The Search For $K_L \rightarrow \pi^0\pi^0\gamma$

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Theoretical Interest

Decay requires pion pair to have 2 units of angular momentum; lowest multipole is E2 (CP-conserving)

Vanishes to order p^4 in Chiral Perturbation Theory; is a probe of the sixth order of ChPT

Estimated Branching Ratio

--Based on $\pi^+\pi^-\gamma$ branching ratio: $1*10^{-8}$ (Sehgal)

--From chiral perturbation theory: $7*10^{-11}$ (Ecker)

Problem: signal is swamped by background, particularly K_L->$3\pi^0$ (21% branching ratio)

References: Sehgal and Helliger, Phys Lett. B 307, p. 182-186.
Ecker, Neufeld and Pich, CERN-TH.6920/93

Matrix Element and Differential Decay Rate

Decay Amplitude (from Sehgal):

$A(K_L \to \pi^0(p_1)\pi^0(p_2)\gamma(k)) =$

$(g_{E2}/M_k^{\ 4})\ (p_1 - p_2)\cdot k/(\Lambda^2) * [(e\cdot p_1)(p_2\cdot k) - (e\cdot p_2)(p_1\cdot k)]$

Differential Decay Rate (calculated):

$d^2\Gamma/dE_\gamma d\theta = A*E_\gamma^{\ 5}*p_1^{\ 4}*\sin^3(\theta)/(E_1E_2)$
$*[(E_1 - E_2) - (p_1\cos(\theta) - p_2\cos(\phi))]^2$

Where A = constant

θ = angle between p_1 and k

ϕ = angle between p_2 and k

(implicit function of E_γ and θ)

Photon Spectrum

The differential decay rate was put into the Monte Carlo (version 6_00).

To check the differential decay rate, compare the photon spectrum it generates to one given by Sehgal:

$$d\Gamma/d\omega = 1/(3840\pi^3 M_K^{\ 7})\ g_{E2}^{\ 2}/\Lambda^4 * (1-2\omega/M_K)\ \beta^5\omega^5$$

where $\beta^2 = (M_K^{\ 2} - 2M_K\omega - 4m_\pi^{\ 2})/(M_K^{\ 2} - 2M_K\omega)$

In PAW, I generated a vector of these values and compared it to the actual photon spectrum—they agreed; conclusion: the differential decay rate I calculated was correct .

Previous Work

--This mode was previously explored by NA31. (Barr, et. al., Phys Lett B 328(1994) 528-534)

Their published result:

Three events found in the box, 2.2+-0.9 $K_L \to 3\pi^0$ background events expected

$BR(K_L \to \pi^0\pi^0\gamma) < 5.6*10^{-6}$ (at 90% confidence level)
This is the PDG result.

--Also, E799I (Douglas Roberts) searched for this mode;

$BR(K_L \to \pi^0\pi^0\gamma) < 2*10^{-4}$ at 90% confidence level

Previous Work, cont'd.

--Valeri Jejer studied $\pi^0\pi^0\gamma^*$
where $\gamma^* \to e^+e^-$

--$\pi^0\pi^0e^+e^-$ has charge radius term, $\pi^0\pi^0\gamma$ (where the photon is real) does not

--Jejer found $BR(K_L \to \pi^0\pi^0e^+e^-) < 6.6 \times 10^{-9}$;
upper limit on $K_L \to \pi^0\pi^0\gamma$ estimated at 3.3×10^{-7}
(factor of 50 higher)

Reference: Alavi-Harati et.al. PRL 89, 211801 (2002)

Data Selection

--For a clean signal, I search for events with a Dalitz pair from one photon (coming from a π^0)
$K_L \to \pi^0 \pi^0_D \gamma$ rather than $K_L \to \pi^0 \pi^0 \gamma$

--This costs factor of 50 in flux, but 2E-NCLUS trigger is most effective for this mode

All events which passed the trigger and crunch described in the following slides are read from tape; three tapes in all, describing 1.2 million total events .

Crunch tapes have been made for 1997 only (which is why I'm starting there).

Trigger: Subset of 2E-NCLUS (trigger one)

Level 1:
--At least 2 hits in 1 VV' bank and at least 1 in the other;
--Etotal > 25 GeV
--One hit in each of the upstream DC OR views
--No hits in MU2
--HA sum below 2.5 MIPs
--No hits above 14 GeV in CA
--No hits above 500 MeV in RCs, (except RC8),SAs or CIA.

Level 2:
--2 or more hits in each DCY view, allowing a missing hit
in either DC1 or DC2;
--Four hardware clusters found by HCC;
--One hit in DC2X bananas.

Level 3:
Two tracks with E/p > 0.75, at least one vertex candidate

Crunch

All events pass through a slightly modified 2E-NCLUS crunch code requiring:

--Two reconstructed tracks
--Six hardware clusters
--Reconstructed two-track vertex
--$0.95 < E/p < 1.05$ (tighter than 2E-NCLUS crunch)
--Tracks have opposite charge
--$p_t^2 < 0.001$ $(GeV/c)^2$
--$M_{ee\gamma\gamma\gamma\gamma} > 0.44$ GeV

Clustering was done with:

--4 slices, 0.9 GeV minimum cluster energy, 0.22 GeV minimum seed block energy
--Overlap seperation, neighbor correction, missing block, threshold, and intra-block corrections.

MC Generation

--$\pi^0\pi^0{}_D\gamma$ signal events and $\pi^0\pi^0\pi^0{}_D$ primary background events were generated with KTEVMC v6_00, with accidentals
--$\pi^0\pi^0\gamma$ was generated using the differential decay rate I calculated
--$\pi^0\pi^0\pi^0$ was generated using only phase space

--Dalitz decays were generated using the Kroll-Wada decay rate and radiative corrections
--Shower libraries from 2000 used in generation
--L2 Acceptance: 5.8% for $\pi^0\pi^0\pi^0{}_D$
6.2% for $\pi^0\pi^0{}_D\gamma$

Combined Vertexing Routine

--The two track vertex is not very accurate in cases with small electron/positron angle (low mee).

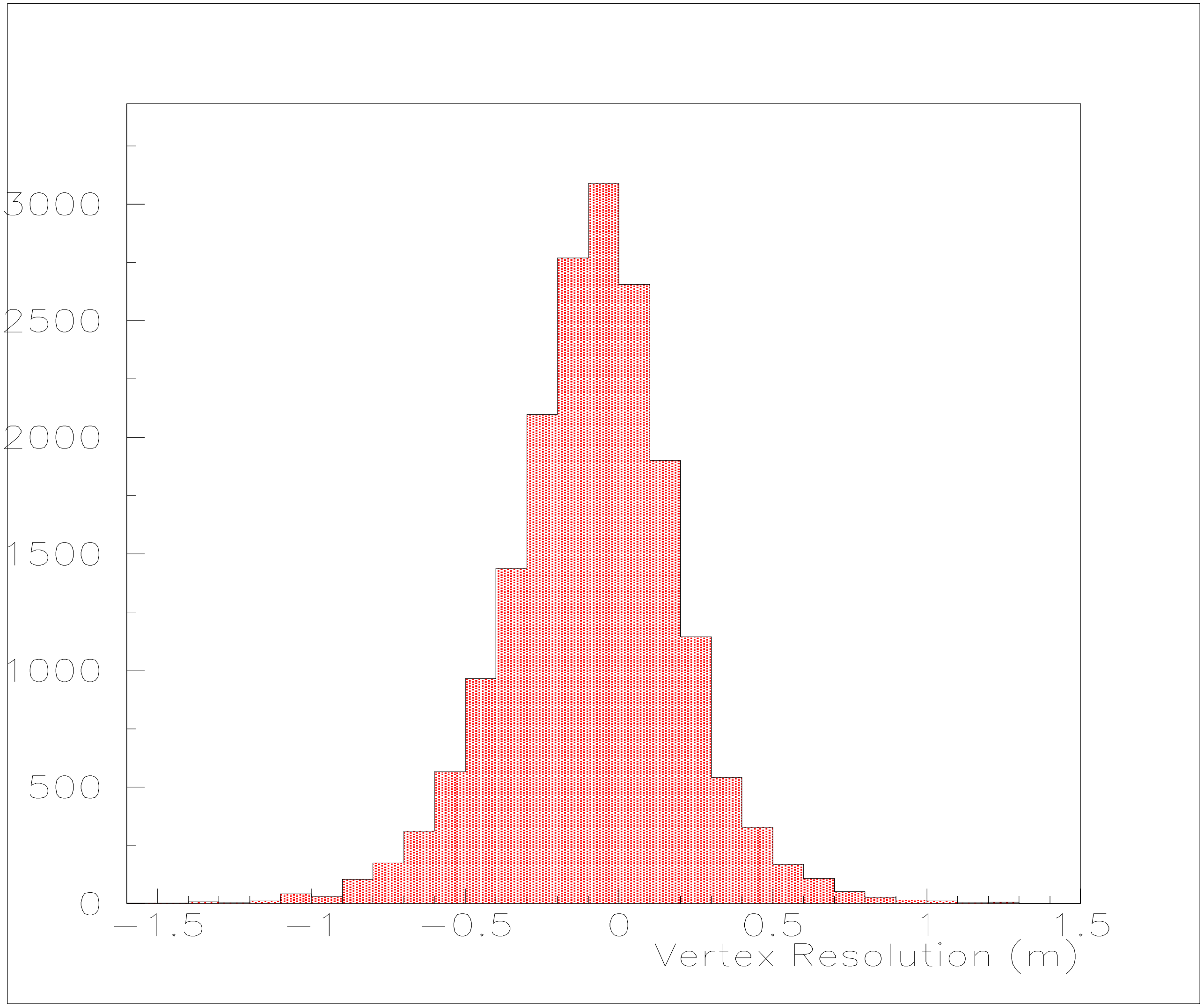
--After the crunch, a combined vertexing routine (due to Sasha Ledovsky) was run on the remaining events.

