FastMC calculations of signal and background

1. Flux assumptions
2. Detection methods
3. Background mechanisms
4. Background from K_L^0 decays
5. Background not from K_L^0 decays
6. Signal losses aside from analysis cuts
7. Outstanding issues

Flux assumptions

Item	FastMC	Taskforce
production angle	$42.5°$	$42.5°$
aspect ratio	100×5 mrad^2	100×4 mrad^2
proton beam energy	25.5GeV	25.5GeV
protons/spill	70TP	100TP
microbunch frequency	25MHz	25MHz
interspill length	2.3s	2.3s
spill length	2.4s	?
average number of K_L^0/μbunch exitting spoiler	3.57	?
Hours of running	12000	?
"1 K_L^0 per microbunch"	0.646	?

Detection methods

1. 2γPR/CAL : both γ convert in CAL, energy in PR & CAL
2. 2γPR/CAL+OV : both γ convert in CAL, energy in PR,CAL & OV (includes 1.)
3. 1γPR/1γCAL : 1 γ converts in PR, 1 in CAL, energy in PR& CAL
4. 1γPR/1γOV : 1 γ converts in PR, 1 in OV, energy in PR& OV
5. 1γPR/1γBV : 1 γ converts in PR, 1 in BV, energy in PR& BV

Vast majority of results shown here are detection method 1.

Background mechanisms

Each K_L^0 decay mode is considered under the following mechanisms that can produce non-signal $K_L^0 \to \pi^0 \nu \bar{\nu}$ candidates.

1. "standard" : K_L^0 decays within microbunch
2. interbunch : K_L^0 decays from interbunch K_L^0 production
3. wrap-around : K_L^0 from previous microbunch
4. accidental photons : K_L^0 decay products combined with "fake" photons from stopped muon decays or neutron-induced showers
5. merged photons : π^0 candidates from γ pairs that are too close to resolve spatially and temporally

"Fake" photon samples generated with GEANT3 and inserted into FastMC.

Merge criteria : $|\vec{x_1} - \vec{x_2}| < 5R_M$, $R_M = 5.98$ cm, $|\Delta T_{\gamma\gamma}| < 15ns$ (CAL APD double-pulse resolution)

K^0_L decay modes considered as background sources

- $\pi^0\pi^0$
- $\pi^+\pi^-\pi^0$
- $\pi^\pm e^\mp \nu\gamma$
- $\pi^0\pi^0\pi^0$
- $\pi^0\gamma\gamma$
- $\pi^0\pi^\pm e^\mp \nu$
- $\gamma\gamma$
- $K^0_L \rightarrow \gamma e^+ e^-$

Arguments and/or calculation of negligible rates from other K^0_L decays exist.

Event selection criteria - Techniques used so far

1. "By hand" (Current best overall performance) :
   - 2γPR/CAL: AK, MZ, AvdS, DJ
   - 1γPR/CAL: AK
   - 1γPR/BV : CS
2. Neural networks (NN) : 2γPR/CAL : DV, JM
3. Likelihood method (LM) : 1γPR/CAL : AS

NN approach has been shown to achieve better (comparable) $\pi^0\pi^0$ background rejection than "by hand" cuts at high (moderate) acceptance. Problem: Suppressing multiple backgrounds with NN. Current solution is to apply NN($\pi^0\pi^0$) as "setup" cut before training NN($\pi^+\pi^-\pi^0$). Iterative procedure looks promising. Advantage: NN($\pi^0\pi^0$) and NN($\pi^+\pi^-\pi^0$) can have different variables as input.

LM also suffers from problem of suppressing multiple backgrounds. In addition, correlations between more than 2 variables are difficult to take into account.

Event selection criteria

For 2γPR/CAL detection mode, I will show results from 13 different cut sets.

1. MZ : Mike's cuts
2. AKprebasic, AKbasic, AKlominal, AKtight, AKtightest : Developed by AK and FM
3. DJ/AvdS : Andries's T^{*2} vs $ln(E_{\rm miss})$ contour cut with my modifications
4. NN-01, NN-02, NN-03, NN-04, NN-05, NN-06 : $\pi^0\pi^0$ Neural network developed by DV, JM

First two sets optimized for different PV, CV assumptions.

NN cuts have large $\pi^+\pi^-\pi^0$ background.

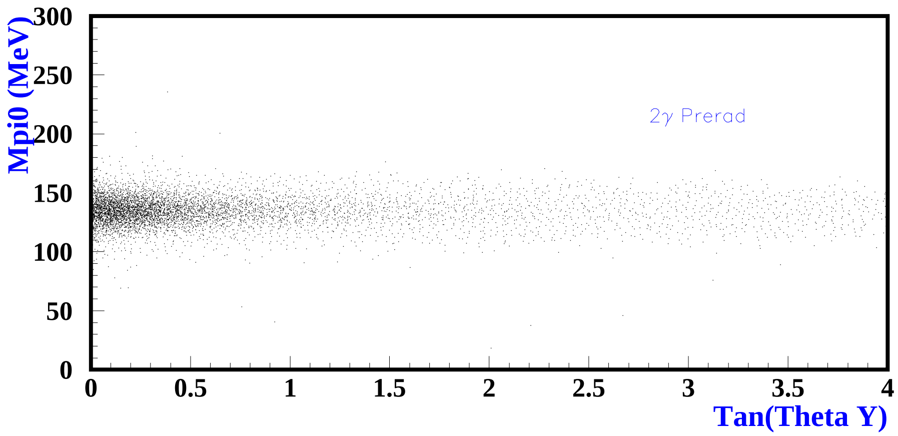
We currently don't have optimal S/B vs S over a range of cuts.

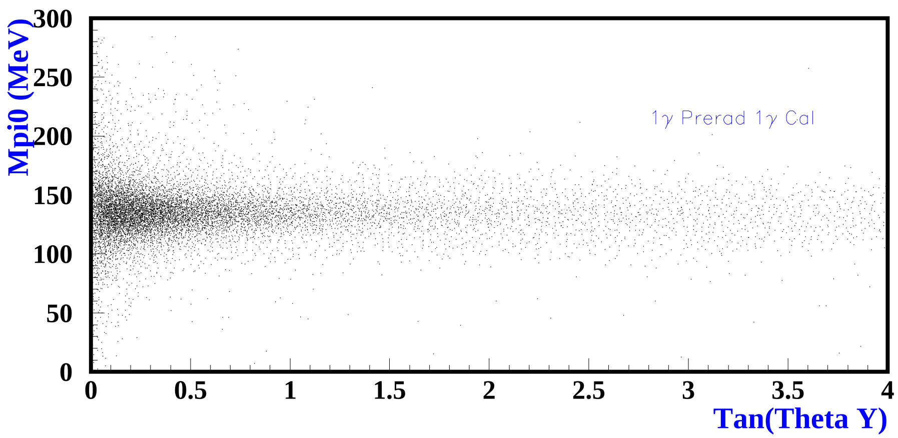
1γPR/BV and 1γPR/OV detection modes, standard

Det. method	$\pi^0\pi^0$	$\pi^\pm e^\mp \nu\gamma$	$\pi^+\pi^-\pi^0$
1γPR/BV	22.00± 2.86	18.29± 1.27	3.71 ± 0.43
1γPR/OV	7.7 ± 1.33	11.5± 0.78	1.1 ± 0.20

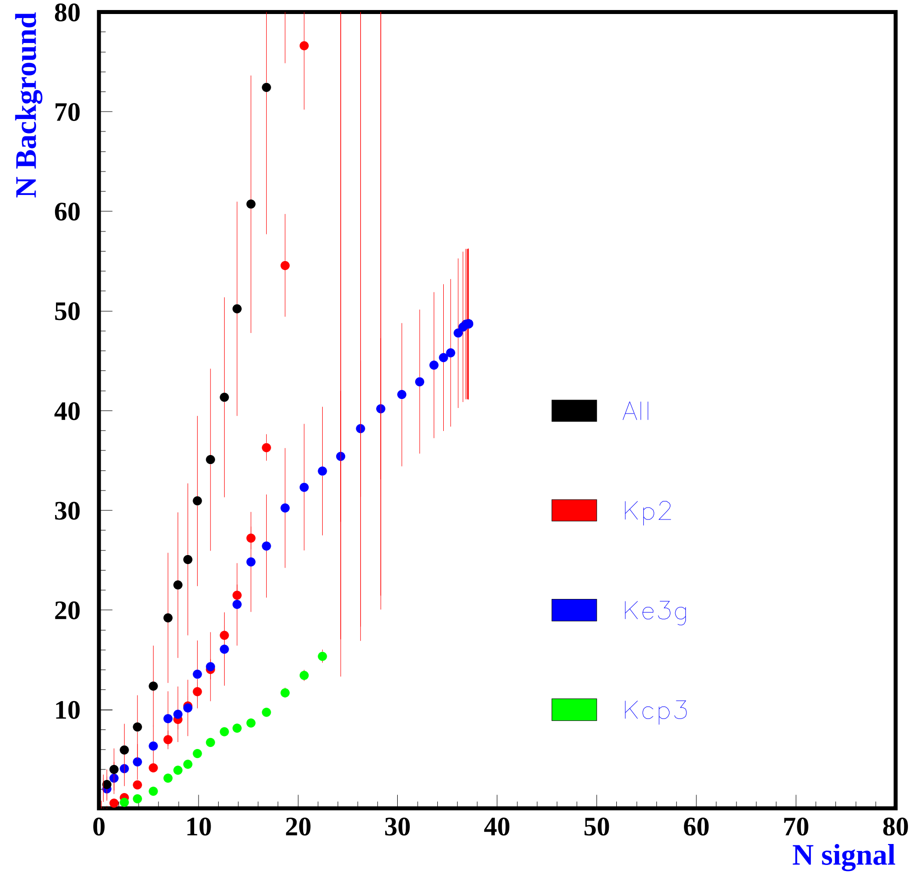
Det. method	$K_L^0 \to \pi^0\nu\bar{\nu}$	Total bkgd
1γPR/BV	53.4±	44.0 ± 3.16
1γPR/OV	30.0±	20.3 ± 1.55

1γPR/1γCAL detection mode, standard



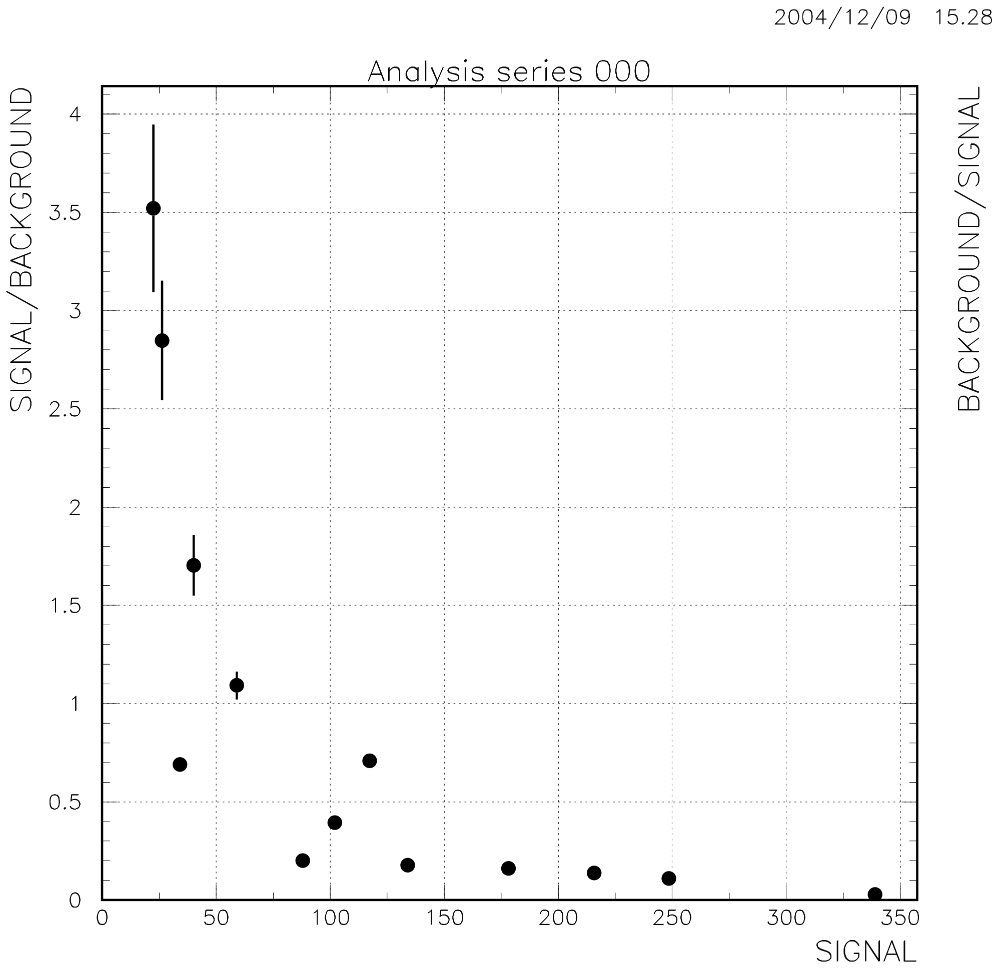


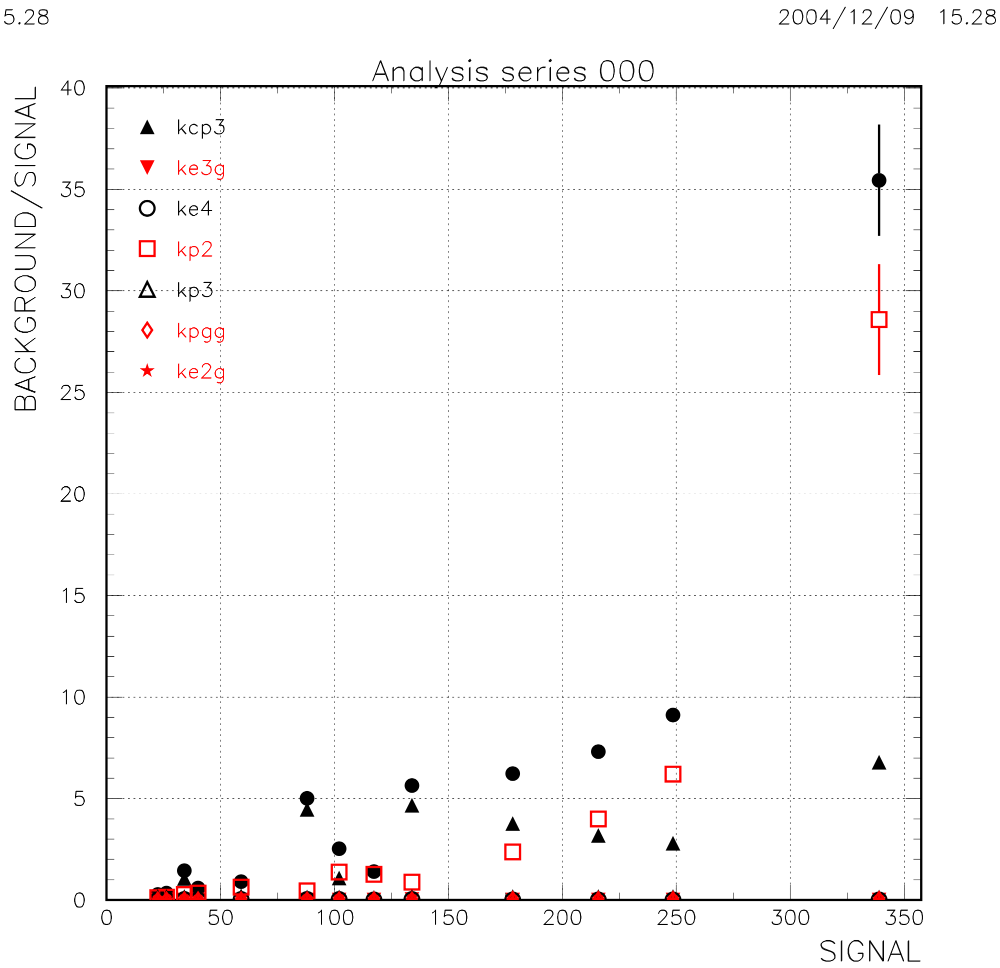
$M_{\gamma\gamma}$ vs $|\tan\theta_Y|$ of photon in PR



