some nuclear de-excitation products (γ's,n's) can fake Michel electron
  - "regain" Michel-like event following ~6% of μ^- captures
- ν-mode data has very little wrong-sign contribution, so we can calibrate nuclear de-excitation and Michel detection models
  - < 5% calibration



Strategy revisited

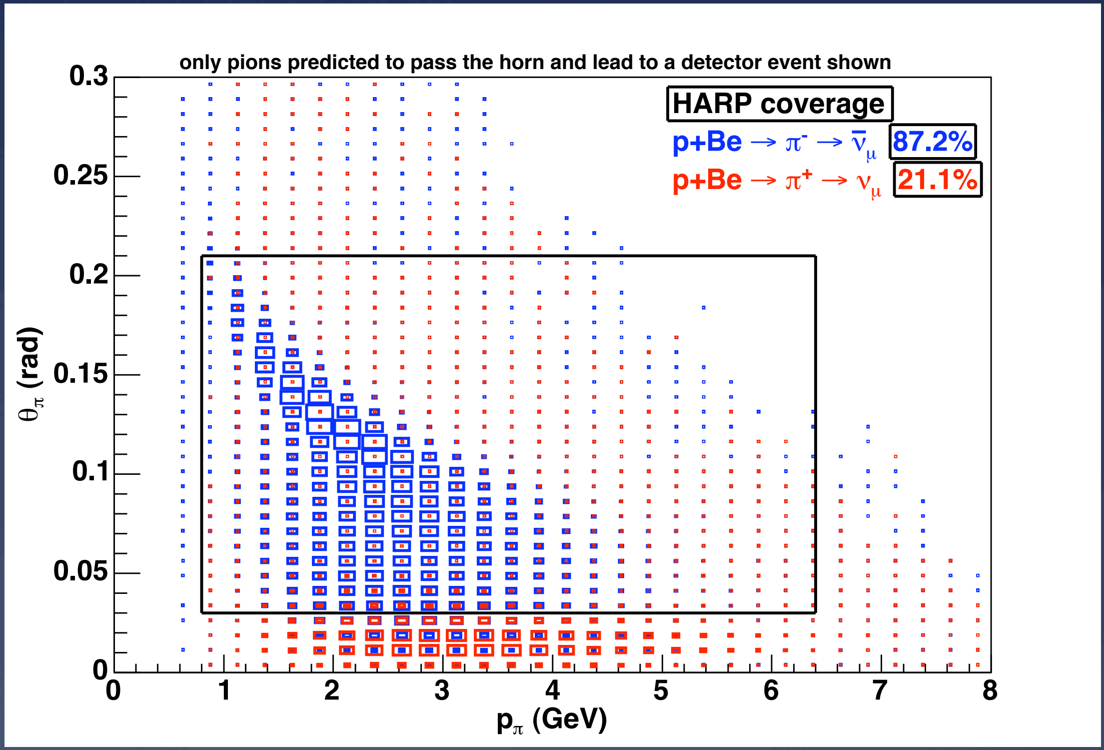
- General strategy: isolate samples sensitive to the ν_μ beam content, apply the measured cross sections from neutrino mode (CCQE, CCπ^+)
  - *Crucial* application of BooNE-measured ν_μ σ's

$$\frac{\mathrm{Rate}^{\mathrm{data}}}{\mathrm{Rate}^{\mathrm{sim}}} = \frac{\Phi^{\mathrm{true}} \times \sigma^{\mathrm{meas}}}{\Phi^{\mathrm{sim}} \times \sigma^{\mathrm{meas}}} = \frac{\Phi^{\mathrm{true}}}{\Phi^{\mathrm{sim}}}$$

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

How wrong signs contribute to flux

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

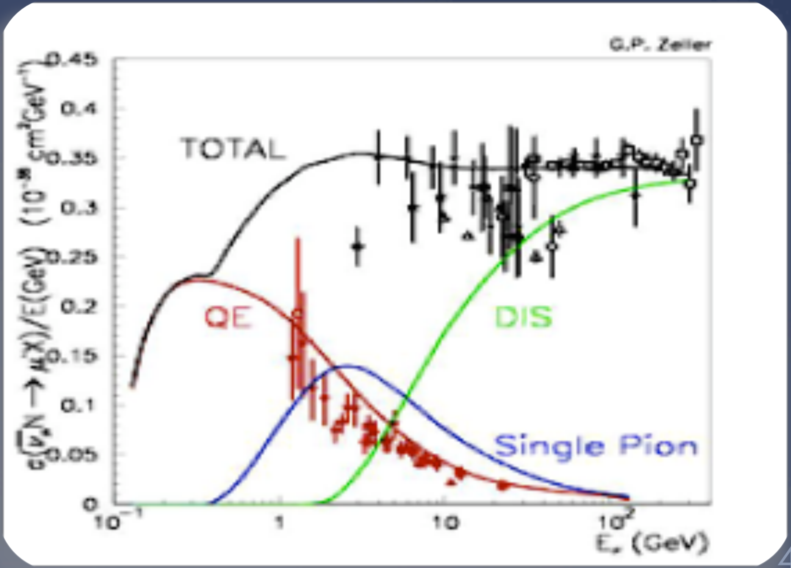


- Another benefit of off-axis beams (Nova, T2K, etc.)

