GEM
PERFORMANCE FEATURES

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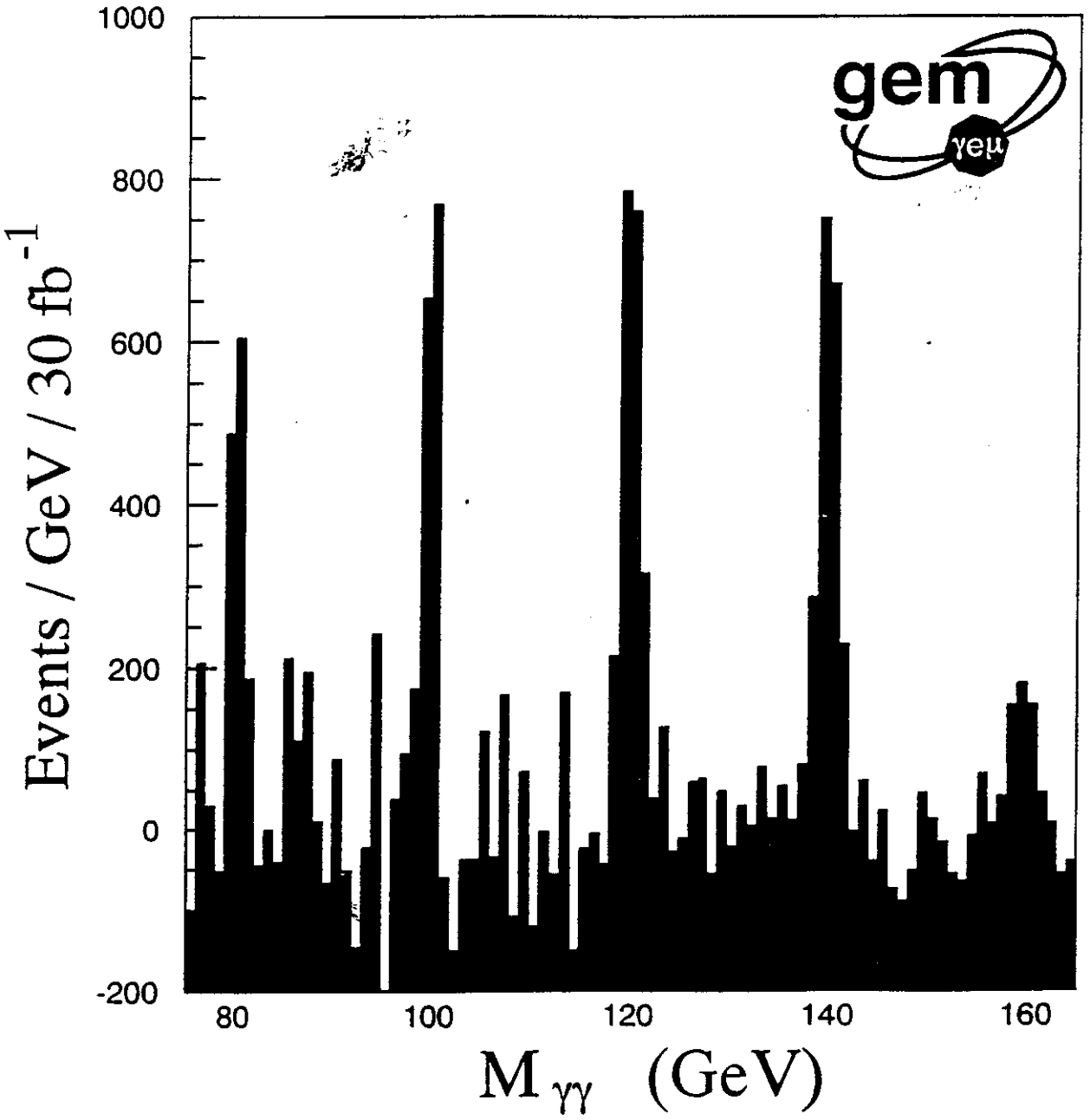
CALTECH

GEM TDR REVIEW
SSC LAB
May 24, 1993

Higgs → 2 γ


gem
γeμ
1000
800
600
400
200
0
-200
80
100
120
140
160
Events / GeV / 30 fb^{-1}
$M_{\gamma\gamma}$ (GeV)

GEM DETECTOR

DESIGN PRINCIPLES:

Explore The New Physics With Multilepton, Multiphoton, Lepton + Jet, $\not{E}_T$ Signatures Across A Wide Range of Physics Scenarios

- High-Precision EM Calorimetry; Excellent e/γ ID With Tracker and Hadron Calorimeter
- Precision Muon ID and Measurement: Open Large Volume Spectrometer, Behind Hermetic Calorimeters and Shielding
- Good Resolution for Jets and $\not{E}_T$
- Robust Calorimetric, Muon and Tracker Measurements To $\mathcal{L} = 10^{34}$

GEM's PHYSICS GOALS

HAVE GUIDED THE DESIGN PRINCIPLES and MAJOR TECHNICAL CHOICES FROM THE OUTSET

- **EM RESOLUTION REQUIREMENTS**
  Stochastic ($6-8\%/\sqrt{E}$) *AND* Systematic ($\leq 0.4\%$)

  Terms Set By the Discovery Potential For
  $H^0 \to \gamma\gamma$, $H^0 \to ZZ^* \to e^+e^-e^+e^-$, $Z' \to e^+e^-$

- **PHOTON POINTING and ANGULAR RESOLUTION**
  $\sigma_\theta = (40-50)/\sqrt{E} + 0.5$ mrad:

  For Clean ID and Measurement of $H^0 \to \gamma\gamma$, $Z' \to e^+e^-$;
  Event Vertex Determination at $\mathcal{L} = 10^{34}$

- **CALORIMETER SEGMENTATION**
  Precision Measurement of EM Processes;
  Rejection of Hadronic Backgrounds;
  Clean Isolation of e, μ, γ (With Tracker)

- **HIGH MUON MOMENTUM RESOLUTION**
  For All $|\eta| < 2.5$
  Detect $Z' \to \mu^+\mu^-, H^0 \to \mu^+\mu^-\mu^+\mu^-$ With High Efficiency

- **FORWARD CALORIMETER COVERAGE**
  To $|\eta| \approx 5$: $\not{E}_T$ Signatures for $H^0 \to \ell^+\ell^-\nu\bar{\nu}$ and SUSY

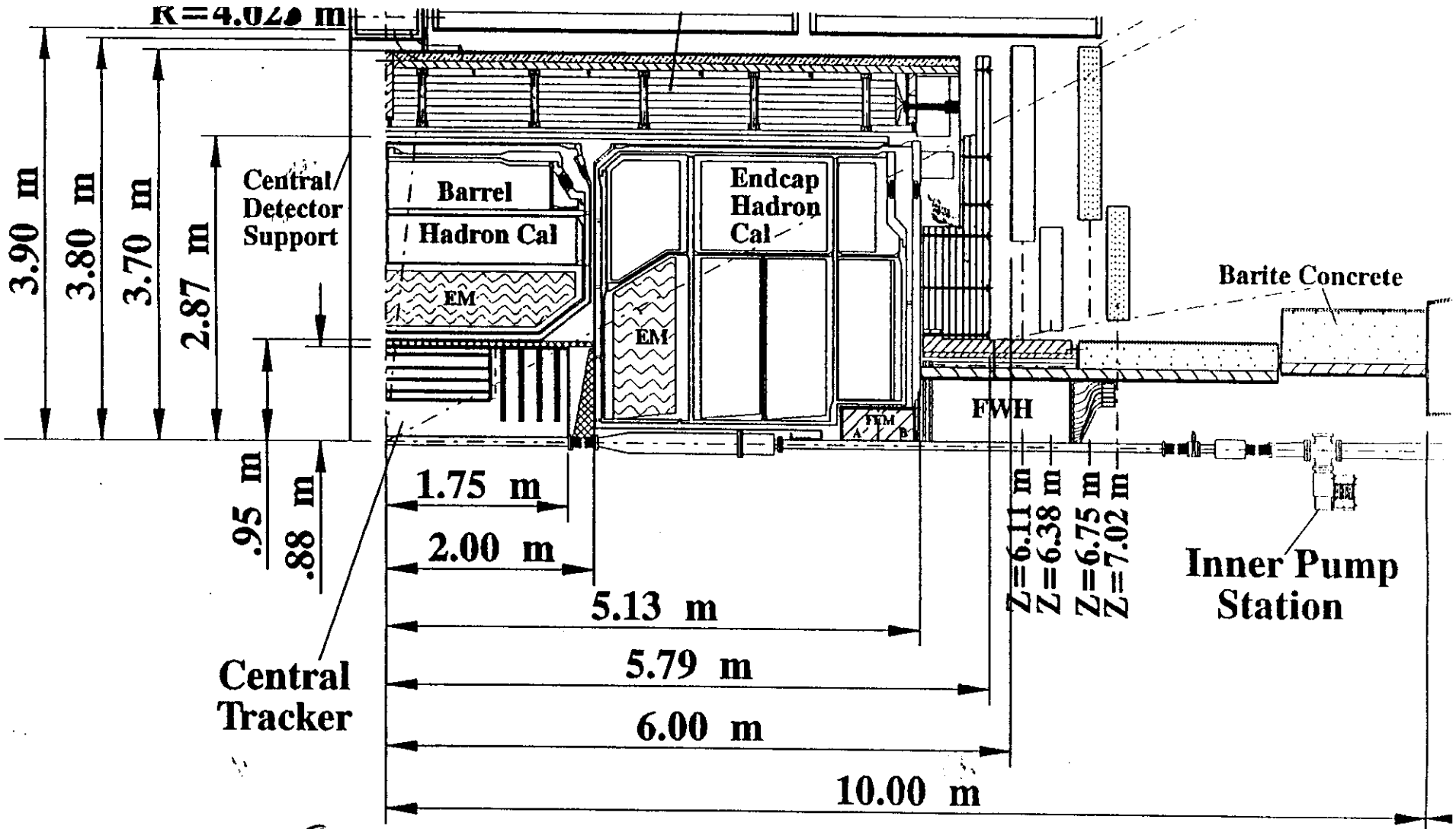
- **COMPACT CENTRAL TRACKER RESOLUTION**
  γ/Jet, e/γ Separation For $H^0 \to \gamma\gamma$;

  Vertex Determination For $H^0 \to \gamma\gamma$, $Z' \to e^+e^-$;
  p_T Resolution For $\tilde{g}\tilde{g} \to \ell^\pm\ell^\pm + X$ in e−Channel

- **ADEQUATE SHIELDING: LOW n, γ FLUX**
  Low Muon Chamber Occupancies To $\mathcal{L} = 10^{34}$

GEM'S STRENGTHS:
PHYSICS CAPABILITY

- NEW PHYSICS: Clean, High Resolution Lepton and Photon Measurements
- Higgs Detection Over The Full Range:
  Low Mass: $H^0 \to \gamma\gamma, \ell\gamma\gamma;\ \ell^+\ell^-\ell^+\ell^-;$
  High Mass: $H^0 \to \ell^+\ell^-\ell^+\ell^-;\ \ell^+\ell^-jj, \ell^+\ell^-\nu\bar{\nu}$
- Quick Discovery of Top;
  Charged Higgs in $t \to H^+b;\ H^+ \to \tau^+\nu$
- Squarks, Gluinos Up To the TeV Range: Jets, $\not{E}_T$; Isolated Lepton Veto for $t\bar{t}$; Like-Sign Dileptons
- Quark Substructure To $\Lambda = 25$ TeV: Jets, $\not{E}_T$
- Z' to 8 TeV: $Z' \to e^+e^-$ Width;
  $Z' \to \mu^+\mu^-$ F-B Asymmetry At $\mathcal{L} = 10^{34}$
- Quark-Lepton Compositeness to $\Lambda = 30$-35 TeV:
  $q\bar{q} \to \mu^+\mu^-$ F-B Asymmetry At $\mathcal{L} = 10^{34}$



- COMPACT TRACKER
- THICK, CLOSE-IN, HERMETIC CALORIMETERS
- Shielding

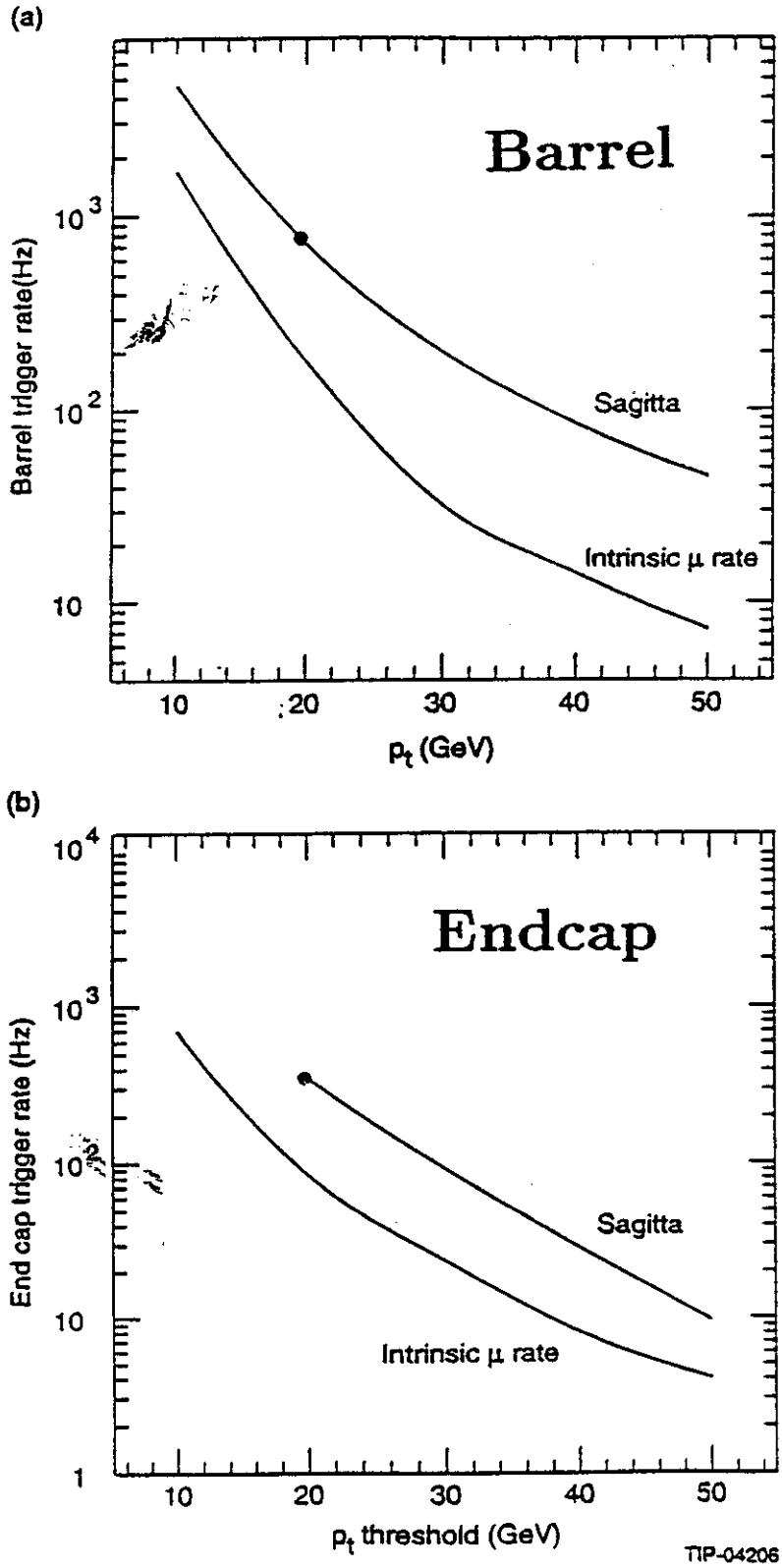
GEM TRIGGER:
ISOLATED EM CLUSTERS, JETS, MUONS, MISSING E_T

Name	Definition	Thresholds
• E_x	EM cluster with $E_T > x$ GeV in 0.16×0.16, isolated in both EM and HAD calorimeters.	E_8, E_{16}, E_{50}, E_{80}
• M_x	Muon with $p_T > x$ GeV.	M_{10}, M_{20}, M_{30}, M_{40}
• J_x	Jet cluster with $E_T > x$ GeV in 0.48×0.48.	J_{16}, J_{50}, J_{80}, J_{200}
• $\not{E}_x$	Missing energy $\not{E}_T > x$ GeV summing whole calorimeter.	$\not{E}_{50}$, $\not{E}_{100}$

Process	Mass	Trigger	Efficiency
$H \to \gamma\gamma$	80 GeV	$2E_{16} \vee E_{50}$	78.7%
$H \to \gamma\gamma$	140 GeV	$2E_{16} \vee E_{50}$	94.7%
$t\bar{t}H \to \gamma\gamma\ell X$	80 GeV	$2E_{16}$	94.4%
$H \to \ell^+\ell^-\ell^+\ell^-$	140 GeV	$2M_{10} \vee 2E_{16}$	81.8%
$H \to \ell^+\ell^-\ell^+\ell^-$	400 GeV	$2M_{10} \vee 2E_{16}$	99.8%
$H \to \ell^+\ell^- jj$	800 GeV	$2M_{10} \vee 2E_{16}$	99.9%
$t\bar{t} \to \ell\nu bX$	140 GeV	$E_{50} \vee M_{30}$	75.3%
$\widetilde{gg}$	500 GeV	$3J_{80} \wedge \not{E}_{100}$	99.9%
$W \to e\nu$	—	$E_{16} \wedge \not{E}_{50}$	15.8%
$W \to \mu\nu$	—	$M_{10} \wedge \not{E}_{50}$	48.7%
$Z \to ee$	—	$2E_{16}$	80.3%
$Z \to \mu\mu$	—	$2M_{10}$	86.9%

MUON SAGITTA TRIGGER

RATE VS. P_T CUT



GEM MUON SPECTROMETER PRECISE, ROBUST DESIGN

- QUIET ENVIRONMENT
  - 11 - 16+ λ Calorimeter: Punch Through Well Below Real Muon Rate (π, K, c, b)
  - Compact Close-In FCAL + Shield: Low n, γ Flux
  - Air Gaps for Associated EM Showers: High Efficiency for Multi-TeV Muon Reconstruction
- HIGH RESOLUTION
  - $\Delta p_T/p_T = 5\%$ (11.5%) (Baseline) At $\eta = 0$ (2.5), for $p_T = 0.5$ TeV
  - Charge Determination: To 6-15 TeV (Baseline); To 13-22 TeV With 200 μm Vertex
  - CSCs: $\rightarrow \sigma_{SAG} \leq 54\ \mu$m;
    - Intrinsic and Alignment Precision
- HIGH PATTERN RECOGNITION and RECONSTRUCTION EFFICIENCY
  - CSCs ➡ Granularity, Two-Track Separation (Charge Profile), Near-Space Points, Speed
  - Full Advantage of Low n, γ and Punchthrough Occupancy: Sub-Percent at $\mathcal{L} = 10^{34}$
  - Local Track Vectors: Cross-Check Centroids In Each SL
  - 0.5 - 1 mm Vertex: Reconstruction In 2 SL With Good Resolution: Added Robustness

