Accelerator Neutrino Beams

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4. Focusing
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   c) narrow-band beams
5. Two-detector experiments
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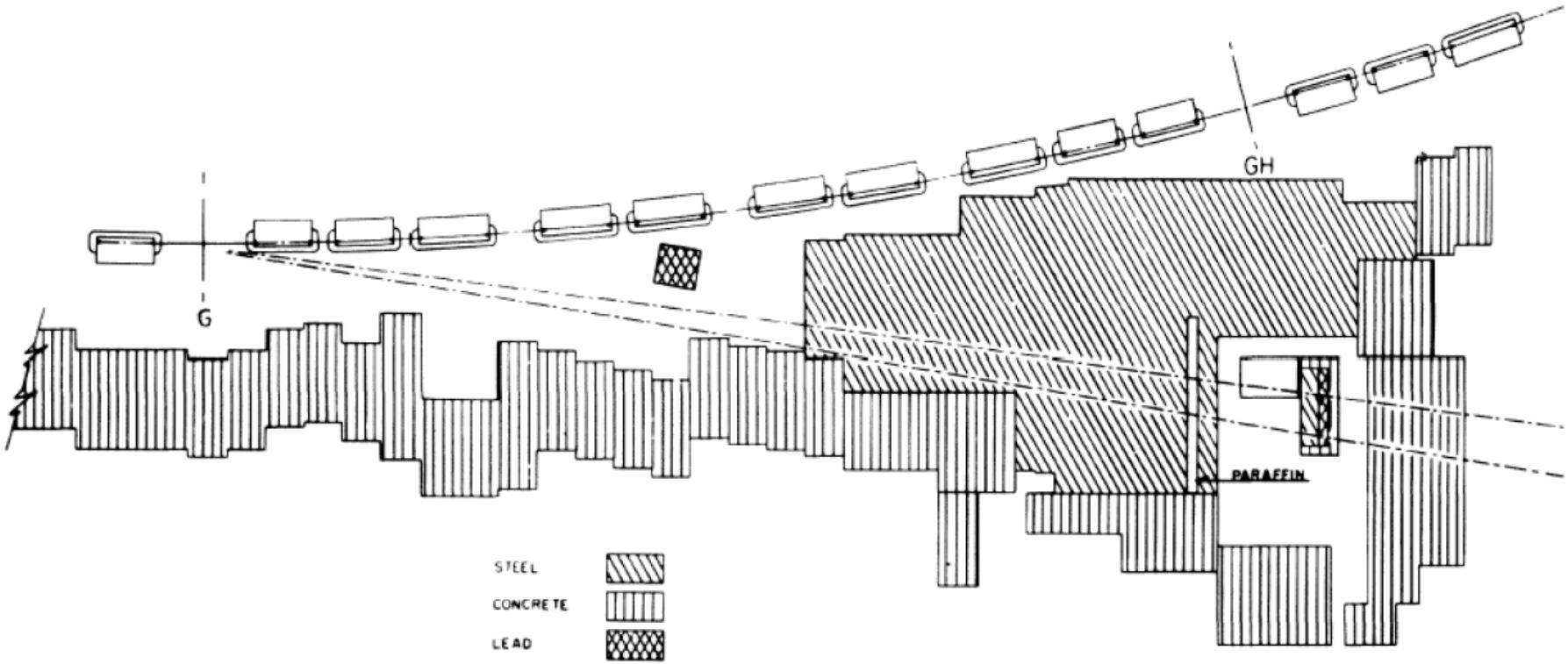
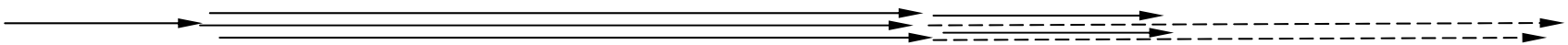
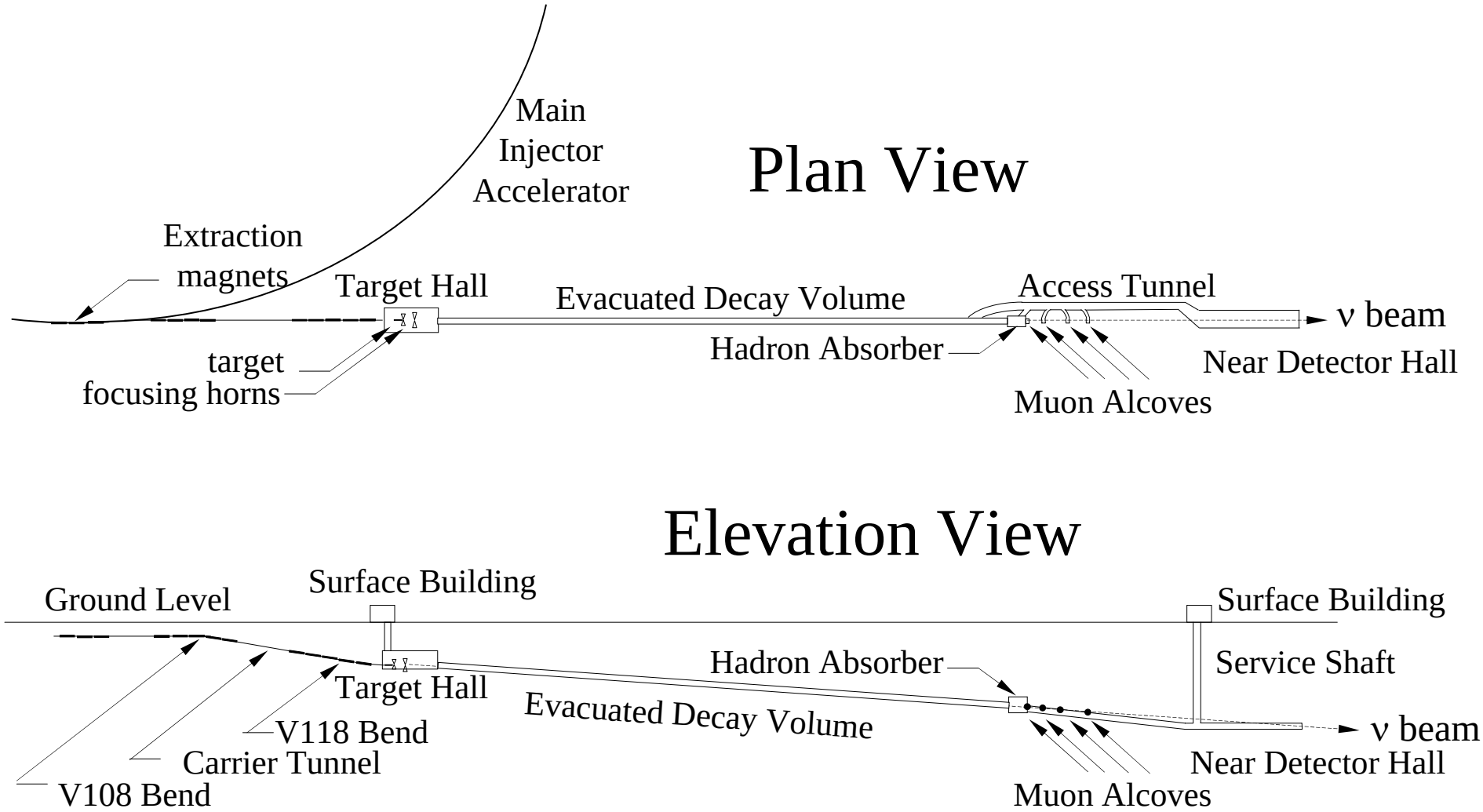
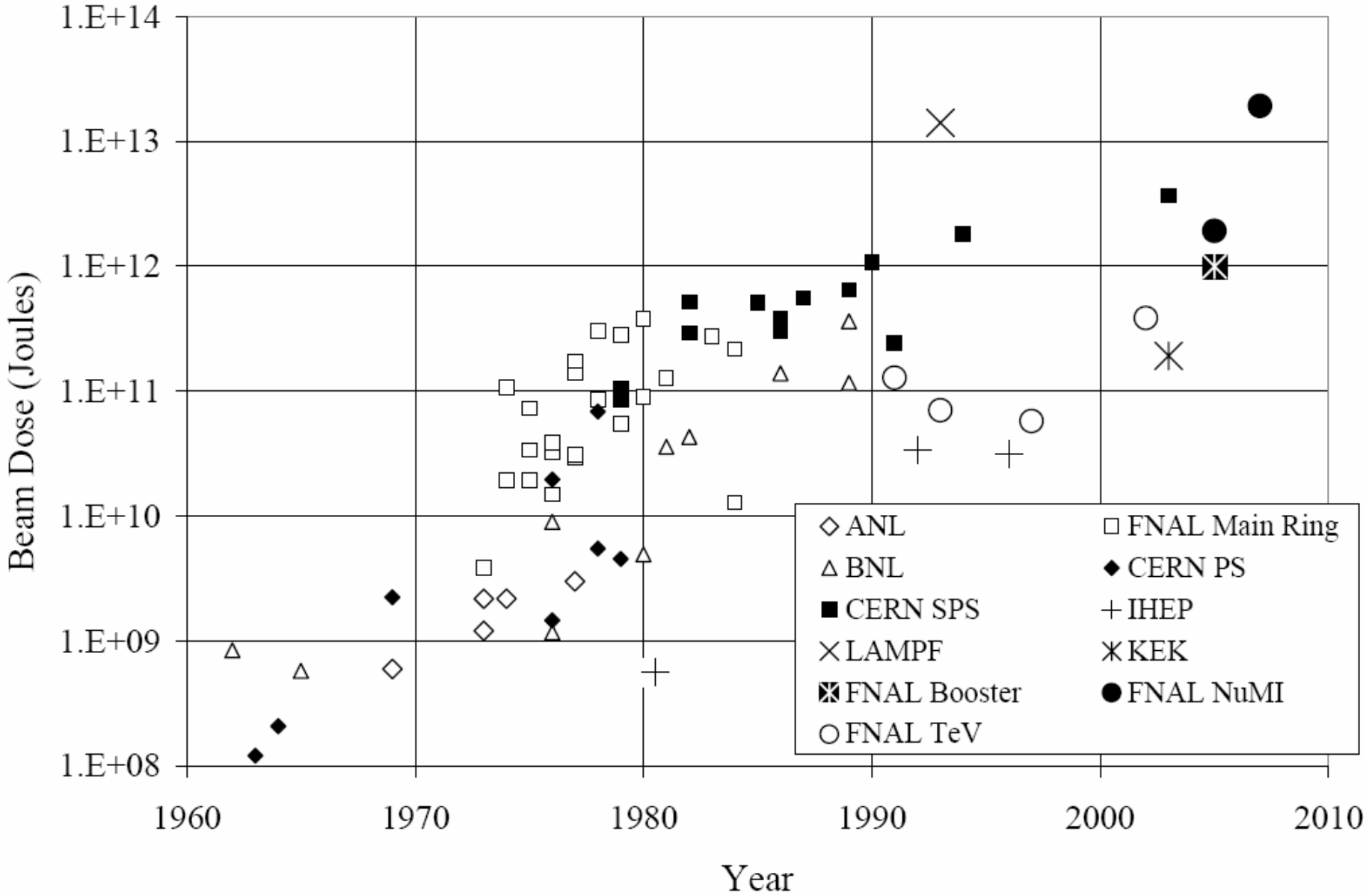
Overview





p p, K, π μ, ν_μ ν_μ

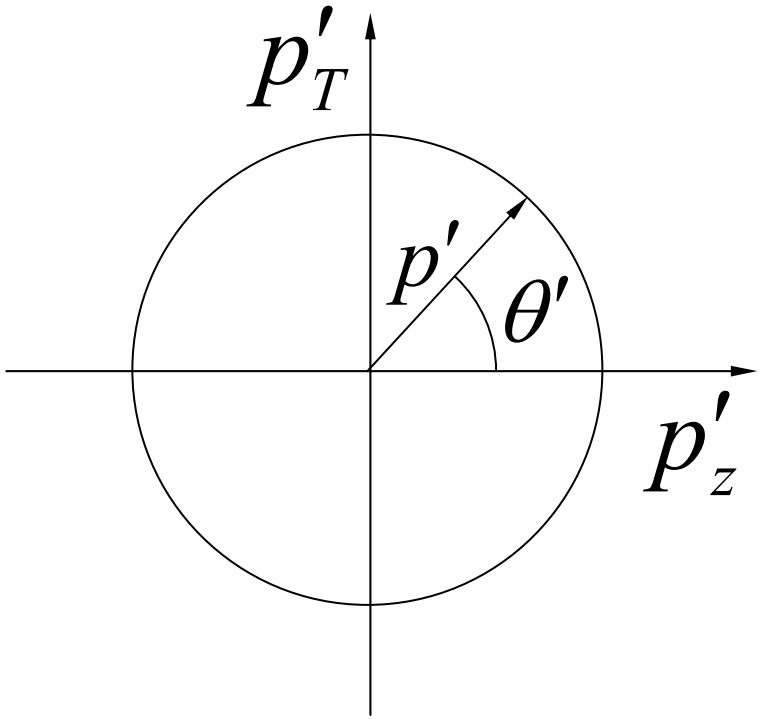

Main
Injector
Accelerator
Plan View
Extraction
magnets
Target Hall
Evacuated Decay Volume
Access Tunnel
ν beam
target
focusing horns
Hadron Absorber
Near Detector Hall
Muon Alcoves
Elevation View
Ground Level
Surface Building
Surface Building
Hadron Absorber
Service Shaft
Target Hall
Evacuated Decay Volume
ν beam
V118 Bend
Carrier Tunnel
V108 Bend
Near Detector Hall
Muon Alcoves
p
p, K, π
μ, ν_μ
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
BNL
CERN SPS
LAMPF
FNAL Booster
FNAL TeV
FNAL Main Ring
CERN PS
IHEP
KEK
FNAL NuMI

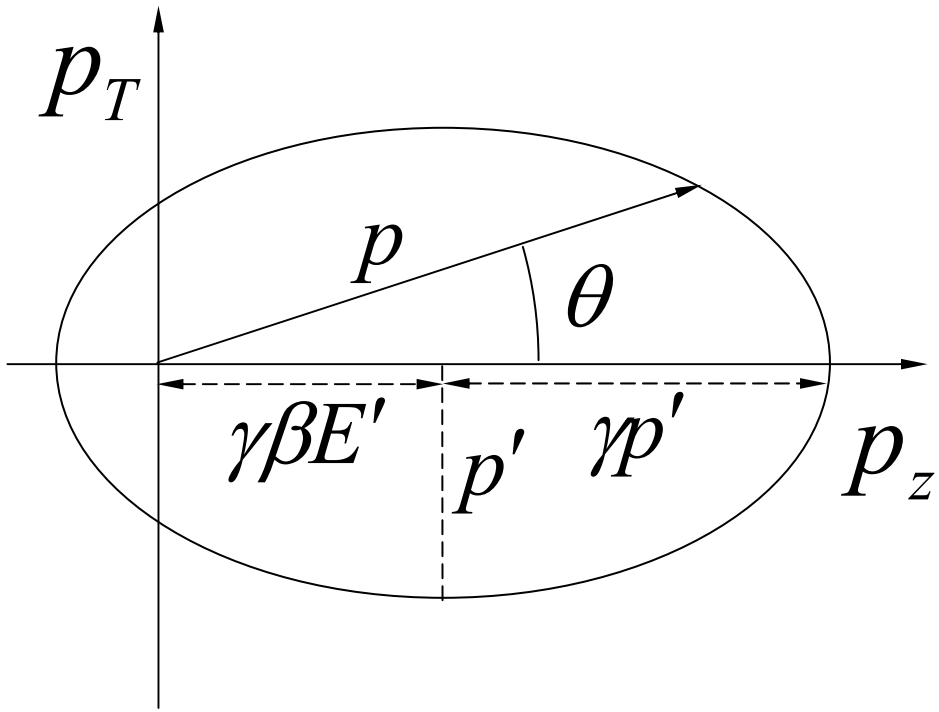
Lab	Year	p_0 (GeV/c)	Protons/ Pulse (10^{12})	Secondary Focusing	Dec. Pipe Length (m)	$\langle E_\nu \rangle$ (GeV)	Experiments
ANL	1969	12.4	1.2	1 horn WBB	30	0.5	Spark Chamber
ANL	1970	12.4	1.2	2-horn WBB	30	0.5	12′ BC
BNL	1962	15	0.3	bare target	21	5	Spark Ch. Observation of 2 ν's
BNL	1976	28	8	2-horn 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.

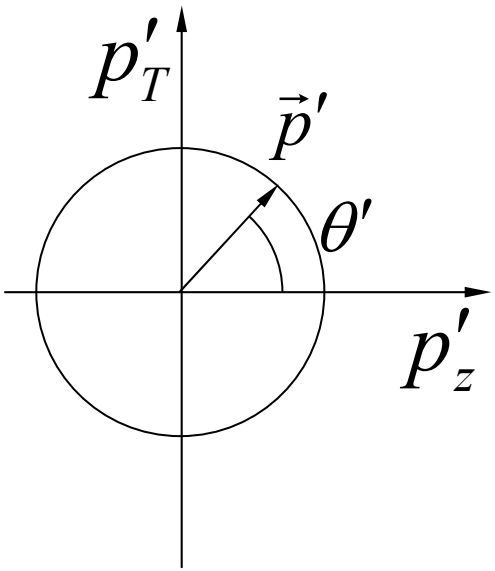
Decay Kinematics



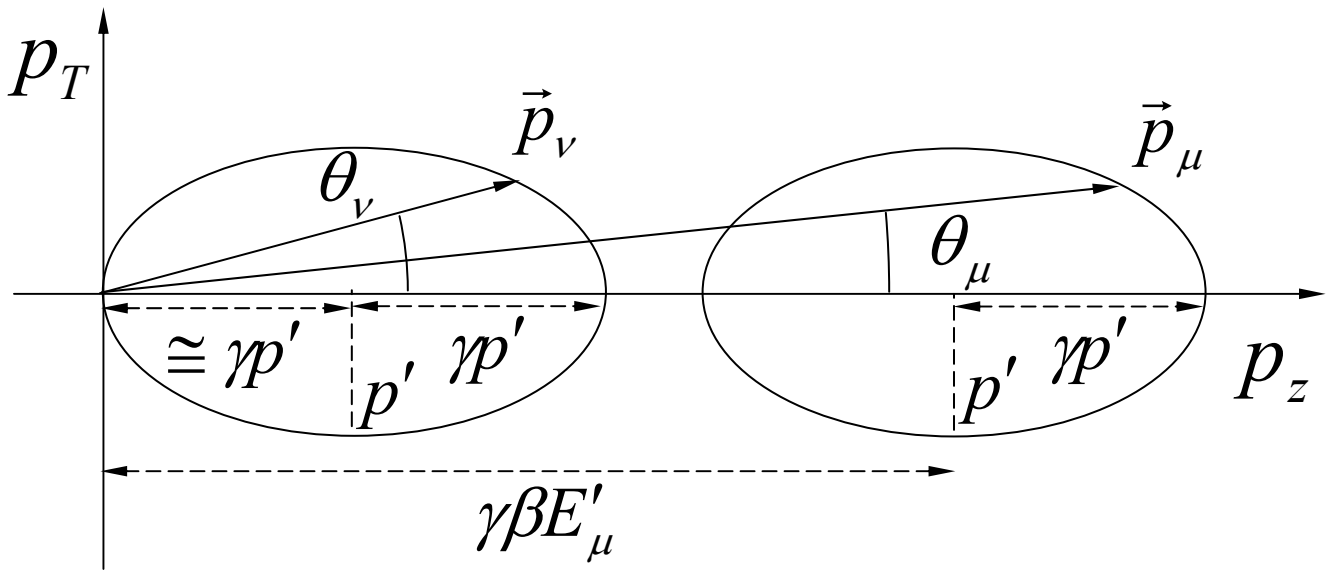
CM Frame



Laboratory Frame



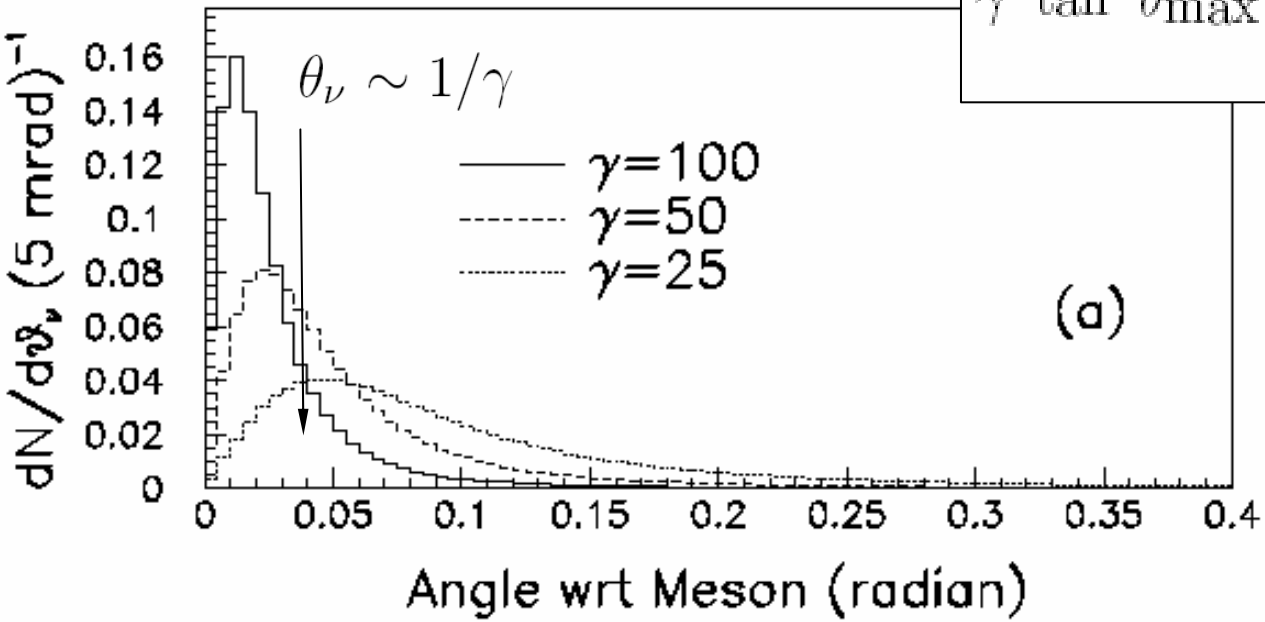
CM Frame

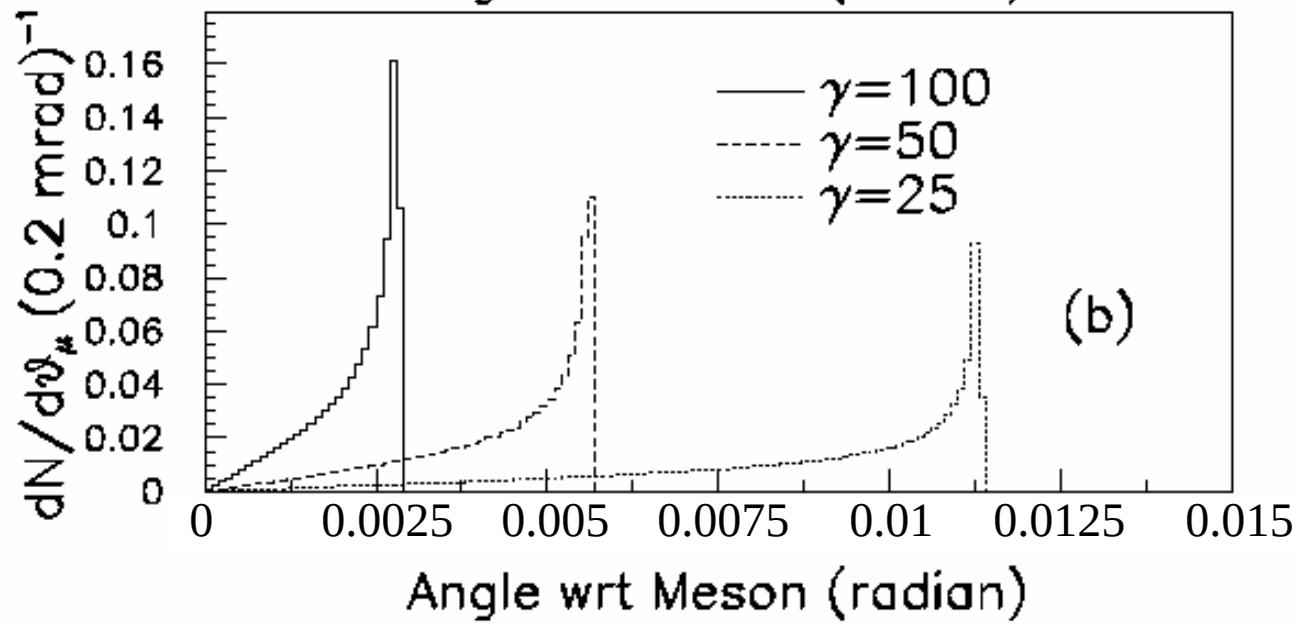


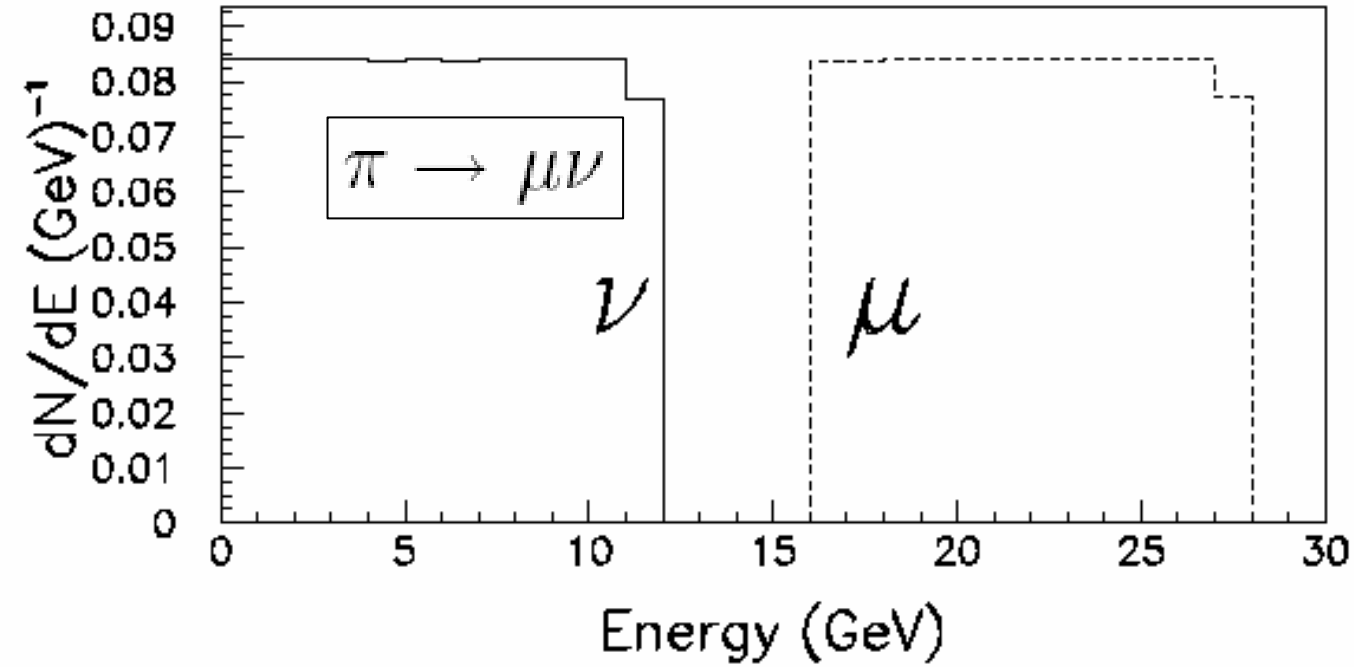
Laboratory Frame

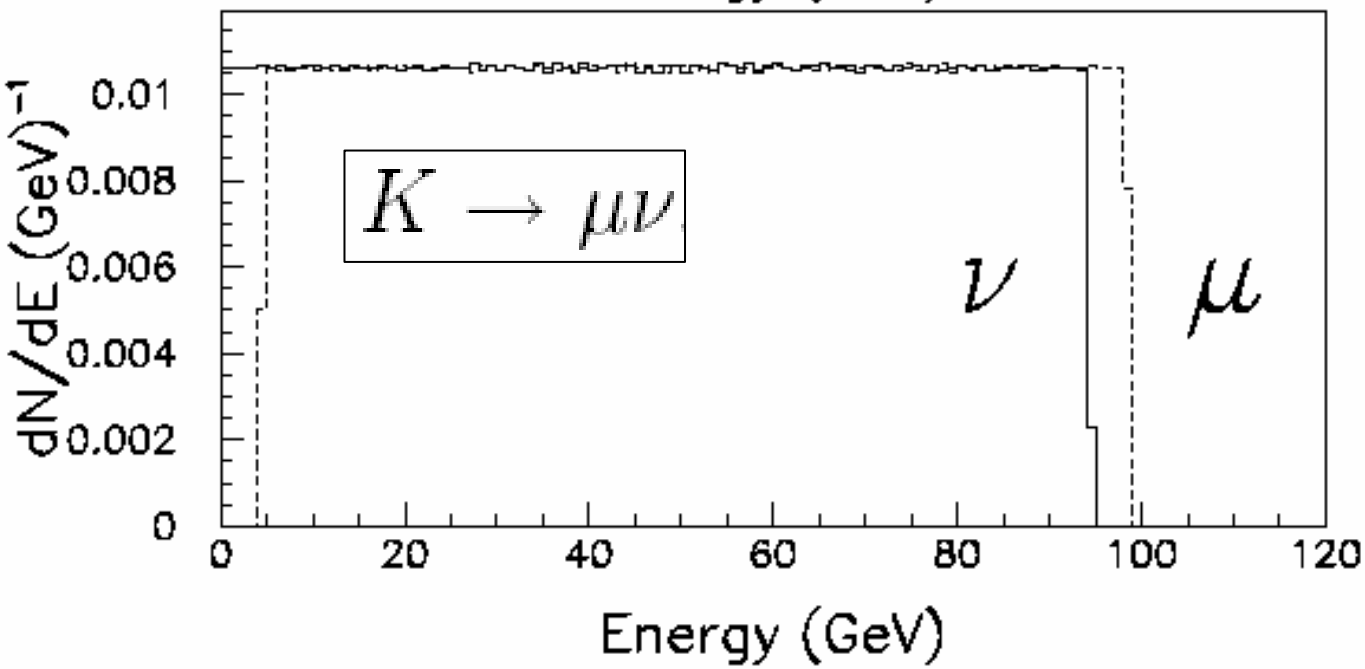
$$\pi \longrightarrow \mu\nu$$

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





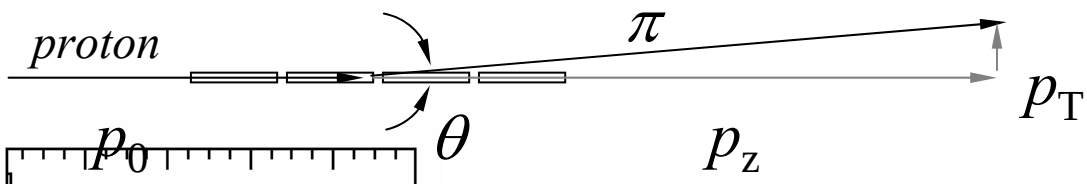


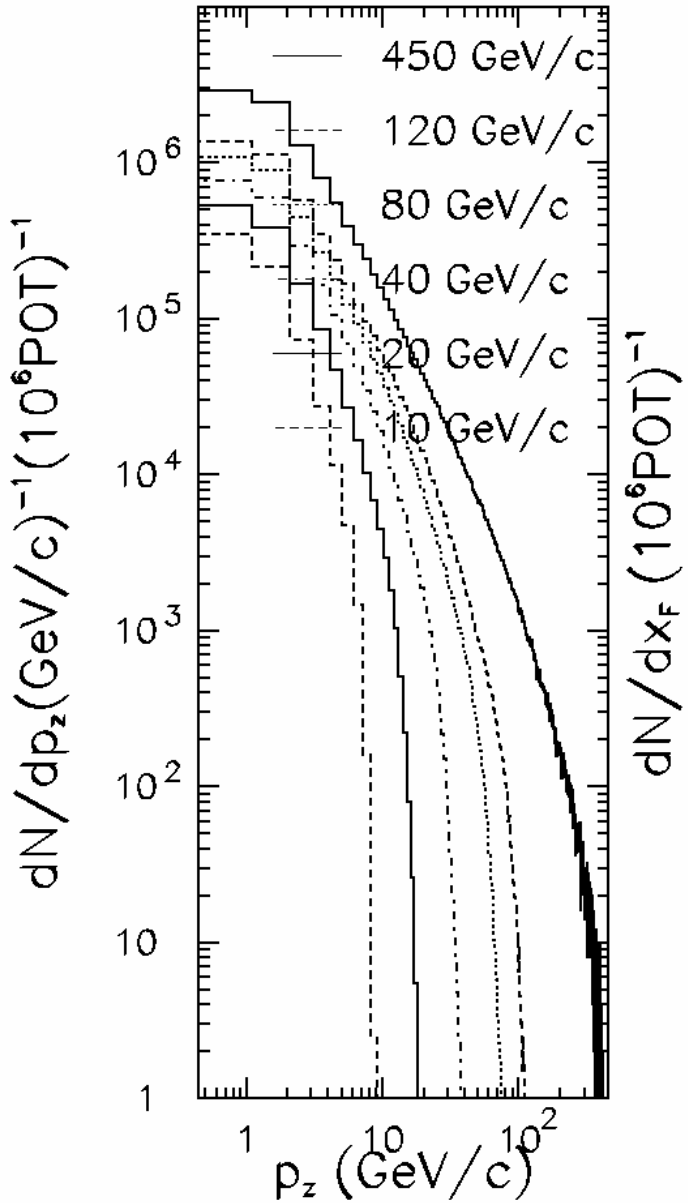


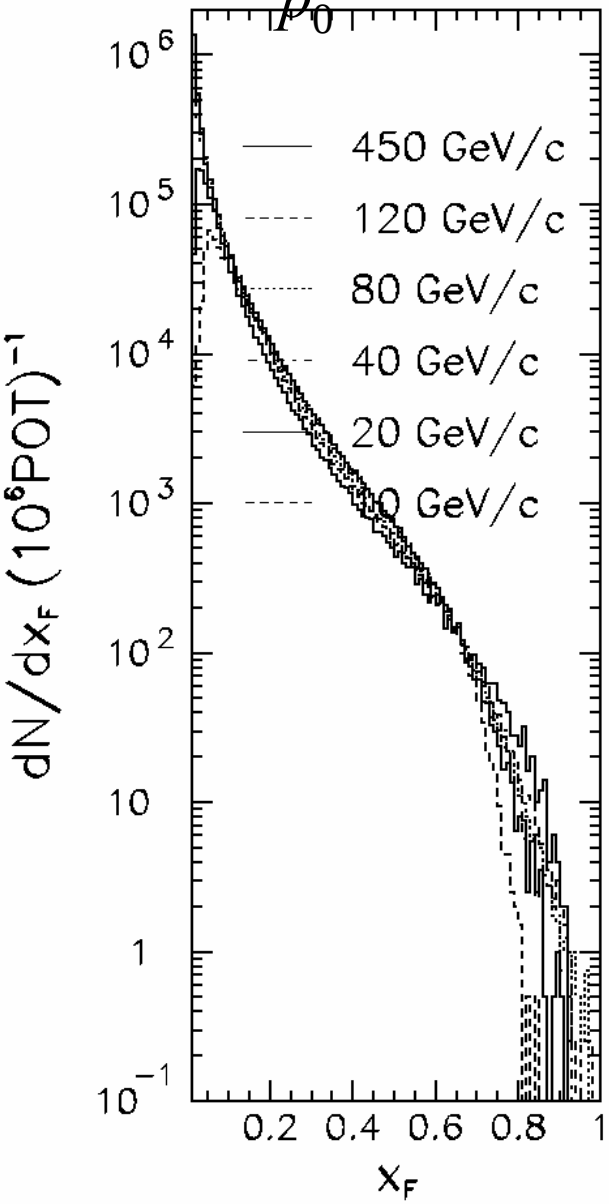
Lab Frame ($\gamma = 200$)

