# Filtering the 4γ Distributions to Reduce Background in $\eta \rightarrow \pi^0\gamma\gamma$ for a Dark Leptophobic Boson Search

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Data plots are from Simon's Aug 16 survey

http://argus.phys.uregina.ca/cgi-bin/private/DocDB/ShowDocument?docid=3082

# Physics Motivations

We want to efficiently isolate the rare, doubly radiative decay $\eta \rightarrow \pi^0 2\gamma$ (BR ~ 2.7E-4).
It represents the small, irreducible background in a search for a leptophobic B boson in the mass range 0.14-0.5 GeV via $\eta \rightarrow \gamma + B \rightarrow \gamma + (\pi^0 \gamma)$.

(while we're at it, we can study axial meson dynamics in SM $\eta \rightarrow \pi^0 2\gamma$, look for other doubly radiative decays like $\eta' \rightarrow \pi^0 2\gamma$ and $\eta' \rightarrow \eta 2\gamma$, and even $\eta \rightarrow 4\gamma$)

With the existing lead glass-based FCAL, Sascha's simulations (Fig 21, JEF 2014 proposal) have shown the purity for this SM rare decay will be very low due to the bkg from $\eta \rightarrow 3\pi^0$ with two missing photons.

Goal #1: Produce data plots to make the case for lead tungstate.

Note that the proposal didn't use a cut on unused calorimeter energy to veto events with low energy photons, and it didn't use a kin fit to optimize the resolution.

Goal #2: Even with base equipment, we may still be able to place the best constraint on the existence of a leptophobic B boson in the mass range 0.14-0.5 GeV via $\eta \rightarrow \gamma + B \rightarrow \gamma + (\pi^0 \gamma)$.

If Nian Qin can start this analysis, and Shuang Hancan continue it, then we'll have a B boson publication next year as well as important material for an updated JEF proposal.

# Challenges of 4γ Final States

Because we don't track photons, each true 4gamma event has 4!/(2!(4-2)!) = 6 combos, one true combo and 5 potential background combos.

Combinatoric backgrounds are less of a problem for channels that contain a narrow meson like the pi0 or eta.

The 2pi0 and pi0+eta channels will be relatively background free because they are dominant (at least for 3-12 GeV) and because any bkg combos would have to pass thru TWO narrow meson filters. Simon's initial filtering for these channels may be good enough to begin a SM hadronic physics program.

The interesting pi0+2gamma channel is going to require careful filtering because the signals are weak and there is only ONE narrow meson filter.

The worst-case scenario may be the true 4γ final state (BR < 2.8E-4) since there are ZERO narrow meson filters.

# Estimate of $\eta \rightarrow \pi^0 2\gamma$ Yield

From Simon's 2γ yields:

$N_{\pi 02\gamma} \sim (N_{2\gamma}/B_{2\gamma}) \times B_{\pi 02\gamma} \times \varepsilon_\gamma \times \varepsilon_\gamma = (2.4E5/0.394) \times 2.7E\text{-}4 \times 0.64 \times 0.64$

$= 67$ events

From Simon's 6γ yields:

$N_{\pi 02\gamma} \sim (N_{6\gamma}/B_{3\pi 0}) \times B_{\pi 02\gamma} \times 1/\varepsilon_\gamma \times 1/\varepsilon_\gamma = (4.E4/0.327) \times 2.7E\text{-}4 \times 1/0.64 \times 1/0.64$

$= 81$ events

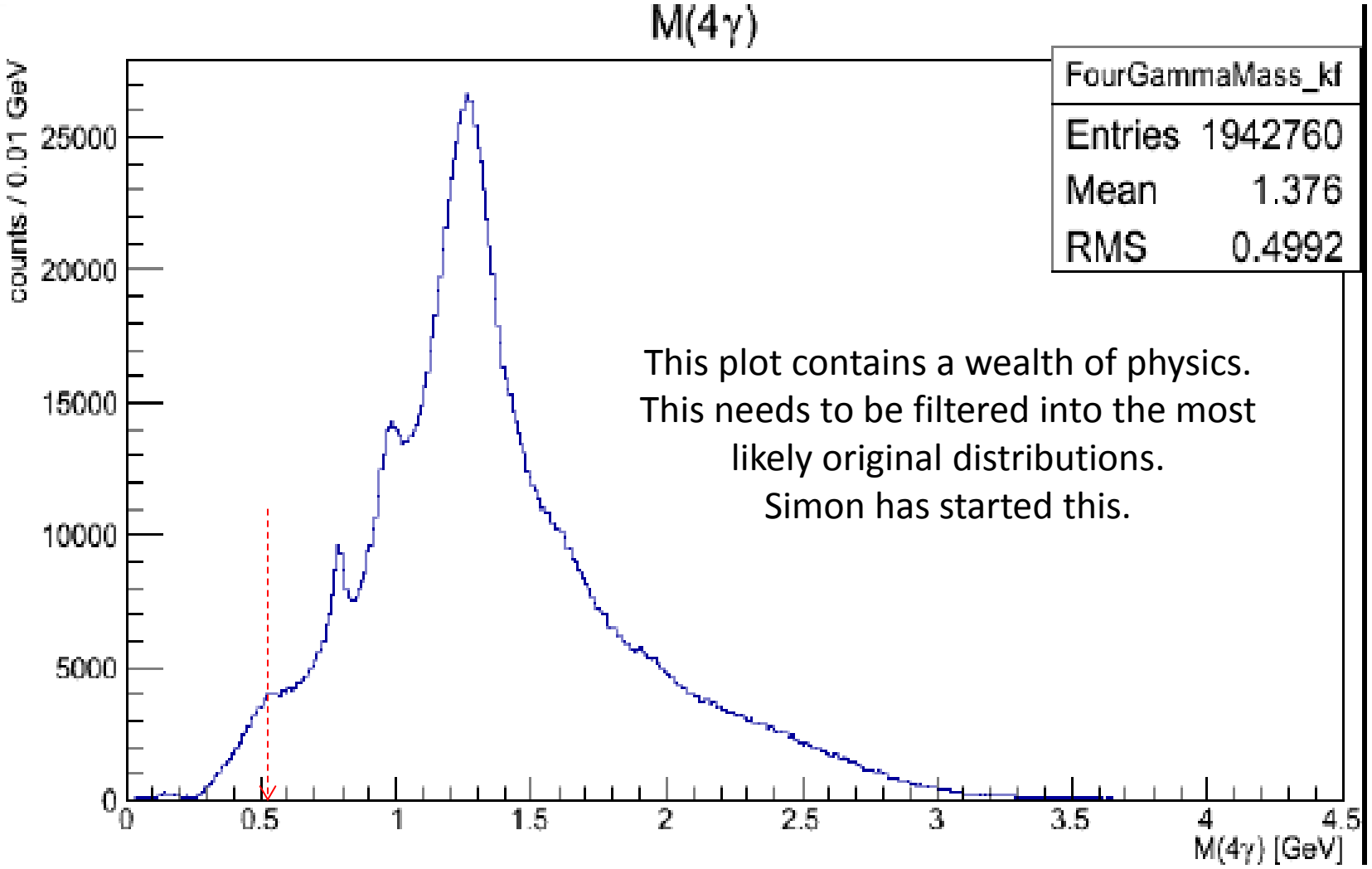
**Let's call it ~75 events.**

Bear in mind that these numbers are not randoms-subtracted.

Where the BR are from the PDG, and I took $\varepsilon_\gamma$ from my slide 3 of v6 at
http://argus.phys.uregina.ca/cgi-bin/private/DocDB/ShowDocument?docid=2985

