Some thoughts on neutrino beams for neutrino cross-section measurements

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The First International Workshop on
Neutrino-Nucleus Interactions in the Few GeV Region

December 13-16, 2001, KEK, Tsukuba, Japan

The low energy region…

Many channels have to be studied ...

Charge Current (CC) interactions ($\nu\,N \rightarrow l\,X$):

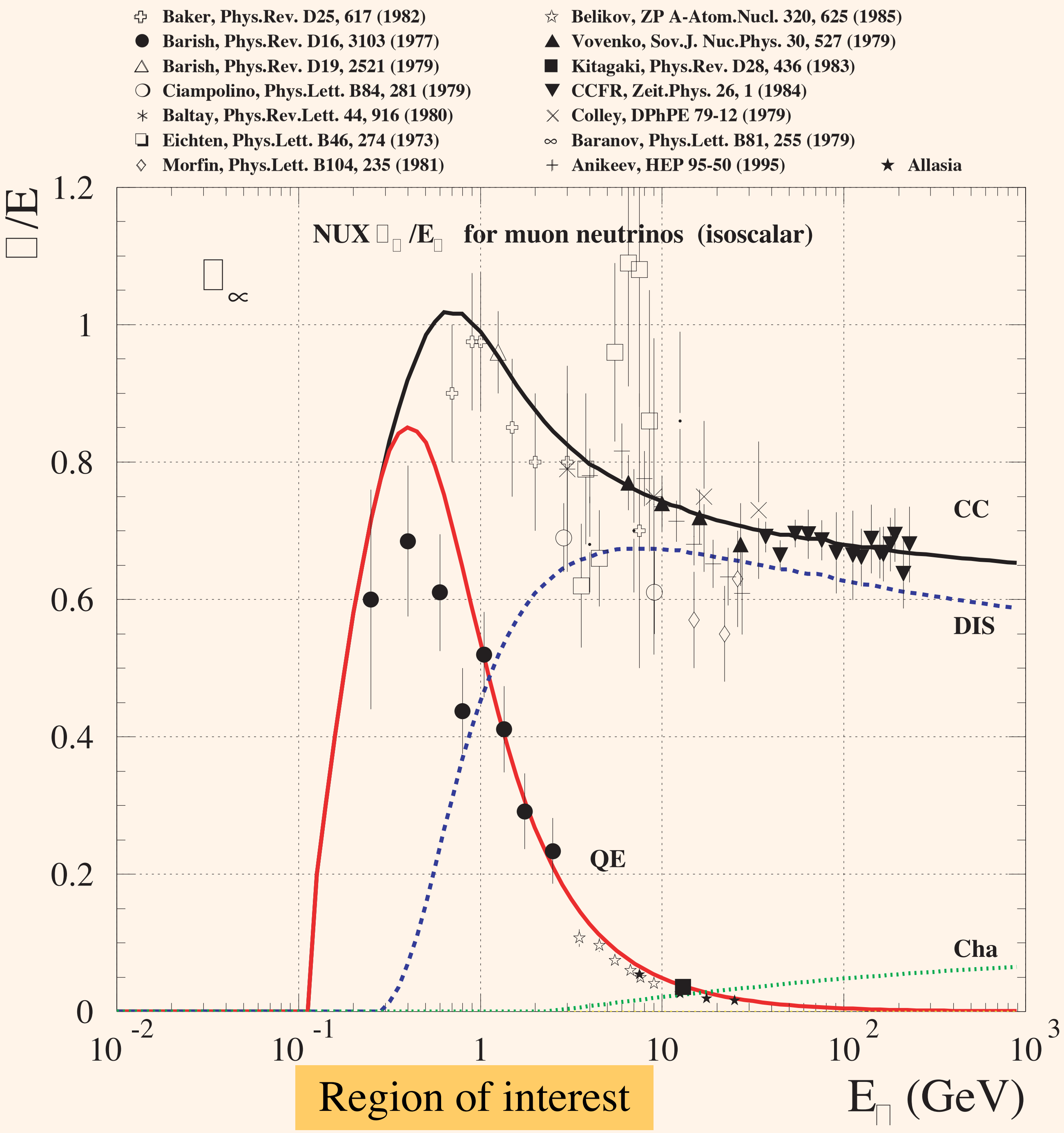
- Quasi-elastic ($\nu\,N \rightarrow l\,N'$) ⇐ dominant atmospheric reaction
- Resonant ($\nu\,N \rightarrow l\,N^*$) and Single/Multi pion production ($\nu\,N \rightarrow l\,N'\,\pi$)
- Deep inelastic ($\nu\,q \rightarrow l\,q'$ or $\nu\,q \rightarrow \nu\,q$) ⇐ multi-pion production via fragmentation

Neutral Current (NC) interactions ($\nu\,N \rightarrow \nu\,N$) ⇐ specially important a

Elastic (electron) scattering ($\nu\,e^- \rightarrow \nu\,e^-$)

Coherent production $\nu\,N \rightarrow \nu\,N$

The physics is complex…
the neutrino flux beam should be « simple »!!



Comparison of σ/E_ν for QE and total processes between data and NUX

The region of interest is certainly between 100 MeV and 10 GeV!

Unfolding cross-sections…

Number of events

Detector systematics

Clean event reconstruction and classification

$$\sigma = \frac{N_{observed} / \varepsilon - N_{background}}{\phi}$$

Neutrino flux!

Shopping list

- **Goals**
  - Measure cross-section from kinematical threshold, through quasi-elastic dominated region, study single-pion production, study opening of multi-pions final states **$\approx 0.1 < E_\nu < \approx 3$ GeV**
  - Study **neutrino and antineutrino** cross-sections
  - Measure both ν_e and ν_μ?
  - Study **nuclear effects (i.e. compile various targets in same beam)**
- **Experimental aspects:**
  - Different types of target (nuclear effects)
  - Capability to measure exclusive final states (low density, high granularity)
  - Capability to measure inclusive final states (high density)
- **Beam aspects**
  - Statistics
    - κ Sufficient flux also at the lowest energies (cross-section decreases and meson decay kinematics less focalized at lower energy)
  - Systematics
    - κ In the range of 1%, 10% or 20% ?

Neutrino beam candidates

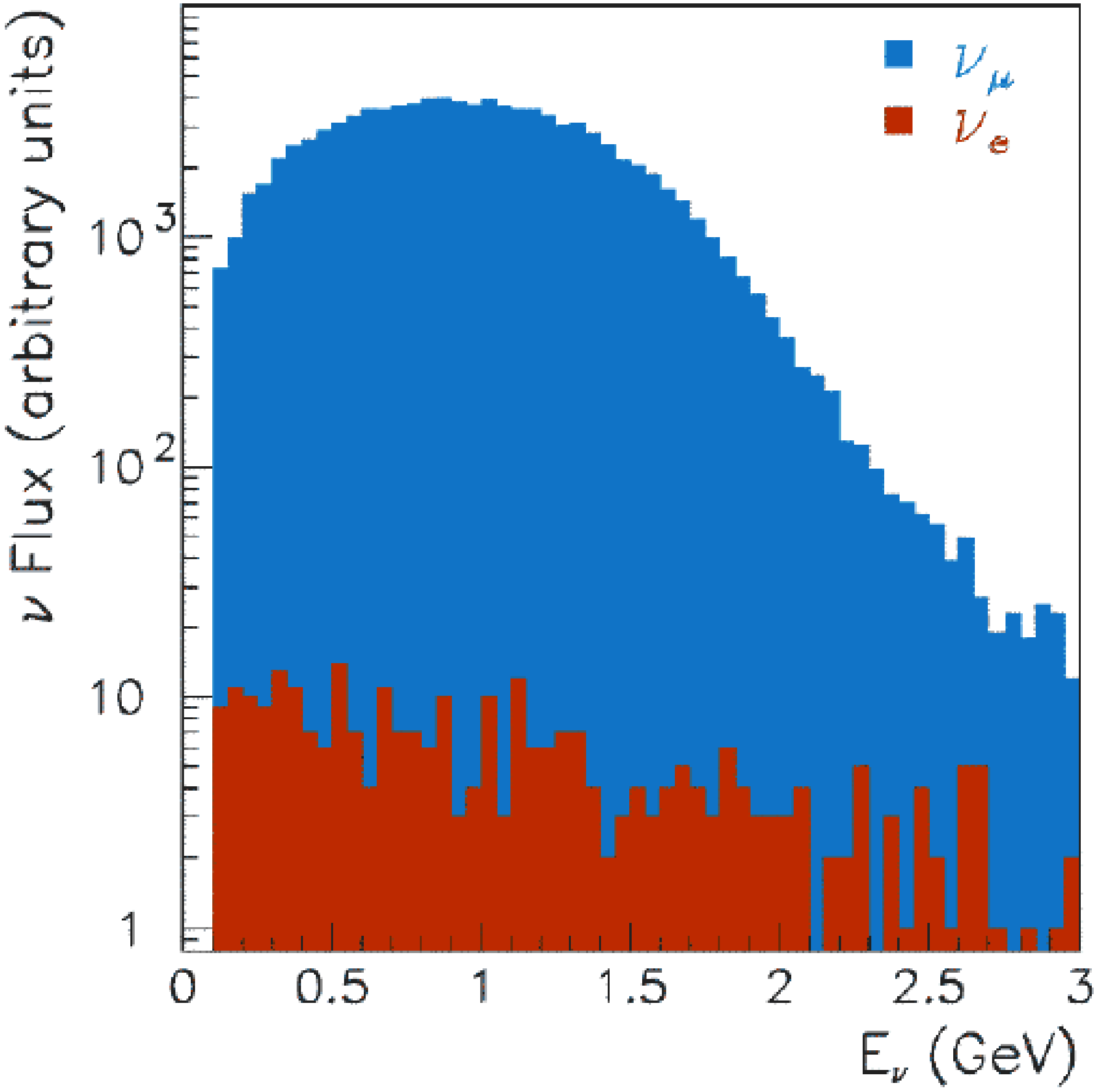
- **Traditional « pion » beams**
  - K2K
  - FNAL Booster
  - NUMI-LE, ME, HE
  - JHF
- **Storage ring beams (e.g. antiproton accumulators)**
  - FNAL Debuncher
  - CERN AD
- **Neutrino factories**
  - …

Traditional beams

	FNAL Booster	NUMI LE	NUMI ME	NUMI HE
Peak E_ν	≈1 GeV	3.5 GeV	7.5 GeV	13 GeV
ν_μ CC rate per ton/year	5000	210000	1100000	2000000
anti-ν_μ CC rate per ton/year	1000	21000	32000	20000
ν_e CC rate per ton/year	1	2300	9500	12000
Anti–ν_e CC rate per ton/year	0.5	630	660	600
Flux uncertainty	10%	20%	20%	20%

