F.E. Taylor - MIT
PAC Review 5/24/93

GEM Muon System

- Physics Objectives
- Design Goals
- General Features
- Chamber Technology
- Drivers of the Design
- System Performance
- Muon Organization
- Summary

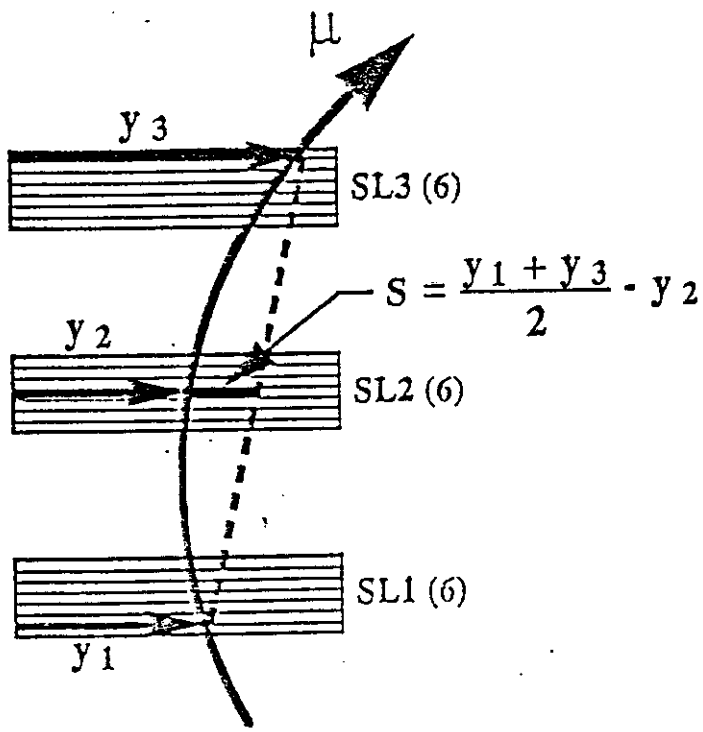
Pt from Sagitta Measurement

- At $|\eta| \approx 0$ (90°) for $\mu \pm$

$$S = \pm \frac{0.3\ BL^2}{8P_t}$$

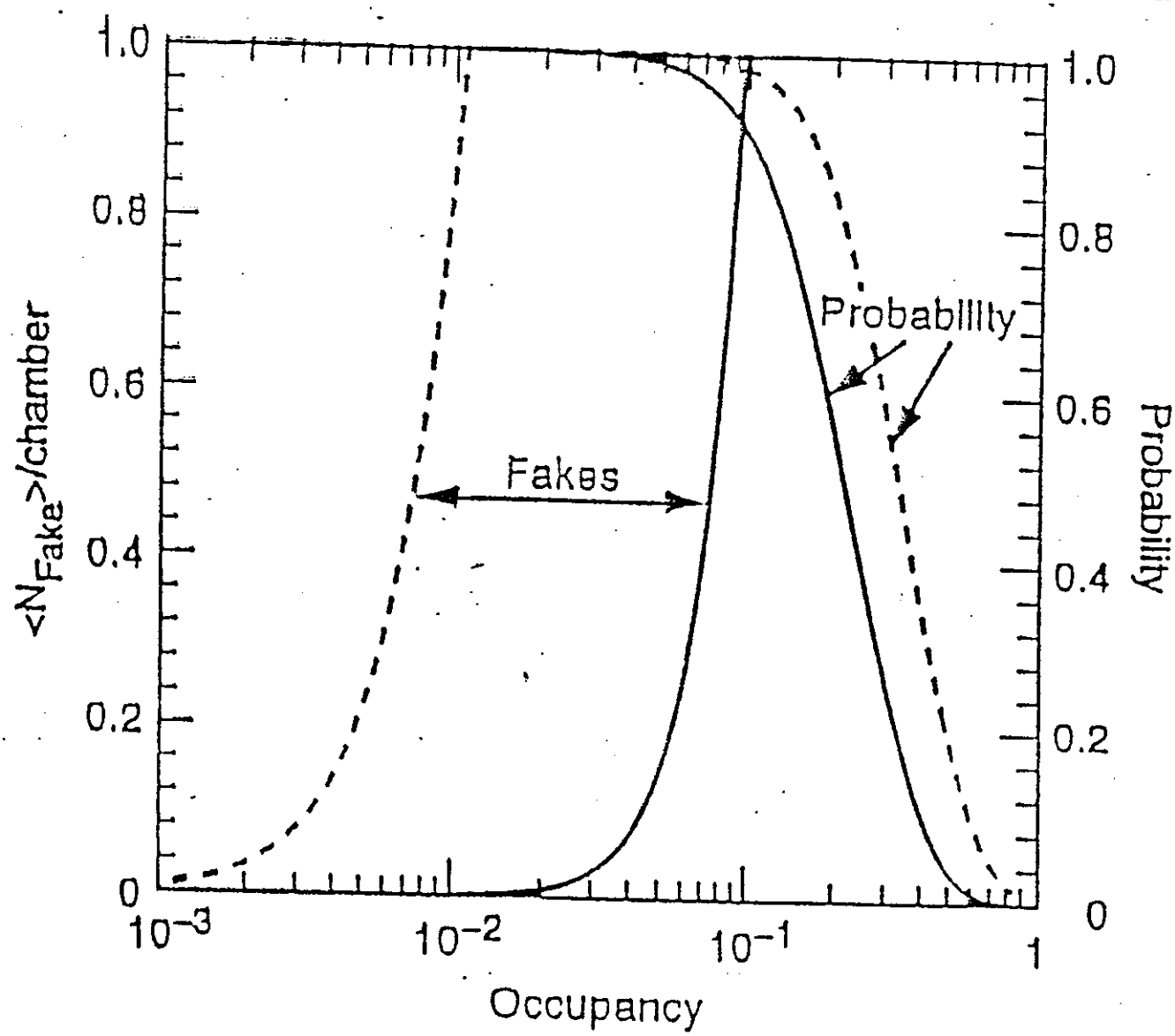
- S = 1.1 mm for Pt = 500 GeV/c

- Total error "budget" at 500 GeV/c $\delta S \approx 50\ \mu m$

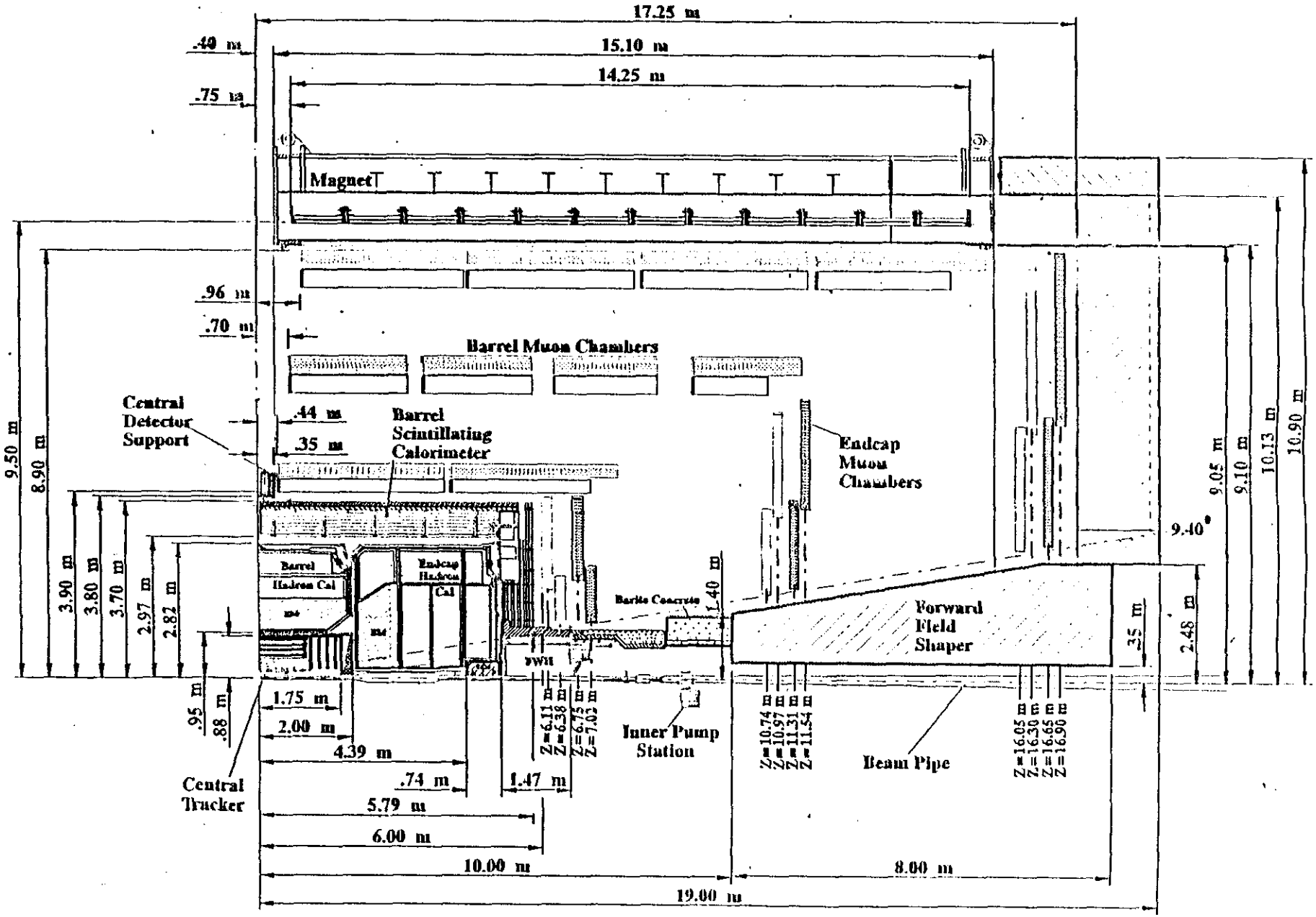


Operation at High Luminosity

- Require chamber occupancy ≤ few %:
  - pattern recognition intact
  - trigger rate tolerable



GEM DETECTOR PARAMETERS
BASELINE 2



(DETpara/930426/ZC)

Features

(1) Large superconducting magnet

- Sagitta method: [BL^2/σ figure of merit]

(2) One technology for all functions

- Cathode strip chambers (CSC)
- Timing, triggering, tracking

(3) Functions stand-alone at $L \approx 10^{34}$

- Shielded by thick calorimeter
- Muon chambers:
  finely segmented
  fast time response

(4) Good resolution up to high Pt

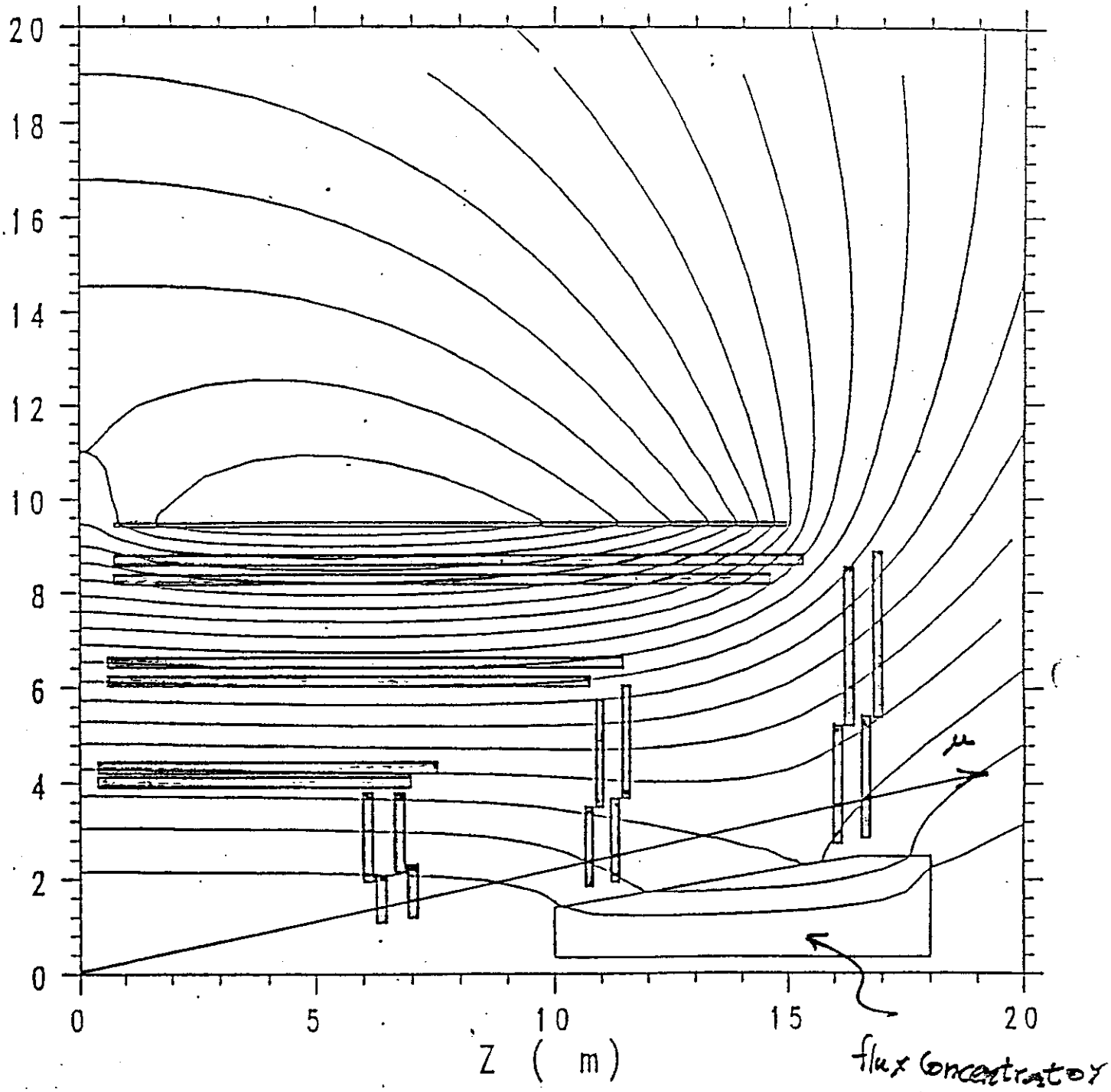
Pt = 500 GeV/c:

$\delta Pt/Pt \approx 5\ \%$ at $|\eta| \approx 0$ ($\theta \approx 90^o$)
$\delta Pt/Pt \approx 12\ \%$ at $|\eta| \approx 2.5$ ($\theta \approx 9.5^o$)

(5) Pt trigger and beam cross tag

- Can select up to Pt ≈ 50 GeV/c

GEM Magnetic Field



2 φ segments of chambers shown

The Muon System in GEM

- Calorimeter:

  Muon Filter - Absorber: 11 λ to 16 λ

  Reconstruct $\Delta E\mu$ - Isolated muons

- Central Tracker:

  Primary vertex constraint

  Vertex resolution $\delta Z \approx 1$ mm
  $\delta b \approx 25$ μm

  Isolation cuts of muon track in calorimeter

  $\Delta E\mu$ correction

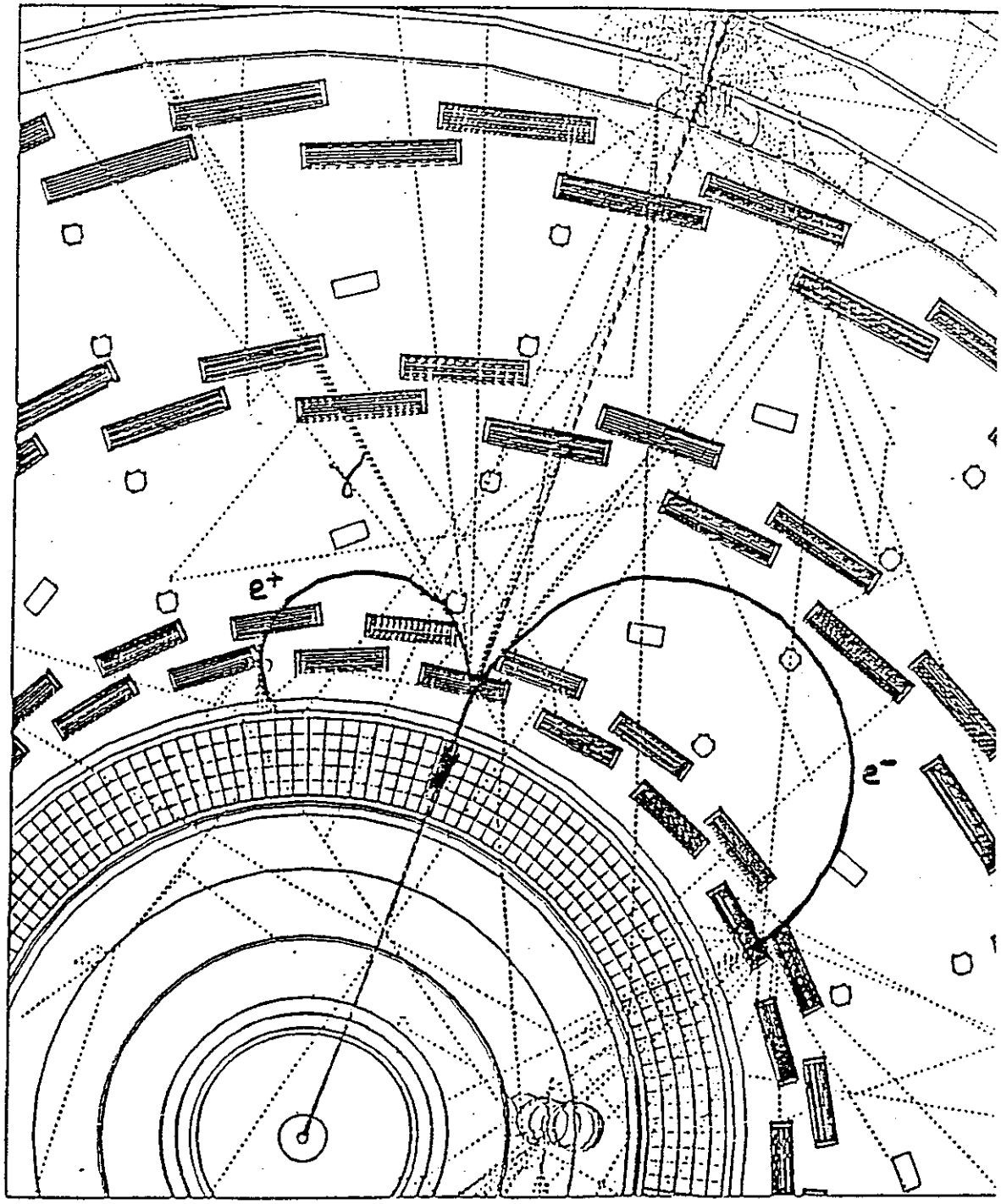
  Muon background rejection by track matching

  Coverage of muon gaps

  Improved momentum resolution at low Pt

  Resolutions - low p $\Delta p/p = 3.5$ %
  - high p $\Delta p/p^2 = (1.2) \times 10^{-3}$ $(GeV/c)^{-1}$

System Performance 1 Tev/c



Chamber Configuration

- Considerations:

inner layer

- δ-rays and EM showers ==> fine segmentation
- enough layers to find local track
- separated from calorimeter

middle layer

- for Pt resolution

==> small X0 and large number of layers $\sigma/\sqrt{N}$

outer layer

- more coarse segmentation to reduce cost
- enough layers to find local track

- Design configuration:

- barrel	6-6-6
- endcap	8-6-6

Parameters of GEM Muon System

Geometry:	
Magnetic field at the IP	0.8 T
Barrel region: ($29^\circ < \theta < 84^\circ$)	$0.1 < \lvert\eta\rvert < 1.3$
Endcap region: ($9.75^\circ < \theta < 29^\circ$)	$1.4 < \lvert\eta\rvert < 2.46$
Number of sectors in ϕ	48
Barrel lever arm	> 4.2 m
Endcap lever arm	> 8.6 m
Chamber parameters:	
Spatial resolutions:	
Single-layer resolution (RMS)	75 μm
Nonbend plane resolution	0.8–1.5 cm
Beam crossing tag efficiency (6 layers)	> 99%
Internal chamber alignment	50 μm
Superlayer-to-superlayer alignment	25 μm
Radiation length/chamber layer	1.1 %
No. of layers per SL (SL1:SL2:SL3)	6:6:6 barrel 8:6:6 endcap
No. of chambers in barrel	960
No. of chambers in endcaps	480
No. of bend plane channels – barrel	645,120
No. of bend plane channels – endcaps	276,480
No. of non-bend plane channels – barrel	221,184
No. of non-bend plane – endcaps	92,160

Chamber Technology

- Baseline for TDR:

  Trigger and Tracking Functions: barrel and endcaps

  CSC = Cathode Strip Chambers

- Considered:

  Tracking Function:

  LSDT = Limited Streamer Drift Tubes

  RDT = Round Drift Tubes (pressurized)

  Triggering Function:

