Search for Rare Z Decays into Two Reconstructed Photons at CDF

April 15th, 2013
Baylor HEP Seminar

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for the CDF collaboration

Public webpage:
http://www-cdf.fnal.gov/physics/exotic/run2/Zgamgam/index.html

Outline

- Introduction
- Tevatron and CDF Detector
- Diphoton Event Selection
- Photon Selection
- Photon ID Efficiency
- Signal MC Samples
- Backgrounds
- Limit Calculation

Introduction

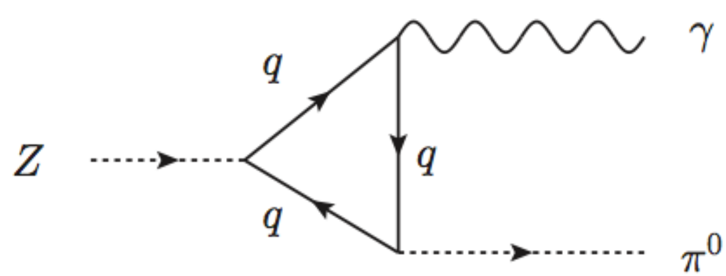
- Properties of the W and Z bosons have been studied extensively by collider experiments
- Most of the information we know about the vector bosons however comes from leptonic decays, $W \rightarrow l^{-}\nu$ and $Z \rightarrow l^{+}l^{-}$
- In addition to hadronic W and Z decays, there has been interest by theorists to further understand properties of the vector (V) bosons by searching for $V \rightarrow P + \gamma$, where P is a pseudoscalar meson (such as a pion)
- Observation of such decays would be a sensitive probe of strong interaction dynamics and vector boson couplings to the photon

Introduction

- The challenge for these decay modes is the very small predicted branching ratios (BR), ranging from about ~10^{-6} to ~10^{-11} in the SM
- However, with an abundance of vector bosons produced at the Tevatron and LHC, further searches can improve the experimental upper bounds on these branching ratios that were obtained from LEP
- Furthermore, any significant deviations of the SM prediction of the BR of these decays to observation could indicate new physics

Introduction

- In the analysis presented here, we focus on both rare and forbidden decays of the Z boson*
- Among the rare Z decays, we focus on $Z \rightarrow \pi^0\gamma$, which is experimentally interesting because of the clean signature the decay products leave in the detector



* CDF has already performed a search for $W \rightarrow \pi^{\pm}\gamma$ using 4.3 fb^{-1} of data and improved the LEP branching ratio upper limit by a factor of 10.. Phys. Rev. D 85, 032001 (2012)

Introduction

- We also search for the forbidden decays, $Z \rightarrow \gamma\gamma$ and $Z \rightarrow \pi^0\pi^0$
- The Z boson is a spin-1 particle
- Along with conservation of angular momentum, the identity of the final-state particles in the $Z \rightarrow \gamma\gamma$ and $Z \rightarrow \pi^0\pi^0$ decays forbids them in the SM
- That the $Z \rightarrow \gamma\gamma$ decay is forbidden is due to the Landau-Yang theorem, which forbids a spin-1 particle decaying to two spin-1 particles[*]
- (Since the Higgs-like particle discovered at the LHC decays to two photons, it is not expected to be a spin-1 particle due to Landau-Yang theorem)
- There exist theory papers that motivate a search for a $Z \rightarrow \gamma\gamma$ decay as a test of Bose-Einstein statistics

[*]A recent paper gives an argument that would allow this process through an axial coupling (arxiv:1109.0926)

Introduction

- No limits from Tevatron or LHC on these decays
- Most stringent limits in PDG on $Br(Z \rightarrow \gamma\gamma)$ and $Br(Z \rightarrow \pi^0\gamma)$ are from LEP
- Both are 5.2×10^{-5} at 95% C.L.
- No search has been performed for $Z \rightarrow \pi^0\pi^0$

$\Gamma(\gamma\gamma)/\Gamma_{total}$

This decay would violate the Landau-Yang theorem.

VALUE	CL%		DOCUMENT ID		TECN
$<5.2 \times 10^{-5}$	95	62	ACCIARRI	95G	L3
$<5.5 \times 10^{-5}$	95		ABREU	94B	DLPH
$<1.4 \times 10^{-4}$	95		AKRAWY	91F	OPAL

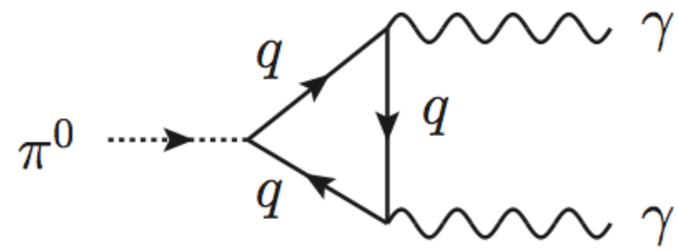
$\Gamma(\pi^0\gamma)/\Gamma_{total}$

VALUE	CL%		DOCUMENT ID		TECN
$<5.2 \times 10^{-5}$	95	61	ACCIARRI	95G	L3
$<5.5 \times 10^{-5}$	95		ABREU	94B	DLPH
$<2.1 \times 10^{-4}$	95		DECAMP	92	ALEP
$<1.4 \times 10^{-4}$	95		AKRAWY	91F	OPAL

