

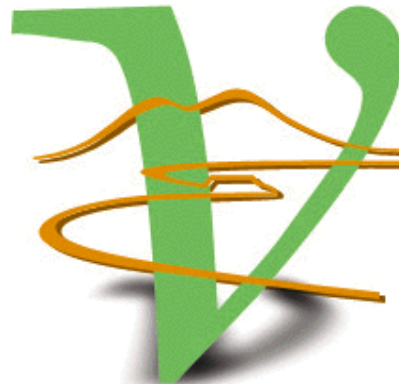
Workshop on

# PHYSICS WITH A MULTI-MW PROTON SOURCE

CERN, Geneva, May 25-27, 2004

## Physics of neutrino interactions (i.e. why do we need good SBL experiments at future facilities?)

Pasquale Migliozzi  
INFN - Napoli





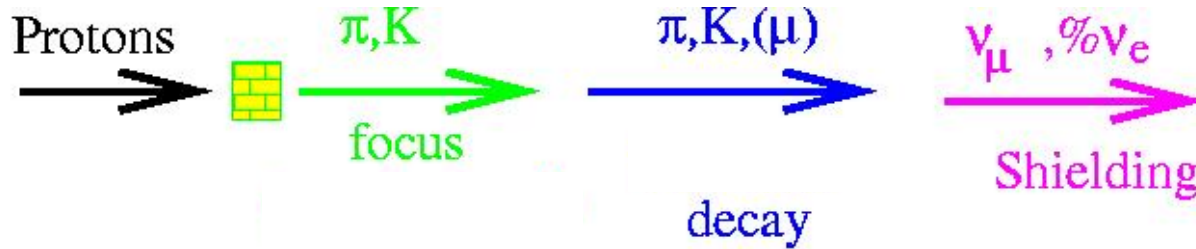
# Motivations

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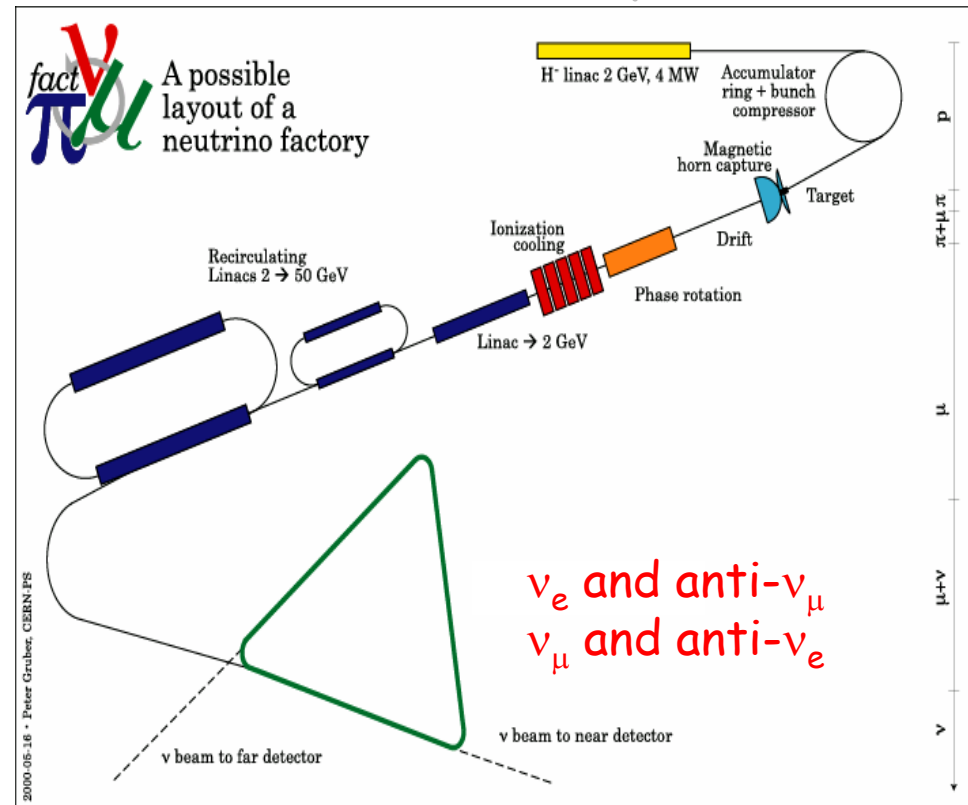
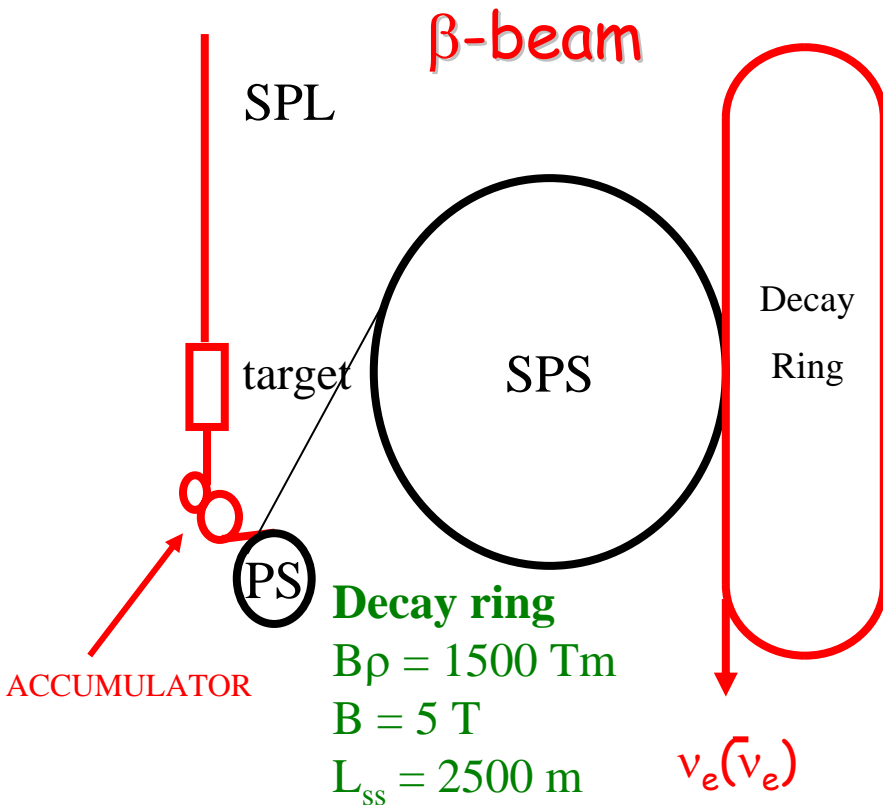
The study of neutrino interactions in a SBL experiment at future facilities follows two lines of research

- **Measurements ancillary to Neutrino Oscillations**
- **Standard neutrino scattering**
  - Quasi-elastic, resonance and coherent pion production
  - $Q^2$  dependence badly known
  - Transition to DIS regime
  - Nuclear effects and their  $A$  dependence
  - Structure functions at low  $Q^2$ 
    - Precise measurement of low energy cross-section
    - Understand the transition to the DIS regime
  - Address the NuTeV anomaly
  - Pentaquark searches
  - Neutrino magnetic moment
  - Strange content of the nucleon
  - ...

