Detectors for Muon Colliders

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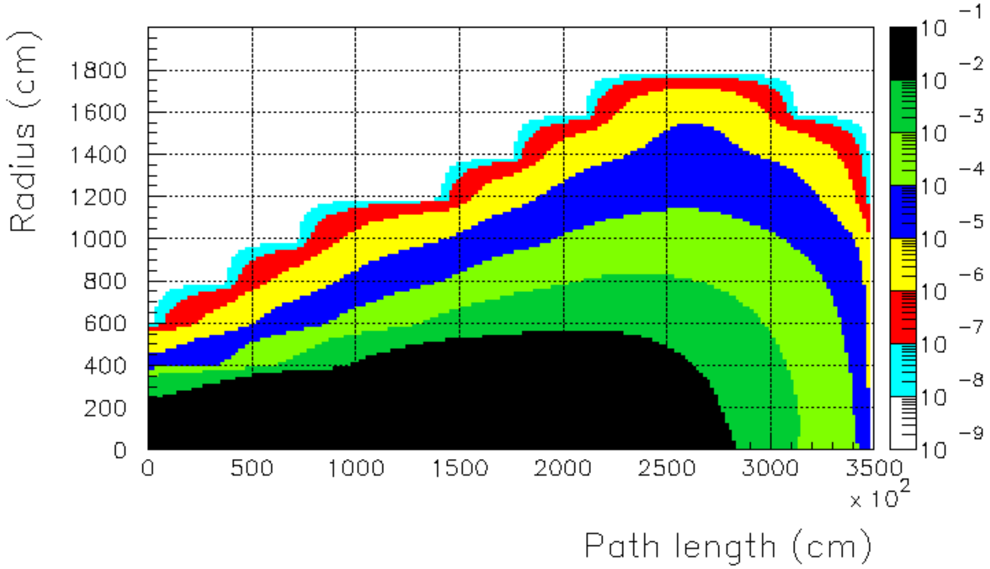
Summary of talk

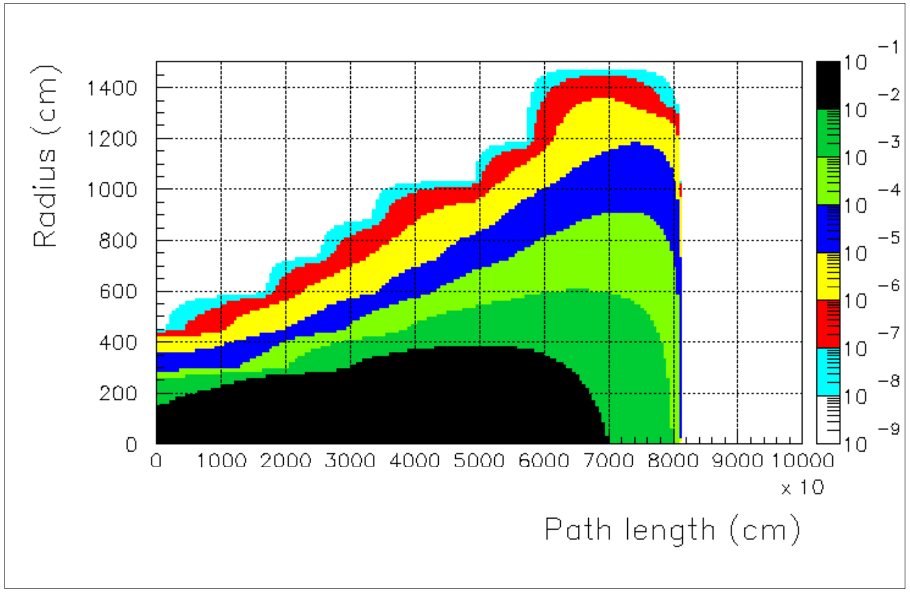
- Backgrounds and radiation near accelerator
- Neutrino Induced Radiation
- Halo Backgrounds
- Pair production at IP
- Muon Decay Background at IP
  - » Design of Interaction area shielding
  - » Neutrons
  - » Photons
  - » Bethe-Heitler Muons
- Detector Options
- Detector Simulation plans
- Measurement of energy scale using g-2 precession

Muon Colliders then and now

Root(s) TeV	0.1	0.1 Scan width	0.4	3.0	1.5
Proton Energy GeV	16		16	16	8
Bunches/ beam	1		2	2	1
Luminosity 10^{34} cm^2/s	2.2×10^{31}	10^{31}	10^{33}	7×10^{34}	1.3×10^{34}
Higgs/yr	3.9×10^{3}	4×10^{3}			

Backgrounds and radiation near accelerator-MARS calculations



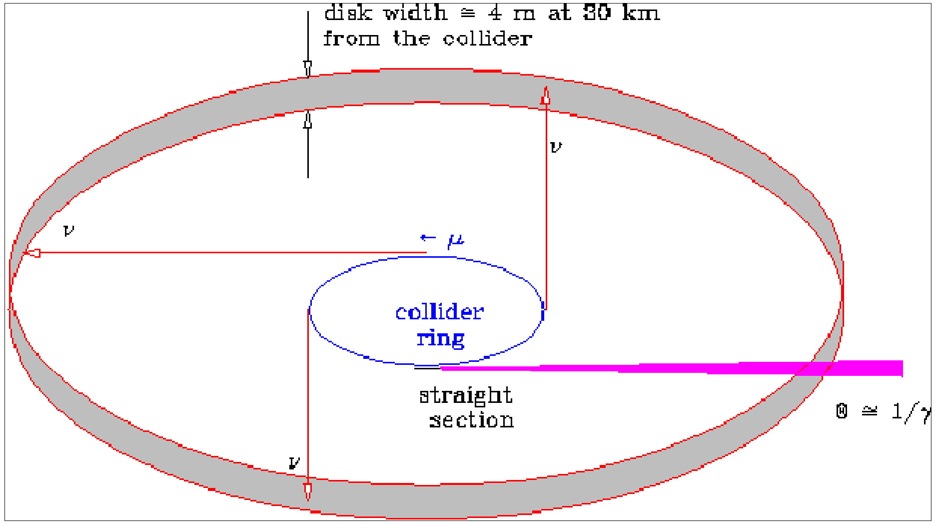


- Isodose contours in soil/rock for 2TeV and 250 GeV muons extracted from ring at $3x10^{13}$/second. Right scale is dose rate in rem/s.

Backgrounds and radiation near accelerator

- 4 Tev collider has the following activation levels immediately and 1 day after turn off after 5 years of operation.
  - » Inside face of shield 9000 (4000)mrem/hr
  - » Outside face of shield 200(170)mrem/hr
  - » Outside of coils 30(14)mrem/hr
  - » Outside of yoke 3(1.4)mrem/hr
- Muons lost from collider have a range of 3.5Km (800 m) at 2TeV(250GeV) beam energy in soil/rock of density 2.24g/cm^3 .
- To confine this radiation beneath the ground, one can deflect extracted beams down by 4.5 mrad at 2TeV and 10 mrad at 250 GeV .
- Federal limit is reached at maximum radii of 18m (2TeV) and 14.5 m (250 GeV)

Neutrino Induced Radiation



$DB = 4.4\times10^{-24}\ I_{\mu}E^{3}t\langle B\rangle/(Bd)$

Where DB(Sv) is the radiation dose acquired over time t sec in the plane of a bending field B(Tesla) in a circular collider of energy E(TeV) and average field <B>(Tesla) and muon current of I_{μ} (muons/sec/sign) buried at depth d (meters)

Neutrino radiation

- In the case of a high beta straight section of length l (meters),

$$D_s = 6.7\times10^{-24}\, I_\mu\, E^3\, t\, l\, \langle B\rangle/d$$

- For a low beta IP region, these formulae do not apply, since they assume that the divergence angles of the beam $\ll 1/\gamma$.
- For 3 TeV Com energy, $I_\mu = 6\times10^{20}\ \mu/yr$, $\langle B\rangle=6T$, $B=10T$ and $d=500m$ and taking the federal off site limit $D_{fed}=1mS_V/year$ (100 mrem/year) the annual dose D_B in the plane of the bending dipole is

$$D_B = 1.07 \times 10^{-5}\ S_V = 1\% D_{fed}.$$

For a straight section of length 0.6m,

$$D_s=9.7\times10^{-5}\ S_V = 10\% D_{fed}.$$

Beam manipulation tricks can be played. We feel that

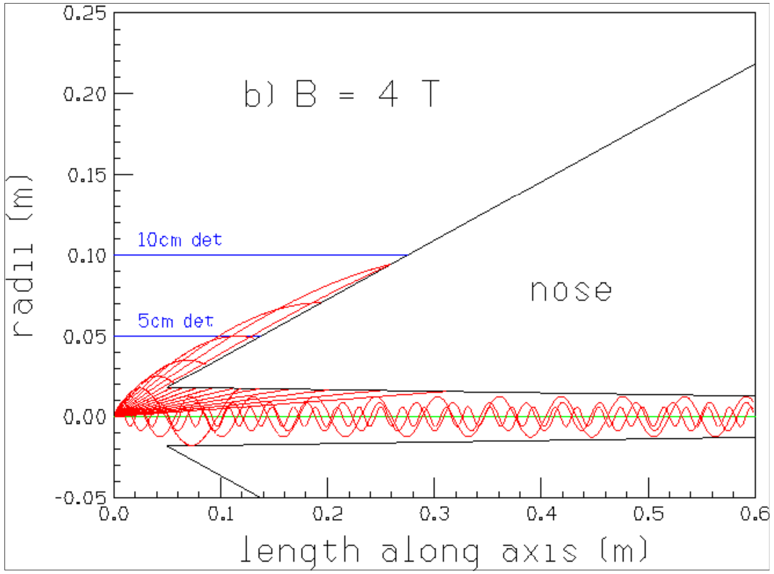
3 TeV collider can be buried at ~300 meters.

Halo Background

- More work needs to be done in calculating injection losses and to develop a credible model for beam halo and beam losses.
- Beam gas scattering has been studied and shown to be a negligible source of beam halo generation.
- Beam-beam effects need further study.
- A scraper system has been studied and shown to suppress halos by a factor of 10^3.