PDG Particle Listings: Z Boson

J. Beringer et al. (Particle Data Group), PR D86, 010001 (2012) (URL: http://pdg.lbl.gov)

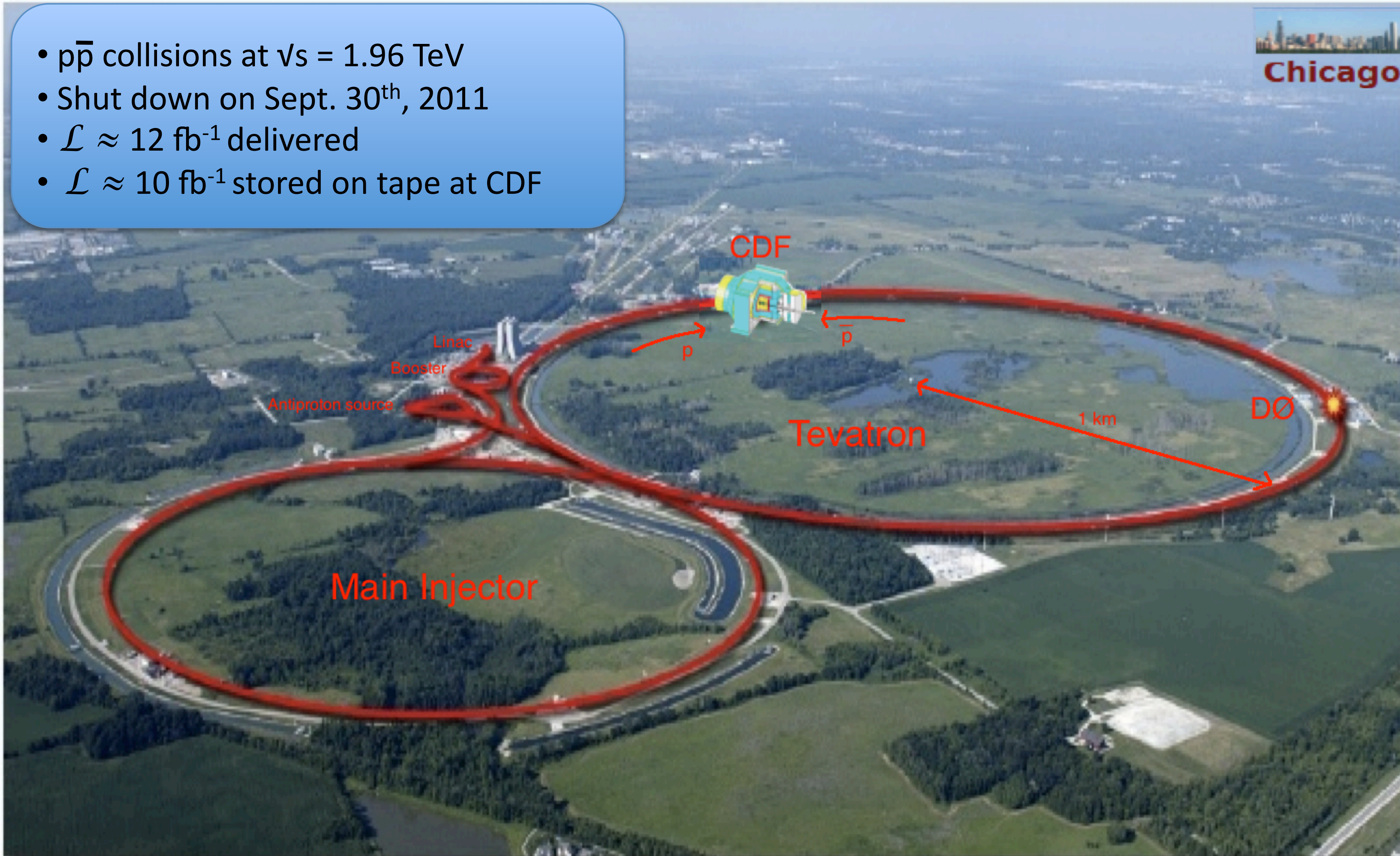
Introduction



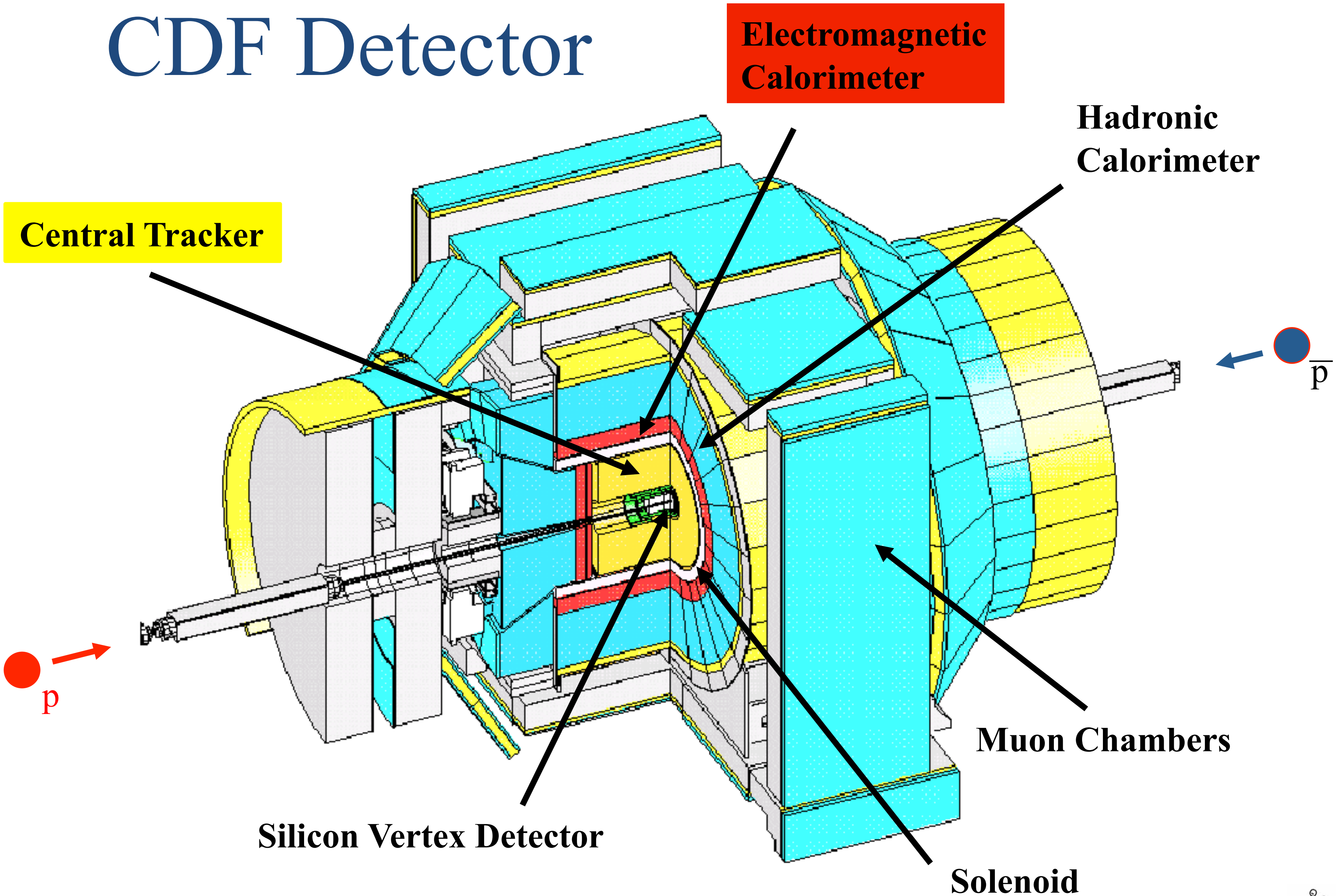
- π^0 from the $Z \rightarrow \pi^0\gamma$ or $Z \rightarrow \pi^0\pi^0$ decay:
  - Isolated (not in a jet)
  - Decays 98.8% to a pair of photons
  - High momentum π^0 from the Z decay leads to collinear pairs of photons, which often appear as a single electromagnetic shower in the detector rather than separated showers
- Experimentally, the isolated π^0 shower in the detector is nearly indistinguishable from the isolated γ shower
- For the $Z \rightarrow \gamma\gamma$, $Z \rightarrow \pi^0\gamma$, and $Z \rightarrow \pi^0\pi^0$ search then, we use already developed tools from $H \rightarrow \gamma\gamma$ analysis at CDF to identify events with two reconstructed photons

