

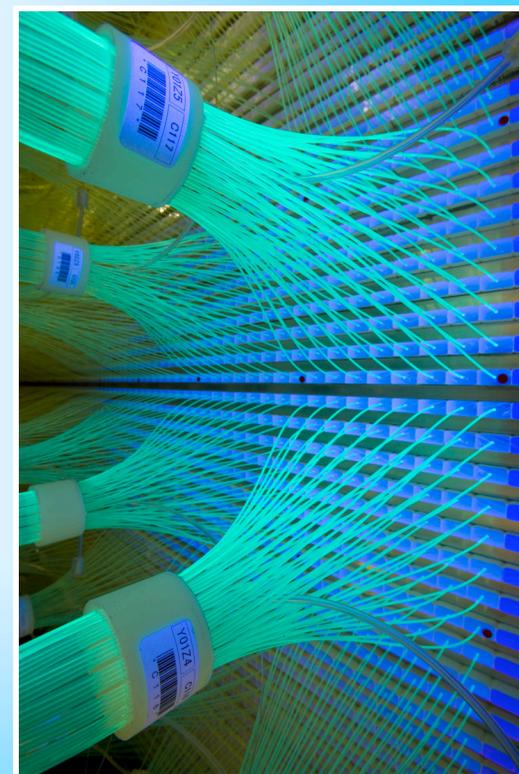
Recent Results from MiniBooNE and SciBooNE



Sam Zeller
LANL

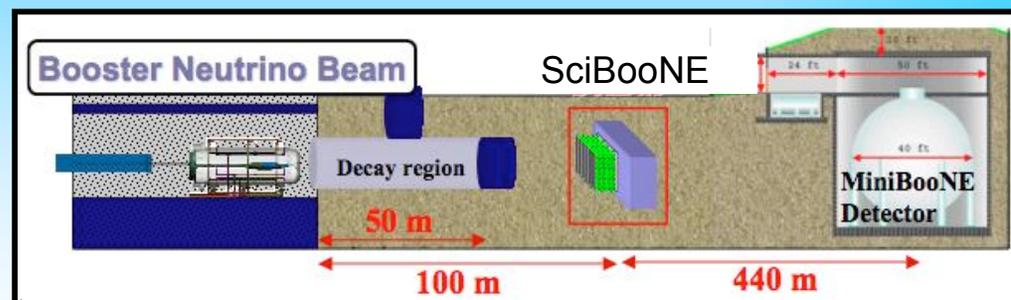
FNAL Users Meeting

June 3, 2009



- will be telling you what's new on the Booster ν beamline at FNAL

Booster ν Experiments

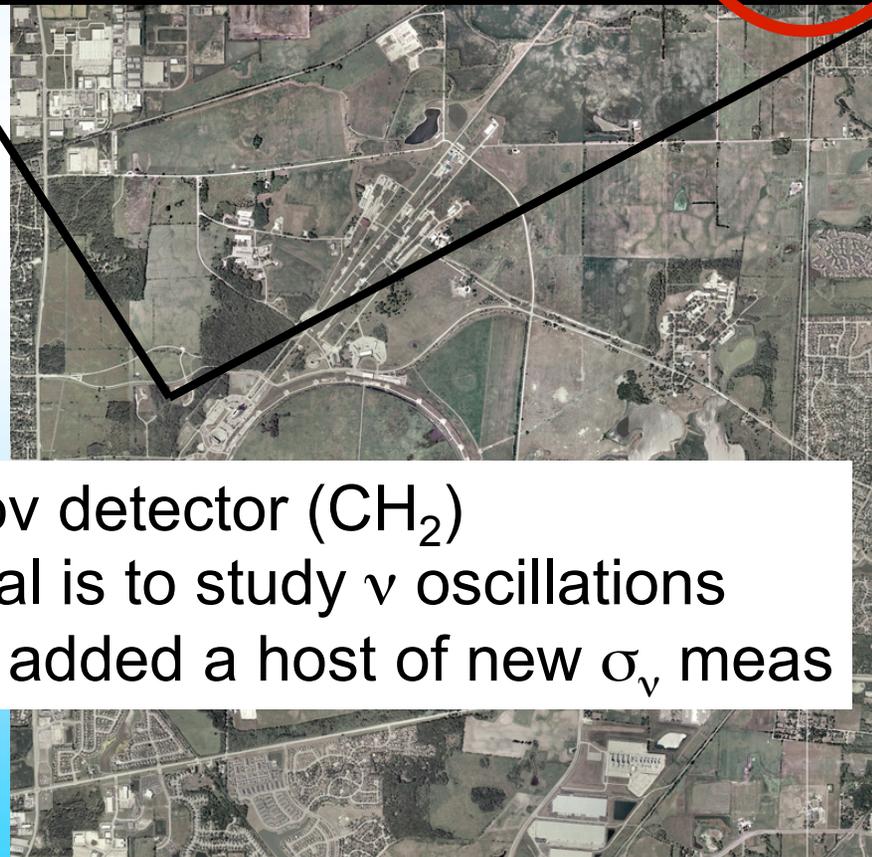
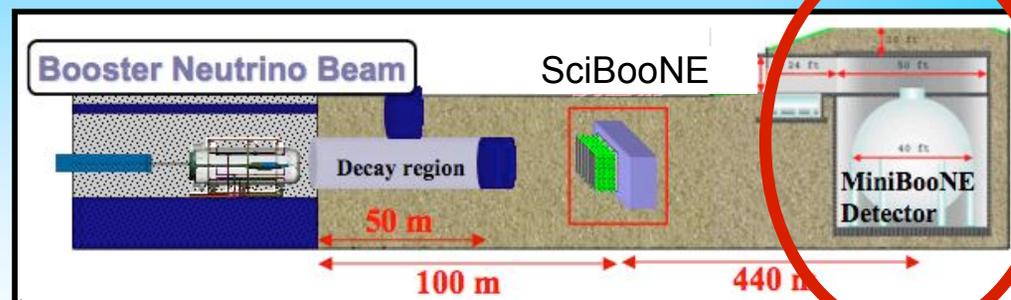


- to remind you of your friends on other side of the ring ...
- two ν experiments make use of 8 GeV Booster beam



Booster ν Experiments

MiniBooNE



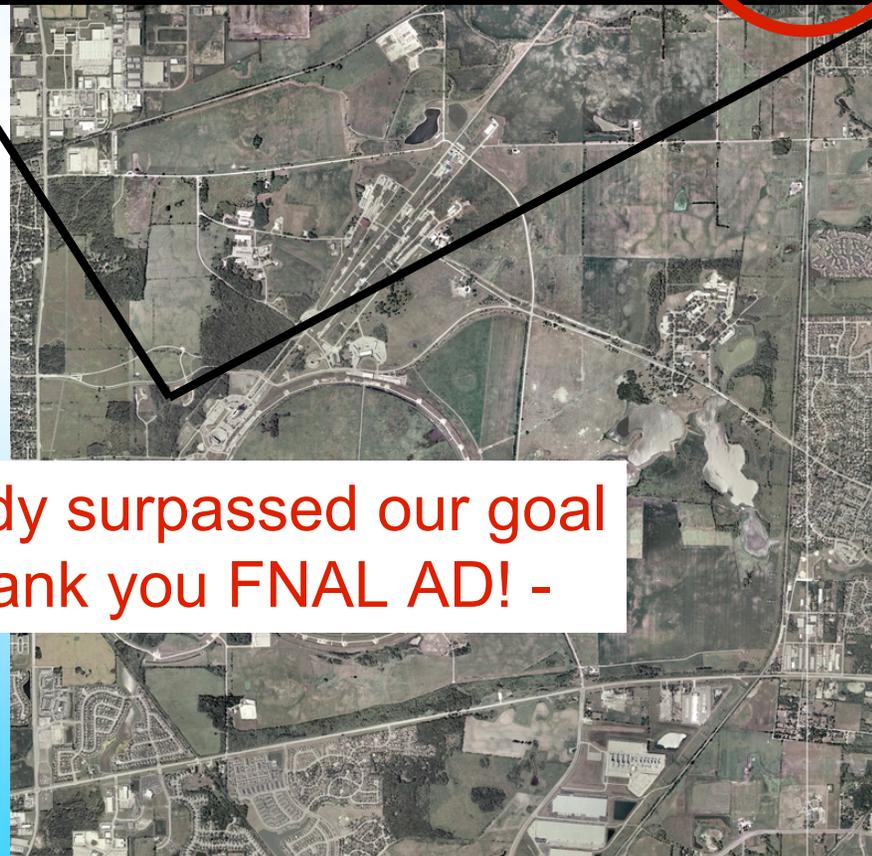
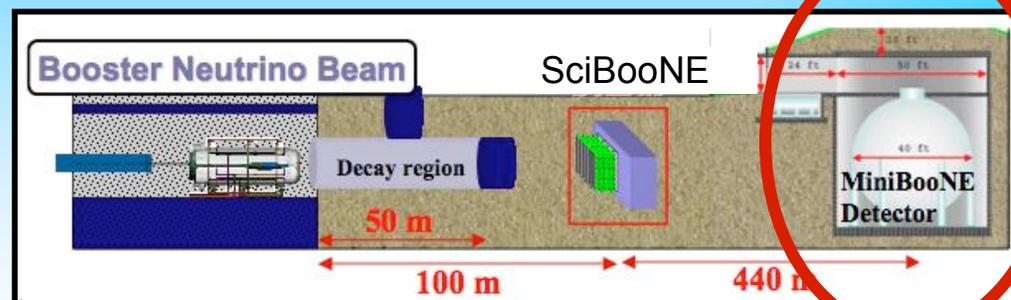
- NIM A599, 28 (2009) -

- Cerenkov detector (CH_2)
- main goal is to study ν oscillations
- recently added a host of new σ_ν meas

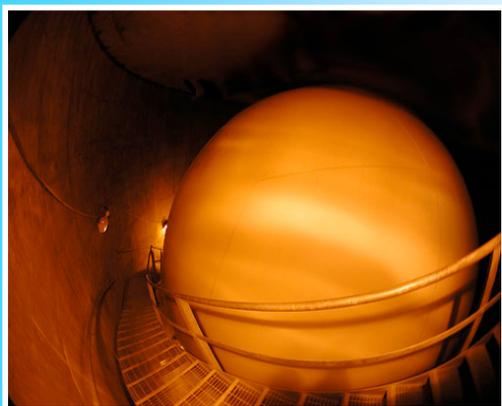
Booster ν Experiments

MiniBooNE

- start: August 2002
 - 6.9×10^{20} POT ν
 - 5.1×10^{20} POT $\bar{\nu}$
- currently running $\bar{\nu}$ mode
- recently approved for extended running (+ 5×10^{20} POT)



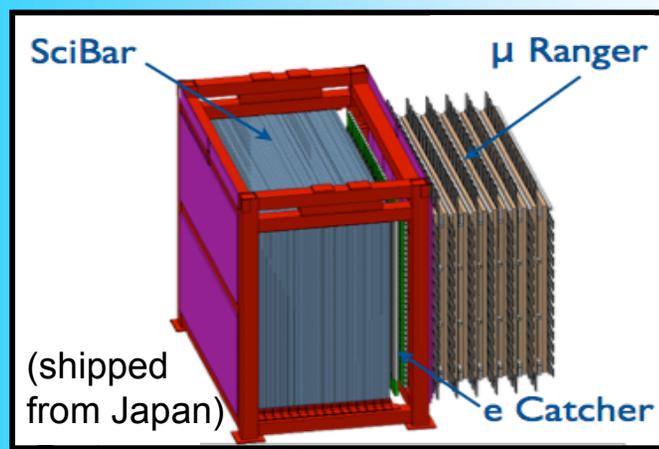
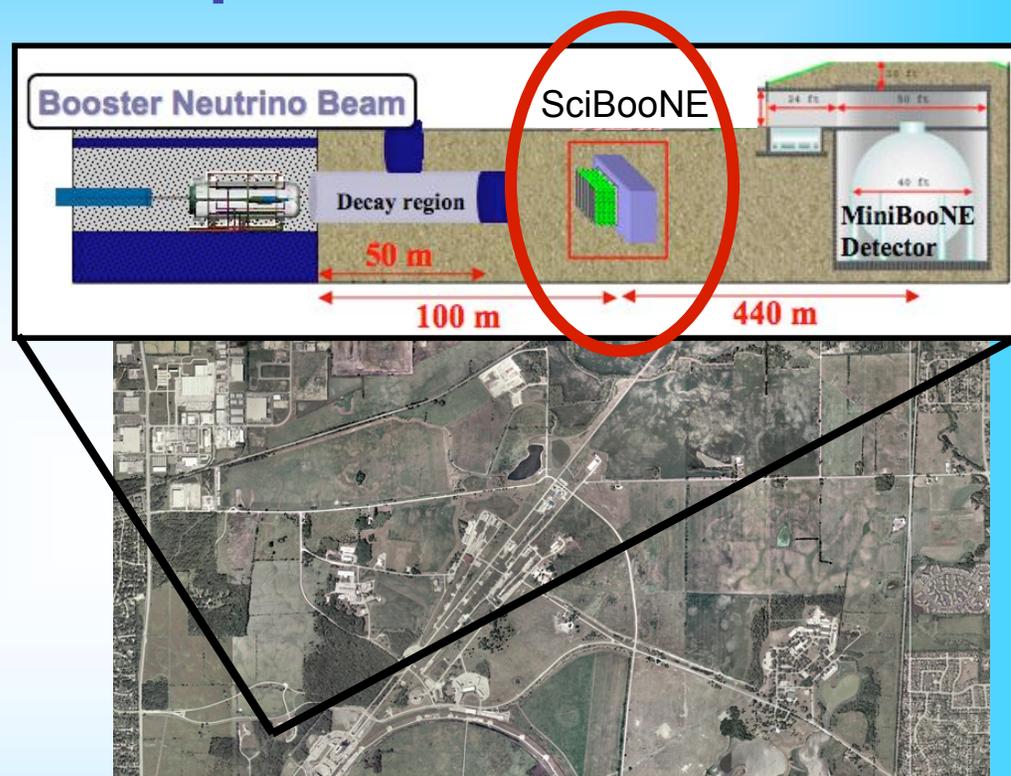
already surpassed our goal
- thank you FNAL AD! -



- NIM A599, 28 (2009) -

Booster ν Experiments

SciBooNE



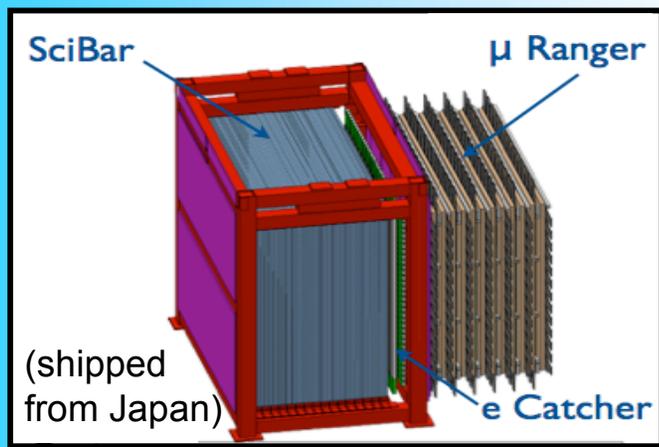
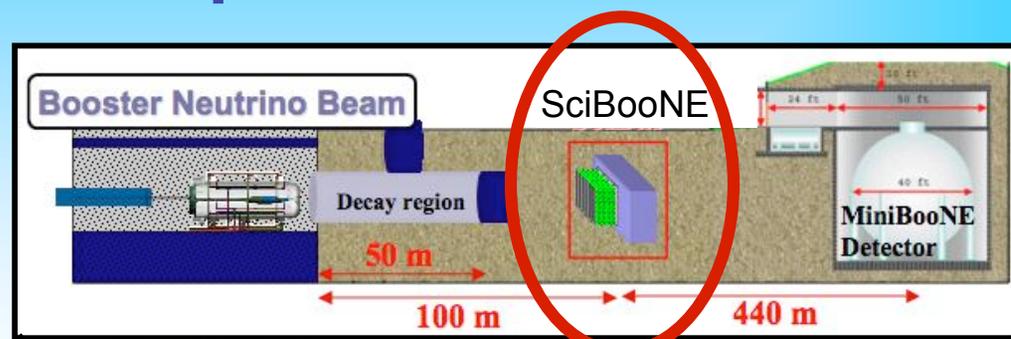
- fine-grained tracking detector (CH) (DOE-wide Pollution Prevention P2 Star Award)
- main goal is dedicated σ_ν (~ 1 GeV, T2K)
- also serves as ND for MiniBooNE



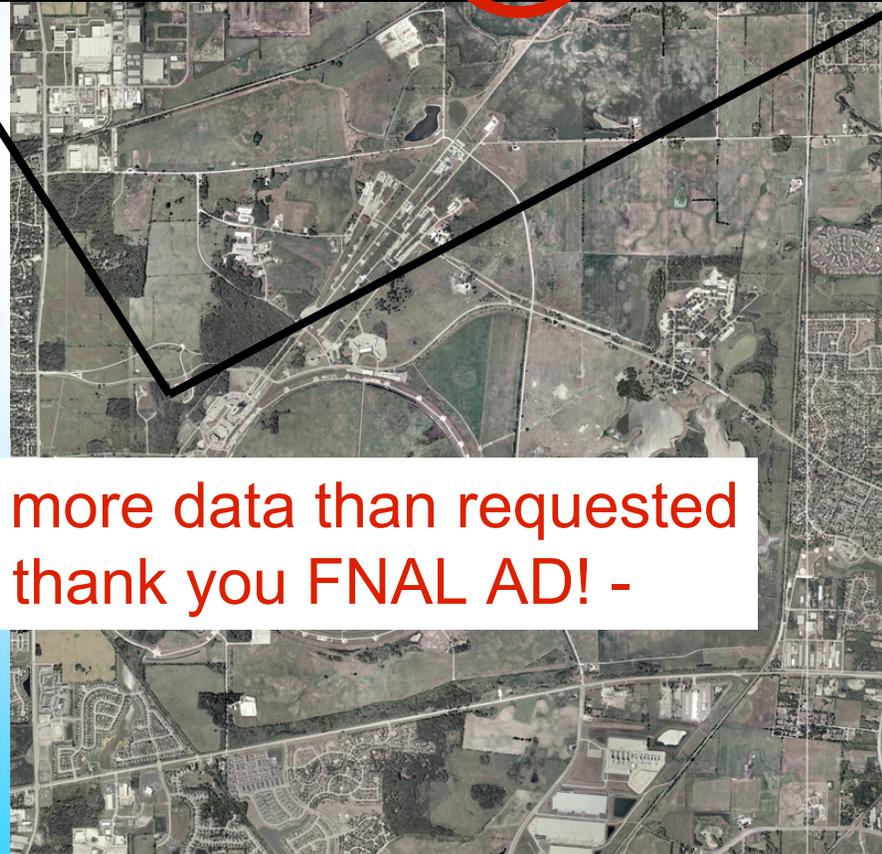
Booster ν Experiments

SciBooNE

- start: June 2007
- $- 0.99 \times 10^{20}$ POT ν
- $- 1.53 \times 10^{20}$ POT $\bar{\nu}$
- completed run Aug 2008
- detectors decommissioned



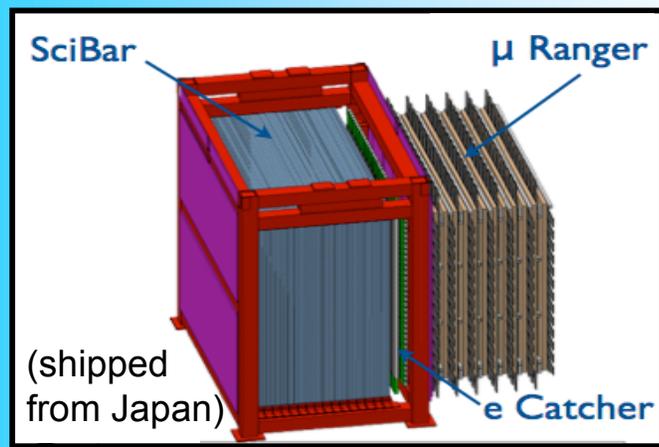
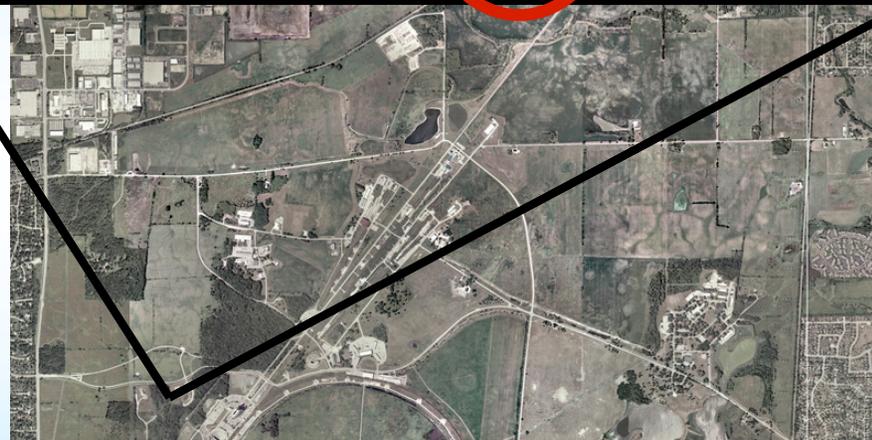
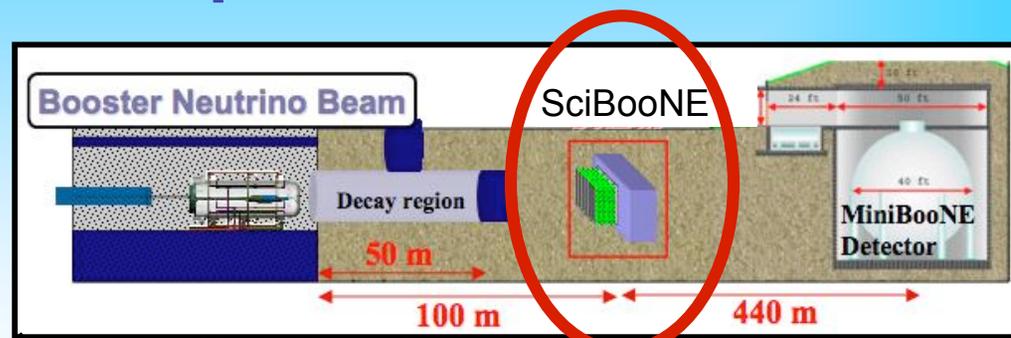
25% more data than requested
- thank you FNAL AD! -



Booster ν Experiments

SciBooNE

- start: June 2007
 - 0.99×10^{20} POT ν
 - 1.53×10^{20} POT $\bar{\nu}$
- completed run Aug 2008
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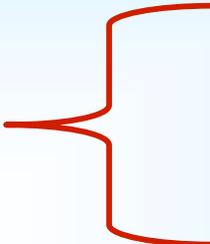
- impressive timeline
- 3 years from formation to first result!



