Chapter 1

Analysis

In this chapter the various parts of the analysis are explained. In Section 3.1, the simulations used to estimate the ~~detector’ s~~ detectors’ ability to measure UPC processes are discussed. Section 3.2 explains the considerations that went into the ~~triggers that~~ ultra-peripheral triggers which were developed for this measurement. The event selection for the various data sets is detailed in Section 3.3. Extraction of the number of events from each of the three physics processes discussed in this thesis, coherent, incoherent, and photon-photon process is discussed is Section 3.5. The determination of the detectors efficiency for measuring UPC events is explained in Section 3.6. Finally ~~, Section 3.7 lays out~~ the systematic uncertainties ~~estimates for the measurements~~ on the measurements are described in Section 3.7.

1.1 MC simulation

Every physical measurement is the product of the underlying physics folded with the response of the detector used to do the measurement. In order to understand the underlying physical process, the detector’s effect on the measurement must be understood and accounted for. As instruments become more and more complicated, the interplay between ~~all of~~ the many parts of the detector makes an analytic approach to the problem untenable. For this reason, the numerical technique of Monte Carlo (MC) simulation is the most useful approach.

MC simulations use random number generation to solve the problem numerically by brute force. First, particles are generated according to theoretical distributions. These particles are then propagated through a simulation of the detector. As the particles pass through the detector, random numbers are again used to determine how these particles interact with the materials of the detector based on the known properties of the ~~material~~particular particles and the material through which they pass. In this way, the theoretical distributions are ~~convolved~~ convoluted with a realistic ~~model of the detector's response . A more detailed picture of how the detectorshapes the underlaying distributions with each successive event. The set of events that are produced resemble as closely as possible~~ response of the ~~results that would be seen were the physical process to be measured by the detector.~~ detector. If this is done for many events it is possible to accurately deduce the response of the detector to a particular physical process.

In this thesis, two main classes of MC simulation samples were used, ~~STARlight~~ STARLight and a particle gun. The STARlight samples ~~corresponds~~ correspond to the theoretical calculations described in Section **??** ~~,~~ while the particle gun generator produces particles with a user defined momentum distribution. For STARlight three different physical process ~~are~~ simulated; coherent J/ψ production, where the photon couples to the nucleus as a whole, incoherent J/ψ production, where the photon couples to a nucleon within the nucleus, and photon-photon ~~interactions, where the~~ collisions, where photons from the two nuclei interact with each other to produce a pair of oppositely ~~charge~~ charged muons directly. All three STARlight samples contain a μ^+ and μ^- in the final state. The second class uses PYTHIA6 to decay J/ψs produced with a user defined p_T and rapidity distribution into muon pairs.

Because STARlight is not integrated into the standard CMS software framework (CMSSW), a simulation software chain with 5 steps was developed. First, STARlight is run in the specified mode, and a single file is created for each physics process. In step 2 the ~~STARlight~~ STARLight output file is converted to the Les Houches (LHE) format ~~[?] ,~~ [?] and the momentum of the ~~parent or the initial~~ original J/ψ or photon-photon pair is added to the record of each event. ~~The event record produced by STARlight only contains the final state particles.~~

~~To process the events in parallel, the STARlight files are subdivided into in step 2, creating~~ To allow parallel processing the events contained in one STARlight file are spread over several LHE files ~~from a single STARlight file. The LHE files are~~ which are then used as input to CMSSW. Steps 3 to 5 take place within ~~CMSSW~~the CMSSW framework. In step ~~three~~ 3 the generated particles are propagated through the GEANT4 ~~[?]~~ detector simulation. This accounts for all the interactions with the detector and produces as output a format identical to the raw data that is recorded during data taking. Steps 4 and 5 are ~~processed using the same software as in datataking~~identical to the treatment of real data. In step 4 the reconstruction software used during data taking is run on the output of the detector simulation~~The~~. Finally in step 5 the output of the reconstruction is reduced to the information that is needed for the final analysis~~in the final step~~.

The particle gun samples were created entirely within CMSSW. J/ψ mesons were created according to ~~user defined~~ use defined p_T and rapidity distributions ~~,~~ and then the PYTHIA6 ~~[?] decays the~~ package is used to decay the J/ψs to μ^+ and μ^- [?]. As with the STARlight samples, these muons are propagated through the GEANT4 simulation of the detector, and the raw data is produced. The remaining steps of running the reconstruction code and reducing the data to the final data needed for the analysis are identical to the STARlight production.

The various MC samples, differ primarily in the ~~distribution and the~~ p_T distribution and polarization of the J/ψs produced. The polarization of the ~~effects the angle at which the muon daughters are emitted relative to the direction in which the is traveling [?] .~~ J/ψs controls the distribution of relative angles between the muon decay products and the original direction of the J/ψ. In Fig. 3.1 the ~~of~~ p_T of J/ψs from the coherent and photon-photon samples are peaked steeply a low p_T, and neither sample extends much beyond 0.15 GeV in p_T. The incoherent sample is peaked near 0.5 GeV and extends beyond 1 GeV. The two particle gun samples resemble the incoherent and coherent samples. The first sample has a Gaussian p_T distribution extending to approximately 0.15 GeV, whereas the second is flat in p_T up to 2 GeV. The particle gun samples are unpolarized, whereas the STARlight samples have transverse polarization. Therefore, the particle gun samples there is no preferred direction for the emission of the daughter muons. In the STARlight samples however the daughters tend to be emitted in line with the direction of the J/ψ's momentum. This is particularly pronounced for the photon-photon process.

Figure 1.2: The J/ψ polarization of the particle gun (red), coherent (blue), and incoherent samples are plotted as the cosine of the helicity angle.

~~The momentum of the final state muons is the main drivers of whether the candidate can be measured. If neither muon daughter of the possess~~

In order for a J/ψ to be reconstructed in CMS both of the muon daughters must have sufficient momentum to be reconstructed in the tracker and at least one must have enough momentum to reach the muon chambers and fire the trigger~~, the event will not be recorded. The polarization and the distribution of dimuons from the generator determine the momentum of~~. The sum of the momentum of both muon daughters equals the momentum of the parent J/ψ while the difference depends upon the J/ψ mass and the decay angle of the ~~daughters.~~ muons relative to the J/ψ direction. The probability of a given decay angle is determined by the polarization of the J/ψ. The polarization effects how the momentum is shared between the daughters. In the rest frame of the parent particle from which the daughters decay, equal momentum is given to each daughter. However in the lab frame of the detector, the muon daughters which are emitted from transversely polarized J/ψ will tend to be emitted ~~in the direction of~~ parallel and antiparallel to direction of the J/ψ and will have unequal momentum in the ~~lab~~ laboratory frame. The daughter ~~traveling in the direction of the~~ parallel to the J/ψ will have increased momentum, whereas the daughter traveling ~~opposite to the~~ to antiparallel to the J/ψ direction will have decreased momentum. The momentum of the lower momentum muon daughters is the main ~~restriction~~ constraint on whether or not ~~the~~ a particular J/ψ can be reconstructed in CMS.

1.2 Trigger development

The ~~increase in collision rate of the LHC PbPb beams from 2010 to 2011 was nearly a factor of 15. To accommodate this increase in rate,~~ luminosity of the 2010 LHC PbPb was so low that

CMS could record every interaction using very simple triggers. The expectation of a significant increase in luminosity for the 2011 ~~trigger scheme needed to be more selective than in~~ run was the motivation for the development of several different triggers designed to capture particular classes of events. These triggers were based on rate estimates from the 2010 ~~where CMS could take any event which appeared to have a collision. The available bandwidth was allocated equally amongst the various heavy ion analysis groups to pursue as wide a physics program as possible . From this consideration, bandwidth limits were placed on the trigger rates for each analysis group's trigger package. To ensure that UPC physics could be explored all while respecting the goals of the CMS Heavy Ions group as a whole, a collection of UPC triggerswere commissioned~~data and the projected increase in luminosity for 2011 as compared to 2010.

Since the bandwidth of CMS is limited it was essential to make the triggers as efficient as possible while ensuring that they captured the desired physics dataset. In order to normalize any triggered data set it is necessary to know the efficiency of the trigger. This typically requires a hierarchy of monitoring triggers.

