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

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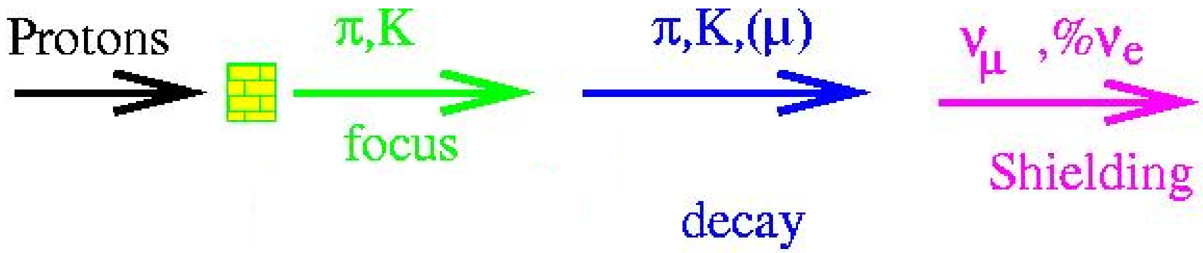
Motivations

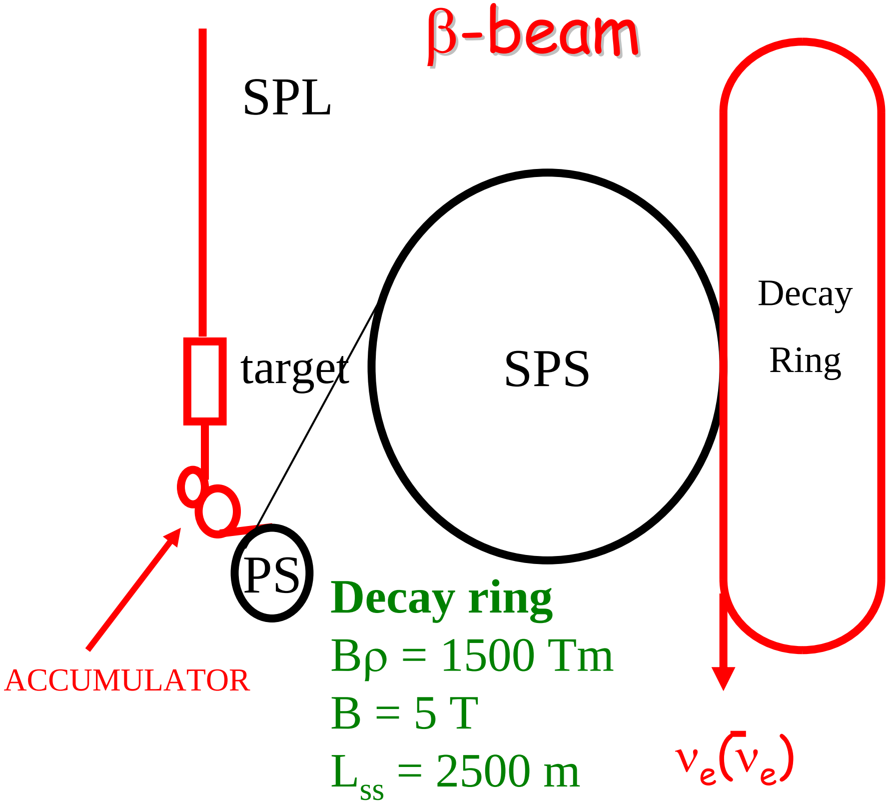
The study of neutrino interactions in a SBL experiment at future facilities follows two lines of research

- 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
  - ...

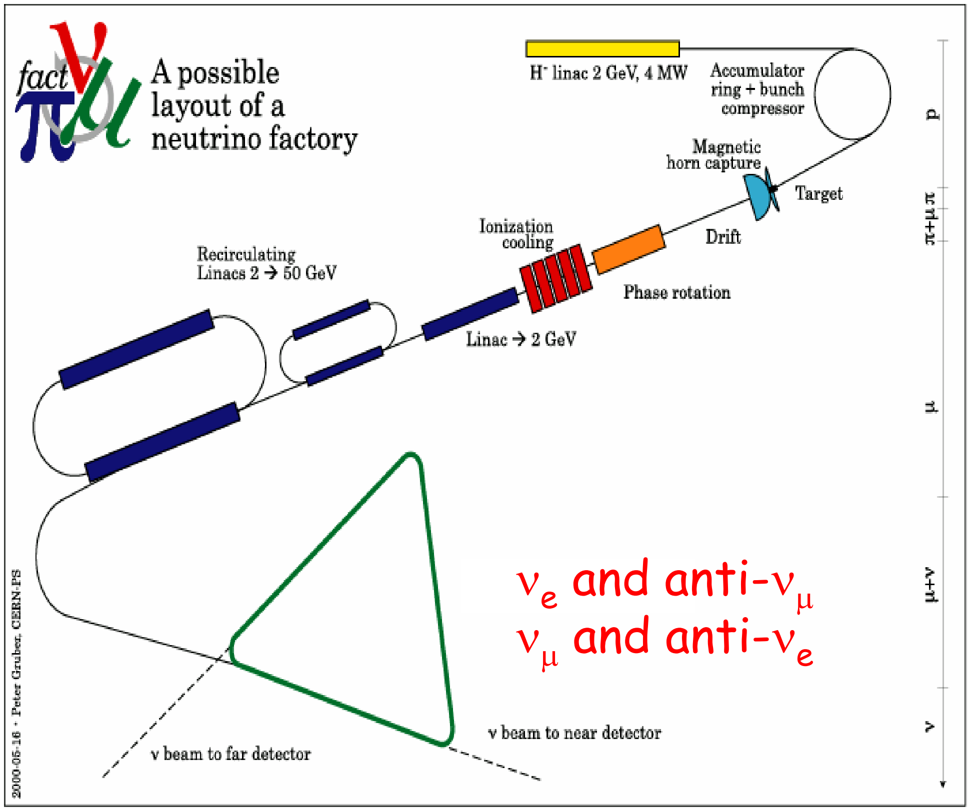
SuperBeams (Conventional ν beam)