Tevatron

- $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV
- Shut down on Sept. 30th, 2011
- $\mathcal{L} \approx 12\ \text{fb}^{-1}$ delivered
- $\mathcal{L} \approx 10\ \text{fb}^{-1}$ stored on tape at CDF



CDF Detector



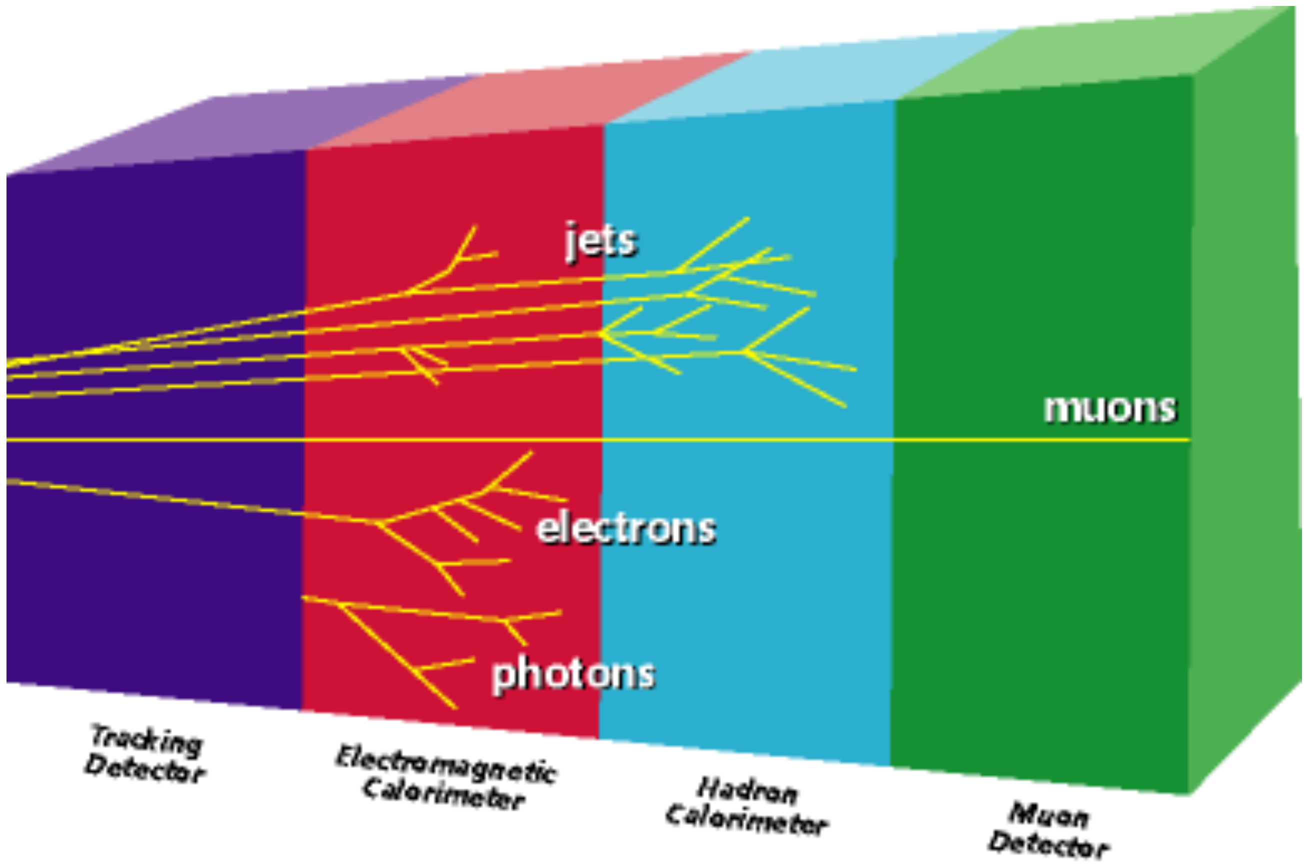
CDF Detector and Particle Identification

e's and *γ*'s interact in calorimetry via electromagnetic cascades

Hadrons interact in calorimetry via cascades of nuclear interactions

"Jets" come from quarks or gluons fragmenting

Charged particles leave a "track" in the tracking chambers



The CDF detector is designed to differentiate between many different types of final state particles

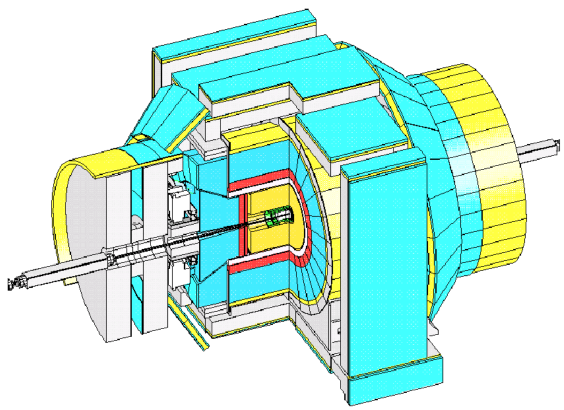
Summary of $H \rightarrow \gamma\gamma$ Techniques

- Event Selection:
  - Isolated photon trigger (25 GeV cut)
  - Identify two 15 GeV CEM photons using central NN selection
- Signal Model:
  - Shape and acceptance from Pythia MC
  - Isolated photon trigger and photon ID efficiency validated in $Z \rightarrow e^+e^-$ data
- Background Model:
  - Exploit resonant feature of H decay into photons
  - Use sideband regions of diphoton mass to determine background shape and rate in signal region

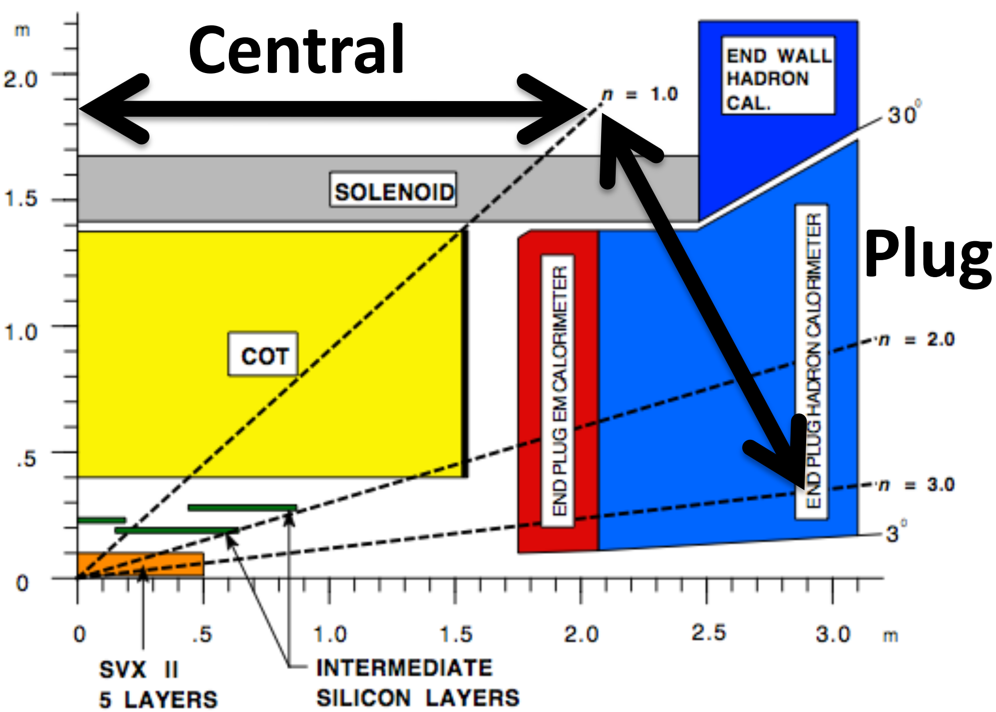
Modifications for $Z \rightarrow \gamma\gamma/\pi^0\gamma$ Analysis

