The evolution of (experimental) neutrino cross sections

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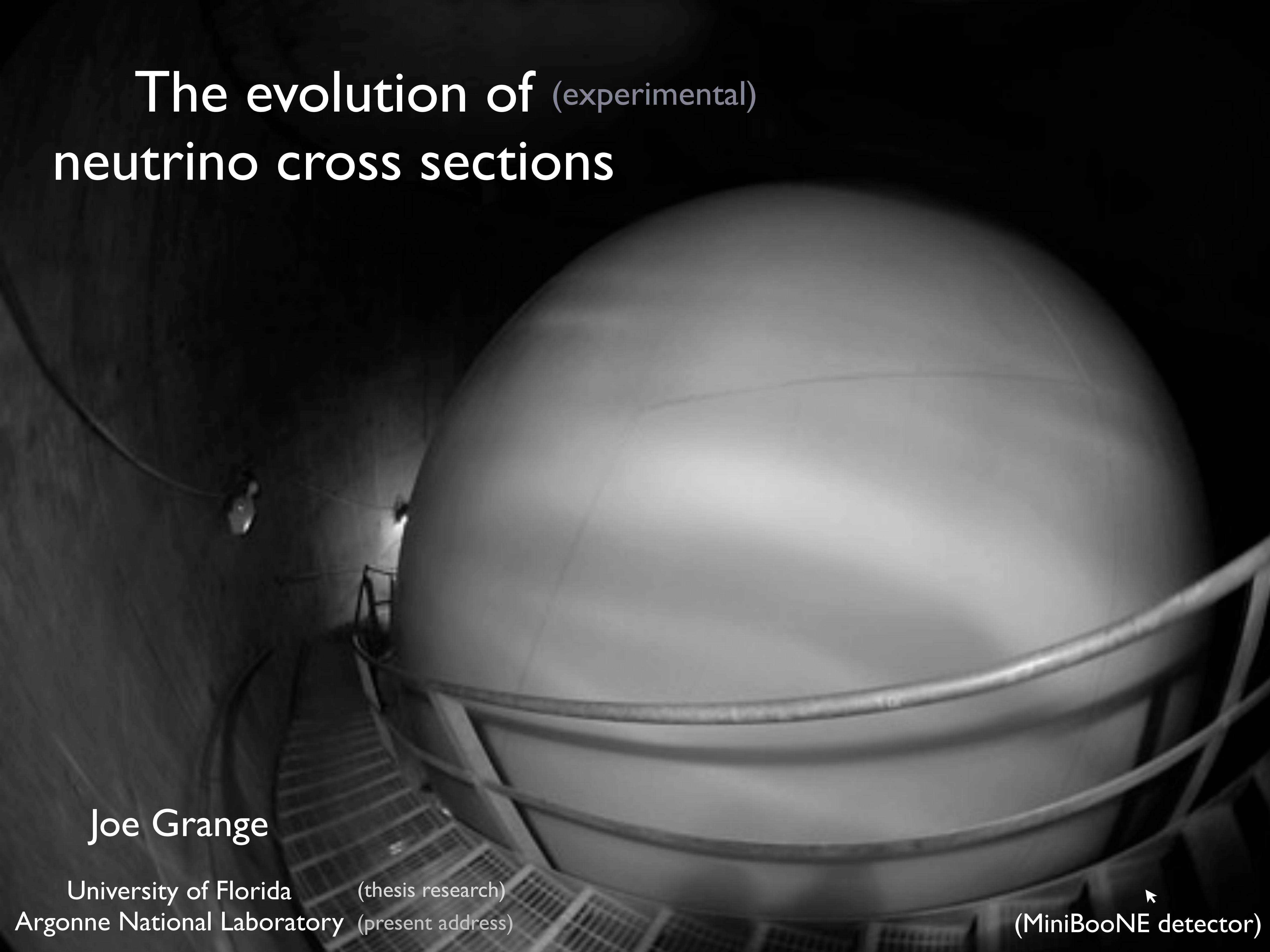


(MiniBooNE detector)

Today

- From first detection towards precision measurements of oscillatory and intranuclear behavior
- Nudging the field along with MiniBooNE antineutrinos
  - large A-dependent enhancements?
  - separating ν from $\bar{\nu}$ without magnets
  - topological cross sections
- Forward

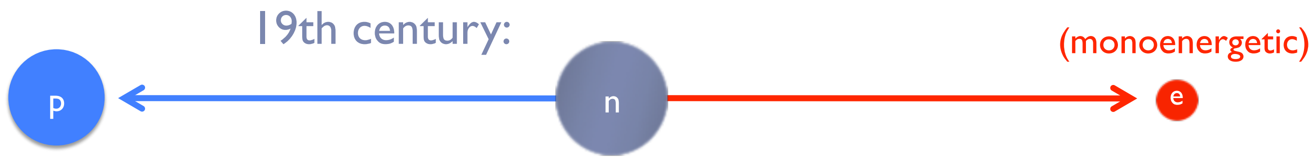
- From first detection towards precision measurements of oscillatory and intranuclear behavior

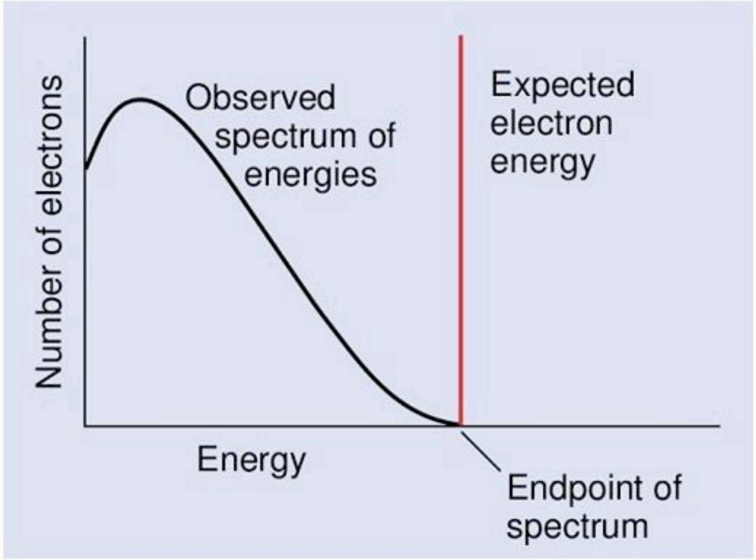
- Nudging the field along with MiniBooNE antineutrinos
  - large A-dependent enhancements?
  - separating ν from $\bar{\nu}$ without magnets
  - topological cross sections

- Forward

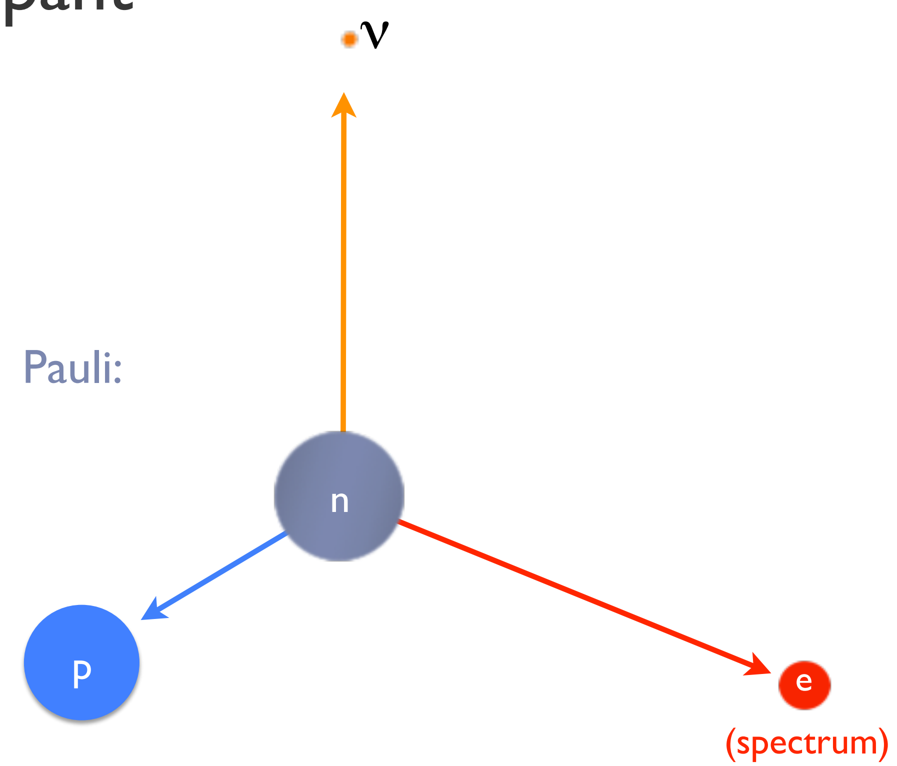
1950's: discovery, first cross-section measurement

- 1914: continuous spectrum ejected electrons from β decay inconsistent with presumed two-body decay





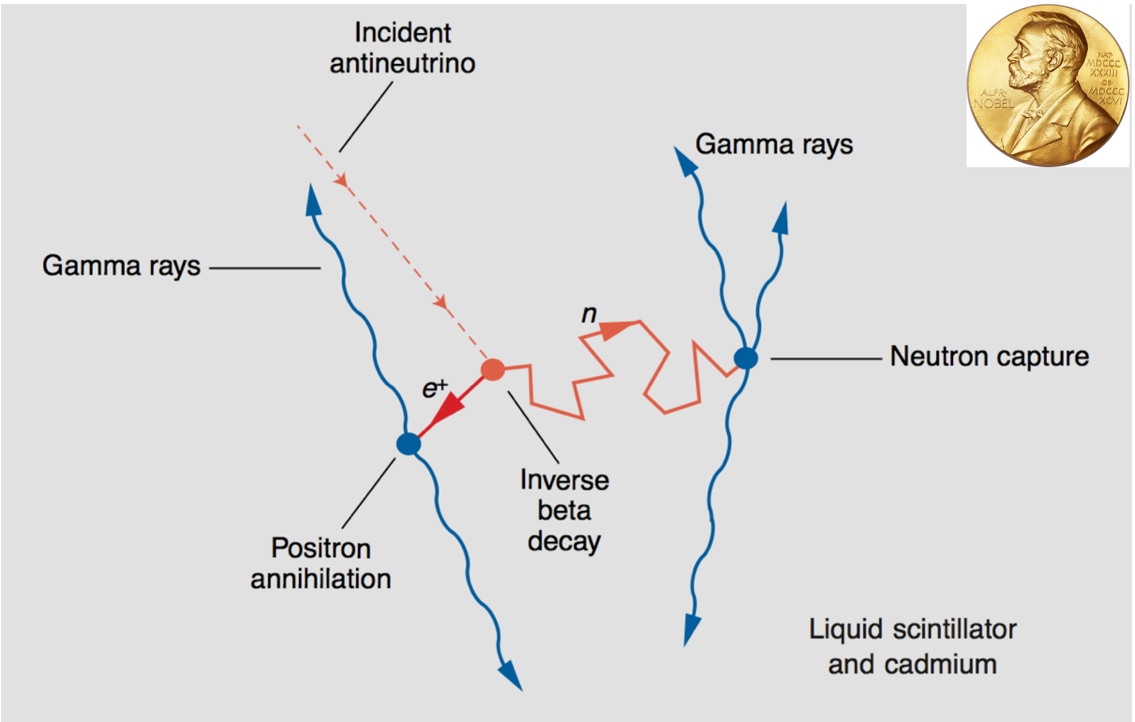
- 1931: following numerous confirmations, W. Pauli proposed a "desperate remedy": a third participant *never before observed* kinematically allows for a continuous β spectrum
  - "I have postulated a particle that cannot be detected..."



1950's: discovery, first cross-section measurement

Fortunately, "never" → 25 years:

1995
Nobel Prize



- Reines and Cowan detected the first definitive neutrino interactions
  - using reactor antineutrino source and doped scintillator bath to provide doubly-coincident signal
- While at it, they calculated the very first ν-induced cross section:

Event rate

$$\sigma = \frac{R}{\Phi \epsilon N}$$

Antineutrino flux
(known to ~25%)

Detection efficiency

Number of proton IBD targets

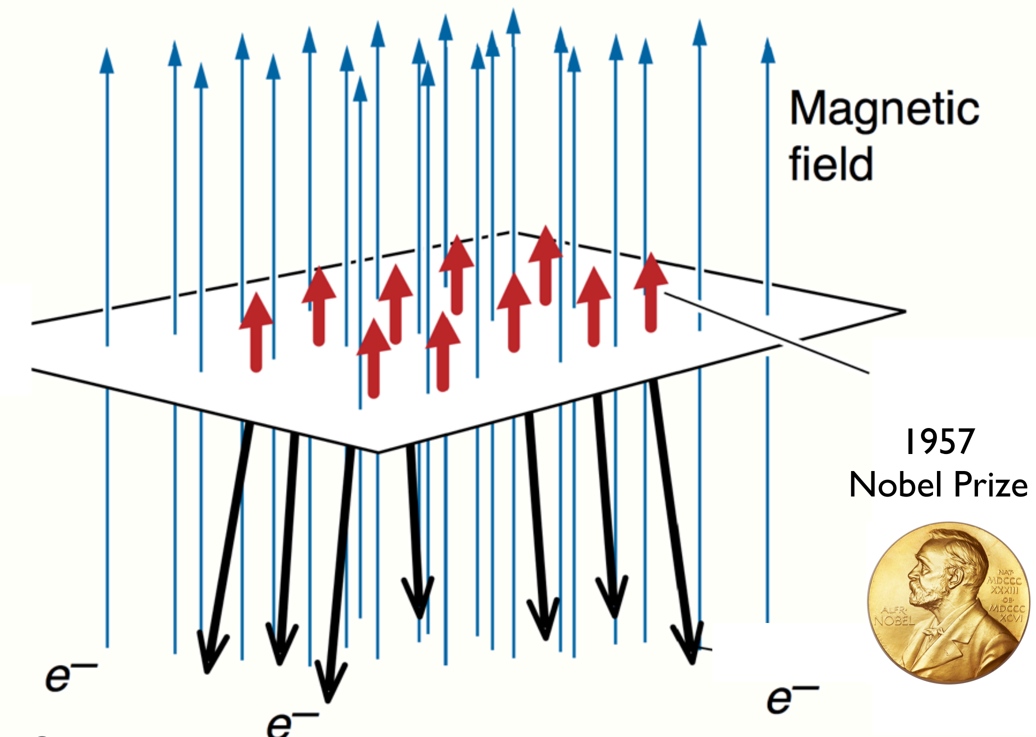
Results:

A reactor-power-dependent signal was observed which was (within 5 percent) in agreement with a cross section for reaction 1 of 6.3×10^{-44} cm².