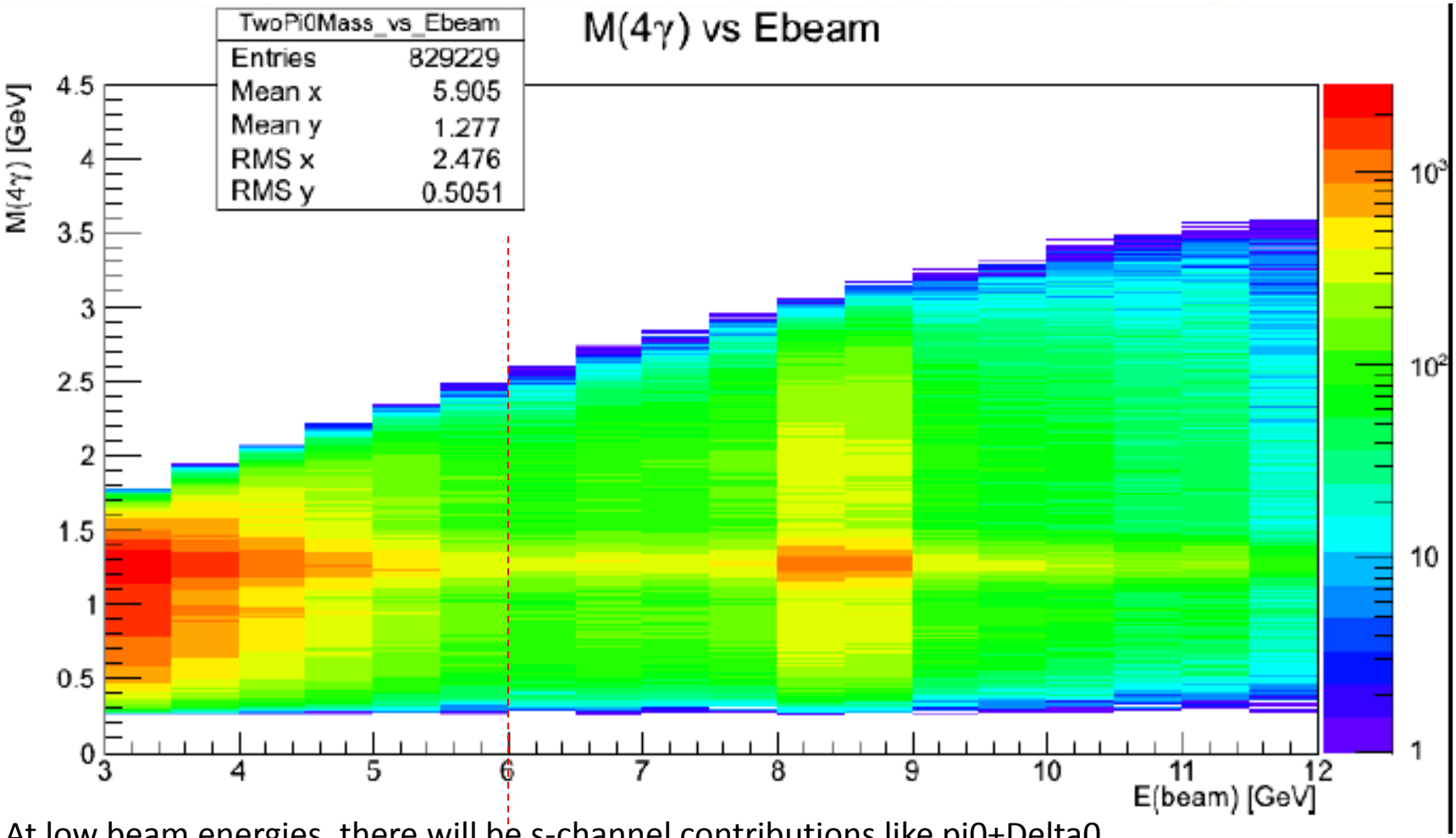
# All Apparent γ+p→p+4γ Events

$E_{\gamma\ beam}$ = 3-12 GeV




There is no point in my trying to mark on this plot what 75 $\eta \rightarrow \pi^0 2\gamma$ events would look like. Bkg/Signal before filtering is O(100).

# M(4gamma) Yield vs Ebeam




At low beam energies, there will be s-channel contributions like pi0+Delta0.

To Do: for now, cut the beam energy > 6 GeV.

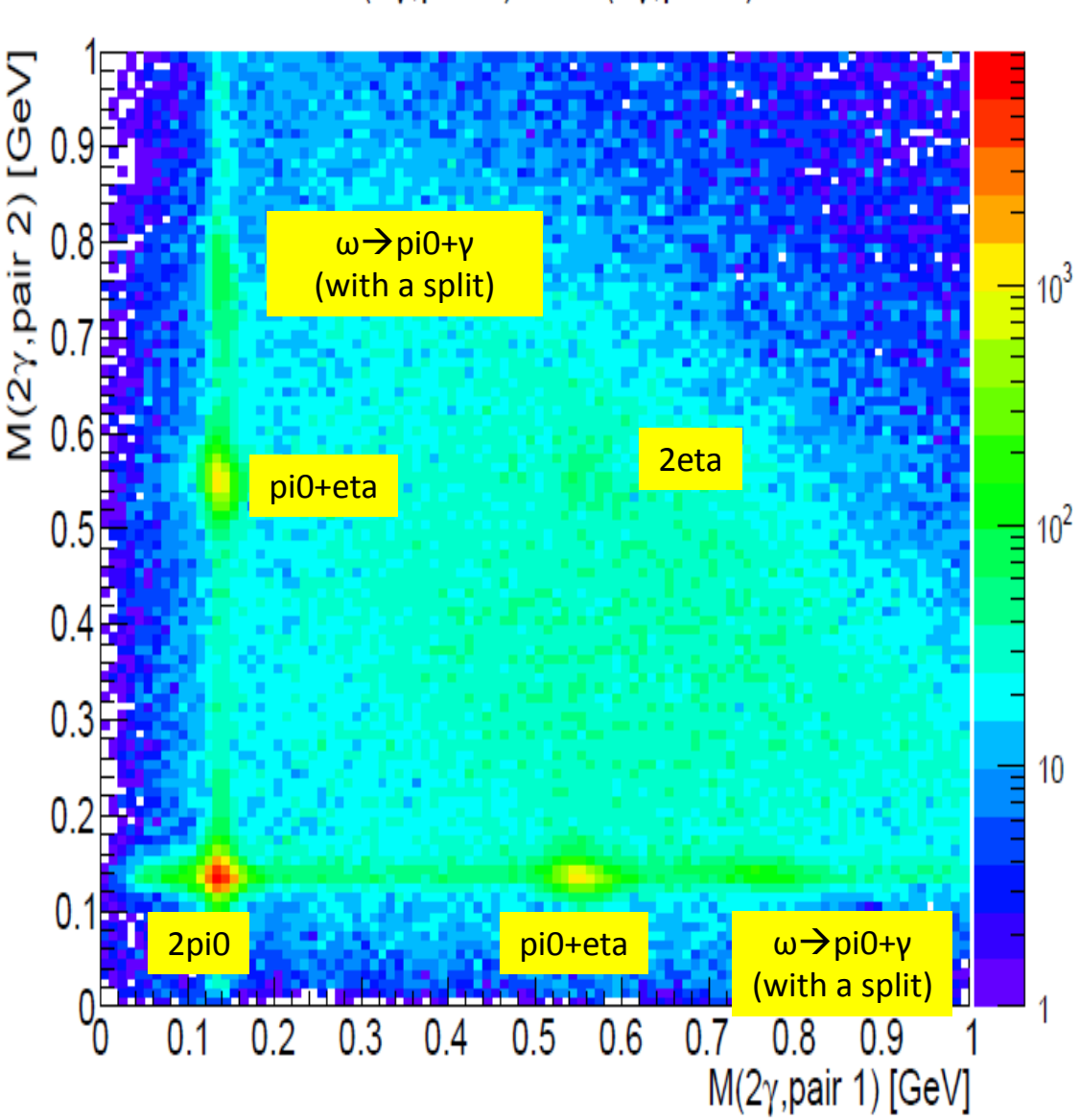
We should study later whether this cut really improves the FOM of the analysis.

# Main 4γ Channels

This plot shows pair-wise mass combos , Clearly revealing the pi0 and eta meson content, and strongly suggesting an omega splits bkg.

The total mass M(4gamma) is the sum of M(pair1), M(pair2), and M(pair1,pair2).

Because the latter is not shown in this plot, it's hard to see where the bkg combos are.




To do:
Make 3 versions of this plot with different cuts on M(4gamma):