Outline

will go through some of **recent results** from two experiments
(a lot has happened in the past year!)

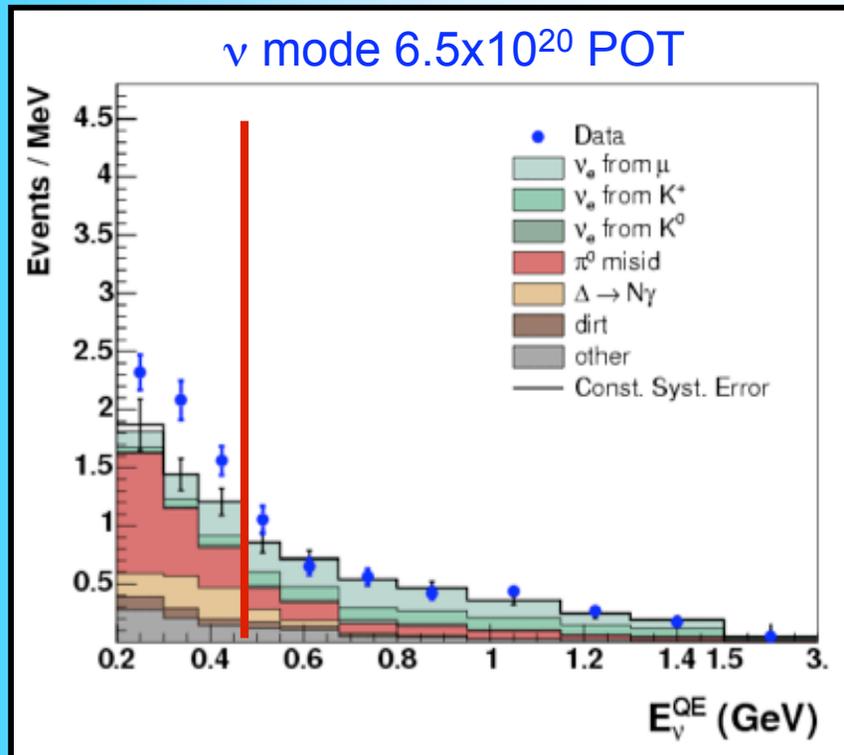
- **ν oscillation results**
from MiniBooNE in past year
- **brand new σ_ν measurements**
from both MiniBooNE & SciBooNE



briefly summarize
three ν oscillation
updates from MB

MiniBooNE Oscillations

$\nu_\mu \rightarrow \nu_e$ analysis



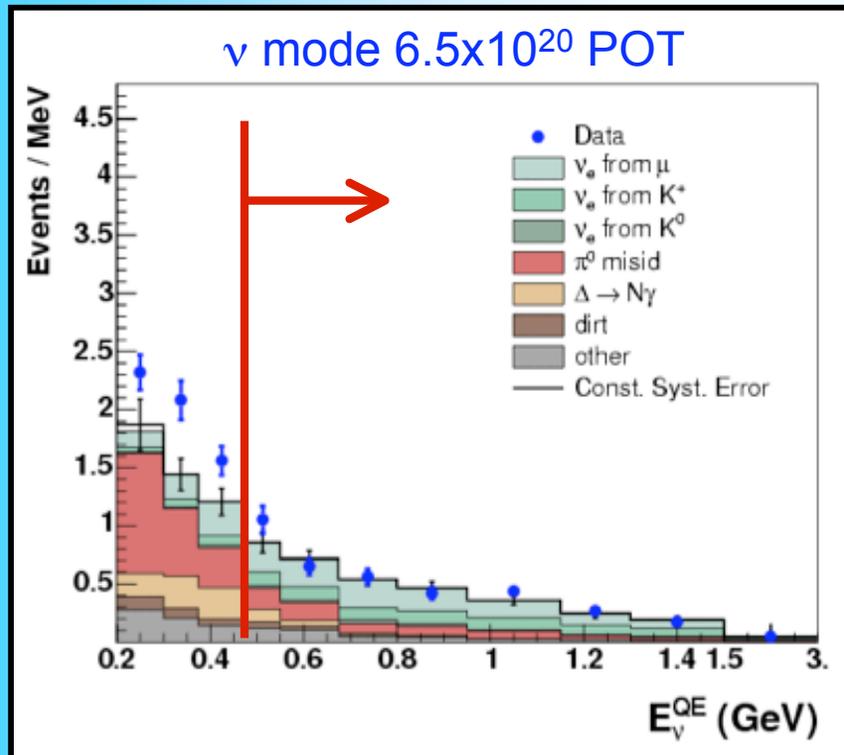
- PRL 102, 101802 (2009) -

- 1st, re-analysis of ν mode
 - review of bkg estimates
 - extension down to 200 MeV
 - increased stats

FNAL W&C August 2008

MiniBooNE Oscillations

$\nu_\mu \rightarrow \nu_e$ analysis



- PRL 102, 101802 (2009) -

- 1st, re-analysis of ν mode

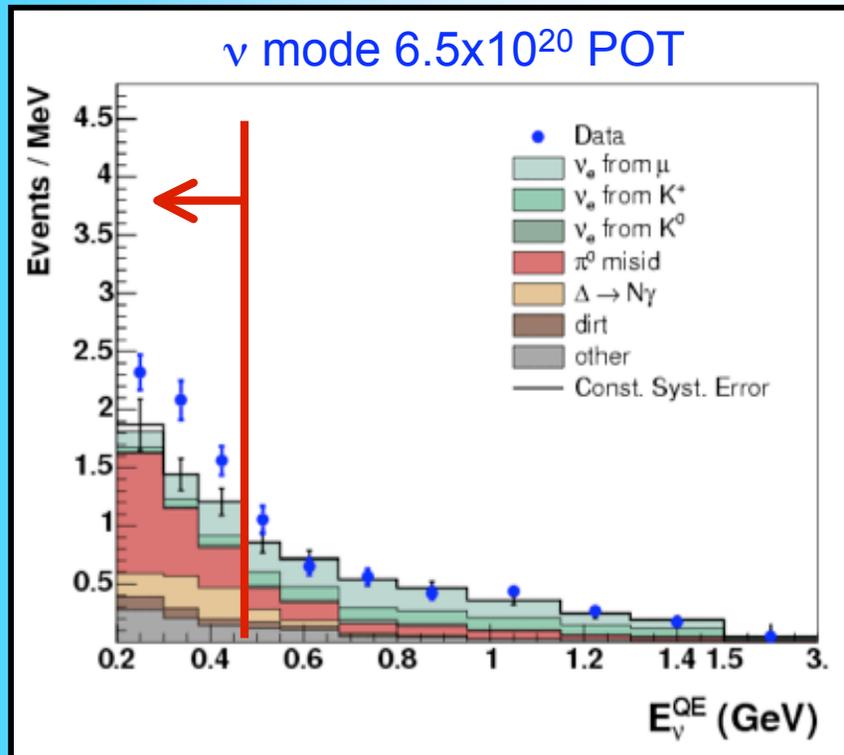
- review of bkg estimates
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FNAL W&C August 2008

> 475 MeV: unchanged
no LSND-like oscillations (2ν)

MiniBooNE Oscillations

$\nu_\mu \rightarrow \nu_e$ analysis



- PRL 102, 101802 (2009) -

- 1st, re-analysis of ν mode

- review of bkg estimates
- extension down to 200 MeV
- increased stats

FNAL W&C August 2008

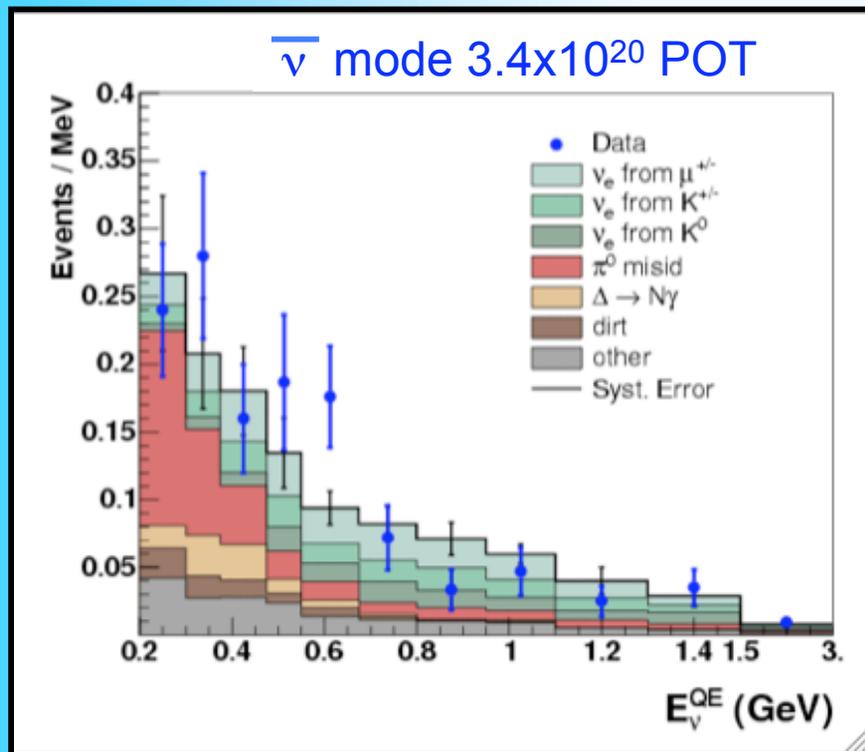
> 475 MeV: unchanged
no LSND-like oscillations (2ν)

< 475 MeV: low energy
excess persists (3σ 200-475 MeV)

MiniBooNE Oscillations

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ analysis

(G. Karagiorgi)



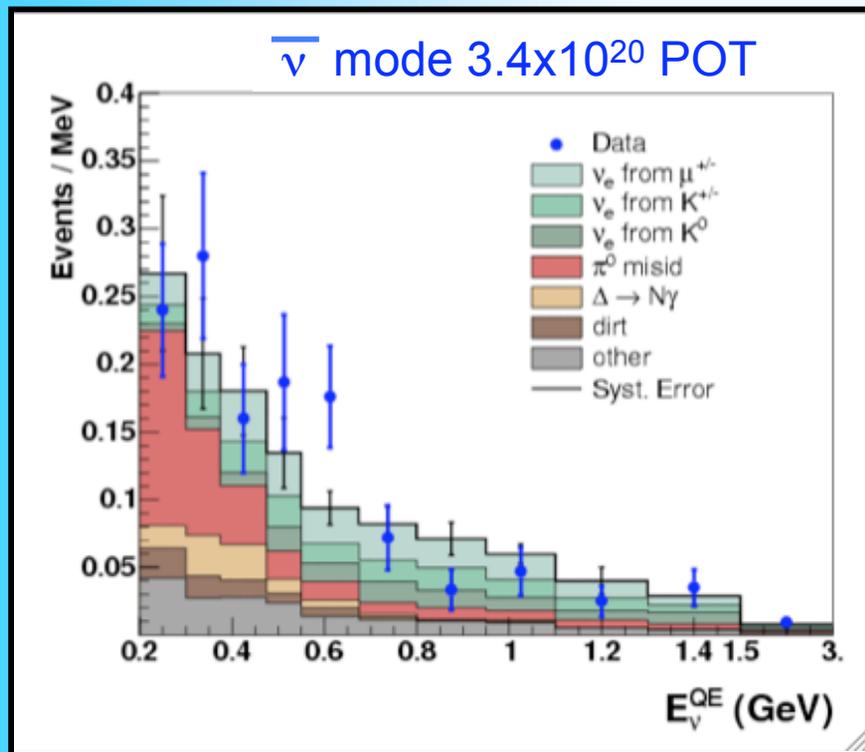
- arXiv:0904:1958 [hep-ex] -

- 1st look at $\bar{\nu}$ mode data unblinded in Nov 2008
FNAL W&C December 2008
- statistics are low
- no statement on LSND yet
- no low energy excess?!
- working on combined $\nu/\bar{\nu}$
+ will benefit from more stats

MiniBooNE Oscillations

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ analysis

(G. Karagiorgi)



- arXiv:0904:1958 [hep-ex] -

- 1st look at $\bar{\nu}$ mode data unblinded in Nov 2008

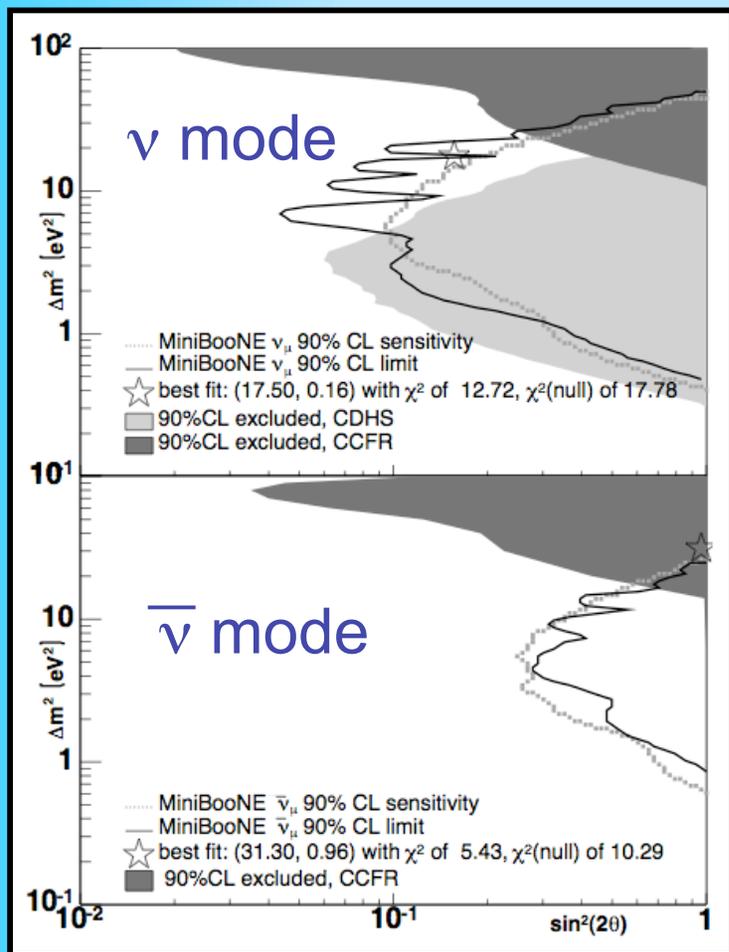
FNAL W&C December 2008

- statistics are low
- no statements

- we'll have to see how this picture evolves
- $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- + $\nu_\mu \rightarrow \nu_\tau$ from more stats

MiniBooNE Oscillations

(K. Mahn)



also performed search for ν_μ and $\bar{\nu}_\mu$ disappearance

- set limits **FNAL W&C October 2008**
- carving out new regions of parameter space
- update incorporating SciBooNE data is currently underway (which should help further improve limits)

- [arXiv:0903:2465 \[hep-ex\]](https://arxiv.org/abs/0903.2465) -

Outline

now let's switch gears ...

- **ν oscillation results**

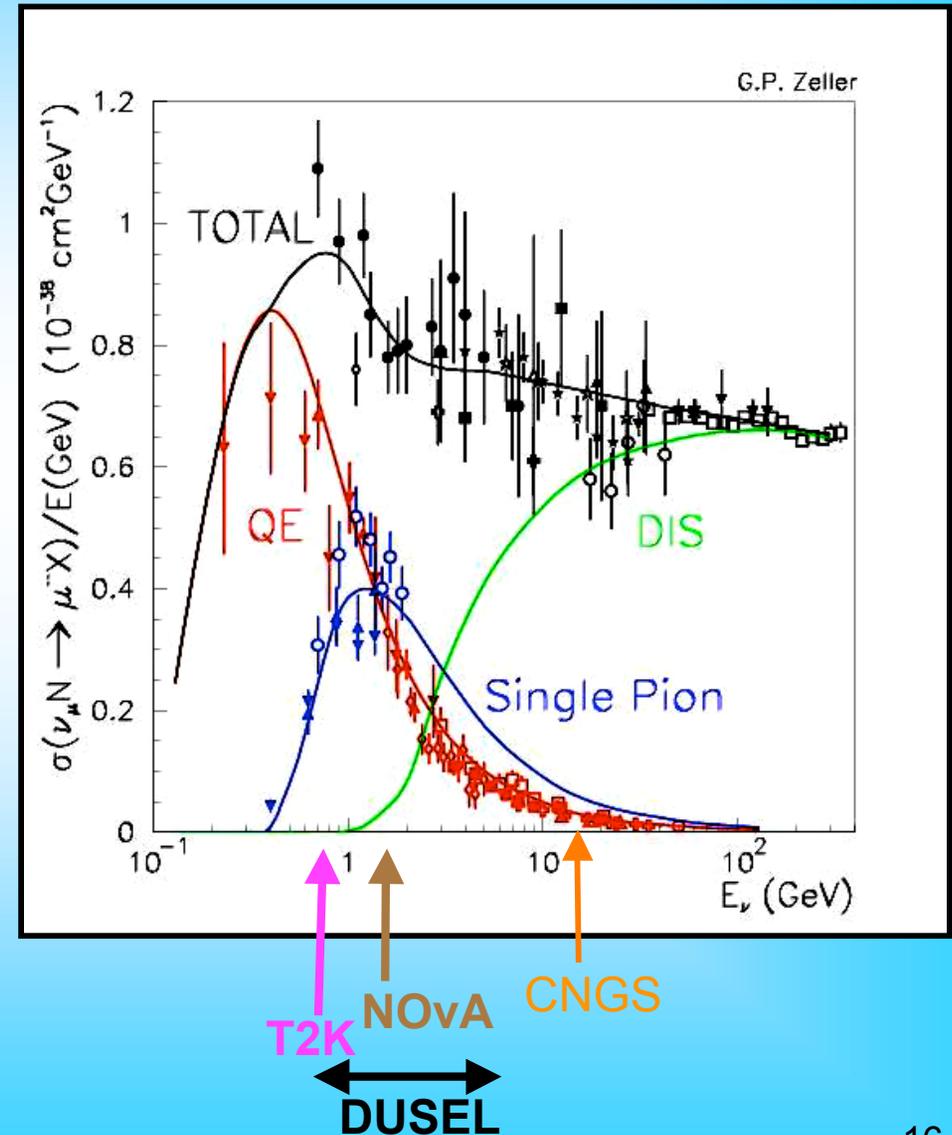
✓ from MiniBooNE in past year

• **brand new σ_ν measurements**
from both MiniBooNE & SciBooNE

- rest of talk
- all results <2 weeks old! (NuInt09)
- a lot of firsts (as you'll see)

Neutrino Cross Sections

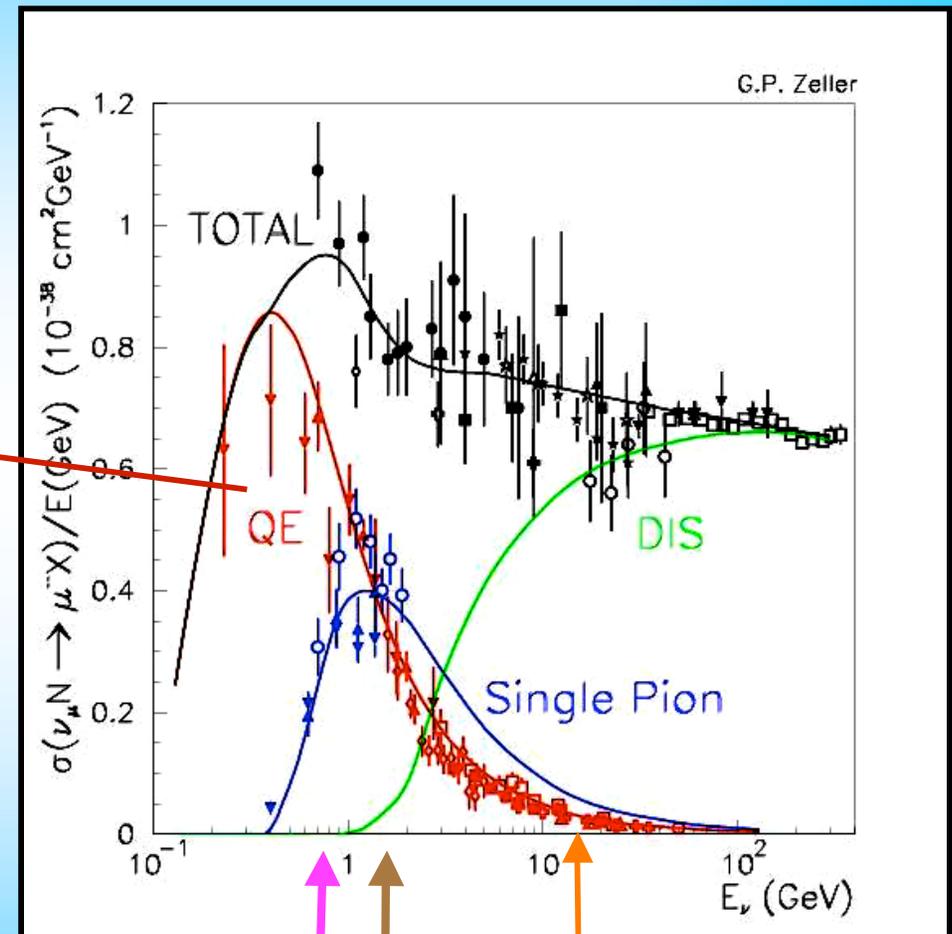
- of critical importance to future ν oscillation exps which will be operating in this few-GeV E range