Production of π/K in a Target

x_F Invariance



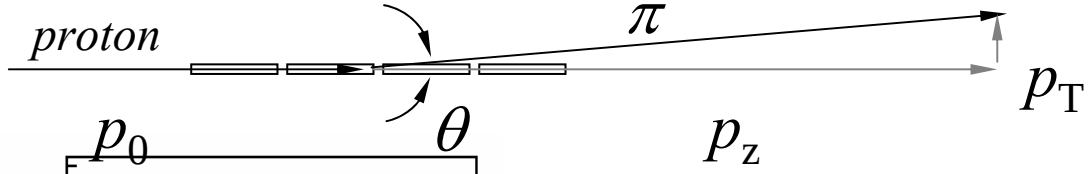


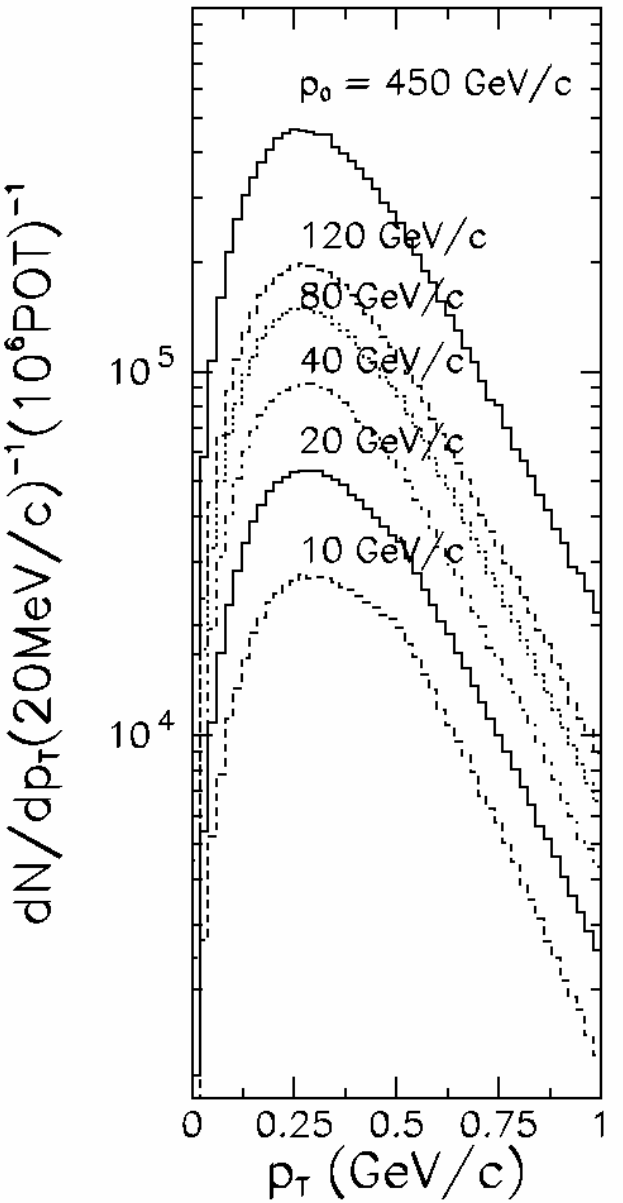


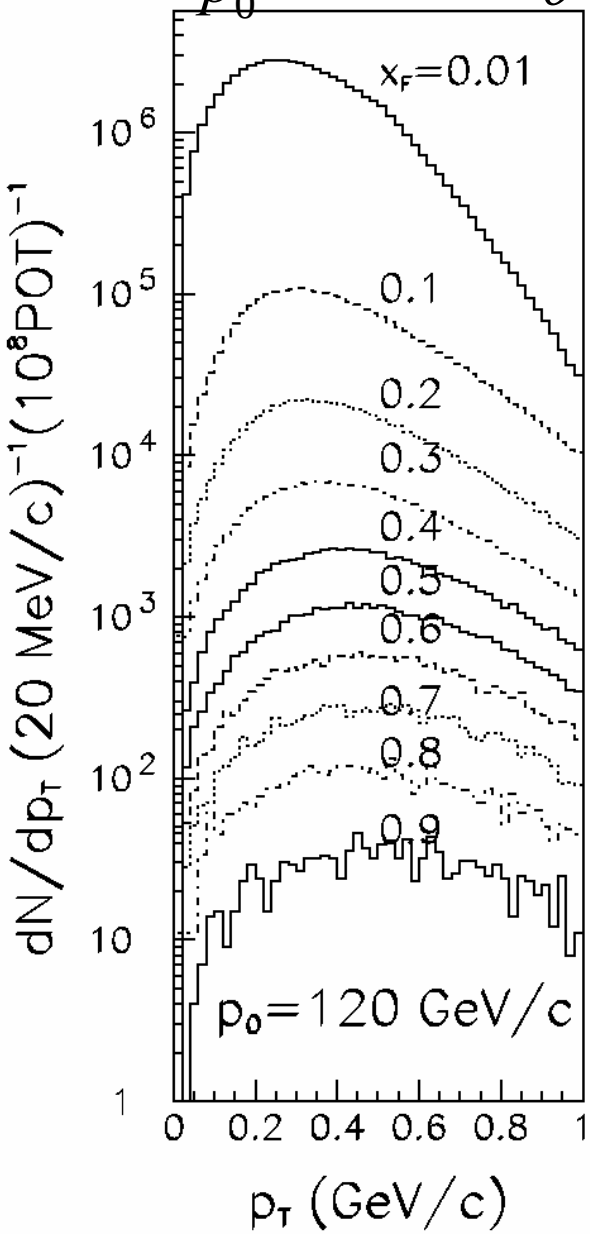
Different primary beam energies p_0

$$x_F \cong \frac{p_z}{p_0}$$

p_T Invariance



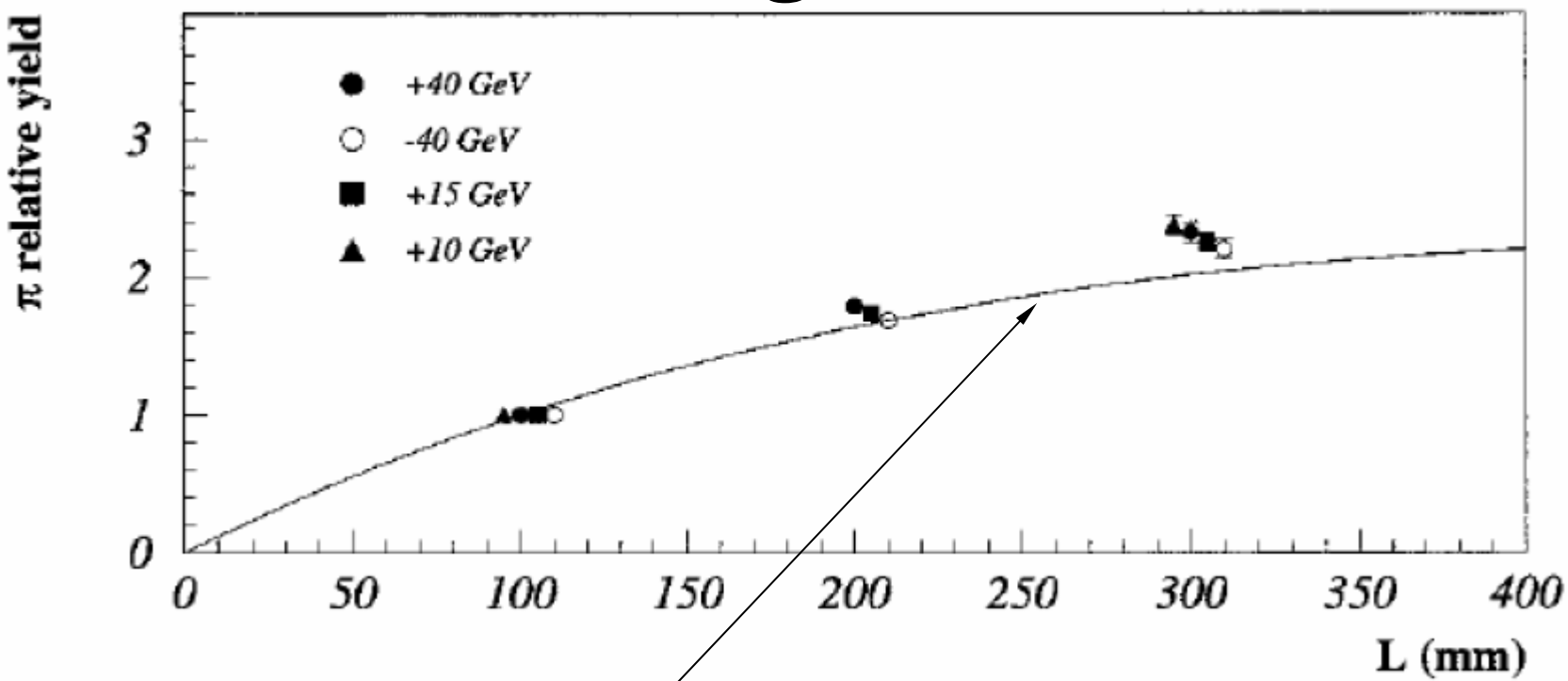




- Invariant with
  - primary beam p_0
  - Secondary particle p_z

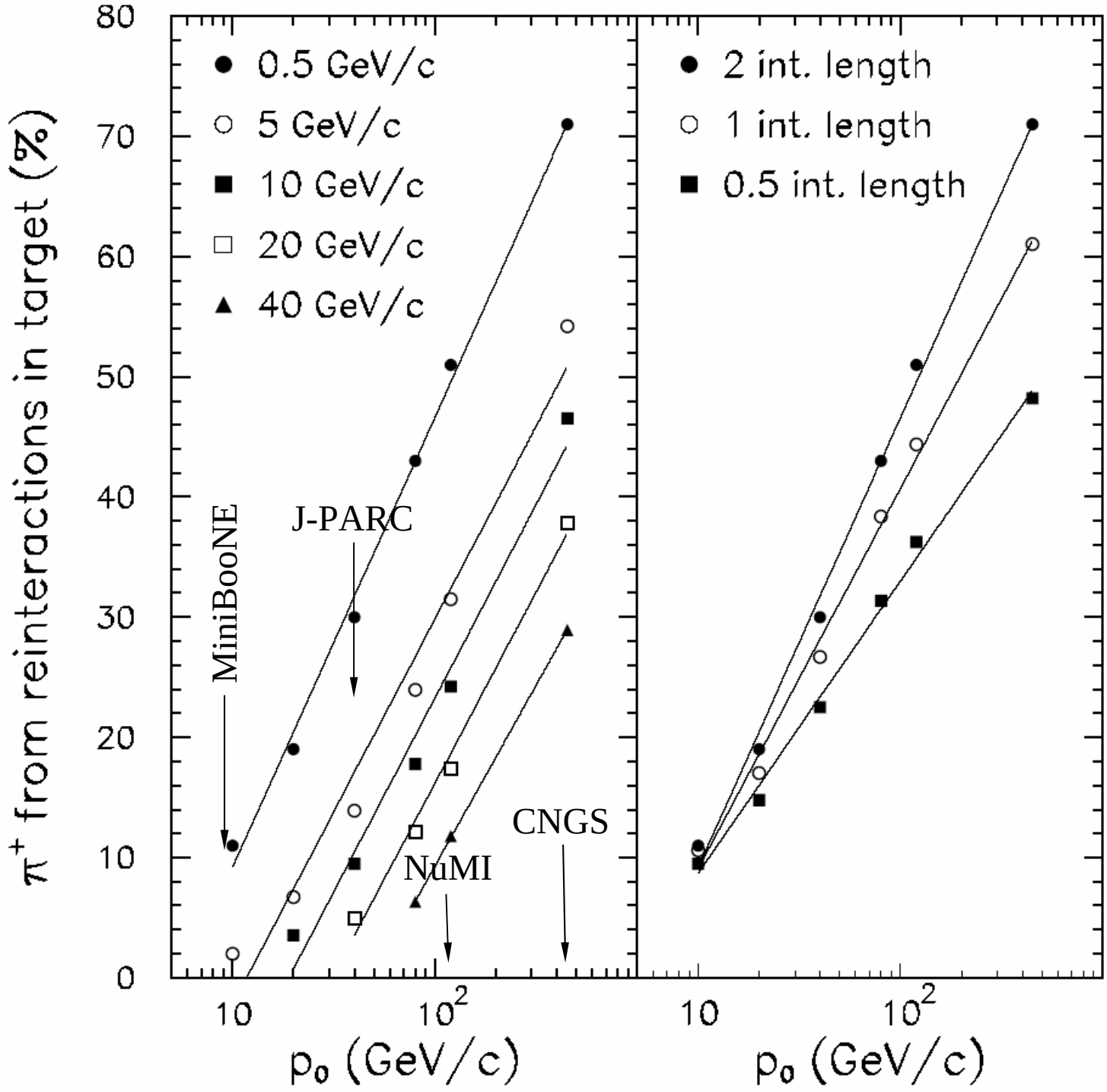
p_0 (GeV/c)	$\langle n_\pi \rangle$	$\langle p_T \rangle$ (MeV/c)	K/π
10	0.68	389	0.061
20	1.29	379	0.078
40	2.19	372	0.087
80	3.50	370	0.091
120	4.60	369	0.093
450	10.8	368	0.098

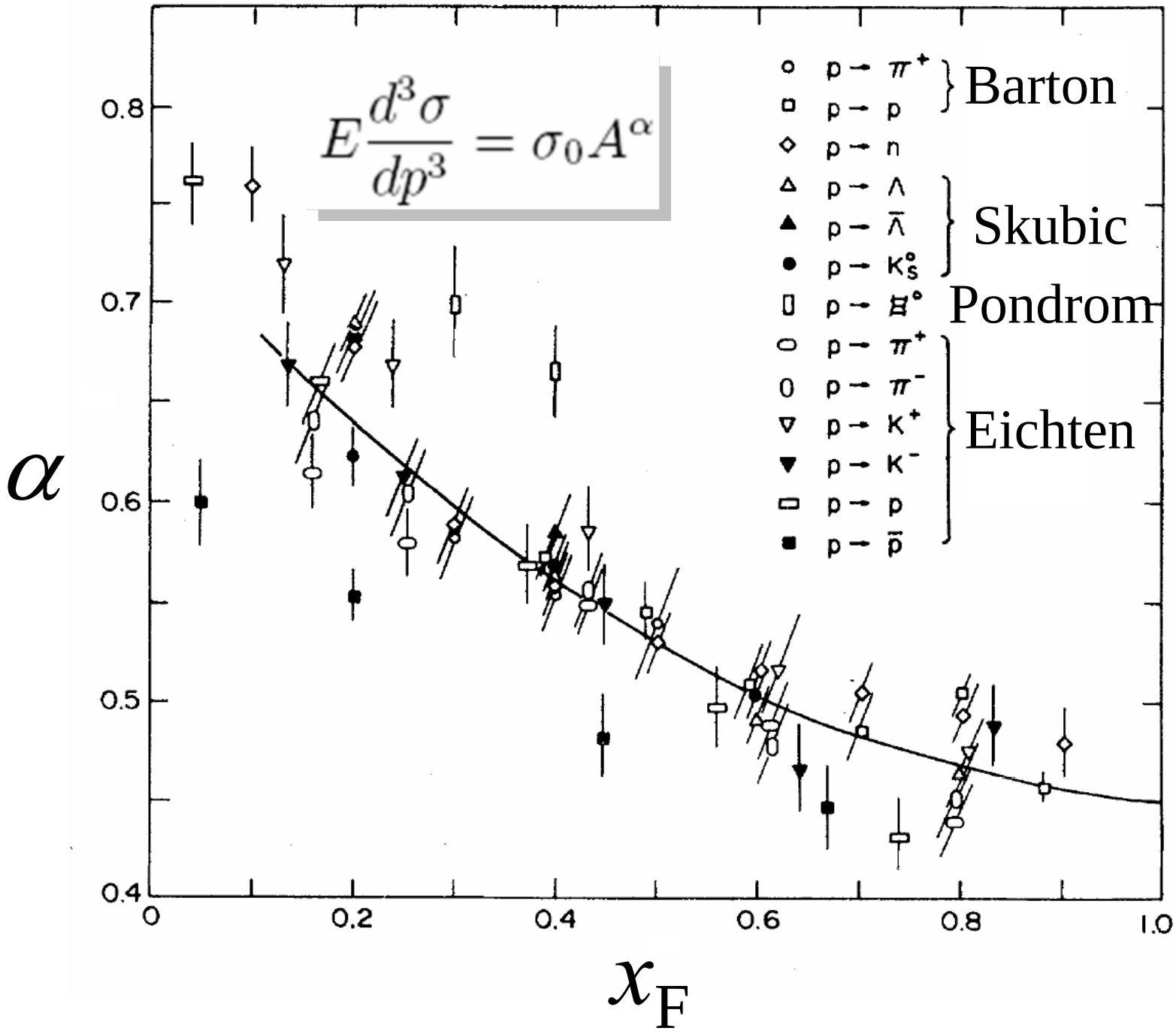
Thick Target Effects



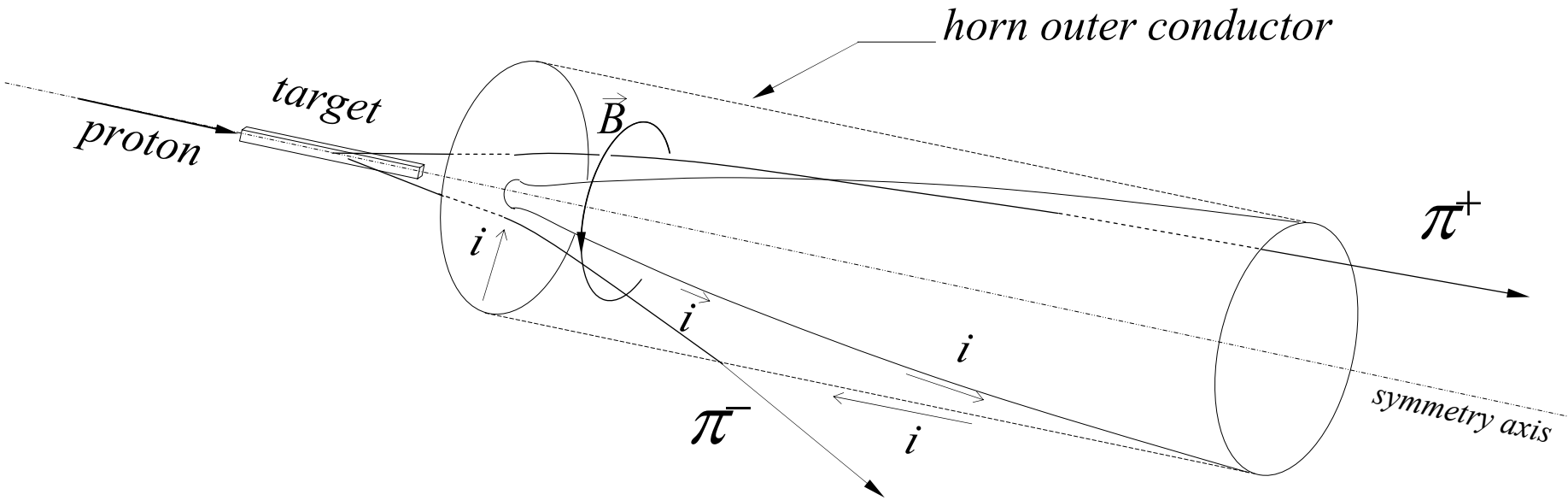
$$f(\theta, L) = \int_0^L \exp(-z/\lambda_p) \exp(-t_{res}(z)/\lambda_s) \frac{dz}{\lambda_p}$$

- p_0=450 GeV/c
- λ_{int}(Be)≅420 mm

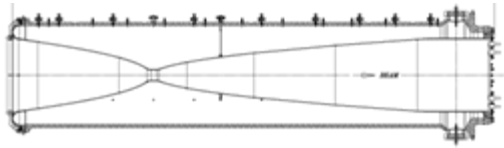

0.5 GeV/c
5 GeV/c
10 GeV/c
20 GeV/c
40 GeV/c
2 int. length
1 int. length
0.5 int. length
MiniBooNE
J-PARC
NuMI
CNGS
π^+ from reinteractions in target (%)
p_0 (GeV/c)
p_0 (GeV/c)


$E\frac{d^3\sigma}{dp^3} = \sigma_0 A^{\alpha}$
p → π+
p → p
p → n
p → Λ
p → Λ̄
p → K°S
p → Ξ°
p → π+
p → π−
p → K+
p → K−
p → p
p → p̄
Barton
Skubic
Pondrom
Eichten
α
0.8
0.7
0.6
0.5
0.4
0
0.2
0.4
0.6
0.8
1.0
x_F