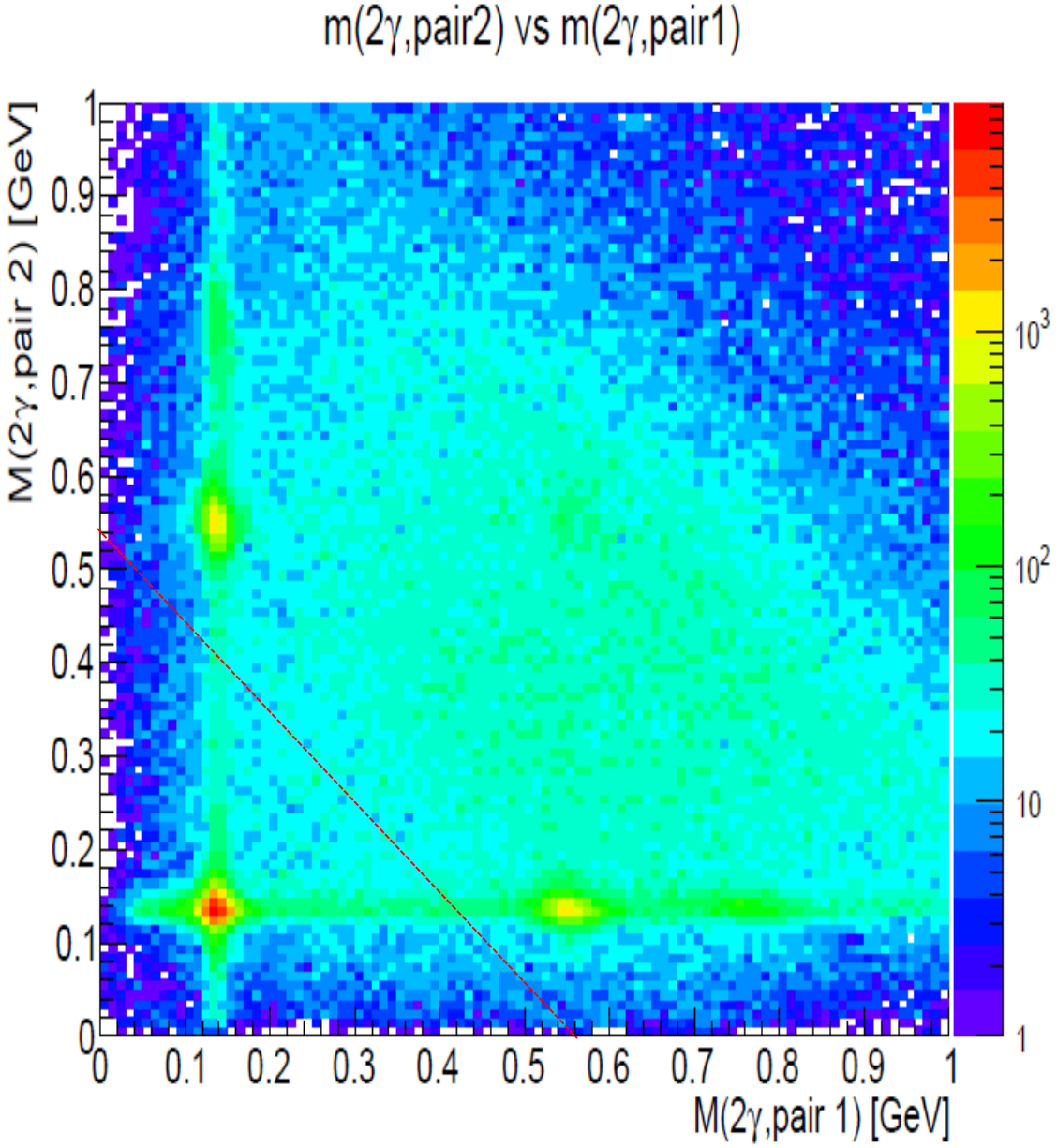
1. no cut (same as Simon's plot on left),

2. constrained to the eta mass +-2sigma, and

3. constrained to the eta' mass +-2sigma.

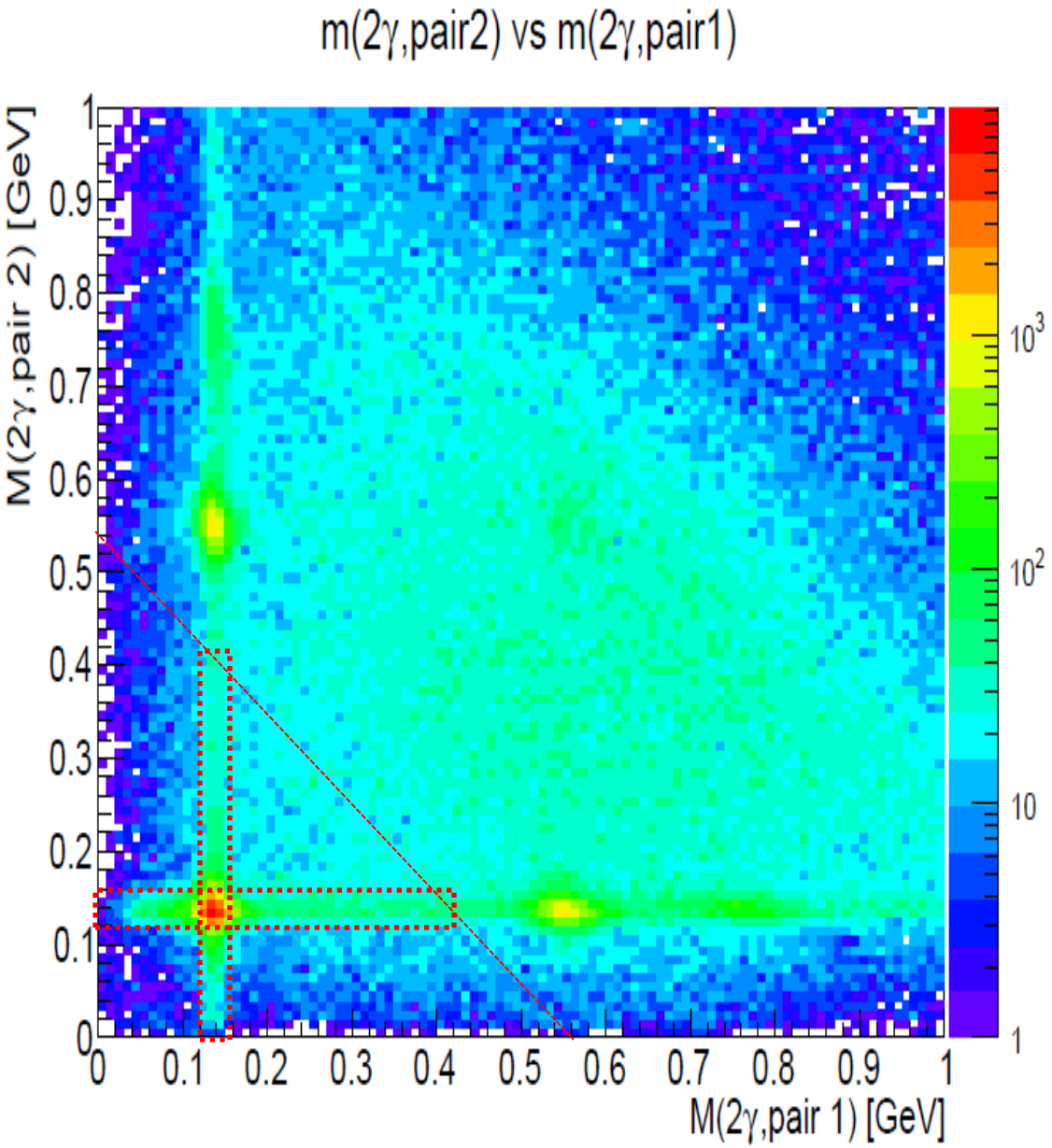
(It should become clearer that the omega splits and bad pi0+eta combos won't matter in the eta mass region.)

# Relevant η→4γ Pair-wise Combinations




If we constrain M(4γ) to ~$M_{eta}$ , only pair combos to the left of the diagonal line are possible.