# SuperBeams (Conventional $\nu$ beam)

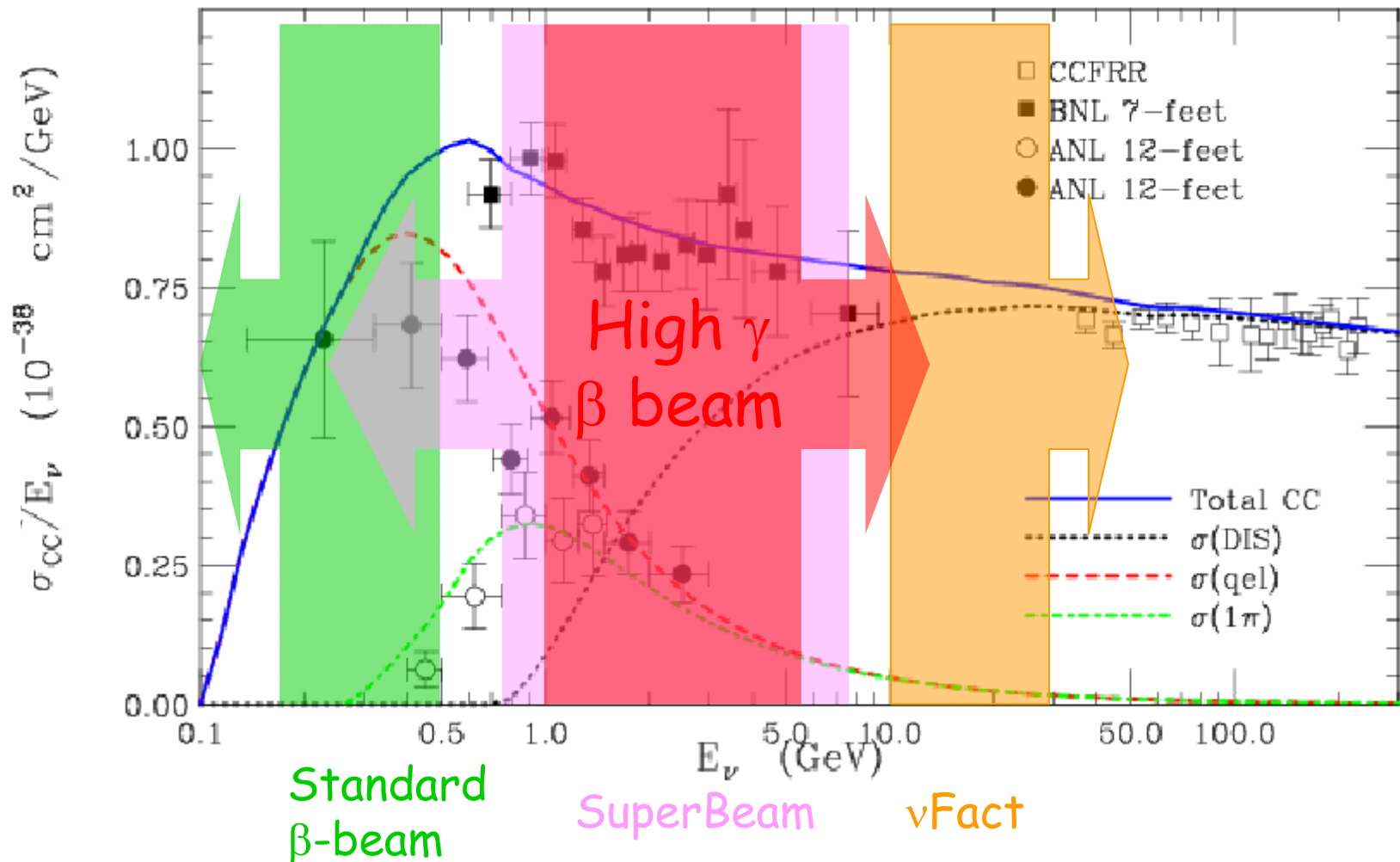


# $\nu$ -Factory

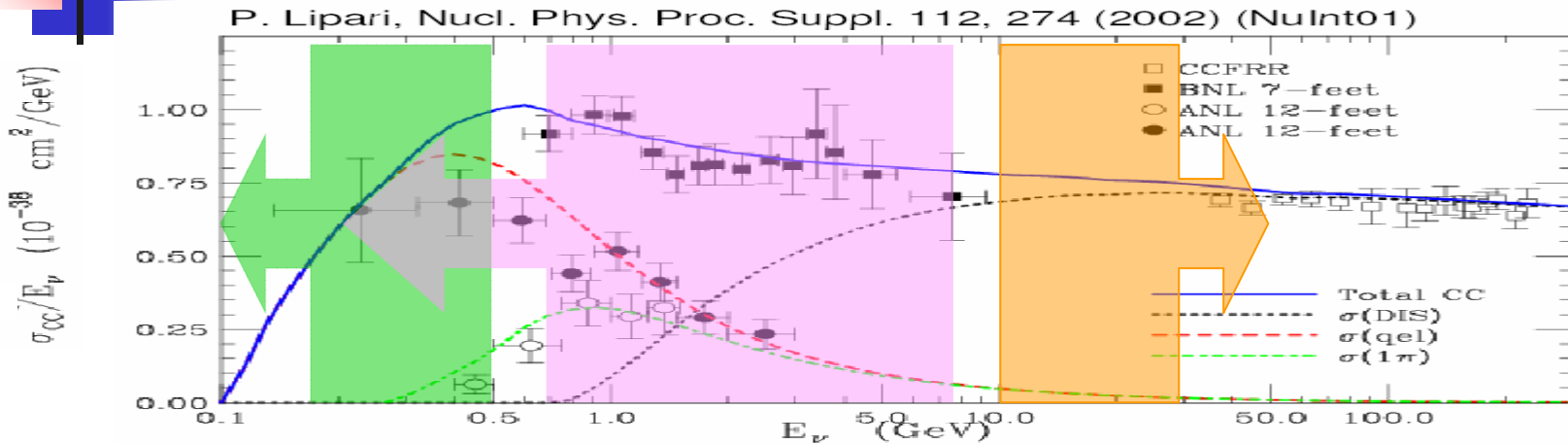


# Different $\nu$ beams $\Rightarrow$ different energy spectra

P. Lipari, Nucl. Phys. Proc. Suppl. 112, 274 (2002) (NuInt01)



# Different energy spectra ⇒ different detectors

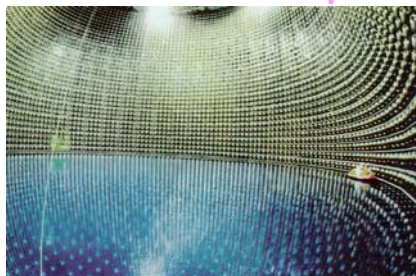


$\beta$ -beam

SuperBeam

$\nu$ Fact

Water Cerenkov  
(SK photo ⇒)

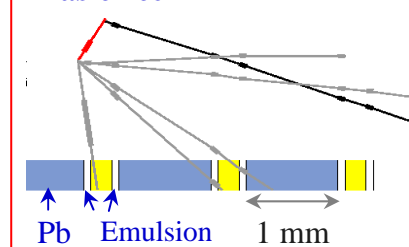


Liquid Argon  
(Icarus T600 ⇒)