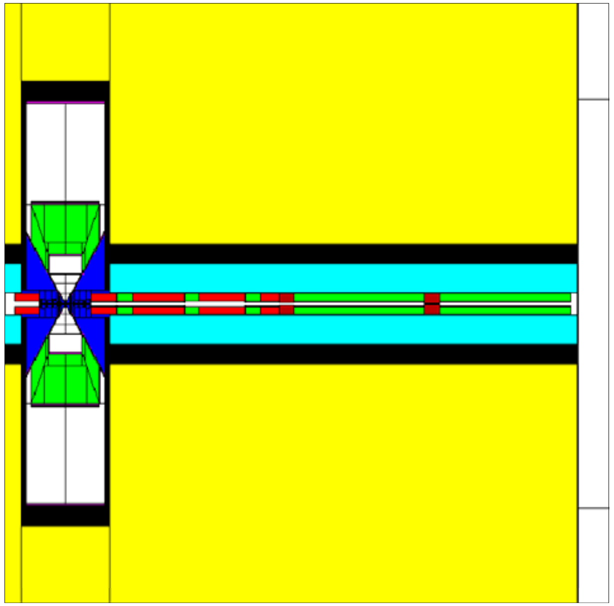
e^+e^- pair production at IP

- Coherent beam-beam electron pair production (beamstrahlung) has been shown to be negligible.
- Incoherent production μμ –> μμee) in the 4 TeV collider case is significant-10mb of cross section!



- Electrons with momenta from 3.8 MeV to 3000 MeV for the 4 Tesla solenoid detector.

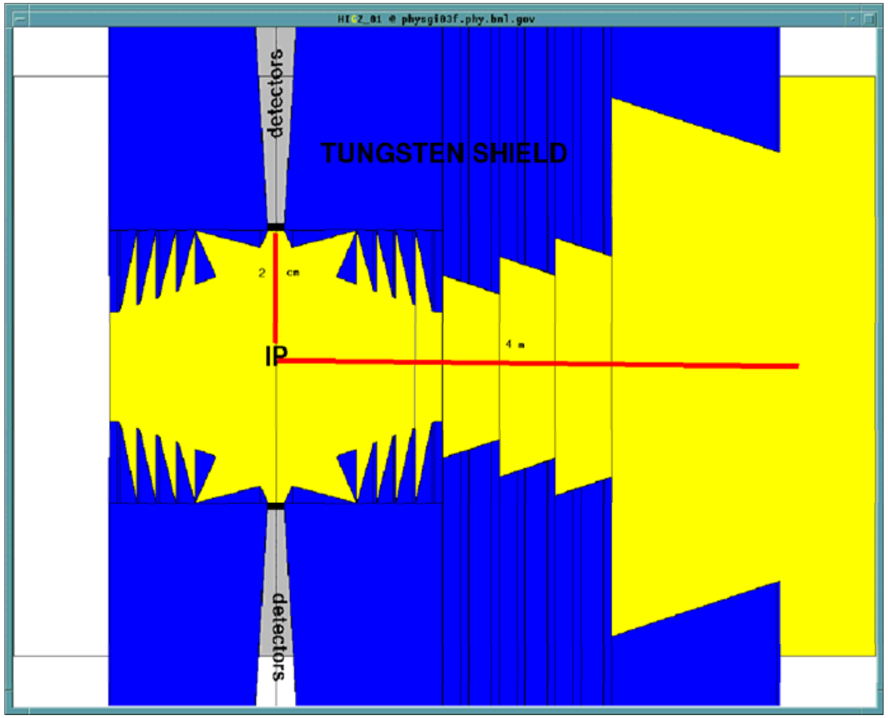
Muon decay background-Design of shielding



- Region up to 130 m from the IP for 4 TeV collider. Triangular blue regions represent tungsten shielding. Red areas represent quadrupoles in beamline. Geant calculations done. Detector (white +green) is 10 m in diameter and 20 meters long.

Muon decay background-Design of shielding

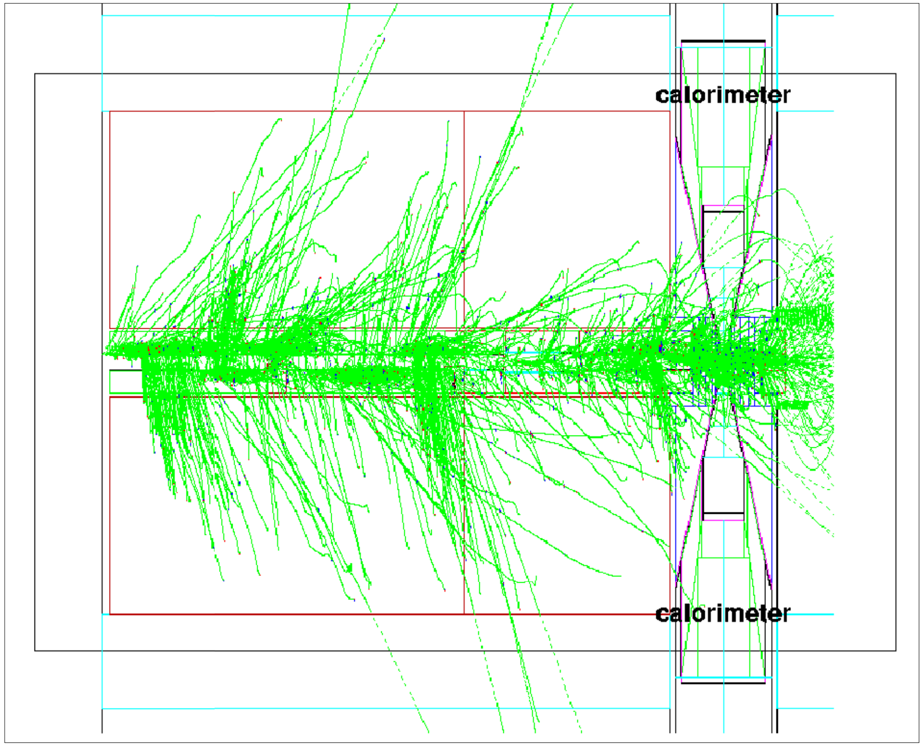
- IP design for 100GeV CoM collider. It is designed so that the detector is not connected by a straight line with any surface hit by decay electrons in forward or backward directions. Y axis goes to 6 cm and X axis 4 meters from IP.

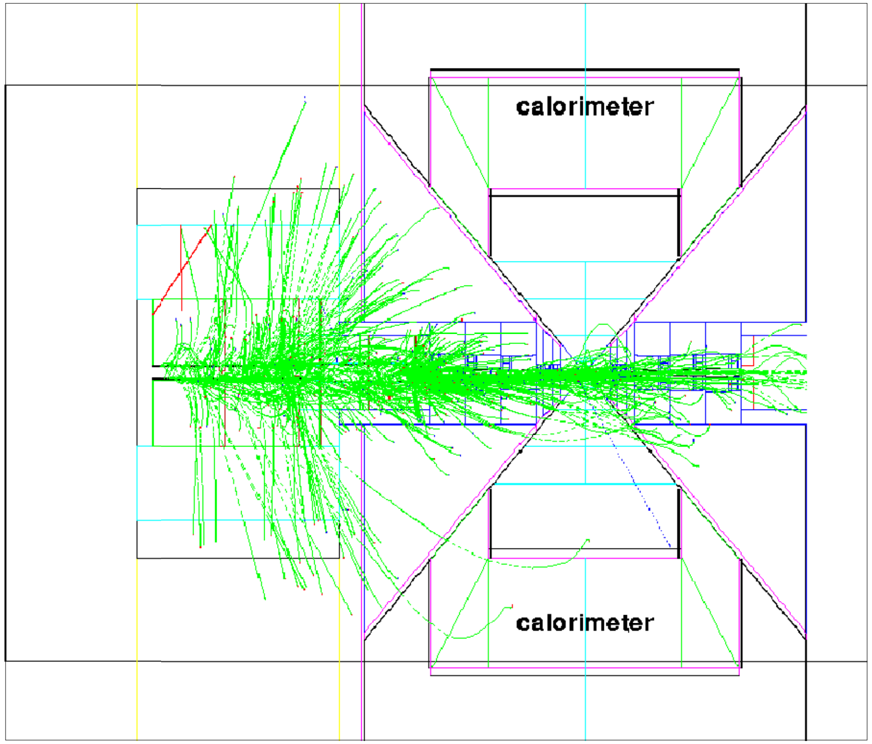


Muon Decay backgrounds

- For a 4 TeV CoM collider, 4 x 10^{12} muon per bunch and 4 x 10^5 muon decays per meter.
- The off-energy, off-axis electrons undergo brehmsstrahlung when they traverse magnetic fields. When they exit the beam pipe, they produce electromagnetic showers and to a lesser extent hadrons and muons (Bethe-Heitler muons).
- The showers produce
  - » Low energy photons of ~1 MeV. These enter the detector and produce knock-on electrons.
  - » Photons interact with nucleii (Giant dipole resonance) and produce neutrons. These enter the detector and produce knock-on protons.
  - » Muon pairs are produced instead of electron pairs (~1/10^4) by photons in EM showers. These are called Bethe_Heitler muons and cause problems when they are energetic and enter the detector