Neutrino Cross Sections

- of critical importance to future ν oscillation expts which will be operating in this few-GeV E range

**quasi-elastic (QE)
signal**

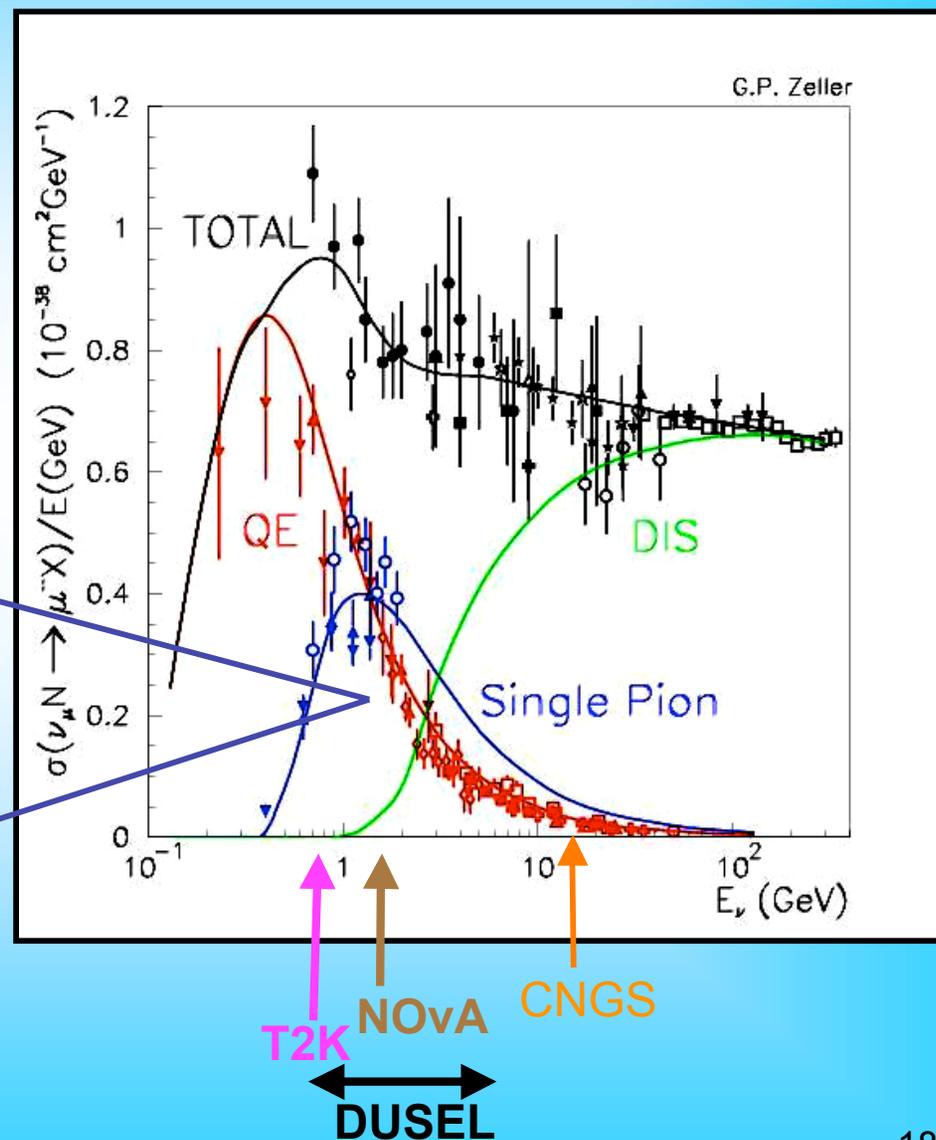


Neutrino Cross Sections

- of critical importance to future ν oscillation expts which will be operating in this few-GeV E range

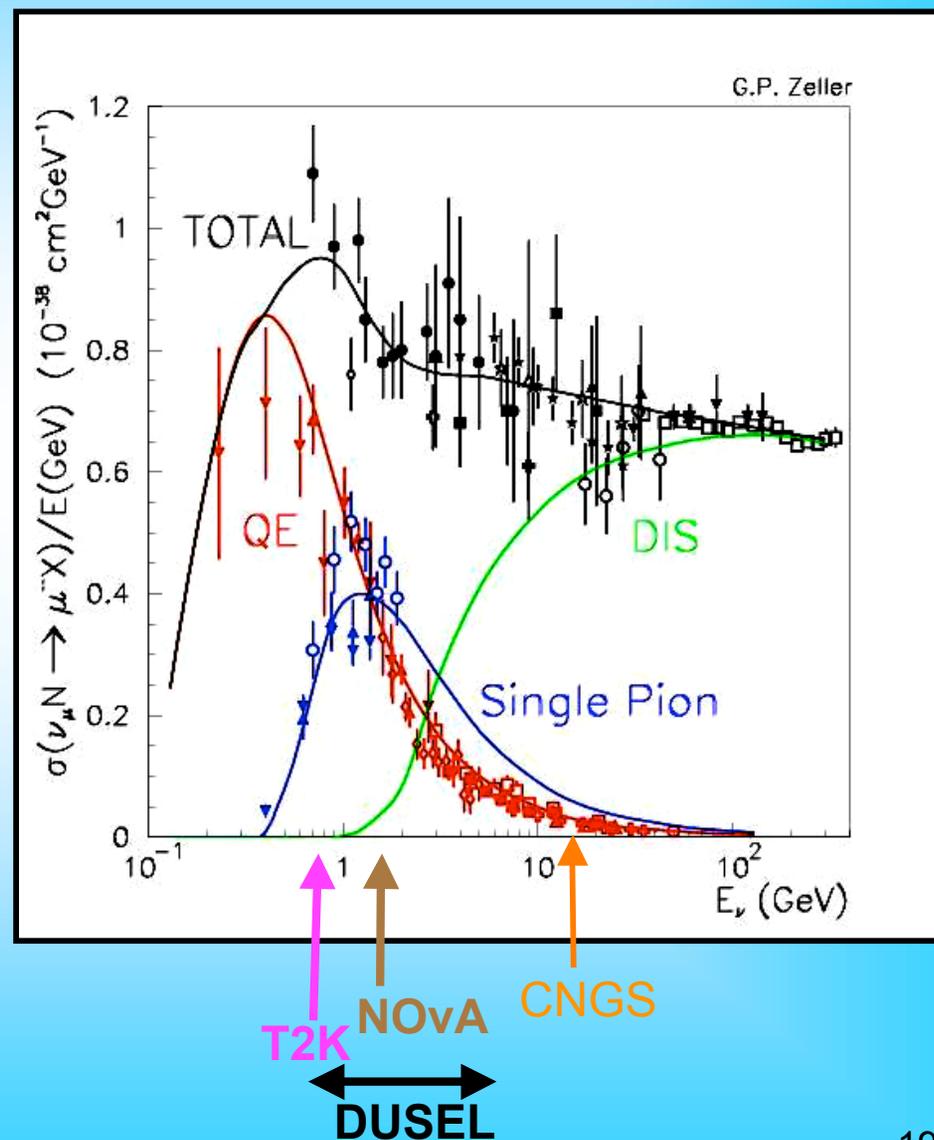
NC π^0
(background to ν_e appearance)

CC π^+
(background to ν_μ disappearance)



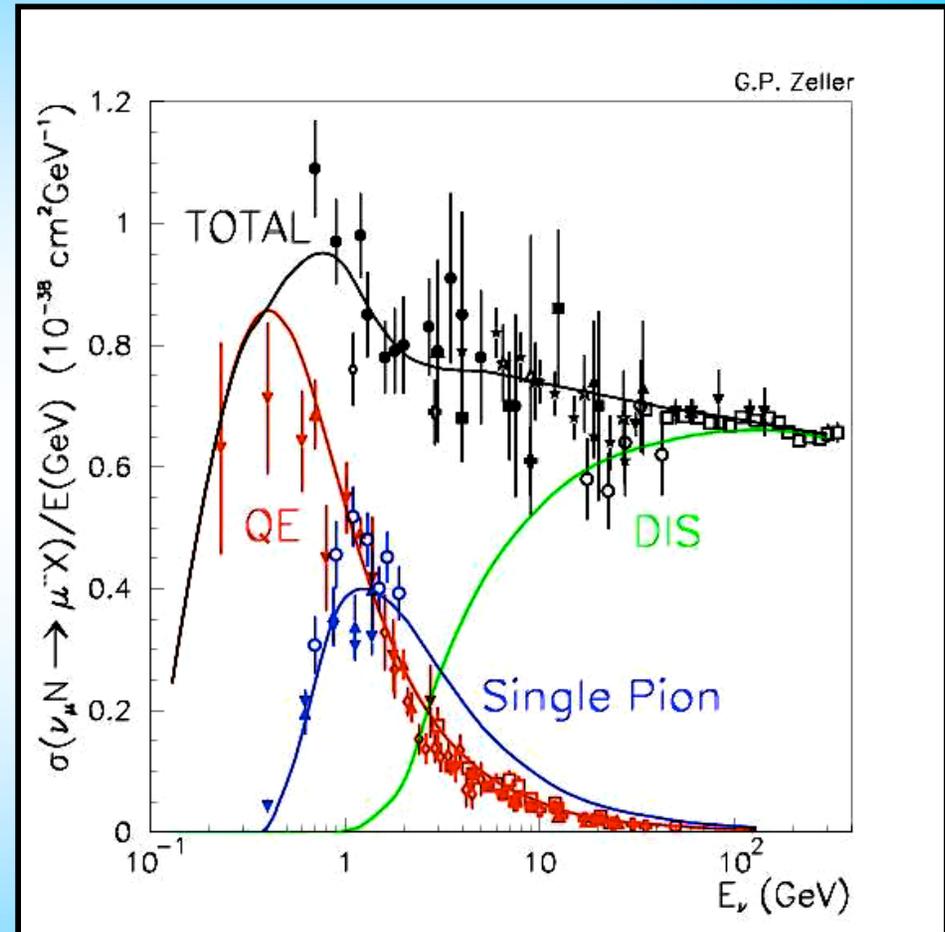
Neutrino Cross Sections

- of critical importance to future ν oscillation exps which will be operating in this few-GeV E range
- data are 20-30 years old
 - 100's of events, mostly D_2
 - calcs we use are also old
- situation have been suffering with for past 30+ years
- rapidly improving (in large part due to efforts at FNAL)



Neutrino Cross Sections

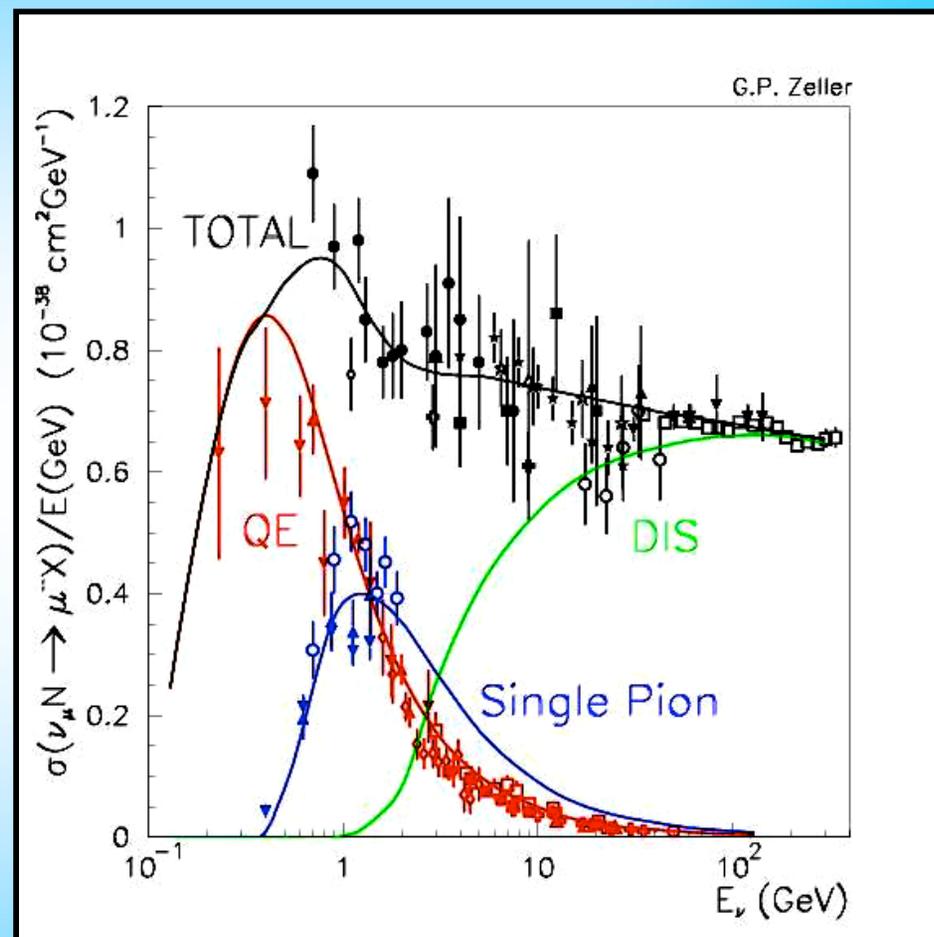
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 MB, SB
 nuclear targets!
 MINOS, MINERvA

Neutrino Cross Sections

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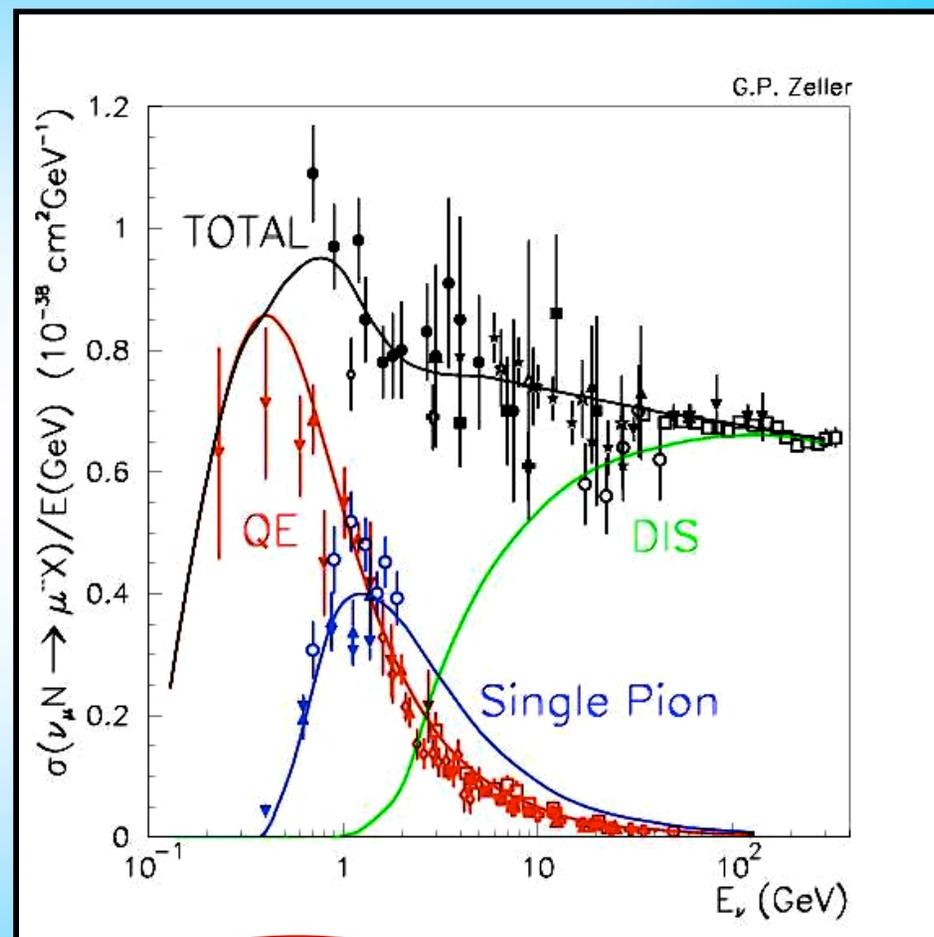
↔ MB, SB

↔ MINOS, MINERvA

next talk!

Neutrino Cross Sections

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- data are 20-30 years old
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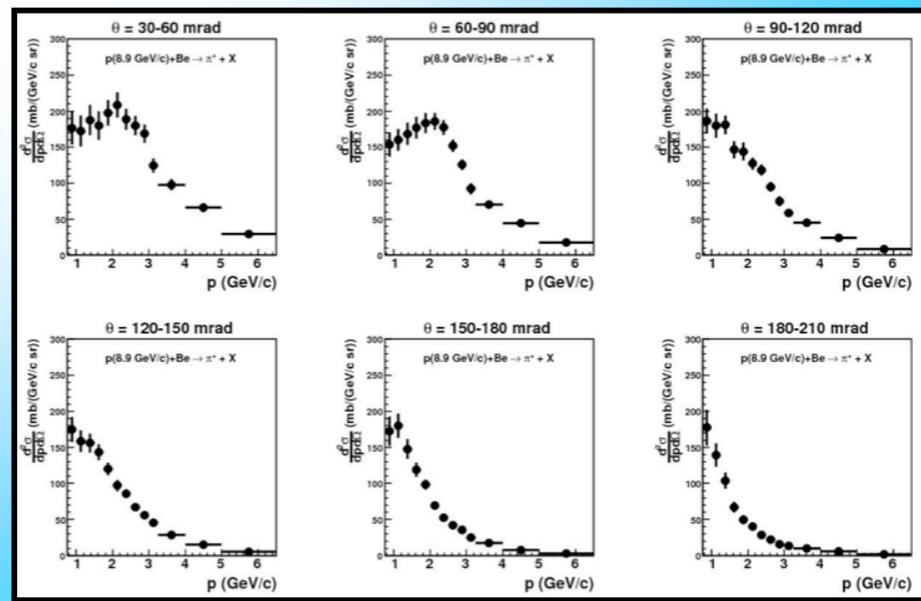
this talk MB, SB next talk!
MINOS, MINERvA

Booster ν Flux Predictions



- make heavy use of $p\text{Be} \rightarrow \pi^{+/-}$ data from **HARP** experiment
 - Eur. Phys. J. C52, 29 (2007) -
 - 8.9 GeV/c protons
 - exact replica target (5% λ)

- caliber of data helped greatly reduce ν flux uncertainties
- comprehensive ν flux paper
 - PRD 79, 072002 (2009) -



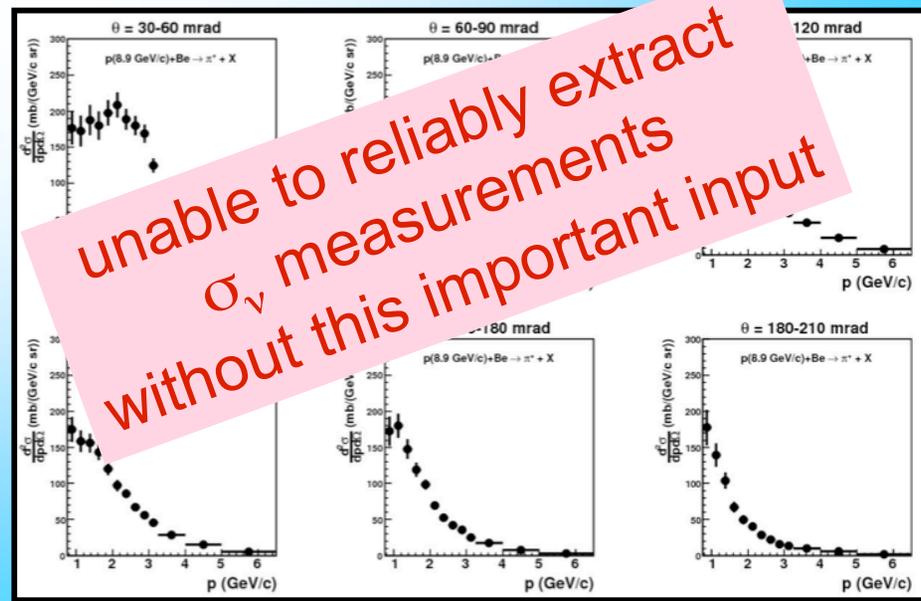
(D. Schmitz)

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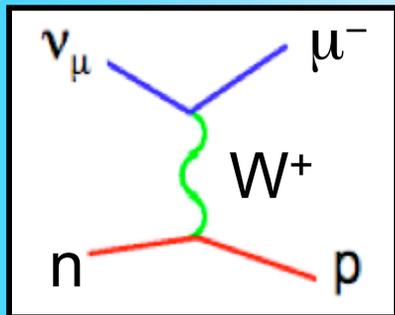
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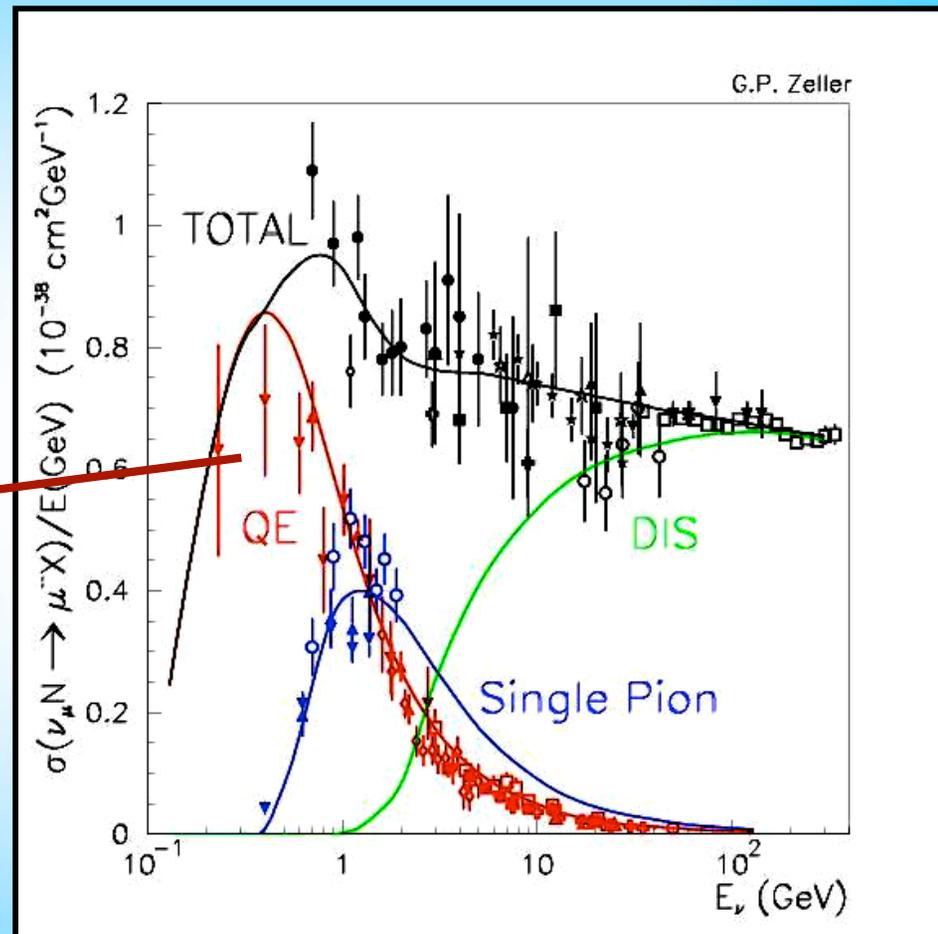
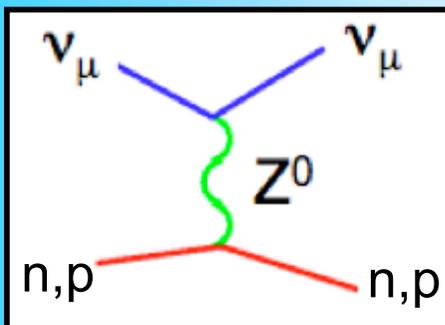
(D. Schmitz)

Elastic Scattering Processes

- CC QE scattering



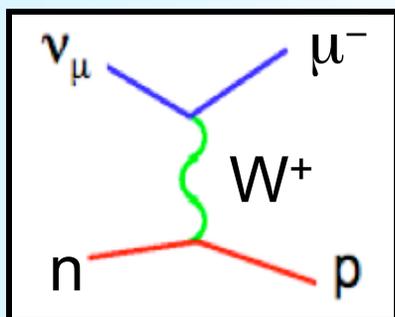
- NC elastic scattering



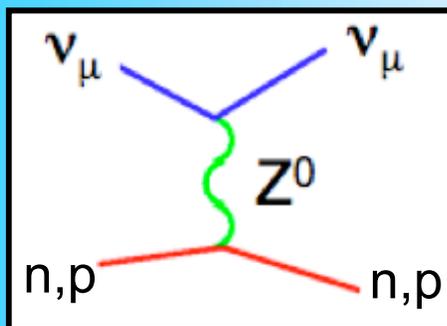
- let's start on the left and work our way up in energy ...