~~The UPC triggers were estimated by combining existing triggers from the 2010 run. By calculating the ratio between the UPC trigger rates and the minimum bias trigger rate, the UPC trigger rates were scaled up to the anticipated~~ During PbPb runs the baseline voltage of small regions of the tracker can fluctuate due to a high local density of tracks. An algorithm to correct for this was developed but in 2011 ~~interaction rates using the 2010 data.~~ it could not be implemented in the firmware of the tracker and had to be run on the HLT farm. This was very slow and meant that the total L1 trigger rate had to be limited to a few kHz. Of this rate the UPC group was assigned a total of 200 Hz for all L1 triggers.

The trigger package for 2011 ~~contained ZDC based efficiency monitoring triggers~~consisted of, muon and electron based triggers for ~~measuring , and~~ capturing J/ψ mesons, backup triggers in case there was a problem with the original muon and electron triggers ~~.~~ and finally ZDC based monitoring triggers. These monitoring triggers were prescaled in such a way that they collected a significant number of the more restrictive lepton triggers while not exceeding the bandwidth allocated to the UPC group.

1.2.1 L1 trigger

The goal of the UPC L1 triggers was to record enough data to measure UPC J/ψ production via the ~~dimuons and dielectrons~~ dimuon and dielectrons decay channels. To achieve this, the loosest muon and electron triggers ~~where~~ were paired with a trigger on energy in the ZDC and a veto on energy in the ~~BSCs~~BSC. Additional triggers that vetoed on energy in HF were commissioned in case radiation damage during the run reduced the sensitivity of the BSCs. These triggers are summarized in Table 3.1. ~~The 5 and 2 for the ECAL triggers in Table 3.1 indicate a 5 and 2 GeV threshold on E_T measured in the ECAL. The Open in the muon trigger indicates that the trigger only requires a muon candidate in one of the three muon sub-systems and that there is not momentum threshold.~~ The prescales of the monitoring triggers represent a balance between the competing objectives of rate reduction and increasing the overlap between the monitoring and signal triggers.

L1 ~~trigger~~ Trigger Seed	~~Rate (Hz) Prescale Id~~ Type
MuonOpen and (ZDC^+ ~~or~~ or ZDC^-) and BSC veto	~~2.1 1 1~~ Physics
ECAL2 and (ZDC^+ ~~or~~ or ZDC^-) and BSC veto	~~1.8 2 2~~ Physics
ECAL5 and (ZDC^+ ~~or~~ or ZDC^-) and BSC veto	~~0.3 1 3~~ Physics
(ZDC^+ ~~or~~ or ZDC^-)	~~35 1500 4~~ Monitor
MuonOpen and (ZDC^+ ~~or~~ or ZDC^-) and HF veto	~~0 off 5~~ Backup
ECAL2 and (ZDC^+ ~~or~~ or ZDC^-) and HF veto	~~0 off 6~~ Backup
ECAL5 and (ZDC^+ ~~or~~ or ZDC^-) and HF veto	~~0 off 7~~ Backup

Table 1.1: List of 2011 L1 seeds. ADD A COLUMN FOR DOWNSCALES

~~The cumulative~~

1.2.2 HLT trigger

As opposed to the L1 ~~trigger rate for all the UPC L1~~ trigger~~seeds was required to be 200 Hz. This requirement stemmed from the need to keep the~~, which has access only to information from the calorimeters and muon chambers, the HLT has access to all detector information in CMS, including that from the tracker~~read-out rate low. The trackers baseline voltage can fluctuate due to the high trackerhit multiplicities in PbPb collisions. In order to monitor the zero suppression of the tracker, the zero suppression algorithm was executed using the HLT computing farm rather than in the tracker firmware.~~

~~In order to record the efficiency monitoring data, the ZDC triggers had to be prescaled to a lower rate. The scaling down of the monitoring trigger was setup to insure overlap with the signal~~. Using the processors of the HLT farm it is possible to fully reconstruct an event before deciding weather to store it. Each HTL trigger path requires a L1 trigger as a “seed", so it is important to match the rates of the L1 and HTL triggers. The ~~prescales for the triggers were set to balance the competing objectives of rate reduction and increasing the overlap between the monitoring and signal triggers.~~

1.2.3 ~~HLT trigger~~

~~As opposed to the L1 trigger, which has access only to information from calorimeters and muon chambers, the HLT has access to all the sub-detectors including the tracker. Reconstruction of a~~ main limitation on the HLT is the amount of computing time needed to process events and the volume of data that must be stored for offline. In 2011 the UPC triggers were assigned an output bandwidth of 20 Hz, a factor of 10 lower than the level 1 input rate. Most of this reduction was achieved by requiring a pixel track in the ~~pixel detector is used by the UPC trigger paths~~physics triggers in order to reject backgrounds where no particles are reconstructed by the tracker. The use of the pixel detector only, as opposed to using the whole tracker including the silicon strip detector, allows for quick track reconstruction saving computing cycles. The ~~requirement of at least one reconstructed pixel track for the HLT triggers was designed to reject backgrounds where no particles are reconstructed by the tracker. For the muon trigger~~ HTL prescales of the monitoring triggers were set as high as possible while keeping the total HLT bandwidth below the limit of 20 Hz. The HLT triggers are summarized in Table 3.2~~the rate was reduced by nearly a factor or 4 compared to its L1 seed rate in Table 3.1. This is due to the additional pixel track requirement.~~.

HLT ~~trigger Rate (Hz) L1 prescale HLT prescale L1 seed Type~~ Trigger	
~~L1UPCMuon and Pixel Track~~ HLT_HIUPCNeuMuPixel_SingleTrack	~~0.52 1 1 1~~ Phy
~~L1UPCECAL2 and Pixel Track~~ heightHLT_HIUPCNeuEG2Pixel_SingleTrack	~~1.65 2 1 2~~ Phy
~~L1UPCECAL5 and Pixel Track~~ heightHLT_HIUPCNeuEG5Pixel_SingleTrack	~~0.26 1 1 3~~ Phy
~~L1ZDCOr~~ HLT_HIMinBiasZDC_Calo_PlusOrMinus_v1	~~3.6 1500 11 4~~
~~L1ZDCOr and Pixel Track~~ heightHLT_HIMinBiasZDC_PlusOrMinusPixel_SingleTrack_v1	~~2.8 1500 1 4~~ M
~~L1UPCMuonHFVeto and Pixel Track~~ HLT_HIUPCNeuHcalHfMuPixel_SingleTrack	~~0 off off 5~~ Bac
~~L1UPCECAL2HFVeto and Pixel Track~~ heightHLT_HIUPCNeuHcalHfEG2Pixel_SingleTrack	~~0 off off 6~~ Bac
~~L1UPCECAL5HFVeto and Pixel Track~~ heightHLT_HIUPCNeuHcalHfEG5Pixel_SingleTrack	~~0 off off 7~~ Bac

Table 1.2: List of 2011 HLT ~~trigger~~triggers. ADD A COLUMN FOR DOWNSCALES, L1 seeds and maybe output rates.

~~The total HLT output for the UPC trigger package was 20 Hz. The limiting factor for the HLT rate was the amount of disk space available to store the data. To meet the bandwidth requirements and collect a significant sample of data for estimating efficiencies, the prescales were balanced with the goal of achieving at least 5% statistical precision on the efficiency estimates. As an example of the balancing of the prescales, the ZDC trigger that was passed through from the L1 was given a additional prescale factor of 11 on the HLT. The ZDC path that also required a pixel track on the HLT, which used the same L1 seed, was only prescaled at the L1. The prescale of 11 was set to ensure that at least 1000 of the pixel track ZDC triggers overlapped with the ZDC L1 only triggers so that efficiency of the pixel track requirement in the trigger could be estimated from the tracks lost.~~

1.3 Event selection

In order to investigate novel physics processes like UPC J/ψ production, the LHC has delivered unprecedented amounts of data. The data for this analysis was recorded during the 2011 LHC PbPb run. During this period, 150 μb^{-1} where recorded by the CMS detector, corresponding to over a billion PbPb collisions. Of this, 143 μb^{-1} were used in this analysis.

1.3.1 Data sets

Three specially selected samples were used for the present analysis, Physics, ~~Monitoring, and Zero bias~~Minimum Bias and Zero Bias, see Table 3.3. By recording this hierarchy of samples, interesting events are selected with a much higher purity in the physics sample, while the ~~zero bias and ZDC triggered~~ minimum and zero bias samples allow for the investigation of the selection criteria. These samples were recorded using subsets of the HLT triggers found in Table 3.2 of Section 3.2. The J/ψ events discussed in this thesis were obtained analyzing the sample labeled in Table 3.3 as physics. A ZDC triggered ~~monitoring~~ minimum bias sample was recorded for the sake of estimating efficiencies. Lastly, a zero bias sample was recored for investigating the ZDC and the noise distributions of HF.