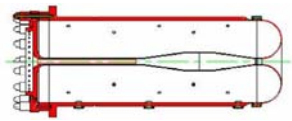
Focusing of WBB


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

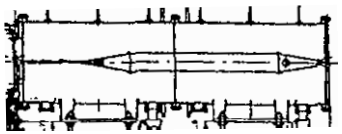
NuMI Horn 1



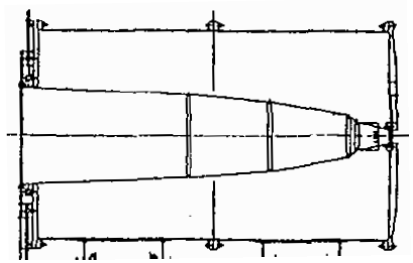
NuMI Horn 2



MiniBooNE

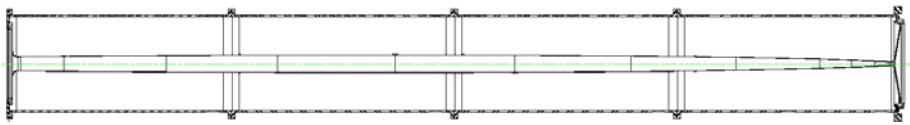


KEK Horn 1

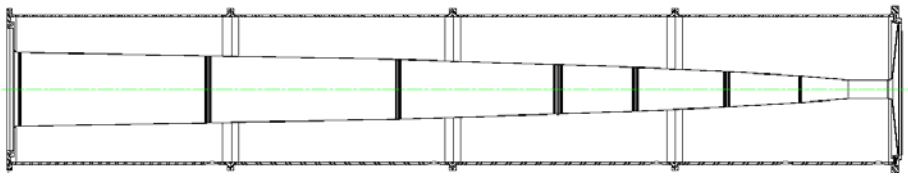


KEK Horn 2

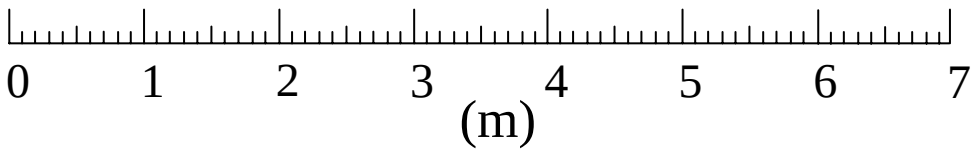
beam direction ⇒

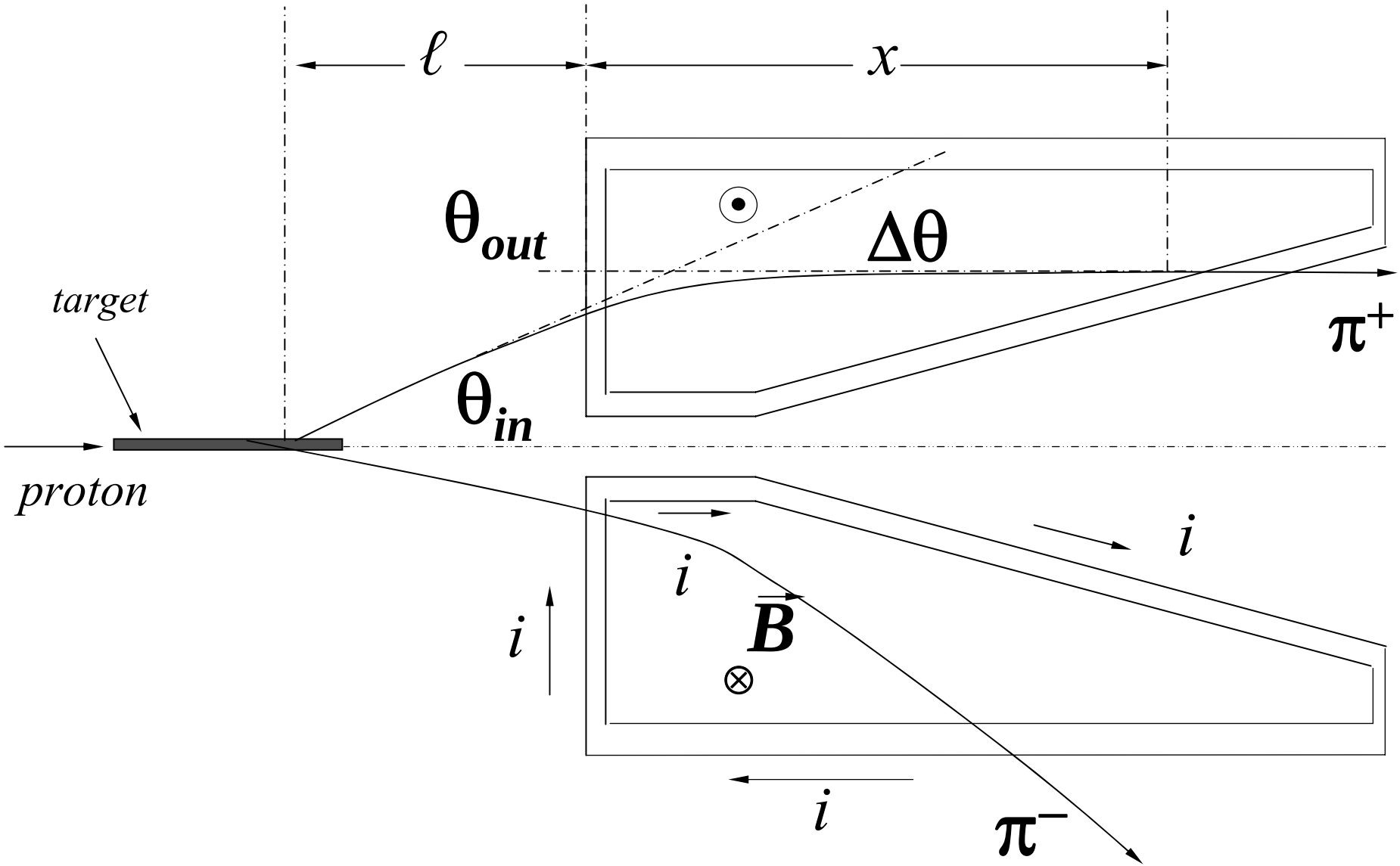


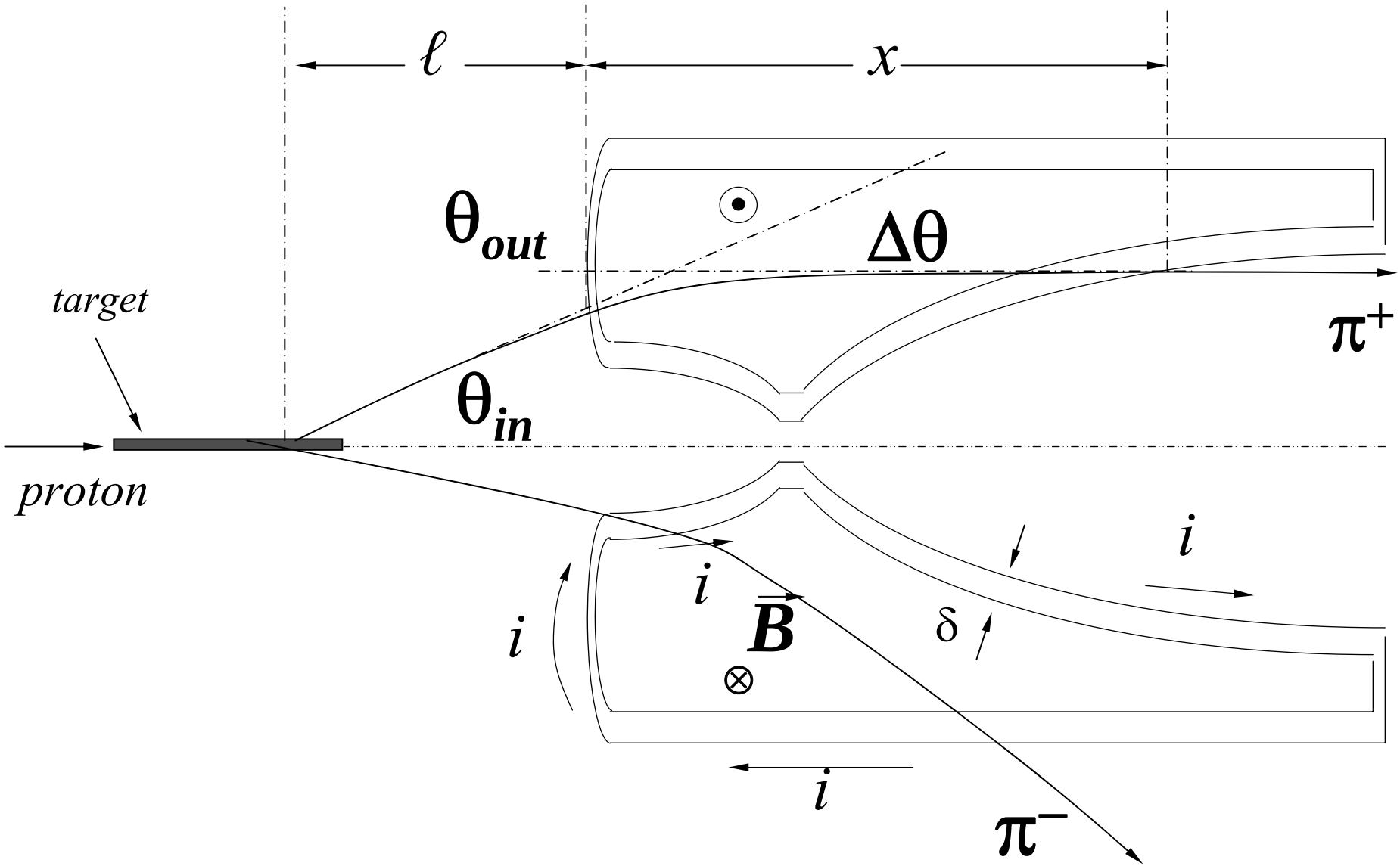
CNGS Horn 1

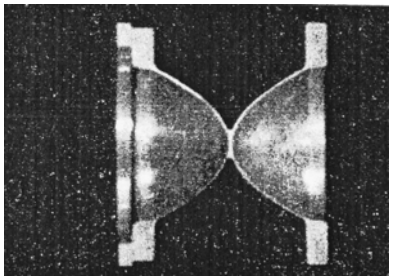


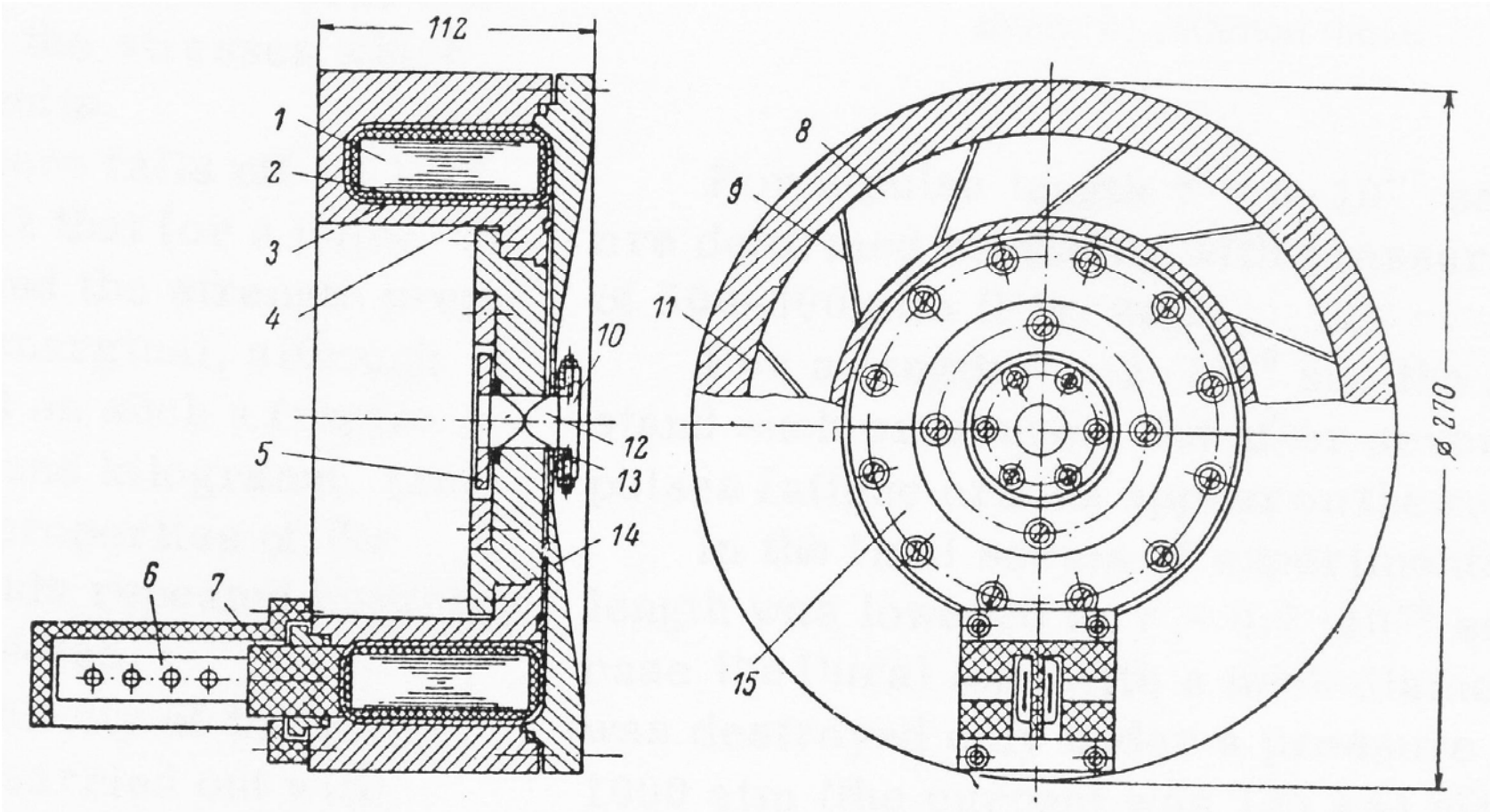
CNGS Horn 2

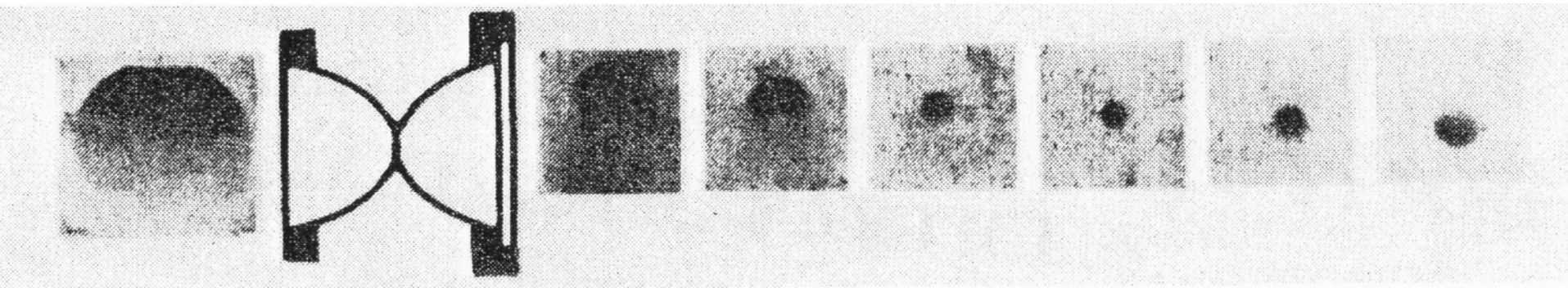


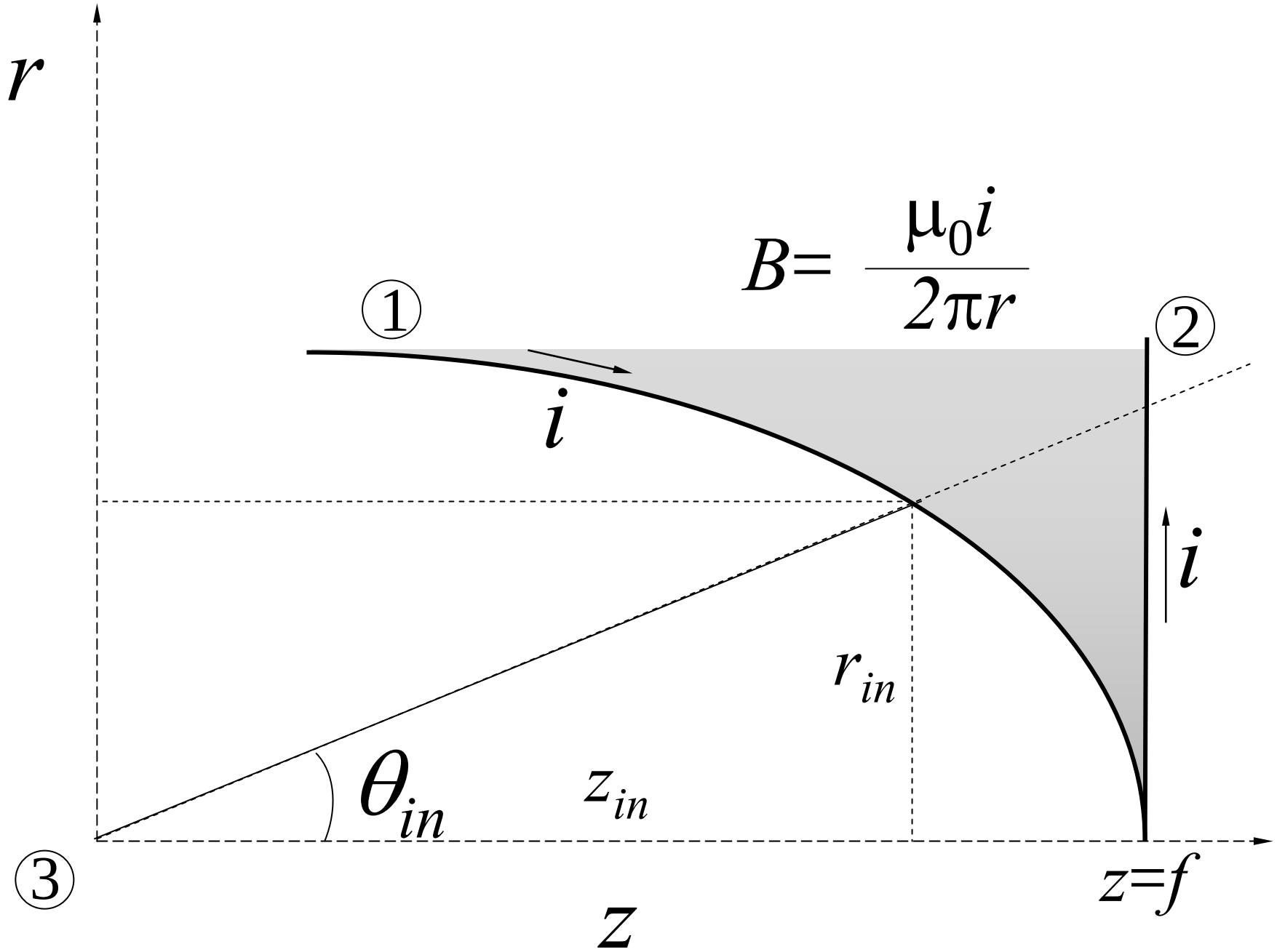

ℓ
x
θout
Δθ
target
π+
θin
proton
i
i
i
B
i
π−

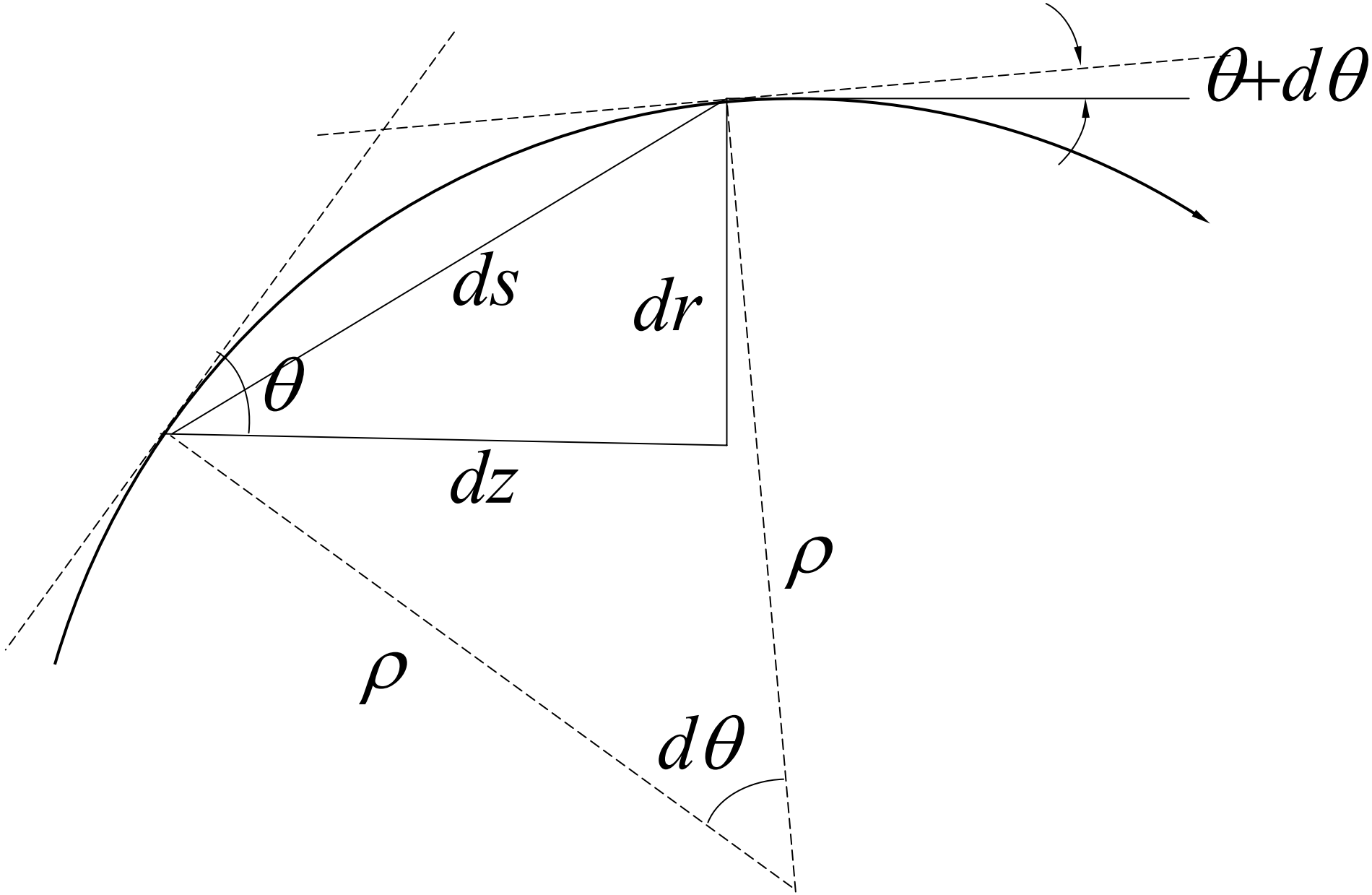

ℓ
x
θout
Δθ
target
π+
θin
proton
i
i
B
δ
i
i
π−

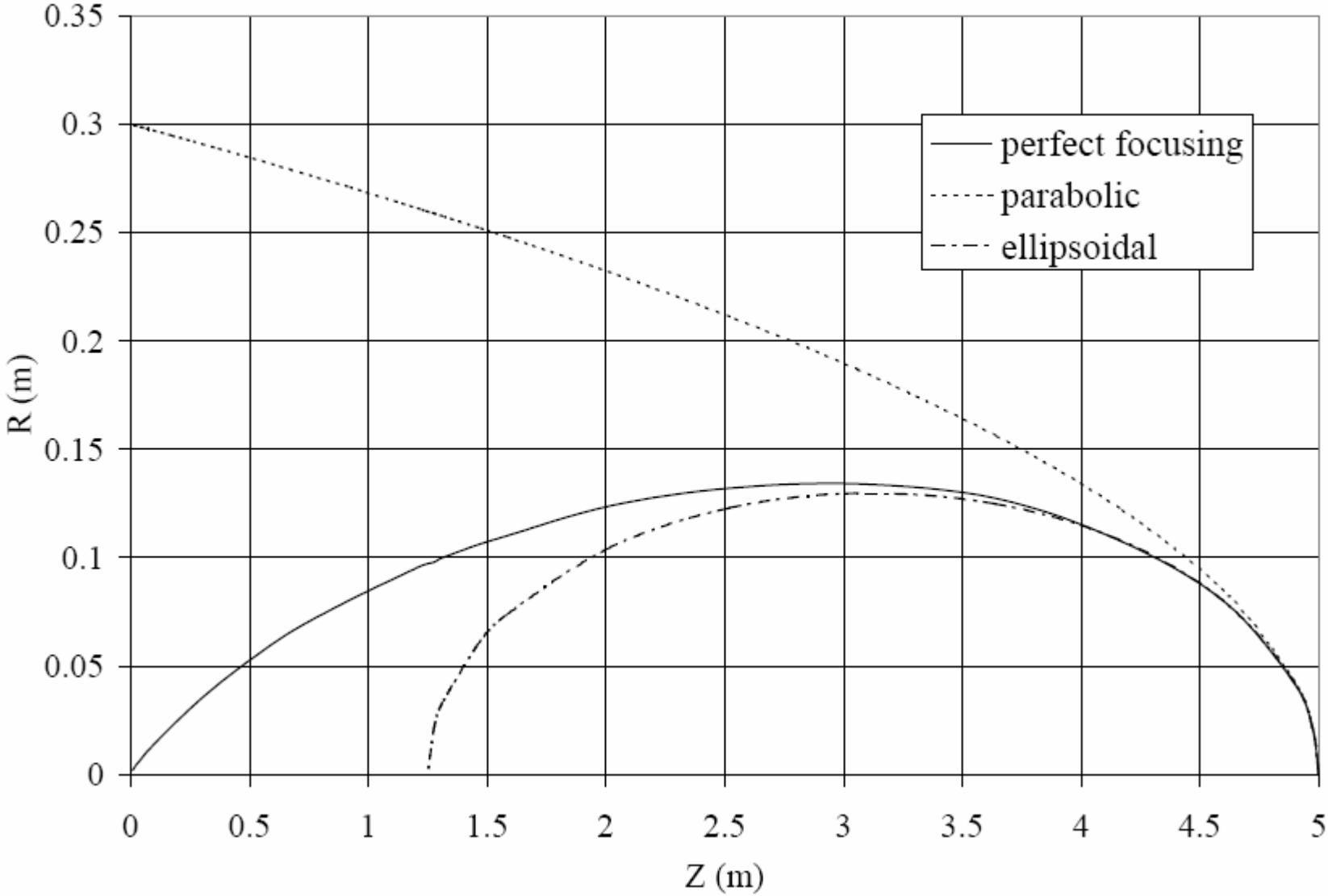



112
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
ø 270

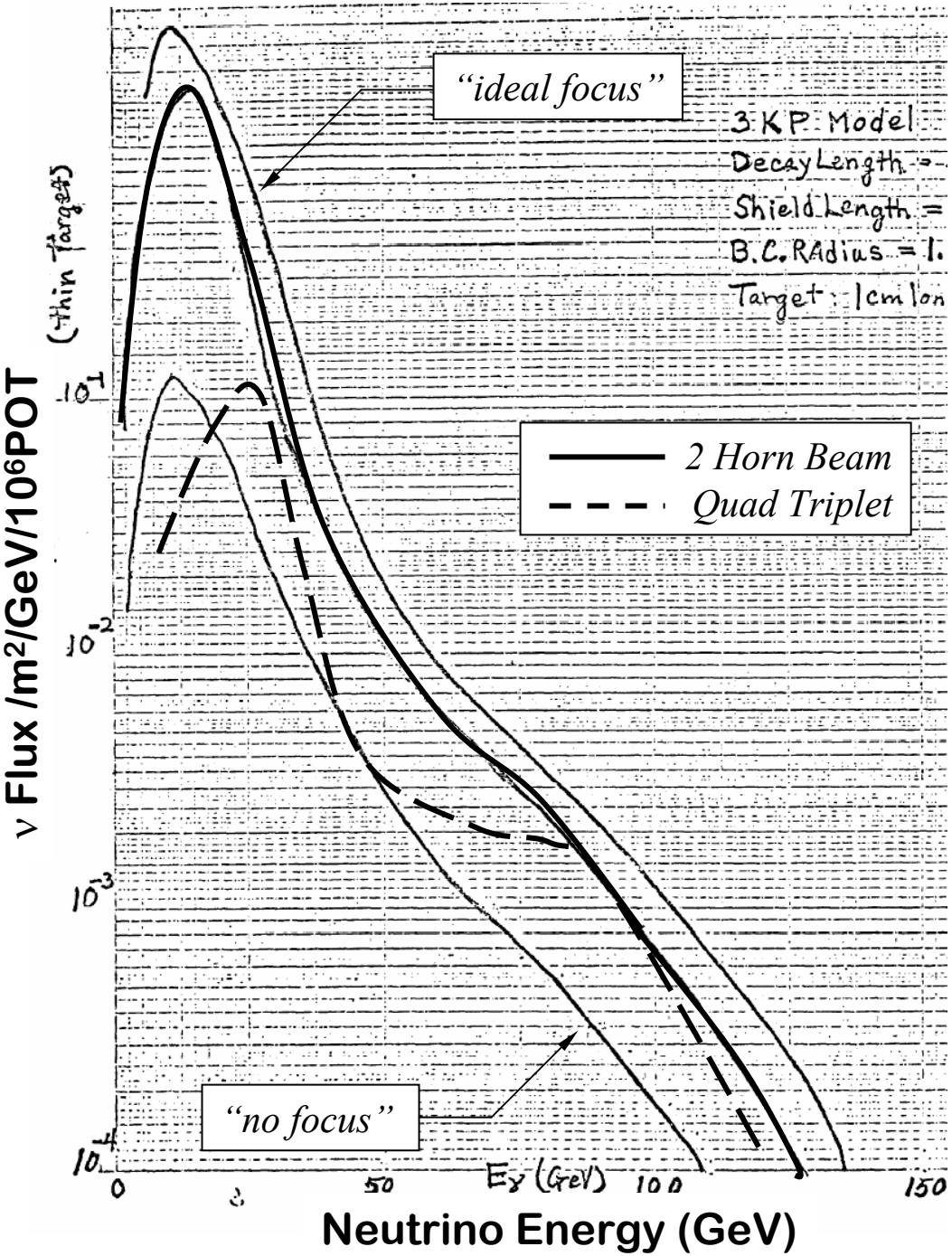


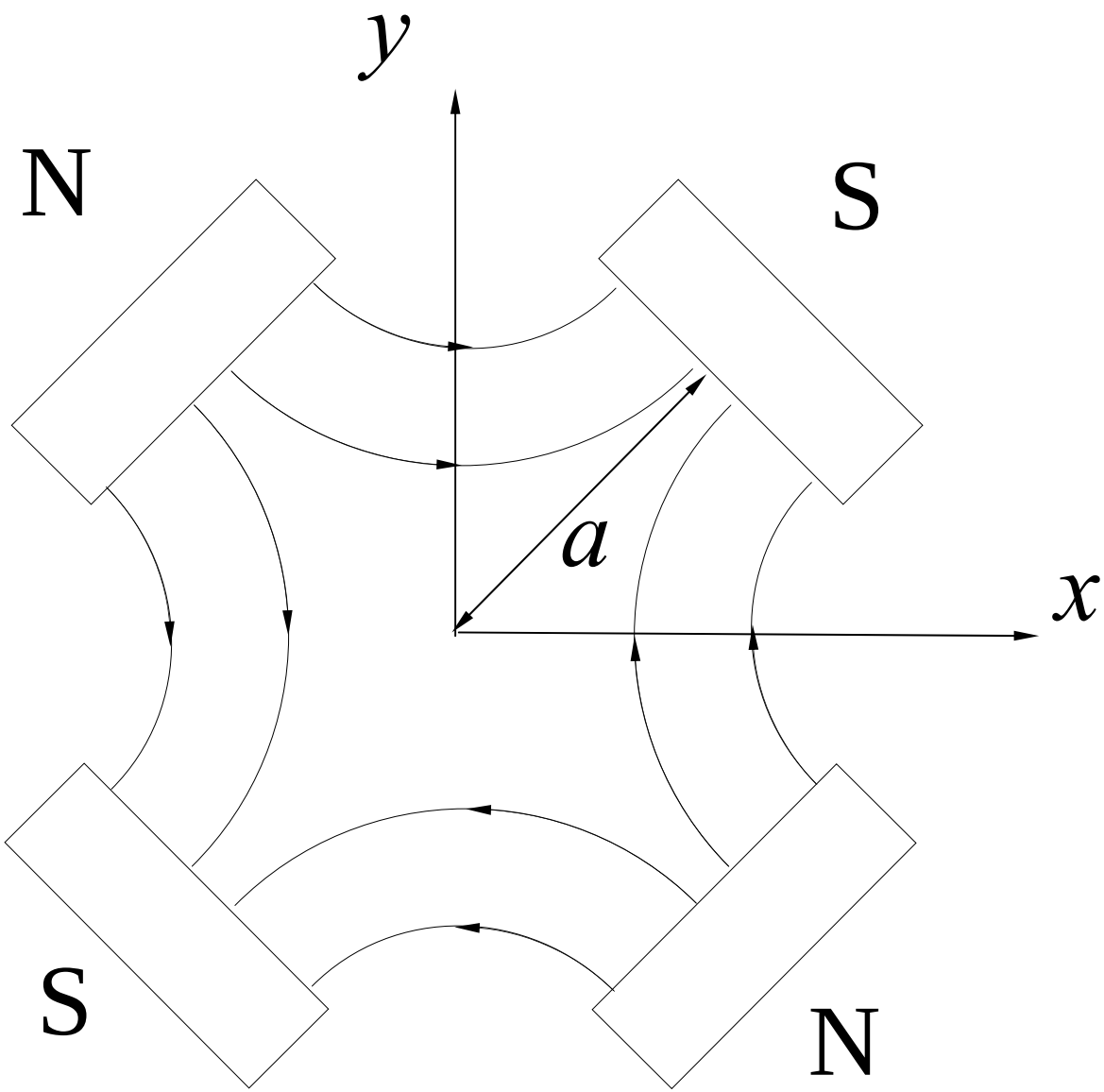

r
B= μ0i / 2πr
①
②
i
i
r_in
θ_in
z_in
③
z
z=f

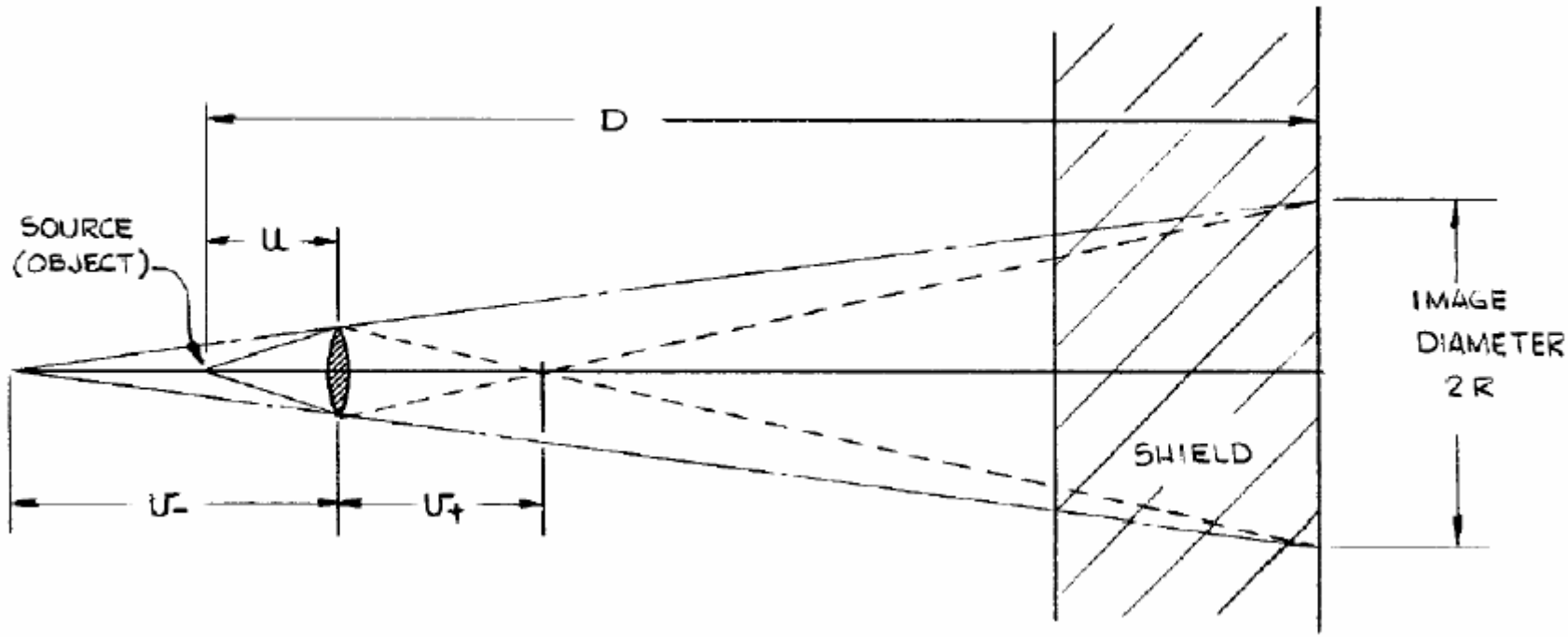

θ+dθ
ds
dr
θ
dz
ρ
ρ
dθ


0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
R (m)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Z (m)
perfect focusing
parabolic
ellipsoidal

Quadrupole-Based Focusing

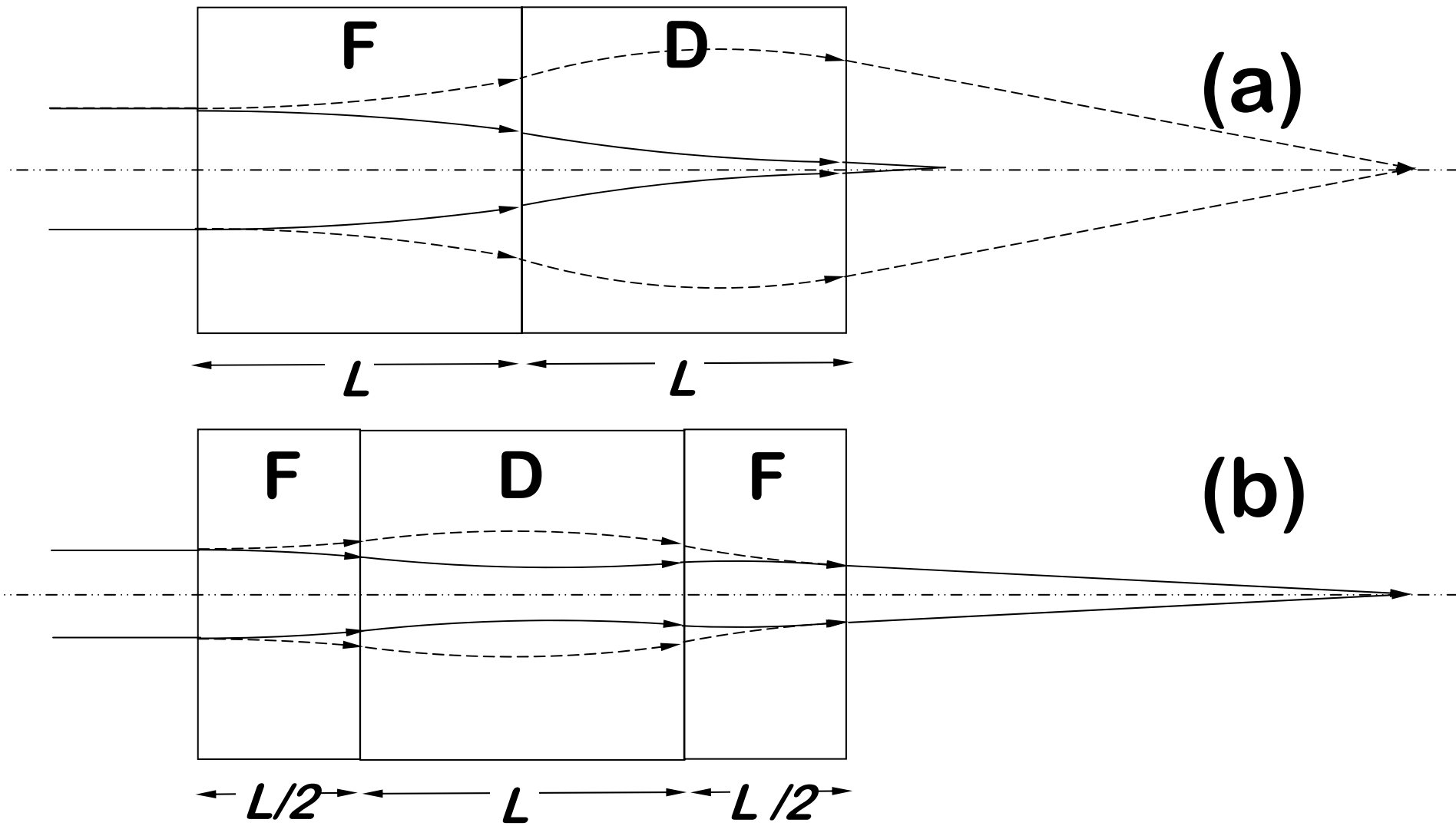



y
N
S
a
x
S
N

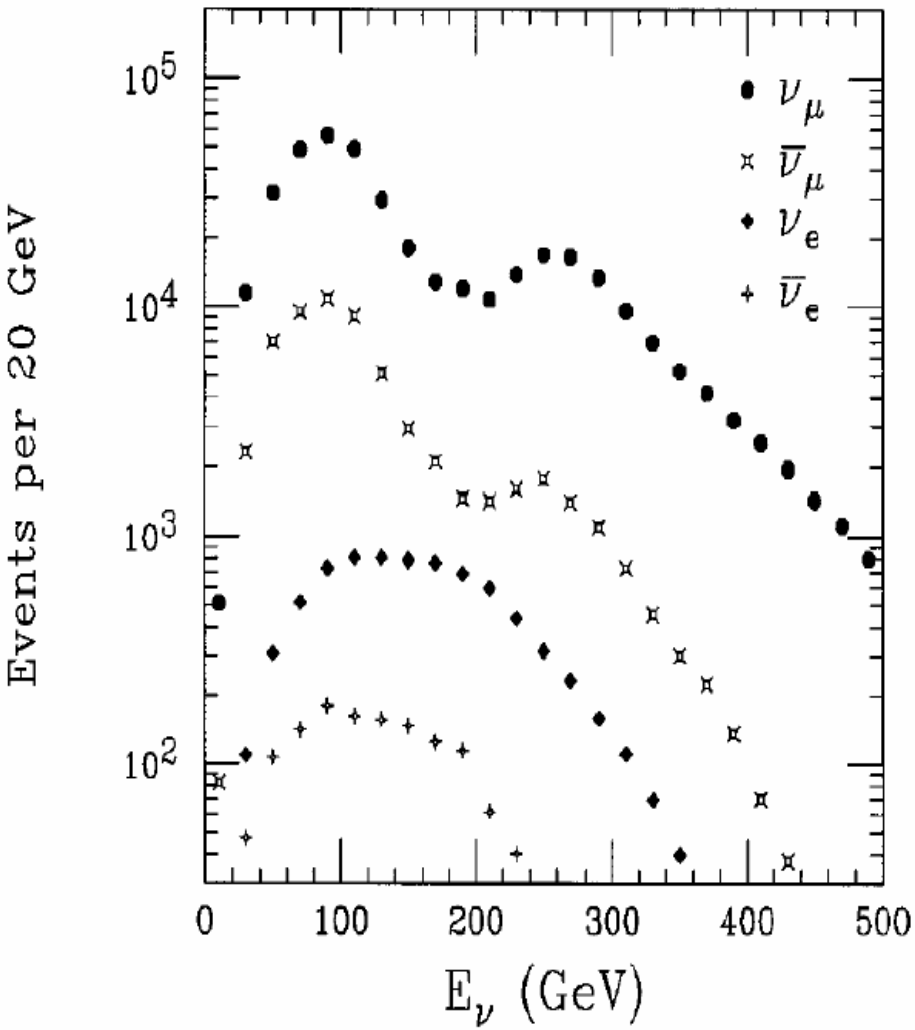


$\langle p \rangle$=225 GeV/c

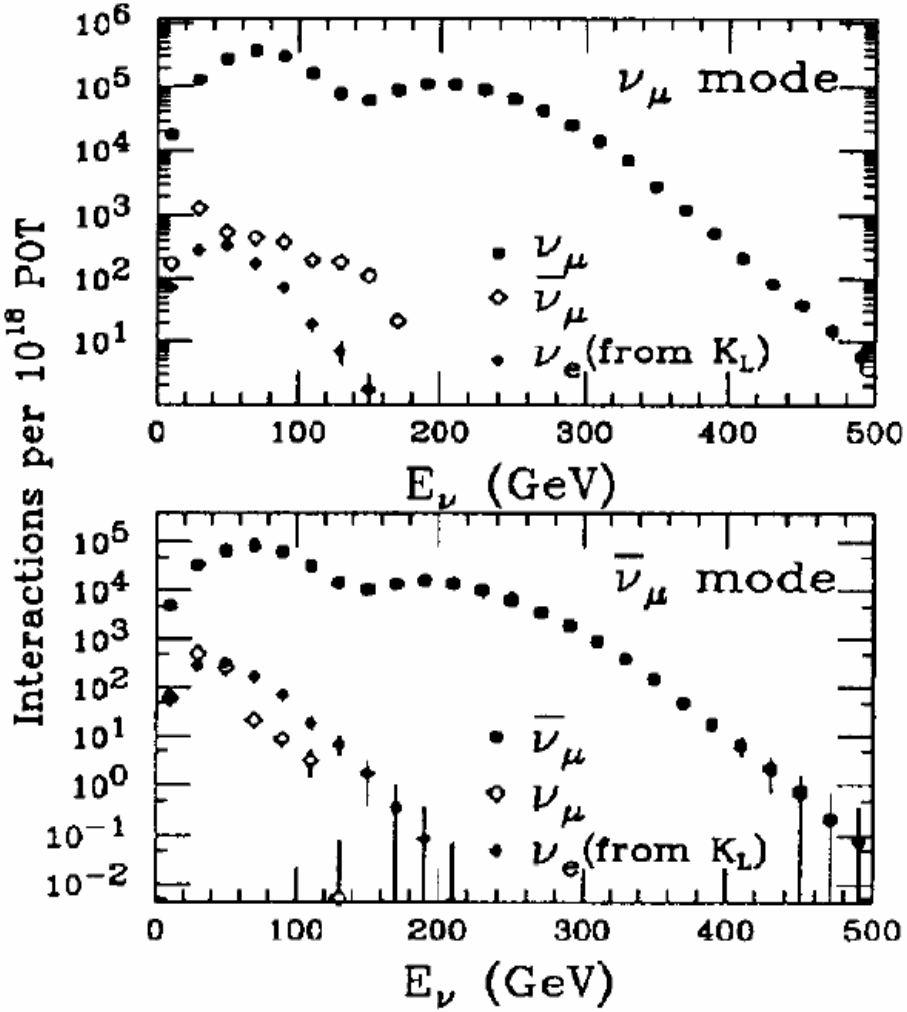
$\theta_{\rm in}$ (mrad)	p_+ (GeV/c)	p_- (GeV/c)
2	183	318
3	195	276
4	201	260
5	205	252
6	208	246
10	215	237