--It looks at all possible vertex locations and photon pairings in an attempt to minimize the vertex χ^2, defined by

$$\chi^2 = \sigma_{trk}{}^2 + \sigma_{Mee\gamma}{}^2 + \sigma_{M\gamma\gamma}{}^2$$

This routine offers good resolution of the z-vertex as seen in the next slide.

Vertex Z Resolution, Combined Vertexing Routine



This is the Monte Carlo VTXZ minus the reconstructed value (found using the combined vertexing routine) for a sample of well-reconstructed events. Resolution is on the order of 30 cm.

Bad Runs + Bad Spills

The following bad runs were removed:
--Any before 8245;
--8437, 8913, 10680, 10721, 10742, 10765,
10904, 10906 ;

--Spills were rejected if any KTSPILL bit was set (except for TRD problems);

--Events were rejected unless
$0.46 \text{ GeV} < M_{ee\gamma\gamma\gamma} < 0.54 \text{ GeV}$ (reduce sample size)

Percentage of Events Past Each Cut

Cut	Data	Background $3\pi^0_D$ MC	Signal $2\pi^0_D\gamma$ MC
Crunch	100.0%	2.9%	16.0%
Bad Runs	93.0%	92.5%	93.4%
Mass	23.4%	24.2%	97.7%
Bad Spills	85.4%	85.4%	85.8%
TOTAL	18.5%	0.5%	12.5%

This is before analysis cuts!

Signal Box and Background

Use a signal box: $|M_{ee\gamma\gamma\gamma} - M_K| < 5$ MeV
and $p_t^2 < 0.0005$ $(\mathrm{GeV/c})^2$

This box has 86.4% efficiency for the signal mode.

Design cuts to remove $3\pi^0{}_D$ events from box
while keeping $2\pi^0{}_D\gamma$ events.

Close control box $|M_{ee\gamma\gamma\gamma} - M_K| < 15$ MeV
and $p_t^2 < 0.0005$ $(\mathrm{GeV/c})^2$

This is a blind analysis!

Normalization Mode: $3\pi^0_D$ w/beam hole γ

We needed a sample of clean, completely reconstructible events to use as a normalization mode.

We used $3\pi^0_D$ events where one photon goes down one of the beam holes.

To find the normalization mode, routine T3MISP was called to find a missing particle assuming a perfect kaon mass and $p_t^2 = 0$.

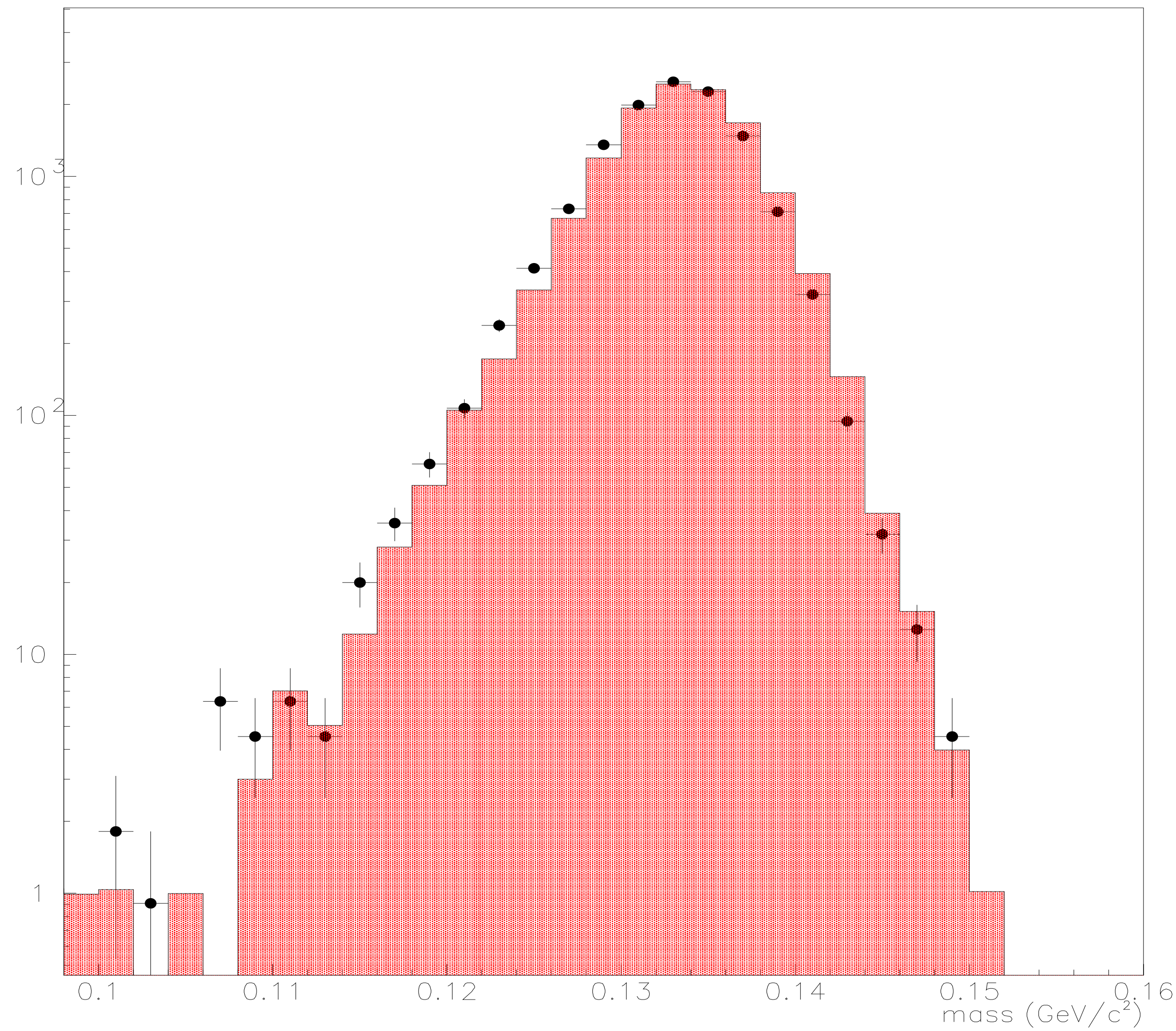
It returns two solutions; the one which gives $m_{\gamma\gamma}$ closest to the π^0 mass when combined with the unpaired 'direct emission' photon is chosen.

If the event in general passes the normalization mode cuts, the event is accepted into the normalization mode.

Normalization Mode Cuts

--T3MISP returns a photon with vertex projection at CSI
 8.5cm < |x| < 21.5 cm and |y| < 6.5 cm (i.e. in beam hole)
--E_γ > 8.0 GeV;
--$|M_{\gamma\gamma} - M_{\pi^0}|$ < 0.05 GeV/c^2 for pairing of missing photon
 with 'direct emission' photon
--PP0KINE > 0.0;
--No other 'good' set of photon pairings;
 i.e. none that give
 $|M_{ee\gamma} - M_{\pi^0}| < 2$ MeV/c^2
 $|M_{\gamma\gamma} - M_{\pi^0}| < 2$ MeV/c^2
 PP0KINE > 0.0;
--Vertex $\chi^2 < 7.0$;
--90m < VTXZ < 150m;
-- $|M_{ee\gamma} - M_{\pi^0}| < 2$ MeV/c^2
-- $|M_{\gamma\gamma} - M_{\pi^0}| < 2$ MeV/c^2
-- Fusion $\chi^2 < 4.0$

Mass of normalization mode π^0, Data vs MC comparison



Dots are data, histogram is MC.

Kaon Flux and Events

The normalization mode has: 13678 events in data
12467 events in MC

The 1997 KteV kaon flux is defined as

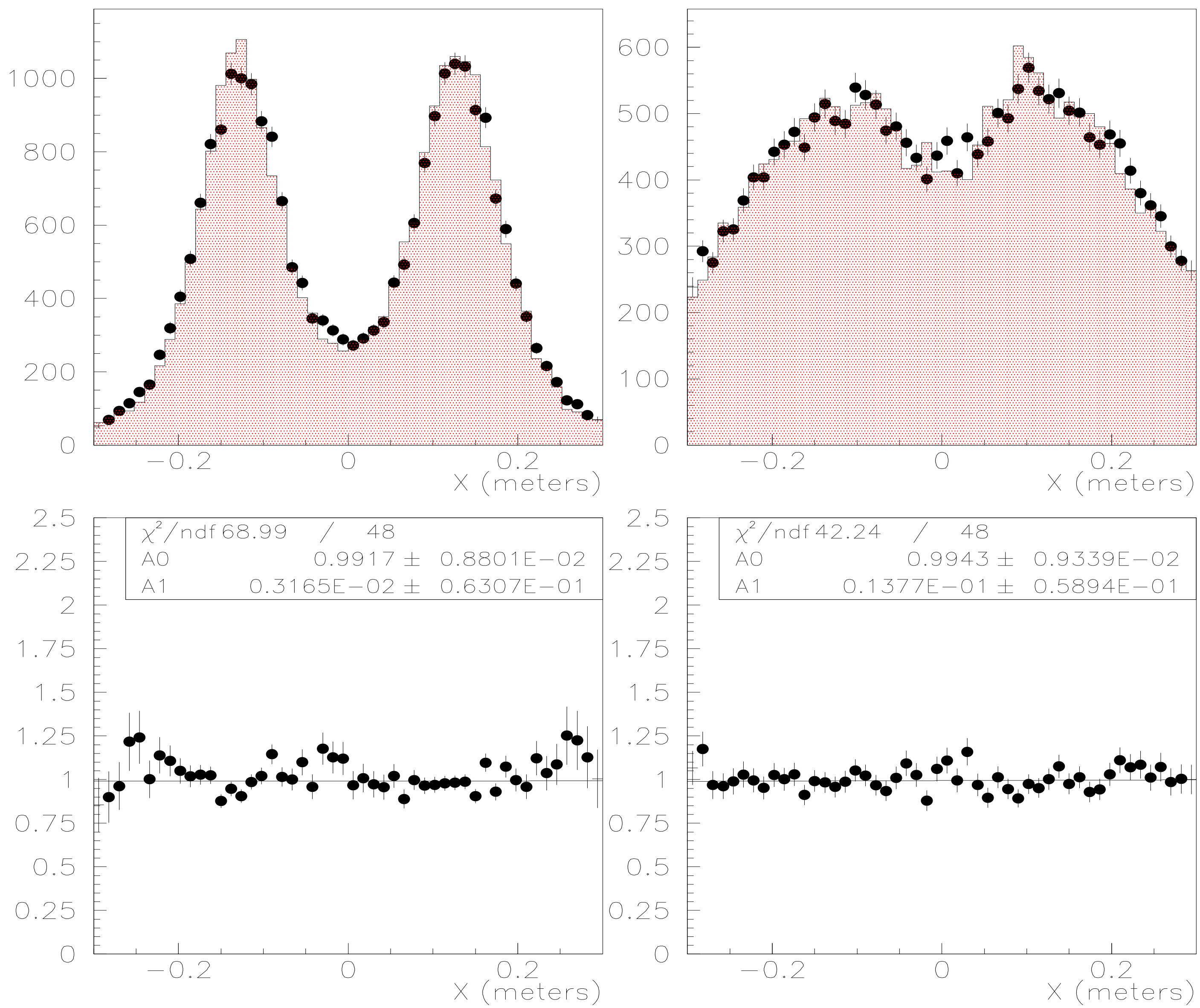
$$K_{flux} = N_d^{norm}/N_{MC}^{norm} * N_{MC}^{gen}/BR(K_L\text{->}3\pi^0{}_D)$$