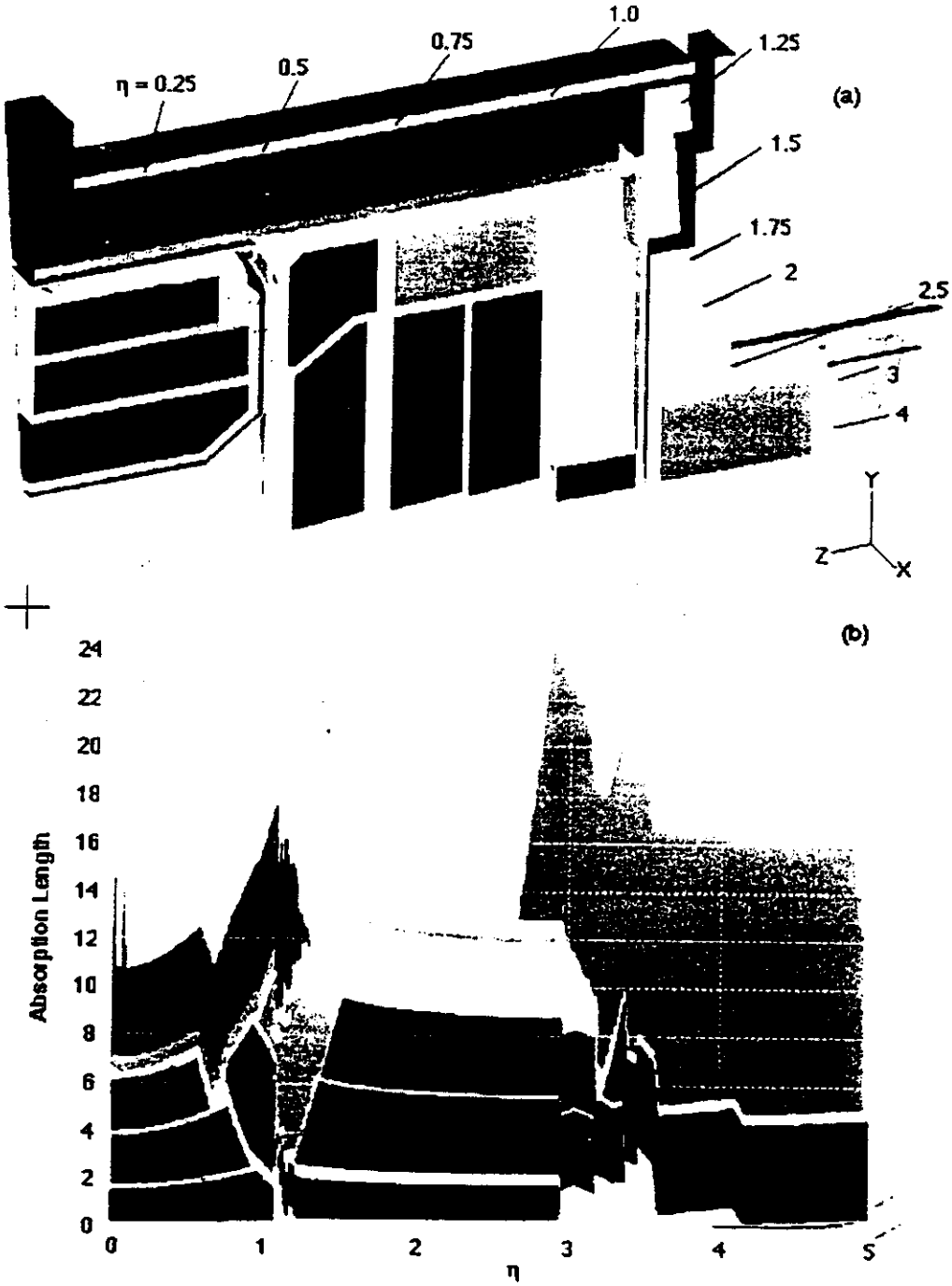
CALORIMETER DEPTH CHOICE

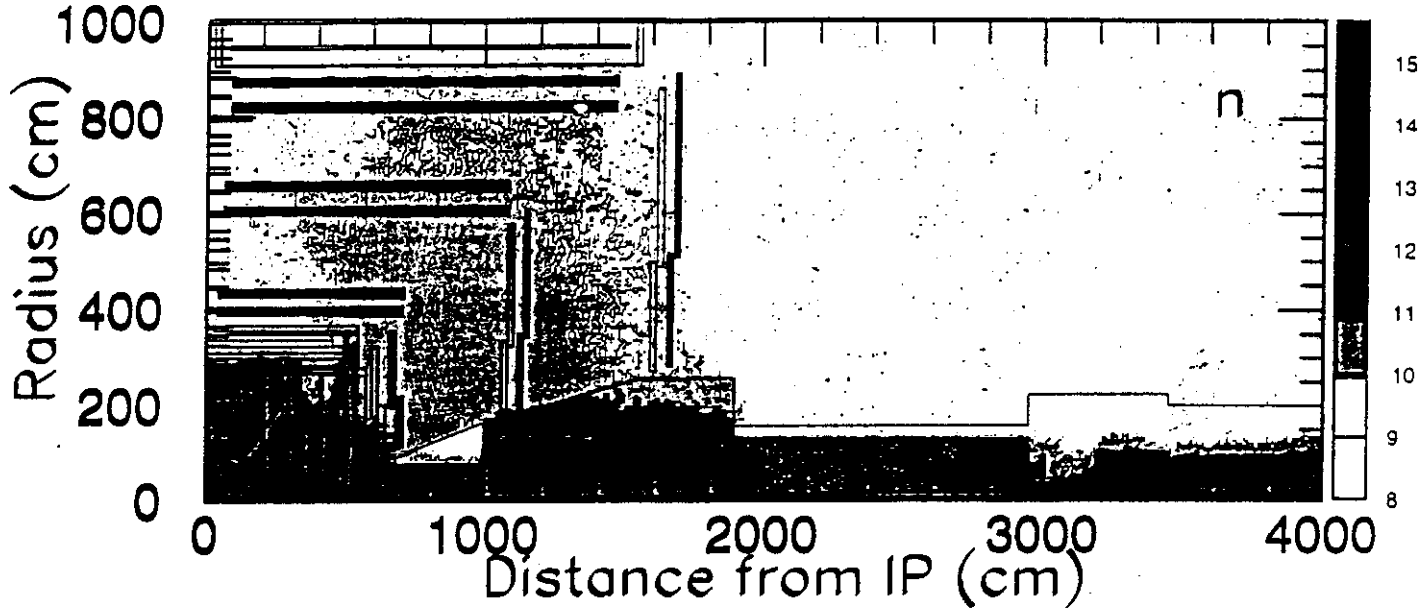
(1) **HIGH PATTERN RECOGNITION EFFICIENCY:**
Overall Punchthrough Rate Well Below
Real Muons (Prompt + Decay) Rate

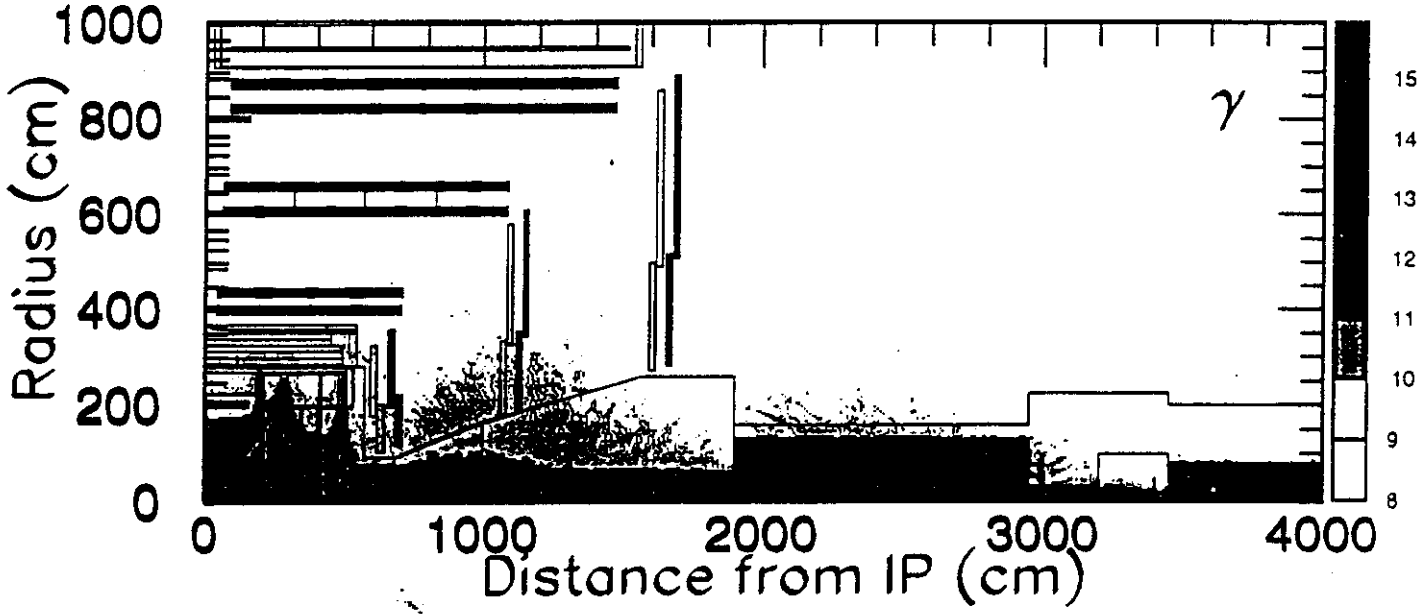
(2) **LOW MUON TRIGGER RATE:**
High-p_T Punchthrough and
Sailthrough Well Below Real Muons

(3) **HIGH TRACK RECONSTRUCTION EFFICIENCY:**
Four-Strip Occupancy $< 1\%$ at $\mathcal{L} = 10^{34}$

Criteria	Min. 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


η = 0.25
0.5
0.75
1.0
1.25
1.5
1.75
2
2.5
3
4
(a)
Y
Z
X
(b)
Absorption Length
24
22
20
18
16
14
12
10
8
6
4
2
0
0
1
2
3
4
5
η





with shielding

10^n cm^{-2} $sscy^{-1}$

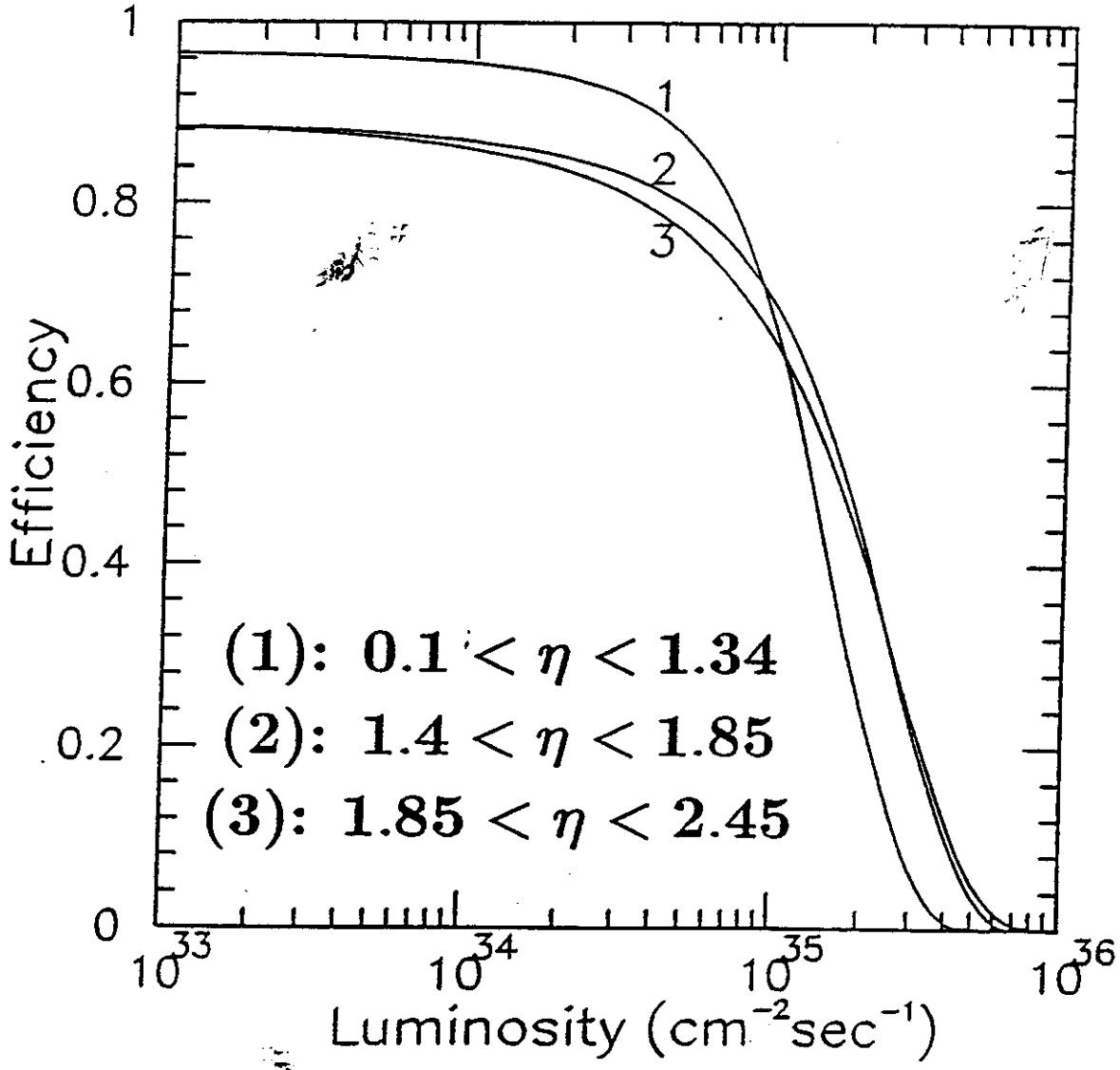
CSC n, γ Occupancy (300 ns)

At $\mathcal{L} = 10^{34}$ $\lesssim 1\%$

	Rapidity Range		
Superlayer	0.08-1.34	1.38-1.86	1.86-2.46
Inner	0.6%	0.3%	0.3%
Middle	0.6%	0.4%	0.4%
Outer	1.1%	0.6%	0.5%

EFFICIENCY FOR 3 GOOD TRACK SEGMENTS VERSUS $\mathcal{L}$

Muon $P_T = 500$ GeV

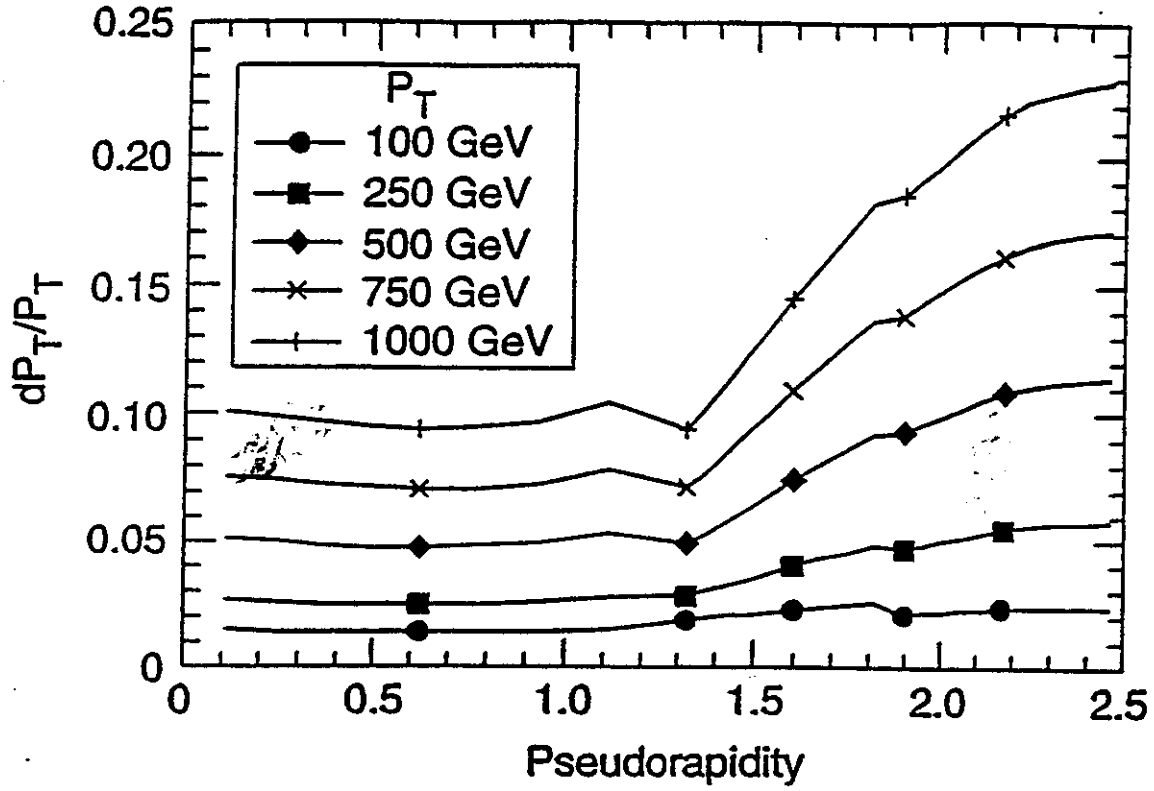


High Efficiency To $\sim 10^5 n/cm^2/sec$

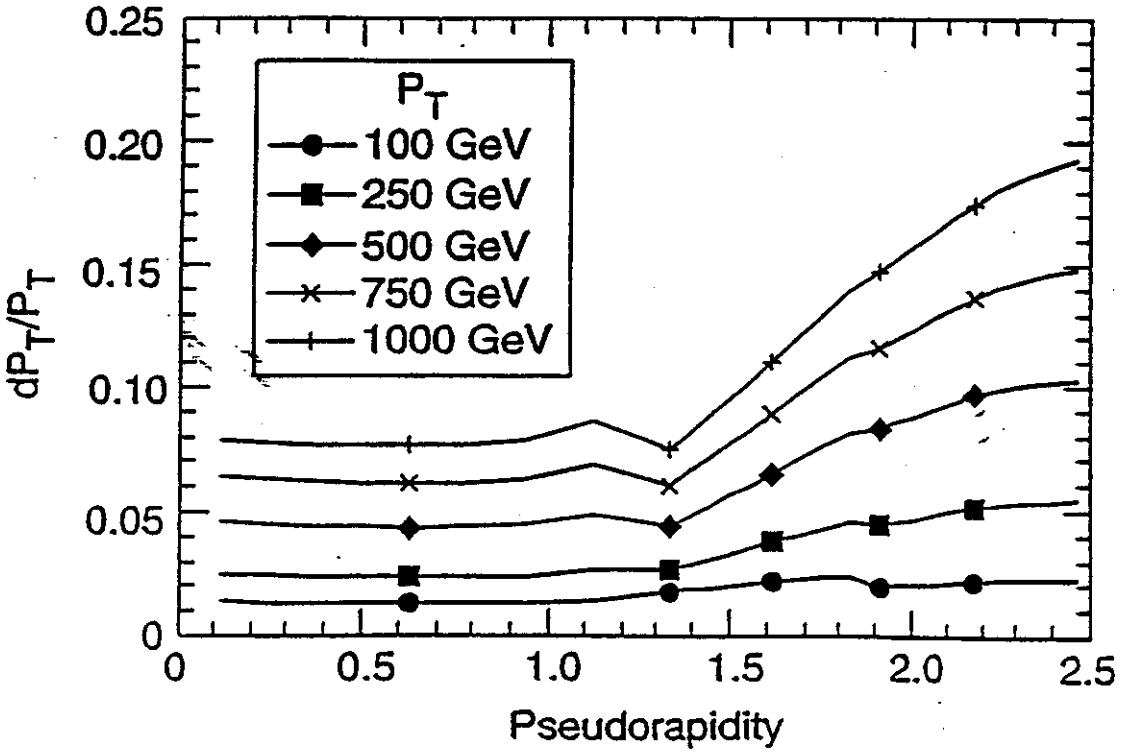
Nearly Unaffected By Punchthrough To Above $\mathcal{L} = 10^{34}$