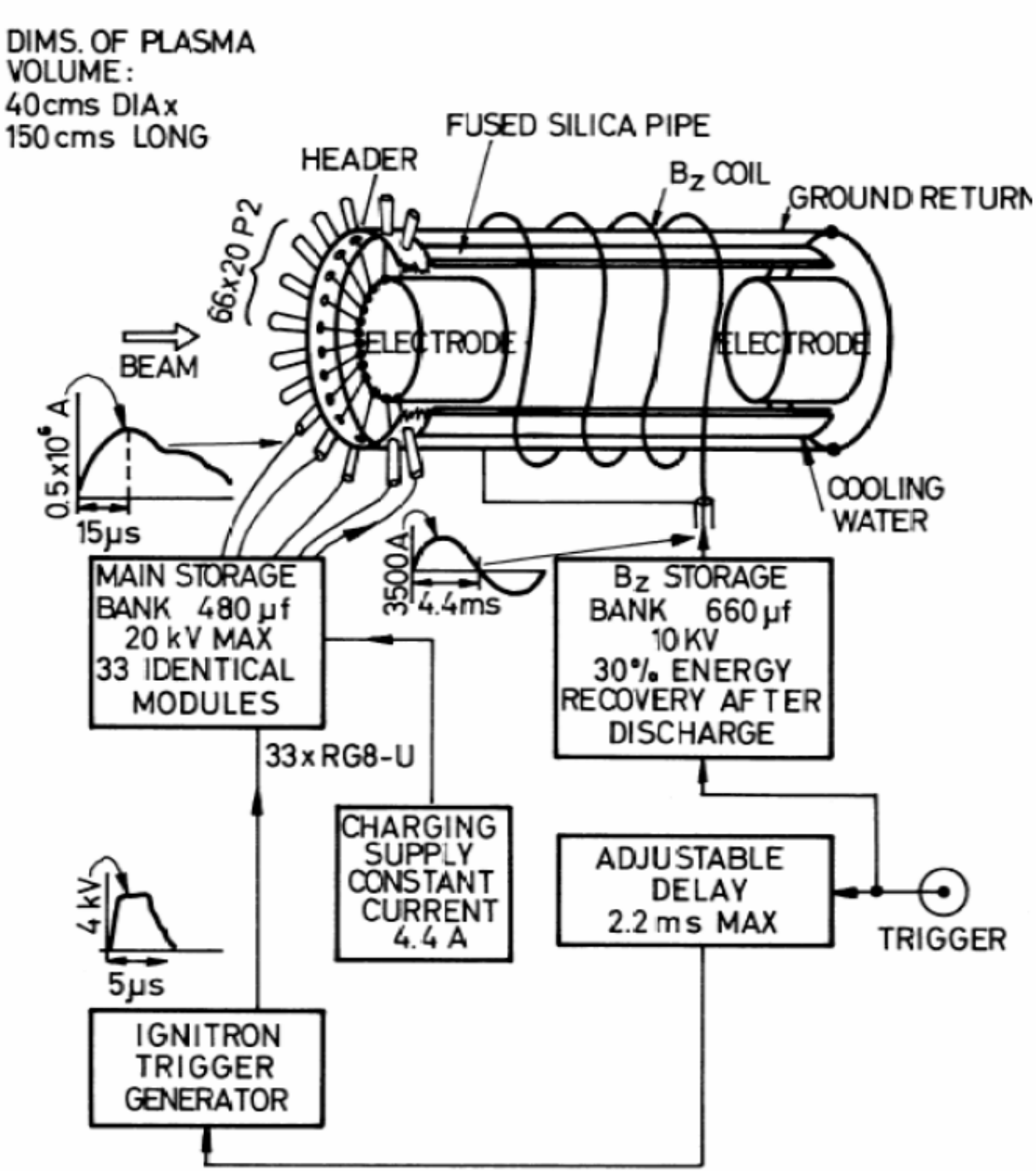

F
D
(a)
L
L
F
D
F
(b)
L/2
L
L /2

Quad Triplet Beam

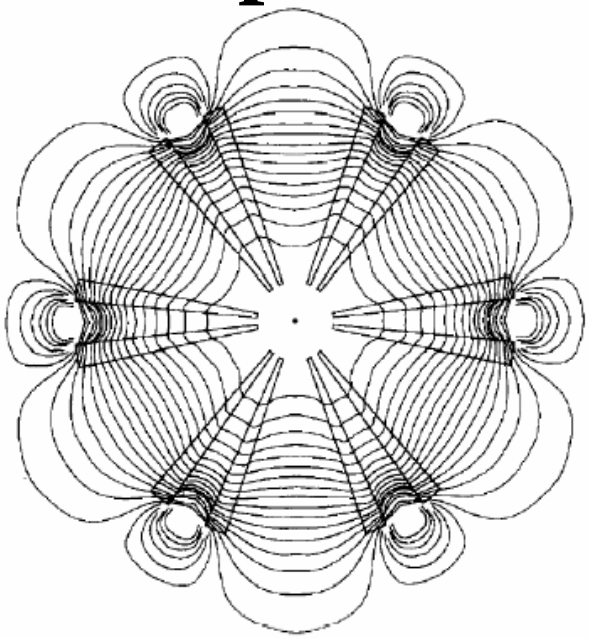


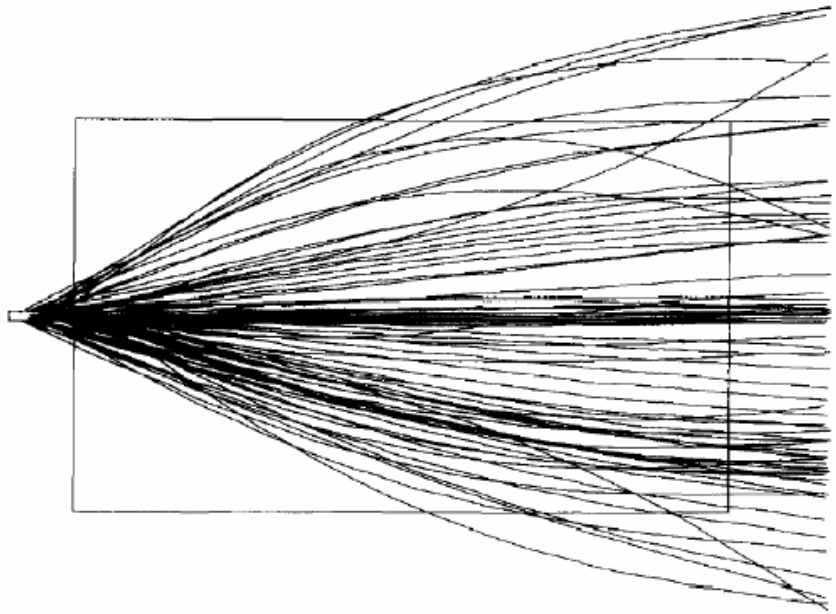
Sign-Selected Quad Triplet Beam



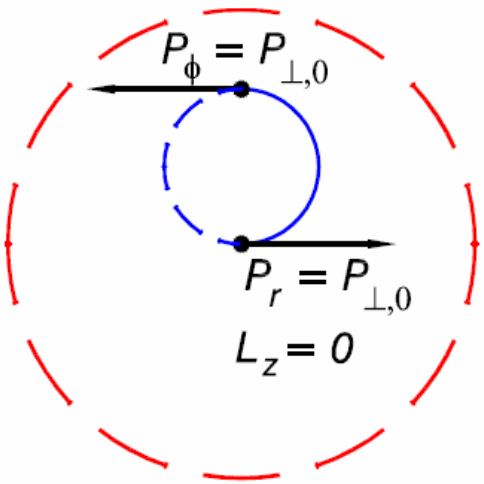

DIMS. OF PLASMA VOLUME:
40cms DIA x
150cms LONG
FUSED SILICA PIPE
HEADER
B_z COIL
GROUND RETURN
66x20 P_2
BEAM
ELECTRODE
ELECTRODE
0.5×10^6 A
15μs
COOLING WATER
3500A
4.4ms
MAIN STORAGE BANK 480 μf 20 kV MAX 33 IDENTICAL MODULES
B_z STORAGE BANK 660 μf 10 KV 30% ENERGY RECOVERY AFTER DISCHARGE
33 x RG8-U
CHARGING SUPPLY CONSTANT CURRENT 4.4 A
ADJUSTABLE DELAY 2.2 ms MAX
TRIGGER
4 kV
5μs
IGNITRON TRIGGER GENERATOR

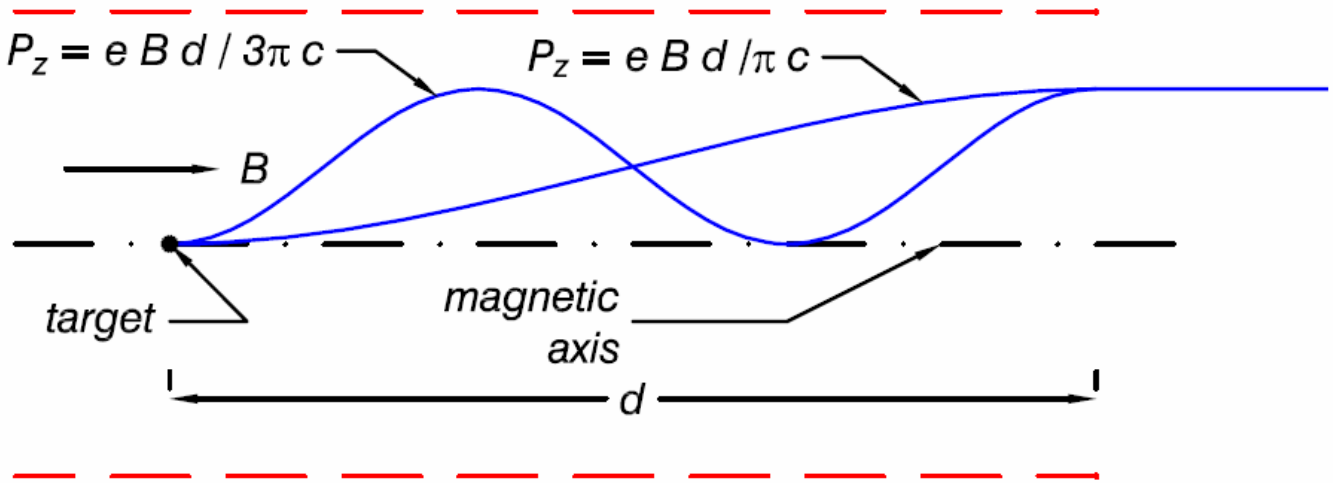
Magnetic Spokes:



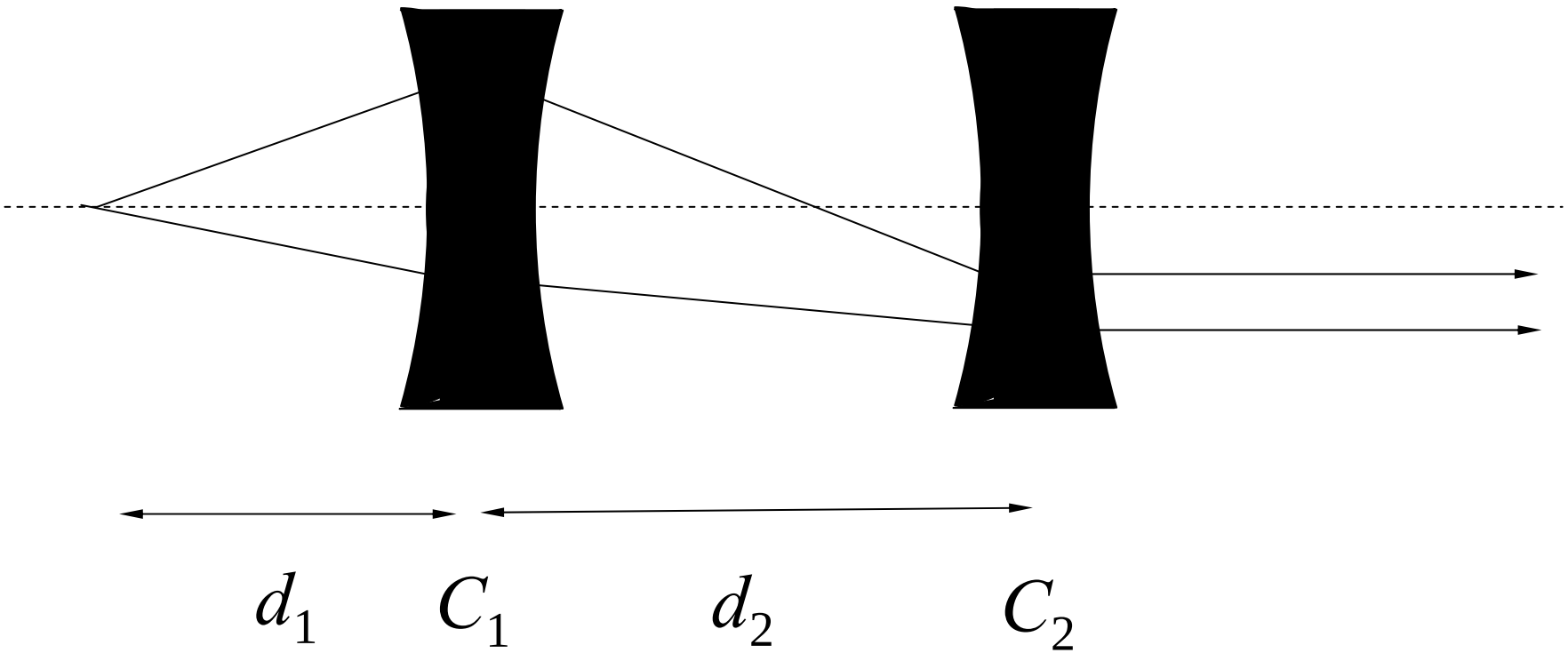


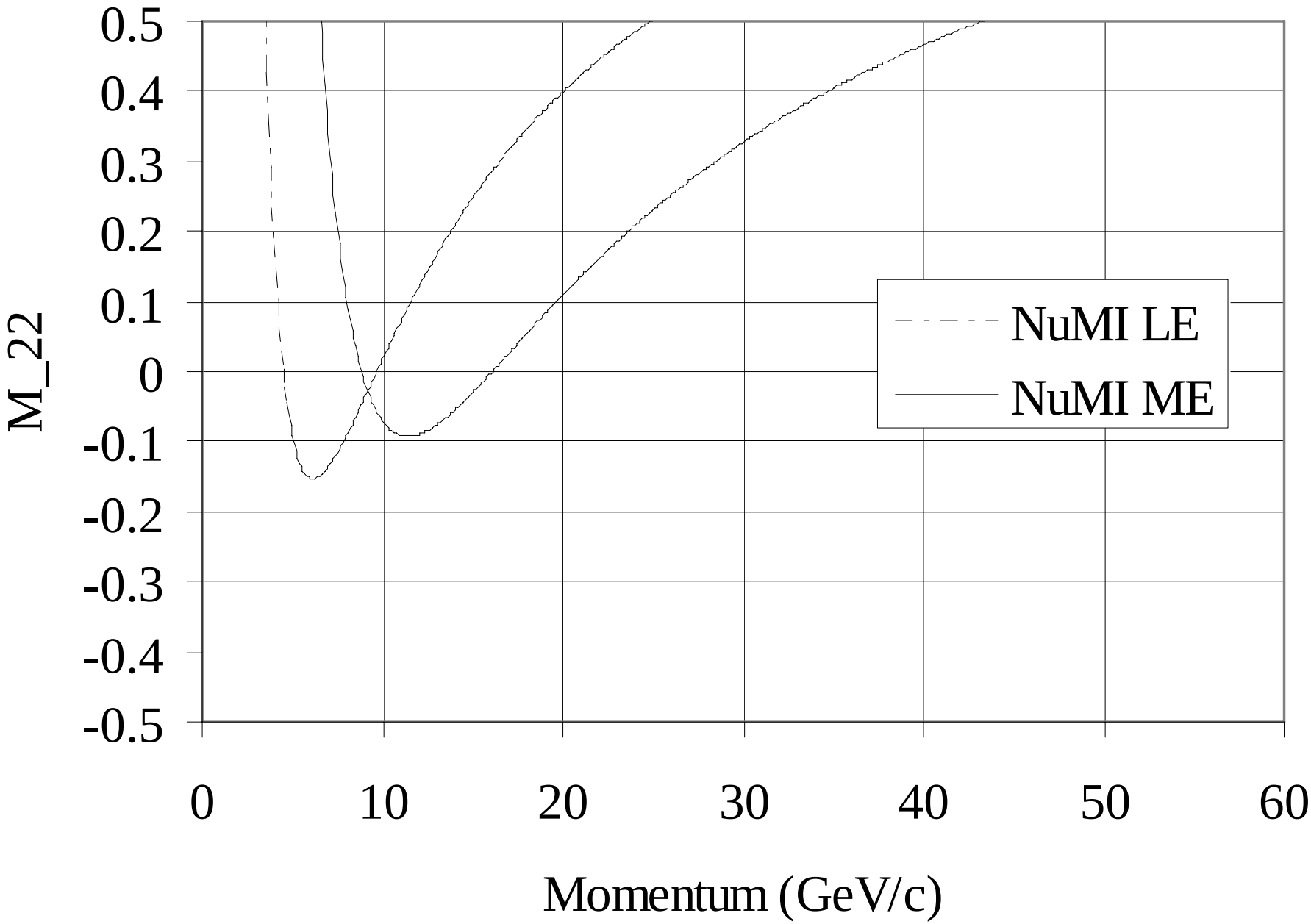
Solenoid:

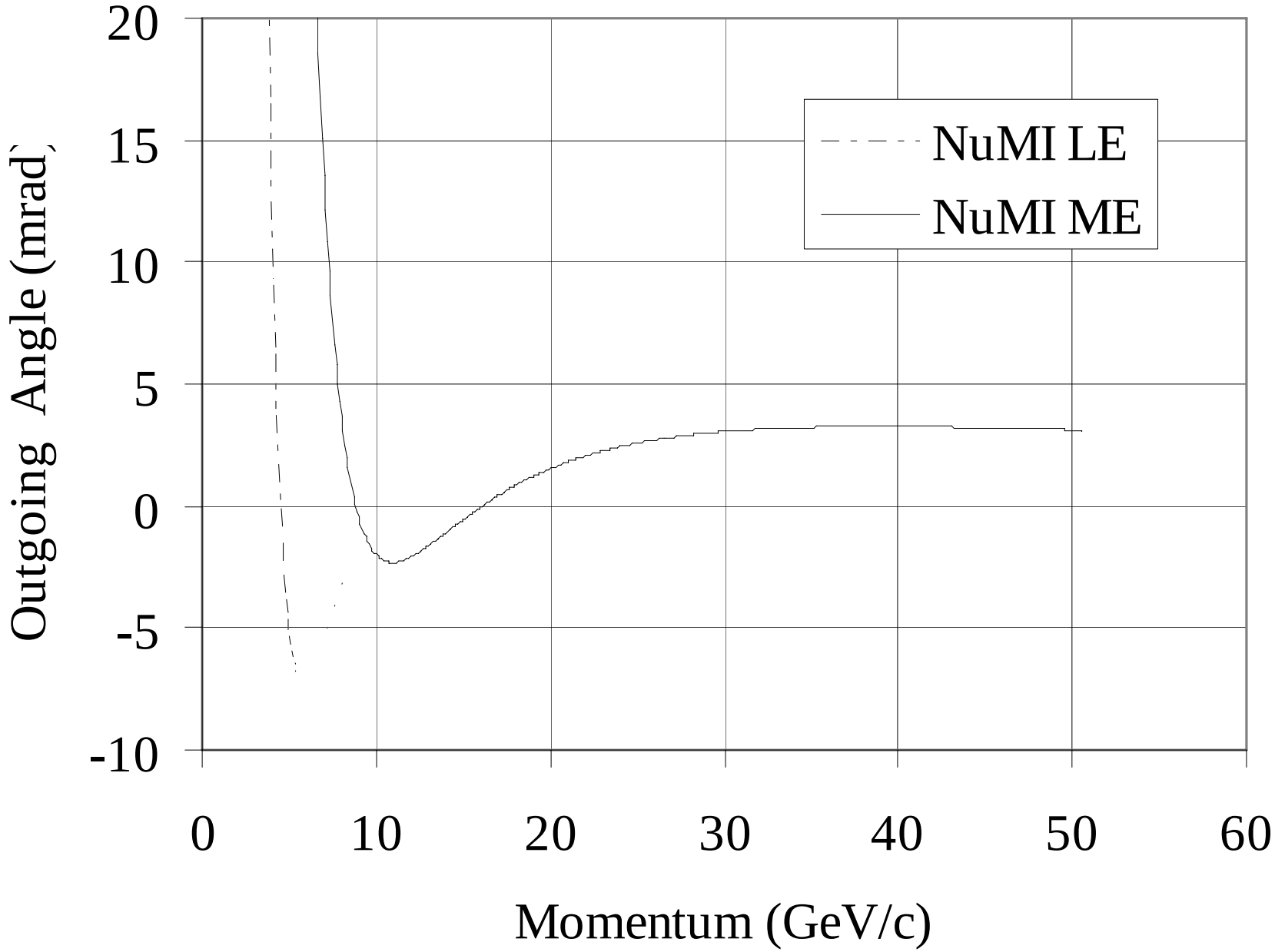


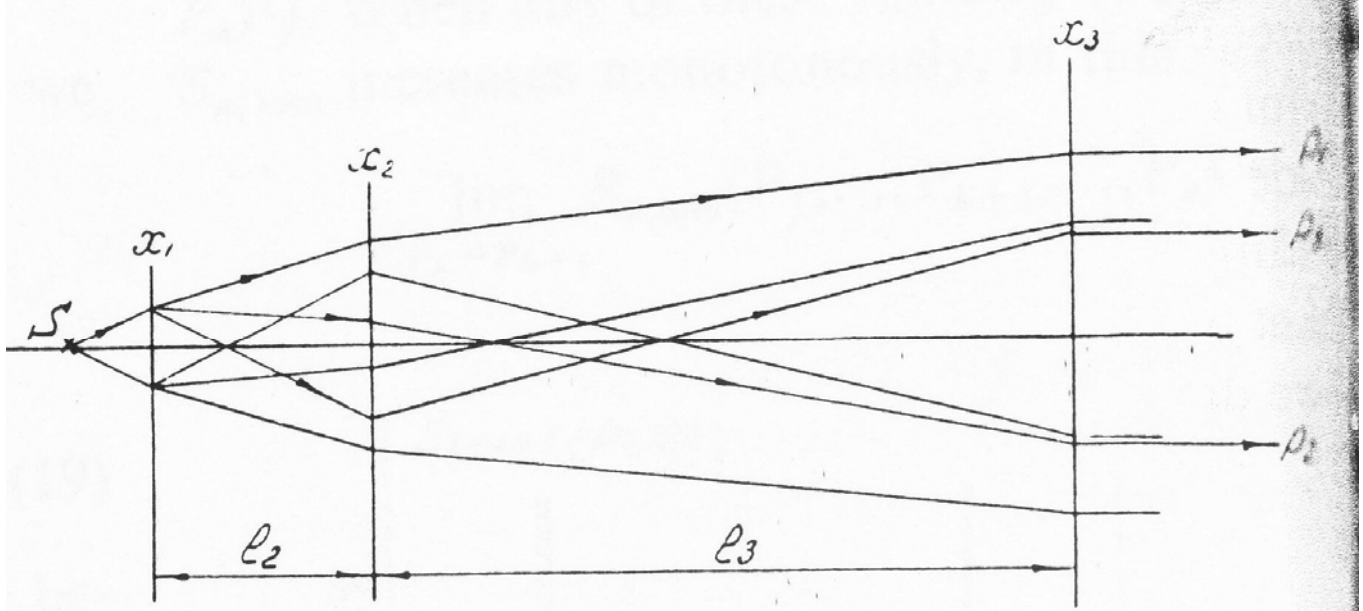


Multi-lens Systems

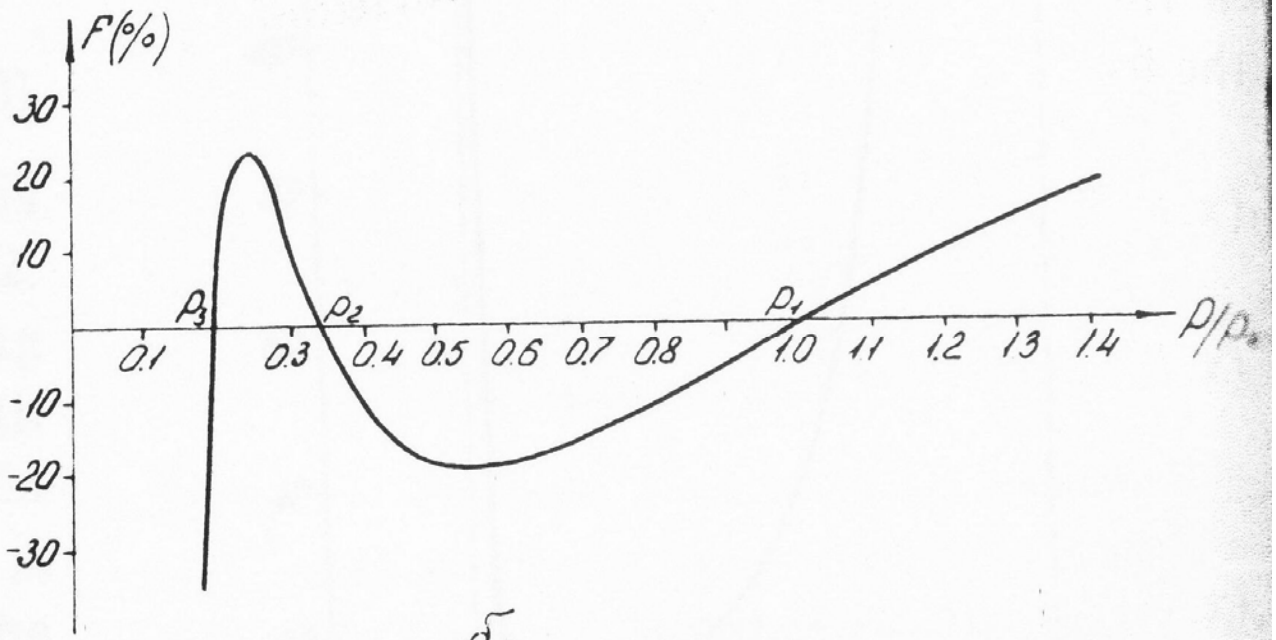

d_1
C_1
d_2
C_2


0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
M_22
0
10
20
30
40
50
60
Momentum (GeV/c)
NuMI LE
NuMI ME

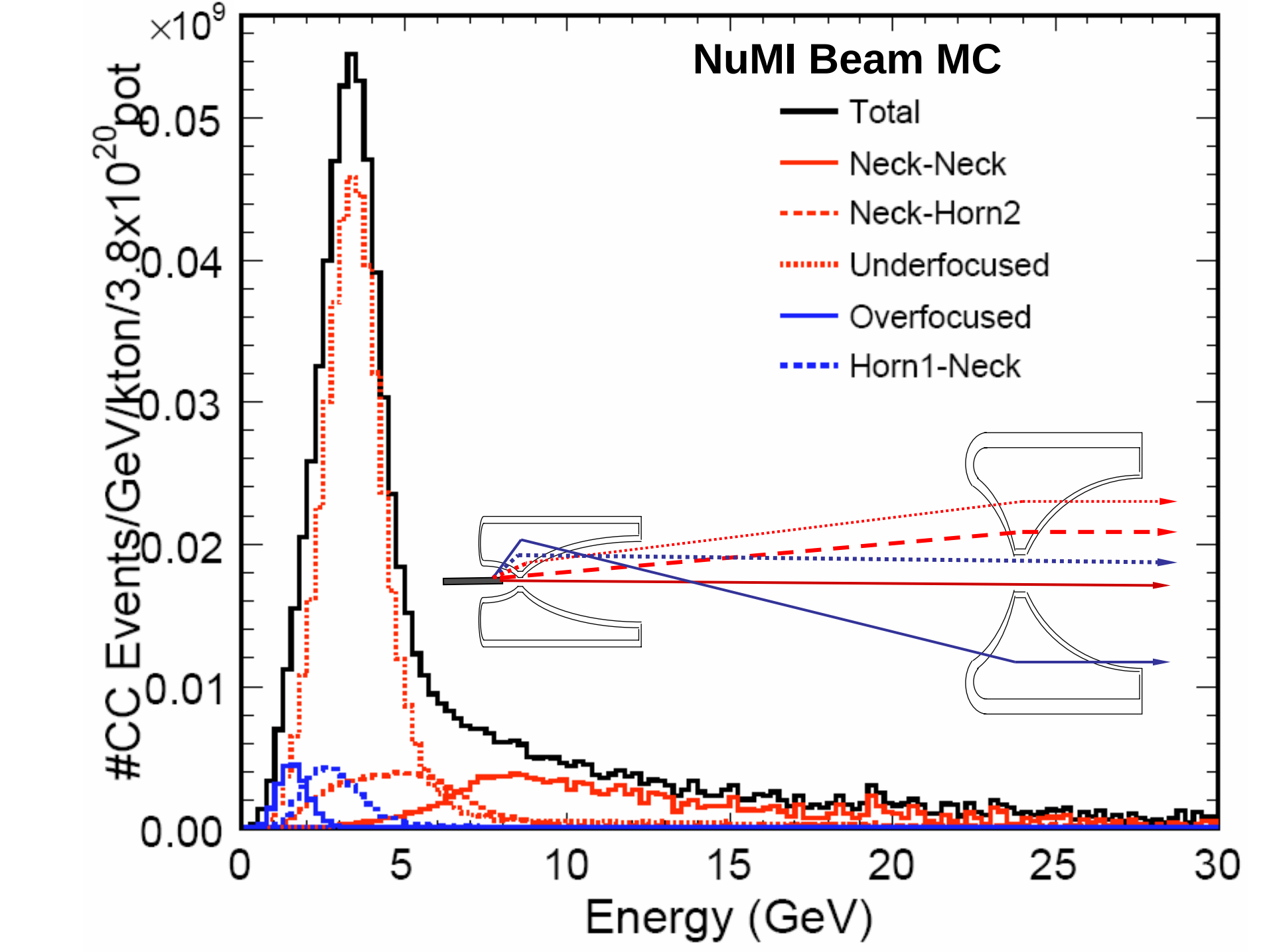

20
15
10
5
0
-5
-10
Outgoing Angle (mrad)
0
10
20
30
40
50
60
Momentum (GeV/c)
NuMI LE
NuMI ME


x3
x2
x1
S
P1
P2
l2
l3

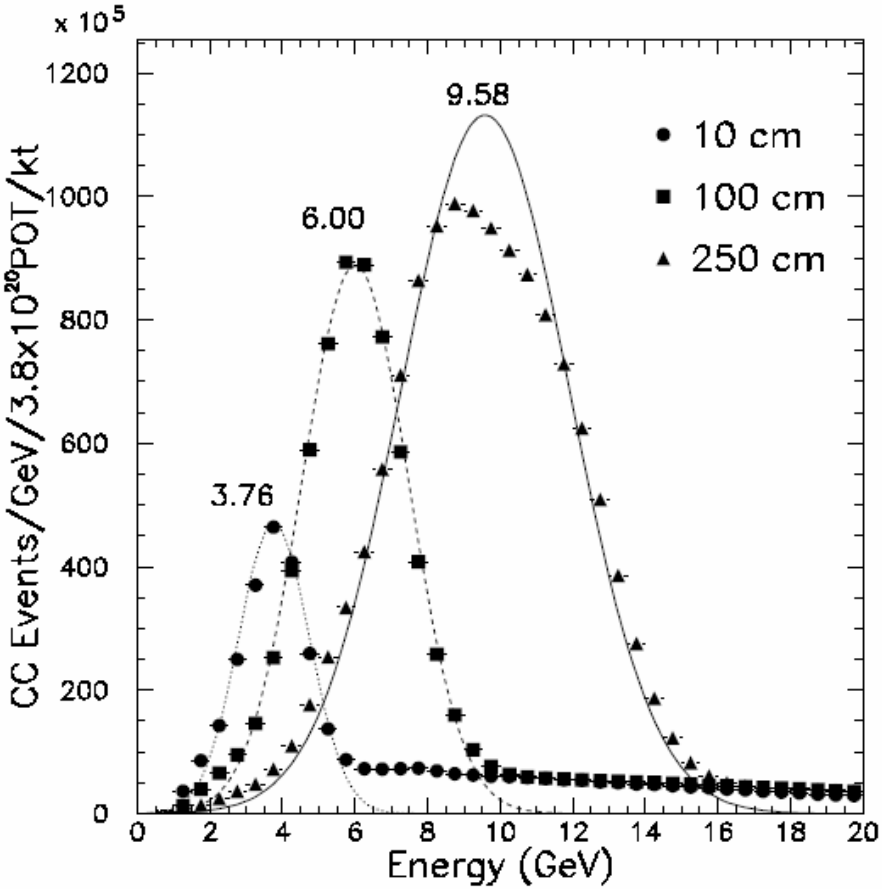
а.

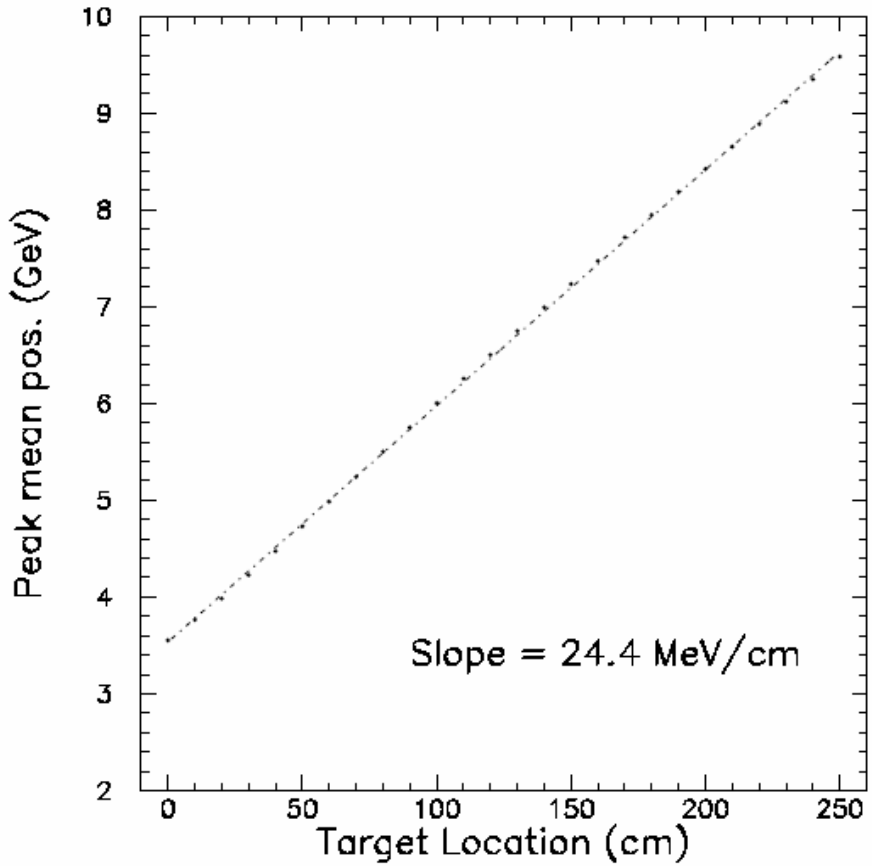

F(%)
30
20
10
-10
-20
-30
P3
P2
P1
0.1
0.3
0.4
0.5
0.6
0.7
0.8
1.0
1.1
1.2
1.3
1.4
P/P0

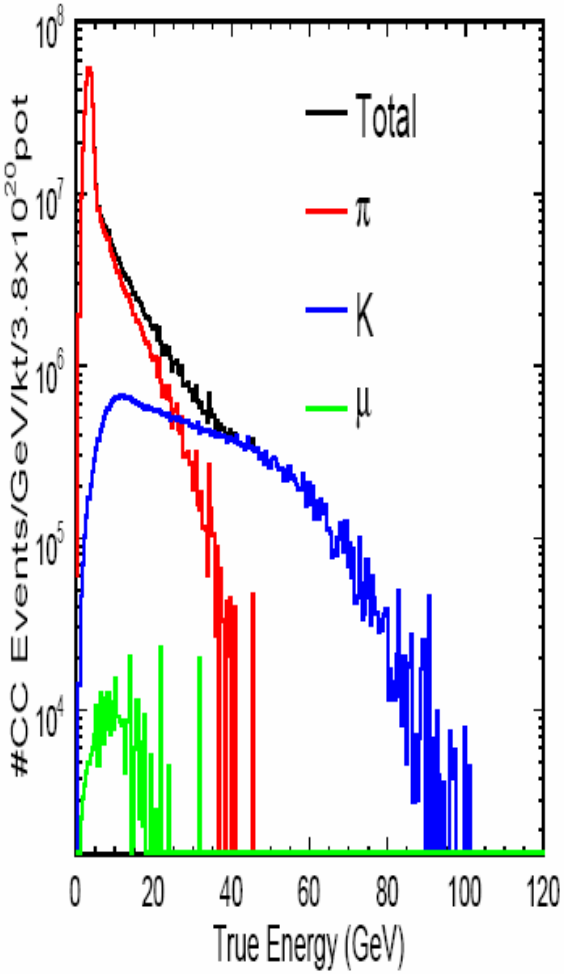
б.