Background vs signal with $|\tan\theta_Y| > 0.25$

2γPR/CAL detection mode, standard

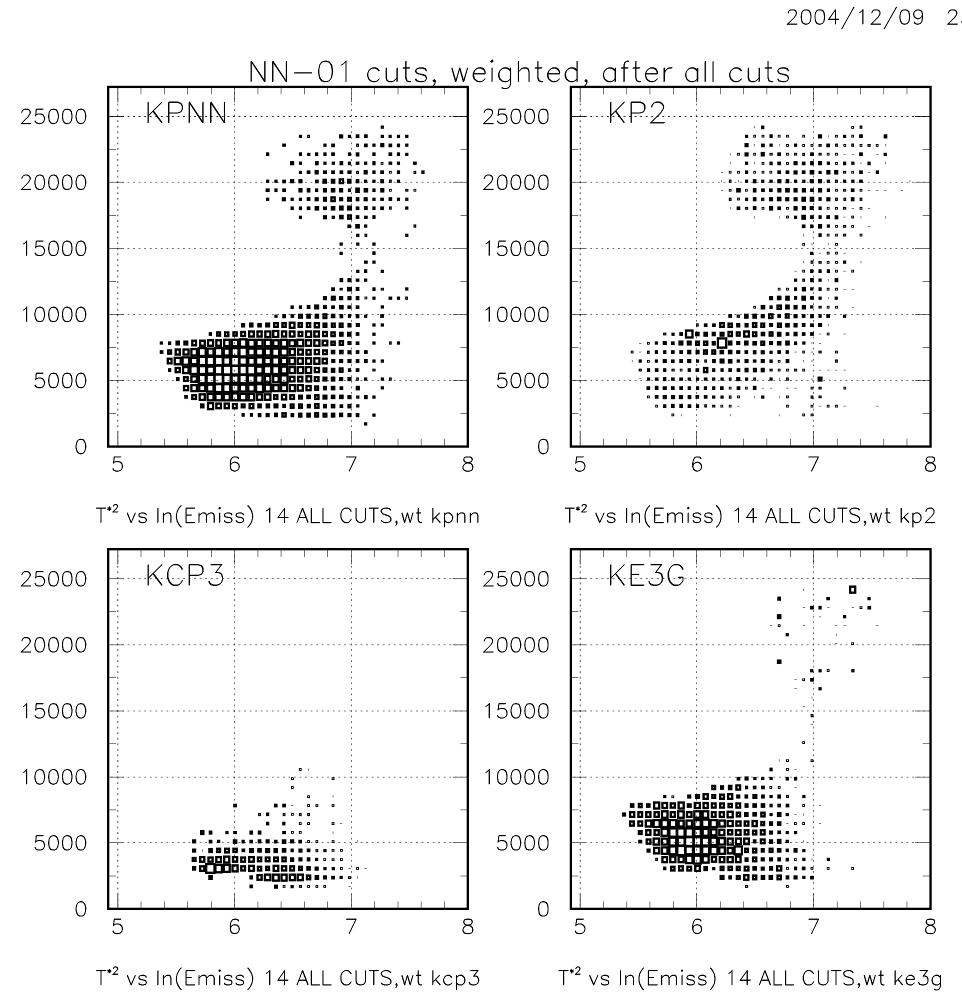




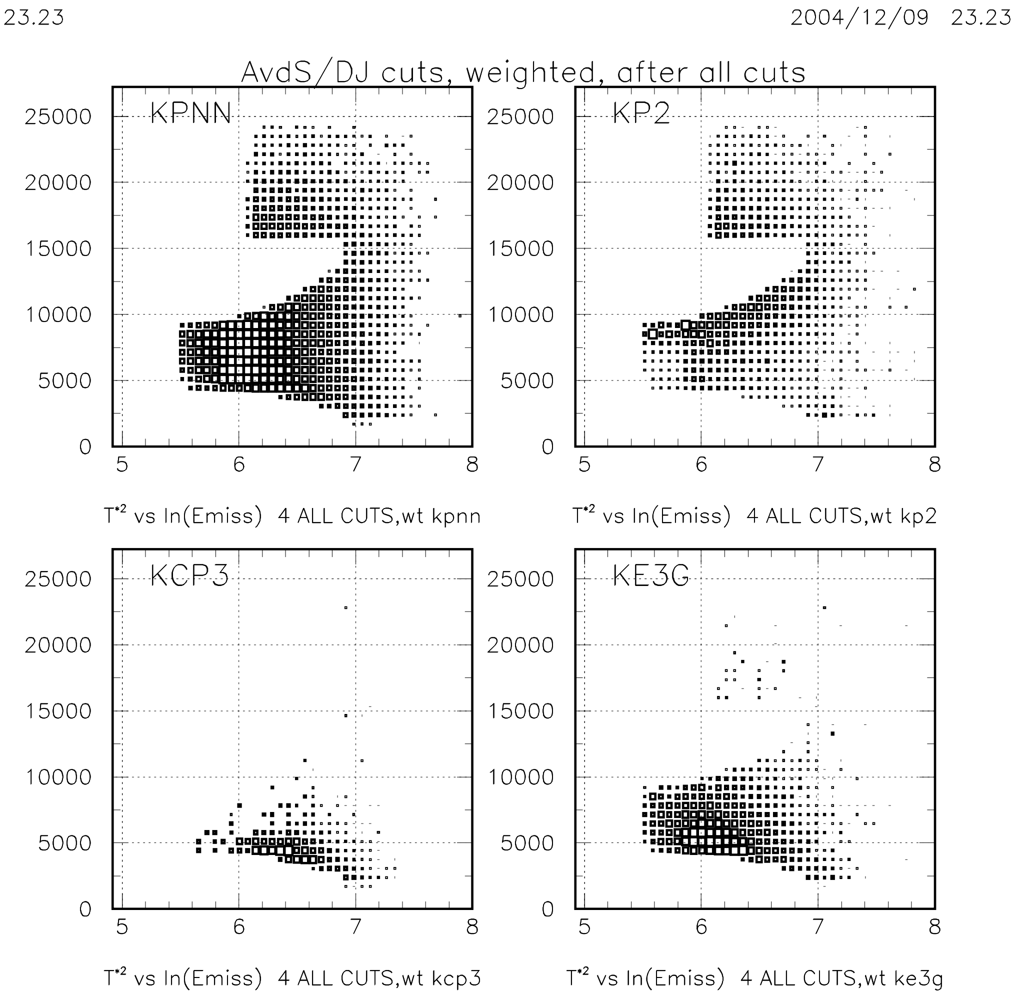
2γPR/CAL detection mode, standard

Cut name	Signal events	Background events	Signal/Bkgd
MZ	26.34$\pm$ 0.40	9.25$\pm$ 0.98	2.85$\pm$ 0.30
AvdS/DJ	117.27$\pm$ 0.82	165.63$\pm$ 5.15	0.71$\pm$ 0.02
AK prebasic	338.93$\pm$ 1.45	12013.00$\pm$ 925.64	0.03$\pm$ 0.00
AK basic	102.12$\pm$ 0.78	258.96$\pm$ 9.84	0.39$\pm$ 0.02
AK lominal	59.09$\pm$ 0.60	54.09$\pm$ 3.48	1.09$\pm$ 0.07
AK tight	40.12$\pm$ 0.49	23.55$\pm$ 2.10	1.70$\pm$ 0.15
AK tightest	22.36$\pm$ 0.37	6.35$\pm$ 0.76	3.52$\pm$ 0.43
NN-01	34.16$\pm$ 0.46	49.46$\pm$ 1.98	0.69$\pm$ 0.03
NN-02	88.04$\pm$ 0.72	440.61$\pm$ 5.40	0.20$\pm$ 0.00
NN-03	134.02$\pm$ 0.89	754.92$\pm$ 8.14	0.18$\pm$ 0.00
NN-04	178.09$\pm$ 1.03	1109.90$\pm$ 38.18	0.16$\pm$ 0.01
NN-05	215.69$\pm$ 1.14	1574.10$\pm$ 64.64	0.14$\pm$ 0.01
NN-06	248.50$\pm$ 1.22	2263.60$\pm$ 89.34	0.11$\pm$ 0.00

2γPR/CAL detection mode, standard

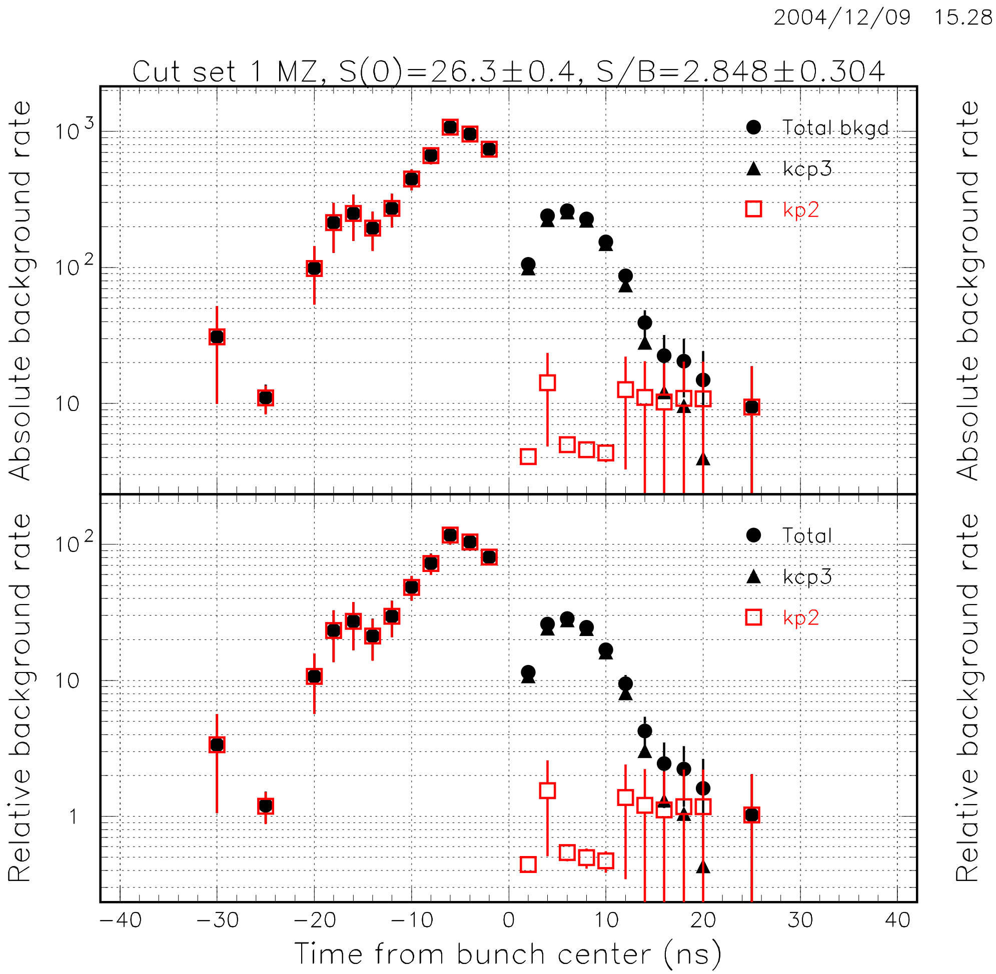


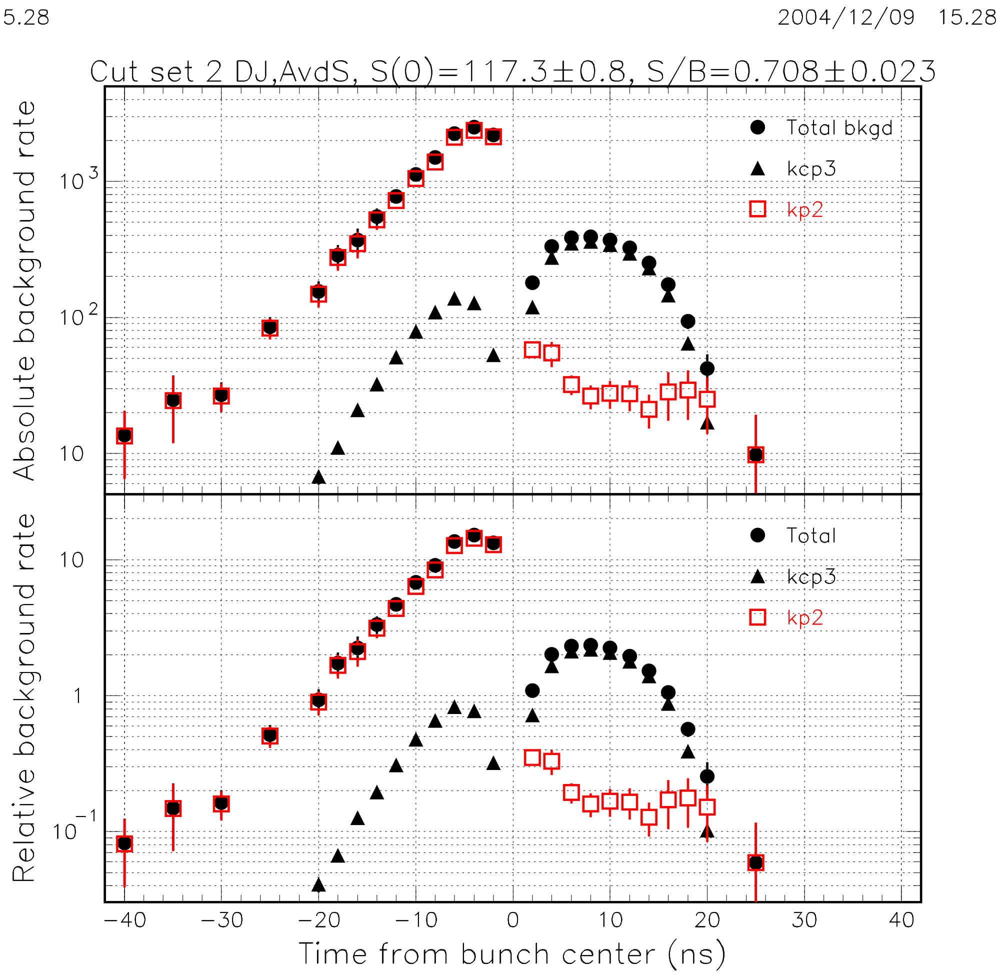
NN-01 cuts, T^* vs $ln(E_{\mathrm{miss}})$



AvdS/DJ cuts, T^* vs $ln(E_{\mathrm{miss}})$

2γPR/CAL detection mode, interbunch rates

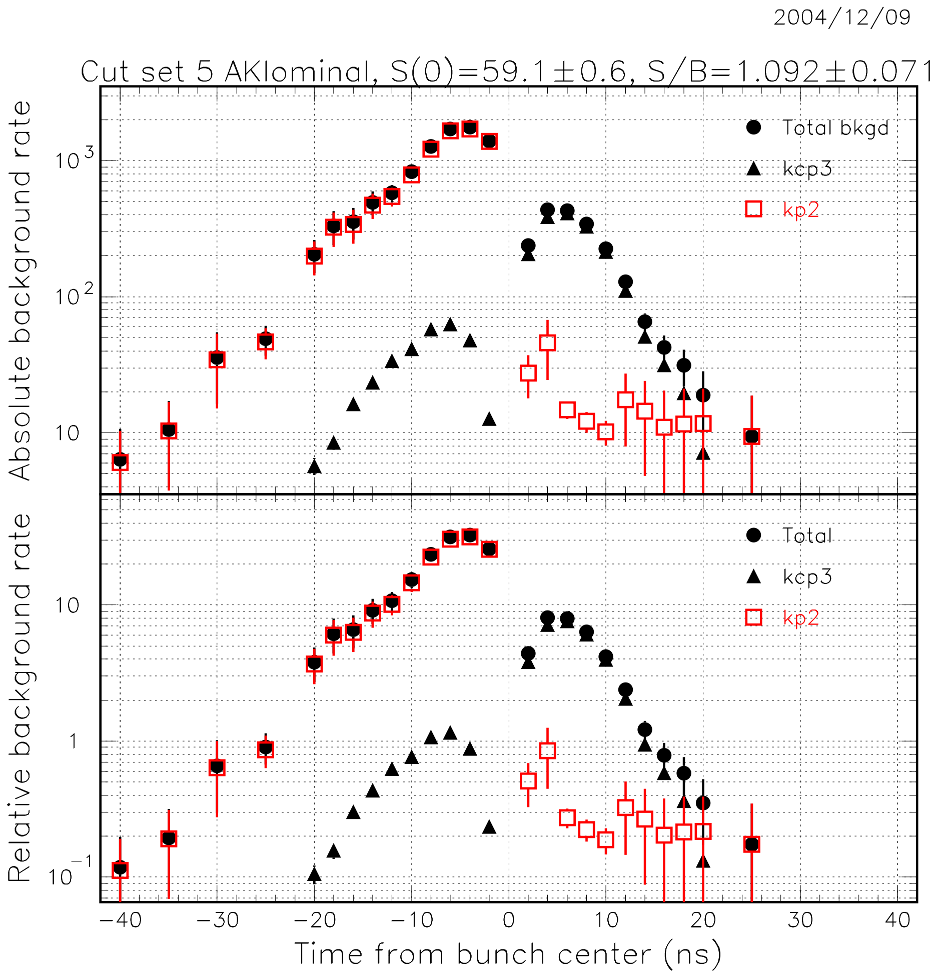




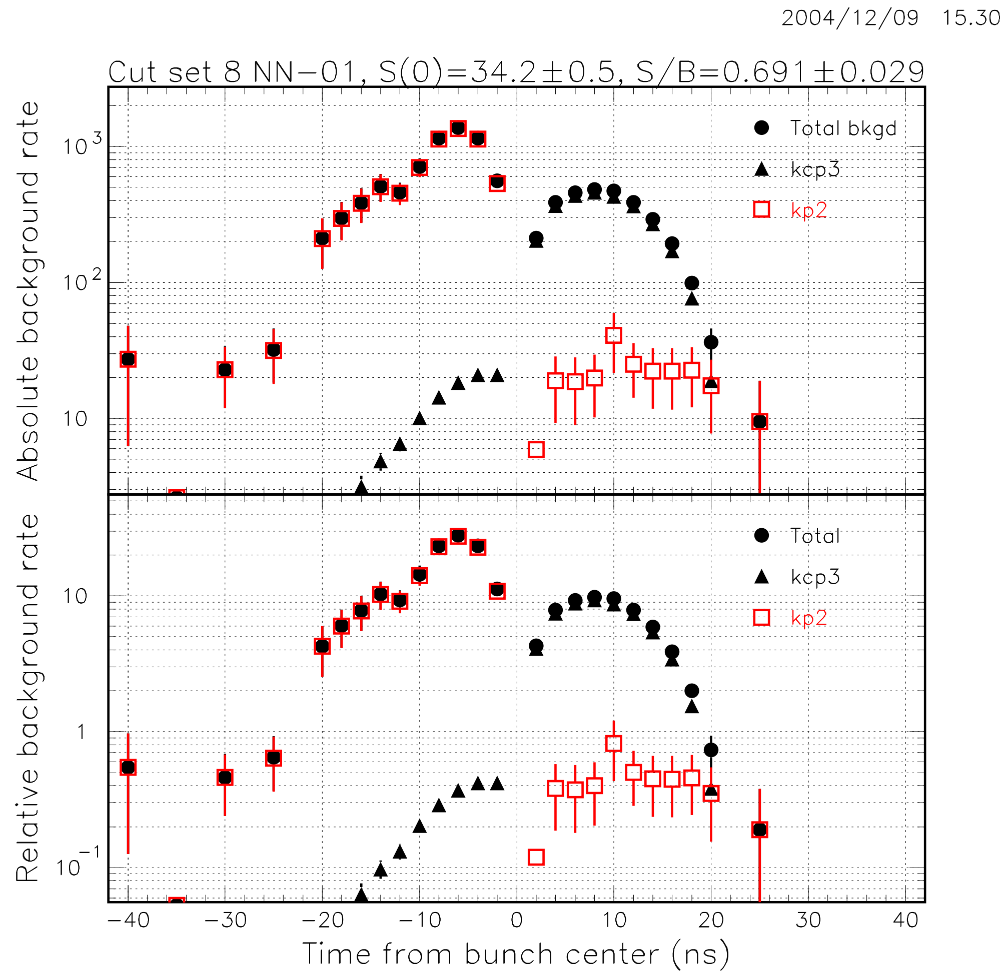
MZ cuts (includes a “wrap-around” cut)