Quasi-Elastic Scattering

- CC QE scattering



- NC elastic scattering



- “golden channel” (**signal sample**)

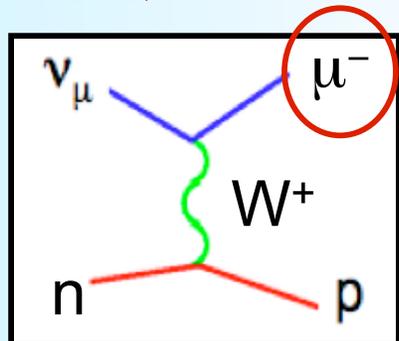
- **cross section** = # of signal events
- **kinematics** = looking for effects as function E_ν

- ν experiments typically simulate with relativistic Fermi Gas model (**RFG**)

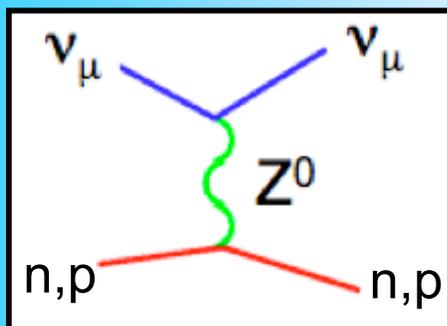
Smith and Moniz, NP B43, 605 (1972)

Quasi-Elastic Scattering

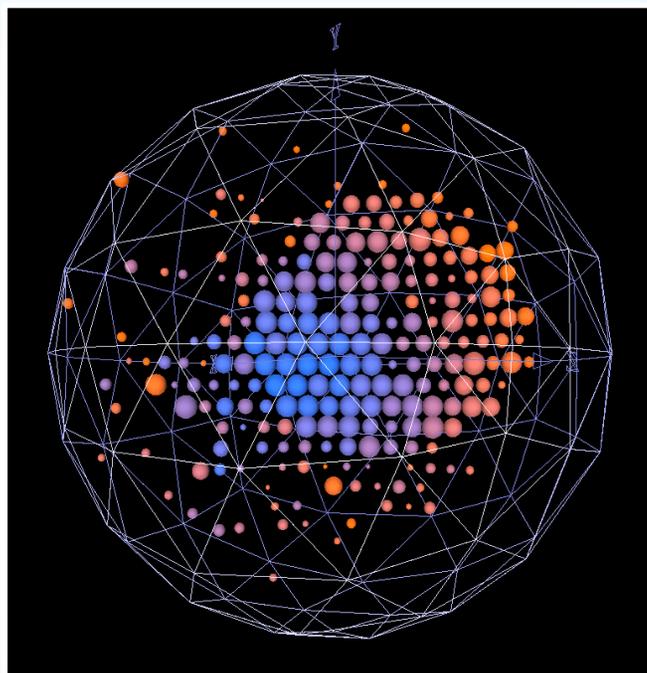
- CC QE scattering



- NC elastic scattering



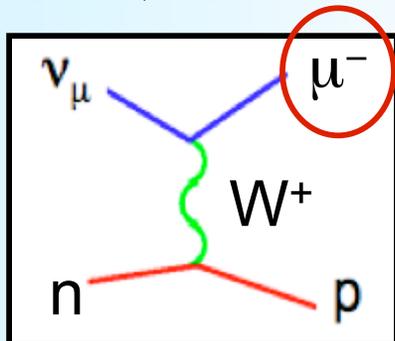
MiniBooNE:



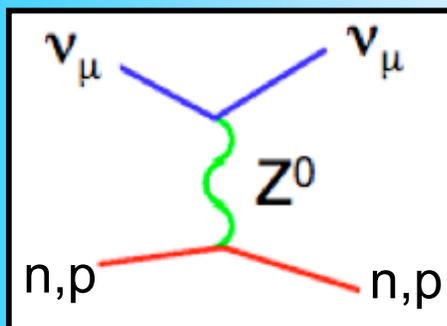
- **reconstruct muon** (T_μ, θ_μ)
- advantage of SB: can reconstruct both μ and p

Quasi-Elastic Scattering

- CC QE scattering

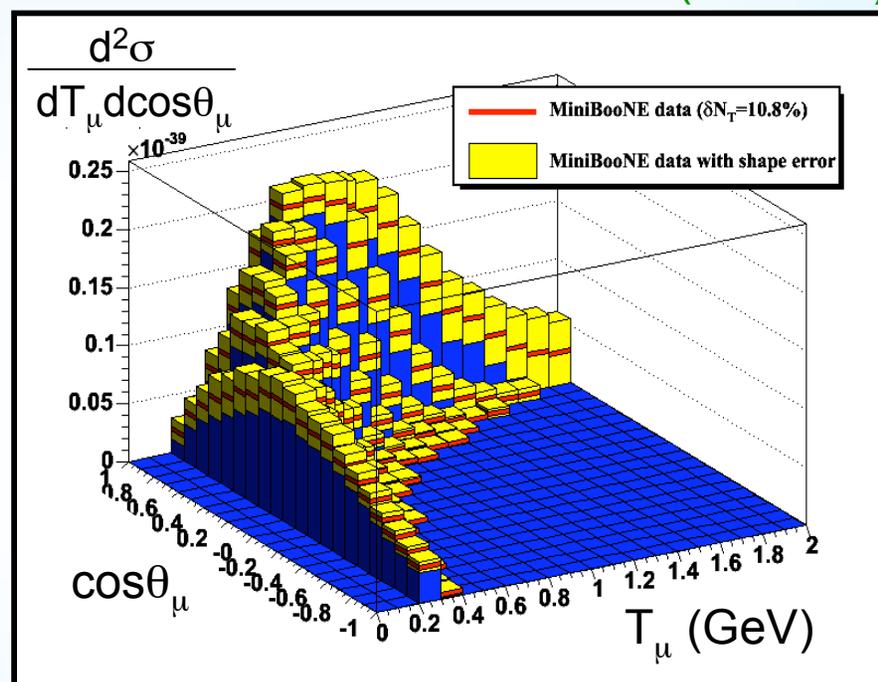


- NC elastic scattering



MiniBooNE:

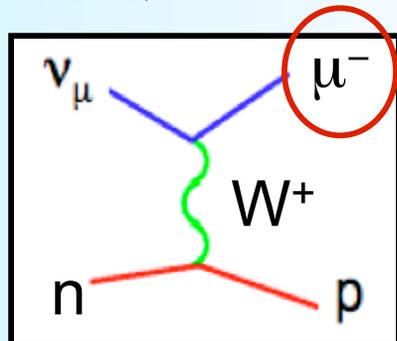
(T. Katori)



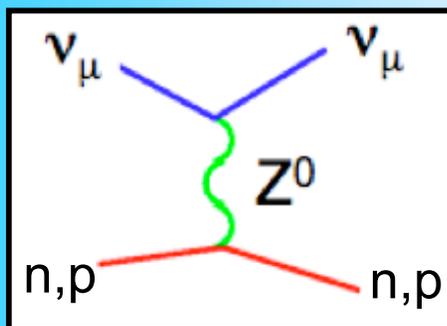
- 146,070 ν_μ QE events (76% purity, 27% ϵ)
- provide most complete information on ν_μ QE scattering to date (full μ kinematics)

Quasi-Elastic Scattering

- CC QE scattering

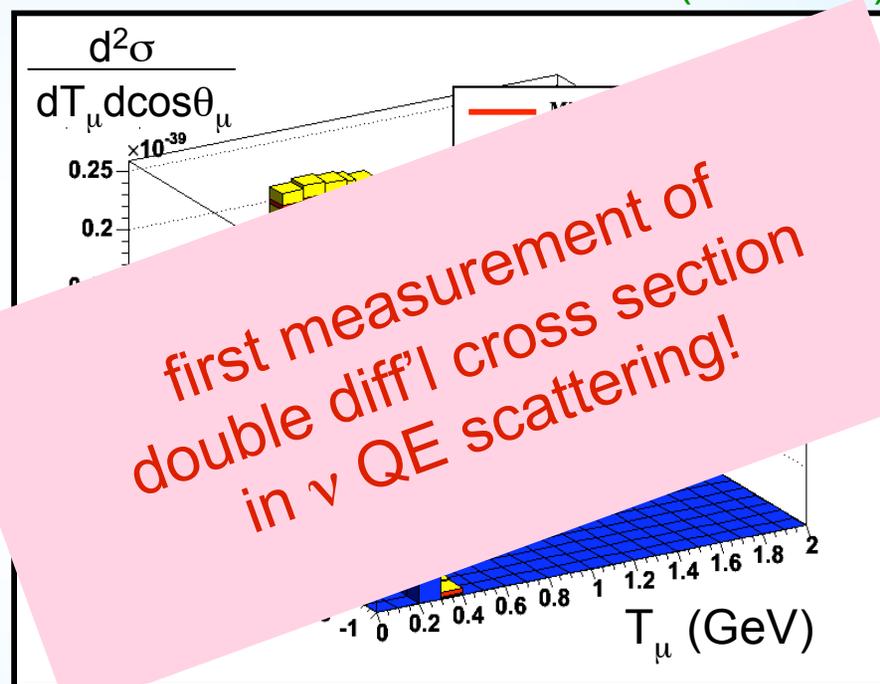


- NC elastic scattering



MiniBooNE:

(T. Katori)

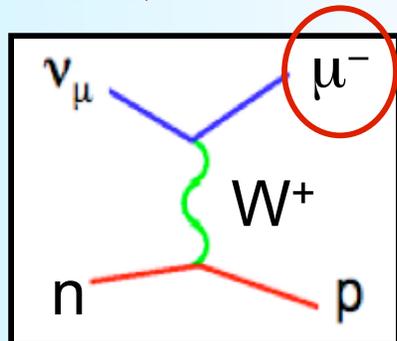


first measurement of
double diff'l cross section
in ν QE scattering!

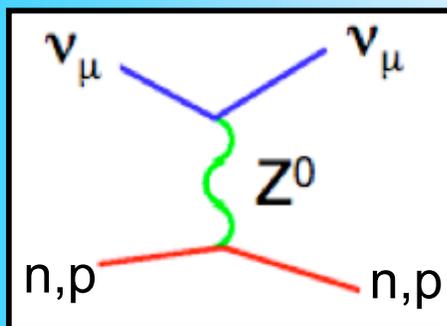
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Quasi-Elastic Scattering

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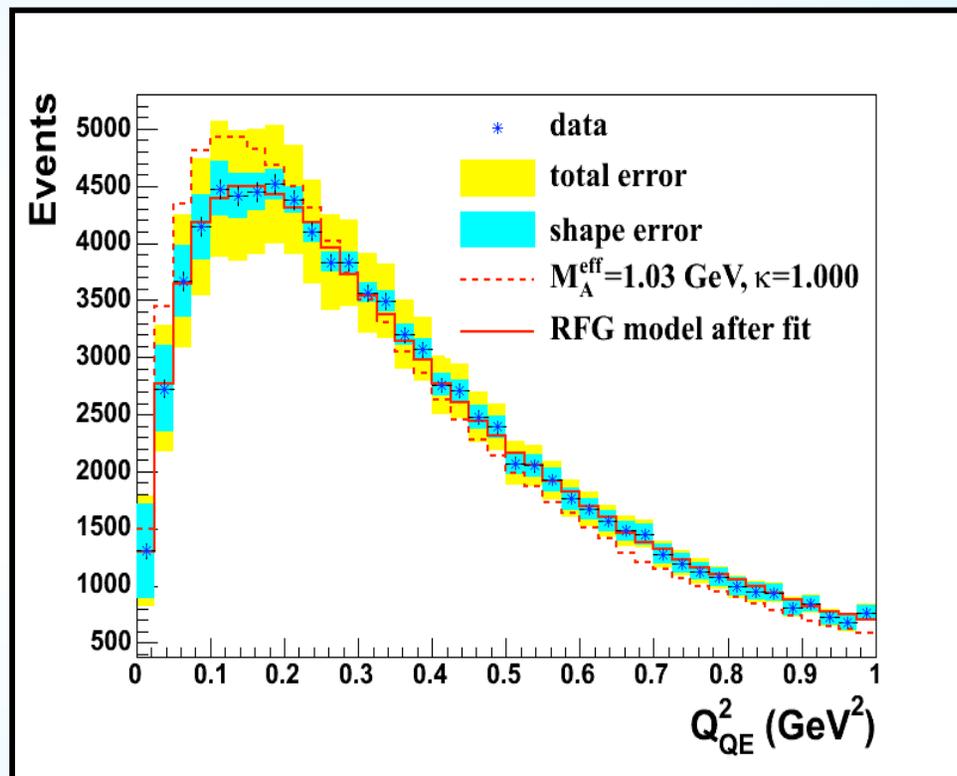


- NC elastic scattering



MiniBooNE:

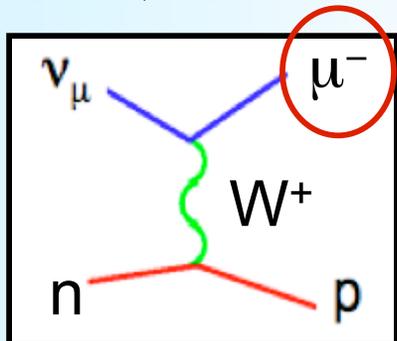
(T. Katori)



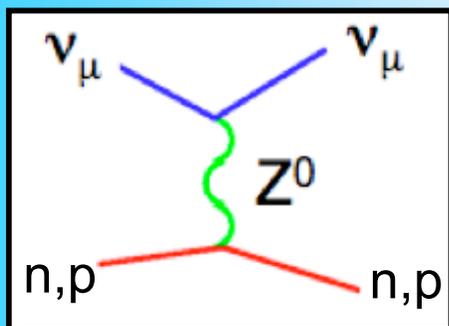
- updated **shape fit** results: $M_A=1.35 \pm 0.17 \text{ GeV}$
(with improved background constraint from MB data)

Quasi-Elastic Scattering

- CC QE scattering

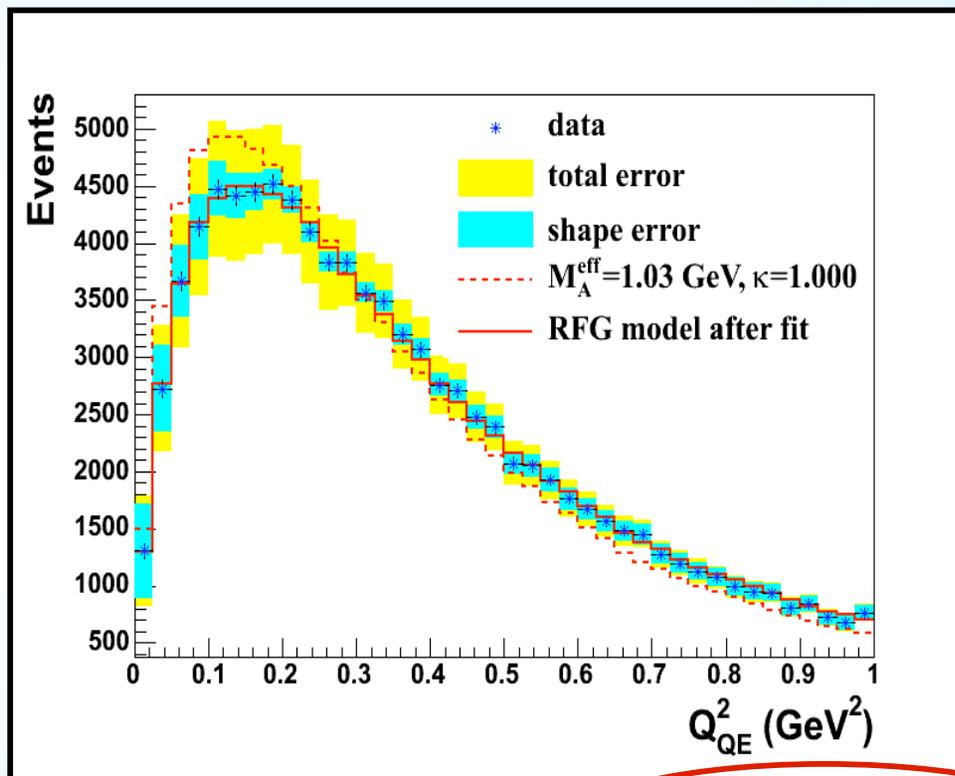


- NC elastic scattering



MiniBooNE:

(T. Katori)

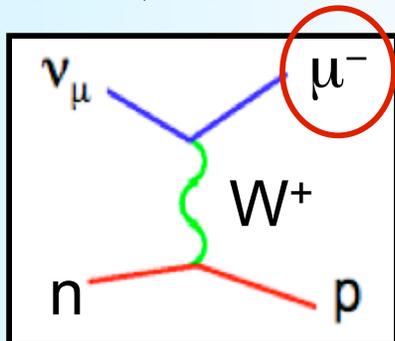


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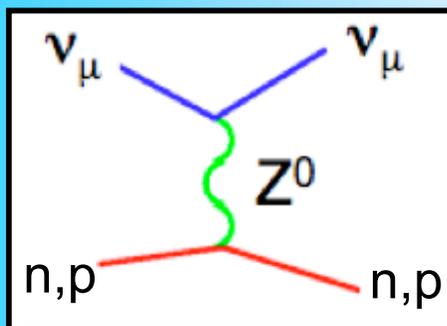
> $M_A^{D2} = 1.03$ GeV, but consistent w/ K2K, MINOS

Quasi-Elastic Scattering

- CC QE scattering

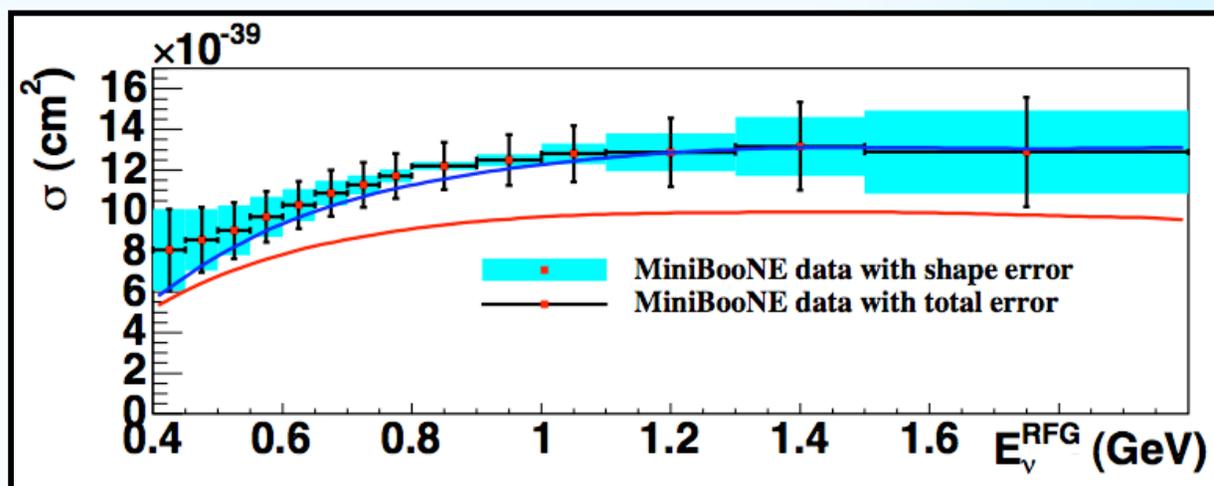


- NC elastic scattering



MiniBooNE:

(T. Katori)