- Event Selection:
  - Isolated photon trigger (25 GeV cut)
  - Identify two 15 GeV CEM photons using central NN selection
- Signal Model:
  - Shape and acceptance from a modified (angle- or π^0 efficiency-weighted) Pythia MC
  - Isolated photon trigger and photon ID efficiency validated in $Z \rightarrow e^+e^-$ data
- Background Model:
  - Exploit resonant feature of Z decay into photons
  - Use sideband regions of diphoton mass to determine background shape and rate in signal region
  - Model $Z \rightarrow e^+e^-$ from Pythia MC

Blue indicates what has dominated our time for transition to the $Z \rightarrow \gamma\gamma/\pi^0\gamma/\pi^0\pi^0$ analysis



Diphoton Event Selection



Cross sectional view of one detector quadrant

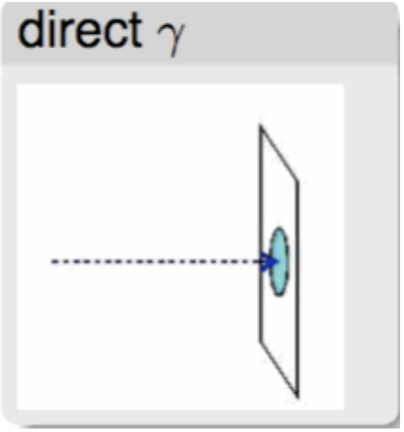
- "Central"
  - $|\eta|<1.1$
- "Plug"
  - $1.2<|\eta|<2.8$
  - Tracking efficiency lower than in central region
  - Easier to miss a track and reconstruct fake object as a photon
  - Higher backgrounds then for plug photons
- We focus on cases where there are ***two reconstructed photons in the central region*** of the detector

Diphoton Event Selection

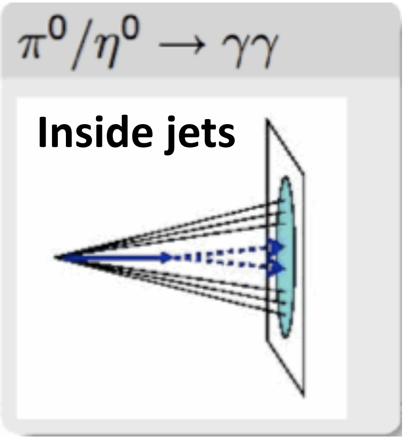
- Use data corresponding to 10.0 fb-1 of integrated luminosity
- Diphoton data collected from an inclusive photon trigger
  - Single EM cluster with $E_T > 25$ GeV
  - Trigger efficiency after offline selection obtained from trigger simulation software (TrigSim)
  - MC samples corrected based on trigger efficiency
- Require two central reconstructed photons with $p_T > 15$ GeV
- Photon selection described in coming slides
- The Z boson mass signal region is chosen to be 80 – 102 GeV, where about 90% of the signal lies

Photon Identification

- Basic Photon Signature:
  - Compact EM cluster
  - Isolated
  - No high momentum track associated with cluster
  - Profile (lateral shower shape) consistent with that of a prompt photon
    - Unlike that of $\pi^0/\eta \rightarrow \gamma\gamma$ decays ***inside of jets*** (the largest background for prompt photons)



Signal



Background

Photon Identification

- Three level selection
- (1) Loose requirements
  - Fiducial in shower max detector
  - Ratio of hadronic to electromagnetic transverse energy (Had/EM) < 12.5%
  - Calorimeter isolation
    - $I = E_T^{Tot}(\Delta R < 0.4) - E_T^{EM}$
    - Cut slides with E_T^{EM}
  - Track isolation

$$\sum_{trk_{|z_0 - z_{trk}| < 5\,cm}^{\Delta R < 0.4}} p_T^{trk} < 5 \text{ GeV}$$

- (2) Track veto
  - Number tracks ≤ 1
  - If 1, then $p_T^{trk1} < 1$ GeV
- (3) Cut on NN Output
  - More details on next slides

Electron Identification

- Three level selection
- (1) Loose requirements
  - Fiducial in shower max detector
  - Ratio of hadronic to electromagnetic transverse energy (Had/EM) < 12.5%
  - Calorimeter isolation
    - $I = E_T^{Tot}(\Delta R < 0.4) - E_T^{EM}$
    - Cut slides with E_T^{EM}
  - Track isolation

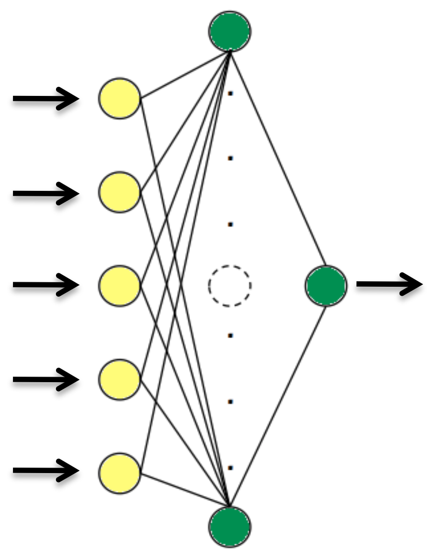
$$\sum_{trk_{|z_0 - z_{trk}| < 5\,cm}^{\Delta R < 0.4}} p_T^{trk} - p_T^{trk1} < 5 \text{ GeV}$$

- (2) Track veto
  - Number tracks ≤ 2
  - If 2, then $p_T^{trk2} < 1$ GeV
- (3) Cut on NN Output
  - More details on next slides
- No pure high statistics data sample of photons to validate ID efficiency
- Selection chosen so can be modified for electrons
- Then use $Z \rightarrow e^+e^-$ decays (more detail later)