DJ/AvdS cuts (no “wrap-around” cut)

2γPR/CAL detection mode, interbunch rates

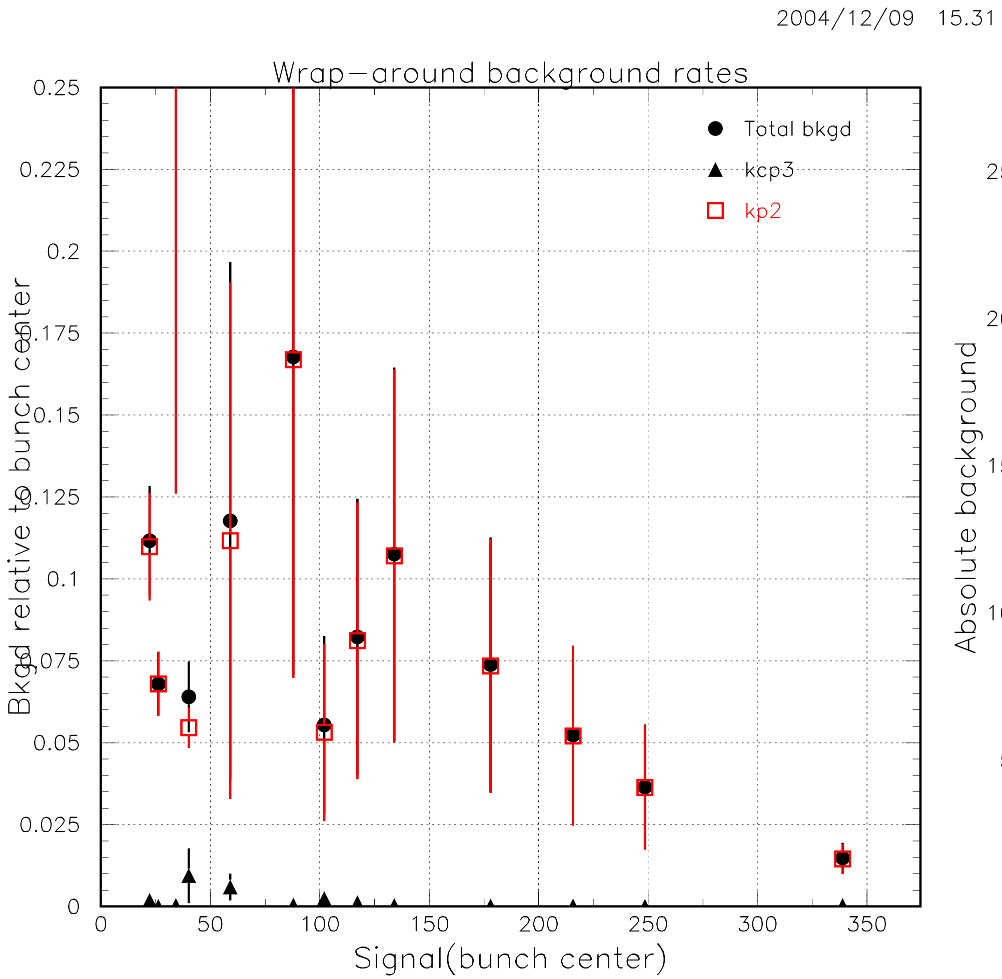


AK lominal cuts (includes a "wrap-around" cut)

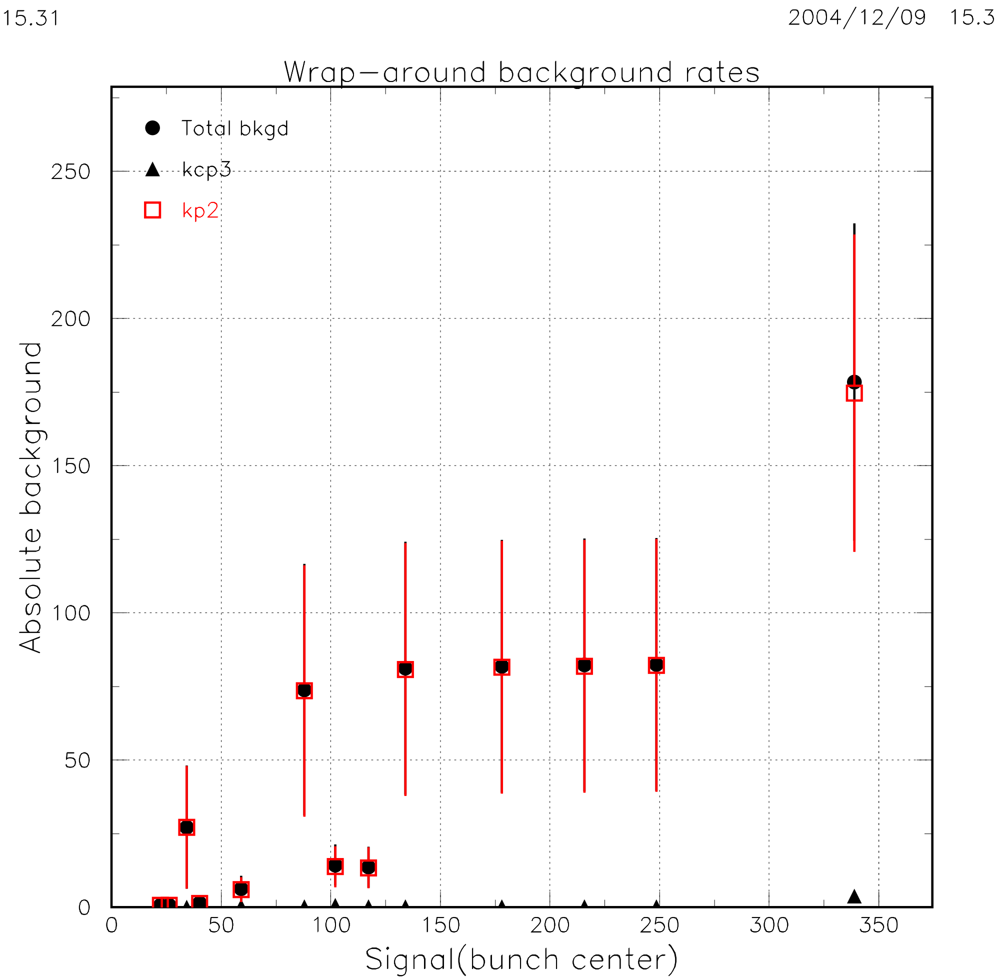


NN-01 cuts (no "wrap-around" cut)

2γPR/CAL detection mode, wrap-around rates

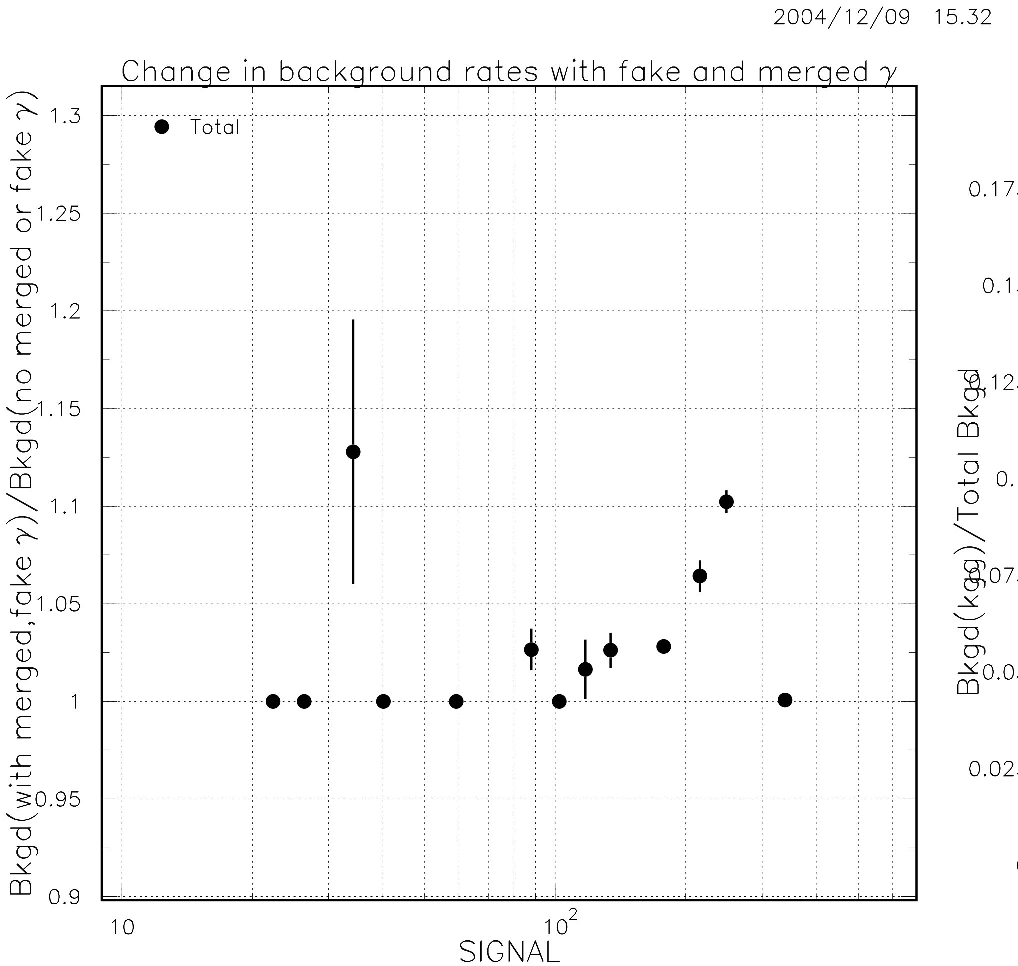


Bkgd(wrap-around)/Bkgd(bunch center) vs Signal(bunch center)

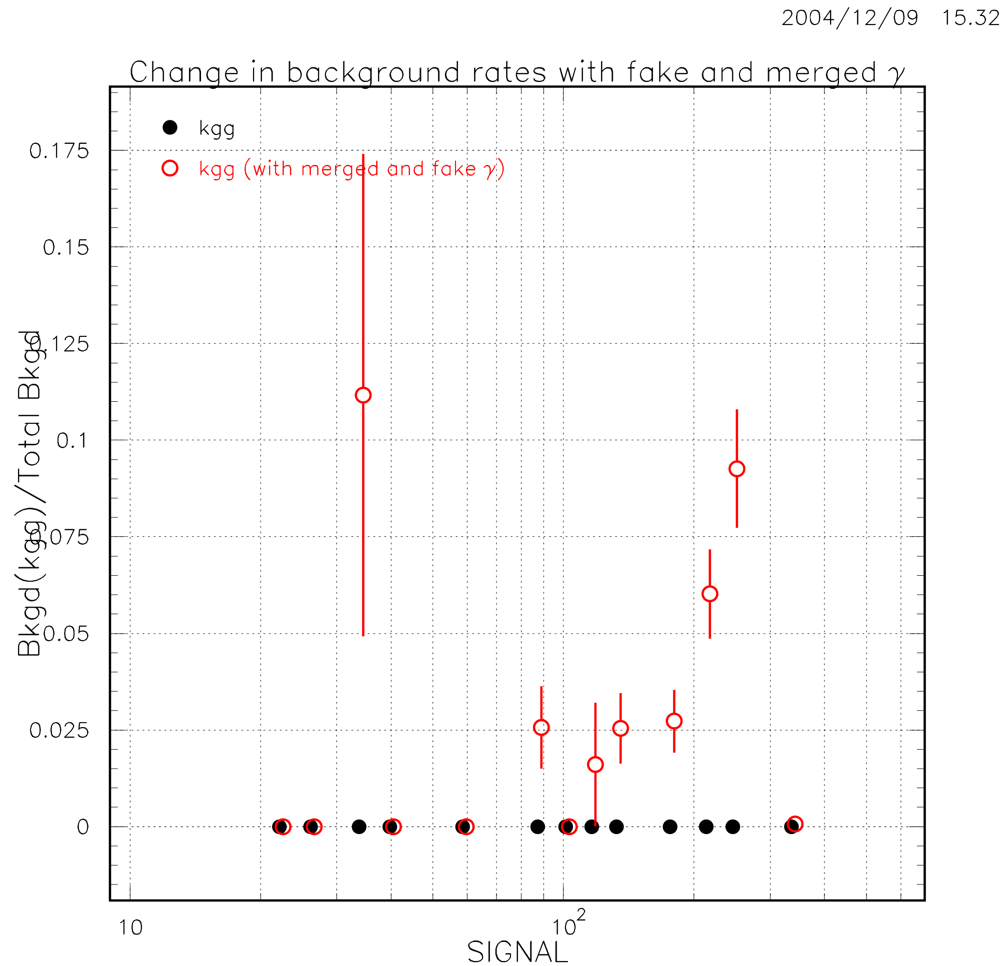


Bkgd(wrap-around) vs Signal(bunch center)

2γPR/CAL detection mode, rates with fake & merged γs



Bkgd(with fake & merged γs)/Bkgd(no fake & merged γs) vs Signal



Bkgd(γγ with fake & merged γs)/Total Bkgd vs Signal

Study catcher double-pulse resolution (δt) for 2γPR/CAL detection mode

Catcher would be blind if γ from $\mathrm{K_L^0}$ arrives too close in time to γ from target produced by proton beam ("γ flash").

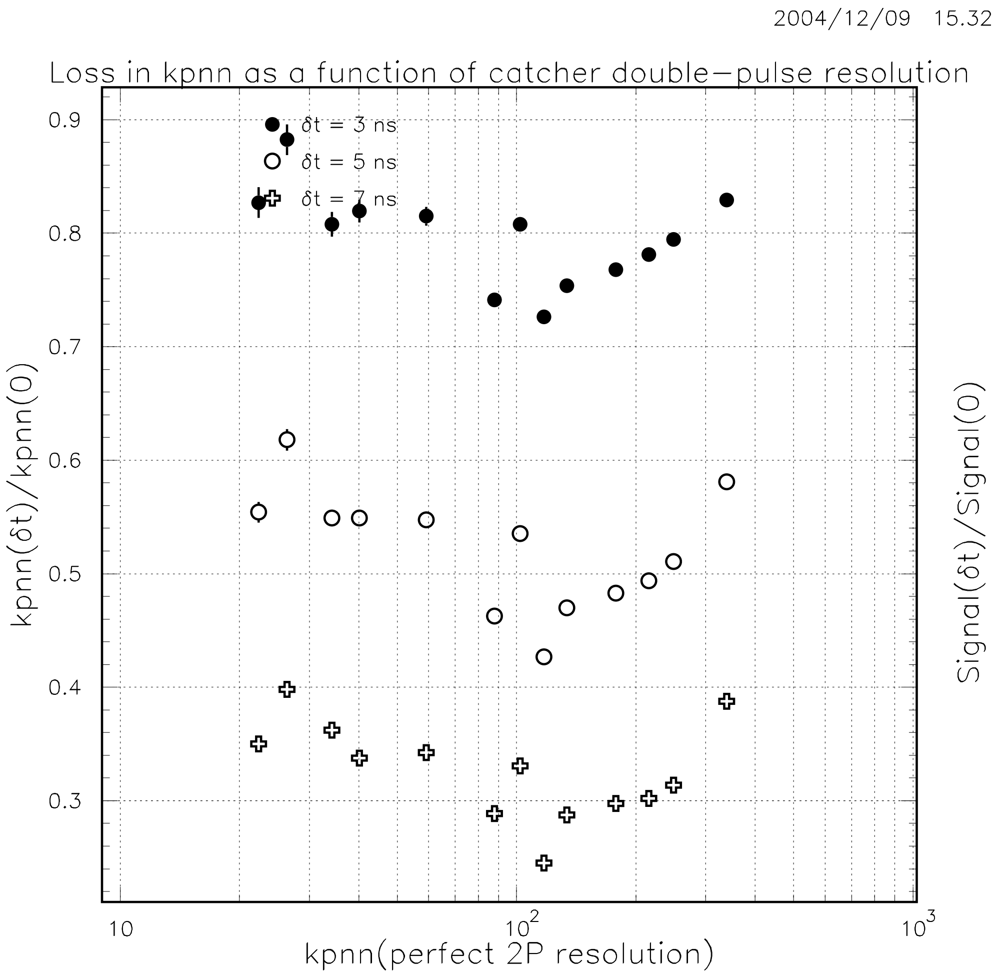
Time of γ at catcher from $\mathrm{K_L^0}$ is $t_c = t_K + d/c$ where d is distance from $\mathrm{K_L^0}$ decay to catcher. Approximate $d \approx z_{\mathrm{catcher}} - z_K \equiv z_c - z_K$ where z_{catcher} is US end of catcher.