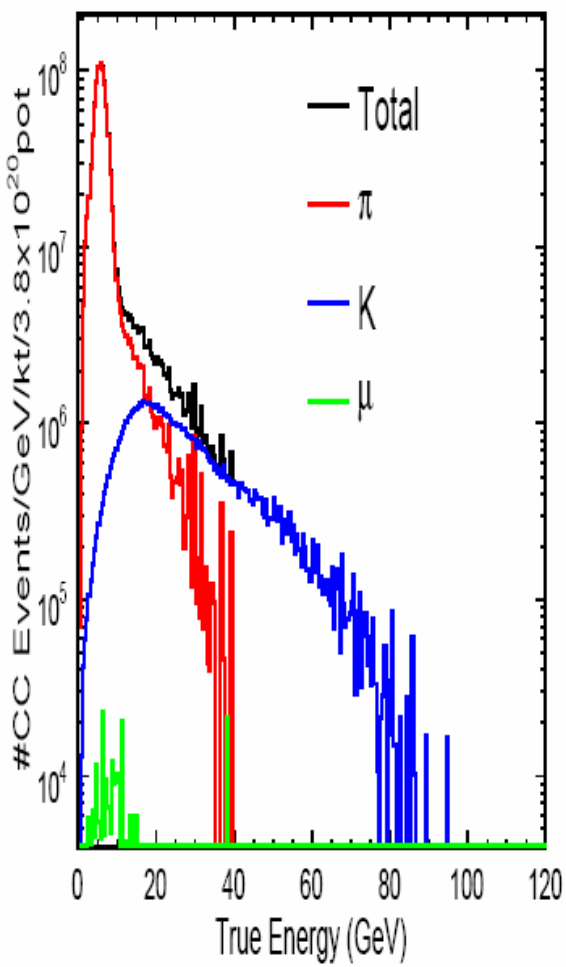

NuMI Beam MC
Total
Neck-Neck
Neck-Horn2
Underfocused
Overfocused
Horn1-Neck
#CC Events/GeV/kton/3.8x10^20 pot
×10^9
0.00
0.01
0.02
0.03
0.04
0.05
0
5
10
15
20
25
30
Energy (GeV)

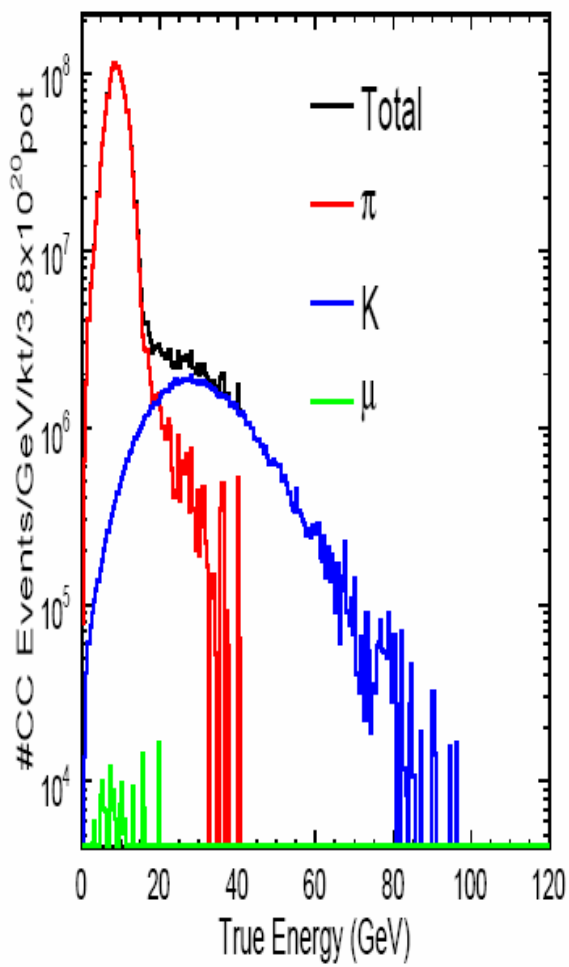
Variable Energy Beam



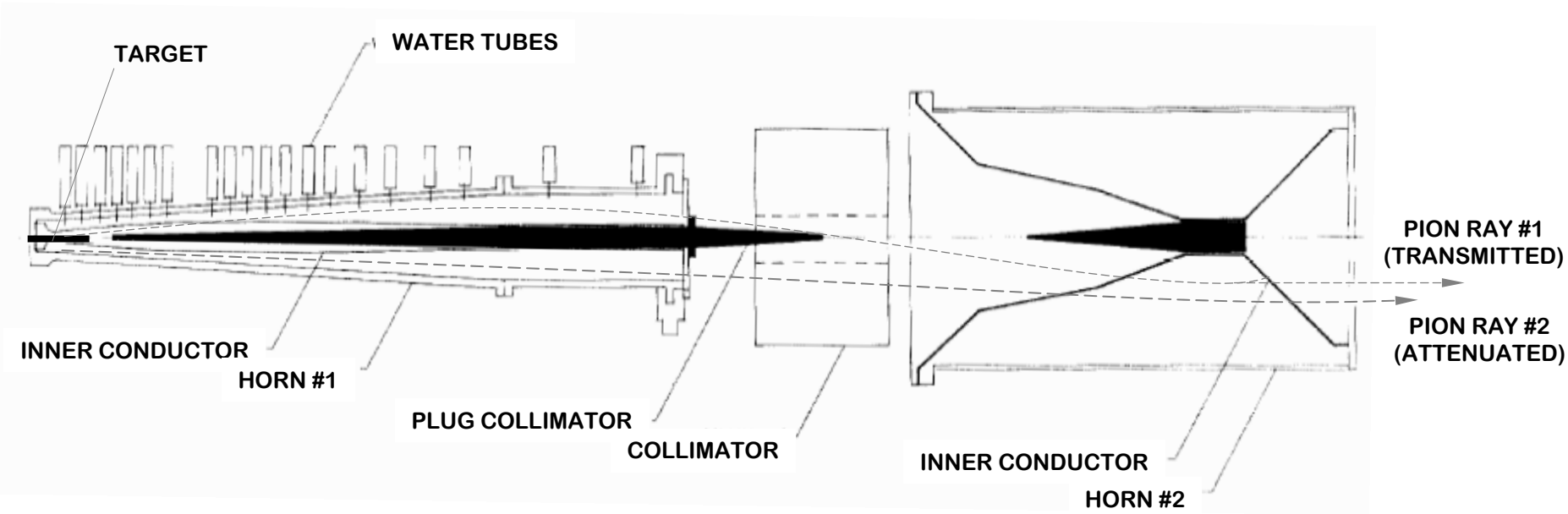


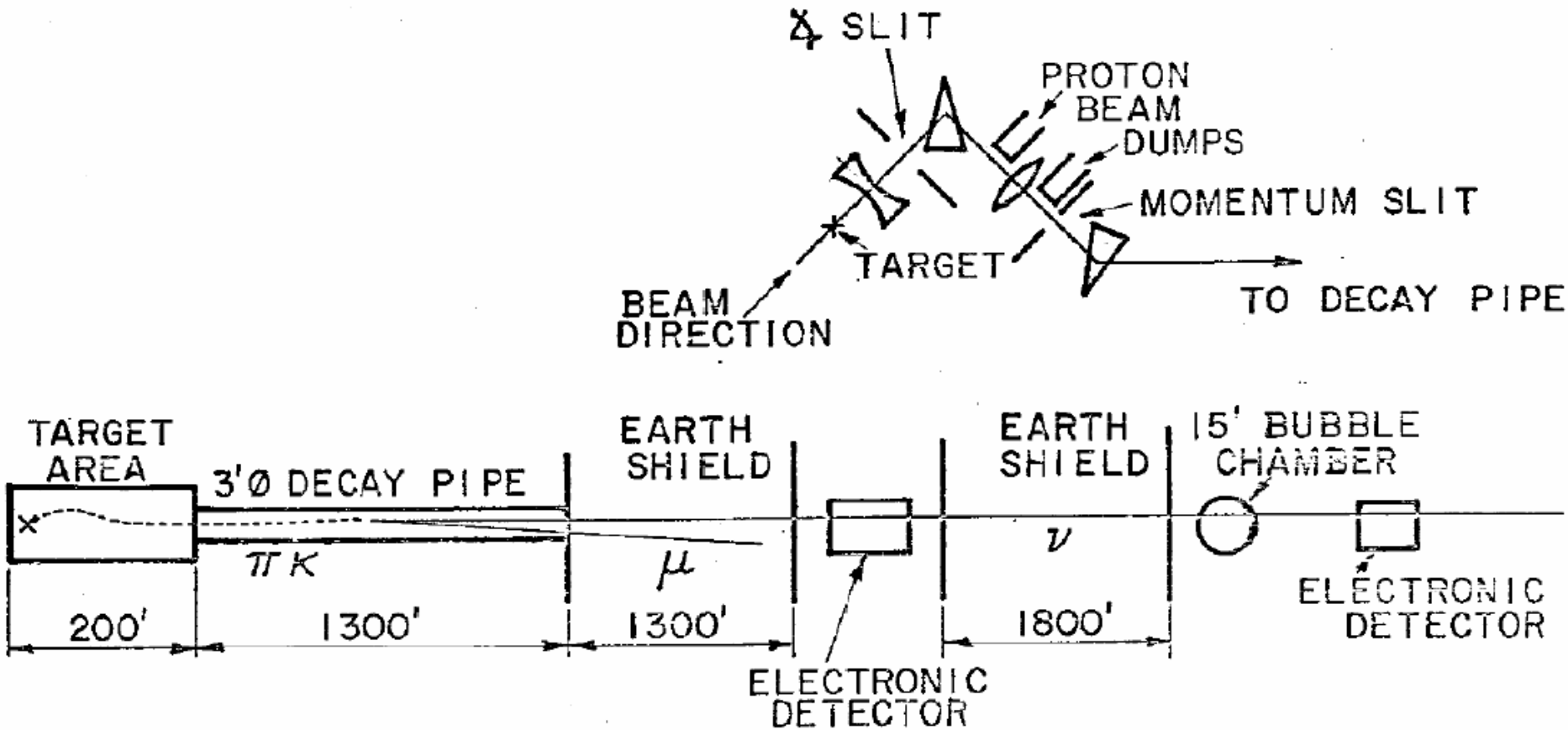

Total
π
K
μ
#CC Events/GeV/kt/3.8x10^20pot
True Energy (GeV)

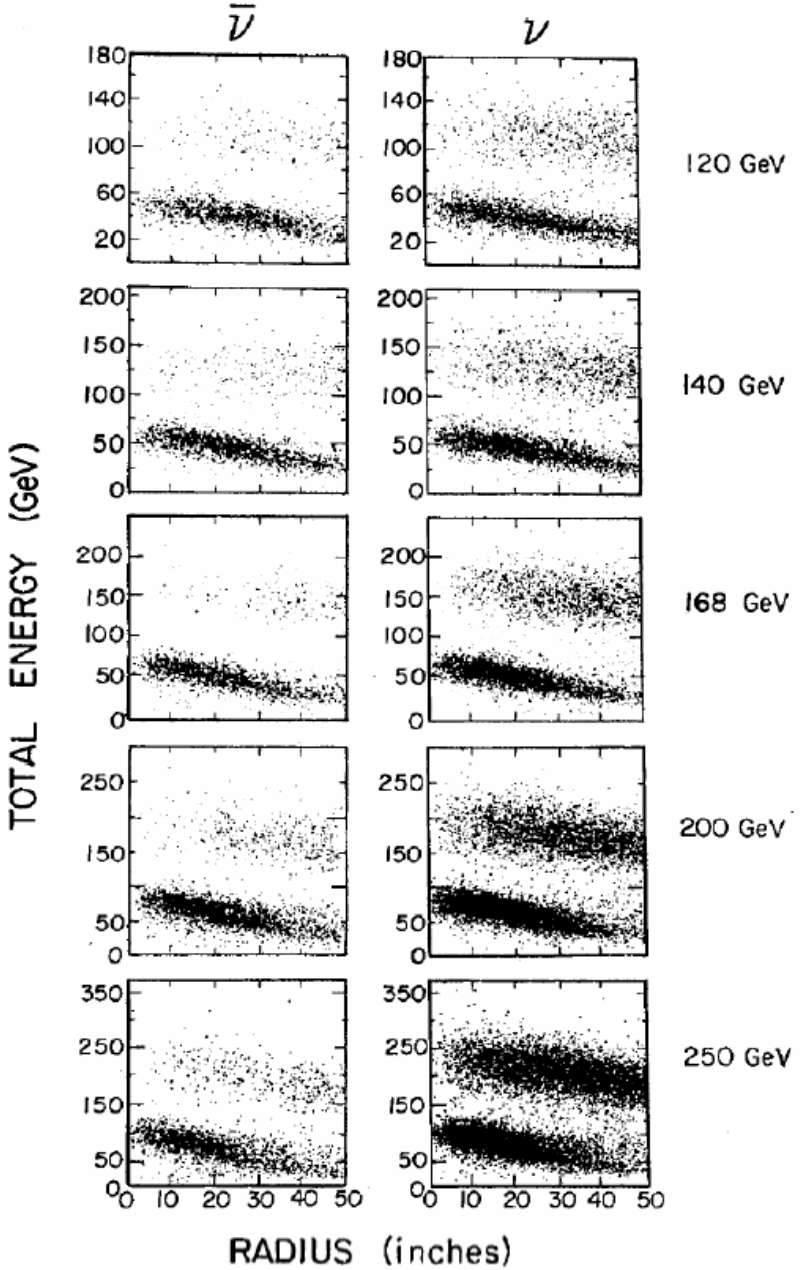

Total
π
K
μ
#CC Events/GeV/kt/3.8x10^20pot
True Energy (GeV)

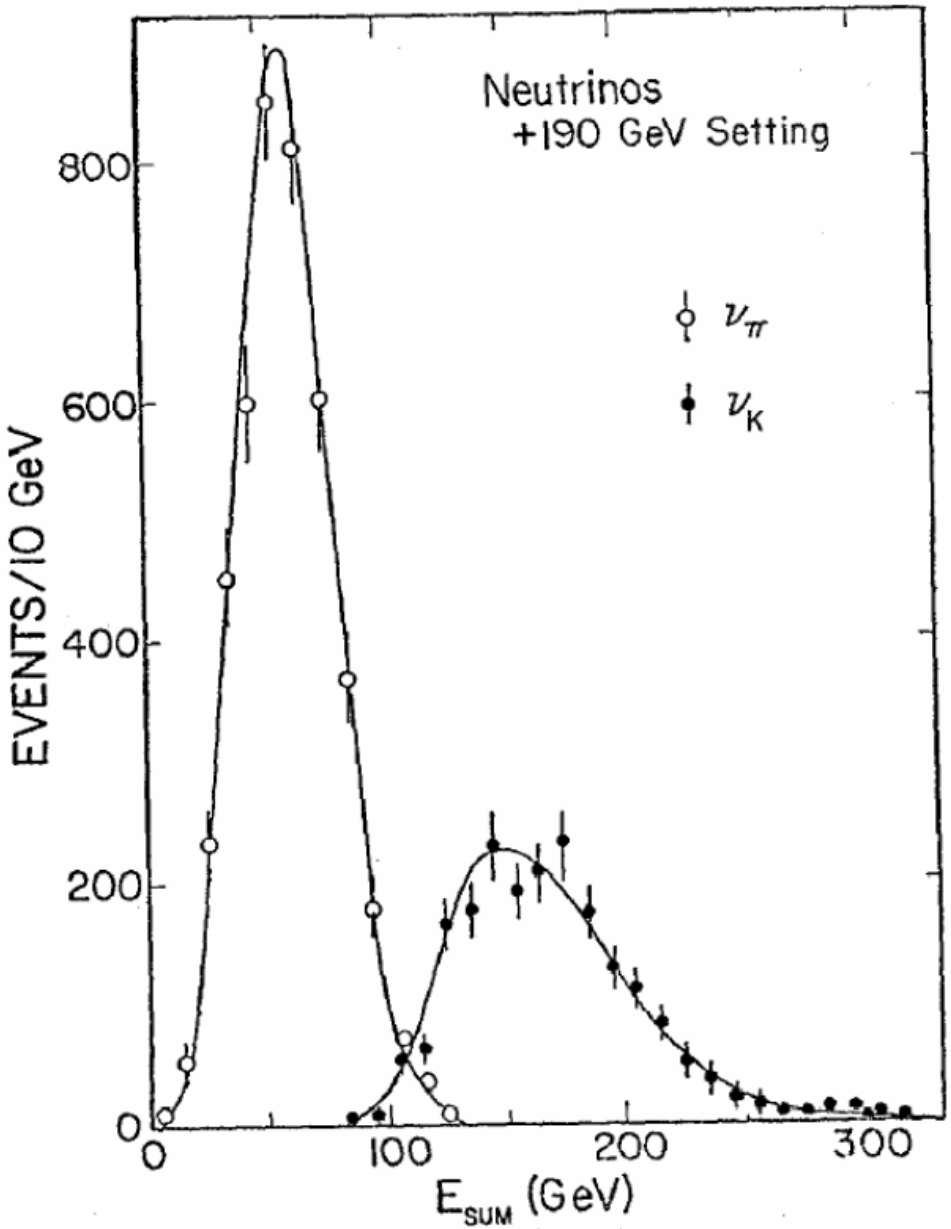

Total
π
K
μ
#CC Events/GeV/kt/3.8x10^20pot
True Energy (GeV)

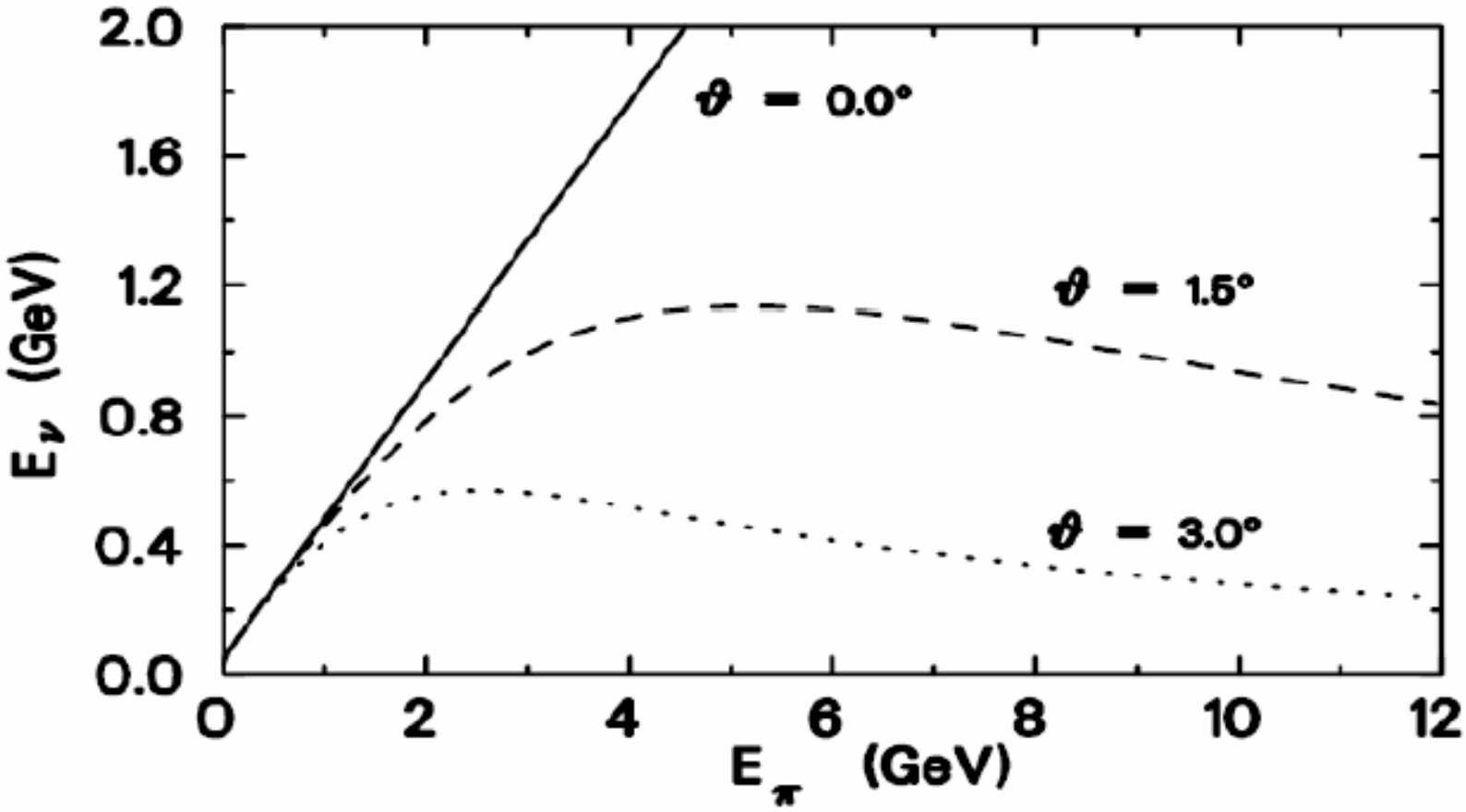
Focusing of NBB’s


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

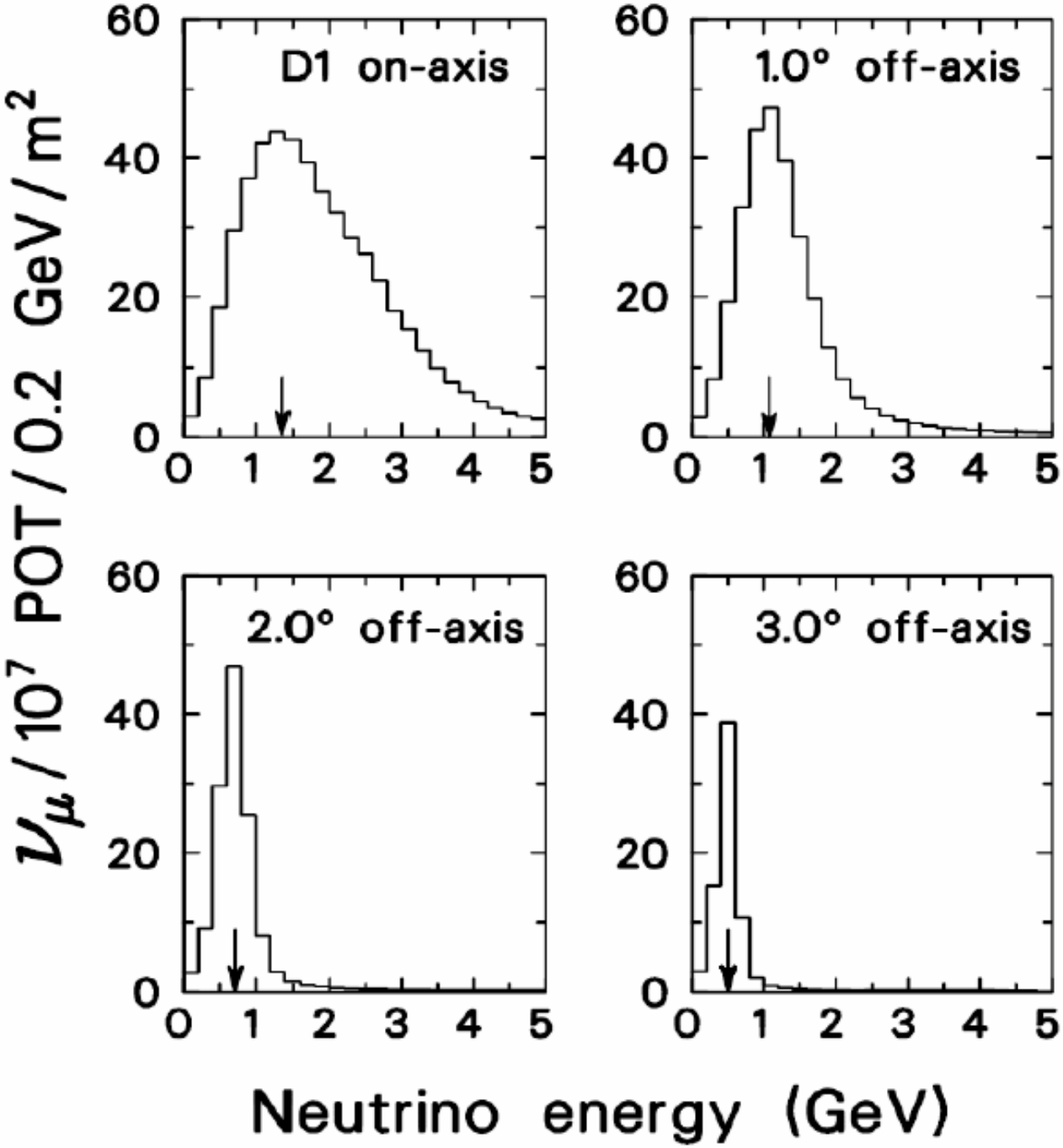

SLIT
PROTON BEAM
DUMPS
MOMENTUM SLIT
TARGET
BEAM DIRECTION
TO DECAY PIPE
TARGET AREA
3'Ø DECAY PIPE
EARTH SHIELD
EARTH SHIELD
15' BUBBLE CHAMBER
π K
μ
ν
200'
1300'
1300'
1800'
ELECTRONIC DETECTOR
ELECTRONIC DETECTOR

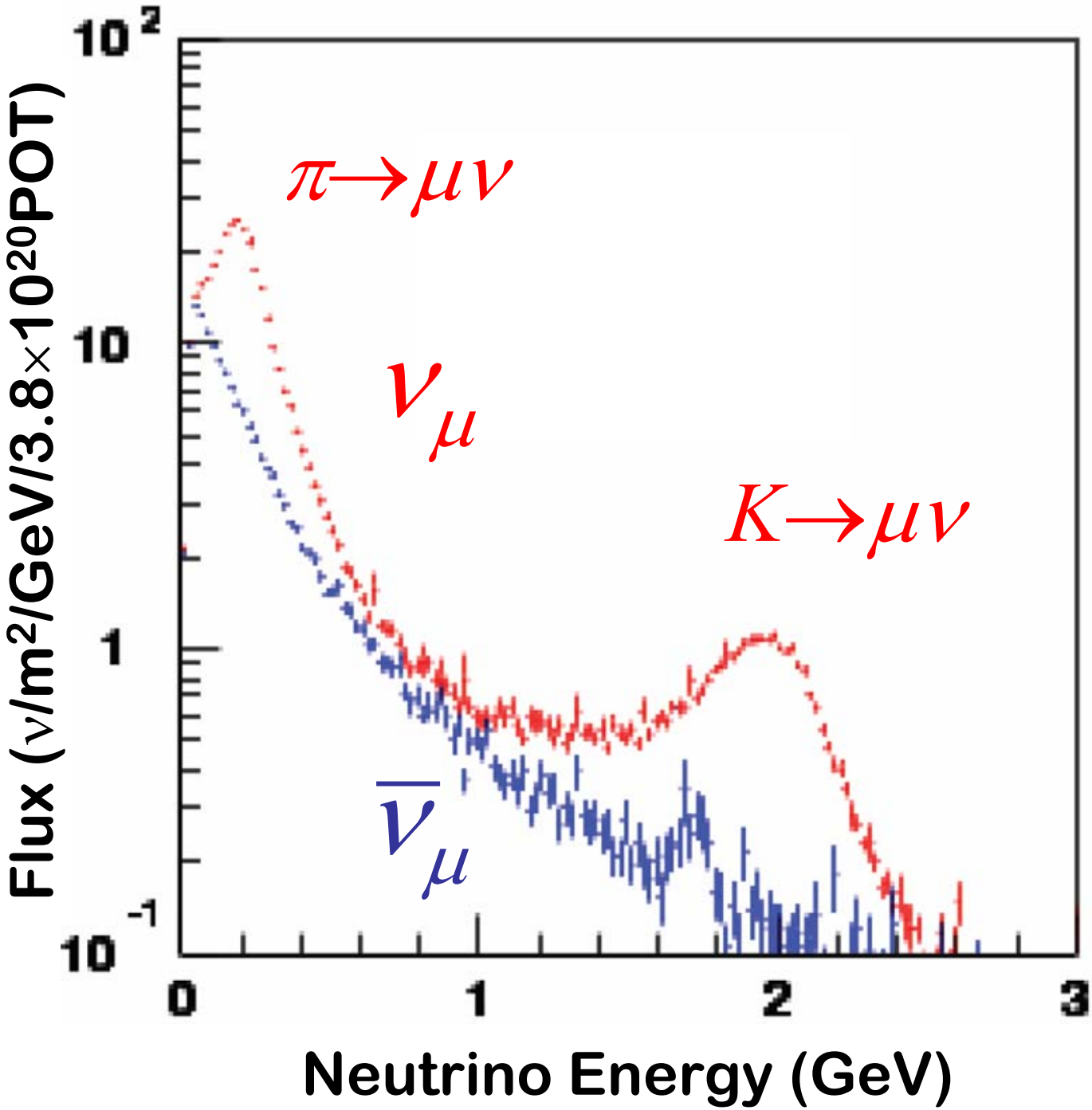

$\bar{\nu}$
ν
120 GeV
140 GeV
168 GeV
200 GeV
250 GeV
TOTAL ENERGY (GeV)
RADIUS (inches)


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

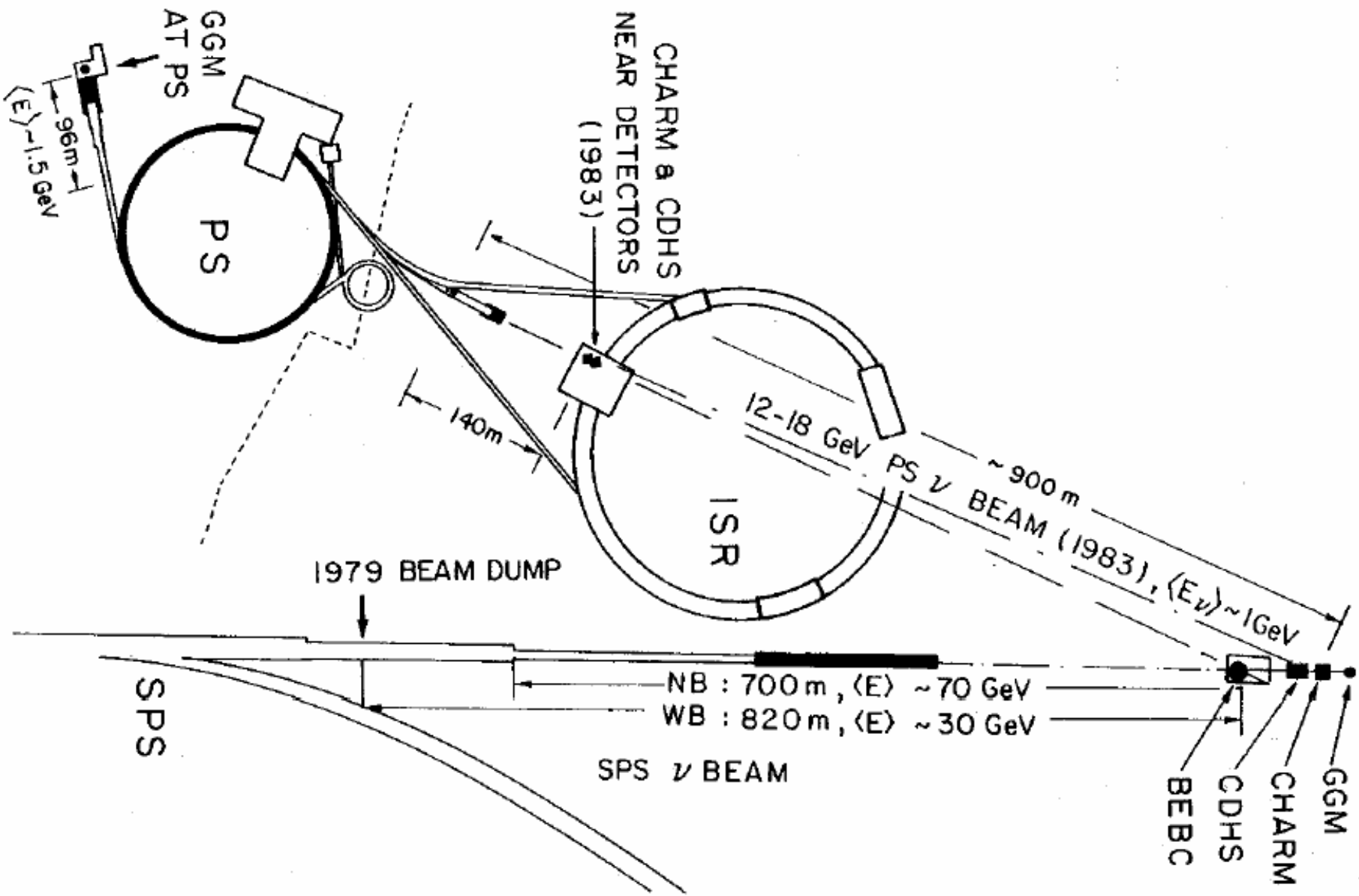


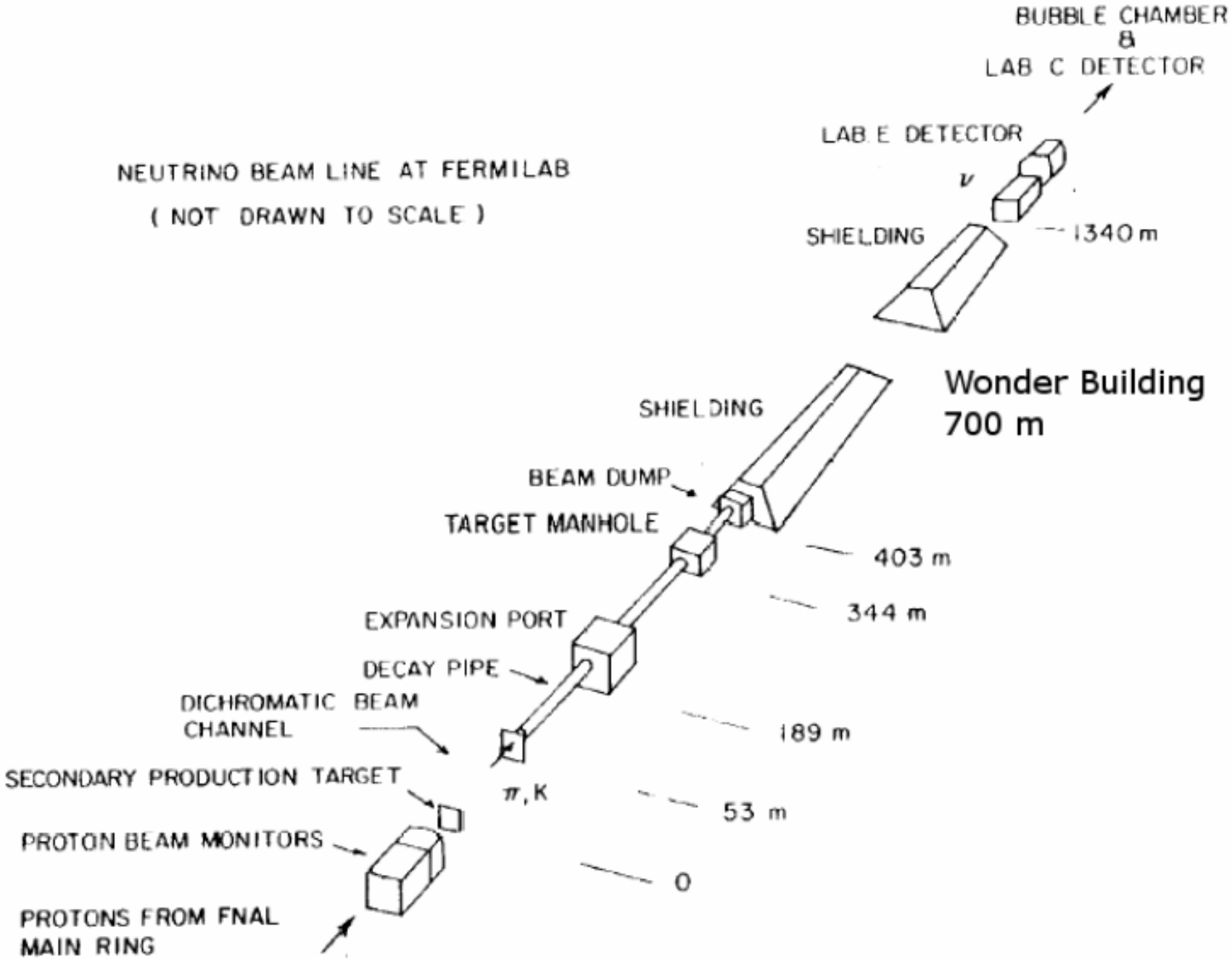
$$E_\nu = \frac{(1-(m_\mu/m_{(\pi,K)})^2)E_{(\pi,K)}}{(1+\gamma^2\theta^2)}$$