# … and with $\eta \rightarrow \pi^0 2\gamma$ Signal Window



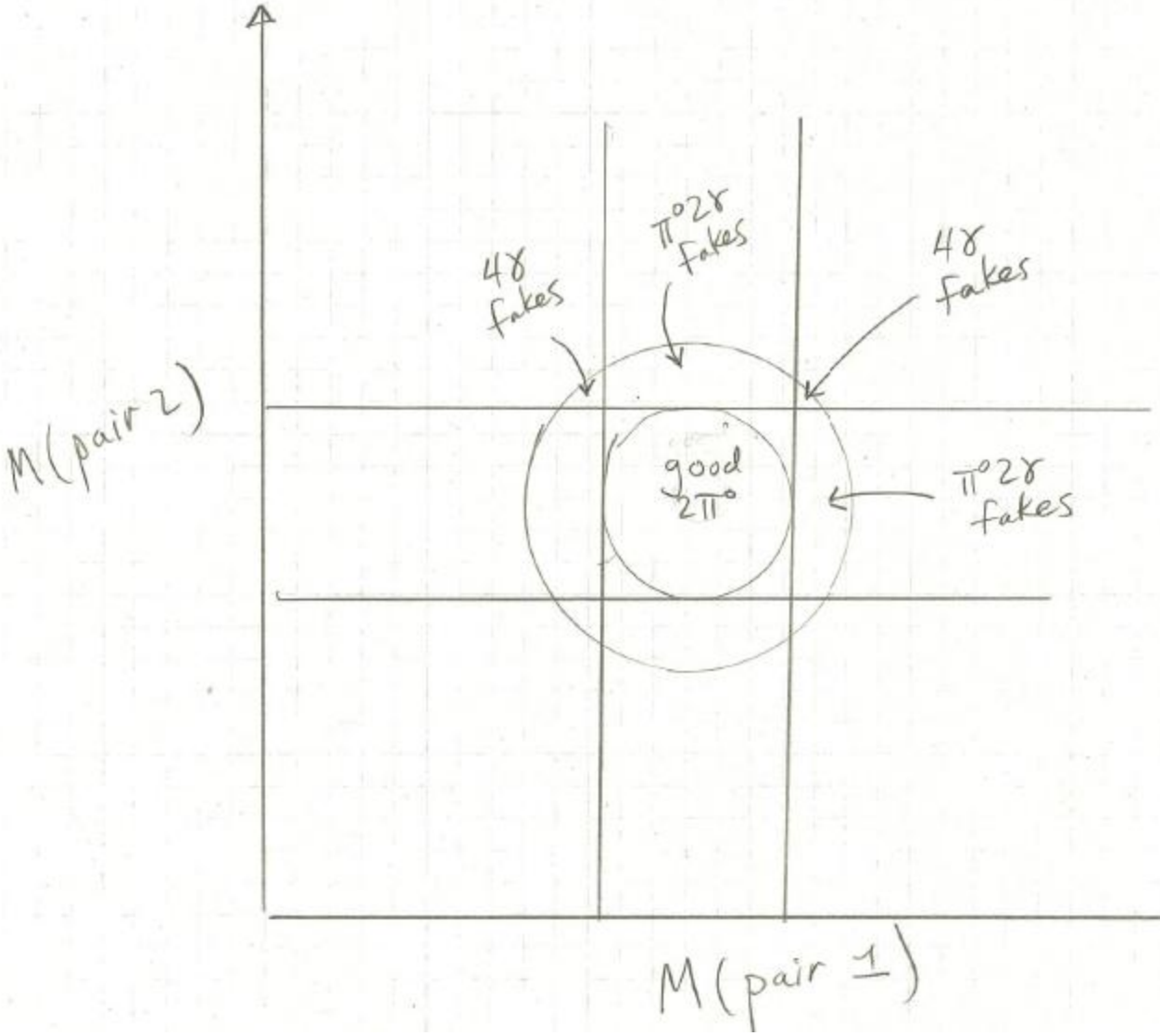

The signal for $\eta \rightarrow \pi^0 2\gamma$ will fall in one of the two dotted boxes.

**The major bkg is obviously 2pi0.**

Simon places a +-2sigma cut on the pi0 mass. That is appropriate for high purity on the 2pi0 signal, but it allows ~10% of the copious 2pi0 events to migrate into pi0+2gamma and true 4γ.

(see next slide)

# Effect of ±2σ π° ID Cuts on 2π°

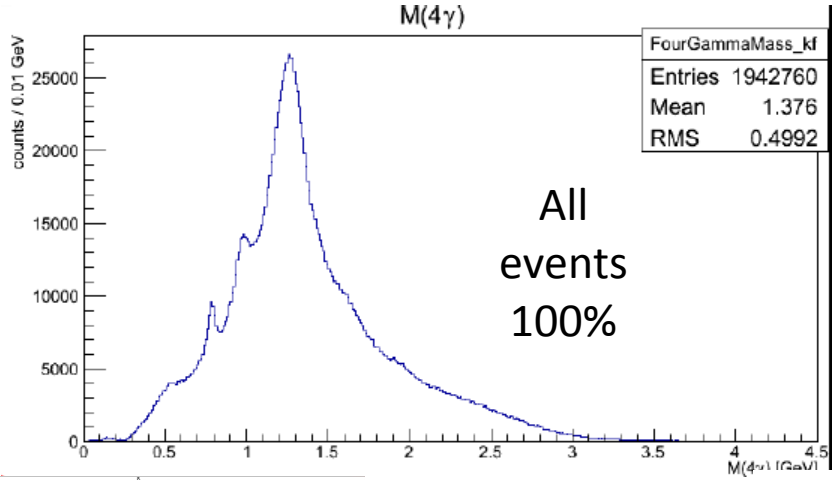



To do: change pi0 cut in the 2pi0 and pi0+eta definitions to +-3sigma.

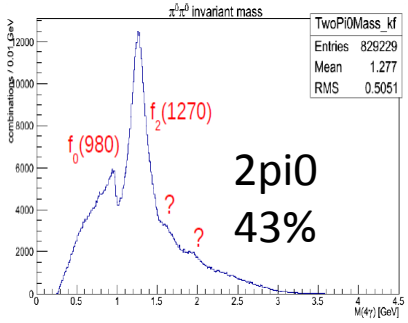
Although pi0+eta is normally too massive to be a significant bkg in $\eta \rightarrow \pi^0 2\gamma$, it is a potential bkg in $\eta' \rightarrow \pi^0 2\gamma$. So let's widen the corresponding eta cut as well.

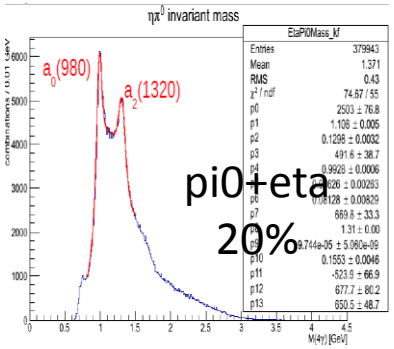
To do: change eta cut in the pi0+eta definition to +-3sigma.

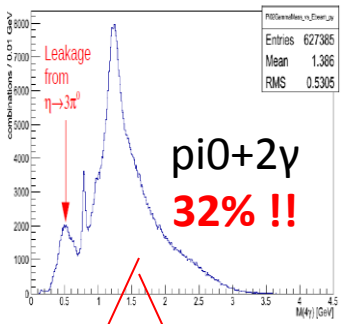
# Simon's Filtering With +-2σ PID Cuts

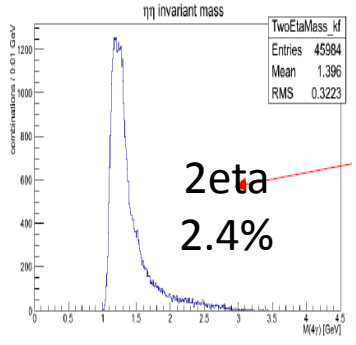



Surprisingly, these combos add up to 97%+ of events.
(Most of the missing 500% bad combos would presumably have landed in "true 4γ" which isn't plotted.)



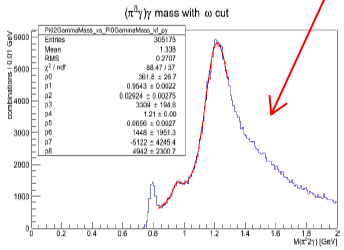




pi0+2gamma is <u>shockingly</u> large. Simon has discovered a large bkg from b1→ωπ$^0$ with a missing photon.

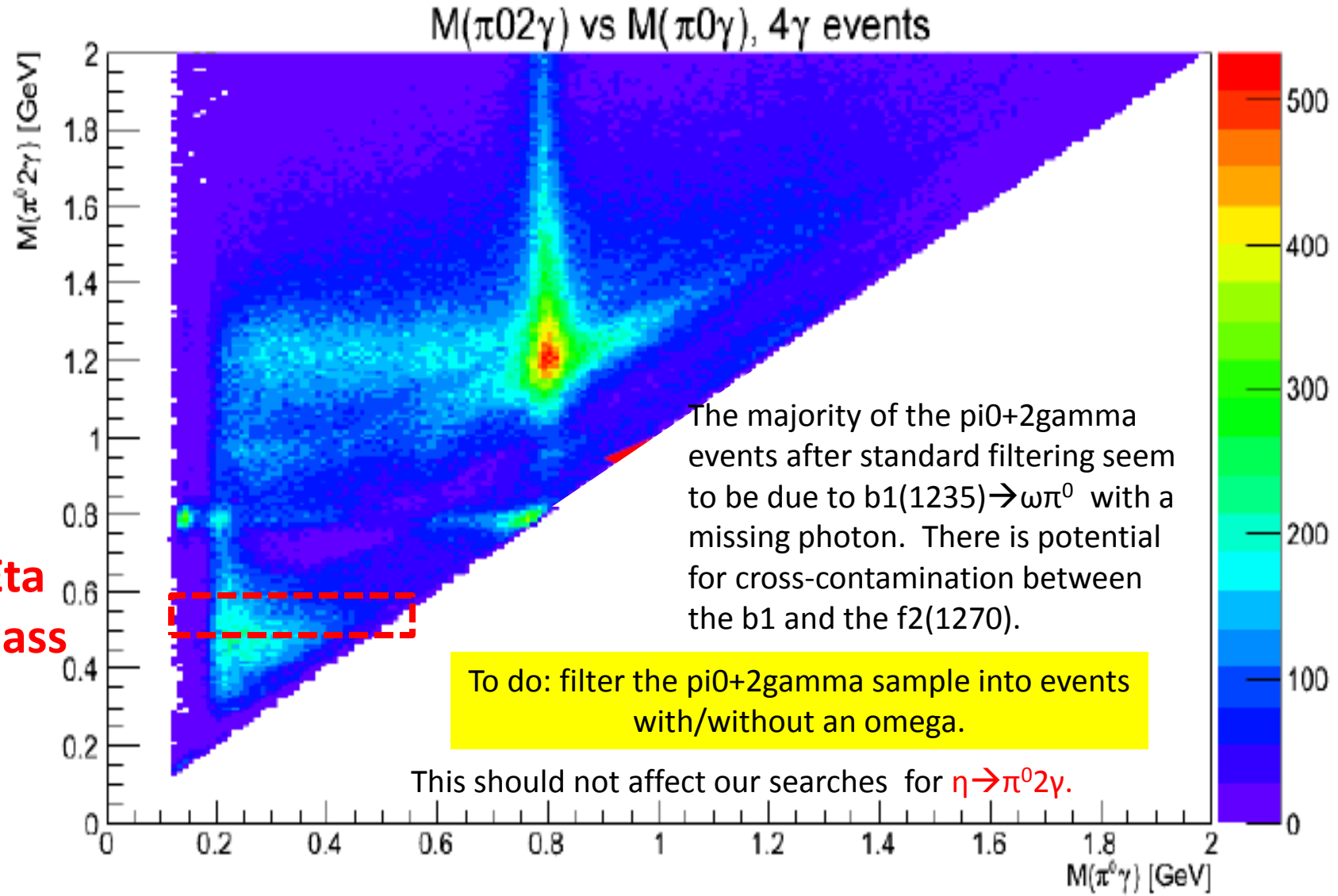
The b1 bkg has too high an invariant mass to contaminate η→π$^0$2γ , but it can contaminate η'→π$^0$2γ .




omega+γ
16%

<u>Not</u> omega+γ
16%?