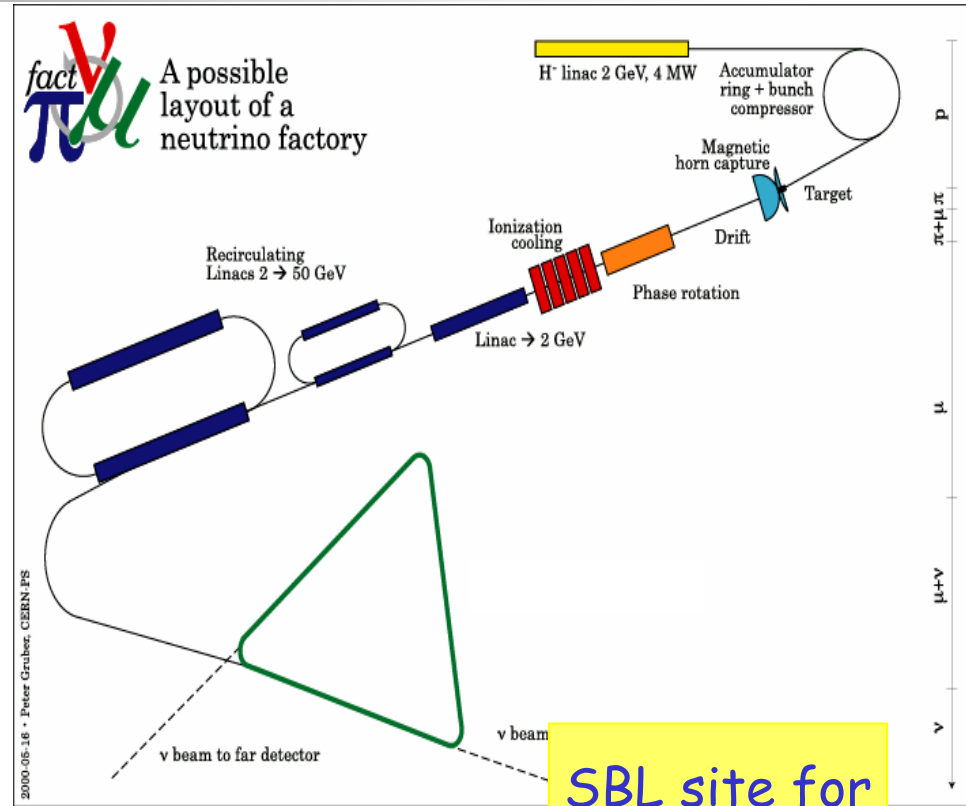
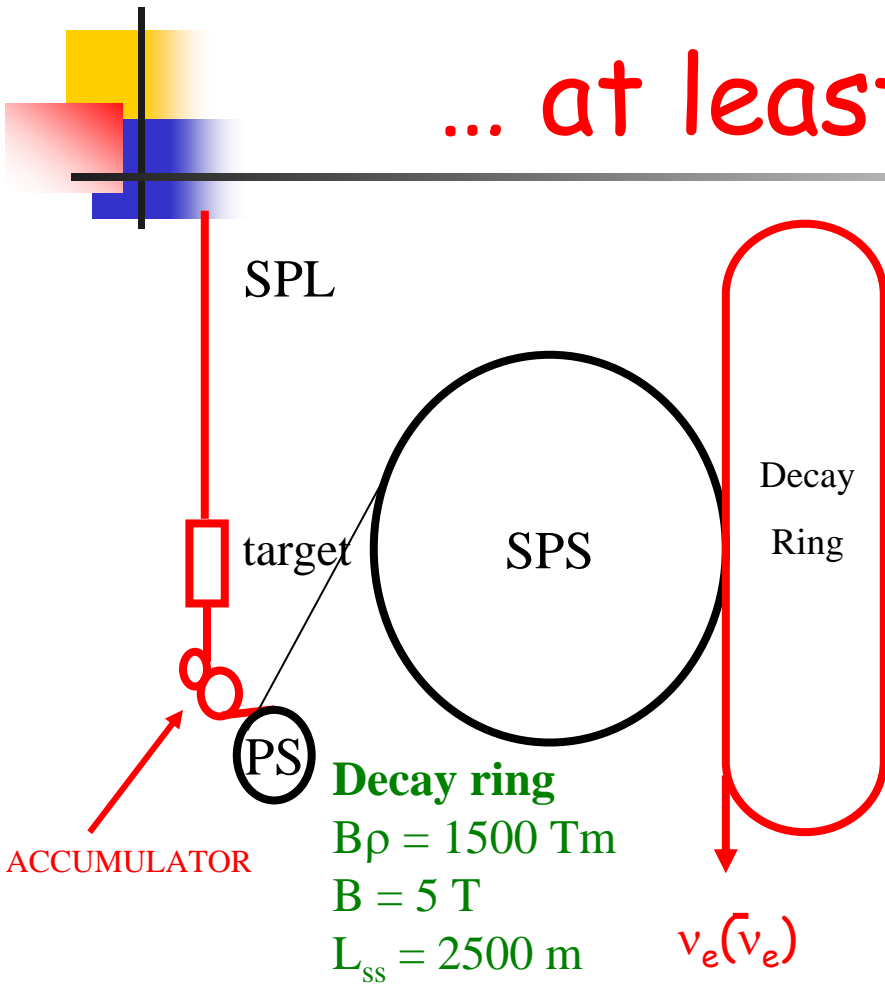
Magnetized calo  
for  $\nu_e \rightarrow \nu_\mu$  search  
(⇐ MINOS photo)

Basic "cell"



ECC technique  
for  $\nu_e \rightarrow \nu_\tau$  search  
(⇐ OPERA concept)

... at least two SBL sites



Common SBL site for both SuperBeam and  $\beta$ -beam



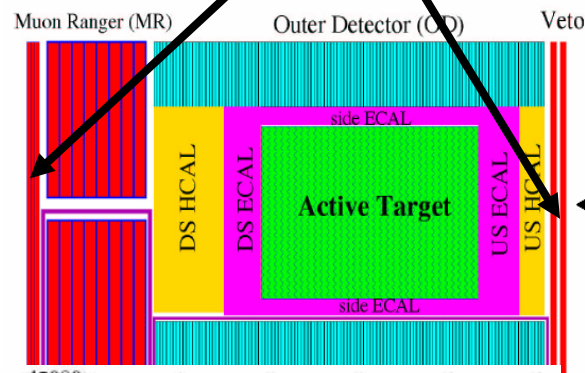
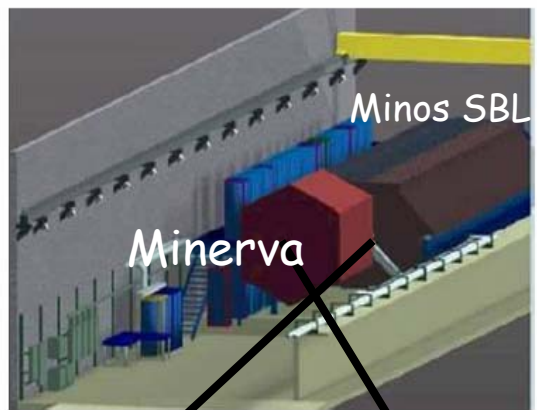
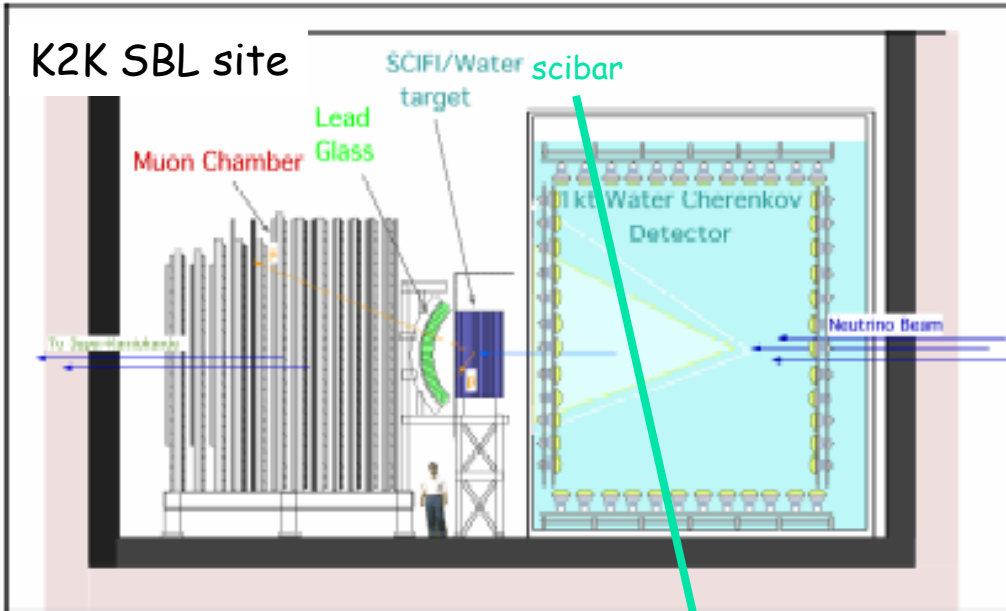
# ... two detectors per site