Using this definition, $K_{flux} = 2.60*10^{11}$ for the 1997 run.

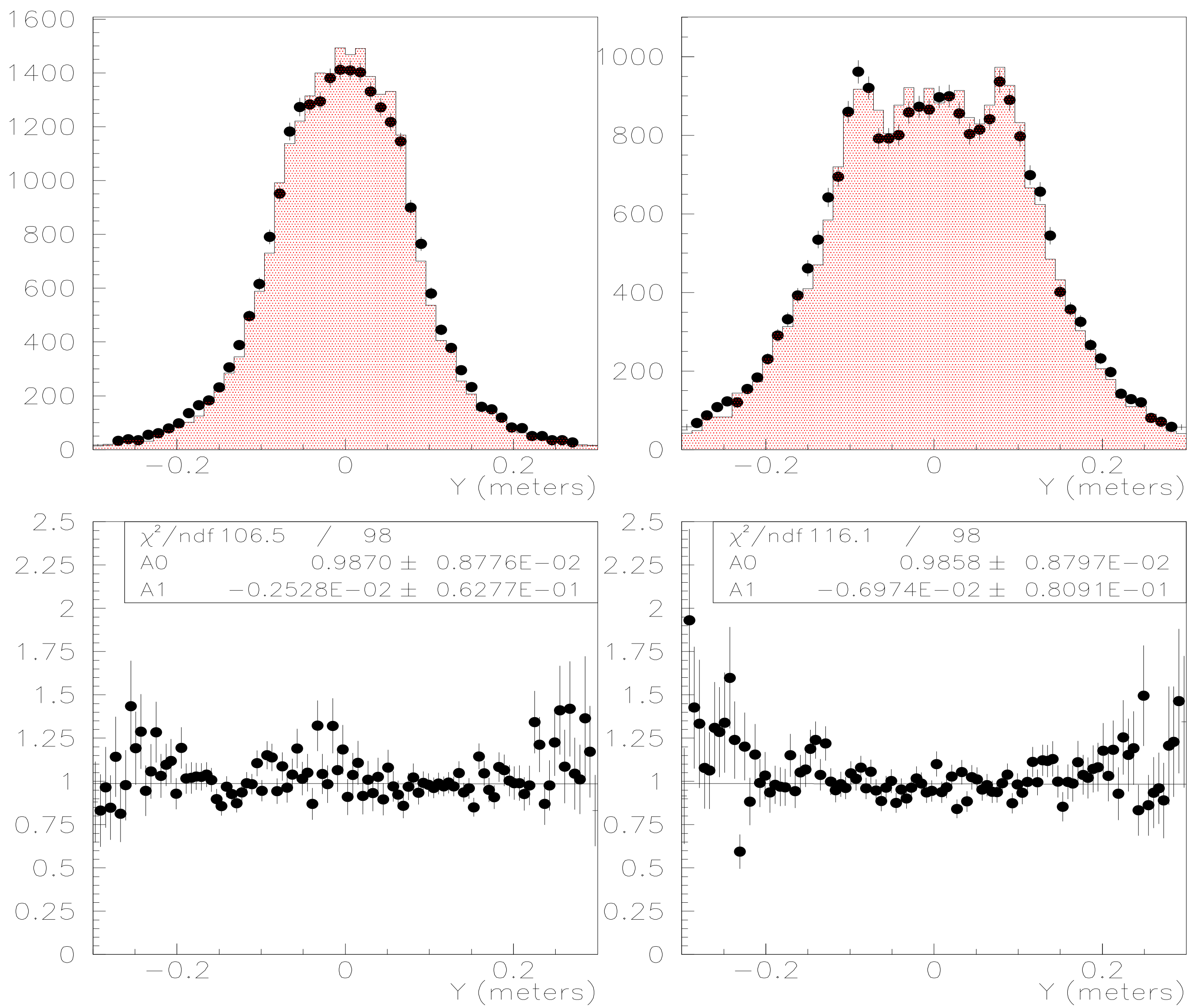
Technical Histograms

In addition to providing a normalization value, 3p0D events which pass these cuts provide a clean sample of events to use in technical histograms.

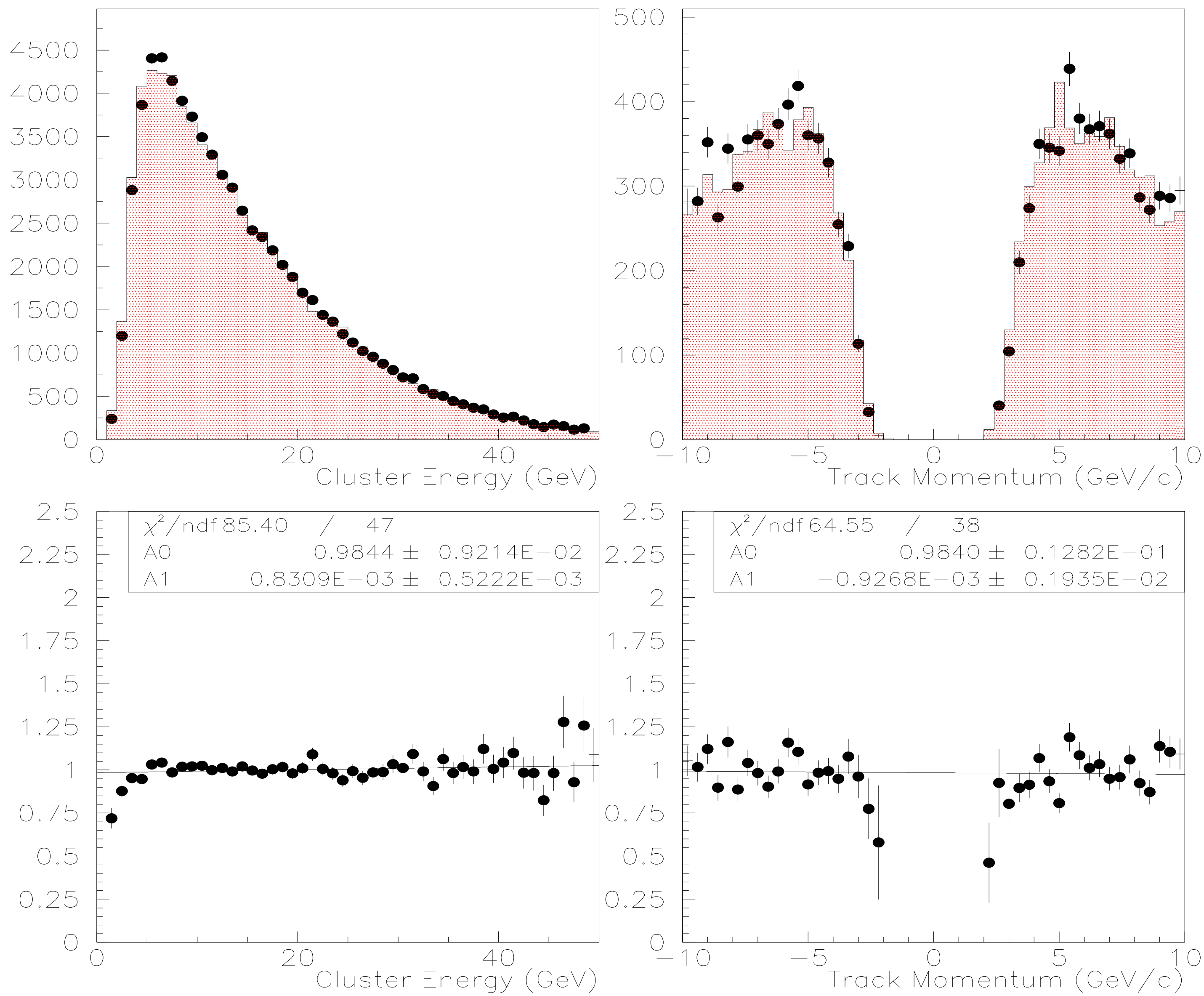
DC hits in X, normalization mode (Data vs. MC)