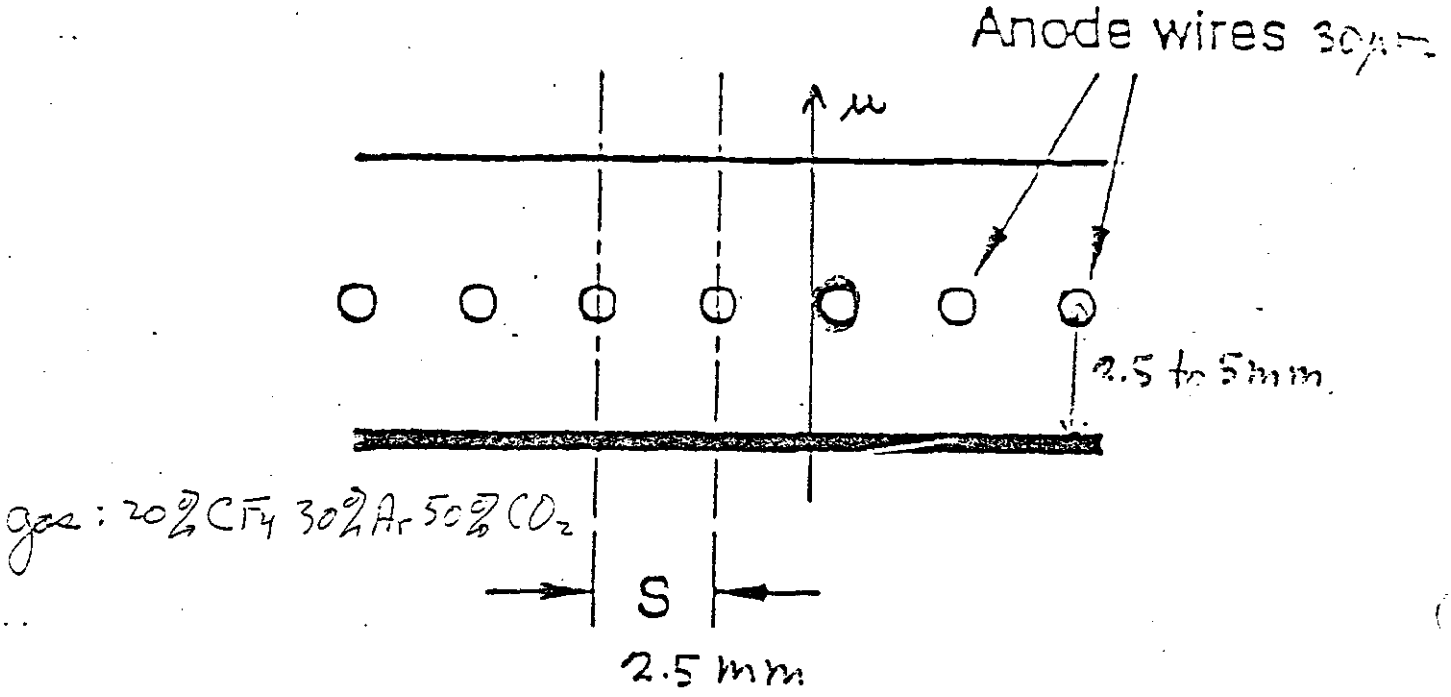
  RPC = Resistive Plate Counters

- Chamber Testing Program:

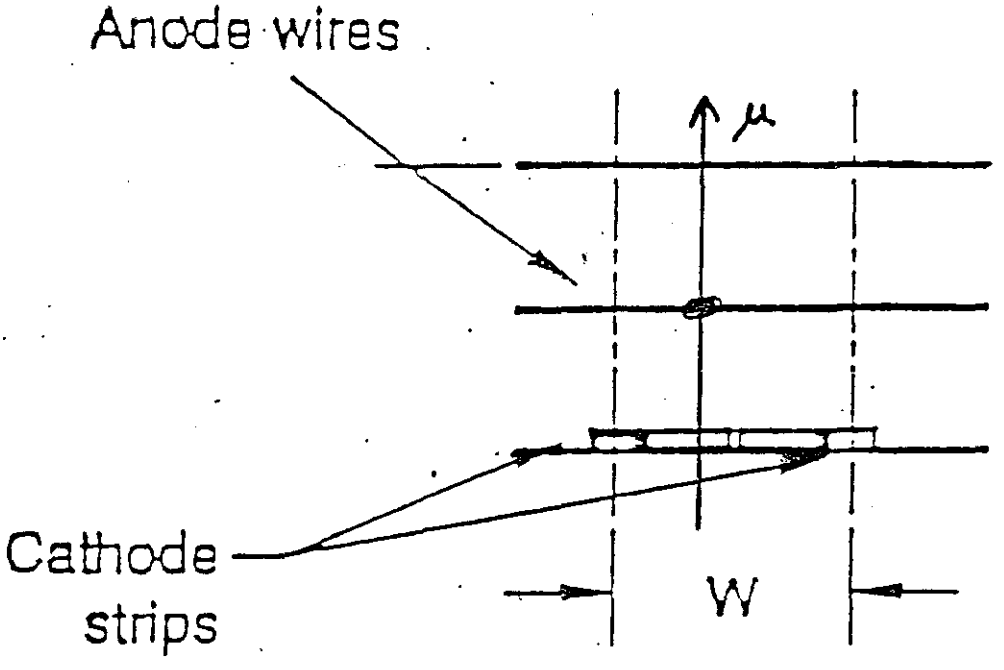
  TTR = Texas Test Rig (Cosmic ray muon laboratory at SSCL)

Cathode Strip Chambers

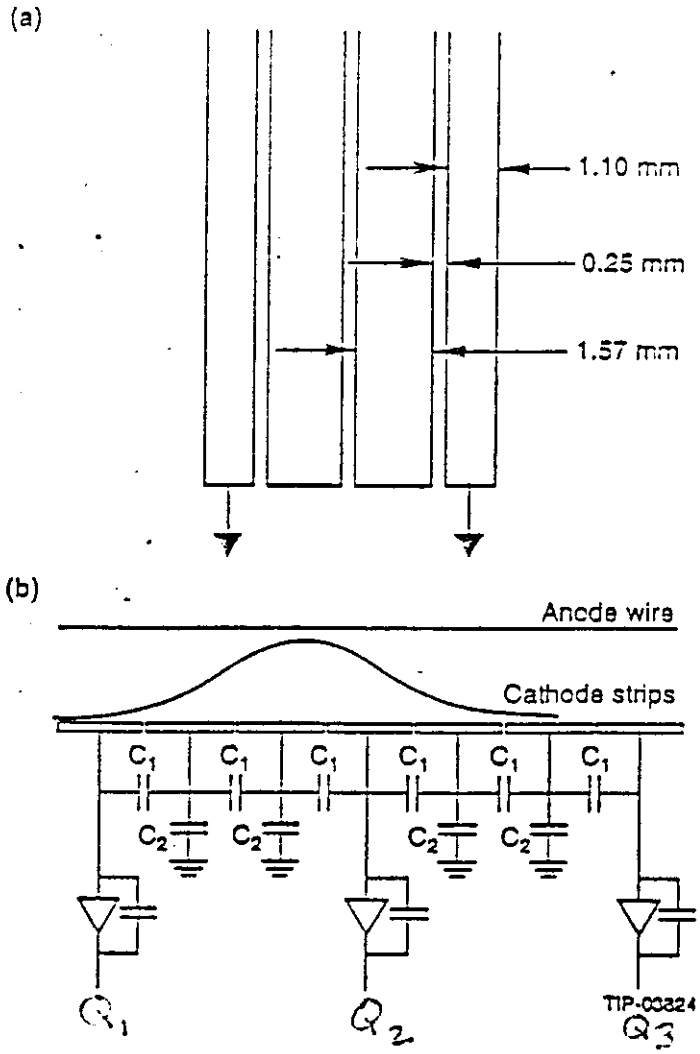
- End view (alone anode wires)

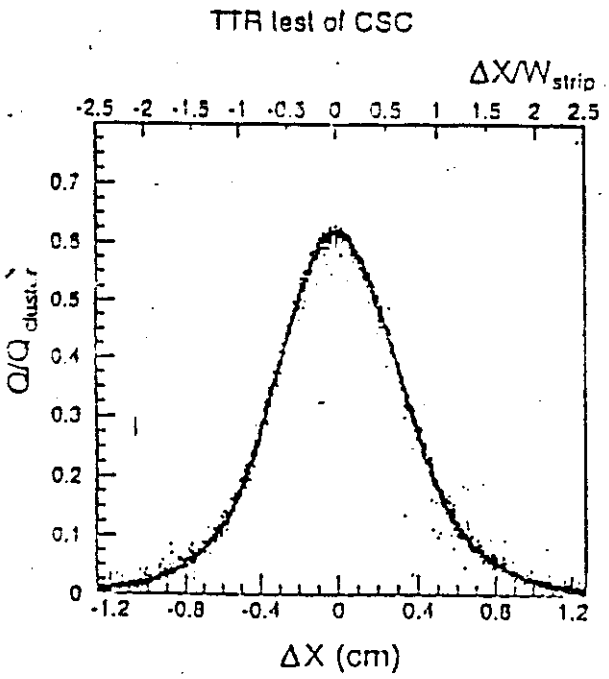


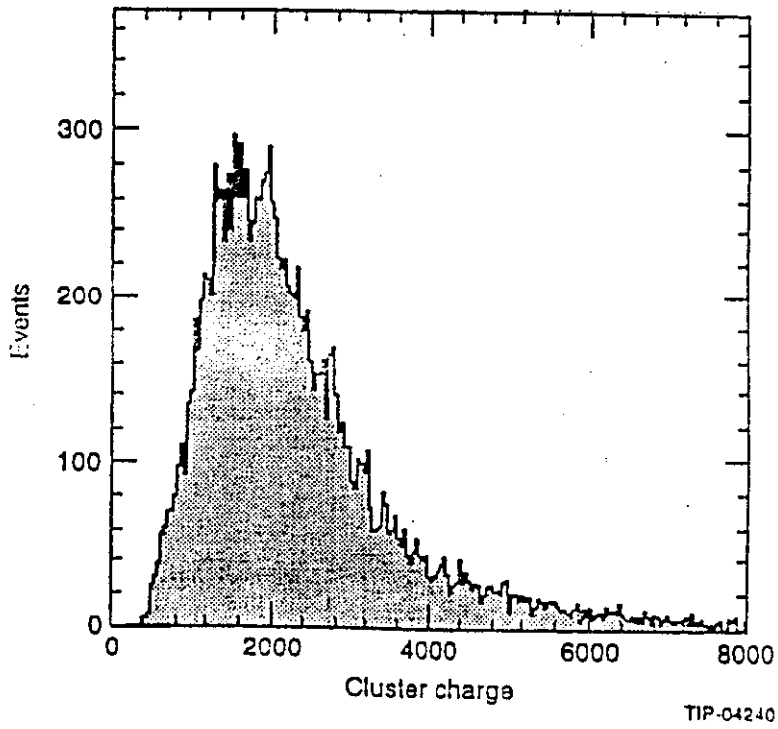
- Side view (alone cathode strips)



Bend Plane Readout

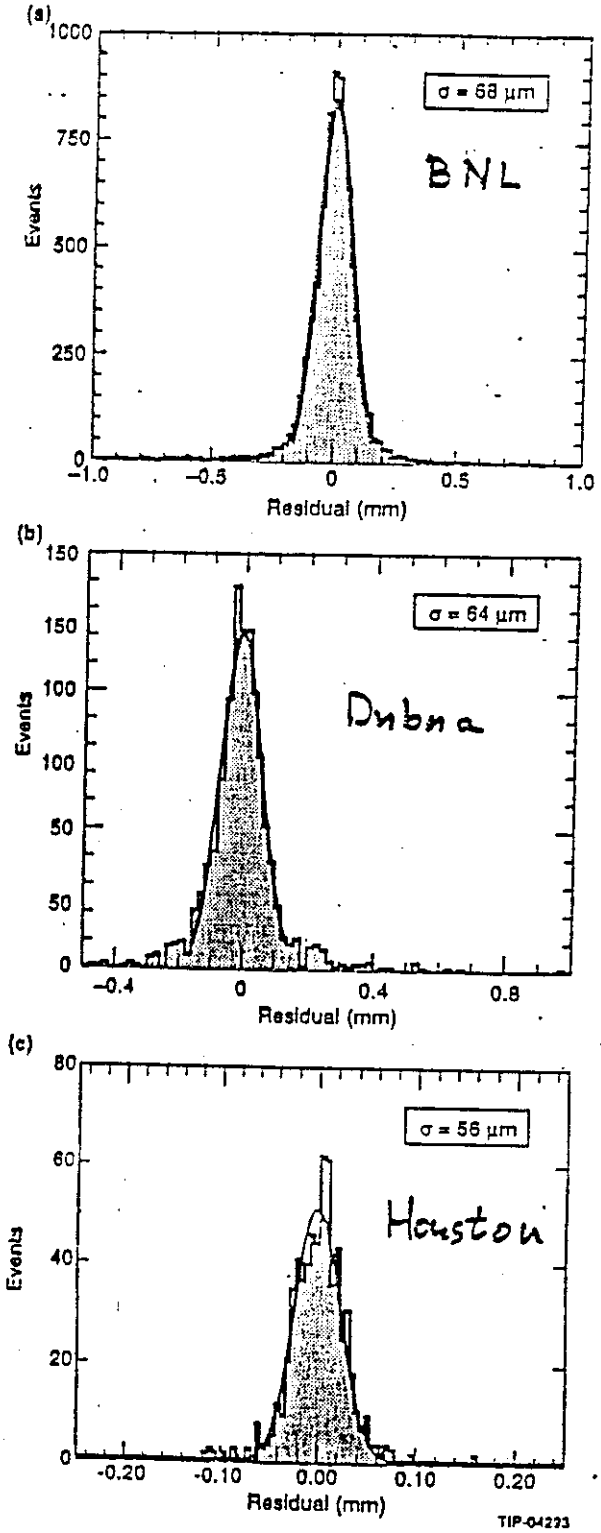




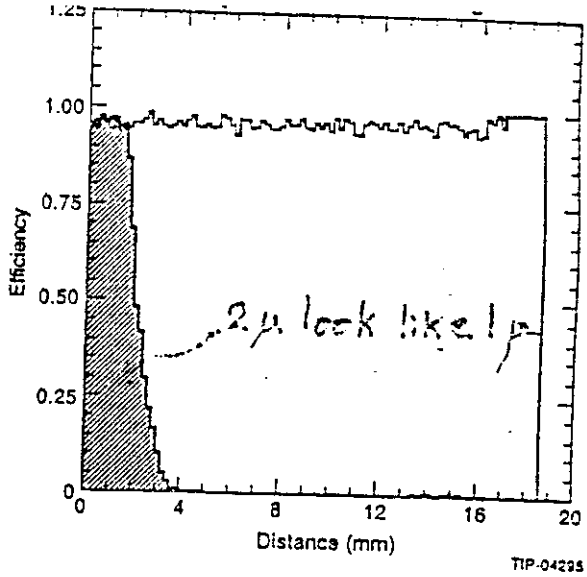


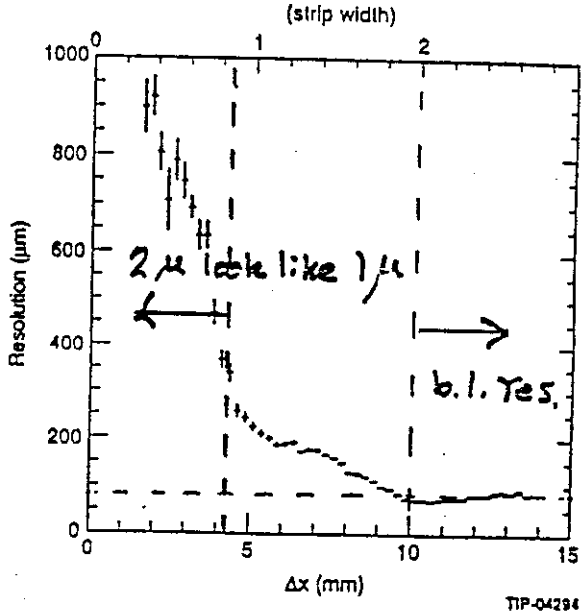
CSC Resolutions

Single Track:

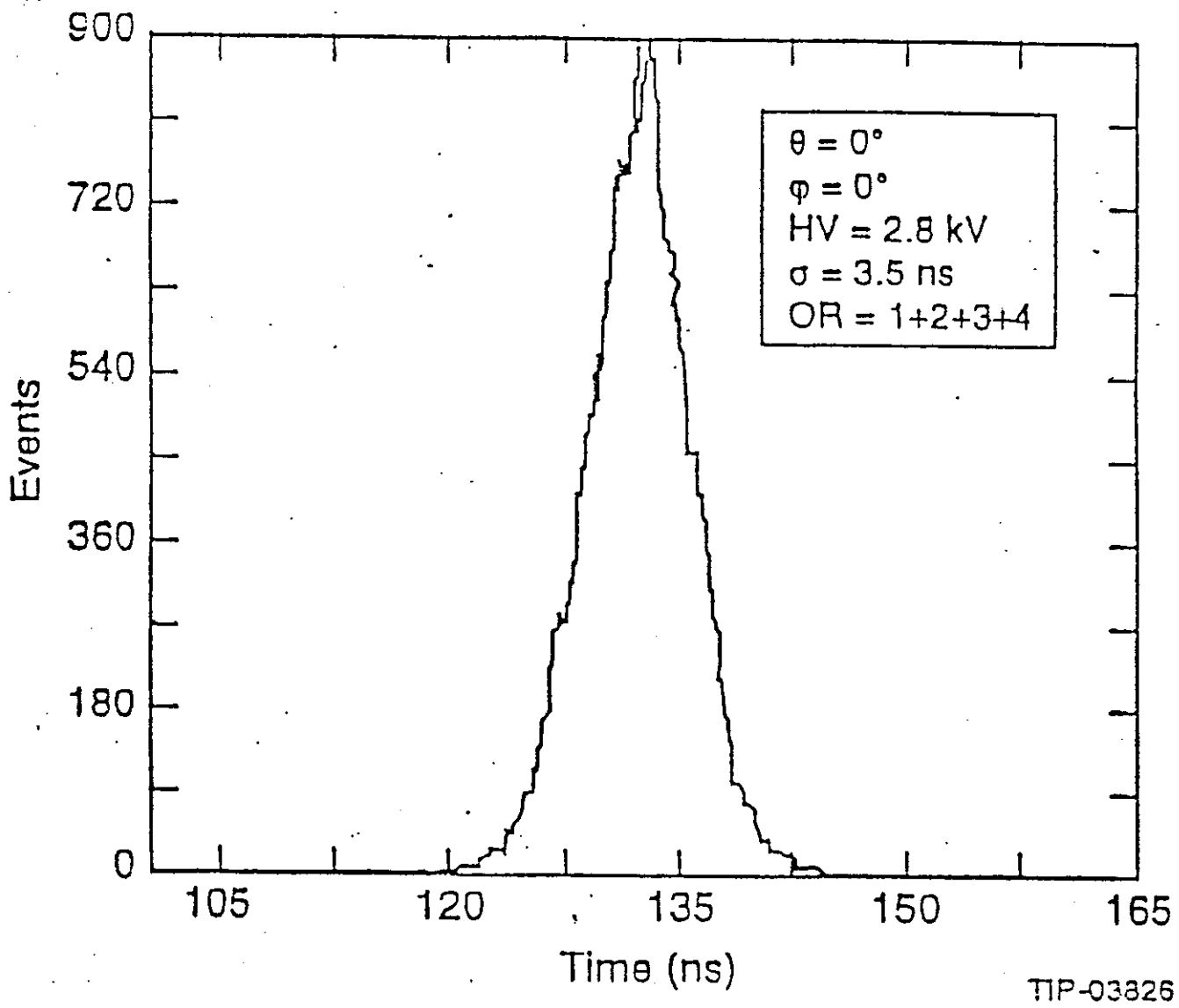


Dual Track:



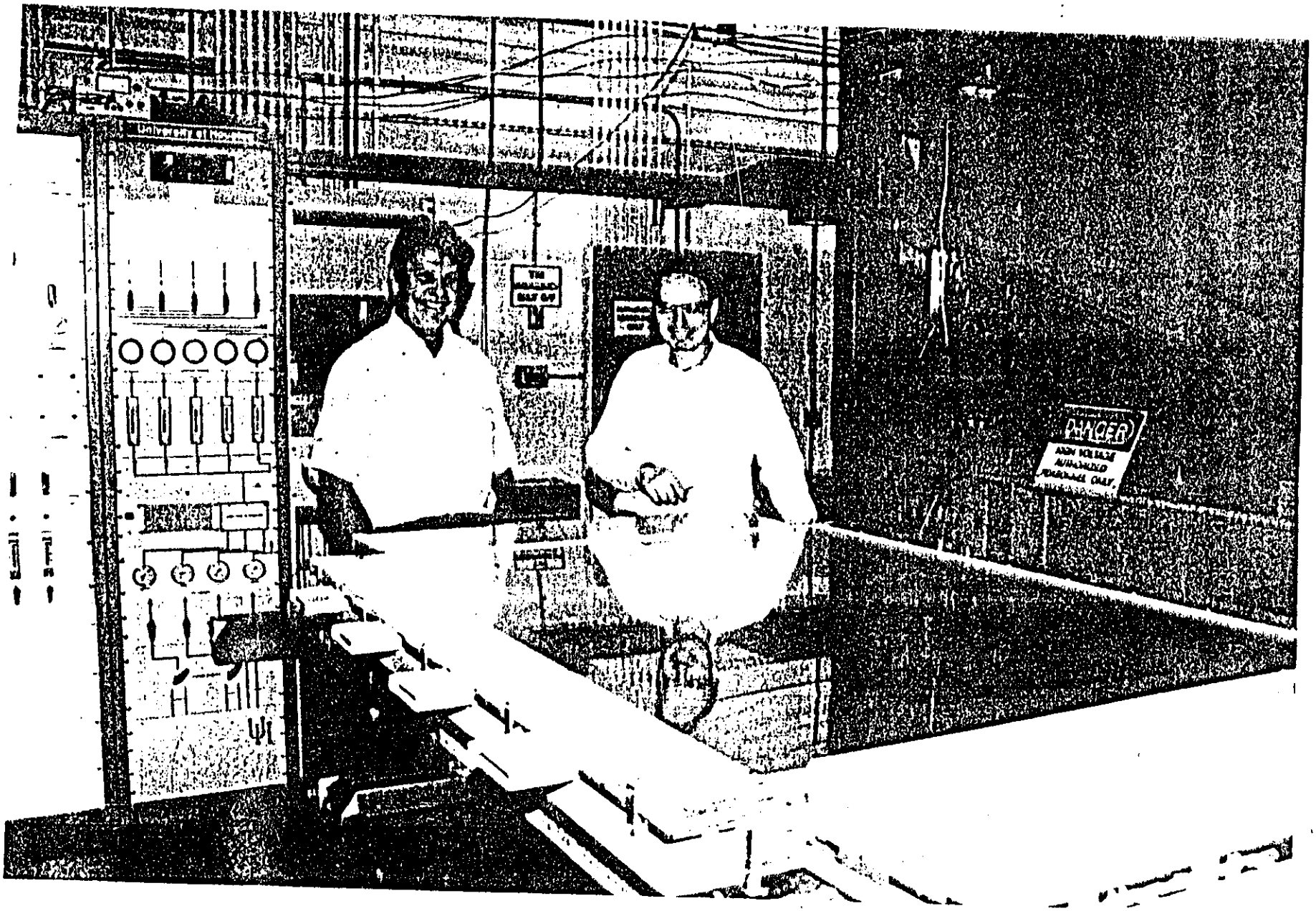


CSC Timing Resolution



OR of 4 planes $\varepsilon_{tag} \approx 98\%$

OR of 6 planes $\varepsilon_{tag} \approx 99\%$


DANGER

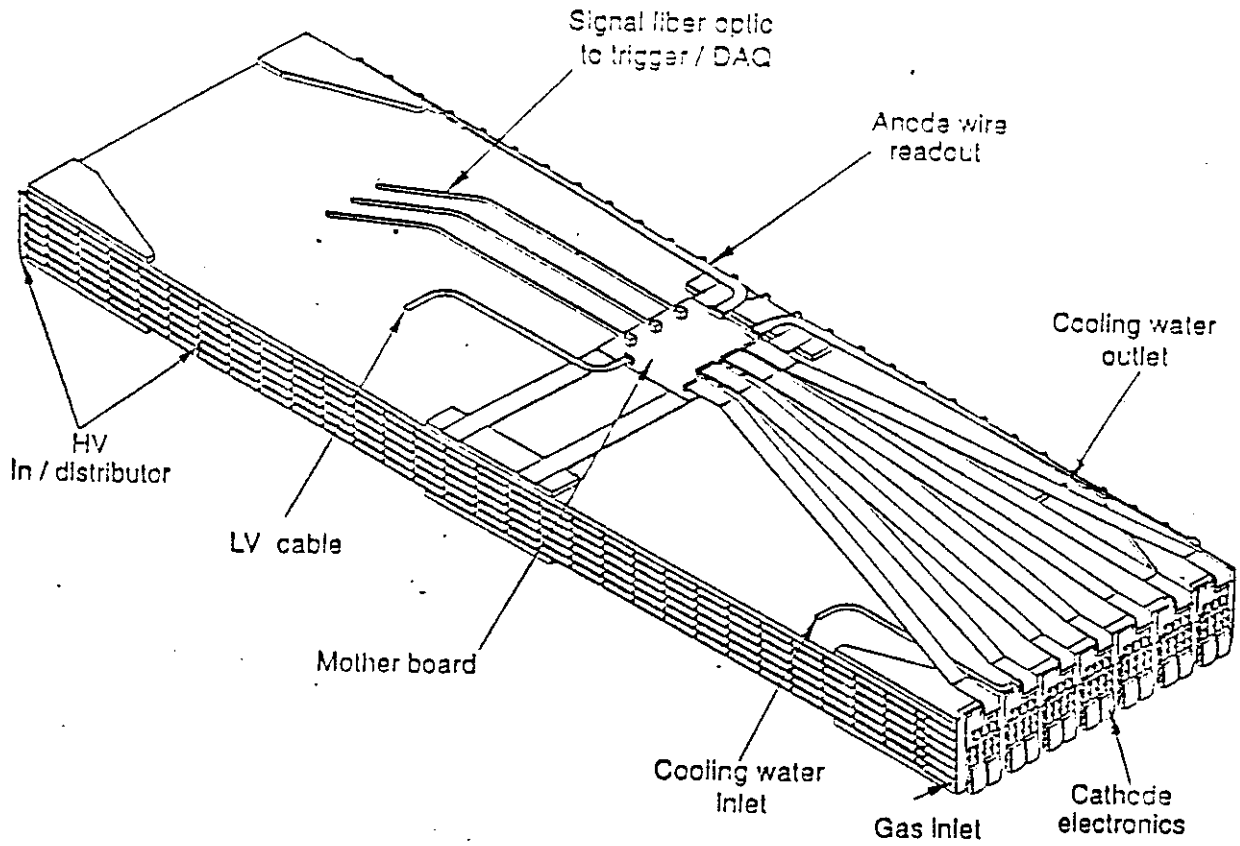


FIG. 4-48. Perspective view of complete CSC barrel chamber.

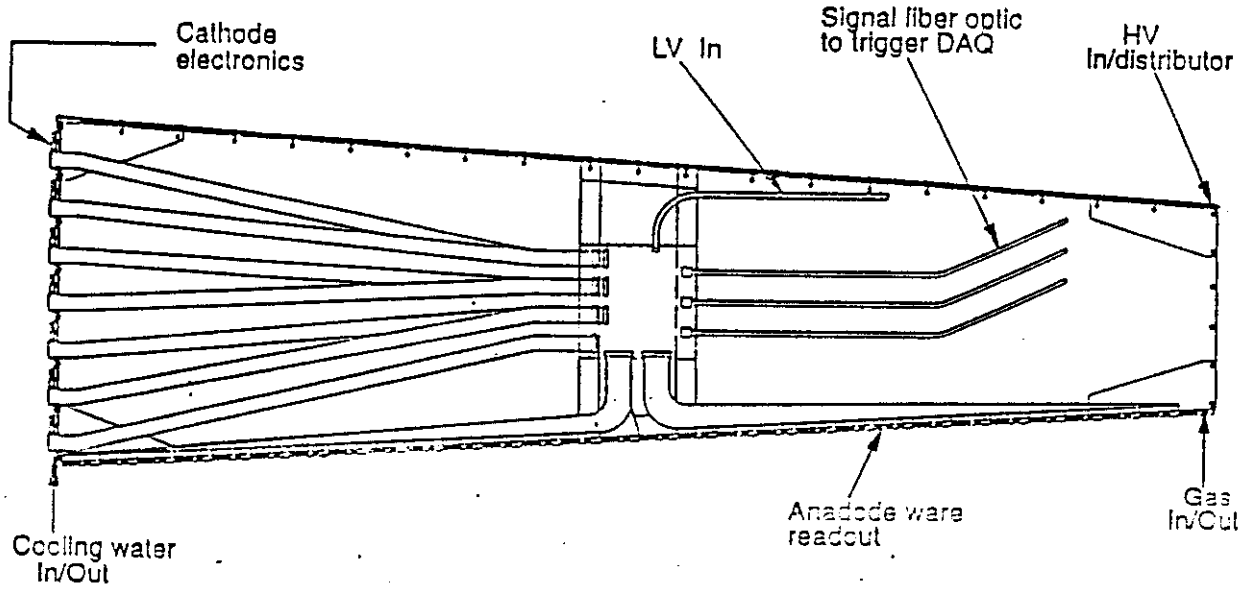
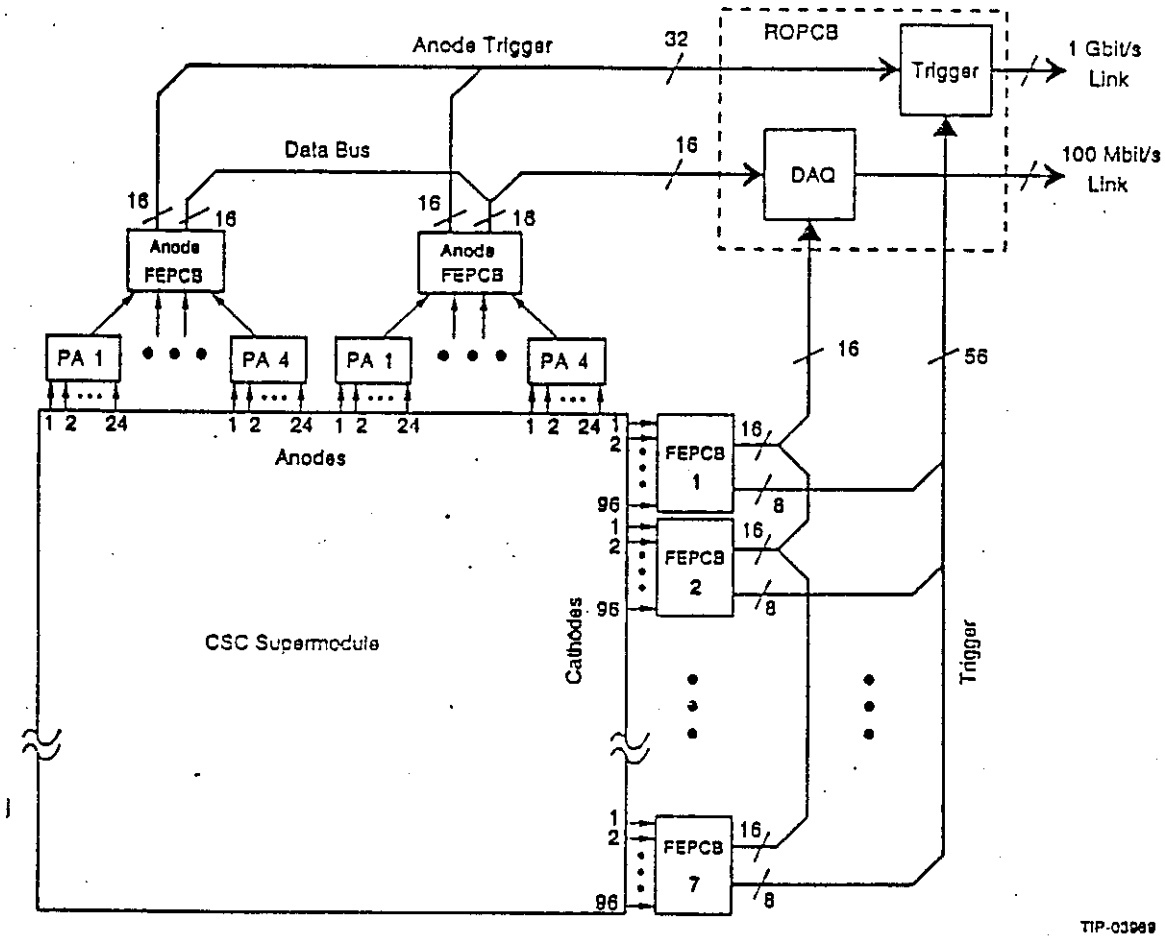


FIG. 4-49. Plan view of endcap chambers.

CSC Electronics

- Functions:
  - Cathode readout (fine resolution and trigger)
    922 k channels
  - Anode readout (coarse resolution and timing)
    310 k channels



Highly Multiplexed & integrated

Table 4-19. Electrical specifications for the CSC readout.

System Section	Parameter	Value
Readout path	Equivalent input noise, RMS	< 2000 e^-
	Pulse peaking time	300 ns
	Overall system gain	0.4 fC/Count
	Dynamic range	10 bits
	Accuracy	7 bits
	Cross talk	< -50 db
	Readout rate	100 kHz
	Readout latency	< 100 μs
Trigger path	Input threshold	16 fC
	Timing jitter, RMS	< 4 ns
	Time walk	< 4 ns
General	Temperature range	20 ± 5°C
	Power per channel	< 100 mW
	Radiation hardness: ionizing	1 krad
	Radiation hardness: neutrons	10^{14} cm^{-2}

Drivers of GEM Muon System

- Alignment

  Projective paths
  - six per chamber tower (5 in endcap)
  - produces gaps in middle super layer of barrel

- Support structure

  Nodes of structure
  - congruent with corners of chamber
  - chamber towers individually supported

  Separate structure for barrel and endcaps

- Properties of Cathode Strip Chambers:

  Anode wire stability
  - width of chamber [anode wire span ≤ 1.2 m]

  Size of precision cathode panels
  - maximum length ≈ 3.5 m
    [source capacitance and industry limit]
  - maximum width ≈ 1.2 m
    [layer resolution > 75μm for $|\Delta\phi| > 6^o$]
    [industry limit consistent with wire stability]

  Lorentz angle nulling
  - barrel chambers rotated by 6° to 8°
    [allows chambers to be overlapped in ϕ barrel]
  - endcap wires asymmetric to radial axis

  Radial strips in endcaps
  - trapezoidal chambers

Alignment

Local:

- Place chambers within $\Delta x, \Delta z \approx \pm 2$ mm,
  $\Delta\theta_x, \Delta\theta_z \approx \pm 1$ mrad

- Use 6 projective straightness monitors per chamber tower

- Determine relative position of hit in SL2 wrt SL1,3

$$Fs = F(\xi i, i=1,2,3,..,6)$$

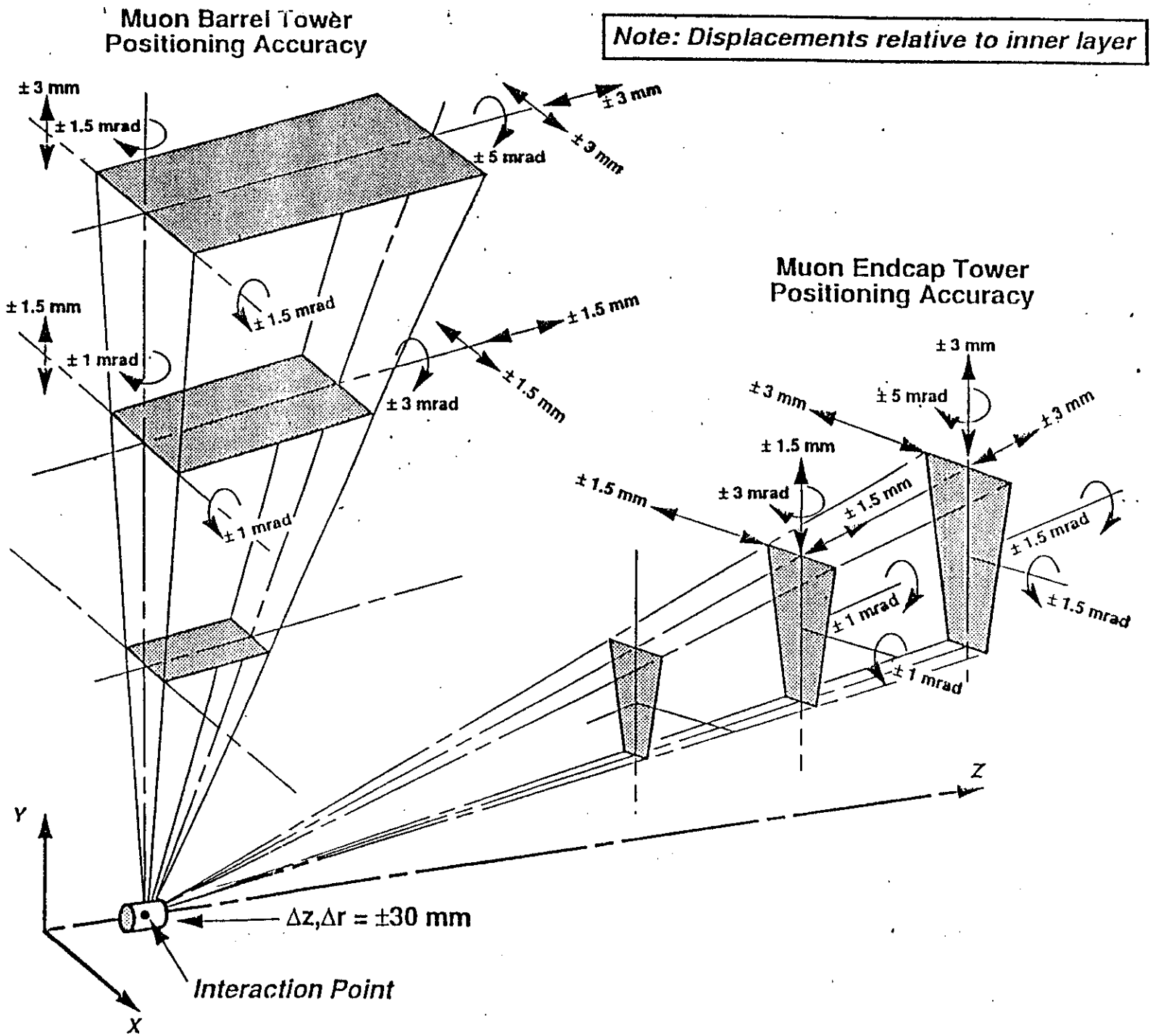
  where ξi are displacements relative to the straightness monitors

- Quadratic interpolation takes out chamber rotations and twists

Global

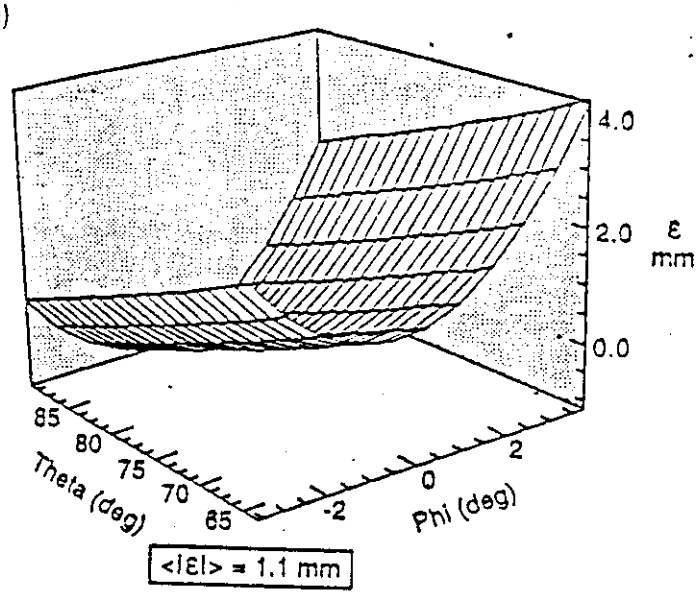
- Placement $\Delta x, \Delta z \approx \pm 2$ mm, $\Delta\theta_x, \Delta\theta_z \approx \pm 1$ mrad
  OK - if no vertex constraint imposed

- Vertex constraint 200 μm
  For Pt > 15 GeV/c need < 35,000 muons
  (corresponds to 5 hr at $L \approx 10^{33}$ cm^{-2} s^{-1})
  For Pt > 50 GeV/c need < 3,500 muons
  (corresponds to 50 hr at $L \approx 10^{33}$ cm^{-2} s^{-1})


Muon Barrel Tower
Positioning Accuracy
Note: Displacements relative to inner layer
± 3 mm
± 1.5 mrad
± 5 mrad
± 3 mm
± 3 mm
± 1.5 mrad
± 1.5 mm
± 1 mrad
± 3 mrad
± 1.5 mm
± 1.5 mm
± 1 mrad
Muon Endcap Tower
Positioning Accuracy
± 3 mm
± 3 mm
± 5 mrad
± 3 mm
± 1.5 mm
± 1.5 mm
± 3 mrad
± 1.5 mm
± 1.5 mrad
± 1 mrad
± 1.5 mrad
± 1 mrad
Z
Y
Δz,Δr = ±30 mm
Interaction Point
X

