Physics Potential of Very Intense Conventional Neutrino Beams

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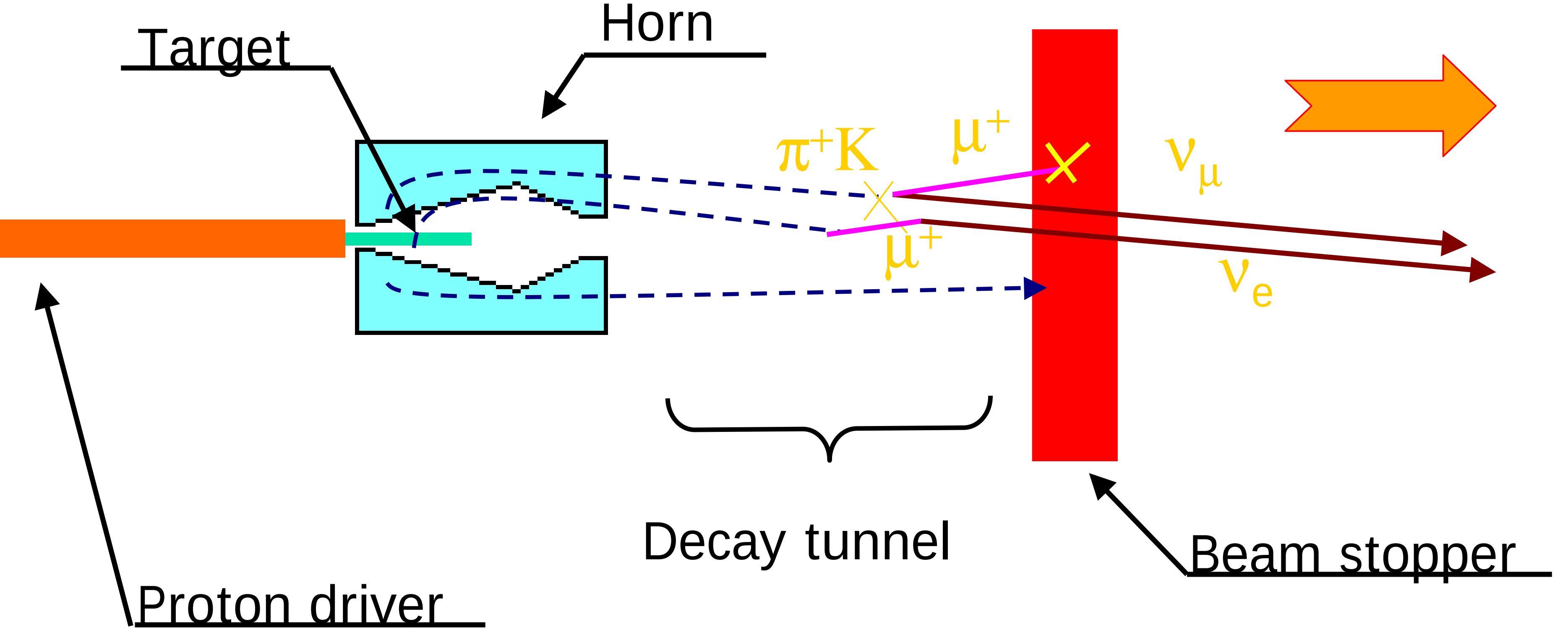
Outline

- Conventional vs. NuFact ν beams
- Super Beam Scenarios
- A concrete scenario. Low energy SB from CERN to Modane
- Summary of Physics Potential
- Comparison with NuFact

Conventional vs. NuFact ν Beams

- Conventional Beams
  - Mainly ν_μ beam but ~1% contamination from other flavors
  - Uncertainties in beam composition (π/K ratio) to the level of 5-10 %
  - Appearance experiments must subtract irreducible beam background $\Rightarrow P(\nu_\mu \to \nu_e) \approx 1/\sqrt{N}$
- NuFact Beams
  - Pure, two flavor beams. No beam bkgnd. If detector backgrounds can be controlled then $\Rightarrow P(\nu_\mu \to \nu_e) \approx 1/N$
  - Small & controlled beam systematic

Conventional ν Beam



NuFact Beam

$\mu^+ \to e^+ \nu_e \ \bar{\nu}_\mu$ ONLY

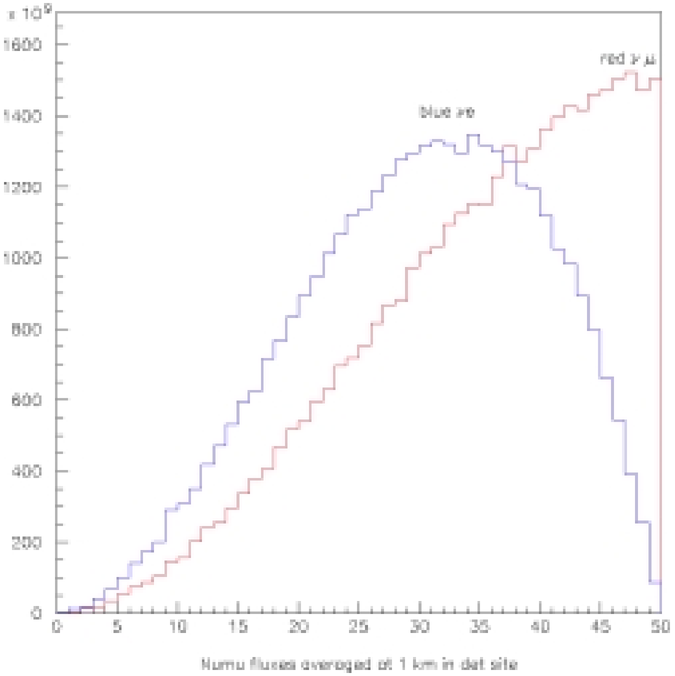
Conventional ν Beam

$\pi^+ \to \mu^+ \nu_\mu$ Horn selected

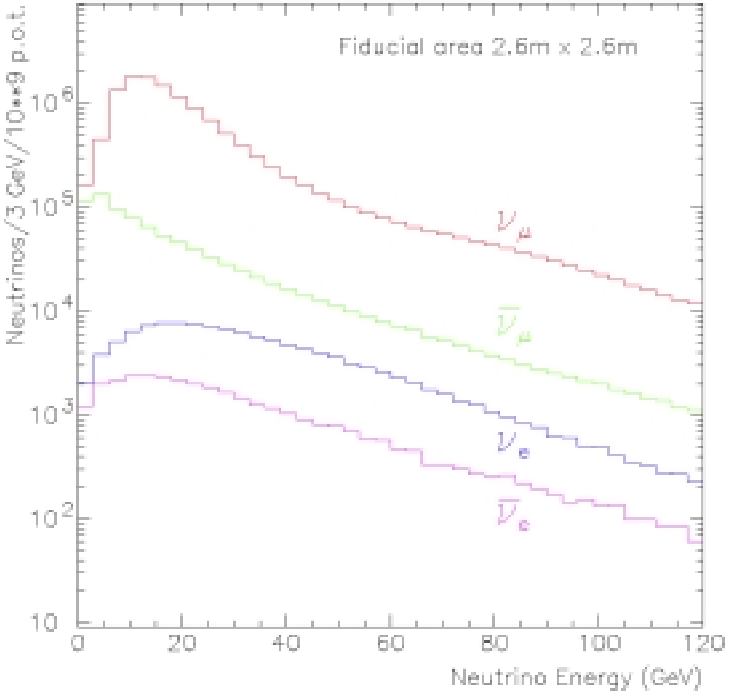
$\pi^- \to \mu^- \ \bar{\nu}_\mu$ Horn feed through

$K^+ \to \mu^+ \nu_\mu$, $K^- \to \mu^- \ \bar{\nu}_\mu$ $K^+ \to \pi^0 e^+ \nu_e$

$\mu^+ \to e^+ \nu_e \ \bar{\nu}_\mu$ (μ from π decays)



Numu fluxes averaged at 1 km in det site



Super Beams

- A super beam is a conventional ν beam of high intensity
- Super beams occur as an (unavoidable) byproduct of a NuFact complex
- The intensity and energy of the beam depends on the proton driver
  - Energies can range from sub- to tenths of GeV
  - Proton driver power in the range 1-4 MW have been considered

SB Studies & Scenarios

- Study group in FNAL
  - Comprehensive paper by Barger,Geer,Raja & Whisnant
  - (S)JHF ➔ 0.77-4MW @ 50 GeV, E_ν~ 1GeV
  - SNuMi ➔ 1.6MW @ 120 GeV, E_ν> 3GeV
  - Various detectors & baselines studied
- Study group at CERN
  - Blondel, Bruguet, Casper, Donega, Gómez, Gilardoni,Hernández,Mezzetto
  - SPL ➔2.2 4MW @ 2.2 GeV E_ν~ 0.25 GeV
  - ~100 Km baseline, Water & Liquid Scintillator detectors

Beam Energy & Baselines

- FNAL group has studied four energy regimes
  - SJHF E_ν ~ 1 GeV
    - Baseline for SJHF ~ 295 km
  - SNuMI, LE(E_ν ~ 3 GeV), ME(E_ν ~ 7 GeV) & HE (E_ν ~ 15 GeV)
    - Baselines: 730,2900,7300,9300 km

- CERN group has studied one energy regime
  - SPL E_ν ~ 250 MeV
    - Baselines: 70km, 120 km

Detectors(I)

- FNAL group has considered three detector scenarios
  - A: Liquid Argon detector with 30 kt fiducial mass
    - $\varepsilon_S \sim 50\ \%$,
    - f_B (π^0/e) ~ 0.001, f_B (Beam) ~ 0.003
  - F: Iron Sampling Calorimeter with 10 kt fiducial mass
    - $\varepsilon_S \sim 90\ \%$,
    - f_B (π^0/e) ~ 0.01, f_B (Beam) ~ 0.003
  - W: Water Cerenkov Detector with 220 kt fiducial mass
    - $\varepsilon_S \sim 70\ \%$,
    - f_B (π^0/e) ~ 0.02, f_B (Beam) ~ 0.003

Detectors(II)

