Accelerator Neutrino Beams

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1. Overview
2. Decay Kinematics
3. Pion/kaon production in a target
4. Focusing
5. Two-detector experiments
6. Flux Measurements/Monitoring

Selected References*

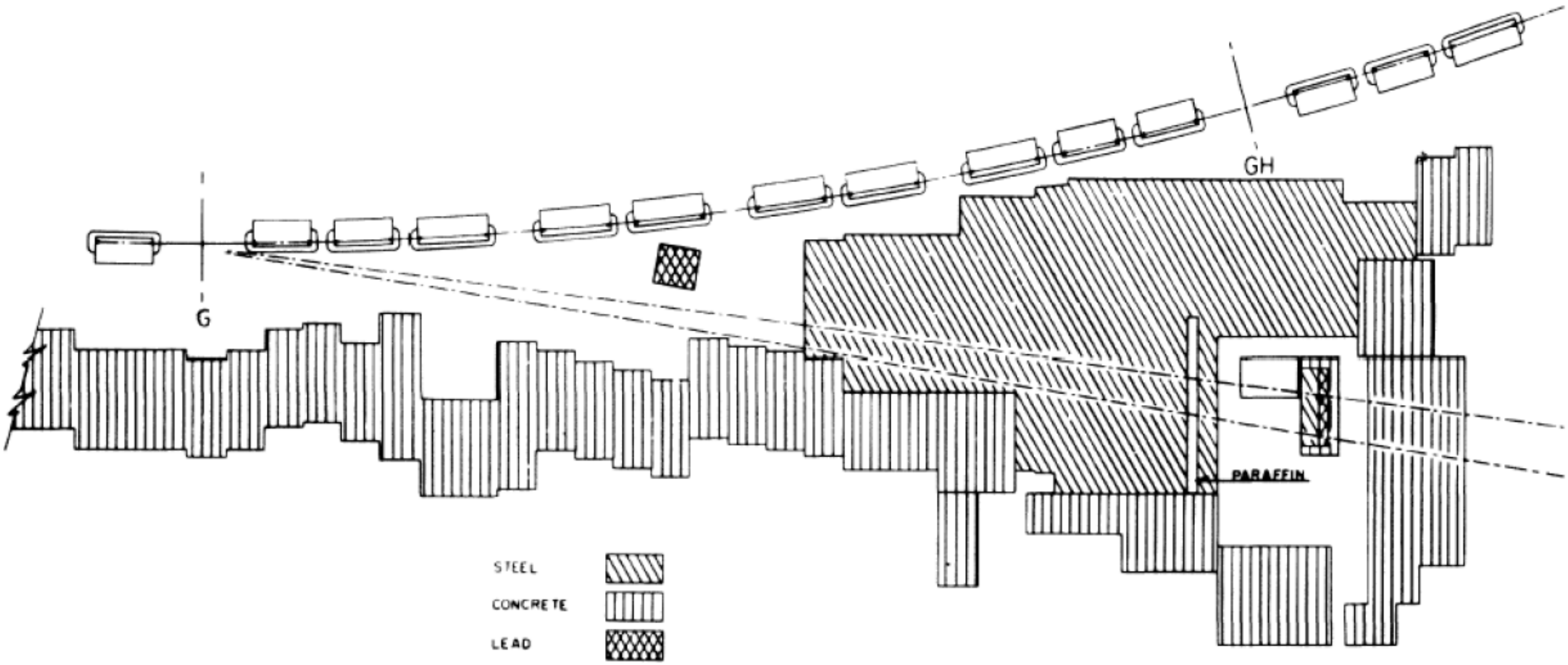
(*which point back to original papers*)

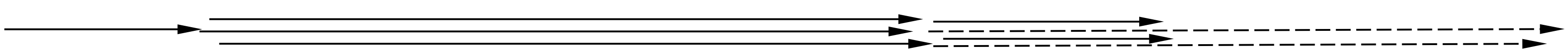
- CERN Informal Workshops ‘63 – ’69
- H. Wachsmuth, Summer School “Enrico Fermi” 1979
- Neutrino Beams & Instrumentation Workshops ‘00 – ’06
- S. Kopp, “Accelerator Neutrino Beams” Phys. Rep.

*I will not cover beam stop experiments. A very good reference:

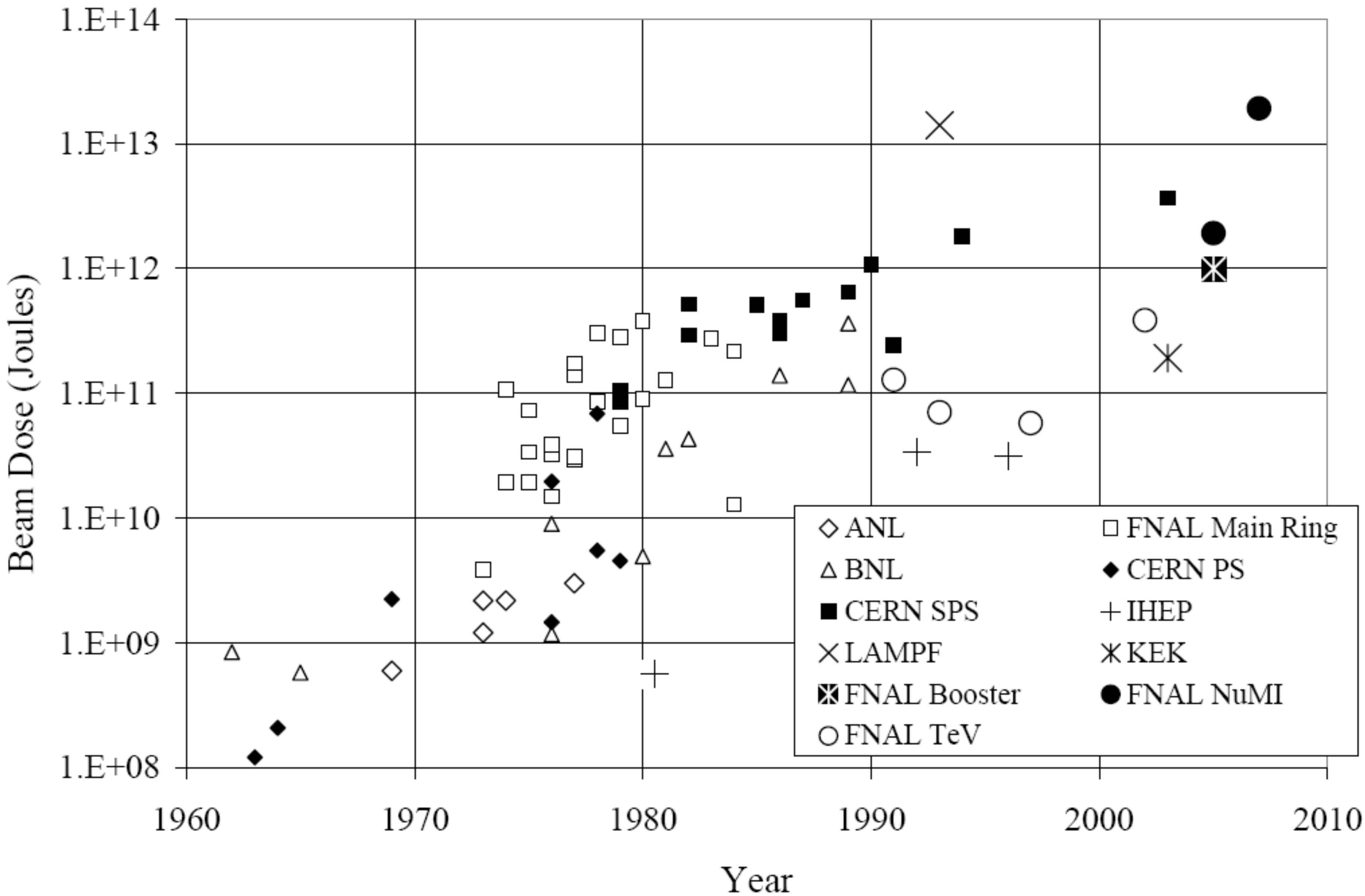
- Burman and Louis, “Neutrino Physics at Meson Factories and Spallation Sources,” J. Phys. G29, 2499 (2003)

Overview





p $\quad$ p, K, π $\quad$ μ, ν_μ $\quad$ ν_μ


1.E+14
1.E+13
1.E+12
1.E+11
1.E+10
1.E+09
1.E+08
Beam Dose (Joules)
1960
1970
1980
1990
2000
2010
Year
ANL
FNAL Main Ring
BNL
CERN PS
CERN SPS
IHEP
LAMPF
KEK
FNAL Booster
FNAL NuMI
FNAL TeV

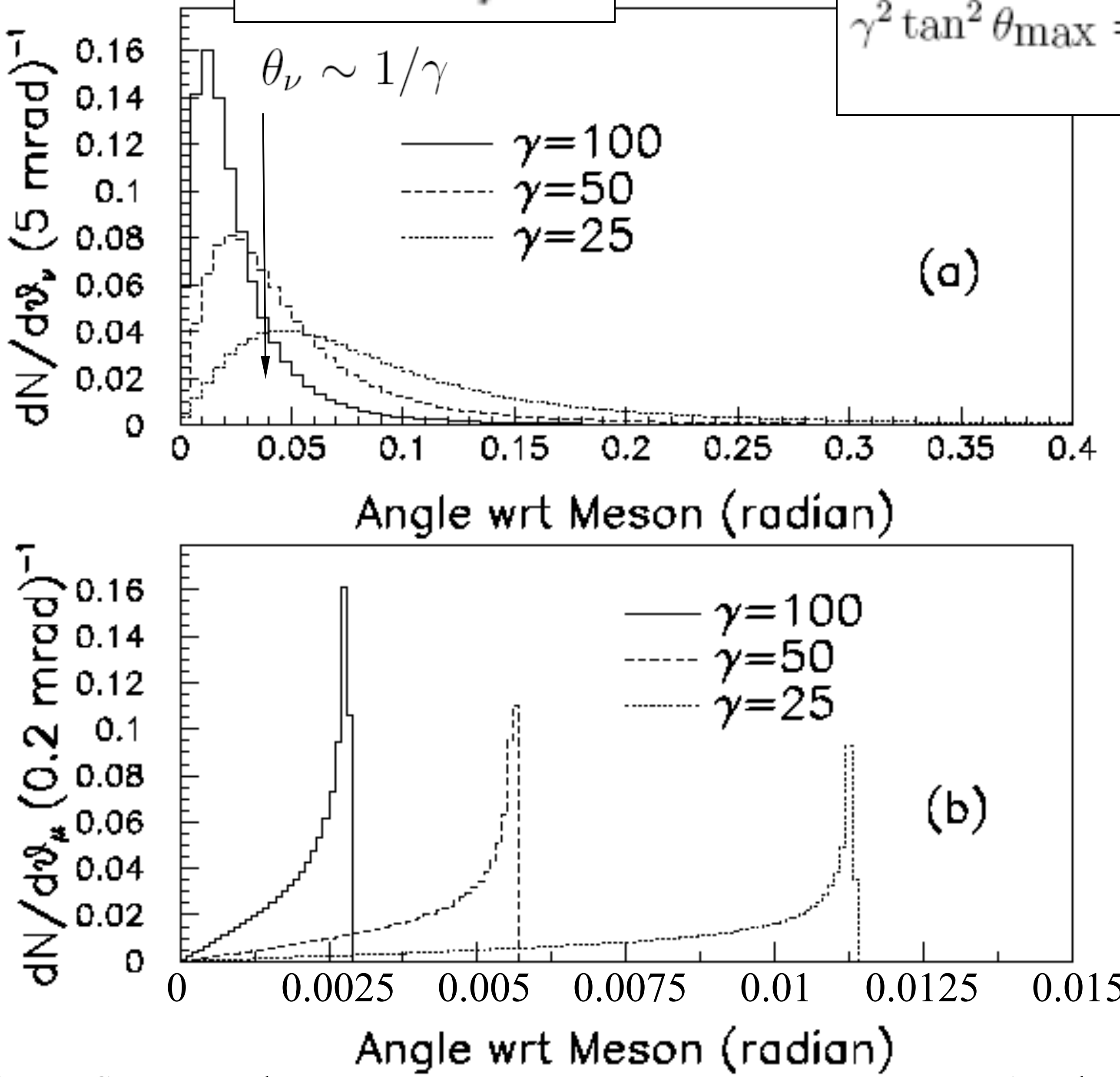
Lab	Year	p_0 (GeV/c)	Protons/ Pulse (10^{12})	Secondary Focusing	Dec. Pipe Length (m)	$\langle E_\nu \rangle$ (GeV)	Experiments
ANL	1969	12.4	1.2	1 horn WBB	30	0.5	Spark Chamber
ANL	1970	12.4	1.2	2-horn WBB	30	0.5	$12'$ BC
BNL	1962	15	0.3	bare target	21	5	Spark Ch. Observation of 2 ν's
BNL	1976	28	8	2-horn WBB	50	1.3	$7'$ BC, E605, E613, E734, E776
BNL	1980	28	7	2-horn NBB	50	3	$7'$ BC, E776
CERN	1963	20.6	0.7	1 horn WBB	60	1.5	HLBC, spark ch.
CERN	1969	20.6	0.63	3 horn WBB	60	1.5	HLBC, spark ch.
CERN	1972	26	5	2 horn WBB	60	1.5	GGM, Aachen-Pad.
CERN	1983	19	5	bare target	45	1	CDHS, CHARM
CERN	1977	350	10	dichromatic NBB	290	50,150$^{(a)}$	CDHS, CHARM, BEBC
CERN	1977	350	10	2 horn WBB	290	20	GGM,CDHS, CHARM, BEBC
CERN	1995	450	11	2 horn WBB	290	20	NOMAD, CHORUS
CERN	2006	450	50	2 horn WBB	998	20	OPERA, ICARUS
FNAL	1975	300, 400	10	bare target	350	40	HPWF
FNAL	1975	300, 400	10	Quad. Trip., SSBT	350	50,180$^{(a)}$	CITF, HPWF
FNAL	1974	300	10	dichromatic NBB	400	50, 180$^{(a)}$	CITF, HPWF, $15'$ BC
FNAL	1979	400	10	2-horn WBB	400	25	$15'$ BC
FNAL	1976	350	13	1-horn WBB	400	100	HPWF, $15'$ BC
FNAL	1991	800	10	Quad Trip.	400	90, 260	$15'$ BC, CCFRR
FNAL	1998	800	12	SSQT WBB	400	70, 180	NuTeV exp't
FNAL	2002	8	4.5	1-horn WBB	50	1	MiniBooNE
FNAL	2005	120	32	2-horn WBB	675	4-15$^{(b)}$	MINOS, MINERνA
FNAL	2009	120	70	2-horn NBB	675	2	NOνA off-axis
IHEP	1977	70	10	4 horn WBB	140	4	SKAT, JINR
JPARC	2009	40	300	3 horn NBB	140	0.8	Super K off-axis
KEK	1998	12	5	2 horn WBB	200	0.8	K2K long baseline osc.

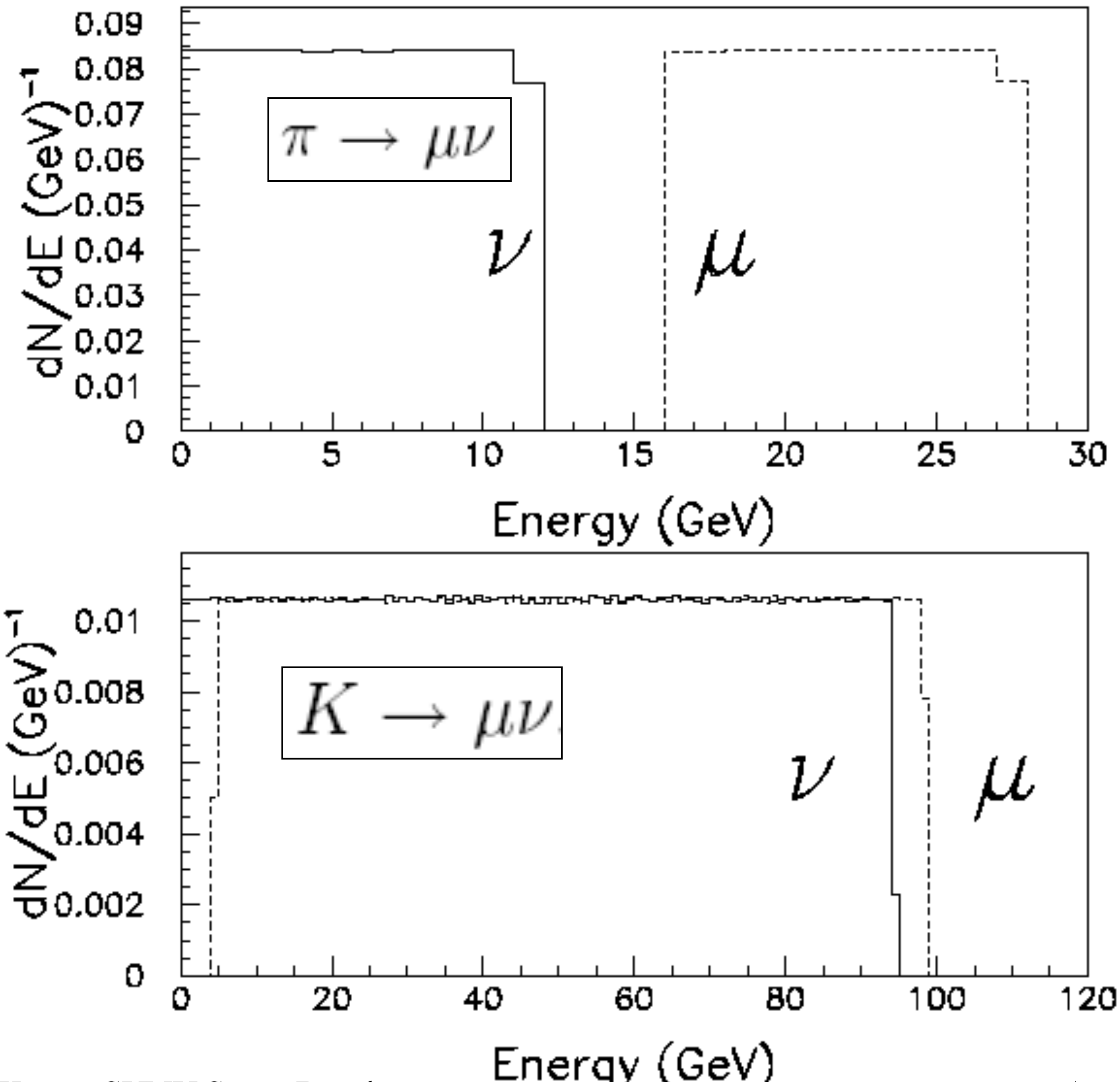
$^{(a)}$ pion and kaon peaks in the momentum-selected channel $^{(b)}$ tunable WBB energy spectrum.