Science 124, 103 (1956)

1950's: discovery, first cross-section measurement

- Same year: discovery of *maximal* weak parity violation
  - immediate implication: neutrino σ's change by factor 2



1957
Nobel Prize

β decay e⁻ only emitted in lower hemisphere

Phys. Rev. 105, 1413 (1957)

- Few years later, Reines & Cowan:

we find the cross section for fission antineutrino absorption by protons:

$$\bar{\sigma} = 11 \pm 2.6 \times 10^{-44}\ \mathrm{cm}^2/\bar{\nu}$$

This value of the cross section is consistent with predictions based on the two-component theory of the neutrino.[9]

(factor 2 change)

Phys. Rev. 113, 273 (1959)

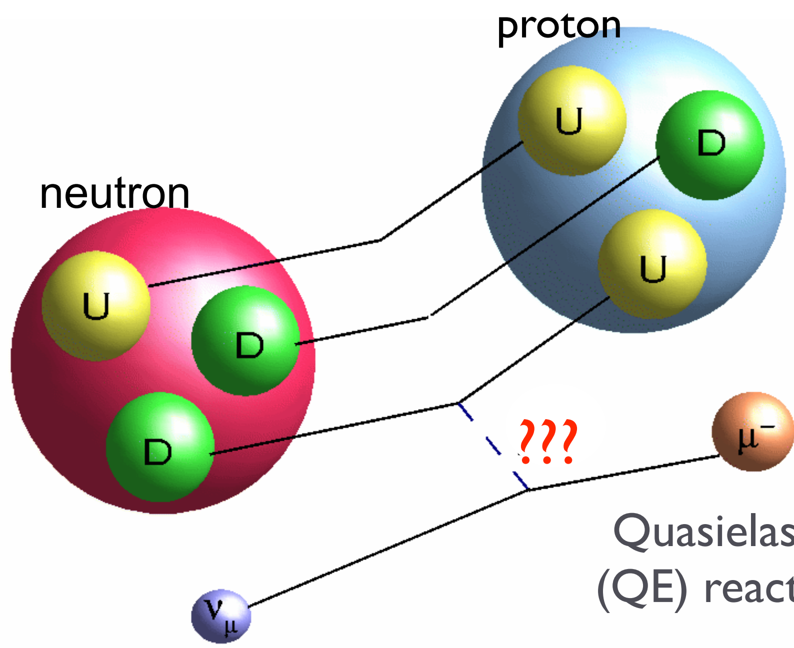
  - Dramatic change due to revised detection efficiency calculation. Hard to imagine *a priori* assumptions weren't involved...

- Field of precision ν cross sections off to an inauspicious start...

1988
Nobel Prize

- Following Lederman *et al.*'s discovery of distinct neutrino states using the first accelerator-based neutrino beam, existing accelerators around the world added studies related to ν interactions to their program

- First and foremost on agenda was to find the weak force carrier
  - unfortunately, only sensitive to m_W < 10 GeV.



Quasielastic (QE) reaction

- Consolation prize: neutrino cross-section physics:

neutrino scattering on "free" targets (H, ^{2}H):

$$\frac{d\sigma}{dQ^2}\left(\begin{array}{c}\nu_l + n \to l^- + p \\ \bar{\nu}_l + p \to l^+ + n\end{array}\right) = \frac{M^2 {G_F}^2 cos^2\theta_c}{8\pi {E_\nu}^2}\left\{A(Q^2) \pm B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right\}$$

Phys. Rep. 3, 261 (1972)

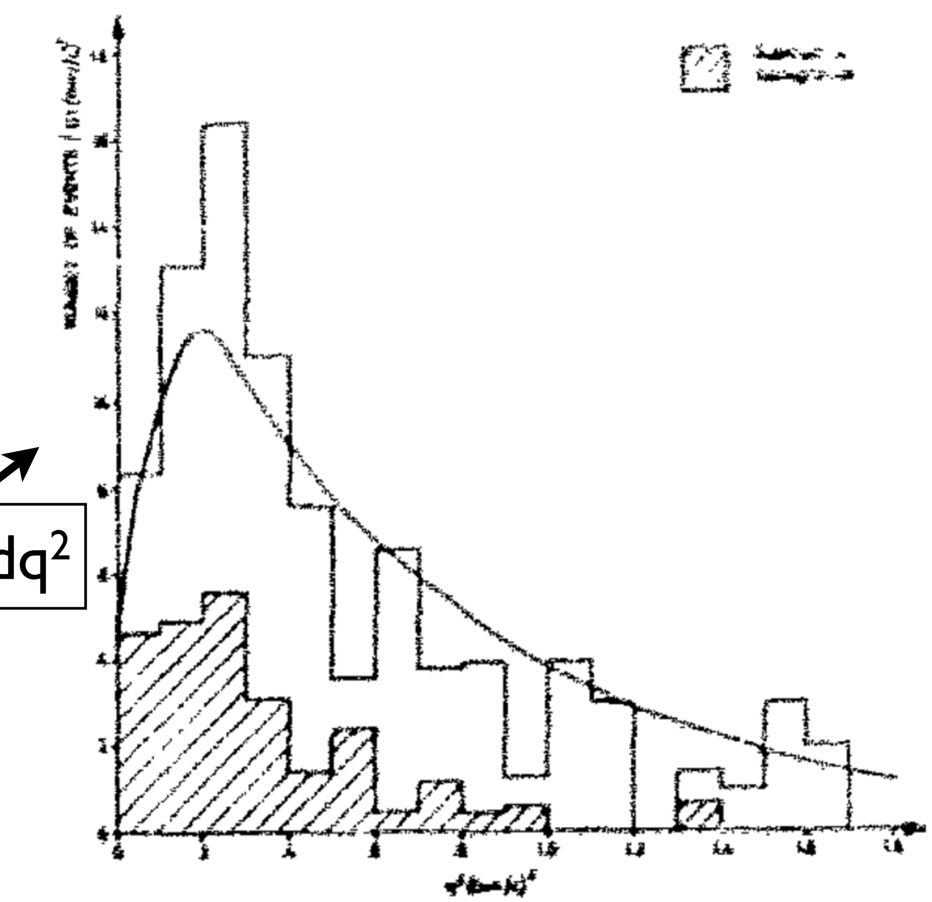
General approach to elastic interactions

$$\frac{d\sigma}{dQ^2}\begin{pmatrix} \nu_l + n \to l^- + p \\ \bar{\nu}_l + p \to l^+ + n \end{pmatrix} = \frac{M^2 G_F{}^2 cos^2\theta_c}{8\pi E_\nu{}^2}\left\{A(Q^2) \pm B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right\}$$

Not-bad historical summary of quasi-elastic analysis technique (1964):

$d\sigma(E_\nu)/dq^2$ can be expressed in terms of the electromagnetic isovector form factors F_1 and F_2, and the axial form factor F_A. Electron scattering experiments are consistent with $F_1 = F_2 = F_V = (1+q^2/M_V{}^2)^{-2}$ with $M_V = 0.84$ GeV. Therefore $d\sigma(E_\nu)/dq^2$ is determined except for F_A. If the parametric form $F_A = (1+q^2/M_A{}^2)^{-2}$ is assumed, M_A can be determined from the experimental data.

This analysis yields $M_A = 1.0^{+0.35}_{-0.20}$ GeV



~dσ/dq^2

q^2

Fig. 2. Corrected four momentum distribution for elastic events with $E_{vis} > 1$ GeV.

Phys. Rev. Lett. 12, 281 (1964)

General approach to elastic interactions

$$\frac{d\sigma}{dQ^2}\begin{pmatrix} \nu_l + n \rightarrow l^- + p \\ \bar{\nu}_l + p \rightarrow l^+ + n \end{pmatrix} = \frac{M^2 {G_F}^2 cos^2\theta_c}{8\pi {E_\nu}^2}\left\{A(Q^2) \pm B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right\}$$

Not-bad historical summary of quasi elastic

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Finally our best thanks to "our scanning girls".

This analysis yields $M_A = 1.0 \begin{smallmatrix} +0.35 \\ -0.20 \end{smallmatrix}$ GeV

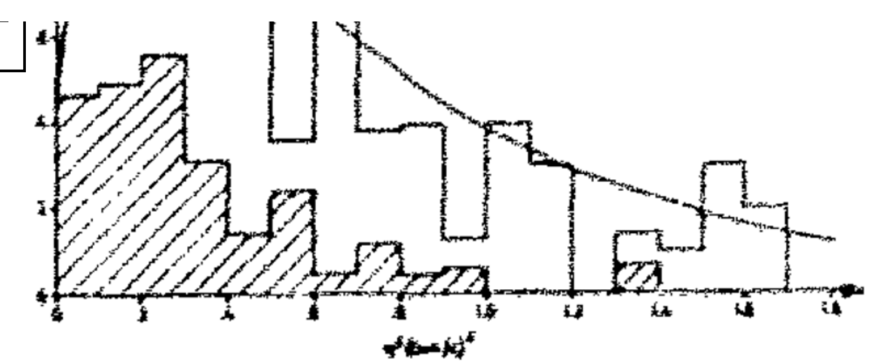


Fig. 2. Corrected four momentum distribution for elastic events with $E_{vis} > 1$ GeV.

q^2

Phys. Rev. Lett. 12, 281 (1964)

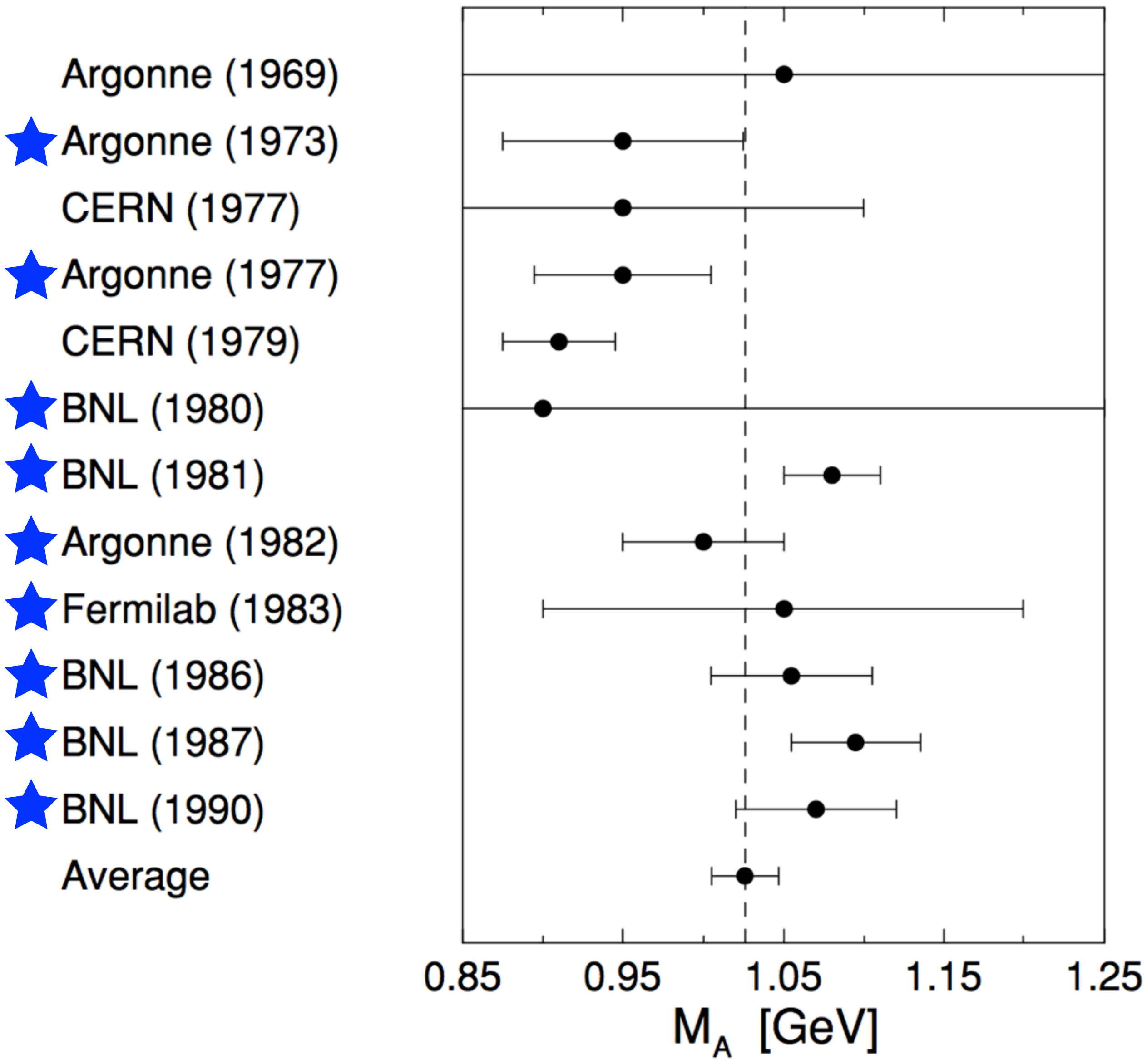
Measuring M_A

- M_A measured for decades in ν scattering on mostly Z = 1 targets

★ H or ^{2}H

- Global average to these data find M_A = 1.03 ± 0.02 GeV
  - values driven by light-target expt's