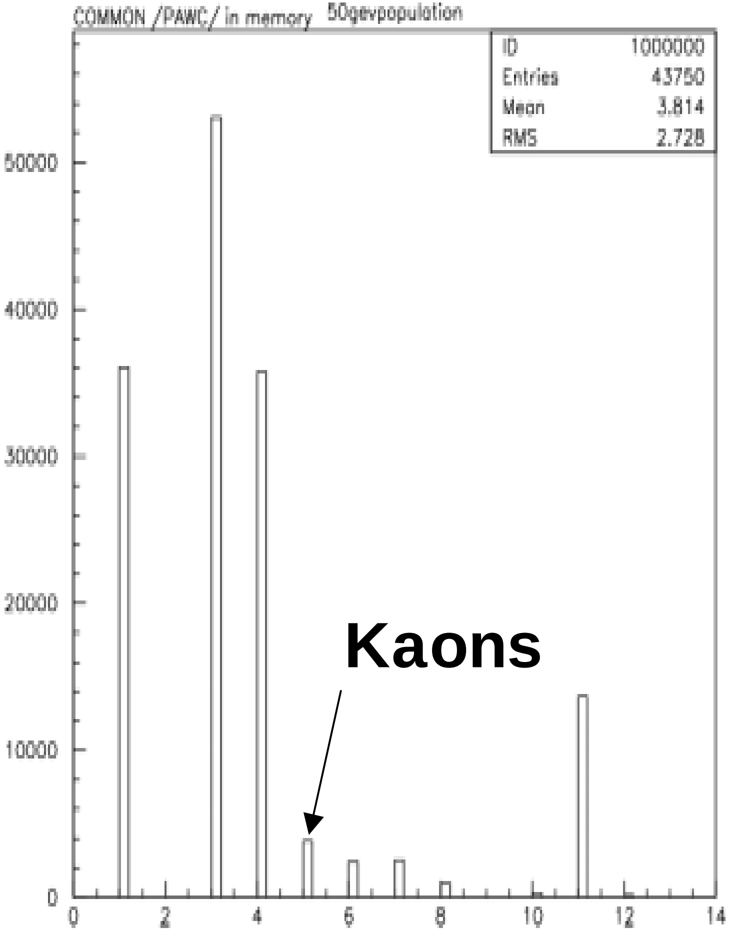
- CERN group has considered two detector scenarios
  - C: Water Cerenkov Detector with 40 kt fiducial mass
    - ε_S ~ 70 % (from a full simulation + analysis)
    - f_B (π^0/e) ~ 0.001 (full simulation + analysis using energy flow fitter to identify π^0)
    - f_B (Beam) ~ 0.005 (full simulation of beam)
  - M: Liquid Scintillator 40 kt fiducial mass
    - ε_S ~ 50 %, (use MiniBoone numbers)
    - f_B (π^0/e) ~ 0.01 (use MiniBoone numbers)
    - f_B (Beam) ~ 0.005 (full simulation of beam)

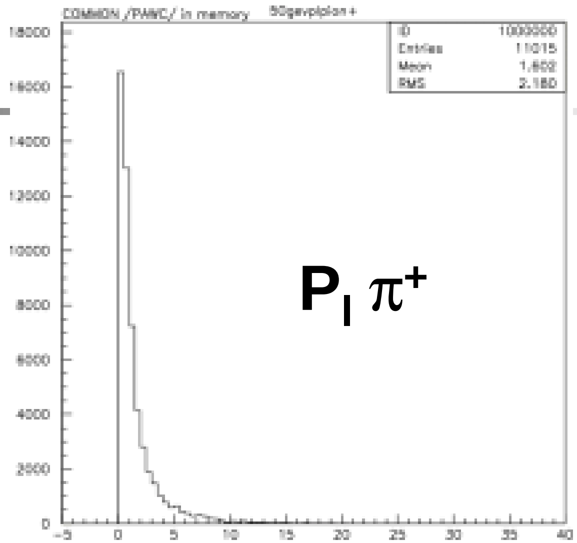
SB of low energy. The best bet?

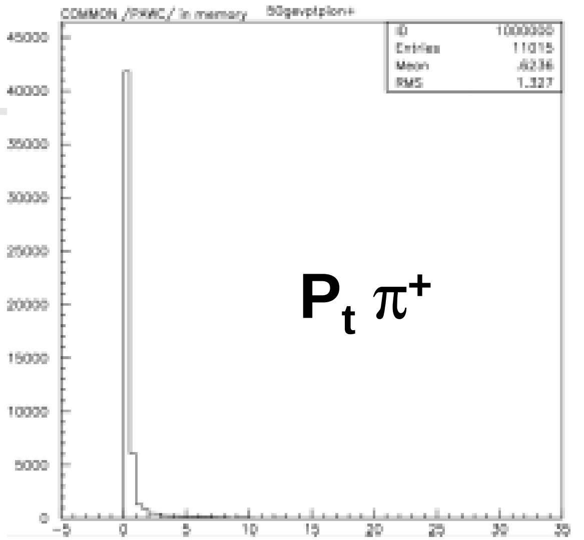
- Beam contamination
  - Best is below Kaon production threshold
  - But $\pi^+/\pi^- \approx 1/3$
- Detector Backgrounds
  - At low energies:
    - Good μ/e π^0/e separation
    - Below charm and tau threshold
- Ideal regime ⇒ $E_\nu < 1$ GeV
- But low rates ⇒ Requires large masses
- Oscillation peaks at short distances (~100 Km)

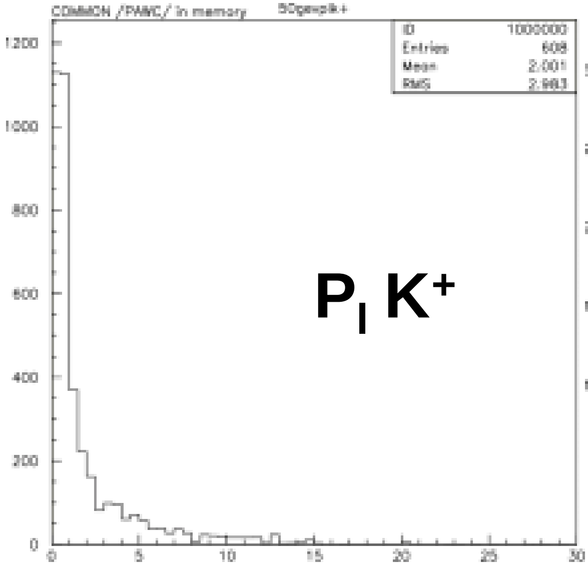
High energy: 50 GeV

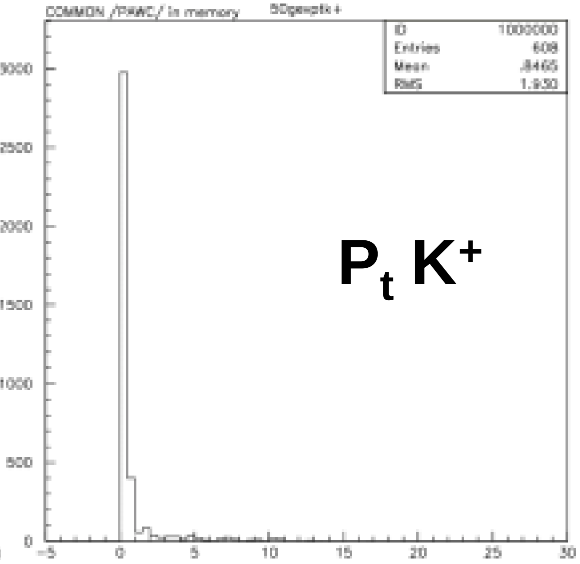
$K^+/\pi^+ \approx 0.07$











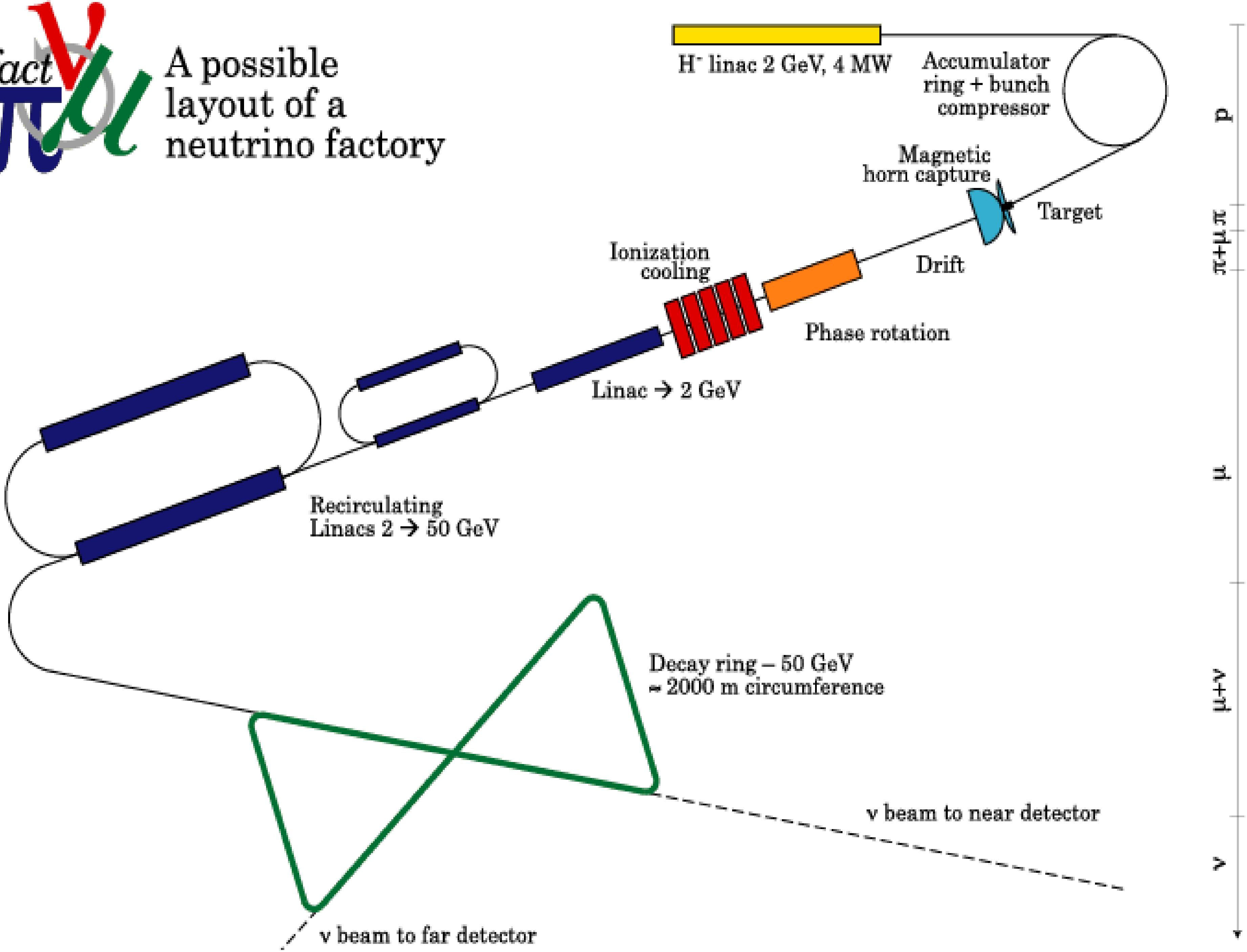
(S)JHF Beam

- JHF approved!
  - 50 GeV protons 0.77 MW upgradable to 4MW
  - ν beam of Eν ~ 1 GeV to SuperK
- Advantages
  - Progressive road to super beam
  - Suitable energy for water detector (already existing)
  - $\pi^+/\pi^- \sim 1$
- Disadvantages
  - Kaon contamination in beam (systematics π/K ratio)
  - Detector backgrounds (π^0/e)