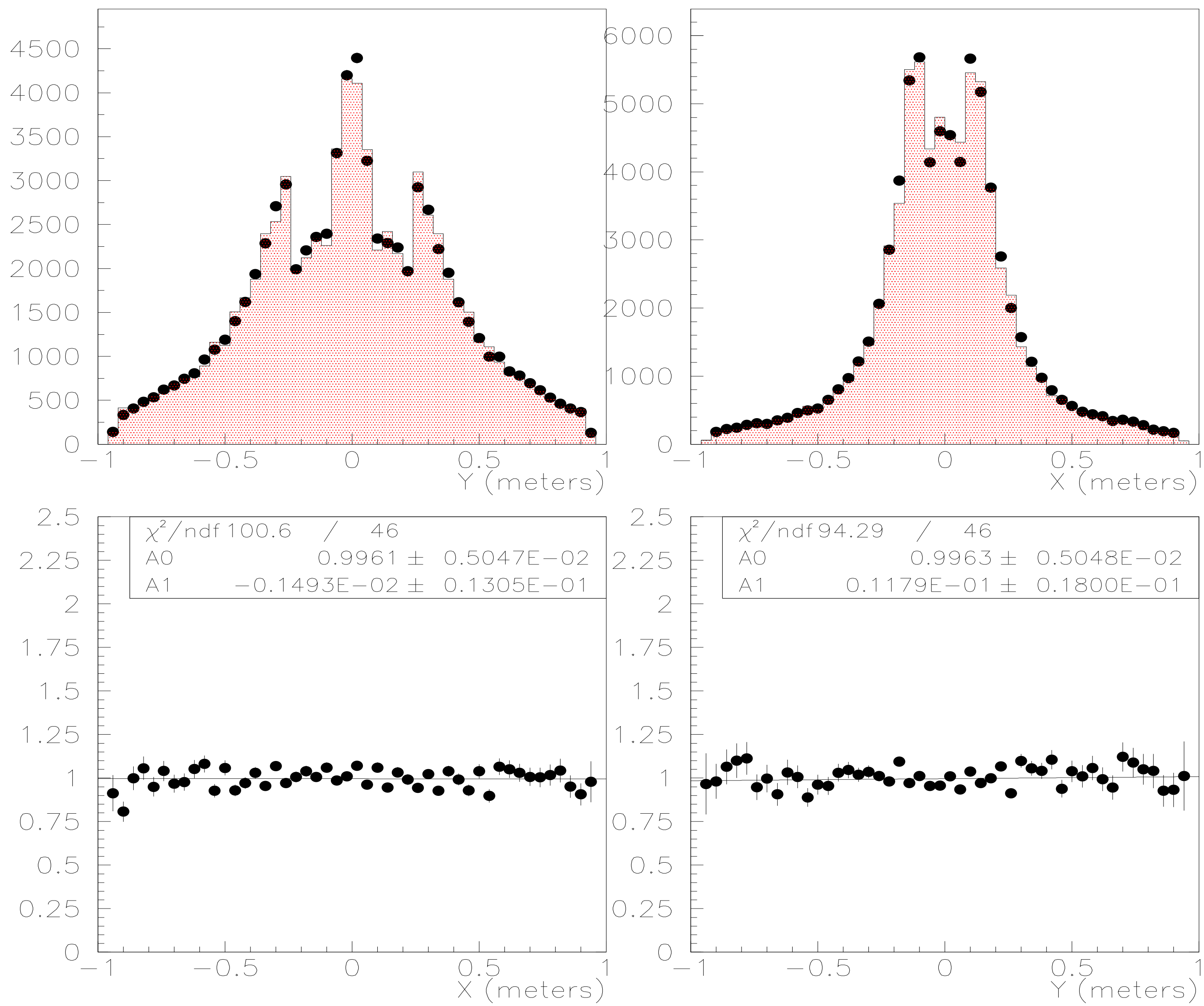
DC hits in Y, Normalization Mode (Data vs. MC)



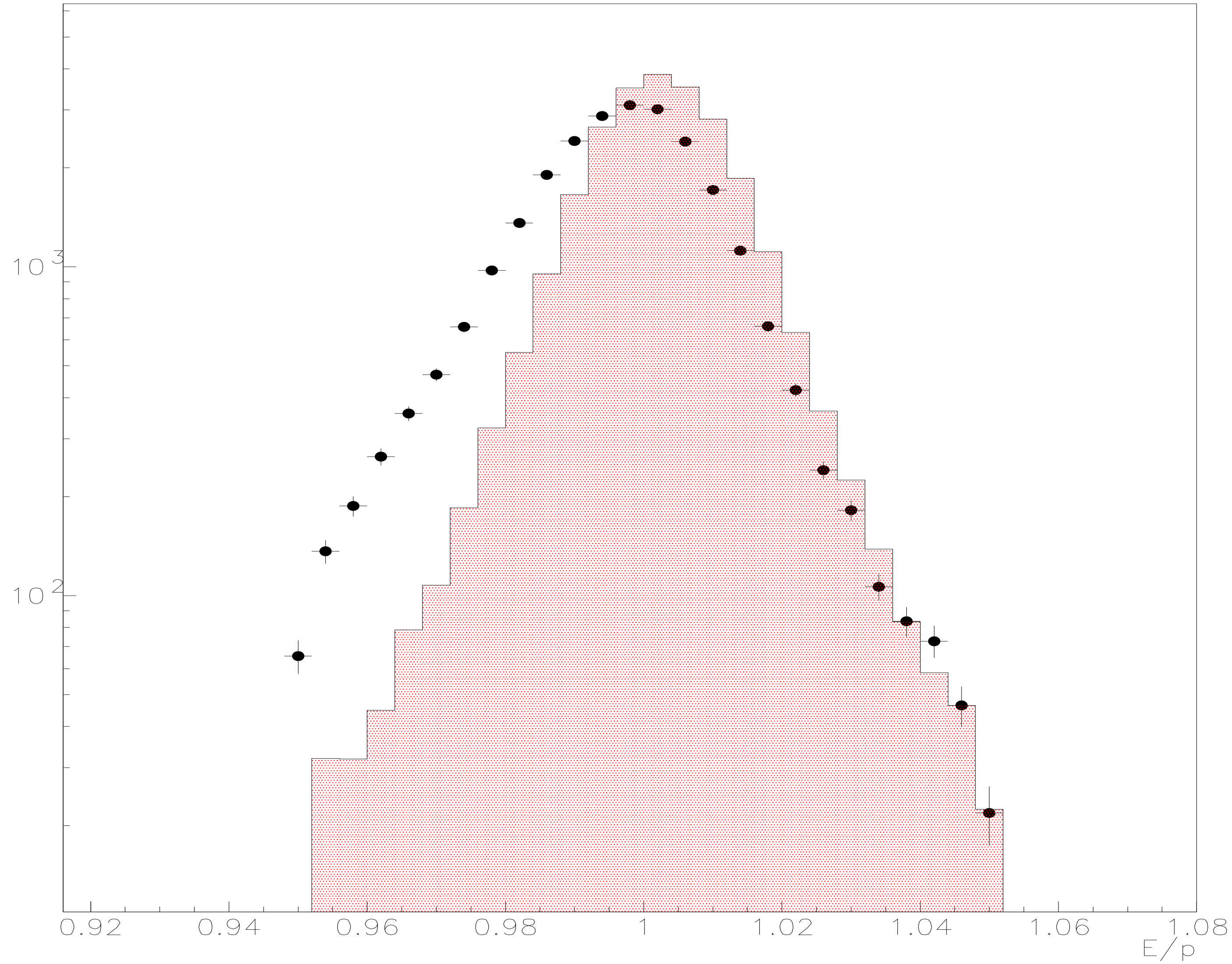
Cluster Energy & Track Momentum Comparisons



Cluster X and Y position comparisons



Track E/p Comparison



There is an obvious disagreement here, particularly in the low E/p tail.

$KL\to\pi^0\pi^0_D\gamma$ Selection: Initial Cuts

The following basic cuts are applied to all events in order to eliminate $3\pi^0_D$ background in the signal box.

--No cluster centered within 2cm of a beam hole;
--Total CSI energy > 25 GeV;
--No other 'good' set of photon pairings;
    i.e. none that give
        $|M_{ee\gamma} - M_{\pi^0}| < 0.10$ GeV/c^2
        $|M_{\gamma\gamma} - M_{\pi^0}| < 0.10$ GeV/c^2
        and PP0KINE > 0.0;
--Vertex $\chi^2 < 7.0$;
--90m < VTXZ < 150m;
--Less than 100 MeV in RC6, 7, 9, and 10;
--Less than 250 MeV in RC8;
-- $|M_{ee\gamma} - M_{\pi^0}| < 2$ MeV/c^2;
-- $|M_{\gamma\gamma} - M_{\pi^0}| < 2$ MeV/c^2;

KL->$\pi^0\pi^0_D\gamma$ Selection Cuts, Continued.