# Search Window for $\eta \rightarrow \gamma + B \rightarrow \gamma + \pi^0\gamma$




**Eta Mass**

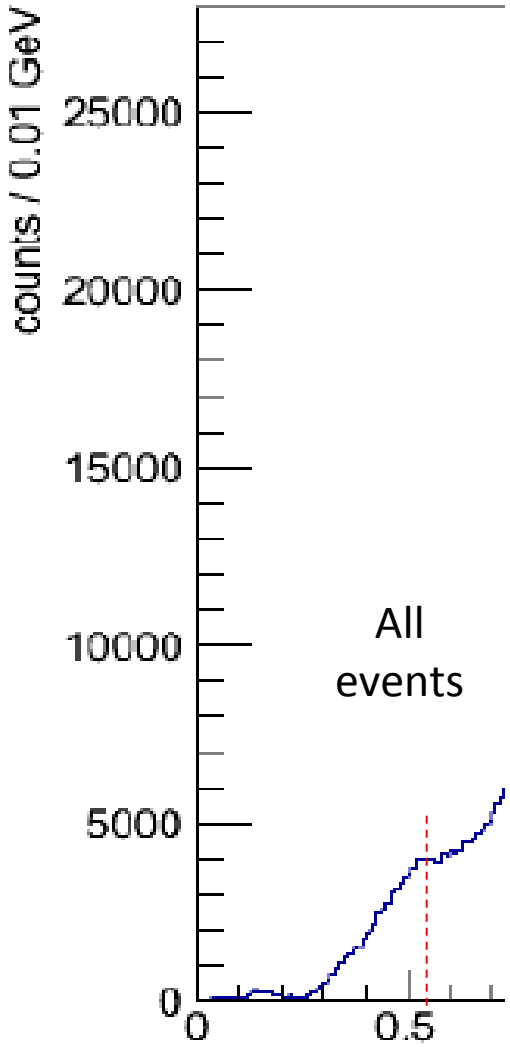
**B Mass**

The majority of the pi0+2gamma events after standard filtering seem to be due to b1(1235)→$\omega\pi^0$ with a missing photon. There is potential for cross-contamination between the b1 and the f2(1270).

To do: filter the pi0+2gamma sample into events with/without an omega.

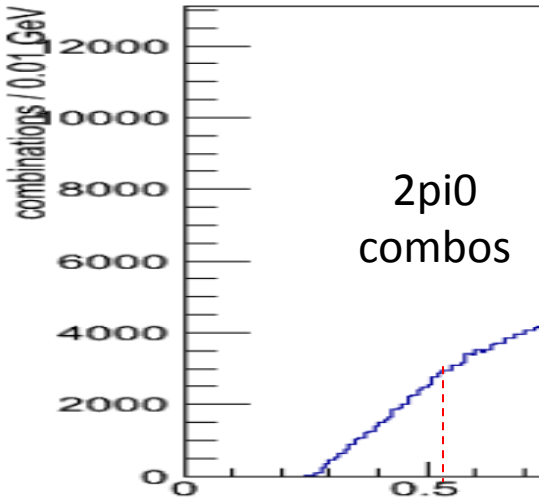
This should not affect our searches for $\eta \rightarrow \pi^0 2\gamma$.

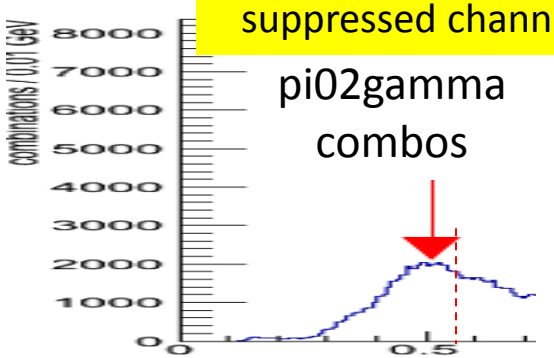
# Evidence for Combinatoric Bkg in Eta Mass Region




Near the location of the eta mass peak:

| Category | After Simon's Cuts | Anticipated with wider pi0 Cut |
|---|---|---|
| All events | ~4000 | ~4000 |
| 2pi0 | ~3000 | ~3300 |
| pi0+2γ | ~1700 | ~1400 |
| true pi0+2γ | ~75 (spread over 4 or so bins) | ~75 (spread over 4 or so bins) |



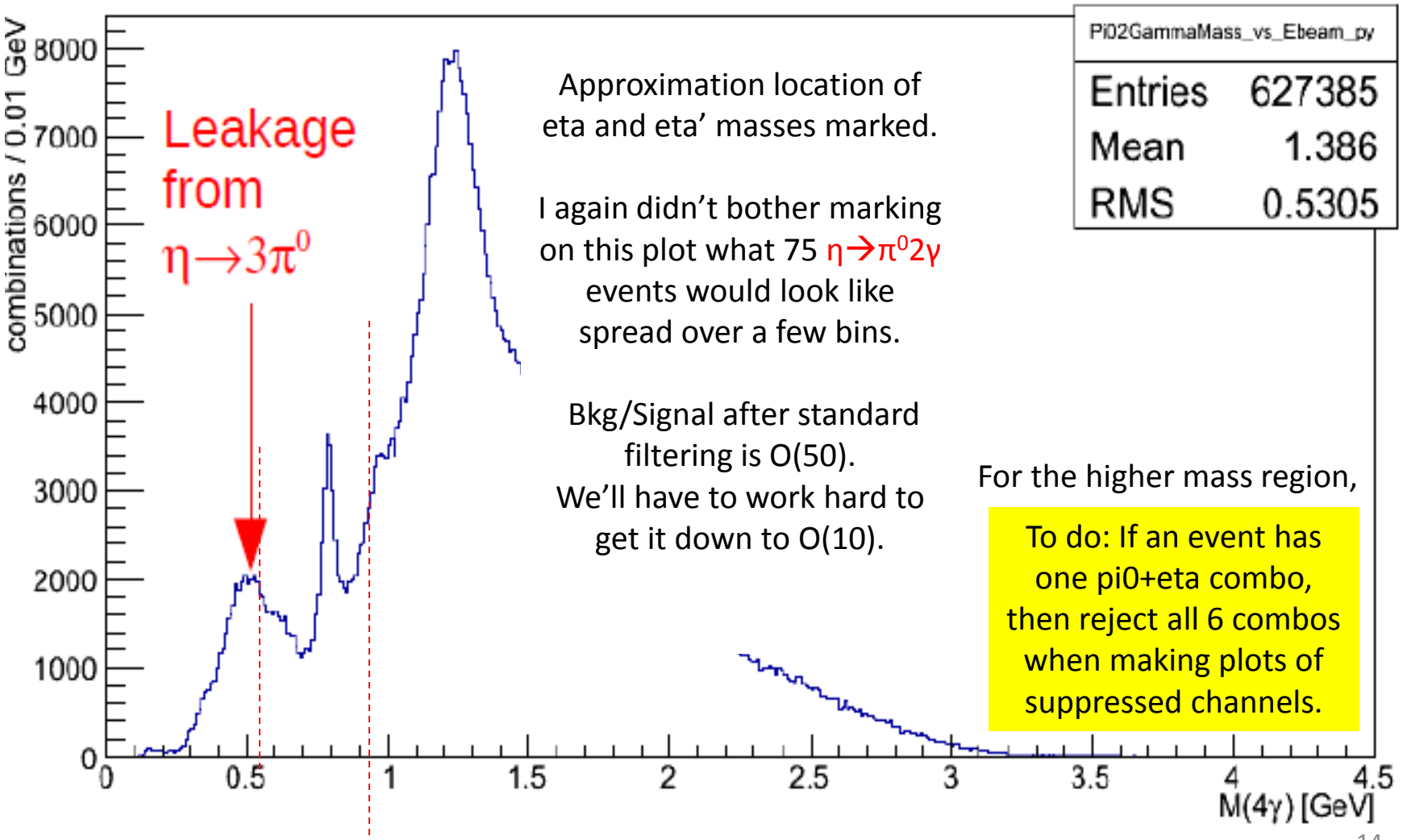

Observations

- 2pi0 accounts for ~80% of events at this mass.
- The 2pi0 and pi0+2γ combo categories already exceed all events by 700. Thus, at least half the pi0+2γ must be bkg combos, mostly from 2pi0.