β-beam



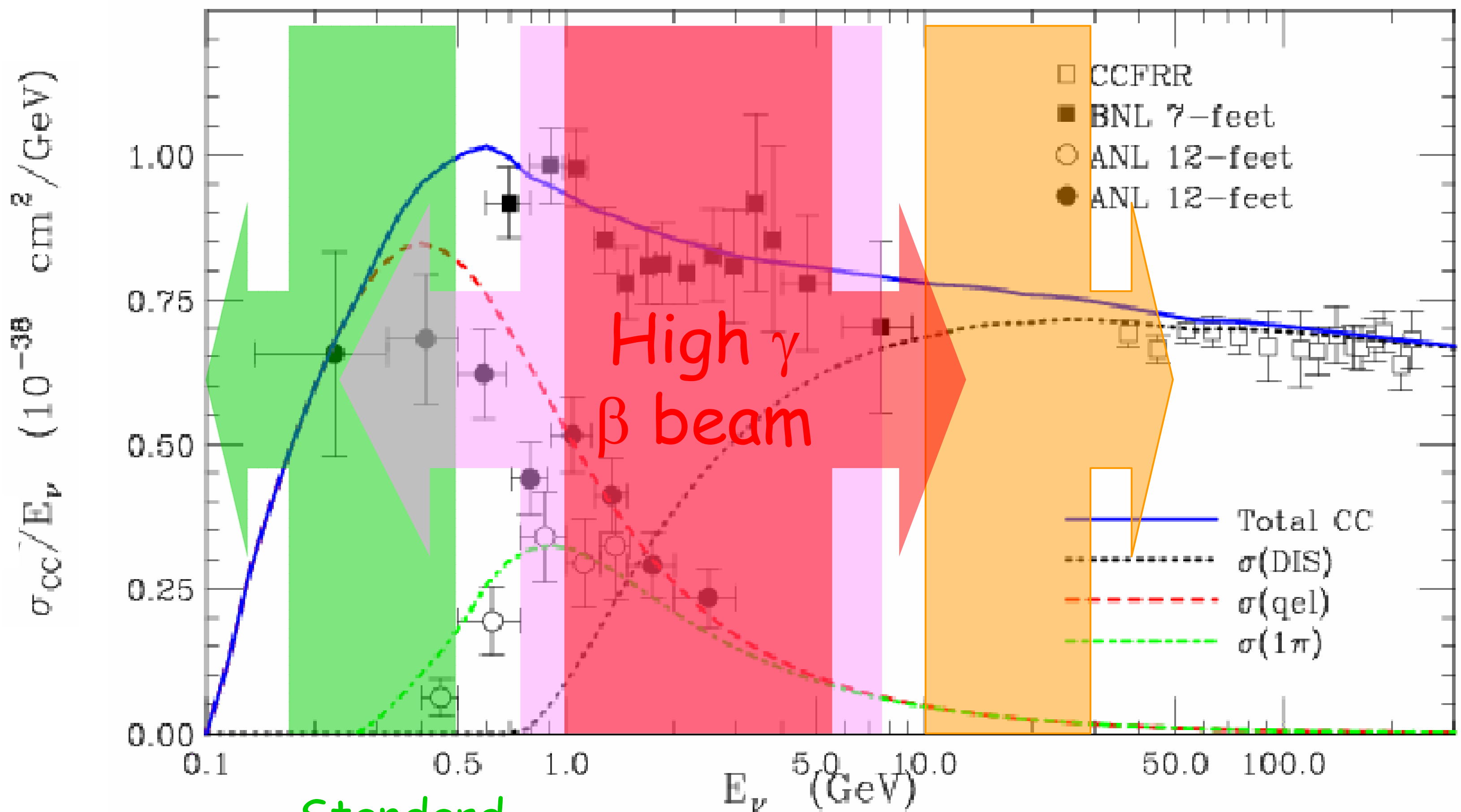
ν-Factory



ν_e and anti-ν_μ
ν_μ and anti-ν_e

Different ν beams
⇒ different energy spectra

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

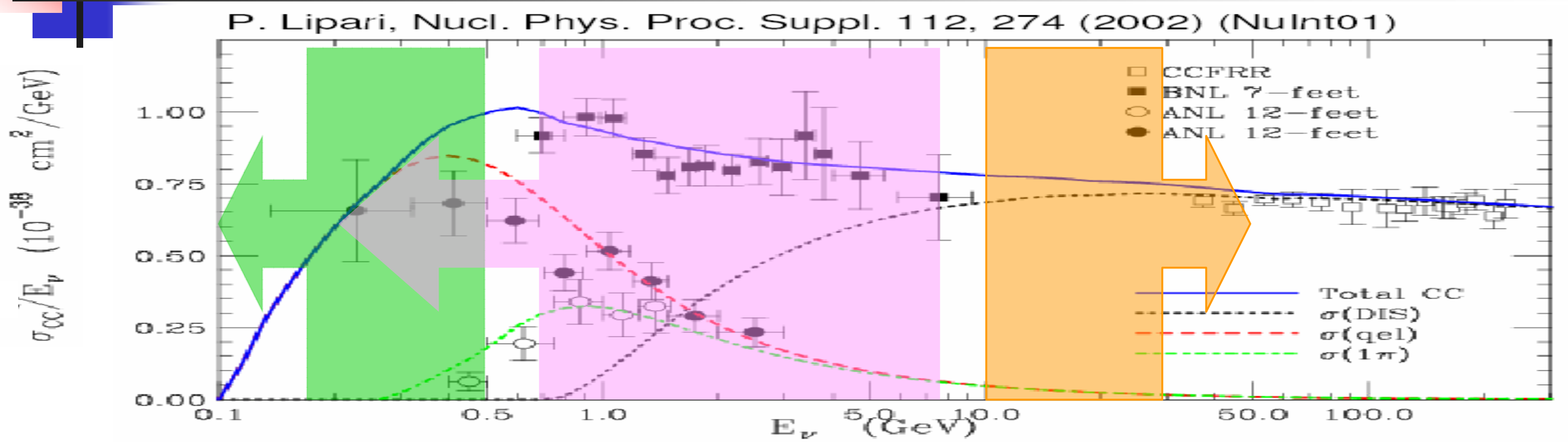


Standard
β-beam

SuperBeam

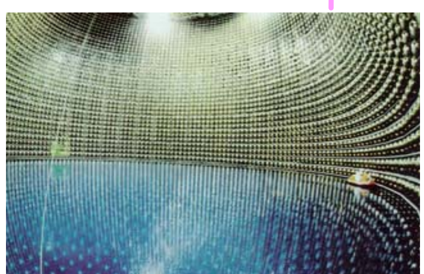
νFact