From S. Geer's page: *http://www.fnal.gov/projects/muon_collider/nu/study/scattering/beam_table.html*

FNAL Booster



Running in 2002

	FNAL Booster
Peak E_ν	**≈1 GeV**
ν_μ CC rate per ton/year	**5000**
anti-ν_μ CC rate per ton/year	**1000**
ν_e CC rate per ton/year	**1**
Anti–ν_e CC rate per ton/year	**0.5**
Flux uncertainty	**10%**

FNAL (NuMI) beam characteristics (low energy configuration):

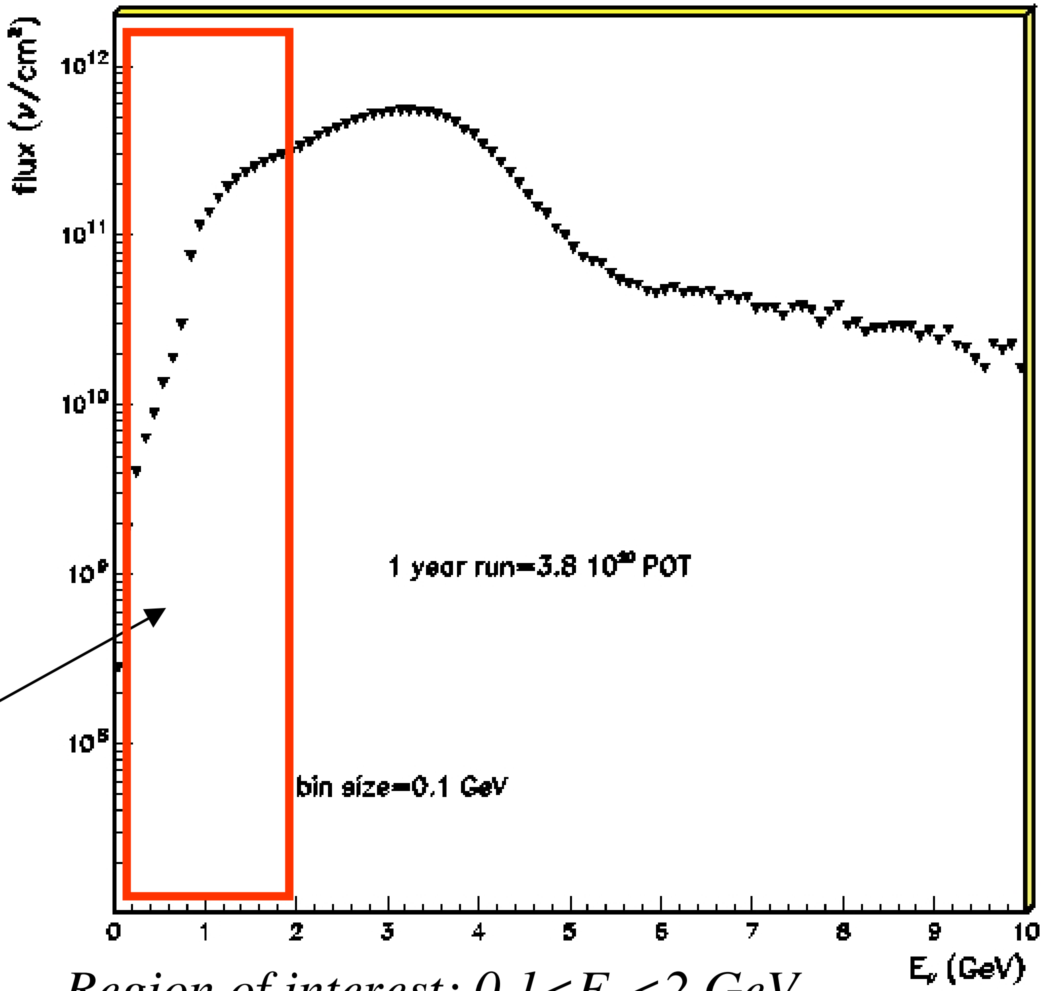
M.I.: 120 GeV/c Proton.

$4*10^{13}$ PoT/spill - 1spill / pulse - pulse=1.87 s

RUN time: 1 year = $3 * 10^7$ s * live time (%)

See talk of F. Cavanna ⇒ Systematics dominated

Systematic error in the range $E_\nu<1.5$ GeV?



Region of interest: $0.1<E_\nu<2$ GeV

KEK beam characteristics:

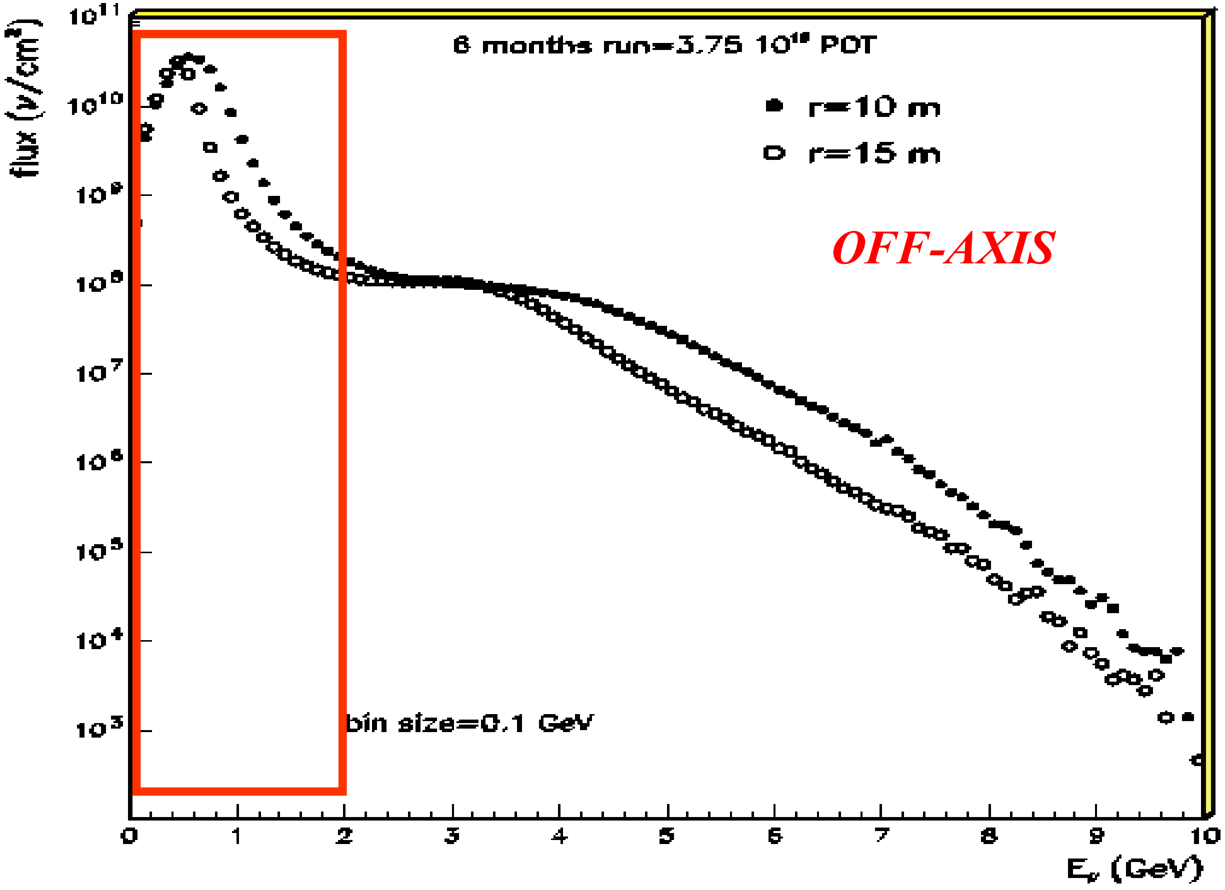
PS: 13 GeV/c Proton.

$5.5*10^{12}$ PoT/spill - 1 spill (1.1μs) /pulse - pulse = 2.2 s

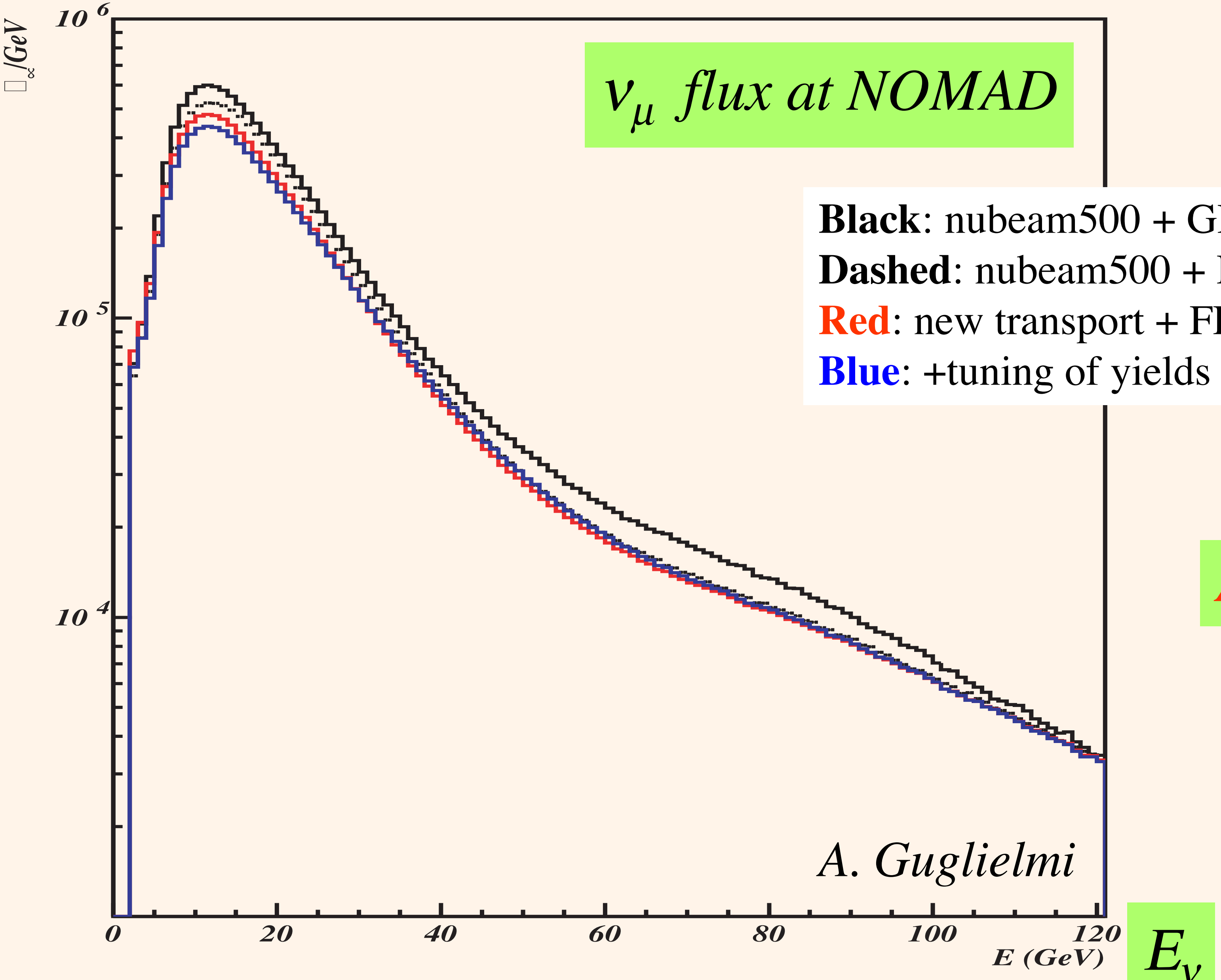
RUN time: 6 months/year = $1.5 * 10^7$ s