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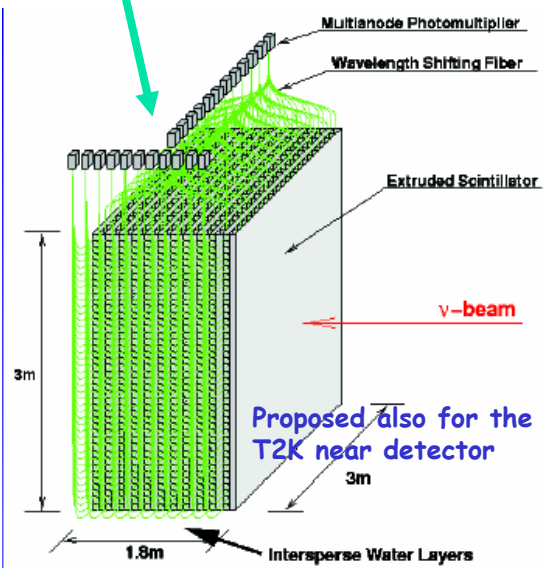
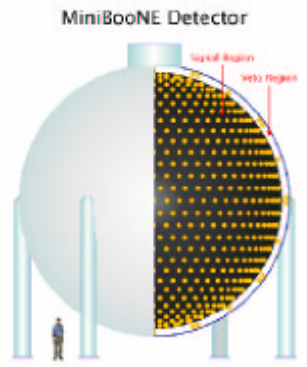
- A coarse grain detector
  - AIM: minimize the near to far extrapolation (important for neutrino oscillation studies)
  - NB: the detector should be built as similar as possible to the far one
- Fine grain detector
  - AIM: study the details of neutrino interactions
  - NB: any suitable technique (not necessarily equal to the one of the far site) is OK

NB At a  $\nu$ Factory, given the huge neutrino flux, a few kg SBL detector is enough!!!  $\Rightarrow$  very detailed study of the events

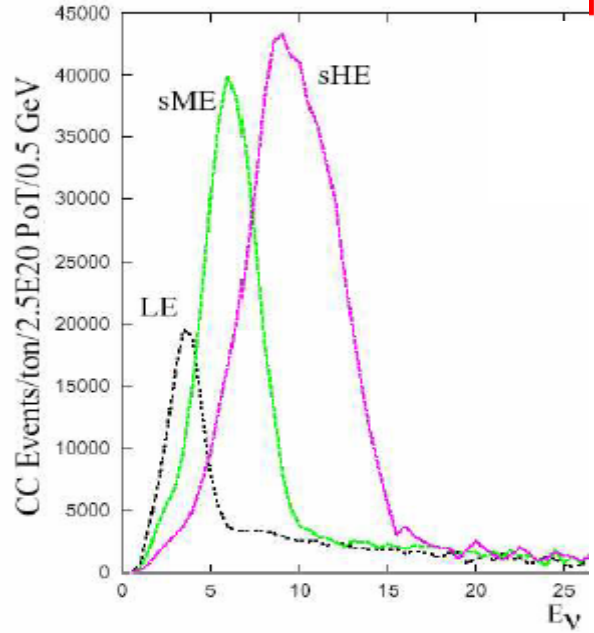
# Examples of existing and foreseen SBL exps



## MiniBooNE



Proposed also for the T2K near detector







# What do we need for $\nu$ oscillations?

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- The accuracy and the information depend on the oscillation channel
  - K2K  $\nu_e$  appearance search (the key channel at the SuperBeam to measure  $\theta_{13}$ ): total uncertainty about 30% out of which more than 20% is accounted for by the uncertainty on the NC cross-section!
  - K2K  $\nu_\mu$  disappearance search: main uncertainties are the far/near ratio ( $\sim 5\%$ ) and the absolute normalization (5%)



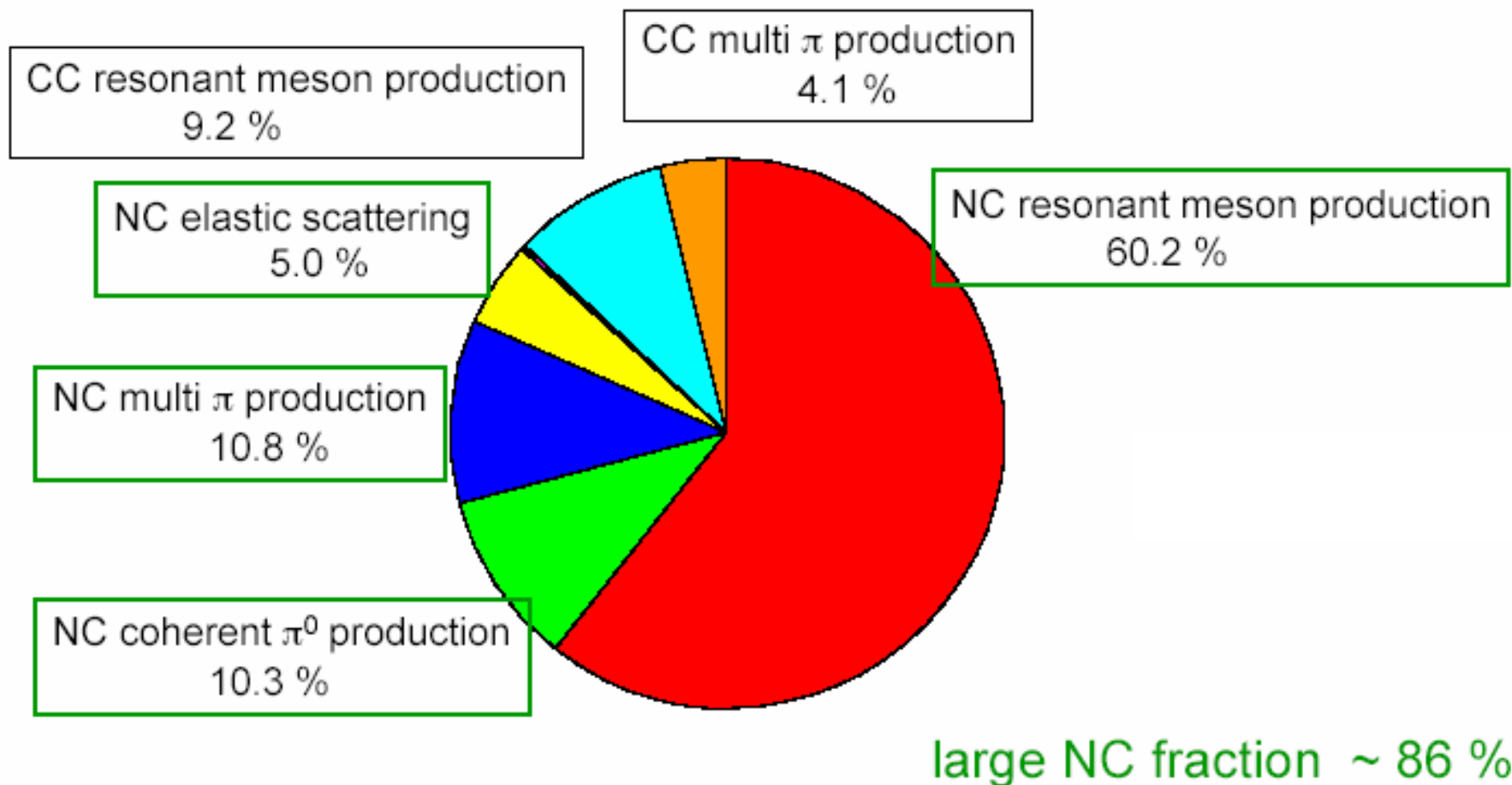
# $\nu_\mu \rightarrow \nu_x$ appearance searches