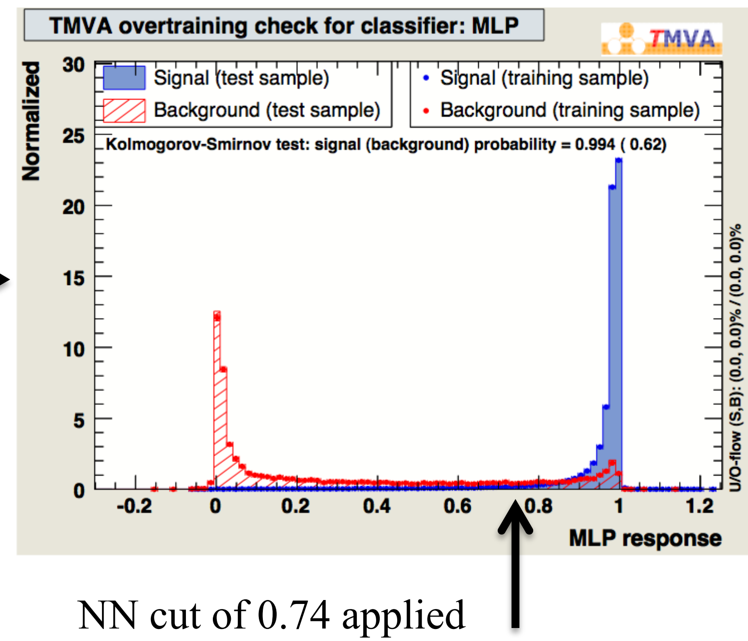
Photon Identification

NN discriminant constructed from seven well understood variables:

- Ratio of hadronic to EM transverse energy
- Shape in shower max compared to expectation
- Calorimeter Isolation
- Track isolation
- Ratio of energy at shower max to total EM energy
- Lateral sharing of energy between towers compared to expectation



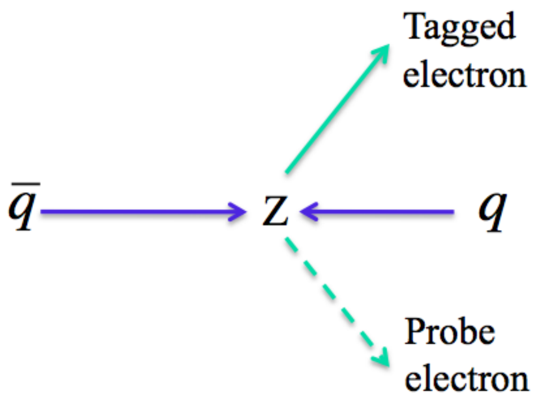
Trained using Monte Carlo (MC) simulated events with photons (blue) and events with jets (red)

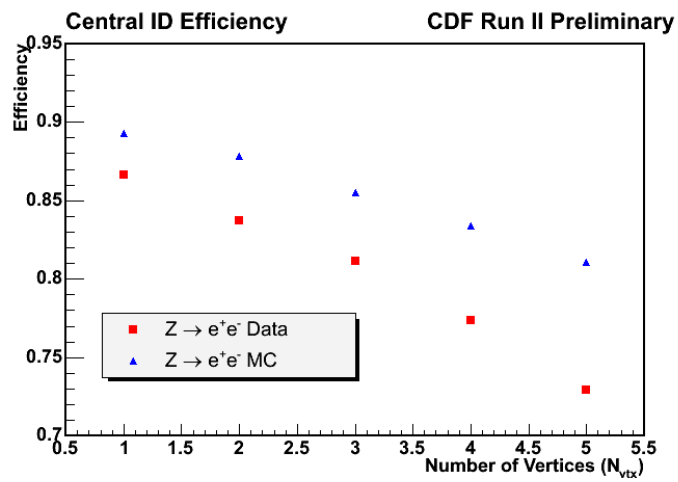


NN cut of 0.74 applied

- *Relative to standard photon selection, increases photon signal efficiency by 5% and jet background rejection by 12%*

Photon ID Efficiency



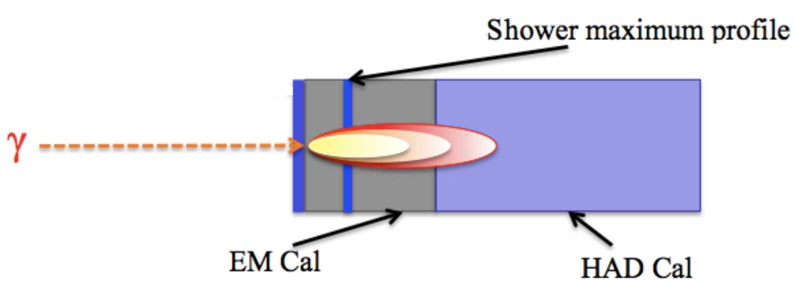


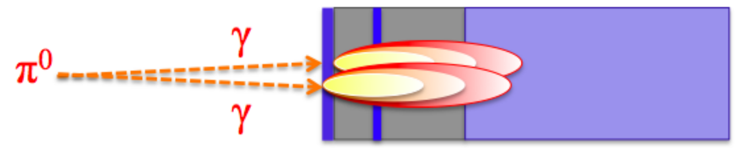
- ID efficiency checked in data and MC from $Z \rightarrow e^+e^-$ decays
- Z mass constraint applied to get a pure sample of electrons to probe
- Effect of overlapping collisions (pile-up) seen through N_{vtx} dependence
- Net efficiencies obtained by folding ε_{vtx} into N_{vtx} distribution of diphoton data and signal MC (a weighted average)

- Net photon ID efficiency:
  Data: 83.3% MC: 88.2%
- Correction factor of 94.4% applied to signal MC simulation
- Total systematic uncertainty of ~2% applied from:
  - Differences between electron vs photon response (checked in MC)
  - Data taking period dependence
  - Fits made to *Z* mass distribution
- Small uncertainties using this method!

π^0 Photon ID Efficiency

- We use γ and π^0 from (particle gun) MC samples to study the photon ID efficiency for neutral pions compared to neutral photons as a function of Et
- π^0's from Z boson decays have an average Et around 45 GeV
- For this Et region, the photons from most π^0 decays is highly collinear, appearing as a single EM shower rather than separated as two EM showers
- We find these isolated π^0's to have an efficiency to our photon ID selection that is about 2% smaller on average than isolated photons





π^0 shower at low Et
(< about 30 GeV)

Signal MC Samples

- Pythia has no decay table for $Z \rightarrow \gamma\gamma$, so we first start with a $Z \rightarrow \nu_e \nu_e$ Pythia sample and then convert the neutrino/antineutrino to photons before showering in Pythia and passing through CDF detector simulation
- This is called the "$Z \rightarrow \gamma\gamma$ unweighted model"
- *The photons of this sample have a generated angular distribution for that of the neutrino/antineutrino*

Signal MC Samples

- $Z \rightarrow \pi^0\gamma$ Model
  - Determined to have the same angular distribution as the neutrinos ~ $(\alpha+\cos^2\theta)$ with α a constant
  - Slightly different photon defection efficiency $\rightarrow$ The π^0 is then corrected for the observed 2% difference in π^0/γ efficiency
- $Z \rightarrow \gamma\gamma$ and $Z \rightarrow \pi^0\pi^0$ Models
  - Determined to have *different* angular distribution as the neutrinos (but same as each other)
  - We then correct the unweighted $Z \rightarrow \gamma\gamma$ sample to the expected angular distribution of these decays ~ $(\beta-\cos^2\theta)$ with β a constant
  - The $Z \rightarrow \pi^0\pi^0$ MC sample is furthermore corrected based on the 2% difference observed in in π^0/γ efficiency
- The next dozen slides describe the method for obtaining angular distributions for each decay mode