See talk of F. Cavanna

⇒ Systematics dominated



NOMAD beam MC prediction



ν_μ *flux at NOMAD*

Black: nubeam500 + GEANT-FLUKA
Dashed: nubeam500 + FLUKA standalone
Red: new transport + FLUKA standalone
Blue: +tuning of yields to SPY data

A. Guglielmi

E_ν

A tough job!

Cross-sections at neutrino factories

1. Use a muon beam : $(\mu \rightarrow \nu_\mu \, \nu_e \, e)$
2. known flux and no contamination
3. Measurement of both, ν_μ and ν_e cross sections

   (and both helicities !!)

M. Campanelli, S. Navas,
A.Rubbia, hep-ph/0107221,
May 2001
Presented at NUFACT'01,
Tsukuba

The assumptions ...

a. low energy beam **$E_\mu \sim 2$ GeV**

b. low intensity beam - **$10^{15}\,\mu$ / year**

c. short baseline experiment - **20 meters**

d. detector mass - **100 tons**

Measure σ_ν /E

below $E_\mu \sim 2$ GeV

with 100 MeV bins in energy

and 6% minimum statistical

error

The « modest » machine…

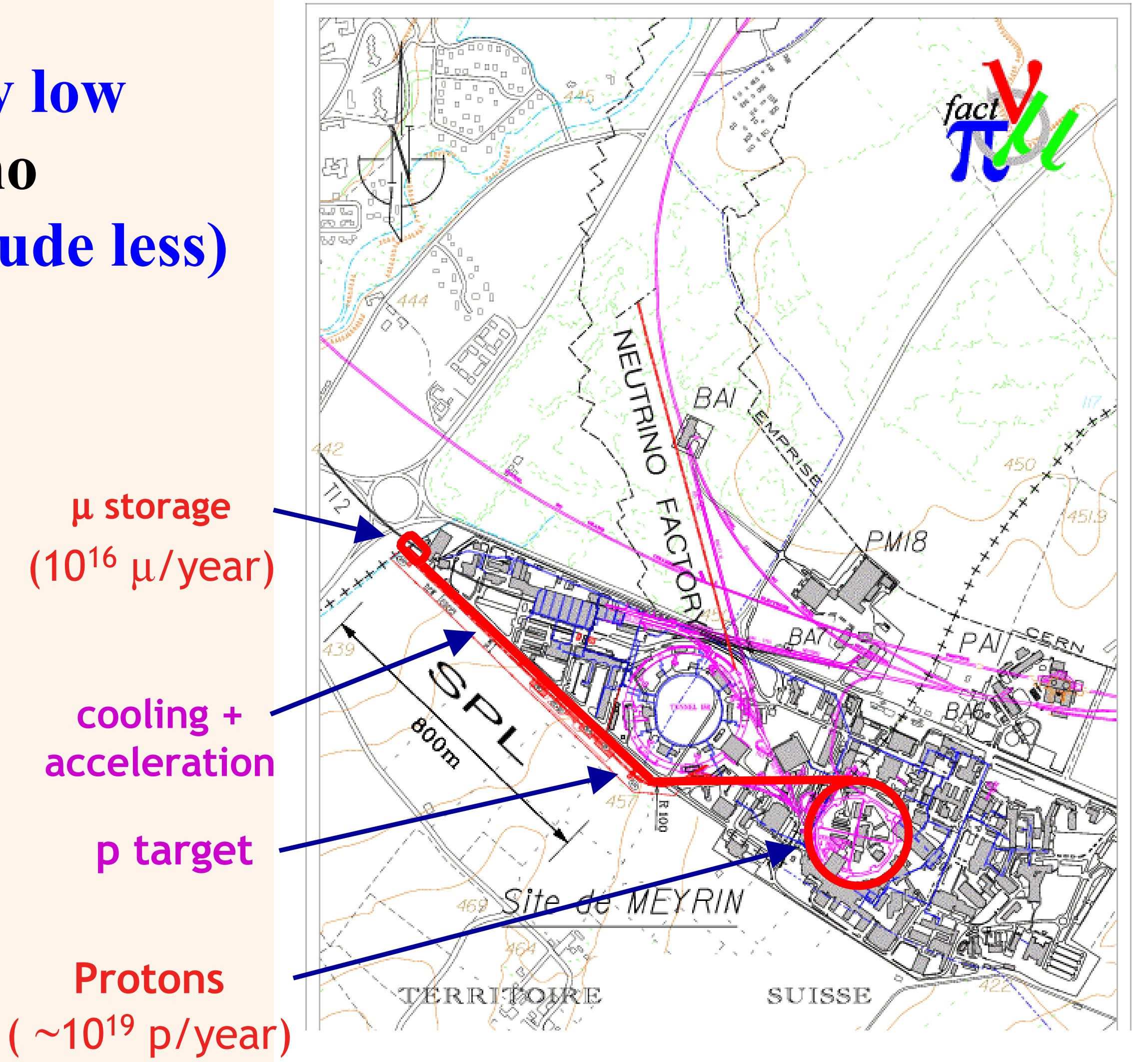
The machine could deliver very low intensities compared to neutrino factories (~ 5 orders of magnitude less)

This could fit to staging scenario
of the neutrino factory

Example : CERN complex

1. The PS as a proton booster
2. The SPL tunnel to focalize and accelerate μ's
3. A μ storage ring ($E_\mu \sim 2$ GeV)

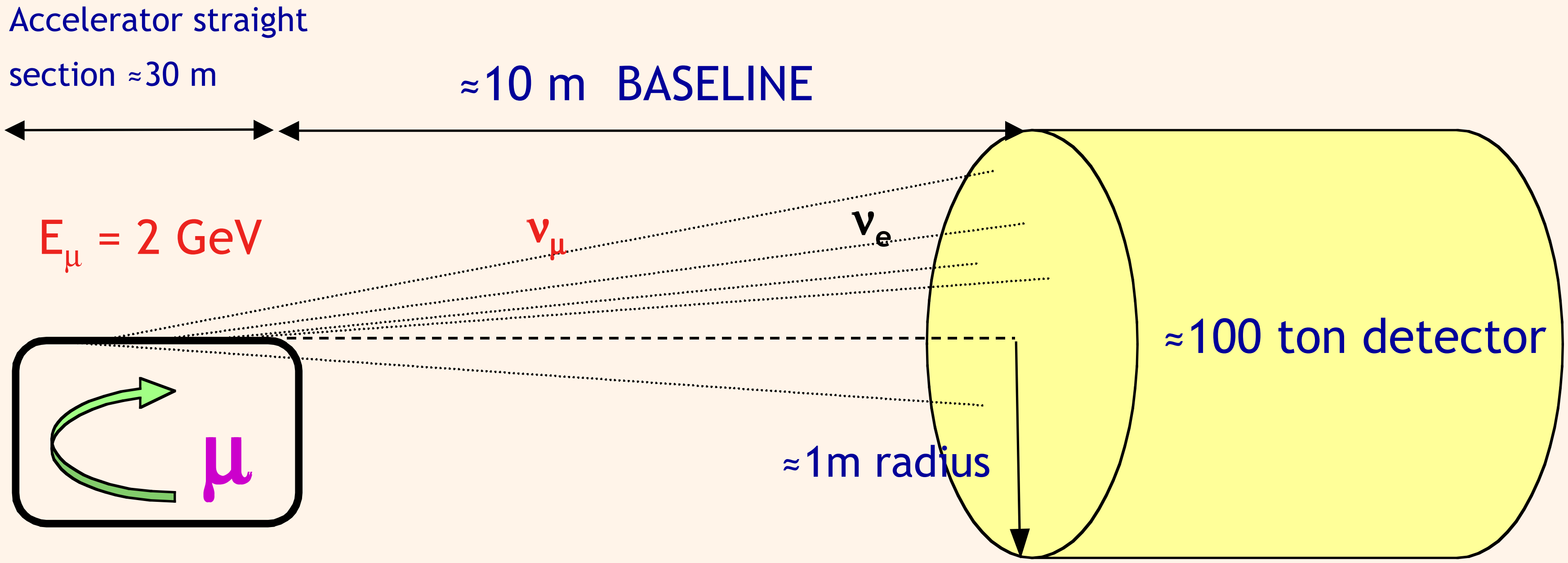
(after discussions with H. Haseroth)



Scenario within the CERN complex

…and the detector

We assume, for definiteness, the following configuration:

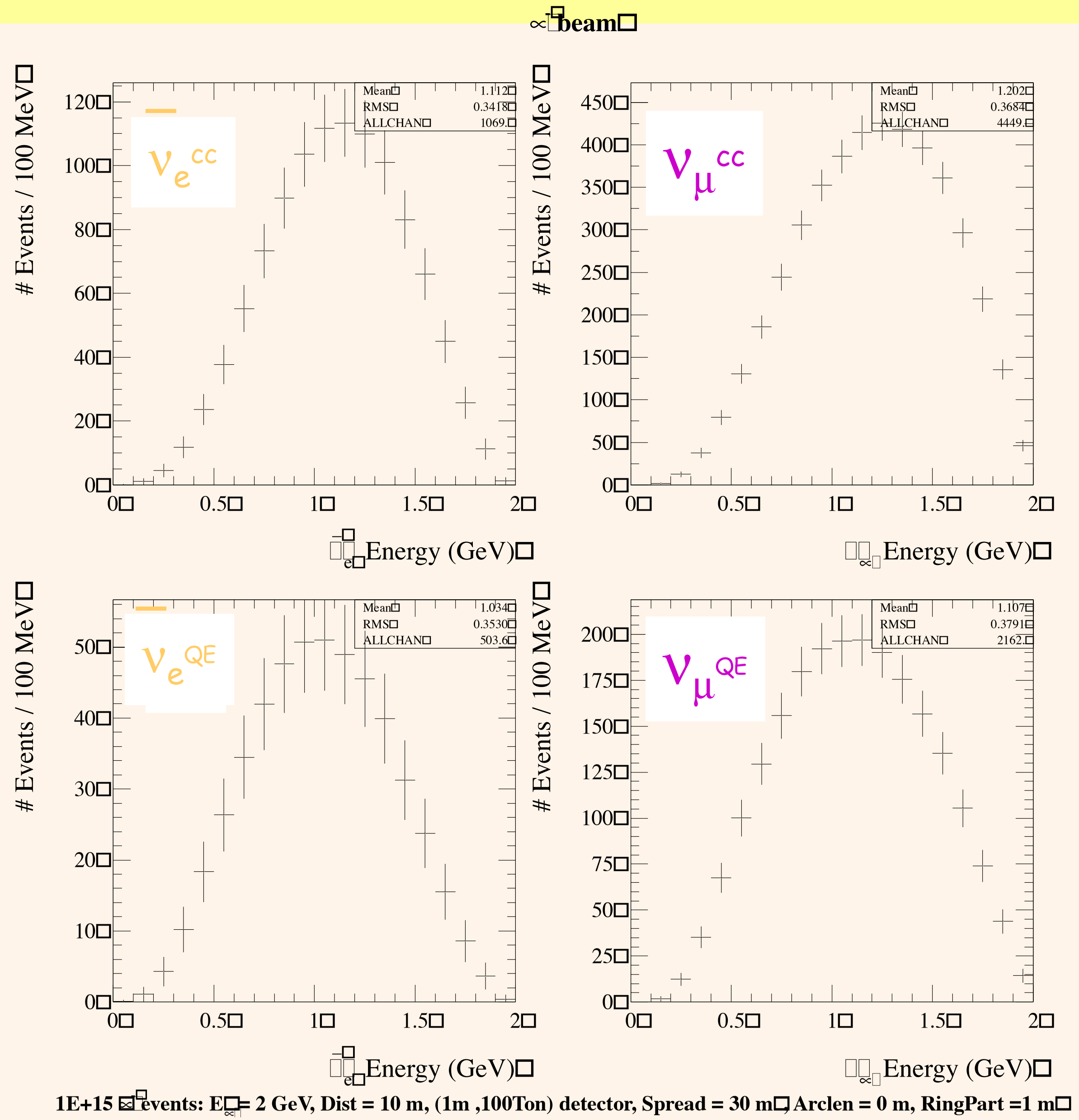


Total number of events

	ν_e	ν_μ
Charge-current (Total)	1070	4450
Quasi-elastic (QE)	500	2160

10^{15} "useful" μ/year

10^{15} useful μ^- decays, $E_\mu = 2$ GeV, **100 Tons** detector, **1m radius**, 10 m baseline, 30 m straight section

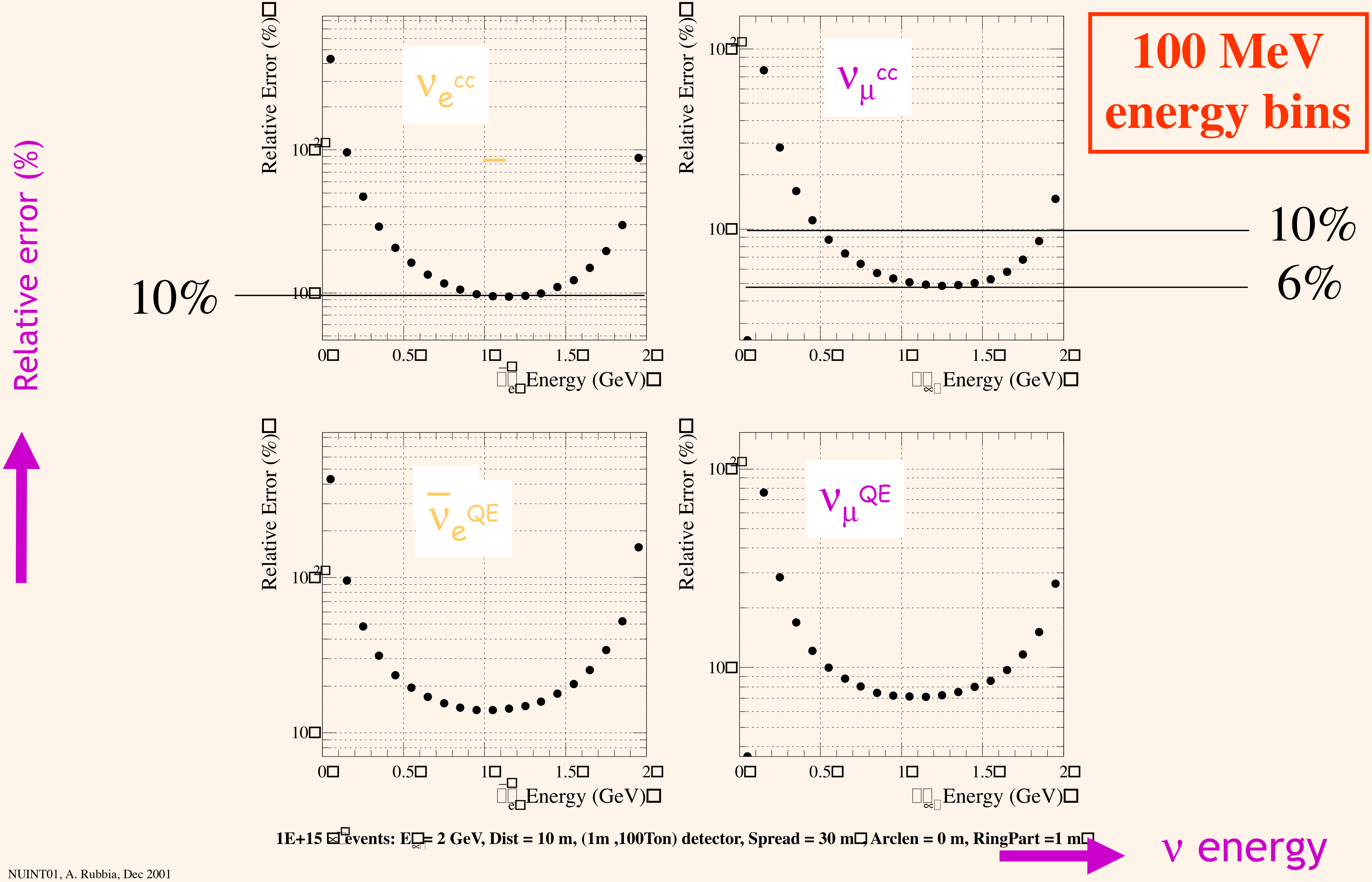


100 MeV bins !

Events / 0.1 GeV

ν energy

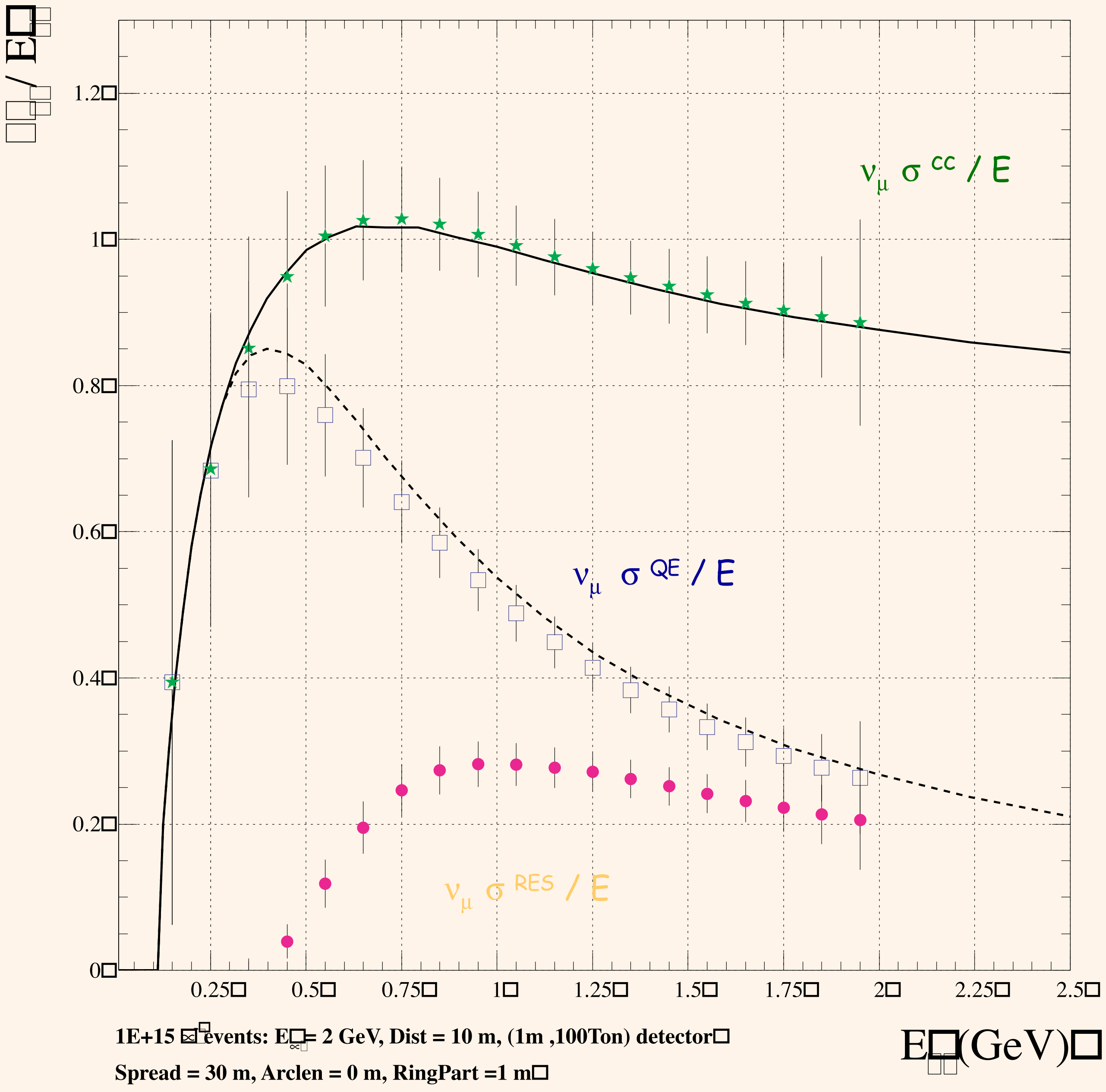
10^{15} **useful μ^- decays, E_μ = 2 GeV,** **100 Tons** detector**, 1m radius,** 10 m baseline, 30 m straight section