Bethe-Heitler Muons





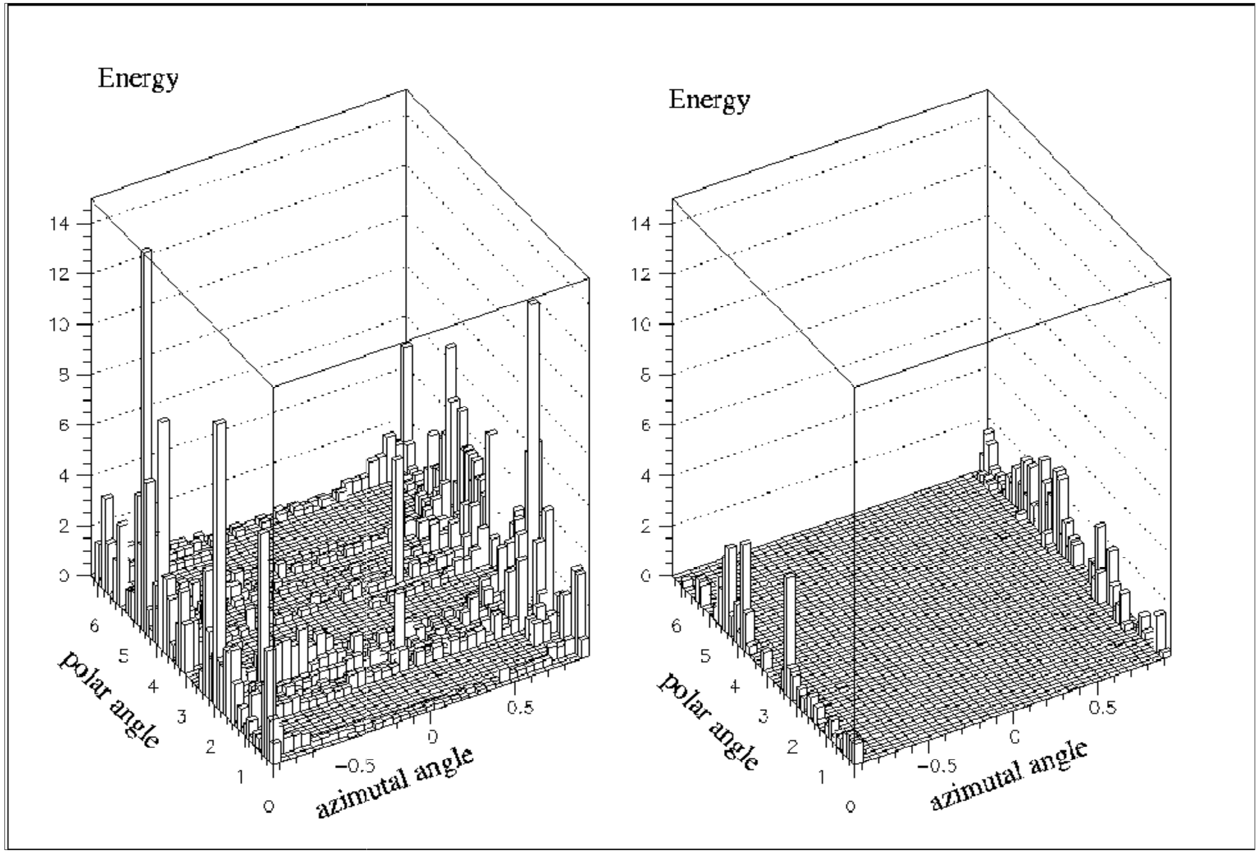
4 TeV cms collider- x =130m, y=4m. <1% tracks end in calorimeter

100 GeVcms collider- x =20m, y=4m. <0.5% tracks end in calorimeter

Bethe-Heitler Muons

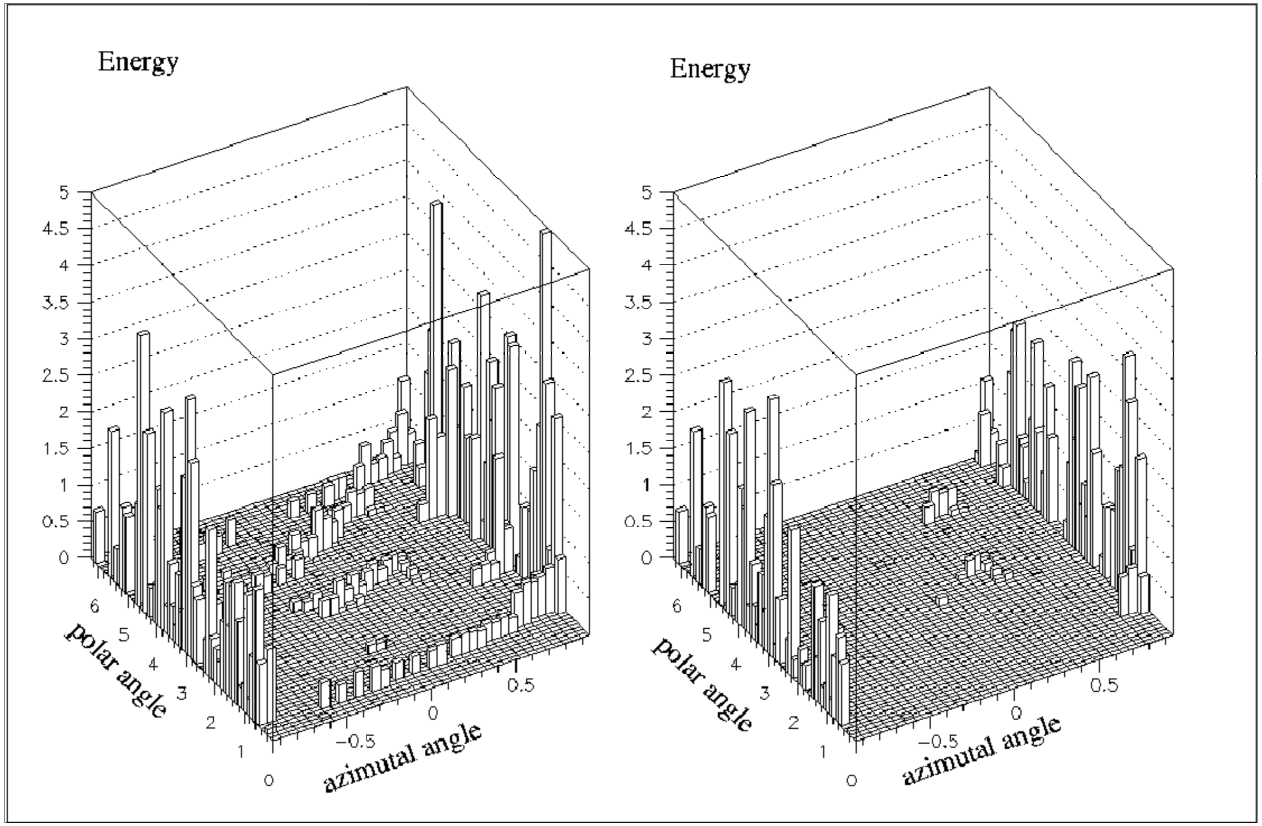
CoM Collider Energy (TeV)	4	0.5	0.1
Assumed source length	`30	33	20
μ (pμ>1 GeV/c) per electron	5.4×10^{-4}	8.3×10^{-5}	9.6×10^{-5}
Beam μ's per bunch	2×10^{12}	2×10^{12}	4×10^{12}
Bethe_Heitler μ's per crossing	28000	17500	6100
<pμ> initial GeV	22	9.5	4.4
μ's in calorimeter	220	160	25
Deposited energy GeV/muon	2.9	1.3	0.4
Total deposited energy GeV	640	210	10
Pedestal Subtracted E dep. GeV	50	25	1
Fluctuation in E dep. GeV	55	15	1
Transverse energy GeV(p.s)	15	15	.5
Fluctuation E trans	40	8	0.5