Angular Distribution Formulas*

We consider the decay of a particle with spin s_0 with polarization state m_0 that decays into two particles that have helicities λ_1 and λ_2. In the helicity basis, the angular distribution of a specific polarization and helicity state is taken to be proportional to a the square of the corresponding d-function:

$$F_{m_0\lambda_1\lambda_2}(\theta) \propto \left| d^{s_0}_{m_0\lambda_1-\lambda_2}(\theta) \right|^2$$

We obtain the net angular distribution by summing over all the polarization and helicity states considered, each weighted by the states probability:

$$F(\theta) = \sum_{m_0\lambda_1\lambda_2} f_{m_0\lambda_1\lambda_2} \left| d^{s_0}_{m_0\lambda_1-\lambda_2}(\theta) \right|^2$$

The following restriction is made on helicity states due to conservation of angular momentum:

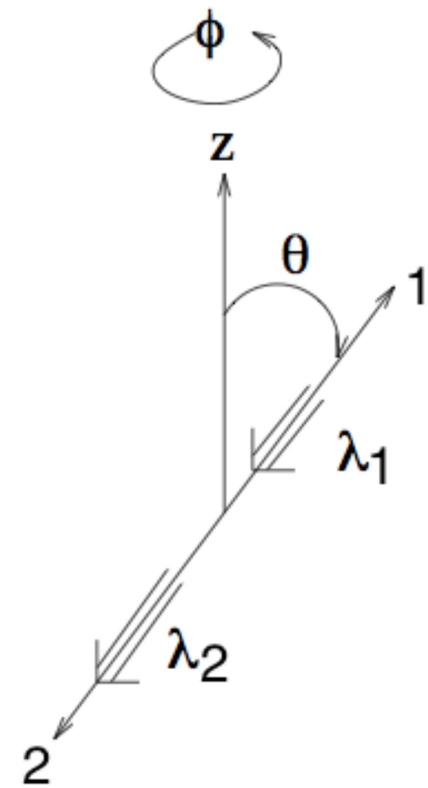
$$\left| \lambda_1 - \lambda_2 \right| \leq s_0$$

We apply these formulas to Z boson decays…

***An Angular Distribution Cookbook* by Rob Kutschke

Angular Distribution Formulas*

- Definition of angle θ:
- In Z boson rest frame, angle between momentum direction of first decay product and spin quantization axis of Z boson (z-axis)

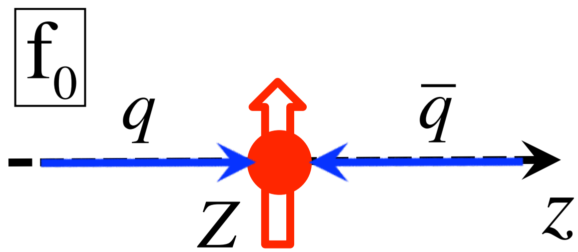


*_An Angular Distribution Cookbook_ by Rob Kutschke

Z boson polarization from Drell Yan

A Z boson decay will have s_0 = 1. Since we model the Z production and decay using Pythia, the Z is expected to be polarized. For head-on collisions of (massless) quarks, conservation of total angular momentum and of the z-component in the lab frame imply the following longitudinal spin orientations:

ISR and UE cause quark collisions to have some angle ≠ 180° which generate a finite transverse f_0, which we include as a contribution to the total angular distribution.

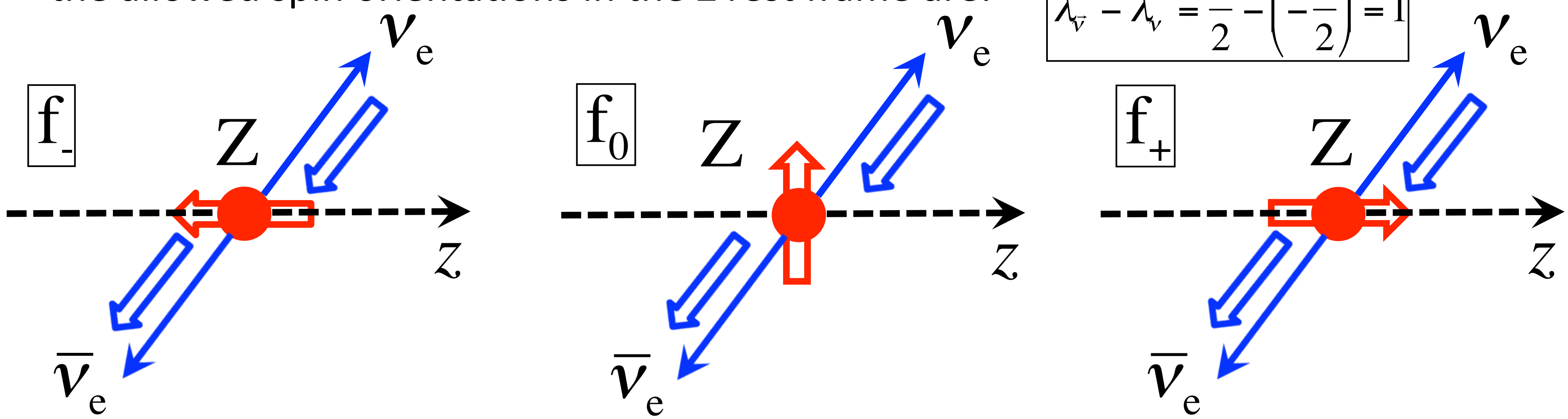


We then allow m_0 = +1, 0, and -1, each occurring with probability f_+, f_-, and f_0, respectively. Due to symmetry, we assume $f_+ = f_-$.