Different energy spectra ⇒ different detectors



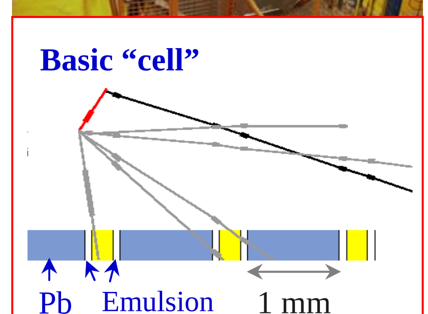
β-beam SuperBeam νFact

Water Cerenkov (SK photo⇒)



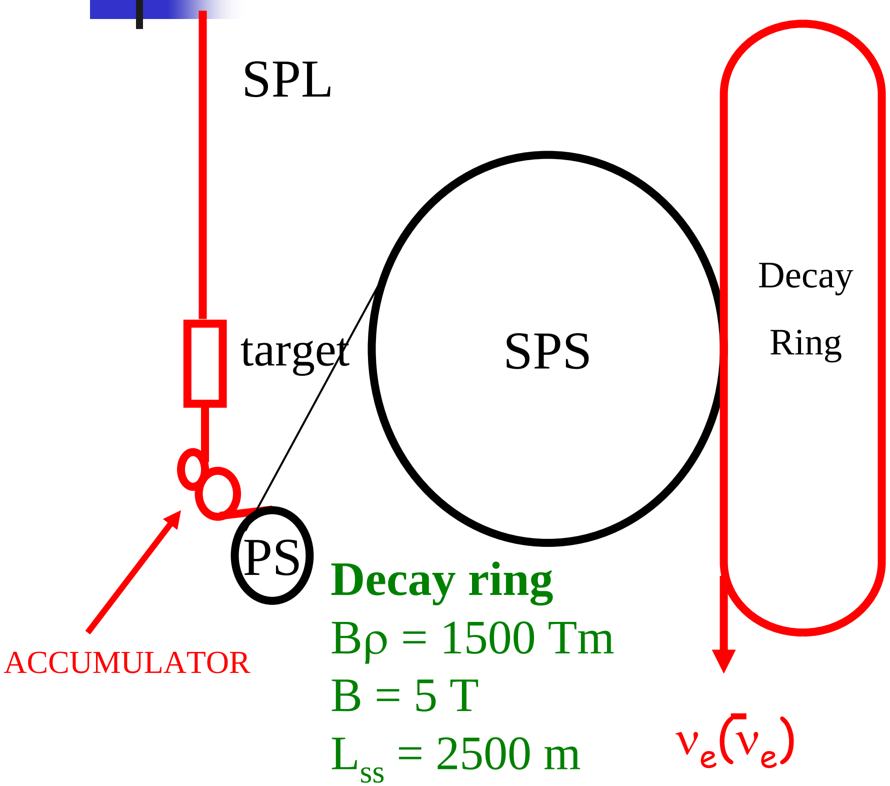
Liquid Argon (Icarus T600 ⇒)

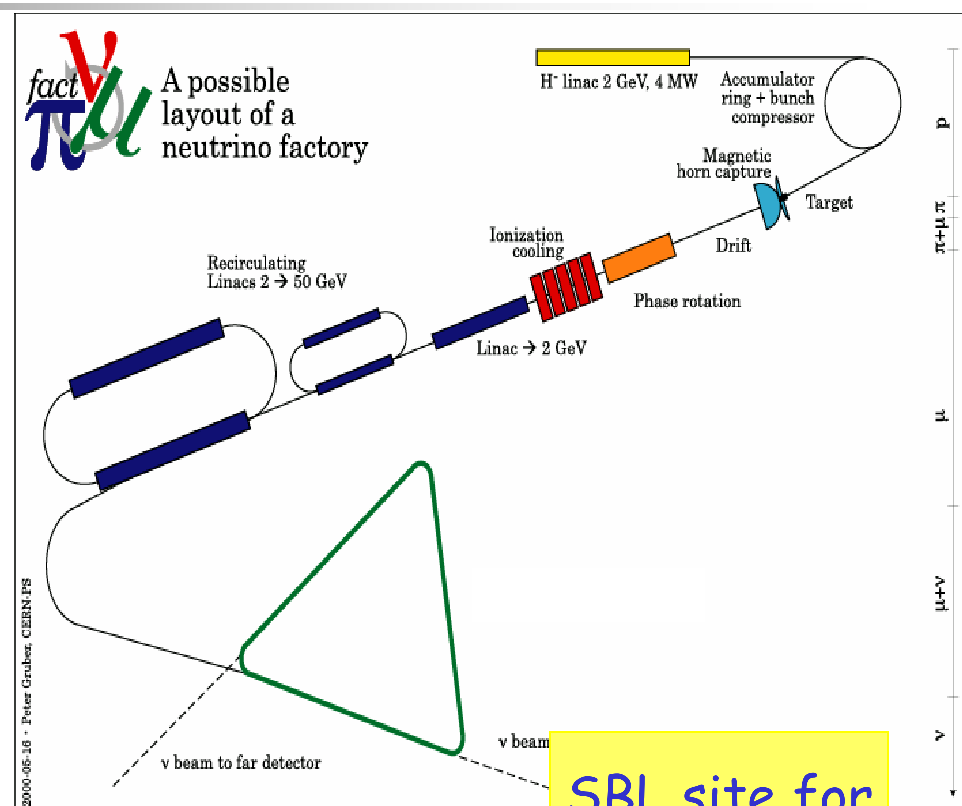
Magnetized calo for $\nu_e \rightarrow \nu_\mu$ search (⇐ MINOS photo)