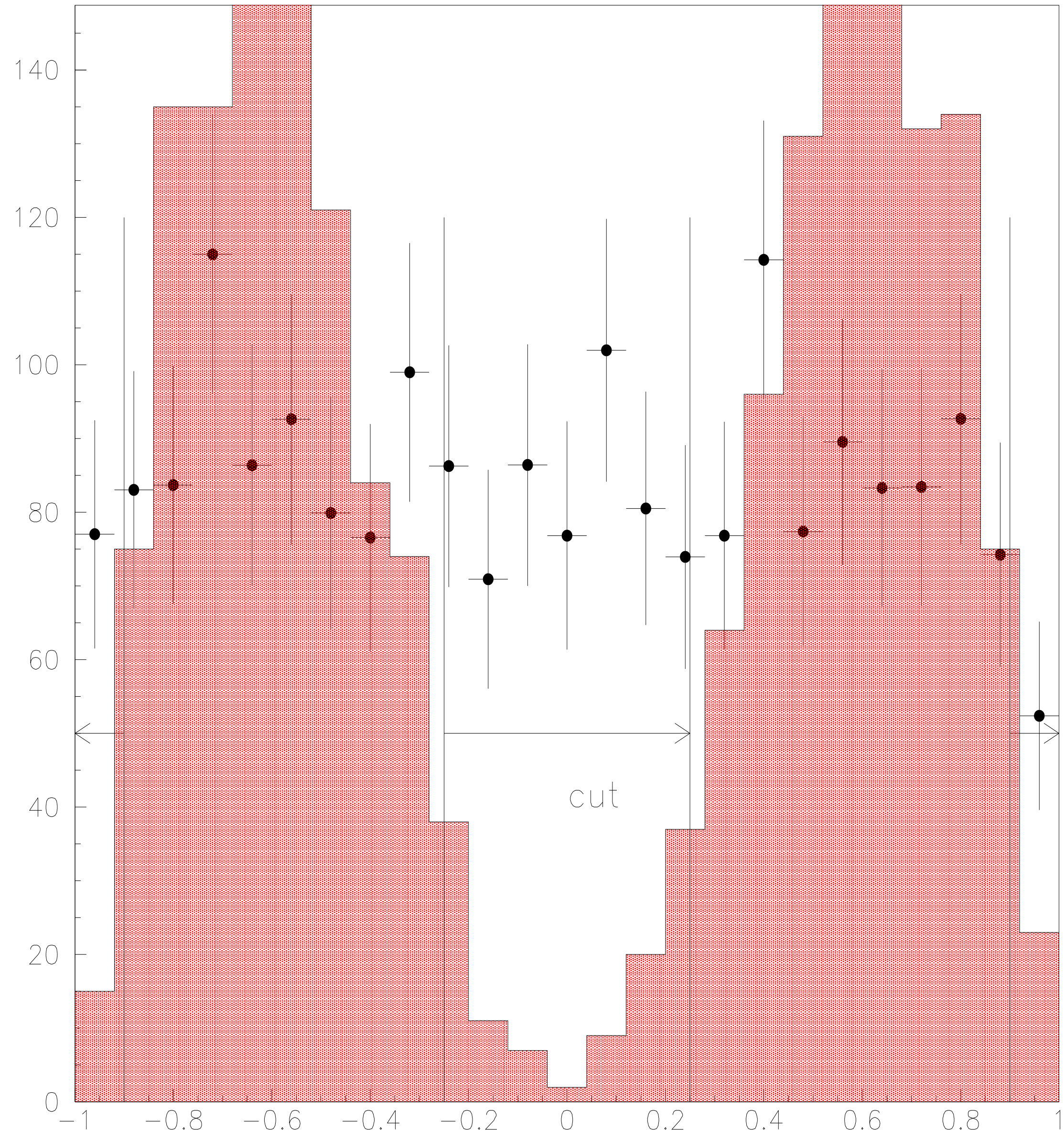
-- Fusion $\chi^2 < 4.0$;
--PP0KINE < -0.02;
-- 0.3 GeV/c^2 < $m_{\pi\pi}$ < 0.45 GeV/c^2
(signal expected in this region)
--π^0-γ angle cut (described below)
--Overlapping clusters cut (described below)

π^0-γ Angular Distribution Cut

If we define α, the angle between a randomly chosen π^0 and the direct emission photon in the $\pi^0\pi^0$ rest frame, it is flat for $3\pi^0$ and peaked for $2\pi^0\gamma$.

We can select for signal by cutting the 'flat' region, outside $0.25 < |\cos(\alpha)| < 0.9$

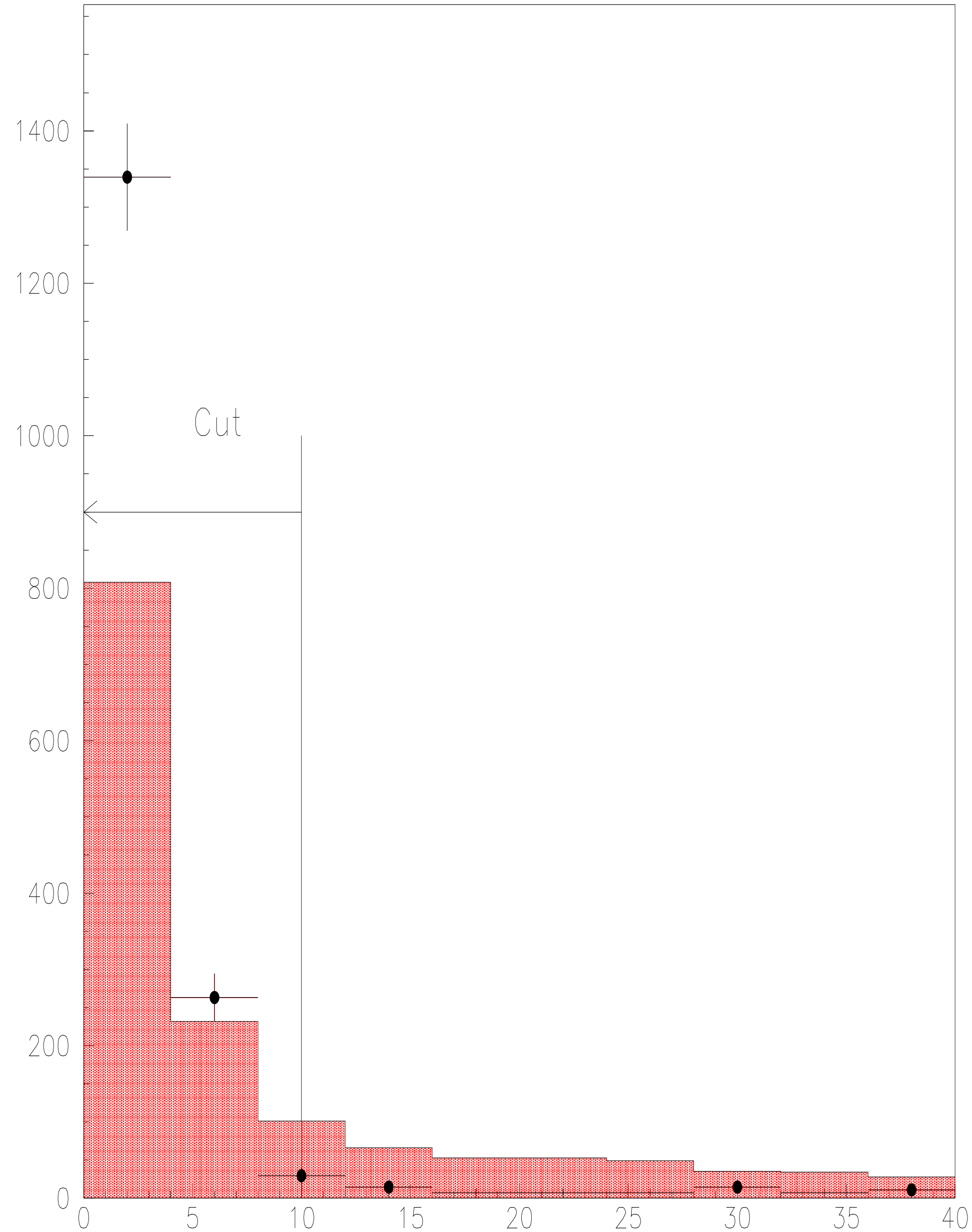
(Dots are $3\pi^0$, histogram is $2\pi^0\gamma$).



Overlapping Cluster Cut

We assume that some fraction of a photon cluster's energy (up to 50%) was deposited by another, overlapping photon and form the seven-body final state.

We do this for each photon cluster using the combined vertex routine; if any combination gives $\chi^2_{over} < 10.0$, cut the event.