CERN to Modane SB

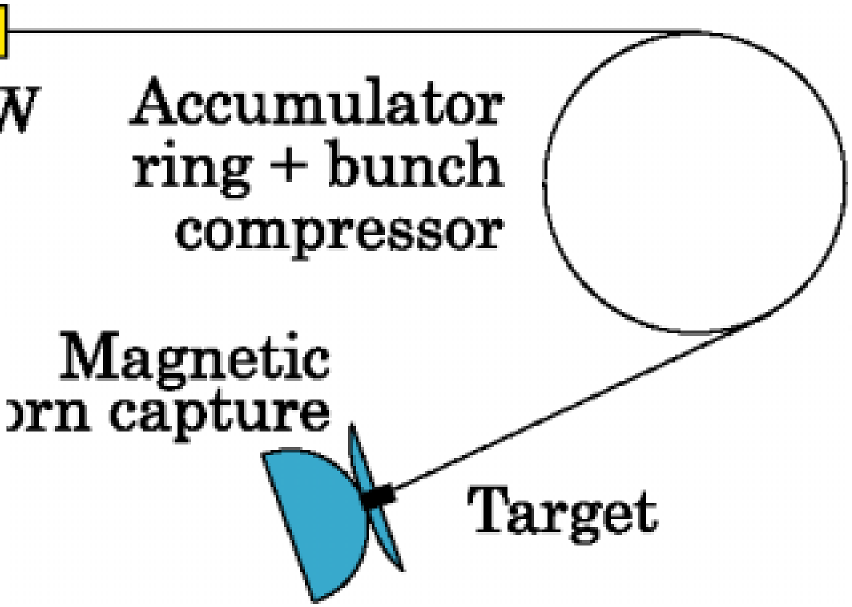
- Design of the CERN NuFact proton driver is based on a 4 MW, low energy proton driver (SPL)
- π collection and sign selection using a magnetic horn
- Resulting ν beam has the following features:
  - Low Energy ($E\nu$ ~ 250 MeV)
    - Oscillation peaks ~ 100 km from source
  - Negligible Kaon content
    - Reduced beam contamination & systematics
  - But π^+/π^- ~ 3