To do: If an event has one 2pi0 combo, then reject all 6 combos when making plots of suppressed channels.

# $\gamma+p \rightarrow p + \pi^0+2\gamma$ Combos

$E_{\gamma\ beam}$ = 3-12 GeV




Approximation location of eta and eta' masses marked.

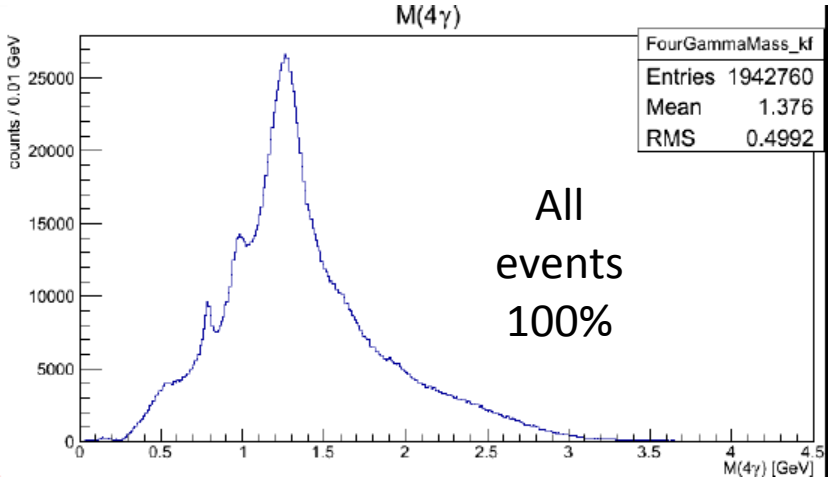
I again didn't bother marking on this plot what 75 $\eta \rightarrow \pi^0 2\gamma$ events would look like spread over a few bins.

Bkg/Signal after standard filtering is O(50). We'll have to work hard to get it down to O(10).

For the higher mass region,

To do: If an event has one pi0+eta combo, then reject all 6 combos when making plots of suppressed channels.

# Overview of Revised Filtering




…….Dominant Channels ……

| **2pi0** | **pi0+eta** | **omega+γ** |
|---|---|---|
| pi0+-3σ | pi0+-3σ | pi0+-3σ |
| pi0+-3σ | eta+-3σ | M(3γ)=omega+-3σ |

….Suppressed Channels (veto on dominant channels)…..

| **pi0+2γ** | **eta+2γ** | **2eta** | **True 4γ** |
|---|---|---|---|
| pi0+-2σ | eta+-2σ | eta+-2σ | |
| M(2γ).not. pi0+-3σ | M(2γ).not. pi0+-3σ | eta+-2σ | |
| M(2γ).not. eta+-3σ | M(2γ).not. eta+-3σ | | |

To do: partition the 4γ events into 2pi0, pi0+eta, omega+gamma, pi0+2gamma, eta+2gamma, 2eta, and "true 4γ".
For plots of suppressed channels, veto all combos of events which have one combo consistent with 2pi0 or pi0+eta or omega+gamma.

The only combo bkgs relevant to $\eta \rightarrow \pi^0 2\gamma$ are 2pi0.

# Estimate of $\eta \rightarrow 3\pi^0$ and $\eta \rightarrow 2\gamma$ Leakage Yield

Leakage from 3pi0 with 2 missing photons:

$N_{6\gamma}$ x (# photons x $\varepsilon_{MP}$ x $\varepsilon_{MP}$) = 4E4 x 6 x 0.025 x 0.025

= 150 fake events (responsive to cuts such as ME and excess energy veto)

Leakage from 3pi0 with two mergers:

$N_{6\gamma}$ x (# mergeable pair combos of 6 x $\varepsilon_{merge}$ )**2

= 4E4 x (12 pairs x 0.024)**2

= 4E4 x 0.083

= 3318 fake events (potentially a super nasty peaking bkg. )

Not sure how this will affect JEF. The high merging probability seen in Simon's survey might be a BCAL issue exacerbated by lower beam energies.

Leakage from 3pi0 with one missing photon AND one merge:

$N_{6\gamma}$ x (# mergeable pairs x $\varepsilon_{merge}$) x (# photons x $\varepsilon_{MP}$ )

= 4E4 x 10-12 pairs x 0.024 x 5-6 x 0.025

= 4E4 x 0.264 x 0.138

~ "1500" fake events (somewhat cuts responsive)

Leakage from 2gamma with two splits:

$N_{2\gamma}$ x (# photons x $\varepsilon_{split}$ ) x (# photons x $\varepsilon_{split}$ )

= 2.4E5 x (2 x 0.019) x (1 x 0.019)

= 2.4E5 x 0.0014

= 347 fake events (peaking bkg but responsive to cuts)

Efficiencies from http://argus.phys.uregina.ca/cgi-bin/private/DocDB/ShowDocument?docid=2985

# Composition of nominal $\pi^0$+2γ Combos near Eta Mass Peak

All events is ~4,000 near the eta mass peak.
True signal is an estimated 75 events spread over 4 or so bins.

| Categories | With Simon's +-2sigma Cuts | After +-3sigma pi0 cut | After rejecting all 2pi0 combos | Address Bkg With: |
|---|---|---|---|---|
| Total nominal pi0+2γ | 1,700 | 1,400 | .ge. 700 | |
| | | | | |
| Breakdown: | | | | |
| 2pi0 | 300 | ~0 | ~0 | |
| bkg combos (mostly from 2pi0) | 700 | 700 | ~0 | |
| 3pi0 + 2 MP (150/8bins) | 19? | 19? | 19? | Low priority bkg: Use excess energy veto. |
| 3pi0 + 2 mergers (3318/4bins) | 830? | 830? | 830? | recalculate after Ebeam > 6 GeV cut. Possibly use shower shape. |
| 3pi0 +1MP +1merger (1500/4bins) | 375? | 375? | 375? | recalculate after Ebeam > 6 GeV cut. Use excess energy veto. |
| 2γ dbl splits (350/4bins) | 90 | 90 | 90 | Low priority bkg: improved splits cuts. |

To do: apply the calorimeter excess energy veto with 10 MeV threshold.

# Summary of To Do's

**1 Set up a 4gamma analysis based on Jane's scripts.**

**2a. Cut data to Ebeam > 6 GeV**
**b. Use the calorimeter excess energy veto with 10 MeV threshold .**
**c. Make sure splits cut is enabled.**

**3. Set up a basic Simon-style filtering, adding some new categories and the following changes:**
**i. change the pi0 and eta definition cuts to +-3sigma.**
**ii. filter the pi0+2gamma sample into those with an omega and those without an omega. The categories will be 2pi0, pi0+eta, omega+gamma, pi0+2gamma, eta+2gamma, 2eta, and "true 4gamma".**

**At this point, Nian Qin should be able to do some simple hadronic physics studies. Pi0+eta?**

**4**. To better understand bkgs for suppressed channels, make 3 versions of the M(pair1) vs M(pair2) plot with different cuts on M(4gamma): no cut, constrained to the eta mass +-2sigma, and constrained to the eta' mass +-2sigma.