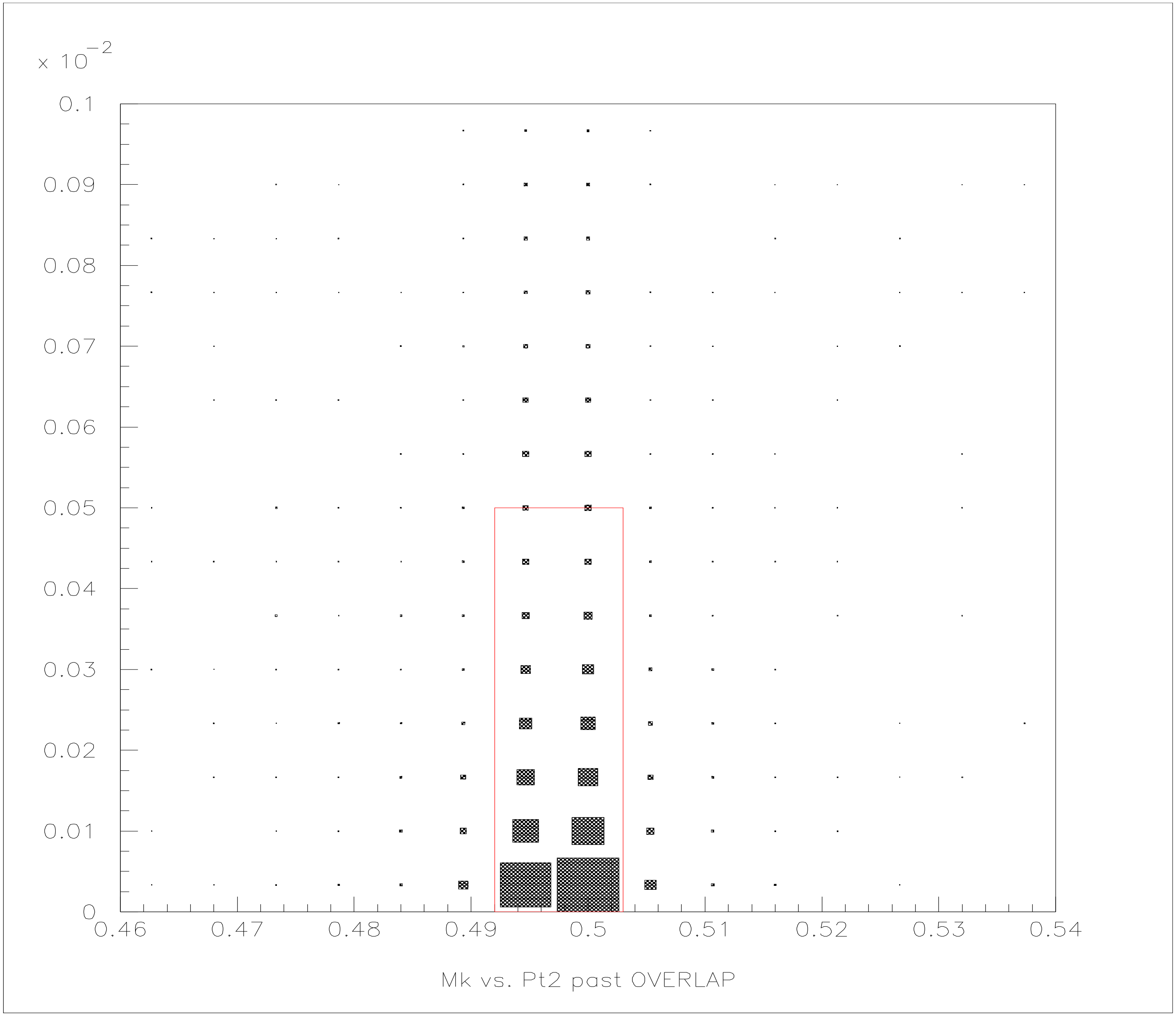


Results: Single Event Sensitivity vs. Background Level

Cut	Single Event Sensitivity $*10^{-8}$	Background Level
START	2.92	45846
Cluster near beam hole	3.03	43907
ERAWCS	3.04	41242
Mispairing	3.34	39156
Vertex χ^2	3.87	12199
VTXZ	4.3	8980
Photon Vetoes	4.3	8980
Meeg	4.68	7588
Mgg	4.7	7468
VTXCSI	4.7	7438
Fusion χ^2	5.4	1103
Normalization Mode	5.4	1103
PP0KINE	5.52	1039
Mpp	5.98	727
Angle	6.28	514
Overlapping Clusters	12.7	50

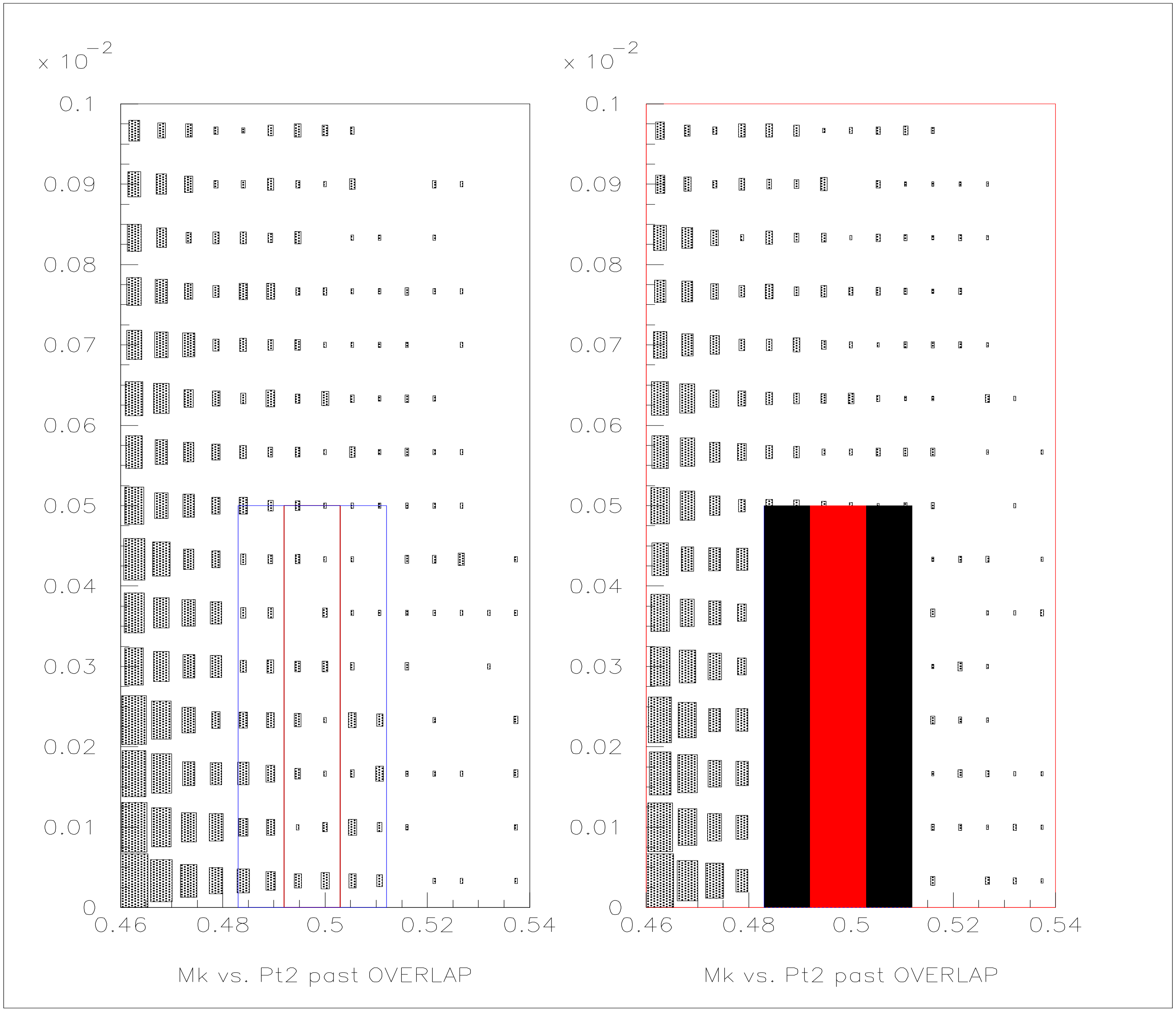
More cuts are currently being studied...

$M_{ee\gamma\gamma\gamma\gamma}$ vs. p_t^2; Signal $2\pi^0{}_D\gamma$ MC After Cuts