- With discovery of ν oscillations (1998), suddenly require nuclear targets to get higher rates needed to nail osc. physics

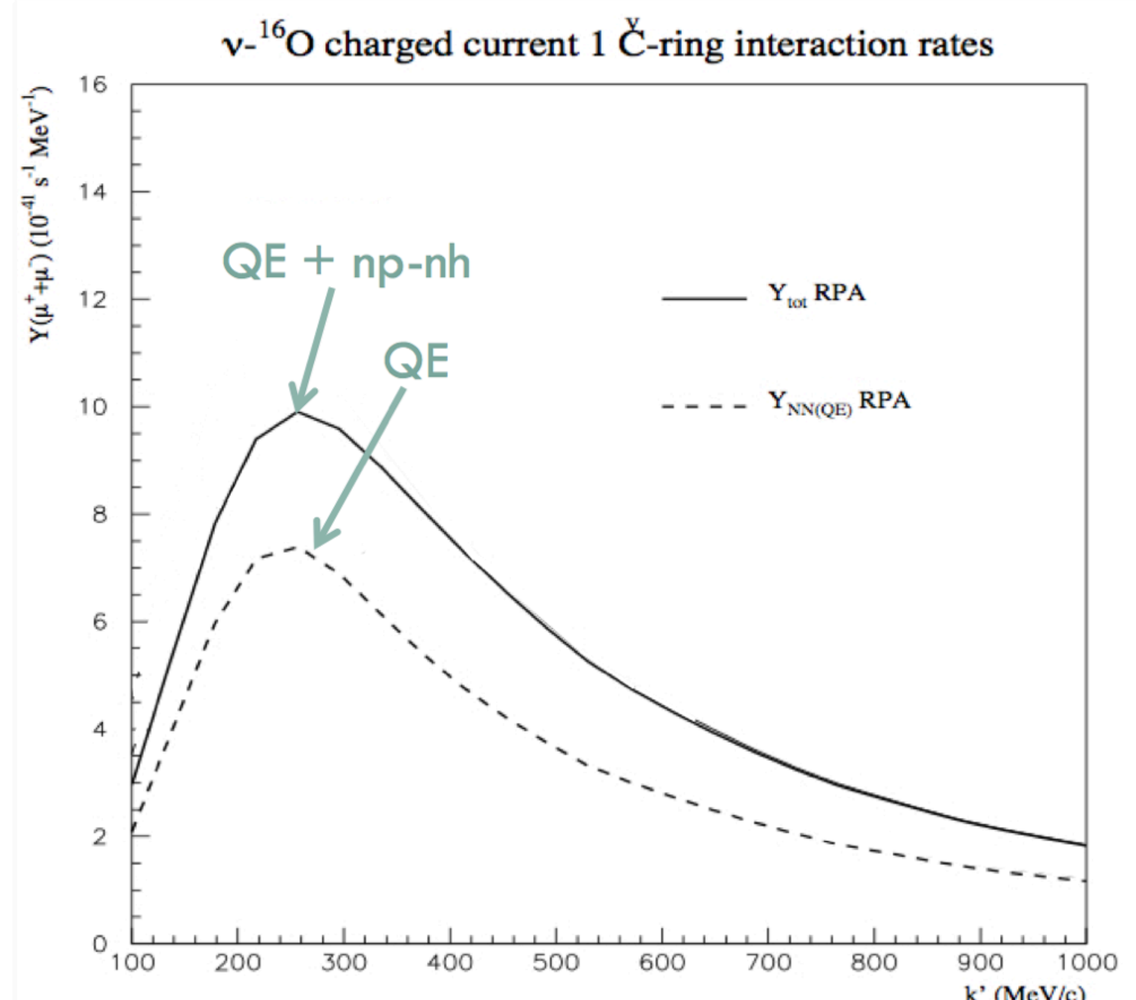


J. Phys. G: Nucl. Part. Phys. 28 R1

1999 forewarning

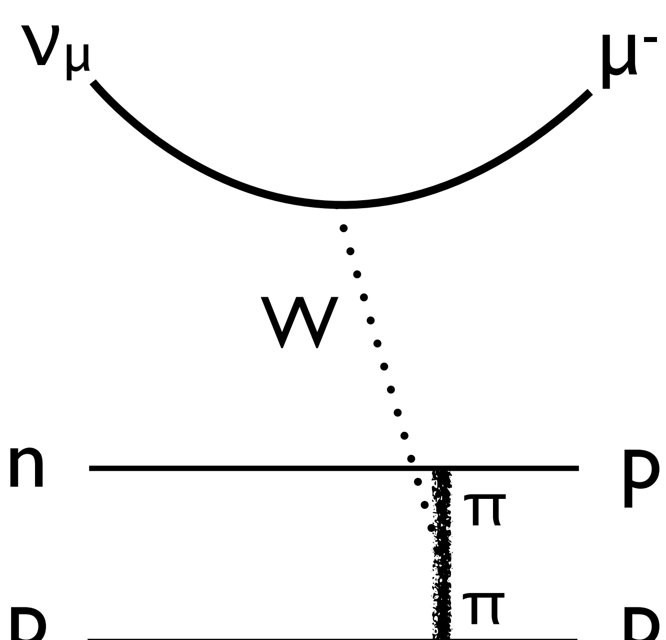
- Prompted by Super-K experiment: quasielastic (QE) scattering in nuclear environment could produce sizable yield increase

> we see an enhacement of the total yield with respect to the free quasi-elastic around 20 %. This result points out the importance of a good evaluation of such neutrino induced *np-nh* excitations.



Eur. Phys. J. A5, 183 (1999)

- These *types* of interactions could be responsible:



- Hints also present in electron scattering data

Phys. Rev. C65, 024002 (2002); Phys. Rev. C38, 1801 (1988)

- *Should have seen this coming*

1999 forewarning

- Promp
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good
excit

Experiment	Target	Cut in Q^2 [GeV^2]	$M_A [GeV]$
K2K[4]	oxygen	$Q^2 > 0.2$	1.2 ± 0.12
K2K[5]	carbon	$Q^2 > 0.2$	1.14 ± 0.11
MINOS[6]	iron	no cut	1.19 ± 0.17
MINOS[6]	iron	$Q^2 > 0.2$	1.26 ± 0.17
MiniBooNE[7]	carbon	no cut	1.35 ± 0.17
MiniBooNE[7]	carbon	$Q^2 > 0.25$	1.27 ± 0.14
NOMAD[8]	carbon	no cut	1.07 ± 0.07

TABLE I. Recent M_A measurements

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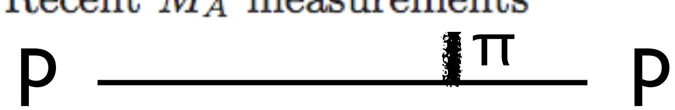
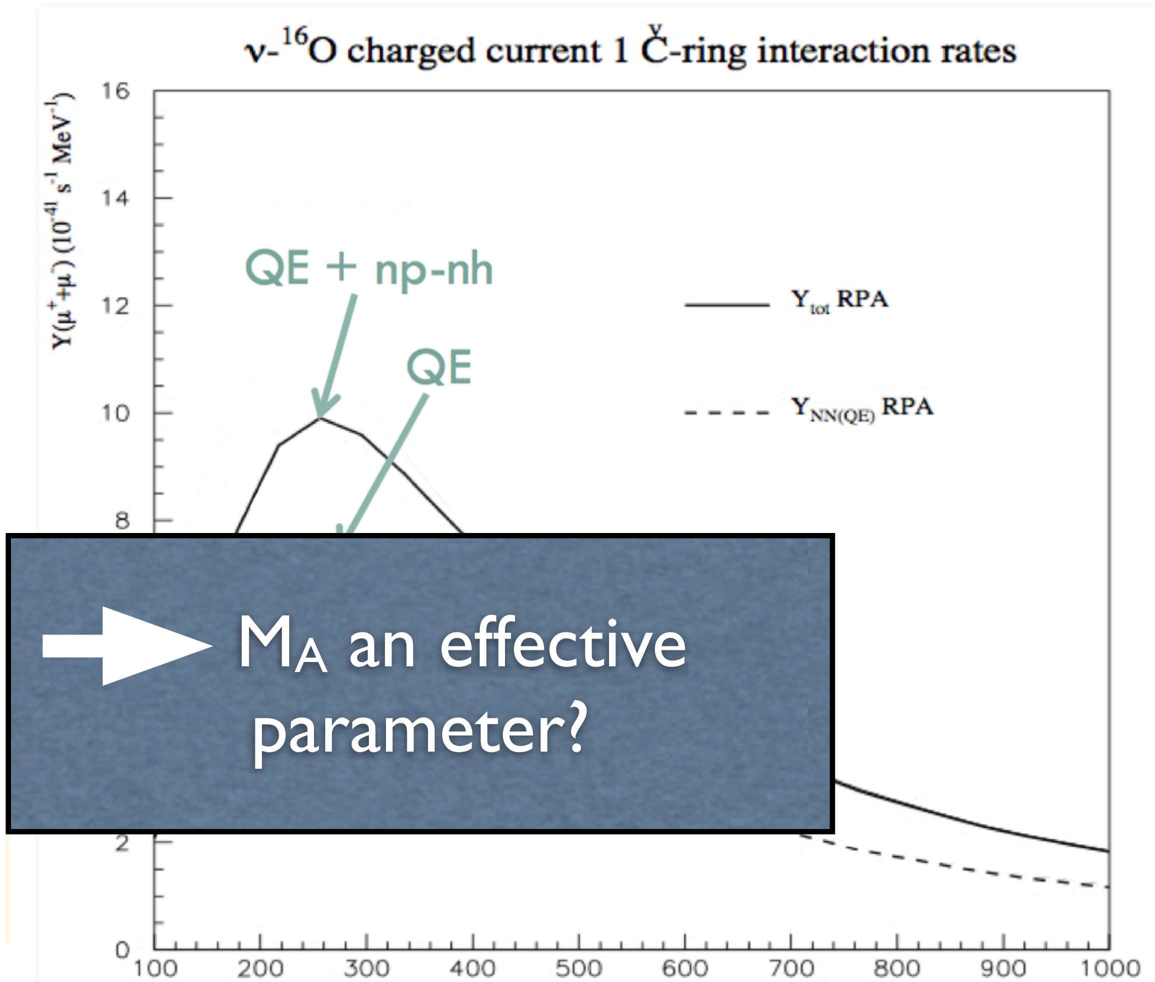




M_A an effective parameter?

Eur. Phys. J. A5, 183 (1999)

- Hints also present in electron scattering data

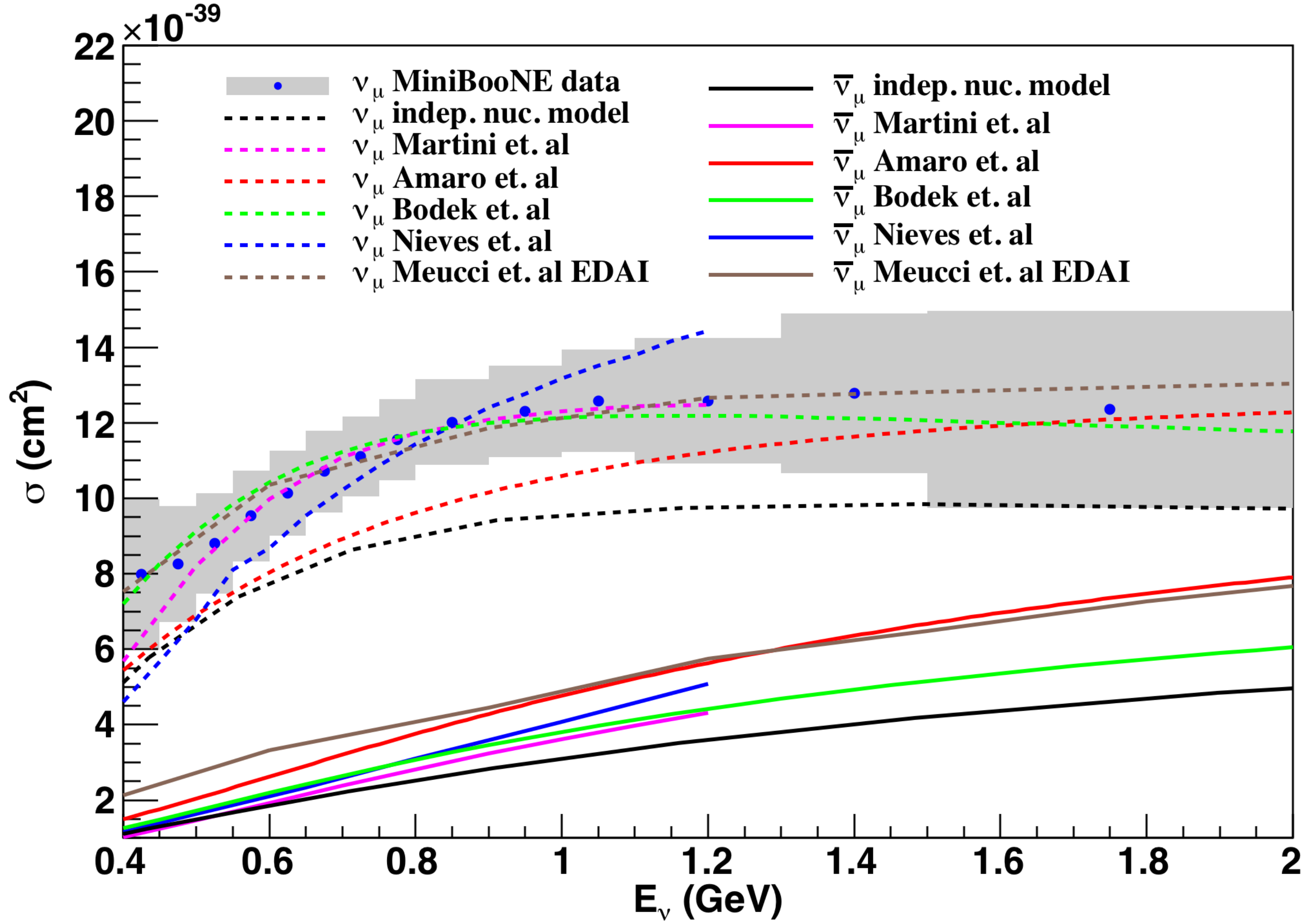
Phys. Rev. C65, 024002 (2002); Phys. Rev. C38, 1801 (1988)

- *Should have seen this coming*

MiniBooNE in 2008

- Confirmation from independent groups that *something like* the np-nh interactions can account for observed enhancement

- Strong test of the underlying physics available with anti-neutrinos
  - probes a different mix of axial, vector σ pieces. How might this new process contribute to anti-neutrino CCQE in MiniBooNE?
  - $\bar{\nu}_\mu$ predictions differ by as much as factor of two!