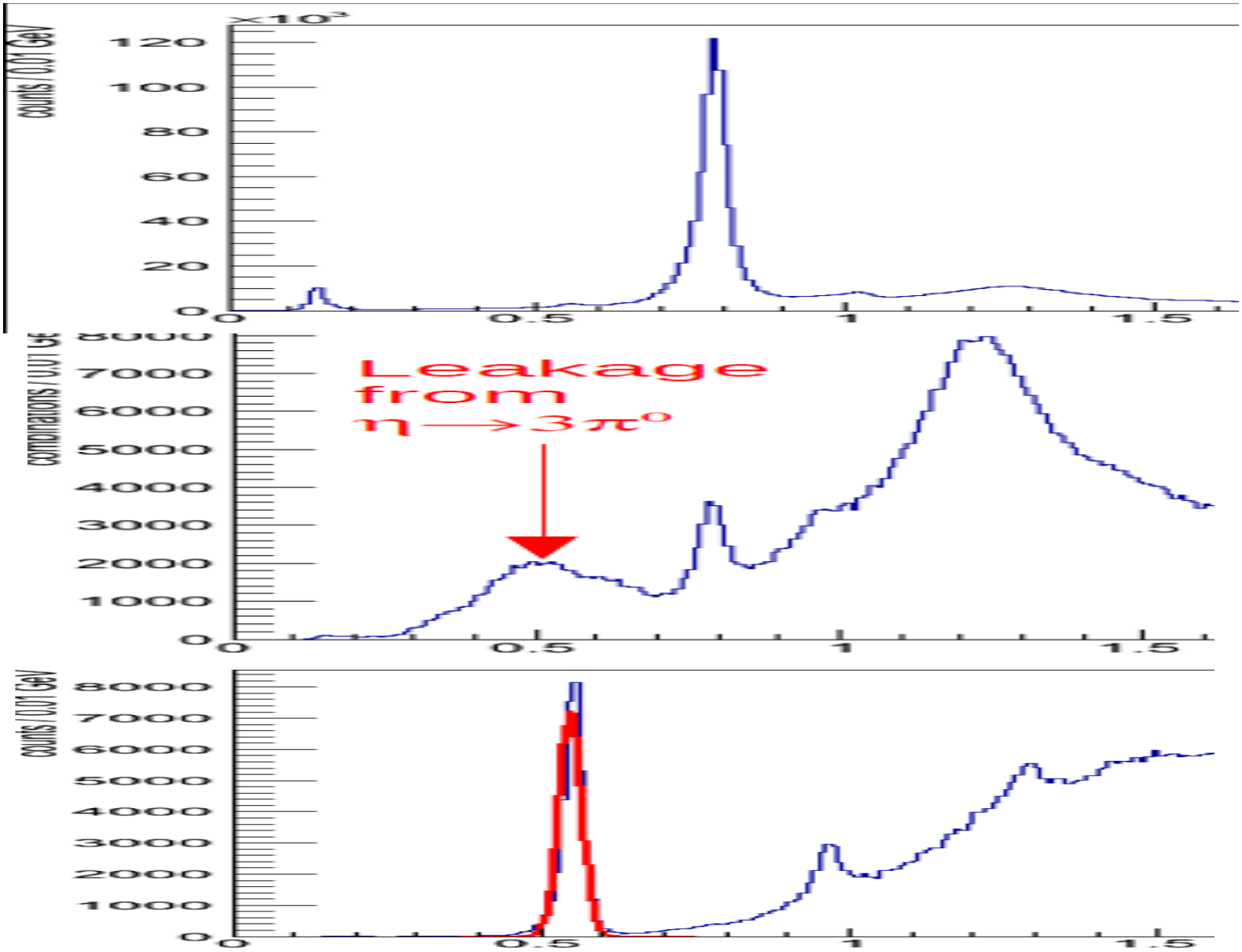
5**. If an event has one 2pi0 combo, then reject all 6 combos when making plots of the suppressed channels.** (Ditto for pi0+eta and possibly omega+gamma, which may be important for $\eta' \rightarrow \pi^0 2\gamma$.)

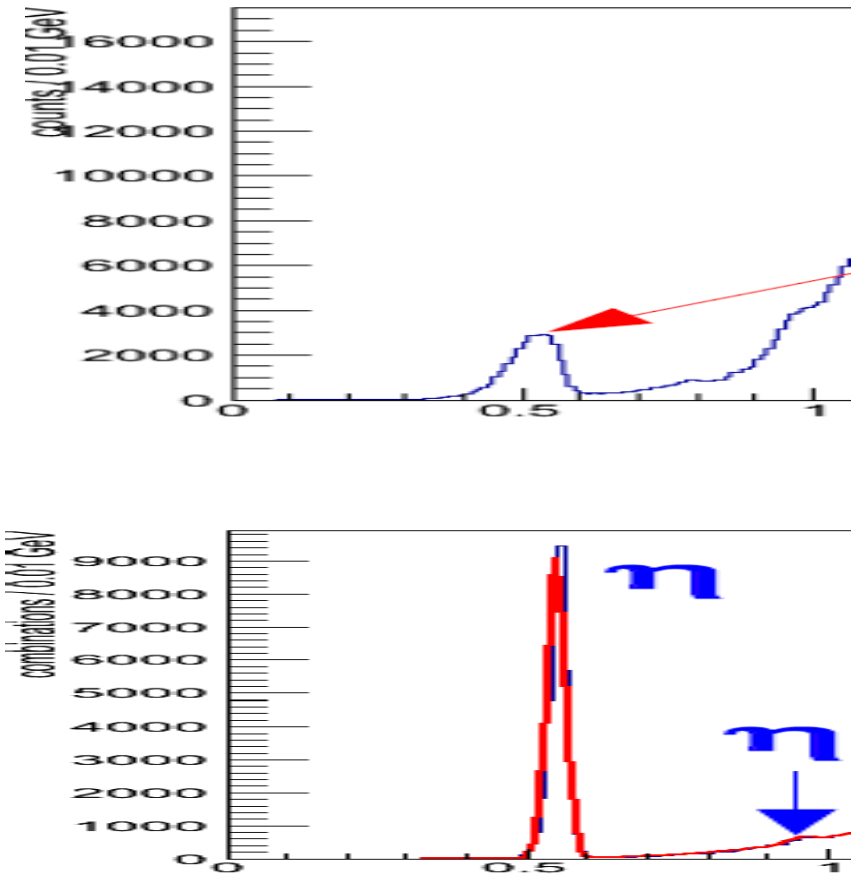
**At this point, we may be within a factor of several of our final Signal/Bkg ratio with GlueX base calorimeters. We might be able to start the B boson search.**

**Longer term:**
*** Better resolution will allow better rejection of non-peaking bgks. Do a simple P4 kin fit to the generic γ+p→p+4γ hypothesis. Recheck the number of events in each category, and adjust the pi0 and eta ID cuts as needed. (As well as the other cuts like ME.) Add the vertex constraint blah blah blah.**
*** See if the pi0 mass constraint significantly improves the resolution for eta →pi0+2gamma candidates. We might try this for eta'→P + 2gamma as well.**
*** If a peaking bkg from double merging in eta→3pi0 is really a problem, see if a shower shape cut can suppress it.**