Bethe-Heitler Muons



LHS 4 TeV collider. RHS with 1 ns timing cut

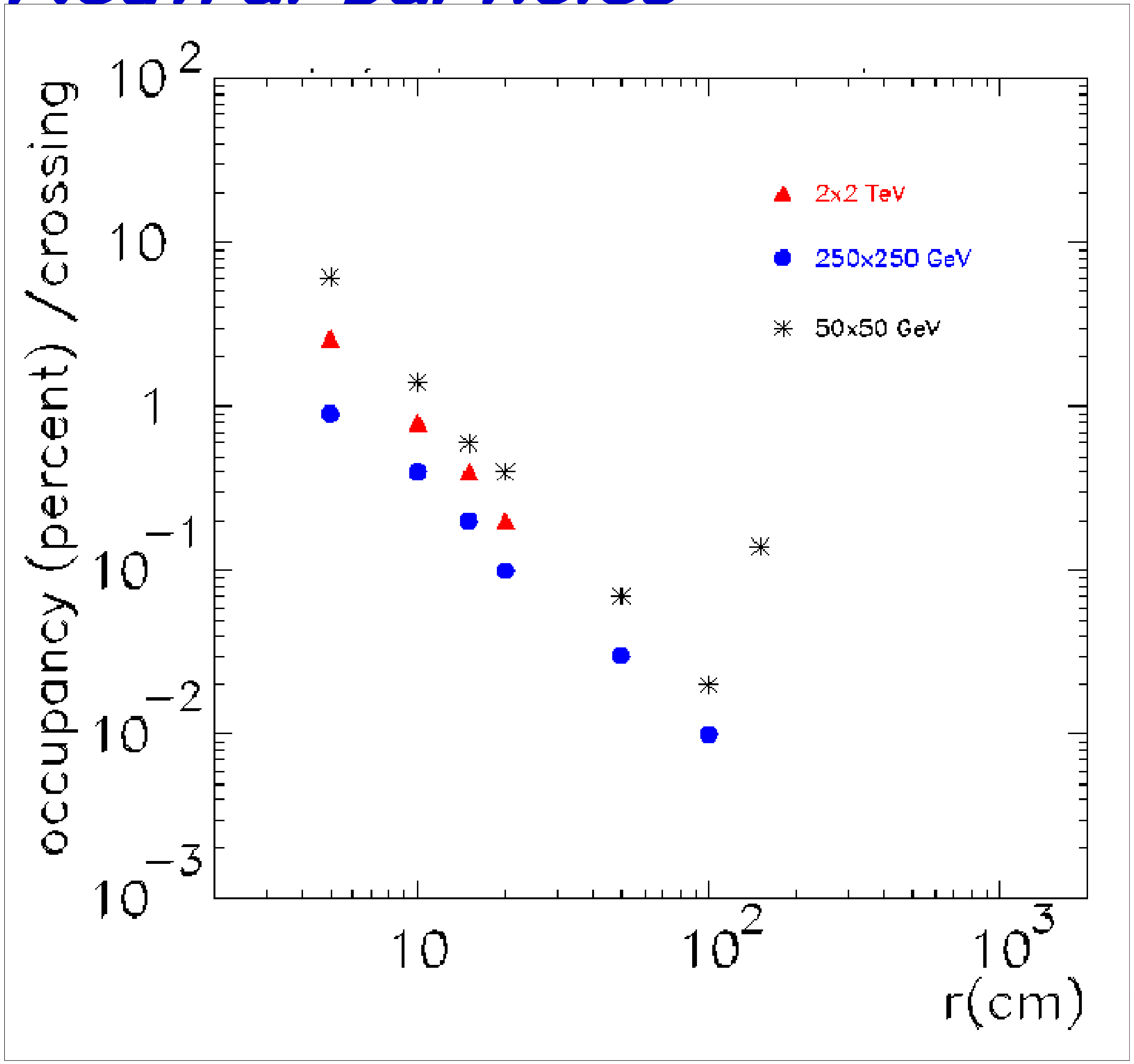
Bethe-Heitler Muons



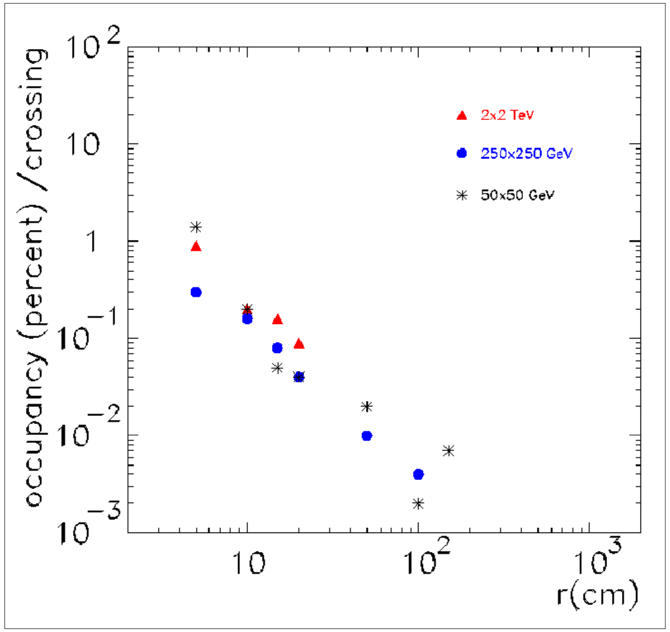
0.5 TeV cms collider. RHS with 1 ns timing cut

Background Summary
Neutral particles

Occupancy for 300 micron square silicon pads as a function of cms energy and radius from IP

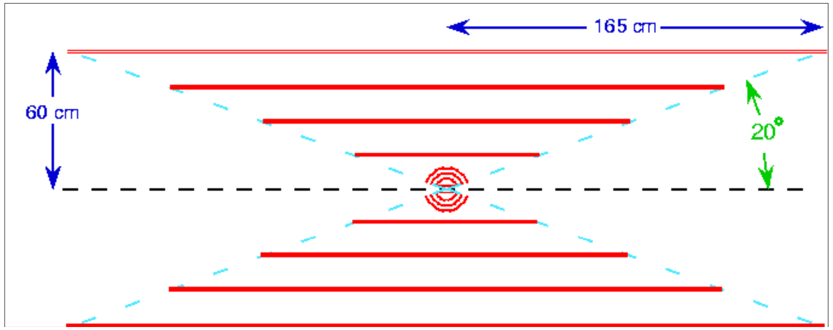


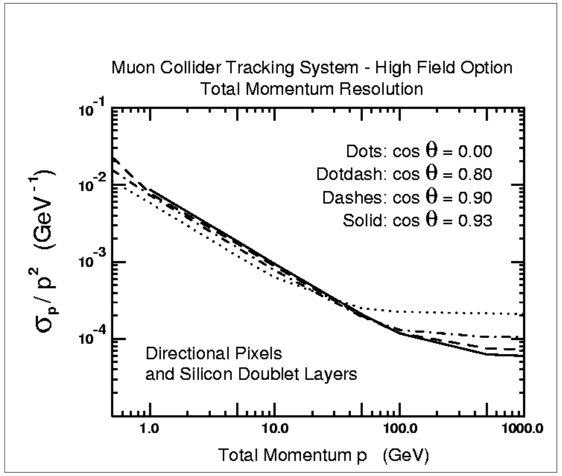
Background Summary
Charged particles



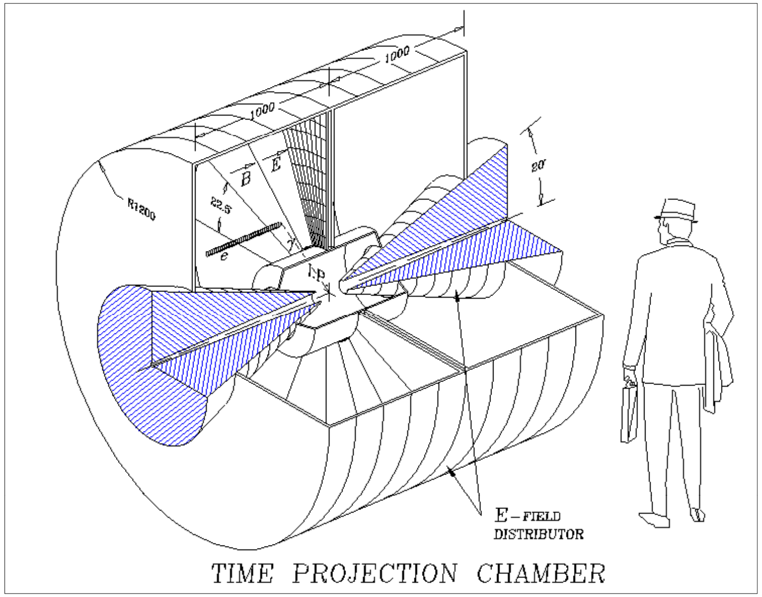
Radius	cm	5	10	20	100
Photon hits	cm^{-2}	26	6.6	1.6	0.06
Neutron hits	cm^{-2}	0.06	0.08	0.2	0.04
Charged hits	cm^{-2}	8	1.2	0.2	0.01
Total hits	cm^{-2}	34	8	2	0.12
Pixel size	µm x µm	60 x 150	60 x 150	300x300	300 x 300
Total occupancy	%	0.6	0.14	0.4	0.02
Occupancy from Charged particles	%	0.14	0.02	0.04	0.002

Detector Scenarios



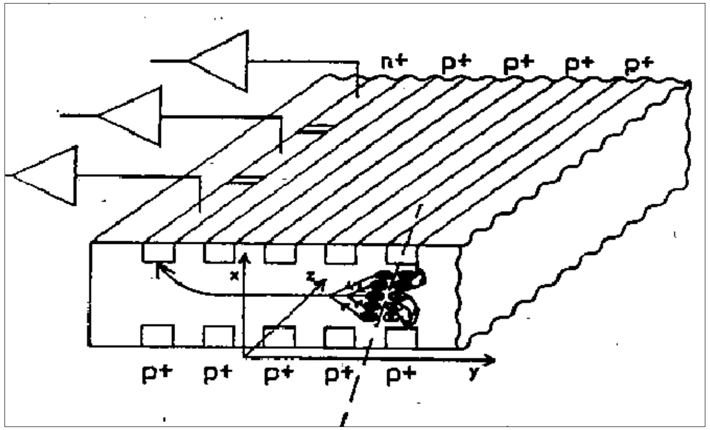


Silicon pixels surrounded by microstrips



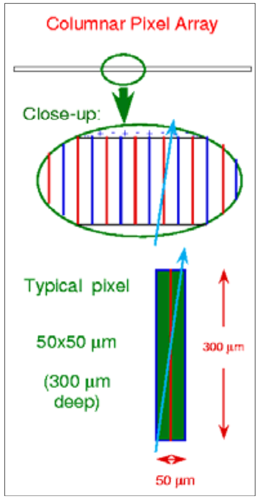
TPC suitable for 3TeV collider. Gas with no hydrogen to minimize knockon protons