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

… at least two SBL sites





SBL site for the νFact

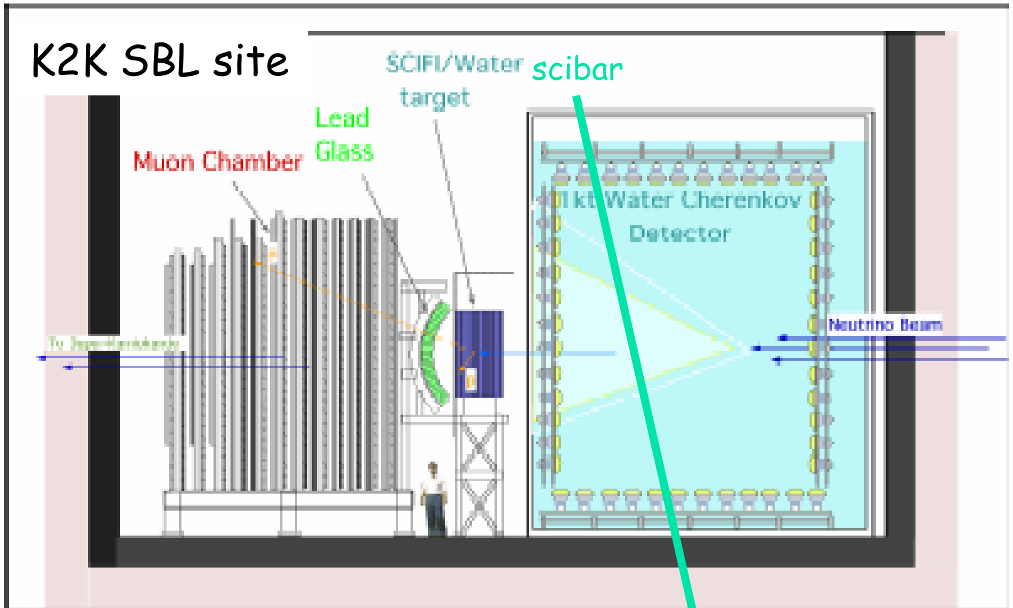
Common SBL site for both SuperBeam and β-beam

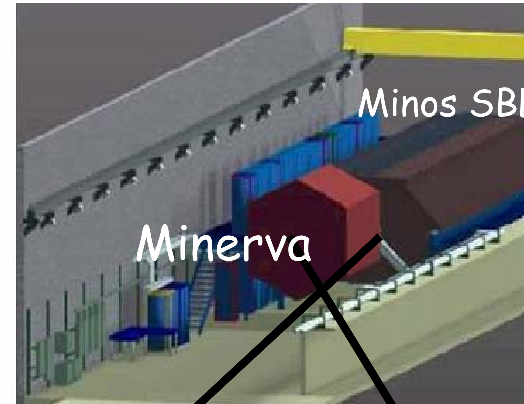
… two detectors per site

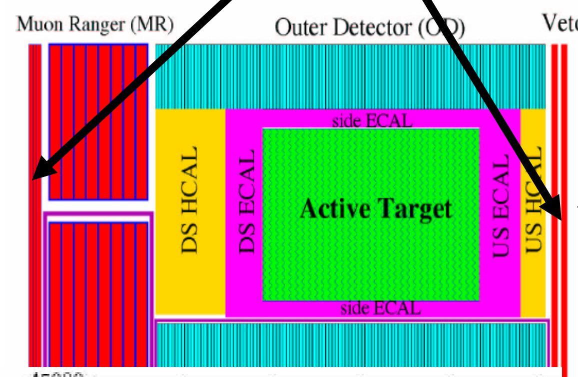
- A coarse grain detector
  - AIM: minimize the near to far extrapolation (important for neutrino oscillation studies)
  - NB: the detector should be built as similar as possible to the far one
- Fine grain detector
  - AIM: study the details of neutrino interactions
  - NB: any suitable technique (not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

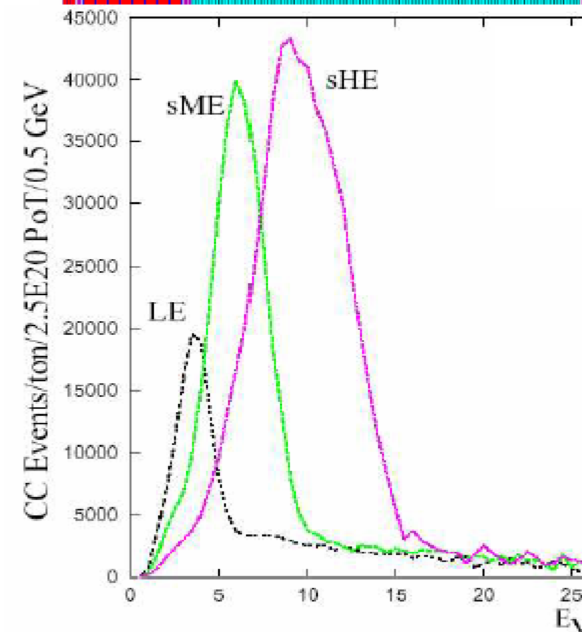
NB At a νFactory, given the huge neutrino flux, a few kg SBL detector is enough!!! $\Rightarrow$ very detailed study of the events

Examples of existing and foreseen SBL exps

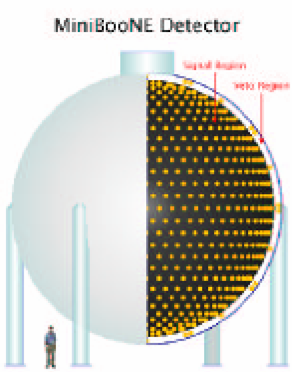


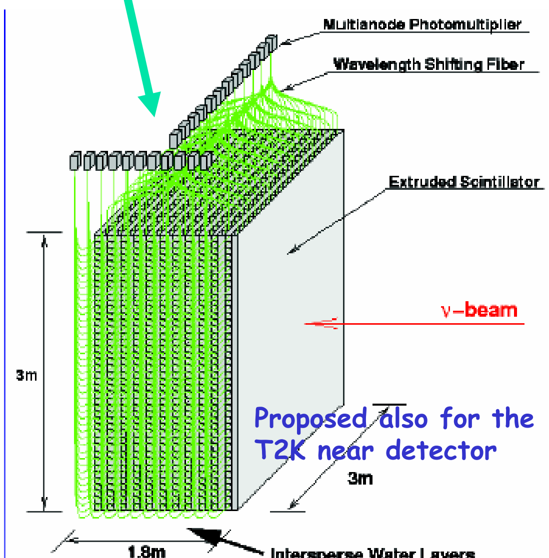






MiniBooNE





What do we need for ν oscillations?