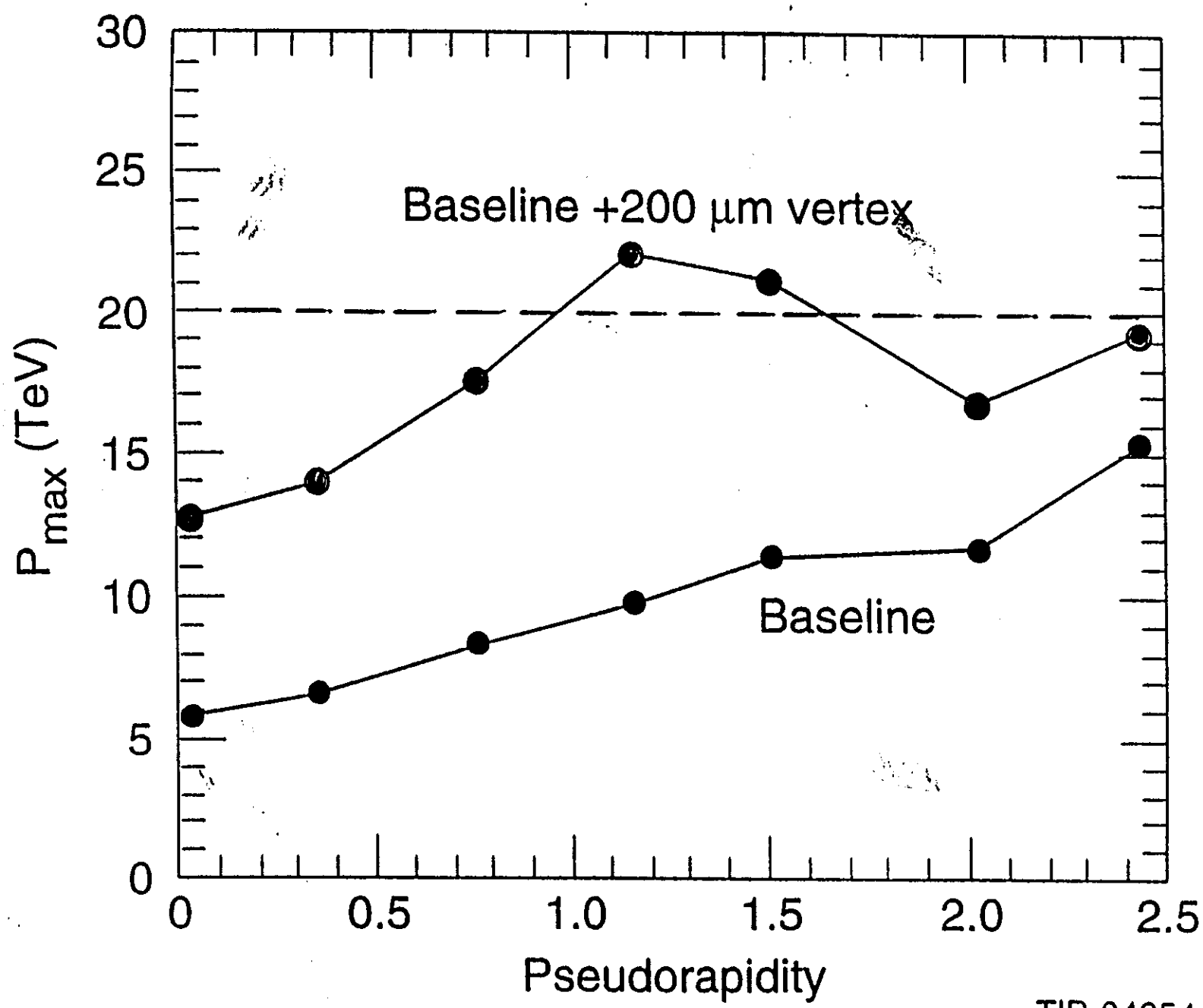
MUON RESOLUTION

STANDALONE SYSTEM



WITH 200 μm $x-y$ VERTEX




30
25
20
15
10
5
0
P_{max} (TeV)
Baseline +200 μm vertex
Baseline
0
0.5
1.0
1.5
2.0
2.5
Pseudorapidity
TIP-04254

QUARK-LEPTON SUBSTRUCTURE:

$q\bar{q} \to \mu^+\mu^-$ AT $\mathcal{L} = 10^{34}$

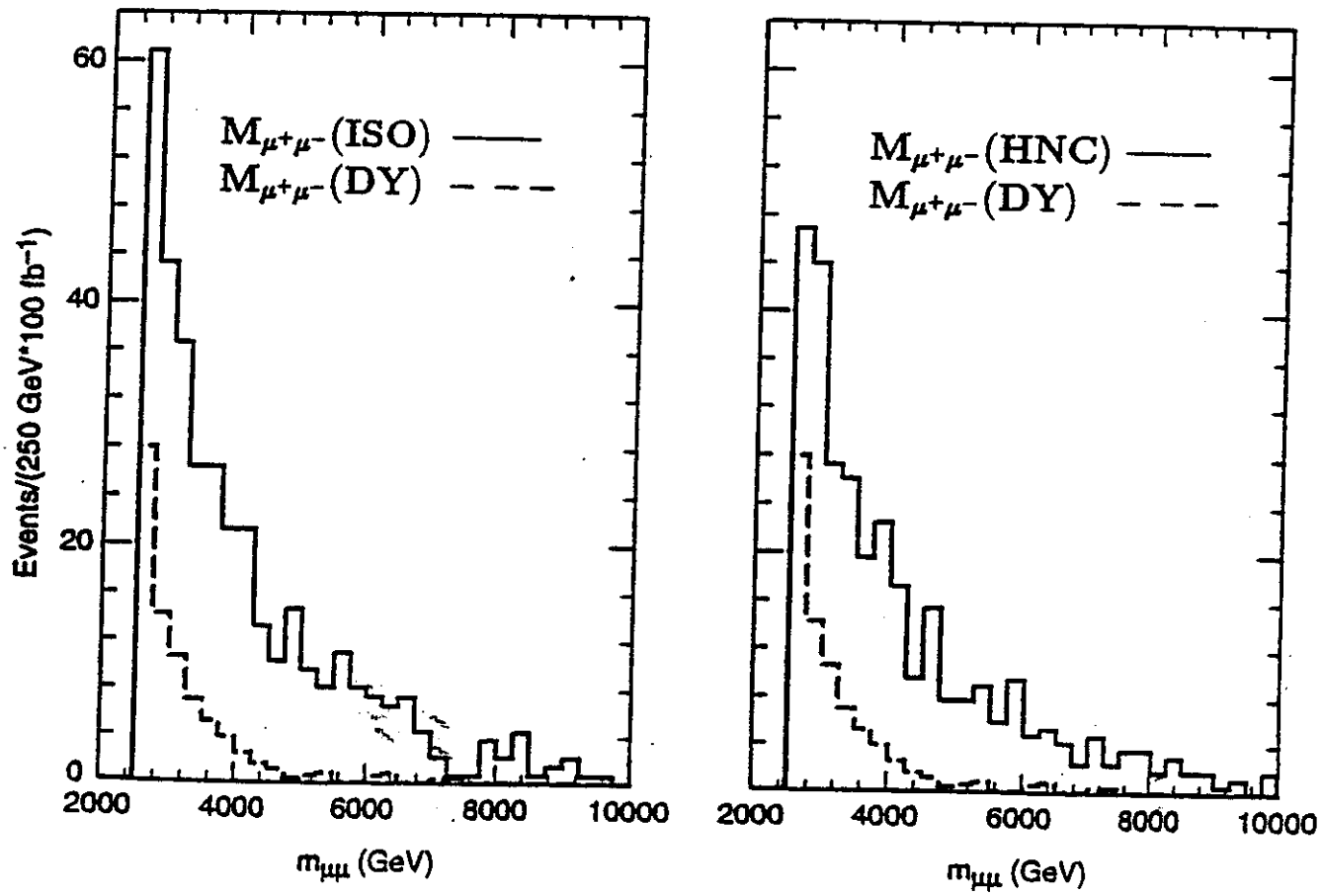
GEM REACH TO Λ = 30-35 TeV

- FOUR FERMION CONTACT INTERACTIONS, SCALE Λ:

$$\mathcal{L}_{\rm ISO} = -\frac{4\pi}{\Lambda^2}\overline{Q_{La}}\gamma^\mu Q_{La}\overline{L_{Lb}}\gamma_\mu L_{Lb}$$

$$\mathcal{L}_{\rm HNC} = -\frac{4\pi}{\Lambda^2}\epsilon_{ij}\overline{Q_{Lia}}u_{Ra}\overline{L_{Ljb}}\ell_{Rb} + {\rm h.c.}$$

Excess Events For $2 \lesssim M_{\mu^+\mu^-} \lesssim 10$ TeV

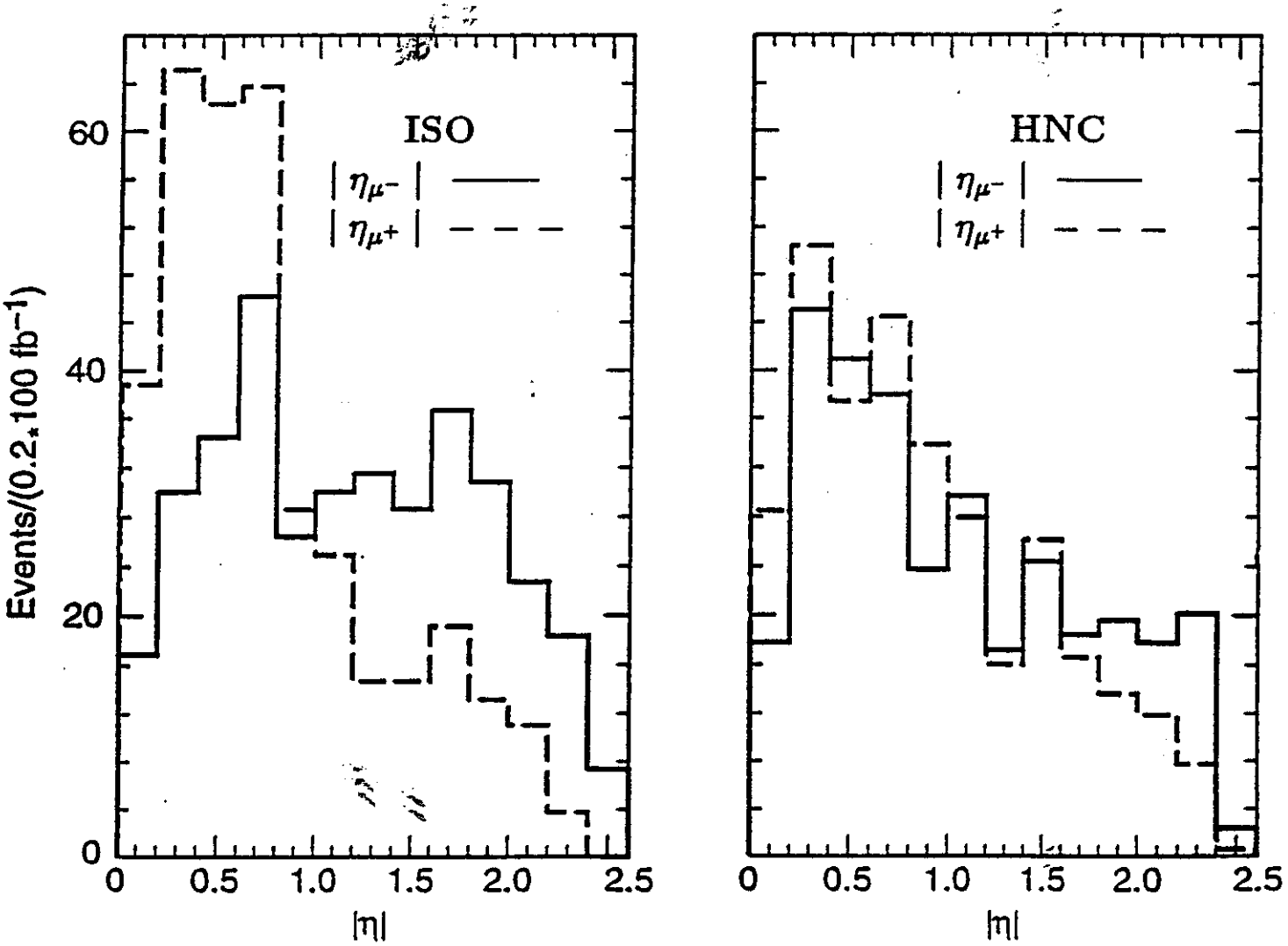


- SIGNAL (Λ = 25 TeV) and DRELL-YAN SAMPLES: $M_{\mu^+\mu^-} > 2$ TeV
  - $\sigma_{\rm ISO} = 9.4, \sigma_{\rm HNC} = 7.9;\ \sigma_{\rm DY} = 2.8$ fb

QUARK-LEPTON SUBSTRUCTURE

$q\bar{q} \to \mu^+\mu^-$ AT $\mathcal{L} = 10^{34}$

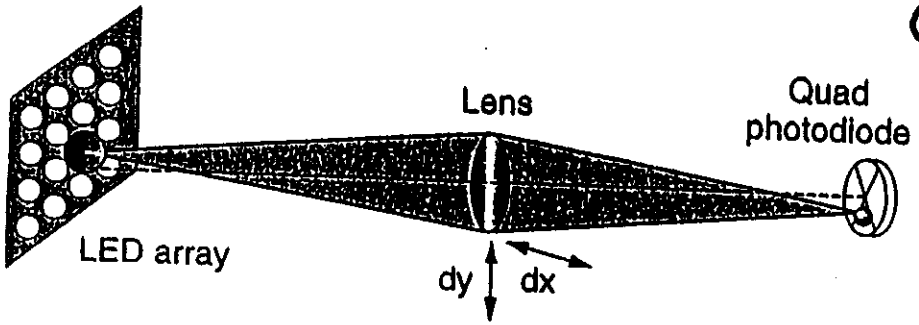
- ANGULAR DISTRIBUTIONS
  DISTINGUISH THE MODELS
  - ISO: $|\eta_{\mu^-}|$ Tends To Be Larger, $|\eta_{\mu^+}|$ Smaller
  - HNC: $|\eta_{\mu^-}|, |\eta_{\mu^+}|$ Identical



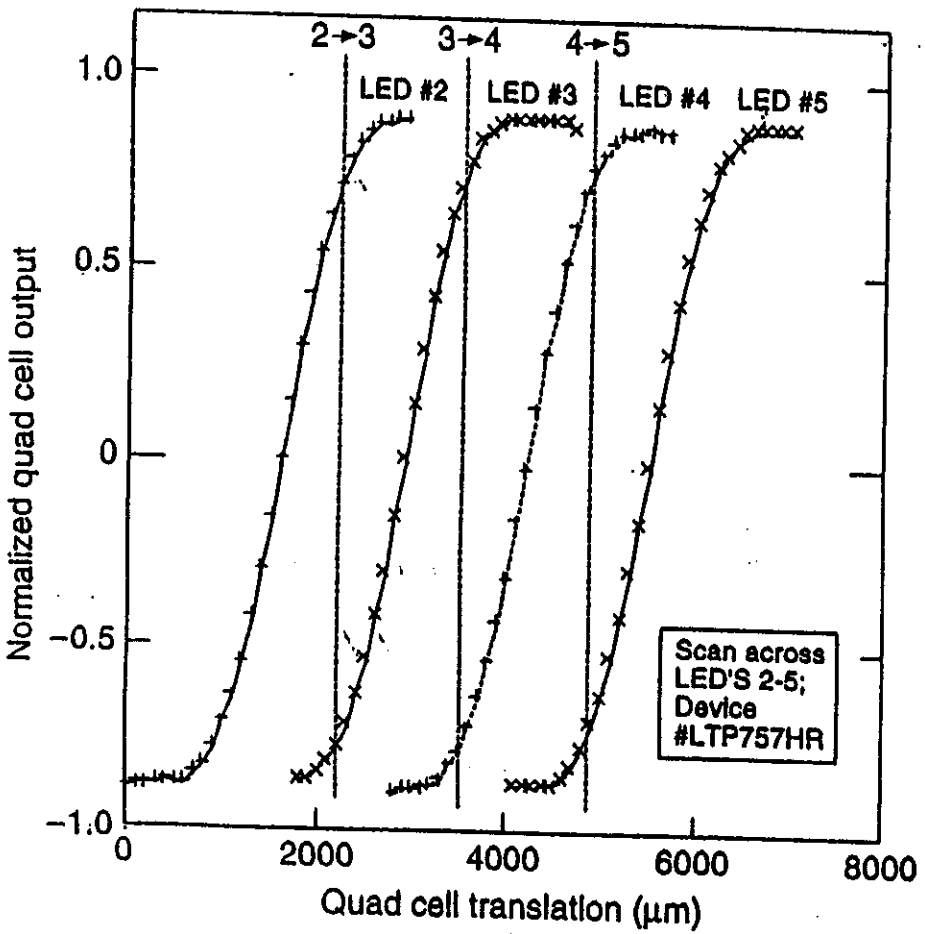
- Unambiguous Charge Signs:
  96% (ISO or HNC); 99.5% (DY)