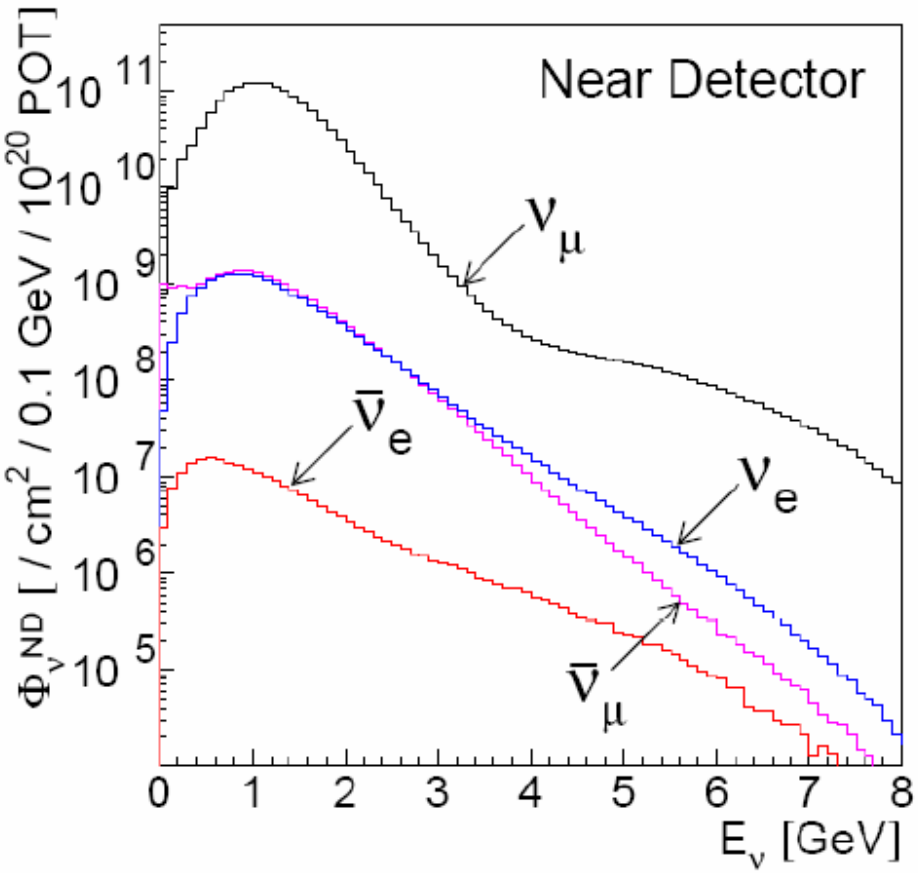

D1 on-axis
1.0° off-axis
2.0° off-axis
3.0° off-axis
ν_μ / 10^7 POT / 0.2 GeV / m^2
Neutrino energy (GeV)
0
20
40
60
0 1 2 3 4 5

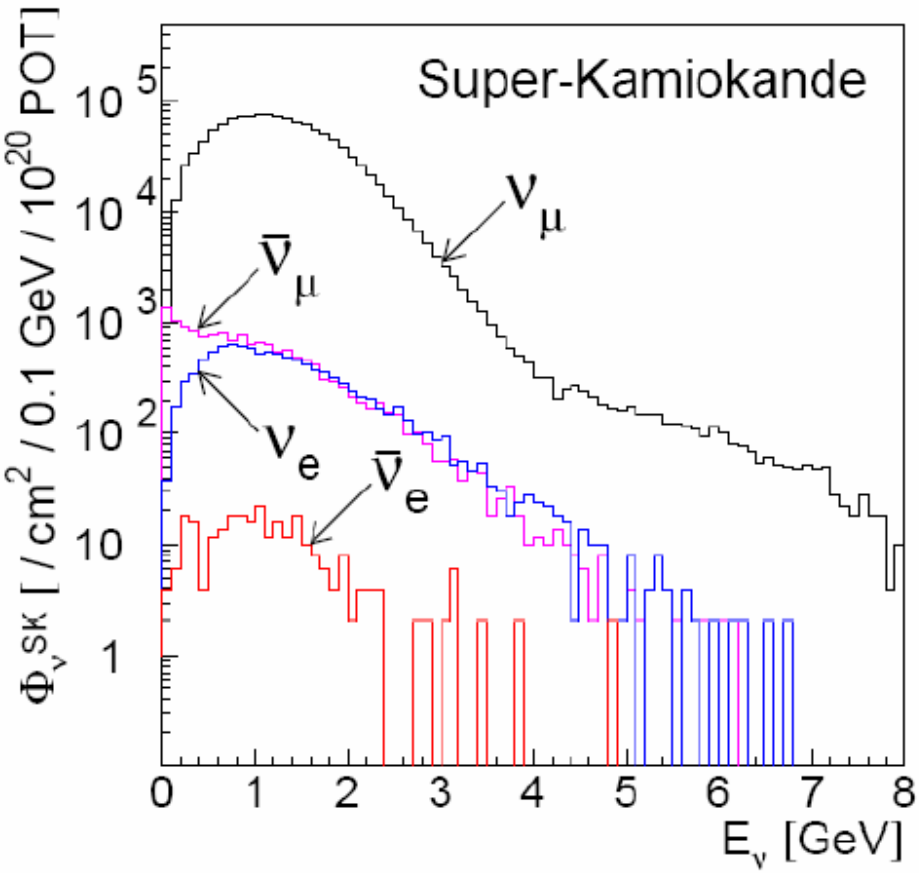

10^2
10
1
10^{-1}
Flux (ν/m^2/GeV/3.8×10^{20}POT)
$\pi \to \mu\nu$
ν_μ
$K \to \mu\nu$
$\overline{\nu}_\mu$
0
1
2
3
Neutrino Energy (GeV)

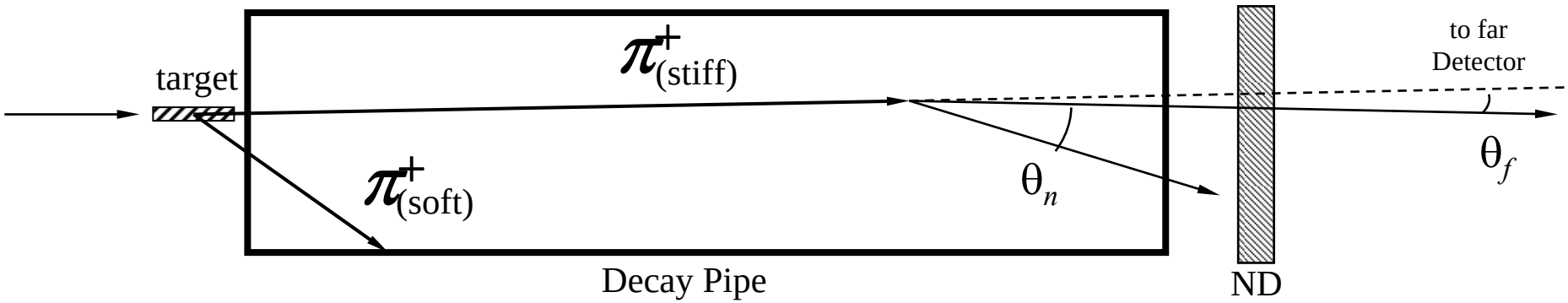
Two-Detector Experiments

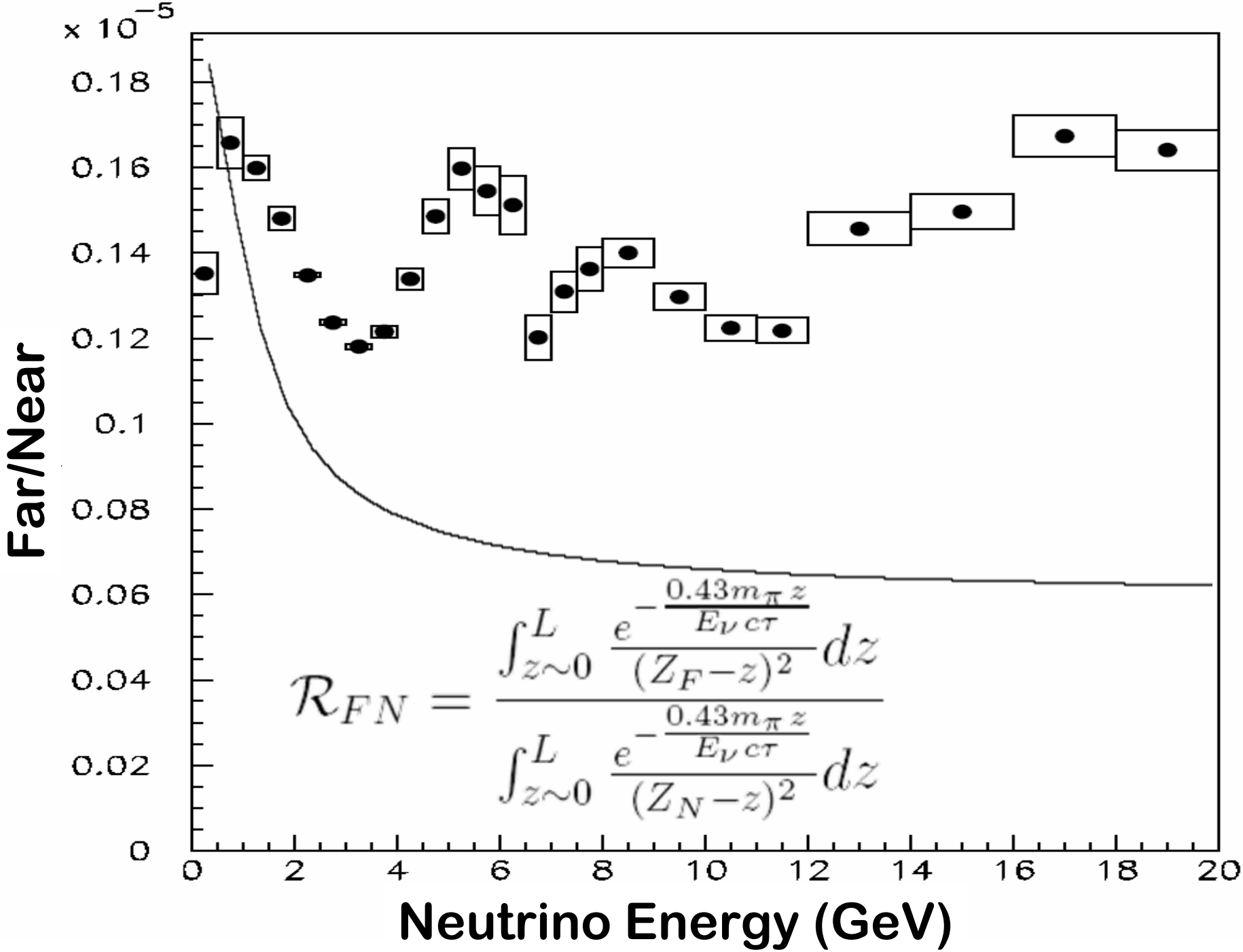

GGM
AT PS
⟨E⟩~1.5 GeV
96m
PS
CHARM & CDHS
NEAR DETECTORS
(1983)
140m
12-18 GeV PS ν BEAM (1983), ⟨Eν⟩~1GeV
~900 m
ISR
1979 BEAM DUMP
SPS
NB : 700 m, ⟨E⟩ ~70 GeV
WB : 820 m, ⟨E⟩ ~30 GeV
SPS ν BEAM
BEBC
CDHS
CHARM
GGM

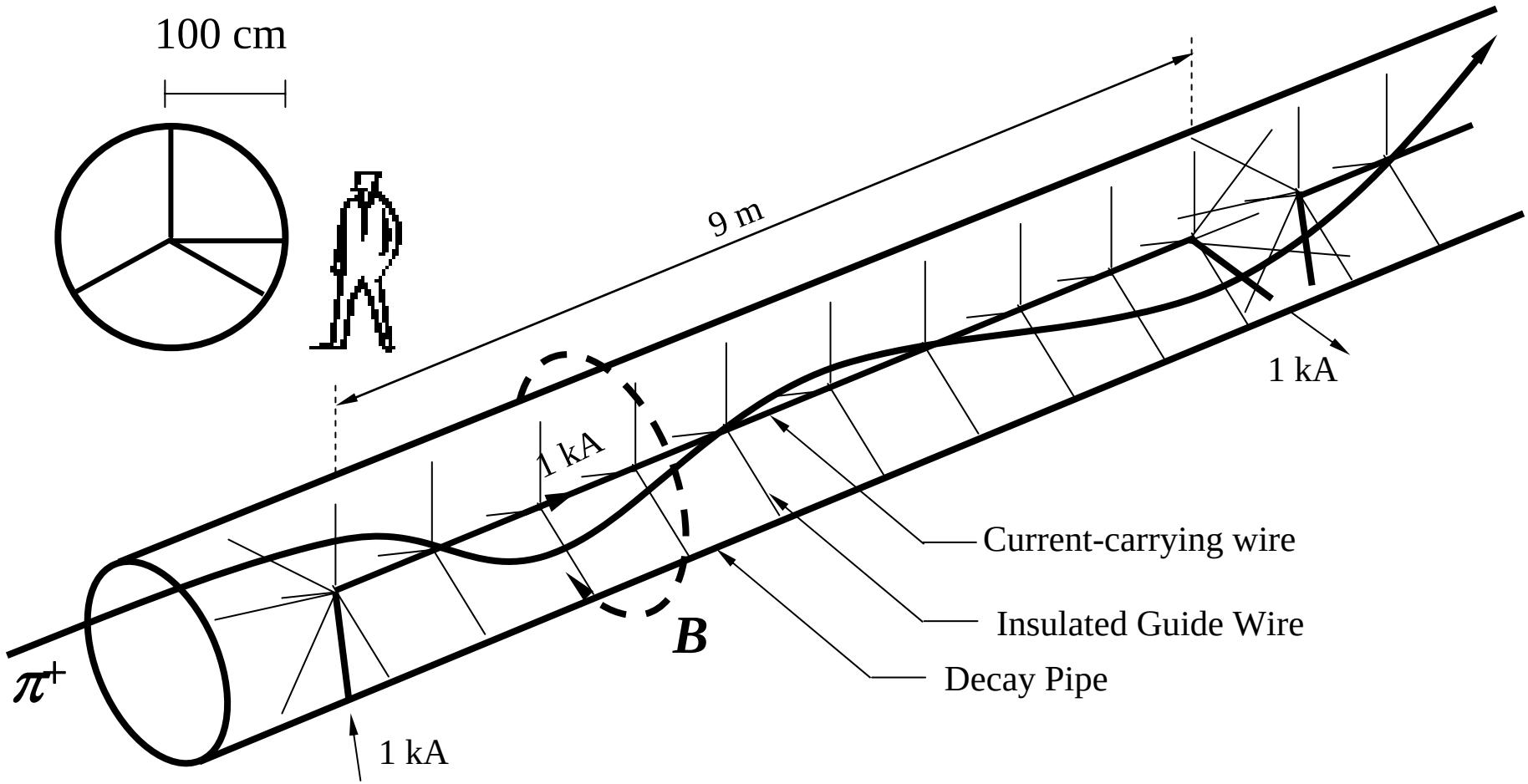

BUBBLE CHAMBER
&
LAB C DETECTOR
LAB E DETECTOR
NEUTRINO BEAM LINE AT FERMILAB
(NOT DRAWN TO SCALE)
ν
SHIELDING
1340 m
Wonder Building
700 m
SHIELDING
BEAM DUMP
TARGET MANHOLE
403 m
344 m
EXPANSION PORT
DECAY PIPE
DICHROMATIC BEAM
CHANNEL
189 m
SECONDARY PRODUCTION TARGET
π, K
53 m
PROTON BEAM MONITORS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

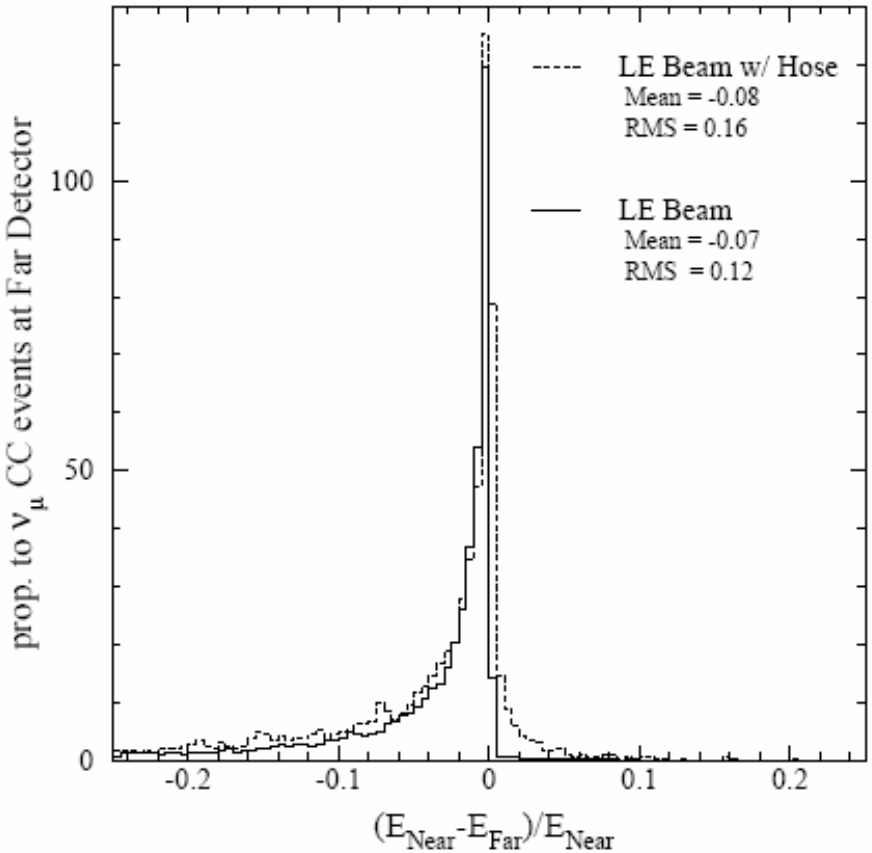

Near Detector
ν_μ
$\bar{\nu}_e$
ν_e
$\bar{\nu}_\mu$
Φ_ν^{ND} [/ cm^2 / 0.1 GeV / 10^{20} POT]
E_ν [GeV]

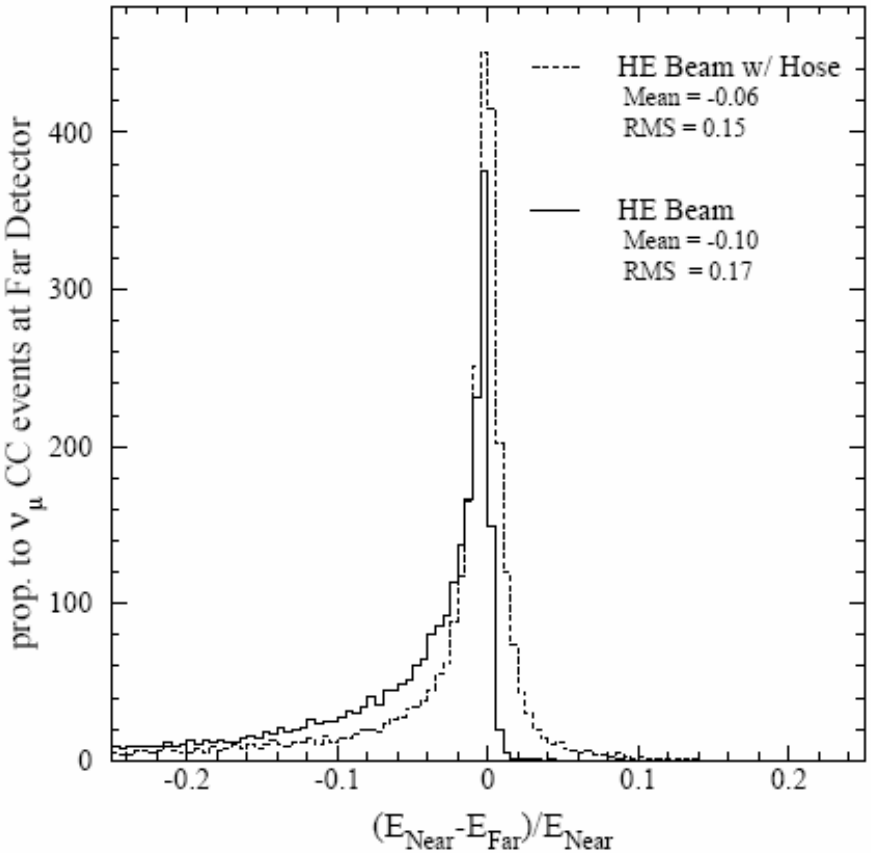

Super-Kamiokande
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
Φ_ν^{SK} [/ cm^2 / 0.1 GeV / 10^{20} POT]
E_ν [GeV]

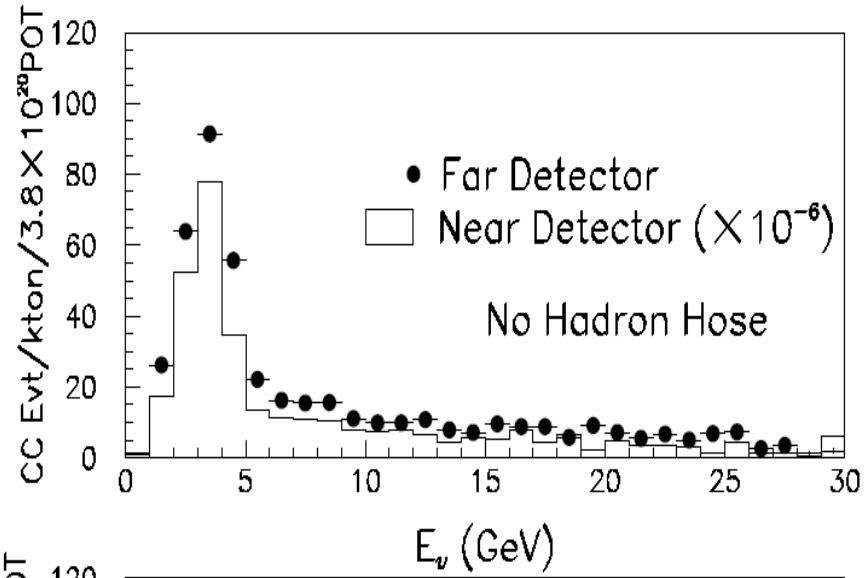

target
$\pi^+_{(\mathrm{stiff})}$
$\pi^+_{(\mathrm{soft})}$
θ_n
θ_f
to far
Detector
Decay Pipe
ND

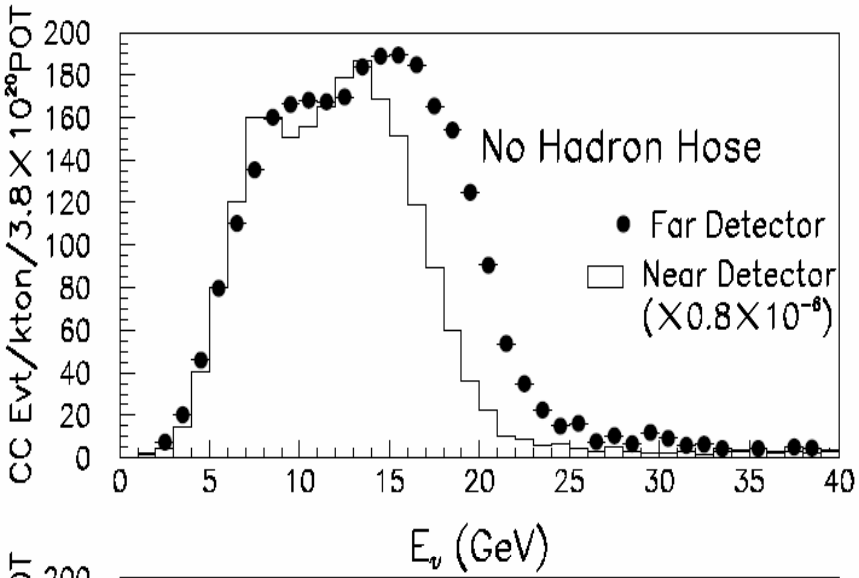

× 10⁻⁵
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Far/Near
0
2
4
6
8
10
12
14
16
18
20
Neutrino Energy (GeV)
$\mathcal{R}_{FN} = \frac{\int_{z\sim 0}^{L} \frac{e^{-\frac{0.43 m_\pi z}{E_\nu c\tau}}}{(Z_F - z)^2} dz}{\int_{z\sim 0}^{L} \frac{e^{-\frac{0.43 m_\pi z}{E_\nu c\tau}}}{(Z_N - z)^2} dz}$

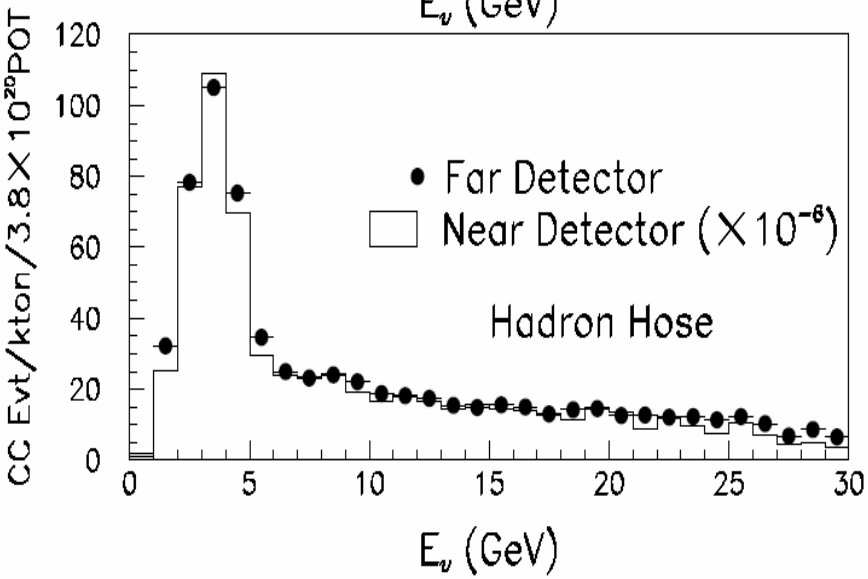

100 cm
9 m
1 kA
1 kA
1 kA
B
π^+
Current-carrying wire
Insulated Guide Wire
Decay Pipe

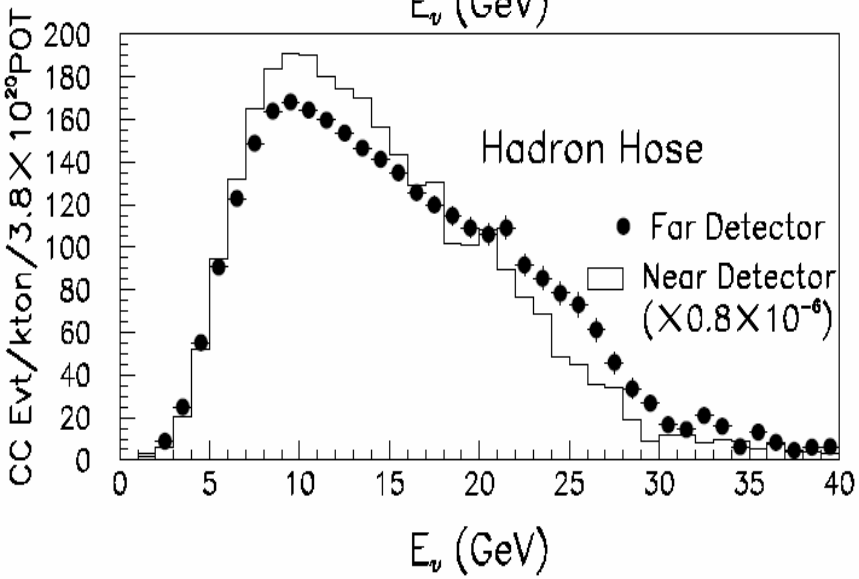

LE Beam w/ Hose
Mean = -0.08
RMS = 0.16
LE Beam
Mean = -0.07
RMS = 0.12
prop. to ν_μ CC events at Far Detector
$(E_{Near}-E_{Far})/E_{Near}$
0
50
100
-0.2
-0.1
0
0.1
0.2

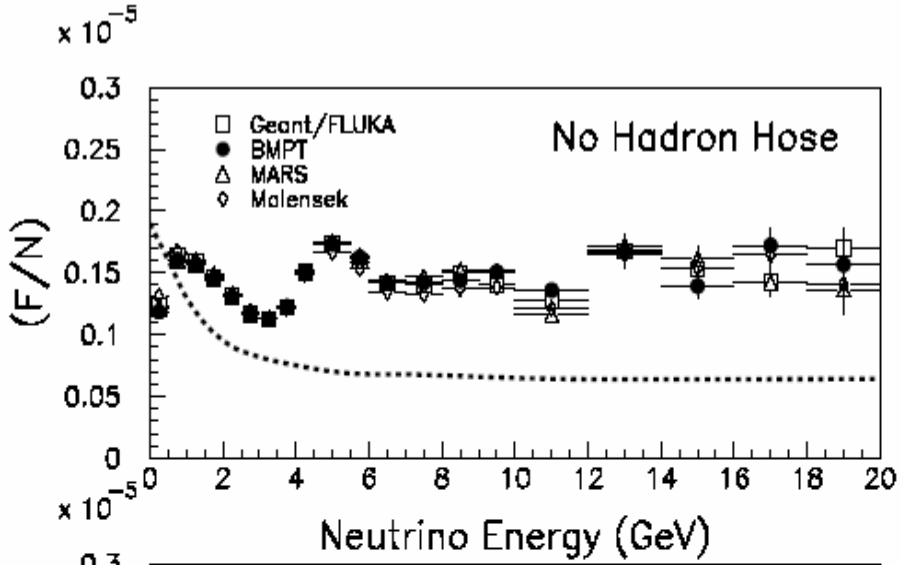

HE Beam w/ Hose
Mean = -0.06
RMS = 0.15
HE Beam
Mean = -0.10
RMS = 0.17
prop. to ν_μ CC events at Far Detector
$(E_{Near}-E_{Far})/E_{Near}$
0
100
200
300
400
-0.2
-0.1
0
0.1
0.2

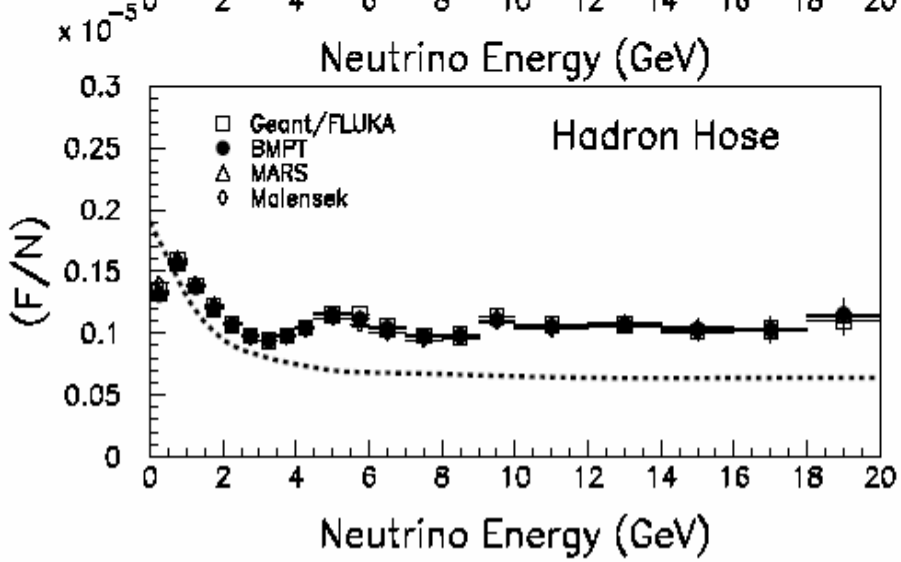

CC Evt/kton/3.8×10²⁰POT
Far Detector
Near Detector (×10⁻⁶)
No Hadron Hose
E_ν (GeV)

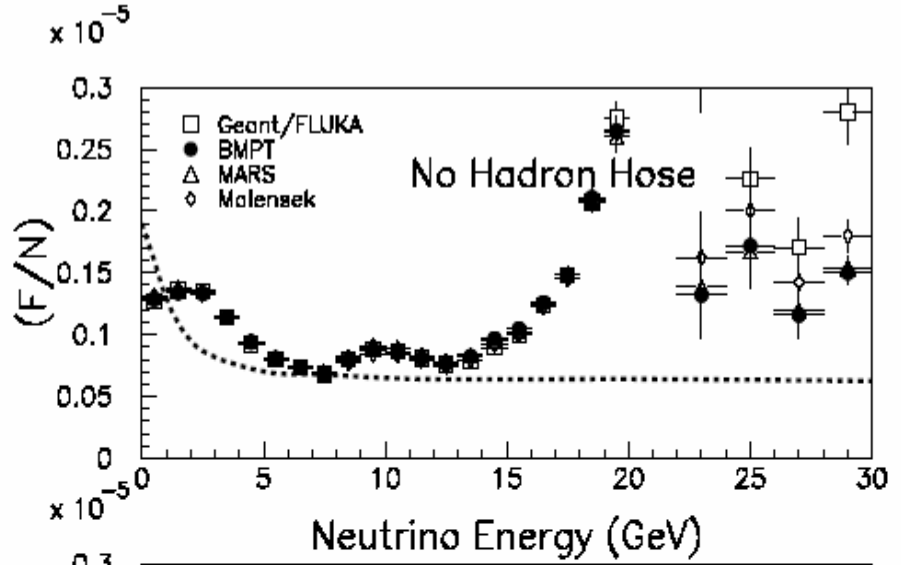

CC Evt/kton/3.8×10²⁰POT
No Hadron Hose
Far Detector
Near Detector
(×0.8×10⁻⁶)
E_ν (GeV)

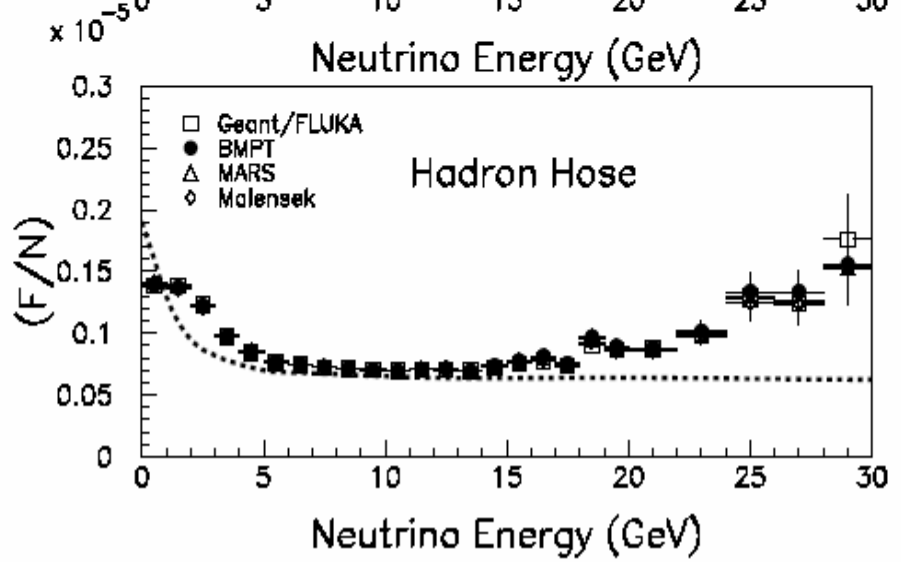

CC Evt/kton/3.8×10²⁰POT
Far Detector
Near Detector (×10⁻⁶)
Hadron Hose
E_ν (GeV)