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

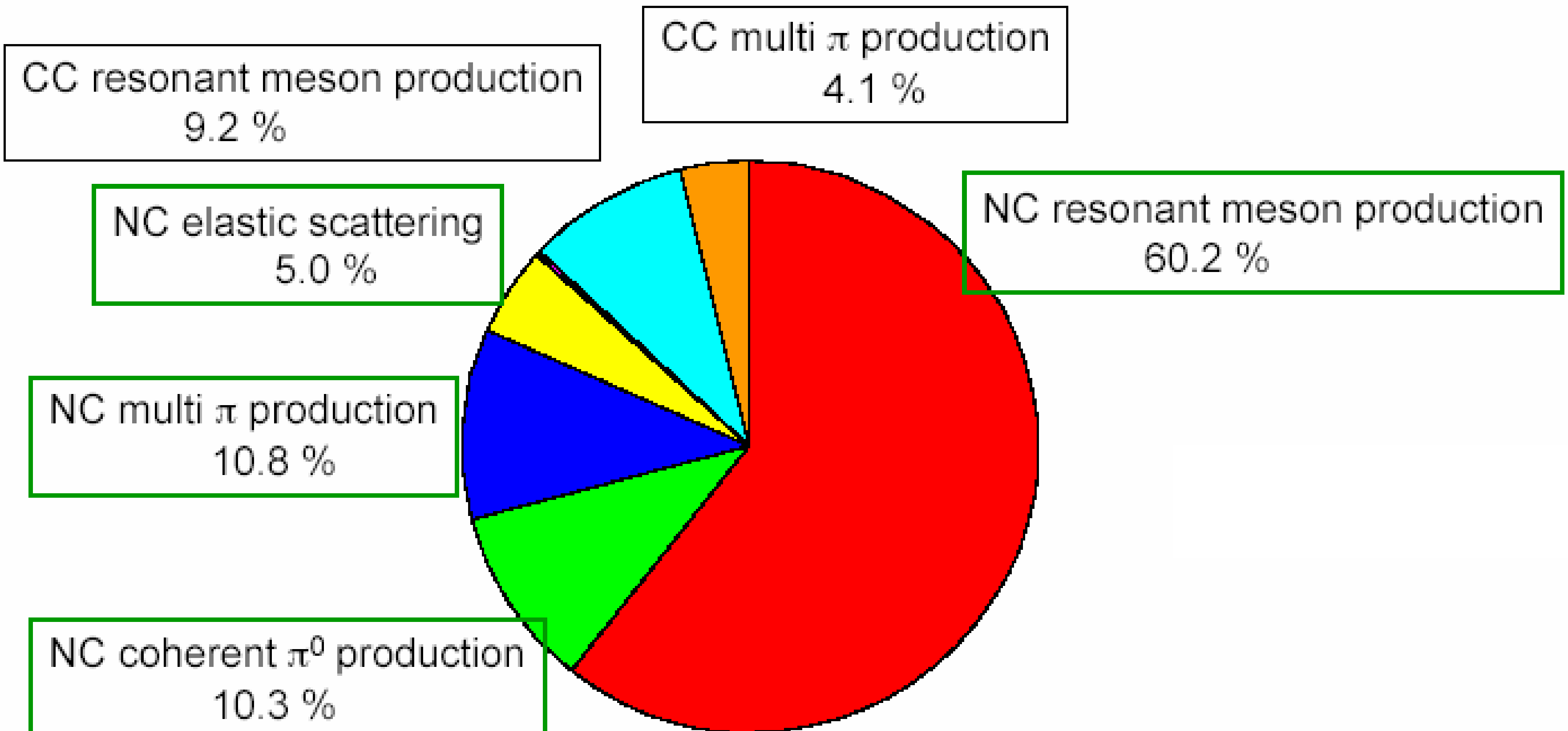
$\nu_\mu \rightarrow \nu_x$ appearance searches

The error on the oscillation probability can be written as

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

- 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



large NC fraction ~ 86 %

Computed for the K2K experiment, but it applies for any experiment running with E_ν below few GeV (e.g. SuperBeam and β-beam)

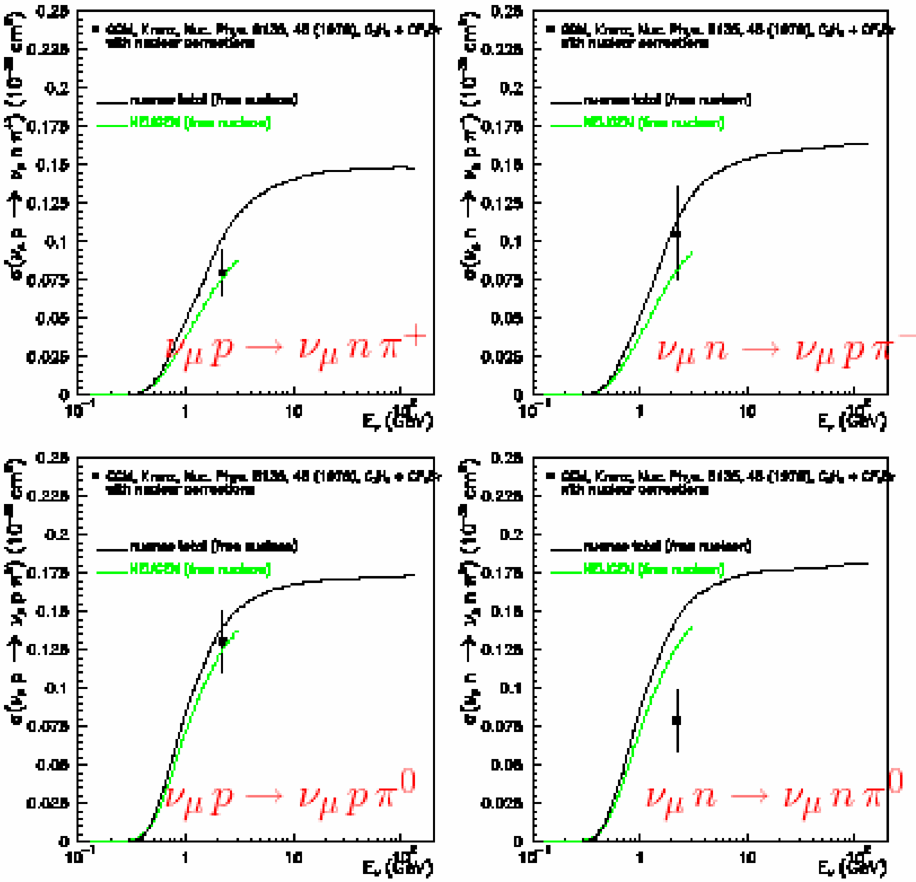
Shoei NAKAYAMA (ICRR, Univ. of Tokyo)
for the K2K Collaboration