Detector Scenarios-Silicon

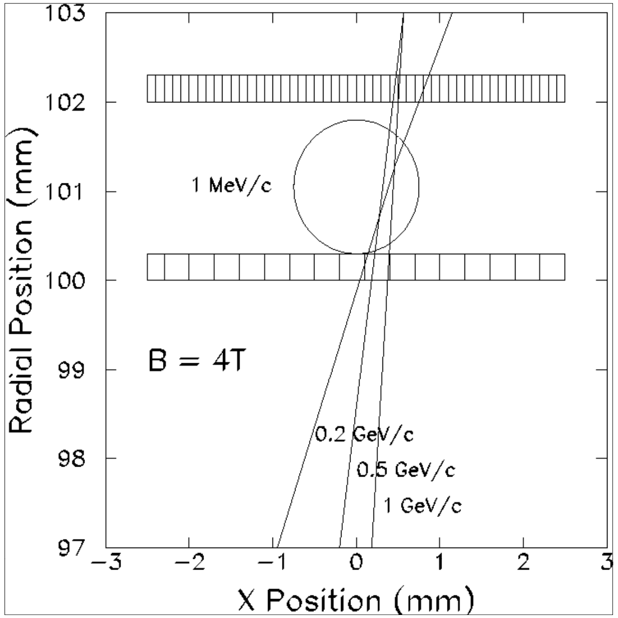


Silicon drift vertex detector

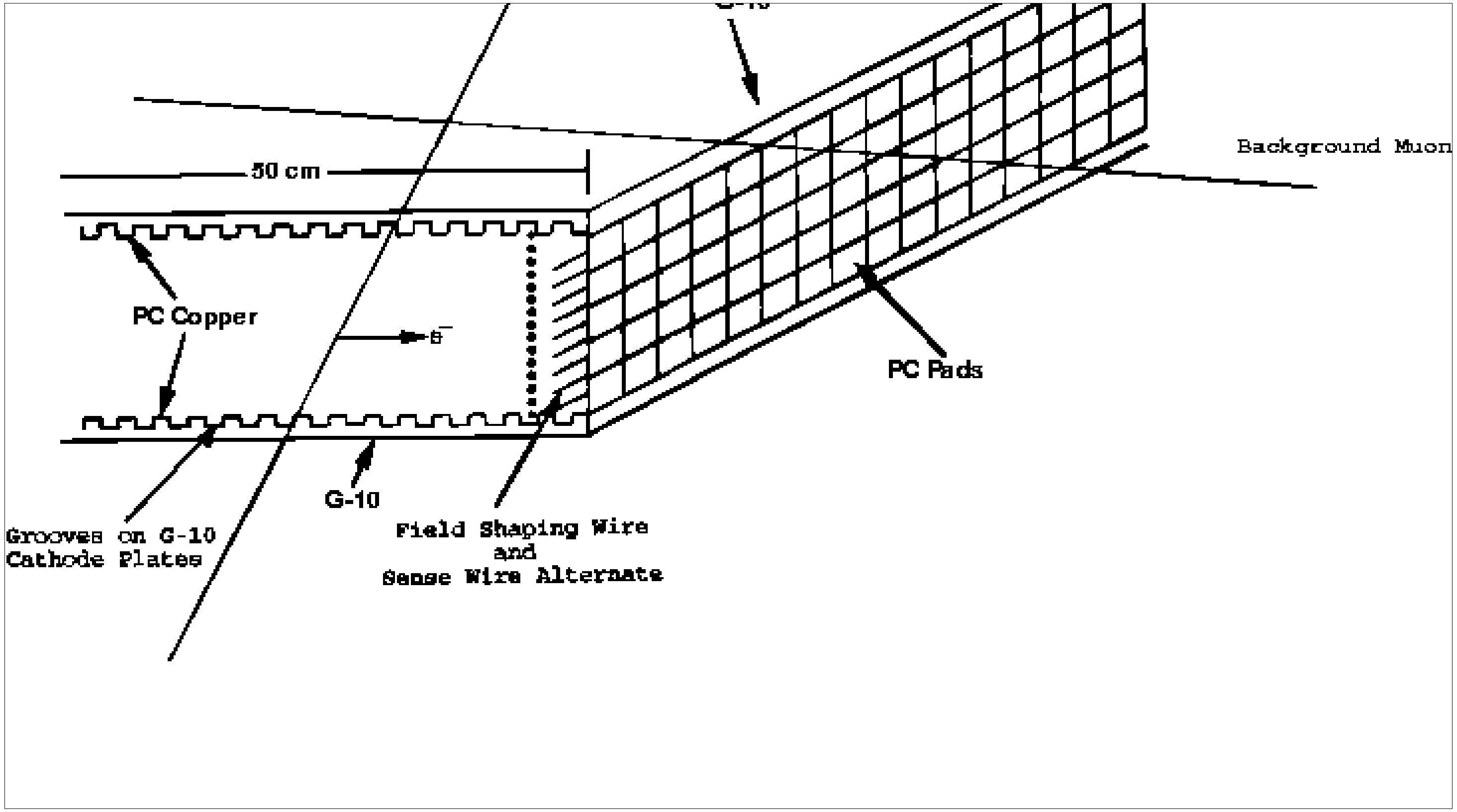
Columnar pixels

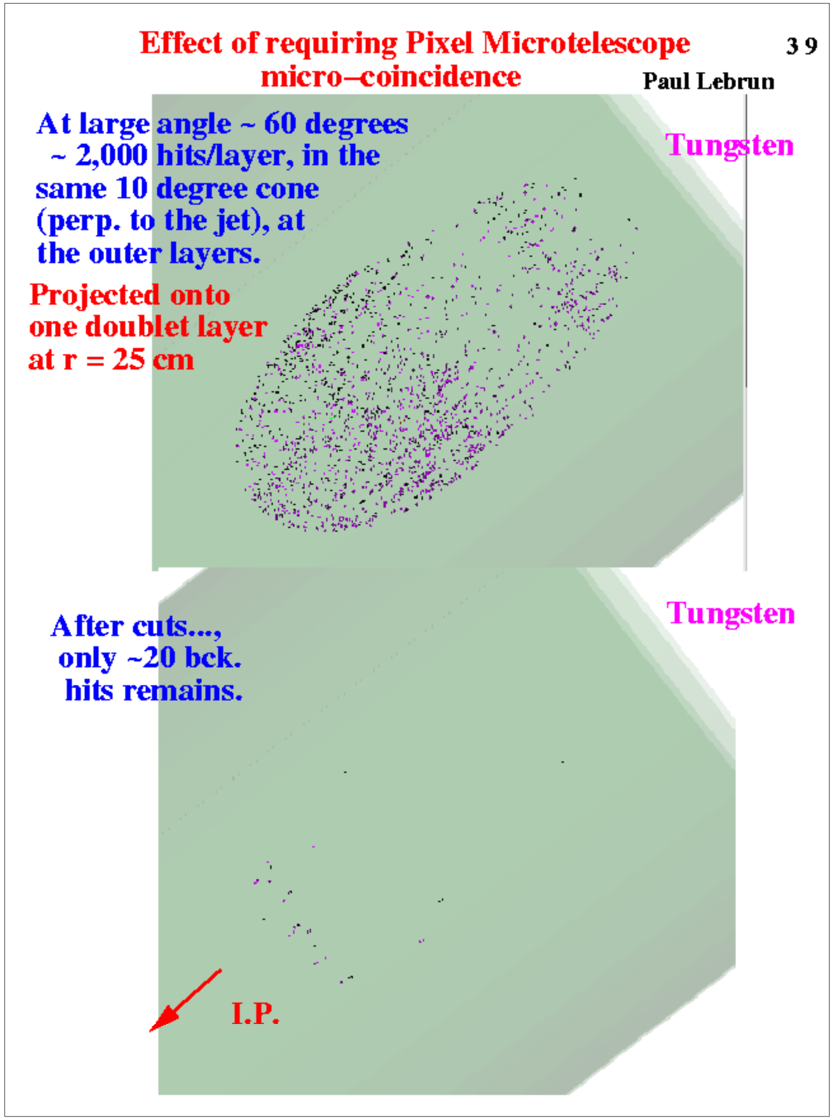


Pixel telescope

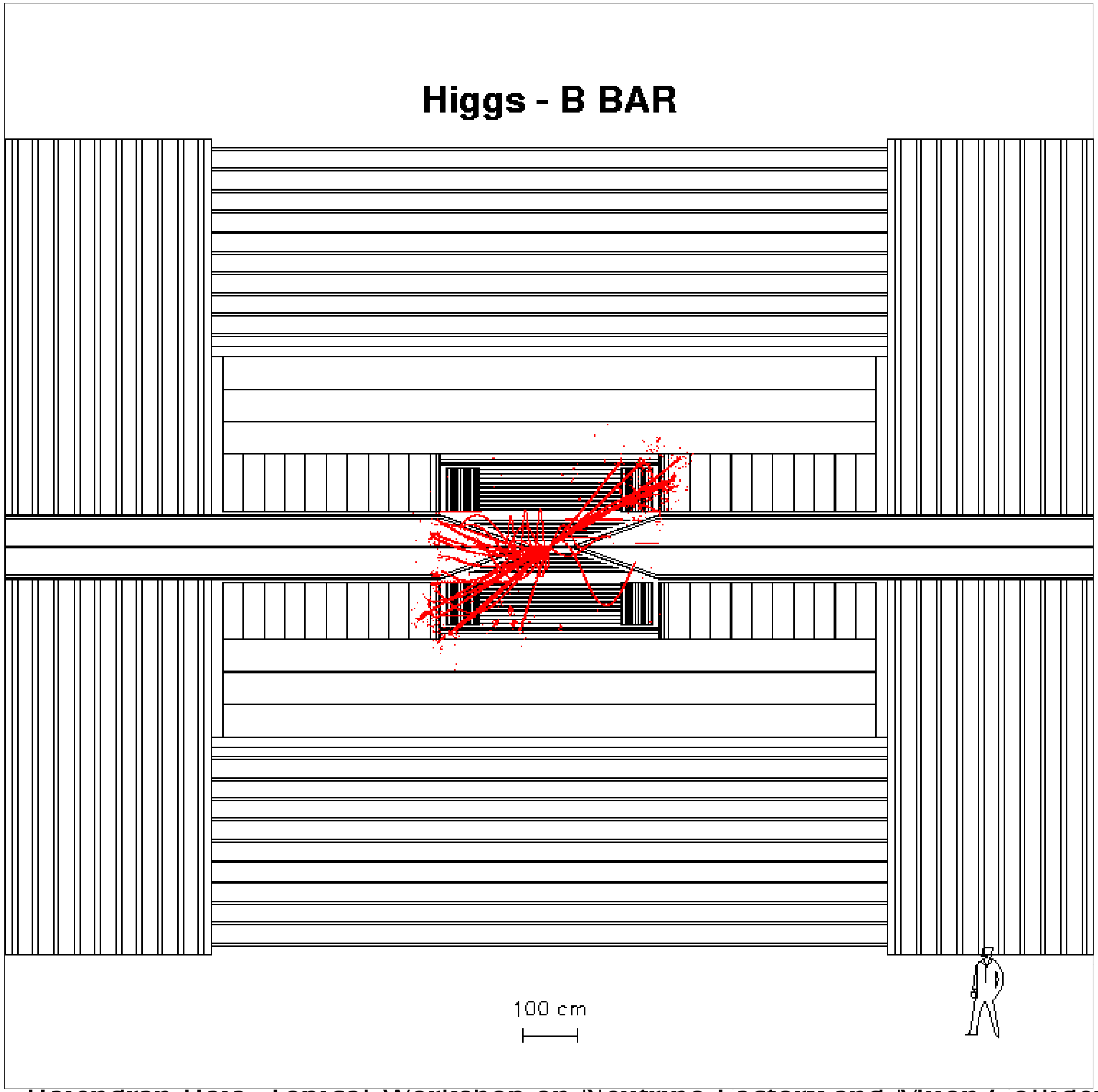


Muon Drift chambers with pads

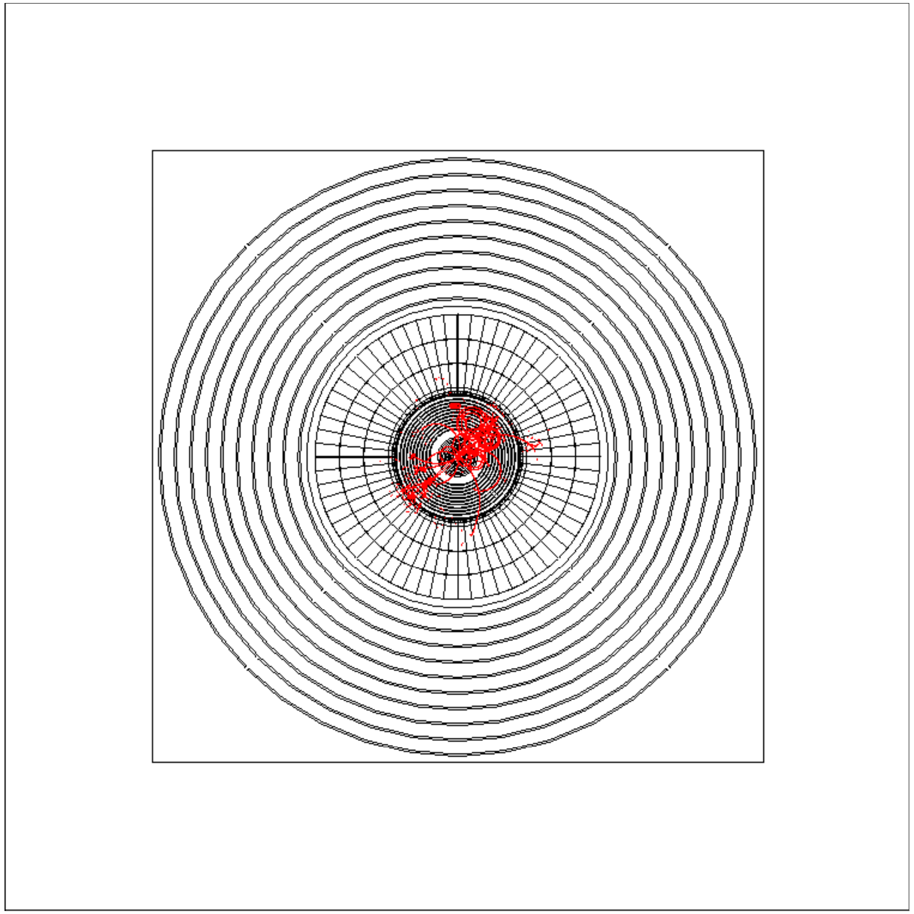



Effect of requiring Pixel Microtelescope
micro–coincidence
3 9
Paul Lebrun
At large angle ~ 60 degrees
~ 2,000 hits/layer, in the
same 10 degree cone
(perp. to the jet), at
the outer layers.
Tungsten
Projected onto
one doublet layer
at r = 25 cm
After cuts...,
only ~20 bck.
hits remains.
Tungsten
I.P.

Detector Simulation



Detector Simulation



Jul 21,1999 Rajendran Raja, Mutac Review, FNAL 3

Simulation Questions to be answered

- Can one optimize the lattice near the interaction region to reduce the backgrounds further? (2 man-years)
- Can one do b-tagging using silicon pixels given the large number of hits caused by the photon background? (1 m.y.)
- What is the efficiency vs. purity of b-tagging? (1 m.y.)
- Can c-tagging be contemplated? (0.5 m.y.)

Simulation Questions to be answered

- How can one design a fast vertex algorithm so that silicon hits are readout only for projective coincidences in a pixel micro-telescope? (1 m.y.)
- Will a TPC work at all energies as an outer tracker? (1 m.y.)
- What segmentation does the calorimeter need to possess to pattern recognize Bethe-Heitler muons? (0.5 m.y.)
- What e/π ratio, linearity and resolution are necessary for the calorimeter? (0.5 m.y.)

Simulation Questions to be answered

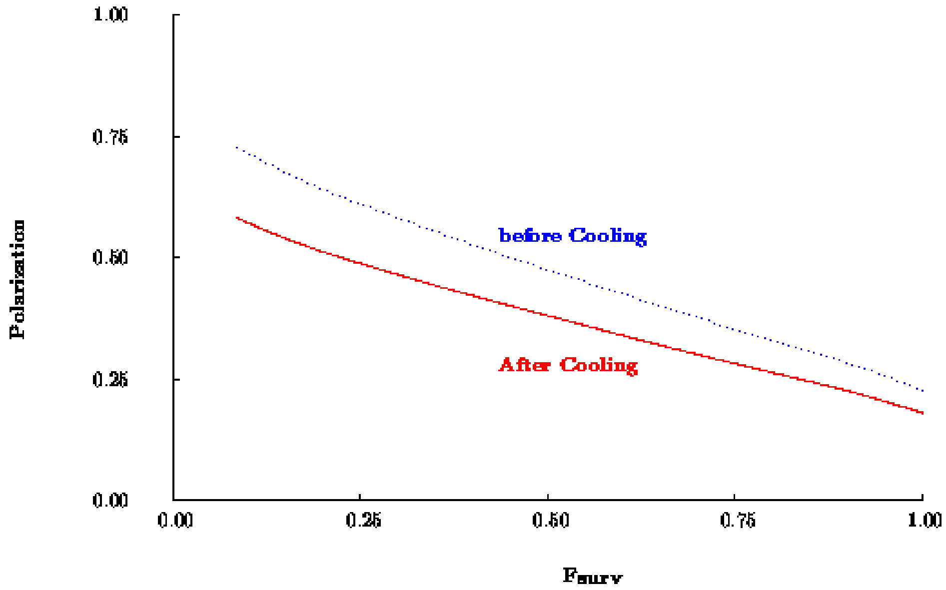
- Are there calorimeters that will permit the measurement of arrival times to 1 ns? (0.5 m.y.)
- How much distortion is there in the measured energies of jets and electrons as a function of background? (0.5 m.y.)
- Can one compute the pedestal energy deposits in the calorimeter resulting from the heavy neutron background which will vary as a function of the turn by turn muon intensity? (0.5 m.y.)

Simulation Questions to be answered

- Do we need a muon system? Or is it better to have a deeply segmented calorimeter that will pattern recognize muons as minimum ionizing tracks? (0.5 m.y.)
- Can one detect forward going muons from the interactions? (0.5 m.y.)
- How do we compare with the NLC in those physics channels outlined above that can be realized in both types of accelerator? (2 m.y.)