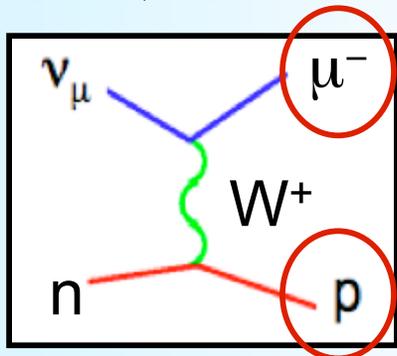
— RFG model with $M_A=1.35$ GeV

— RFG model with $M_A=1.03$ GeV (D_2)
(most widely used prediction for this process)

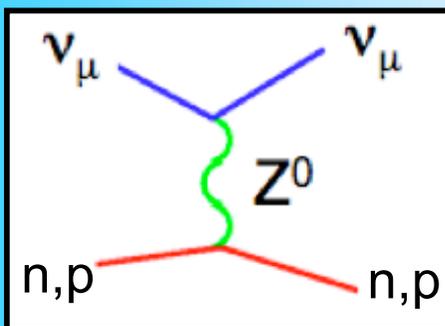
- 35% higher than RFG w/ world avg $M_A=1.03$ GeV
- in better agreement with RFG w/ params coming from shape only fit ($M_A=1.35$ GeV)

Quasi-Elastic Scattering

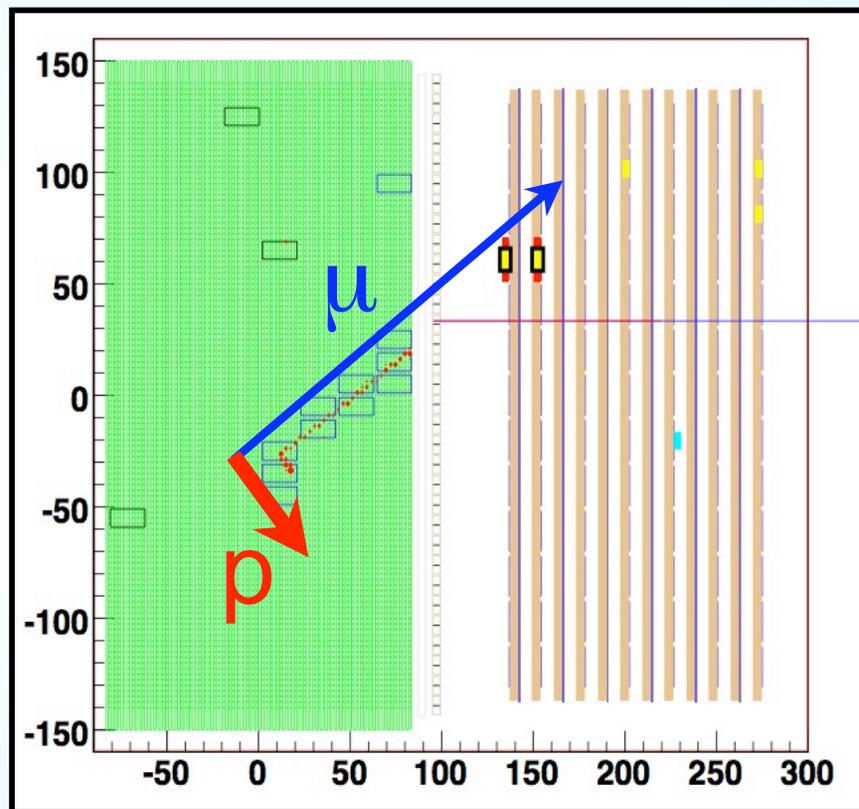
- CC QE scattering



- NC elastic scattering



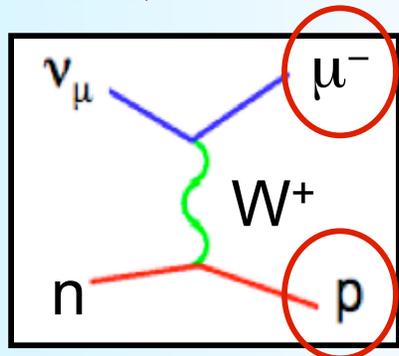
SciBooNE: can clearly resolve final state



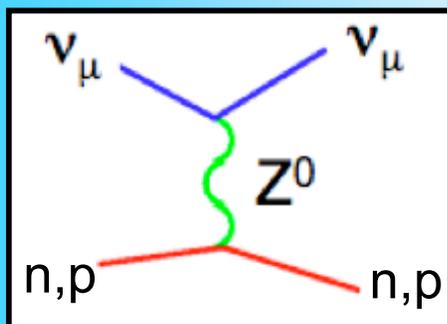
- reconstruct **both** μ and **proton** (2 track analysis)
- 2,680 ν_μ QE events (69% purity, 2.3% ϵ)

Quasi-Elastic Scattering

- CC QE scattering

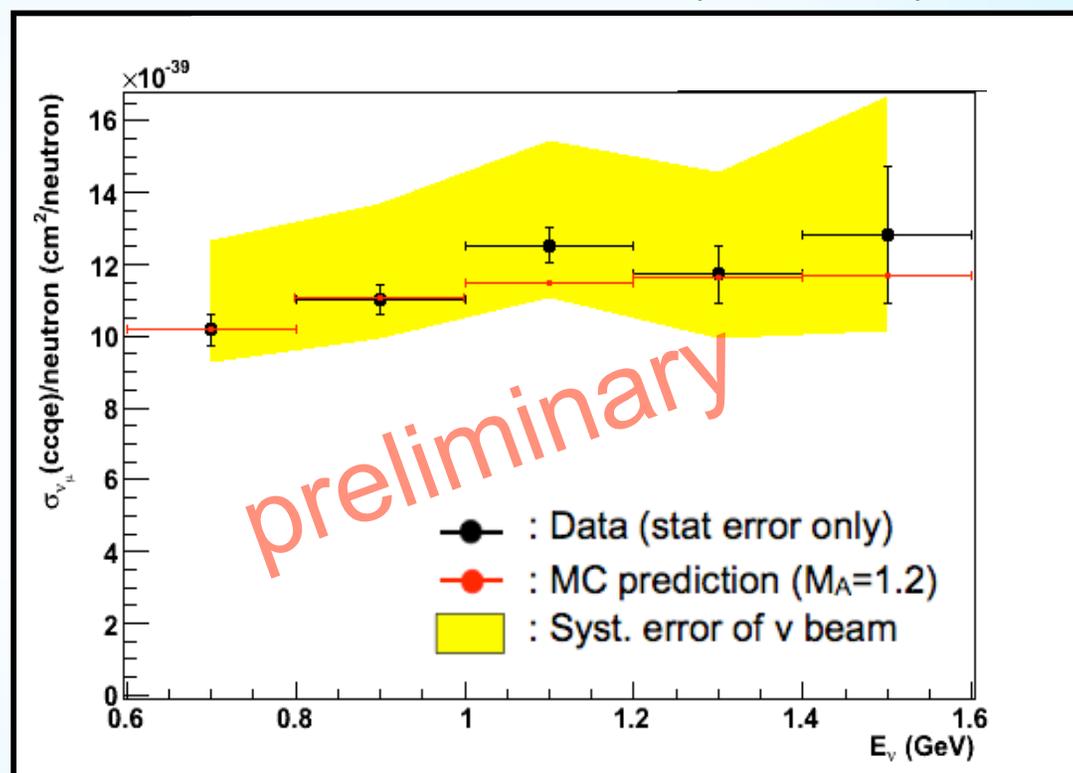


- NC elastic scattering



SciBooNE:

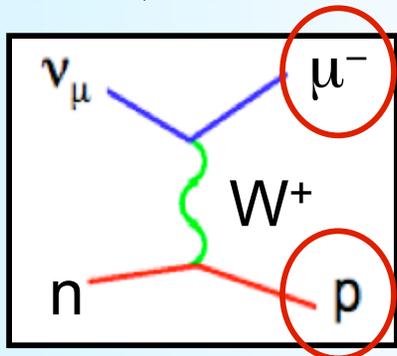
(J. Alcaraz)



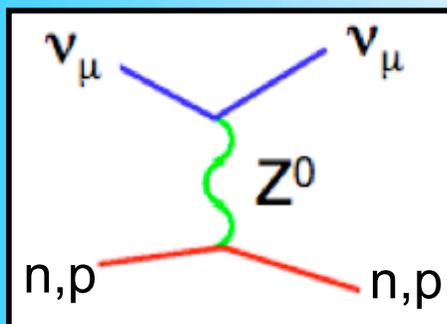
- agrees with RFG prediction (with a higher M_A)
- ~ consistent with MiniBooNE measurement

Quasi-Elastic Scattering

- CC QE scattering

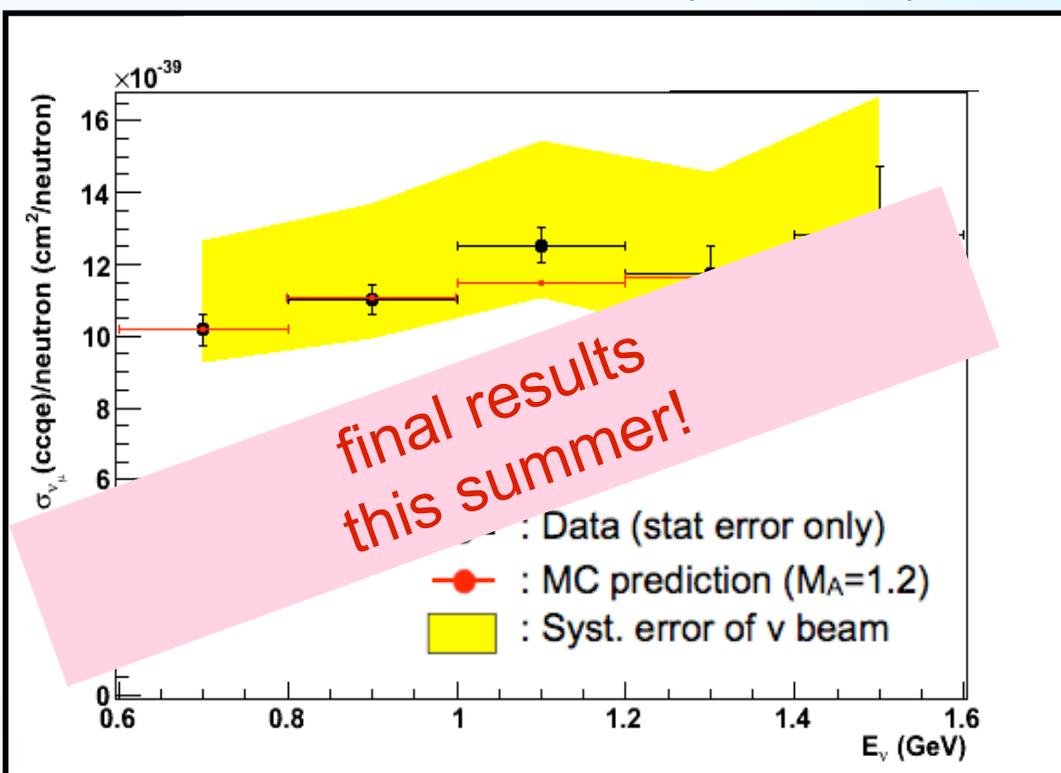


- NC elastic scattering



SciBooNE:

(J. Alcaraz)

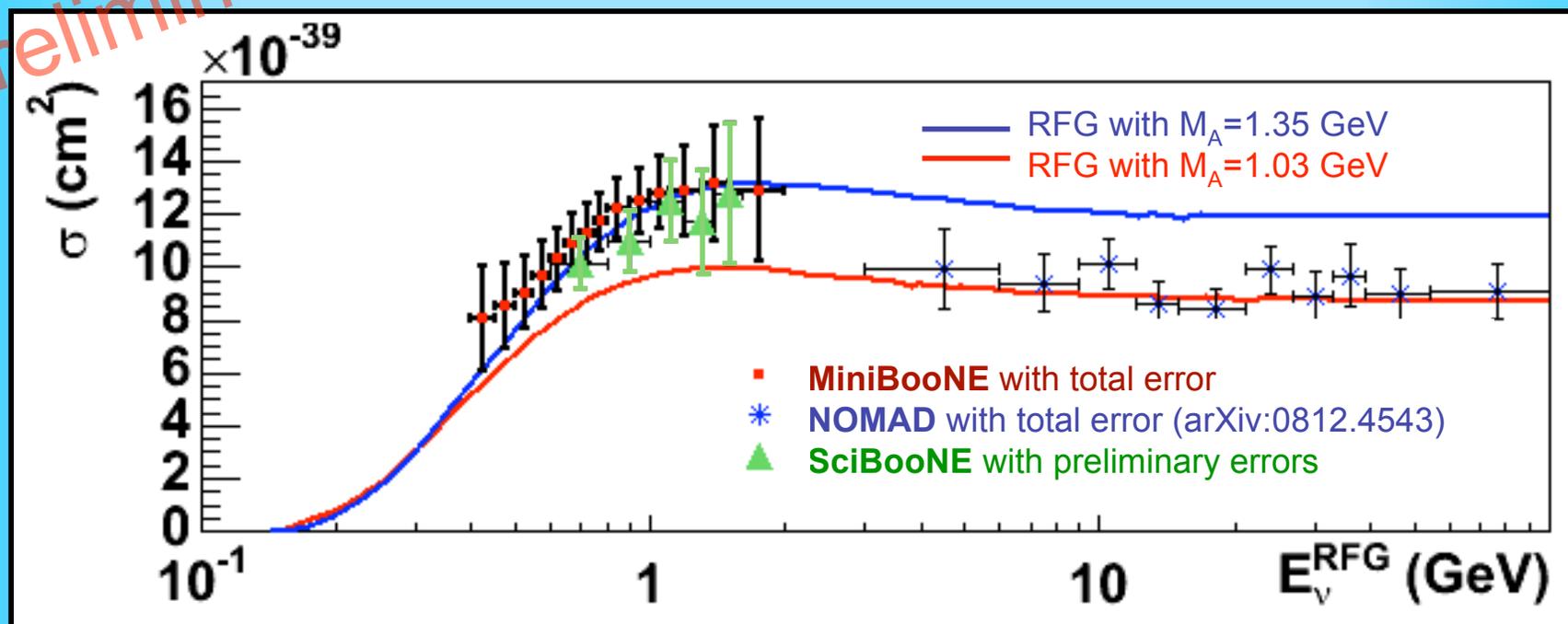


- agrees with RFG prediction (with a higher M_A)
- ~ consistent with MiniBooNE measurement

Current Situation

(T. Katori)

preliminary

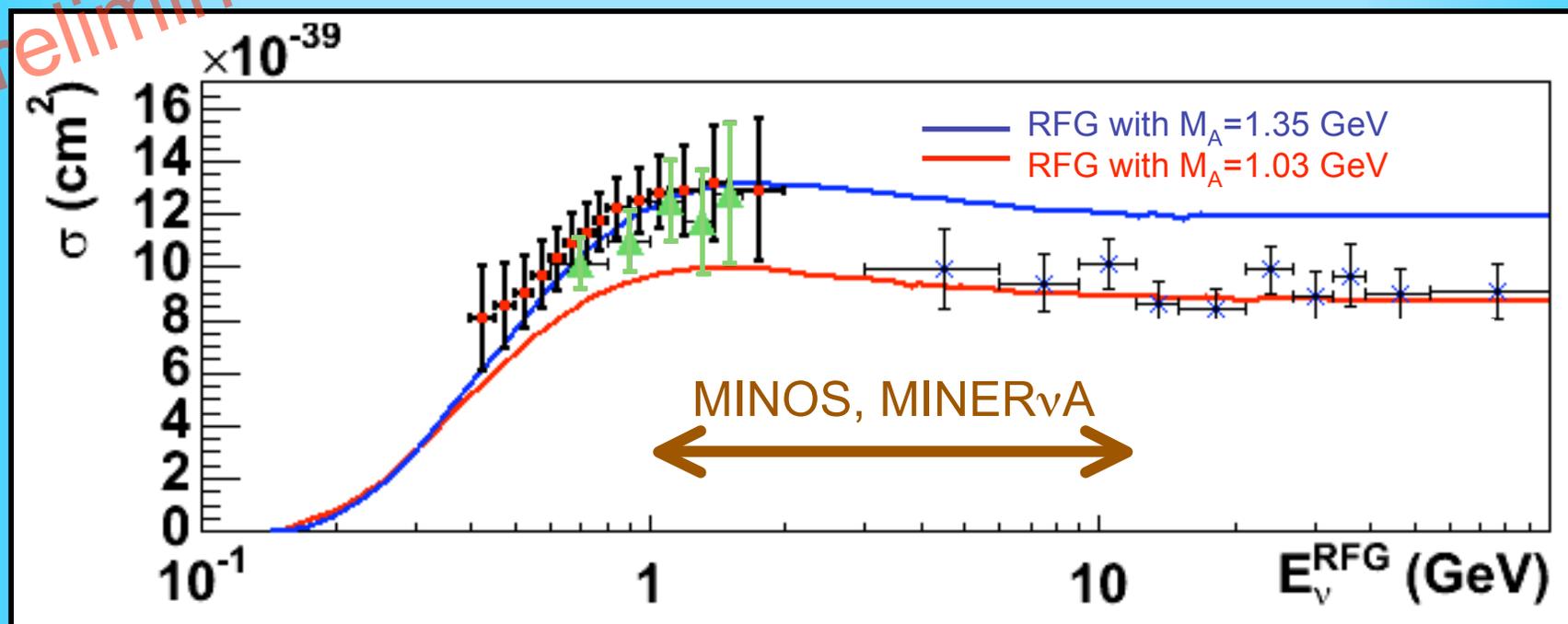


- **MiniBooNE** and **SciBooNE** in good agreement
1st meas on nuclear target at low energy ($E_\nu \lesssim 2$ GeV)
- both higher than recent σ_{QE} from **NOMAD**?! all three on ^{12}C

Current Situation

(T. Katori)

preliminary

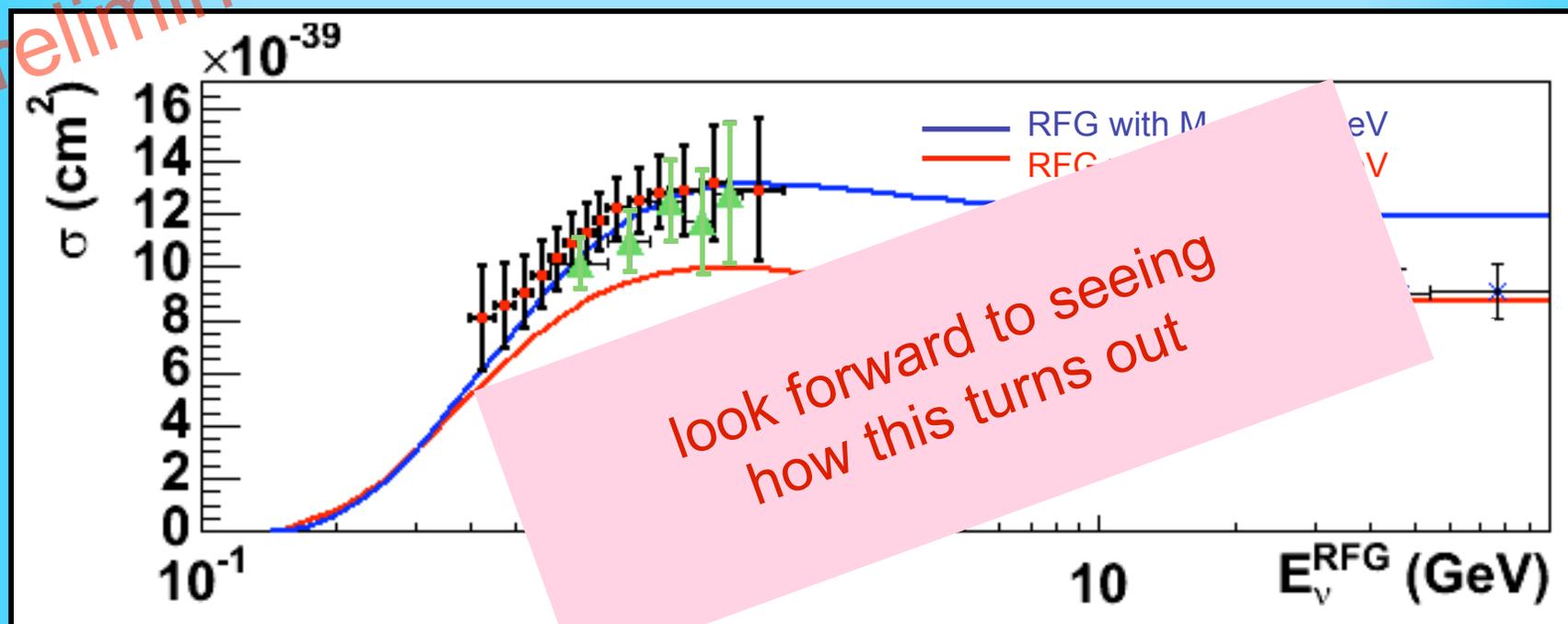


- importance of NuMI data (**MINOS ND, MINER_{vA}**)!
- FNAL exps will make the defining statement on this σ
(in doing so, will populate plot better than has ever been done in history)

Current Situation

(T. Katori)

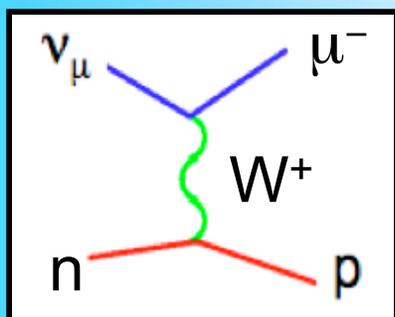
preliminary



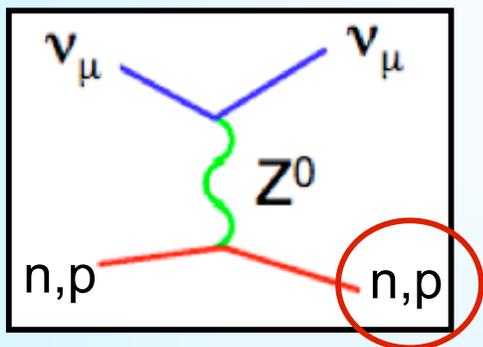
- importance of NuMI data (**MINOS ND**, **MINERvA**)!
- FNAL expts will make the defining statement on this σ
(in doing so, will populate plot better than has ever been done in history)

NC Elastic Scattering

- CC QE scattering



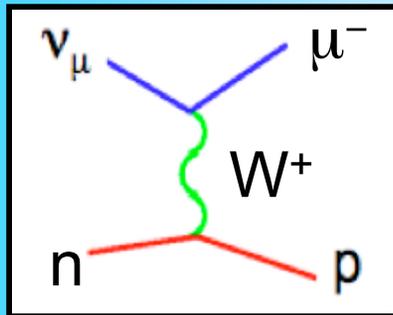
- NC elastic scattering



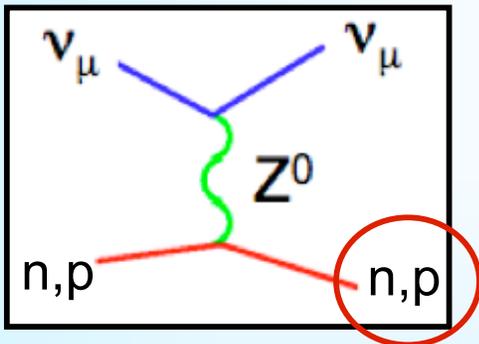
- can study NC counterpart of this reaction (M_A , σ , eventually Δs)
- MiniBooNE: 94,500 ν_μ NC EL events (65% purity, 26% ϵ)
- using this high quality data ...