100 MeV energy bins

1E+15 events: E = 2 GeV, Dist = 10 m, (1m ,100Ton) detector, Spread = 30 m, Arclen = 0 m, RingPart =1 m

100 Tons detector, **1m radius,** 10 m baseline, 30 m straight section



10^{15} useful μ^- decays,

$E_\mu = 2$ GeV,

Antiprotons Accumulators

- **P-pbar physics is based on technique of beam cooling, which allows to accumulate pbar in sufficient number within a phase-space of an accelerator.**
- **Design of pbar sources has led to extensive studies of production and capture of pbar in storage rings, in order to optimize the accumulation rate**
  - Optimum choice of target, incident proton beam parameters, focusing optics to provide largest possible particle density inside transverse and longitudinal admittance of storage ring
- **Two machines:**
  - CERN AC & AA, PS proton energy=26GeV, **p=3.57 GeV/c**, admittance **200π mm.mrad** in both planes, **Δp/p=±3%**, circumference = 182m, four straight sections, longest account for **14%** of total
  - FNAL AD, **p=8.9 GeV/c**, admittance **25π mm.mrad** in both planes, **Δp/p=±2%**, circumference = 500m, triangular, longest straight section account for **13%** of total

A parasitic run…

- **During their normal operation, the ring accumulates negative particles, including π^-, K^-, μ^- and e^-'s.**
- **To a large extent, the optimization for the pbar's is also an optimum focalization for other negative particles like pions!**
- **The muons are produced in the decays of π^- and K^-'s.**
  - These decays can occur anywhere, that is, within the focusing system, the transfer lines between the target region and the storage ring, or within the storage ring itself.
  - Only a small fraction of the muons has a sufficiently small transverse emittance and a momentum within the required bite of the ring to stay captured as well.

A parasitic run is fully justified!!

W. Lee et al., FNAL PROPOSAL P-860, December 1992
« A Search for nu oscillations using the FNAL Debuncher »

What do we expect?

- **For simplicity we consider only particles stored into the ring.**
- **The lifetime of pions is sich that they will decay within a few revolutions.**
- **The few captured muons that remain trapped into the ring will subsenquently decay.**

$$\pi^-, K^- \rightarrow \mu^- \bar{\nu}_\mu$$

Short burst

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

Long burst

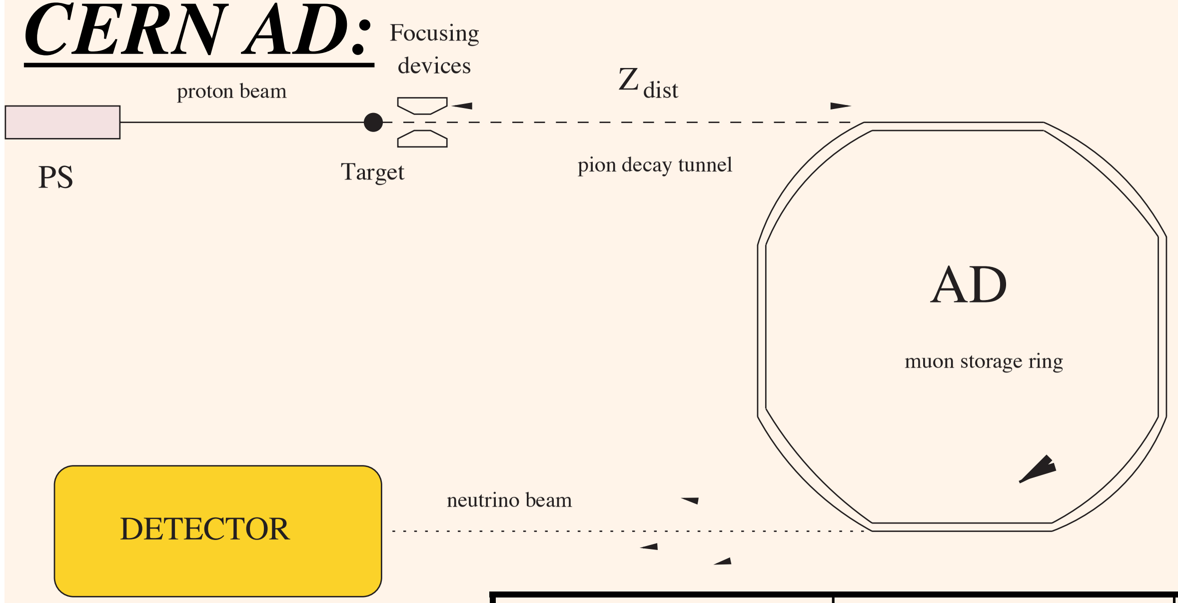
This has been measured!

A. Bross et al., FNAL-PUB-92/357, December 1992
« Measurement of the Circulating Muon Flux in the FNAL Debuncher Ring »

$$\begin{cases} \mu^- / \bar{p} = 1.0 \pm 0.2 \\ \mu^- / pot = (2.0 \pm 0.4) \times 10^{-5} \end{cases}$$

	FNAL Debuncher		CERN AC	CERN AD
	FNAL-PUB-92/357	Geer, FNAL-FN-706	(80's)	(2000)
Proton beam energy	120 GeV		26 GeV	
Circumference Length	505 m		182 m	
Momentum acceptance	8.9 GeV/c ± 2%		3.5 GeV/c ± 3%	
POT/year	1.5×10^{19}	—	5×10^{19}	2×10^{18}
Fraction of π/POT	8×10^{-4}		6×10^{-4}	
Fraction of μ / POT	2×10^{-5}		2.4×10^{-5}	
Total useful π /year	1.7×10^{15}		3×10^{15}	1.2×10^{14}
Total useful μ /year	$\boxed{4.2\times10^{13}}$	$\boxed{1.3\times10^{14}}$	$\boxed{1.7\times10^{14}}$	$\boxed{6.7\times10^{12}}$

CERN AD:

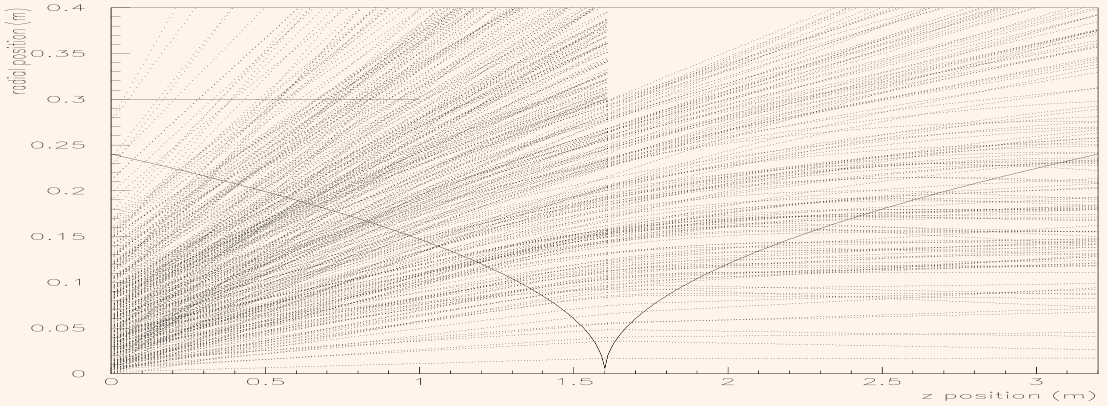


$p_\mu = 3.57$ GeV/c(–3%),

	CC (total)	QE	DIS
Anti-ν_μ	8525	4230	4290
ν_μ	3410	1165	2245
Anti-ν_e	1080	415	670

Estimated event rate for 5×10^{19} pots in a 0.1 kton detector 10m downstream of a CERN AD straight section

CERN AD optimization study:



Full MC simulation

Focusing horn shape optimized for AD acceptance

FLUKA on Be target, 70cm long, 2cm radius

200πmm.mrad admittance

$$N_{\mu} = N_{pots} \times Y_{\pi} \times A_{optics} \times \varepsilon_{\pi\to\mu}$$
$$\approx N_{pots} \times (0.02) \times (0.03) \times (0.04)$$
$$\approx 2.5 \times 10^{-5} \times N_{pots}$$