Muon Collider Physics—Polarization Precession

- Polarization of muons will play a crucial role in many physics areas.
- Both charges polarizable.
- Physics with rotating polarization addressed by Grzadkowski,Gunion et al **Nucl.Phys.B583:49-75,2000**



Calibrating the energy of the collider to 1E-6

Bargmann-Michel-Telegdi Equation

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}$$

$$\vec{\Omega} = -\frac{e}{m\gamma}((1+a\gamma)\vec{B}_{\neg} + (1+a)\vec{B}_{\Uparrow} - (a\gamma + \frac{\gamma}{1+\gamma})\vec{\beta} \times \frac{\vec{E}}{c})$$

$$\vec{\Omega} = \vec{\Omega}_{cyc}(1+a\gamma)$$

$$a = (g-2)/2$$

$B_{\neg}, B_{\Uparrow}$ are the components of magnetic field perpendicular and parallel particle direction

This equation controls the evolution of the spin vector $\vec{S}$. Polarization is the average of the spin vectors over the muon ensemble. Per revolution spin rotates by $a\gamma 2\pi$ radians more than momentum

Method described in R.Raja and A. Tollestrup, Phys. Rev. D58(1998)013005

Decay particle energy distribution

In the muon rest frame, E is the energy of the electron. Its fractional energy expressed in terms of the maximum energy ($m_\mu/2$) is x. N is the number of muon decays. θ is the angle of the electron in the muon center of mass w.r.t muon direction. <E> is the average electron energy and <PL> is the average longitudinal electron momentum in the muon rest frame.

P is the z component of the muon polarization along the muon direction. $\hat{P}$ is charge*P of the muon.

$$x = 2E / m_\mu$$

$$\frac{d^2 N}{dx\,d\cos\theta} = N(x^2(3-2x) - \hat{P}x^2(1-2x)\cos\theta)$$

$$< E >= \frac{m_\mu}{2N} \iint x \frac{d^2 N}{dx\,d\cos\theta} dx\,d\cos\theta = \frac{7}{10}\frac{m_\mu}{2}$$

$$< P_L >= \frac{m_\mu}{2N} \iint x\cos\theta \frac{d^2 N}{dx\,d\cos\theta} dx\,d\cos\theta = \frac{\hat{P}}{10}\frac{m_\mu}{2}$$

Muon neutrinos have identical distribution to electrons. Electron anti-neutrinos have the following distribution.

$$\frac{d^2 N}{dx\,d\cos\theta} = 6(x^2(1-x) - \hat{P}\,x^2(1-x)\cos\theta)$$

$$< E >= \frac{6}{20} m_\mu$$

$$< P_L >= -\frac{\hat{P}}{10} m_\mu$$

Electron energy distributions

$$< E_{lab} >= \frac{7}{20} E_{\mu} (1 + \frac{\beta}{7} \hat{P})$$

$$E(t) = Ne^{-\alpha t} (\frac{7}{20} E_{\mu} (1 + \frac{\beta}{7} (\hat{P} \cos \omega t + \phi)))$$