March 18, 2004 @ NuInt04

Absolute NC 1π Cross Sections

- re–analysis of Gargamelle 1970's bubble chamber data
- using published Φ, σ at $< E_\nu >= 2.2$ GeV

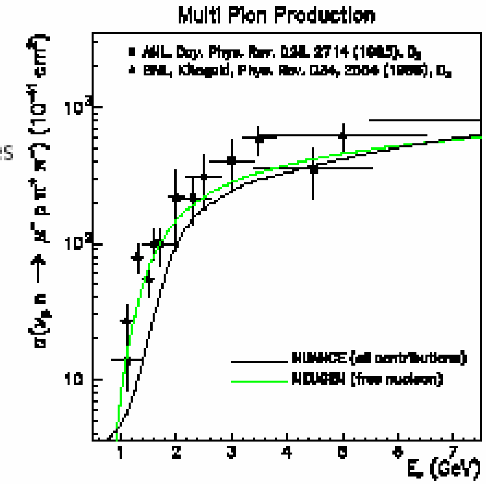
(E. Hawker with help from Morfin, Pohl - shown at NuInt02)



Multi Pion Production

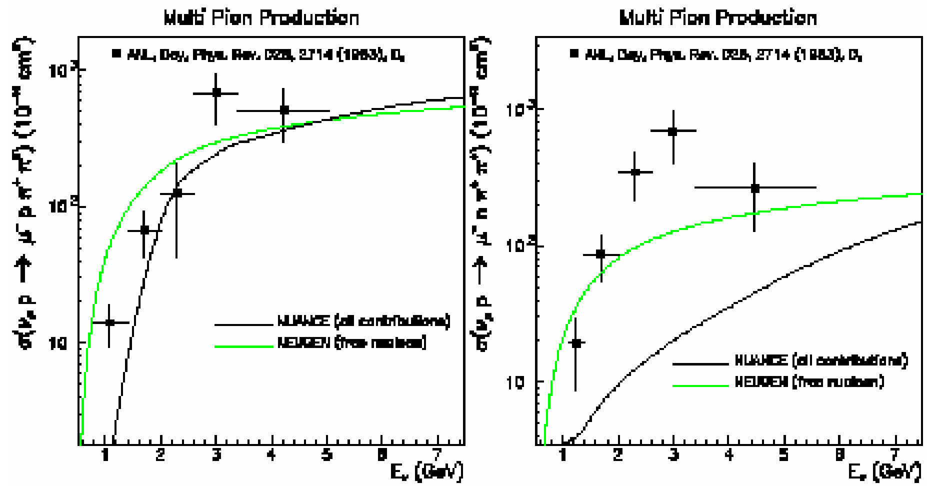
Large 40%-ish uncertainties on dipion production data at $E_\nu \sim 1$ GeV:

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



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

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



S. Zeller
@NuFact03

S. Zeller
@NuFact03

ν Cross Section Score Card

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

Relevant for low energy neutrino beams

http://www-boone.fnal.gov/cross-sections/boone_reference.html

Disappearance searches

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

#evts expected at the Far Detector (FD)

#evts observed in the Near Detector (ND)

Live time correction using proton on target

$$R_{FD/ND} = \frac{\int \Phi_{FD}\sigma_{FD}\,\mathrm{d}E}{\int \Phi_{ND}\sigma_{ND}\,\mathrm{d}E} \times \frac{N_{FD}^{\text{target}}}{N_{ND}^{\text{target}}}$$