Growing theoretical field

- Intense theoretical activity (*hundreds* of papers) in last five years on this topic. Incomplete list:
  - Butkevich, arXiv:1204.3160
  - Lalakulich *et al.*, arXiv:1203.2935
  - Mosel, arXiv:1204.2269, 1111.1732
  - Barbaro *et al.*, arXiv:1110.4739
  - Giusti *et al.*, arXiv:1110.4005
  - Meloni *et al.*, arXiv:1203.3335, 1110.1004
  - Martini *et al.*, arXiv:1202.4745, 1110.0221, 1110.5895, Phys. Rev **C81**, 045502 (2010)
  - Paz, arXiv:1109.5708
  - Sobczyk, arXiv:1201.3673, 1109.1081, 1201.3673
  - Nieves *et al.*, arXiv:1204.5404, 1106.5374, 1110.1200, Phys. Rev. **C83**, 045501 (2011)
  - Bodek *et al.*, arXiv:1106.0340
  - Amaro, *et al.*, arXiv:1112.2123, 1104.5446, 1012.4265, Phys. Lett **B696**, 151 (2011)
  - Antonov, *et al.*, arXiv:1104.0125
  - Benhar, *et al.*, arXiv:1012.2032, 1103.0987, 1110.1835
  - Meucci *et al.*, arXiv:1202.4312, Phys. Rev. **C83**, 064614 (2011)
  - Ankowski *et al.*, Phys. Rev. **C83**, 054616 (2011)
  - Alvarez-Ruso, arXiv:1012.3871
  - Martinez *et al.*, Phys. Lett **B697**, 477 (2011)

Dedicated bi-annual conference series, numerous workshops, online forum, etc.

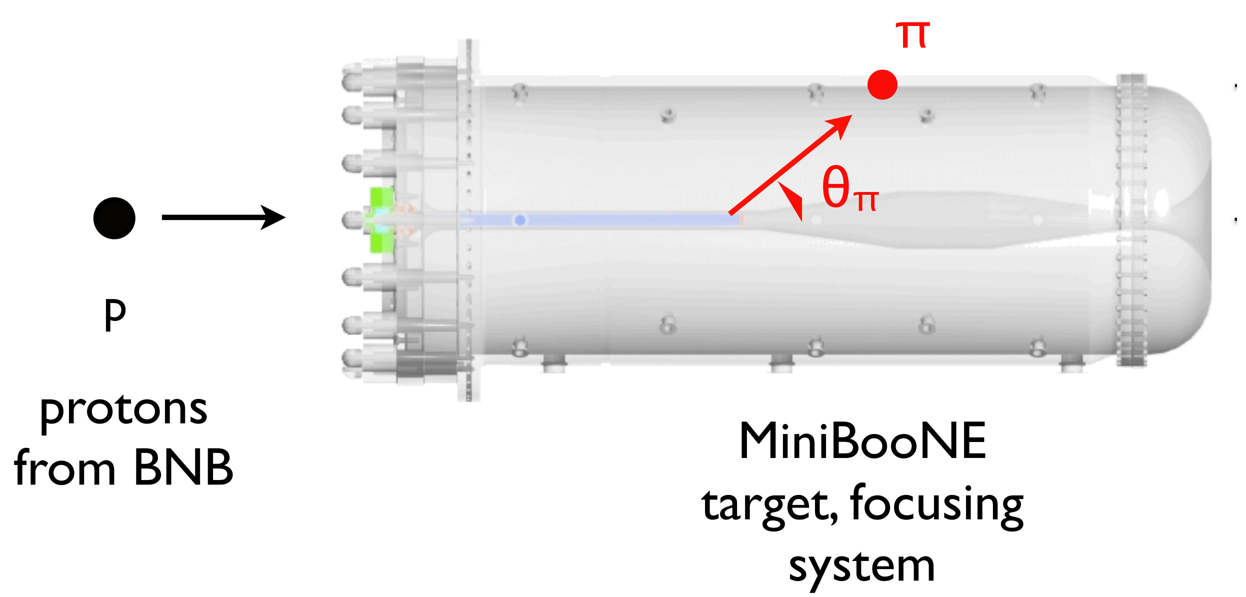
- From first detection towards precision measurements of oscillatory and intranuclear behavior

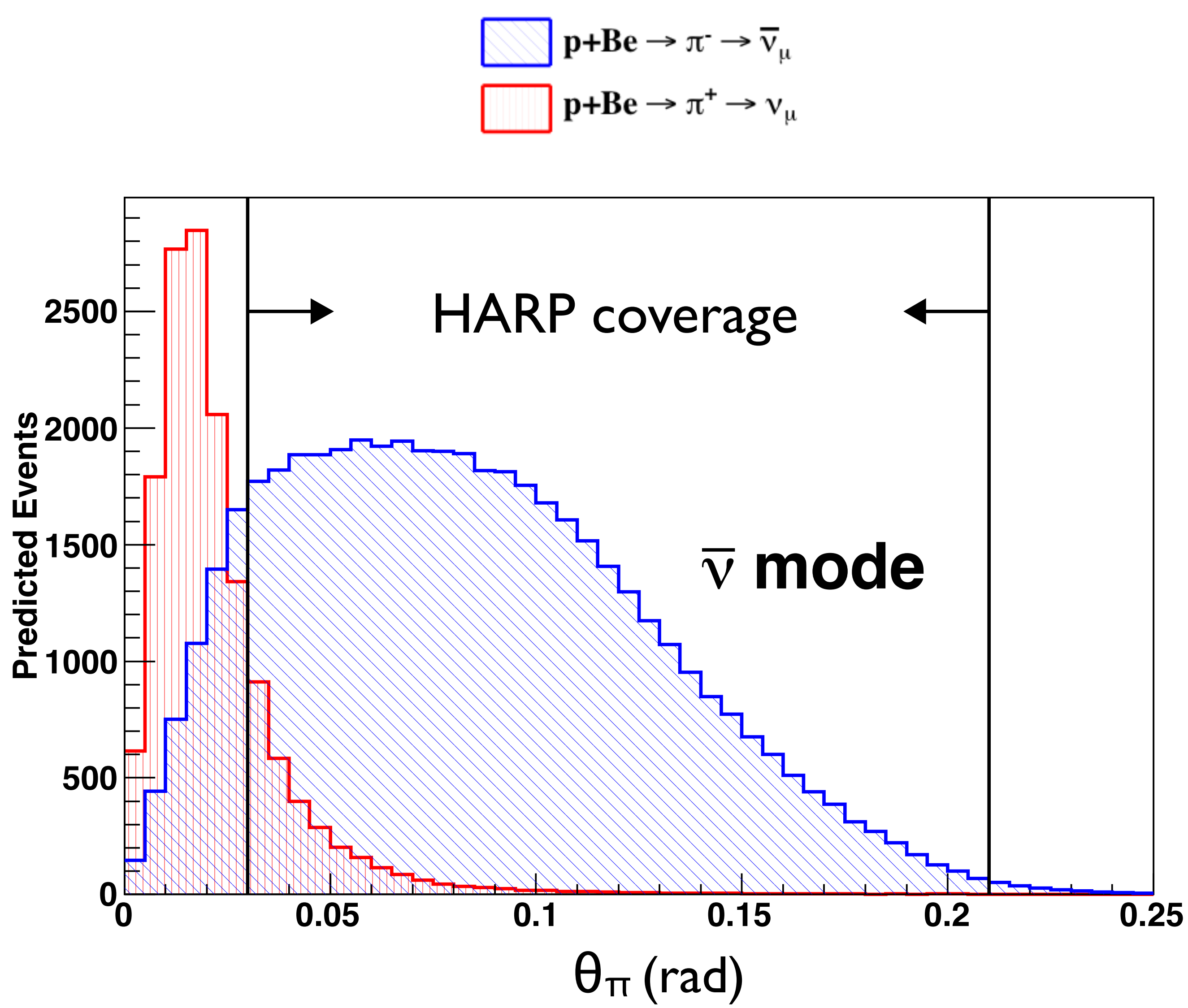
- Nudging the field along with MiniBooNE antineutrinos
  - large A-dependent enhancements?
  - separating ν from $\bar{\nu}$ without magnets
  - topological cross sections

- Forward

Background complications

- Flip horn polarity to focus antineutrinos towards MiniBooNE.
- Immediate complication: ν_μ parent π^+ production ("wrong signs") mostly not constrained by dedicated HARP hadroproduction data
  - overall rate highly uncertain





Strategies

- Other detectors employ magnetic field to separate CC ν_μ / $\bar{\nu}_\mu$
  - MiniBooNE unmagnetized, must use statistical techniques

- Never done before, had to get creative. General strategy: exploit asymmetries between ν_μ, $\bar{\nu}_\mu$ interactions in the detector.

- Executed three complementary measurements based on:
  1. ν_μ CCπ^+ sample (exploits π^- nuclear capture)

$$\nu_\mu + N \rightarrow \overset{\checkmark}{\mu}{}^- N \overset{\checkmark}{\pi}{}^+ \qquad \bar{\nu}_\mu + N \rightarrow \overset{\checkmark}{\mu}{}^+ N \overset{\times}{\pi}{}^-$$

$\checkmark$: observed

$\times$: lost

  2. μ-only and μ+e rates (exploits ~8% μ^- nuclear capture)

$$\overset{\checkmark}{\mu}{}^- \overset{\times}{\rightarrow} e^- \nu\nu \qquad \overset{\checkmark}{\mu}{}^+ \rightarrow \overset{\checkmark}{e}{}^+ \nu\nu$$

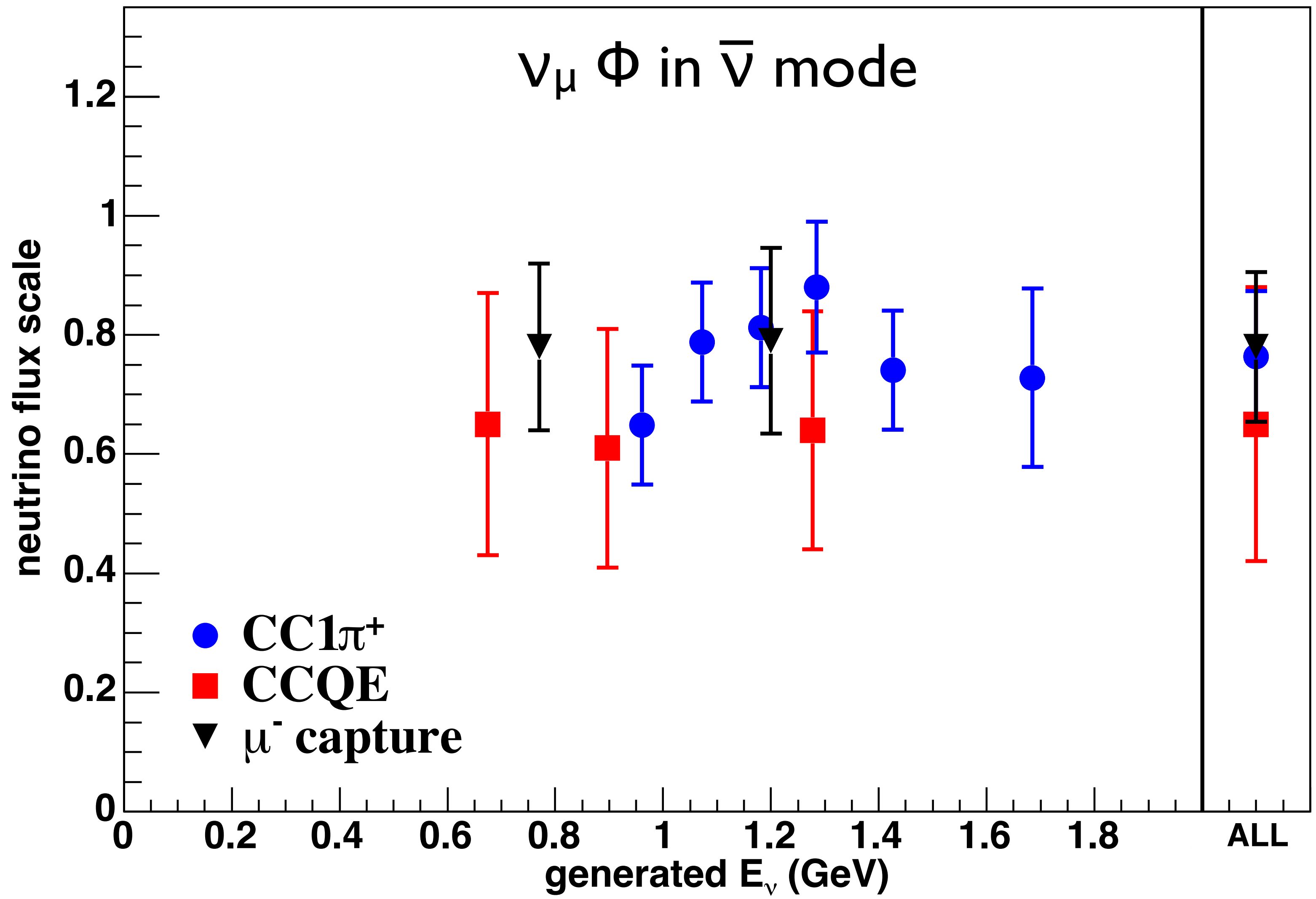
  3. backward scattering region in CCQE sample (dominated by ν_μ)