Time of γ flash at catcher is $t_f = z_c/c$, so arrival time difference is $\delta t = t_k - t_f = t_k + (z_c - z_K)/c - z_k/c = t_k - z_k/c = t_k(1 - \beta_z)$.

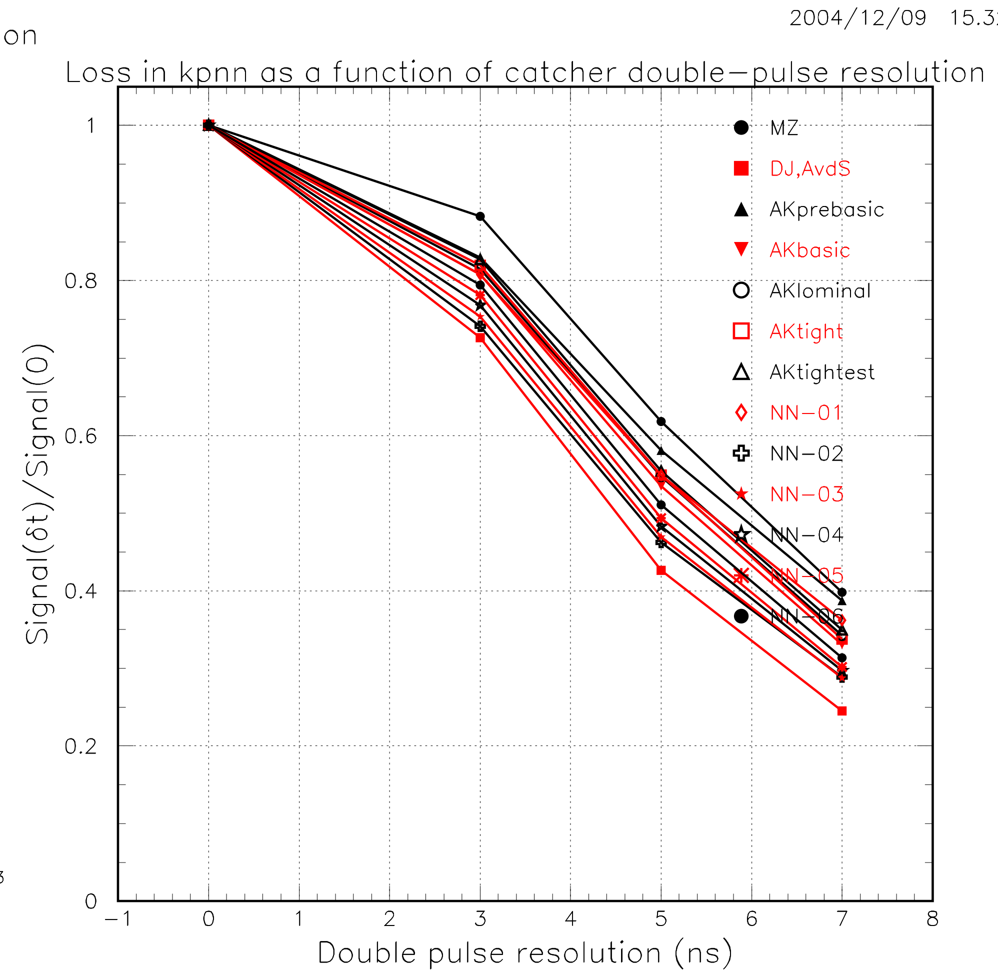
Next page shows signal loss as a function of a cut on δt.

The δt cut is effectively a high momentum cut and removes $\mathrm{K_L^0}$ for which we otherwise have the best veto efficiency.

Study catcher double-pulse resolution (δt) for 2γPR/CAL detection mode

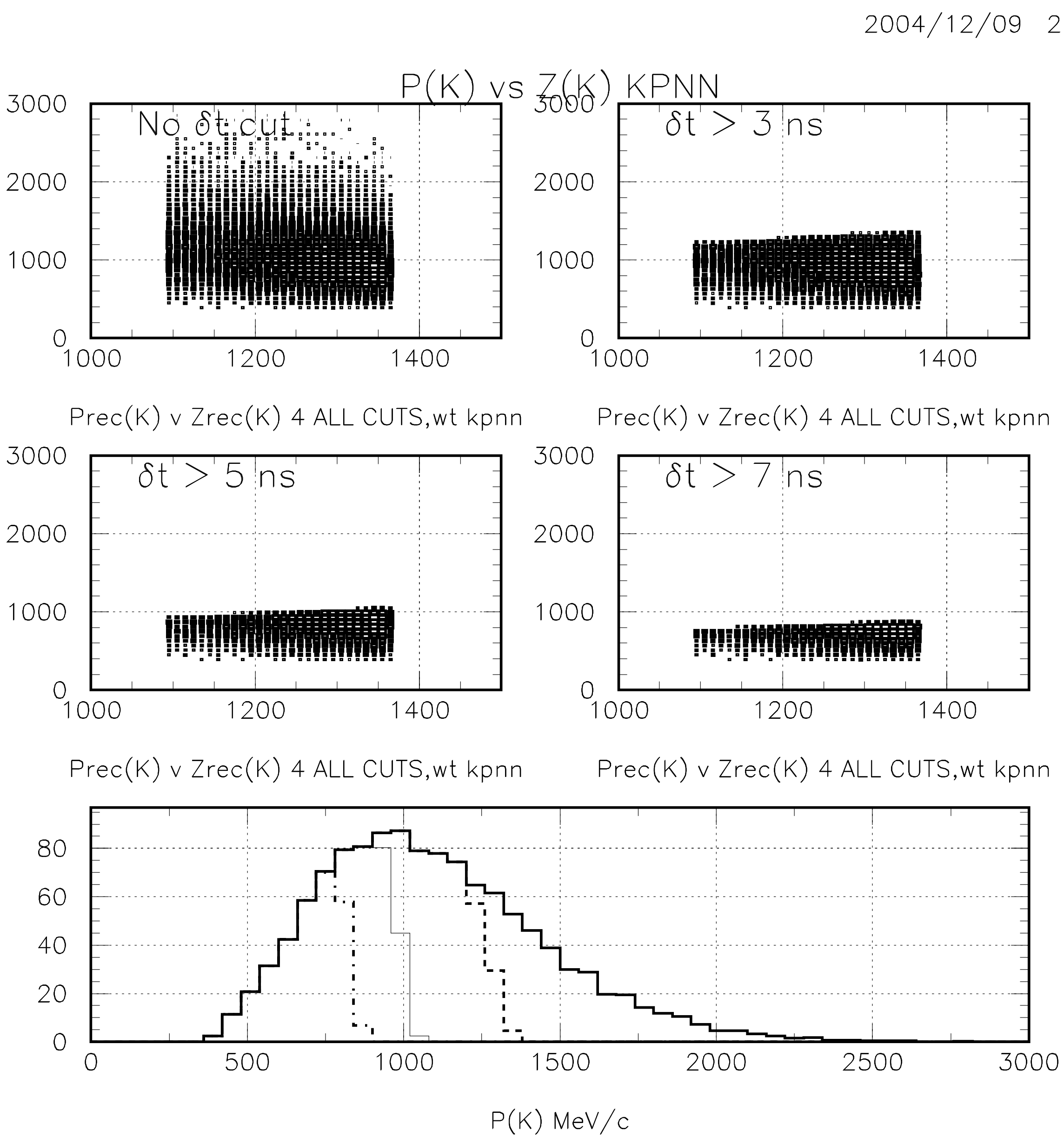


Signal(δt)/Signal(0) vs Signal(0) for $\delta t = 3, 5, 7$ ns



Signal(δt)/Signal(0) vs δt

Study catcher double-pulse resolution (δt) for 2γPR/CAL detection mode



Veto studies for 2γPR/CAL detection mode

1. Veto timing both for PV and CV
2. Thickness of window at DS end of decay volume/entrance to DS beam pipe
3. Effect of position of CV in decay region
   - "far" position - veto lines inner wall of decay region
   - "near" position - veto has half-dimensions 111cm $\times$ 50 cm

Keep in mind that kinematic rejection of $\pi^+\pi^-\pi^0$ is not optimal for some cut sets.

Veto timing for 2γPR/CAL detection mode

All results up to now have ignored timing. Define

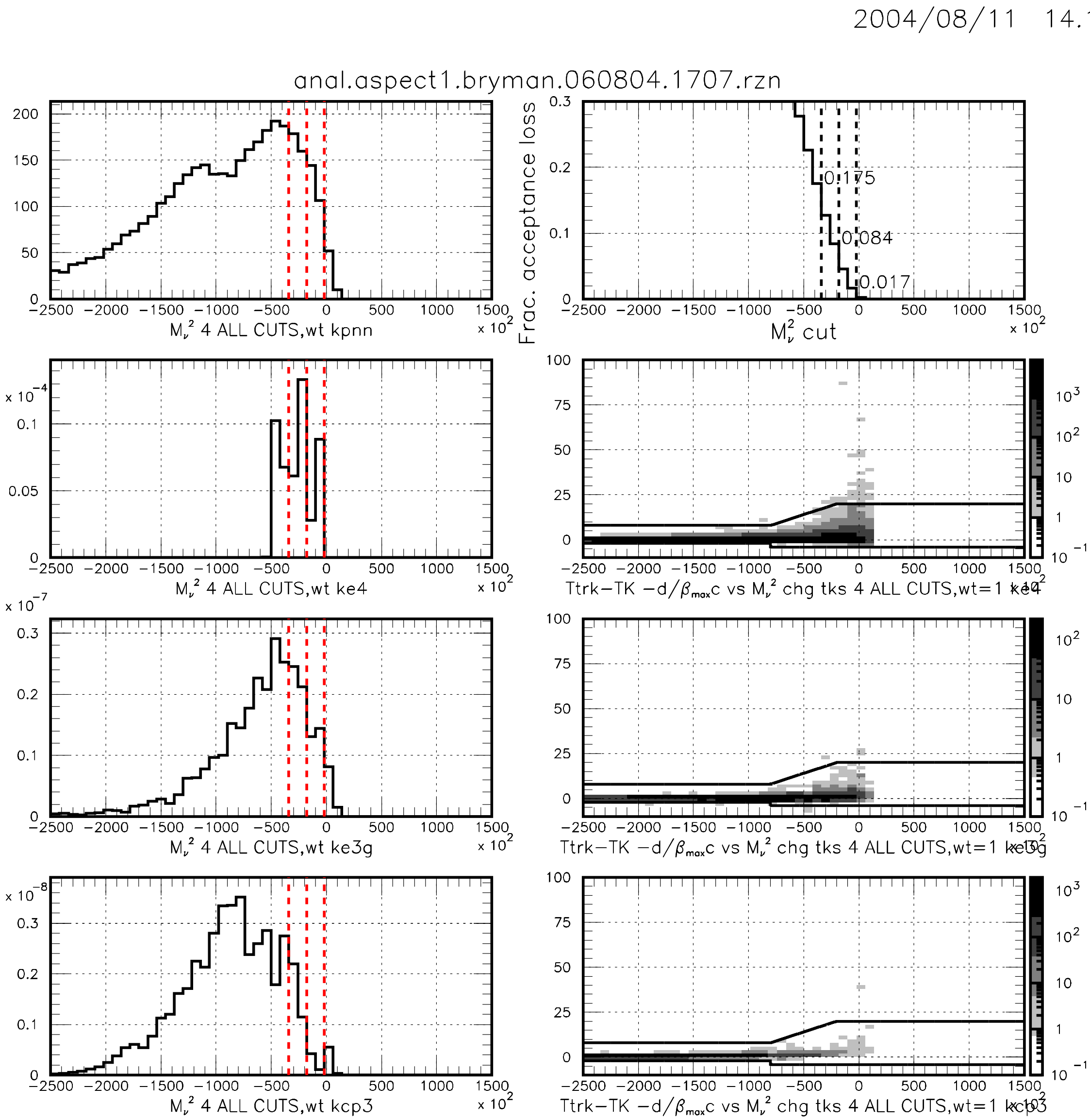
$$\Delta \equiv T_{\rm hit} - T_{\rm K^0_L} - |\vec{x}_{\rm hit} - \vec{x}_{\rm K^0_L}|/c$$

where $T_{\rm hit}, \vec{x}_{\rm hit}$ are the time and position of veto hit, and $T_{\rm K^0_L}, \vec{x}_{\rm K^0_L}$ are the reconstructed time and position of the $\rm K^0_L$ decay. Resolution on $T_{\rm hit}, \vec{x}_{\rm hit}$ is currently ignored.

With no bias in reconstructed $T_{\rm K^0_L}, \vec{x}_{\rm K^0_L}$, expect Δ to be symmetric about zero for γs and have a tail at $\Delta > 0$ due to slow charged tracks and decay-in-flight.

To suppress this tail, I tried a M^2_ν-dependent cut shown on next page. $M^2_\nu \equiv (P({\rm K^0_L}) - P(\pi^0) - P(\pi))^2$ with $P(\pi) = M(\pi)$. Note that $M^2_\nu = M^2_K + M^2_{\pi^0} + M^2_\pi - 2M_K E^*_{\pi^0} - 2M_\pi E_{\rm miss}$, so a cut on M^2_ν is a line in the $E^*_{\pi^0}, E_{\rm miss}$ plane.

Veto timing for 2γPR/CAL detection mode

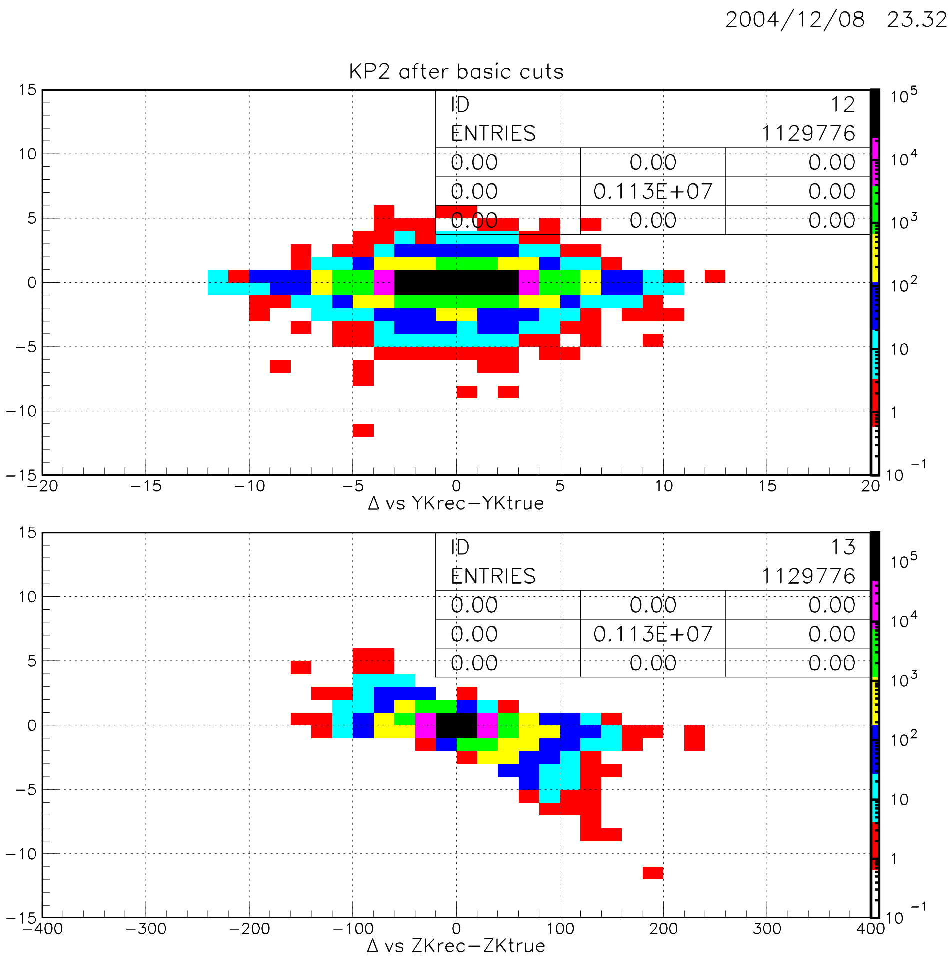


Left column: M_ν^2 distributions for $K_L^0 \to \pi^0\nu\bar{\nu}$, $\pi^0\pi^\pm e^\mp\nu$, $\pi^\pm e^\mp\nu\gamma$, $\pi^+\pi^-\pi^0$.