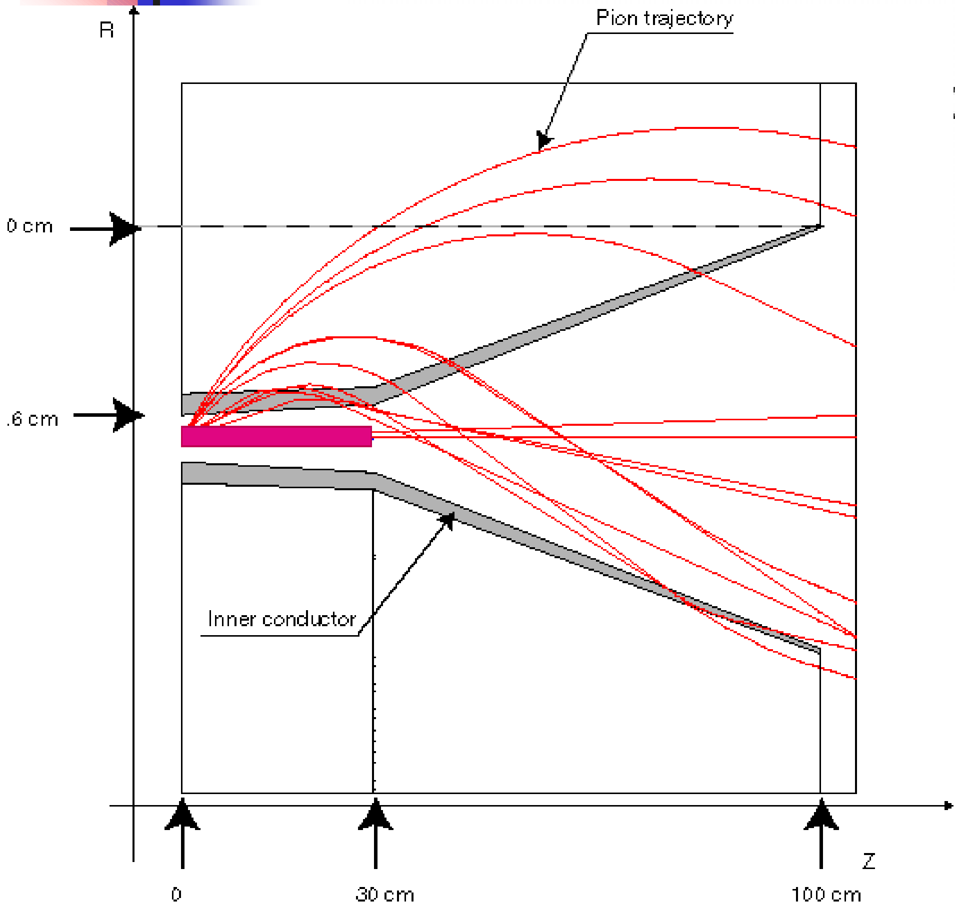
A possible layout of a neutrino factory



2000-05-16 • Peter Gruber, CERN-PS

H^- linac 2 GeV, 4 MW



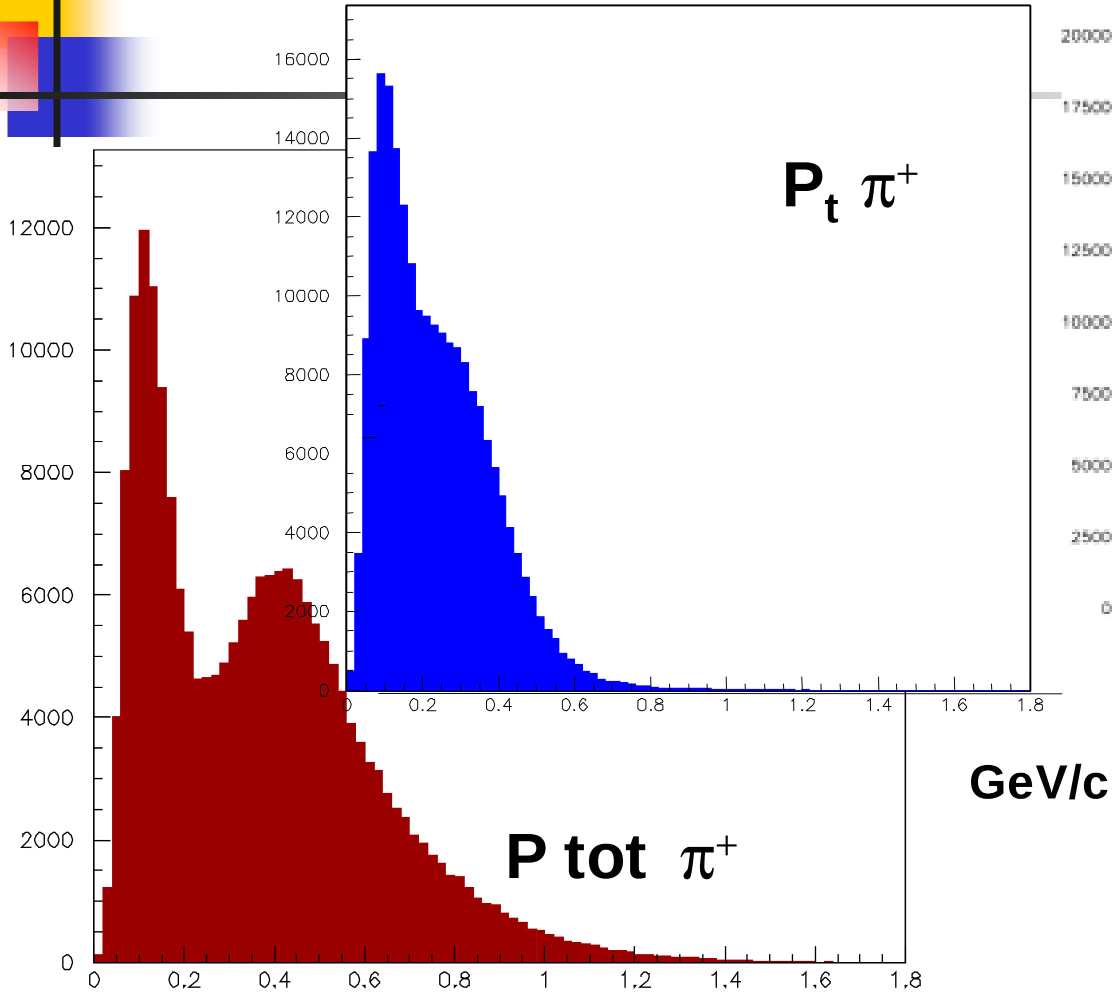


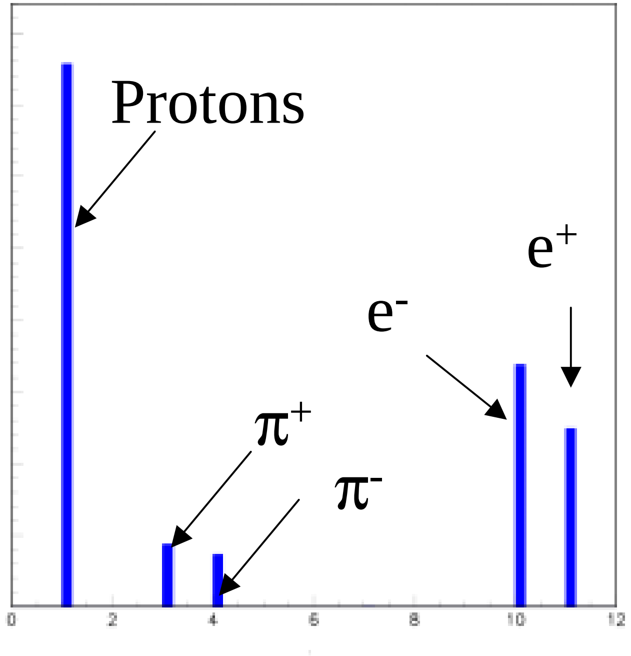
- 4 MW proton beam at 2.2 GeV

  $\approx 10^{16}$ p.o.t./sec

  Rep. Rate = 75 Hz
- Hg liquid target
- Focusing system: Horn

Particles at target



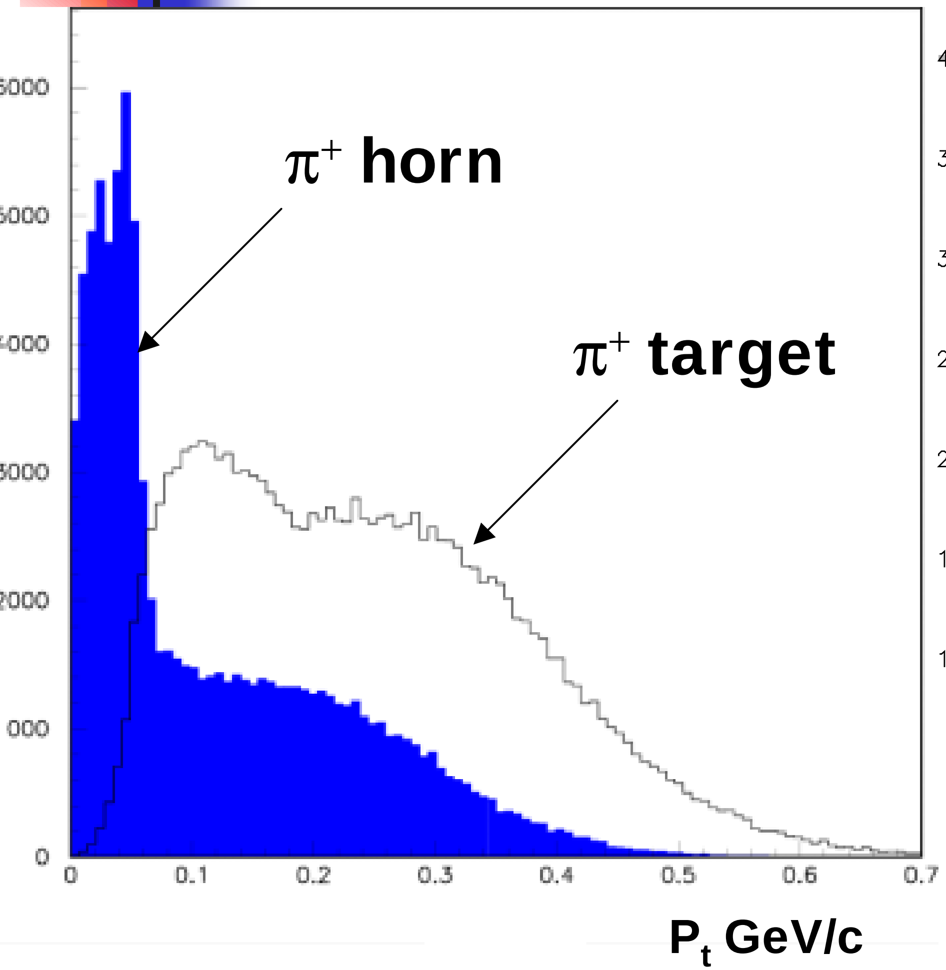


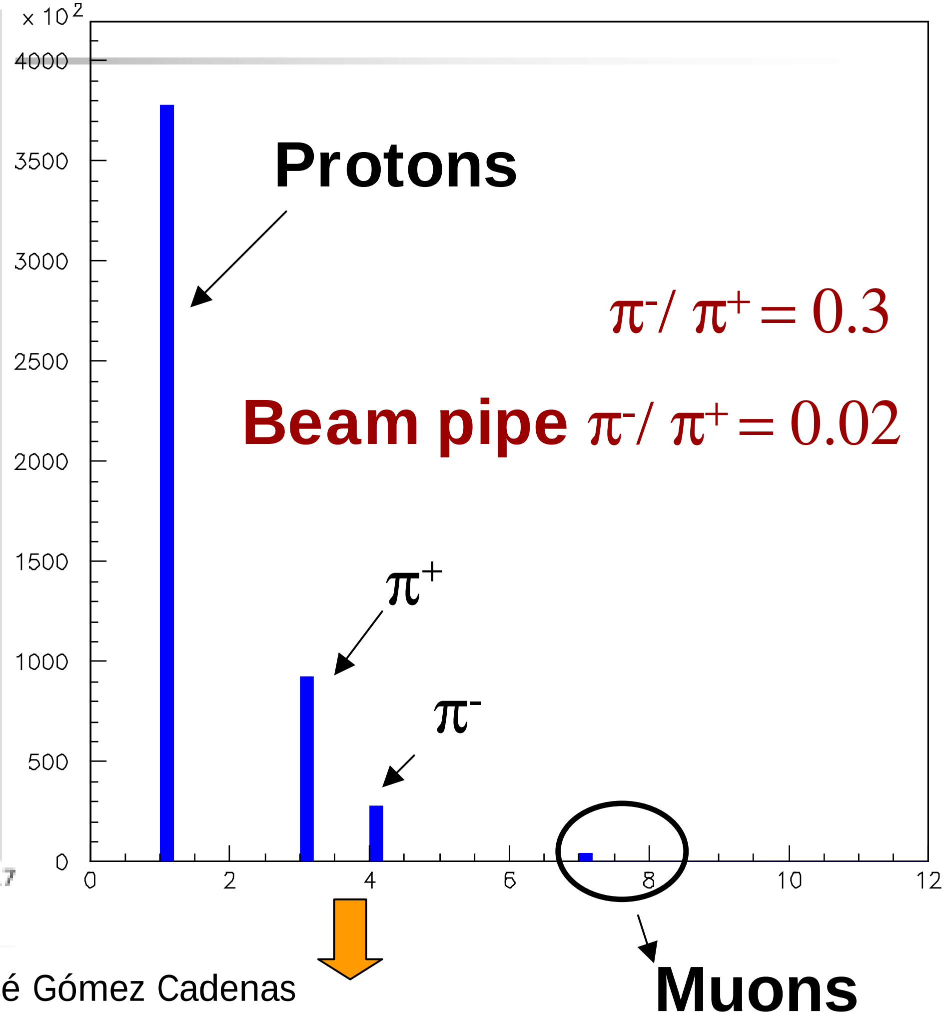
Mars simulation of particle production

After the horn

Sign selective

P_t distribution

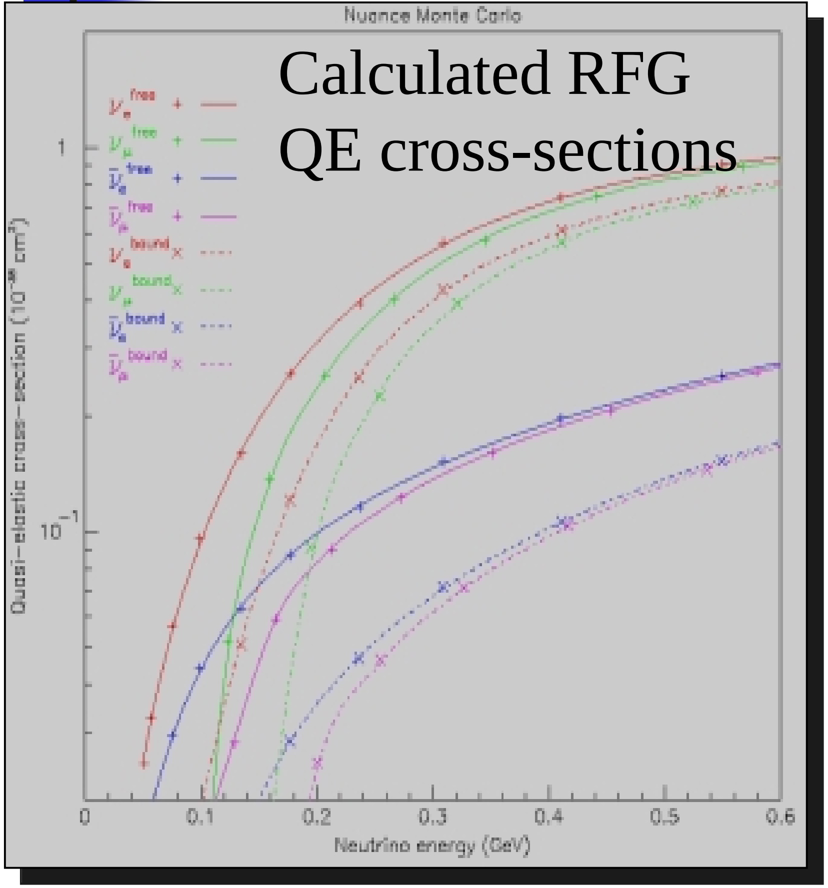




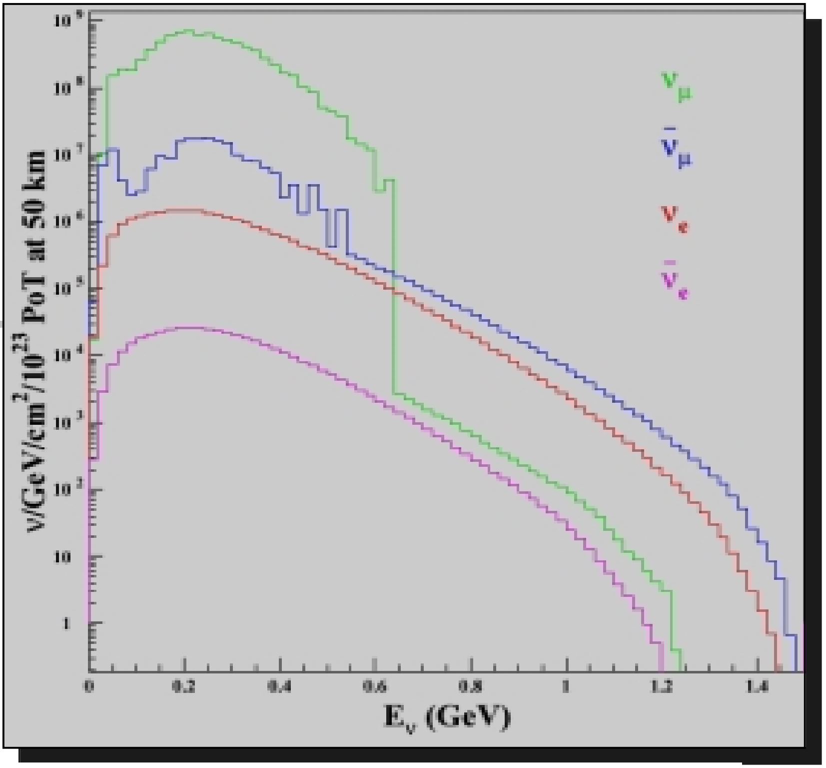
$\pi^-/\pi^+ = 0.3$

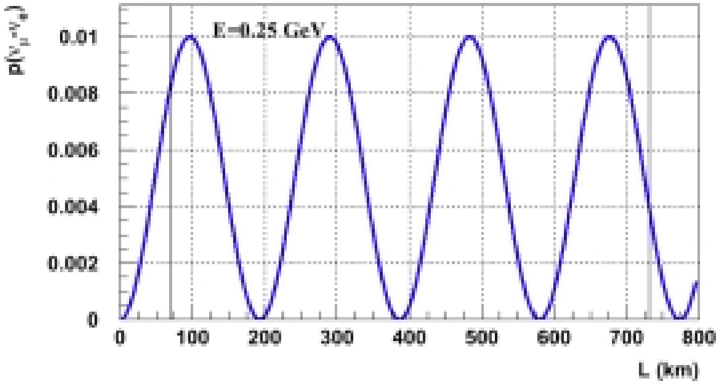
Beam pipe $\pi^-/\pi^+ = 0.02$

Resulting ν Beam



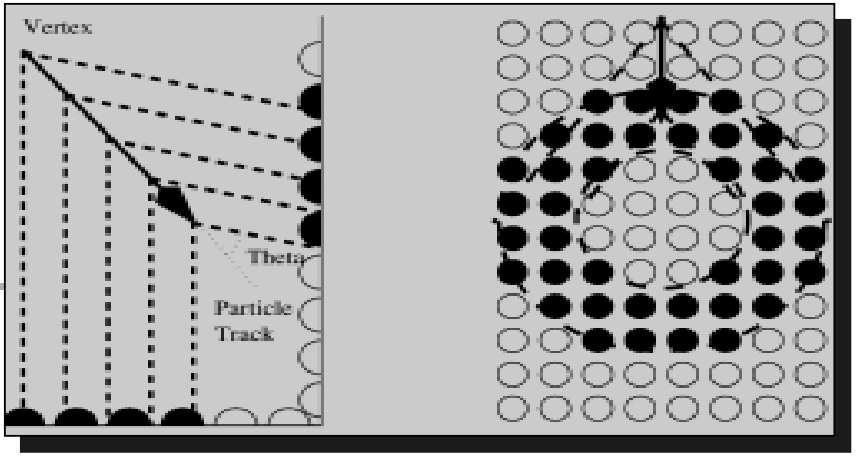