$\nu_\mu/\bar{\nu}_\mu$ separation results

- Analyses binned in energy as finely as allowed by statistics

Phys. Rev. D84 072005 (2011)

- First demonstration of charge separation in non-magnetized environment
- ν_μ contamination in $\bar{\nu}$ mode measured to < 15%. Not bad for no magnetic field!
- Future FNAL customers?
  - NOνA
  - MINERνA
  - MicroBooNE, LBNE

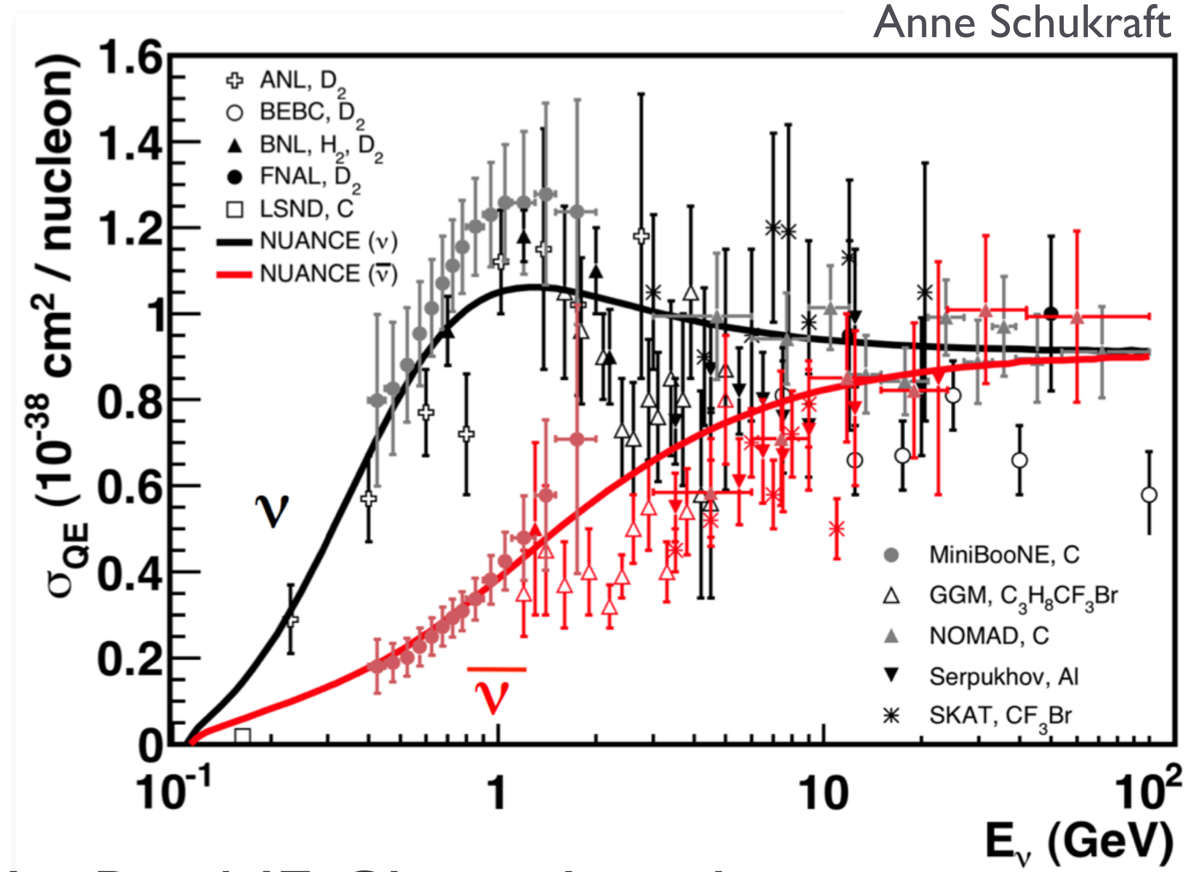


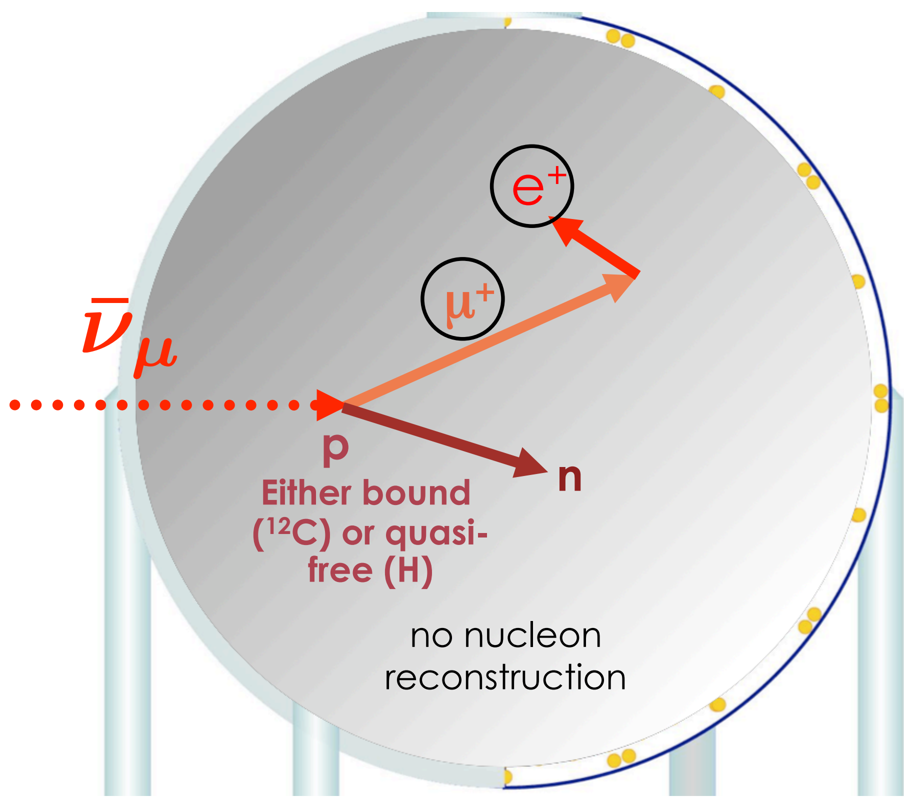
μ^- capture ~75% in argon, almost get event-by-event charge discrimination!

Minimizing exp't biases

- Total cross section $\sigma(E_\nu)$ nice tool to compare historical results, but comes with pitfalls
  - How is QE defined? How do you measure E_ν?
  - Which outgoing particles are measured? Nucleon tracking efficiency?
- Much cleaner to report *what you measure.*

Anne Schukraft





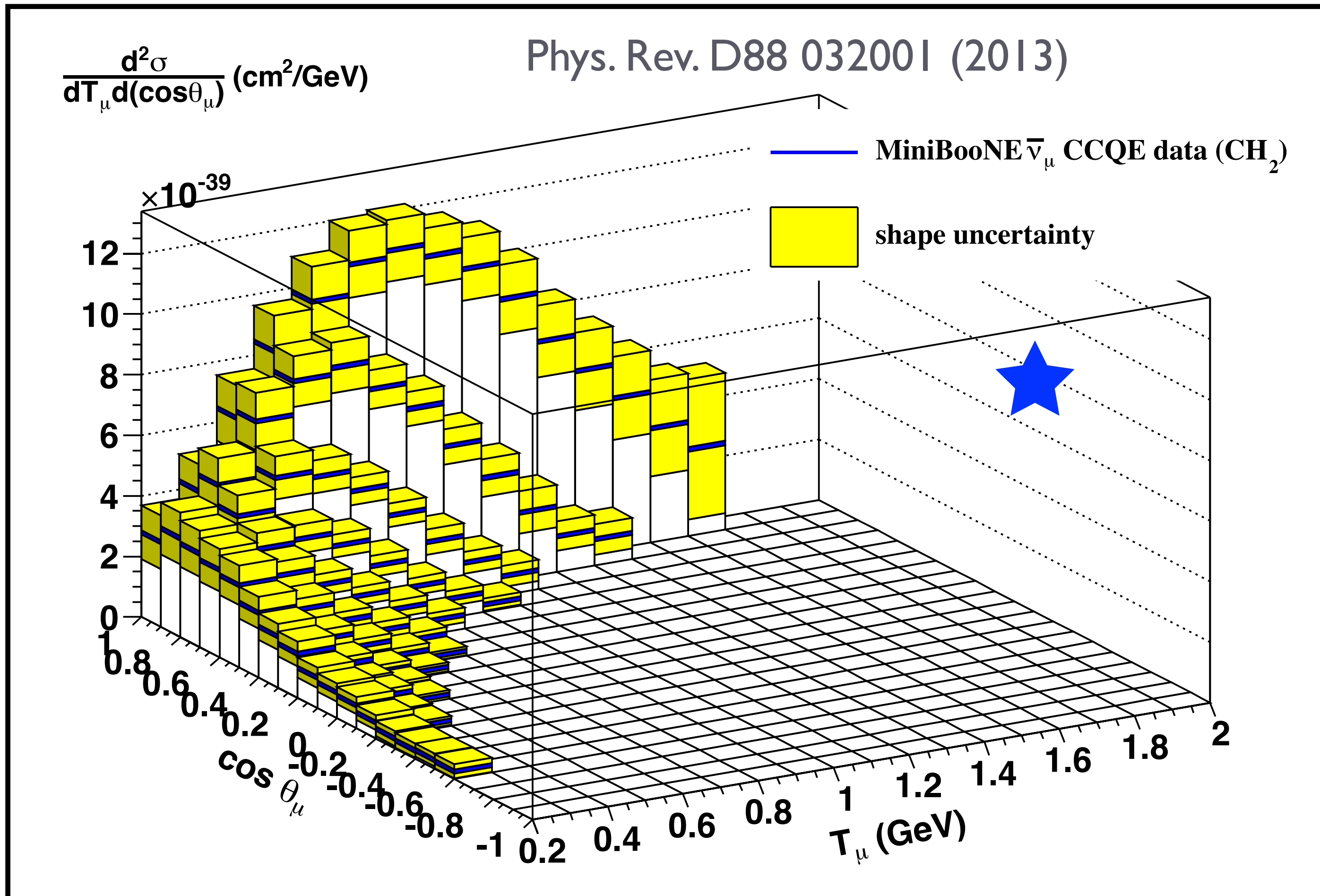
- MiniBooNE Cherenkov detector, exceeds at measuring lepton kinematics.
- $>10^5$ neutrino events recorded by MiniBooNE, must exploit stats

Primary physics result $\dfrac{d^2\sigma}{dT_\mu d\theta_\mu}$

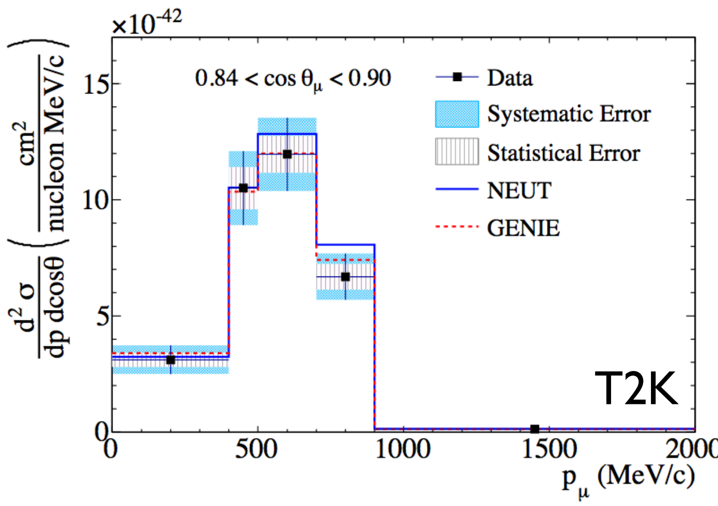
Topological cross sections

- First measurement of antineutrino QE dbl-diff'l cross section (right) small contribution to growing field of topological cross section measurements.