This motivates a dedicated study of ν_μ content of the beam

anti-ν cross section dependence?

- The μ+e sample is ~60% anti-ν_μ, how much model dependence enters from assumption on anti-ν_μ σ?
- Flux measurement negligibly sensitive to anti-ν_μ σ: model would have to be wrong by > 50% to see an impact on extracted ν_μ Φ (it's not)
- This is accomplished with 8% μ^- capture for carbon. Can do much better with argon at ~75%!



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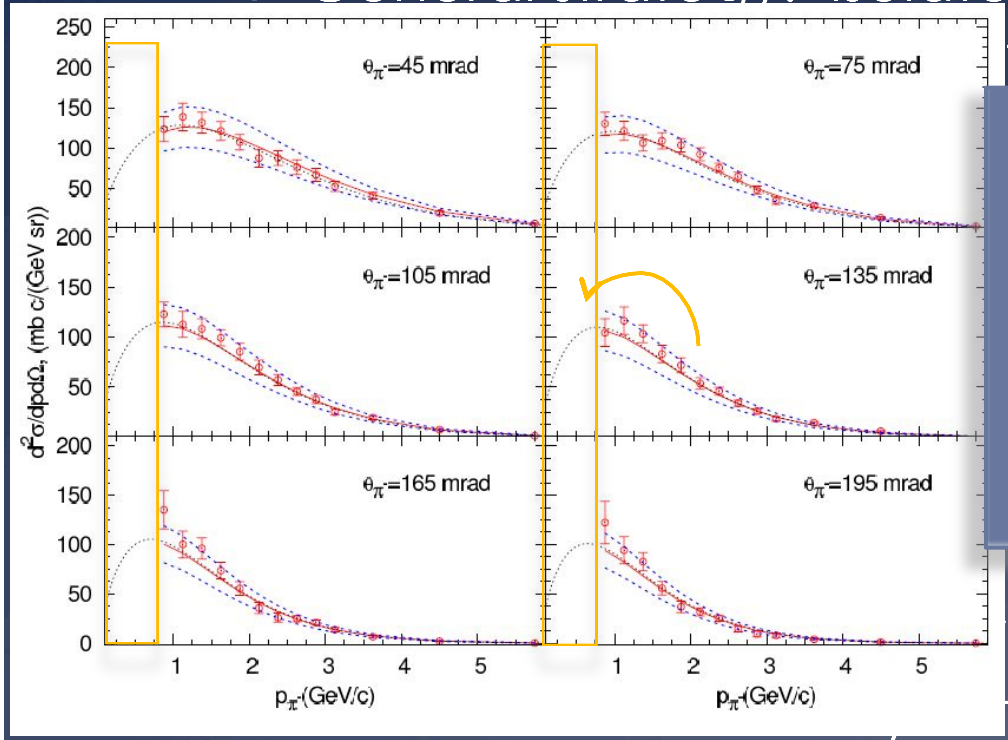