Decay Kinematics

$$\pi \longrightarrow \mu\nu$$

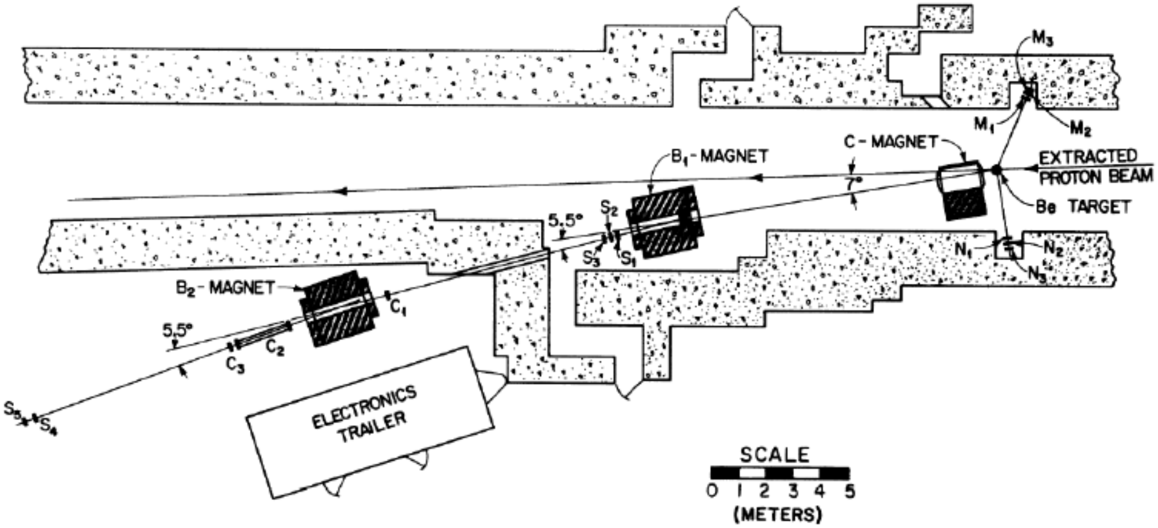
$$\gamma^2 \tan^2 \theta_{\max} = \frac{(\beta')^2}{\beta^2 - (\beta')^2}$$



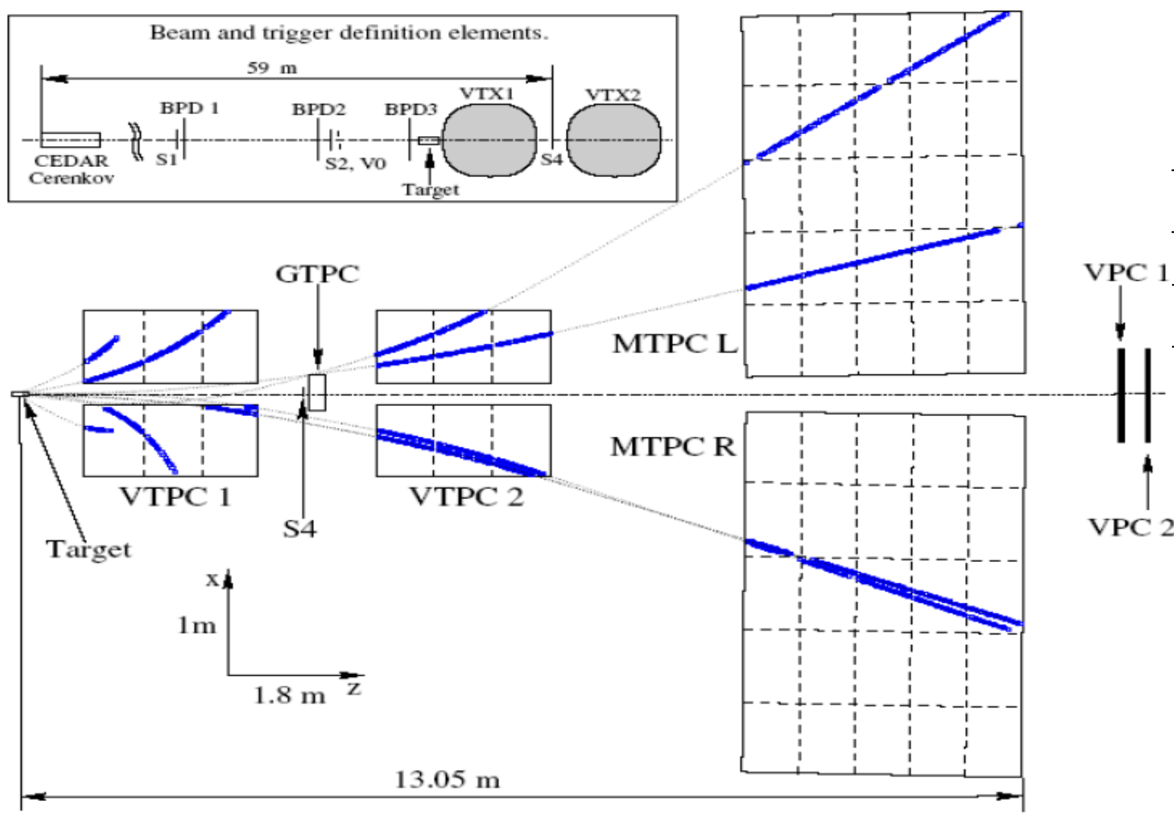


Lab Frame ($\gamma = 200$)

Production of π/K in a Target



Spectrometer Experiments

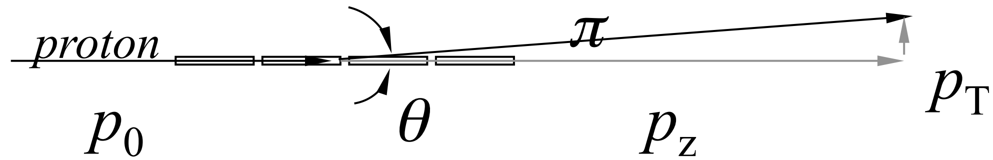


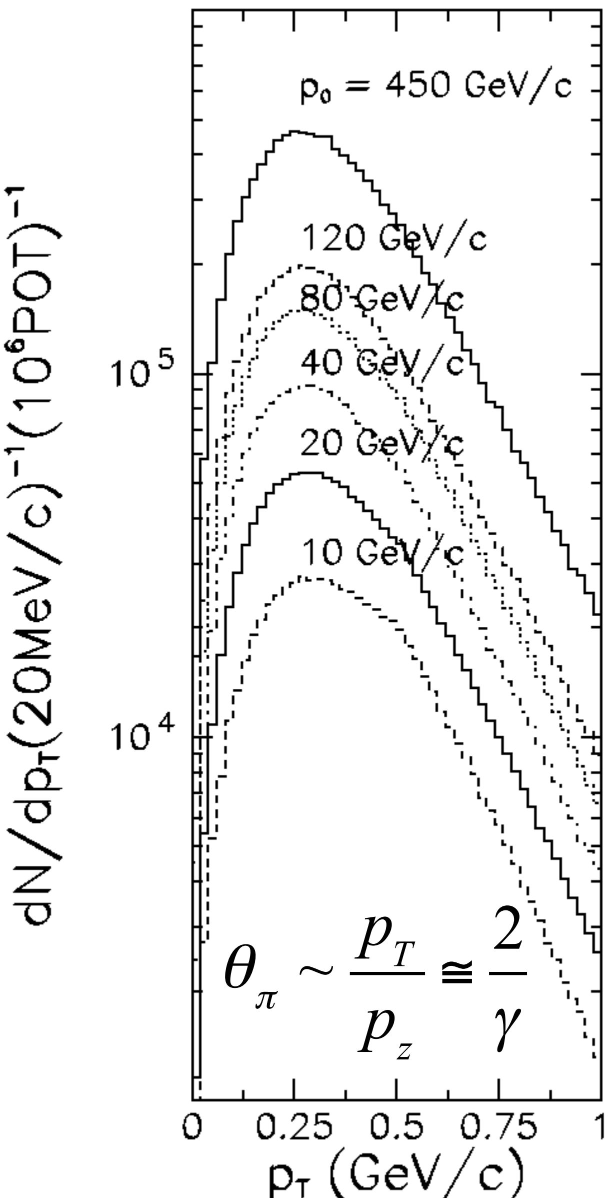
Full Acceptance Experiments

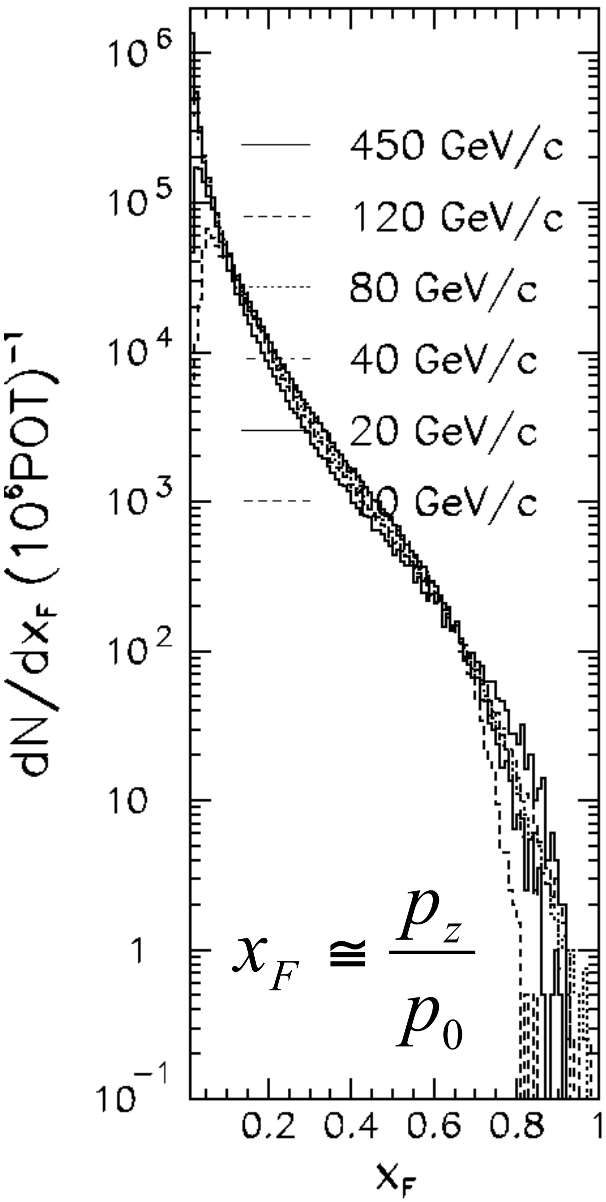
Reference	p_0 (GeV/c)	Beam	Target Material	$t/\lambda_{\rm int}$ (in %)	Secondary Coverage
HARP [81]	12	PS	Al	5	$0.75 < p < 6.50$ GeV/c, $30 < \theta < 210$ mrad [d]
Asbury[25]	12.5	ANL	Be	4.9, 12.3	p =3, 4, 5, $\theta = 12°, 15°$
Cho [84]	12.4	ANL	Be	4.9, 12.3	$2 < p < 6$ GeV/c, $0° < \theta < 12°$
Lundy[153][a]	12.4	ANL	Be	25,50,100	$1 < p < 12$ GeV/c, $2° < \theta < 16°$
Marmer[160]	12.3	ANL	Be, Cu	10	p =0.5, 0.8, 1.0 GeV/c, $\theta = 0°, 5°, 10°$
Abbot [11]	14.6	AGS	Be, Al, Cu, Au	1.0-2.0	$0 < p < 8$ GeV/c, $\theta = 5°, 14°, 24°, 34°, 44°$
Allaby [17]	19.2	PS	Be, Al, Cu, Pb, B_4C	1-2	p =6, 7, 10, 12, 14 GeV/c, θ =12.5, 20, 30, 40, 50, 60, 70 mrad
Dekkers [91][b]	18.8, 23.1	PS	Be, Pb	"thin"	$1 < p < 12$ GeV/c, $\theta = 0, 100$ mrad
Eichten [102]	24	PS	Be, Al, Cu, Pb, B_4C	1-2	$4 < p < 18$ GeV/c, $17 < \theta < 127$ mrad
Baker [31]	10,20,30	AGS	Be, Al	??	$1 < p < 17$ GeV/c, $\theta = 4.75°, 9°, 13°, 20°$
Barton[48]	100	FNAL	C,Al,Cu,Ag,Pb	1.6-5.6	$0.3 < x_F < 0.88$, $0.18 < p_T < 0.5$ GeV/c
NA49 [21]	158	SPS	C	1.5	$0.05 < p_T < 1.8$ GeV/c, $-0.1 < x_F < 0.5$[c]
Aubert [30]	300	FNAL	Al	76	$\theta = 0.8$ mrad, x_F =0.083, 0.17, 0.25, 0.33, 0.42, 0.5, 0.58, 0.67, 0.0.75
Baker [32]	200, 300	FNAL	Be	50	$\theta = 3$ mrad[d], $60 < p < 370$ GeV/c
Baker [33]	400	FNAL	Be	75	$\theta = 3.6$ mrad, $23 < p < 197$ GeV/c
Atherton[29]	400	SPS	Be	10,25,75,125	x_F =0.15, 0.30, 0.50, 0.75, p_T =0, 0.3, 0.5 GeV/c
NA56/SPY [22]	450	SPS	Be	25,50,75	x_F =0.016, 0.022, 0.033, 0.044, 0.067, 0.089, 0.15, 0.30, p_T=0, 75, 150, 225, 375, 450, 600 MeV/c

[a] Possible normalization discrepancy with [160, 25, 84].
[b] Possible normalization discrepancy with Allaby *et al.*[17].
[c] Full-acceptance spectrometer.
[d] They report angular variation between 2-3.5 mrad, consistent with then-running FNAL neutrino experiments.