The error on the oscillation probability can be written as

$$\left(\delta P\right)^2 = \frac{\left(N_{far} + \delta B_{far}\right)^2}{\left(\phi_{\nu_\mu} \sigma_{\nu_x} \varepsilon_x M_{far}\right)^2} + \left(N_{far} - B_{far}\right) \left( \left[ \frac{\delta \phi_{\nu_\mu}}{\phi_{\nu_\mu}} \right]^2 + \left( \frac{\delta \sigma_{\nu_x}}{\sigma_{\nu_x}} \right)^2 + \left( \frac{\delta \varepsilon_{\nu_x}}{\varepsilon_{\nu_x}} \right)^2 \right)$$

- Uncertainty on the expected background
- Uncertainty on the neutrino flux (normalization and energy dependence)
- Uncertainty on the neutrino cross-sections
- Uncertainty on the detection efficiencies (energy dependence and absolute value)

# The fraction of each interaction channel



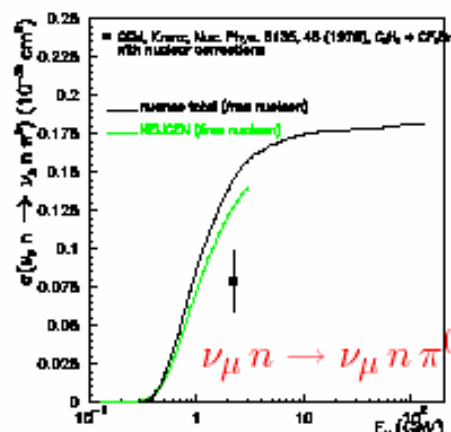
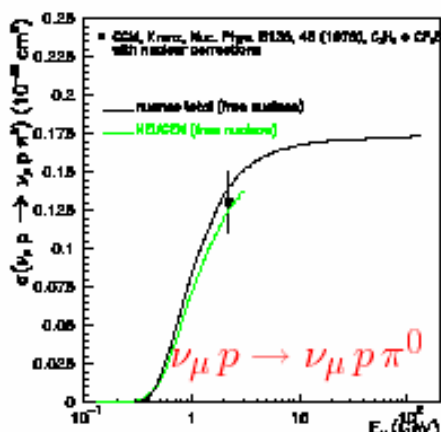
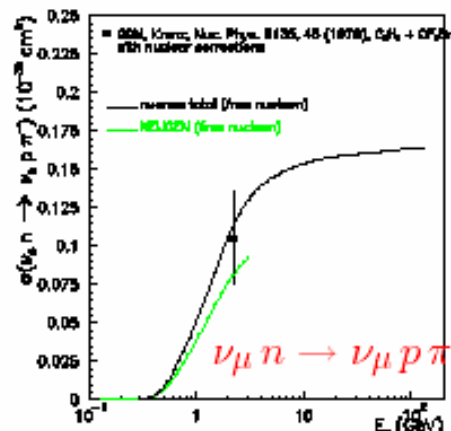
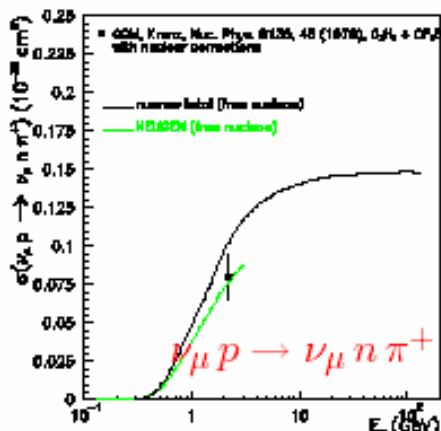
Computed for the K2K experiment, but it applies for any experiment running with  $E_\nu$  below few GeV (e.g. SuperBeam and  $\beta$ -beam)

Shoei NAKAYAMA (ICRR, Univ. of Tokyo)  
for the K2K Collaboration

March 18, 2004 @ NuInt04

# Absolute NC $1\pi$ Cross Sections

- re-analysis of Gargamelle 1970's bubble chamber data
- using published  $\Phi$ ,  $\sigma$  at  $\langle E_\nu \rangle = 2.2$  GeV  
(E. Hawker with help from Morfin, Pohl - shown at NuInt02)

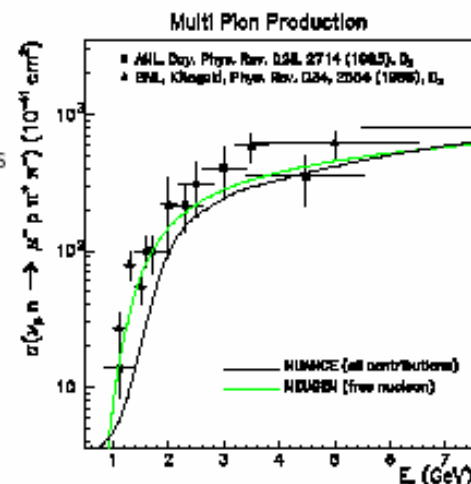


# Multi Pion Production

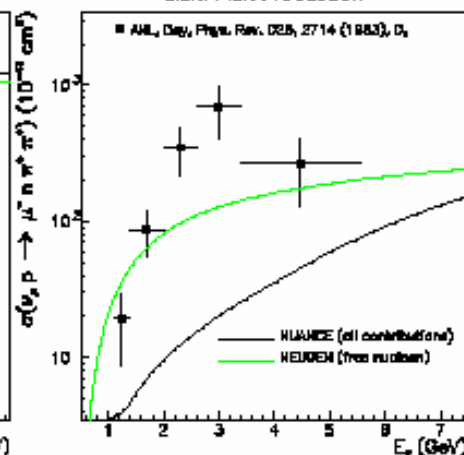
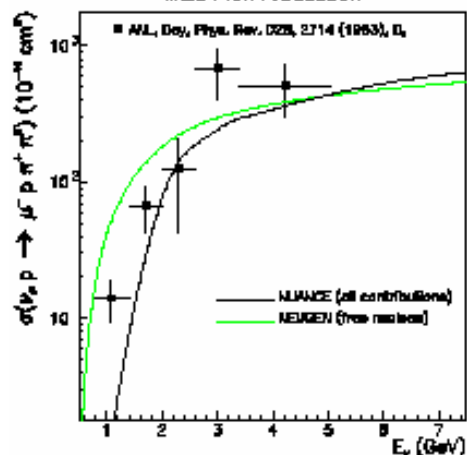
Large 40%-ish uncertainties on dipion production data at  $E_\nu \sim 1$  GeV:

$$\nu_\mu n \rightarrow \mu^- p \pi^+ \pi^-$$

$$\nu_\mu p \rightarrow \mu^- p \pi^+ \pi^0$$



$$\nu_\mu p \rightarrow \mu^- n \pi^+ \pi^+$$



## $\nu$ Cross Section Score Card

Cross Section	Present Knowledge	$\nu$ Data	Theor. Models
DIS	Excellent ★★★	many exps	parton model
Quasi-Elastic	Good ★★★	bc	form factors
Resonant $1\pi$	Fair★★	bc	Rein-Sehgal
Coherent $\pi$	Poor (low $E$ ) ★1/2	bc, counter	several
Combining $\sigma$ 's	Poor ★	little	several +
Nuclear Targets	Poor ★1/2	very limited	variety