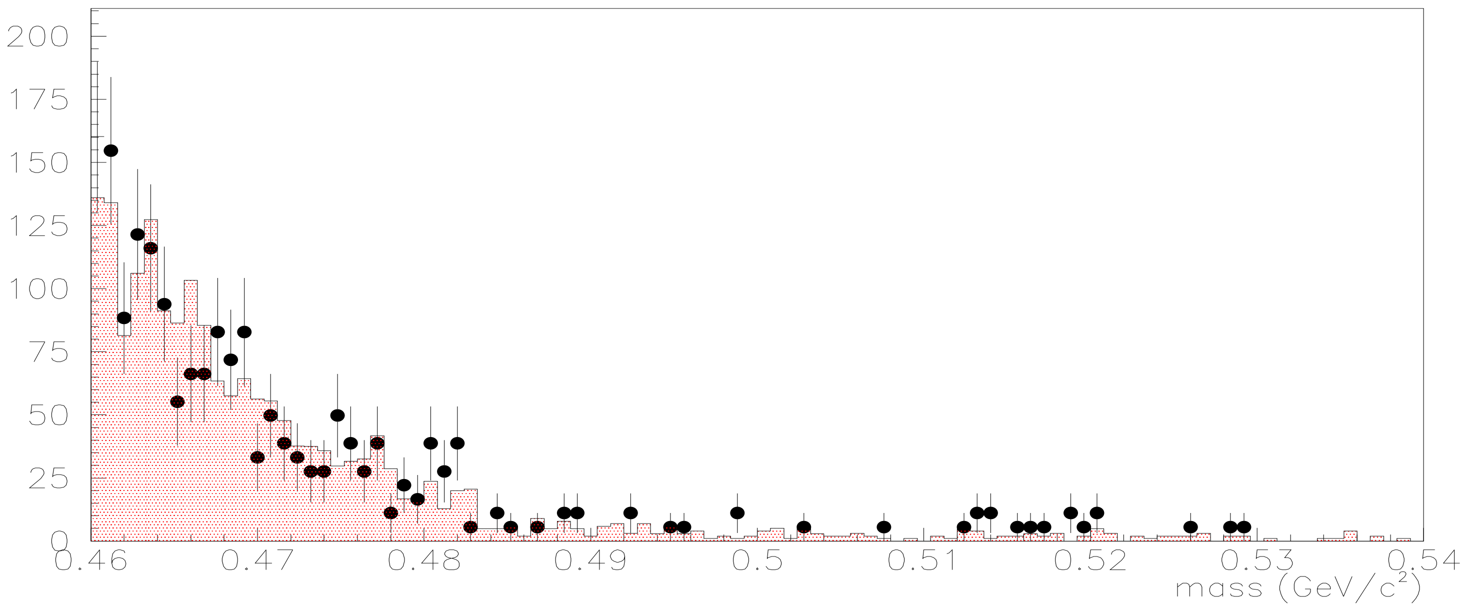


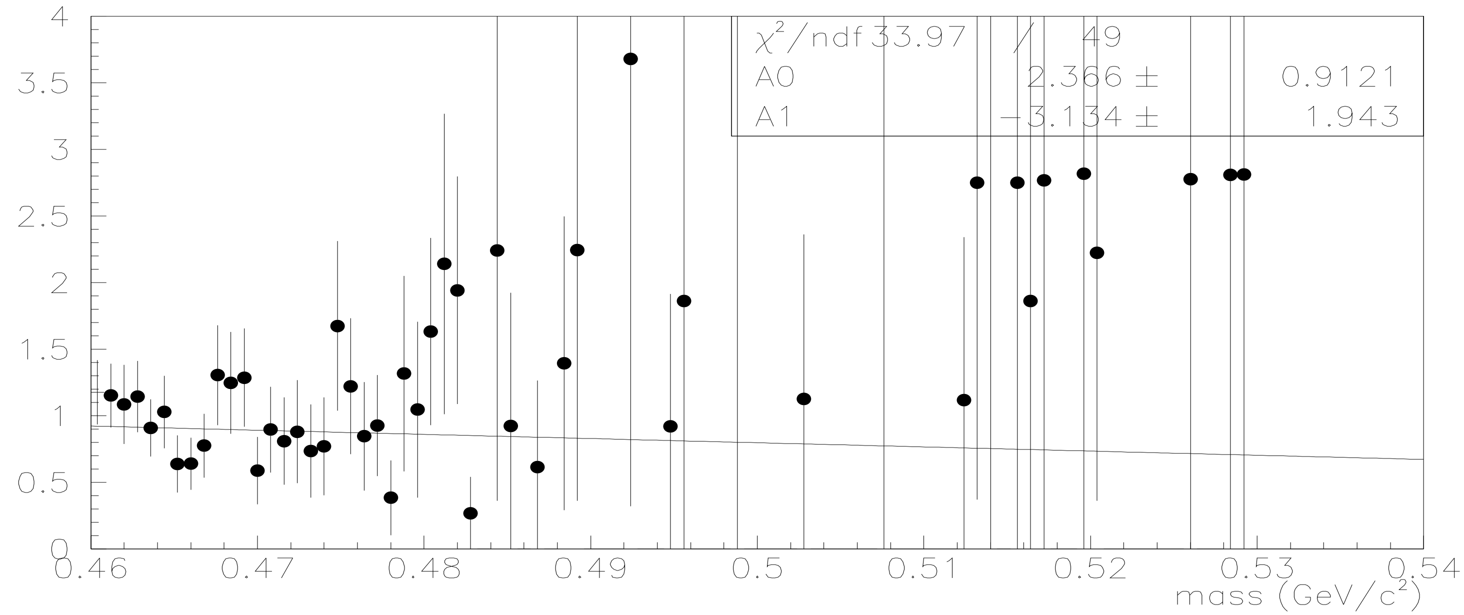
$M_{ee\gamma\gamma\gamma\gamma}$ vs. p_t^2; Data vs. Background $3\pi^0_D$ MC After Cuts

MC | Data

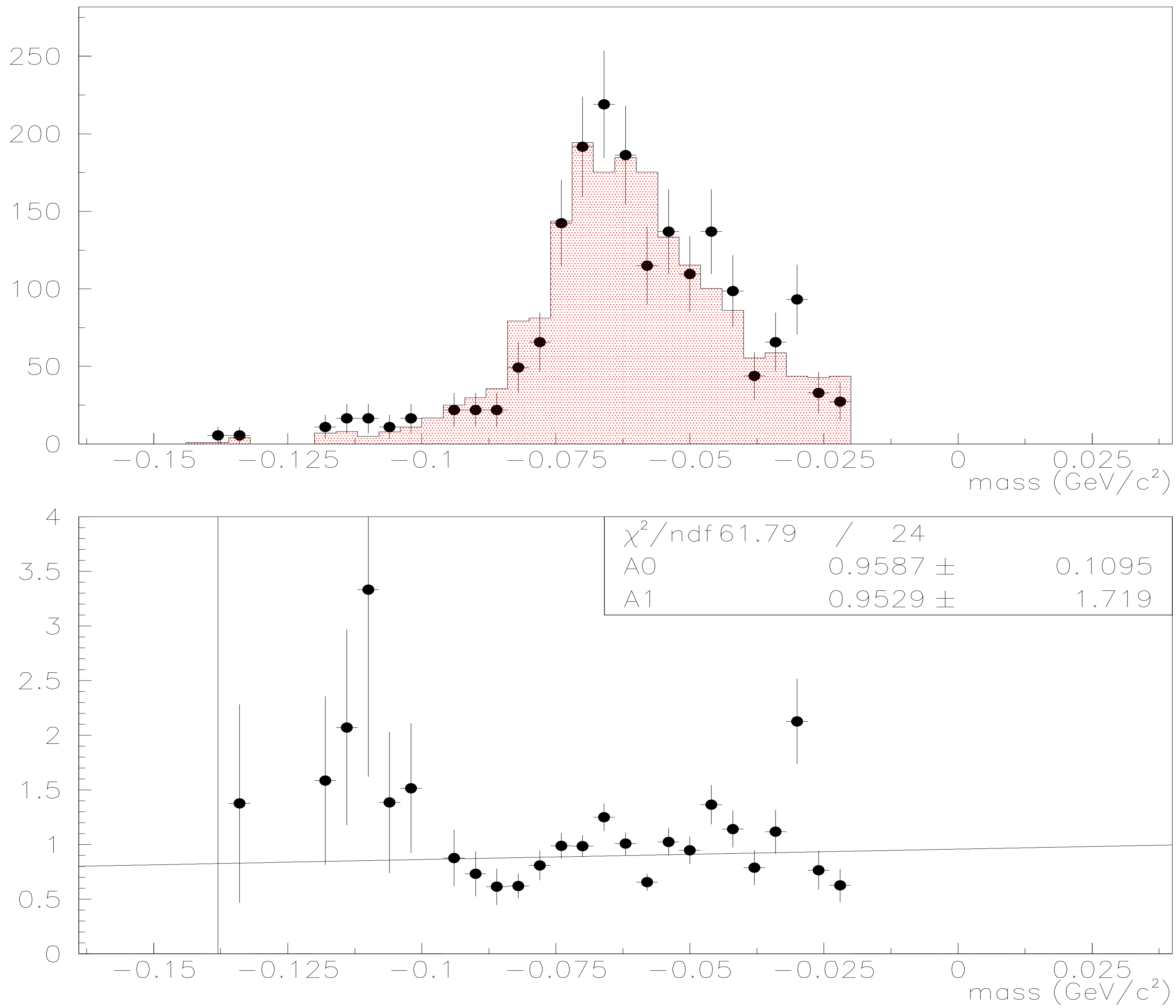


$M_{ee\gamma\gamma\gamma\gamma}$ Data vs. $3\pi^0_D$ MC After Cuts (outside box)