x_F, p_T Invariance

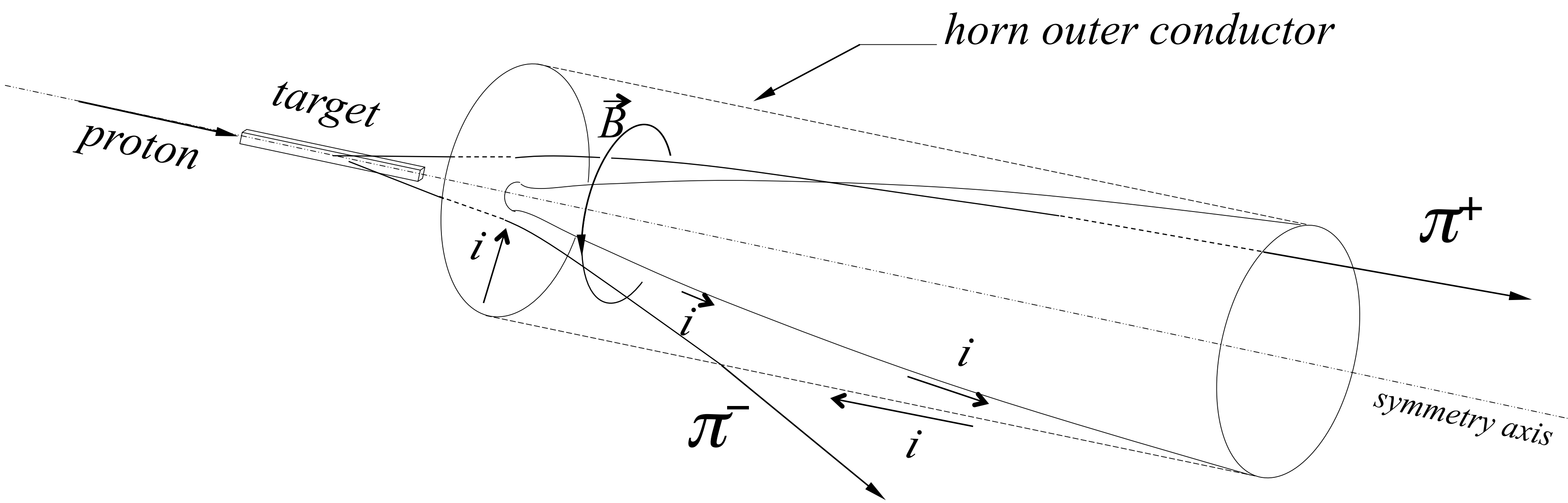




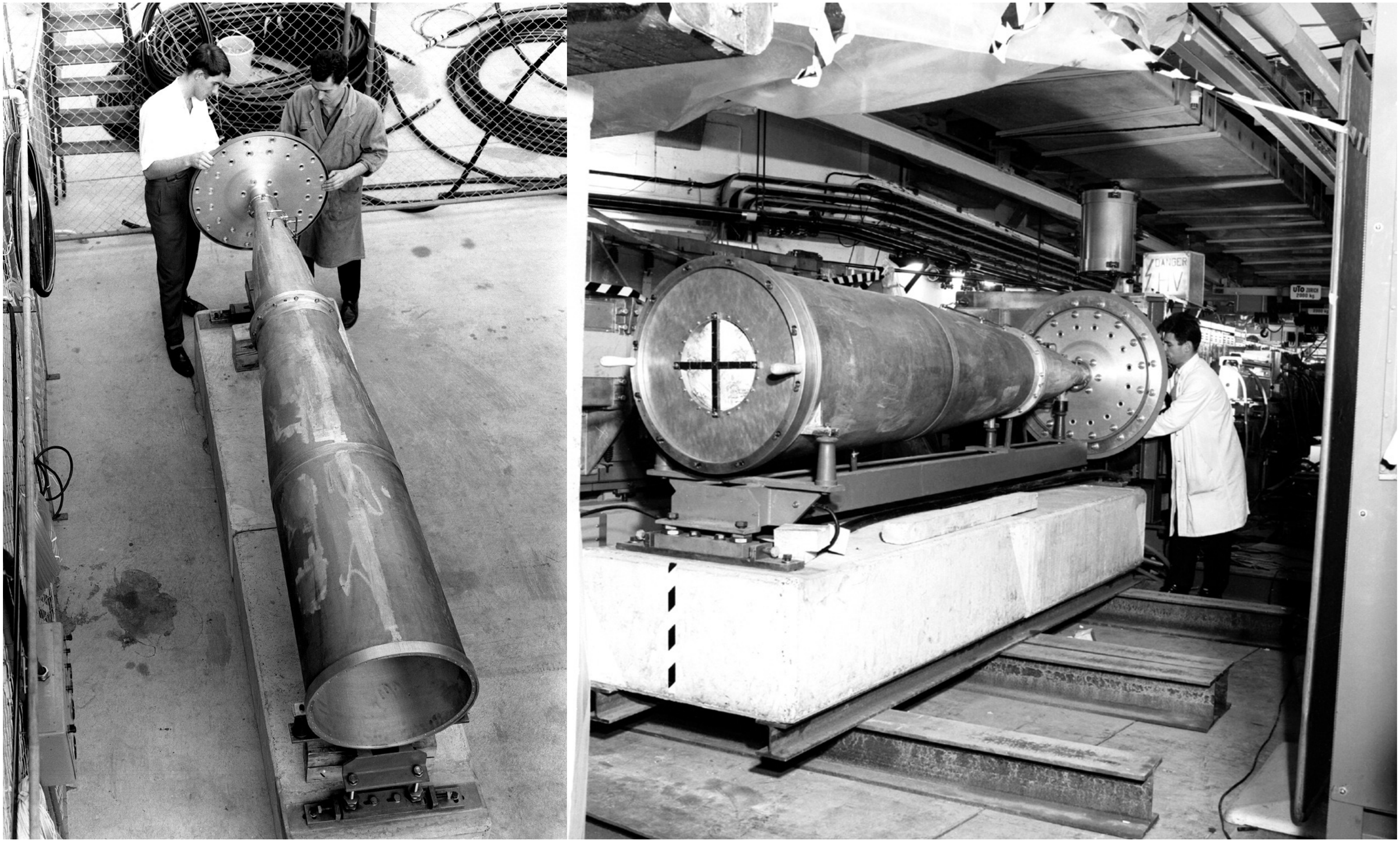


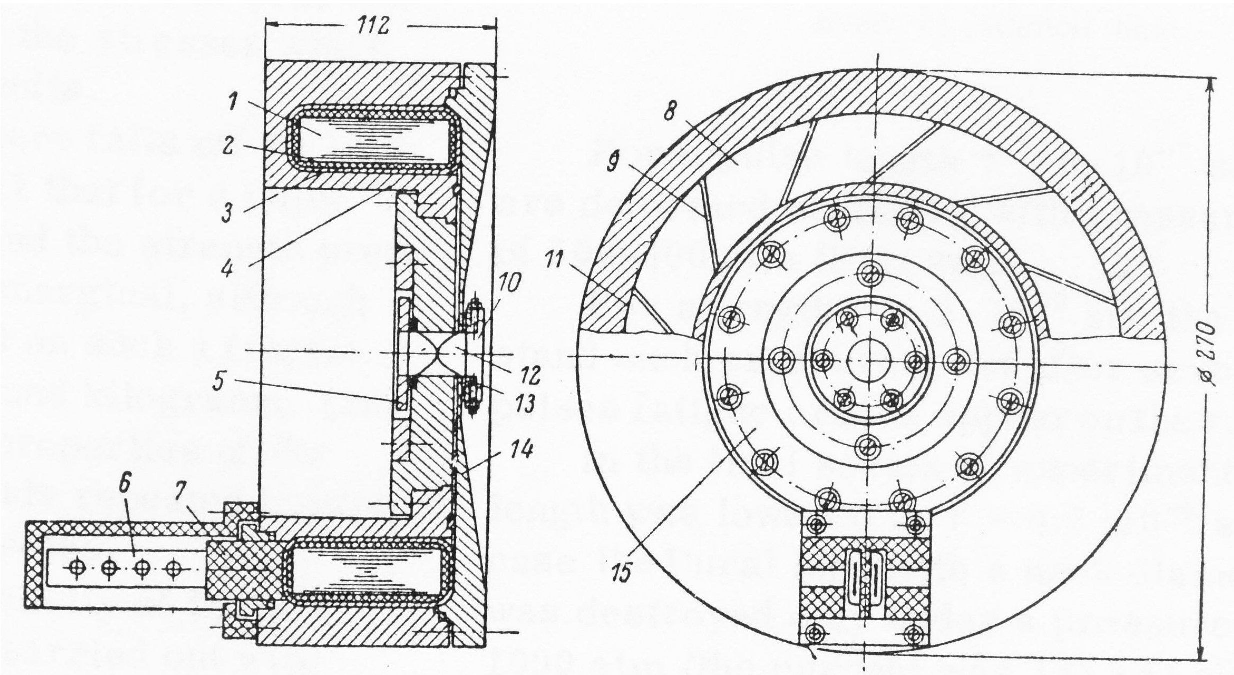
- Calculated with FLUKA cascade monte carlo
- Some exp'ts used parametric models (Sanf-Wang, BMPT, CKP, ⋯)

Focusing of WBB

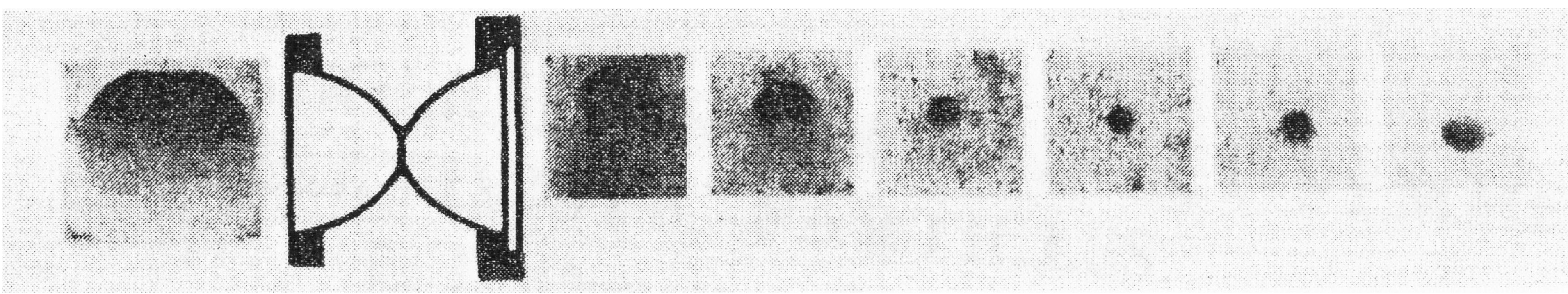

horn outer conductor
target
proton
$\vec{B}$
i
$\vec{i}$
i
i
π^+
π^-
symmetry axis

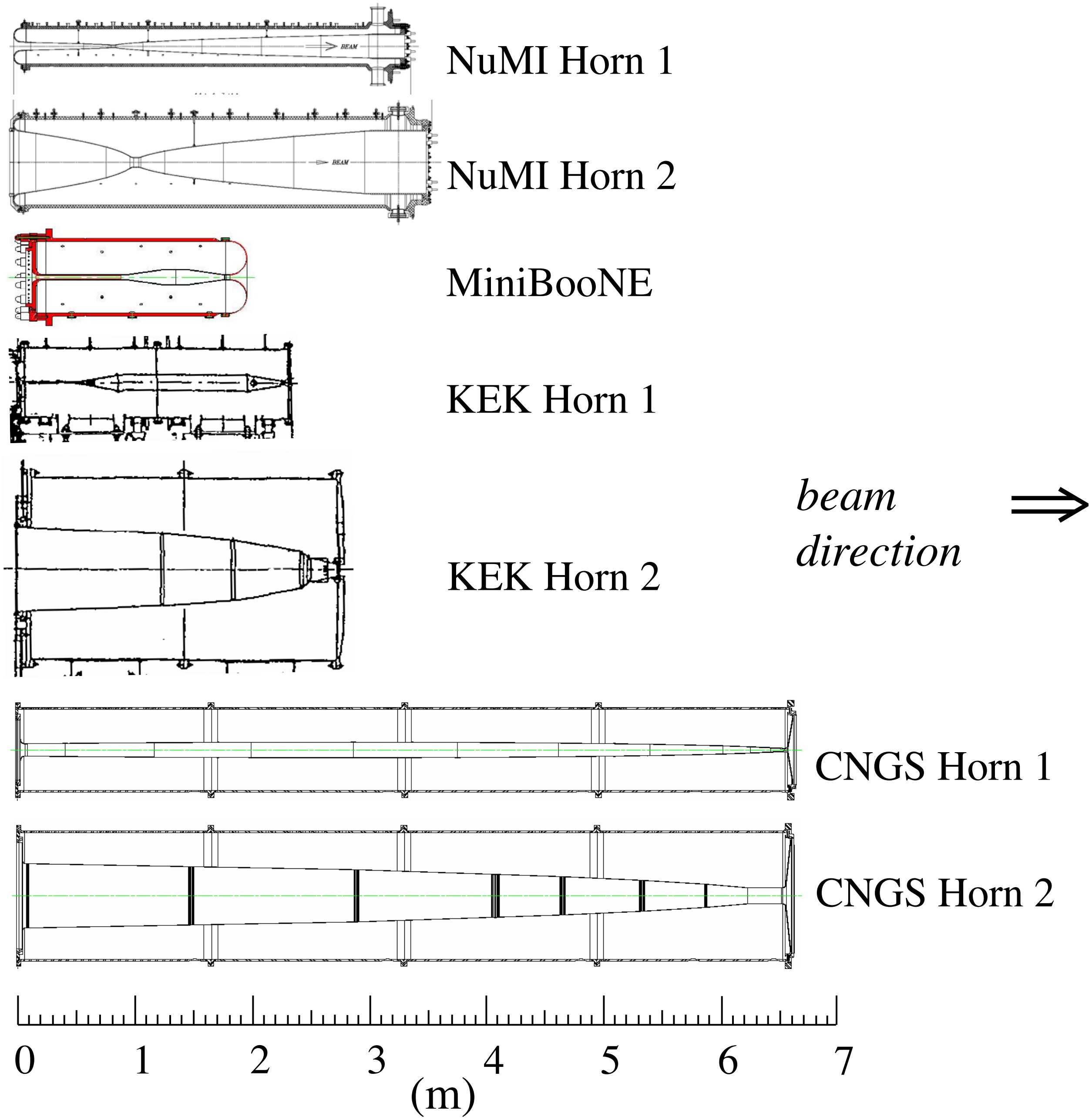
CERN magnetic ‘horn’ (S. van der Meer)





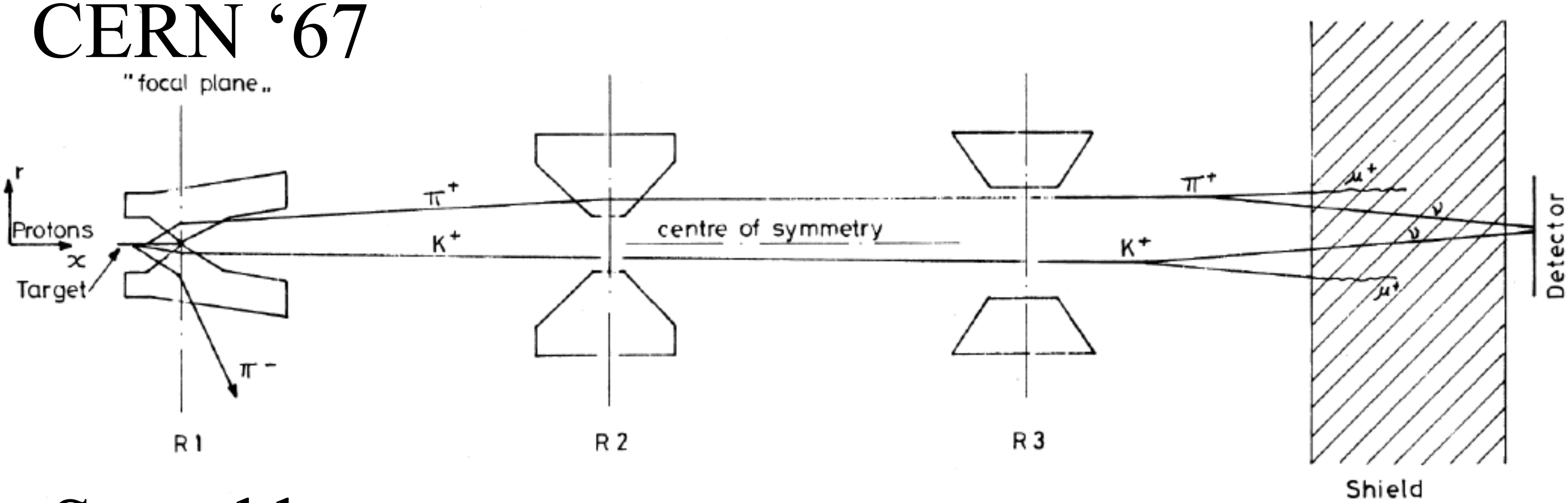
Parabolic horn (Budker)



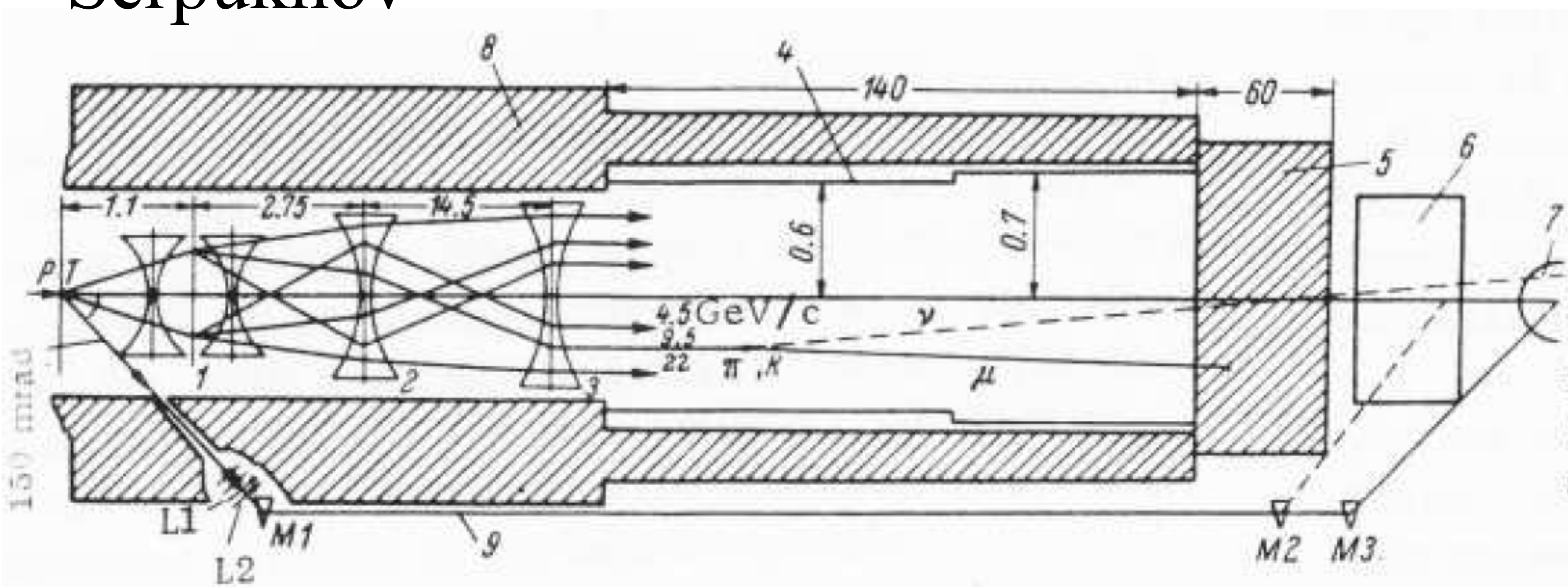

NuMI Horn 1
NuMI Horn 2
MiniBooNE
KEK Horn 1
KEK Horn 2
beam
direction
CNGS Horn 1
CNGS Horn 2
0
1
2
3
4
5
6
7
(m)