Relevant for low energy neutrino beams

# Disappearance searches

$$N_{\text{expected}} = N_{\text{observed}} \times \frac{1}{\epsilon_{ND}} \times R_{FD/ND} \times \epsilon_{FD} \times \frac{L.T. \cdot_{FD}}{L.T. \cdot_{ND}}$$

#evts expected at the Far Detector (FD)

#evts observed in the Near Detector (ND)

Live time correction using proton on target

$$R_{FD/ND} = \frac{\int \Phi_{FD} \sigma_{FD} dE}{\int \Phi_{ND} \sigma_{ND} dE} \times \frac{N_{FD}^{\text{target}}}{N_{ND}^{\text{target}}}$$

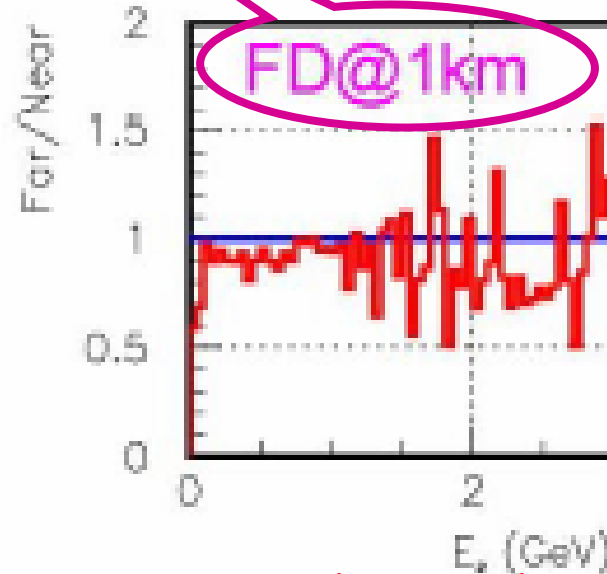
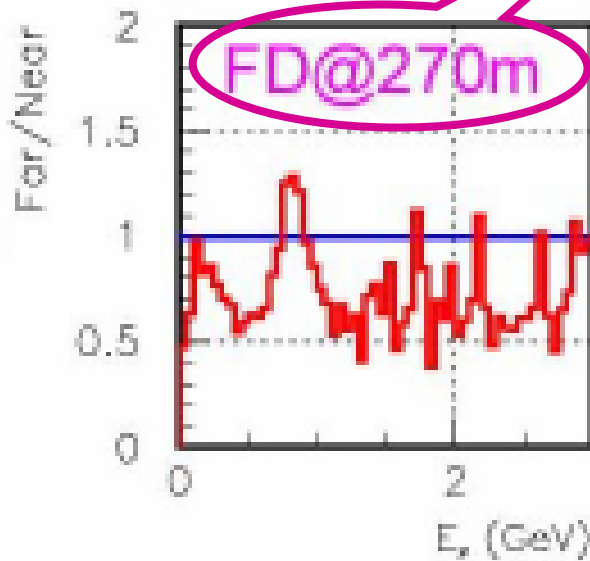
Event ratio R from MC calculation but, many tiny effects may increase the systematic uncertainty in the extrapolation...

...why?

Let's consider the Far/Near ratio @T2K Vs  $\nu$  energy

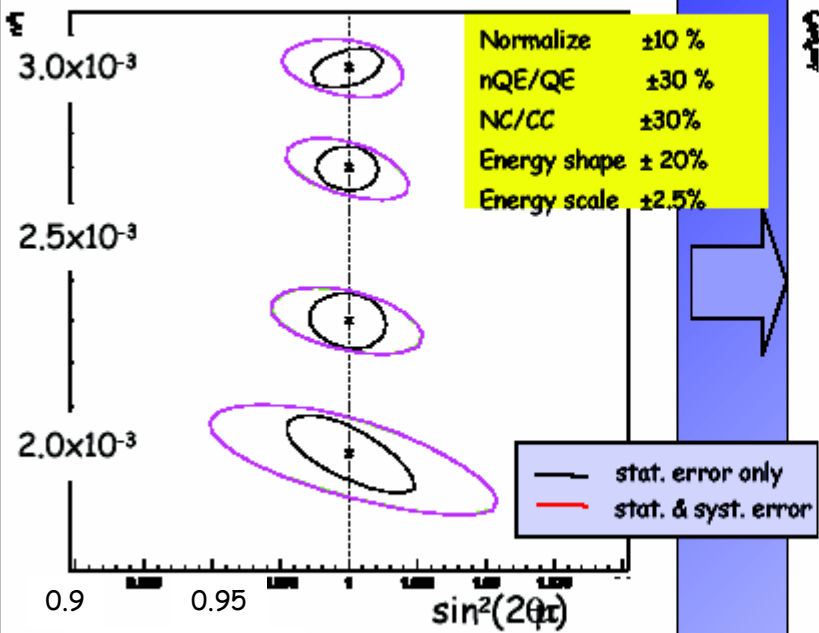
Baseline of the Near Detector

Similar to K2K

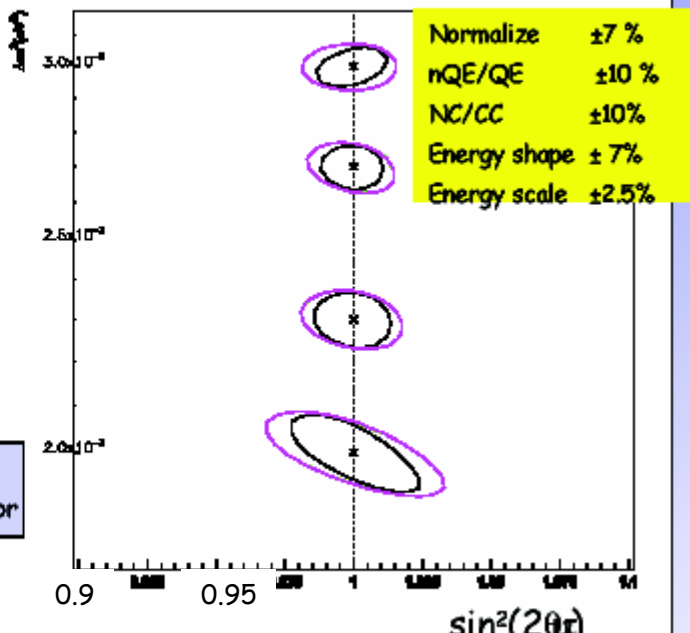


The Far/Near ratio has a strong energy dependence that depends on the Near Baseline

J-Parc 5yr, 90% C.L.