Top right: signal acceptance of M_ν^2 cuts.

Lower right: Δ vs M_ν^2 for $\pi^0\pi^\pm e^\mp\nu$, $\pi^\pm e^\mp\nu\gamma$, $\pi^+\pi^-\pi^0$ showing M_ν^2-dependent cut.

Veto timing and misreconstructed $Z_{\mathrm{K^0_L}}$ for 2γPR/CAL detection mode



$Z_{\mathrm{K^0_L}}$ is mis-reconstructed for photon candidate pairs that do not originate from a π^0 . Examples are photon pairs from $\pi^0\pi^0$ and $\pi^\pm e^\mp \nu\gamma$.

Lower plot shows Δ vs $Z(\mathrm{K^0_L}, \mathrm{recon}) - Z(\mathrm{K^0_L}, \mathrm{true})$ for $\pi^0\pi^0$ after basic cuts ($|M_{\gamma\gamma} - M(\pi^0)| < 20$ MeV, $\chi^2 < 100$, DOCA < 60 cm, $1015 + 75 < Z(\mathrm{K^0_L}) < 1415 - 50$ cm and the photons are required to pass fiducial cuts to satisfy 2γPR/CAL. DOCA is the distance of closest approach between the measured photon trajectories.

Misreconstructed $Z_{K^0_L}$ for 2γPR/CAL detection mode

The cause of the misreconstruction was partially described by Akira in TN047 for $nN \rightarrow \pi^0 X$ background.

It is caused by large scattering in Y direction on 1 γ coupled with energy mismeasurement of one or both γ.

In particular, it occurs when one photon has a relatively small Y angle. When the γs are not from a π^0 and the energy is mismeasured, imposing the π^0 mass constraint shifts the reconstructed $Z_{K^0_L}$.

We preferentially accept $Z(K^0_L, \text{recon}) > Z(K^0_L, \text{true})$, because $P(K^0_L, \text{recon}) > P(K^0_L, \text{true})$ and $E_{\text{miss}}(\text{recon}) > E_{\text{miss}}(\text{true})$.

There is a correlated effect that makes Δ more negative for $\pi^0\pi^0$: $Z(K^0_L, \text{recon}) > Z(K^0_L, \text{true})$ sometimes implies $d(\text{recon}) > d(\text{true})$ for $\pi^0\pi^0$ -odd with backward-going photons.

Misreconstructed $Z_{K_L^0}$ for 2γPR/CAL detection mode

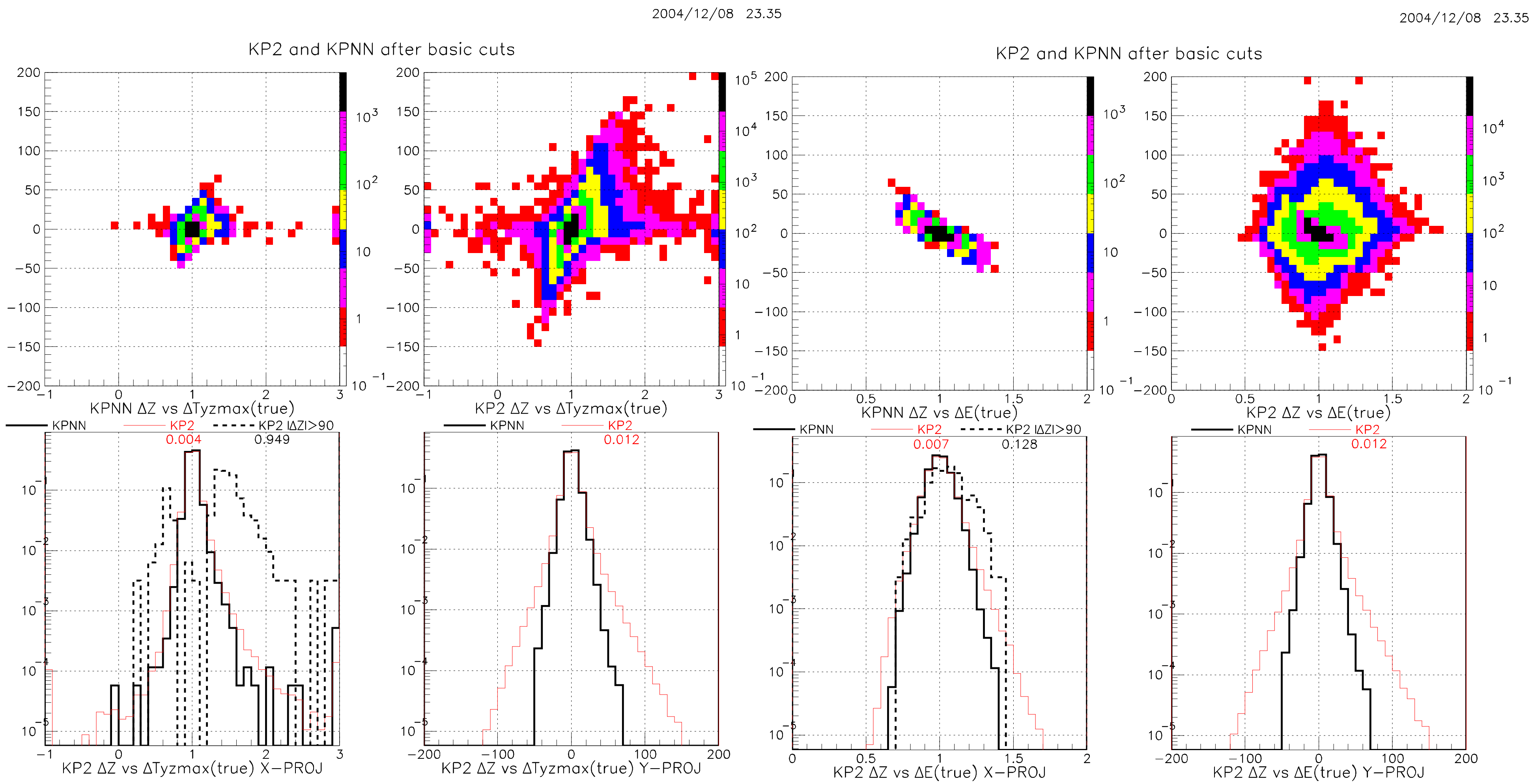
Define $\Delta Z \equiv Z(\mathrm{K_L^0}, \mathrm{recon}) - Z(\mathrm{K_L^0}, \mathrm{true})$

There is a greater correlation of Δ and ΔZ with the **absolute magnitude** of the mis-measurement rather than the relative magnitude. The latter would be expected to show up as a large χ^2.

The former shows up in $\Delta Tyzmax \equiv Tyzmax(\mathrm{fit})/Tyzmax(\mathrm{true})$ where $Tyzmax = max(|P_y(\gamma,1)/P_z(\gamma,1)|, |P_y(\gamma,2)/P_z(\gamma,2)|)$ and in $\Delta E \equiv \frac{E_1(\mathrm{fit})}{E_1(\mathrm{true})} \frac{E_2(\mathrm{fit})}{E_2(\mathrm{true})}$.

It turns out that two useful variables to identify large $|\Delta Z|$ are DOCA1+DOCA2 and $Z(\mathrm{K_L^0}, \mathrm{fit1}) - Z(\mathrm{K_L^0}, \mathrm{fit2})$, where DOCA$i$ is the distance of closest approach of the i^{th} measured photon to $Z(\mathrm{K_L^0}, \mathrm{fit2})$ and $Z(\mathrm{K_L^0}, \mathrm{fit}i)$ is the reconstructed $Z_{\mathrm{K_L^0}}$ from the i^{th} fit. Fit 1(2) fits the 2 γ to a common vertex without(with) a π^0 mass constraint.

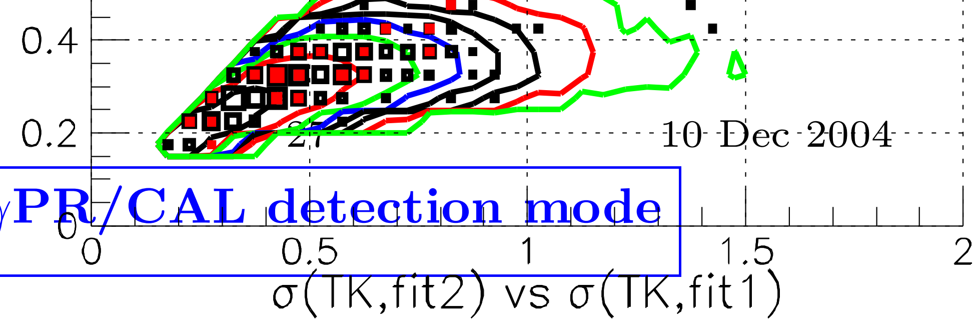
Misreconstructed $Z_{K^0_L}$ for 2γPR/CAL detection mode



ΔZ vs $\Delta Tyzmax$

ΔZ vs ΔE

Misreconstructed $Z_{K_L^0}$ for 2γPR/CAL detection mode

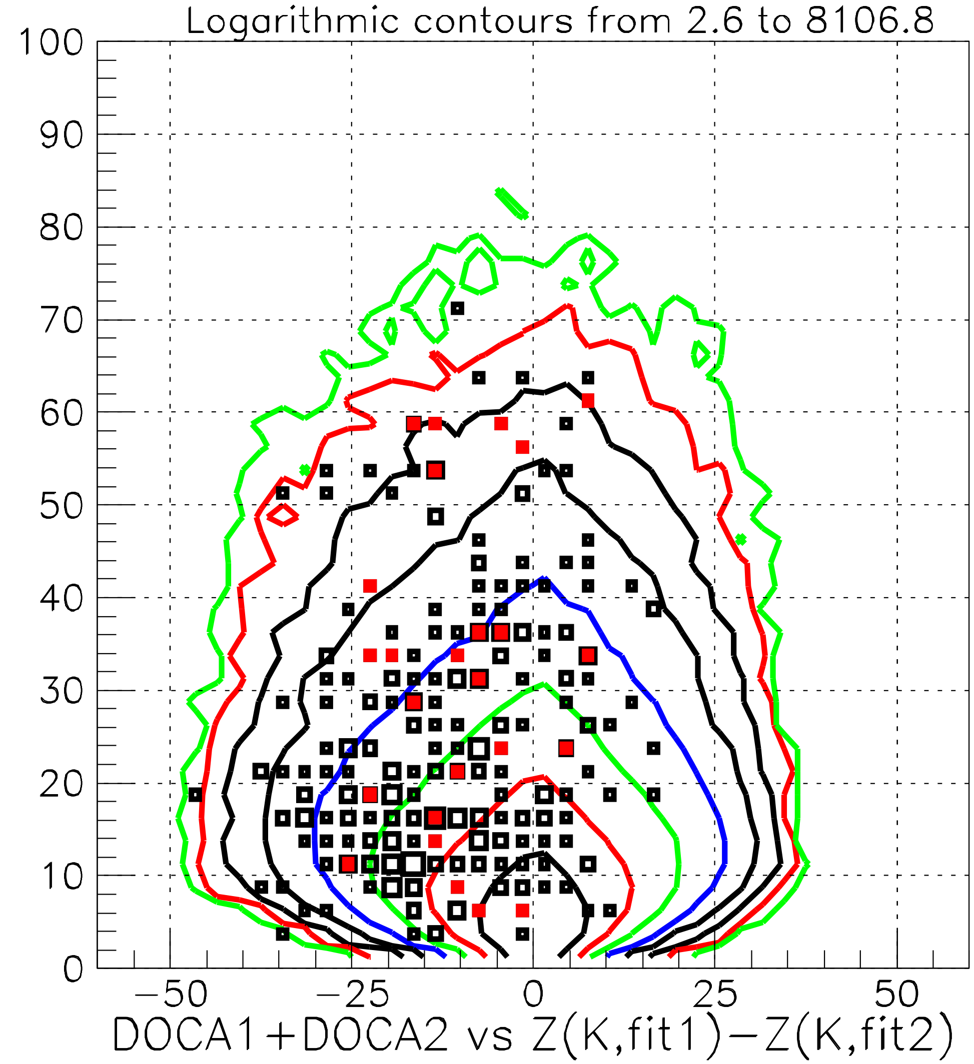


DOCA1+DOCA2 vs $Z(K_L^0, \text{fit1}) - Z(K_L^0, \text{fit2})$ for $\pi^0\pi^0$.

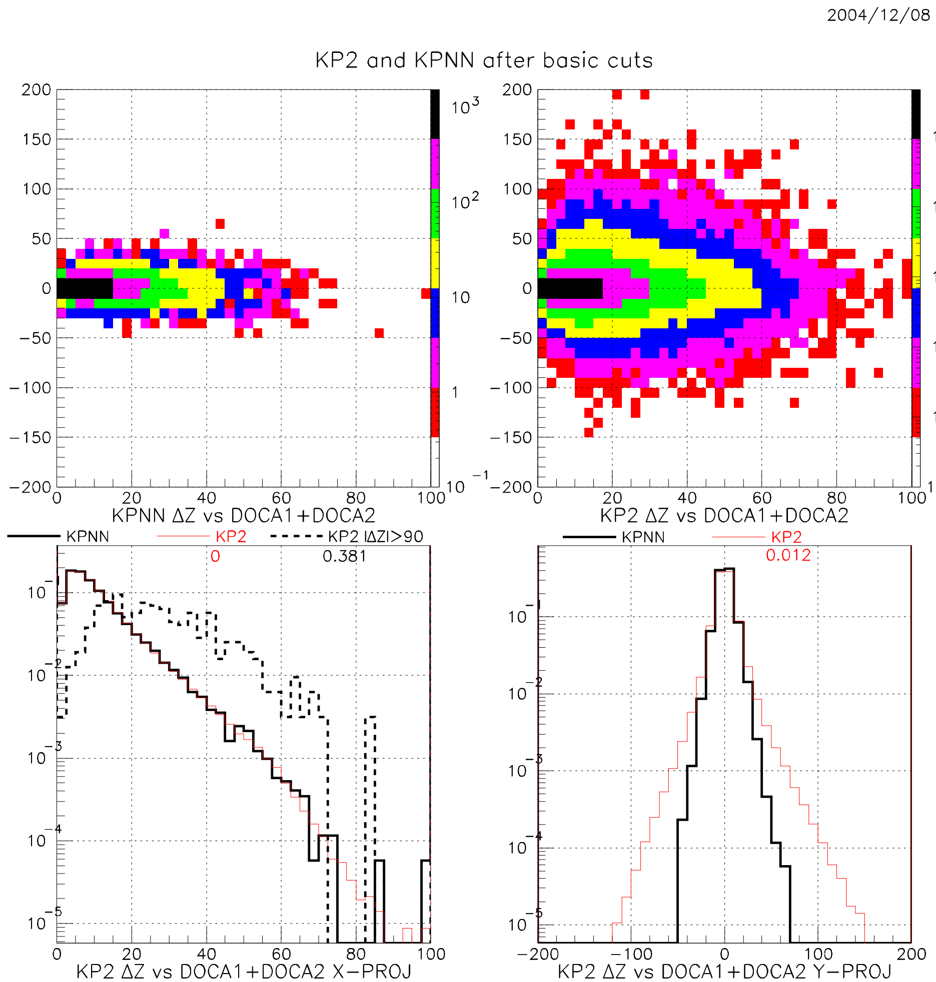
Black open boxes : $\Delta < -3$ ns

Red boxes : $\Delta < -5$ ns

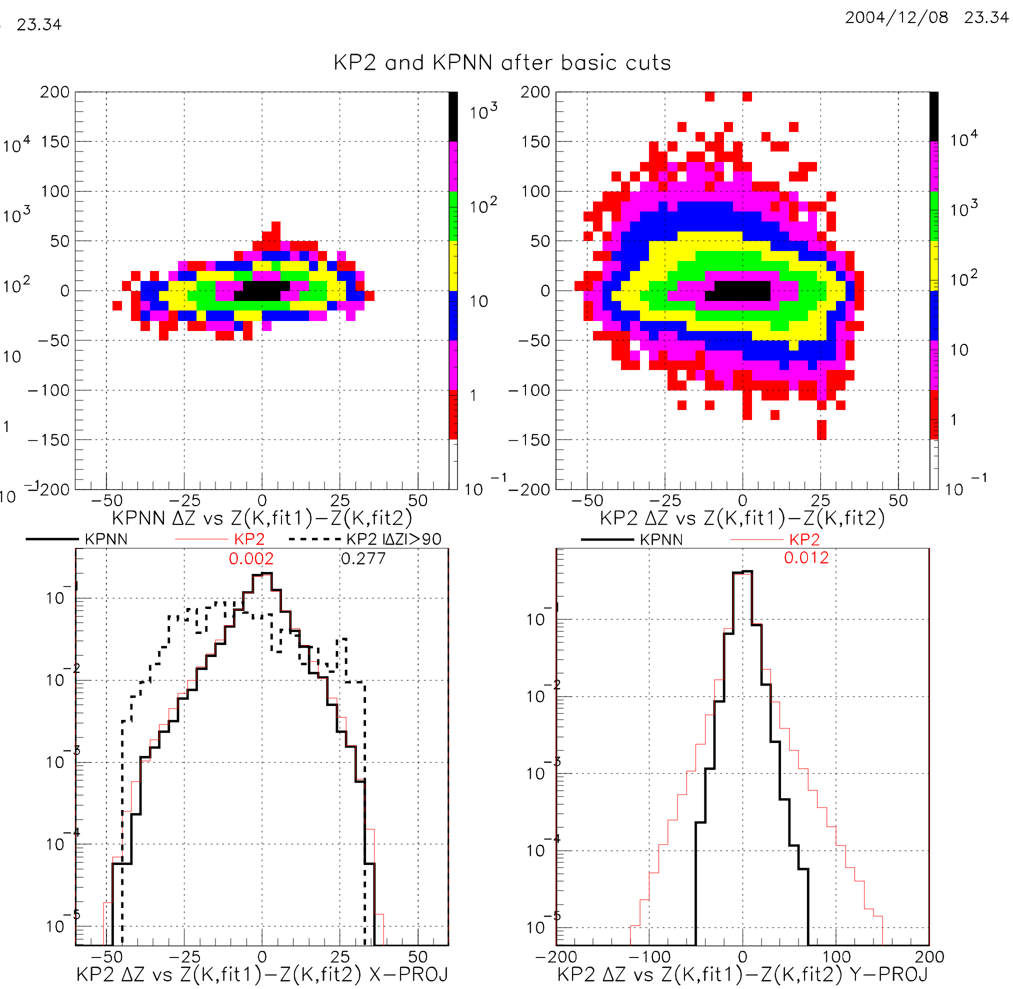
Contours drop by $\sqrt{10}$ from maximum value.