~~The~~ To record the physics sample containing the ~~signalwas recorded by the muon trigger labeled "L1UPCMuon and Pixel Track" in Table 3.2.~~ J/ψ signal, a muon trigger was paired with a veto on energy in the BSC and a requirement that there be energy, typically from a neutron, in at least one of the ZDCs. This trigger was designated HLT_HIUPCNeuMuPixel_SingleTrack. Because of the characteristically low momentum of UPC J/ψ as compared to J/ψ created by any other physics ~~processes~~process, the loosest muon trigger was used. ~~The noise trigger rate for the muon trigger alone was 50Hz, but in coincidence with the BCS veto and the ZDC trigger the noise rate was below 2Hz. By pairing the muon trigger with the ZDC on the L1, the noise contribution was reduced from the noise contribution from either of the two sub-detectors to the noise coincidence between the two sub-detectors. Contributions from hadronic interactions are reduced by the veto on the BSCs.~~ This trigger has a significant noise rate and is sensitive to muons from both ultra-peripheral and nuclear interactions. Muons from nuclear interactions are almost eliminated by the veto on the BSC. The requirement of a neutron one of the ZDCs significantly cuts the noise rate in the trigger since it is unlikely that both the muon chambers and the ZDCs would both fire on noise within 25ns of each other. The muon requirement does of course eliminate UPC events that do not produce a forward neutron. This trigger was designed to ~~balance~~ strike a balance between reducing the rate ~~with~~ and maximizing the efficiency, allowing for the data to be

Sample	Events	$\mathscr{L}_{int}$
Physics	~~346K~~ 300K	~~143.3 μb^{-1}~~ 143.3 μb^{-1}
~~Monitor~~ Minimum Bias	~~1.1M~~ 100K	~~31.6 mb^{-1}~~ X
Zero Bias	~~8.8M~~ 5M	~~580 b^{-1}~~ 580 b^{-1}

Table 1.3: Integrated luminosities and number of events for the three samples used in this analysis.

recorded without producing high rates resulting in dead time for the detector.

In order to investigate the muon trigger and the other parts of the event selection, a ~~monitoring~~ minimum bias sample was recorded by requiring energy consistent with at least one neutron in either of the ZDCs. This process is much more common than the UPC ~~production. Neutron production has cross sections on the order of 100 b compared to 10 mb from production.~~ J/ψ production. For this reason, the rates of this trigger are much higher than the physics trigger, and only a small sub set of these events are recorded. From this trigger the pixel track portion of the HLT trigger efficiency was estimated~~as well as the ZDC trigger efficiency as will be described in Section 3.6~~.

In addition to the ~~monitoring~~ minimum bias and physics sample, a zero bias sample was recorded to ~~examine the ZDC neutron reconstruction~~ allow for studies of the ZDC trigger and the HF noise distributions. The zero bias trigger fired every time both beams passed through CMS. Only 4 events out of every million triggered were recorded for this sample. This sample allowed for an unbiased measurement of the ZDC ~~neutron threshold energies~~ trigger efficiency as discussed in Section ~~3.4~~3.6. Because the zero bias trigger does not require any activity in any of the CMS sub detectors, the sample contains very few hadronic collisions. This allowed for a measurement of the electronic noise ~~distribution~~ distributions in the HF, which ~~are important to reducing contamination from hadronic interactions~~will be discussed below.

The integrated luminosity for each of the three samples is calculated by recording activity in HF [**?**]. The cross section for HF activity is measured from a van der Meer scan, and the cross section was found to be ~~45 mb for proton-proton running~~X. In this way ~~,~~ the amount of integrated luminosity for any running period is related to the activity in HF.

~~Cut~~ cut	cut type	~~Cut Events~~ events
~~–~~all triggered	–	346841
good vertex requirement	beam background rejection	340997
beam halo muon rejection	beam background rejection	302777
cluster shape compatibility requirement	beam background rejection	233590
single-sided neutron requirement	hadronic interaction rejection	149992
two track requirement	hadronic interaction rejection	32732
HF signal rejection	hadronic interaction rejection	5392
~~fake muon rejection~~ muon quality requirement	~~2047~~ fake muon rejection	1956
J/ψ mass requirement	~~696~~ kinematic cut	662
muon detectability cuts	~~567~~ kinematic cut	541

Table 1.4: Effects of event selection cuts.

1.3.2 Event selection cuts

The analysis described in this thesis focuses on UPC J/ψs decaying to muons. The trigger used for this analysis ~~recored~~ recorded 346841 events. A set of off-line cuts were applied to increase the relative contribution of UPC events compared to background processes. Two sets of event selection cuts were applied to reject background events. The first set rejects background from the beam. The second rejects events where hadronic collisions have occurred. The these cuts, and their effect on the data sample are summarized in Table 3.4 ~~summarizes all the event selection cuts~~were applied.

To reject beam induced background the following cuts were applied:

- The reconstructed vertex must be within ~~2~~ X cm in the transverse direction and ~~25~~ X cm in the longitudinal direction. This cut ~~ensures~~ insures that reconstructed particles come from interactions between the two beams rather than event where one of the two beams interact with gas particles near the interaction point.

- Beam halo muons, from upstream interactions, were rejected using the timing of the muon hits. ~~The beam halo cut rejects events where muons surrounding the beam stream through the detector.~~

- ~~Pixel cluster shape should be compatible with the vertex. This cut requires~~ Upstream interactions were rejected with the pixel cluster shape cut. This cut required that energy deposits in the silicon tracker ~~point back to~~ should be consistent with tracks coming from the reconstructed primary vertex.

These beam background cuts do not reject any UPC J/ψ candidates.

The second set of background rejection cuts were designed to reduce contamination from hadronic interactions.

- No more than 2 reconstructed tracks in the event. The track requirement rejects events that produce many charged particles.

- Maximum reconstructed hit energy in HF was required to be below the threshold for electronic noise. Nearly all hadronic interactions (about 98%) produce particles in the range $3 < |\eta| < 5$ covered by the HF detector. By requiring that the energy deposits in HF resemble noise, ~~nearly all elastic hadronic collisions are expected to be~~ almost all inelastic hadronic collisions were rejected.

- Energy in the ZDCs consistent with neutrons on only one side of the interaction point. In hadronic interactions both nuclei break-up. By requiring that ZDC only reconstruct neutrons on one side of the interaction point, hadronic interactions that produce neutrons on both sides were rejected.

Each of these cuts were designed to reject topologies produced by hadronic interactions. The effect of these cuts can be seen in Table 3.4 and are denoted hadronic interaction rejection.

To establish the HF noise thresholds, the noise distributions were measured in zero bias events ~~.~~ which required only the presence of both beams. An offline selection of events with no reconstructed tracks was used to ensure that no collision had taken place. The ~~HF noise threshold was defined as the cut that keeps 99% of the zero bias events. The noise~~ noise distribution from this zero bias sample is compared to the physics sample and MC in Fig. 3.3. The HF noise threshold was defined as the cut that keeps 99% of the zero bias events. This value was found to be 3.85 GeV.

The following standard muon quality cuts are applied:

Figure 1.3: Comparison of HF noise distributions in zero bias data, physics triggered data, and MC.

- Tracker track matched with at least one muon segment (in any station) in both X and Y coordinates (~~$< 3\ \sigma$~~ $< 3\sigma$).
- Cut on number of tracker layers with hits > 5.
- Number of pixel layers > 0.
- The χ^2 per degrees of freedom of the track fit < 3.
- Loose transverse and longitudinal impact parameter cuts, ~~with in~~ within 3 ~~cm~~ cm of the primary vertex in the transverse direction and ~~withing~~ 30 cm in the longitudinal direction~~with respect to the primary vertex~~.

These cuts are applied to reduce the number of fake muons and have been validated for standard muon analyses.