• Precision Alignment

(a)

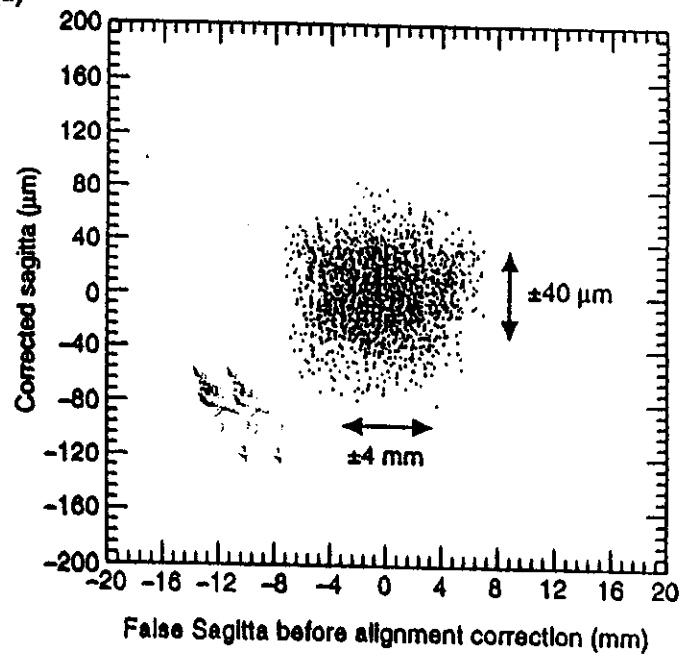


(b)

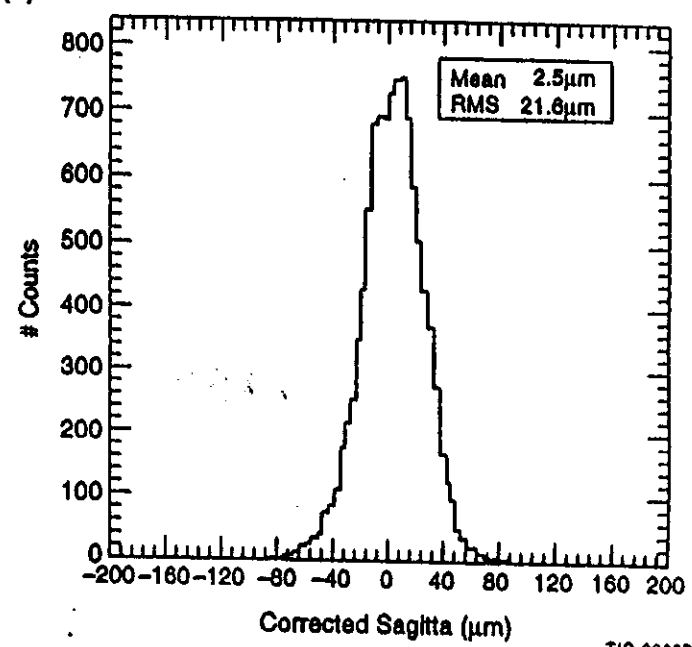


TIP-03898

(a)



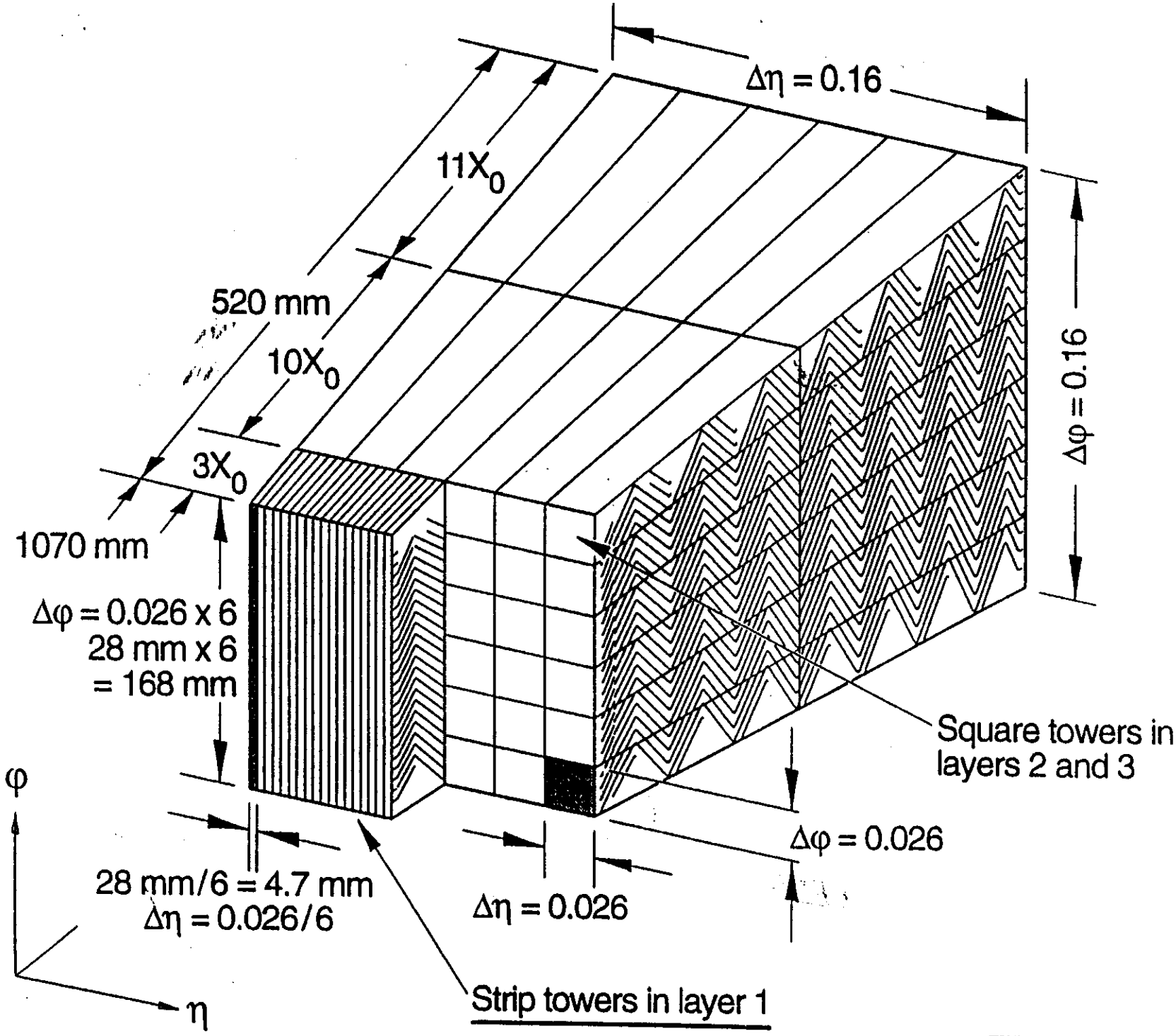
(b)



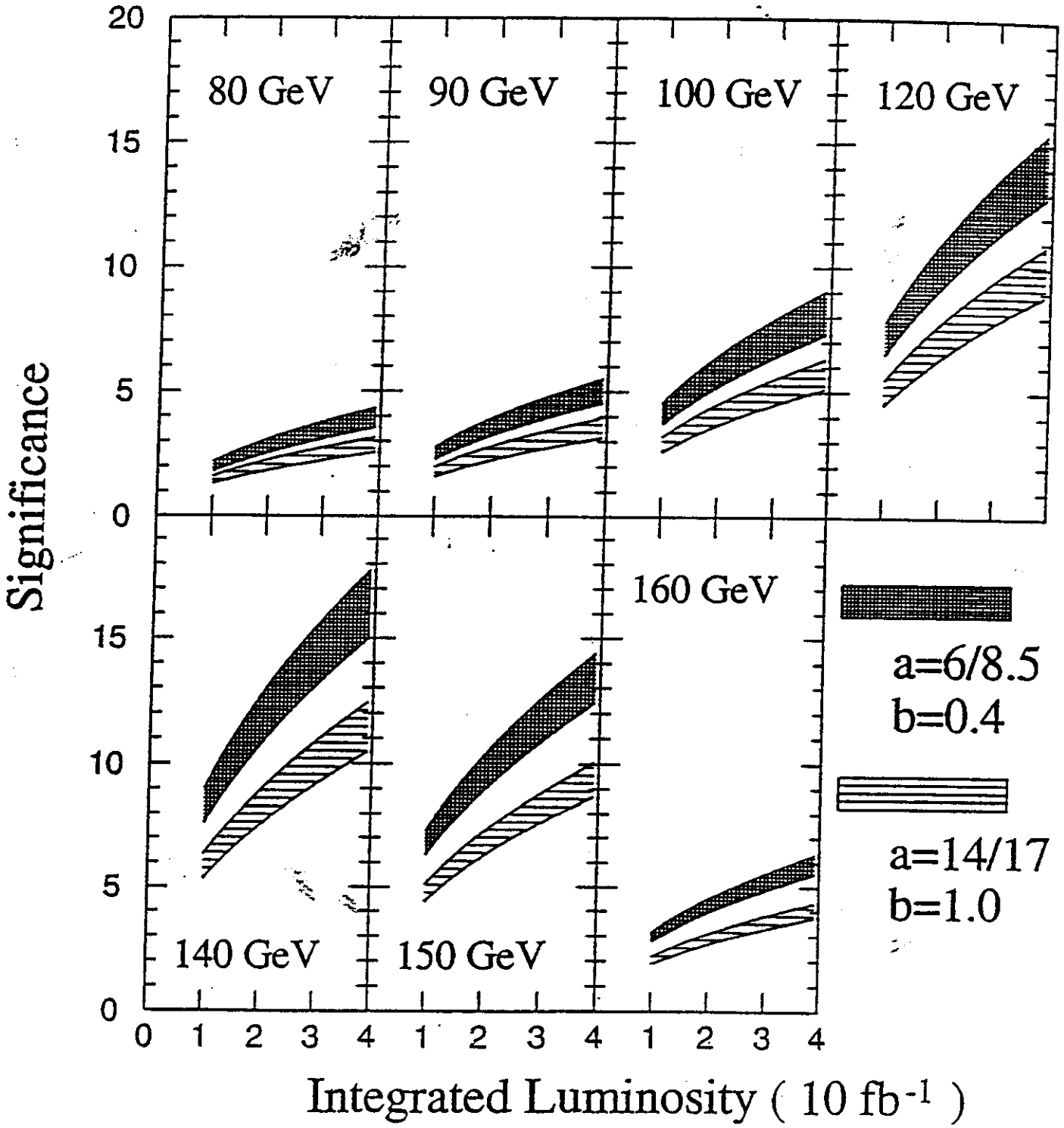
TIP-03897

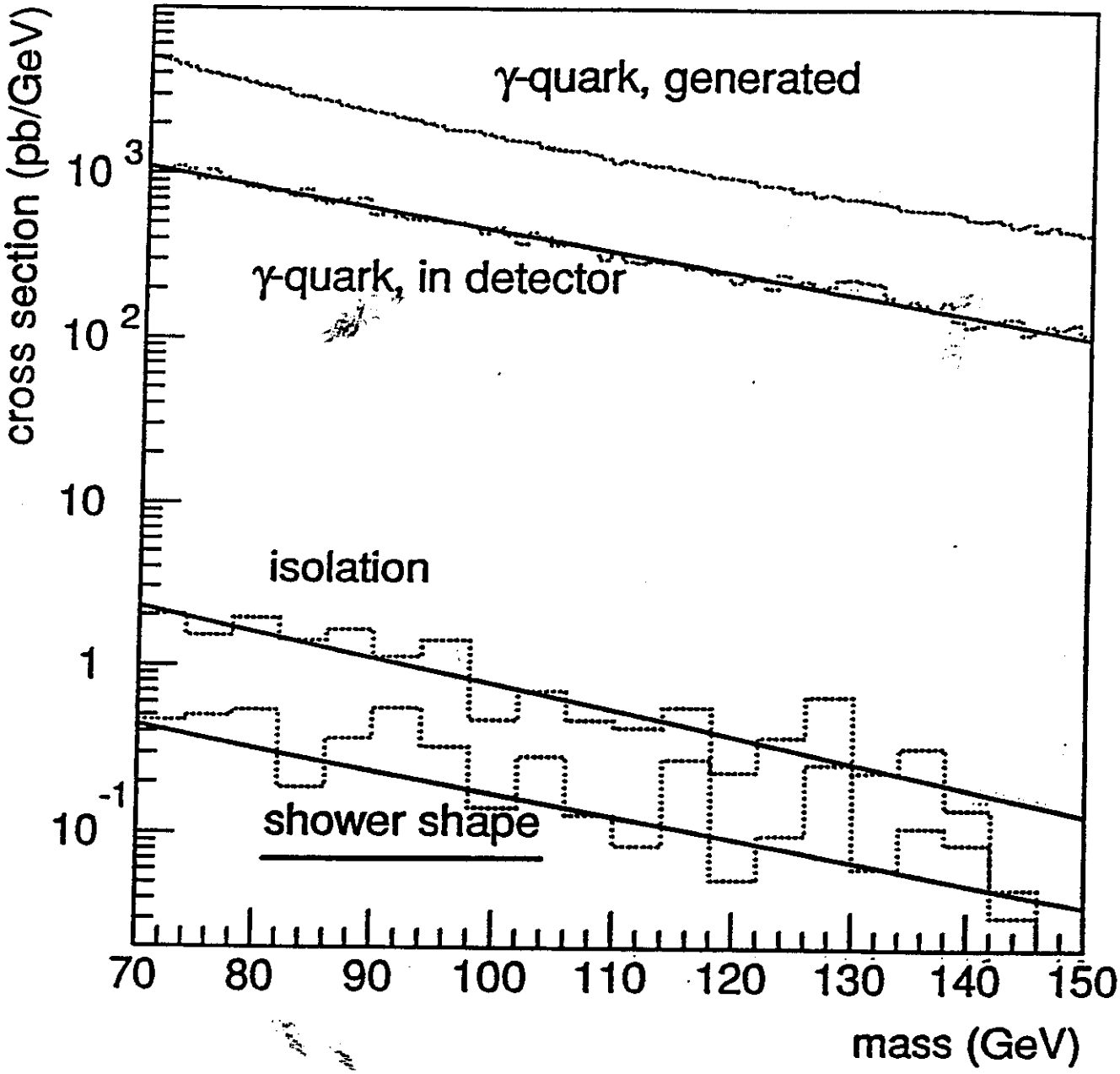
GEM CALORIMETERS

- STABLE, ROBUST OPERATION
  - LKr/LAr EM Accordion:
    - * Intrinsically Stable ⇒ Small Systematics
    - * Fast Signals ⇒ Low Noise; Clean Lepton and Photon Isolation
  - Longitudinal and Fine Transverse EM, HCAL Segmentation:
    - * Photon Pointing With η-Strips: H^0 Vertex At $\mathcal{L} = 10^{34}$
    - * Clean γ/Jet Separation, With Strips, Tracker: $1 - 4 \times 10^{-4}$;
    - * e/Jet Separation $\sim 10^{-5}$
    - * γ/e Separation With Tracker: $\mathcal{R}(\gamma/e)$ =0.5% for $M_H \approx M_Z$
- HIGH EM RESOLUTION
  - $\sigma_E/E = 6\%/\sqrt{E} \oplus 0.4\%$ (Barrel);
  - $\sigma_E/E = 8\%/\sqrt{E} \oplus 0.4\%$ (Endcap);
  - Sufficient for Higgs Discovery:
    - * 10 fb^{-1} Will Cover $M_H \geq 100$ GeV
    - * 30 fb^{-1} Will Cover $80 < M_H < 100$ GeV
- GOOD JET RESOLUTION AND COVERAGE ($|\eta| < 5$)
  - $\sigma_E/E = 60\%/\sqrt{E} \oplus 4\%$ (Weighting); Lightly Instrumented Scintillating Barrel
  - Sufficient E_T Resolution for $H^0 \to \ell^+\ell^- jj$; Discovery of Quark Substructure
  - Sufficient $\not{E}_T$ Resolution for $H^0 \to \ell^+\ell^-\nu\bar{\nu}$; Supersymmetry Signatures


Δη = 0.16
11X0
520 mm
10X0
3X0
1070 mm
Δφ = 0.16
Δφ = 0.026 x 6
28 mm x 6
= 168 mm
Square towers in
layers 2 and 3
φ
Δφ = 0.026
28 mm/6 = 4.7 mm
Δη = 0.026/6
Δη = 0.026
η
Strip towers in layer 1

TIP-04023


80 GeV
90 GeV
100 GeV
120 GeV
140 GeV
150 GeV
160 GeV
a=6/8.5
b=0.4
a=14/17
b=1.0
Significance
Integrated Luminosity (10 fb^{-1})
0
5
10
15
20
0 1 2 3 4



$R(\gamma, \text{Jet}) \approx 1 \times 10^{-4}$ (gluon)

$\approx 3\text{-}4 \times 10^{-4}$ (Quark)