NC Elastic Scattering

- CC QE scattering

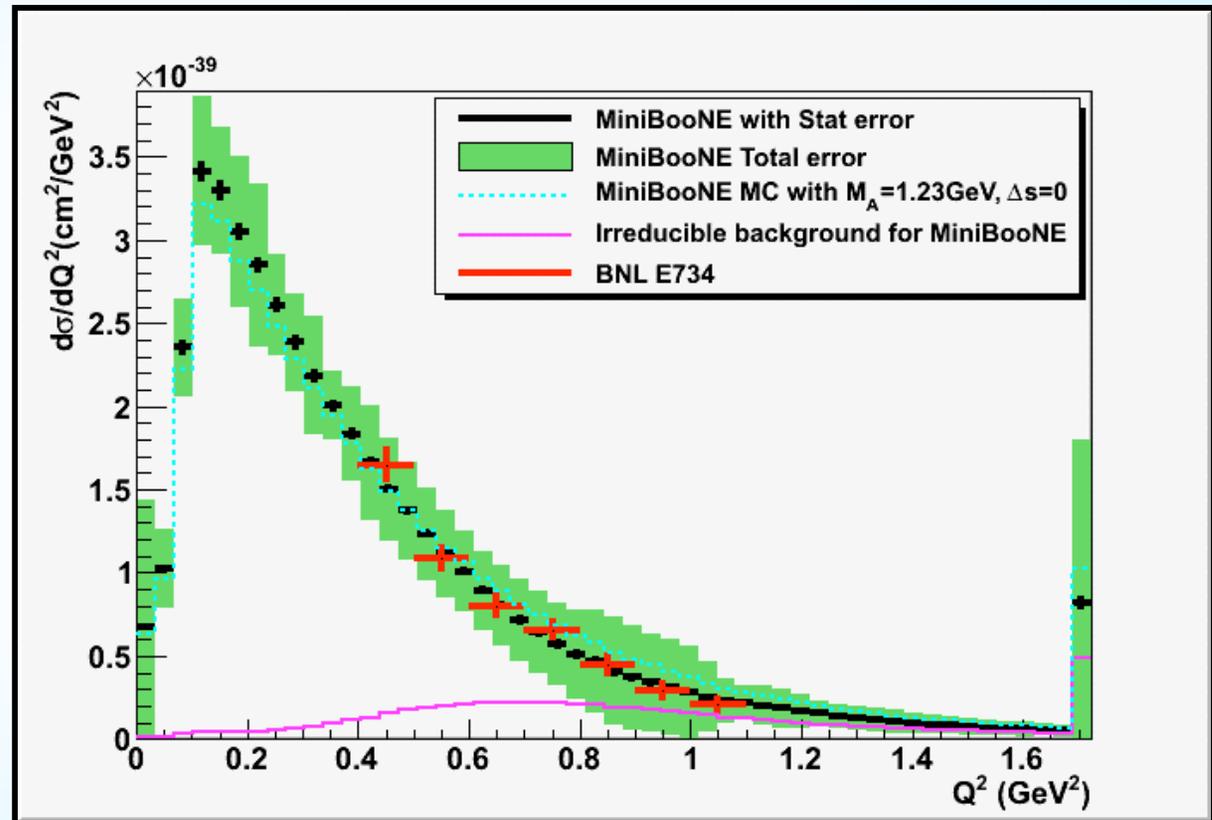


- NC elastic scattering



MiniBooNE:

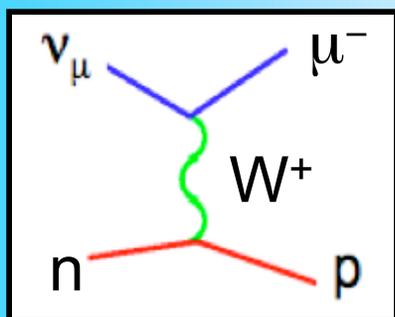
(D. Perevalov)



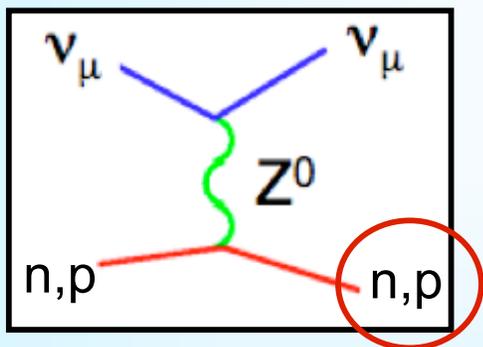
- in agreement w/ **BNL E734 (1987)**; both on ^{12}C
- first to extend reach below $Q^2 < 0.4 \text{ GeV}^2$

NC Elastic Scattering

- CC QE scattering

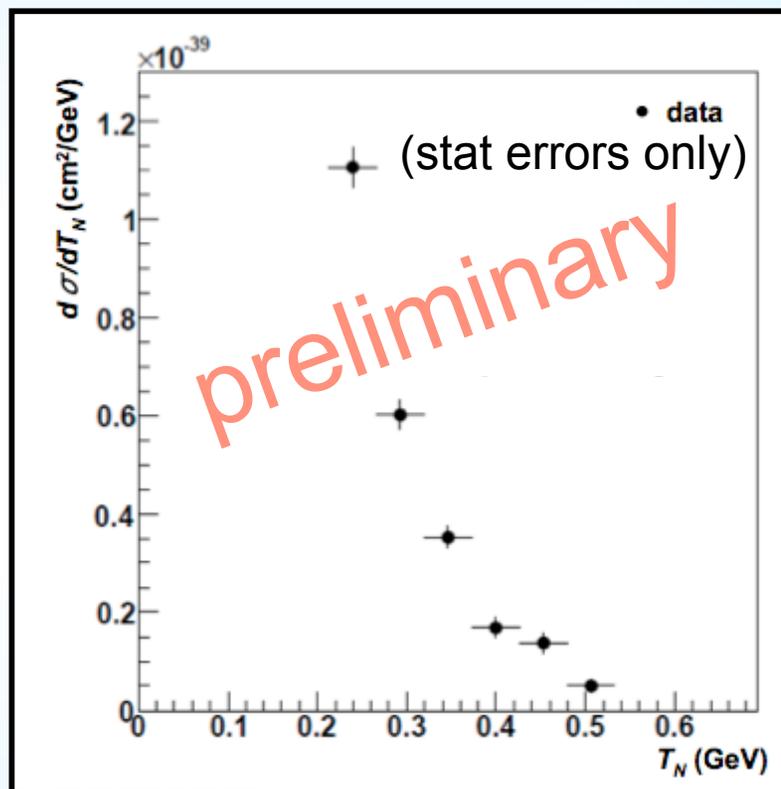


- NC elastic scattering



SciBooNE:

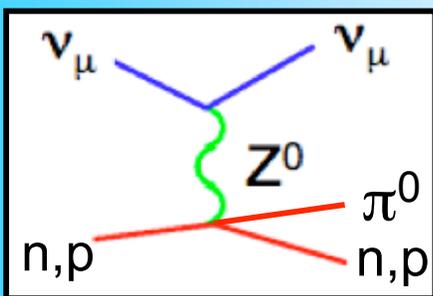
(H. Takei)



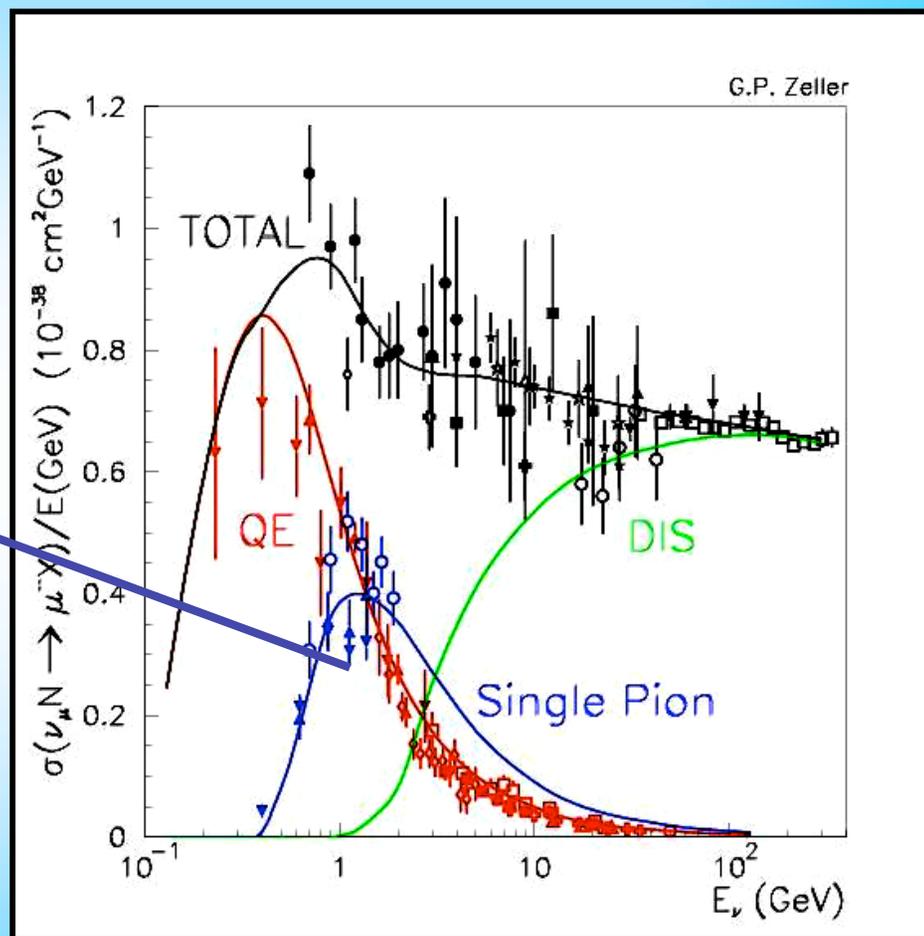
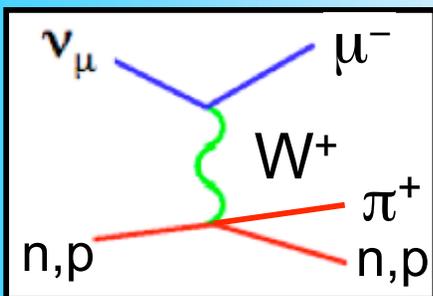
- adding important new data; also on ^{12}C
- 8,441 ν_μ NC EL events (57% purity)

Single π Production

- NC π^0 production



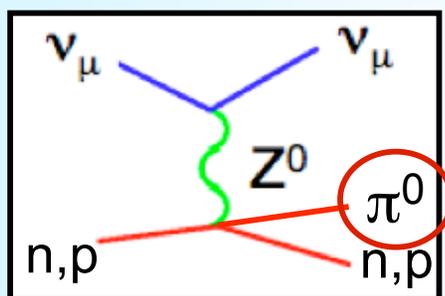
- CC π^+ production



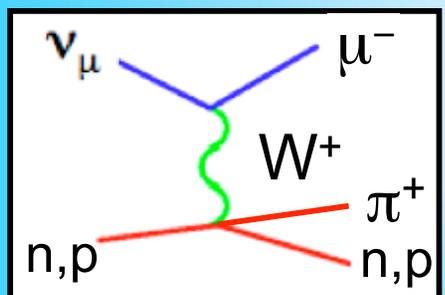
- have both NC and CC counterpart

NC π^0 Production

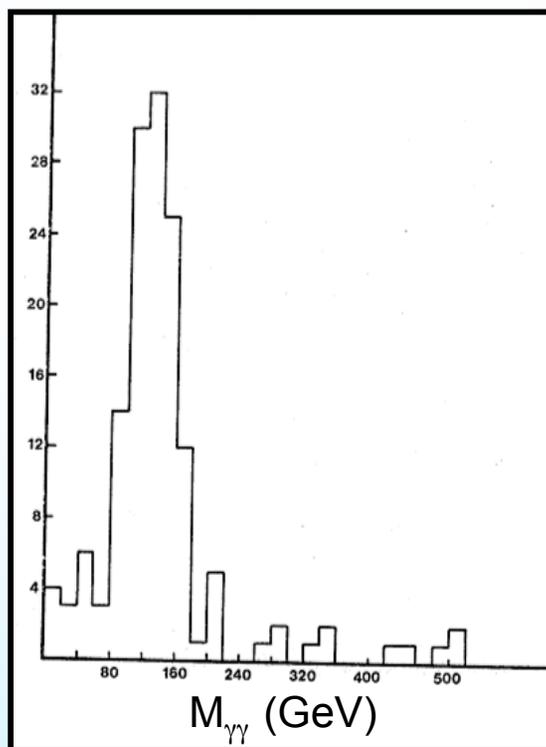
- NC π^0 production



- CC π^+ production



- **background** to $\nu_\mu \rightarrow \nu_e$ searches, θ_{13} final state can mimic a ν_e interaction, $\pi^0 \rightarrow \gamma\gamma$
- very little historical data on this channel

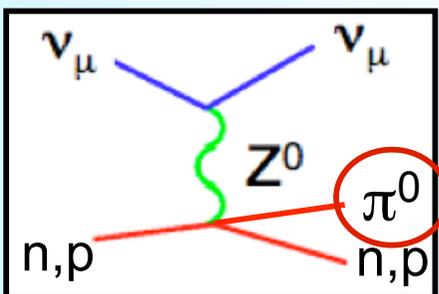


- **cross section** =
of bkg events

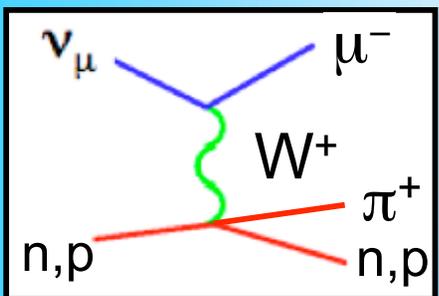
GGM, 240 NC π^0 events
Nucl. Phys. **B135**, 45 (1978)

NC π^0 Production

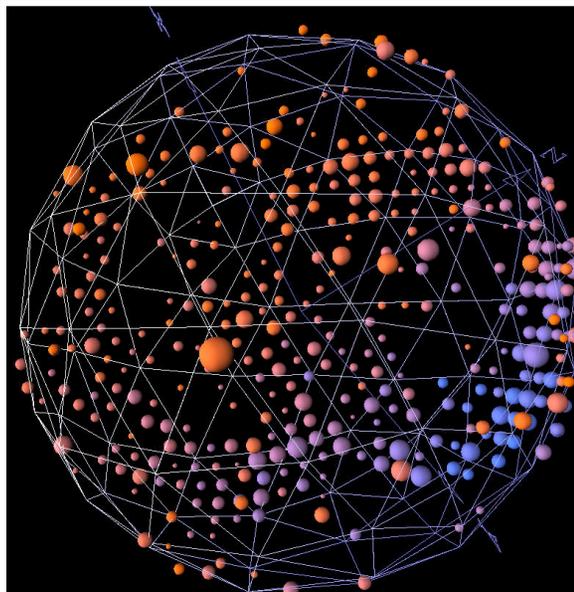
- NC π^0 production



- CC π^+ production



MiniBooNE:



$$\pi^0 \rightarrow \gamma\gamma$$

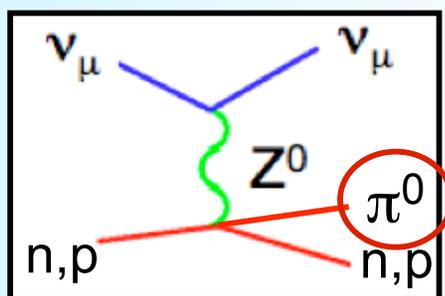
world's largest sample of NC π^0 events
(important constraint for ν_e)

21,542 ν_μ NC π^0 events (73% purity, 36% ϵ)

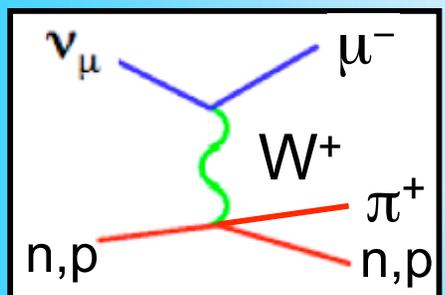
2,305 $\bar{\nu}_\mu$ NC π^0 events (58% purity, 36% ϵ)

NC π^0 Production

- NC π^0 production

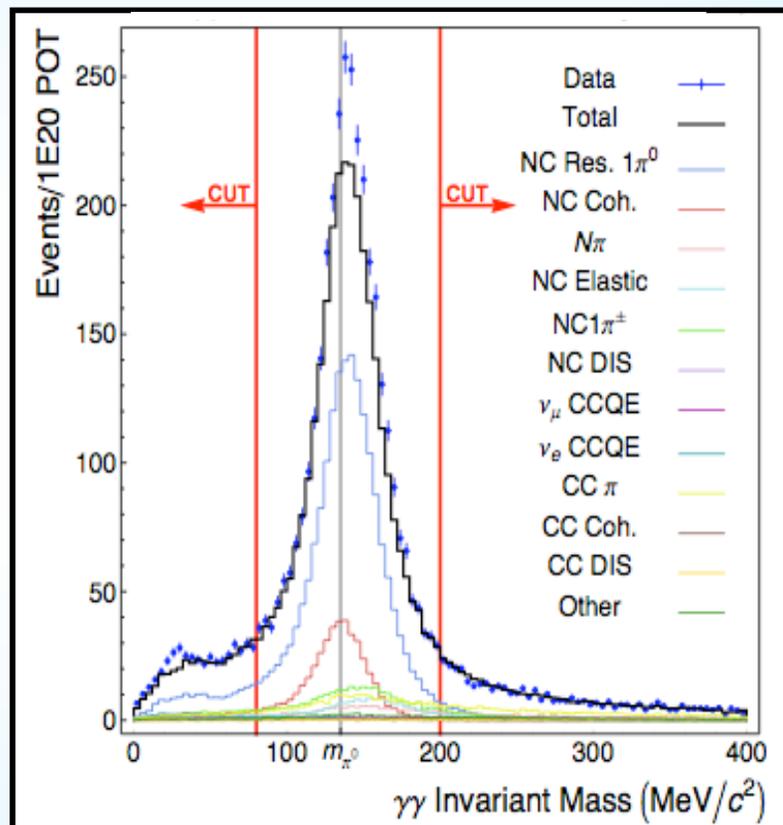


- CC π^+ production



MiniBooNE:

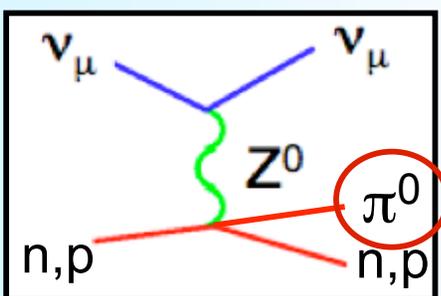
(C. Anderson)



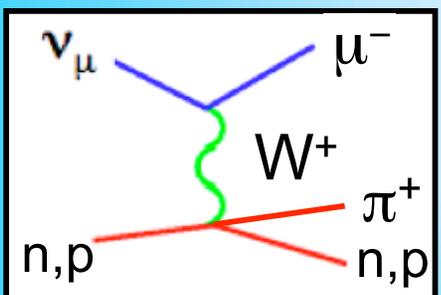
- absolutely normalized (ν mode NC π^0 data/MC = 1.10)
- not so useful outside MB, so ...