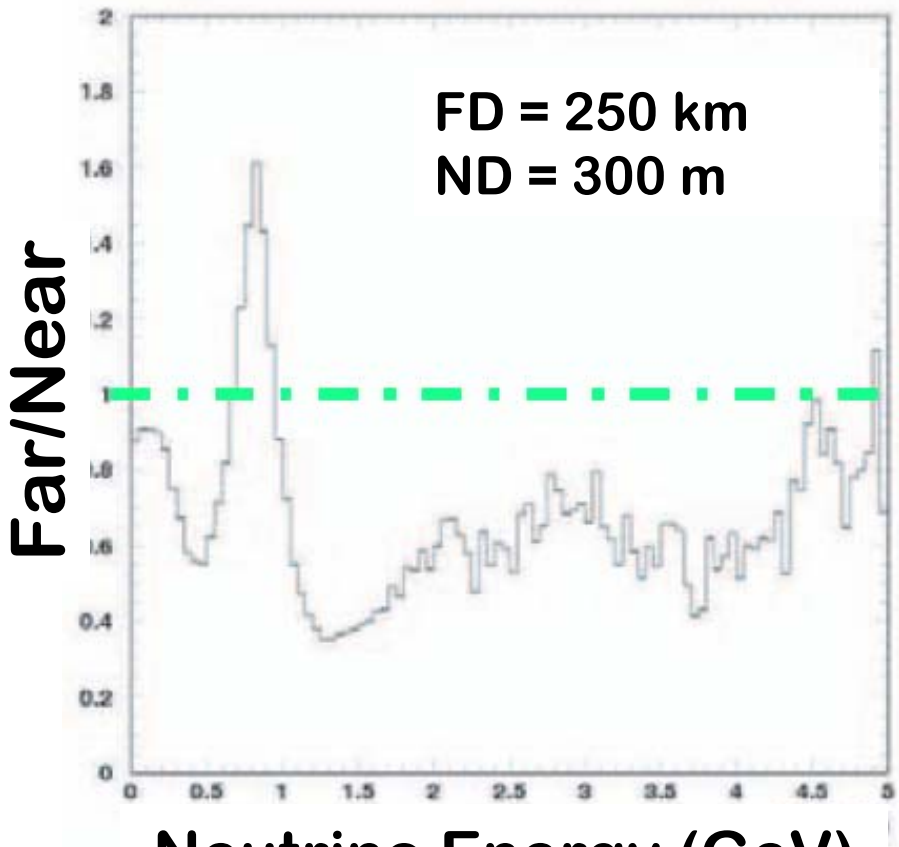

CC Evt/kton/3.8×10²⁰POT
Hadron Hose
Far Detector
Near Detector
(×0.8×10⁻⁶)
E_ν (GeV)

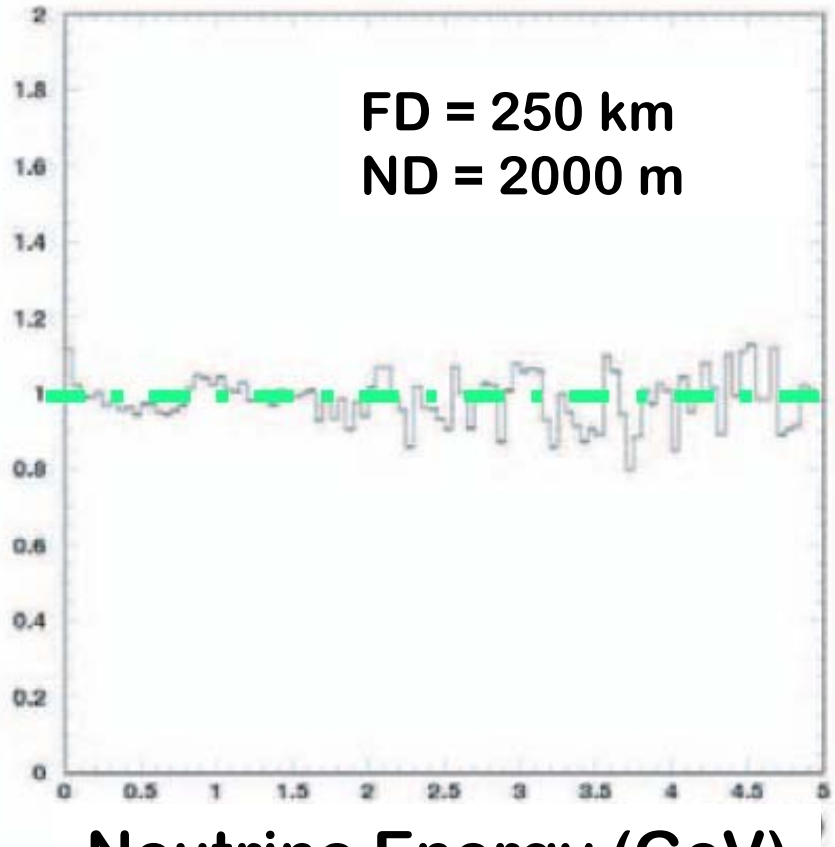

x 10^-5
(F/N)
Geant/FLUKA
BMPT
MARS
Malensek
No Hadron Hose
Neutrino Energy (GeV)

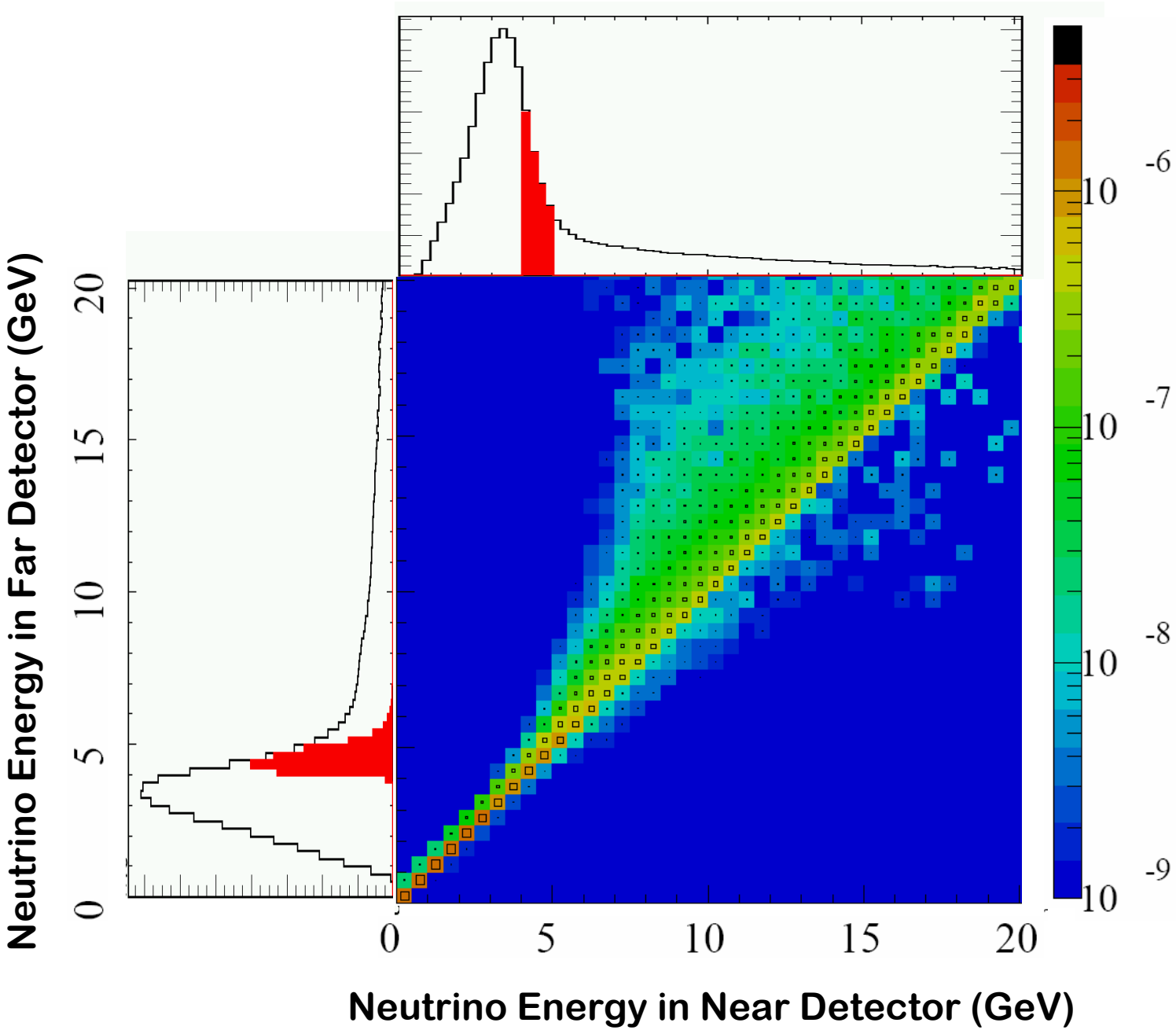

x 10^-5
(F/N)
Geant/FLUKA
BMPT
MARS
Malensek
Hadron Hose
Neutrino Energy (GeV)


x 10^-5
(F/N)
Geant/FLUKA
BMPT
MARS
Malensek
No Hadron Hose
Neutrino Energy (GeV)

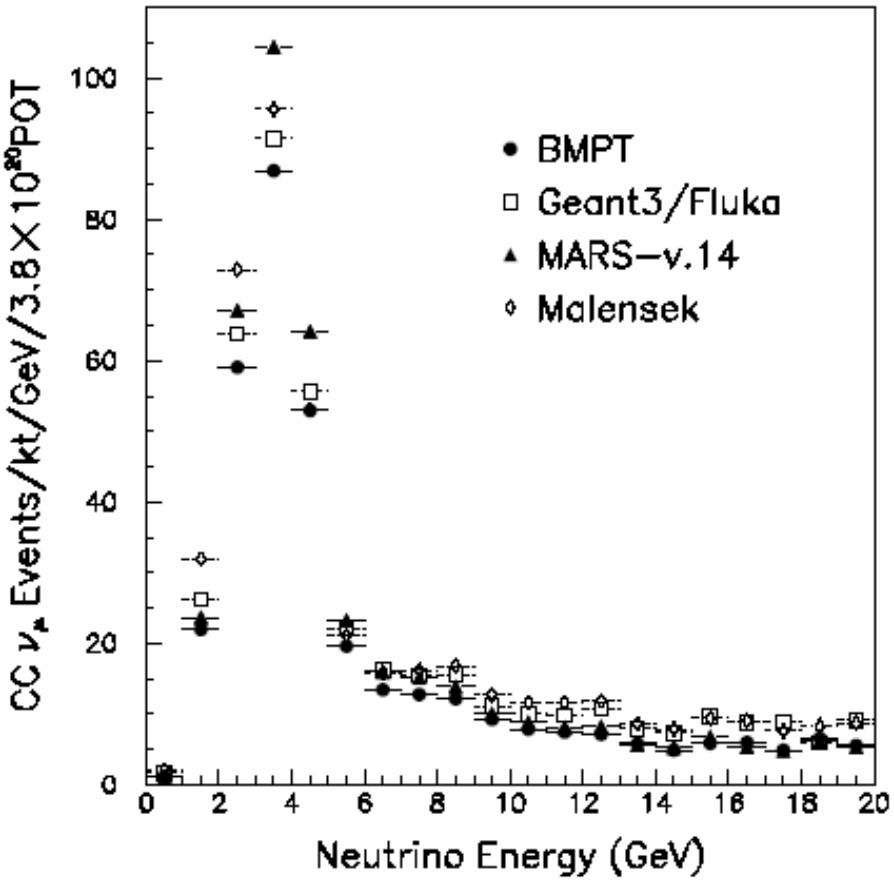

x 10^-5
(F/N)
Geant/FLUKA
BMPT
MARS
Malensek
Hadron Hose
Neutrino Energy (GeV)

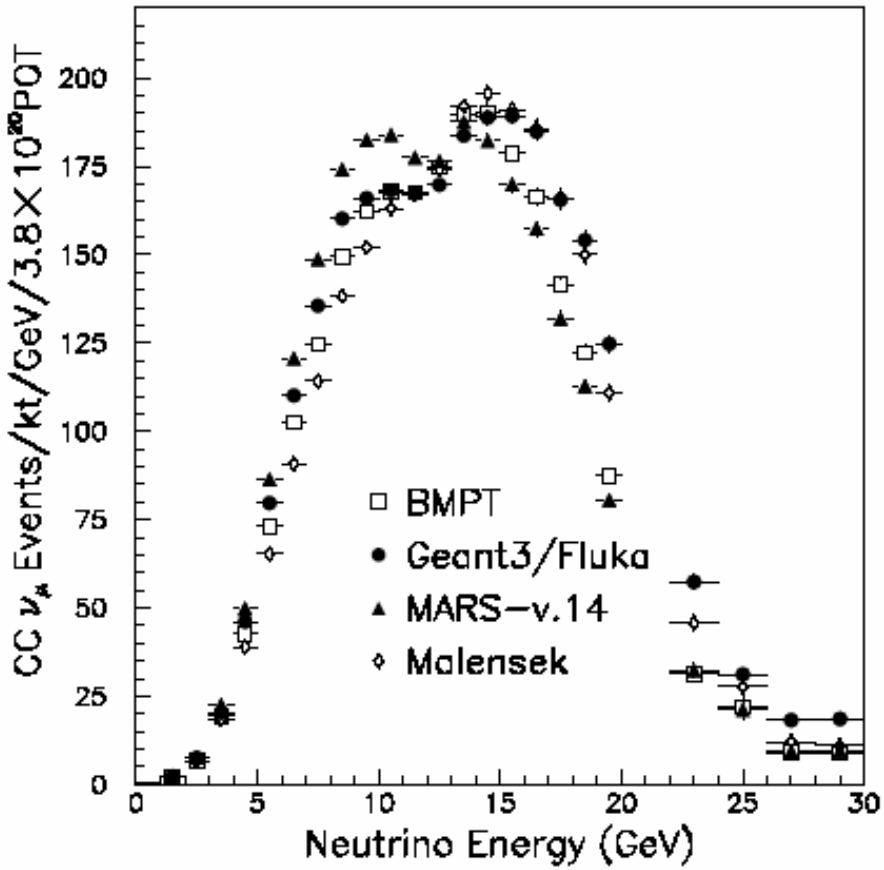

Far/Near
FD = 250 km
ND = 300 m
Neutrino Energy (GeV)

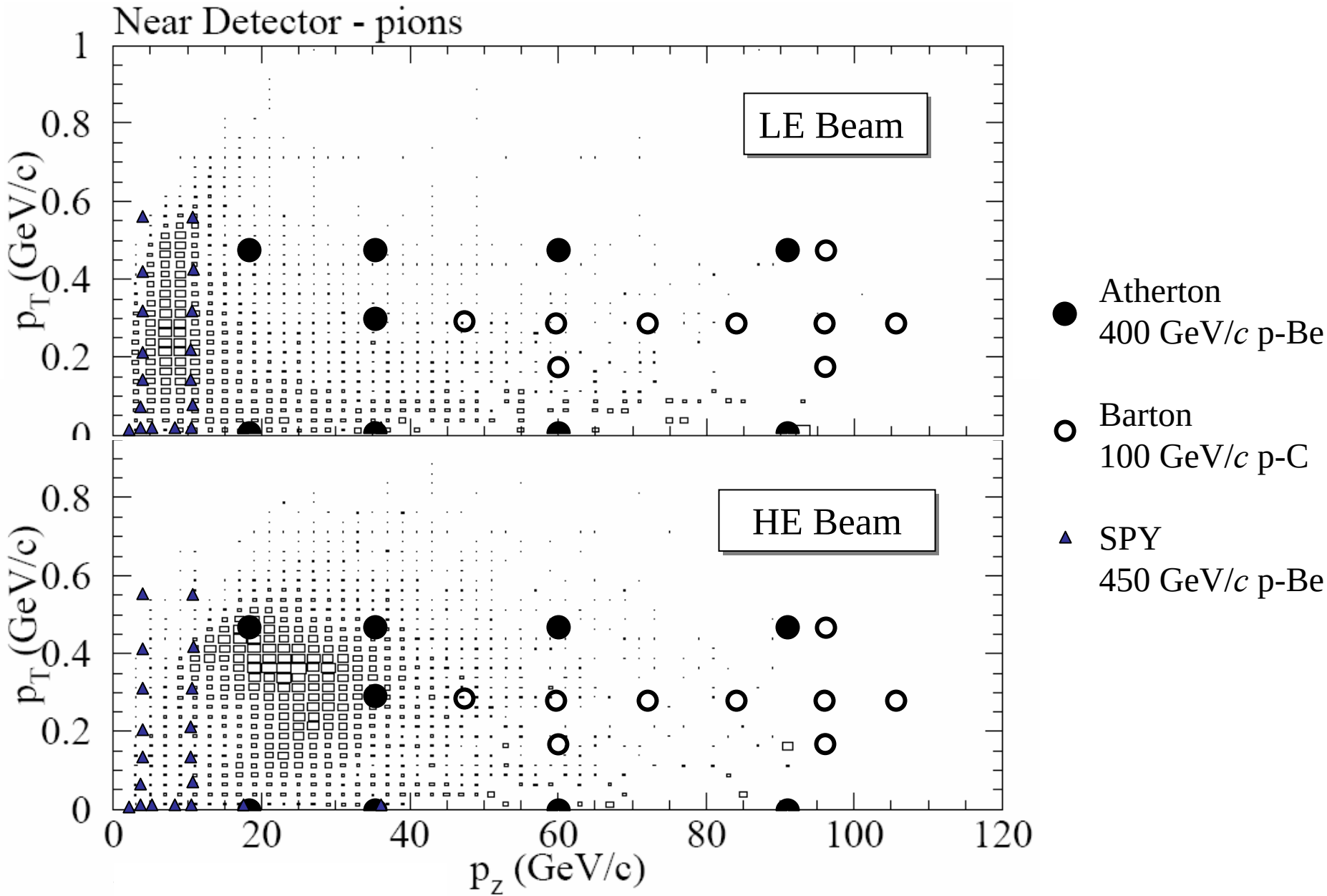

FD = 250 km
ND = 2000 m
Neutrino Energy (GeV)

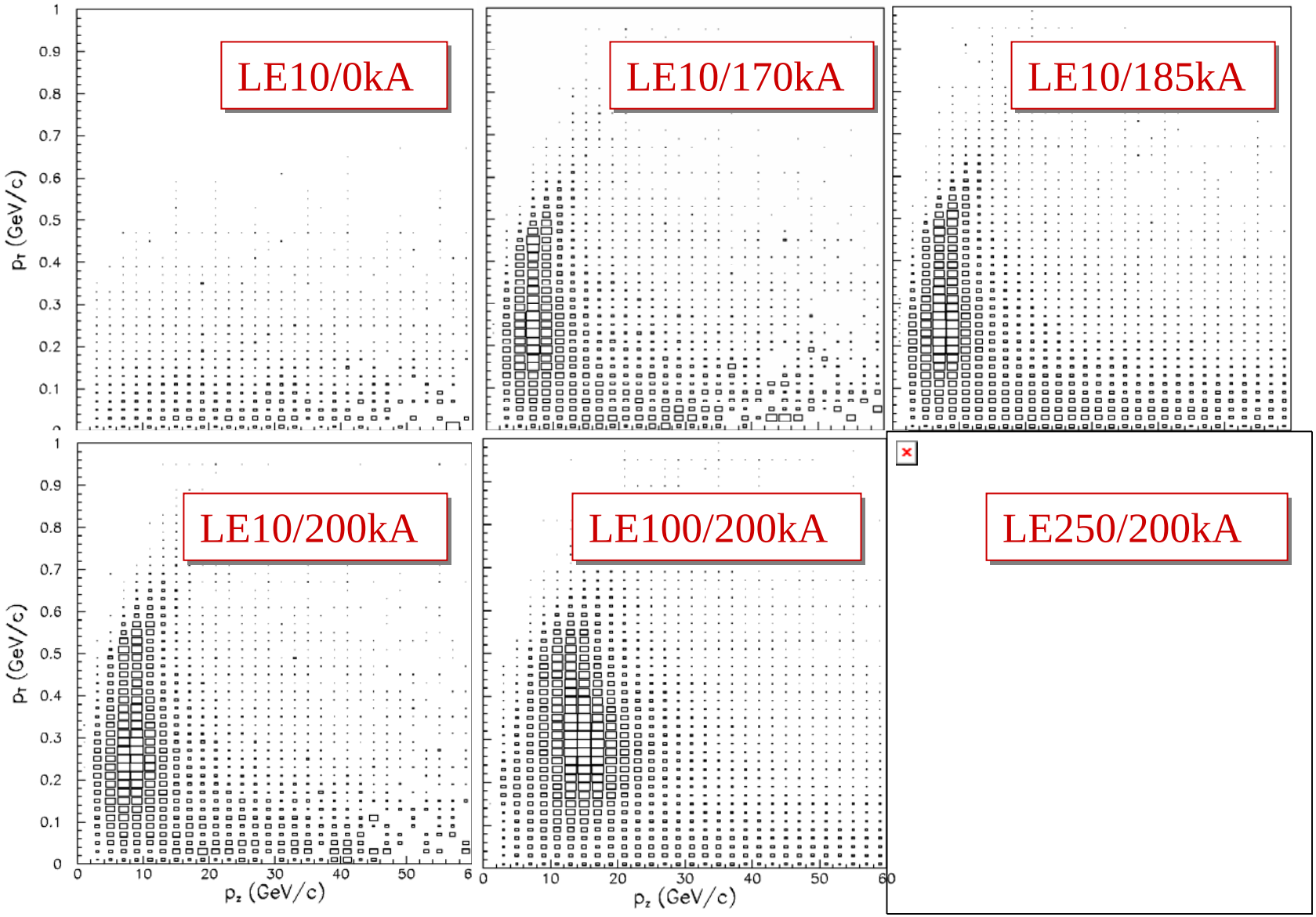

Neutrino Energy in Far Detector (GeV)
0
5
10
15
20
Neutrino Energy in Near Detector (GeV)
0
5
10
15
20
-6
10
-7
10
-8
10
-9
10

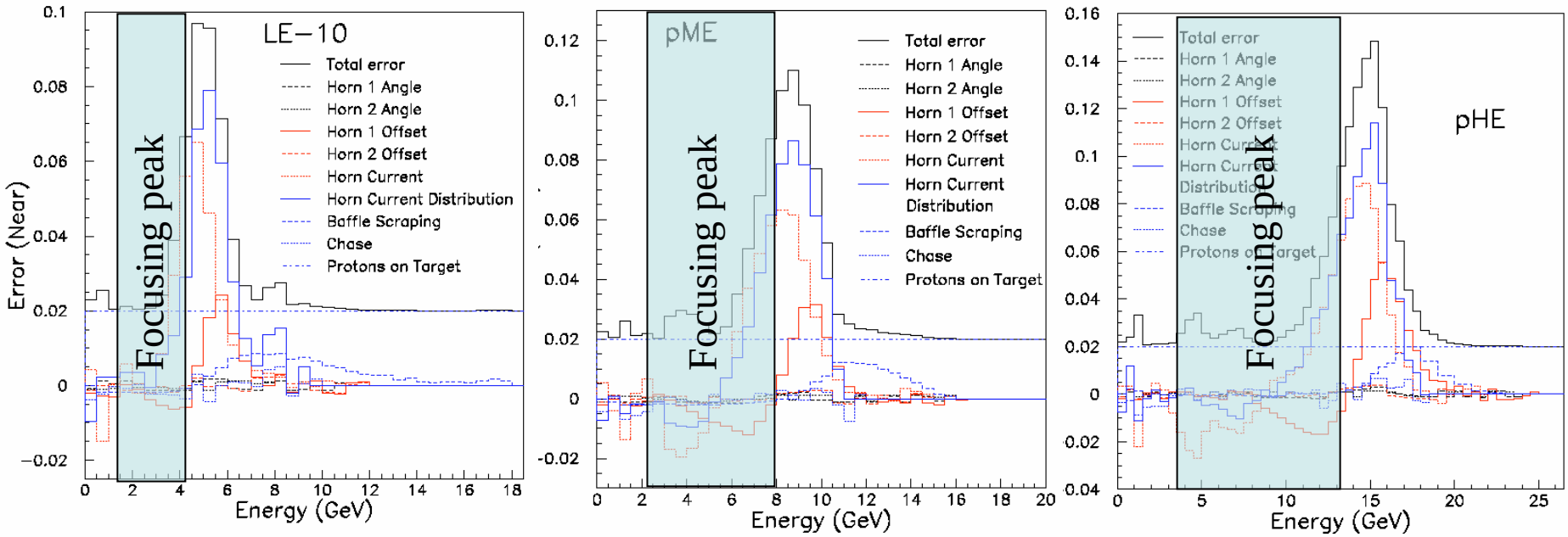
Typical Uncertainties


CC ν_μ Events/kt/GeV/3.8×10^{20}POT
Neutrino Energy (GeV)
BMPT
Geant3/Fluka
MARS−v.14
Malensek

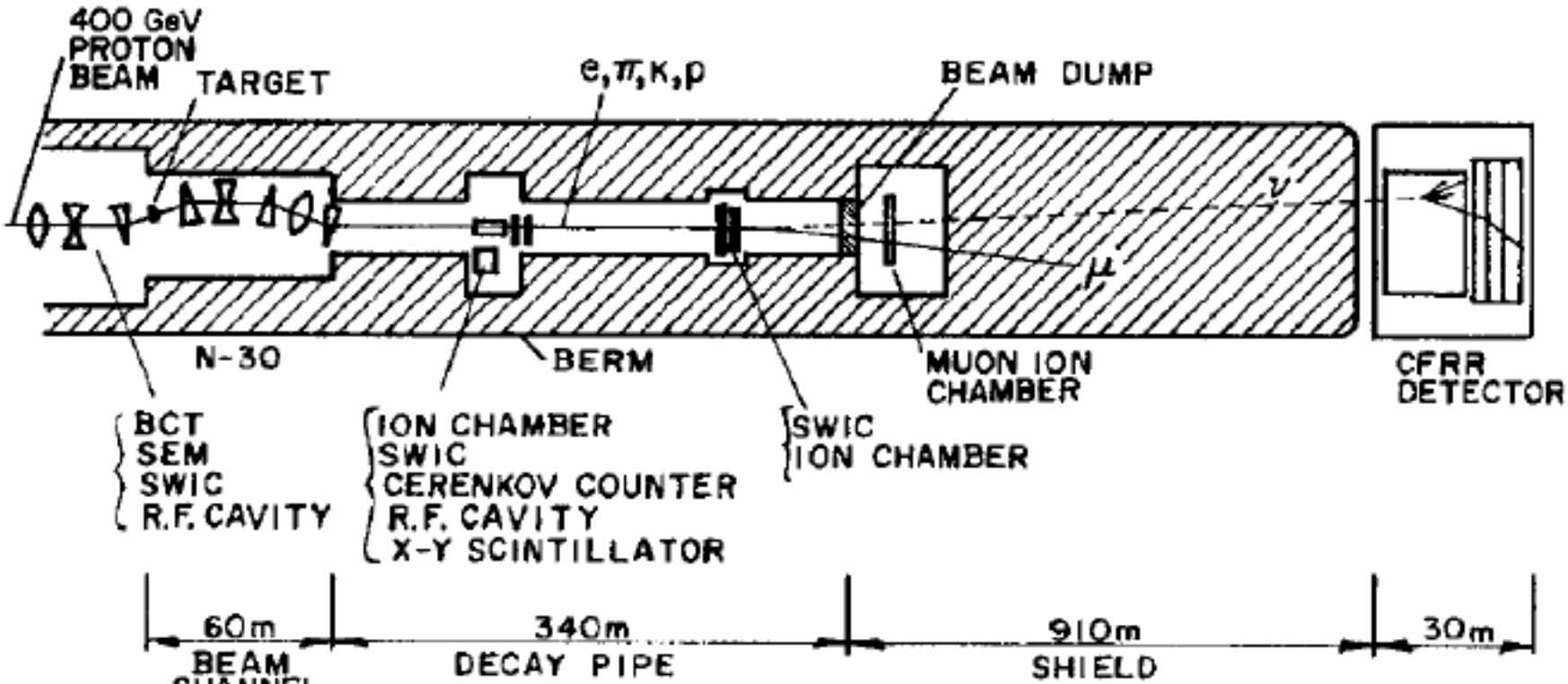

CC ν_μ Events/kt/GeV/3.8×10^{20}POT
Neutrino Energy (GeV)
BMPT
Geant3/Fluka
MARS−v.14
Malensek

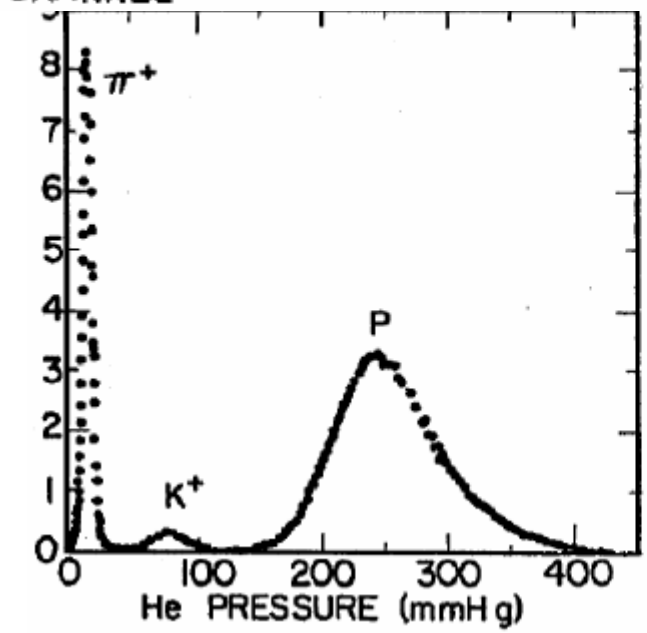

Near Detector - pions
LE Beam
HE Beam
p_T (GeV/c)
p_z (GeV/c)
0
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100
120
Atherton
400 GeV/c p-Be
Barton
100 GeV/c p-C
SPY
450 GeV/c p-Be

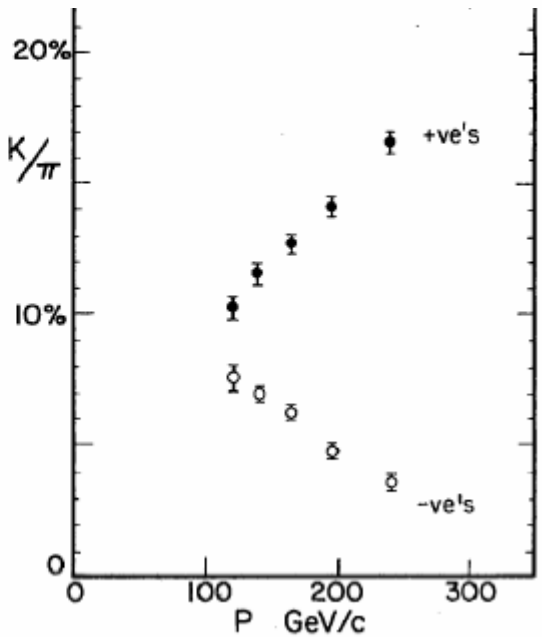

LE10/0kA
LE10/170kA
LE10/185kA
LE10/200kA
LE100/200kA
LE250/200kA
p_T (GeV/c)
p_z (GeV/c)

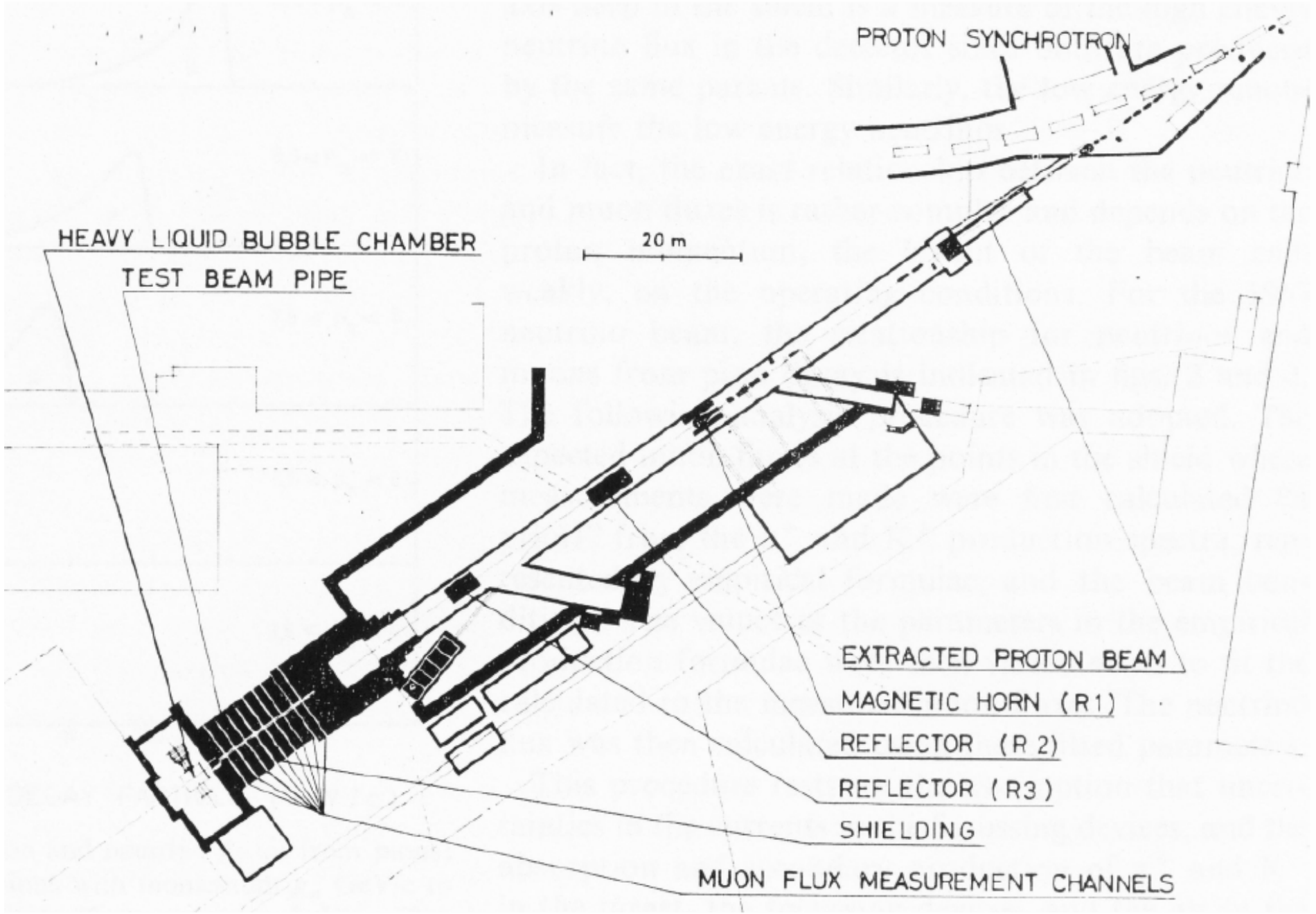

LE−10
Focusing peak
Total error
Horn 1 Angle
Horn 2 Angle
Horn 1 Offset
Horn 2 Offset
Horn Current
Horn Current Distribution
Baffle Scraping
Chase
Protons on Target
Error (Near)
Energy (GeV)
pME
Focusing peak
Total error
Horn 1 Angle
Horn 2 Angle
Horn 1 Offset
Horn 2 Offset
Horn Current
Horn Current Distribution
Baffle Scraping
Chase
Protons on Target
Energy (GeV)
pHE
Focusing peak
Total error
Horn 1 Angle
Horn 2 Angle
Horn 1 Offset
Horn 2 Offset
Chase
Energy (GeV)