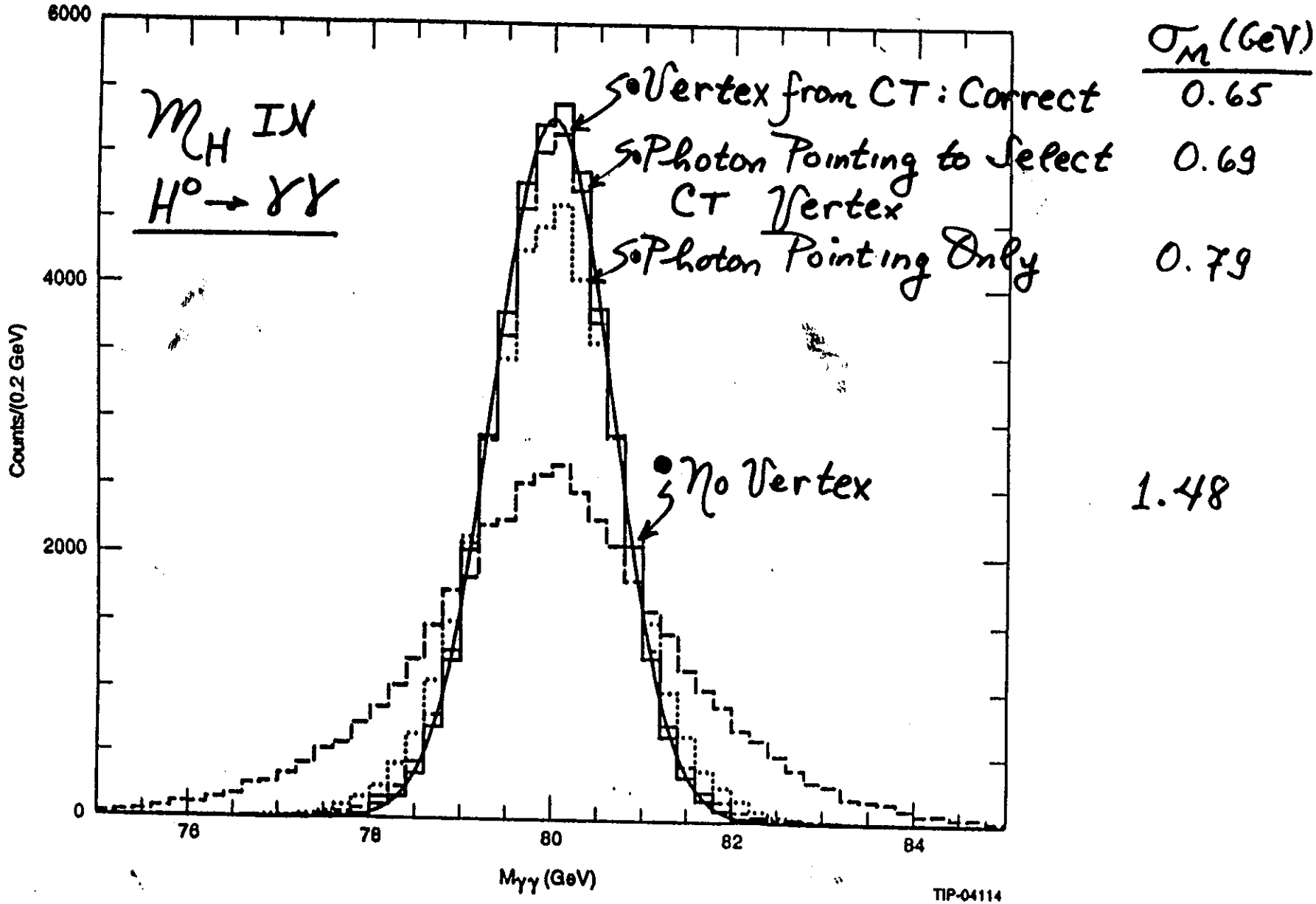
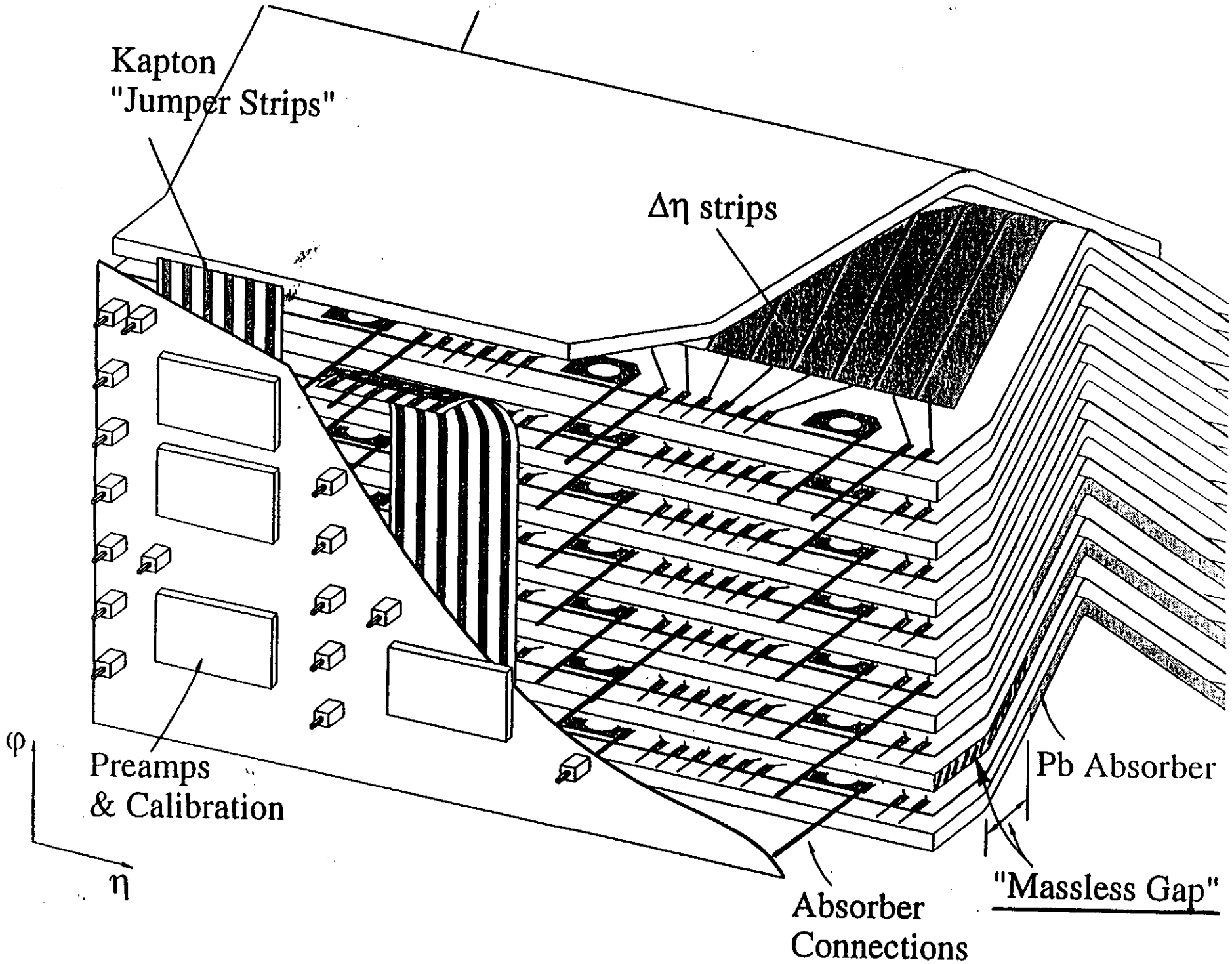
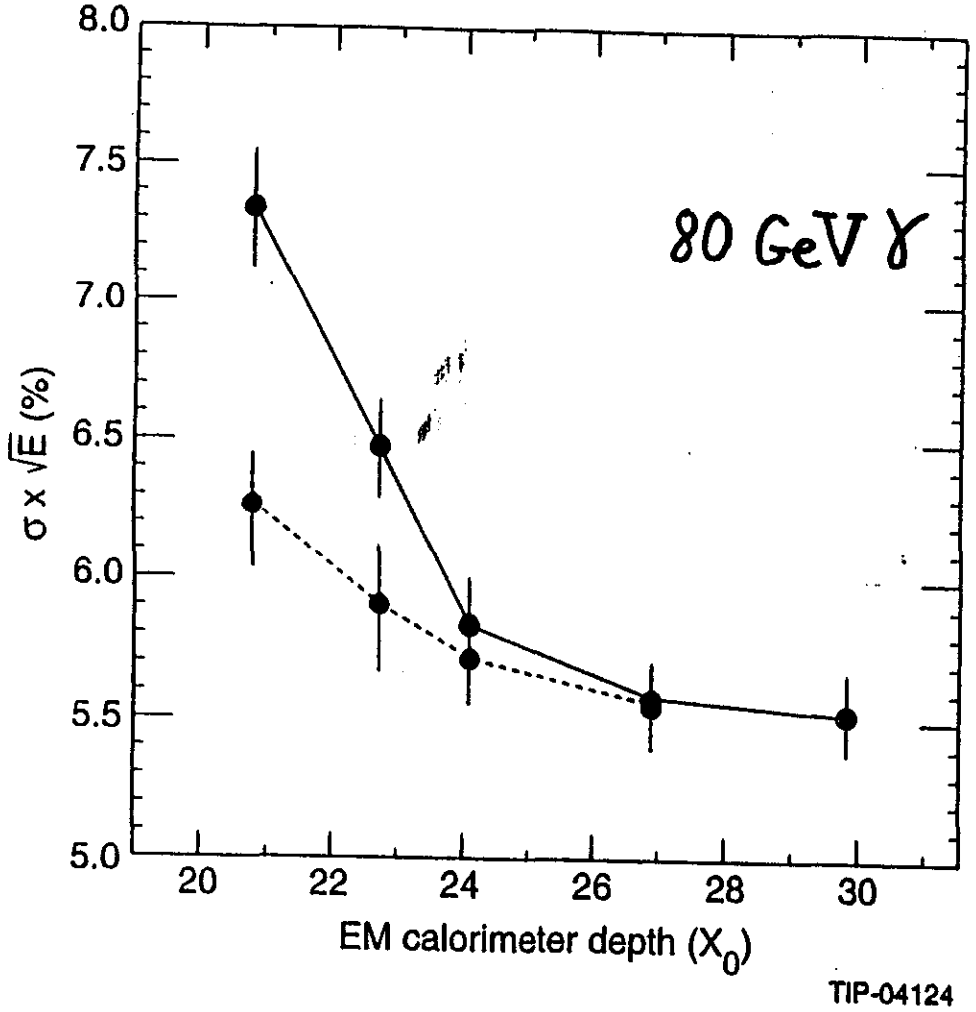
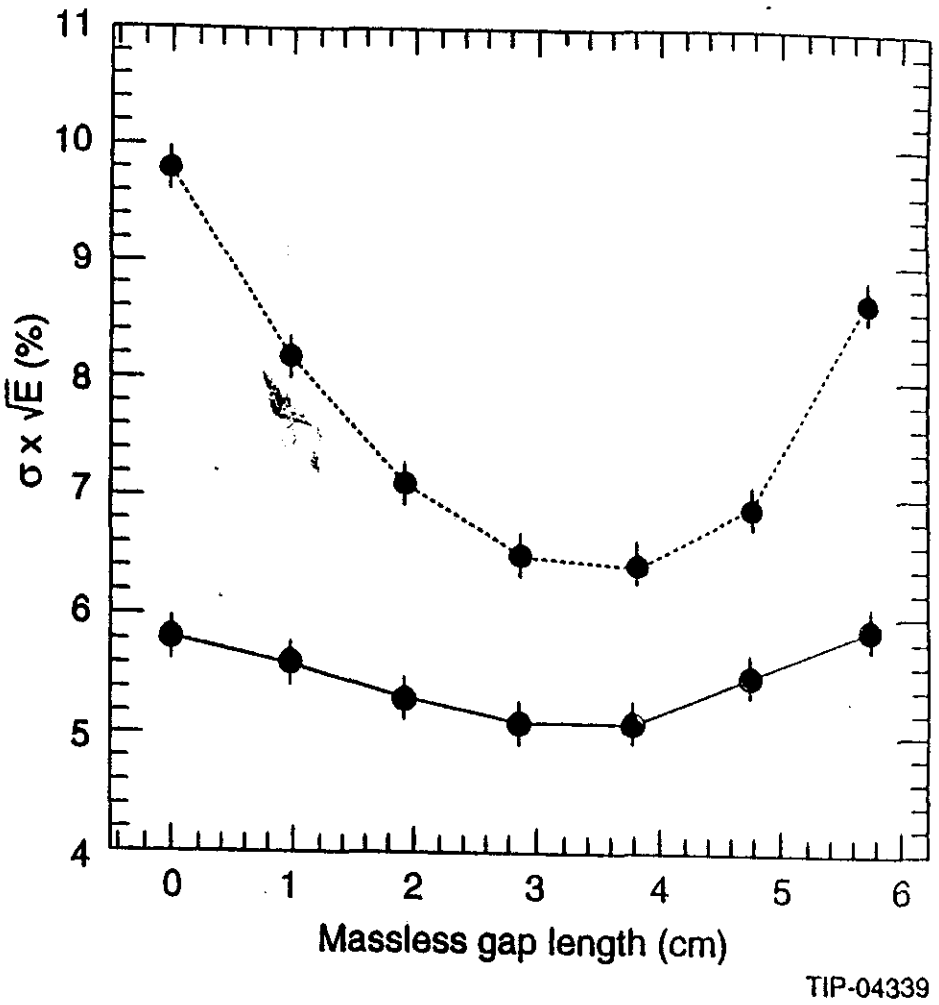


FIG. 5-10. Invariant mass of two photons from H^0 with mass of 80 GeV. Solid histogram and fitted line are with all resolution and expected noise at standard luminosity ($\sigma = 0.65$ GeV). The long dash–short dash histogram puts in the uncertainty of the vertex as determined using the pointing resolution to find the most probable Higgs vertex, out of all the vertices reconstructed by the tracker ($\sigma = 0.69$ GeV). The dotted histogram uses only the angular resolution of the calorimeter to determine the vertex ($\sigma = 0.79$ GeV). The dashed histogram is obtained when no vertex information is used ($\sigma = 1.48$ GeV).


Kapton
"Jumper Strips"
Δη strips
φ
η
Preamps
& Calibration
Pb Absorber
"Massless Gap"
Absorber
Connections


80 GeV γ
σ x √E (%)
EM calorimeter depth (X_0)
TIP-04124


σ x √E (%)
Massless gap length (cm)
TIP-04339

GEM
QUARK COMPOSITENESS
HIGH E_T JET STUDY

- FOUR FERMION CONTACT INTERACTION, SCALE Λ:

$$\mathcal{L} = -\frac{4\pi}{2\Lambda^2}\overline{Q_{La}}\gamma^\mu Q_{La}\overline{Q_{Lb}}\gamma_\mu Q_{Lb}$$

Excess Jet Production For Large E_T ($<< \Lambda$)

- SIGNAL ($\Lambda = 25 - 30$ TeV) and QCD BACKGROUND SAMPLES: $\Sigma E_T > 9$ TeV
  - → QCD Normalization Sample (PDF Systematics Study): $\Sigma E_T > 4.8$ TeV
  - → Study Effects of Non-Linear Calorimeter Response; Jet Energy Weighting
  - → Include Non-Gaussian Response In `Gemfast` (1% Level: D0 Experience)

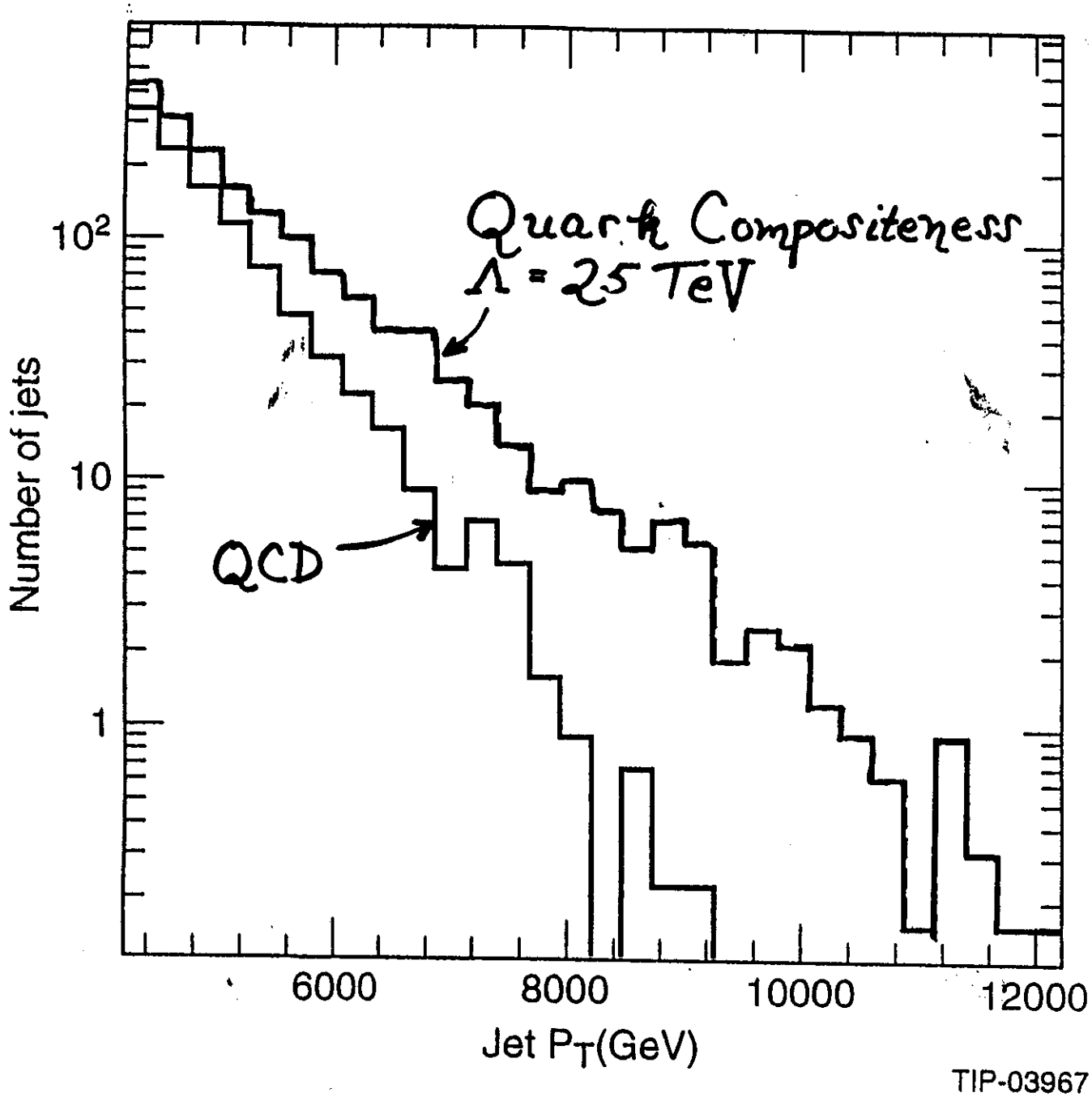
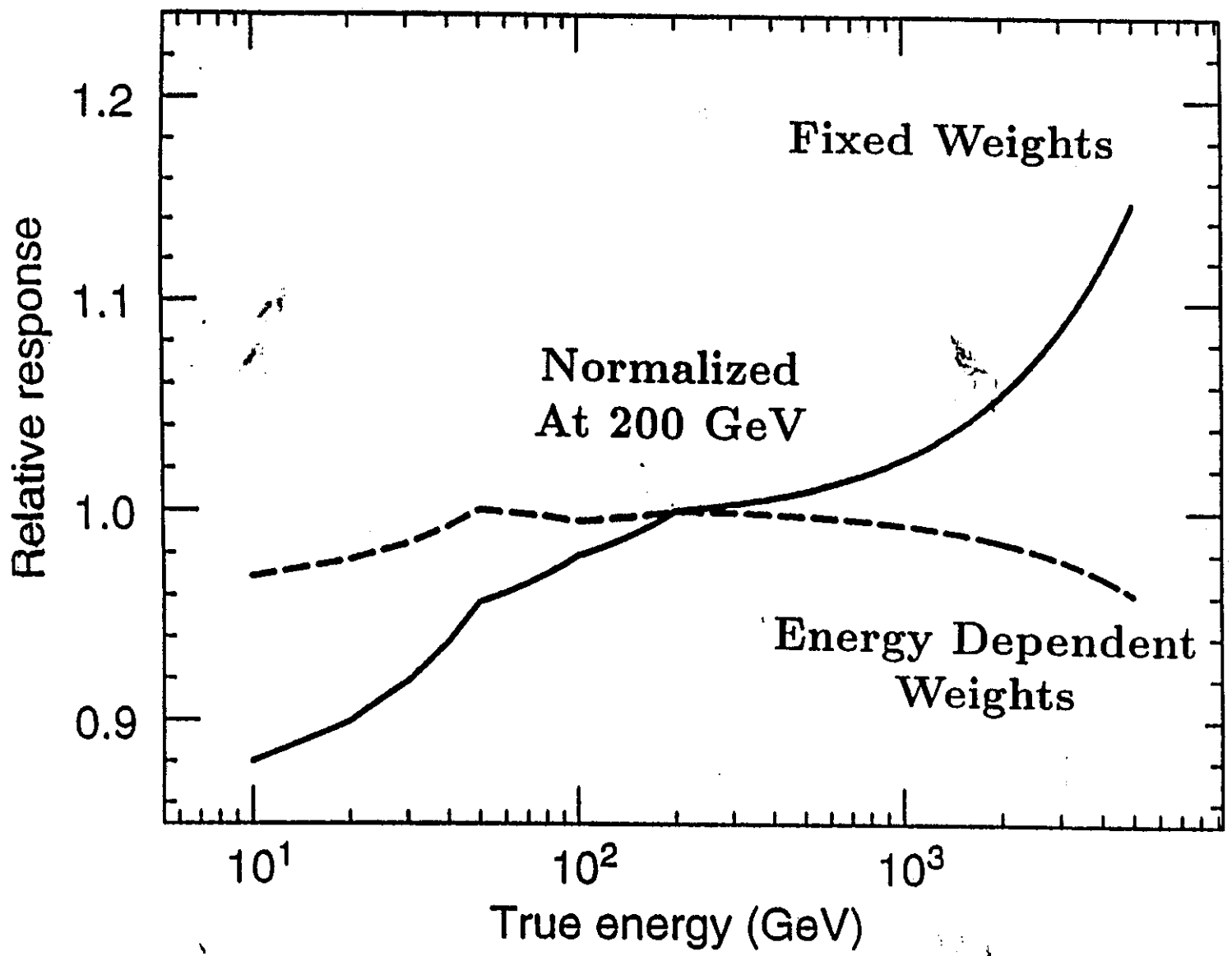