1.4 Break up determination

As described in Section **??**, UPC J/ψ photoproduction can be accompanied by the emission of neutrons from either of the two colliding nuclei. The various neutron emission scenarios, or break-up modes, can be distinguished by the two ZDCs. By separating events where the ZDC signal is consistent with 1 neutron versus several neutrons, or where neutrons are present on only one or both sides, the different break-up modes can be separated and compared to theory. For this reason, reconstruction of the ZDC signal plays an important role in this thesis. In order to maximize the ability to explore the one neutron peak, which sits at the bottom of the ZDCs dynamic range, a new ZDC reconstruction method was devised. This new reconstruction method was then used to establish a one neutron and many neutron threshold. This section describes the ZDC signal reconstruction and how the neutron thresholds on this signal were set.

1.4.1 ZDC signal reconstruction

The signal from each ZDC is built up from the pulse shapes for each of the ~~18 individual ZDC~~ 5 electromagnetic and 4 hadronic channels. The pulse shape is recorded in 250 ns second chunks and is divided into 10 time slices of 25 ns (See Fig 3.4). Counting from 0, the 4th time slice is synced with the timing of the rest of the detector and corresponds to when the products of the recorded collision reached the ZDC. ~~The~~ For this reason the channel signal is ~~therefore~~ taken from the 4th time slice.

Figure 1.4: Average ZDC pluse shape is plotted as the charge as a function of time slice for the first hadronic from ZDC^{-} (left) and ZDC^{+} (right).

The ZDC signal sits on top of a low frequency noise ~~pedestal~~ with a period of about 2μ seconds. Over the time scale of 250 ns, this low frequency noise ~~signal~~ sl appears as a constant charge offset that shifts randomly from event to event. The contribution from this noise is therefore measured event by event in order to subtract it. Time slice 5 is used for this purpose. Time slices 1 and 2 could also be used to estimate the low frequency noise. However because the noise fluctuates to negative values of charge that cannot be measured, these time slices can only provide a measurement of the noise half the time. By using time slice 5 which contains the falling tail of the signal, the noise can be measured any time the signal raises significantly above the noise. If the fraction of signal in time slice 4 and 5 are constant and the noise contributes the same value to both time slices, the following formula is applicable:

$$Ts4 \propto (Ts4+C)-(Ts5+C) = Ts4 - R_{Ts5/Ts4}Ts4 = Ts4(1-R_{Ts5/Ts4}), \qquad (1.1)$$

where $Ts4$ is the signal contribution in time slice 4, $Ts5$ is the signal contribution to time slice 5, C is a random noise constant from the low frequency noise, and $R_{Ts5/Ts4}$ is the ratio between the signal contribution from time slice 5 over time slice 4. Fig. 3.5 demonstrates the consistence of the fraction and validates the unconventional method of using the falling tail of the signal to estimate the low frequency noise. By using time slice 5, the chances of measuring the noise are maximized.

Separating the signal from the noise is especially important because the ZDC signal for the one neutron peak sits near the noise at the bottom of the ZDC dynamic range.

When summing the 9 channels in each ZDC only channels with signals above zero in time slices 4 and 5 were included. The EM section of the calorimeter is more densely packed with quartz fibers and therefore has a higher gain relative to the HAD section. To account for this, the EM channels were weighted with a factor of 0.1 to match the HAD channel gains.

1.4.2 Determination of the one neutron thresholds

The ZDC thresholds used to establish the various break-up modes were measured from zero bias data. Figure 3.6 shows the weighted sum of the EM and ~~HAD~~ Hadronic sections for ZDC^{-} and ZDC^{+} for the zero bias dataset. The neutron spectrum for this dataset does is biased since the trigger only required that both beams were present in CMS. ~~This does, however, include a significant electronic noise contribution due to events where no neutrons are emitted in the direction of the ZDC~~Of course this implies that most events contain only electronic noise in the ZDCs. It is clear from Fig. 3.6 that the ~~gain of ZDC^{+} is lower~~ resolution of ZDC^{+} is worse than that of ZDC~~$^{-}$~~$^{-}$. This is because of a damaged phototube on the first ~~HAD~~ hadronic section of ZDC~~$^{\pm}$~~$^{+}$.

To determine the thresholds for one and multiple neutrons, the ZDC^{+} and ZDC^{-} spectra were ~~fit. Four Gaussian functionswere combined to fit the spectra~~each fit with a sum of four Gaussian functions. The electronic noise was fit to a Gaussian around zero. The one, two, and three neutron peaks ~~are~~ were fit to Gaussians that are successively broader. The mean of each peak was initially set to multiples of the mean of the one neutron peak.

The threshold for a neutron in the ZDC was taken from the fits in Fig. 3.6. Any signal greater than 2σ below the mean of the one neutron peak was considered signal. Any signal greater than 2σ above ~~was considered~~ the one neutron peak was classified as containing multiple neutrons. ~~The~~ In this way the single neutron break up modes ~~were~~ could be separated from the multiple neutron modes~~by use of these definitions~~.

Several of the break-up mode calculations that have been done involve single sided configurations where neutrons are present on one side of the interaction point and not the other. ~~These modes can be hard to identify because the single neutron peak in ZDC^{+} overlaps with the noisepeak at zero. To identify events where the ZDCs only measured noise, the noise spectrum were measured directly. Placing an additional criteria based on the ZDCs noise distributions for when the ZDCs are devoid of signal provides assurance that the events tagged as single sided events are truly single sided.~~

~~The noise distributions for the~~ To identify signal consistent with noise, noise distributions for the combined EM sections and the combined HAD sections were measured~~separately from out of time time slices.~~ . The beams are only made to collide every 200 ns. In Fig. 3.4 higher than average signal can be seen in the 0th time slice, which precedes the main signal time slice time slice 4 by 200 ns. This is due to events where activity was present in the ZDC for two consecutive collisions. Time slices 1 and 2, however, occurred between collisions. These time slices ~~, which occur out of time,~~ were used to ~~measure~~ estimate the noise spectrum.

I don't understand how you set the noise threshold

Fig 3.7 shows the noise spectrum for each of the EM and HAD sections for the two sides of the ZDC. As with the signal measurements, the low frequency noise pedestal is subtracted event by event by subtracting time slice 2 from time slice ~~1 leaving only the high frequency noise. The noise distributions do not depend on the amount of quartz fibers, but because the signal does, the noise distributions for EM and HAD sections are measured separately. Fig 3.7 shows the noise spectrum for each of the EM and HAD sections for the two ZDCs. If the HAD or EM signals measured from the in time time slices, time slices~~ one before the channel signals are combined for each section.

Surely everything in TS 1 and 2 is noise so subtracting 1 from 2 should give you nothing

A side is considered consistent with noise if both HAD section and EM section signal measurements from the signal method involving time slice 4 and time slice 5 ~~, are less~~ are lower than 2 ~~σ above the mean of the noise distribution or lower, these sections are considered consistent with noise . A ZDC is considered consistent with noise if both the HAD section and EM section from that ZDC have signal measurements consistent with noise~~sigma below the mean in Fig. 3.7. With the single neutron, multi-neutron, and noise thresholds established, the contributions to the various break-up modes were estimated and compared to theory.

1.5 Signal extraction

After all event selection cuts, the coherent ~~, incoherent~~ J/ψ, incoherent J/ψ, and photon-photon process all contribute to the remaining events. Each process must be separated from the final mix. To achieve this, the invariant mass and p_T distributions are used to distinguish between the three processes. The photon-photon process is extended in invariant mass whereas the J/ψ is peak strongly near 3.1 GeV. In p_T the photon-photon and coherent process have similar distributions, both peaked shapely below 0.1 GeV, whereas the incoherent process is more broadly distributed across an interval extending to nearly 1 GeV. The mass distribution was fit to separate the photon-photon process from the J/ψ process. The p_T distribution was used to separate the incoherent process from the photon-photon process, and the coherent process. In this way, a separate yield was extracted for all three processes.

The invariant mass distribution for opposite sign dimuons is shown in Fig. 3.8. A ~~signal~~ peak at the J/ψ mass is clearly visible together with tails at higher and lower mass due to the photon-photon process. A fit to the invariant mass distribution was done using a Gaussian to account for the J/ψ signal and a first order polynomial function for the photon-photon process. The extracted number of J/ψ candidates from this fit includes all J/ψs in the mass window that passed the analysis cuts, i.e. both coherent and incoherent process contribute to yield from the mass fit. The p_T distribution is needed to separate the two different contributions to the J/ψ peak.