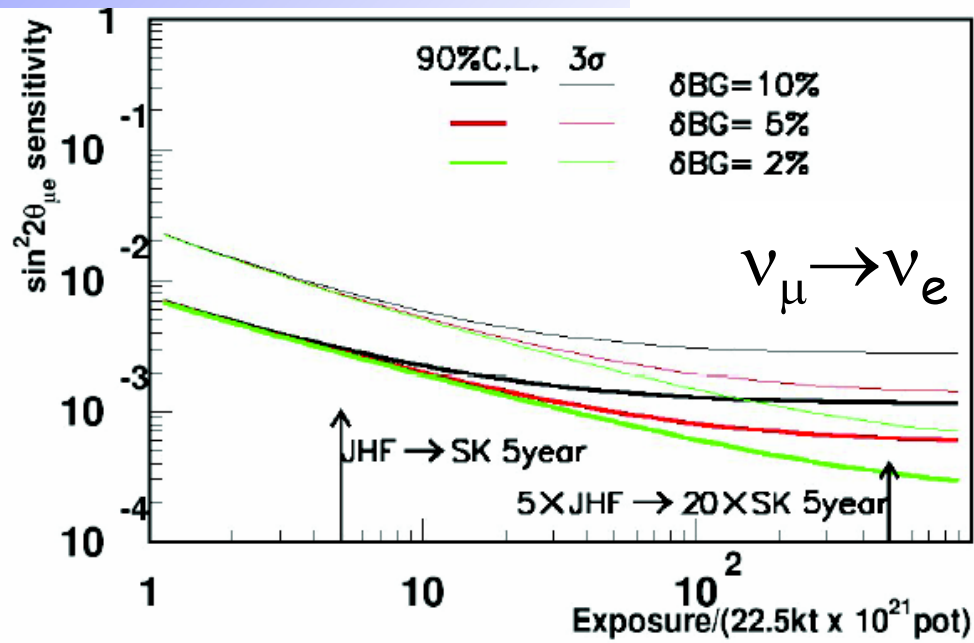


J-Parc 5yr, 90% C.L.



$$\nu_{\mu} \rightarrow \nu_{\tau}$$

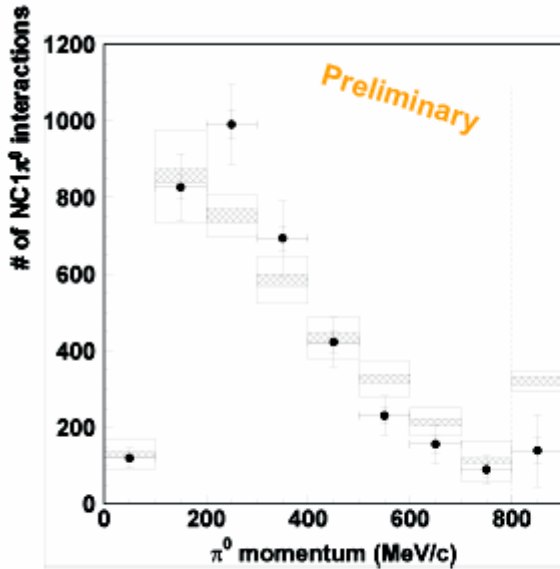
Impact of systematic errors on the T2K sensitivity





# Example of future cross-section measurements

## $\pi^0$ rate measured in K2K SBL



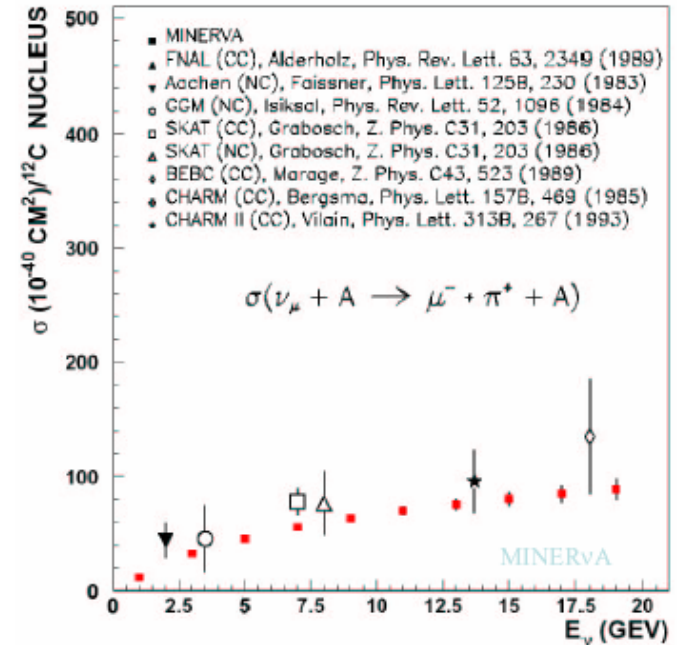
+ data (inner: stat, outer: stat+sys)  
 □ MC true  
 (inner: MC stat,  
 outer: MC stat + sys error on shape  
 from our MC model  
 uncertainties)

$$N(\text{NC}1\pi^0) : 3.67 \pm 0.07 \pm 0.32$$

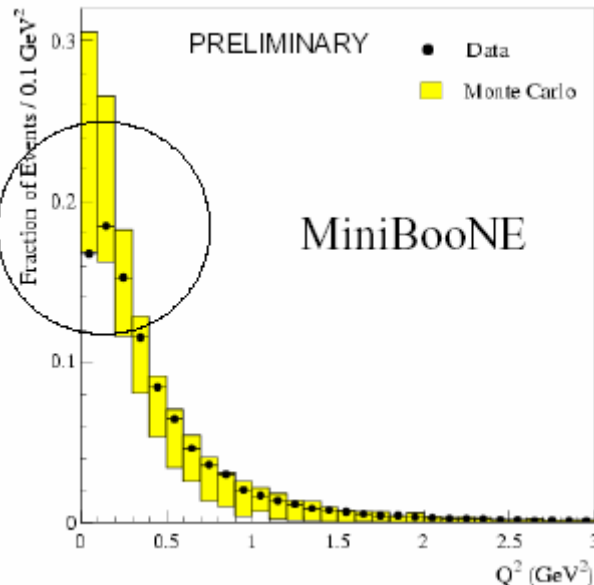
Preliminary  
x 10<sup>4</sup>

normalized by the number of all events in 25t fiducial

## CC Coherent Pion Production Cross Section



MINERvA is a good starting point, but the energy spectrum does not entirely fits the future  $\beta$ -beam and SuperBeam spectra



Could be a “nuclear effect”

- too large to be explained by Pauli Blocking
- At NuInt03 problem was “fixed” by changing  $M_A$  by 10% (unphysical)
- Other nuclear models?

Need to understand this for oscillation measurements!!!

The “ $M_A$  fix” lowered the expected QE  $\sigma$  in the energy-region where SK is most sensitive (a significant source of the recent  $\Delta m^2$  change)



# Conclusion on $\nu$ oscillation oriented measurements (I)

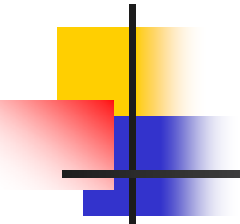
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## ■ Cross-section knowledge

- Nowadays it is the major problem for neutrino energies below few GeV (SuperBeam and  $\beta$ -beam)
  - Present uncertainties larger than 20-30%
- Minor problem for  $\nu$ Factory ( $E_\nu > 10$  GeV)
- AIM at SBL: measure cross-sections at few % level
  - $\beta$ -beam and  $\nu$ Factory are the ideal places: the absolute flux, the beam composition and the energy spectra are well known

## ■ Efficiency determination

- Important for any experiment running at any neutrino beamline



# Conclusion on $\nu$ oscillation oriented measurements (II)

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- Neutrino flux and energy spectra predictions
  - Major problem for SuperBeam
    - Description of the proton beam
    - Particle yield in the p-Target interaction (HARP will improve present knowledge)
    - Description of the focusing system
    - Therefore, very difficult to determine
      - ⇒ The relative fractions of different neutrino flavors
      - ⇒ The energy spectra of the different flavors
      - ⇒ The absolute normalization
  - Minor problem for  $\beta$ -beam and  $\nu$ Factory
    - The absolute number of  $\nu$  parents (ions and muons) and their energy are well known
    - The energy spectrum of  $\nu$  from a  $\beta$ -decay or a  $\mu$ -decay is well known



# Non oscillation physics

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# Physics reach of SBL exp with a SuperBeam

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How much we can improve with SuperBeams?  
When the measurements are limited by systematics?