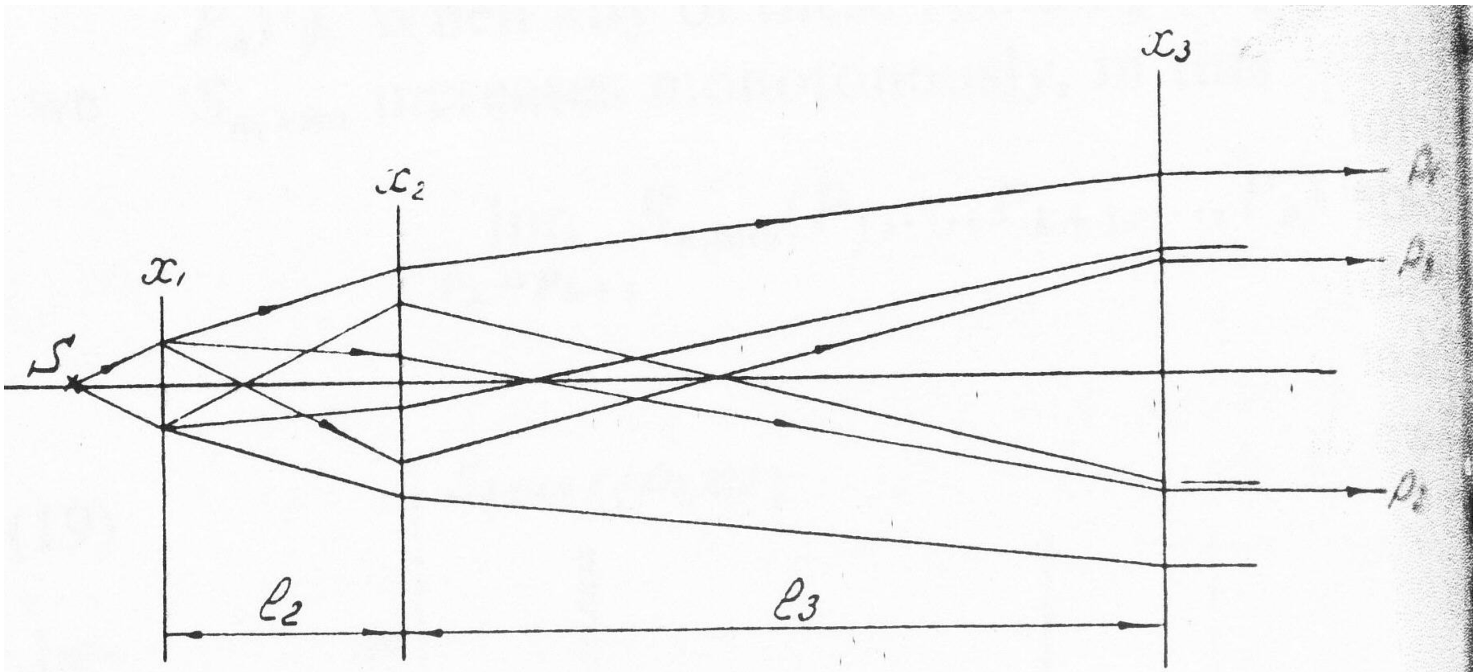
Multi-Lens Systems

CERN '67

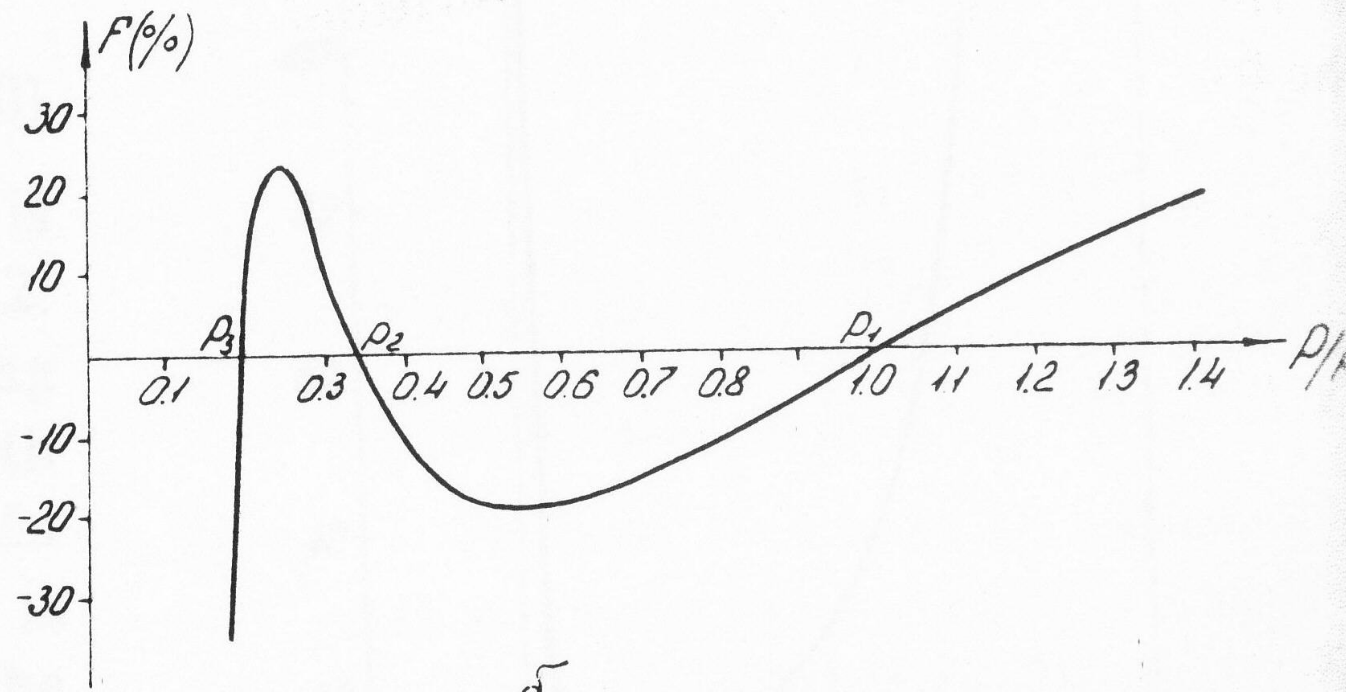


Serpukhov



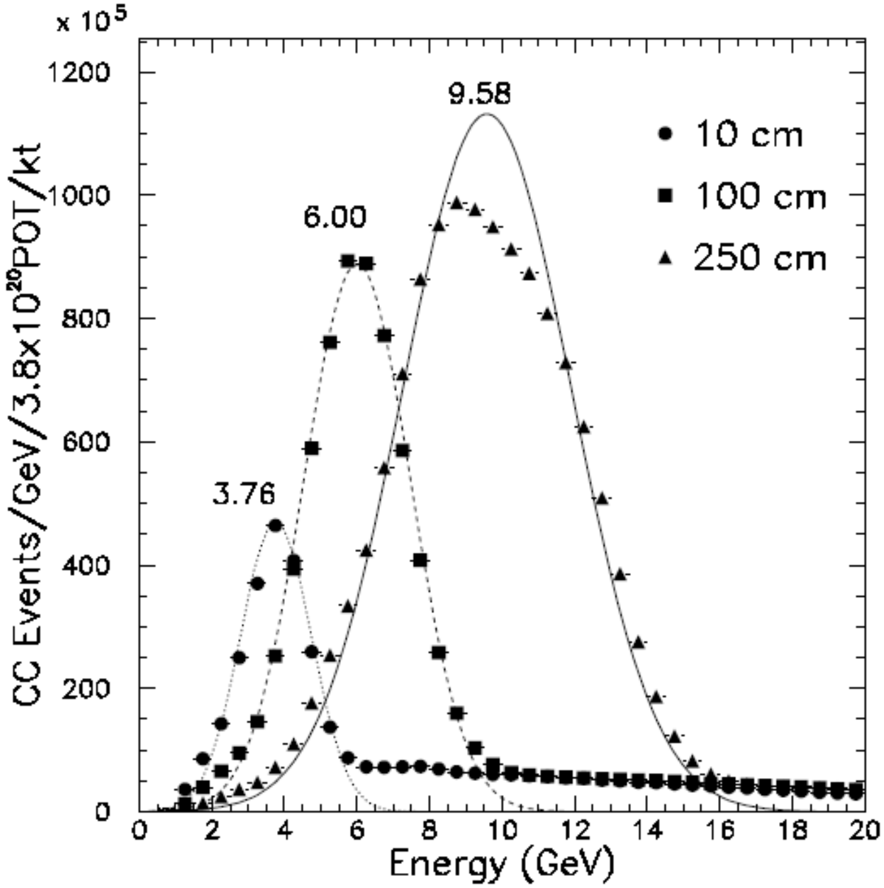

x₃
x₂
x₁
S
l₂
l₃

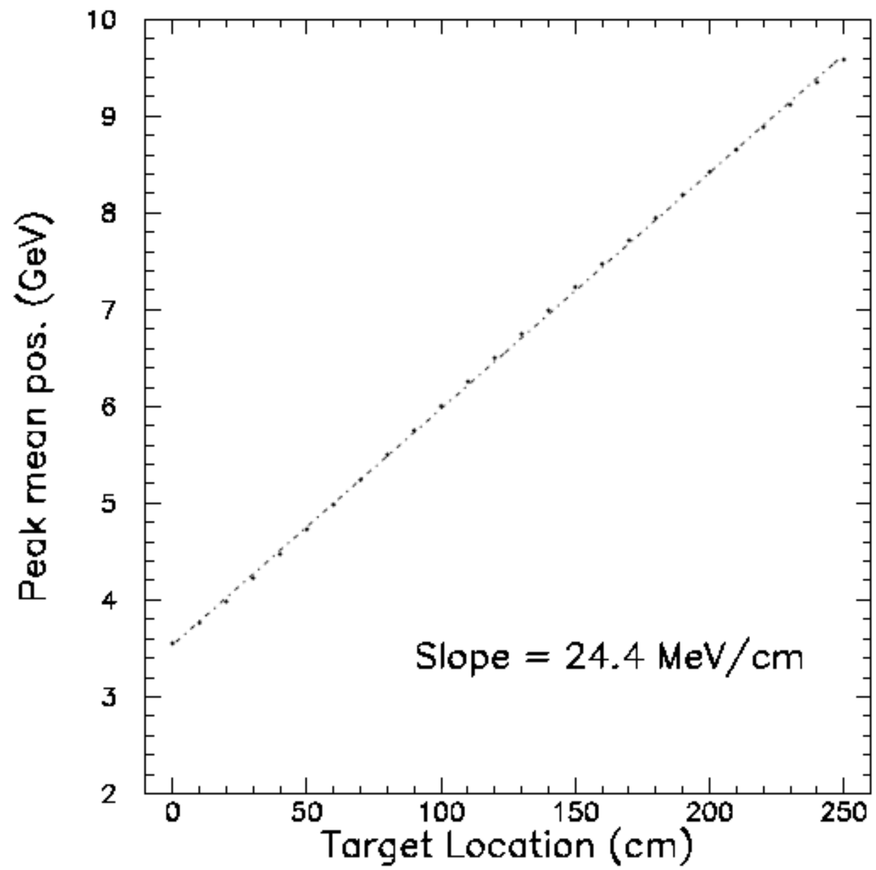
a.


F(%)
30
20
10
-10
-20
-30
p₃
p₂
p₁
0.1
0.3
0.4
0.5
0.6
0.7
0.8
1.0
1.1
1.2
1.3
1.4
p/p*