$$\omega = \gamma \frac{g-2}{2} 2\pi$$

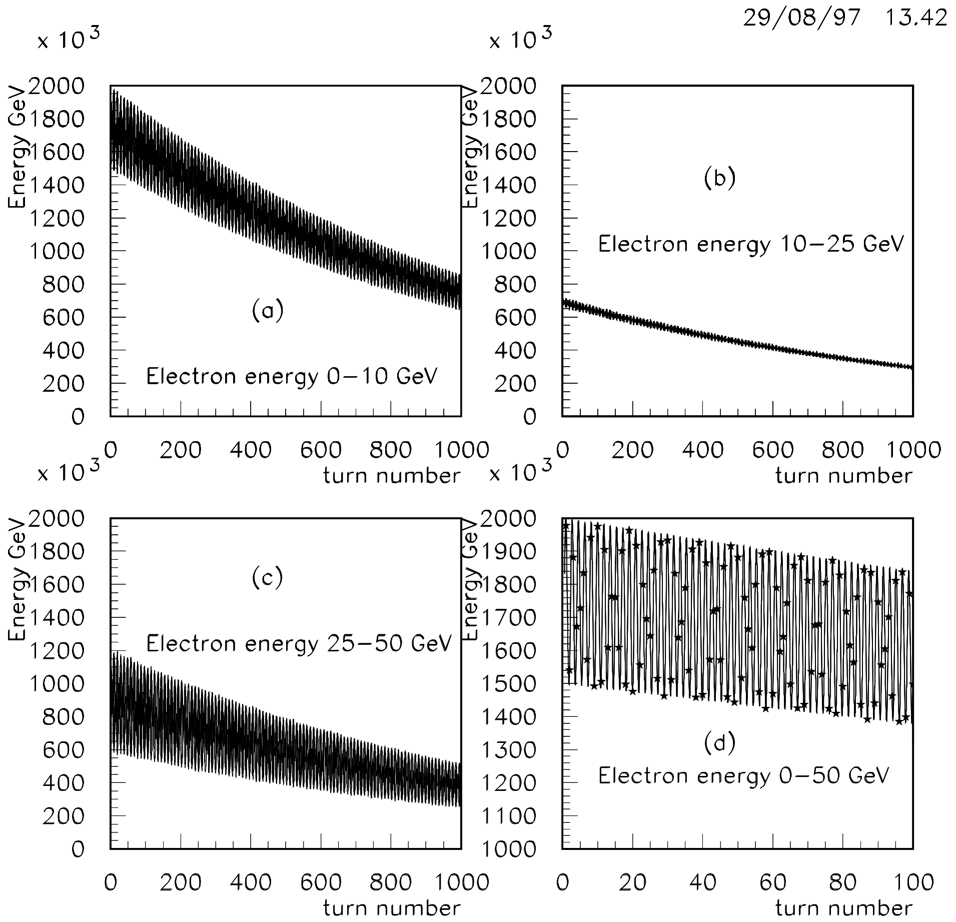
$$\alpha = \frac{t_{circ}}{\gamma t_{life}} = \frac{2\pi m_{\mu}}{0.3Bct_{life}}$$

$$f(t) = Ae^{-Bt} (C \cos(D + Et) + F)$$

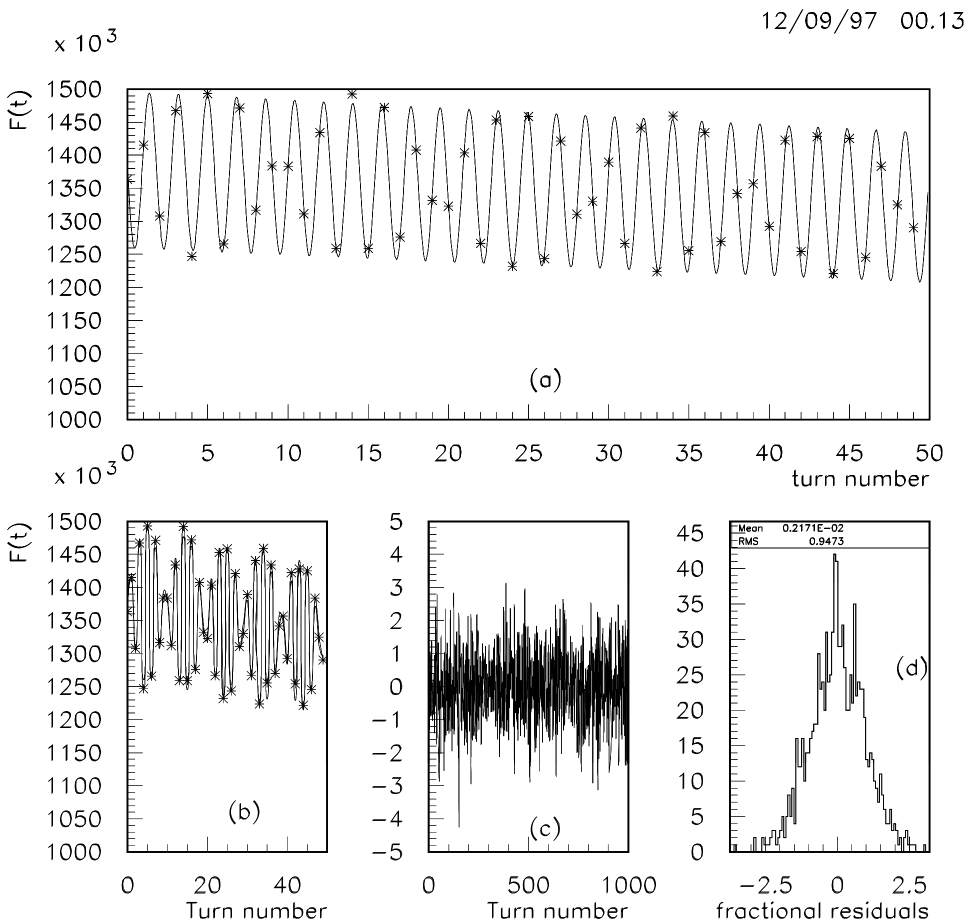
<E_{lab}> is the average electron energy in lab. E(t) is the total electron energy during turn t. Determine ω to get γ. γ information also present in α.

f(t) is the fitting function. MINUIT used to fit and extract information.

Electron lab energy spectrum Pol=1.0, 100K decays



Fit to 50 GeV μ^-, P=0.26 $\delta p/p$=0.03E-2



$\delta\gamma/\gamma$ vs measurement error and Polarization $\delta p/p$=0.03E-2

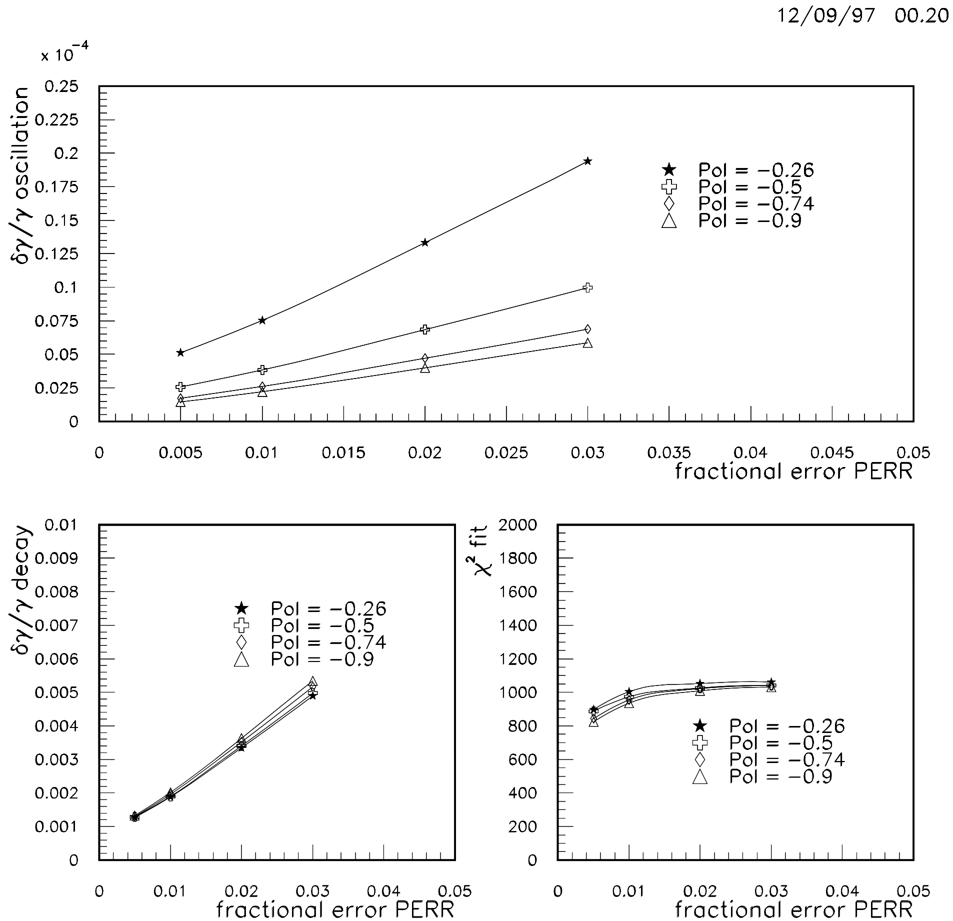
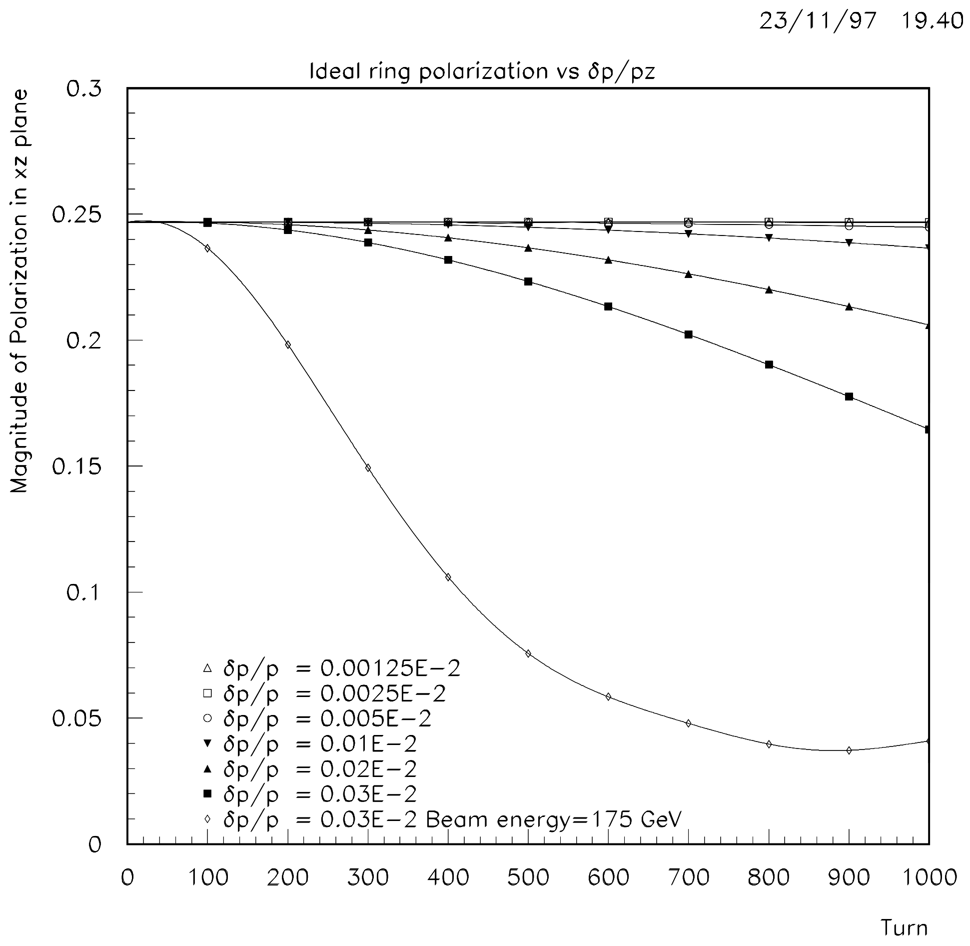