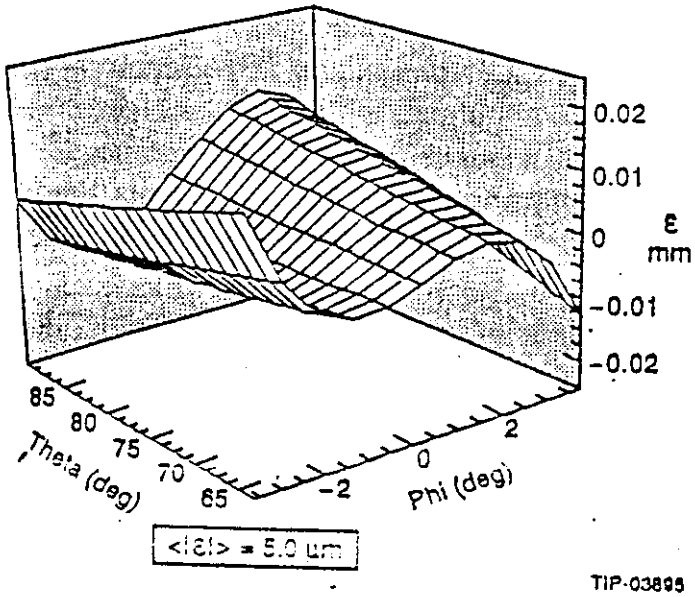
input

(a)



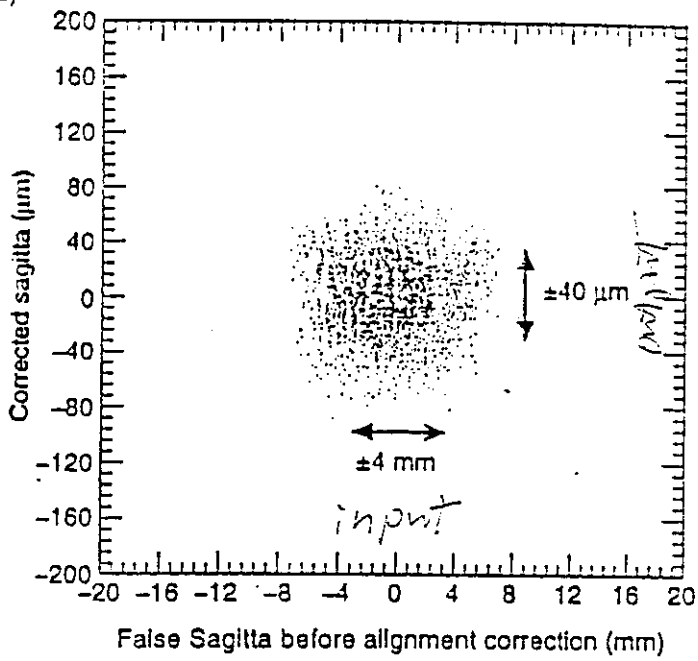
output

(b)

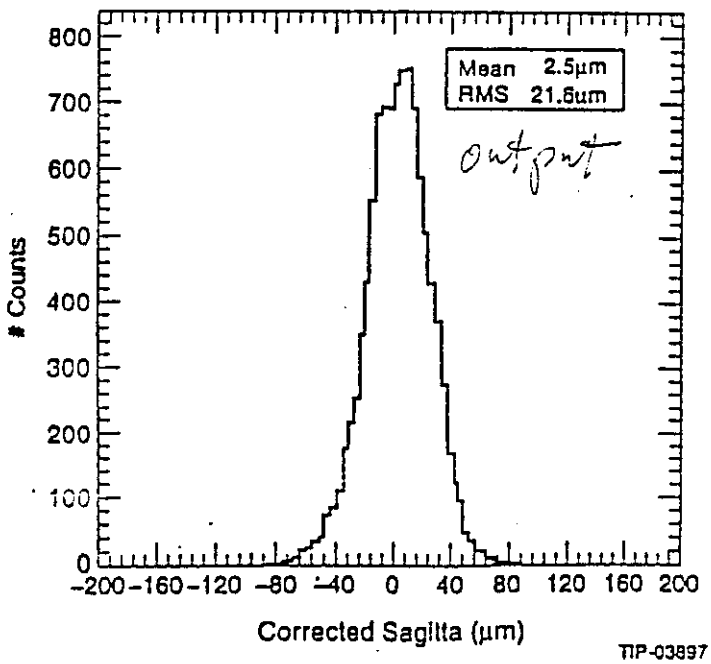


TIP-03896

(a)

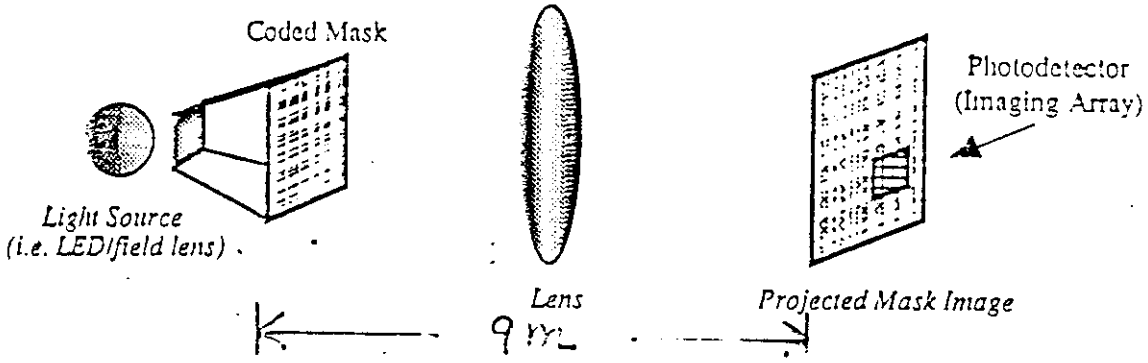


(b)

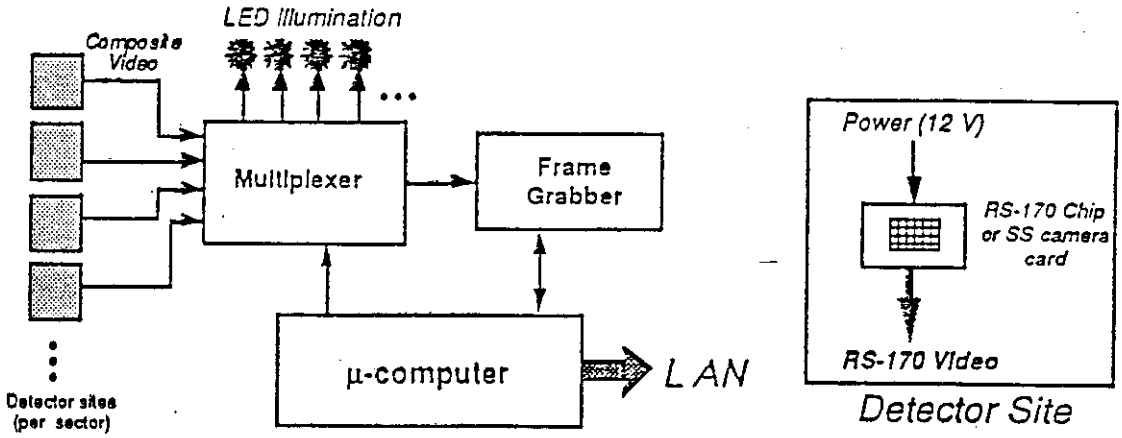


TIP-03897

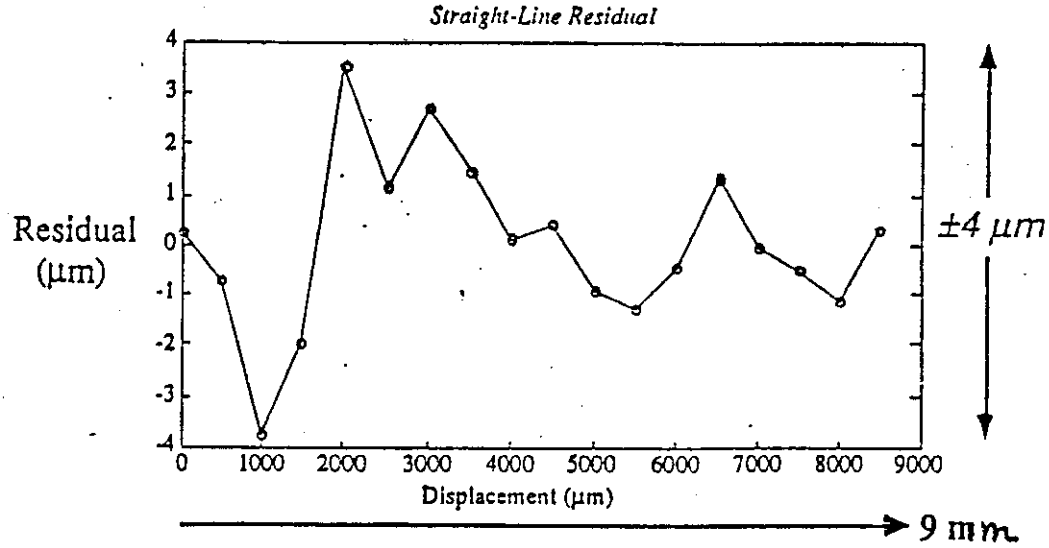
Straightness Monitor



a) Wide-range video straightness monitor

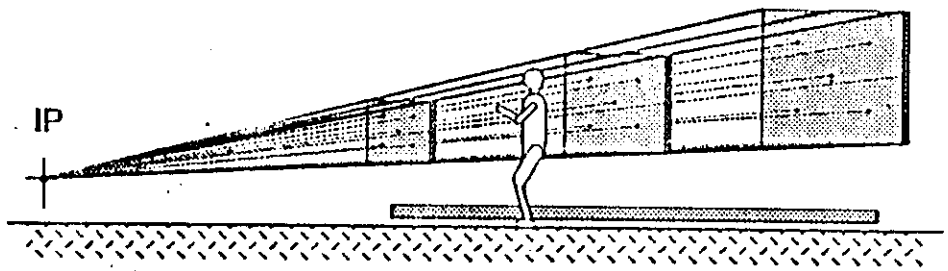


b) Implementation in GEM muon system

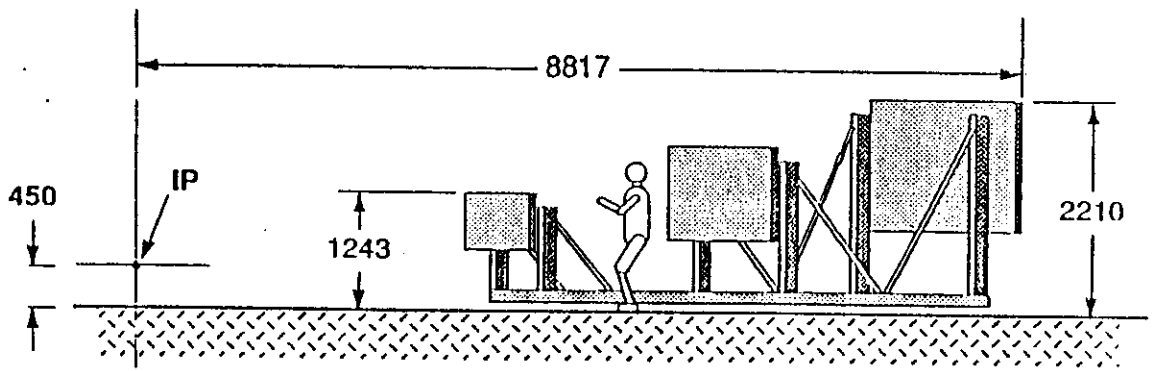


c) Preliminary test results

Alignment Test Stand



Proposed Projective Alignment Lines of Sight



Mechanical Design and Fixturing

Chamber Support Structure

- Engineering Group:

  Draper Lab. - Cambridge, MA
  LLNL - Livermore, CA
  SGH - Arlington, MA
  SSCL /EFD - Dallas, TX

- Stable platform for chambers

  Error budget:

  $\sigma \leq 25\ \mu m$ inter - superlayer alignment
  $\sigma \leq 50\ \mu m$ intra - superlayer alignment - random
  $\sigma \leq 75\ \mu m$ single layer resolution - random

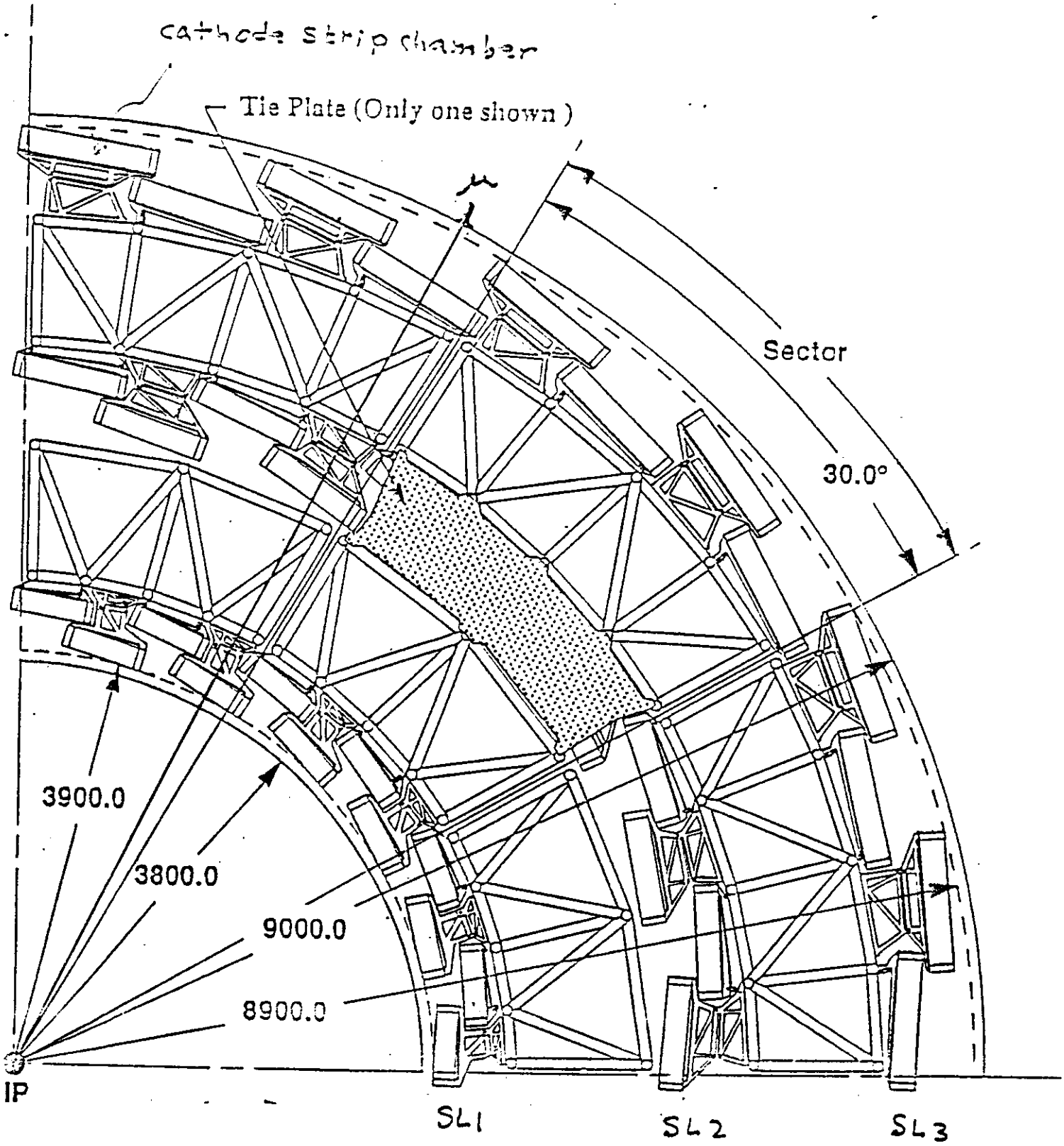
- Considered:

  Performance (stability to vibrations)
  Cost
  Fabrication and installation requirements
  Schedule impact on GEM construction
  Access

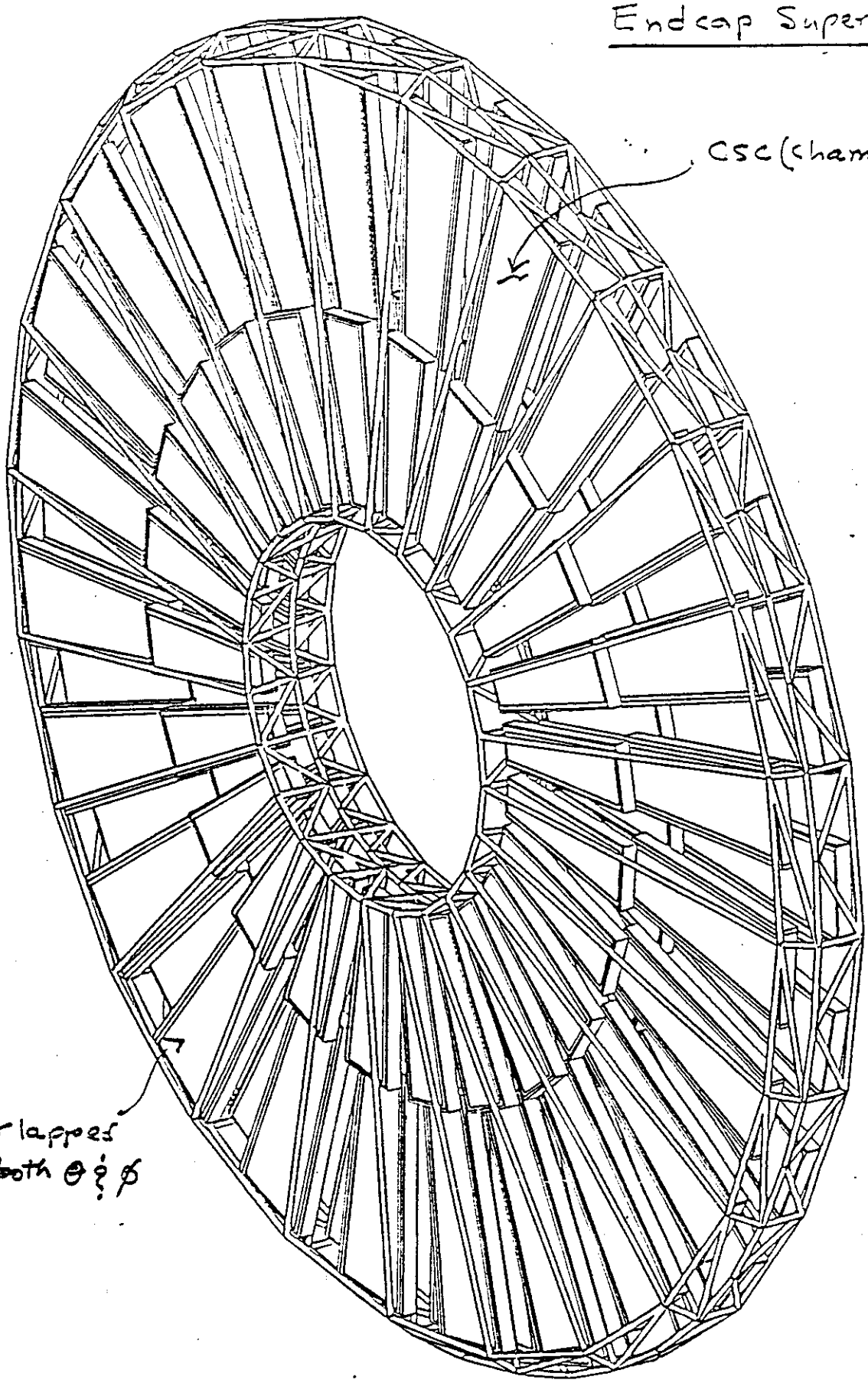
- Propose to build:

  Barrel: sectors (1/12) tied together as a monolith
  good vibration characteristics
  ease of construction in small parts
  prototype testing possible