Figure 1.8: Mass fit to J/ψ using Gaussian for the signal and a first order polynomial for the photon-photon continuum

Figure 3.9 shows the p_T spectrum of the events plotted in Fig. 3.8. There is a clear coherent peak at ~~$= 60$ MeV~~ $p_T = 60$ MeV/c followed by broad distribution that peaks near ~~$= 450$ MeV~~ $p_T = 450$ MeV/c. To extract the contribution of coherent, incoherent and gamma-gamma processes in the data the spectrum in Fig. 3.9 was fit to the sum of three MC templates corresponding to the final output of the MC simulations for these three processes. The ~~clear overlap of the coherent and photon-photon process, and the clear separation of these two lower processes from the incoherent process is apparent. The~~ shape of the p_T distribution for the coherent, incoherent, and photon-photon process ~~are~~ were taken from the final output of MC after applying all analysis cuts. The clear overlap of the coherent and photon-photon process, and the clear separation of these two lower p_T processes from the incoherent process is apparent. In Fig.3.9, the yield parameters ~~that were~~ of the fit were left unconstrained for all three process.

Figure 1.9: Fit to MC p_T templates.

The shape of the photon-photon and coherent J/ψ process are very similar in p_T. Accordingly, the contribution from the photon-photon process and the coherent process are difficult to separate from the p_T distribution. The confidence contours in Fig. 3.10 from the template fit in Fig. 3.9 demonstrate the strong anti-correlation between the coherent yield parameter, nCo, and the yield parameter for the photon-photon process, $nGamma$. Because of the anti-correlation, the statistical uncertainty on nCo and $nGamma$ from the fit are larger than $\sqrt{nCo}$ and $\sqrt{nGamma}$ expected from Poisson statistics. The information from the invariant mass and p_T distributions were combined to break this correlation. Through this combination, the contribution to the final yield from the three process was measured.

Figure 1.10: 68%, 95%, and 99% confidence contours from the p_T template fit.

~~A simultaneous fit to the mass spectrum and spectrum was preformed to utilize the mass fits ability to distinguish the~~ The photon-photon process has a very different mass distribution from the coherent and incoherent ~~process all while utilizing the fits ability to separate the coherent and~~ processes and the incoherent process has a very different p_T spectrum from the photon-photon ~~processes from the incoherent~~and coherent processes. To maximize the precision of the measurement a simultaneous fit to the mass spectrum and p_T spectrum was preformed. Fig. 3.11

shows the result of the simultaneous fit. The simultaneous fit forces the parameter *nGamma* to both describe the photon-photon continuum present in the side bands of the J/ψ mass peak as well the photon-photon contribution to the low-p_T part of the p_T spectrum. In addition, the J/ψ yield from the mass fit is forced to equal the contribution from the incoherent and coherent process in the fit to the p_T distribution. In this way, the correlation between the yield parameters was broken, and the contribution from the three process were made independent of each other.

Figure 1.11: Simultaneous fit to the mass (left) and p_T spectra (right). The purple curve on the left is the sum of the coherent and incoherent processes shown as red and blue on the right.

Fig. 3.12 shows the confidence contours for *nCo* and *nGamma* from the simultaneous fit in Fig. 3.11. The slope of the confidence contours in Fig. 3.12 is noticeably ~~than~~ smaller than in Fig. 3.10. The contours for the simultaneous fit are also ~~reduced~~ narrower compared to Fig. 3.10 with widths in *nCo* and *nGamma* similar to those expected from Poison statistics. From the simultaneous fit, reasonable statistical errors were obtained along with the yields for the three processes.

Figure 1.12: 68%, 95%, and 99% confidence contours from the simultaneous fit.

1.6 Efficiency determination

Each step of the triggering, event selection and analysis has an associated efficiency that must be accounted for in the measurement of the J/ψ cross section. ~~The ZDC trigger efficiency, the muon trigger efficiency, and the muon reconstruction efficiency are the two most significant contributors to the total efficiency measurement. The efficiency of the pixel track requirement, and the veto on activity in the BSCs from the trigger are also estimated but found to be consistant with fully efficient~~Whenever possible these efficiencies were estimated using data based methods.

1.6.1 Muon efficiencies

The muon efficiencies ~~are measured from MC and data~~ were measured using a combination of data and MC based methods. The MC based measurement accounts for the detector acceptance and the efficiency of the muon quality cuts discussed in Section 3.3. The trigger efficiencies were measured in data using the tag and probe method [**?**], which is discussed below.

CMS has a limited acceptance for ~~s, particularly in the case of~~ J/ψ mesons, particularly for J/ψs with low momentum ~~like~~ such as those produced in UPC events. To measure the acceptance of CMS for ~~s, reconstructed~~ J/ψs, dimuon candidates were considered detectable if both ~~reconstructed~~ of the muon daughters fell into ~~a detectability region . This region~~ the region of rapidity and p_T were muons were detectible. This “detectibility region" was defined using ~~the coherent~~ coherent J/ψ events obtained from STARlight. The efficiency for reconstructing single muons ε^{μ}_{reco} is defined by $\varepsilon^{\mu}_{reco} = \frac{N^{\mu}_{reco}}{N^{\mu}_{gen}}$, where N^{μ}_{reco} is the number reconstructed muons ~~obtained~~ that pass the standard muon quality cuts after the full CMS detector simulation and ~~that passed the standard muon quality cuts,~~ and N^{μ}_{gen} is the number of generated muons from STARlight. Fig. 3.13

Figure 1.13: Muon daughter detectability from coherent J/ψ

shows the efficiency for reconstructing single muons from coherent J/ψ events. To avoid the edges of the detectors acceptance, all reconstructed muons that fall into a (p_T,$|\eta|$) bin that has an efficiency less than 20% were rejected~~thus defining~~. This condition defined the detectability region.

The acceptance for reconstructing J/ψ decaying into dimuons was calculated from MC using the following formula:

$$A = \frac{N_{det}(|y|, p_T)}{N_{gen}(|y|, p_T)}, \tag{1.2}$$

where N_{det} is the number of reconstructed dimuons ~~where both daughters fall into~~ with both daughters in the detectability region, and N_{gen} is the number of generated dimuons. From Eq. 3.2, the acceptance for J/ψ was calculated as a function of $|y|$, and p_T (see Fig. 3.14).

The tag and probe method is a data driven approach used to measure the trigger efficiency of the muon daughters ~~, which is a data driven approach. In this method there are three categories of daughter muons~~of J/ψ mesons. Each dimuon will have one daughter classified as a tag and the other as a probe. *Tag muons* are high quality muons ~~.~~ that are matched to the trigger. while *probes muons* are their oppositely charged partners of the tag muons. These conditions ensures that the distribution of the probes is not biased by the trigger requirement. The probes were required to pass all muon quality cuts. *Passing probes* are reconstructed muons that match the muon trigger, while *failing probes* do not. ~~Each dimuon will have one daughter classified as a tag and the other as a probe. From here three invariant mass histograms are studied. One histogram is created~~Using this scheme three histograms of invariant mass were created; one from all pairs~~. The second comes~~ , a second from pairs where the probe is a passing probe ~~. The last histogram comes from~~ and the third from from pairs where the probe fails to fulfill the trigger, *i.e.* the probe is a failing probe. ~~Because this depends on the~~

Because the trigger efficiency depends upon the p_T and $|\eta|$ of the probe, ~~one~~ a set of three histograms was produced for each (p_T,$|\eta|$) bin of the probe~~is created.~~

. To extract the single muon trigger efficiency ε^{μ}_{trig}, each set of invariant mass histograms was simultaneously ~~fitted~~fit. The signal was fitted using a Crystal Ball function, and the background was fitted to an exponential. The Crystal Ball parameters were simultaneously fitted to all three histograms. The exponential function was fitted to the failing and passing probe histograms separately. Because the background shapes are in principle different for the two samples, the efficiency is driven by this difference.

~~To measure the trigger efficiency a tag is required to pass all muon quality cuts and matched to the trigger. The probe is required to pass all quality cuts. A passing probe is a probe that is also matched to the trigger. In this way, the tag~~ Since the tag leaves the probe unbiased by the trigger ~~and~~ the efficiency can be measured by fitting the mass distribution.