Calculated RFG QE cross-sections





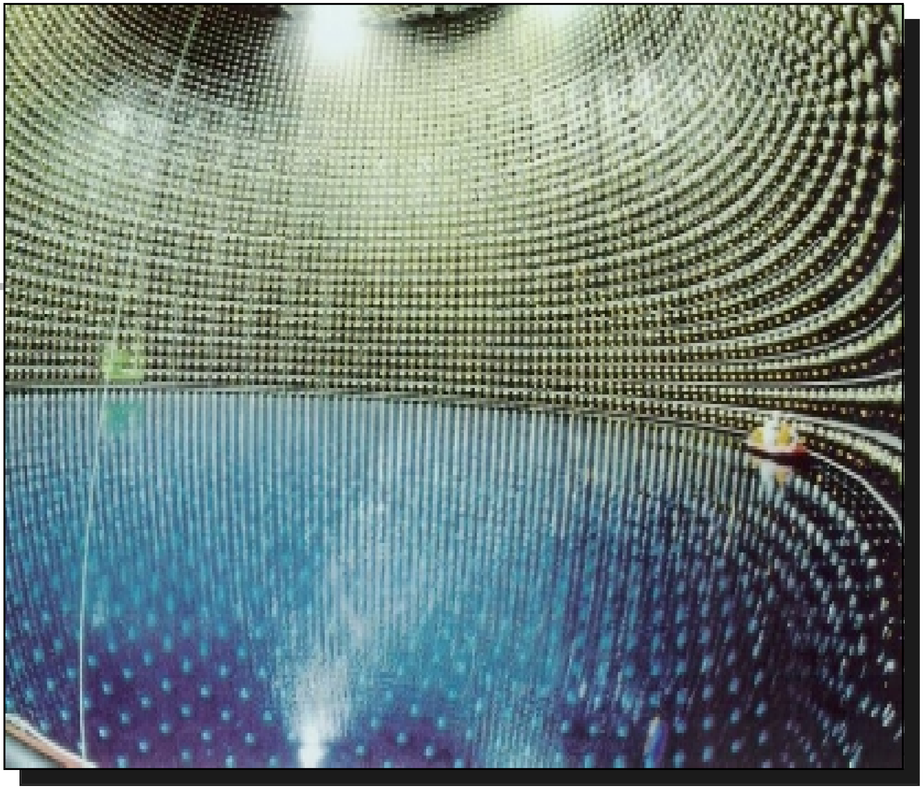
Detectors

1. Water Cerenkov (á la SuperK)
   - Full simulation of detector response
2. Liquid Scintillator (á la Boone)
   - Extrapolation from Mini Boone studies



- Vertex from timing
- Direction(s) from ring edge
- Energy from pulse height, range, opening angle
- Particle ID from hit pattern, opening angle, muon decay

Water Detector



- 40 Kt fiducial mass. Half SuperK PM coverage?
- Excellent particle ID. Minimize μ/e π^0/e confusion
- Good efficiency at low energies

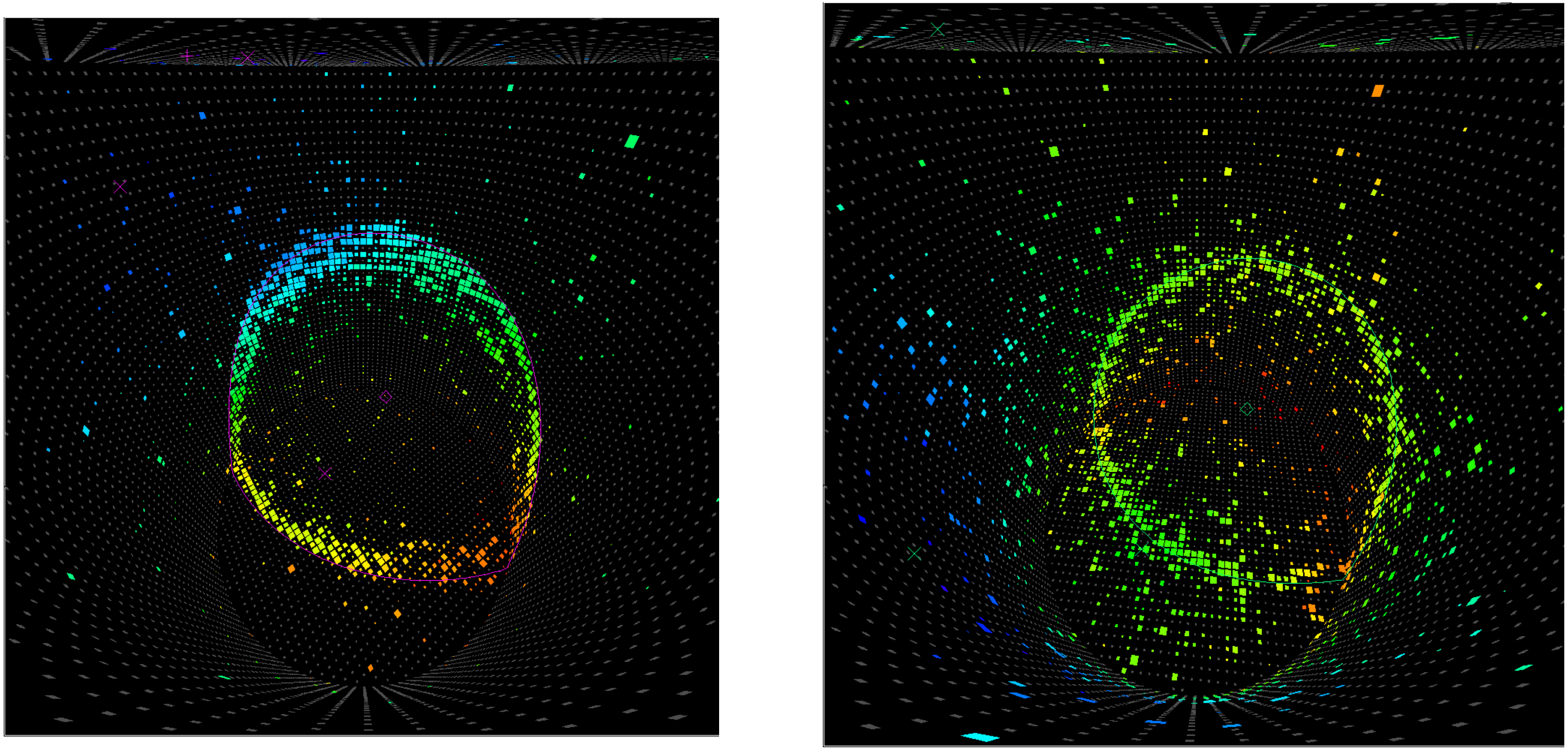
- Attenuation length (@420 nm): ~100m
- Energy scale: ±2.4%
- Particle ID: ~98%

- Momentum resolution: ±2.5%/$\sqrt{E}$ + 0.5% (e), ±3%(μ)
- Vertex resolution: 40cm