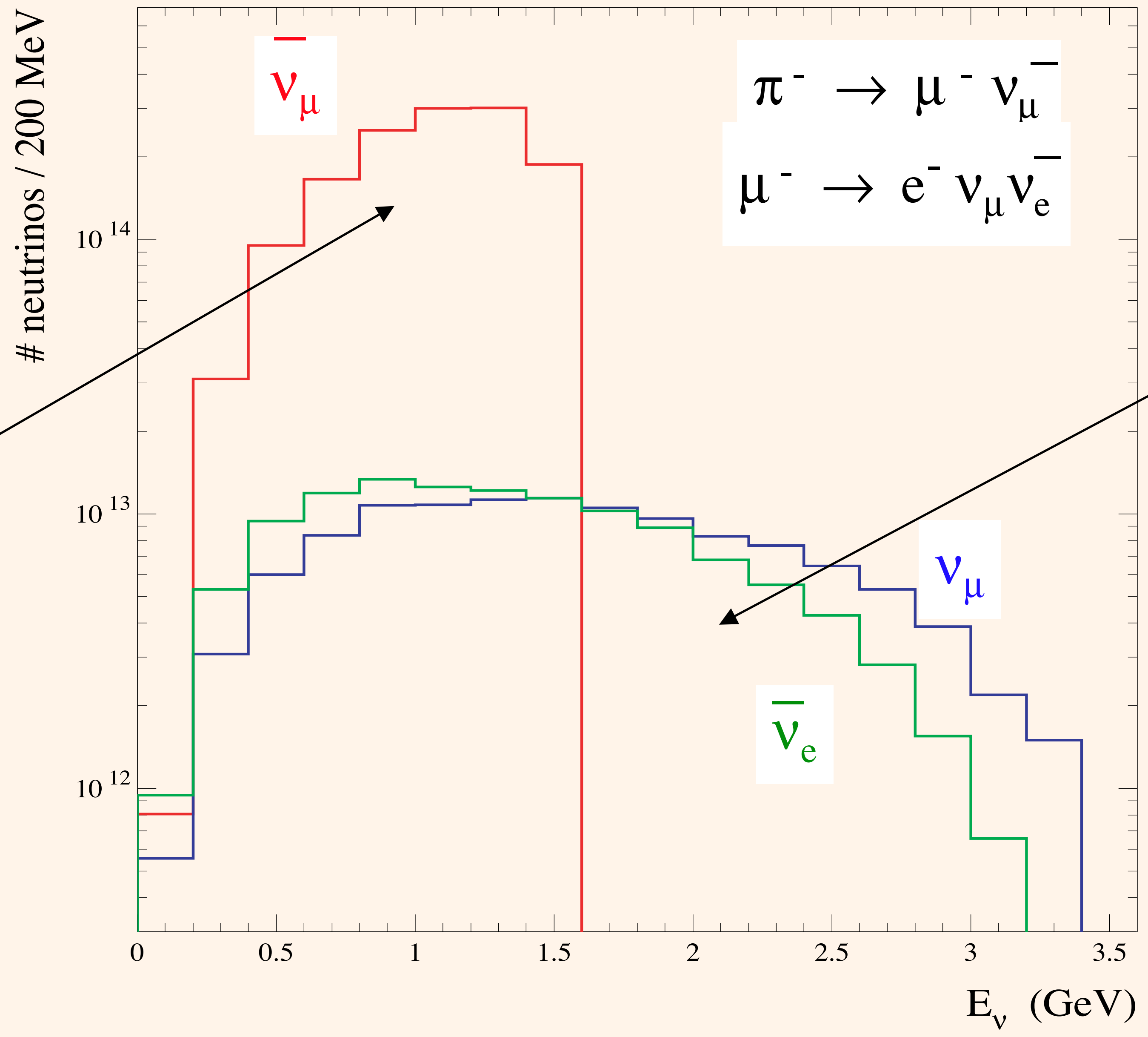
Consistent with measurement at FNAL

	Debuncher	AC	AD	
a. Number of “useful” seconds/year	10^7	10^7		
b. Protons on target per pulse	3×10^{12}	1.2×10^{13}		
c. Repetition time (sec)	2	2.4	60	
d. Protons on target (POT)/year	1.5×10^{19}	$5\ \times10^{19}$	$2\ \times10^{18}$	a·b/c
e. Pion production efficiency (3.5 GeV/c ± 3%)		2×10^{-2}		
f. Horn efficiency to capture pions		3×10^{-2}		
g. Efficiency to capture muon from pion (μ/π)	2.5×10^{-2}	4×10^{-2}		
h. Fraction of π / POT	8×10^{-4}	6×10^{-4}		e·f
i. Fraction of μ / POT	2×10^{-5}	2.4×10^{-5}		e·f·g
j. Fraction of pions decaying in straight section	20×10^{-2}	10×10^{-2}		
k. Fraction of muons in straight section	14×10^{-2}	14×10^{-2}		
l. Number of useful pions/year	1.7×10^{15}	3×10^{15}	1.2×10^{14}	d·h·j
m. Number of useful muons/year	4.2×10^{13}	1.7×10^{14}	6.7×10^{12}	d·i·k

CERN AD :

Normalized to 5×10^{19} protons on target

Expected number of neutrinos reaching the detector ($5\Xi10^{19}$ protons)

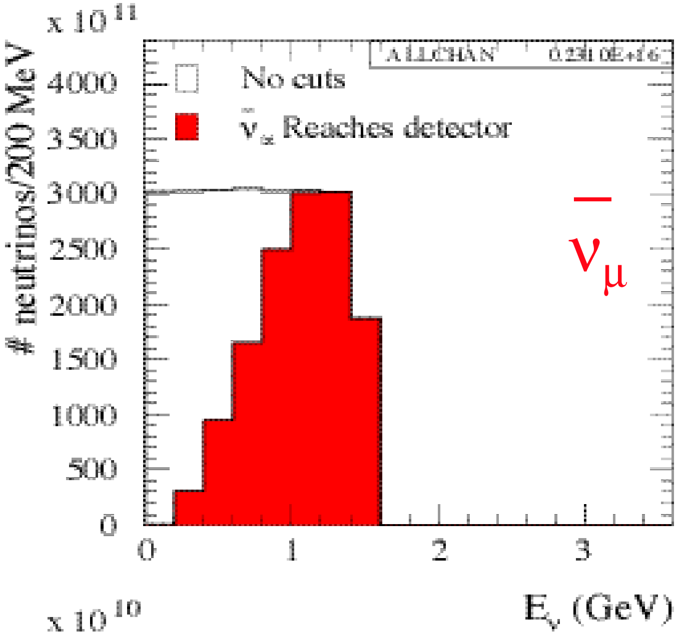


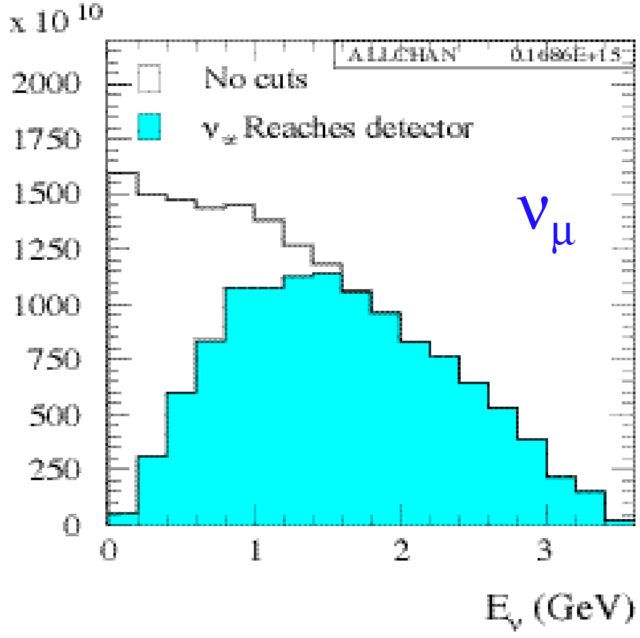
prompt

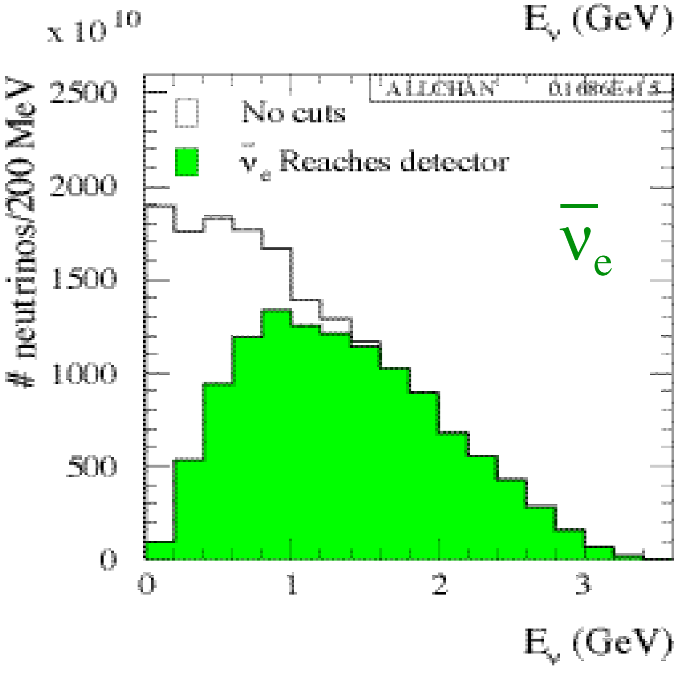
delayed

CERN AD : Normalized to 5×10^{19} protons

200 MeV energy bins







Very strong energy-angle correlation

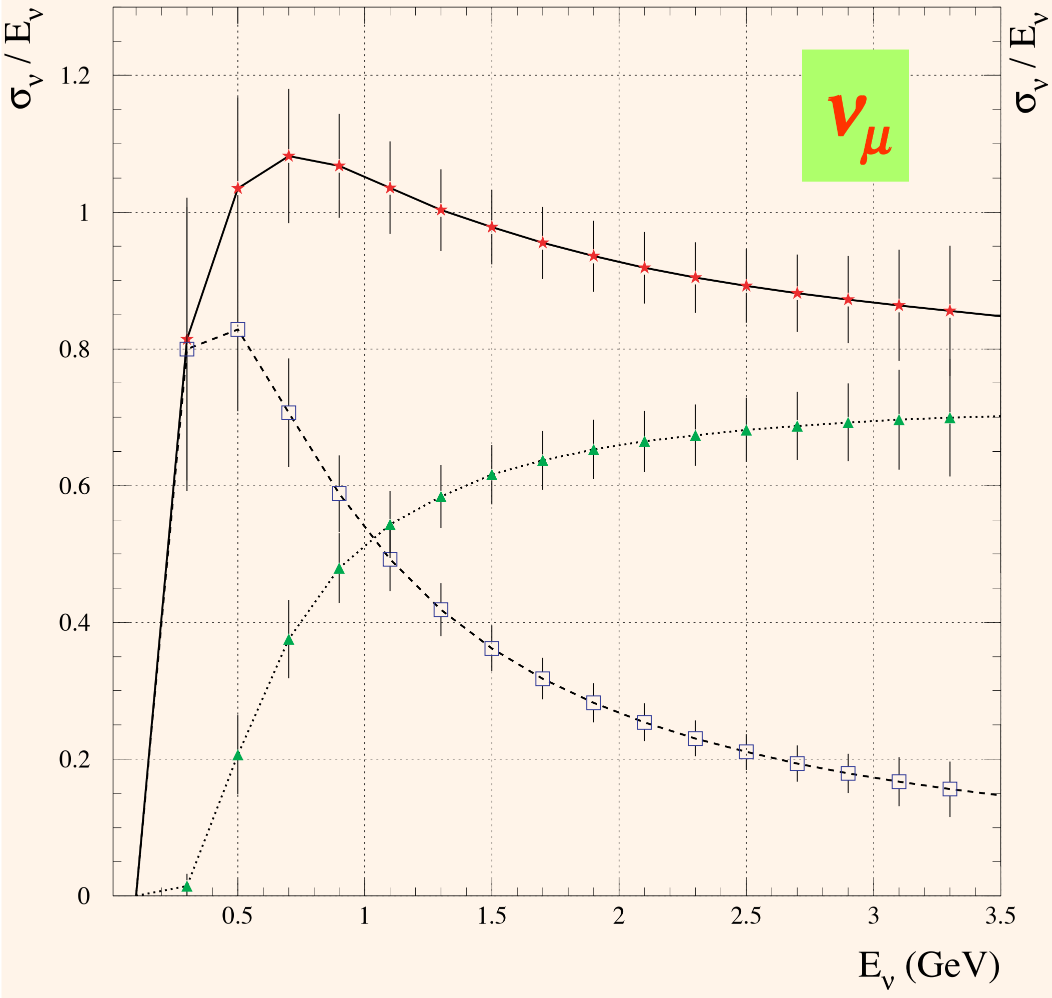
⇒ ***Lowest energies (unfortunately) are cut out***