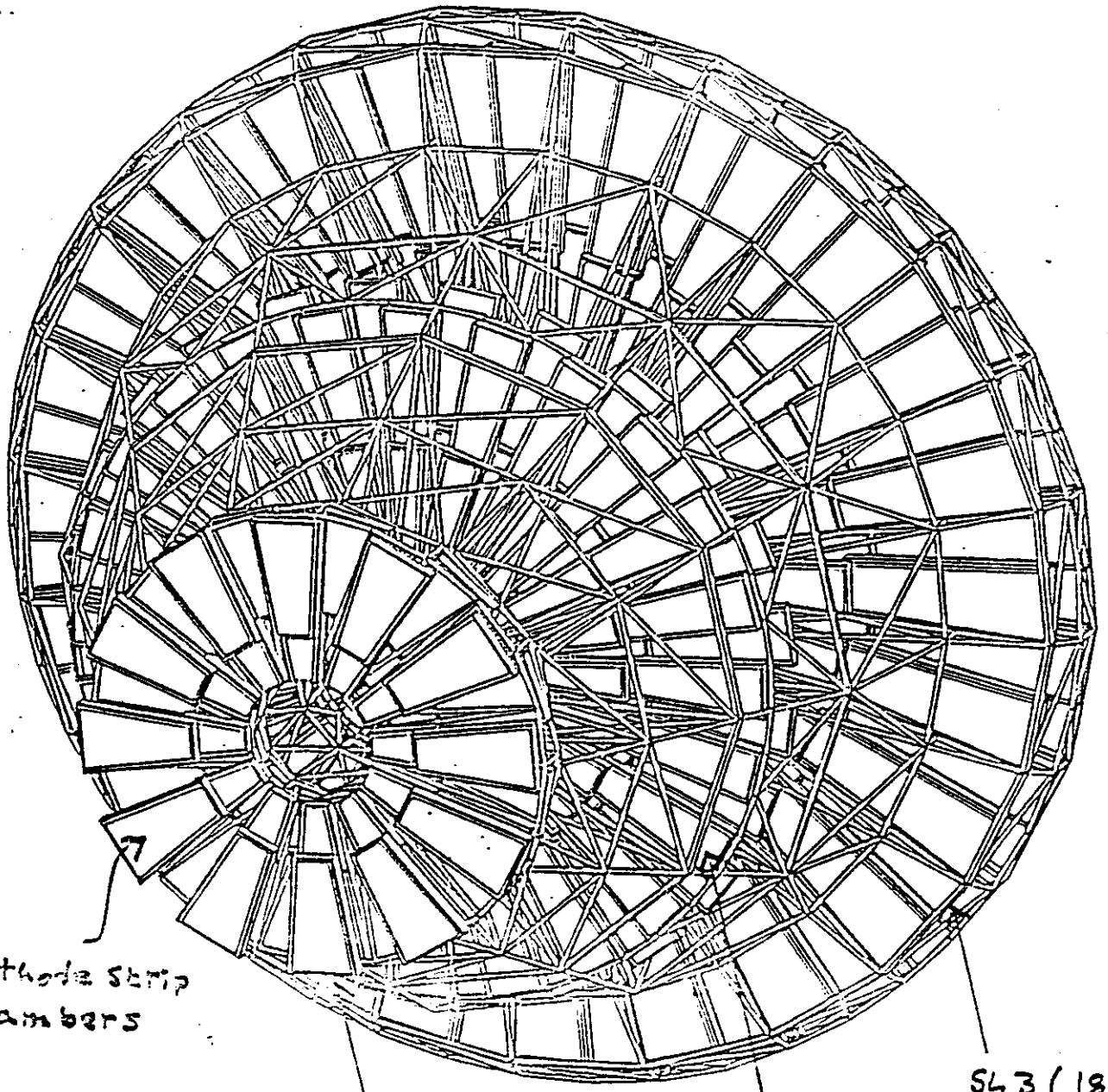
  Endcap: super-wheels (one/superlayer)
  reduces intra-layer structural elements
  monolith has good stability performance

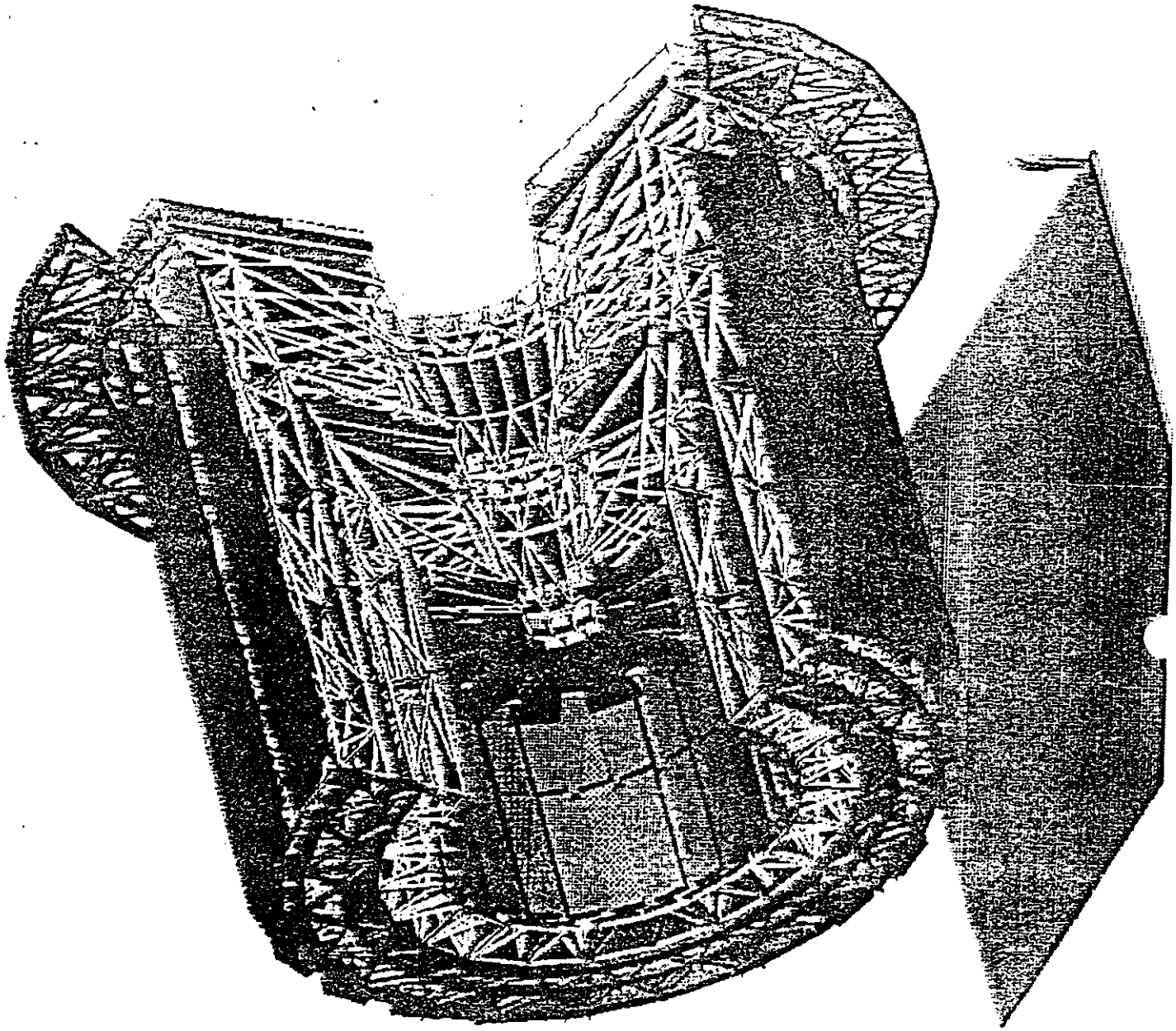

cathode strip chamber
Tie Plate (Only one shown)
μ
Sector
30.0°
3900.0
3800.0
9000.0
8900.0
IP
SL1
SL2
SL3

Endcap Super Wheel



Endcap Support structure





Performance of System

- Momentum reconstruction
- Solid angle coverage
- Triggering
- Rate capability

Momentum Reconstruction

Baseline

Case 1: Muon system stand-alone

- Track identified in all 3 superlayers
- Sagitta method

Baseline exploiting strengths of GEM detector

Case 2: Muon system with vertex constraint

- Track identified in all 3 superlayers
- Vertex constraint (200 μm to 500 μm)
- Better high Pt resol'n

Case 3: Muon system with central tracker

- Track identified in all 3 superlayers
- Muon track matched with CT track
- Low Pt resolution improved

Case 4: Muon reconstructed by central tracker

- Muon identified by Calorimeter and one SL

Muon system is robust

Case 5: One plane of muon system missing

- Track identified in SL2 and SL3 only (catastrophic brem)
- Vertex constaint (200 μm to 500 μm)
- Turning angle

Factors Affecting Pt Resolution

Parametric Model of Resolutions*

Barrel:

$$S_{total} \approx \frac{0.3B(R_3-R_1)^2}{8p_t}$$

$$\sigma_{1,3}^2 = \sigma_e^2 + \frac{(\sigma_i^2+\sigma_c^2)}{N_{1,3}}$$

$$\sigma_2^2 = \sigma_e^2 + \frac{(\sigma_i^2+\sigma_c^2)}{N_2} + \sigma_{ms}^2$$

$$\sigma_{ms}^2 = \left(\frac{0.015(R_3-R_1)}{Pt}\right)^2 \frac{X_0 N_2}{16 \sin\theta}$$

$$\sigma_{total}^2 = \sigma_2^2 + \frac{\sigma_1^2+\sigma_3^2}{4}$$

where: $\sigma_e \leq 25\ \mu m$, $\sigma_i \leq 50\ \mu m$, $\sigma_c \leq 75\mu m$, $N_{1,2,3} = 6$, $X_0 = 0.011$/layer

Low Pt (< 100 GeV/c)

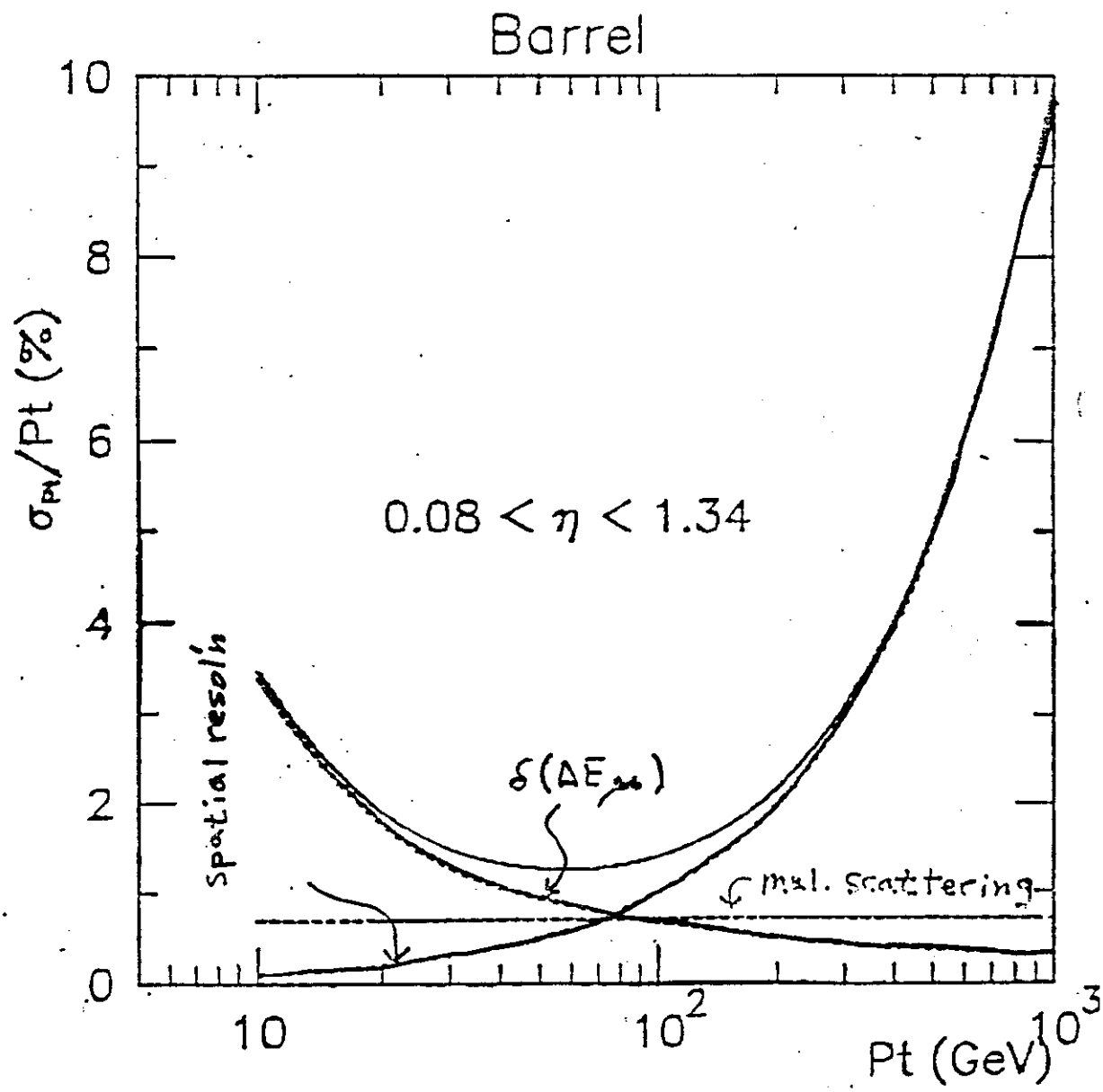
- Multiple scattering in SL2 material
- Fluctuations in energy loss in calorimeter

High Pt (≥ 100 GeV/c)

- Spatial resolution error budget: $s_{total} \leq 50\ \mu m$ at 500 GeV/c

* Actual calculations are done with non-uniform field

Factors in resolution



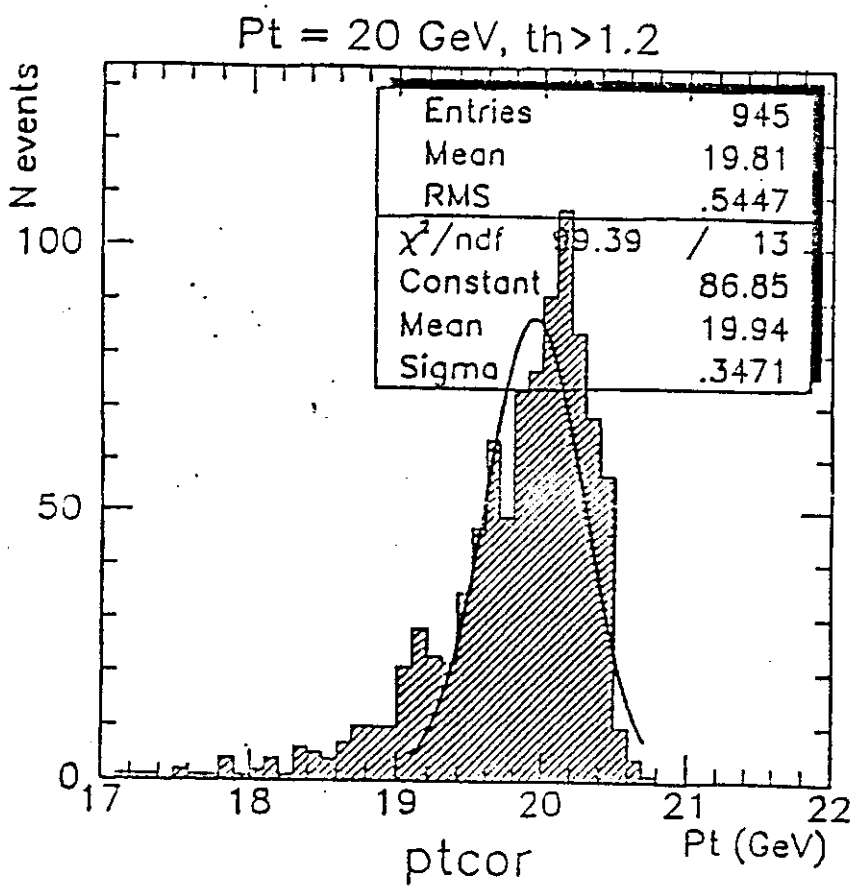
Treatment of Energy Loss in Calorimeter

- Affects low Pt (< 100 GeV/c) resolution
- Algorithm:

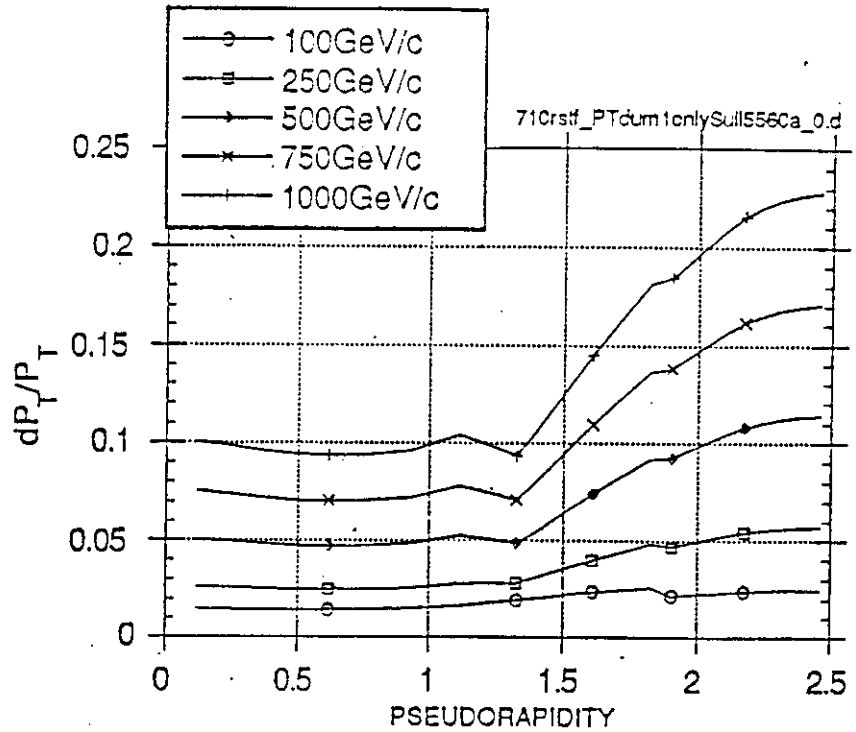
  (1) Use CT information

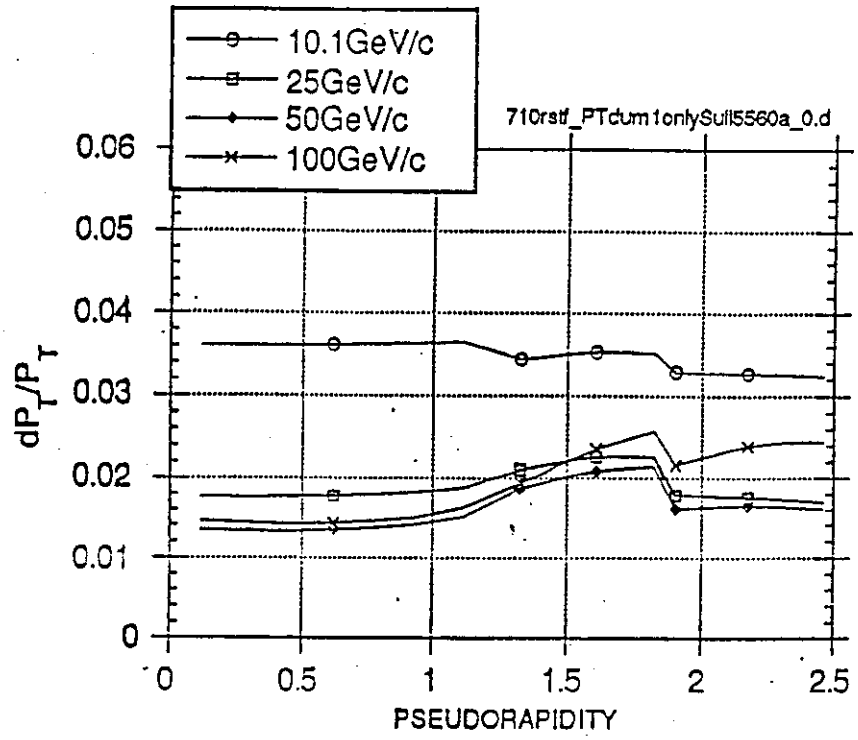
  (2) Use calorimeter information

  - from Pμ determined by muon system estimate most probable value of (ΔEμ).
  - if k = (ΔEμ)measured/(ΔEμ)calculated > 1.5 use (ΔEμ)measured.
  - otherwise use (ΔEμ)truncated mean (containing 95 % of sample)