NC π^0 Production

- NC π^0 production

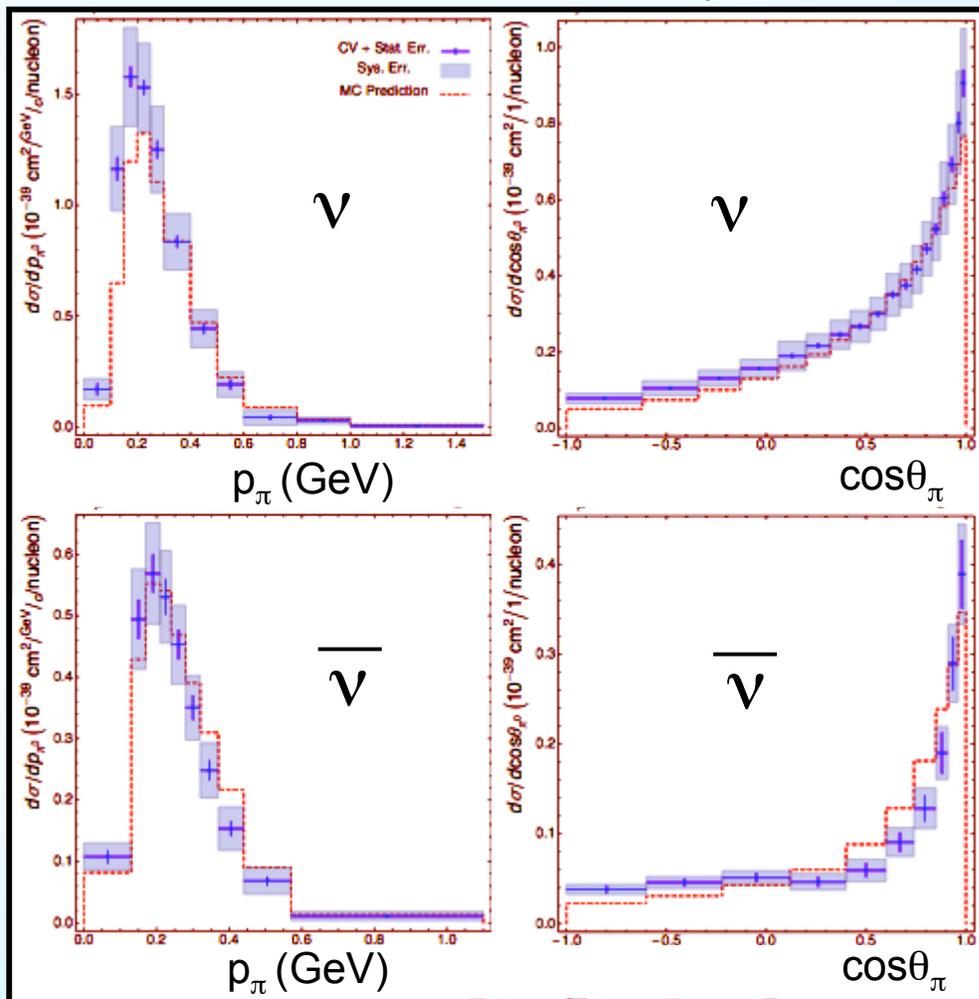


- CC π^+ production



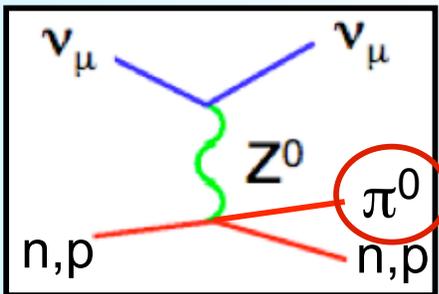
MiniBooNE:

(C. Anderson)

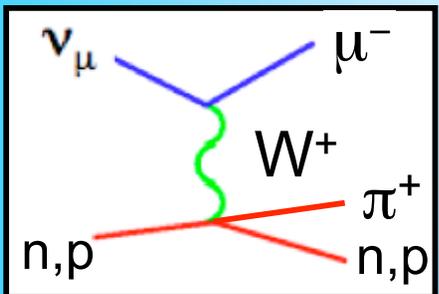


NC π^0 Production

- NC π^0 production

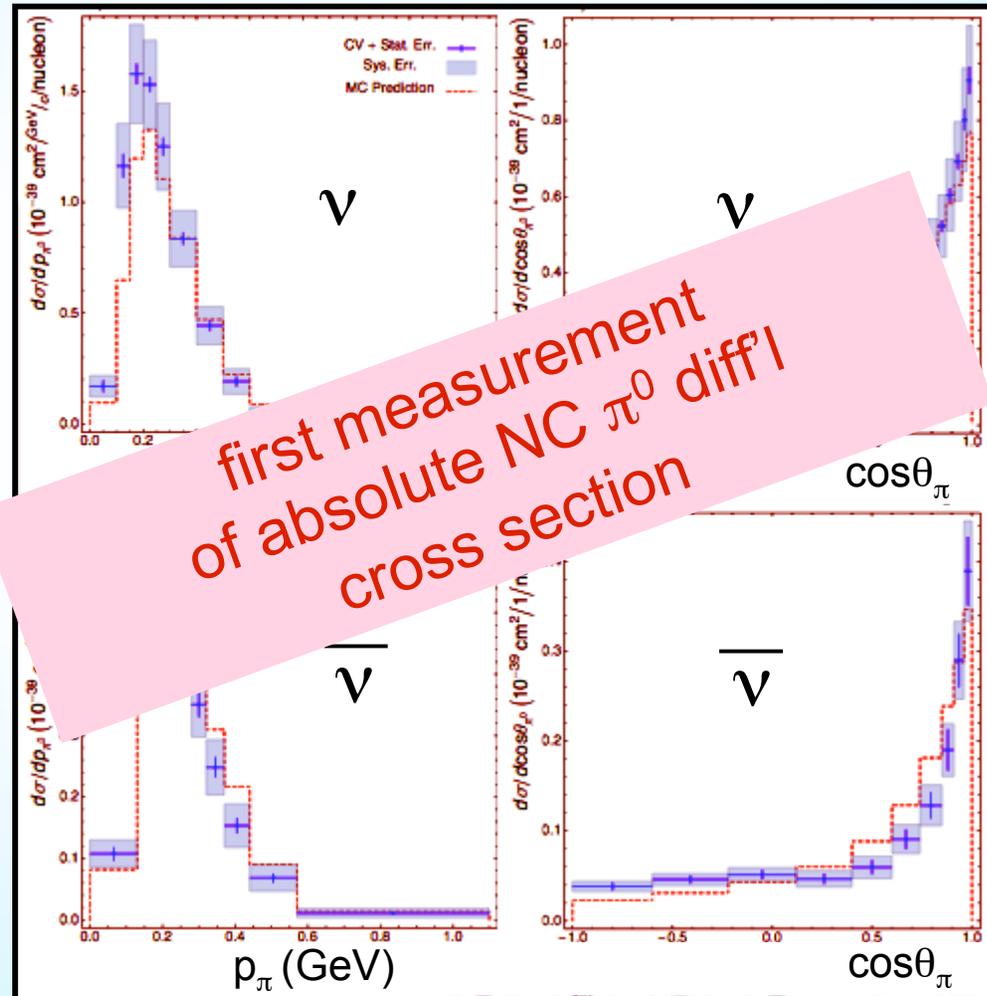


- CC π^+ production



MiniBooNE:

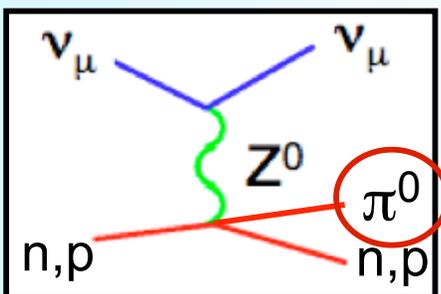
(C. Anderson)



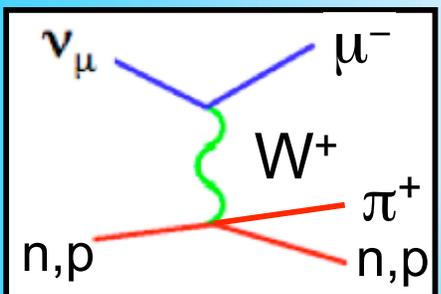
first measurement
of absolute NC π^0 diff'l
cross section

NC π^0 Production

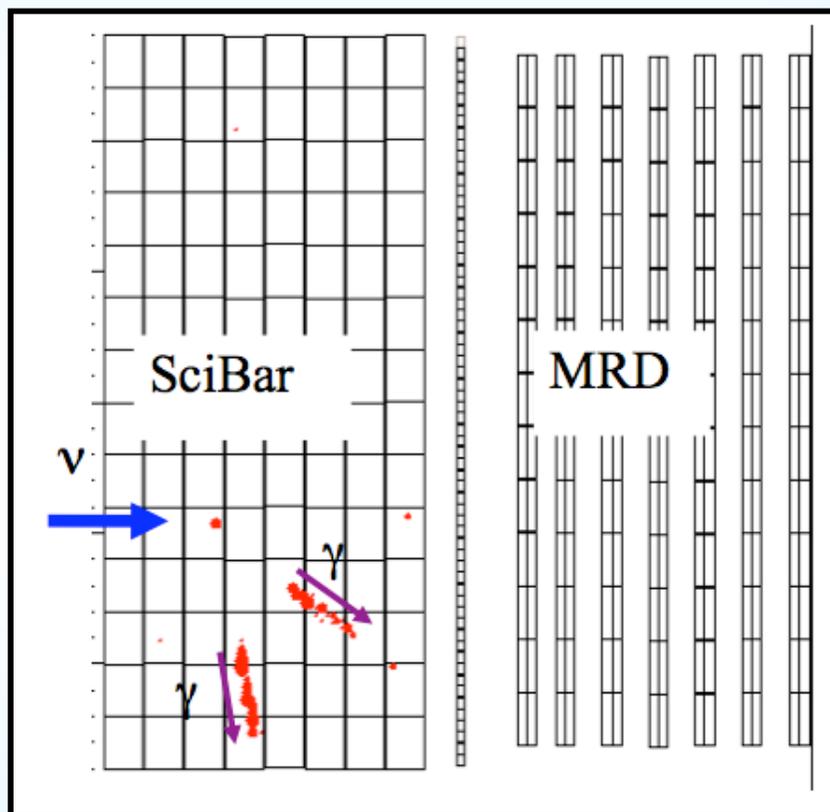
- NC π^0 production



- CC π^+ production



SciBooNE: this is what a π^0 event looks like in SB

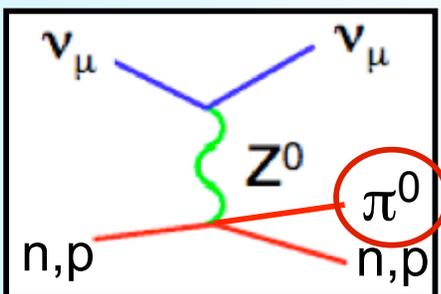


$$\pi^0 \rightarrow \gamma\gamma$$

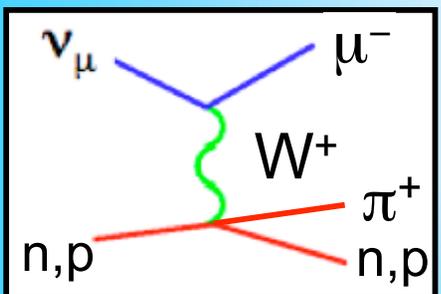
- 545 ν_μ NC π^0 events (63% purity)

NC π^0 Production

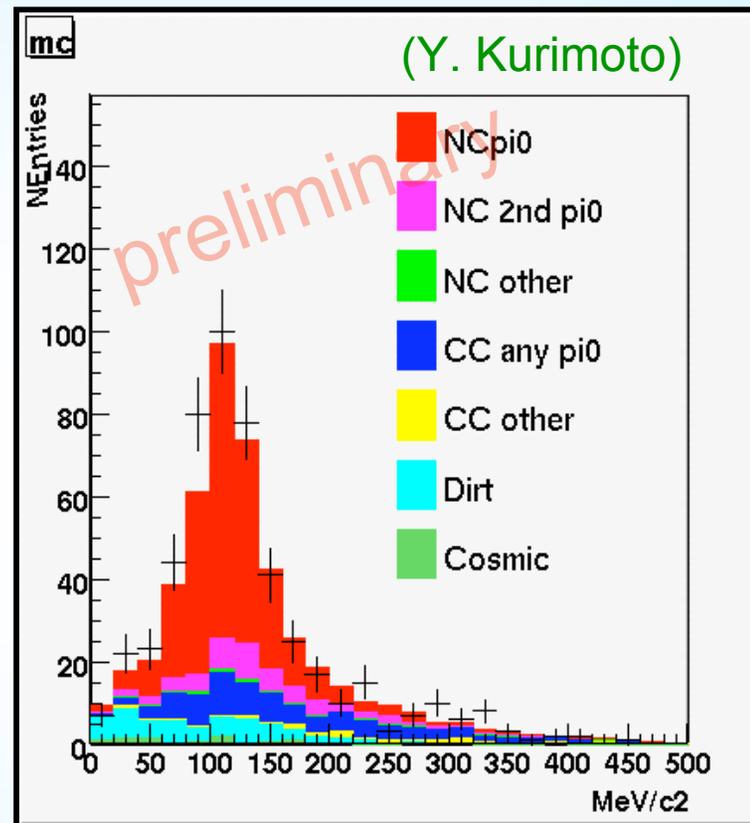
- NC π^0 production



- CC π^+ production



SciBooNE:

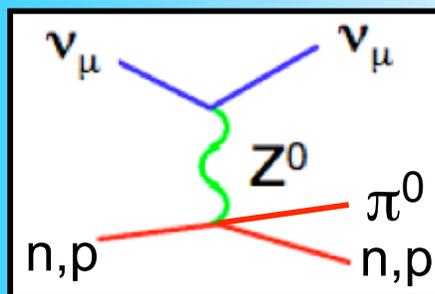


$$\frac{\sigma(\text{NC } \pi^0)}{\sigma(\text{CC inclusive})} = 7.7 \pm 0.6(\text{stat}) \pm 0.6(\text{prelim syst}) \times 10^{-2}$$

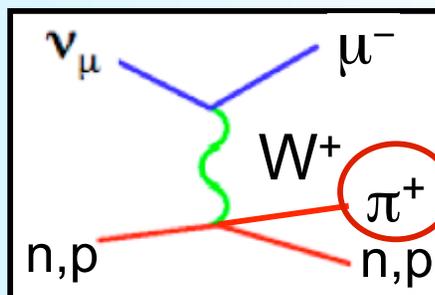
- agrees with NEUT (6.8×10^{-2}), K2K ($6.4 \pm 0.7 \times 10^{-2}$)

CC π^+ Production

- NC π^0 production



- CC π^+ production



- **background to ν_μ disappearance**

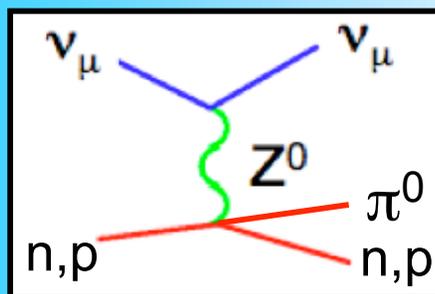
- π^+ absorption = missing E = mis-estimate E_ν
can spoil ν_μ disappearance signal

- future experiments must know CC π^+ fraction to a few-% to measure $\Delta m^2_{23}, \theta_{23}$
(example: 5-10% is quoted goal for T2K)

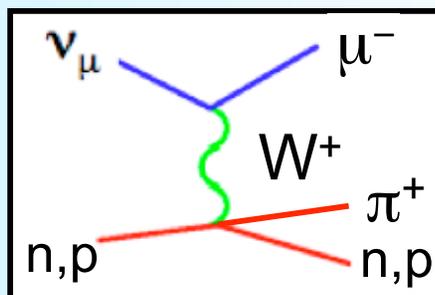
- want to know cross section as fcn E_ν

CC π^+ Production

- NC π^0 production

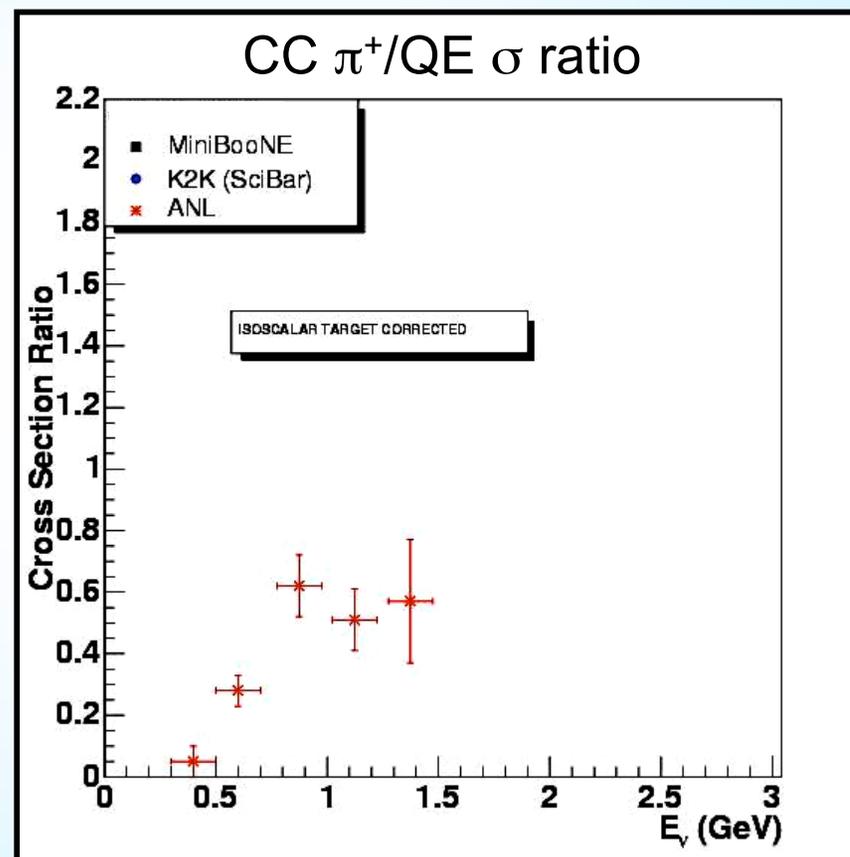


- CC π^+ production



this has been
state of the art

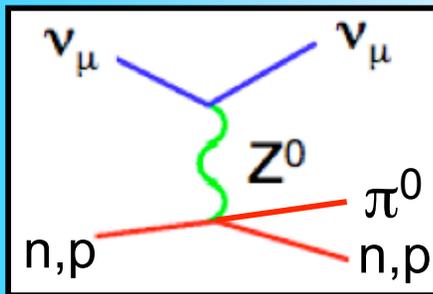
(S. Linden)



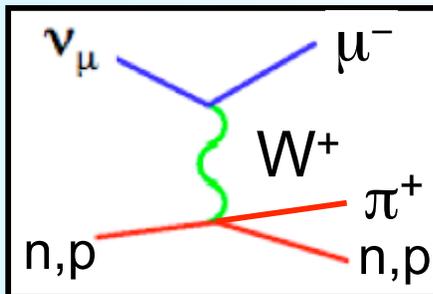
ANL: Phys. Rev. **D25**, 1161 (1982), deuterium

CC π^+ Production

- NC π^0 production

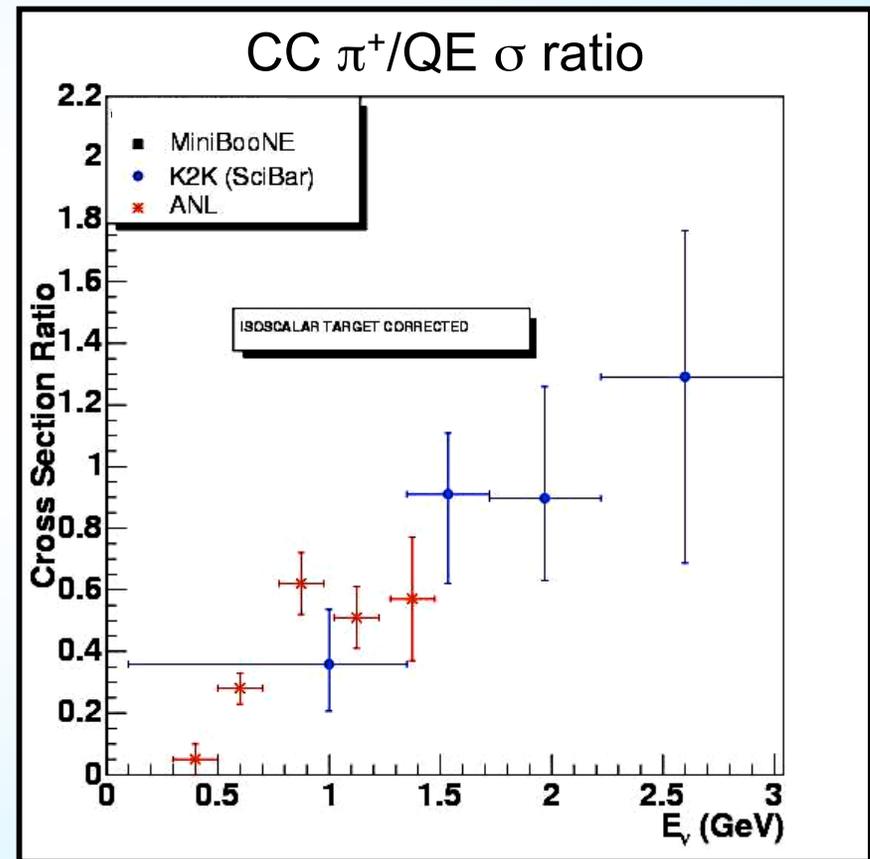


- CC π^+ production



26 years
later ...