Pion Flux = 2.31E+15 and Muon Flux = 1.68605E+14

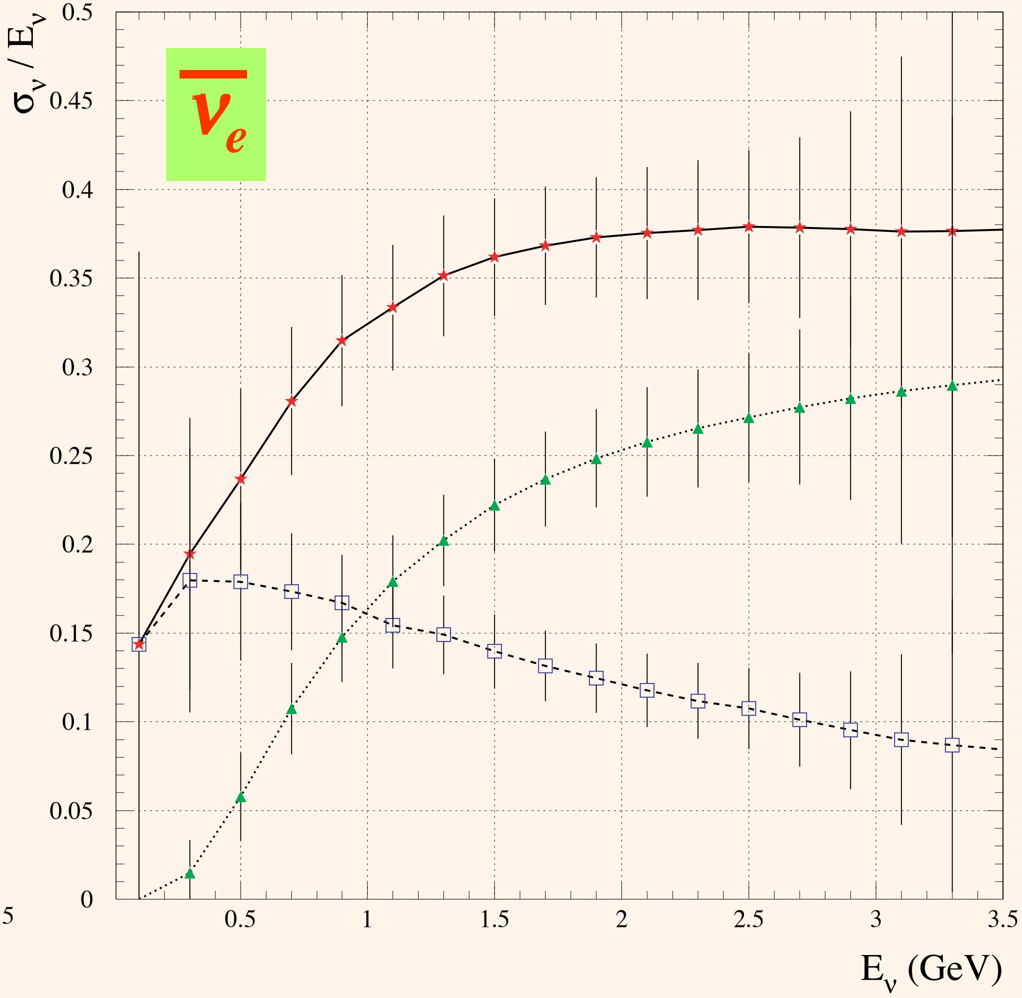
CERN AD :

200 MeV energy bins

ν cross section spectrum



$\bar{\nu}_e$ cross section spectrum



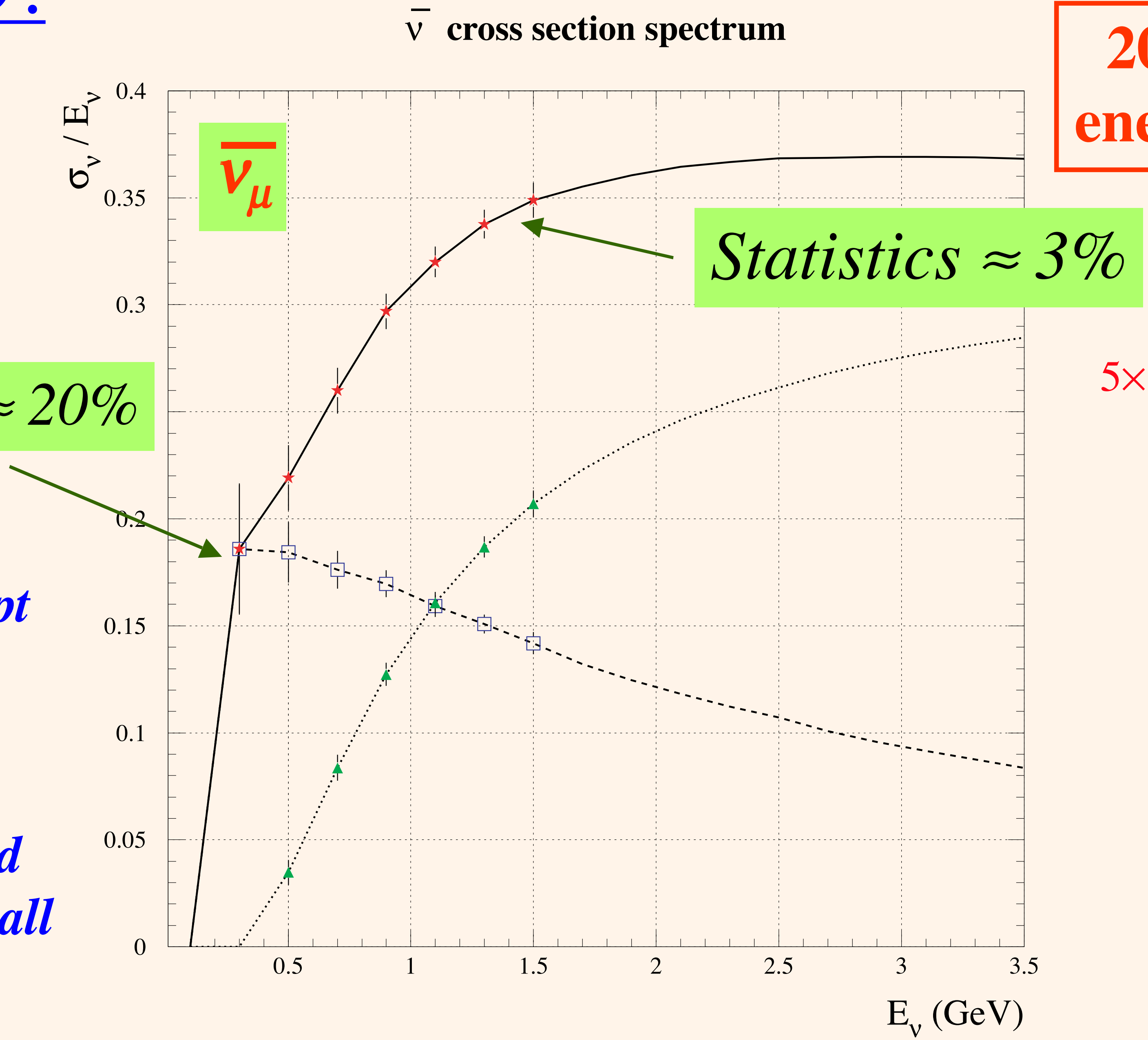
Statistics ≈ 6%

5×10^{19} protons

Statistics ≈ 10%

CERN AD :

200 MeV energy bins



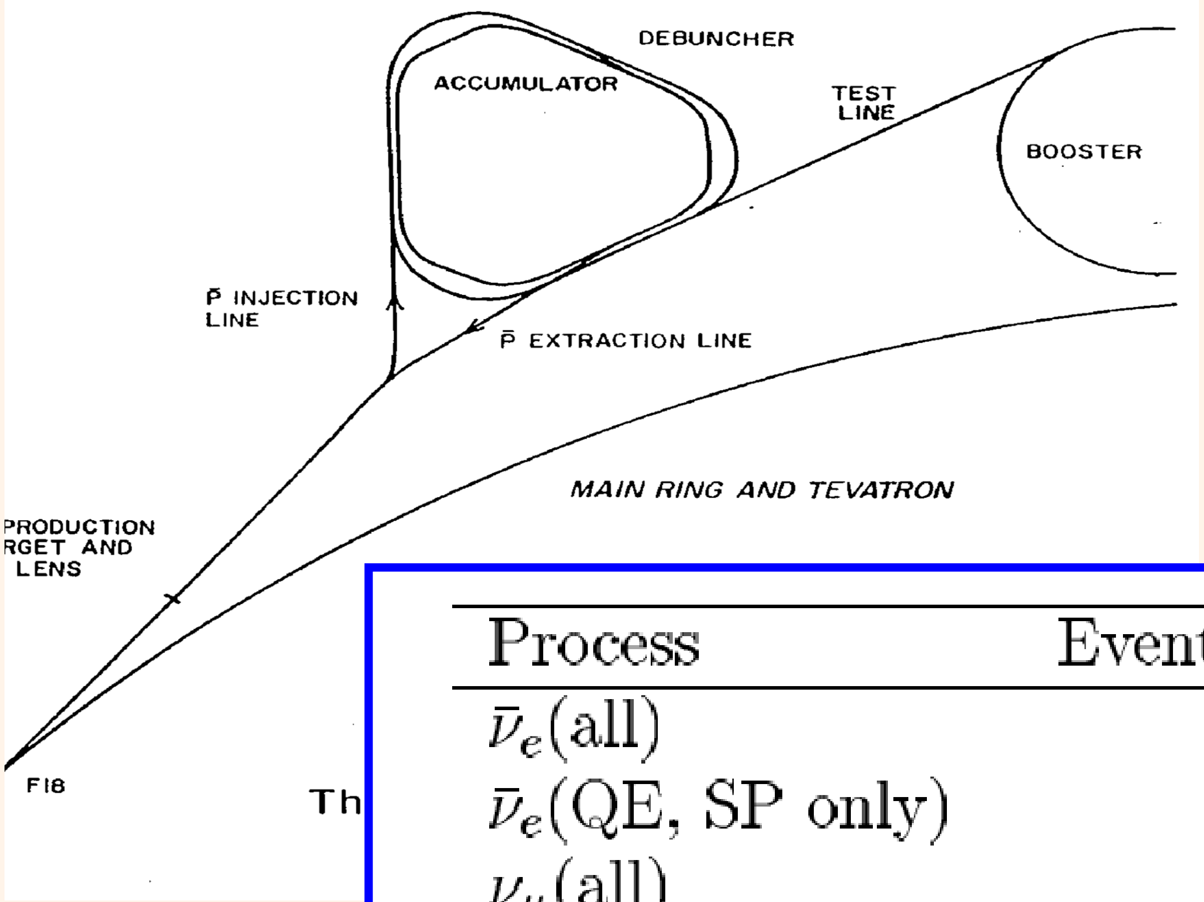
Statistics ≈ 3%

Statistics ≈ 20%

$5{\times}10^{19}$ protons

The prompt neutrinos are much more than the delayed ones, and all at lower energy!