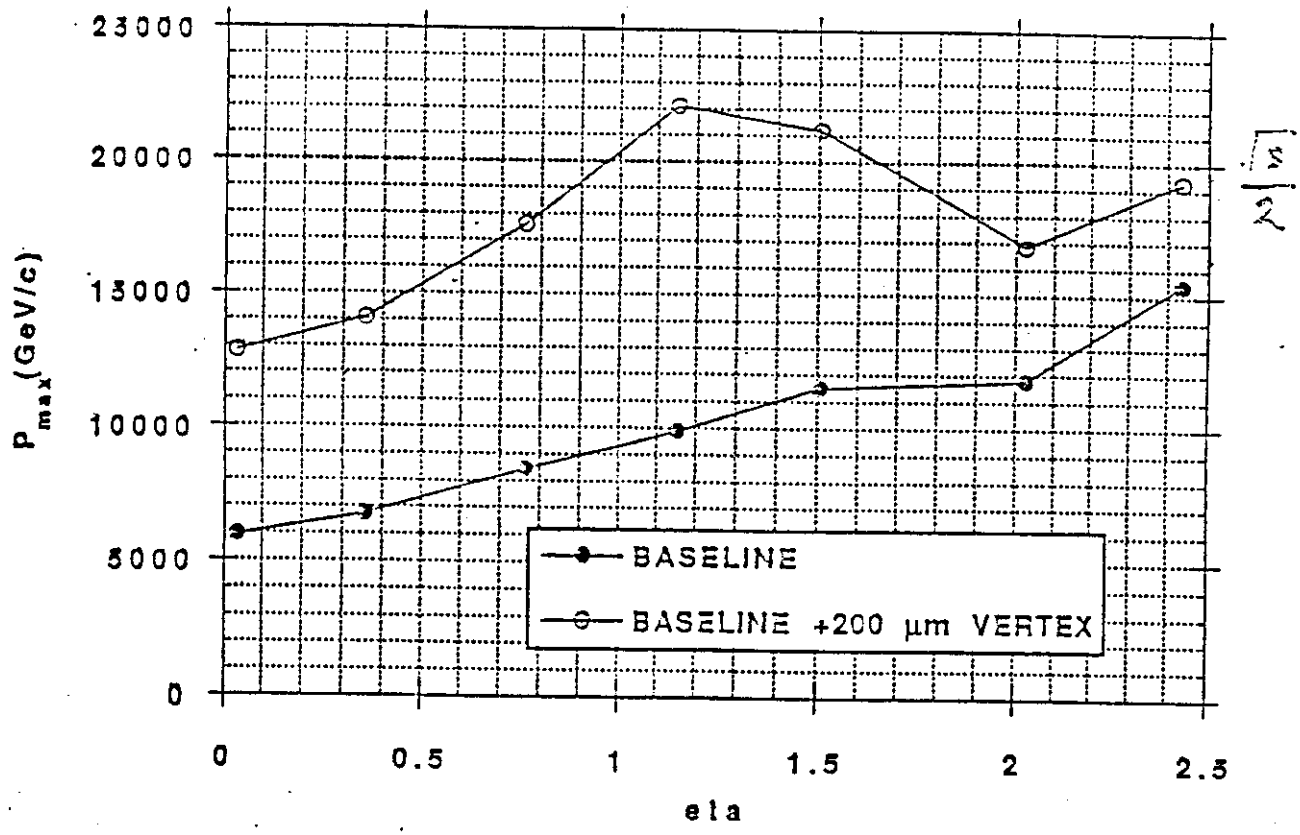


BASELINE STANDALONE Pt RESOLUTION

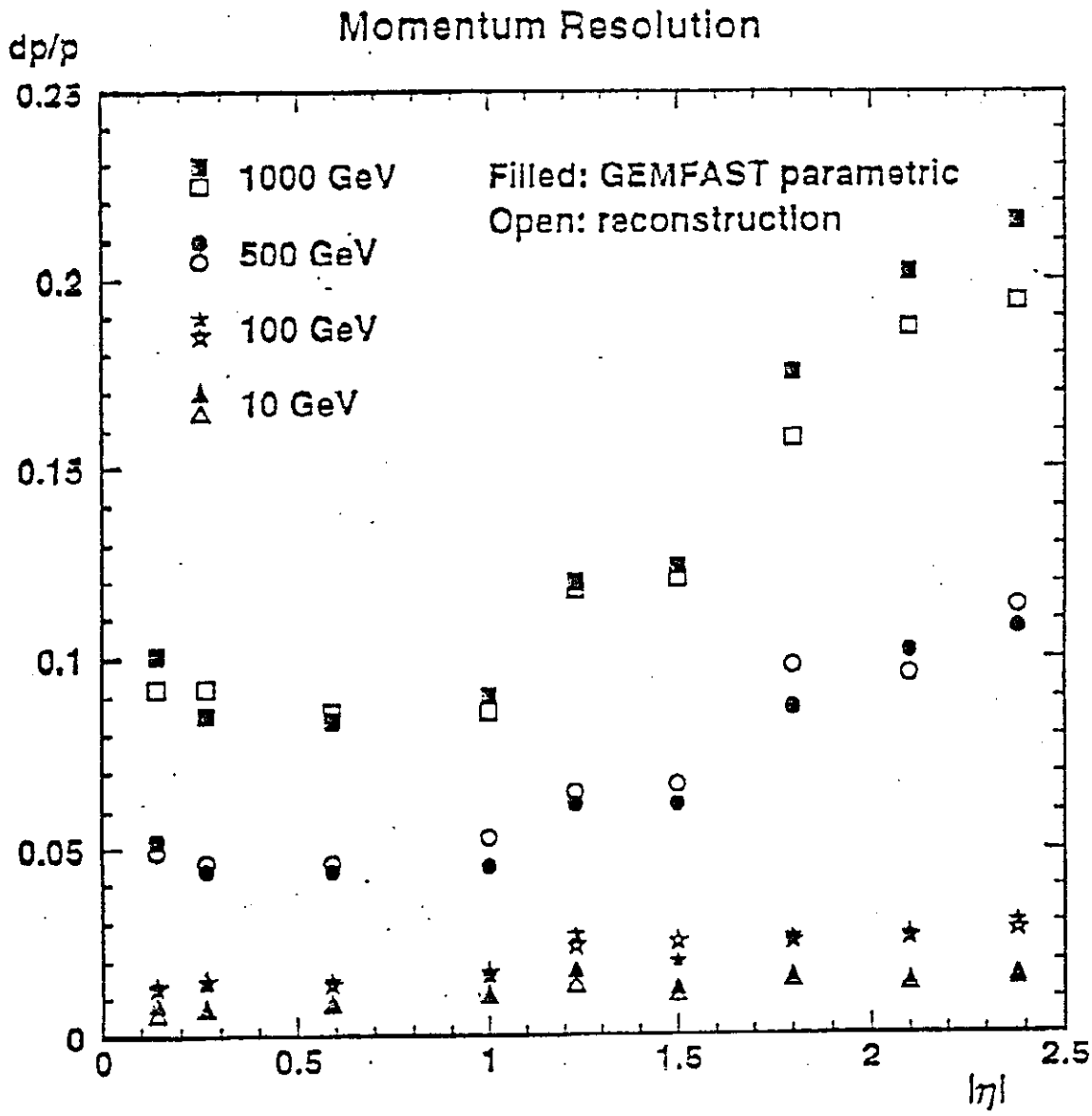




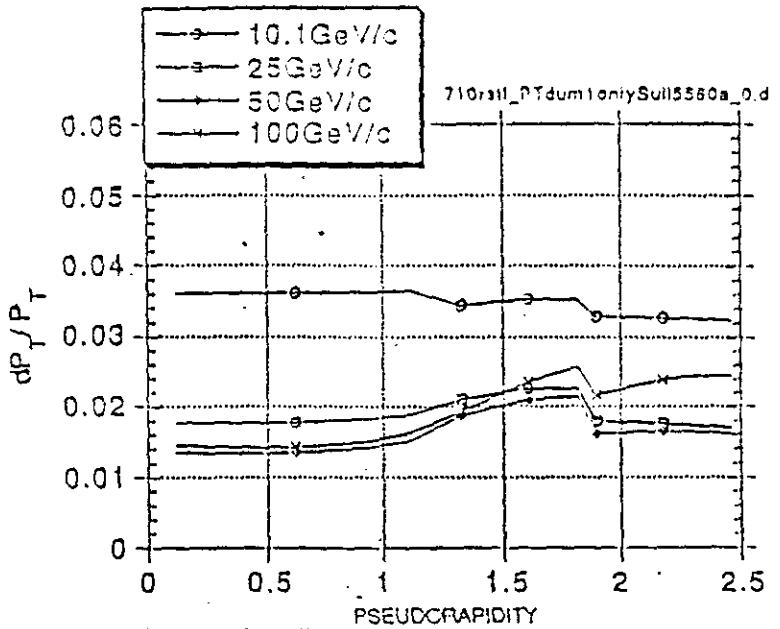
CHARGE DETERMINATION AT THE 95% CONFIDENCE LEVEL
WITH AND WITHOUT A VERTEX CONSTRAINT



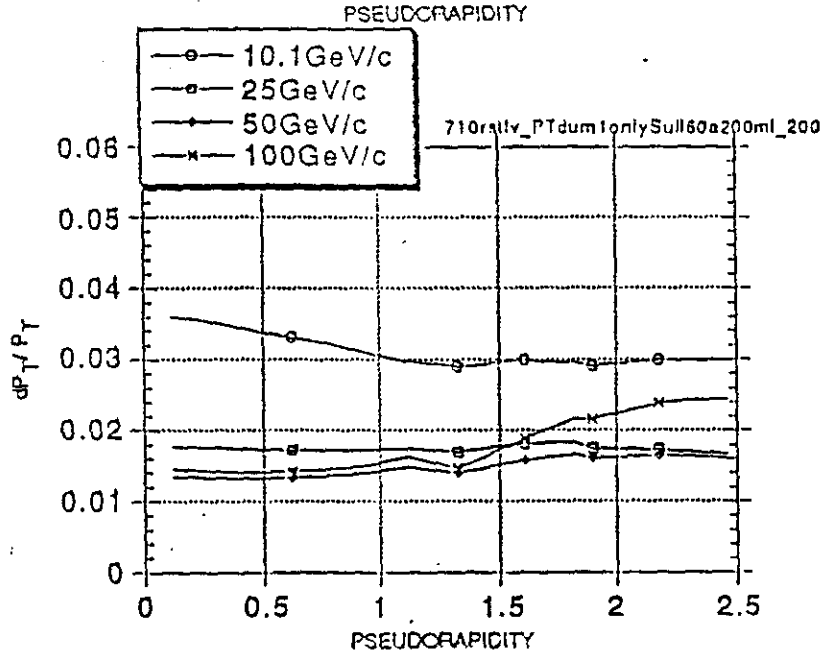
Hit level MC agrees with parametric



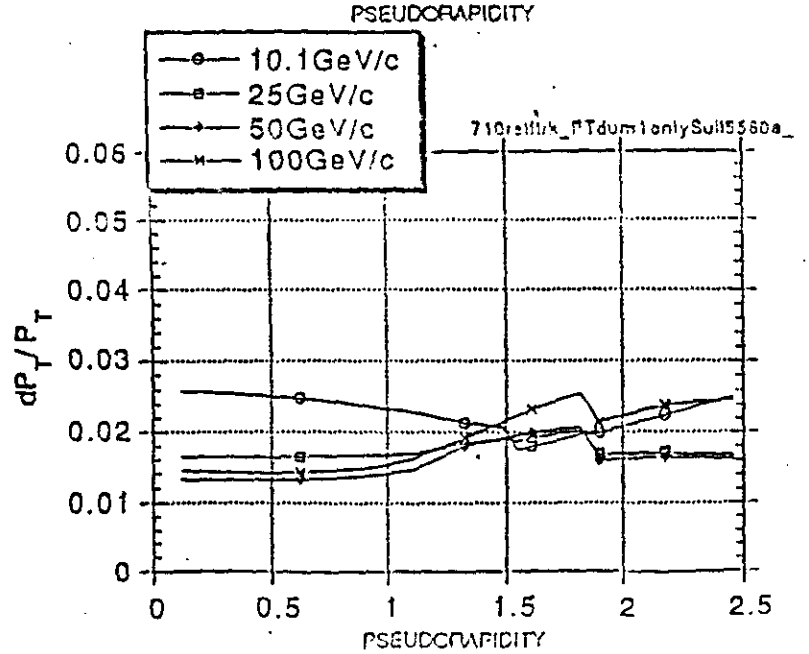
LOW TRANSVERSE MOMENTUM RESOLUTION



Case 1
3 POINT MEASUREMENT

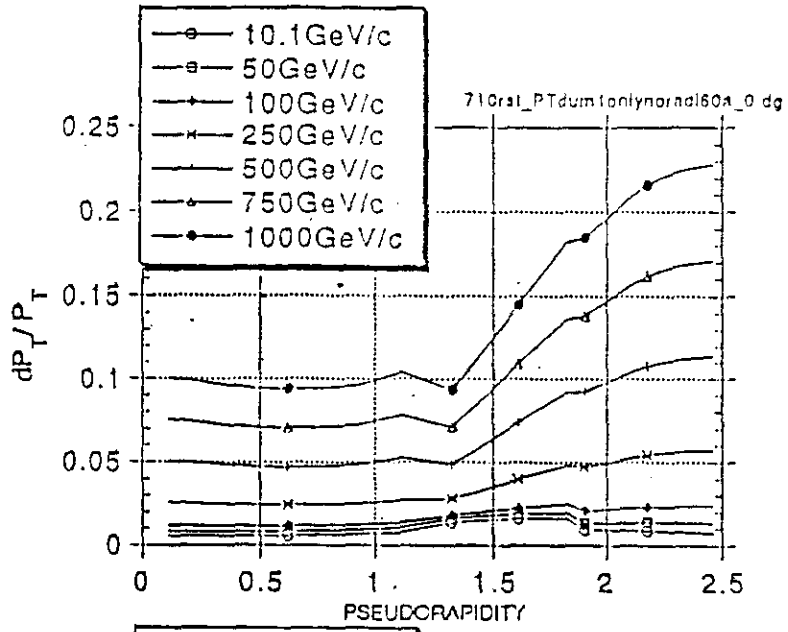


Case 2
3 POINT +200μm.
VERTEX CONST.

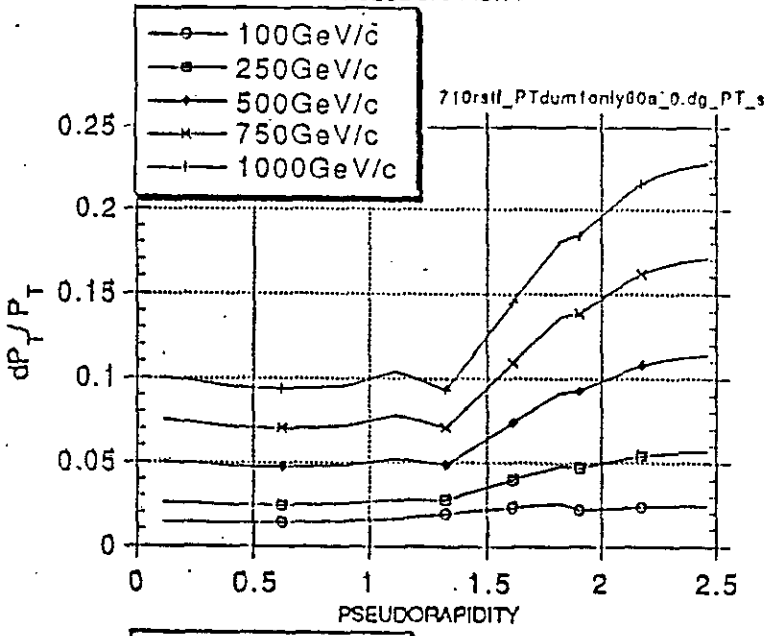


Case 3
3 POINT + INDEPENDENT
CENTRAL TRACKER

HIGH TRANSVERSE MOMENTUM RESOLUTION

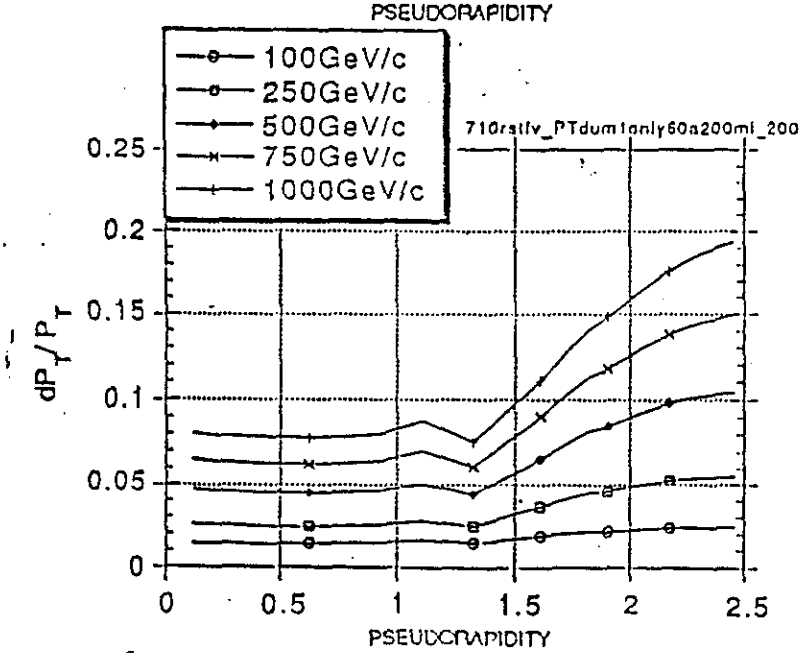


POST CALORIMETER
P_T RESOLUTION



Case 1

P_T RESOLUTION AT
THE VERTEX WITH
dE/dX FLUCTUATIONS

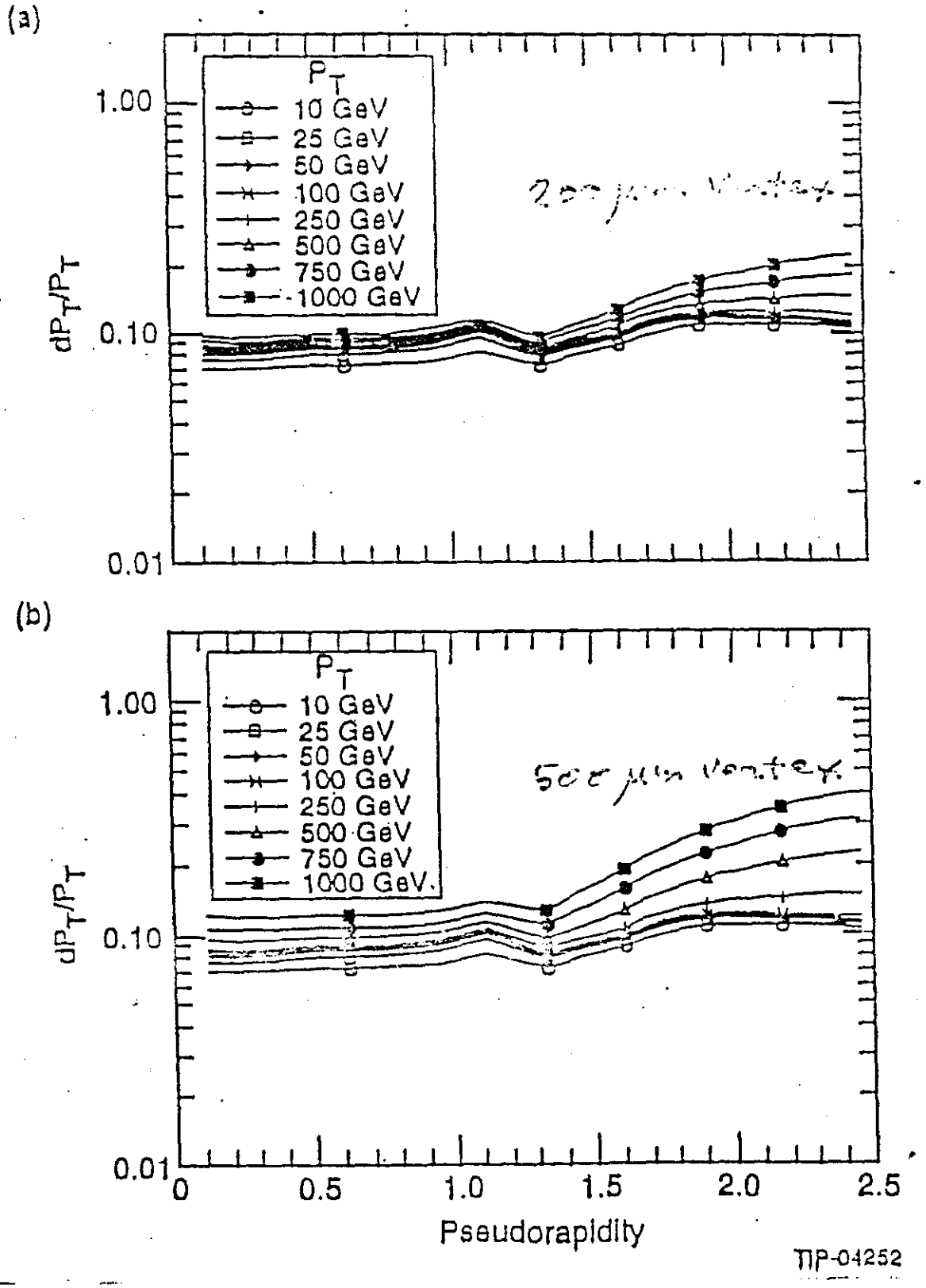


Case 2

P_T RESOLUTION AT THE
VERTEX WITH dE/dX
FLUCTUATIONSAND A
200μm.VERTEX CONST.