This will address a fundamental aspect of nucleon structure:

- What carries the nucleon spin! valence quarks, sea quarks, gluons?
- Can we describe the proton in terms of a fundamental theory?

These are still open questions!

Bonnie T. Fleming  
SB Workshop  
March 5th, 2004

APS Neutrino Study -- 2004

→  $\Delta s$  is important for certain dark matter searches  
where the neutralino-nucleus cross section depends on quark spins.



## Some useful links

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- APS Neutrino Study, 2004  
Superbeams Working Group  
Short Baseline Neutrino Physics

[http://home.fnal.gov/~bfleming/sbl\\_sb.html](http://home.fnal.gov/~bfleming/sbl_sb.html)

- NuFact03

<http://www.cap.bnl.gov/nufact03/index.xhtml>

- NuFact02

<http://www.hep.ph.ic.ac.uk/NuFact02/>



# Physics reach with a $\beta$ -beam

## Prospects for Detecting a Neutrino Magnetic Moment with a Tritium Source and Beta-beams

G. C. McLaughlin\*

*Department of Physics, North Carolina State University, Raleigh, North Carolina 27695-8202 and  
Institut de Physique Nucléaire, F-91406 Orsay cedex, France*

C. Volpe†

*Institut de Physique Nucléaire, F-91406 Orsay cedex, France*

(Dated: December 11, 2003)

We compare the prospects for detecting a neutrino magnetic moment by the measurement of neutrinos from a tritium source, reactors and low-energy beta-beams. In all cases the neutrinos or antineutrinos are detected by scattering of electrons. We find that a large (20 MCurie) tritium source could improve the limit on the neutrino magnetic moment significantly, down to the level of a few  $\times 10^{-12}$  while low-energy beta-beams with sufficiently rapid production of ions could improve the limits to the level of a few  $\times 10^{-11}$ . The latter would require ion production at the rate of at least  $10^{15} \text{ s}^{-1}$ .

PACS numbers: 13.15+g,14.60.Lm

## Neutrino-Nucleus Cross Section Measurements using Stopped Pions and Low Energy Beta Beams

G. C. McLaughlin\*

*Department of Physics, North Carolina State University, Raleigh, North Carolina 27695-8202*

Two new facilities have recently been proposed to measure low energy neutrino-nucleus cross sections, the  $\nu$ -SNS (Spallation Neutron Source) and low energy beta beams. The former produces neutrinos by pion decay at rest, while the latter produces neutrinos from the beta decays of accelerated ions. One of the uses of neutrino-nucleus cross section measurements is for supernova studies, where typical neutrino energies are 10s of MeV. In this energy range there are many different components to the nuclear response and this makes the theoretical interpretation of the results of such an experiment complex. Although even one measurement on a heavy nucleus such as lead is much anticipated, more than one data set would be still better. We suggest that this can be done by breaking the electron spectrum down into the parts produced in coincidence with one or two neutrons, running a beta beam at more than one energy, comparing the spectra produced with pions and a beta beam or any combination of these.



# The weak mixing angle

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Studies have been done on this for Neutrino Factories,  
but are missing for SuperBeam and  $\beta$ -beam !!!





# Conclusion on SuperBeam and $\beta$ -beam

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The non oscillation physics reach of these facilities (mainly at low energies) is very interesting. However ...

**Extensive studies are still missing**

There is not (at least Europe) a large community (like in the oscillation case) working on this subject

It would be worthwhile to have a working group in Europe to study the potentiality of a SB and  $\beta$ -beam for non oscillation physics (in the USA it already exists)

# Other physics with a $\nu$ Fact

Although in the time schedule of future neutrino facilities the  $\nu$ Fact is very far, its physics potentiality for non oscillation physics is the best known!

hep-ph/0105155/CERN-TH-2002-131

## PHYSICS AT THE FRONT-END OF A NEUTRINO FACTORY: A QUANTITATIVE APPRAISAL

M.L. Mangano<sup>a</sup> (convener), S.I. Alekhin<sup>b</sup>, M. Anselmino<sup>c</sup>, R.D. Ball<sup>a,d</sup>, M. Boglione<sup>e</sup>, U. D'Alesio<sup>f</sup>, S. Davidson<sup>g</sup>, G. De Lellis<sup>h</sup>, J. Ellis<sup>a</sup>, S. Forte<sup>i</sup>, P. Gambino<sup>a</sup>, T. Gehrmann<sup>a</sup>, A.L. Kataev<sup>a,j</sup>, A. Kotzinian<sup>a,k</sup>, S.A. Kulagin<sup>f</sup>, B. Lehmann-Dronke<sup>l</sup>, P. Migliozi<sup>h</sup>, F. Murgia<sup>f</sup>, G. Ridolfi<sup>a,m</sup>

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<sup>b</sup> Institute for High Energy Physics, Protvino, Russia

<sup>c</sup> Dipartimento di Fisica Teorica dell'Università e Sezione INFN di Torino, Turin, Italy

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<sup>e</sup> Dept. of Physics and IPPP, University of Durham, U.K.

<sup>f</sup> Dipartimento di Fisica dell'Università e Sezione INFN di Cagliari, Cagliari, Italy

<sup>g</sup> Theoretical Physics, Oxford University, U.K.

<sup>h</sup> INFN, Sezione di Napoli, Naples, Italy

<sup>i</sup> INFN, Sezione di Roma III, Rome, Italy

<sup>j</sup> Institute for Nuclear Research, Academy of Sciences, Moscow, Russia

<sup>k</sup> JINR, Dubna, Russia

<sup>l</sup> Institut für Theoretische Physik, Universität Regensburg, Germany

<sup>m</sup> INFN, Sezione di Genova, Genoa, Italy

N.L.J.

Phys. Rept.371:151-230,2002

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Physics Reports 371 (2002) 151–230

PHYSICS REPORTS

www.elsevier.com/locate/physrep

The potential for neutrino physics at muon colliders and dedicated high current muon storage rings

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<sup>a</sup>Notre Dame University, South Bend, IN, USA

<sup>b</sup>Kansas State University, Manhattan, KS, USA

<sup>c</sup>Columbia University, New York, NY, USA

<sup>d</sup>Fermilab, Batavia, IL, USA

<sup>e</sup>National Science Foundation, Washington, DC, USA

<sup>f</sup>Brookhaven National Laboratory, P.O. Box 5000, Upton, NY, 11973-5000, USA

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<sup>i</sup>Northwestern University, Evanston, IL, USA

<sup>l</sup>State University of New York, Stonybrook, NY, USA

It is highly desirable that in the future the same degree of knowledge will be achieved also for SuperBeam and  $\beta$ -beam



# Conclusion

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- The physics case of SBL experiments at neutrino facilities has been pointed out since several years (several SBL expts either are running or have been already planned; there are a lot of papers on their physics goals)
- The ultimate precision on the measurement of the PMNS matrix elements and the sensitivity on the discovery of the CP phase in the leptonic sector depend on the knowledge of the cross-section at low neutrino energies
- A lot of great physics, other than neutrino oscillations, could be performed with SBL experiments at present and future facilities