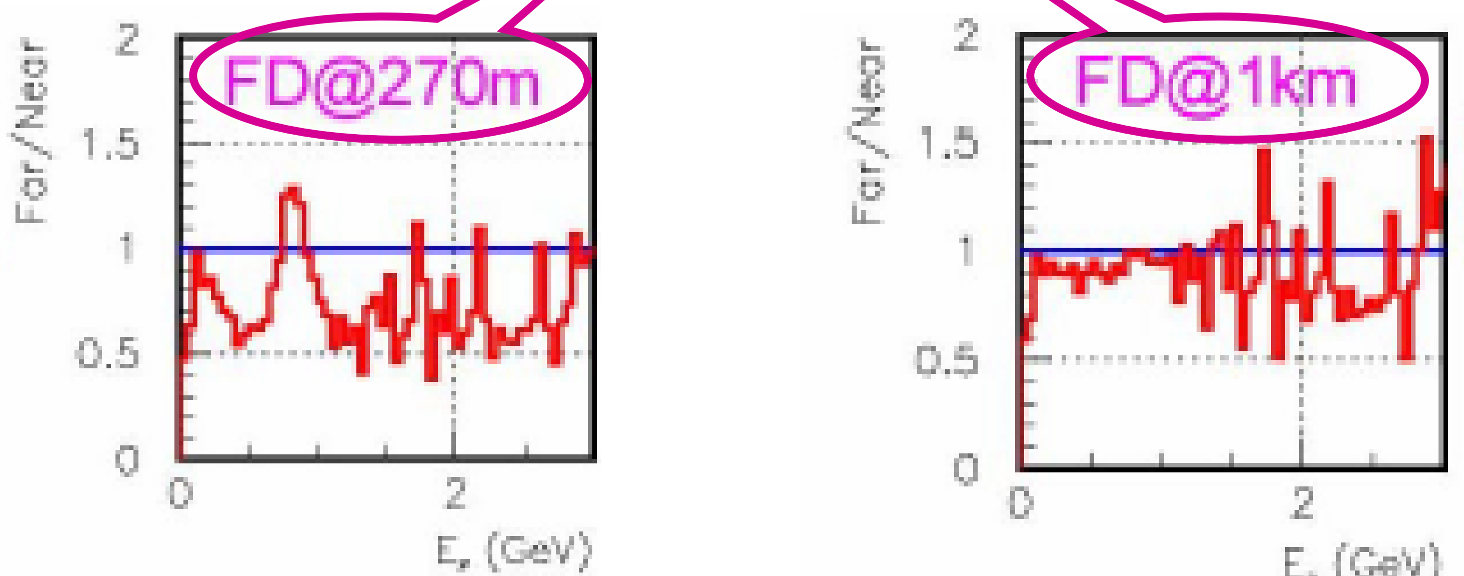
Event ratio R from MC calculation but, many tiny effects may increase the systematic uncertainty in the extrapolation…

…why?

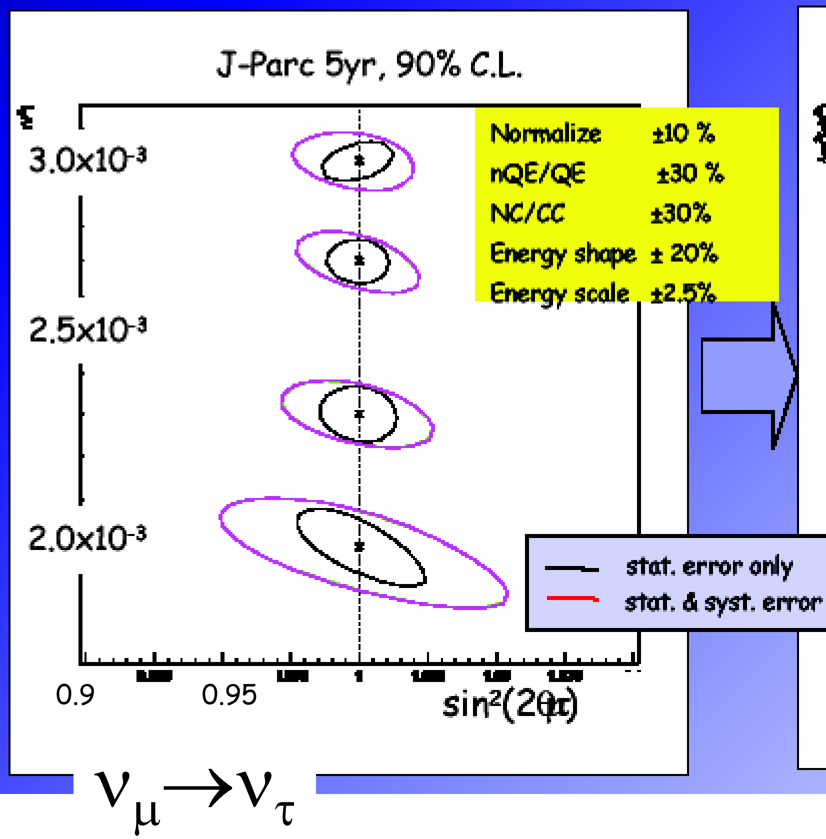
Let's consider the Far/Near ratio @T2K Vs ν energy