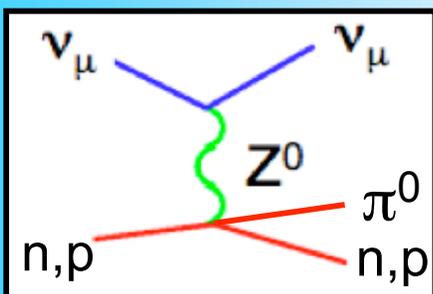
(S. Linden)



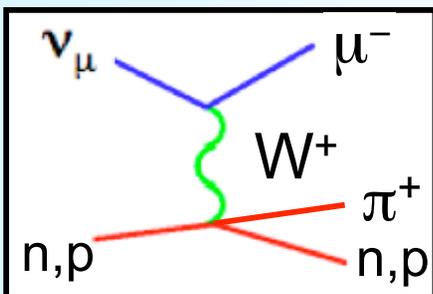
K2K: Phys. Rev. **D78**, 032003 (2008), carbon

CC π^+ Production

- NC π^0 production

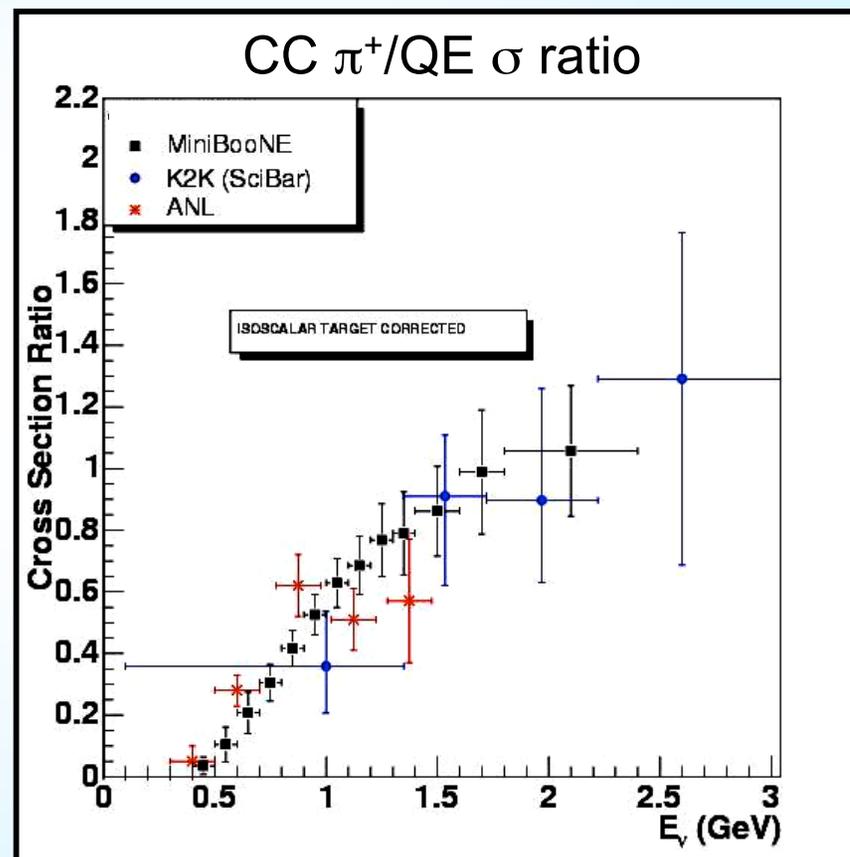


- CC π^+ production



paper
submitted
last month

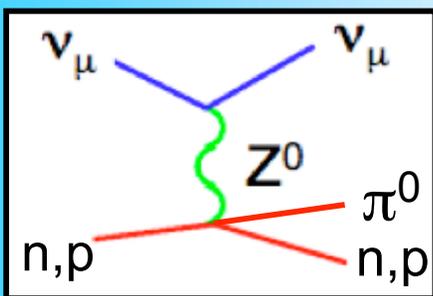
(S. Linden)



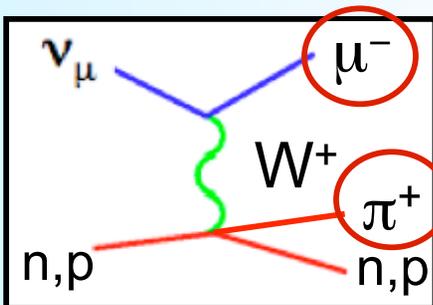
MiniBooNE: arXiv:0904.3159 [hep-ex], carbon

CC π^+ Production

- NC π^0 production



- CC π^+ production



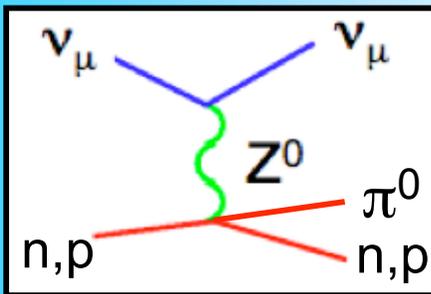
MiniBooNE:

(M. Wilking)

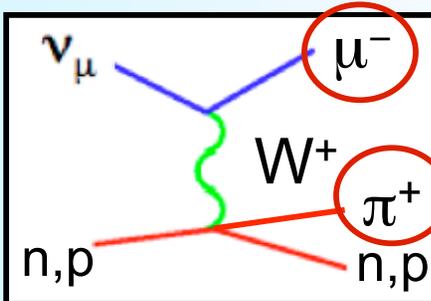
- developed new $\mu + \pi^+$ fitter (a first for $\bar{\nu}_\mu$)
- correctly identify μ, π^+ 88% of time
- 48,000 CC π^+ events (90% purity)

CC π^+ Production

- NC π^0 production

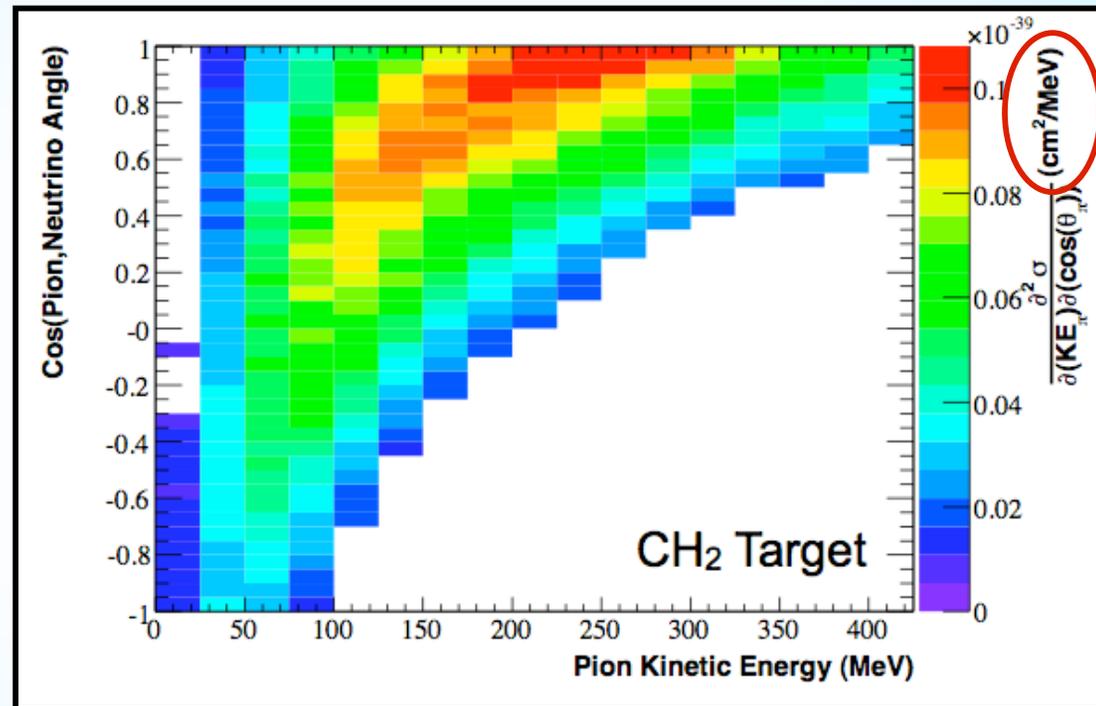


- CC π^+ production



MiniBooNE:

(M. Wilking)

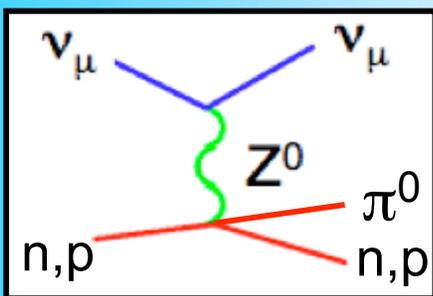


- measured 8 different cross sections:

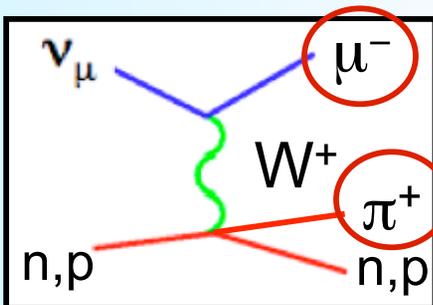
$$\sigma(E_\nu), d\sigma/dQ^2, d^2\sigma/dT_\mu d\theta_\mu, d\sigma/dT_\mu, d\sigma/d\theta_\mu, d\sigma/dT_\pi, d\sigma/d\theta_\pi, d^2\sigma/dT_\pi d\theta_\pi$$

CC π^+ Production

- NC π^0 production

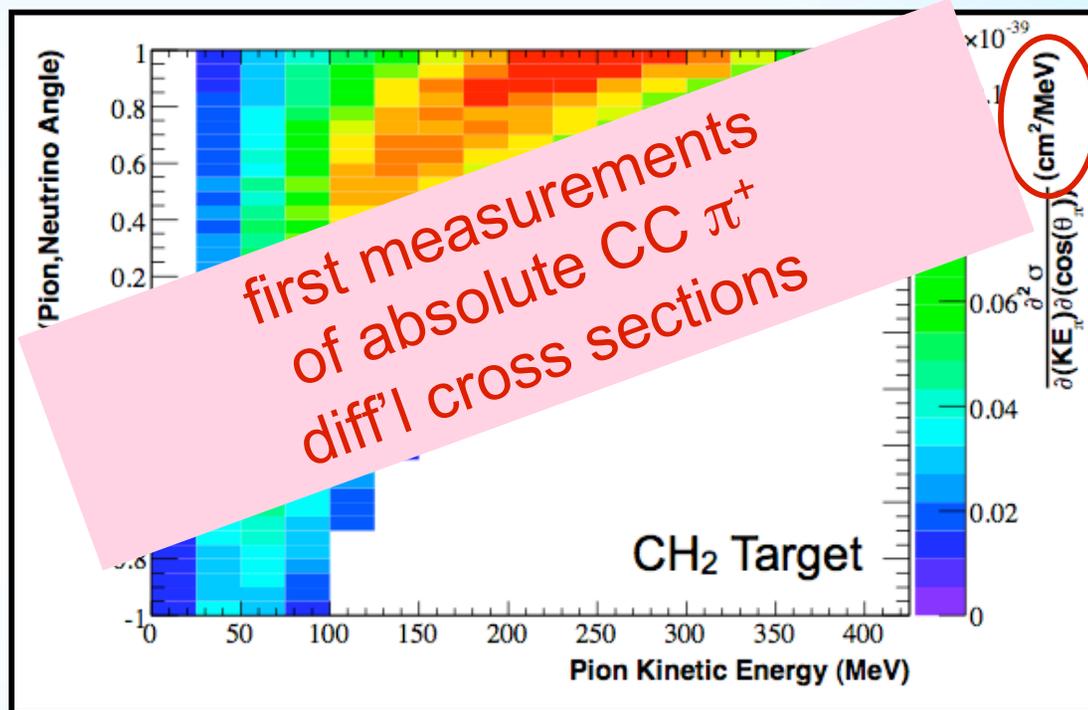


- CC π^+ production



MiniBooNE:

(M. Wilking)

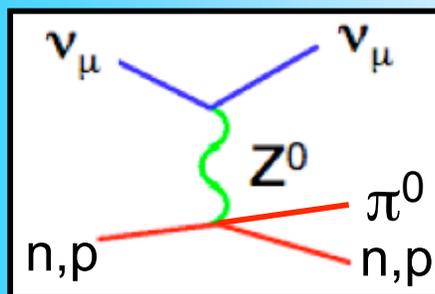


- measured 8 different cross sections:

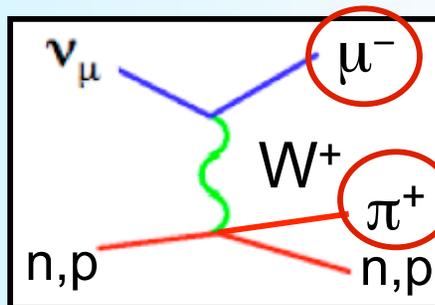
$$\sigma(E_\nu), d\sigma/dQ^2, d^2\sigma/dT_\mu d\theta_\mu, d\sigma/dT_\mu, d\sigma/d\theta_\mu, d\sigma/dT_\pi, d\sigma/d\theta_\pi, d^2\sigma/dT_\pi d\theta_\pi$$

CC π^+ Production

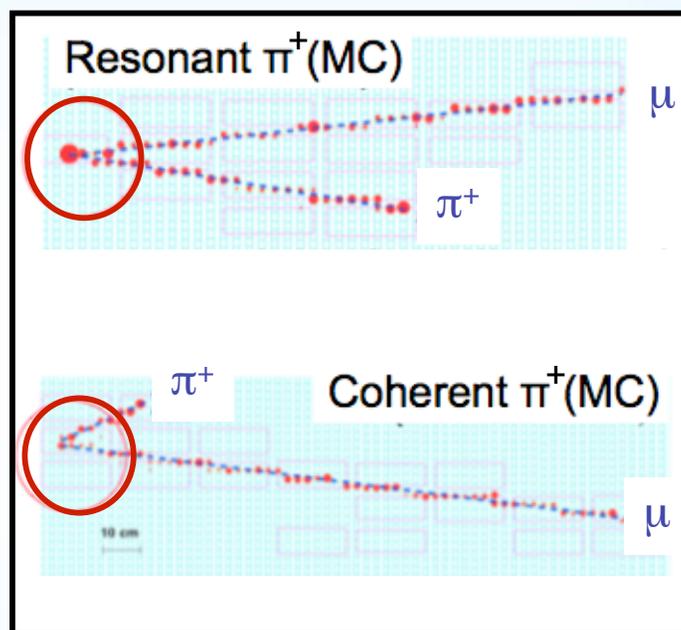
- NC π^0 production



- CC π^+ production



SciBooNE: has probed this interaction even further

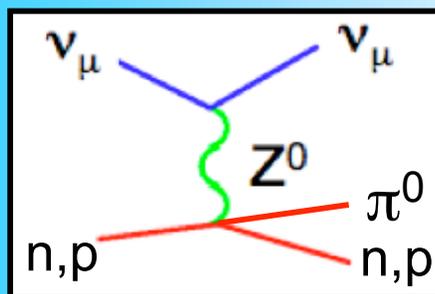


← rare

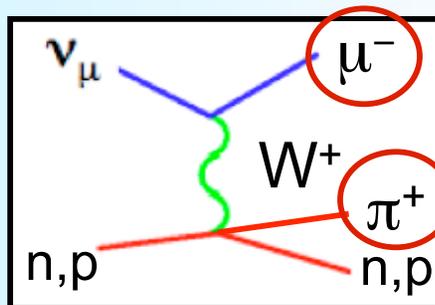
- two ways can be produced
- SB can isolate coherent mode of production
- search for events with small vertex activity
- can't be done on MiniBooNE

CC π^+ Production

- NC π^0 production

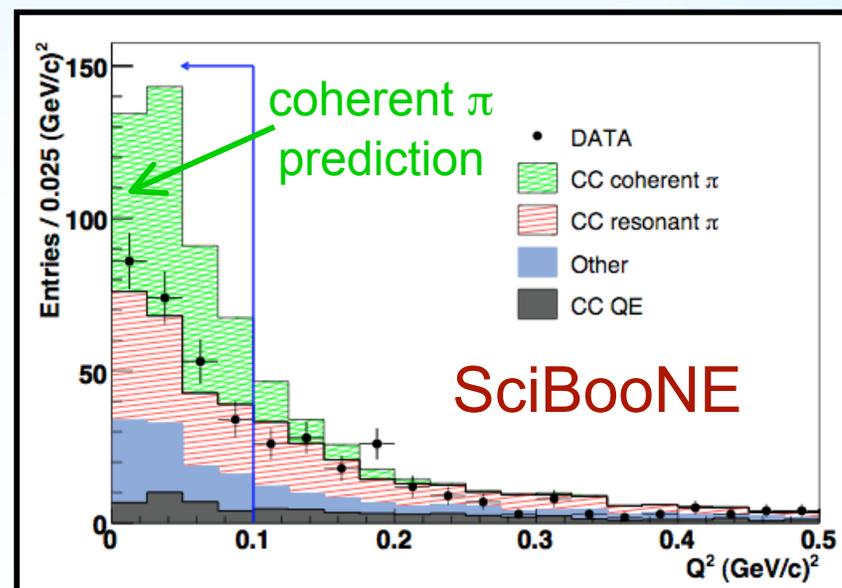


- CC π^+ production



SciBooNE:

(K. Hiraide)

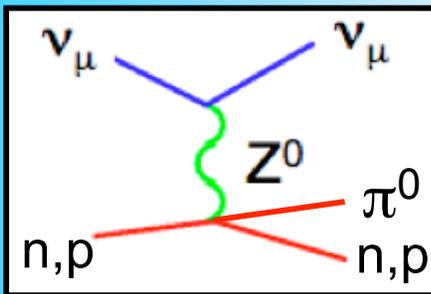


PRD 78, 112004 (2008)

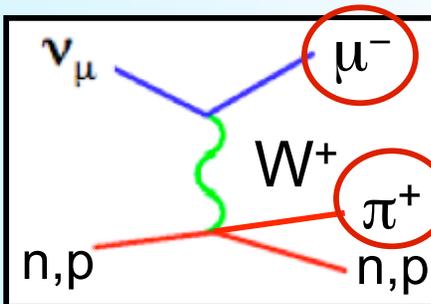
- first physics publication from SciBooNE
FNAL W&C November 2008
- updated analysis currently underway
(expanded kinematic search, both ν and $\bar{\nu}$)

CC π^+ Production

- NC π^0 production

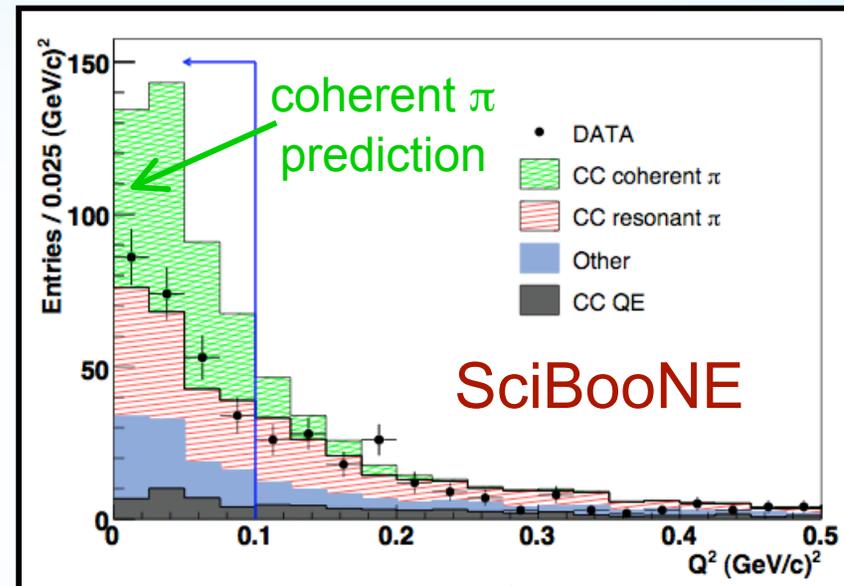


- CC π^+ production



SciBooNE:

(K. Hiraide)



PRD 71 012004 (2008)

- first physics publication
FNAL W&C November 2008
- updated analysis currently under review
(expanded kinematic search, both ν and $\bar{\nu}$)

stay tuned!

to recap:

	neutrino σ results
CC π^+ /QE (S. Linden, J. Nowak)	σ ratio in E_ν
ν_μ CC QE (T. Katori)	$d^2\sigma/dT_\mu d\theta_\mu$ $d\sigma/dQ^2, \sigma(E_\nu)$
ν_μ NC EL (D. Perevalov)	$d\sigma/dQ^2$
ν_μ CC π^+ (M. Wilking)	$d\sigma/dT_\mu, d\sigma/d\theta_\mu, d^2\sigma/dT_\mu d\theta_\mu$ $d\sigma/dT_\pi, d\sigma/d\theta_\pi, d^2\sigma/dT_\pi d\theta_\pi$ $d\sigma/dQ^2, \sigma(E_\nu)$
$\nu_\mu, \bar{\nu}_\mu$ NC π^0 (C. Anderson)	$d\sigma/dp_\pi$ $d\sigma/d\theta_\pi$
ν_μ CC QE (J. Alcaraz)	$\sigma(E_\nu)$
ν_μ NC EL (H. Takei)	$d\sigma/dT_N$
$\nu_\mu, \bar{\nu}_\mu$ CC π^+ (K. Hiraide, H. Tanaka)	coherent π^+ σ
ν_μ NC π^0 (Y. Kurimoto)	$\sigma(\text{NC}\pi^0)/\sigma(\text{CC})$

MiniBooNE
(2002-2009)

many firsts!

SciBooNE
(2007-2009)

Recent Publications

- since 2008, **MB** has published/submitted 10 papers
 - “Measurement of CC π^+ /QE σ Ratio on CH_2 in a 0.8 GeV ν Beam”, [arXiv:0904.3159](#), submitted to PRL
 - “A Search for ν_e Appearance at the $\Delta m^2 \sim 1 \text{ eV}^2$ Scale”, [arXiv:0904.1958](#), submitted to PRL
 - “A Search for ν_μ and $\bar{\nu}_\mu$ Disappearance in MiniBooNE”, [arXiv:0903.2465](#), submitted to PRL
 - “Unexplained Excess of Electron-Like Events from a 1 GeV ν Beam”, [PRL 102](#), 101802 (2009)
 - “1st Measurement of ν_μ, ν_e Events in Off-Axis Horn-Focused ν Beam”, [PRL 102](#), 211801 (2009)
 - “The MiniBooNE Detector”, [NIM A599](#), 28 (2009)
 - “The ν Flux Prediction at MiniBooNE”, [PRD 79](#), 072002 (2009)
 - “Compatibility of High $\Delta m^2 \nu_e$ and ν_e Oscillation Searches”, [PRD 78](#), 012007 (2008)
 - “1st Observation of Coherent π^0 Production in ν -Nucleus Interactions with $E_\nu < 2 \text{ GeV}$ ”, [PL B664](#), 41 (2008)
 - “Measurement of ν_μ Quasi-Elastic Scattering on Carbon”, [PRL 100](#), 032301 (2008)
 - graduated 6 PhD students (more to come!)
-
- **SB** published 1st physics paper 4 months after 1 year run
 - “Search for CC Coherent π^+ Production on Carbon in a Few-GeV ν Beam”, [PRD 78](#), 112004 (2008)
 - plus many conference proceedings
 - graduated 3 PhD students (more to come!)

Conclusions

- both collaborations have been extremely active in past year
- **MiniBooNE** released 3 new neutrino oscillation results (& associated publications)
- both **MiniBooNE** and **SciBooNE** have a flood of new low energy σ_ν measurements ($E_\nu < 2$ GeV)
 - important for ν oscillation exps
 - **Fermilab** poised to dramatically change current landscape & our understanding of ν interactions:
 - **MiniBooNE, SciBooNE ... Booster ν 's**
 - **MINOS, MINER ν A ... MI ν 's**
- can look forward to even more to come!