б

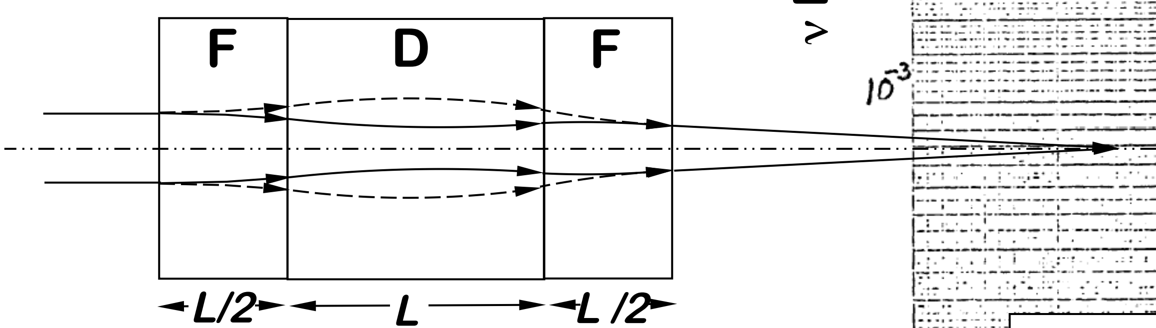
Variable Energy Beam

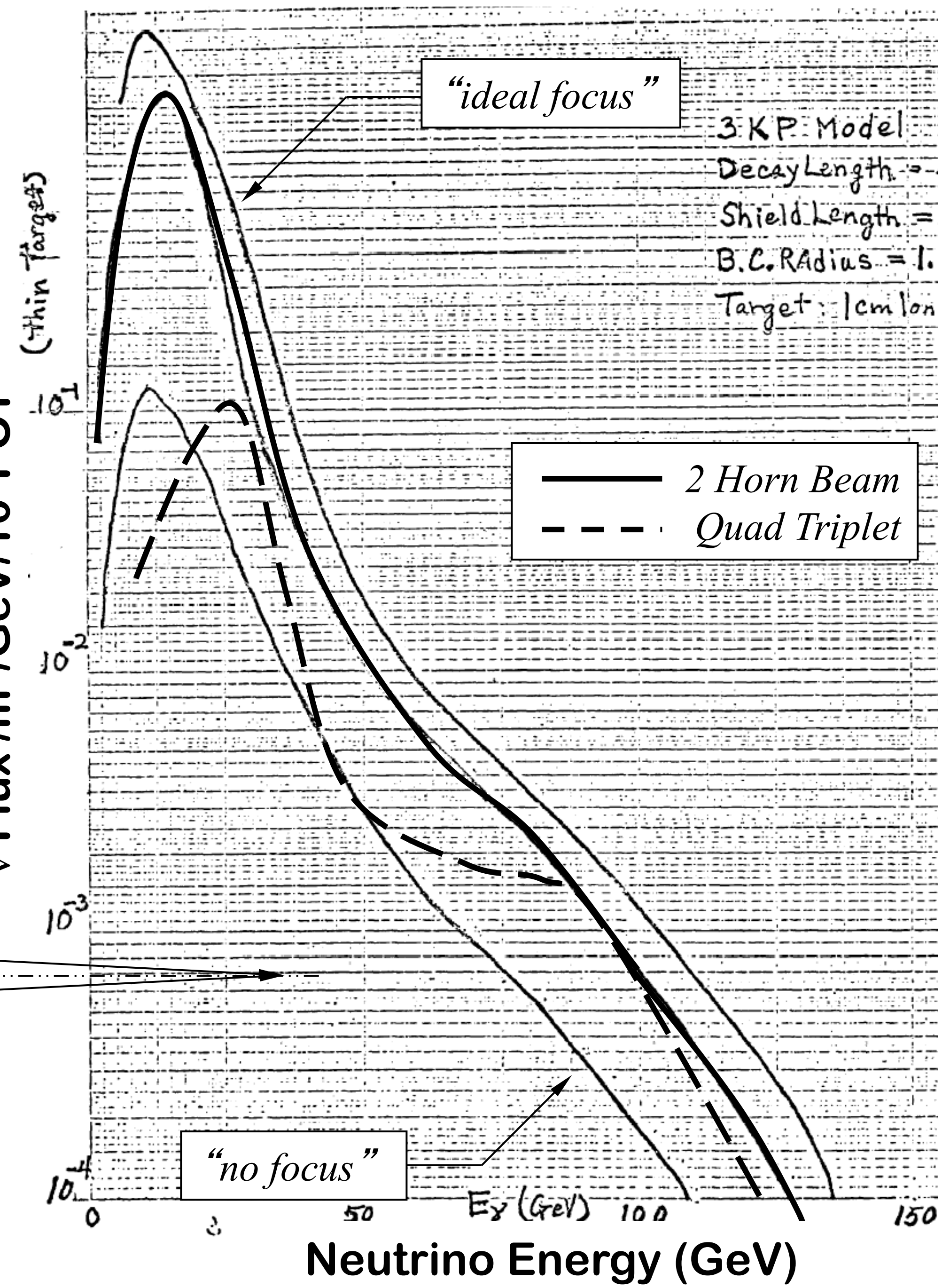




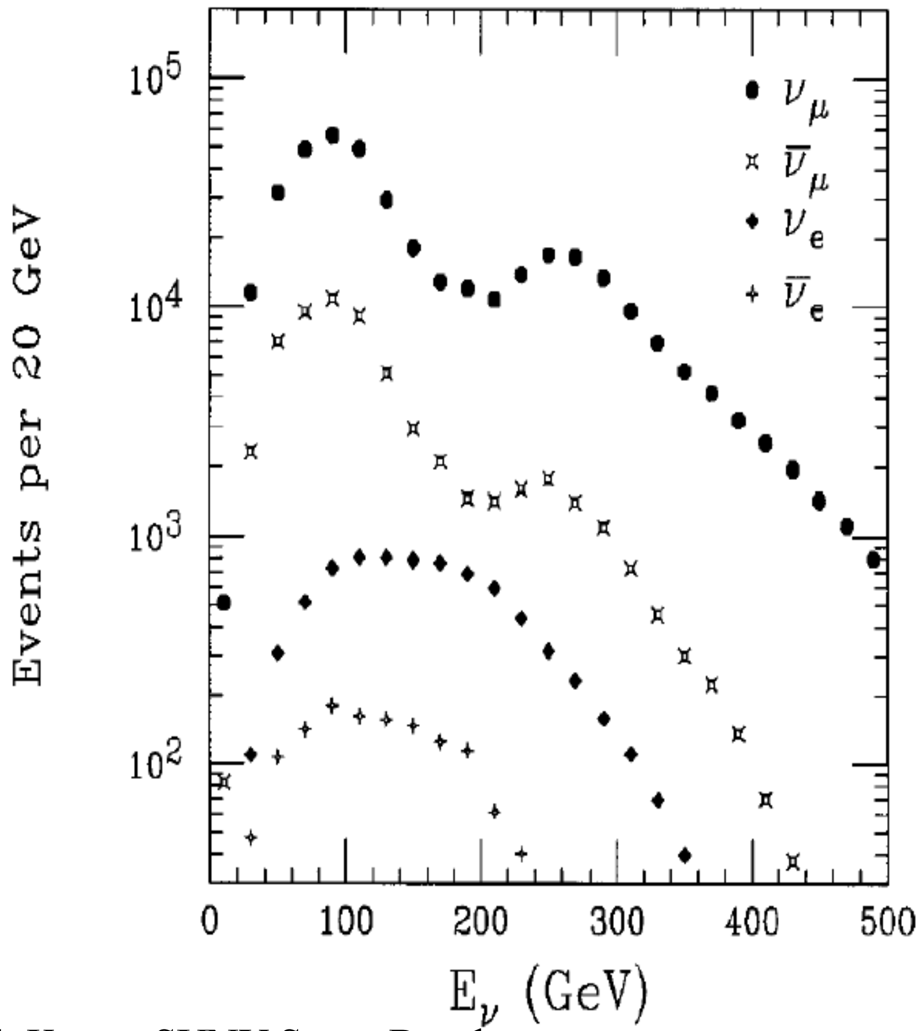
Other WBB Focusing Systems

Quadrupole-Based Focusing

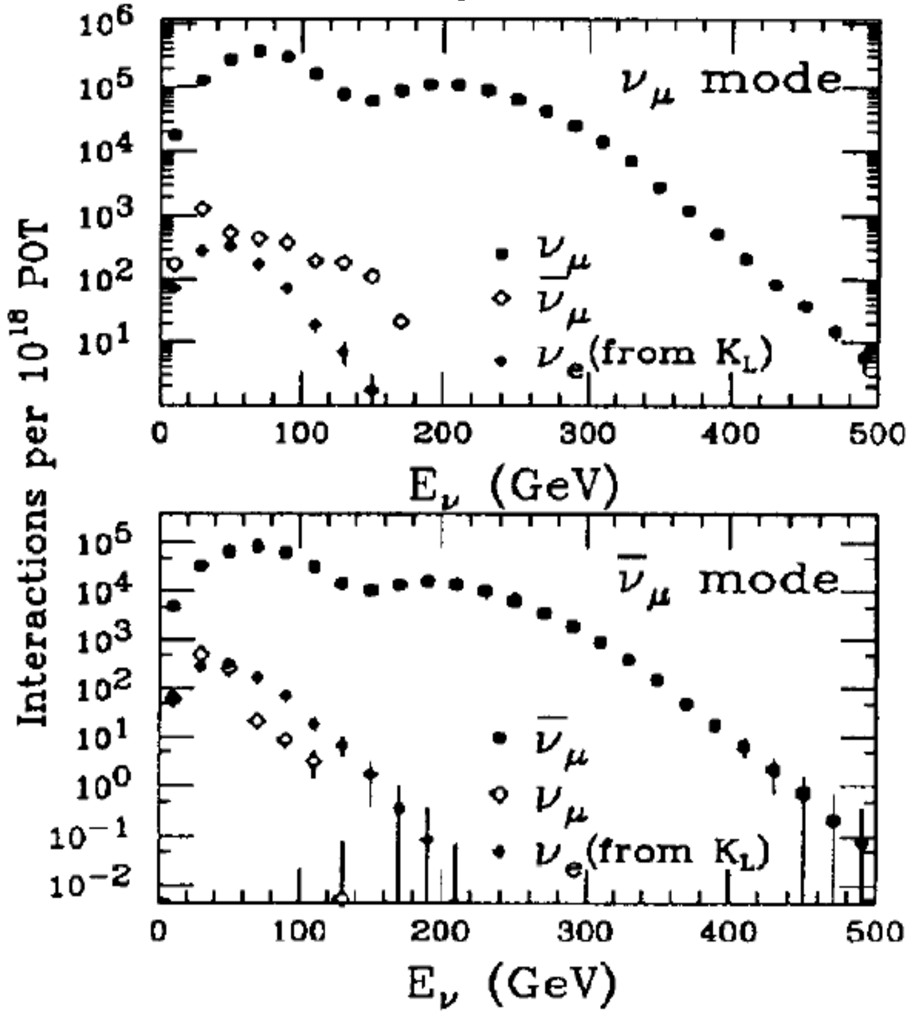




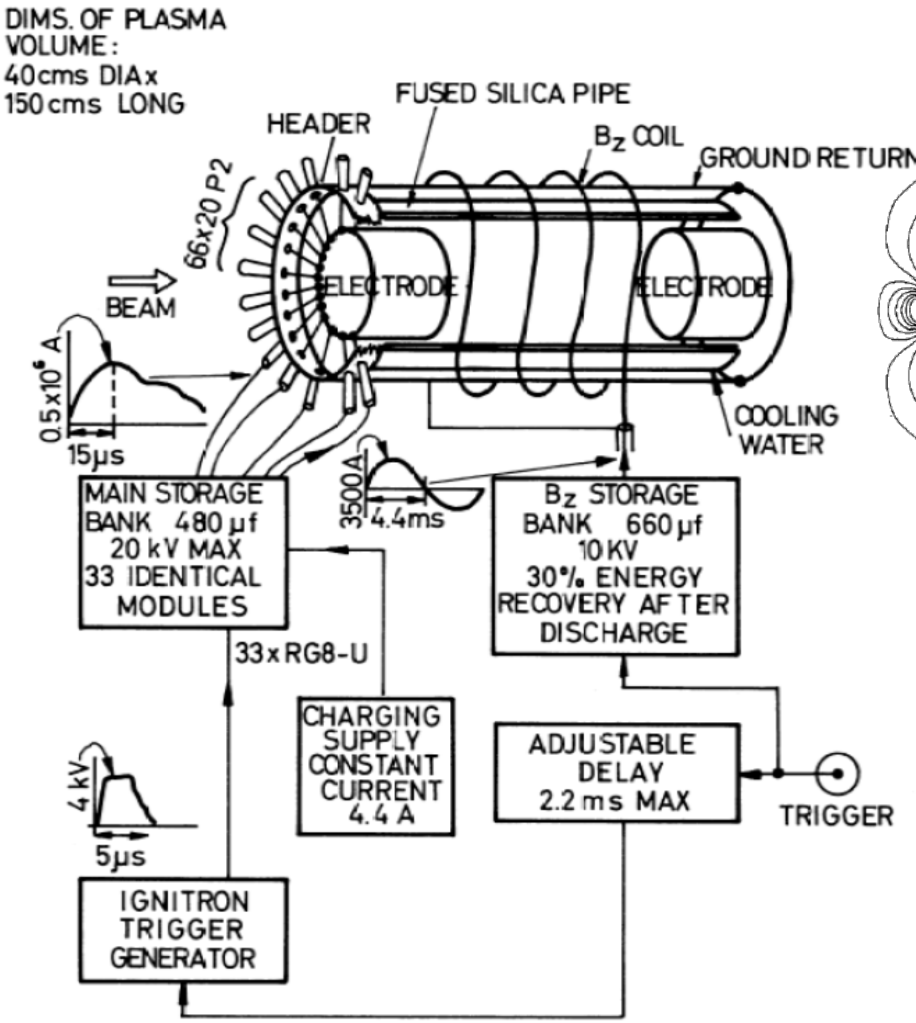
Quad Triplet Beam



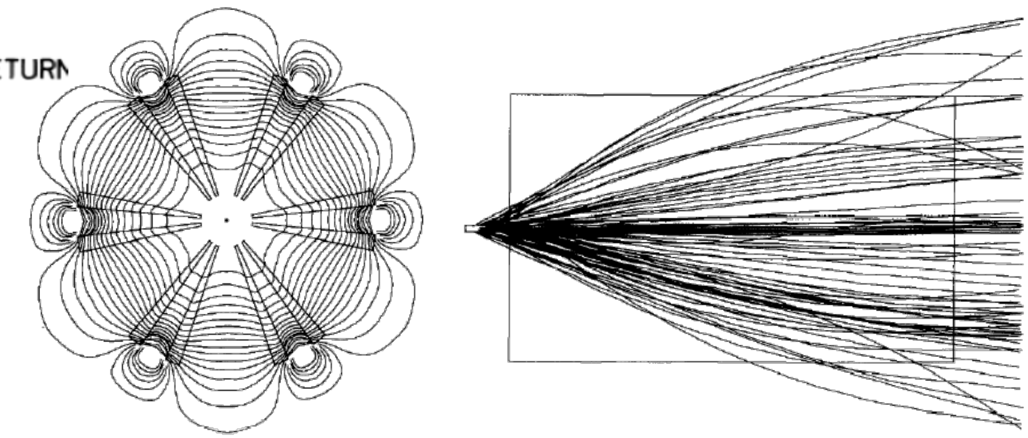
Sign-Selected Quad Triplet Beam



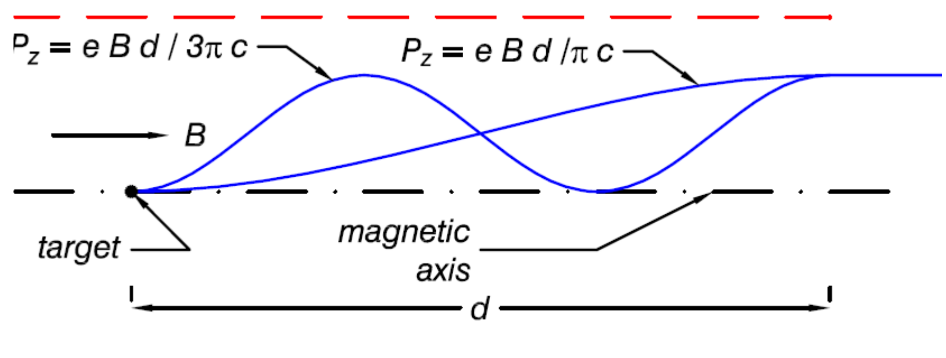
Plasma Lens:



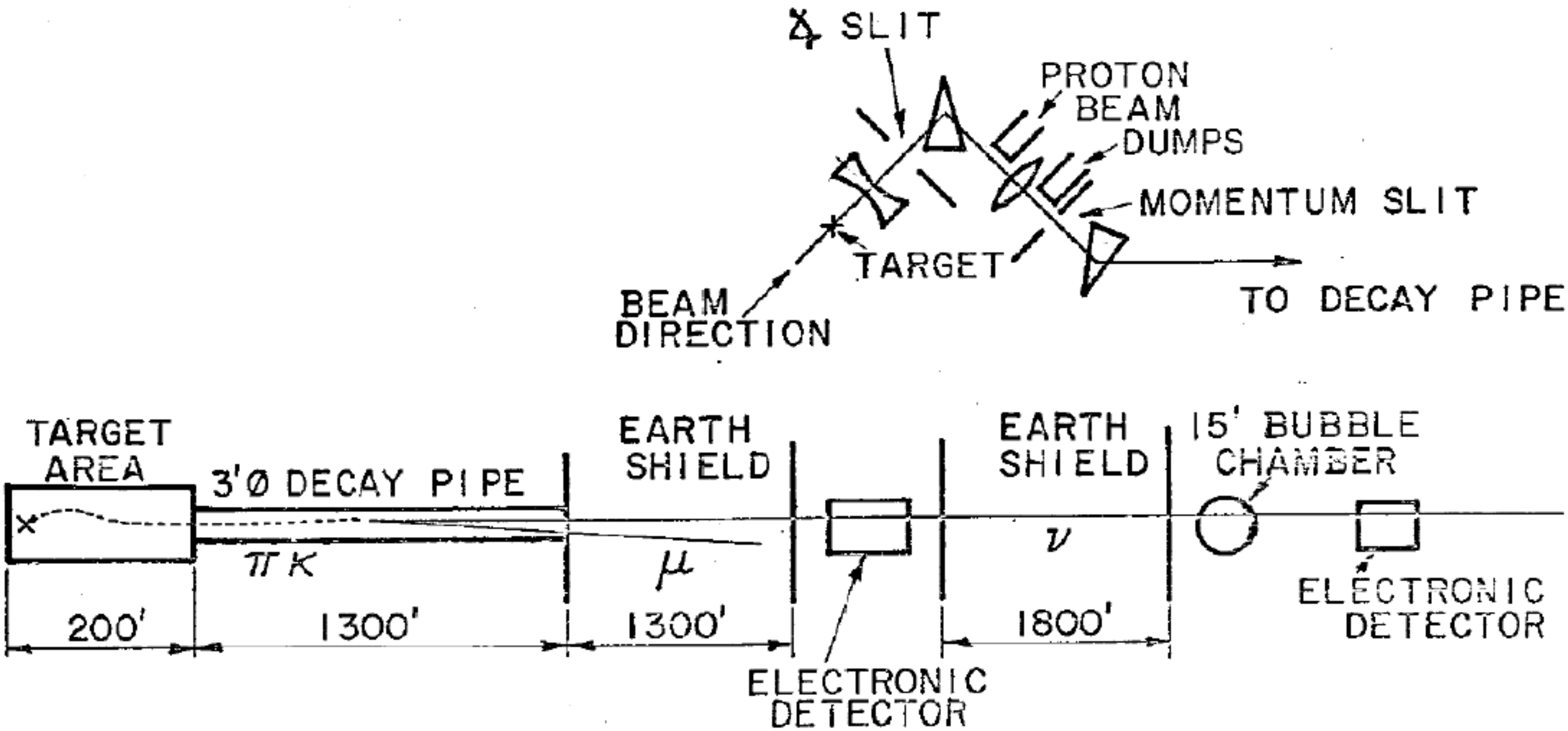
Magnetic Spokes:



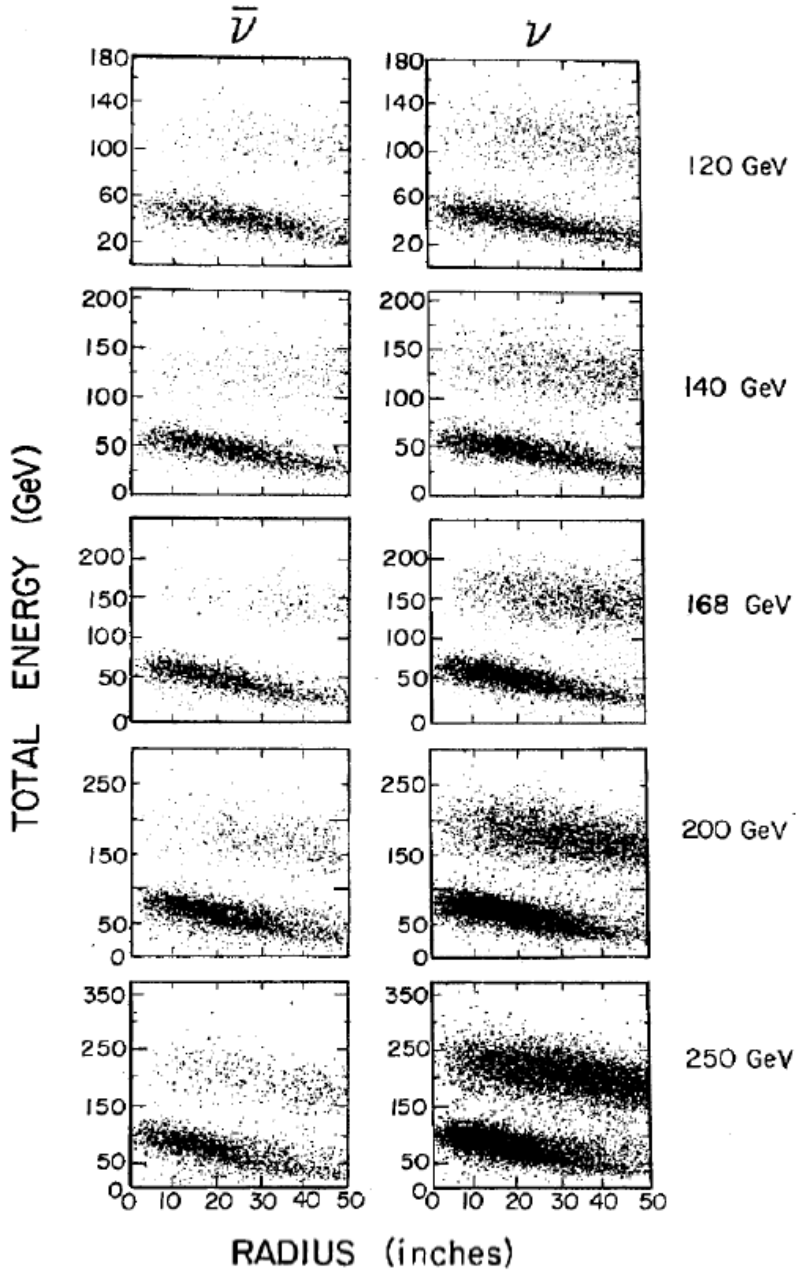
Solenoid:

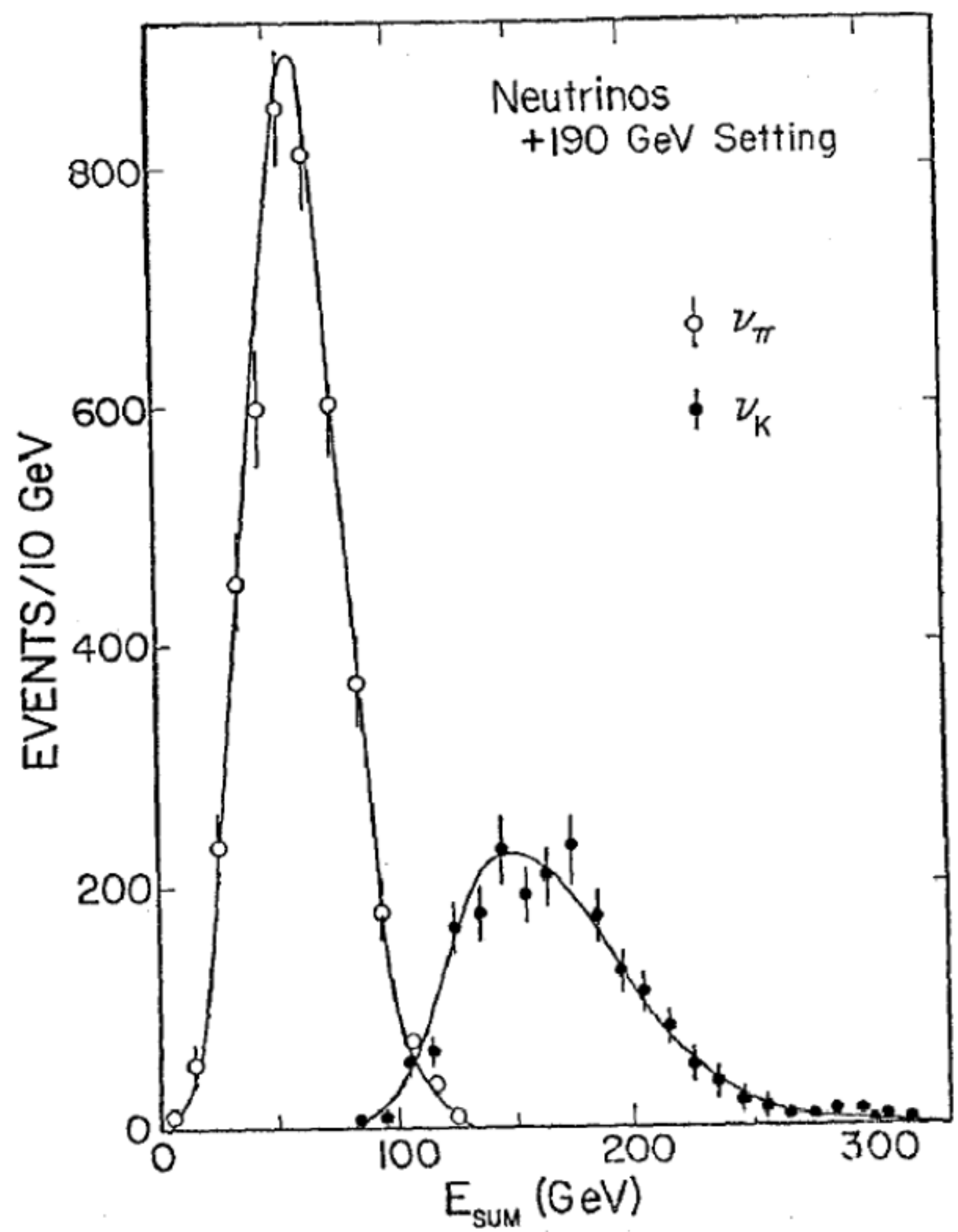


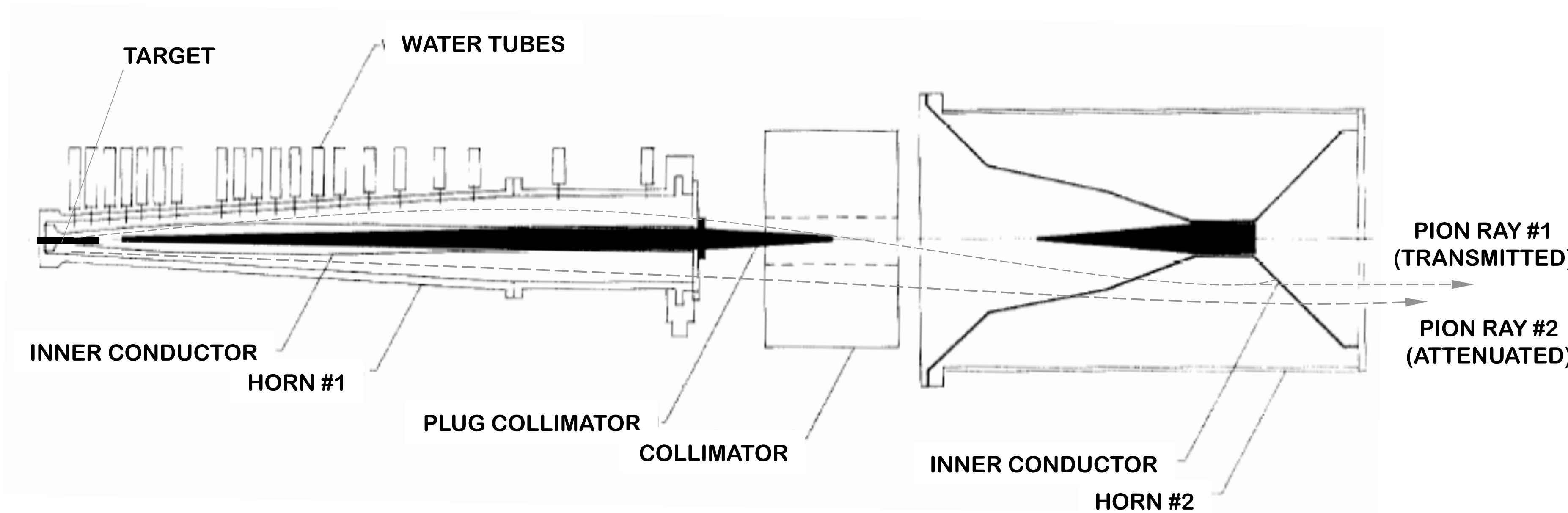
Focusing of NBB’s



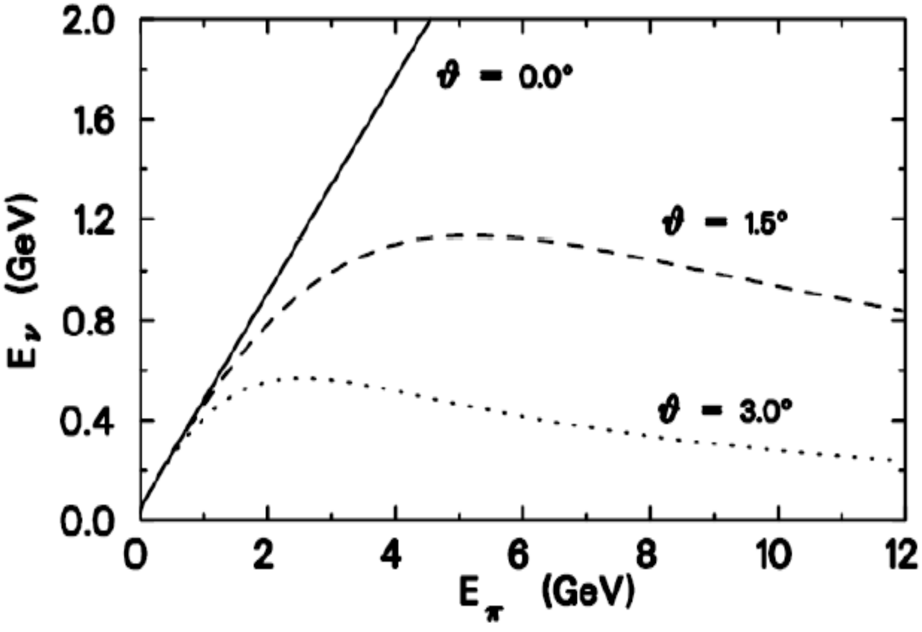
SLIT
PROTON
BEAM
DUMPS
MOMENTUM SLIT
TARGET
BEAM
DIRECTION
TO DECAY PIPE
TARGET
AREA
3'Ø DECAY PIPE
EARTH
SHIELD
EARTH
SHIELD
15' BUBBLE
CHAMBER
π K
μ
ν
200'
1300'
1300'
1800'
ELECTRONIC
DETECTOR
ELECTRONIC
DETECTOR

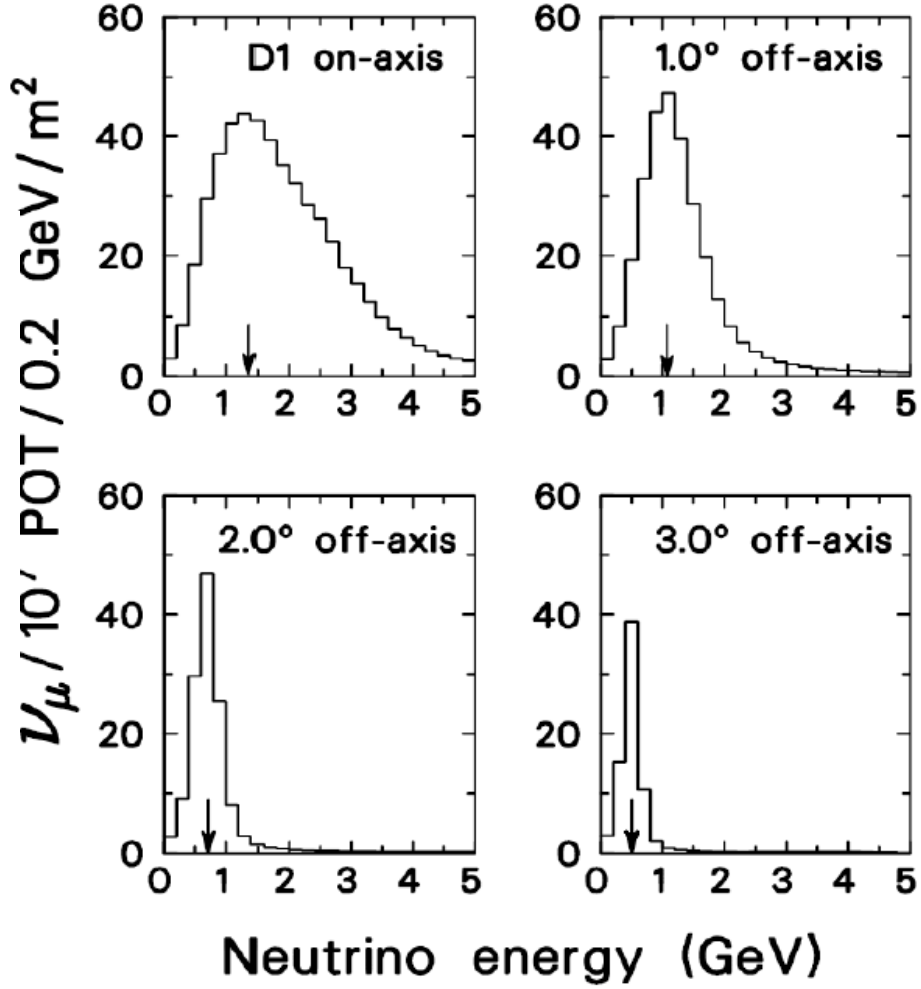

$\bar{\nu}$
ν
120 GeV
140 GeV
168 GeV
200 GeV
250 GeV
TOTAL ENERGY (GeV)
RADIUS (inches)


Neutrinos
+190 GeV Setting
ν_π
ν_K
EVENTS/10 GeV
E_{SUM} (GeV)

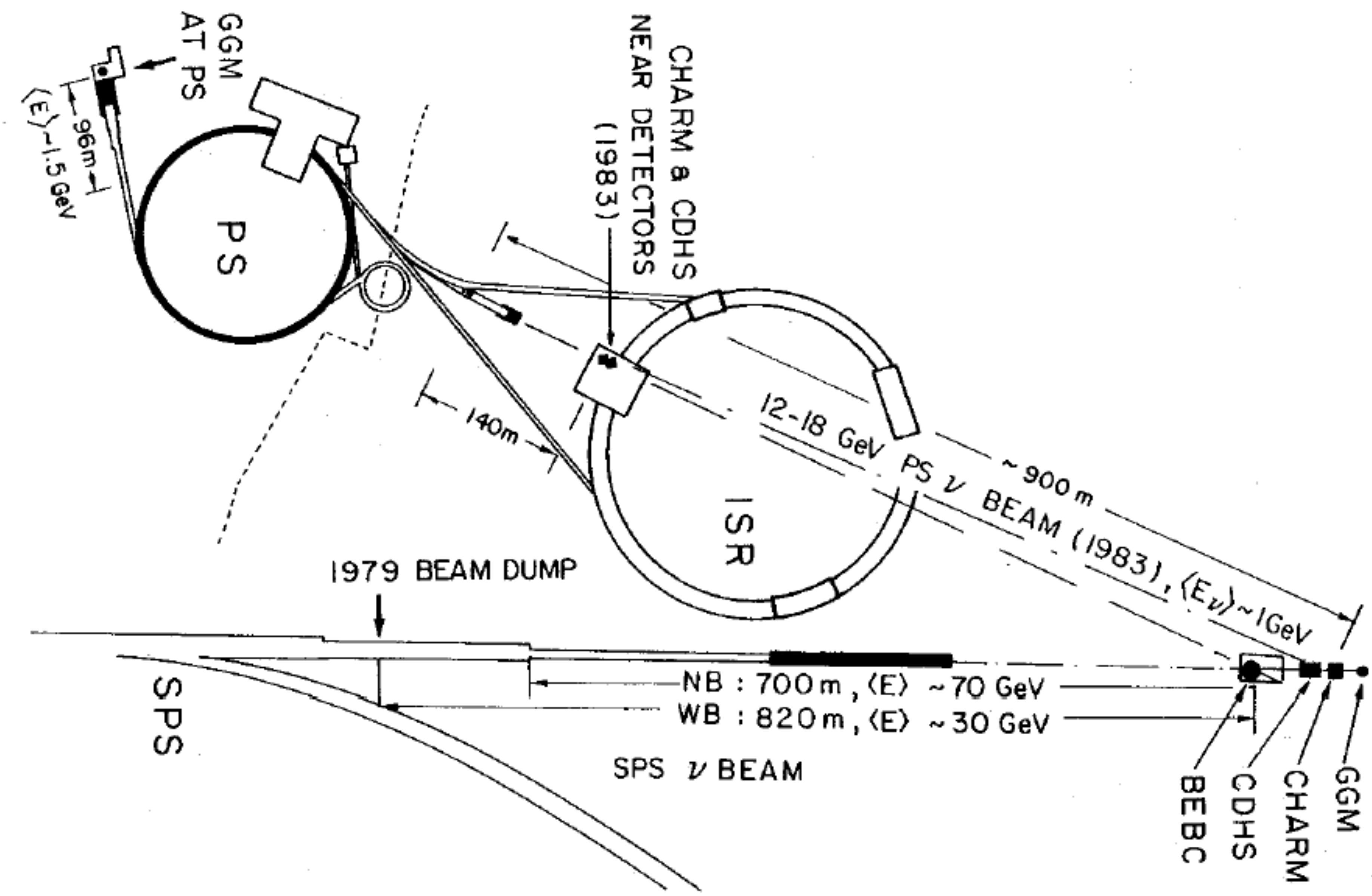

TARGET
WATER TUBES
INNER CONDUCTOR
HORN #1
PLUG COLLIMATOR
COLLIMATOR
INNER CONDUCTOR
HORN #2
PION RAY #1
(TRANSMITTED)
PION RAY #2
(ATTENUATED)