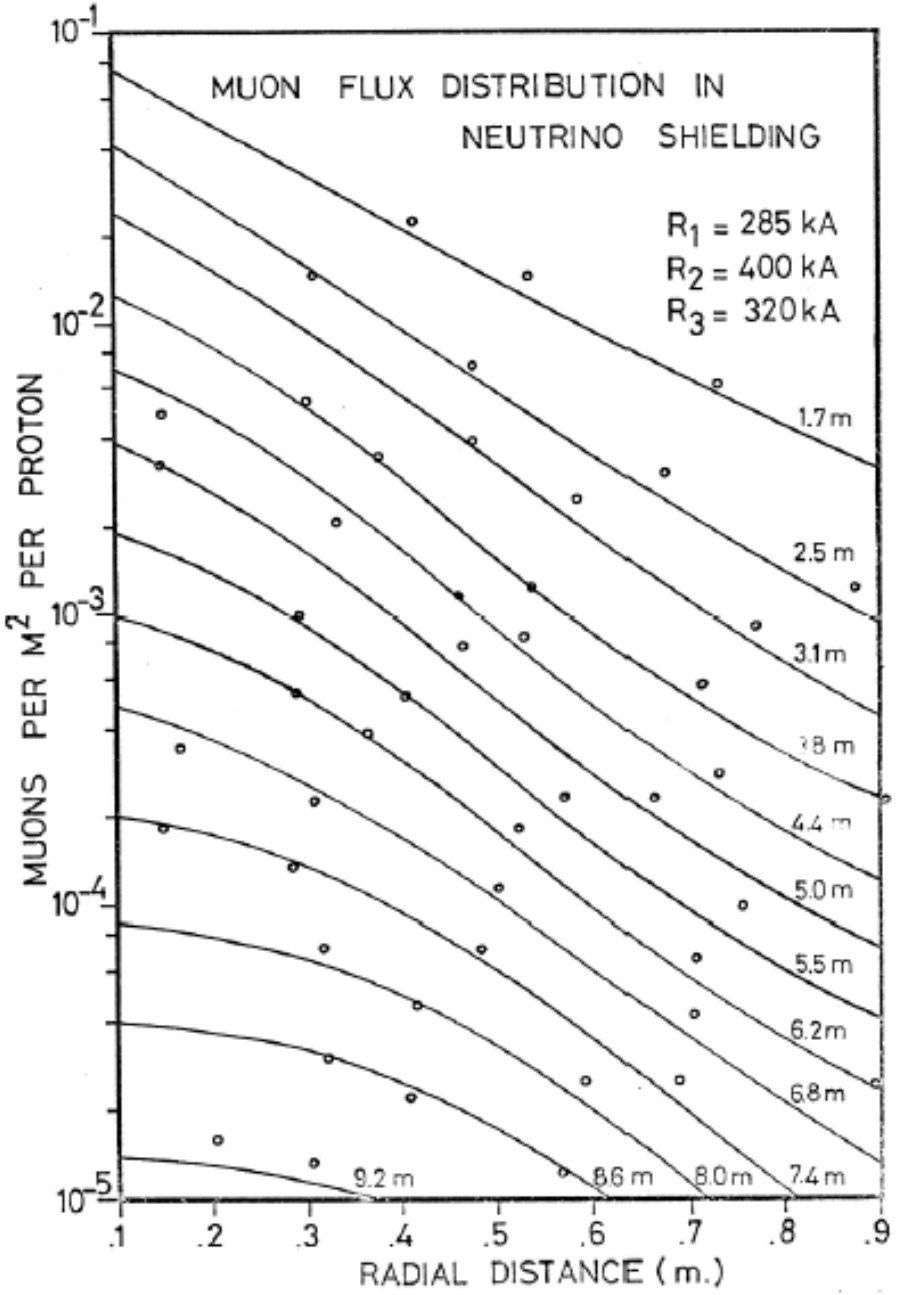
Monitoring/Measuring the ν Flux

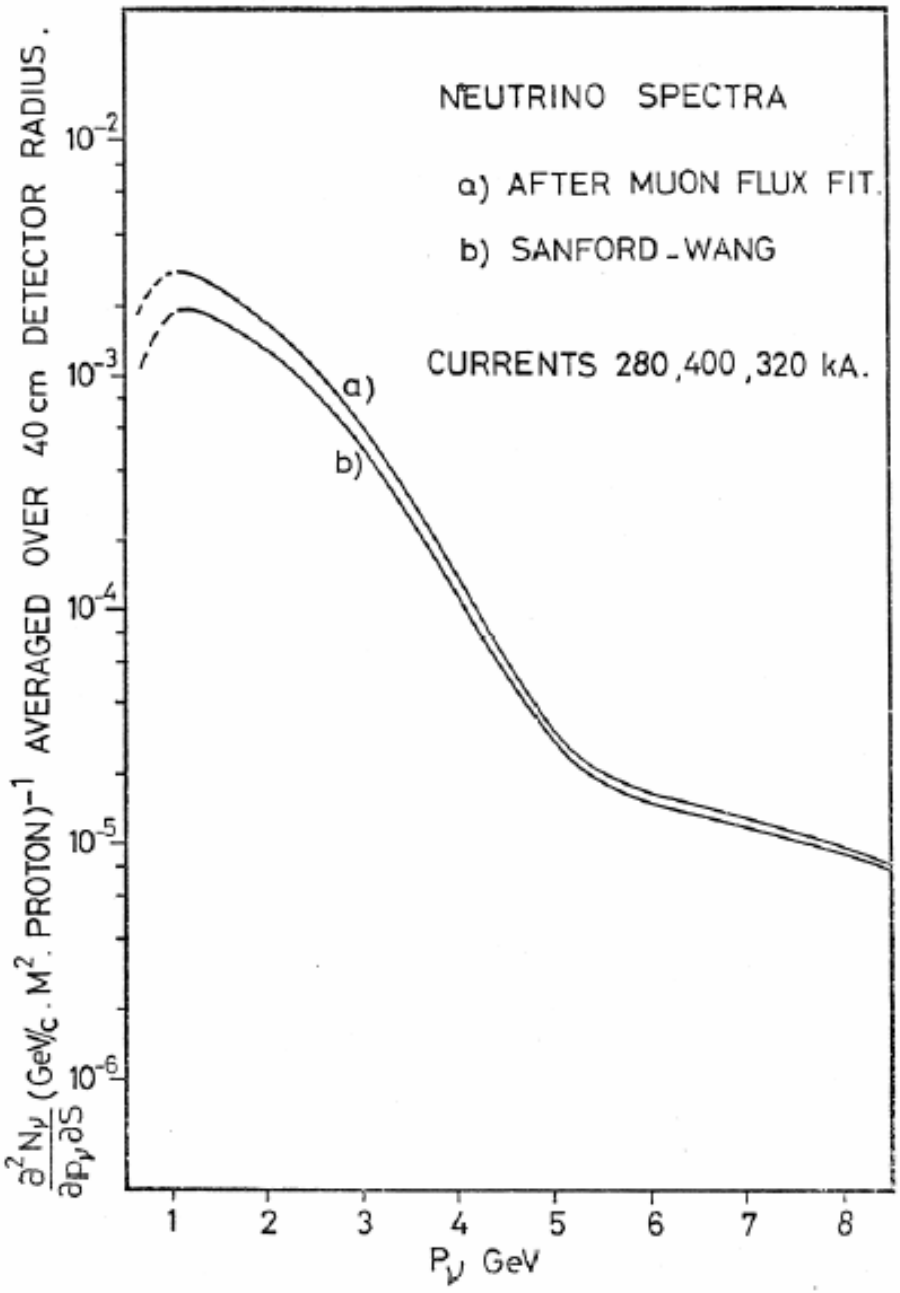

400 GeV
PROTON
BEAM
TARGET
e, π, K, p
BEAM DUMP
ν
μ
N-30
BERM
MUON ION
CHAMBER
CFRR
DETECTOR
BCT
SEM
SWIC
R.F. CAVITY
ION CHAMBER
SWIC
CERENKOV COUNTER
R.F. CAVITY
X-Y SCINTILLATOR
SWIC
ION CHAMBER
60m
BEAM
CHANNEL
340m
DECAY PIPE
910m
SHIELD
30m

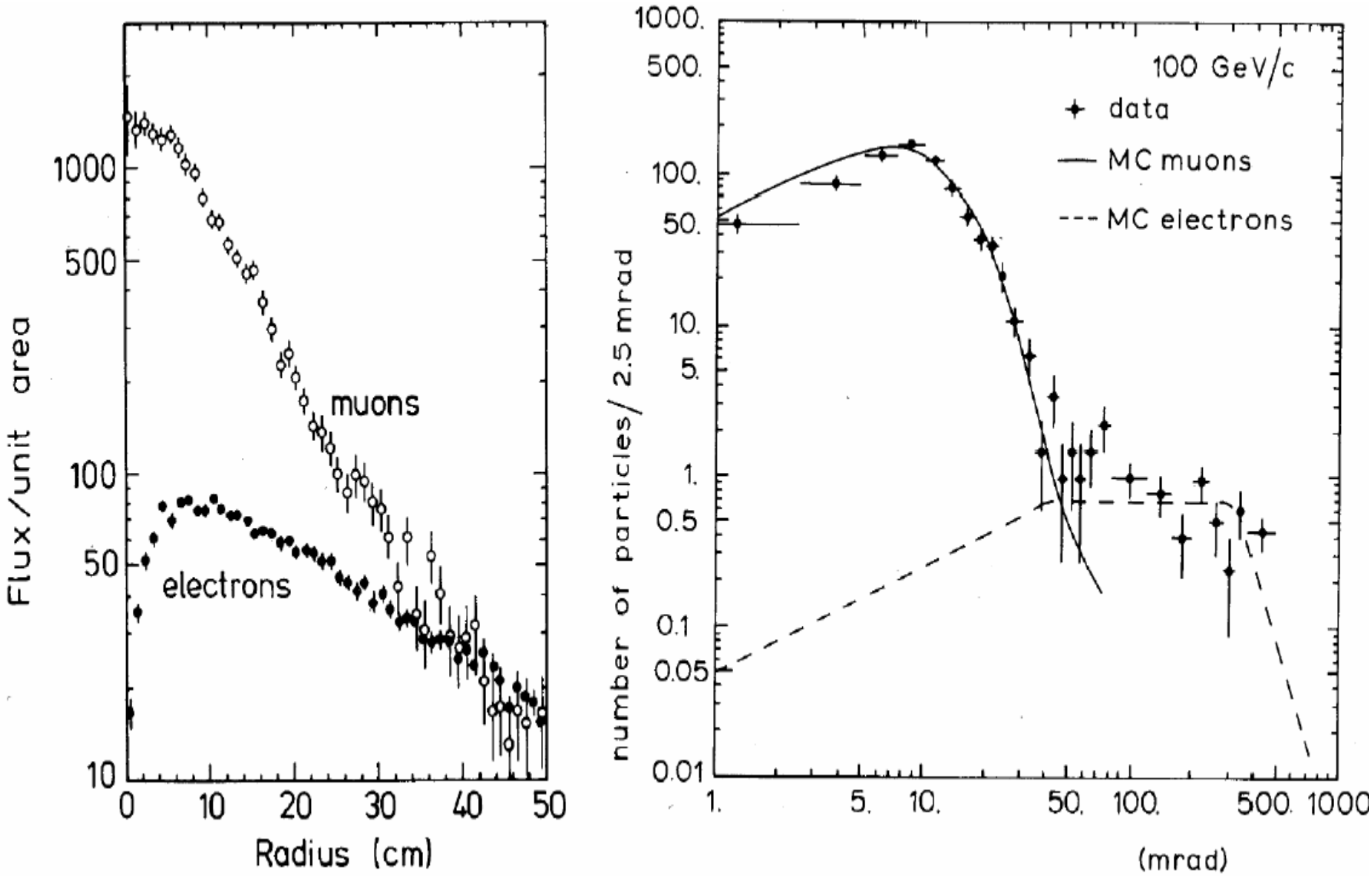

π+
K+
P
0
1
2
3
4
5
6
7
8
0
100
200
300
400
He PRESSURE (mmHg)

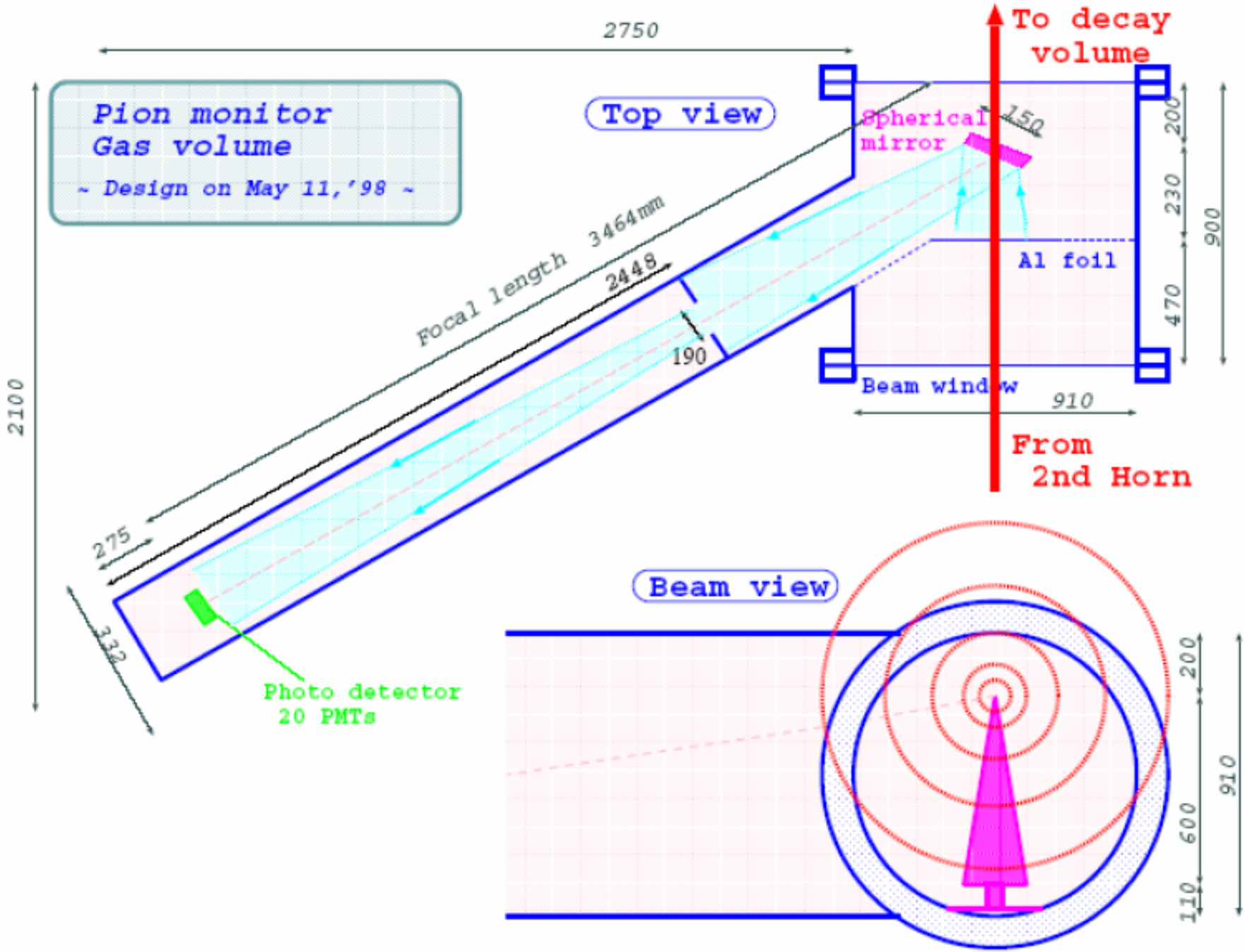

20%
10%
0
K/π
+ve's
-ve's
0
100
200
300
P GeV/c

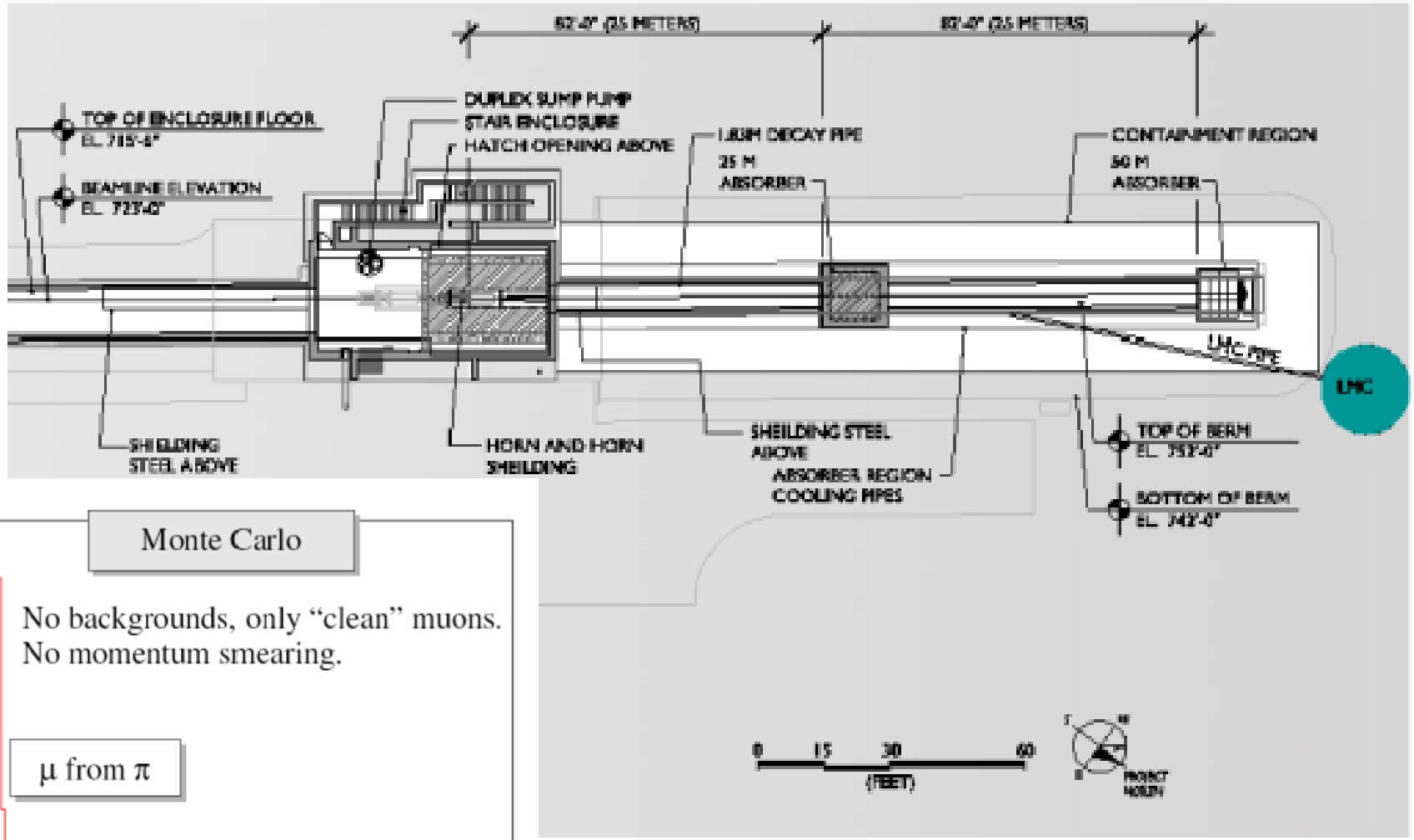

PROTON SYNCHROTRON
HEAVY LIQUID BUBBLE CHAMBER
TEST BEAM PIPE
20 m
EXTRACTED PROTON BEAM
MAGNETIC HORN (R1)
REFLECTOR (R 2)
REFLECTOR (R3)
SHIELDING
MUON FLUX MEASUREMENT CHANNELS

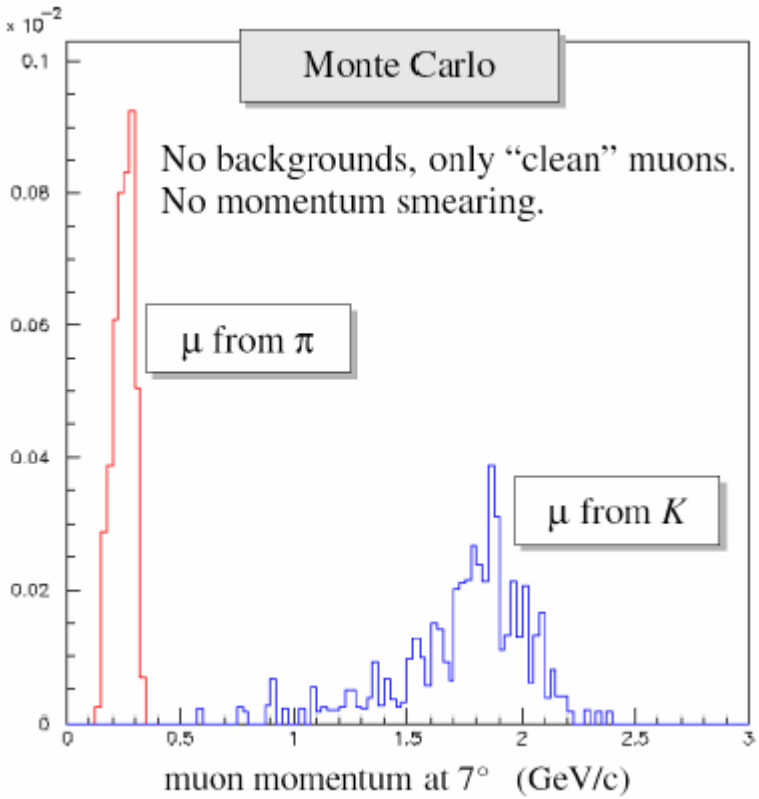

MUON FLUX DISTRIBUTION IN
NEUTRINO SHIELDING
R_1 = 285 kA
R_2 = 400 kA
R_3 = 320 kA
1.7 m
2.5 m
3.1 m
4.4 m
5.0 m
5.5 m
6.2 m
6.8 m
7.4 m
8.0 m
8.6 m
9.2 m
MUONS PER M^2 PER PROTON
RADIAL DISTANCE (m.)

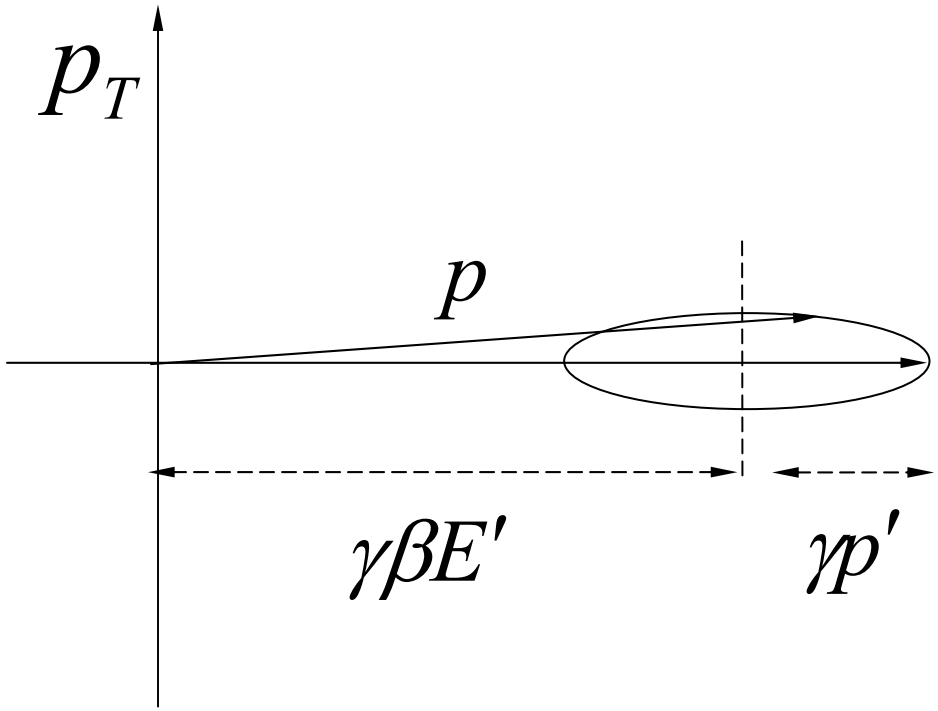

NEUTRINO SPECTRA
a) AFTER MUON FLUX FIT.
b) SANFORD - WANG
CURRENTS 280, 400, 320 kA.
a)
b)
$\frac{\partial^2 N_\nu}{\partial p_\nu \partial S}$ (GeV/c . M^2 . PROTON)$^{-1}$ AVERAGED OVER 40 cm DETECTOR RADIUS.
P_ν GeV

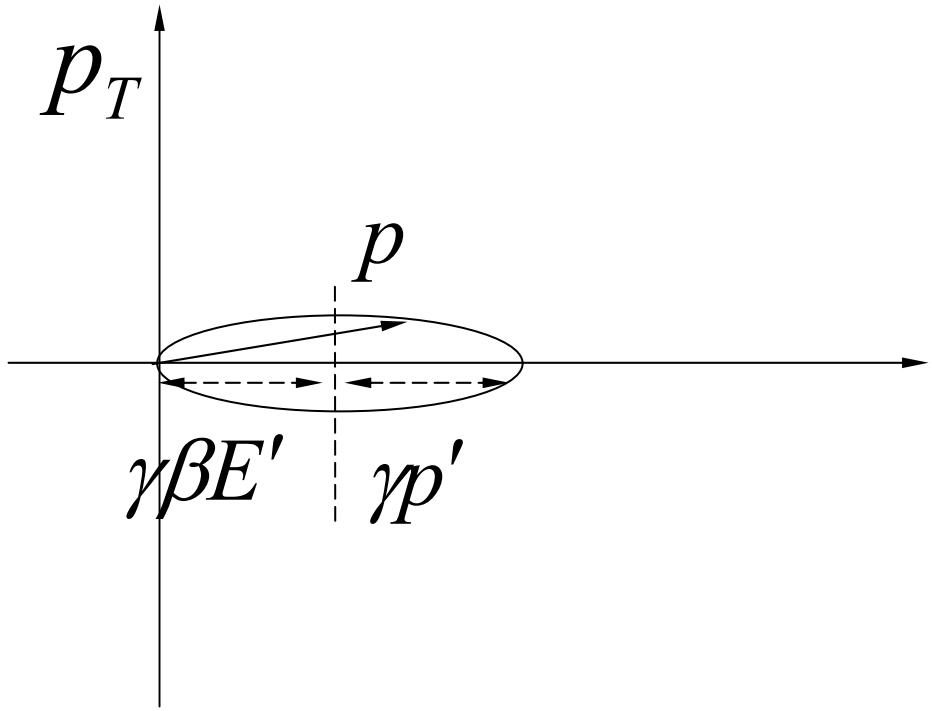

Flux/unit area
1000
500
100
50
10
muons
electrons
0
10
20
30
40
50
Radius (cm)
1000.
500.
100.
50.
10.
5.
1.
0.5
0.1
0.05
0.01
number of particles/ 2.5 mrad
100 GeV/c
data
MC muons
MC electrons
1.
5.
10.
50.
100.
500.
1000
(mrad)


Pion monitor
Gas volume
~ Design on May 11,'98 ~
Top view
2750
2100
Focal length 3464mm
2448
190
275
332
Photo detector
20 PMTs
Spherical mirror
150
Al foil
Beam window
910
200
230
470
900
To decay volume
From 2nd Horn
Beam view
200
600
110
910


TOP OF ENCLOSURE FLOOR
EL. 715'-9"
BEAMLINE ELEVATION
EL. 723'-0"
DUPLEX SUMP PUMP
STAIR ENCLOSURE
HATCH OPENING ABOVE
SHIELDING STEEL ABOVE
HORN AND HORN SHIELDING
1.8M DECAY PIPE
25 M ABSORBER
SHEILDING STEEL ABOVE
ABSORBER REGION COOLING PIPES
CONTAINMENT REGION
50 M ABSORBER
LMC
TOP OF BERM
EL. 753'-0"
BOTTOM OF BERM
EL. 742'-0"
0 15 30 60
(FEET)


Monte Carlo
No backgrounds, only "clean" muons.
No momentum smearing.
μ from π
μ from K
muon momentum at 7° (GeV/c)





Muon in Lab

$E'_\mu = 109 MeV$

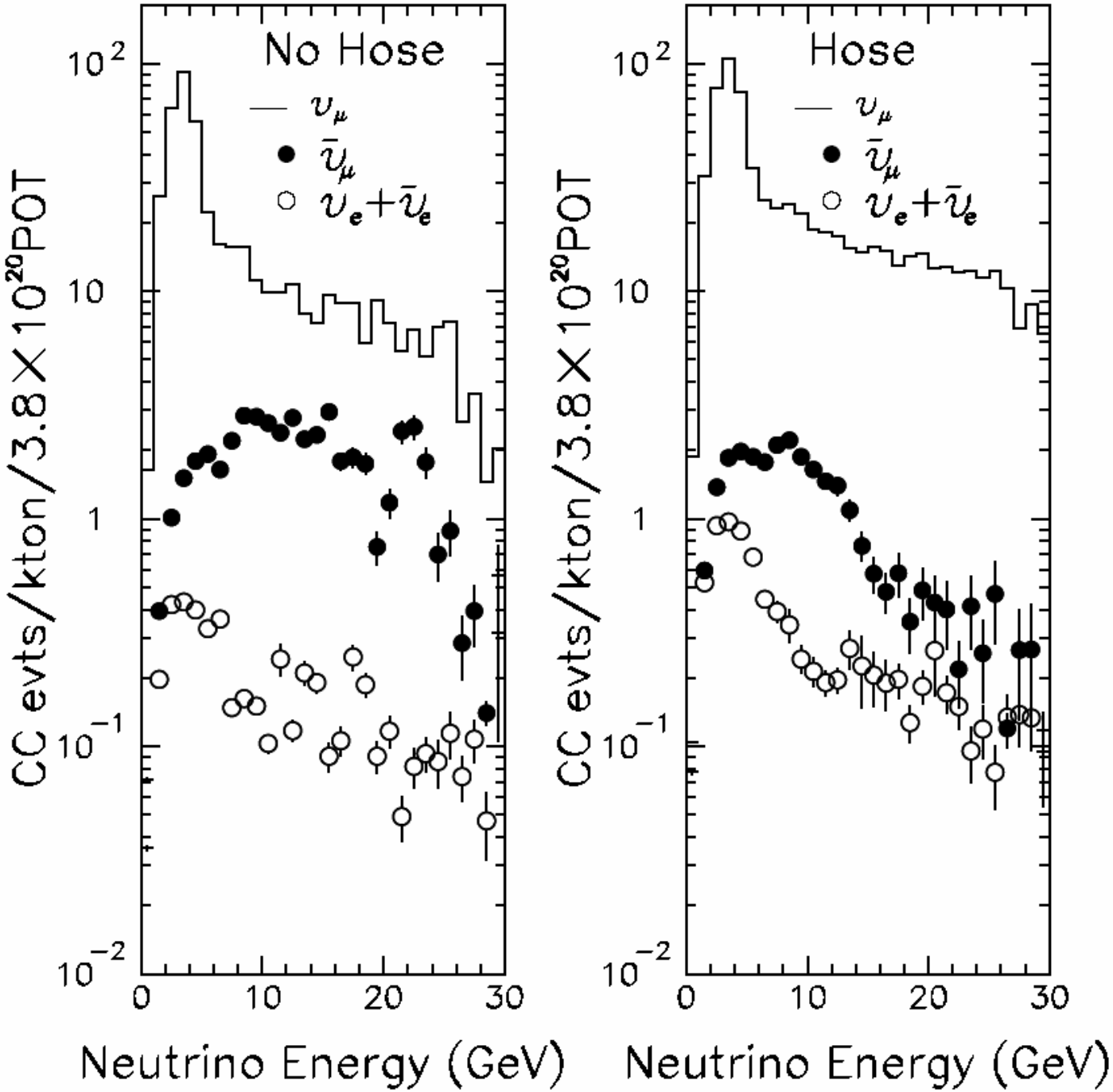
$p' = 30 MeV$

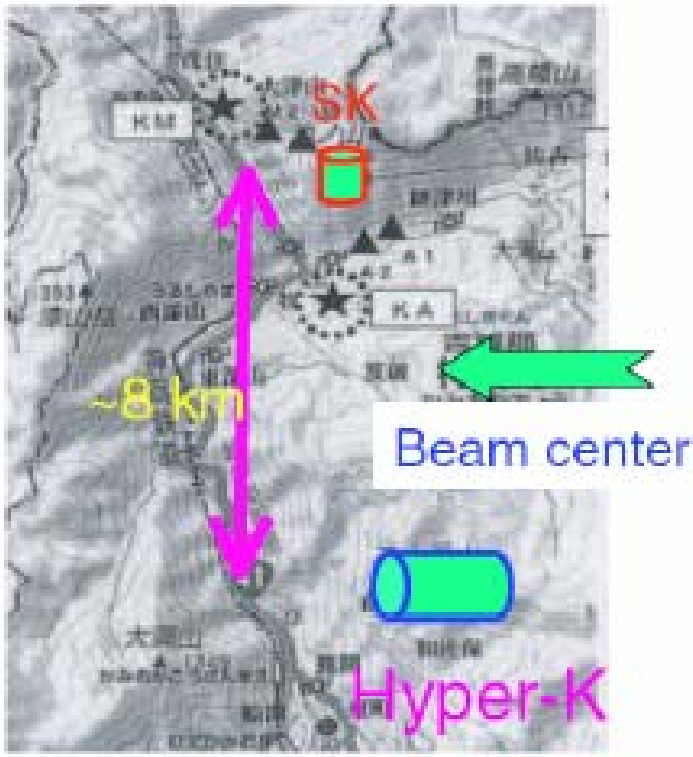
$\theta_\mu^{\max} \approx \beta' / \beta\gamma$

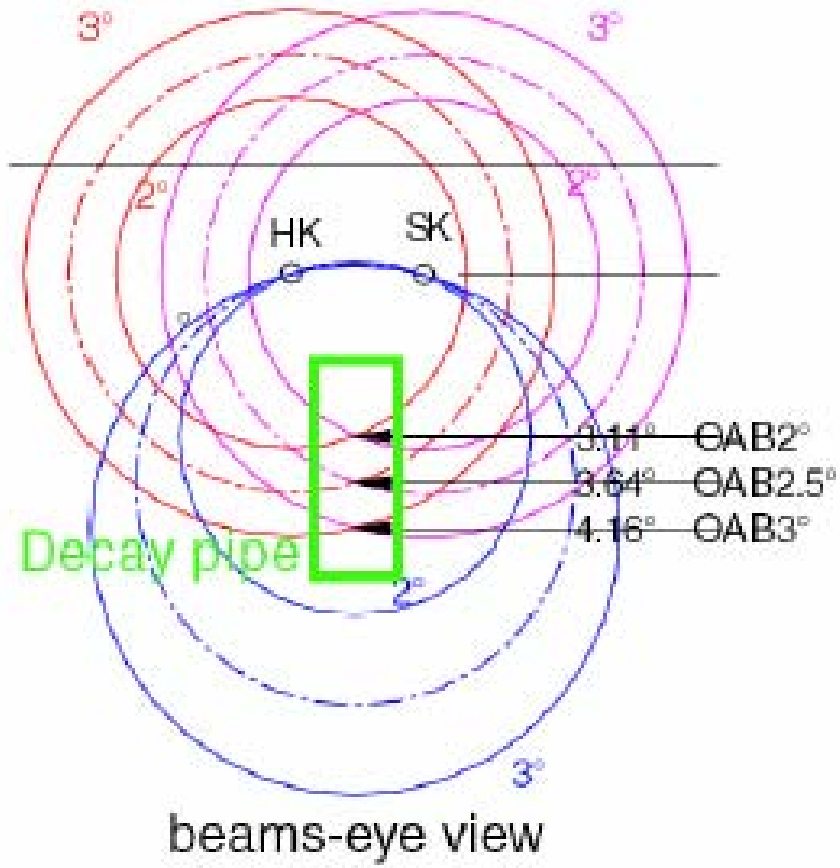
Neutrino in Lab

$E'_\nu = p' = 30 MeV$

$\theta_\nu^{\max} \approx \beta' / \beta\gamma = 1/\beta\gamma$


No Hose
Hose
ν_μ
$\bar{\nu}_\mu$
$\nu_e+\bar{\nu}_e$
CC evts/kton/3.8×10^{20}POT
Neutrino Energy (GeV)
Neutrino Energy (GeV)
10^2
10
1
10^{-1}
10^{-2}
0
10
20
30





beams-eye view