~~Fig.~~

Figure 3.15 shows the fit of the three sets of pairs ~~. Fits to tag and probe pairs in the mass region for pairs with a probe $2 < |\eta| < 2.2$ and $1.55 < < 1.8$ GeV. This fit is~~ for a particular p_T and

$|\eta|$ region. Similar fits were done for each bin of the ~~probes and η. The resulting fit is~~ probe's p_T and $|\eta|$ and the results are summarized in Fig. 3.16.

Figure 1.15: Fits to tag and probe pairs in the J/ψ mass region.

Figure 1.16: Muon trigger efficiencies in p_T and η bins from the tag and probe method.

The dimuon trigger efficiency $\varepsilon^{dimuon}_{trigger}$ was measured ~~from~~ by convoluting the single muon efficiencies. The efficiency of each ~~candidate~~ dimuon pair was calculated using the following equation:

$$\varepsilon^{dimuon}_{trigger} = 1 - (1 - \varepsilon^{\mu_1}_{trigger})(1 - \varepsilon^{\mu_2}_{trigger}), \tag{1.3}$$

where $\varepsilon^{\mu_1}_{trigger}$ is the tag and probe efficiency of the first dimuon daughter, and $\varepsilon^{\mu_2}_{trigger}$ is the efficiency of the second muon daughter. In Eq. 3.3 the probability of at least one daughter firing the trigger is calculated by subtracting one from the probability that neither daughter fires the trigger, thus giving the dimuon trigger efficiency.

The average dimuon trigger efficiency for each ~~dimuon (~~(p_T,$|y|$) bin was calculated by ~~averageing the individual dimuon~~ averaging the individual efficiencies of candidates in each bin~~. The trigger efficiency from tag and probe averaged over candidates in each (,$|y|$) bin. The~~ , see Fig. 3.17. The J/ψ trigger efficiency ranges from $\approx 50\%$ to 87%. As expected the J/ψ trigger efficiency increase with rapidity since the longitudinal momentum of the J/ψ is given $p_Z = M_{J/\psi} \cdot sinh(y)$. Thus J/$\psi$ mesons at forward rapidity distribute more momentum to their daughter muons which therefore have a greater chance of punching through into the muon chamber. Finally the average trigger efficiency was multiplied by the acceptance from the MC to produce a total factor for both efficiency and acceptance. This is shown in Fig. 3.18. Since the acceptance drops quickly as the rapidity approaches 2.4 the combined trigger efficiency*acceptance is peaked near y=2.1.

Figure 1.17: The trigger efficiency from tag and probe averaged over candidates in each (p_T,$|y|$) bin.

Figure 1.18: The acceptance times averaged trigger efficiency from tag and probe.

The total combined efficiency and acceptance factor ~~coherent between 2.0 < |y| 2.2~~ for coherent J/ψ between $2.0 \leq |y| \leq 2.2$ was found to be ~~around 5~~ ≈ 5%. The acceptance factor of roughly 7% ~~acceptance factor~~ from the MC ~~is~~ was found to be the main contributor to the total efficiency. ~~Primarily, the~~ The interplay of the polarization of the J/ψ and the material in detector ~~drive~~ drives down the efficiency by creating an effective momentum threshold for detection (see Section 3.1). The reconstruction efficiency of the daughters range between 20%-60% for muons in the defined detectability range. The trigger efficiency for the detectable muons ranges from 30%-80% depending on ~~. The typical trigger efficiency for the dimuons ranges from 60% to 80%.~~ p_T.

1.6.2 ZDC trigger efficiency

As discussed in Section 3.4, ~~a special~~ the HLT_HIMinBiasZDC_PlusOrMinusPixel_SingleTrackl_v1 trigger was prepared to monitor the ZDC trigger efficiency. This trigger required either a ZDC^{+} or ZDC^{-} trigger, together with at least one pixel track. Events were accepted offline if there was no activity in the BSCs~~or activity on a single side.~~. or activity on a single side. What does this mean?

~~This sample suffers from a trigger bias. For example, a sample triggered by ZDC+ would always produce a ZDC+ trigger efficiency of one. To avoid this, the special trigger sample was divided into two subsamples in the following way. A first sample triggered by the ZDC+ input and second one triggered by the ZDC −. The ZDC+ trigger efficiencyis measured from the ZDC− sample, and vice versa.~~

~~The trigger efficiency for reconstructed ZDCenergies above the single neutron threshold were estimated (see for Sec. 3.4). The~~ A modified tag and probe method was used to study the ZDC efficiency. For example in order to study the efficiency of ZDC^{+} events that fired both HLT_HIMinBiasZDC_PlusOrMinusPixel_SingleTrackl_v1 and the simple ZDC^{-} triggers were selected as Tags. The probes were events in which the ZDC^{+} signal was above the one neutron

ZDC Side	Reco Method	N_{events}	N_{trig}	ε_{ZDC}
ZDC^{+}	1	72946	71688	0.982 ± 0.005
ZDC^{+}	2	73028	71706	~~0.9819~~ 0.982 $\pm$ 0.005
ZDC^{-}	1	76137	71786	~~0.9429~~ 0.943 $\pm$ 0.005
ZDC^{-}	2	76132	71859	~~0.9439~~ 0.944 $\pm$ 0.005

Table 1.5: ZDC trigger efficiencies for ZDC reconstruction method 1 and 2

threshold. Passing probes were those events where the Level 1 ZDC^{+} trigger fired and failing probes were those events where the ZDC~~$^{+}$ efficiency was calculated using the ZDC^{-} triggered sample. To estimate the efficiency, the number of events with energy in ZDC^{+} greater than the single neutron threshold, N_{events}, were measured. From this set of events , the number of events that also fire the ZDC^{+} was measured. The ratio between the number of single neutron events that fired the trigger and all single neutron events was taken as the estimate of trigger efficiency.~~ $^{+}$ trigger did not fire.

The same procedure was applied for each side of the ZDC, using two different methods to reconstruct the ZDC energy. The trigger efficiency of the ZDC was found to be 98% for ZDC^{-} and 94% for ZDC^{+}, see Table 3.5.

1.7 Systematic checks

Table 3.6 shows the systematic errors that were estimated. The method used to separate the coherent from the photon-photon process is the most dominant error. The ZDC reconstruction method used to estimate the neutron thresholds is the next most dominant, followed by the method used to estimate the HF noise threshold.

1.7.1 HF noise threshold

The way in which the HF noise distribution is measured effects the event selection and therefore the final candidate ~~yeild~~yield. This cut plays a significant role in rejecting hadronic events. In Table 3.4 the importance of cutting on HF noise is evident. The HF noise cut rejects a little less

systematic	uncertainty in %
Template fit normalized	+9.5% -12%
ZDC reconstruction	2.9%
ZDC trigger efficiency	2.2%
HF noise threshold	+1.3% -3.4%
MC acceptance	1.1%
Total systematic	8.1%

Table 1.6: Summary of systematic uncertainties

than 1/5 of the remaining events ~~. The~~ and for this reason the systematic uncertainties on the HF noise requirement ~~is importantfor this reason. The result must not depend significantly on the method used to apply the cut on the noise because of the large reduction of events that result from it~~are important.

~~Four different approaches were employed to estimate the systematic effect arising from picking a particular method for setting the HF noise threshold. By looking at the variation of the number of events that remain after applying the thresholds derived from these four methods, the systematic uncertainty for the HFnoise cut was estimated. The four methods are derive from combinations of two variations.The type of object was varied from a low-level detector object called a RecHit to a higher level physics object called a CaloTower. The RecHit is the energy deposited in a single calorimeter detector element, where as the CaloTower is a collection of RecHits with varrious threholds, which represent a full energy deposit that would come from a particle or a collection of particles from a jet passing through the detector. The second variation is on the separation of the two sides. In one case the threshold is derived for the two sides combined. In another case the thresholds are calculated separately for the two sides of HF. By combining these two variations, a total of four estimates of the effect of the HF noise cut were made~~

The most fine grained data from the HF detectors are called RecHits. Their is one RecHit per phototube on HF. The RecHit signal is calibrated in GeV and no noise subtraction is done. The CaloTowers are formed from geometrical groups of RecHits. They are the first stage of the CMS jet trigger and perform some noise suppression.

The default HF noise cut required that the total sum of the Rechit energy in both HF+ and HF- be less than 3.85 GeV. This cut was designed to accept 99% of the noise events, see Fig. 3.3. The stability of this cut was tested by

1. Summing CaloTowers instead of RecHits
2. Making separate cuts on HF- and HF+
3. Tightening the threshold so that only 98% or 97% noise events passed the cut.