FIG. 2–42. Inclusive jet E_T spectrum for substructure at the scale $\Lambda = 25\,\mathrm{TeV}$ (dashed) and for QCD (solid).

GEM
QUARK SUBSTRUCTURE
STUDY RESULTS

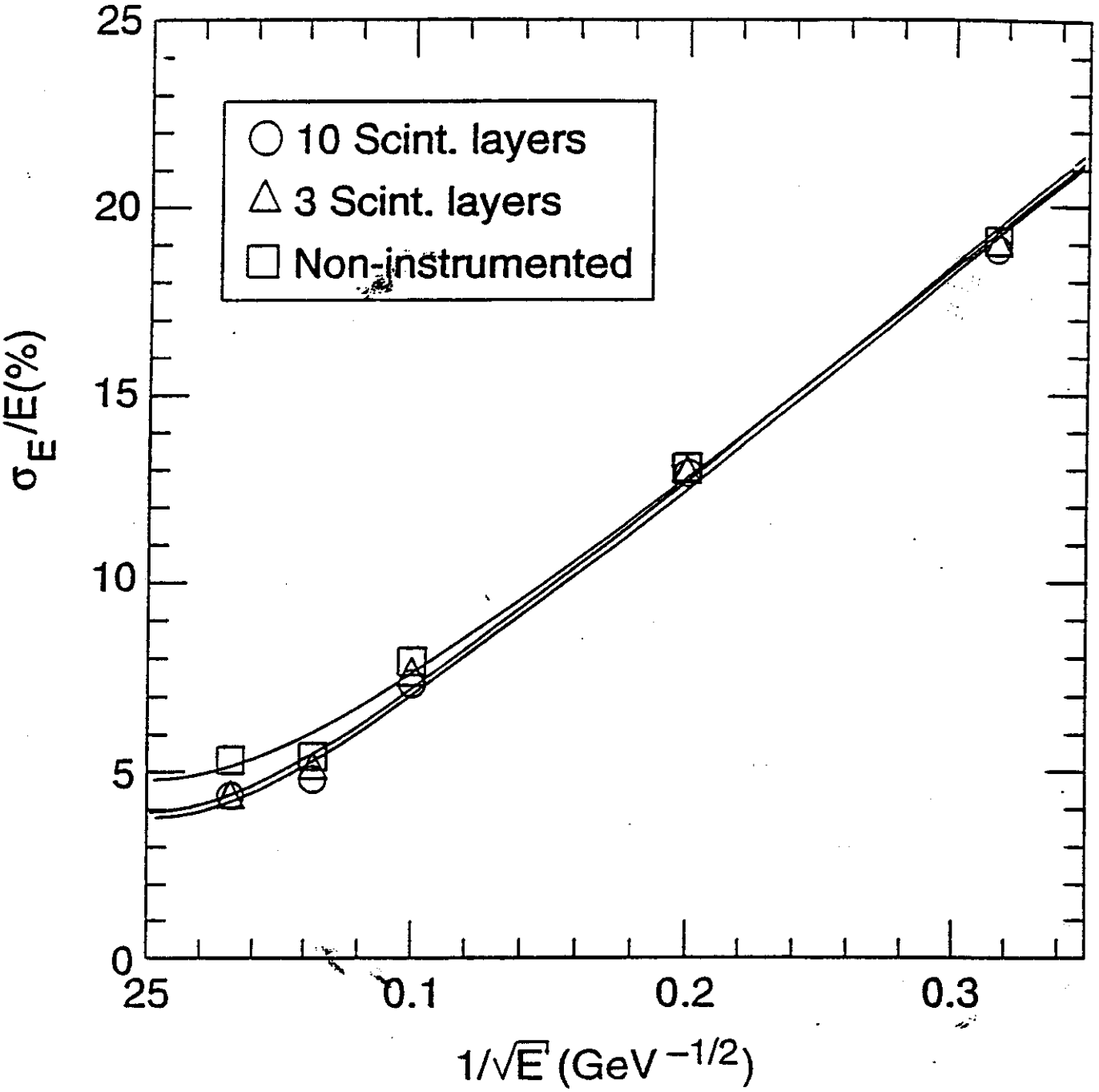
- COMPOSITENESS SCALE $\Lambda = 25 - 30$ TeV
  Reachable in One Year At $\mathcal{L} = 10^{33}$
- RESULTS ARE INSENSITIVE TO PDF CHOICE: CTEQ-1L, EHLQ-1, MT-2
- JET ENERGY WEIGHTING SCHEME:
  REACH IN Λ UNCOMPROMISED
- OUTLOOK FOR $\mathcal{L} = 10^{34}$:
  Λ TO ≈ 45 TeV



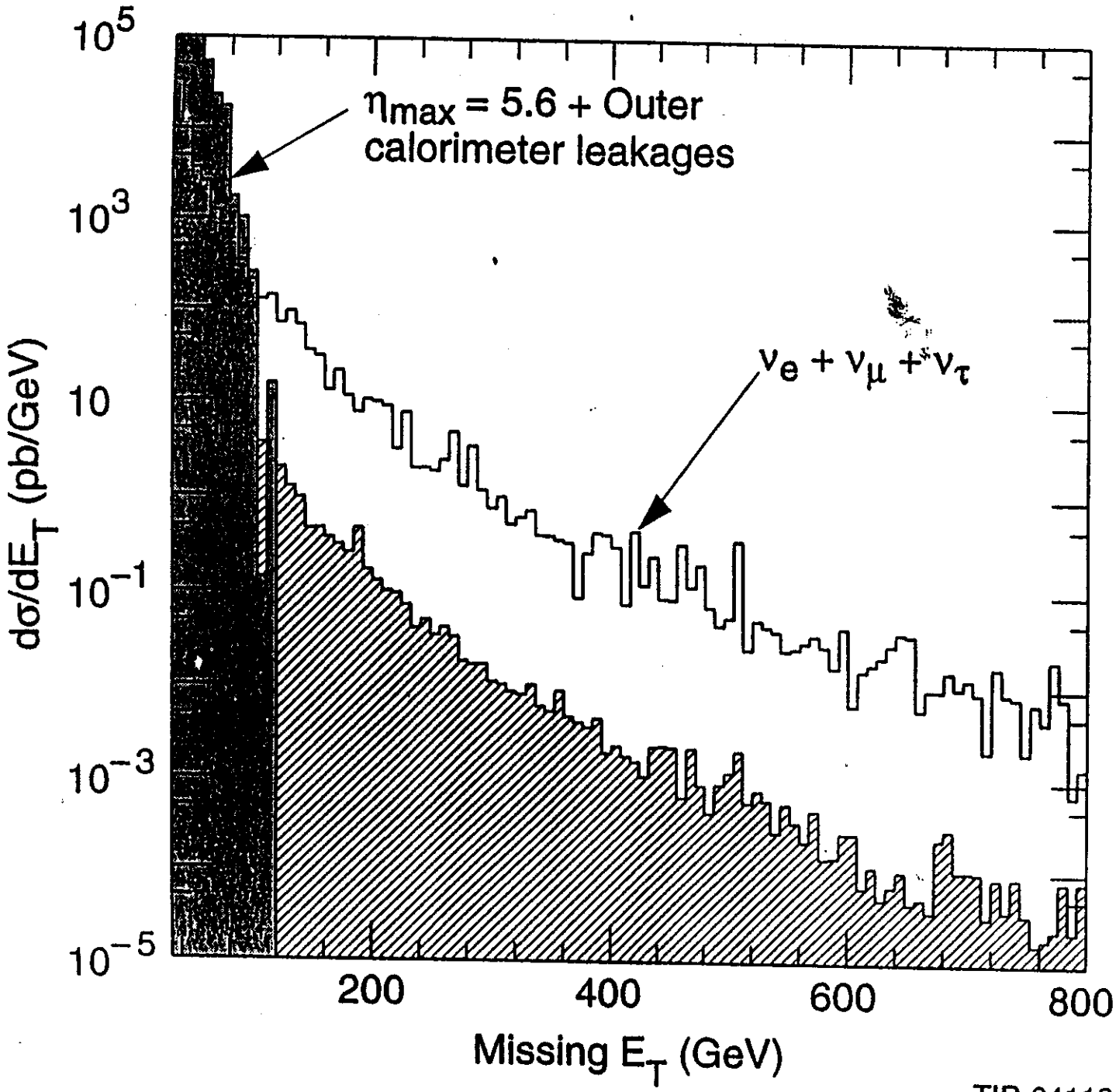
Nonlinearity of calorimeter response to pions after employing corrections with energy-independent weights (solid curve) and energy-dependent weights (dotted curve).

E_T^{cut} (GeV)	4500	5000	5500	6000
CTEQ-1L Distributions				
$\Lambda = \infty$	704	339	155	74
25 TeV	1226	724	447	276
Energy-independent Weights				
$\Lambda = \infty$	718	349	167	79
25 TeV	1257	739	468	286
Energy-dependent Weights				
$\Lambda = \infty$	676	321	148	70
25 TeV	1189	701	435	267

• SCINTILLATING BARREL HCAL:
INSTRUMENTED WITH 4 LAYERS

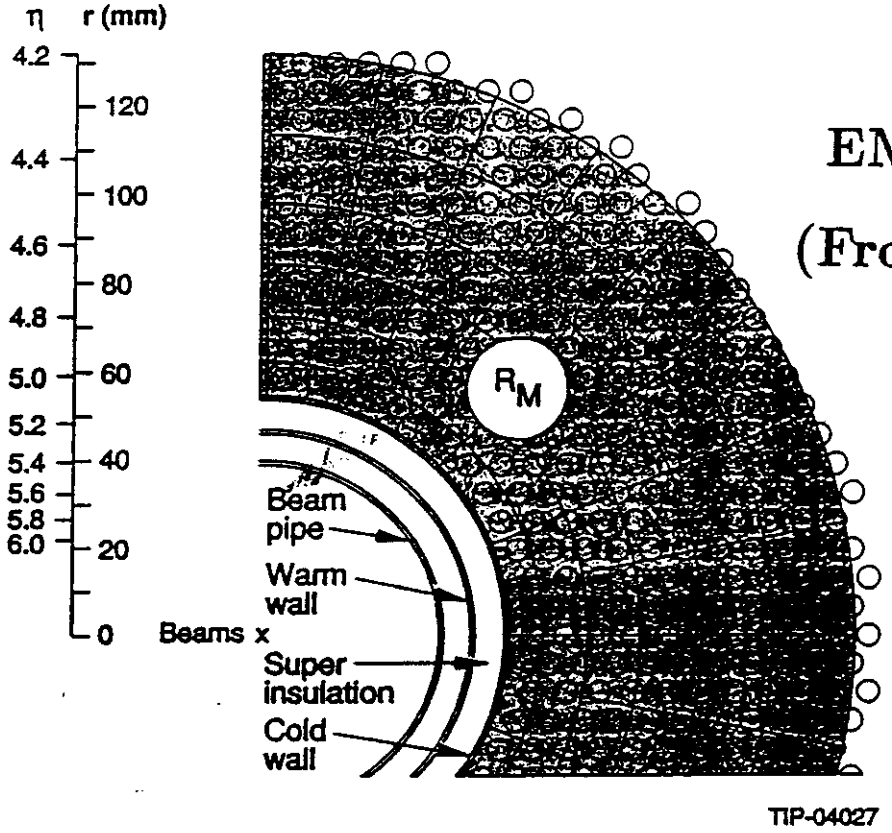


TIP-03837


η_{max} = 5.6 + Outer calorimeter leakages
$\nu_e + \nu_\mu + \nu_\tau$
$d\sigma/dE_T$ (pb/GeV)
10^5
10^3
10
10^{-1}
10^{-3}
10^{-5}
200
400
600
800
Missing E_T (GeV)

TIP-04118

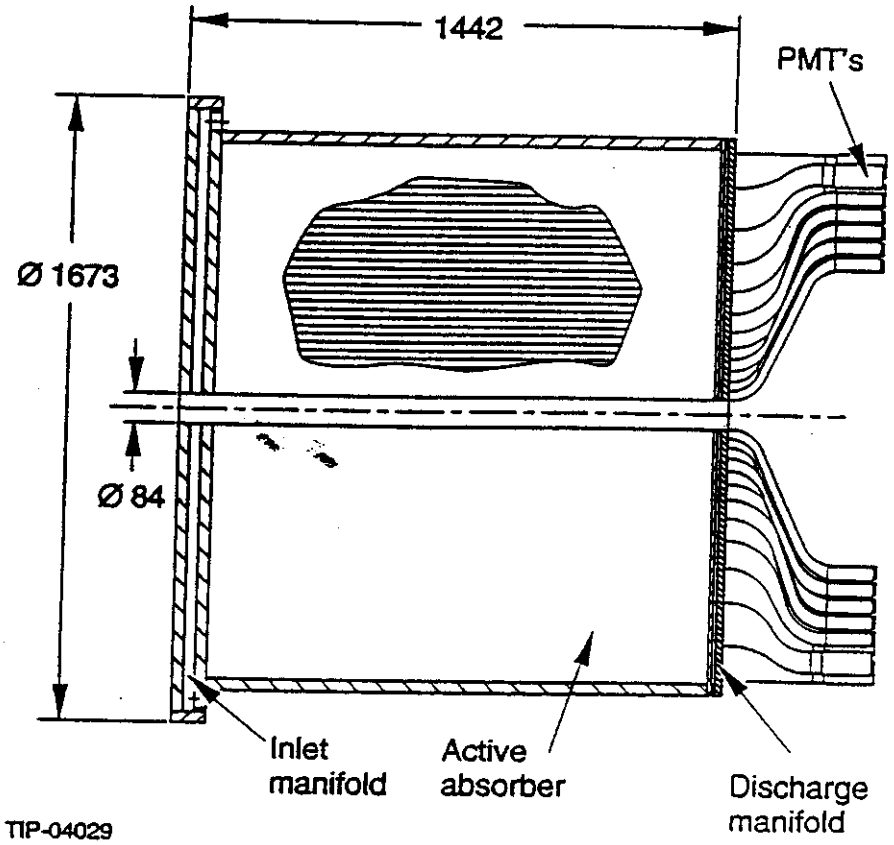
GEM FCAL



EM Section

(Front View)