Misreconstructed $Z_{K_L^0}$ for 2γPR/CAL detection mode



ΔZ vs DOCA1+DOCA2



ΔZ vs $Z(K_L^0, \mathrm{fit1}) - Z(K_L^0, \mathrm{fit2})$

Veto timing for 2γPR/CAL detection mode

New variable

$$\mathrm{DK12} \equiv \sqrt{(\mathrm{DOCA1} + \mathrm{DOCA2} - 5.)^2 + (Z(\mathrm{K_L^0}, \mathrm{fit1}) - Z(\mathrm{K_L^0}, \mathrm{fit2}))^2}$$

if DK12 < 15 cm, veto on $-6 < \Delta < +6$ ns

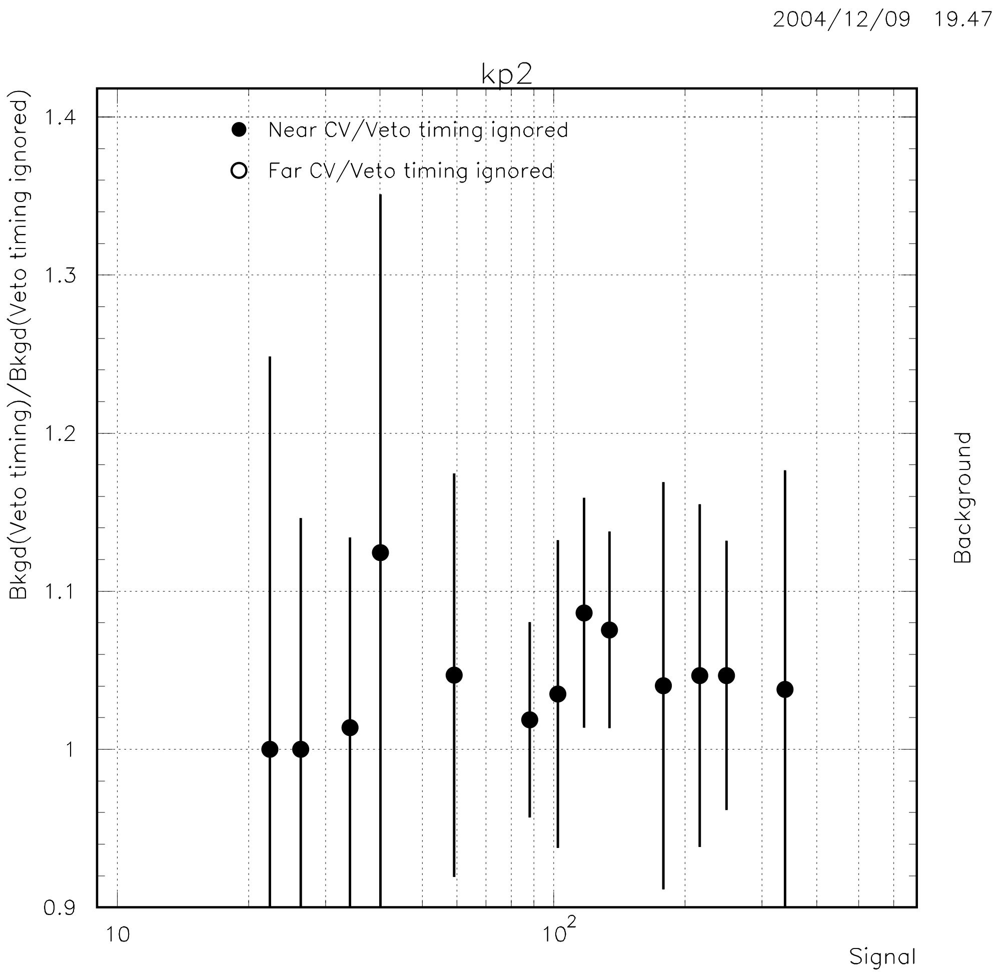
if DK12 > 15 cm, veto on $-12 < \Delta < +6$ ns

(These veto windows may be too wide.)

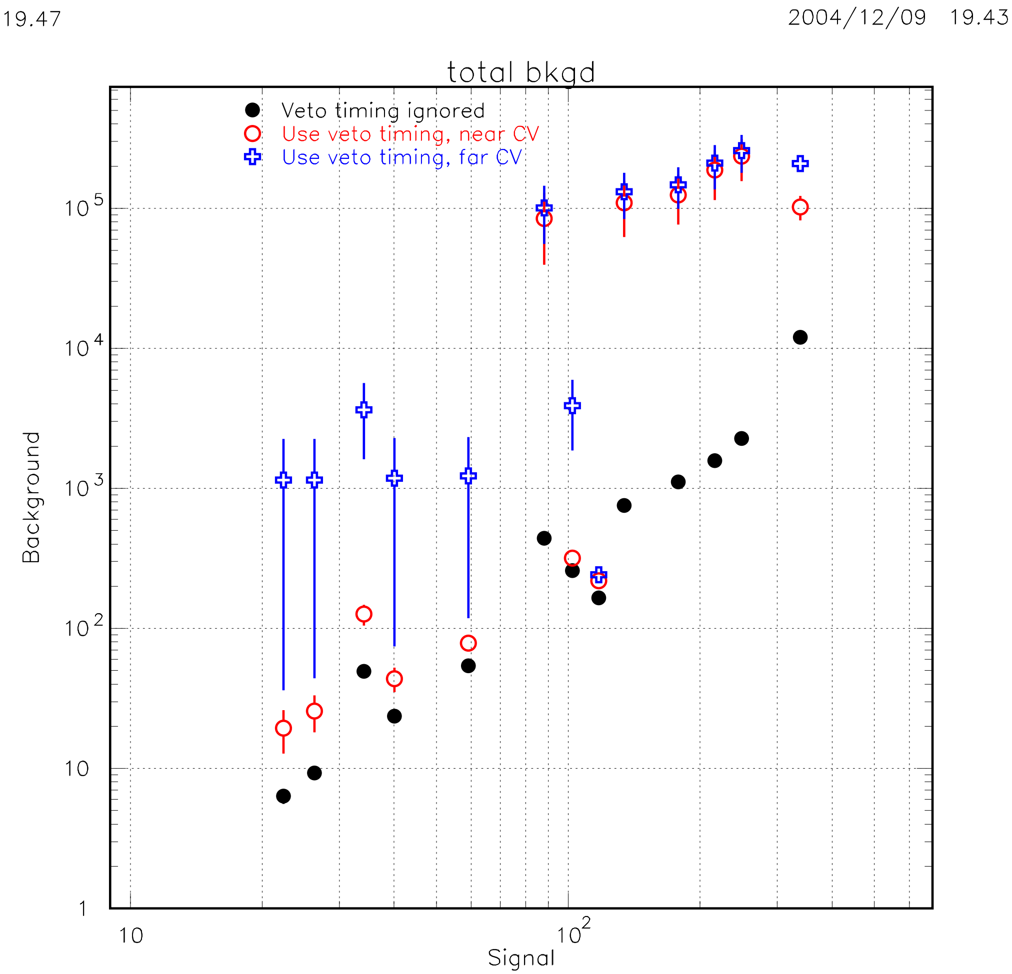
Result is that $\pi^0\pi^0$ rate increases by $\sim 1.05 \pm 0.10$ (Probably dominated by a single event.)

However, CV rate increase when timing is taken into account is significantly higher. More work is needed.

Veto timing and 2γPR/CAL detection mode

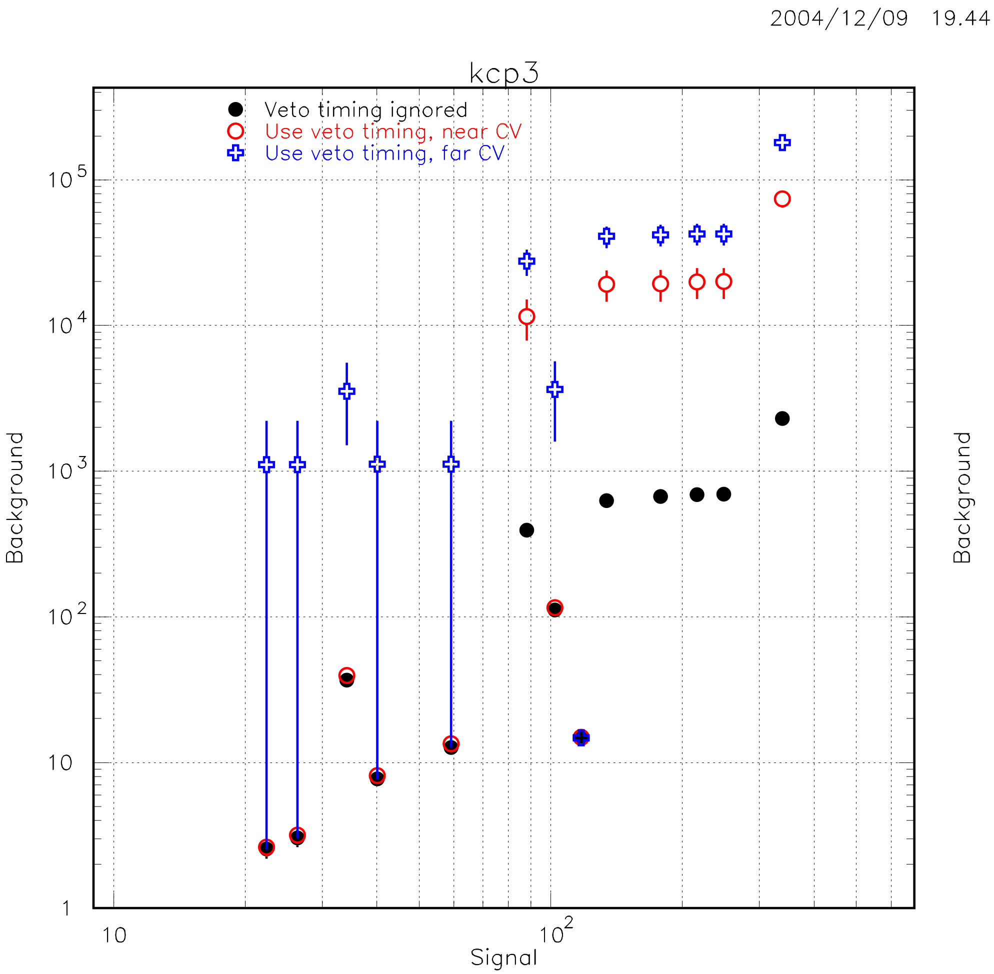


$\pi^0\pi^0$ rate with/without veto timing.

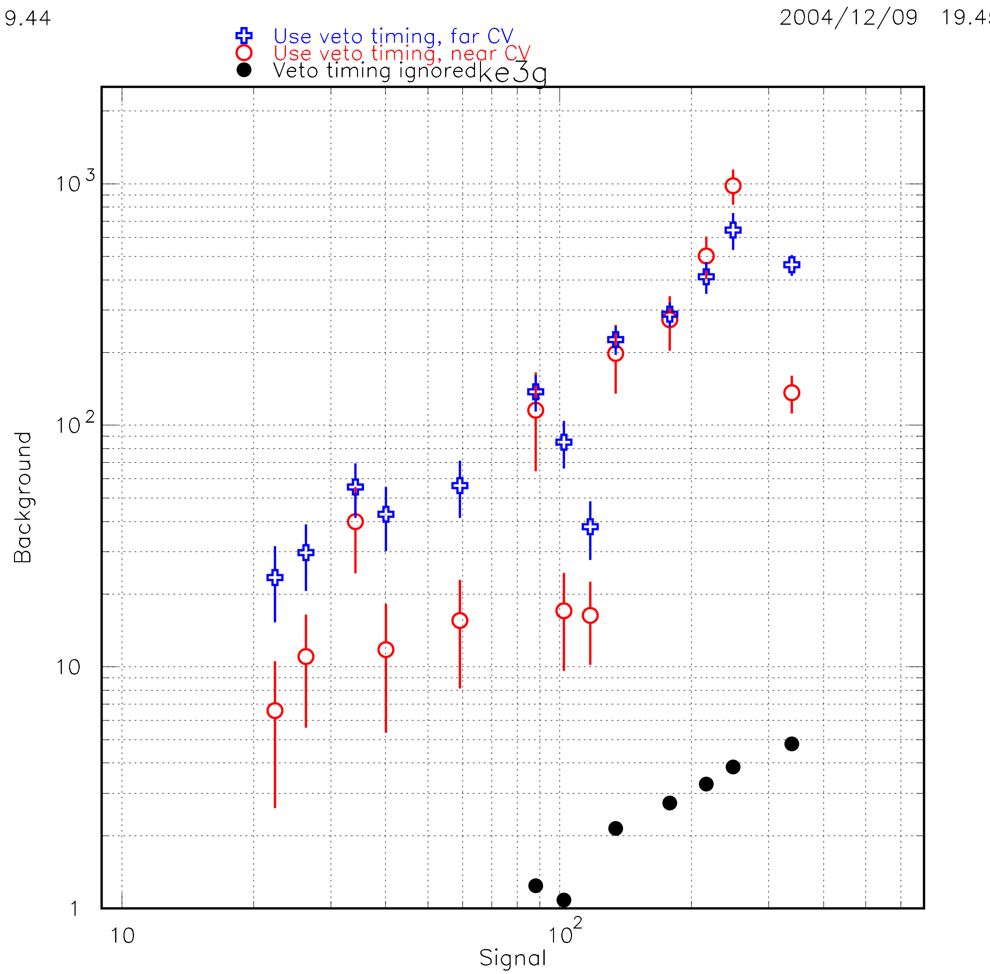


Total bkgd rate with & without veto timing.

Veto timing and 2γPR/CAL detection mode



$\pi^+\pi^-\pi^0$ rate with & without veto timing.



$\pi^\pm e^\mp \nu\gamma$ rate with & without veto timing.