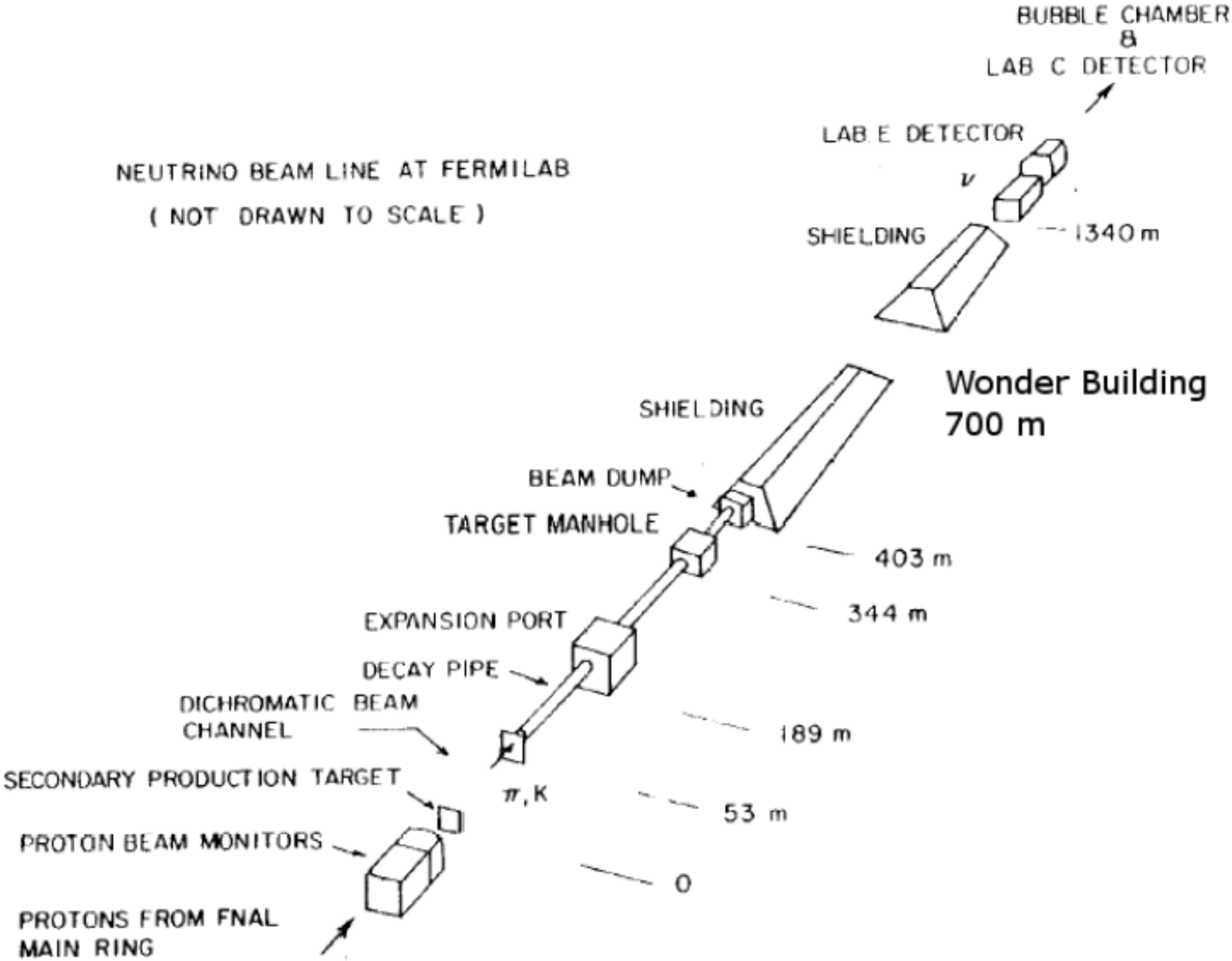
Off-Axis Beam



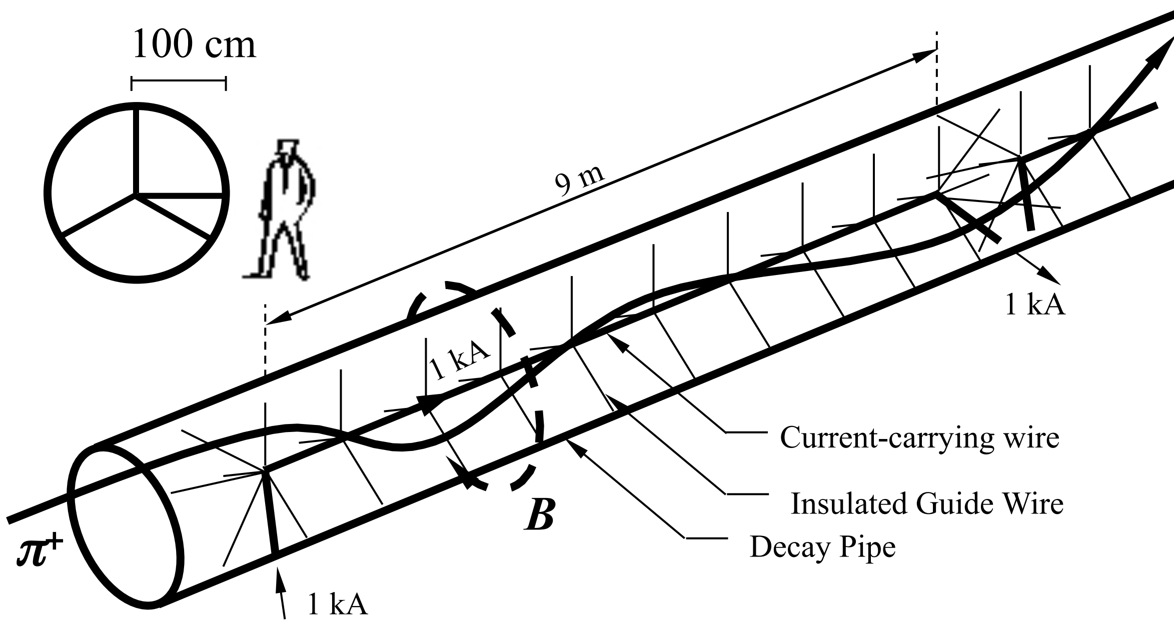


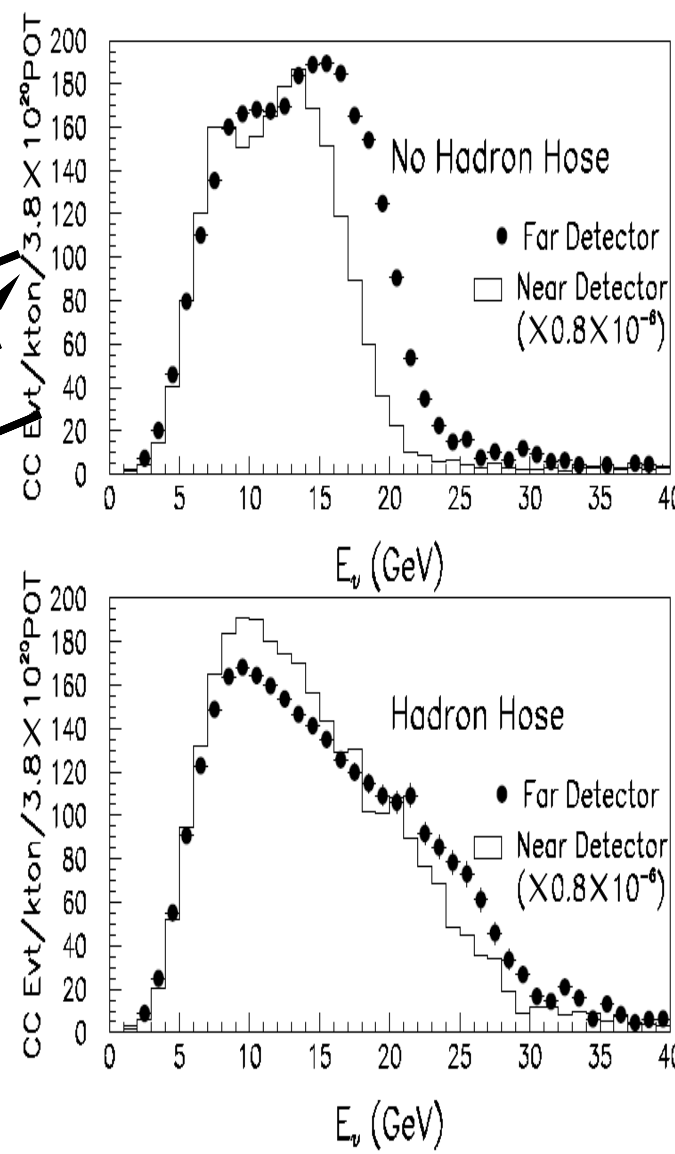
Two-Detector Experiments


GGM
AT PS
⟨E⟩~1.5 GeV
96m
PS
CHARM & CDHS
NEAR DETECTORS
(1983)
140m
ISR
12-18 GeV
~900 m
PS ν BEAM (1983), ⟨Eν⟩~1GeV
1979 BEAM DUMP
SPS
NB : 700m, ⟨E⟩ ~70 GeV
WB : 820m, ⟨E⟩ ~30 GeV
SPS ν BEAM
BEBC
CDHS
CHARM
GGM

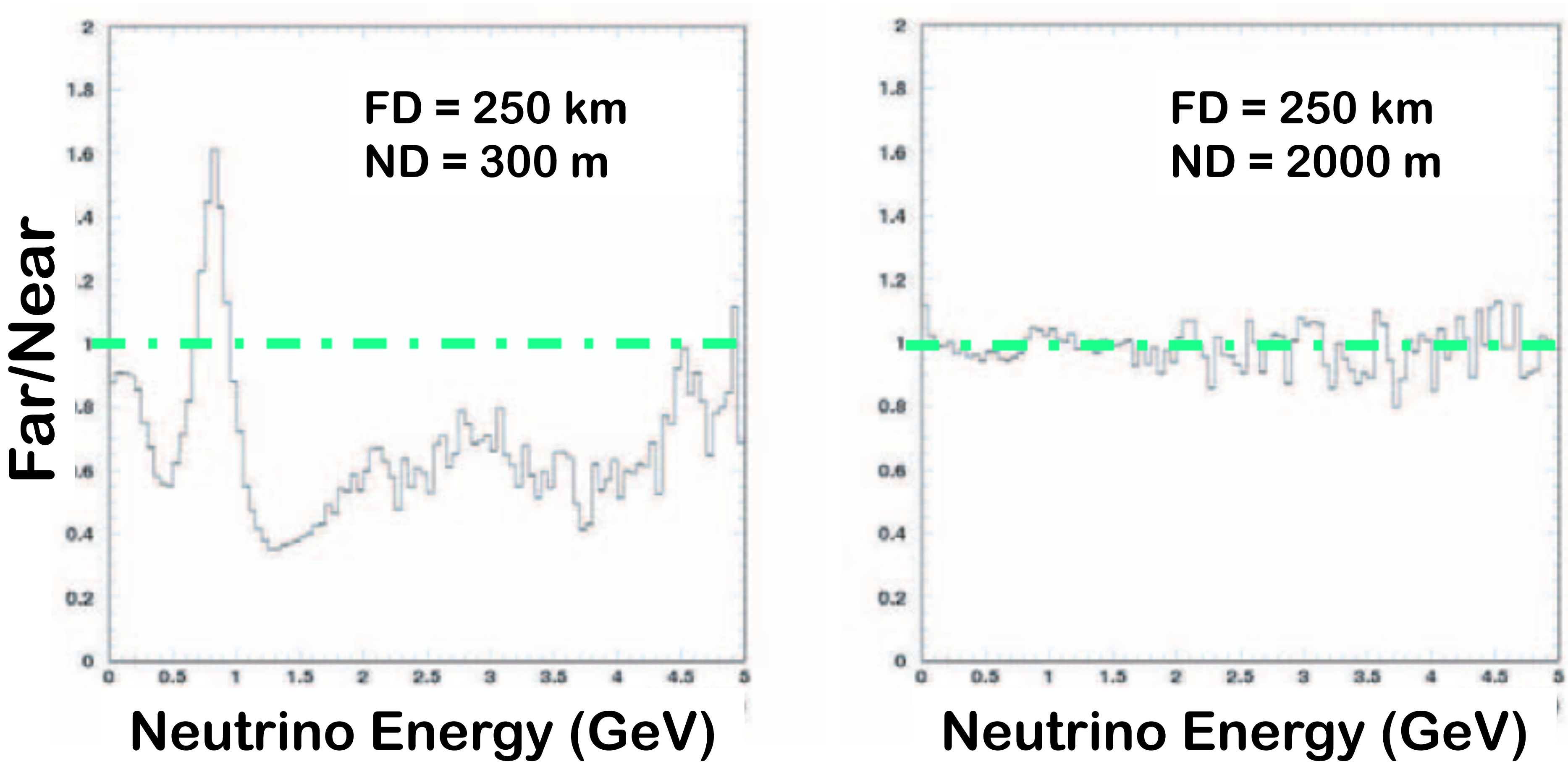

NEUTRINO BEAM LINE AT FERMILAB
(NOT DRAWN TO SCALE)
BUBBLE CHAMBER
&
LAB C DETECTOR
LAB E DETECTOR
ν
SHIELDING
1340 m
Wonder Building
700 m
SHIELDING
BEAM DUMP
TARGET MANHOLE
403 m
344 m
EXPANSION PORT
DECAY PIPE
DICHROMATIC BEAM
CHANNEL
189 m
SECONDARY PRODUCTION TARGET
π, K
53 m
PROTON BEAM MONITORS
0
PROTONS FROM FNAL
MAIN RING

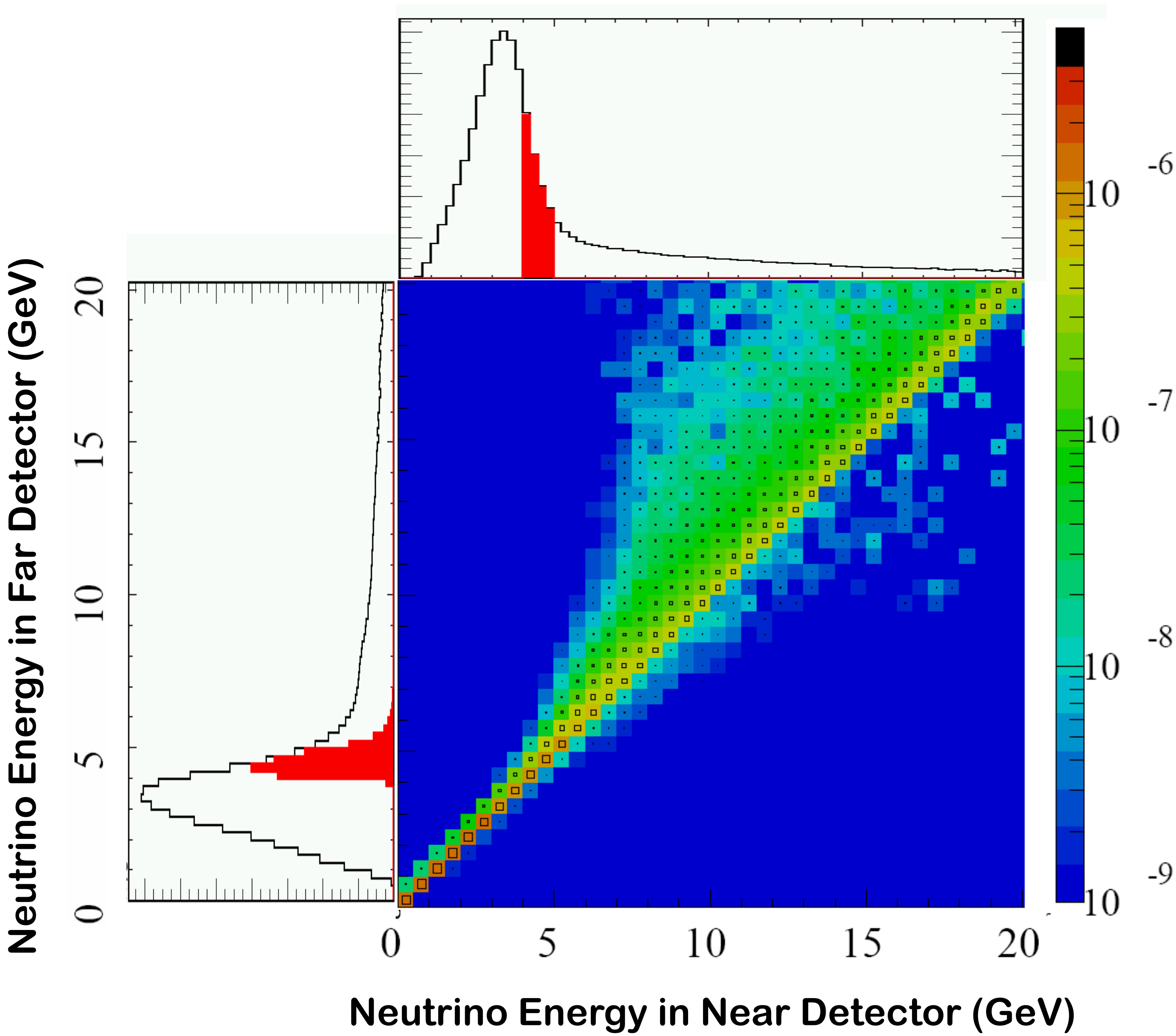
Hadron Hose


100 cm
9 m
1 kA
1 kA
1 kA
Current-carrying wire
Insulated Guide Wire
Decay Pipe
B
π+

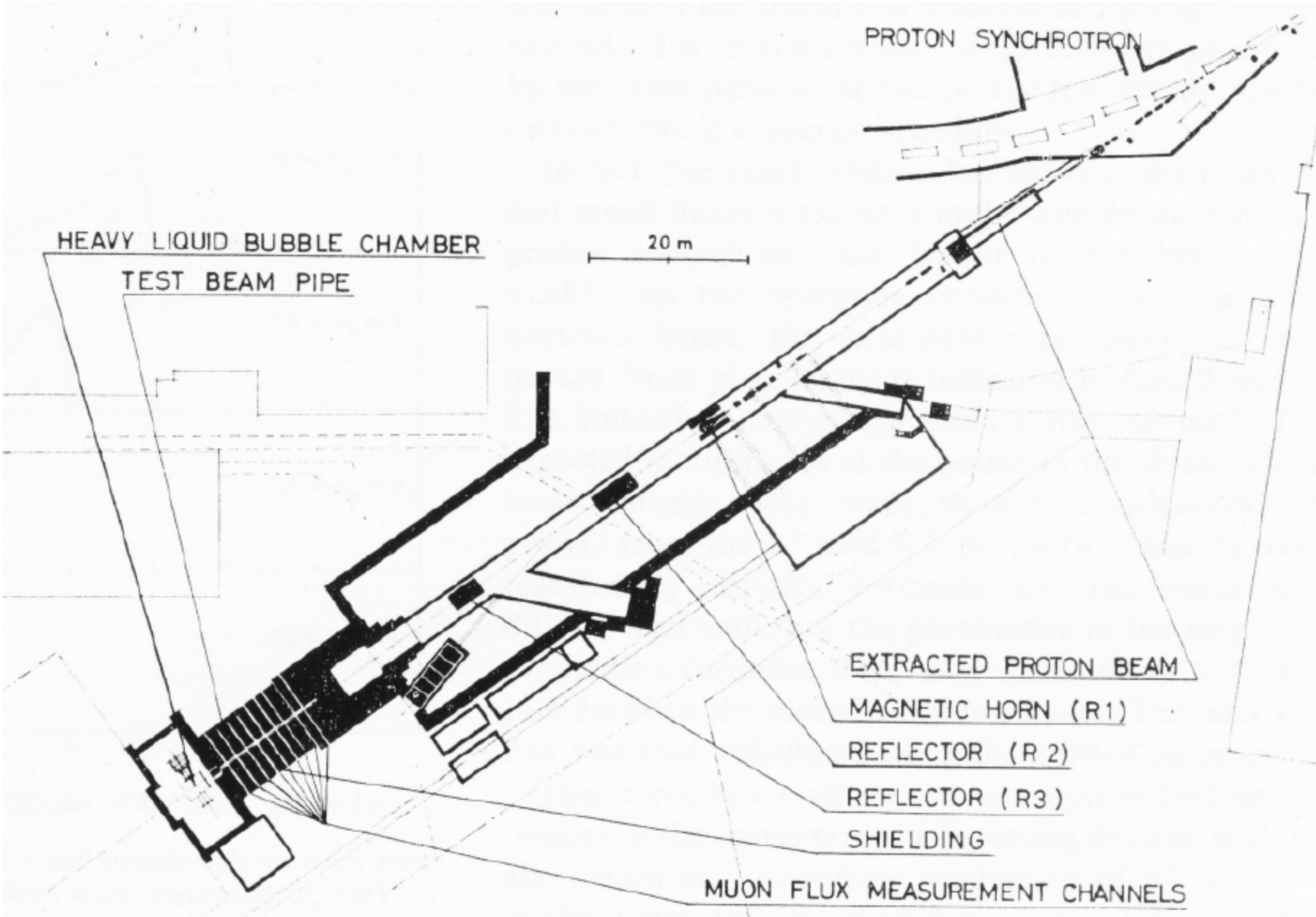

CC Evt/kton/3.8×10²⁰POT
No Hadron Hose
Far Detector
Near Detector
(×0.8×10⁻⁶)
E_ν (GeV)
Hadron Hose
Far Detector
Near Detector
(×0.8×10⁻⁶)
E_ν (GeV)