FNAL PROPOSAL P-860, December 1992



Estimated event rate for 4 years running in a 0.1 kton detector 15m downstream of a FNAL-Debuncher straight section

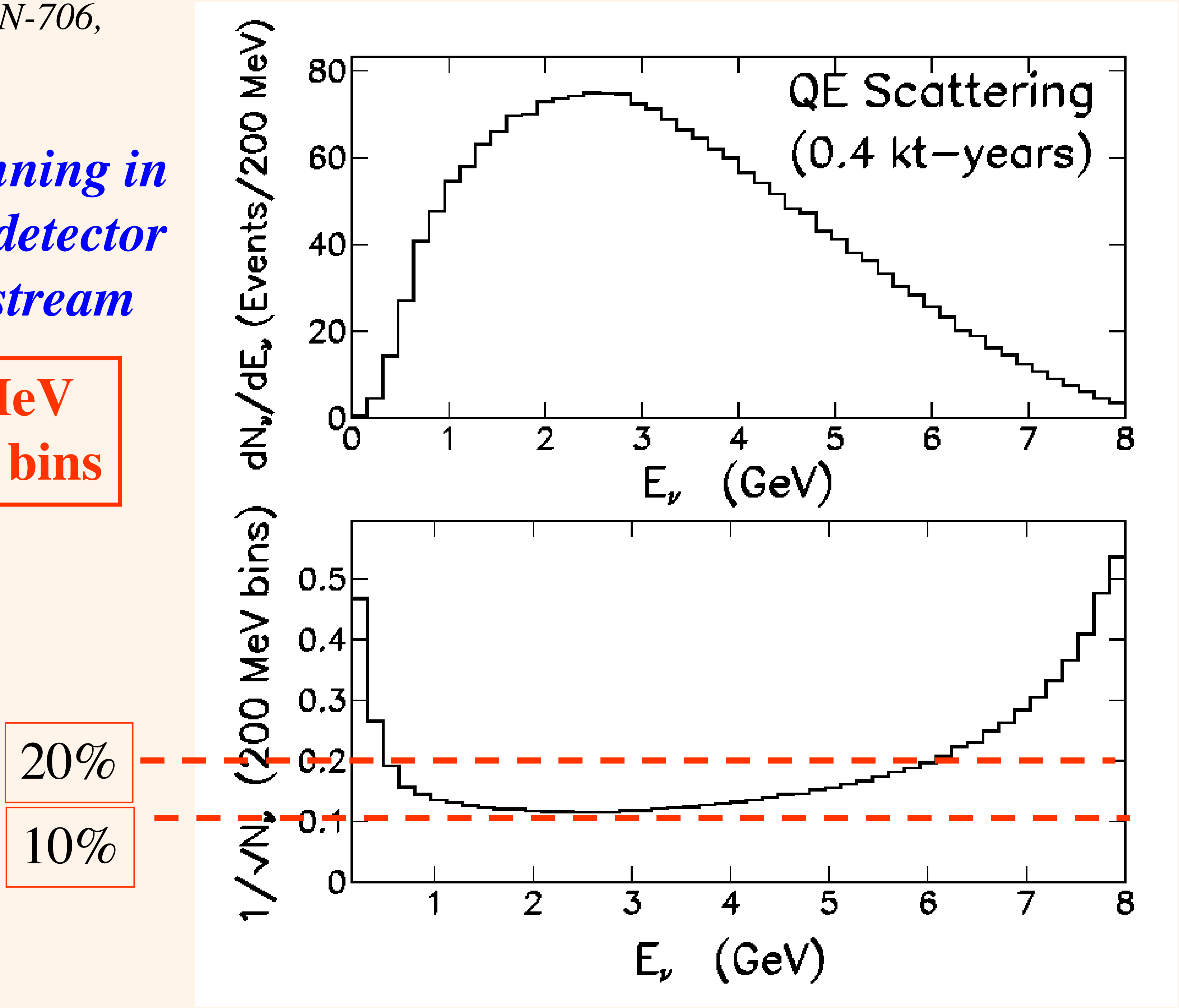
Process	Events / 0.4 kt-years
$\bar{\nu}_e$(all)	6330
$\bar{\nu}_e$(QE, SP only)	1440
ν_μ(all)	14500
ν_μ(QE,SP,DEEP)	4370
$\bar{\nu}_\mu$(π decay)(all)	181000
$\bar{\nu}_\mu$(QE,SP)	54600

S. Geer, FNAL-FN-706, June 2001.

S. Geer, FNAL-FN-706,
June 2001.

4 years running in a 0.1 kton detector 15m downstream

200 MeV energy bins



Systematics…

- **Storage ring of pions or muons provide the cleanest way to measure neutrino cross-sections**
- **In particular, muons are the cleanest**
  - since they can be better monitored (long lifetime)
  - Muon polarization
    - κ Not dominant
- **Bending arcs of storage ring**
  - Negligible

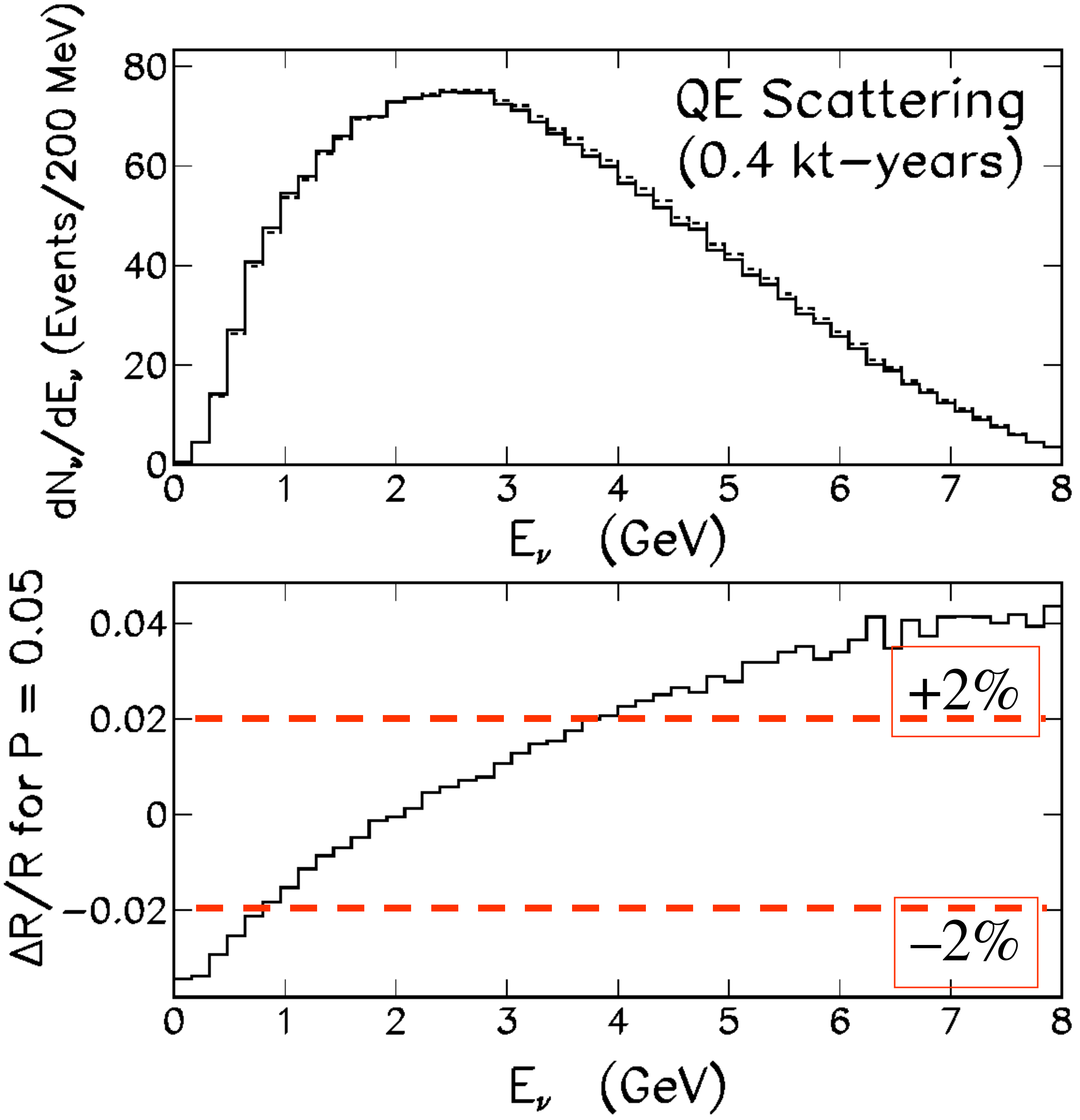
Statistics ≈ *5-10% for* ≈10^{15} *muons*
Systematics ≈ *1%*

(Could aim at ≈10^{16} *muons)*

Effect of muon polarization

⇒Not dominant!

S. Geer, FNAL-FN-706, June 2001.



Conclusion

- **Traditional « pion » beams are the most realistic choice for performing neutrino cross-section measurements**
  - Already existing
  - Event rates are generally very high
  - But systematics dominated !
- **Low energy neutrino factories will provide the « cleanest » environment to measure cross-sections**
  - Equal amount of neutrinos and antineutrinos
  - Flux systematics small, certainly at the level of few %’s
  - But is it (financially) realistic?
- **Antiproton accumulators are certainly an interesting compromise.**
  - They already exist
  - A parasitic run is possible
  - Pion and muon decays offer interesting features