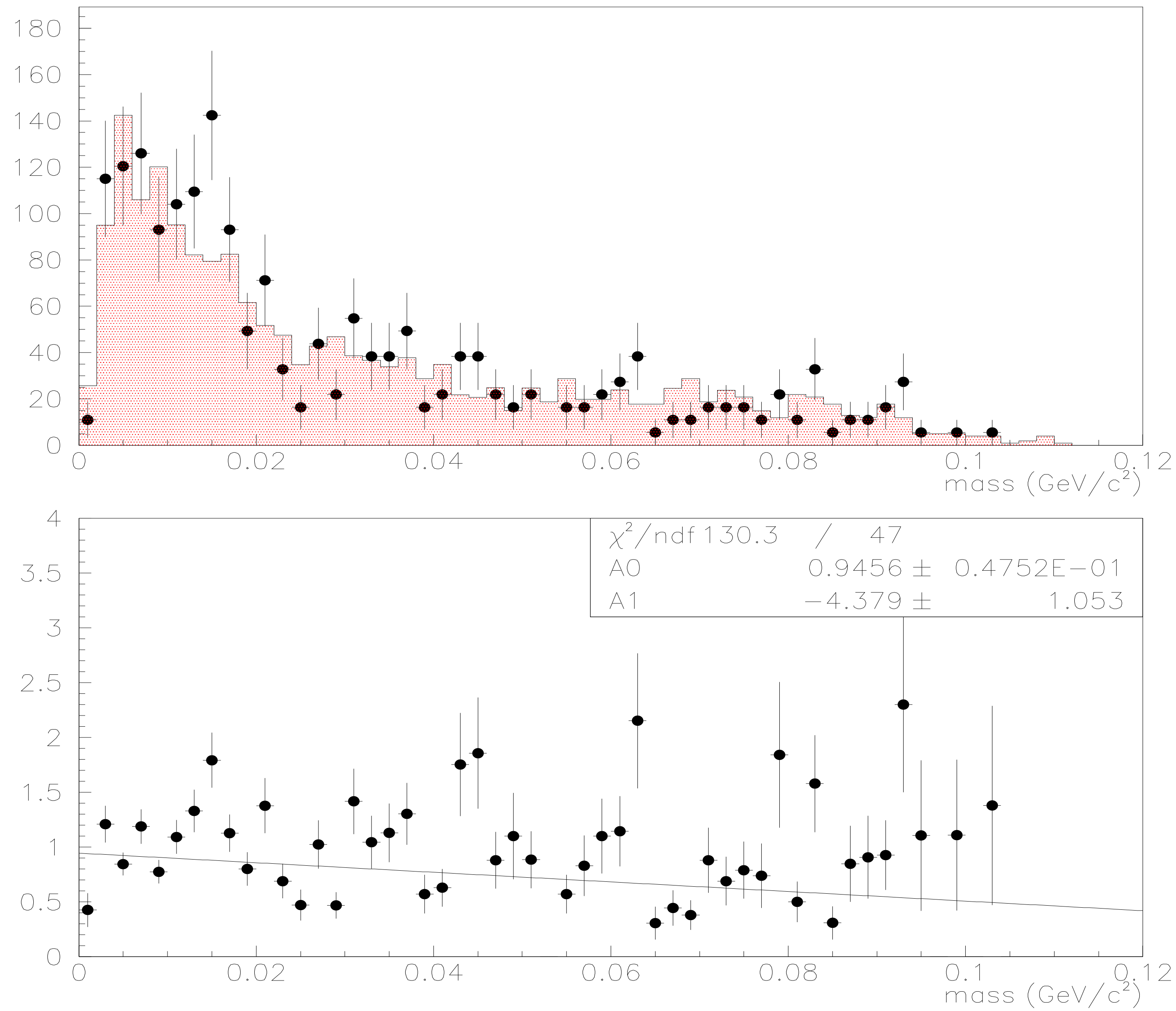




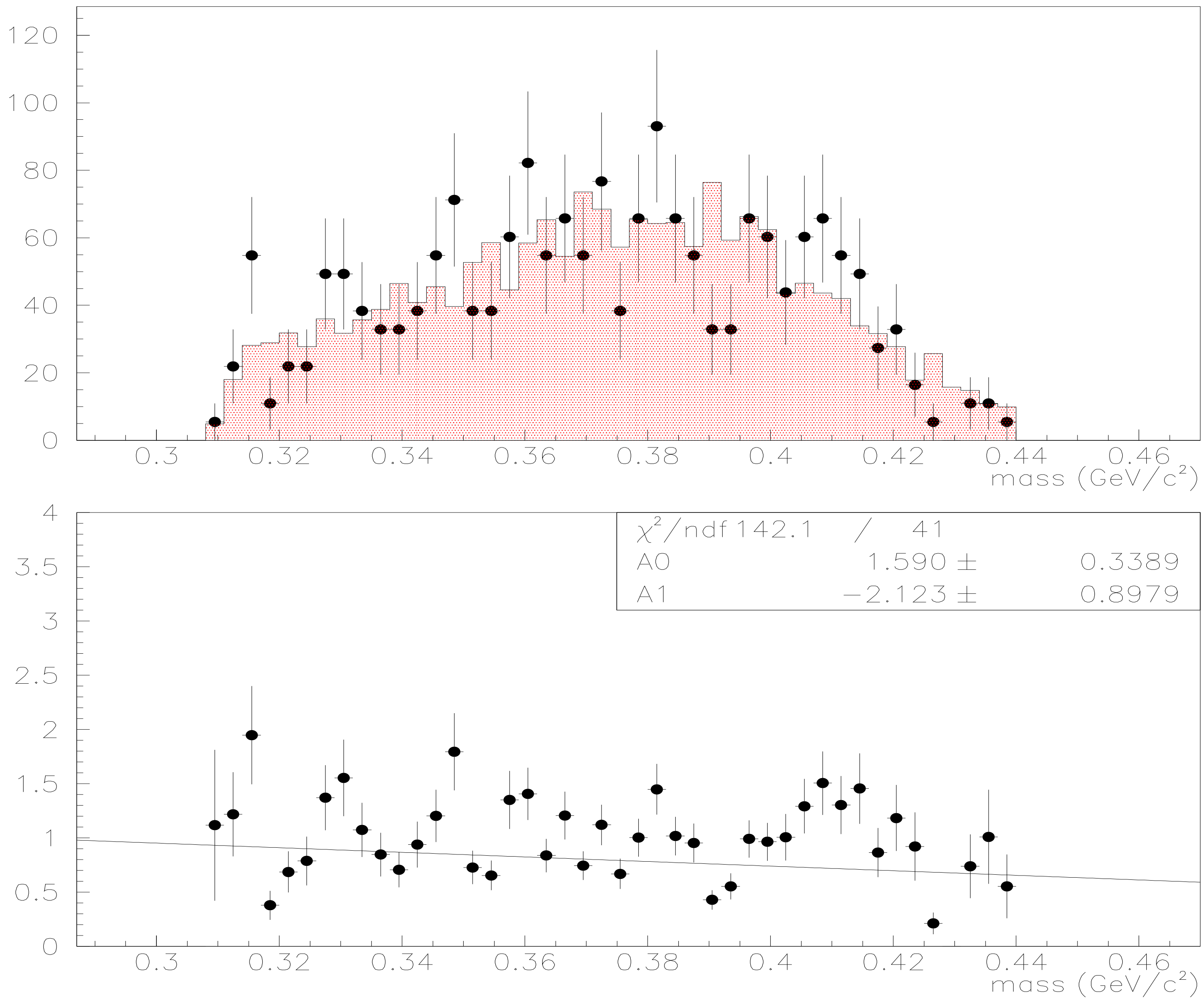
PP0KINE; Data vs. $3\pi^0_D$ MC After Cuts (outside box)



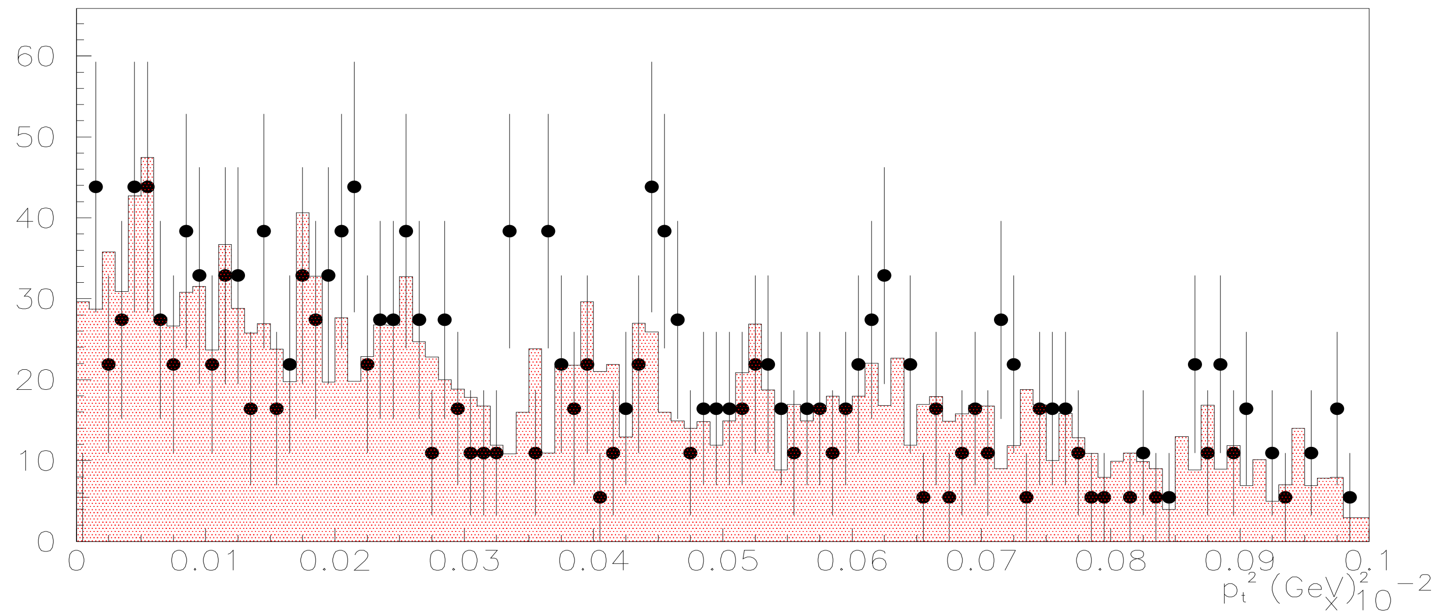
m_{ee}; Data vs. $3\pi^0_D$ MC After Cuts (outside box)

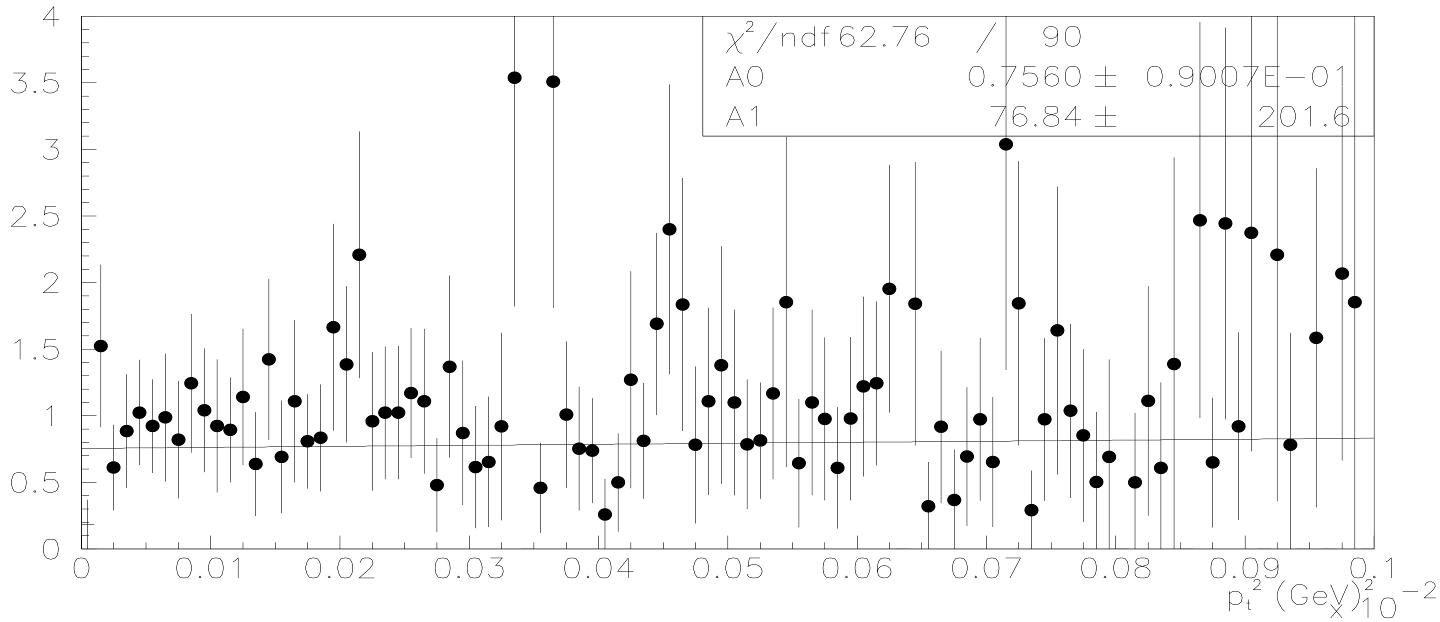


$m_{\pi\pi}$; Data vs. $3\pi^0_D$ MC After Cuts (outside box)



$p_t^{\,2}$; Data vs. $3\pi^0_D$ MC After Cuts (outside box)





Summary & Future Work

--Currently at $1.27*10^{-7}$ SES, 50 events in box

--More work needed to eliminate remaining $3\pi^0_D$ background, other two track backgrounds (eg $2\pi^0_D$ w/accidental)

--Switch to KTEVMC v6_03
- --better treatment of particle scattering
- --may eliminate E/p disagreement
- --not yet configured for 799

--Extend work to 1999 data