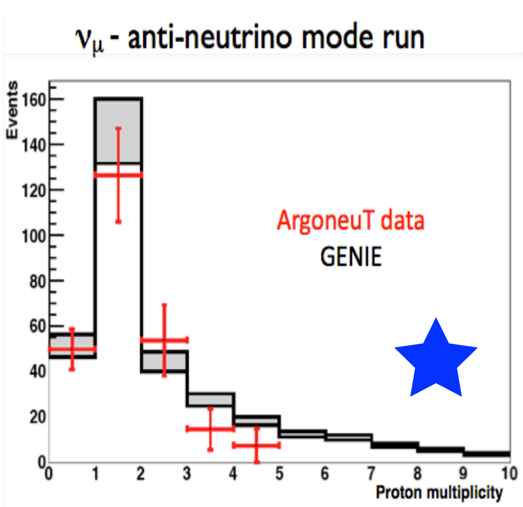
★: FNAL

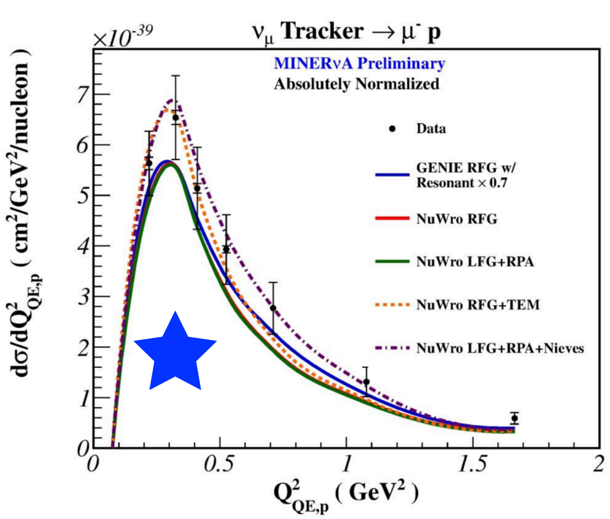


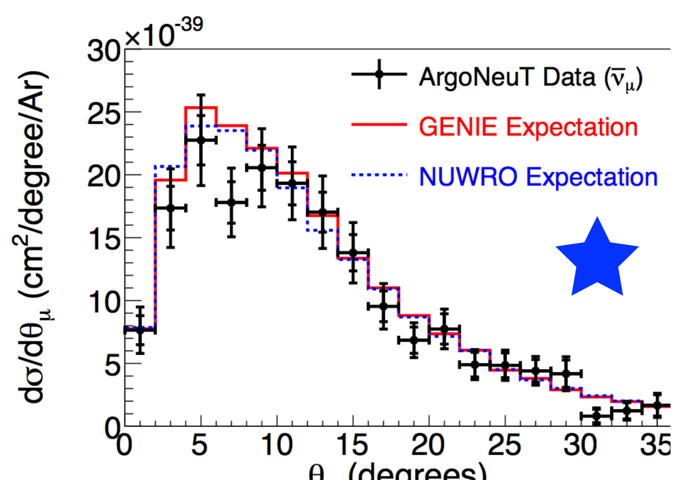
Phys. Rev. D88 032001 (2013)

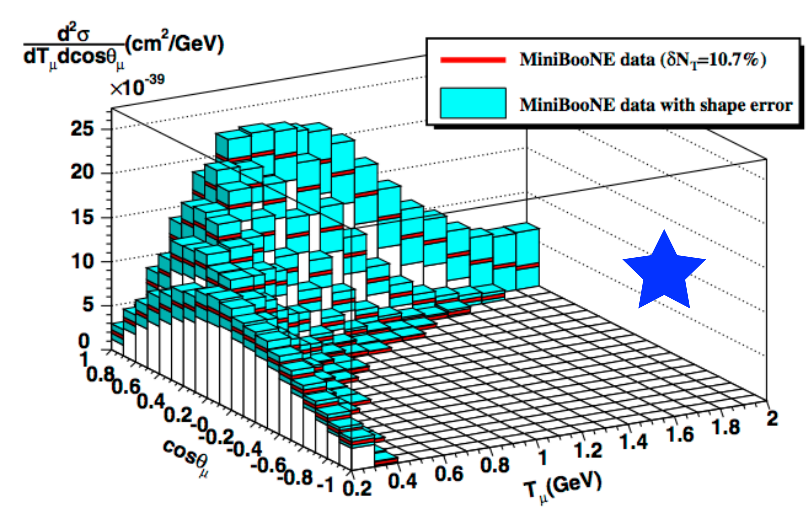


PRD 87, 092003 (2013)









Phys. Rev. D81, 092005 (2010)

K. Partyka thesis (Yale)

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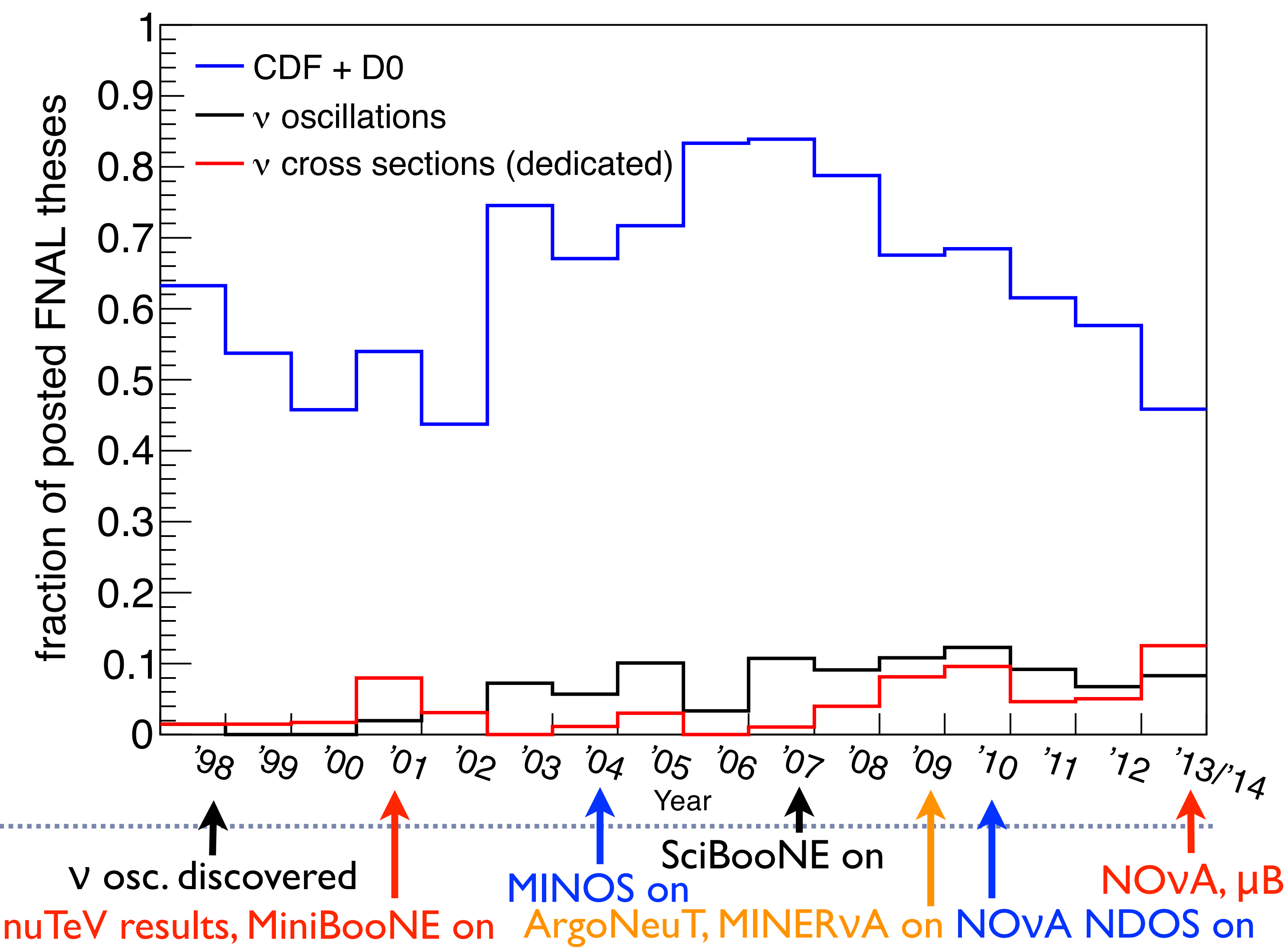
FNAL and ν cross sections

- FNAL hugely invested into ν physics. Primary goal oscillations, along with them many interesting cross-section physics processes will be accessible:
  - Intranuclear behavior ➔ ~10-30% A-dependent yield increase? More outgoing nucleons than expected? Final-state interactions major challenge to disentangle.
  - Inelastic structure functions: EMC effect?
  - Detection of coherent ν-nucleus interactions (largest SM σ yet to be observed!)

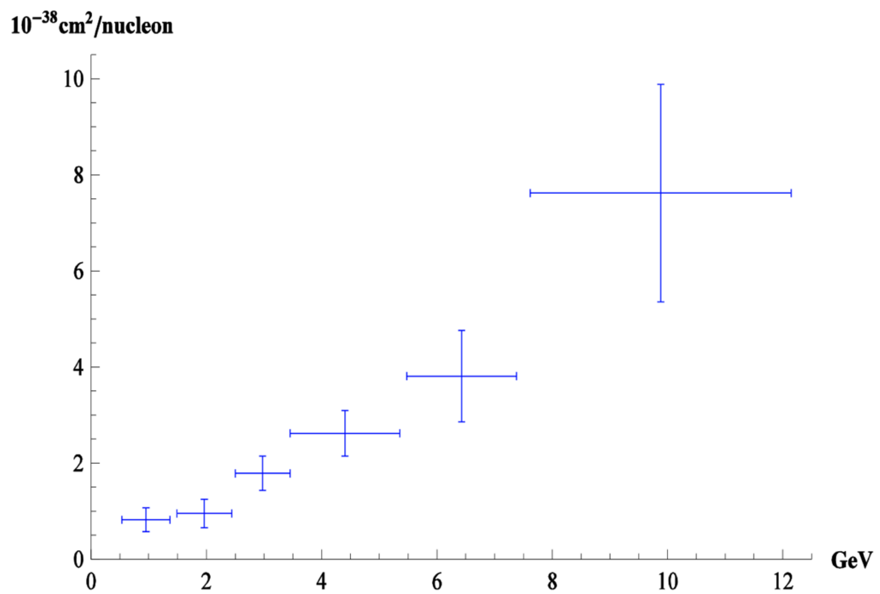
- Distribution of posted FNAL theses over time offers glimpse into how we are training next gen scientists:
  - clear and natural dominance of Tevatron experiments
  - steady growth of neutrino physics, in particular the litany of σ topics available



backup

1964 CERN bubble chamber (500 liters, freon)

- Hand-scan of 459 events, separated into visible energy and by multiplicity
- For W boson search, found 1 event, predicted background also 1 event
  - m_W > 1.8 GeV
- Showed for the first time $\sigma(E_\nu)$ linear with E_ν
  - resolving individual quarks, though discovery some yrs away



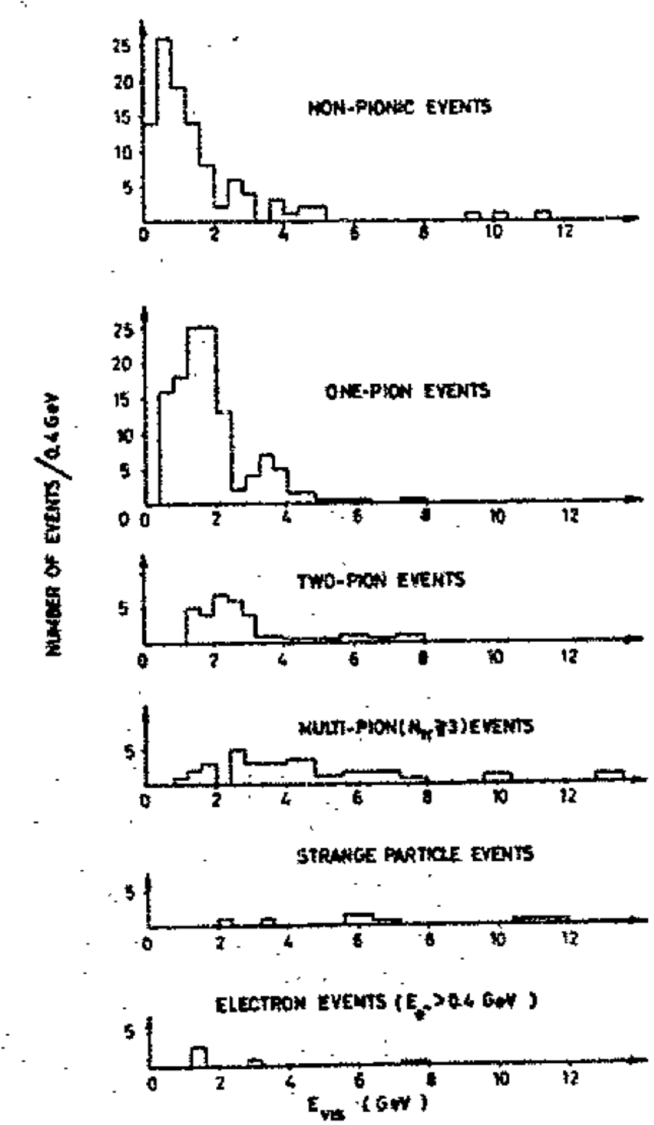
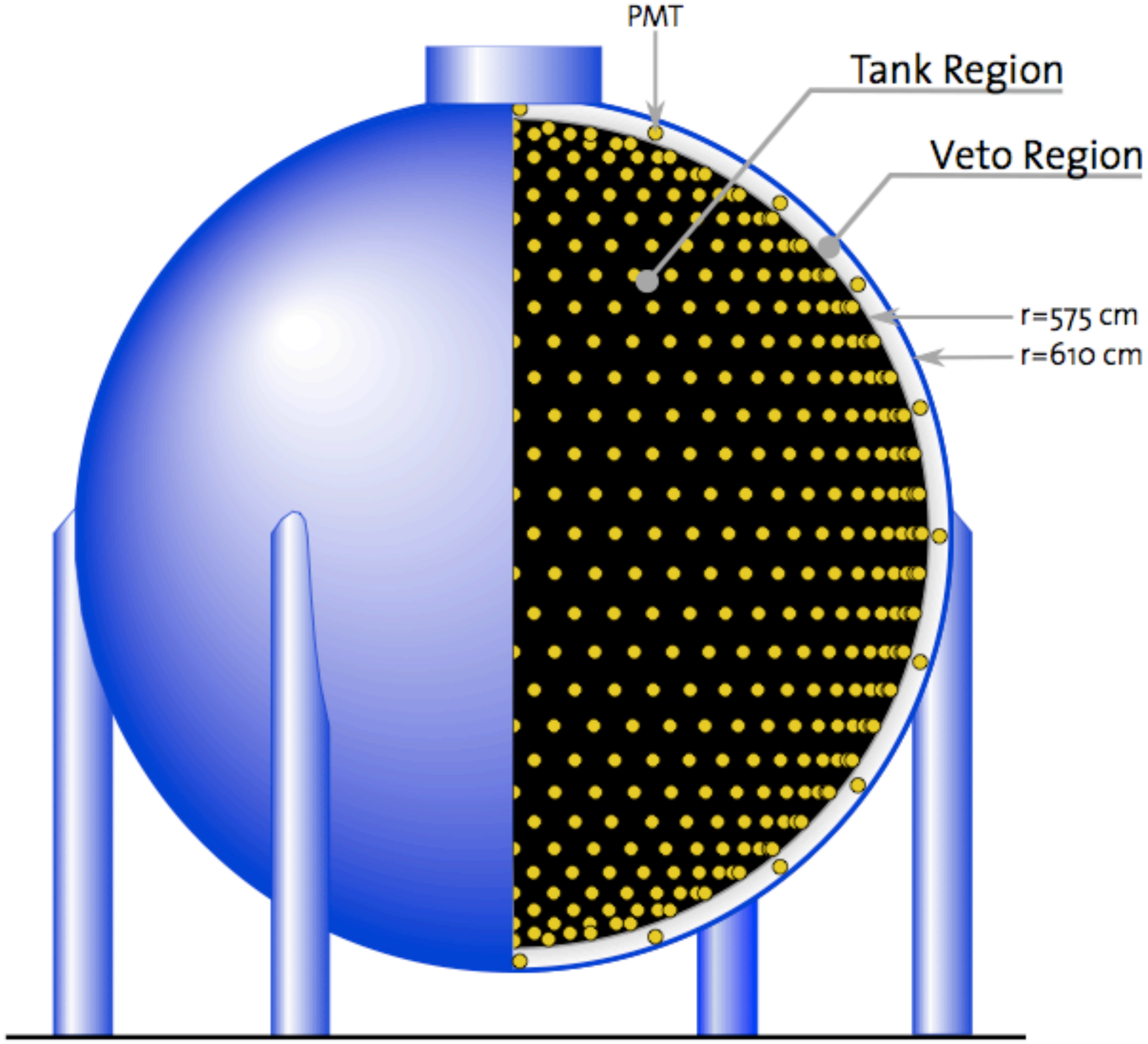