Table 3.7 shows the noise thresholds for RecHits and CalowTowers for both the combined HF+ and HF- calorimeters and the individual calorimeters when 99% of noise events are accepted. Table ~~3.7 below shows the thresholds that are measured for each of the four methods.~~ 3.10 shows how compares the threshold for the cases when 99%, 98% and 97% of noise events are accepted. The number of J/ψ events remaining after these cuts is shown in EXPANDED TABLE. The efficiency corrected numbers are also shown. The fractional systematic error is then estimated by finding the maximum and minimum deviation from the default method. This error is

The resulting yields from the four different methods are displayed in Table 3.8.

Object type	HF (GeV)	HF^{-} (GeV)	HF^{+} (GeV)
RecHits	3.85	3.25	3.45
CaloTowers	4.25	3.25	3.75

Table 1.7: Combined and single sided HF noise ~~theresholds~~ thresholds for ~~various~~ RecHits and CaloTowers. These thresholds capture 99% of the noise ~~measurement methods~~events.

Object type	Combinded HF threshold	Two-sided thresholds
RecHits	298	290
CaloTowers	302	288

Table 1.8: ~~Candidate~~ Raw and efficiency corrected candidate yields below 1.05 GeV p_T for various HF noise cuts.

The threshold was adjusted to estimate the effect of tightening the requirement on the zero bias data. By successively lowering the percentage of the zero bias sample that was included, the HF noise cut was made more restrictive including first 98%, than 97% of all zero bias events. This was done for both object types, RecHits and CaloTowers. This allows for an estimate of the systematic uncertainty on selecting a 99% cut. Table 3.9 shows the effect on the thresholds themselves for both RecHits and CaloToweres, whereas Table 3.10 shows the effect on the candidate yields.

Table 1.9: Values of the energy cuts for the HF calorimeter for RecHit and CaloTower in GeV.

%	E_{RecHit} GeV	$E_{CaloTower}$ GeV
99	3.85	4.25
98	3.25	3.75
97	2.95	3.25

Table 1.10: Number of dimuon candidates with p_T <1.05 when changing HF calorimeter cuts for RecHit and CaloTower.

%	RecHit cut	CaloTower cut
99	298	302
98	287	294
97	284	280

The systematic uncertainty in the HF noise threshold measurement was calculated taking the difference from the 99% combined RecHit method with the upper and lower extrema. The systematic uncertainty from this method is calculated to be +1.3% -3.4%.

1.7.2 Template fit normalization

Figure 1.19: Coherent, incoherent, and photon-photon process p_T template fit to data.

The p_T template fit depends on the functions chosen for the fit to the mass distribution. As described in Section 3.5, the similarity of the of the p_T distribution for the coherent and photon-photon process make the contributions from the two process difficult to separate from the p_T distribution alone. The mass distribution was used to distinguish between these two processes. In turn, the p_T becomes dependent on the mass fit.

The systematic uncertainty due to the choose of functions used to fit the mass distribution was estimated by varying the signal and background functions. The contribution to the background from the mass fit was used to fix the contribution from the photon-photon process in the p_T template fit. Two functions were used to describe the signal, a Gaussian, and a Crystal ball function. The background was fit to a linear function, a 2nd order polynomial, and a 2nd order Cheby-Chev polynomial. The resulting variation on the coherent contribution was used to as an estimate of this systematic effect.

Moving from left to right in Fig 3.20, the contribution from the photon process increases. The χ^2 pre degree of freedom is similar between the three fits indicating a similar goodness of fit. On this basis, neither fit is preferred. The left most fit uses a Crystal Ball function to account for the radiative decay of the final state daughters of the J/ψ. The low mass exponential portion however picks up background events and overestimates the J/ψ contribution. The right most plot fits the background to a 2nd order Cheby-Chev polynomial. Because the Cheby-Chev peaks just below the J/ψ peak, this fit overestimates the background and in turn underestimates the signal contribution. The Gaussian fit with a linear background however does a reasonable job of fitting both the background and the signal.

From these three fits an upper and lower bound of the systematics due the choice of fit functions was estimated. The difference between the Gaussian-Linear fit and the Crystal Ball-polynomial fit was taken as an upper bound. The difference between the Gaussian-Linear fit and the Gaussian-Cheby-Chev fit was taken as a lower bound. The overall systematic uncertainty due to the choose of mass fit functions is found to be +9.5% -12%.

1.7.3 Mass fit

Fig. 3.21 demonstrates the small dependence the raw J/ψ yield has on the fitting function. Both fit functions agree well, with reduced χ^2 values below one. The Crystal ball fit give an upper estimate for the J/ψ yield. The Gaussian fit gives an lower estimate. The main difference comes from the lower mass tails. In the Crystal ball fit the lower tail is considered to be signal due to shifting of the mass spectrum to lower mass due to radiation from the final state muons. In the Gaussian fit the lower mass tail is considered to be background and the signal is sharper.

As check on the simultaneous p_T and mass fit, the mass fit is done using mass templates from STARlight.

Figure 1.22: Simultaneous fit to the mass and p_T using mass templates for the mass fit.

1.7.4 MC acceptance

The MC derived acceptance correction factors depend on the input physics generator. The underlaying p_T distribution was assumed to be correctly described by STARlight for the coherent cross section measurement. To estimate the effect of changing the underlaying p_T distribution on the acceptance measured from the MC, the incoherent sample was used to correct the coherent yield. By using the broader p_T distribution of the incoherent process, an estimate of acceptance measurements dependence on the assumed shape of the p_T distribution was obtained. The systematic uncertainty due to the dependence of the acceptance correction on the p_T distribution of the input physics generator was estimated by the difference between the correction factors from the coherent and incoherent MC samples. Half the difference was used as the estimate and was found to be 1.1%.

Figure 1.23: Yields corrected by the MC incoherent acceptance map.

The effect of polarization was estimated by correcting by the acceptance for an unpolarized J/ψ sample.

Figure 1.24: Yields corrected by an unpolarized J/ψ sample.

1.7.5 ZDC reconstruction

An additional method for estimating the ZDC neutron thresholds was used to estimate the systematic errors on the threshold measurements. This additional method, used in previous ZDC measurements, differs in the way the signal time slices are used to calculate the signal from each channel. In the standard method, the signal is taken from the sum of time slices 4, 5, and 6. To estimate the event by event noise pedestal the sum of time slice 1 and 2 are used. The signal for an individual ZDC channel is then calculated as the sum of the signal time slices minus the sum of the noise time slices weighted by a factor of 3/2 to account for the differing number of noise versus signal time slices. The advantage of the standard method is that by using multiple signal and noise time slices the signal and noise are effectively averaged reducing time slice to time slice fluctuations. However, by using time slices 1 and 2 for measuring the noise, the noise can only be measured half the time due to unmeasurable negative fluctuations of the dominant low frequency component of the noise.

As in the new method described in Section 3.4, the standard method combines the channels to create a signal measurement from the whole of each side of the ZDC, one measurement for ZDC^{+}, and one for ZDC^{-}. The noise subtracted signal from each of the HAD channels are added together. Then the EM section channels are summed. The EM section is weighted by a factor of 0.1 as in the new method. After the weighting the EM and HAD channels are added to each to create one measurement for ZDC^{+} and another measurement for ZDC^{-}.

Fig. 3.25 shows the spectra for ZDC^{+} and $ZDC-$ using the standard method. The same fit used for the new method is applied to standard method. As in the new method, the single neutron threshold is set to 2σ below the mean from the fit to the one neutron peak. The multi-neutron threshold was set to 2σ above the one neutron peak.

The systematic uncertainty due to the ZDC reconstruction method are estimated from the difference between the UPC J/ψ candidate yields. Both the reconstruction method and thresholds were changed to calculate the effect of the reconstruction method. The yields for the new and standard ZDC reconstruction method in the Xn0n break up were found to be 298 and 315 respectively. Half the difference between the two methods was used as an estimated of the systematic uncertainty. The systematic uncertainty due to the ZDC reconstruction method was found to be 2.9%.

1.7.6 ZDC trigger efficiency

The ZDC trigger efficiency measurement is sensitive to the underlying neutron distribution. The more neutrons that high the ZDC the higher the trigger efficiency will be. To estimate the effect the input sample has on the efficiency, the ZDC trigger efficiency was measured from five different samples. The Table 3.11 shows the results from the five samples. Both the new and standard ZDC reconstruction methods are shown for comparison.