the measured cross

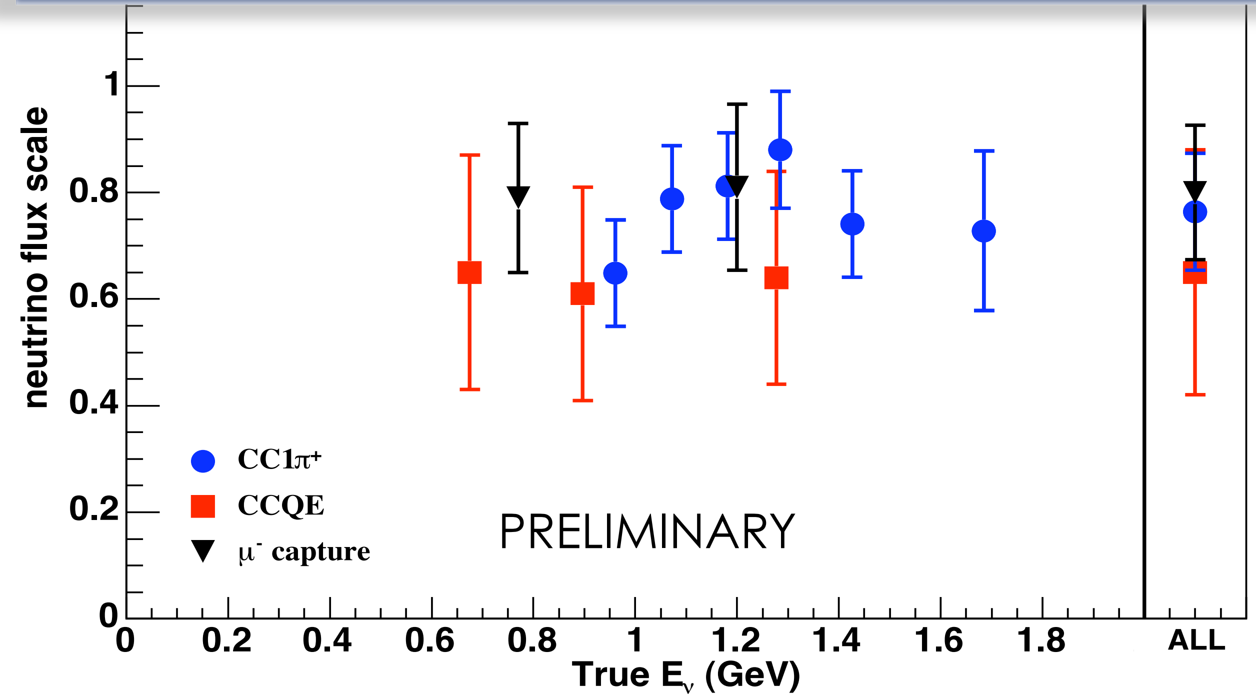
Takes hadro-production data, uses it to place similar constraints on the flux region *not measured*

ion agreement then

the ν_μ flux prediction

Strategy revisited

Another way to say it: wrong-sign Φ measurements limited onlyby ν-mode Φ knowledge (+ statistics)



μ^- capture measurement

- 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)
- We isolate a > 90% CC sample for both μ-only and μ+e samples

Other ICARUS details

- Michel energy resolution 11%/√E + 2%
- 0.6mm drift direction resolution, drift distance is ~3mm in 2μs, so probably can't measure μ lifetime well

ν_μ vs $\bar{\nu}_\mu$ rate difference

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

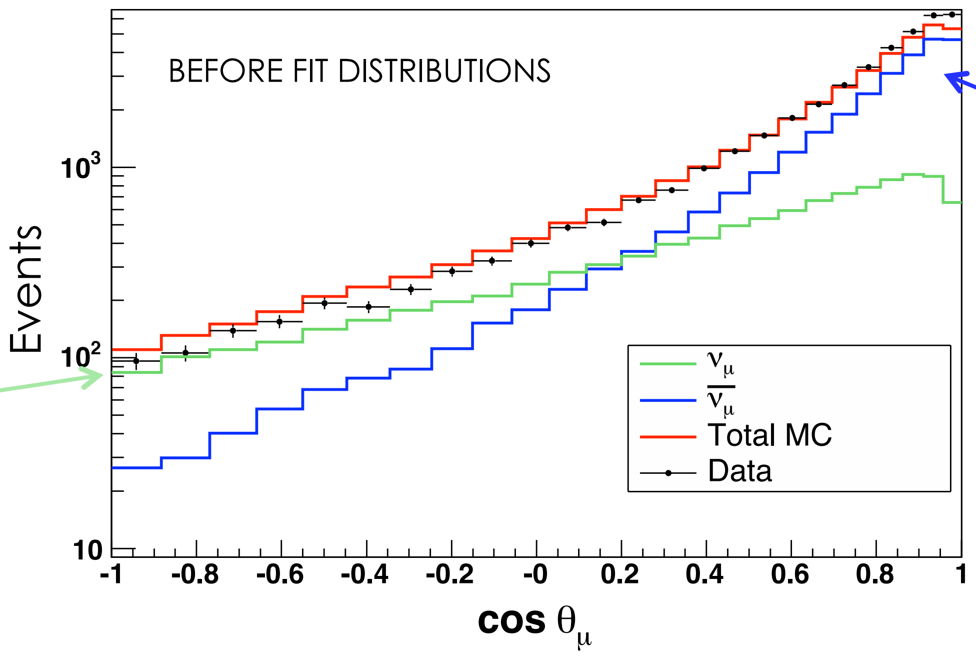
$$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 |V_{ud}|^2}{8\pi E_\nu^2} \left[A\left(Q^2\right) \boxed{\pm} B\left(Q^2\right) \left(\frac{s-u}{M^2}\right) + C\left(Q^2\right) \left(\frac{s-u}{M^2}\right)^2 \right]$$

A CCQE model: + for ν, - for $\bar{\nu}$

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

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 $\bar{\nu}_\mu$ template by "$\alpha_{\bar{\nu}}$"

Scale the ν_μ template by "α_ν"