Fig. 1. Visible energy distribution of various event types.

Block *et al.*, Phys. Rev. Lett. 12, 281 (1964)

- Able to peer in better detail to elastic cross sections...

Detector

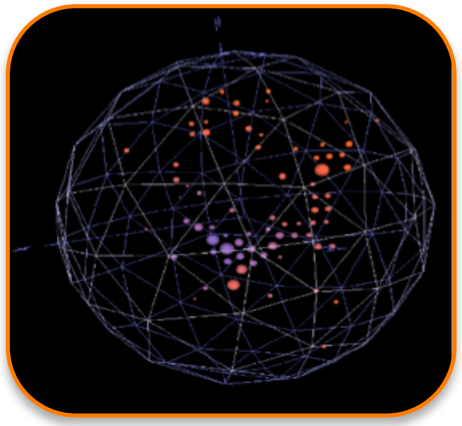


Nucl. Instr. Meth. A599, 28 (2009)

- 6.1m radius sphere houses 800 tons of undoped mineral oil
- Primarily a Cherenkov detector, best at reconstructing leptons

μ candidate

long track, filled-in Cherenkov sig.



e candidate

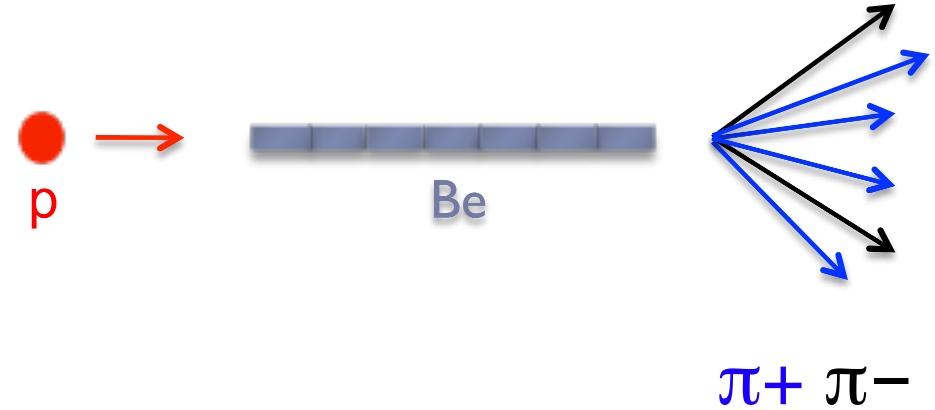
short track, fuzzy Cherenkov sig.

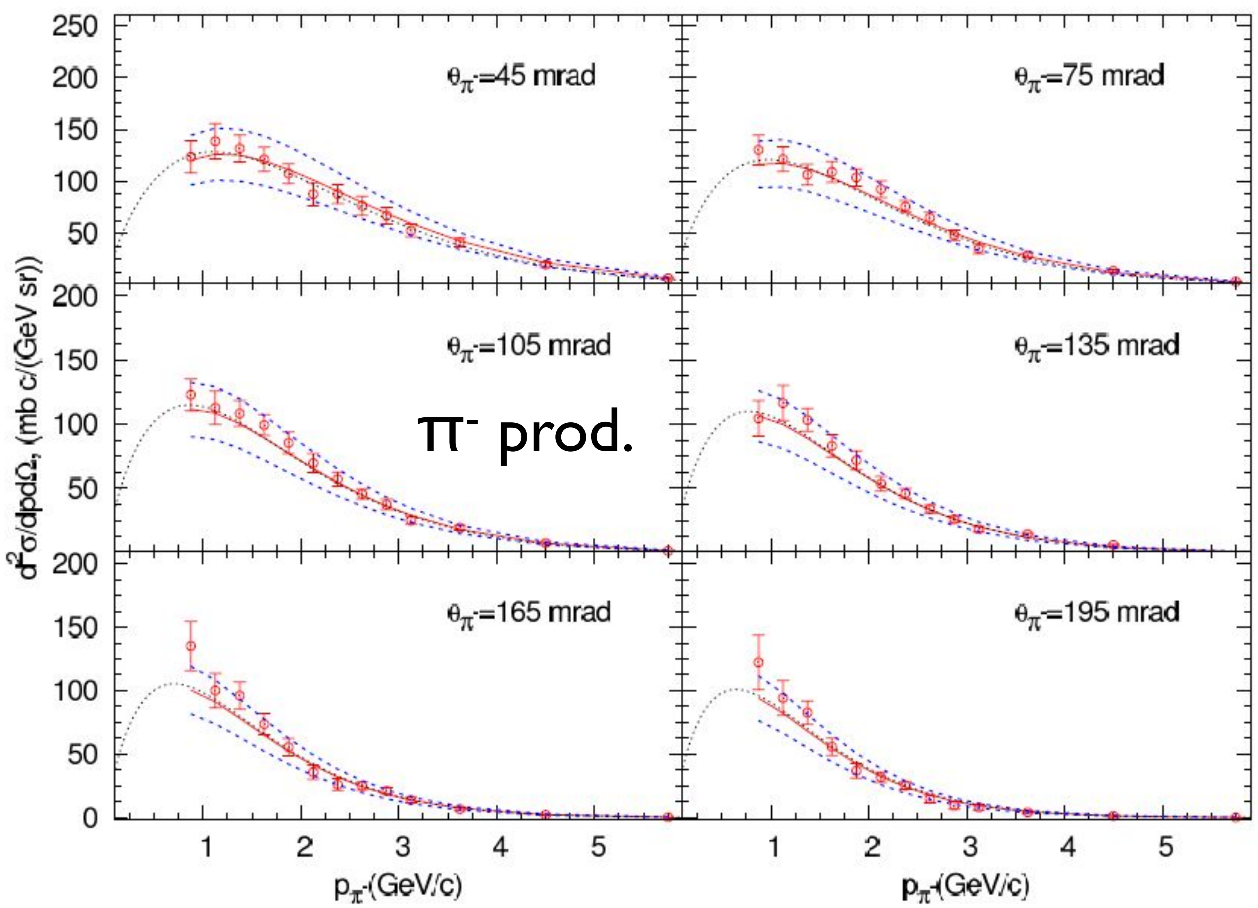
Flux

- With measurements of

$$\frac{d^2\sigma}{dp_\pi d\theta_\pi}(p + \mathrm{Be} \to \pi^\pm + X)$$

can predict ν, anti-ν flux at detector

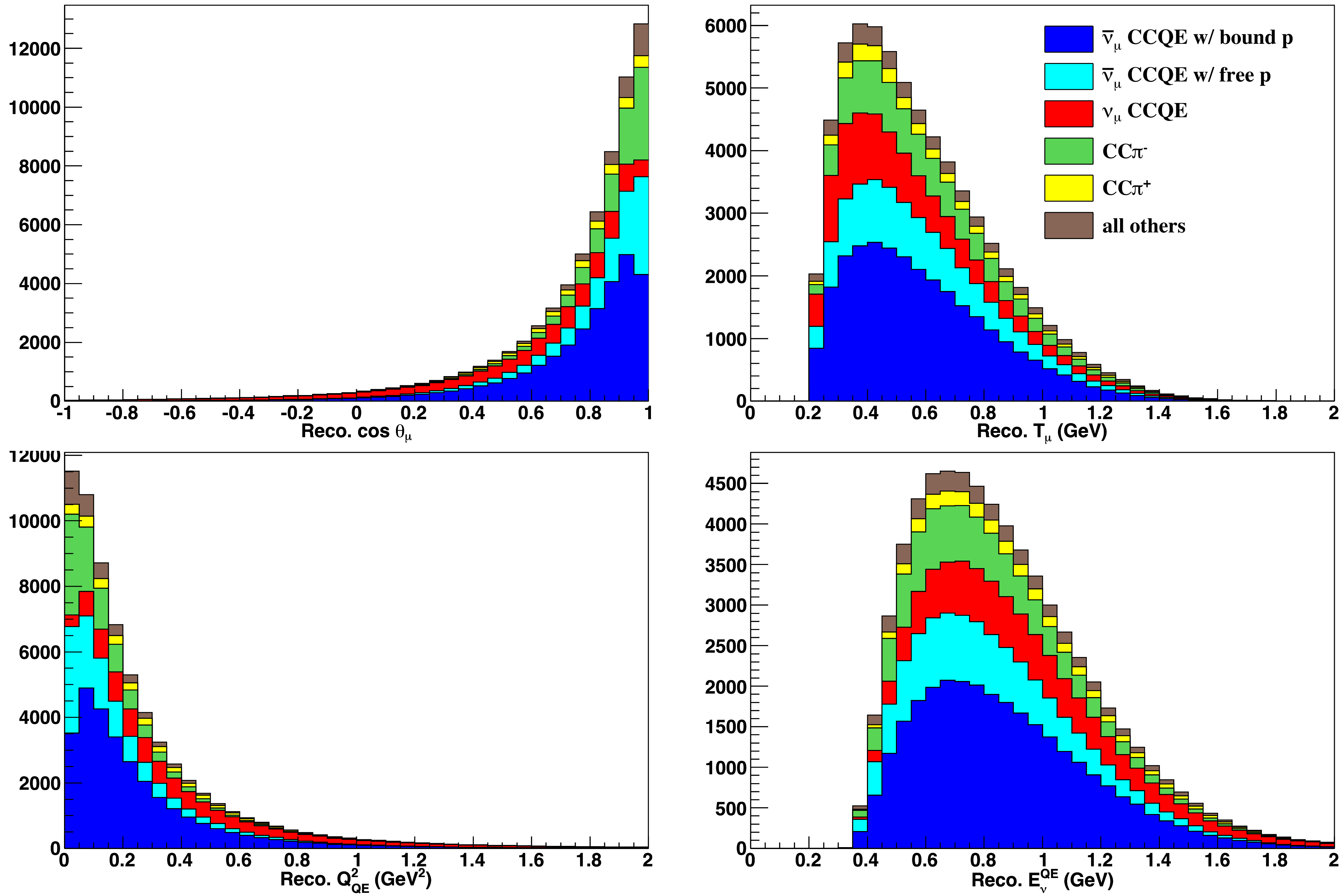




- Dedicated π production data taken by HARP experiment (CERN)
  - "thin target" results used (5% λ), thick target data also taken and actively being analyzed
- Spline fit to these data (along with beamline geometry simulation) brings ν flux uncertainty to ~9%
  - only valid for ν parent π's constrained by these data - important later!
- Absolute Φ knowledge nearly model independent