Rates and DS window thickness for 2γPR/CAL detection mode

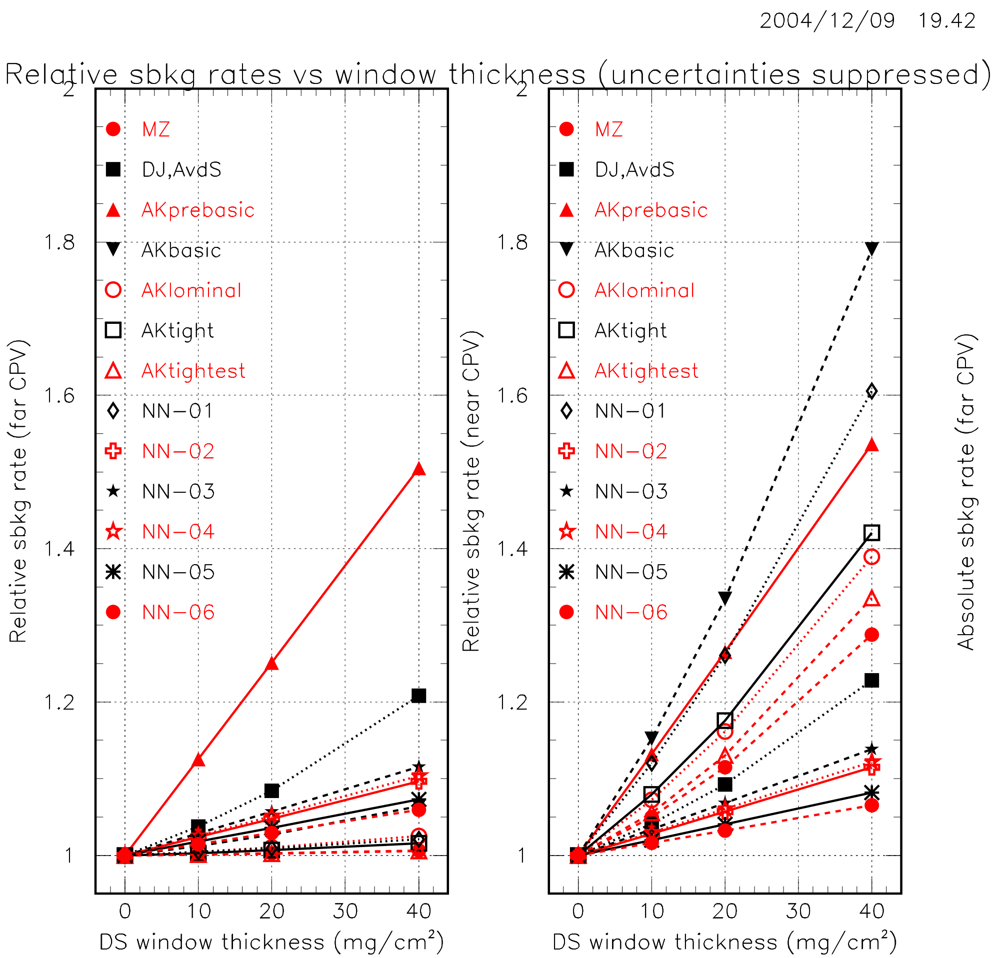
It has been proposed that a wire chamber be installed at the DS end of the decay volume as a CV. Even if this device is not installed, it is proposed to put a barrier at this point to separate the high and low vacuum regions.

The increase in rate as a function of the thickness of such a barrier was estimated by assuming that the thickness of the barrier would have the same effect as increasing the thickness of the wrapping on the CV counters in the DS beam hole. This effect was measured in the PSI tests.

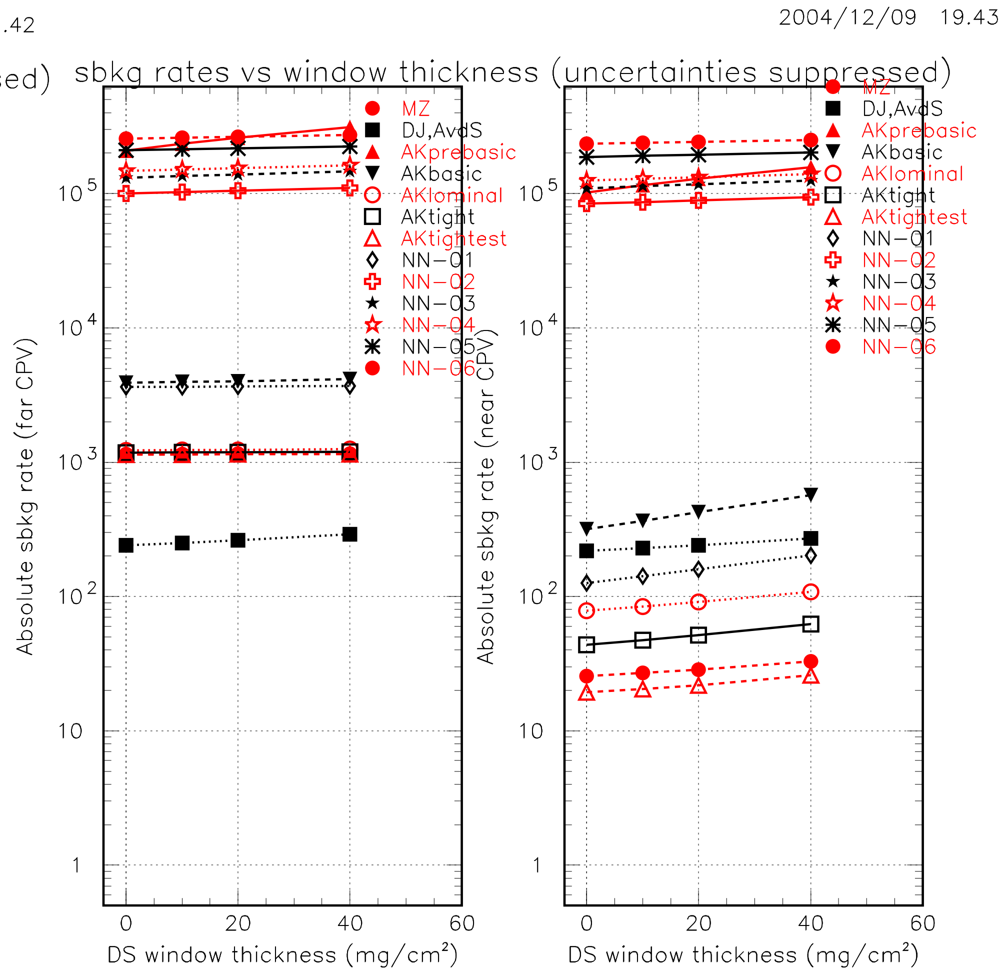
Thicknesses of 0, 10, 20 and 40 mg/cm^2 were studied.

The effect of such a barrier is most profound for $\pi^+\pi^-\pi^0$ background.

Rates and DS window and 2γPR/CAL detection mode

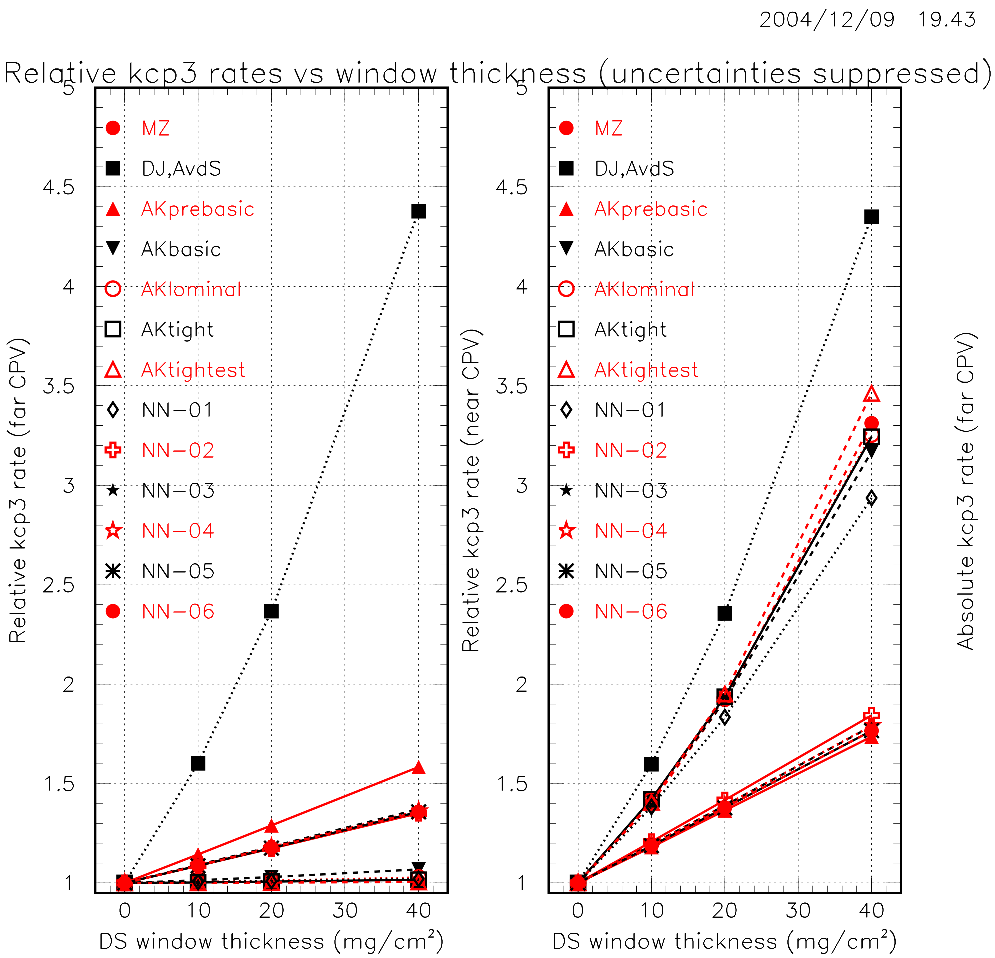


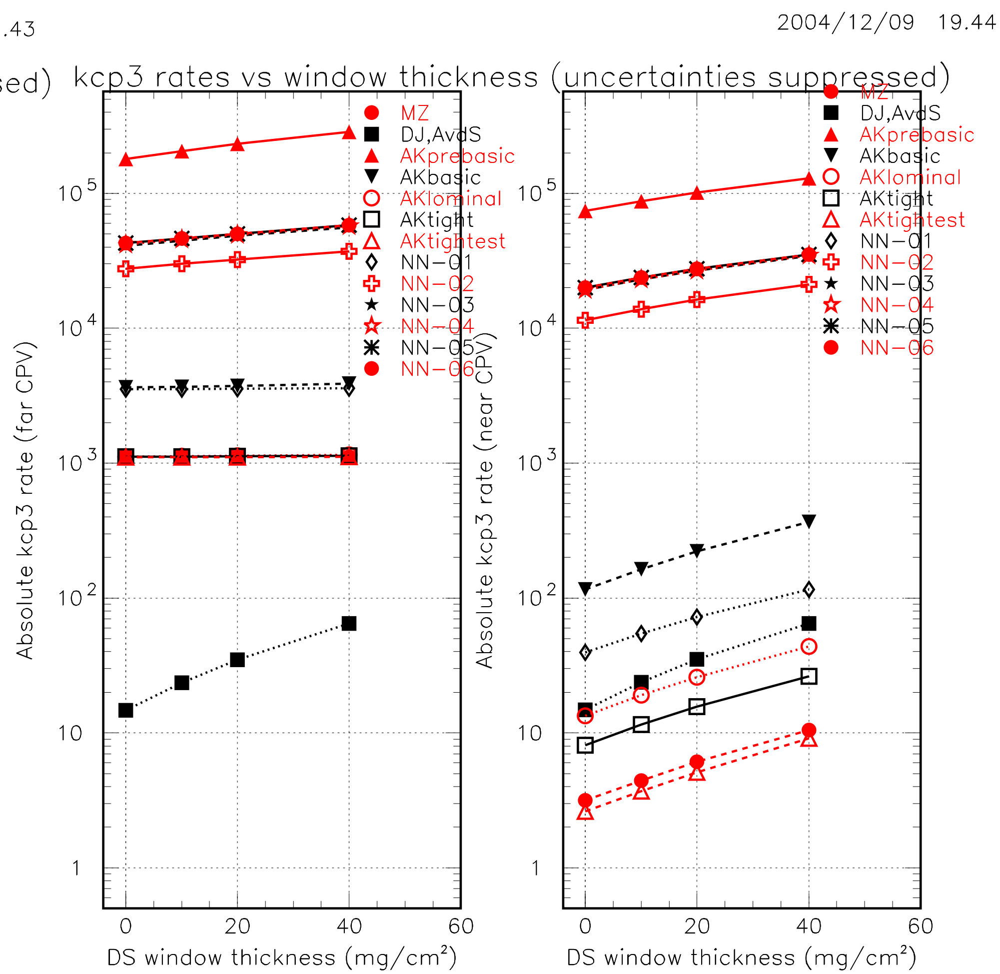
Relative bkgd rates vs thickness.



Absolute bkgd rates vs thickness.

Rates and DS window and 2γPR/CAL detection mode

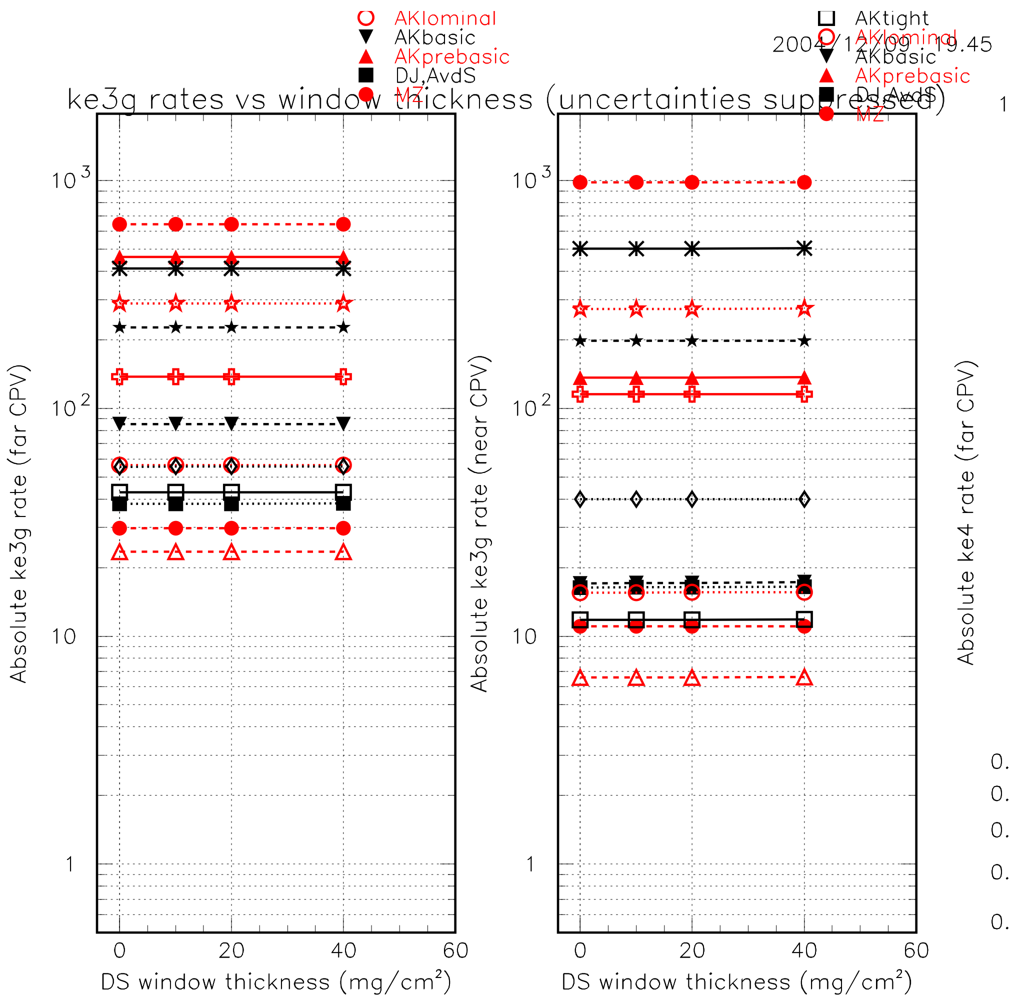




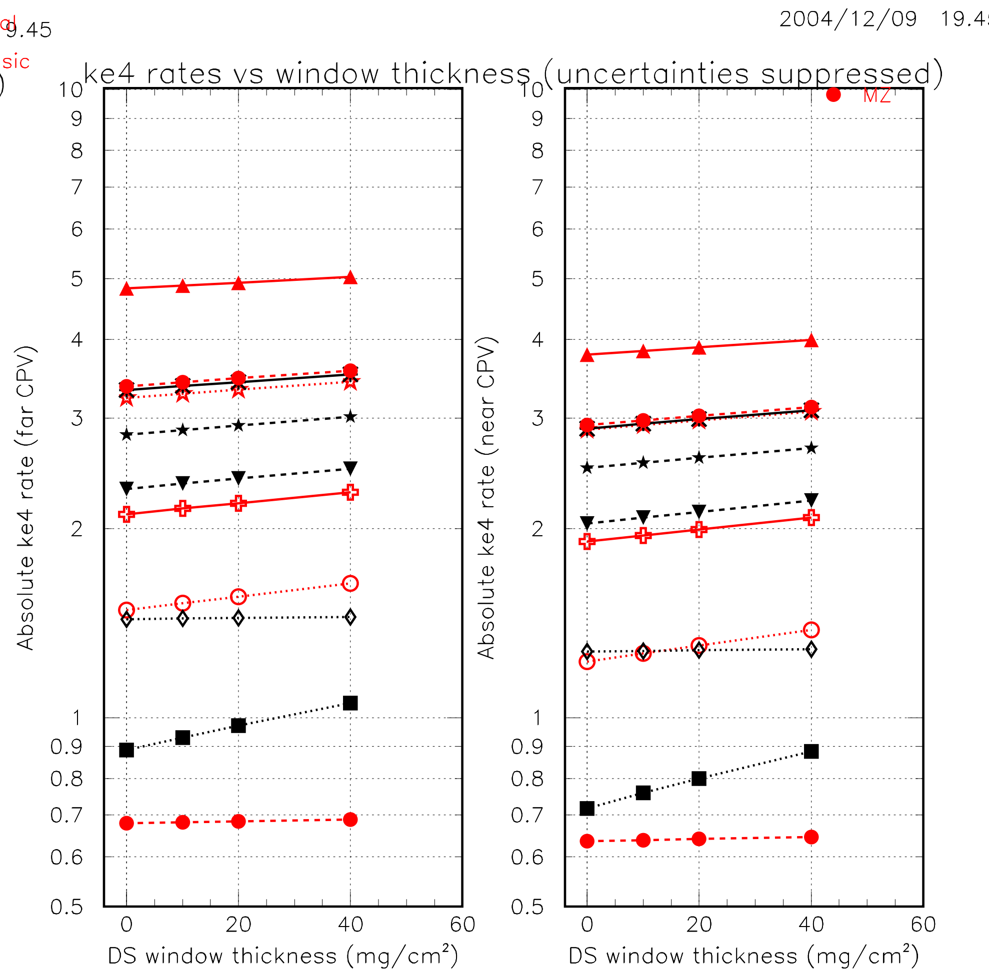
Relative $\pi^+\pi^-\pi^0$ rates vs thickness.