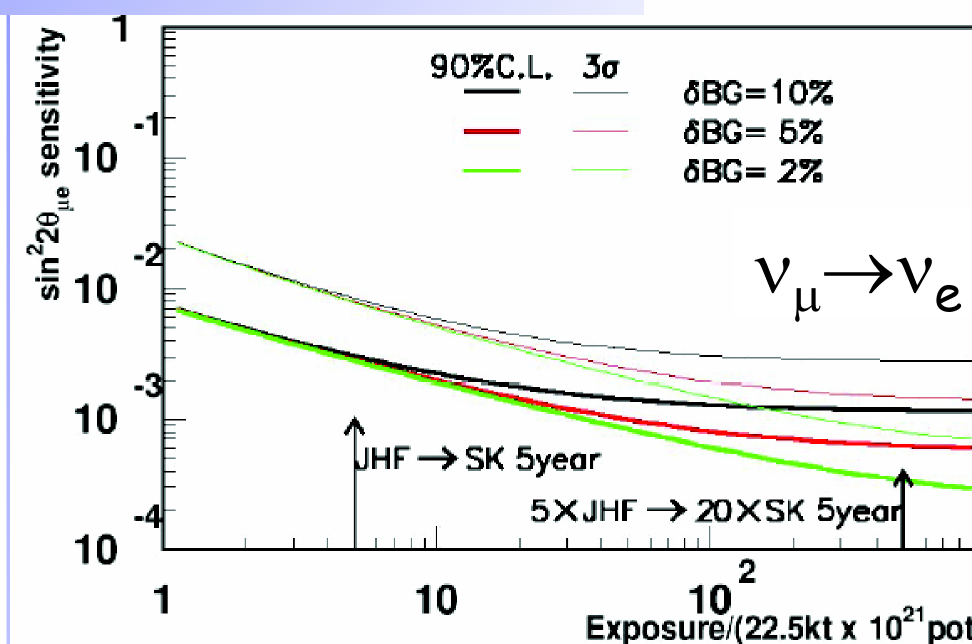
Baseline of the Near Detector

Similar to K2K



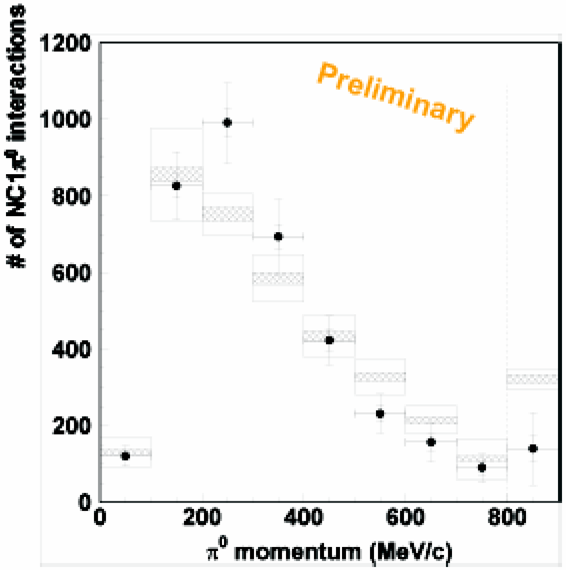
The Far/Near ratio has a strong energy dependence that depends on the Near Baseline





Impact of systematic errors on the T2K sensitivity

π^0 rate measured in K2K SBL



data (inner: stat, outer: stat+sys)

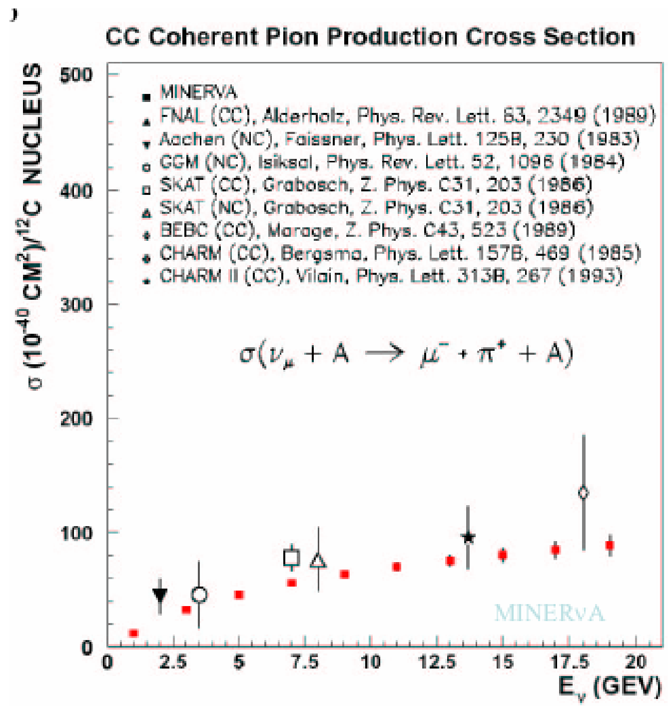
MC true (inner: MC stat, outer: MC stat + sys error on shape from our MC model uncertainties)

N(NC1π^0) : 3.67 ± 0.07 (stat.) ± 0.32 (sys.) x 10^4

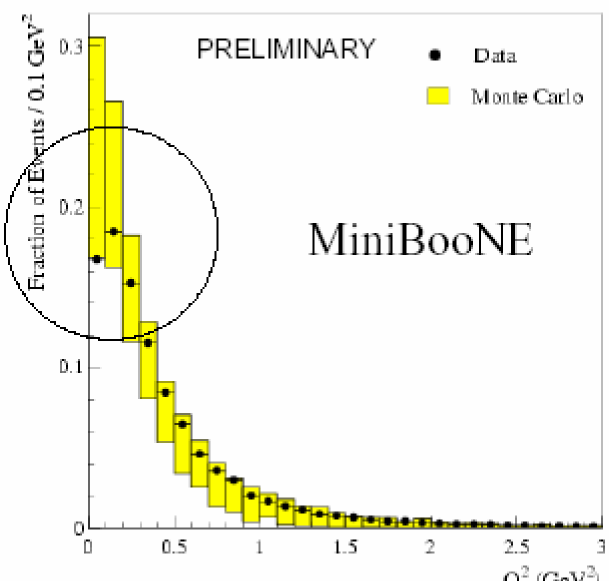
Preliminary

normalized by the number of all events in 25t fiducial

Example of future cross-section measurements



MINERνA is a good starting point, but the energy spectrum does not entirely fits the future β-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 σ in the energy-region where SK is most sensitive (a significant source of the recent Δm^2 change)

Conclusion on ν oscillation oriented measurements (I)

- Cross-section knowledge
  - Nowadays it is the major problem for neutrino energies below few GeV (SuperBeam and β-beam)
    - Present uncertainties larger than 20-30%
  - Minor problem for νFactory (E_ν > 10 GeV)
  - AIM at SBL: measure cross-sections at few % level
    - β-beam and νFactory 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 ν oscillation oriented measurements (II)

- 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 β-beam and νFactory
    - The absolute number of ν parents (ions and muons) and their energy are well known
    - The energy spectrum of ν from a β-decay or a μ-decay is well known

Non oscillation physics

Physics reach of SBL exp with a SuperBeam

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!

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

Bonnie T. Fleming
SB Workshop
March 5th, 2004

Some useful links

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

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 β-beam

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

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(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} s^{-1}.

PACS numbers: 13.15+g,14.60.Lm

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

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Two new facilities have recently been proposed to measure low energy neutrino-nucleus cross sections, the ν-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

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

Conclusion on SuperBeam and β-beam

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 β-beam for non oscillation physics (in the USA it already exists)

Other physics with a νFact

Although in the time schedule of future neutrino facilities the νFact 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 [a] (convener), S.I. Alekhin [b], M. Anselmino [c], R.D. Ball [a,d], M. Boglione [e], U. D'Alesio [f], S. Davidson [g], G. De Lellis [h], J. Ellis [a], S. Forte [i], P. Gambino [a], T. Gehrmann [a], A.L. Kataev [a,j], A. Kotzinian [a,k], S.A. Kulagin [j], B. Lehmann-Dronke [l], P. Migliozzi [h], F. Murgia [f], G. Ridolfi [a,m]
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Phys. Rept.371:151-230,2002

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

Conclusion

- The physics case of SBL experiments at neutrino facilities has been pointed out since several years (several SBL exps 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