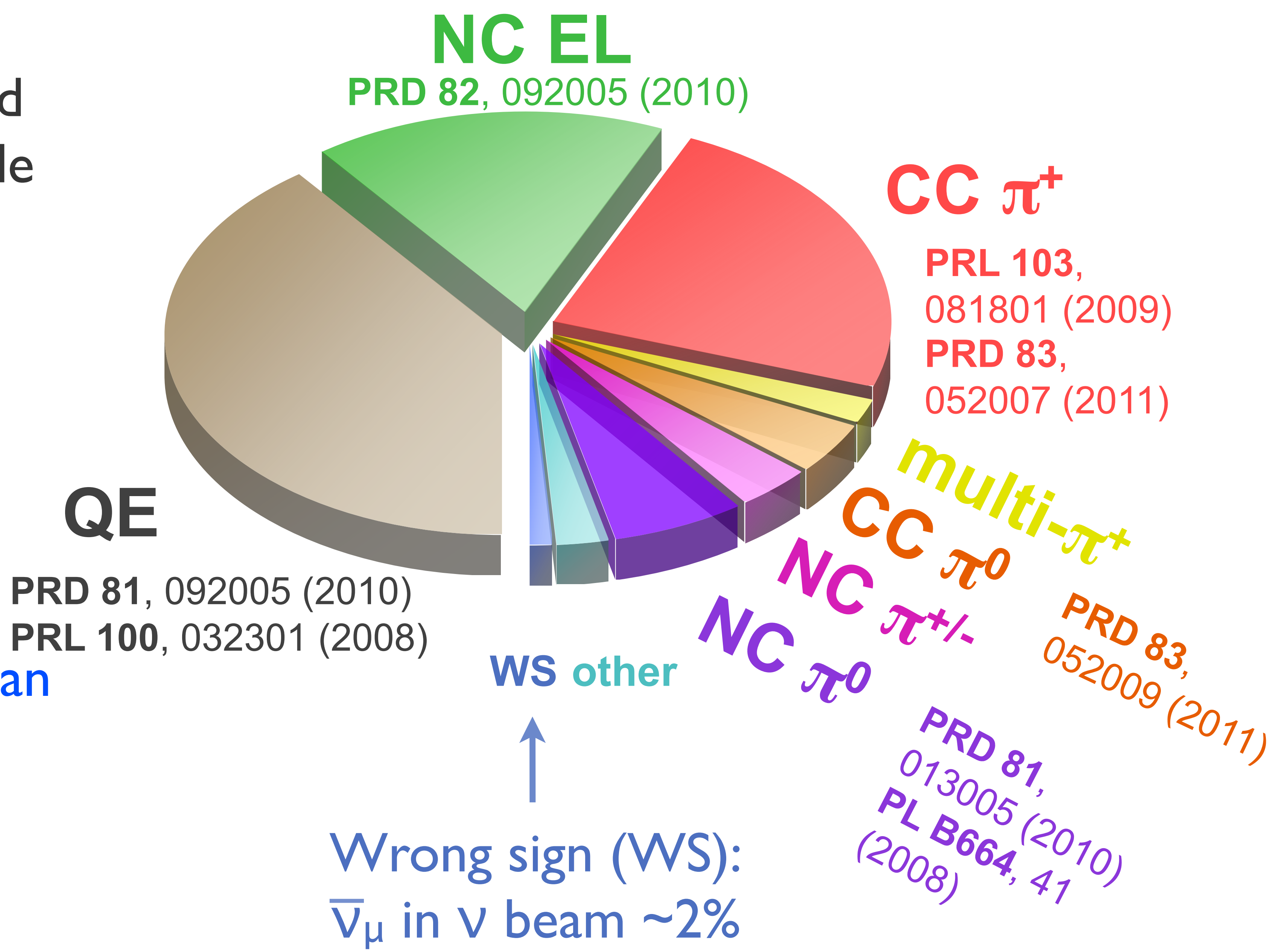
HARP collaboration, Eur. Phys. J. C52 29 (2007)

Sample composition



ν-mode rate

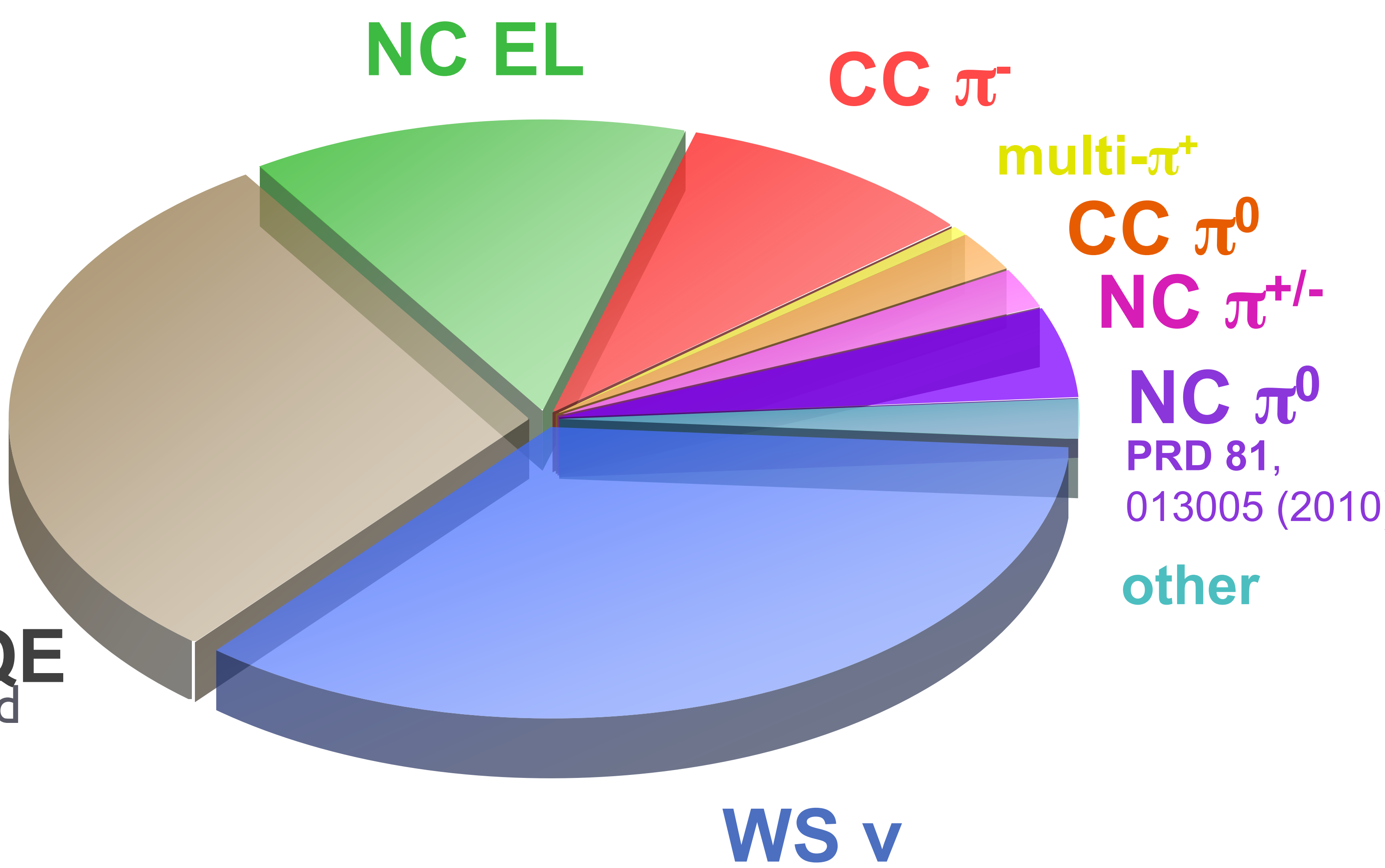
- MiniBooNE has published ~90% of the total ν-mode rate



- Lots of interest: more than 500 citations from these papers in < 4 yrs!

$\bar{\nu}$-mode rate

- Before able to make precision $\bar{\nu}_\mu$ σ's, must deal with largest background: wrong-sign ν_μ



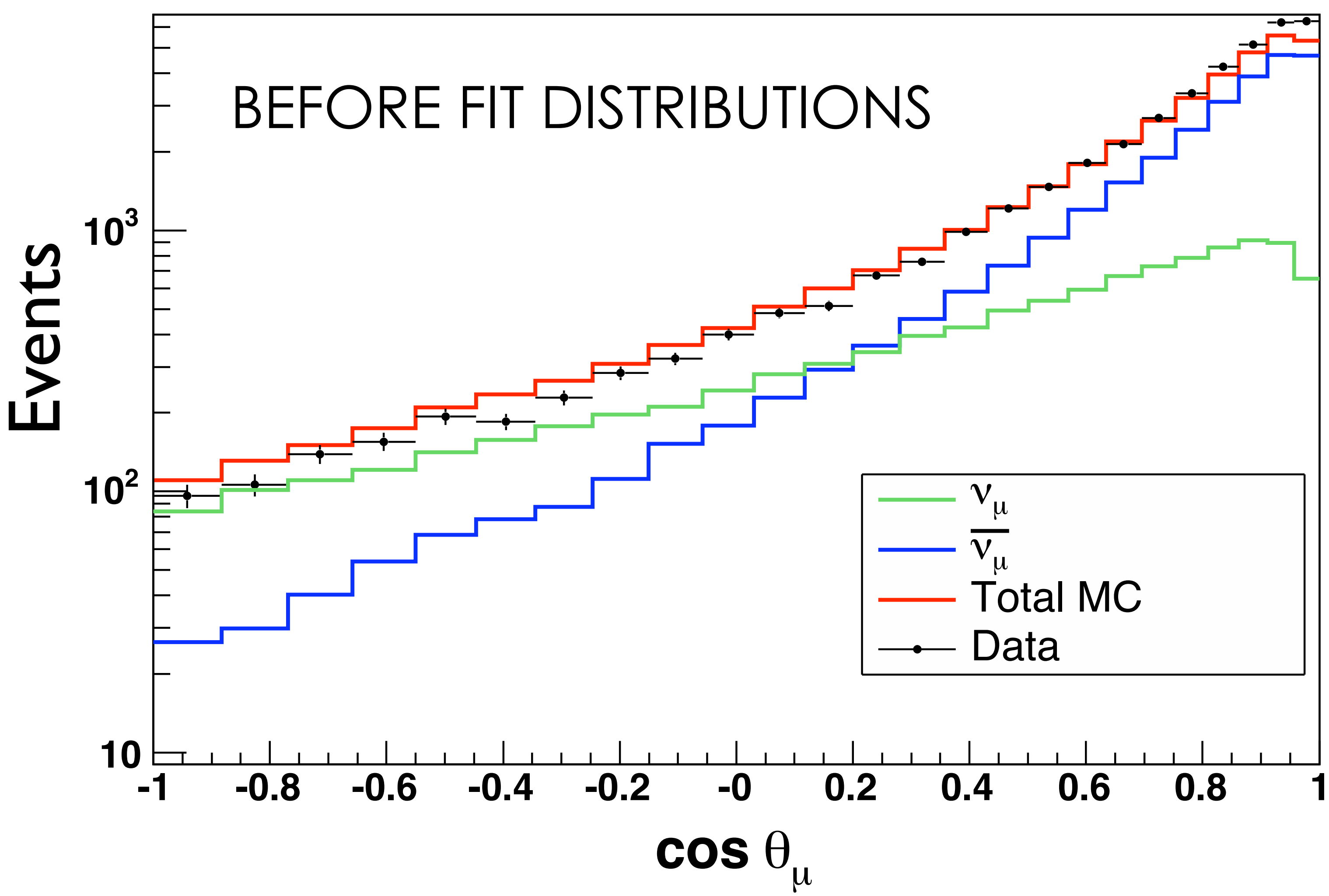
- Unprecedented $\bar{\nu}$ statistics
  - 1.0 x 10[21] POT in an unexplored energy region

PRD 84, 072005 (2011)

Wrong sign:
ν_μ in $\bar{\nu}$ beam ~40%!

CCQE angular fits

- Due to axial-vector interference term in CCQE σ, $\bar{\nu}_\mu$ events expected to be much more forward-going compared to ν_μ
  - perform simple fit to data in reconstructed energy bins



Uncertainties in μ^- capture measurement

TABLE IX: Uncertainty summary for this analysis. Included are the assumed errors on physics processes and their contributions to the total errors in α_ν and $\alpha_{\bar{\nu}}$ in the regions of reconstructed neutrino energy studied. The statistics of the ν-mode data enter the uncertainty from the calibration procedure described in Section IV B.

Source	Fractional uncertainty (%)	Uncertainty contribution to α_ν			Uncertainty contribution to $\alpha_{\bar{\nu}}$		
		$E_\nu^{QE} < 0.9$ GeV	$E_\nu^{QE} \geq 0.9$ GeV	All	$E_\nu^{QE} < 0.9$ GeV	$E_\nu^{QE} \geq 0.9$ GeV	All
$\nu_\mu n \rightarrow \mu^- p$	10	0.07	0.08	0.07	0.00	0.00	0.00
$\bar{\nu}_\mu p \rightarrow \mu^+ n$	20	0.04	0.02	0.03	0.20	0.20	0.21
$\nu_\mu(\bar{\nu}_\mu)N \rightarrow \mu^-(\mu^+)N\pi^+(\pi^-)$	20	0.04	0.05	0.04	0.02	0.02	0.01
$\nu_\mu(\bar{\nu}_\mu)N \rightarrow \nu_\mu(\bar{\nu}_\mu)N$	30	0.00	0.00	0.00	0.00	0.00	0.00
$\nu_\mu(\bar{\nu}_\mu)N \rightarrow \nu_\mu(\bar{\nu}_\mu)N\pi^0$	25	0.02	0.01	0.01	0.01	0.01	0.01
$\nu_\mu(\bar{\nu}_\mu)N \rightarrow \nu_\mu(\bar{\nu}_\mu)N\pi^\pm$	50	0.05	0.02	0.01	0.03	0.03	0.01
μ^- capture	2.8	0.00	0.00	0.00	0.00	0.00	0.00
$\bar{\nu}$-mode statistics	-	0.10	0.11	0.08	0.08	0.08	0.06
ν-mode statistics	-	0.04	0.05	0.04	0.03	0.03	0.03
All	-	**0.14**	**0.16**	**0.12**	**0.22**	**0.22**	**0.22**