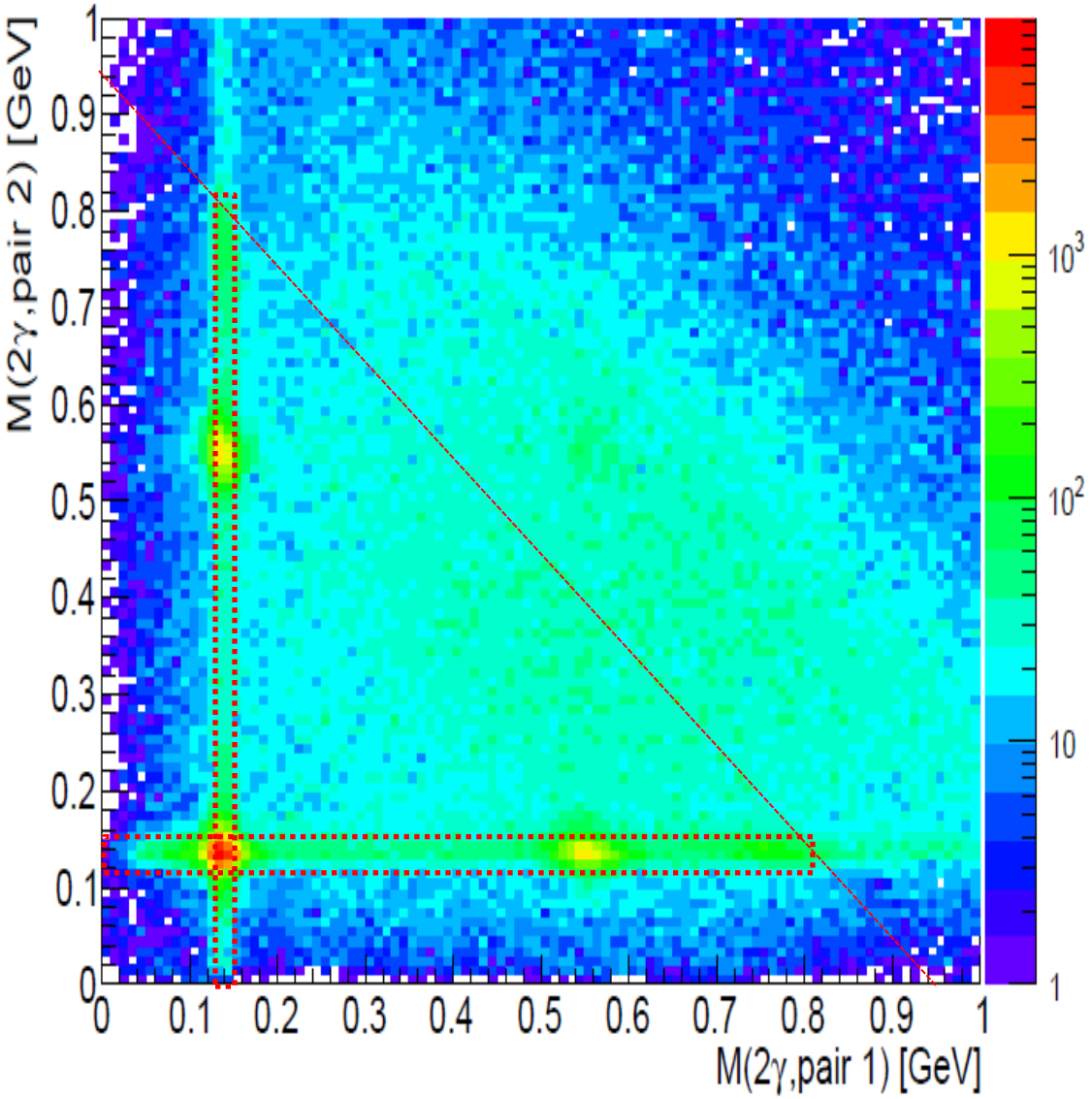
# Extras

# Leakage from 3γ and 6γ Events into $\pi^0$+2γ




counts / 0.01 GeV
6000
4000
2000
10000
8000
6000
4000
2000
0
0
0.5
1
combinations / 0.01 GeV
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.5
1
η
η

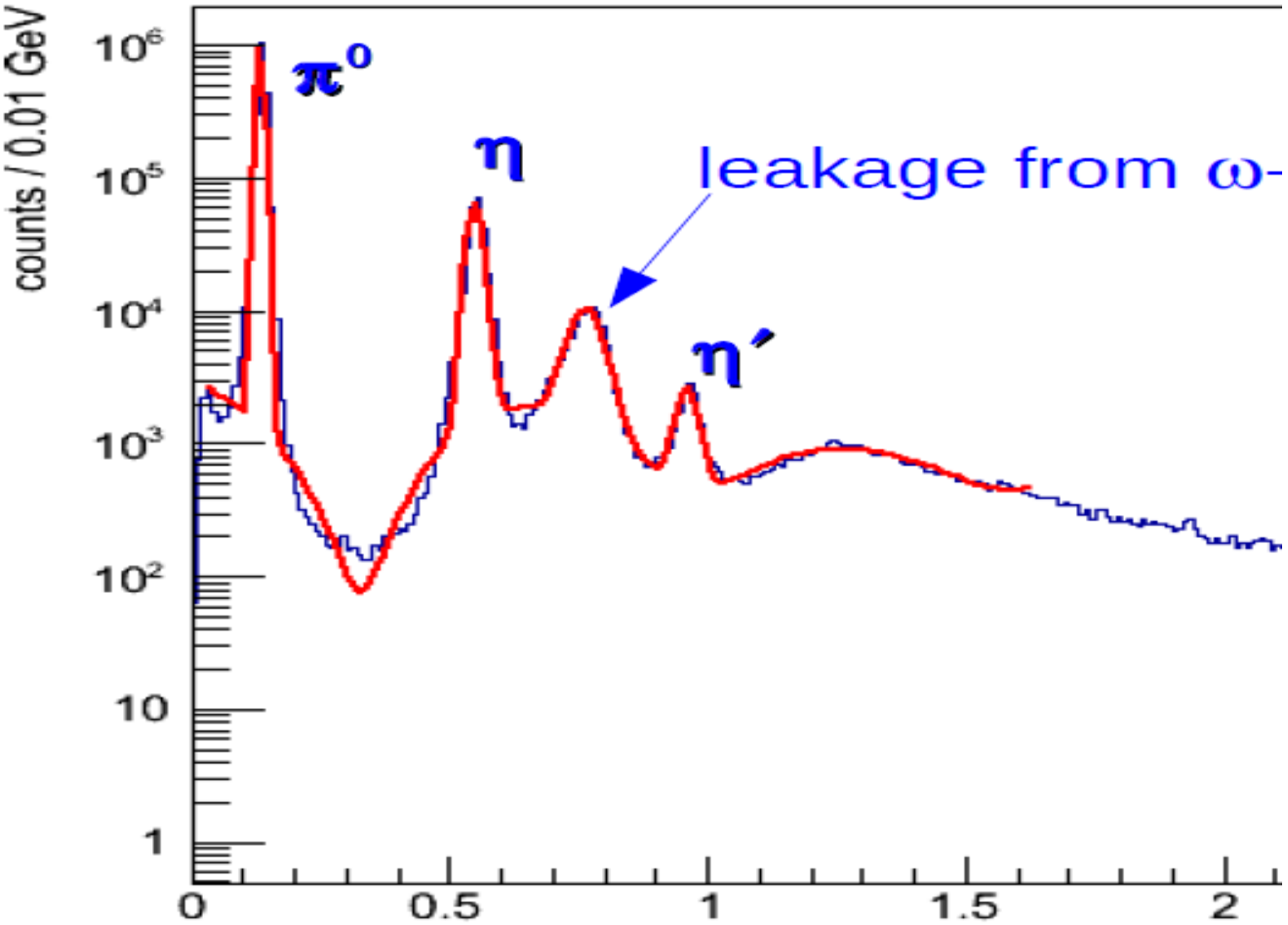
# … and with η'→π$^0$2γ Signal Window

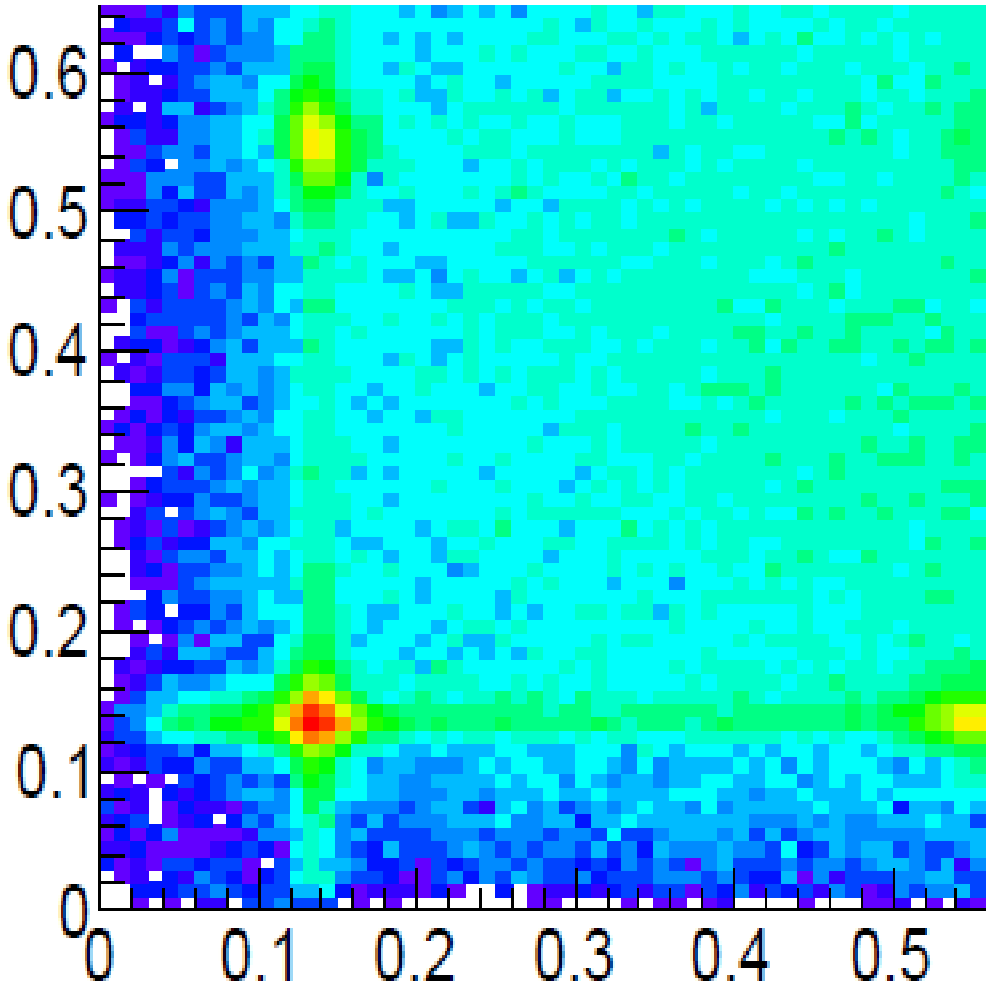



The signal for η'→π$^0$2γ will fall in one of the two dotted boxes.

**Some of the major bkgs are probably 2pi0 and pi0+eta.**

To do: change eta cut in the pi0+eta definition to +-3sigma.


counts / 0.01 GeV
$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
10
1
0
0.5
1
1.5
2
$\pi^0$
$\eta$
$\eta'$
leakage from ω-


0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5