ν_e Appearance Backgrounds

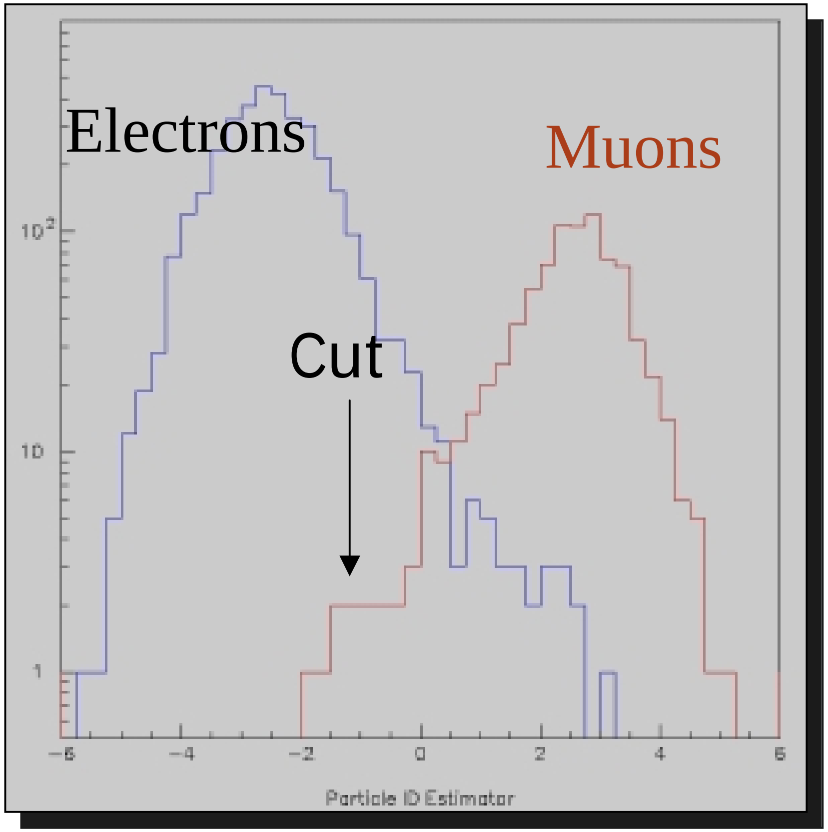
- Detector backgrounds
  - μ miss-identification
  - Neutral Current π^0 production
    - Resonant
    - Coherent
    - Diffractive
  - Hadronic interactions
    - In Oxygen nucleus
    - In water
- Beam background

μ/e Background Rejection



Particle Identification Cut

- Use Cerenkov light pattern (including opening angle, if possible) as primary μ rejection
- Tighten cut to reduce miss-ID further
- ν_e CC Efficiency: 94%
- ν_μ CC Efficiency: ~1%

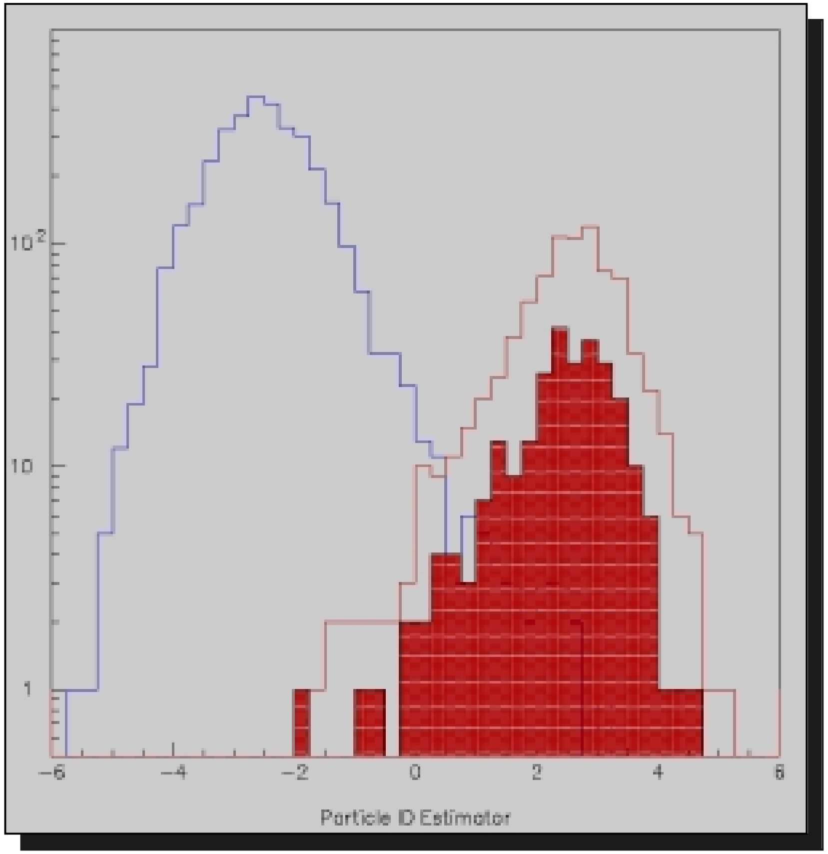


Muon Decay and Visible Energy Cuts

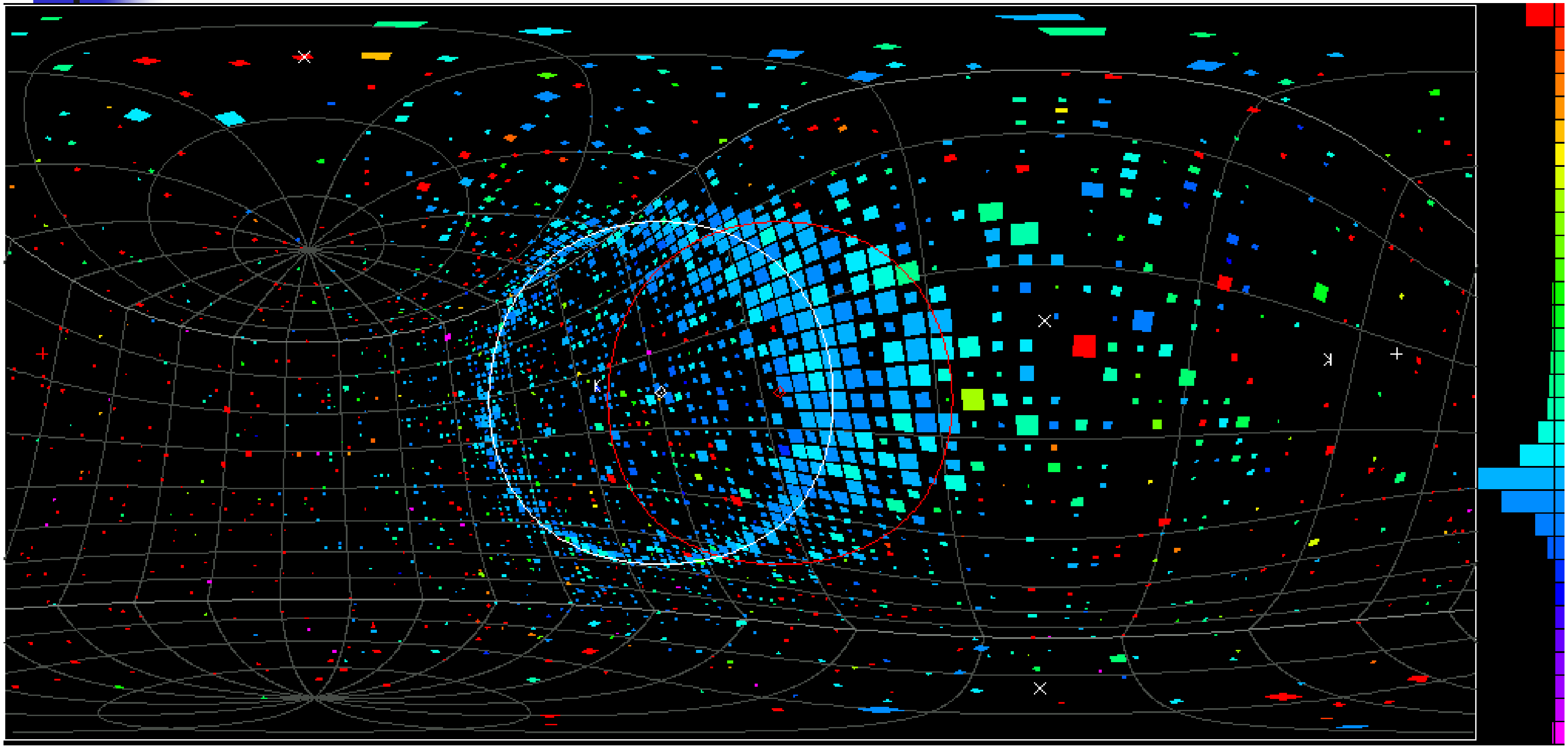
- Muon decay identification using delayed coincidence
- Only ~22% of μ^- absorbed before decay
- Visible Energy cut:

E_{vis} (= $p_{electron}$) > 100 MeV

- $\varepsilon_\mu \sim 0.1$ %

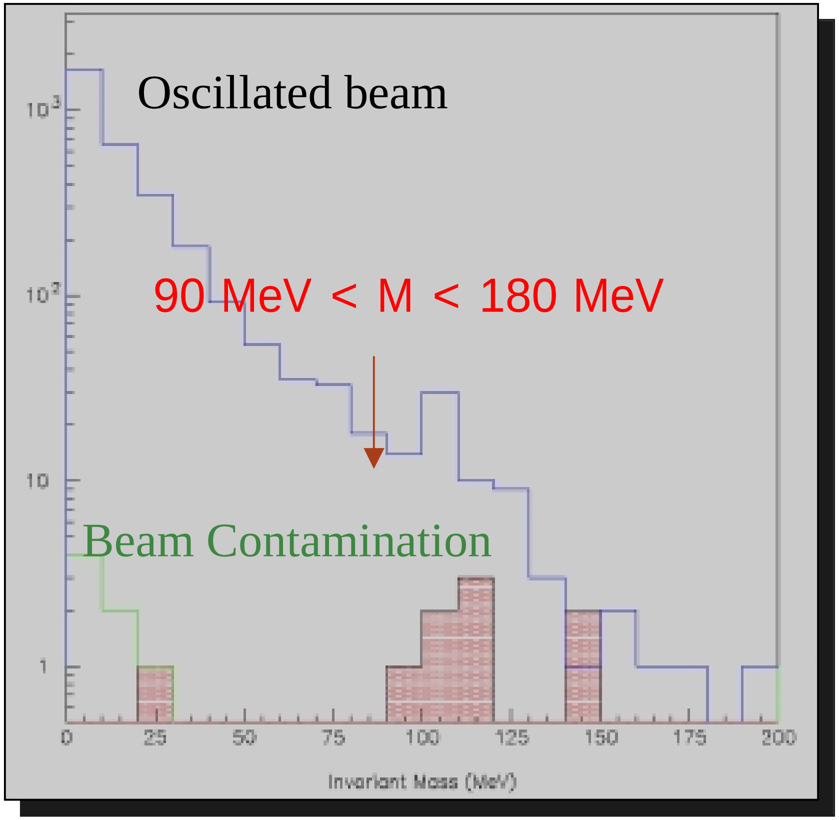


π^0/e Background Rejection based on sophisticated energy flow fitter



Summary on Background Rejection

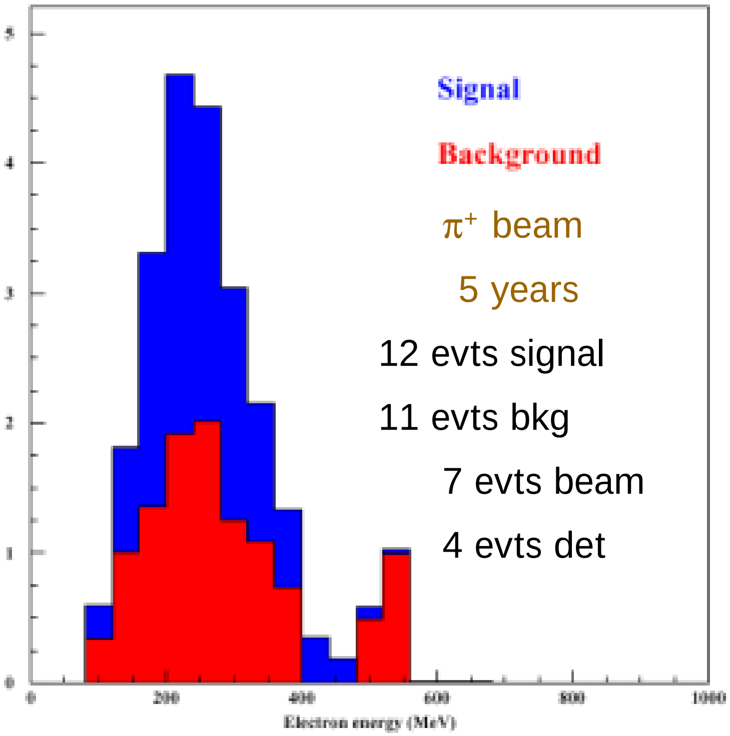
- Apply energy-flow fitter to surviving events
- π^0/e at 0.1 % level
- μ/e at 0.1 % level
- Signal efficiency very high (~80 %)



Assumed oscillation Parameters

- $\sin^2 2\theta_{12} = 0.8$
- $\sin^2 2\theta_{23} = 1$
- $\sin^2 2\theta_{13} = 0.01$
- $\Delta m^2_{12} = 5\times10^{-5}\ \mathrm{eV}^2$
- $\Delta m^2_{23} = 3\times10^{-3}\ \mathrm{eV}^2$