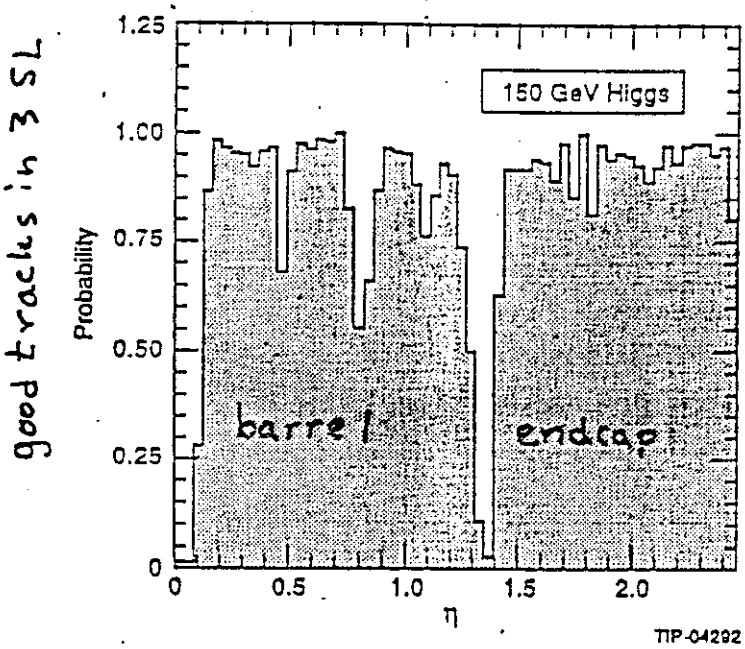
Momentum Reconstruction-Case 5

- Muon system with vertex, SL2, and SL3:



Coverage

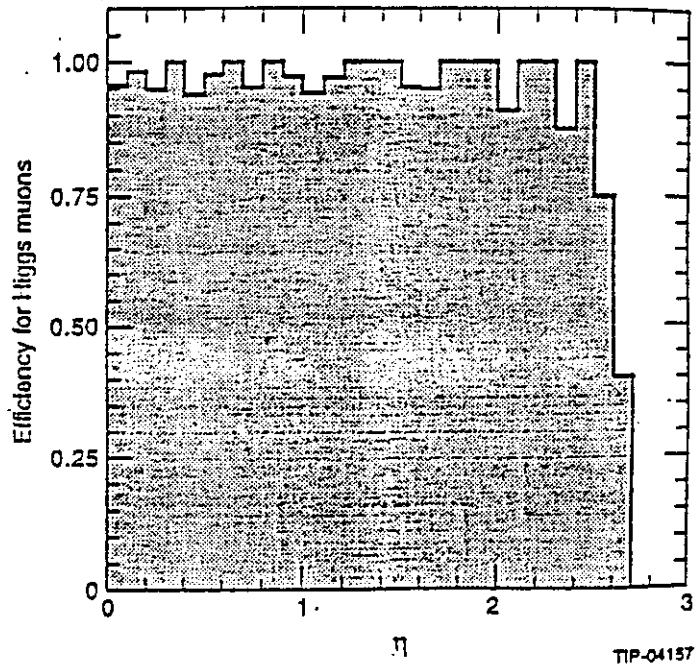
- Muon System:



$\varepsilon_{1\mu} \approx 83\%$

$\varepsilon_{4\mu} \approx 43\%$

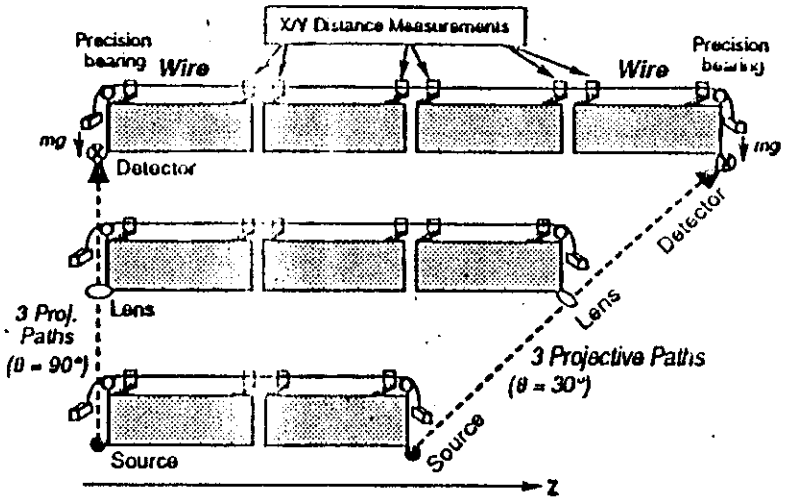
- Central Tracker:



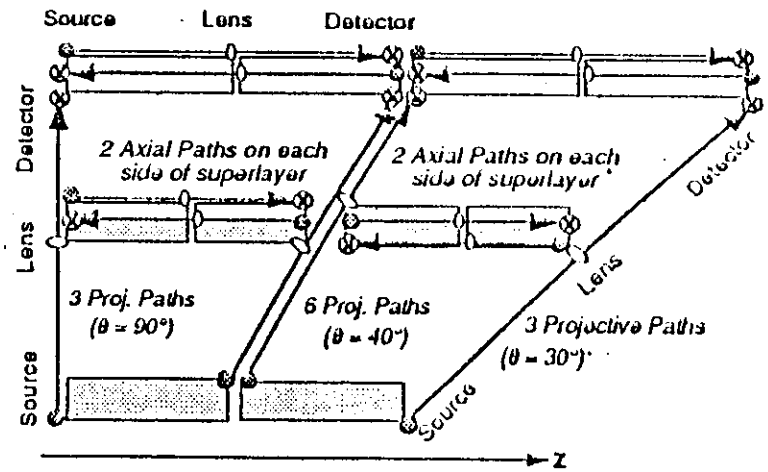
$\varepsilon_{1\mu} \approx 97\%$

$\varepsilon_{3/4\mu} \approx 86\%$

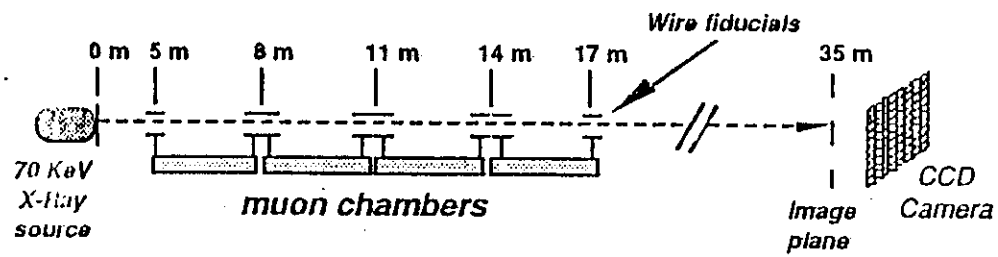
Alternative Alignment to improve coverage



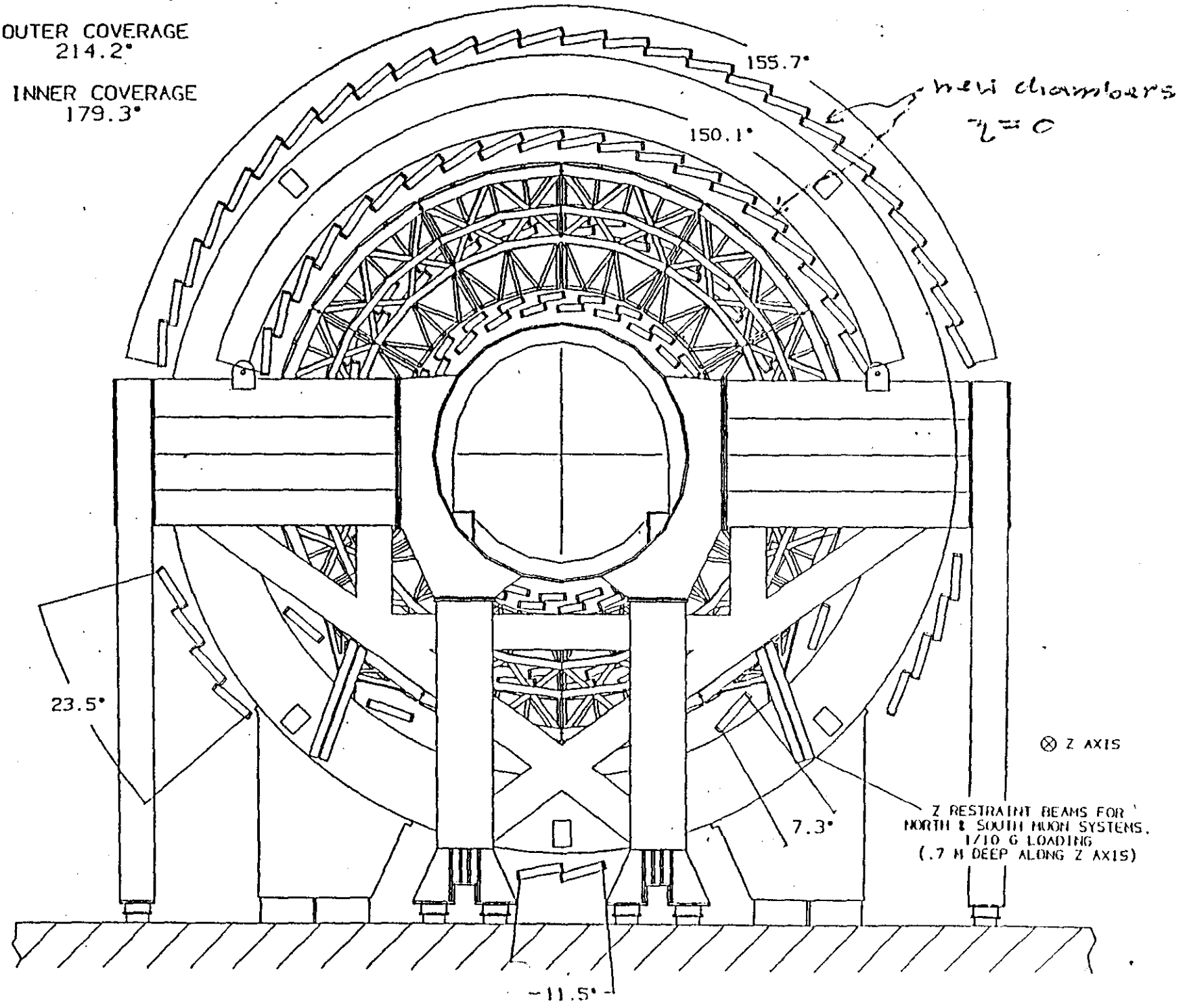
a) Hybrid Axial/Projective Scheme

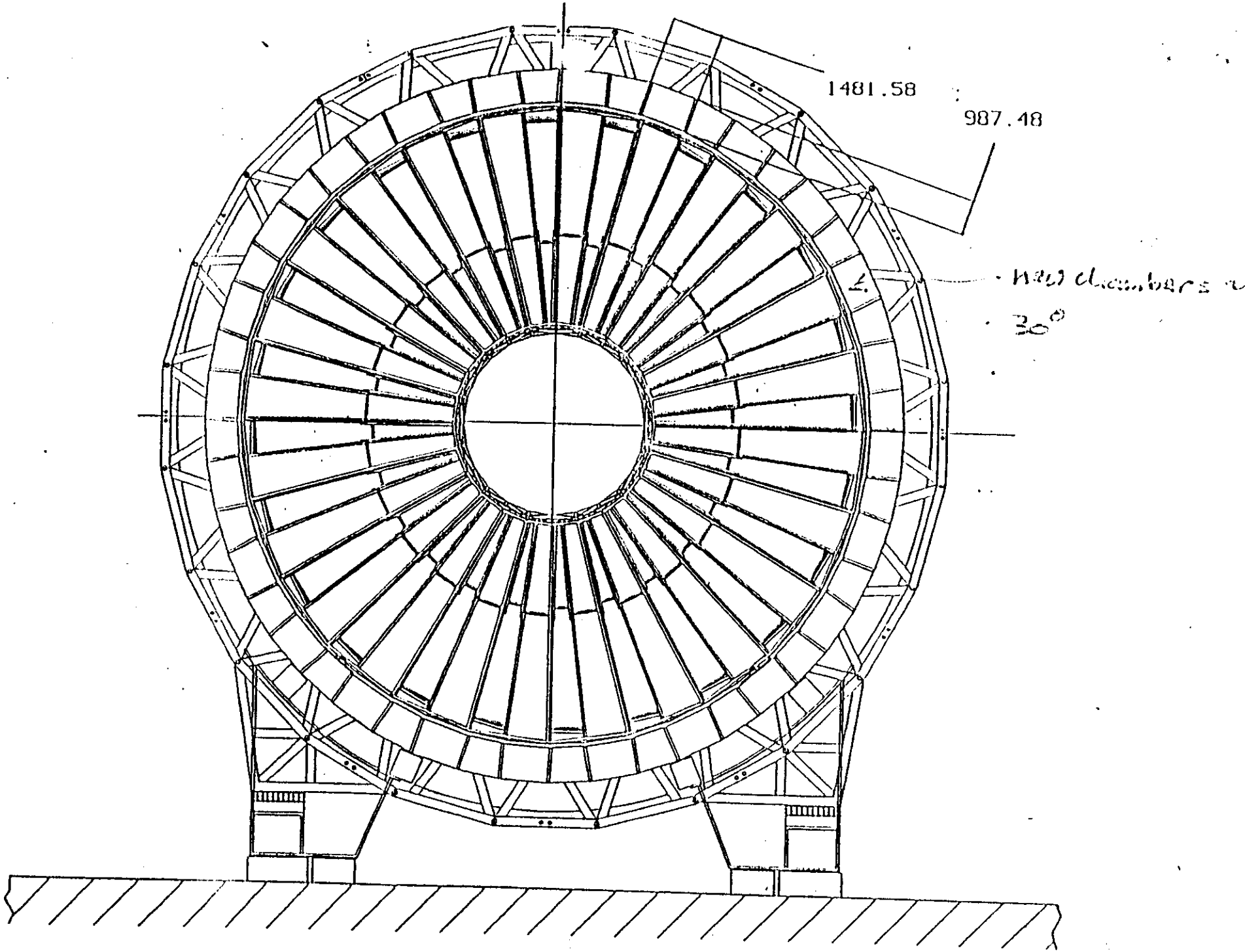


b) All-Optical Axial/Projective Comprimise



c) X-Ray Alignment using Tungsten Wire Fiducials


OUTER COVERAGE
214.2°
INNER COVERAGE
179.3°
155.7°
150.1°
new chambers
η = 0
23.5°
7.3°
11.5°
⊗ Z AXIS
Z RESTRAINT BEAMS FOR
NORTH & SOUTH MUON SYSTEMS.
1/10 G LOADING
(.7 M DEEP ALONG Z AXIS)


1481.58
987.48
30°

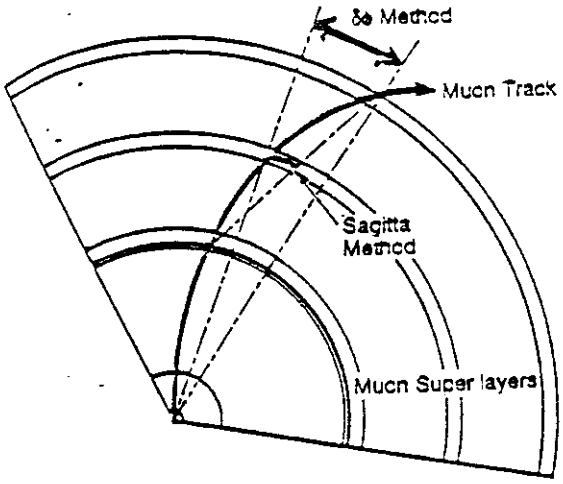
Triggering

- Bend Plane

  - Information: hits in each of 3 SLs

  - Signal generated by coincidence with lookup table of correct hit combinations for given Pt

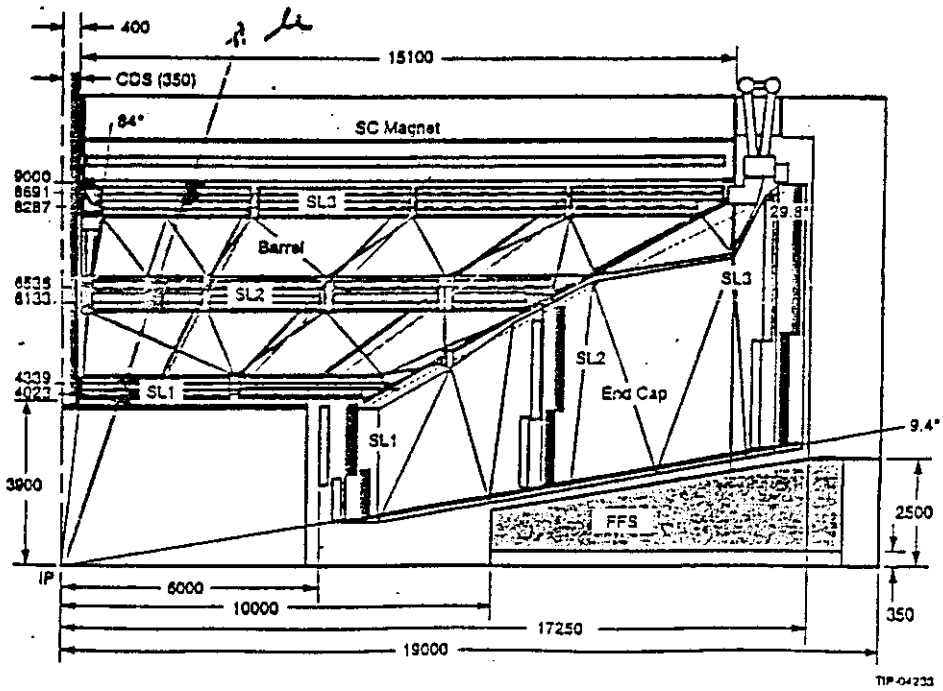
  - Trigger primitives: $\Delta\phi$ or sagitta, but always 3-Point



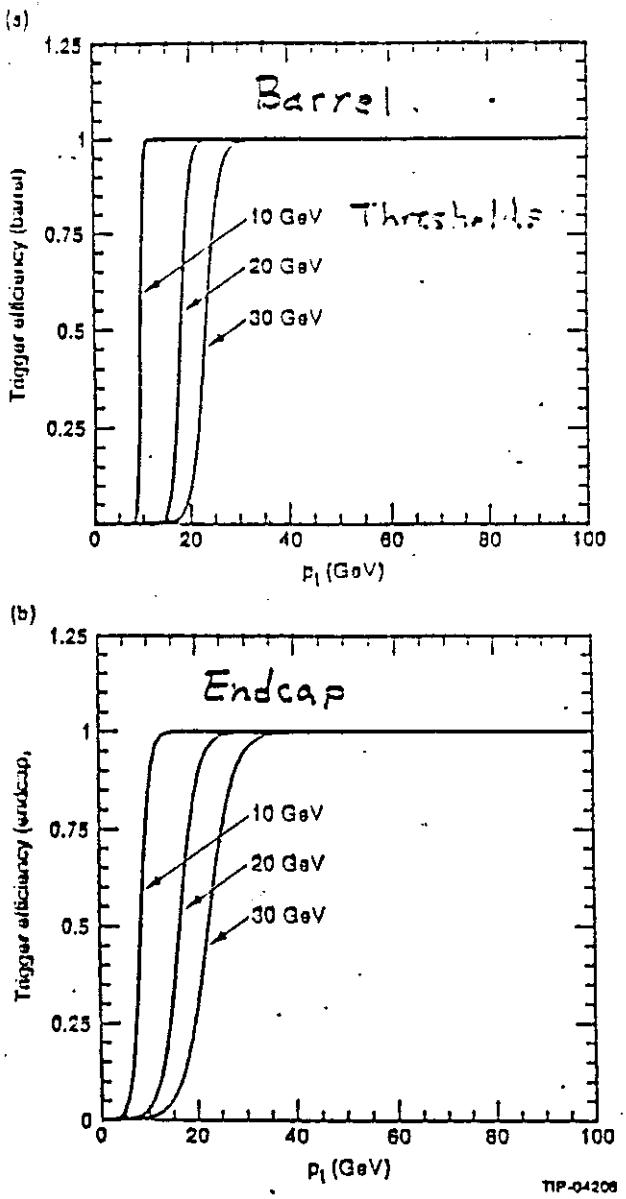
sagitta better at low Pt

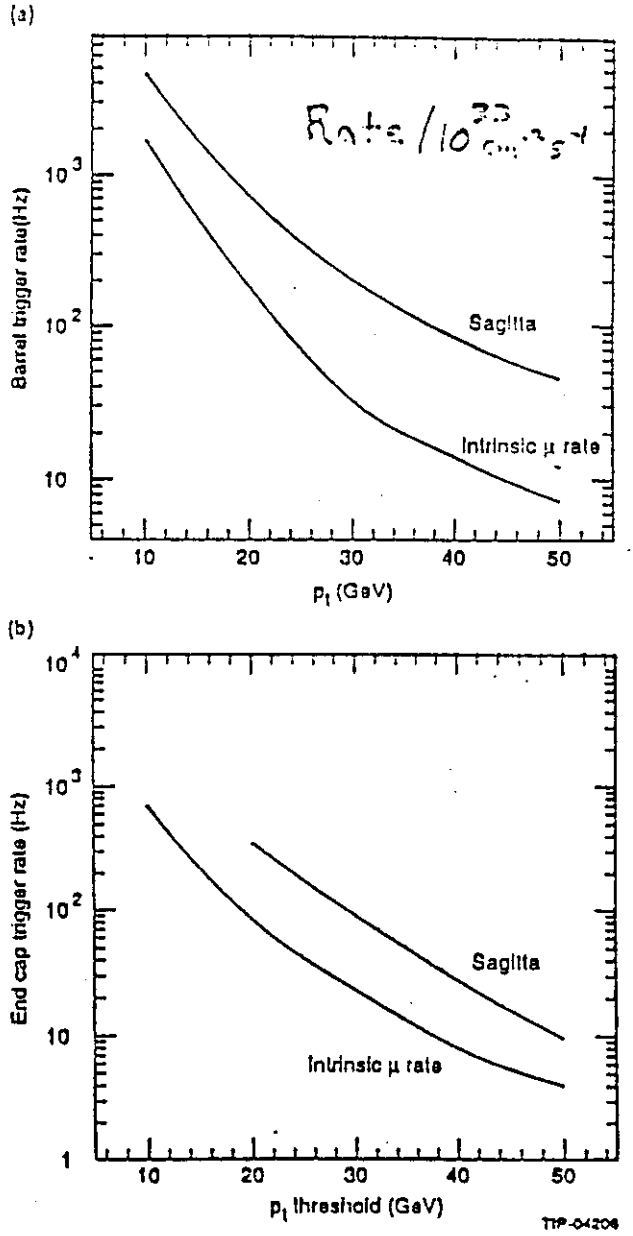
$\Delta\phi$ better at high Pt

- Non-bend Plane



Trigger Performance





Operation of Muon System in Radiation Environment

Sources:

- Hadron punchthrough
- π/K decay in CT and Calorimeter
- Uncorrelated neutrons and γ–rays
- Muon-induced showers and δ-rays

Design Criteria:

(1) Rate of punchthrough
$\ll$ (π/K decay + prompt μ)

(2) Rate of punchthrough for Pt > threshold
$\ll$ (π/K decay + prompt μ)

(3) Calorimeter depth sufficient for charged particle 4-strip occupancy in each layer of first superlayer
< 1 % at $L = 10^{34}$.