$Z \rightarrow \nu_e \, \bar{\nu}_e$ decay

With left-handed (massless) neutrinos and right-handed (massless) antineutrinos, the allowed spin orientations in the Z rest frame are:

$$\lambda_{\bar{\nu}} - \lambda_{\nu} = \frac{1}{2} - \left(-\frac{1}{2}\right) = 1$$



$$\left(d^1_{-1,1}\right)^2 = \left(d^1_{1,-1}\right)^2 = \frac{1}{4}(1-\cos\theta)^2$$

$$\left(d^1_{0,1}\right)^2 = \left(d^1_{1,0}\right)^2 = \frac{1}{2}\sin^2\theta$$

$$\left(d^1_{1,1}\right)^2 = \frac{1}{4}(1+\cos\theta)^2$$

where f_-, f_0, and f_+ are the left-handed, longitudinal, and right-handed polarizations of Z, and θ is the angle between ν_e and the z axis. From symmetry, $f_- = f_+$. For unpolarized Z ($f_+ = f_0$) the sum of the three angular distributions is a constant:

$$\left(d^1_{1,1}\right)^2 + \left(d^1_{1,0}\right)^2 + \left(d^1_{1,-1}\right)^2 = 1$$

For polarized Z ($f_+ \neq f_0$):

$$F_{\nu\bar{\nu}}(\theta) = f_+\left(d^1_{1,1}\right)^2 + f_0\left(d^1_{1,0}\right)^2 + f_-\left(d^1_{1,-1}\right)^2 = \frac{f_+ - f_0}{2}\left(\frac{f_+ + f_0}{f_+ - f_0} + \cos^2\theta\right)$$

Angular Distribution of Unweighted Z→γγ MC Sample

$$F_{\nu\bar{\nu}}(\theta) = \frac{(f_+ - f_0)}{2}\left(\frac{f_+ + f_0}{f_+ - f_0} + \cos^2\theta\right)$$

We determine the unknown values of the f_+ and f_0 parameters by fitting to the neutrino angular distributions in the Z rest frame using the MC simulated data.

We fit to the MC histogram with:

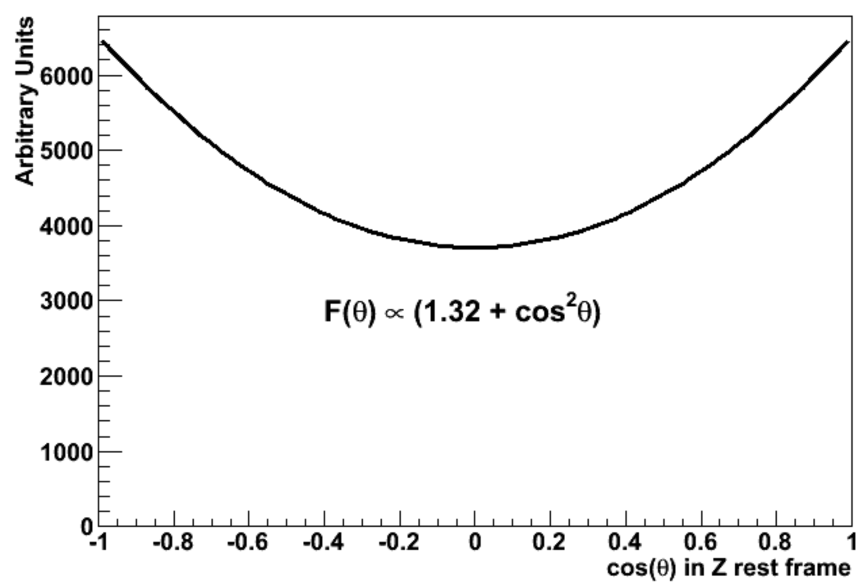
$$F(\theta) = p_0\left(p_1 + \cos^2\theta\right)$$

With best fit parameters of
p0 = 2811 and p1 = 1.32, we obtain

$$F_{\nu\bar{\nu}}(\theta) = 2811\left(1.32 + \cos^2\theta\right)$$

Which gives $f_+ = 7.26 f_0$.

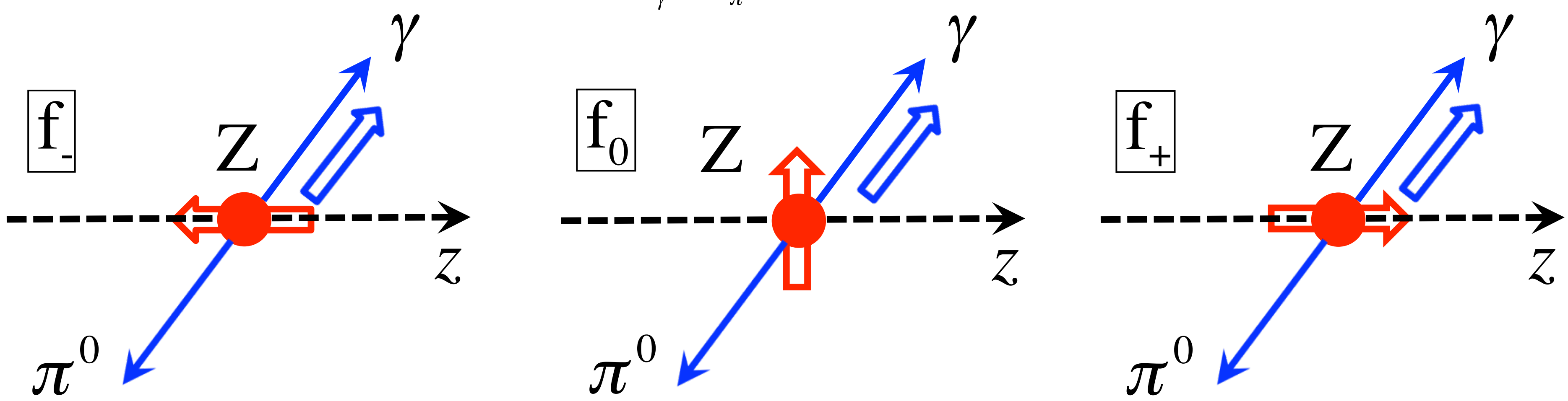
$Z \rightarrow \nu_e \bar{\nu}_e$ decay



$Z \rightarrow \pi^0 \gamma$ decay

λ_γ can be ±1 and λ_π can be only zero. We then have the following spin states:

$$\lambda_\gamma - \lambda_\pi = 1 - 0 = 1$$



$$\left(d^1_{-1,1}\right)^2 = \left(d^1_{1,-1}\right)^2 = \frac{1}{4}(1-\cos\theta)^2$$

$$\left(d^1_{0,1}\right)^2 = \left(d^1_{1,0}\right)^2 = \frac{1}{2}\sin^2\theta$$

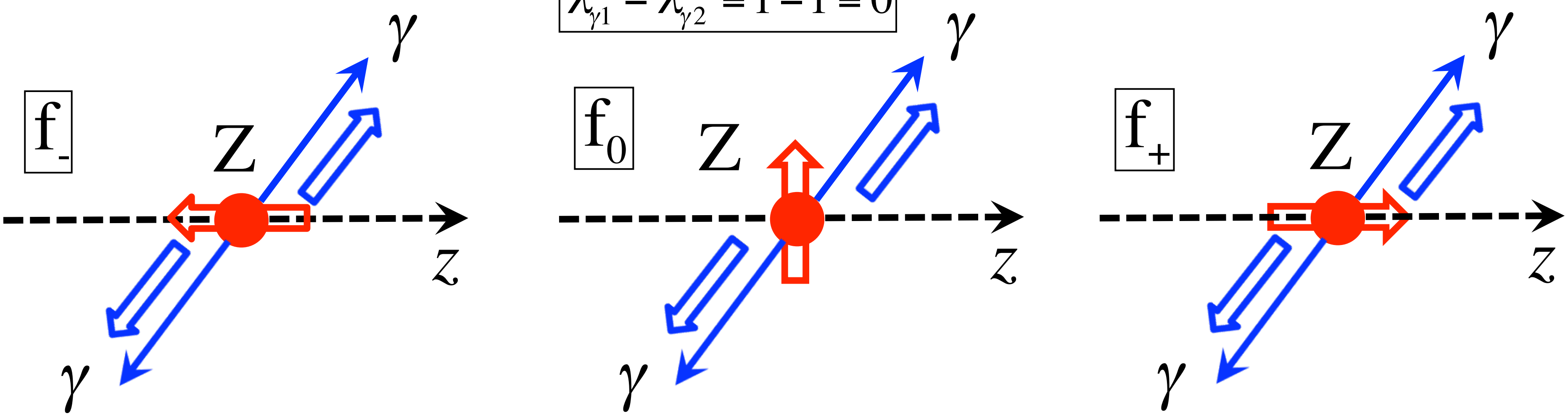
$$\left(d^1_{1,1}\right)^2 = \frac{1}{4}(1+\cos\theta)^2$$