Results at 130 Km



π^+ beam

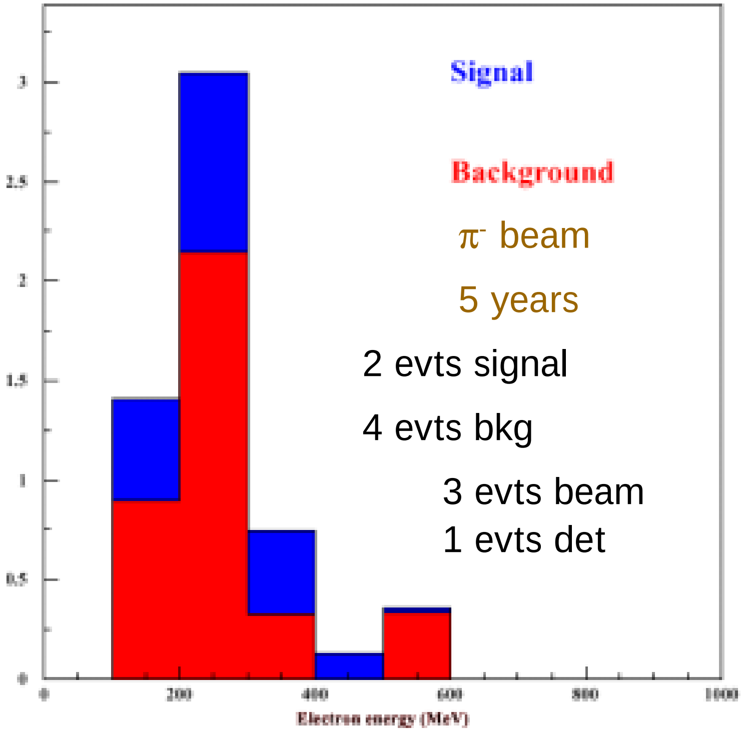
5 years

12 evts signal

11 evts bkg

7 evts beam

4 evts det



π^- beam

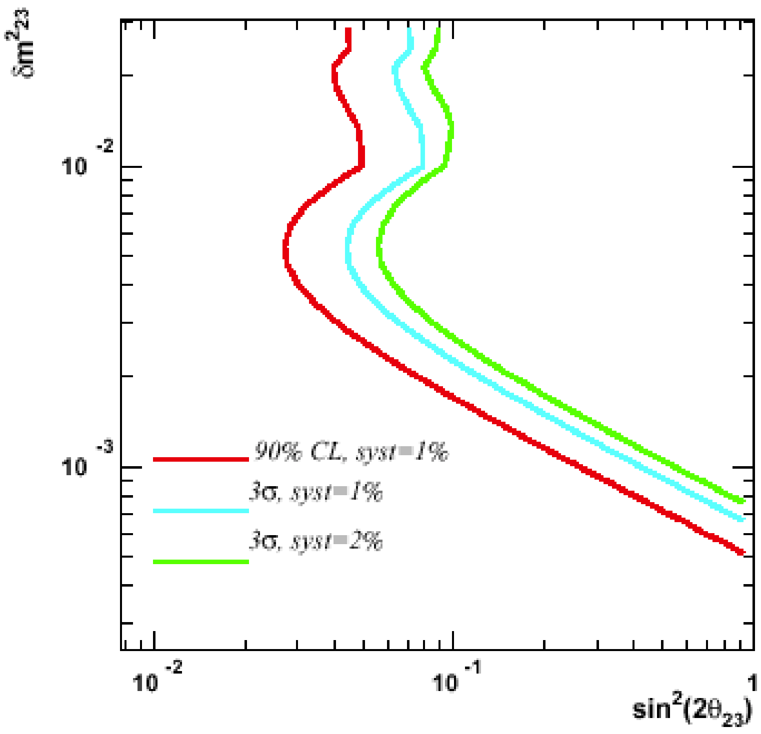
5 years

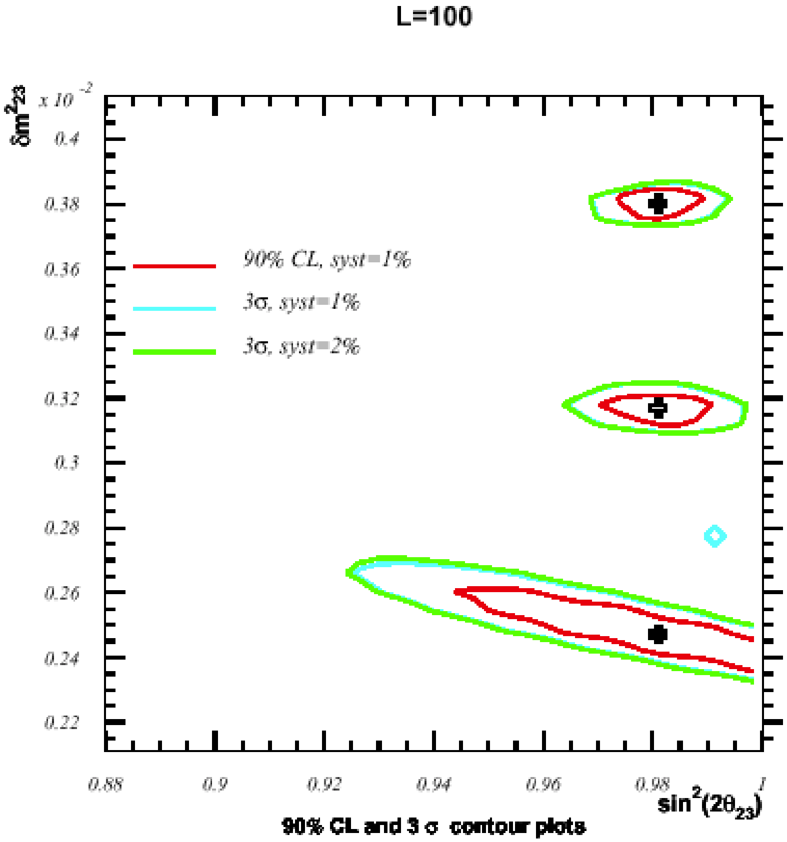
2 evts signal

4 evts bkg

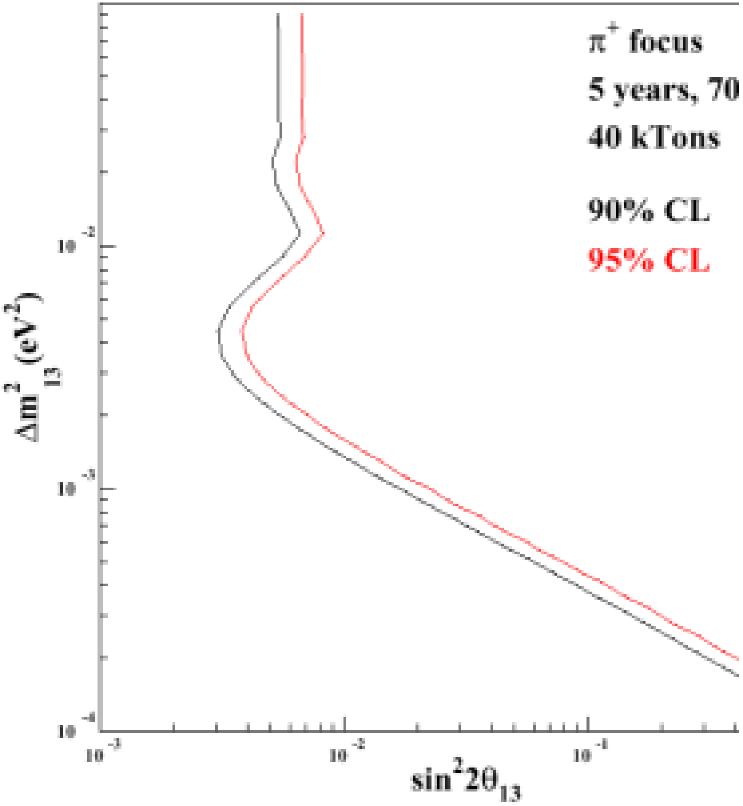
3 evts beam
1 evts det

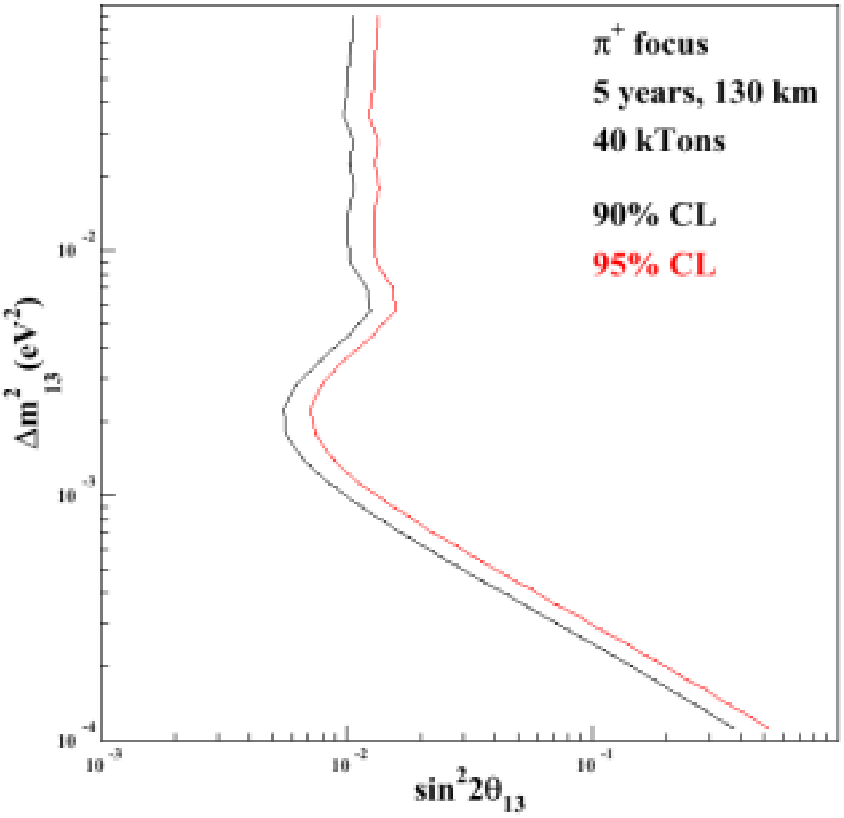
Sensitivity to θ_{23}(Scint. detector)



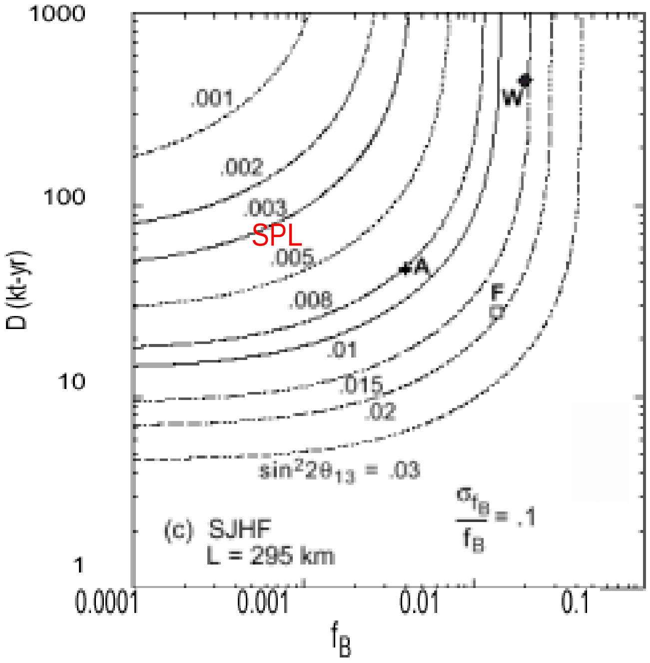


Sensitivity to θ_{13}(Water detector)

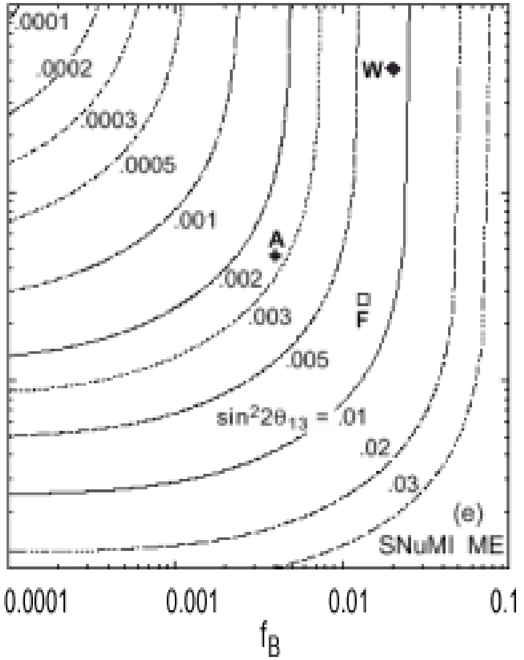




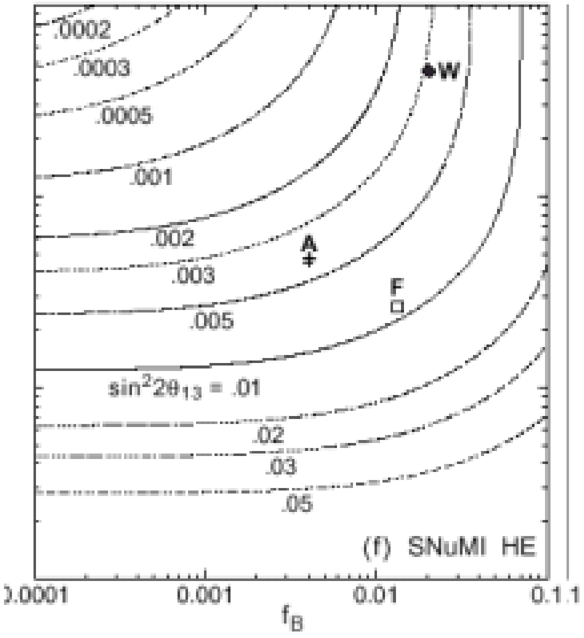
FNAL study. Sensitivity to θ_{13}



E_ν ~ 1 GeV, L = 295 Km



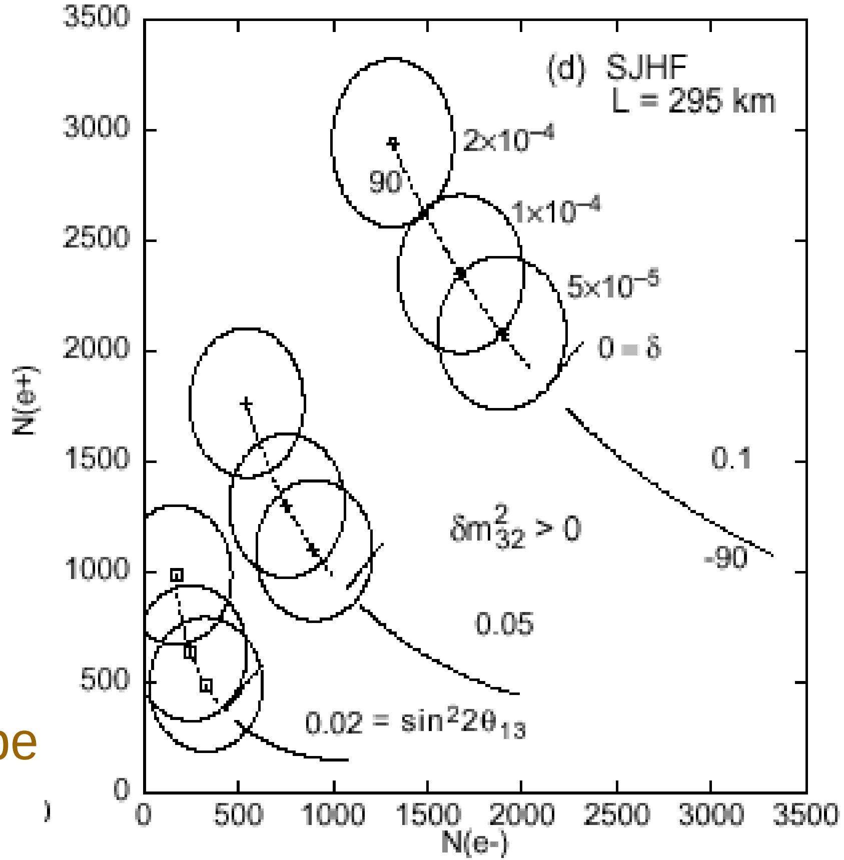
E_ν ~ 7 GeV, L = 2900 Km



E_ν ~ 15 GeV, L = 7300 Km

Sensitivity to CP violation (FNAL study)

- SJHF + 220 kt water det + 2% systematics
- 3 σ effect for:
  - $\sin^2\theta_{13}$ =0.1
  - δm^2_{12} = 510^{-5} eV^2
  - $\delta=90^0$
- 3 σ effect also for:
  - $\sin^2\theta_{13}$ =0.02
  - δm^2_{12} = 10^{-4} eV^2
  - $\delta=90^0$
- Small region for which maximal CP violation may be observed



Summary (I)

- Most of the phase space covered by FNAL + CERN studies
- A personal opinion
  - Most realistic/interesting scenarios are SJHF and CERN to Modane scenario
    - Low energy superbeams to short distances
    - Available large mass detector (SuperK like)
  - SJHF vs SPL?
    - SJHF (-) K contamination in beam + π^0/e separation
    - SPL (-) π^- production $\approx\pi^+/3$ Bad for CP studies

Summary(II)

- Super Beams can do well in “precision” measurement of oscillation parameters
  - Sensitivity to s_{23},θ_{23} At 1 % level
  - Sensitivity to $s_{13} \approx 3\text{-}5\ 10^{-3}$,
    - one-two orders of magnitude better than MINOS/OPERA
    - Two orders of magnitude worst than NuFact
- Marginal sensitivity to δ
  - Limited by
    - π^- Beam (at low energy)
    - Beam background
    - Systematic errors on cross sections

Super Beams vs NuFact

- Super Beams are no alternative to NuFact
  - Marginal sensitivity to a CP violating phase
  - Limited sensitivity to θ_{13}
- Super Beams are not “fast & dirty” intermediate experiments “while we wait for NuFact”
  - They require a very large detector 1-5 x SuperK
  - Very long runs (≈10 years)
- However, SJHF may be there before NuFact (and SuperK is already there!)
- Perhaps the way to go if nature has not chosen LMA