(4) Occupancy of 1-strip from neutrons and γ-rays
< 3 % at $L = 10^{34}$.

Table 4-6. CSC single and 4 strip occupancy at 10^{34} cm^{-2} s^{-1} luminosity from particles exiting the calorimeter in two rapidity intervals as a function of calorimeter th. 4-strip occupancy refers to any hit in a given 4 contiguou strips. The rates shown are for the highest rate strips in each rapidity region.

$0.1 < |\eta| < 1.34$

Calorimeter thickness (λ)	6	8	10	12	14
Rate per strip (Hz) Strip size 350 cm × 0.5 cm	33000	6600	2200	800	480
Single strip occupancy 300 nsec integration time	2.6%	0.40%	0.13%	0.05%	0.03%
4-strip occupancy	10.4%	1.6%	0.52%	0.20%	0.12%

$1.86 < |\eta| < 2.46$

Calorimeter thickness (λ)	10	12	14	16
Rate per strip (Hz) Strip size 93 cm × 0.5 cm	13100	10500	6640	4320
Single strip occupancy 300 nsec integration time	0.78%	0.64%	0.40%	0.26%
4-strip occupancy	3.1%	2.6%	1.6%	1.0%

Table 4-7. Depth Requirements imposed by criteria 1, 2, and 3.

Criteria	Minimum Depth required		
	$0.1 < \|\eta\| < 1.34$	$1.38 < \|\eta\| < 1.86$	$1.86 < \|\eta\| < 2.46$
1	11	11	11
2	10	10	10
3	10	12	16
Overall	11	12	16

Radiation Environment

- Charged particles:

  - hadron punchthrough
  - decay μ
  - prompt μ

- 4-strip occupancy at $L = 10^{34}$

  - 0.44 % in barrel
  - 1.0 % in endcap

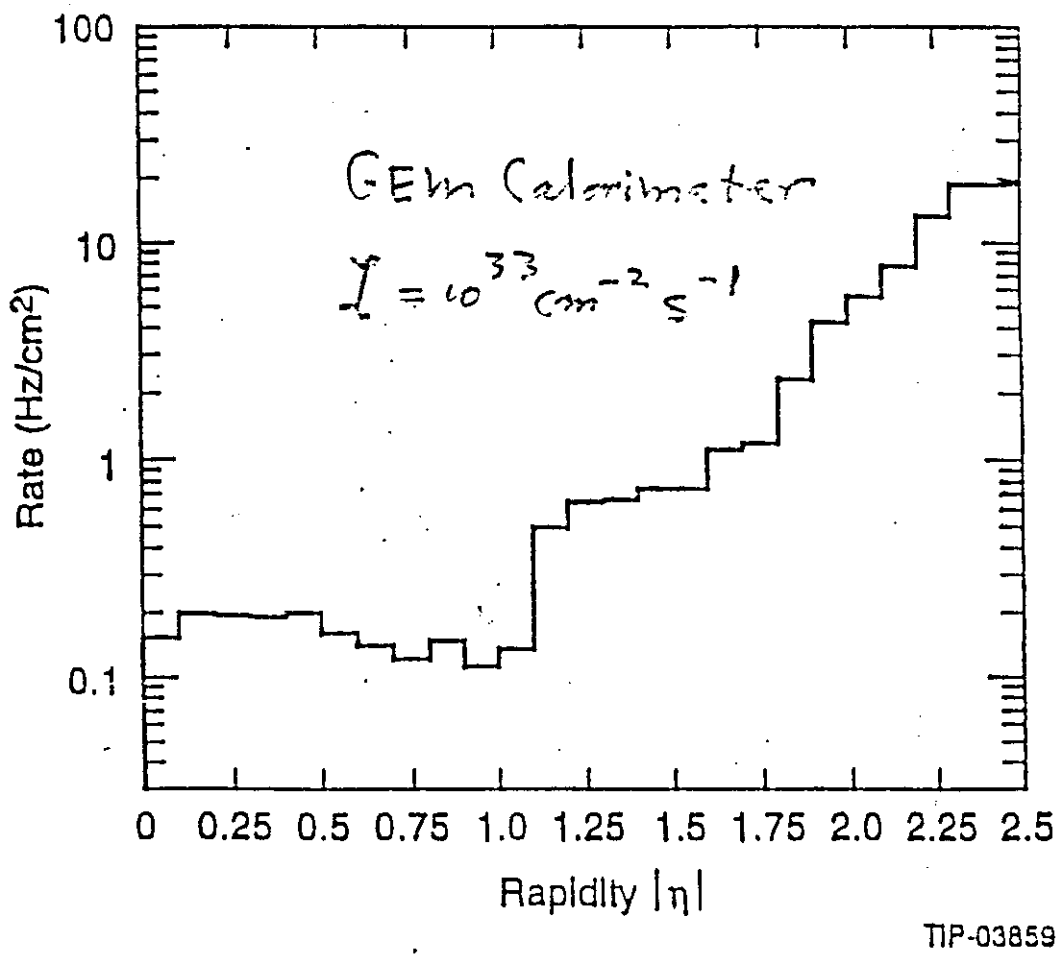
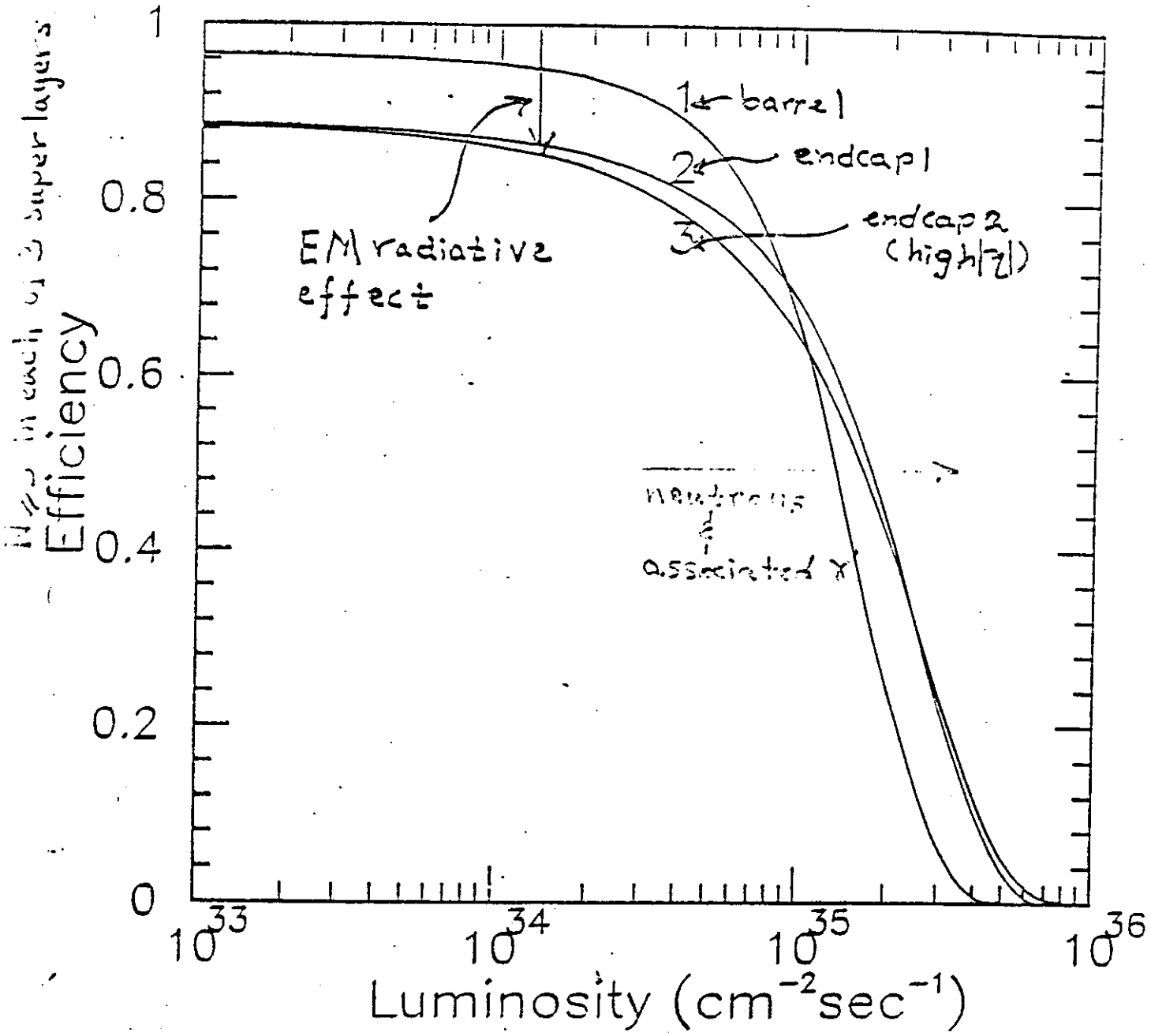
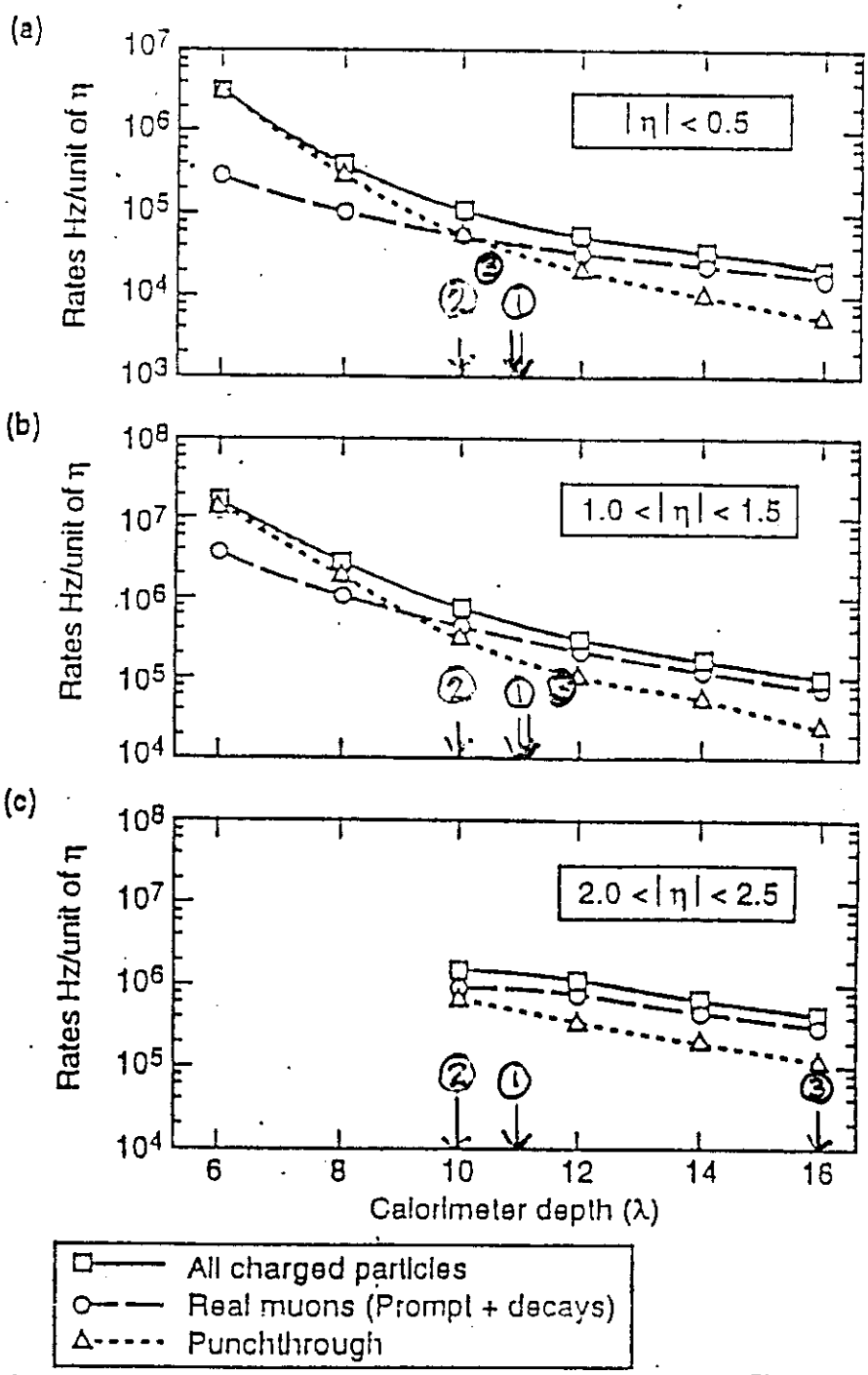


FIG. 4-11. Charged particle rate versus rapidity in the first muon system superlayer.

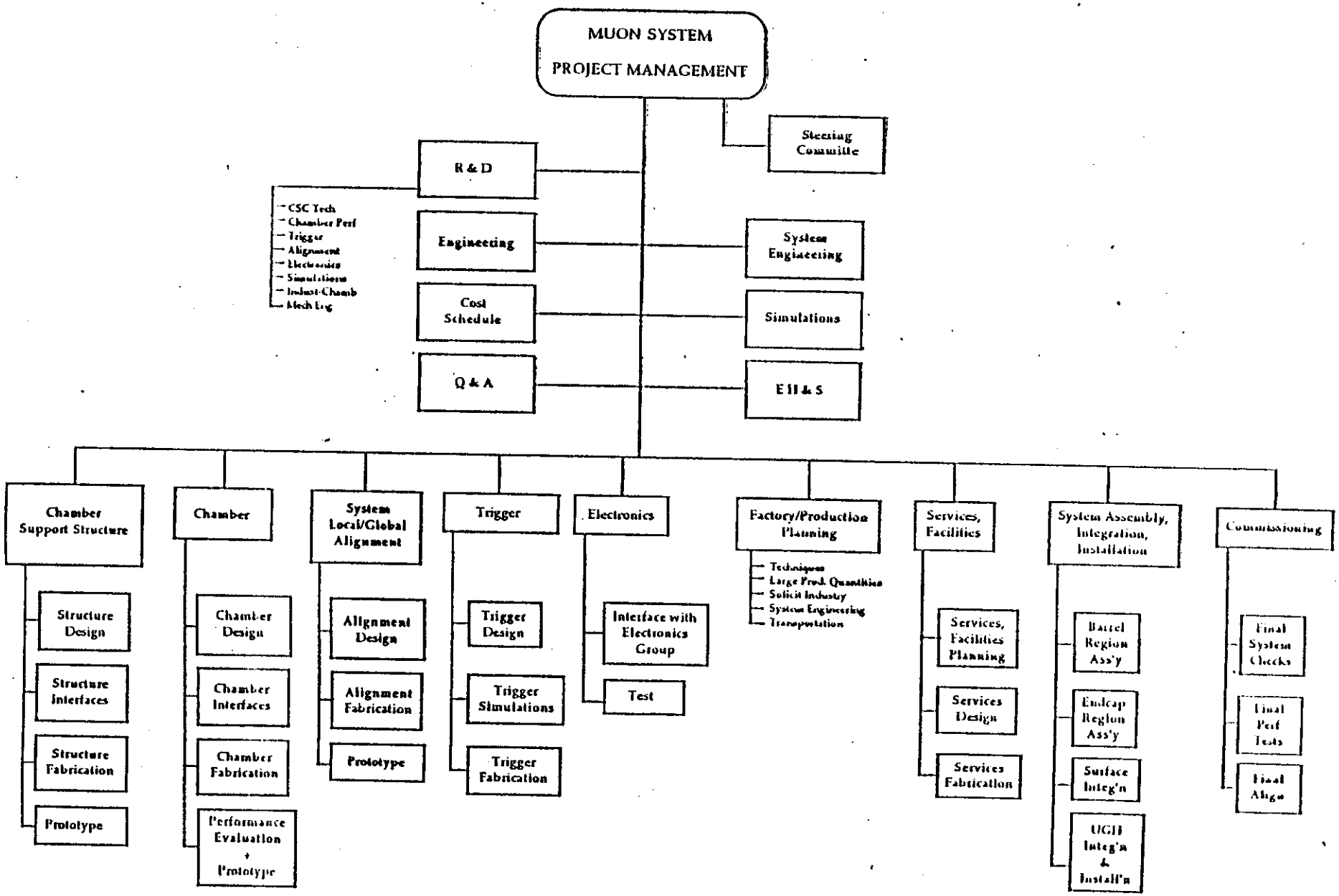
$P_\perp = 500$ GeV/c




(a)
(b)
(c)
Rates Hz/unit of η
|η| < 0.5
1.0 < |η| < 1.5
2.0 < |η| < 2.5
Calorimeter depth (λ)
All charged particles
Real muons (Prompt + decays)
Punchthrough

TIP-03842

GEM MUC System Organization



List of Institutions

Institutions

University of Arizona
Boston University
Brookhaven National Laboratory
Brown University
BSU-Minsk
Carnegie Mellon University
Charles Stark Draper Laboratory
University of Houston-SCARF
IHEP-Beijing
ITEP-Moscow
JINR-Dubna
Lawrence Livermore National Laboratory
LeCroy Corporation
Louisiana State University
Massachusetts Institute of Technology
Michigan State University
Moscow State University
Oak Ridge National Laboratory
PNPI-St. Petersburg
State University of New York-Stony Brook
Superconducting Super Collider Laboratory
University of Tennessee
Tsinghua University-Beijing

Institutional Commitments

Task	Institutions
Support structure engineering	CSDL, SSCL, LLNL
Chamber engineering	LLNL, JINR, SSCL, BU, MIT, BNL, UH
Chamber R&D	BU, BNL, IHEP, ITEP, JINR, LLNL, MIT, MSU, PNPI, SSCL, UH
Chamber performance	BU, SSCL, SUNY-SB, UH, MIT
Chamber construction	IHEP-China JINR-Russia PNPI-Russia USA
Alignment system	CSDL, LLNL, MIT, SSCL
Trigger	BNL, SUNY-SB
Electronics R&D	BNL, BU, PNPI, PU
Assembly and installation	CSDL, SSCL, LLNL
Simulations	All institutions

Summary

- Stand-alone system

  - Operates up to $L \doteq 10^{34}$ $cm^{-2}s^{-1}$

  - Good resolution
    3 SL sagitta method

  - Robust (can miss one SL)
    vertex and 2 SLs
    turning angle from extended 2 SLs

- With GEM central tracker

  - Enhanced resol'n at low Pt

  - Improved coverage

- Physics

  Higgs --> 4 μ:

  - $\sigma(M_h) \approx 1.6$ GeV/c^2 for $M_h \approx 150$ GeV/c^2

  Z' --> 2 μ:

  - Identify charge of $\mu^{\pm}$ up to kinematic limit of SSCL with 200 μm vertex constraint