- HERMETIC
- ENCAPSULATED
- 16 λ

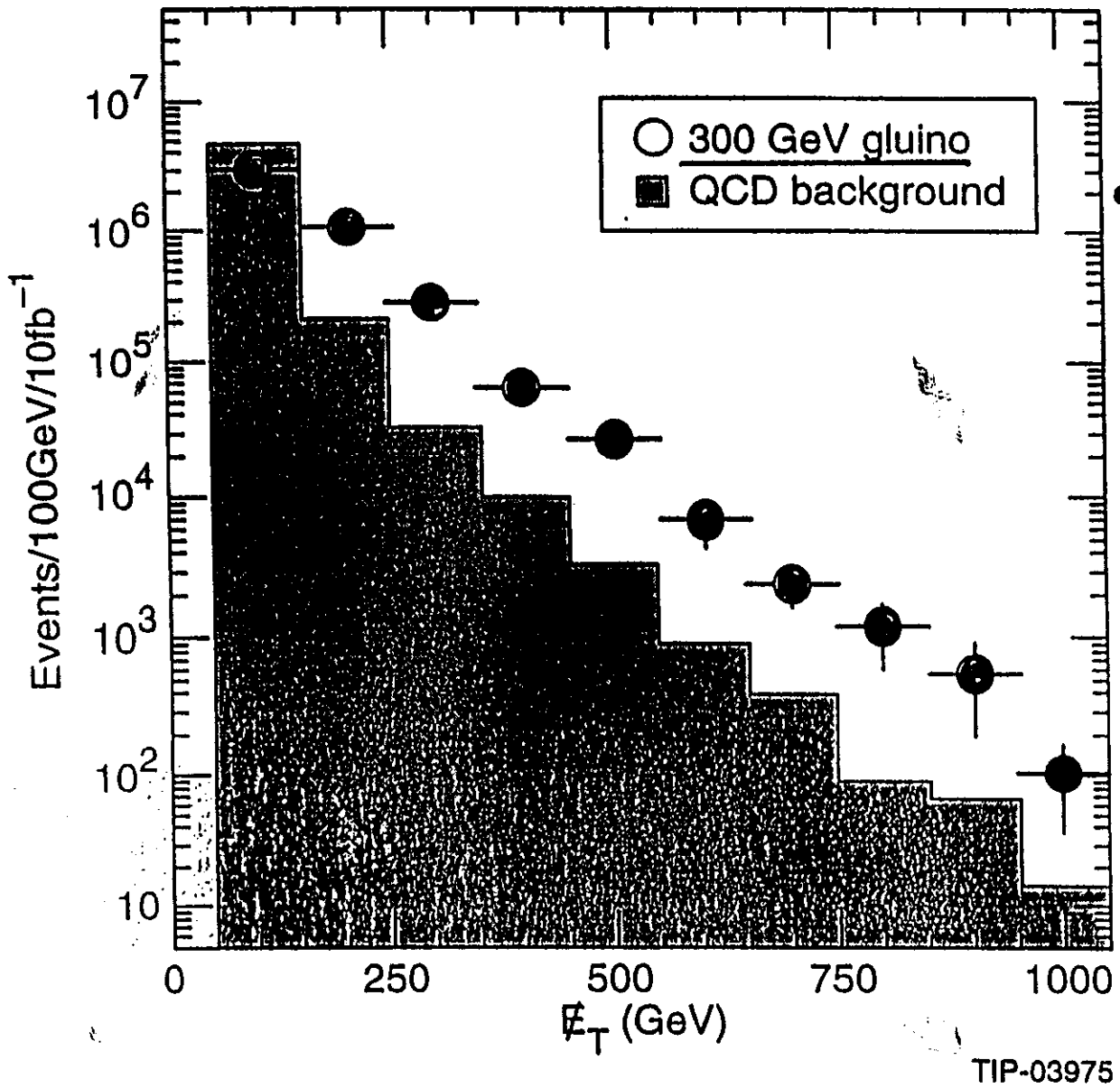


Scint. HCal

(Side View)

GEM FORWARD HADRON CALORIMETER PHYSICS PARAMETERS

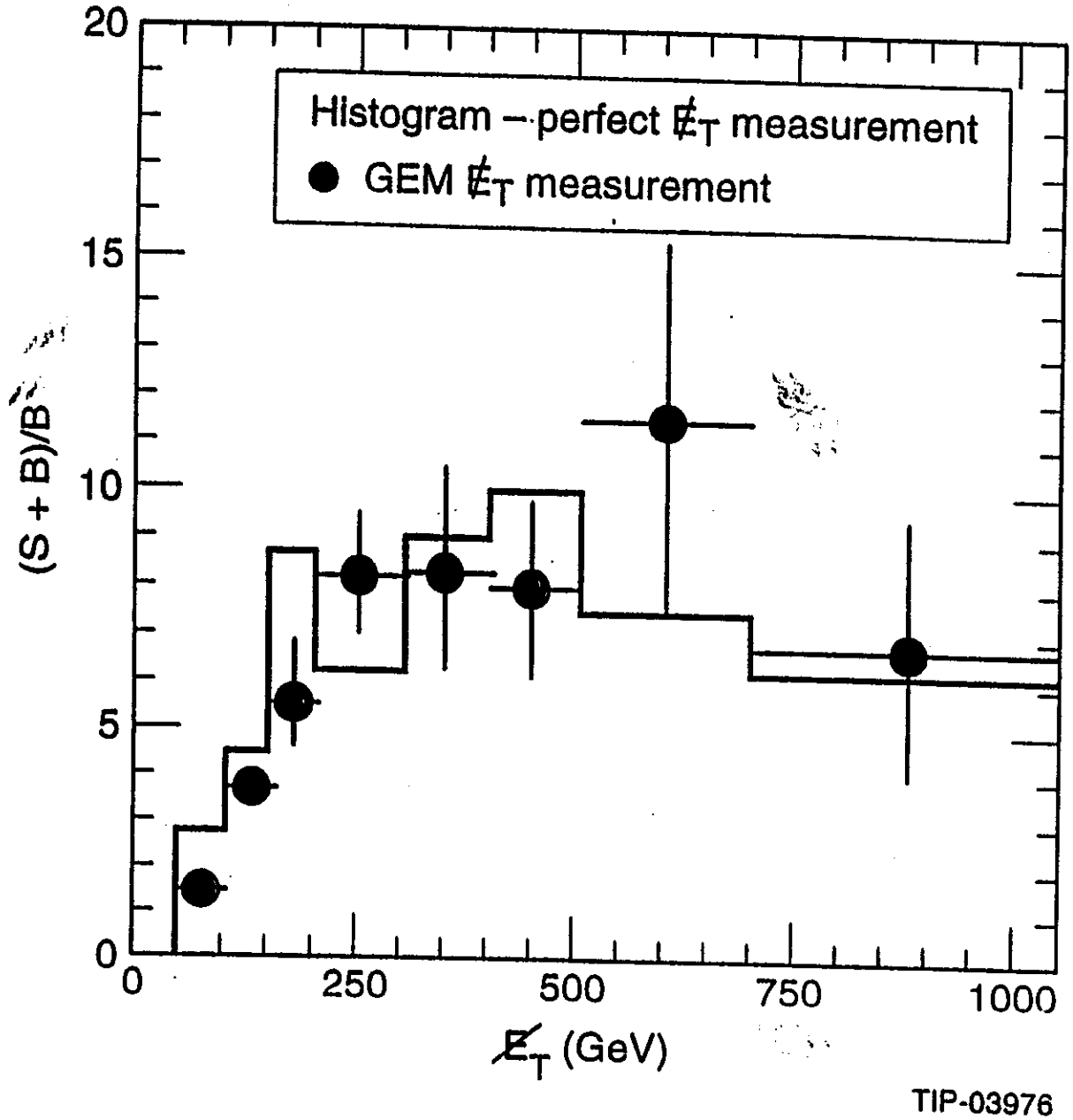
p_T Jet Resolution	$\Delta p_T/p_T < 10\%$
Angular Resolution	$\Delta\eta < 0.07$
Fiducial Coverage	$3 < \lvert\eta\rvert < 5$
Lateral Segmentation	$\Delta\eta \times \Delta\phi = 0.2 \times 0.2$
Longitudinal Segmentation	$2.4 + 2.4 + 11.4 = 16.2\lambda$
Dynamic Range	10^5
Speed (Shaping Time)	16 ns



$\tilde{g}$

• MISSING E_T SIGNATURE

FIG. 2–53. $\not{E}_T$ signal for Case I MSSM parameters defined in Table 2–17 (open circles) and for QCD background (histogram) after requiring at least 5 jets with $p_T > 75$ GeV and the sphericity and lepton veto cuts described in the text.



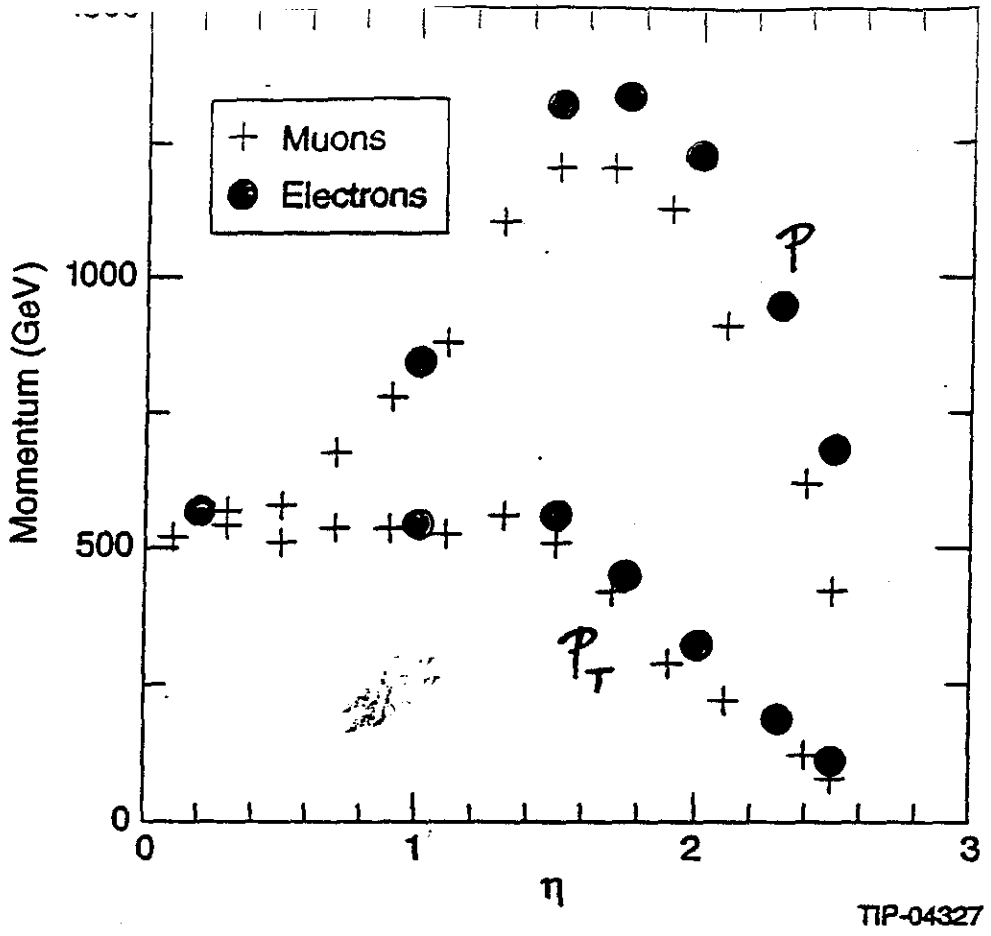
$\tilde{g}$

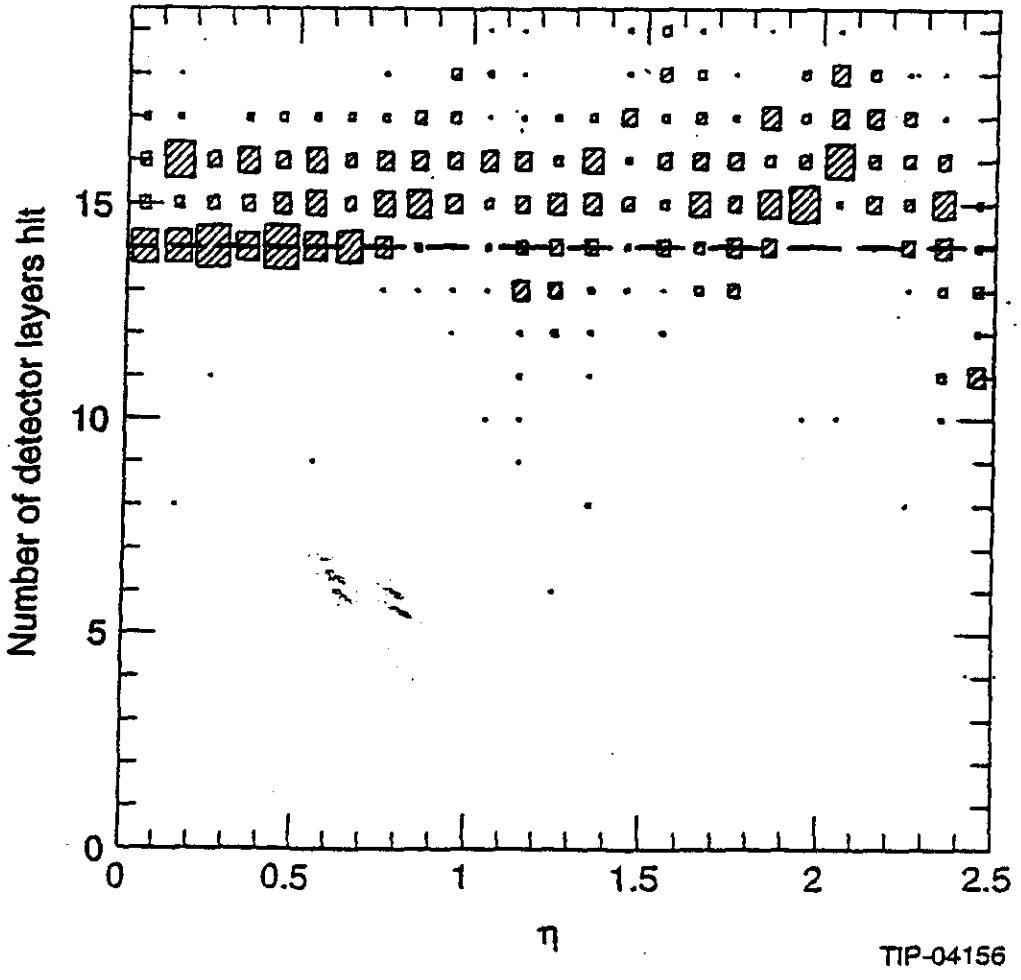
$\frac{(S+B)}{B}$

Open circles: Ratio of signal and background curves from Fig. 2–53. Histogram: The same ratio for a perfect $\not{E}_T$ measurement.

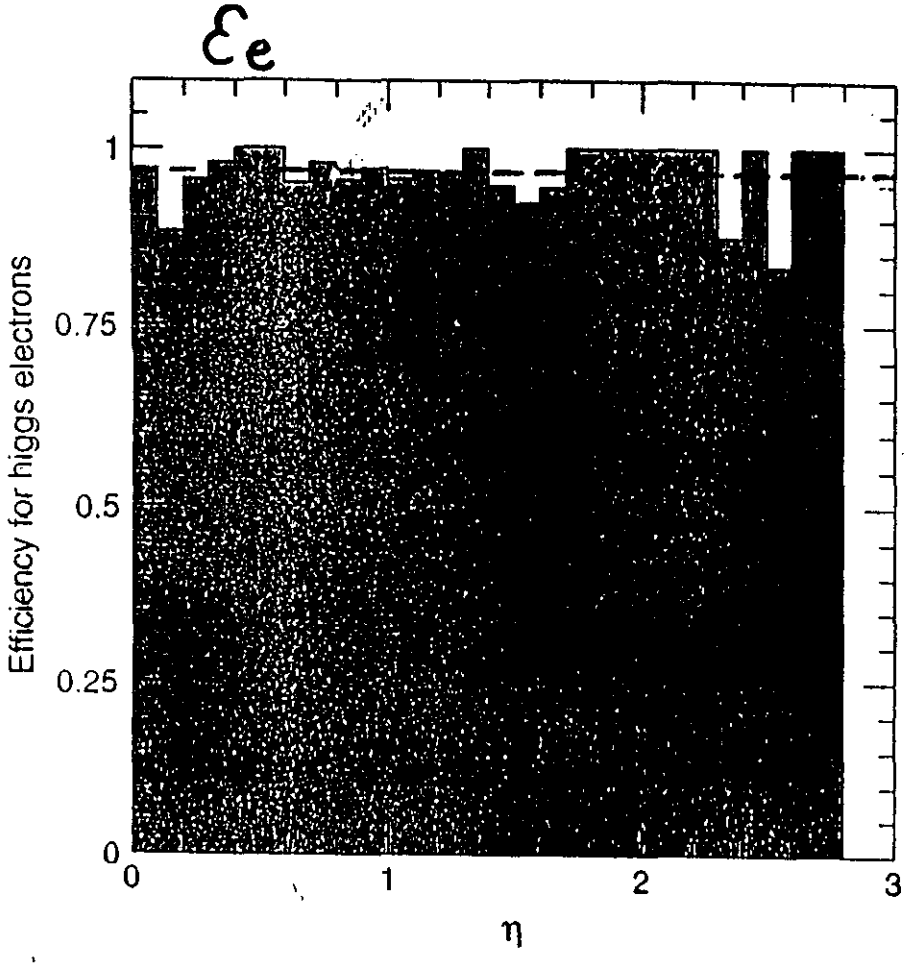
GEM CENTRAL TRACKER
PHYSICS PERFORMANCE

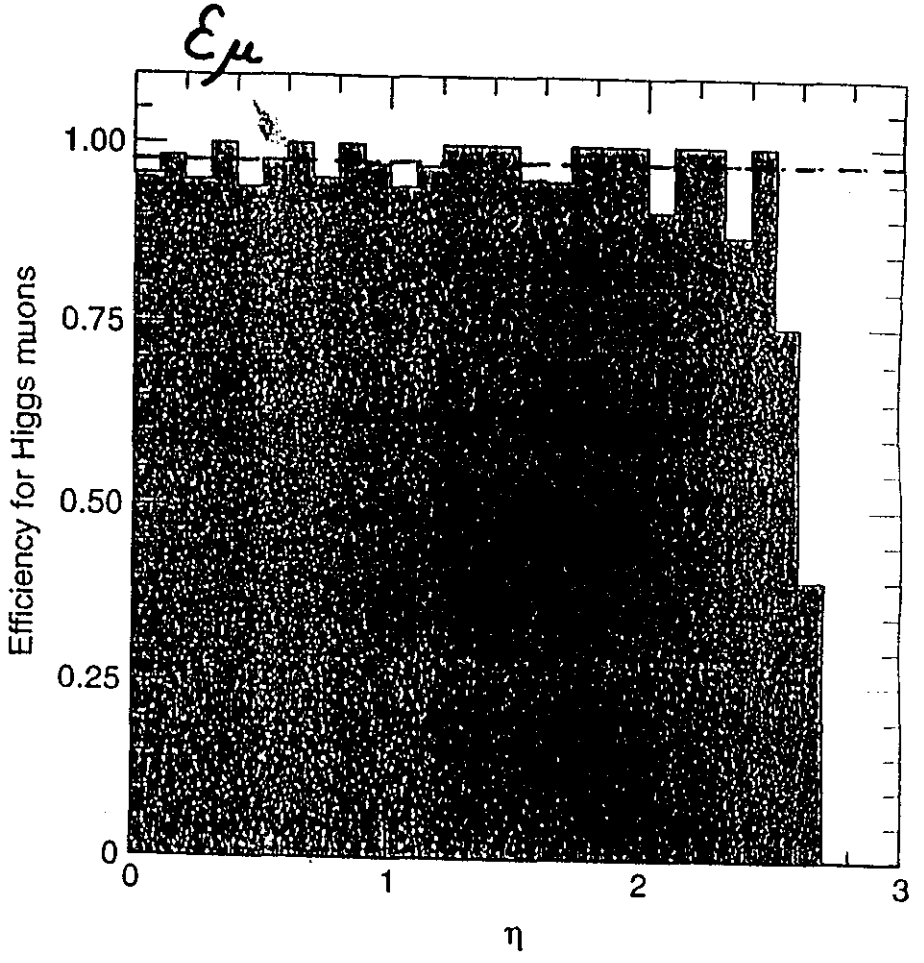
- Electron ID: $e/\pi^0 = 0.1\%$; $e/\pi^- = 0.08\%$; e/Jet $\doteq 0.02\%$; e/Jet (Isolated) $= 0.001\%$
- $\epsilon_e \approx 97\%; \epsilon_\mu \approx 97\%$ in $H^0 \to \ell^+\ell^-\ell^+\ell^-$
- Correct Higgs Vtx ($\Delta z < 5$ mm): $\epsilon = 95\%$ (L $= 10^{33}$); $\epsilon = 75 - 80\%$ (L $= 10^{34}$)
- b-Tagging: Efficiency = 30 % + (Preliminary)
- $\tau \to 3$ Prong Tagging: Efficiency = 75 (33)% At $p_T = 50\,(150)$ GeV
- Momentum Resolution Sufficient For Like-Sign Dilepton Studies: $\tilde{g}\tilde{g}$; WW-Scattering.
- To Be Studied: CP Violation In $B \to J/\Psi\, K^0_s \to \mu^+\mu^-\,\pi^+\pi^-$