Absolute $\pi^+\pi^-\pi^0$ rates vs thickness.

Rates and DS window and 2γPR/CAL detection mode

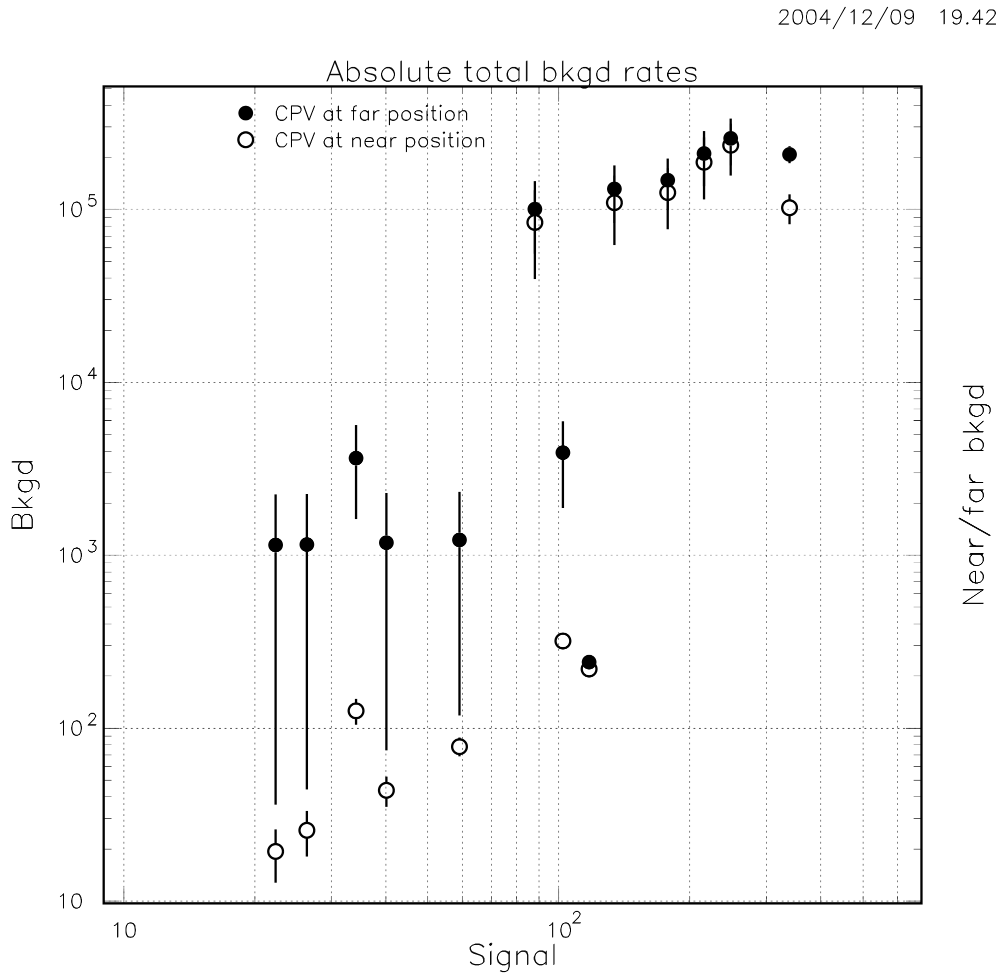


Absolute $\pi^{\pm}e^{\mp}\nu\gamma$ rates vs thickness.

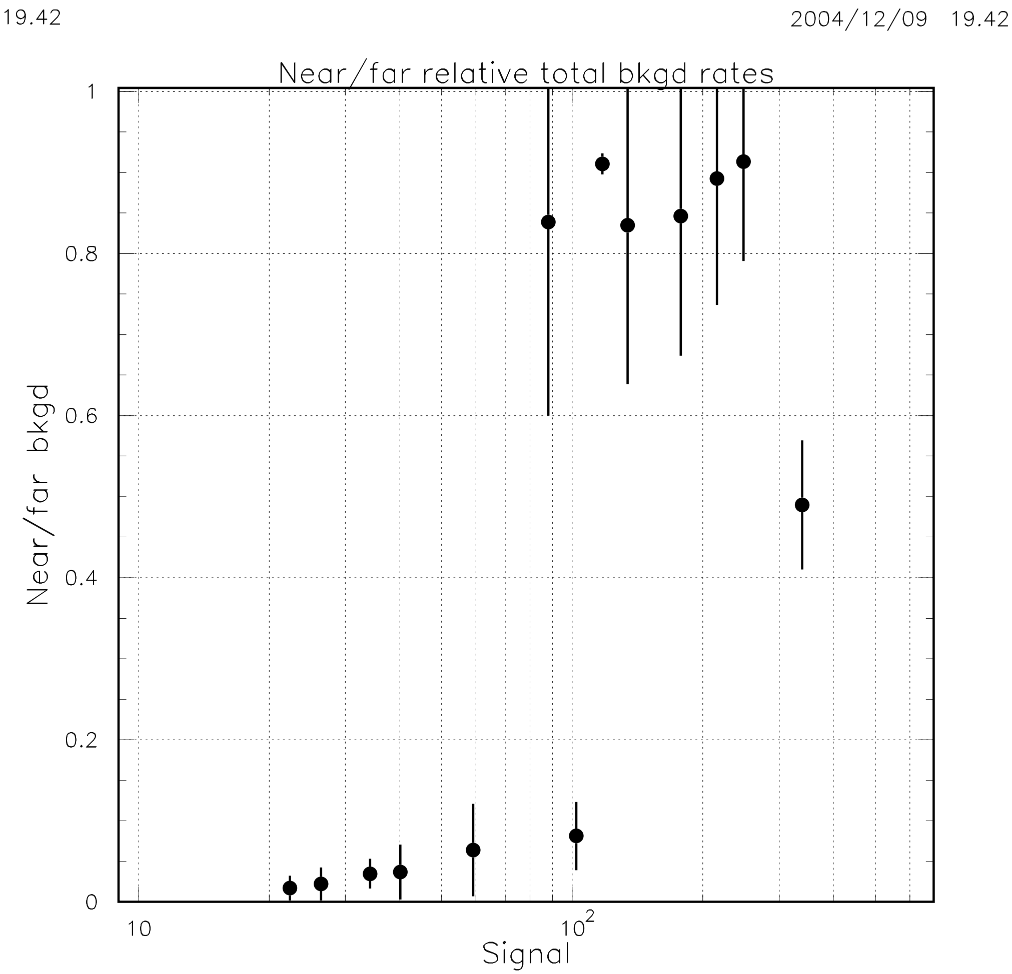


Absolute $\pi^{0}\pi^{\pm}e^{\mp}\nu$ rates vs thickness.

Rates and CV position and 2γPR/CAL detection mode

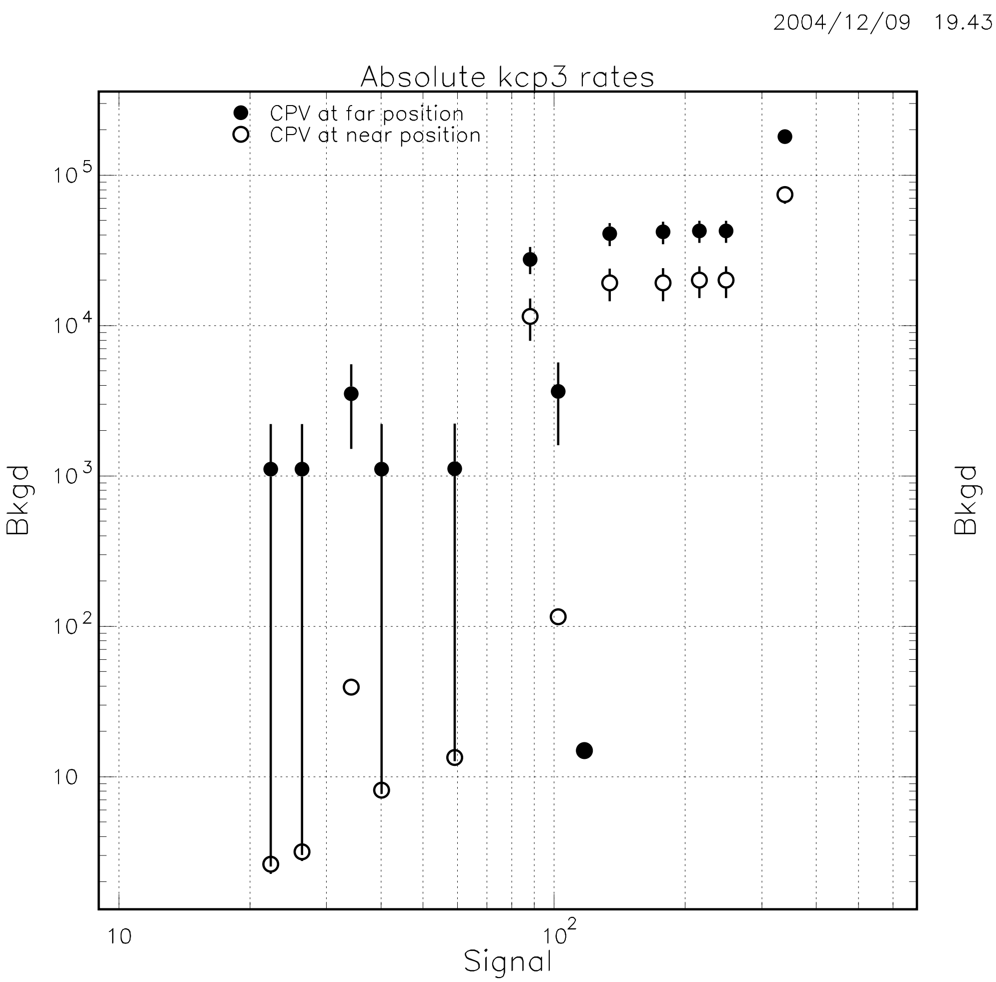


Absolute bkgd rates for far and near CV positions

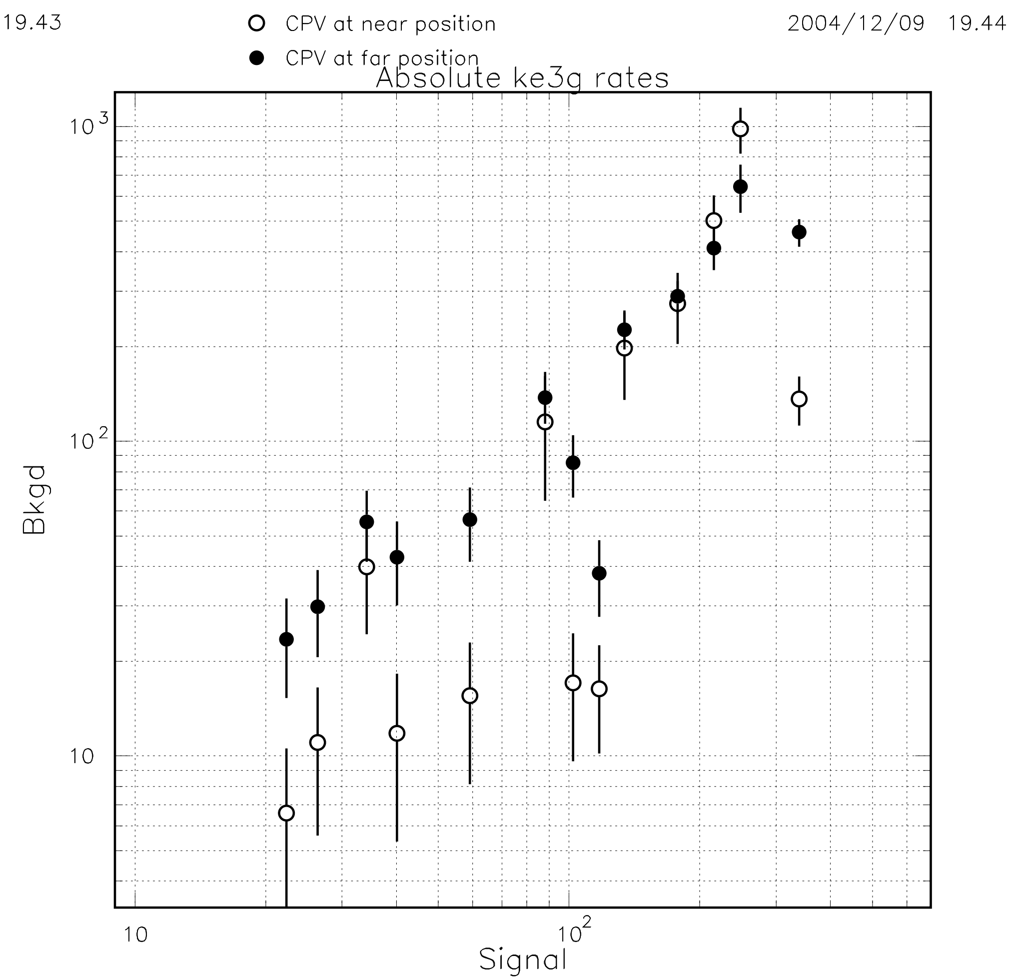


Relative bkgd rates for far and near CV positions

Rates and CV position and 2γPR/CAL detection mode



Absolute $\pi^+\pi^-\pi^0$ rates for far and near CV positions



Absolute $\pi^\pm e^\mp \nu\gamma$ rates for far and near CV positions

Veto studies for 2γPR/CAL detection mode

Some tentative conclusions:

1. PV timing under control with DK12-dependent gate
   - Loss due to accidentals?
   - Other effects of $Z_{\mathrm{K}^0_\mathrm{L}}$ misreconstruction
2. CV timing still problematic
   - Need DK12-dependent gate for CV?
   - Better kinematic suppression needed for charged modes
3. The effect of a window at the DS end of the decay volume is most profound for $\pi^+\pi^-\pi^0$ background.
4. Effect of position of CV in decay region: far/near rates ~ 5 for some cut sets.

Studies need to be repeated when more optimal kinematic cuts are available.

(Mostly) non-K^0_L background sources

1. K^+ contamination of beam: < 0.013 of signal rate without considering kinematic suppression or divergence to due B field (TN101)
2. $K^0_L \rightarrow K^\pm e^\mp \nu$: < 0.1 K^+ contamination of beam
3. $nN \rightarrow \pi^0 X$: negligible for 2γPR/CAL mode (TN047). **Should be checked for other detection modes**
4. $\bar{n}$: Not a problem. (TN122)
5. Hyperons: TDR claimed 0.2 events **Should be rechecked**
6. Fake photons: **Try to check with FastMC**
7. Multiple K^0_L : negligible
8. $\pi^\pm \rightarrow \pi^0 e^\pm \nu$? **Should be checked with FastMC.**
9. $nN \rightarrow \gamma\gamma X$ **Should be checked with in light of $Z_{K^0_L}$ misrecon**
10. K^0_L scattering in collimator (like interbunch bkgd) **Should be checked**

Signal losses other than analysis cuts

- Trigger $<$ 20% GR
- Accidentals
  1. Stopped muons: 1.38% and 0.24% per ns of PV and CV gate, resp. (TN109) ≥12ns PV gate & ≥10 ns CV gate implies ≥18.96%
  2. Neutron-induced showers: AP working on it.
- γ absorption : 2% per 1% of rad. len.(TN024) 4% RL implies 8% loss
- Reconstruction-related (MB GEANT3 studies)
  1. Self-veto: $20.4 \pm 0.9\%$
  2. Vetos from other K_L^0 in microbunch : $56.5 \pm 1.5\%$
  3. Vetos from K_L^0 in other microbunches : 3.79% (TN106)

Signal losses other than analysis cuts

Relative acceptance after all losses : 19.9%

Corrected for the "1 K_L^0/μbunch" factor of 0.656 in quoted FastMC yields: 30.3%.

Some comments:

- PV gate perhaps too wide.
- Correlations between PV and CV in assessment of accidental losses.
- Neutrons ignored.
- High veto rate from other K_L^0 in μbunch implies that we should reduce mean K_L^0/μbunch
- We need higher signal rates

Some outstanding issues

1. Quantitative results needed
2. More optimal cuts
3. Re-visit wrap-around cut
4. Convolution of interbunch extinction with calculated interbunch rates
5. Non-K^0_L background studies of non-2γPR/CAL det. methods
6. Neutron-induced losses
7. Other implication of $Z_{K^0_L}$ mis-reconstruction?
8. Correlations between PV and CV in assessment of accidental losses
9. Optimize average K^0_L/μbunch
10. 100×5 mrad^2 vs 100×4 mrad^2 for rates
11. Fake γ background
12. K^0_L scattering in collimator
13. How do we measure veto inefficiency with data?