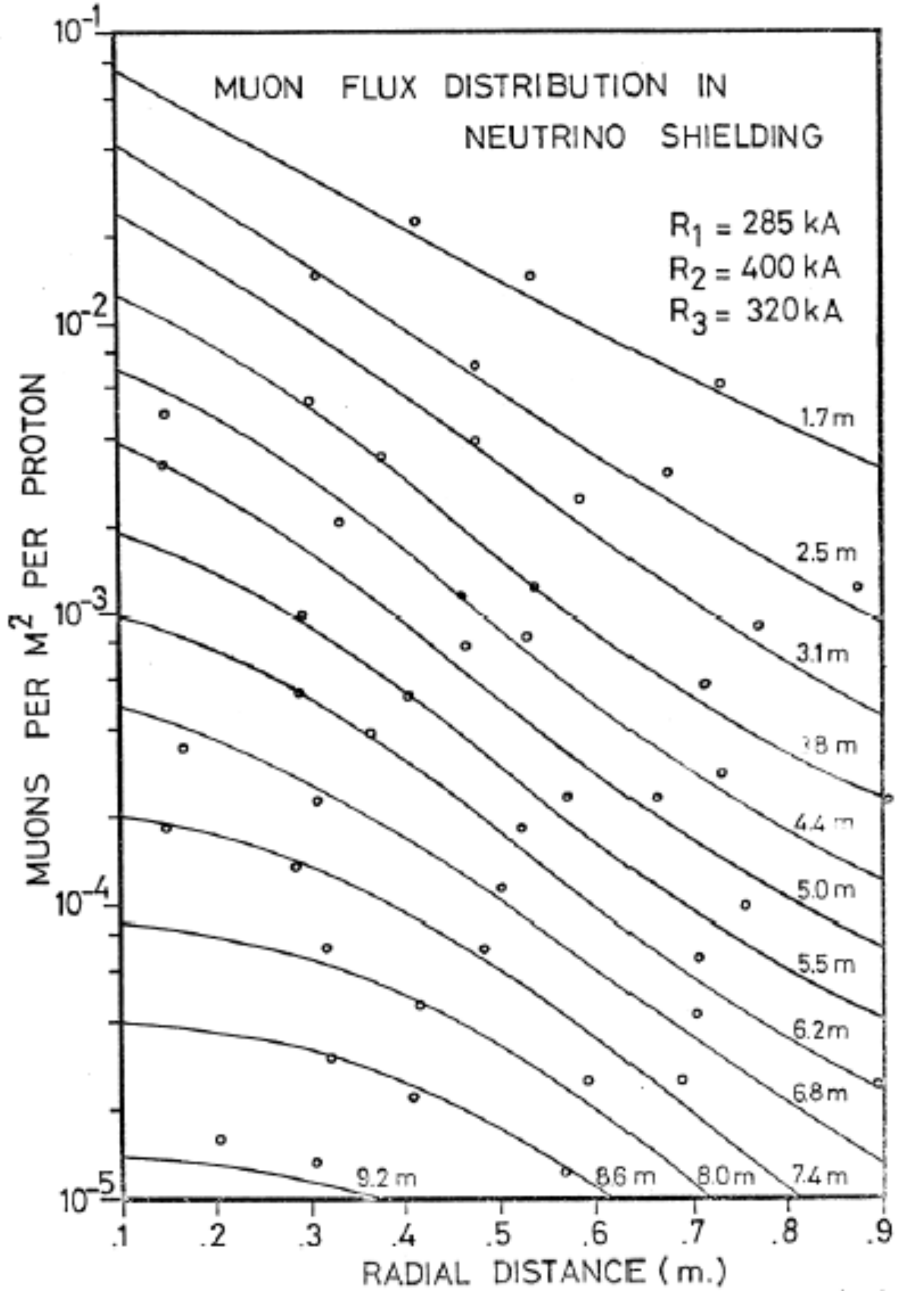
T2K Not-So-Near Detector

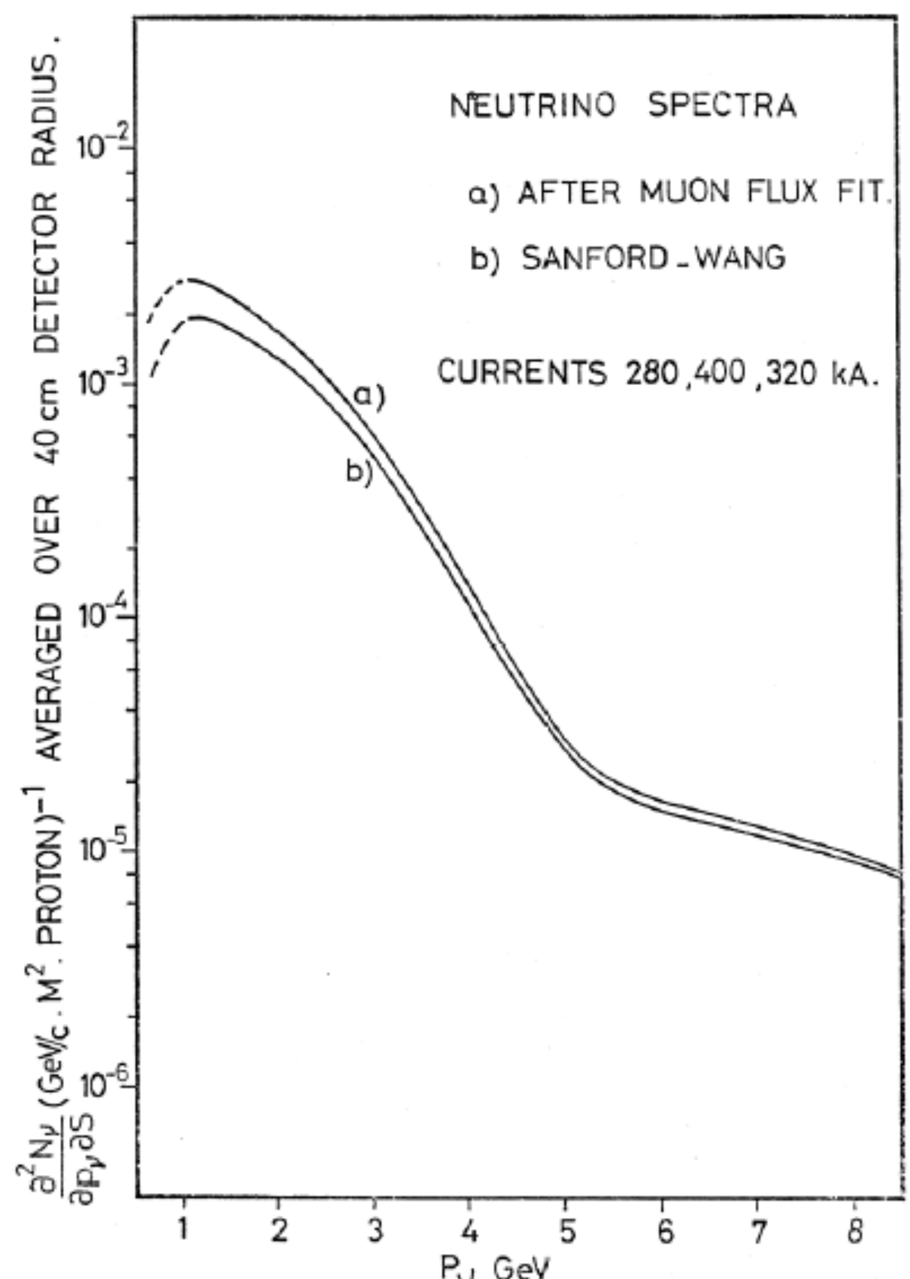


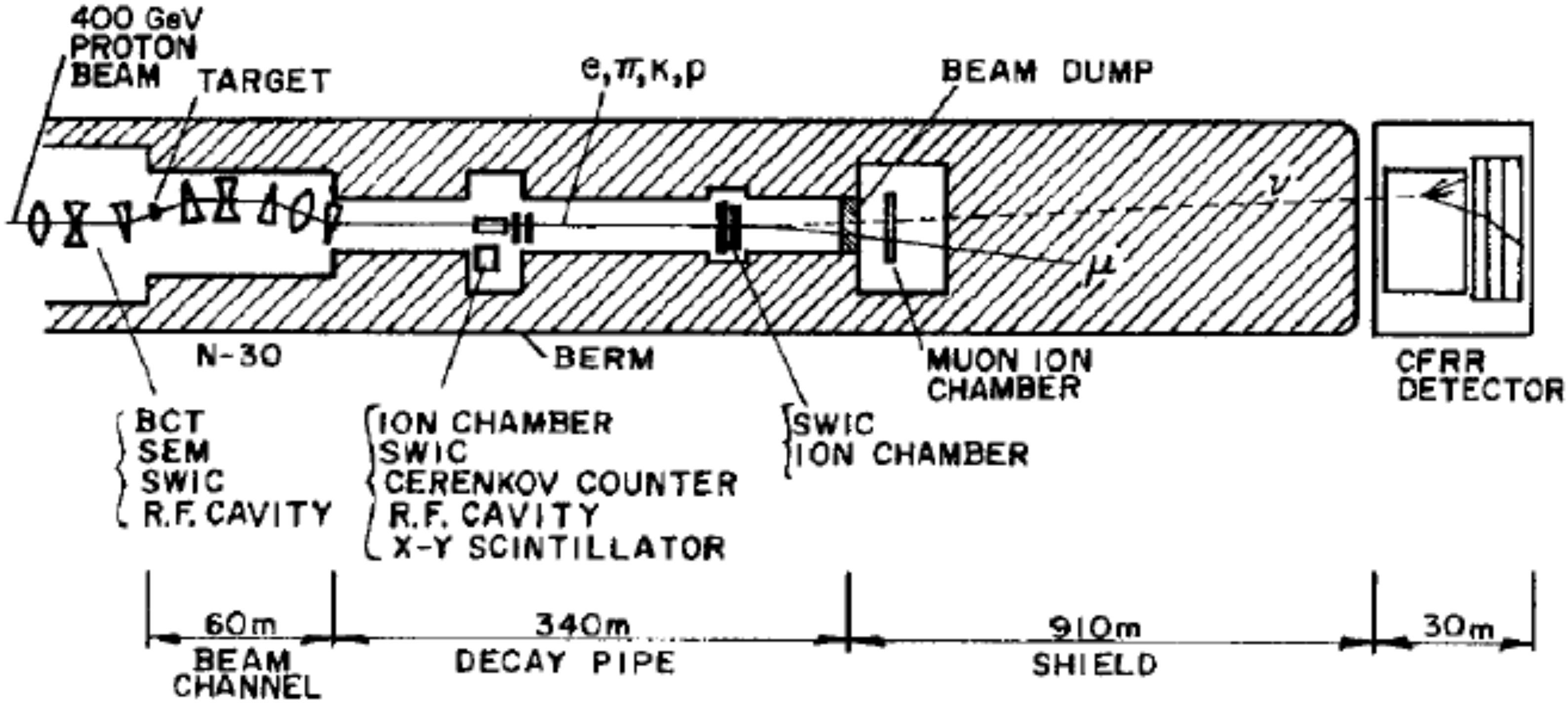

Neutrino Energy in Far Detector (GeV)
0
5
10
15
20
0
5
10
15
20
Neutrino Energy in Near Detector (GeV)
10 -6
10 -7
10 -8
10 -9

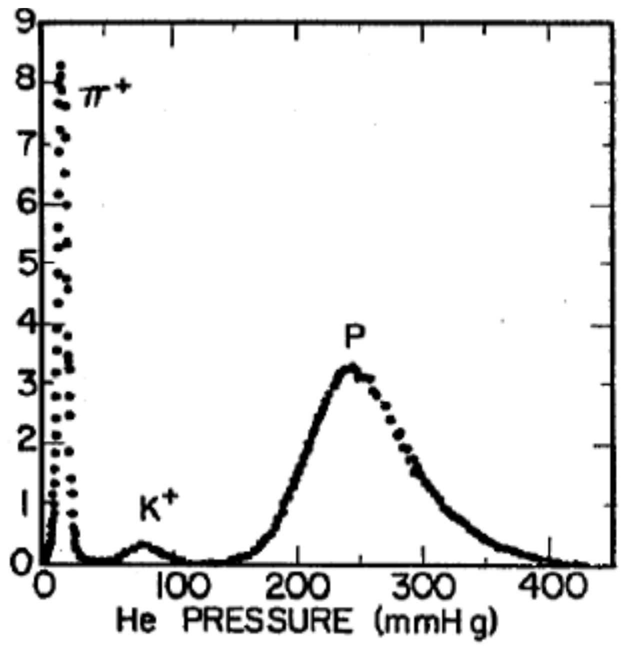
Monitoring/Measuring the ν Flux

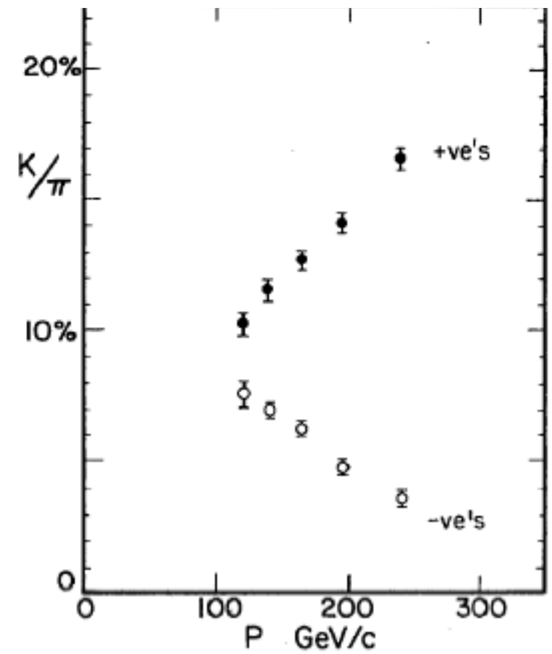

PROTON SYNCHROTRON
HEAVY LIQUID BUBBLE CHAMBER
TEST BEAM PIPE
20 m
EXTRACTED PROTON BEAM
MAGNETIC HORN (R1)
REFLECTOR (R 2)
REFLECTOR (R3)
SHIELDING
MUON FLUX MEASUREMENT CHANNELS


MUON FLUX DISTRIBUTION IN NEUTRINO SHIELDING
R_1 = 285 kA
R_2 = 400 kA
R_3 = 320 kA
1.7 m
2.5 m
3.1 m
4.4 m
5.0 m
5.5 m
6.2 m
6.8 m
7.4 m
8.0 m
8.6 m
9.2 m
MUONS PER M^2 PER PROTON
RADIAL DISTANCE (m.)


NEUTRINO SPECTRA
a) AFTER MUON FLUX FIT.
b) SANFORD - WANG
CURRENTS 280, 400, 320 kA.
a)
b)
$\frac{\partial^2 N_\nu}{\partial p_\nu \partial S}$ (GeV/c . M^2. PROTON)$^{-1}$ AVERAGED OVER 40 cm DETECTOR RADIUS.
P_ν GeV


400 GeV
PROTON
BEAM
TARGET
e, π, K, p
BEAM DUMP
ν
μ
N-30
BERM
MUON ION
CHAMBER
CFRR
DETECTOR
BCT
SEM
SWIC
R.F. CAVITY
ION CHAMBER
SWIC
CERENKOV COUNTER
R.F. CAVITY
X-Y SCINTILLATOR
SWIC
ION CHAMBER
60m
BEAM
CHANNEL
340m
DECAY PIPE
910m
SHIELD
30m


π+
K+
P
He PRESSURE (mmHg)


K/π
20%
10%
0
+ve's
-ve's
P GeV/c

Accelerator Neutrino Beams

1. Evidence for the *W* and *Z* bosons
2. Validation of the *V-A* model
3. Deep inelastic scattering & QCD
4. Discovery of lepton flavors
5. Neutrino masses and mixing

A World-Wide Effort!