Muons
Electrons
Momentum (GeV)
1000
500
0
0
1
2
3
η
P
P_T
TIP-04327


Number of detector layers hit
15
10
5
0
0
0.5
1
1.5
2
2.5
η
TIP-04156

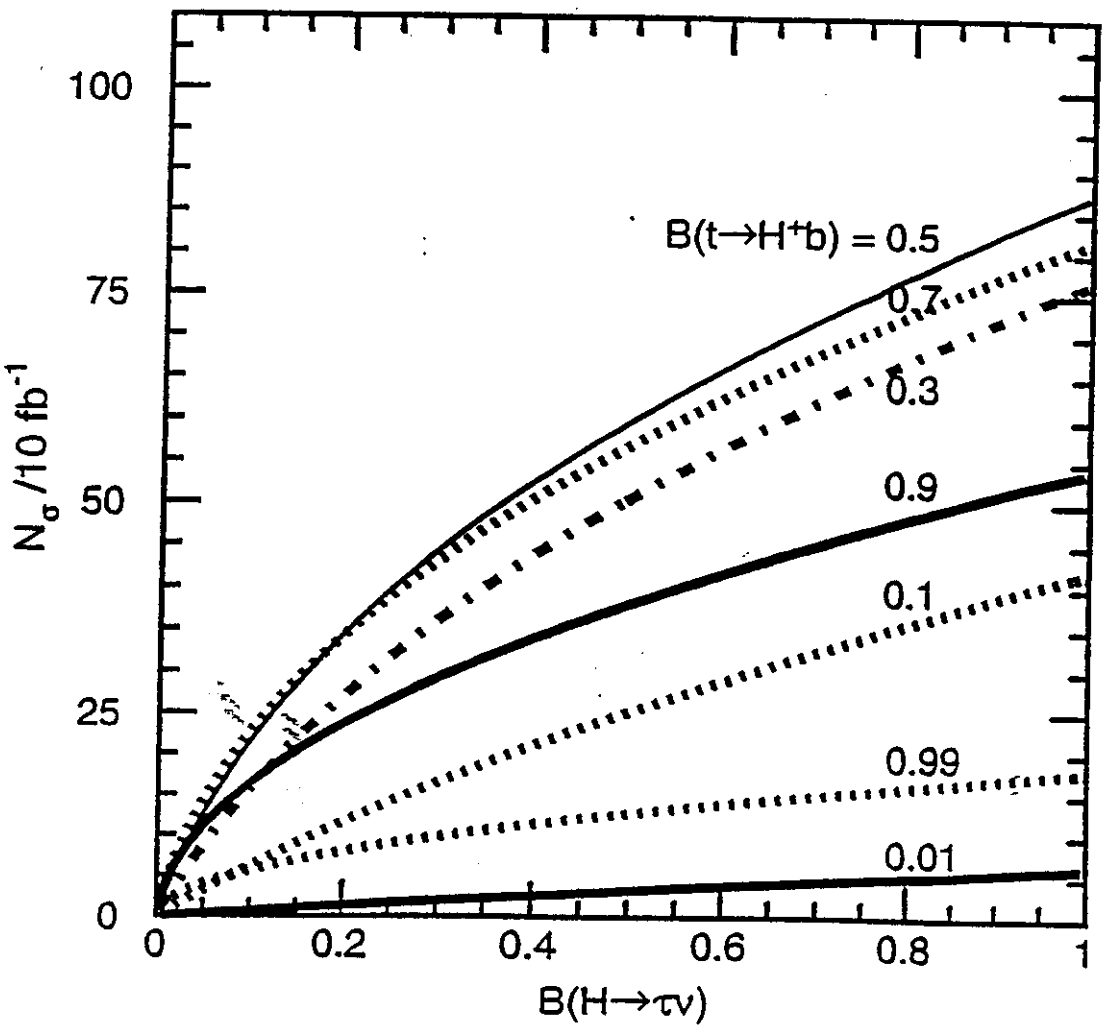
High Uniform Efficiency
For Electrons and Muons
In $H \to ZZ* \to \ell^+\ell^-\ell^+\ell^-$





GEM DISCOVERY OF CHARGED HIGGS
In $t\bar{t} \to WH^{\pm} \to \ell_{\text{ISOLATED}} + \tau_{\text{ISOLATED}} + X$

- Isolated e or μ; Isolated τ
- 1 or 3 Prong τ In Tracker; Leading Prong With $p_T > 15$GeV
- b Jet-Tag In CT; $E_T^{Jet} > 30$ GeV
- $\delta\phi(\ell\tau) > 100°$; $\delta\phi(\ell b) \leqslant 100°$
- Background Study: $\mathcal{R}(\tau/\text{Jet}) = 2.7 \times 10^{-3}$
- Conservative: $\epsilon(b - \text{tag}) = 20\%$ Assumed

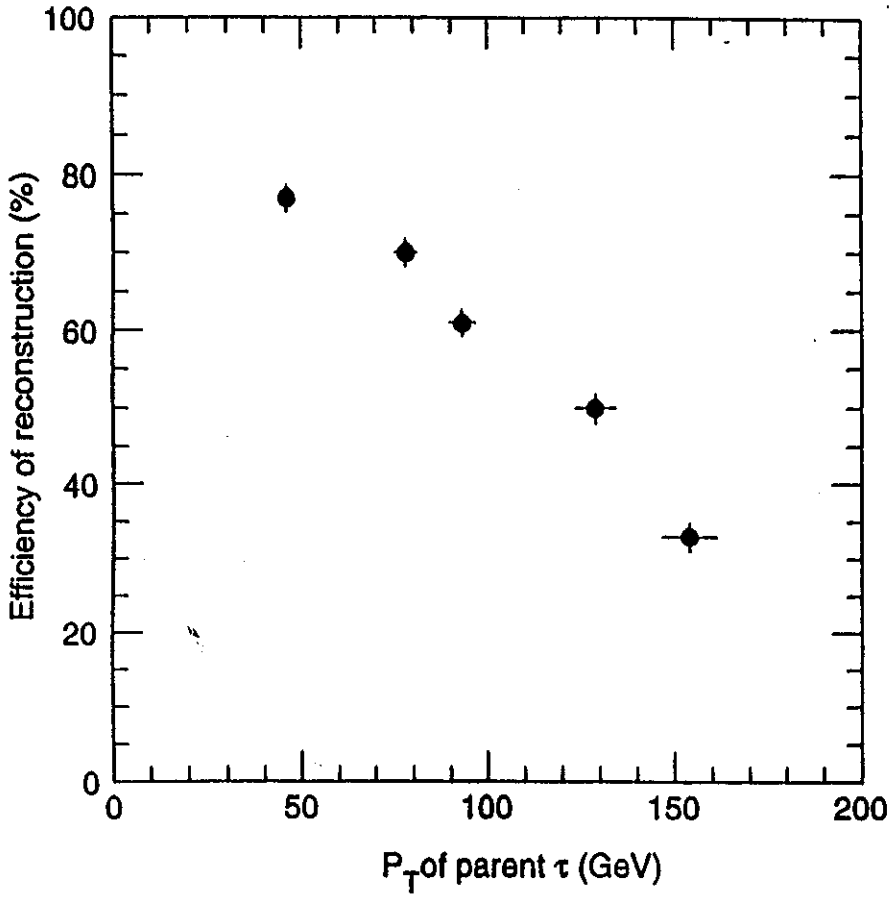


Central Tracker: Efficient 3-Track Reconstruction; Full 1-2-3 Charge Separation In IPCs

$\tau \rightarrow$ 3-Prongs: Efficiency For Reconstructing All Three Tracks.

Δx_{min}(Closest) = 1 Pad

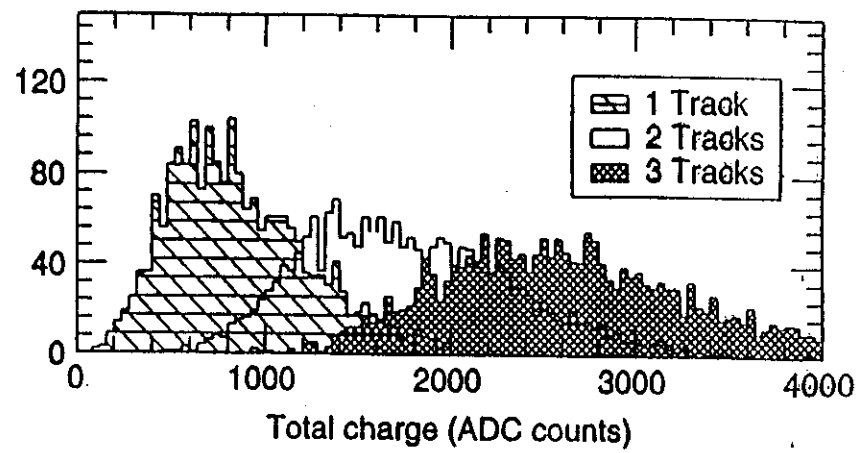
Δx_{min}(Farthest) = 2 Pads

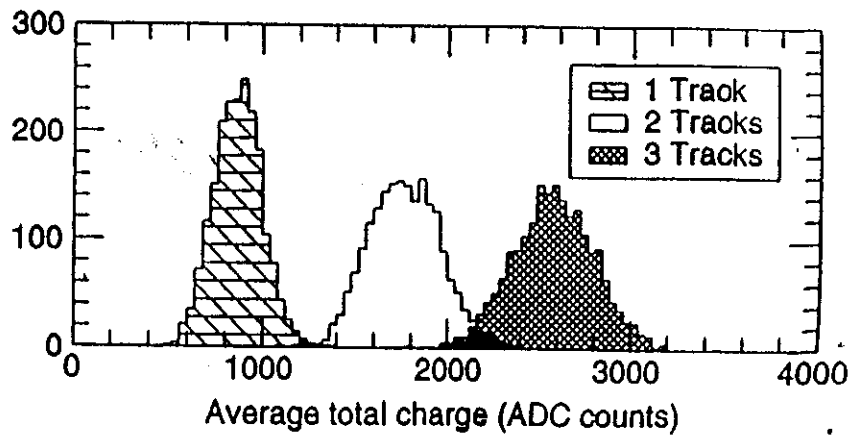


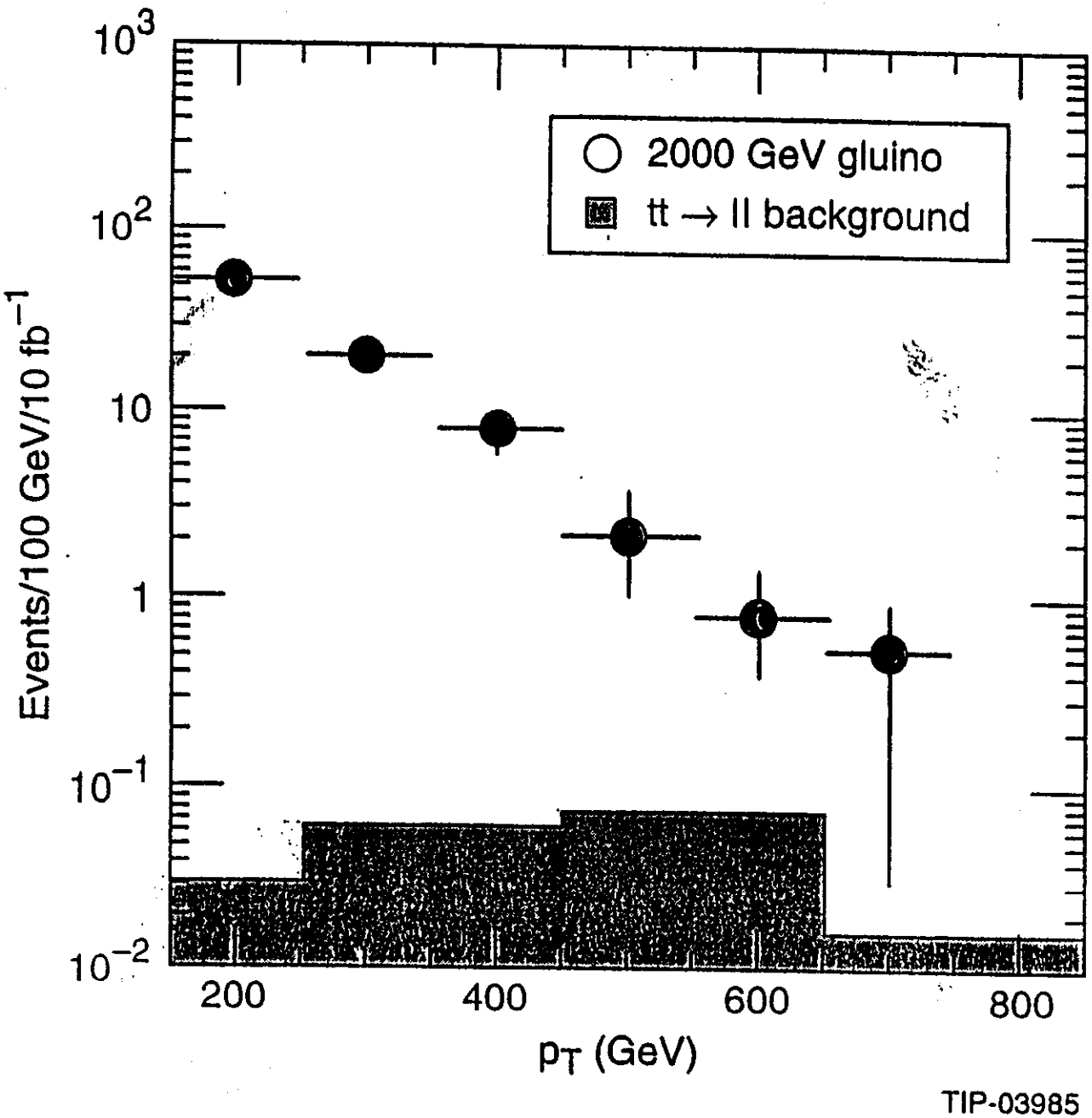
IPC 1-2-3 Charged Track ID:

One IPC Layer (Top)

8-Layer Average (Bottom)







High Mass $\tilde{g}$
$e^\pm e^\pm$ in CT

FIG. 2–58. p_T distributions for the highest-p_T isolated lepton in dilepton events containing two isolated like-sign leptons. Open circles: Signal events generated with Case III MSSM parameters. Histogram: $t\bar{t}$ background from mismeasured electrons in the GEM central

GEM DESIGN

A Precision Lepton - Photon Detector To Explore New Physics At The TeV Scale

- PRECISION OPEN MUON SYSTEM
  - Quiet Environment: Very Low Occupancy
  - High Pattern Recognition, Reconstruction Efficiency for Multi-TeV Muons
  - Robust Operation: Beyond $\mathcal{L} = 10^{34}$
- CLOSE-IN CALORIMETERS AND SHIELDING
  - Thickness, Layout Optimized for Low (n, γ) and Punchthrough Backgrounds
  - Air Gap To Separate Muon – Initiated EM Showers
- PRECISION EM CALORIMETER
  - Thin-Plate LKr/LAr Accordion $\Rightarrow$ Precision
  - Stability, Uniformity, Linearity, Rad Hardness, Calibration $\Rightarrow$ Small Systematics
  - Segmentation: Clean Isolation of e, μ, γ; Suppression of Jet Backgrounds (With Tracker, HCAL)
  - Photon Pointing $\Rightarrow$ Clean Photon ID; Robust Angle or Vertex Measurement To $\mathcal{L} = 10^{34}$
- HADRON CALORIMETERS
  - Instrumentation, Granularity: Cost-Optimized for E_T, $\not{E}_T$ Measurements
  - Energy Resolution: Sufficient For Dijet, Trijet Mass Reconstruction

GEM DESIGN

Compact Inner and Forward Detectors To Explore New Physics At The TeV Scale

- CENTRAL TRACKER – Silicon/IPC
  - Clean e, γ ID: Roads With EM Cluster
  - $e^{\pm}$ Charge Sign to the 0.5 - 1 TeV Range
  - e/h Separation: E – p Matching
  - Assist μ ID (p_T–Match); Low-p_T Measurement
  - Precision Vertex; Robust To $\mathcal{L} = 10^{34}$
  - COMPACTNESS $\Rightarrow$ Low π, K Decay Muon Rate; Thick Calorimeters At Moderate Cost
- FORWARD CALORIMETER COVERAGE
  - Compact, Encapsulated, 16λ
  - To $|\eta| \approx 5$: $\not{E}_T$ Signatures
- ROBUST TRIGGER SYSTEM
  - Isolated e or γ, Muons, Jets, $\not{E}_T$
  - Selectable, Relatively Low Threshholds At Level 1
  - → Flexibility To Cover the Full Range of SSC Physics