Table of fit parameters

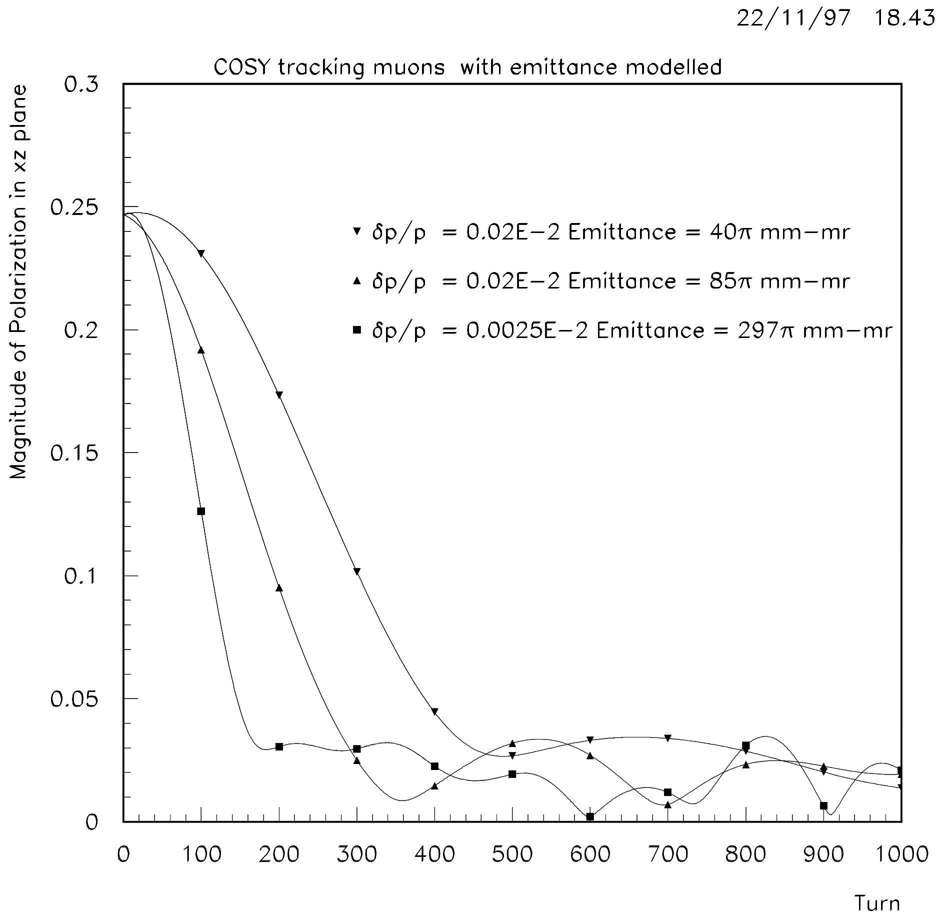
$\hat{P}$	PERR	Number of electrons sampled	$\delta\gamma/\gamma oscillations$	$\delta\gamma/\gamma decay$	χ^2 for NDF=1000
-0.90	0.50E-02	41261	0.14568E-05	0.13227E-02	824.
-0.90	0.10E-01	10315	0.22147E-05	0.20124E-02	936.
-0.90	0.20E-01	2579	0.39999E-05	0.36398E-02	1009.
-0.90	0.30E-01	1146	0.58659E-05	0.53457E-02	1030.
-0.74	0.50E-02	41261	0.17418E-05	0.13019E-02	843.
-0.74	0.10E-01	10315	0.26183E-05	0.19591E-02	954.
-0.74	0.20E-01	2579	0.46981E-05	0.35229E-02	1021.
-0.74	0.30E-01	1146	0.68765E-05	0.51672E-02	1039.
-0.50	0.50E-02	41261	0.25903E-05	0.12813E-02	888.
-0.50	0.10E-01	10315	0.38407E-05	0.19029E-02	973.
-0.50	0.20E-01	2579	0.68338E-05	0.33972E-02	1026.
-0.50	0.30E-01	1146	0.99744E-05	0.49749E-02	1041.
-0.26	0.50E-02	41261	0.51242E-05	0.12688E-02	898.
-0.26	0.10E-01	10315	0.75317E-05	0.18791E-02	1004.
-0.26	0.20E-01	2579	0.13324E-04	0.33447E-02	1053.
-0.26	0.30E-01	1146	0.19380E-04	0.48950E-02	1061.

TABLE I. Results of fits for $\delta\gamma/\gamma$ as a function of polarization $\hat{P}$ and noise PERR. Also shown is the χ^2 of the fit for 1000 turns.

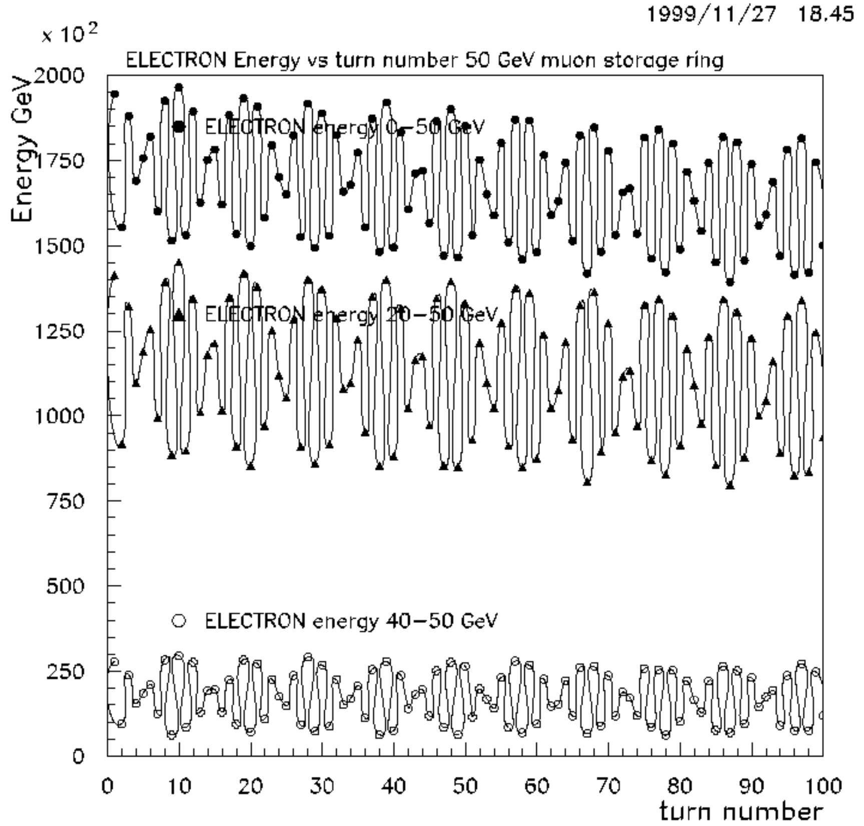
Polarization vs turn for various δp/p



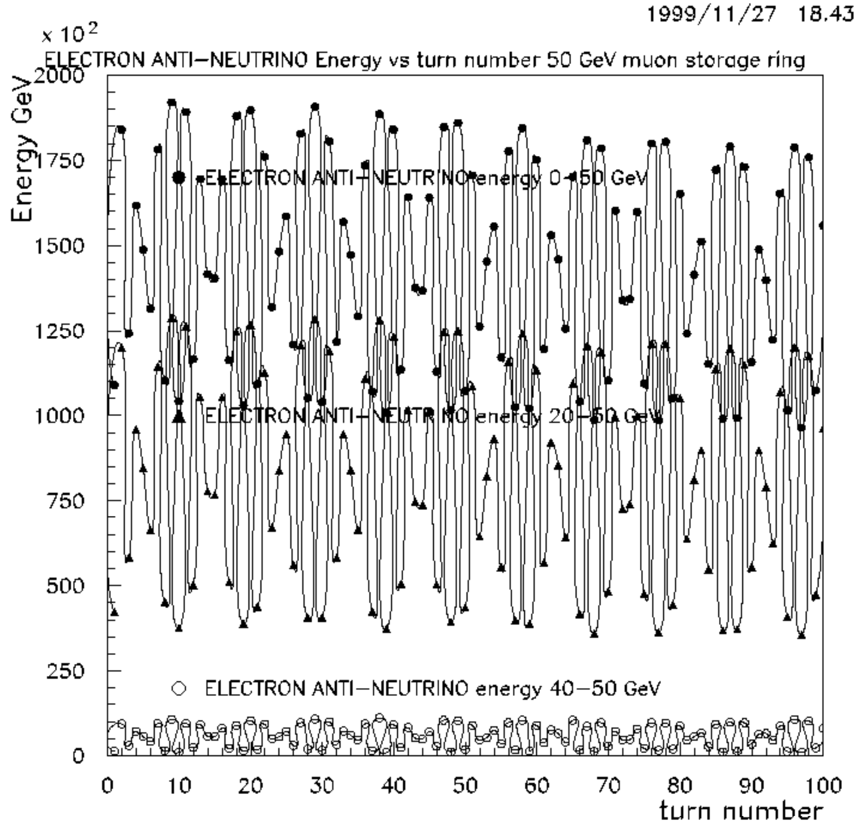
Polarization of 1000 muons vs turn number in COSY



Energy distribution of electrons



Energy distribution of electron anti-neutrinos



Conclusions

- Small amounts of polarization are valuable.(~10%)
- Muon Collider detectors can be made to work
- The biggest challenge to my mind is the targetry, collection and phase rotation scheme. We should consider making a proposal to FNAL to build such a device for the period when the Tevatron shuts down that is ready to take beam either from the present booster or from Project X when it turns on. The opportunities are ripe for the picking.
- This effort must be started soon and can go concurrently with the cooling demonstrations.
-