The amount of electronic noise in the sample also effects the measurement. The more noise sits below the one neutron peak, the worse the efficiency is. In Table 3.11, the Zero Bias sample compared the Zero Bias sample with the timing cuts the described in the previous section shows a significant increase in efficiency in the sample with reduced noise. The same increase is seen when comparing the ZDC triggered sample with the ZDC triggered sample that also requires a pixel track. The effect of the electronic noise is also present in the difference seen in using the two methods. As seen in Fig. 3.26, the new reconstruction method shows better separation of the one neutron peak from the electronic noise, in particular in ZDC^{+} where the signal gain is lower. For this reason, the Zero Bias data, which contains that largest contribution from electronic noise, shows the most separation between the two methods and give the lowest estimate for the ZDC trigger efficiency.

The systematic uncertainty due to the uncertainty in the underlying distribution was estimated by calculating the standard deviation of the least extreme values from Table 3.11. Any value greater than three standard deviations from the mean was thrown out.

ZDC Side	Reco Method	N_{events}	N_{trig}	ε_{ZDC}
(ZDC^{+} or ZDC^{-}) and 1 pixel track				
ZDC^{-}	1	72946	71688	0.982 ± 0.005
ZDC^{-}	2	73028	71706	0.9819 ± 0.005
ZDC^{+}	1	76137	71786	0.9429 ± 0.005
ZDC^{+}	2	76132	71859	0.9439 ± 0.005
(ZDC^{-} or ZDC^{+}), 1 pixel track, and L1 EG trigger				
ZDC^{-}	1	613758	602123	0.9810 ± 0.0018
ZDC^{-}	2	614014	601863	0.9802 ± 0.0018
ZDC^{+}	1	643905	602671	0.9360 ± 0.0017
ZDC^{+}	2	647888	603089	0.9309 ± 0.0017
(ZDC^{-} or ZDC^{+}), 1 pixel track, and L1 Muon trigger				
ZDC^{-}	1	65466	63376	0.9681 ± 0.0054
ZDC^{-}	2	65543	63358	0.9667 ± 0.0054
ZDC^{+}	1	71929	63512	0.8830 ± 0.0048
ZDC^{+}	2	72932	63582	0.8718 ± 0.0047
Zero Bias with ZDC timing cuts				
ZDC^{-}	1	88676	84429	0.9521 ± 0.0046
ZDC^{-}	2	88480	84202	0.9517 ± 0.0046
ZDC^{+}	1	59878	54728	0.9140 ± 0.0054
ZDC^{+}	2	60467	54733	0.9052 ± 0.0053
(ZDC^{-} or ZDC^{+})				
ZDC^{-}	1	30986	30333	0.9789 ± 0.0079
ZDC^{-}	2	31029	30339	0.9778 ± 0.0079
ZDC^{+}	1	39178	30164	0.7699 ± 0.0059
ZDC^{+}	2	35703	30443	0.8527 ± 0.0067
Zero Bias				
ZDC^{-}	1	109967	101598	0.9239 ± 0.0040
ZDC^{-}	2	110230	101561	0.9214 ± 0.0040
ZDC^{+}	1	253241	86660	0.3422 ± 0.0013
ZDC^{+}	2	156336	87401	0.5591 ± 0.0024

Table 1.11: ZDC trigger efficiencies for ZDC reconstruction method 1 and 2 for different trigger samples

1.7.7 ZDC reconstruction method comparison

The new method relative to the standard method separates low signal from the noise more effectively for both sides of the ZDC. This is particularly important for ZDC$^+$ where the 1st HAD section had a lower gain than the other sections. The ZDC$^+$ and ZDC$^-$ signals near the one neutron peak using the standard and new reconstruction methods were plotted for comparison in Fig. 3.26. In Fig. 3.26, the shrinking of width of the noise peak around zero in the new method versus the old

Figure 1.26: Comparison of the new ZDC reconstruction method and the standard method for ZDC$^-$ (left) and ZDC$^+$ (right).

method is apparent for both ZDC$^+$ and ZDC$^-$. For the standard method no single neutron peak is resolved in ZDC$^+$, whereas the single neutron peak is resolved using the new method.

Timing cuts were applied to enhance the signal relative to the background in order to resolve the one neutron peak in ZDC$^+$ using the standard method. Because the products of the collision are synced with time slice 4, noise can be rejected by selecting channels where the maximum signal falls into time slice 4. The noise will have no preferred time slice (see Fig. 3.4). Using this fact, signal can be preferably selected by requiring that the hadronic channels of the ZDC have a peak signal in the fourth time slice. Through these timing cuts the single neutron peak was recovered using the standard reconstruction for ZDC$^+$.

To examine the effectiveness of the timing cuts, event by event noise subtraction was removed from the standard reconstruction. The signal from each channel was taken from time slices 4,5, and 6 with out subtracting 1 and 2. The signal spectrum from ZDC$^-$ was then plotted with the result shown in Fig. 3.27. As each additional hadronic channel is required to have a maximum

Figure 1.27: Effects of requiring in-time signal in successively more ZDC hadronic channels, no timing, at least one, at least two, at least three, and all four HAD channels have a maximum signal in the fourth time slice.

signal in the fourth time slice, the single neutron peak emerges. Fig. 3.27 demonstrates that the single neutron peak can be recovered from the noise using timing cuts alone.

Using the standard noise subtraction method, the same signal that emerges from the timing cuts alone appear without timing cuts. Fig. 3.28 confirms that both noise subtraction and the

Figure 1.28: Effect of ZDC signal timing requirements after noise subtraction.

timing requirement produce the same signal. This gives confidence that the signal is not an artifact of either cut, but the true neutron signal.

Fig. 3.28 and Fig. 3.26 demonstrate the consistence of the using timing cuts and noise subtraction to enhance the signal neutron peak. Fig. 3.28 confirms the legitimacy of the timing requirement method in ZDC$^-$ by showing the that the same signal emerges from the noise subtraction method as the timing method. Fig. 3.26 demonstrates the corresponds between the new noise subtraction method and the standard method on in ZDC$^-$ where signal is better separated from the electronic noise. This allows for confidence that the signal seen in ZDC$^+$ using the new method is the one neutron peak.

1.7.8 Tag and probe

The main purpose for fitting the mass spectra to estimate the efficiency is to separate the background from true signal. The background may not have the same efficiency as the signal, so separating the two is important if this is the case. In the tag and probe fit the signal peak from the J/ψ resonance is fit to the probes, passing probes, and failing probes alike (see Fig. 3.15). The signal shape, if from the same physical signal, will be identical in each of the three distributions. The background is for the passing and failing probes is fit using different parameters for the background because the background may come from different physical processes than the signal or non-physical sources like combinatorial backgrounds or misidentified fake particles. When the background comes from sources other than the physical signal, the background may give an efficiency estimate that is lower than the signal.

The trigger efficiency measured by the tag and probe method depend on the fitting functions use to estimate the background and signal contributions. Depending on what functions is used to fit the spectra, the amount of amount of background can be over or underestimated and effect the efficiency measurement. To estimate this effect, the tag and probe efficiencies were additionally measured by counting probes in the J/ψ mass window. The whole mass window is used to estimate the efficiency including all the events from the mass side bands. In this way, a worst case scenario estimate is given where all background events are included as signal.

From Fig. 3.29 it is apparent that the choice of fit function and therefore the amount of background from the mass side bands is included in the signal measurement has very little effect on the tag and probe efficiency measurement. The small effect of including the side bands is due to the side bands being comprised mostly of photon-photon events. Because this background is neither decays from other particles like pions nor is it non-physical background like combinatorics, the efficiency for muons from the sidebands are nearly identical to J/ψ signal. The photon-photon process directly produces two muons just like the J/ψ, therefore efficiency estimated from the side bands has little effect on the measurement because of this similarity. The counting and fitting trigger efficiency measurements agree within statistcal uncertainties, so this uncertianty was taken to be negliable.

1.7.9 MC vs Data compairson

Figure 1.30: Comparison of the of the dimuon rapidity distributions between coherent MC sample and Data.

Figure 1.31: Comparison of the of the dimuon φ distributions between coherent MC sample and Data.

Figure 1.32: Comparison of the of the dimuon p_T distributions between coherent MC sample and Data.