The angular distributions are the same as with the neutrino decay. No neutrino to reweighting function is then needed to correct the unweighted Z→γγ (neutrino) angular distributions to the expected $\pi^0\gamma$ angular distributions.

$Z \rightarrow \gamma\gamma$ decay

Angular momentum conservation ($|\lambda_{\gamma 1} - \lambda_{\gamma 2}| \le s_Z = 1$) excludes parallel photon spins and $\lambda_{\gamma 1} = \lambda_{\gamma 2} = 0$ scenarios are excluded because photons are massless. We then have:

$$\lambda_{\gamma 1} - \lambda_{\gamma 2} = 1 - 1 = 0$$



$$\left(d^1_{-1,0}\right)^2 = \left(d^1_{1,0}\right)^2 = \frac{1}{2}\sin^2\theta \qquad \left(d^1_{0,0}\right)^2 = \cos^2\theta \qquad \left(d^1_{1,0}\right)^2 = \frac{1}{2}\sin^2\theta$$

For unpolarized Z ($f_+ = f_0$) the sum of the three angular distributions is a constant:

$$\left(d^1_{1,0}\right)^2 + \left(d^1_{0,0}\right)^2 + \left(d^1_{1,0}\right)^2 = 1$$

For polarized Z ($f_+ \neq f_0$):

$$F_{\gamma\gamma}(\theta) = f_+\left(d^1_{1,0}\right)^2 + f_0\left(d^1_{0,0}\right)^2 + f_-\left(d^1_{1,0}\right)^2 = \left(f_+ - f_0\right)\left(\frac{f_+}{f_+ - f_0} - \cos^2\theta\right)$$

Neutrino to Photon Angle-Weight Function

We insert $f_+ = 7.26 f_0$ (which we got from the Z→νν sample) into

$$F_{\gamma\gamma}(\theta) = \left(f_+ - f_0\right)\left(\frac{f_+}{f_+ - f_0} - \cos^2\theta\right)$$

to obtain the formula we expect for the photons from Z→γγ in the Pythia sample:

$$F_{\gamma\gamma}(\theta) = 2811\left(1.16 - \cos^2\theta\right)$$

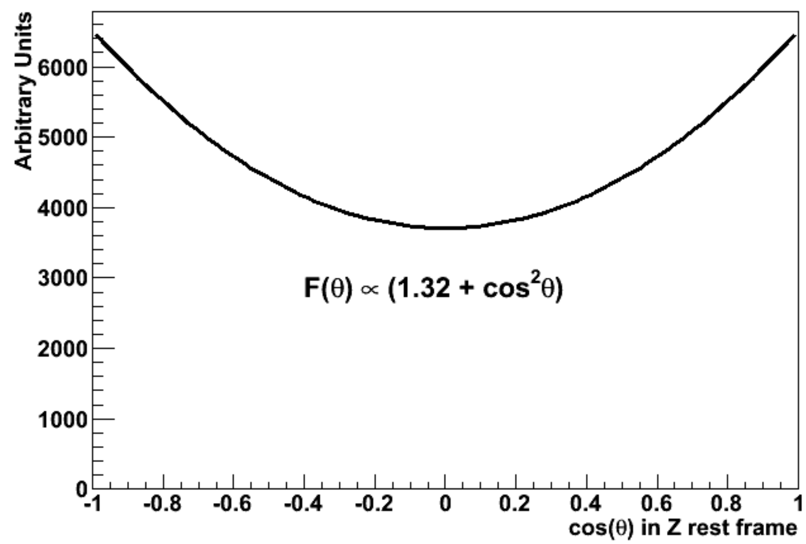
This gives the following neutrinos-to-photons reweighting function to be used to correct the unweighted Z→γγ to what we expect for photons:

$$w_{\gamma\gamma}(\theta) = \frac{F_{\nu\bar{\nu}}(\theta)}{F_{\gamma\gamma}(\theta)} = \frac{1.16 - \cos^2\theta}{1.32 + \cos^2\theta}$$

Neutrino-photon angular weights correct the unweighted Z→γγ sample to the expected angular distribution

Unweighted

Z → γγ decay



Neutrino to Photon Angle-Weight Function

We insert $f_+ = 7.26 f_0$ (which we got from the Z→νν sample) into

$$F_{\gamma\gamma}(\theta) = (f_+ - f_0)\left(\frac{f_+}{f_+ - f_0} - \cos^2\theta\right)$$

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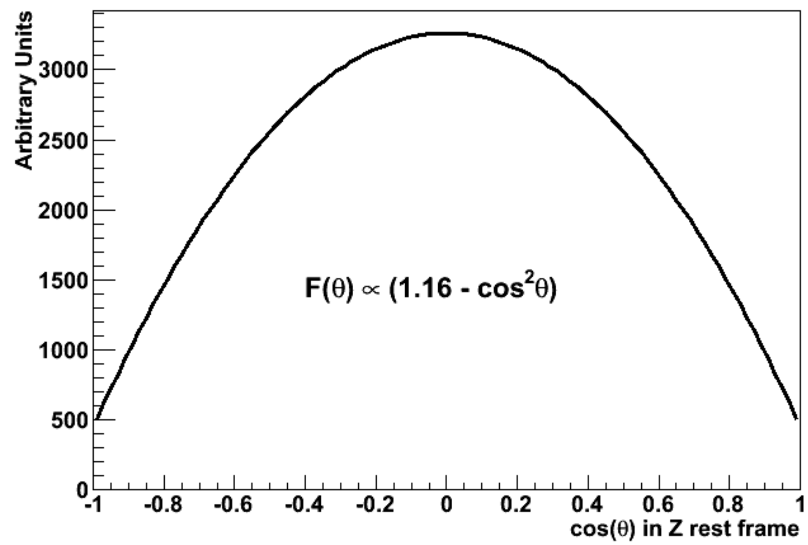
Neutrino-photon angular weights correct the unweighted Z→γγ sample to the expected angular distribution

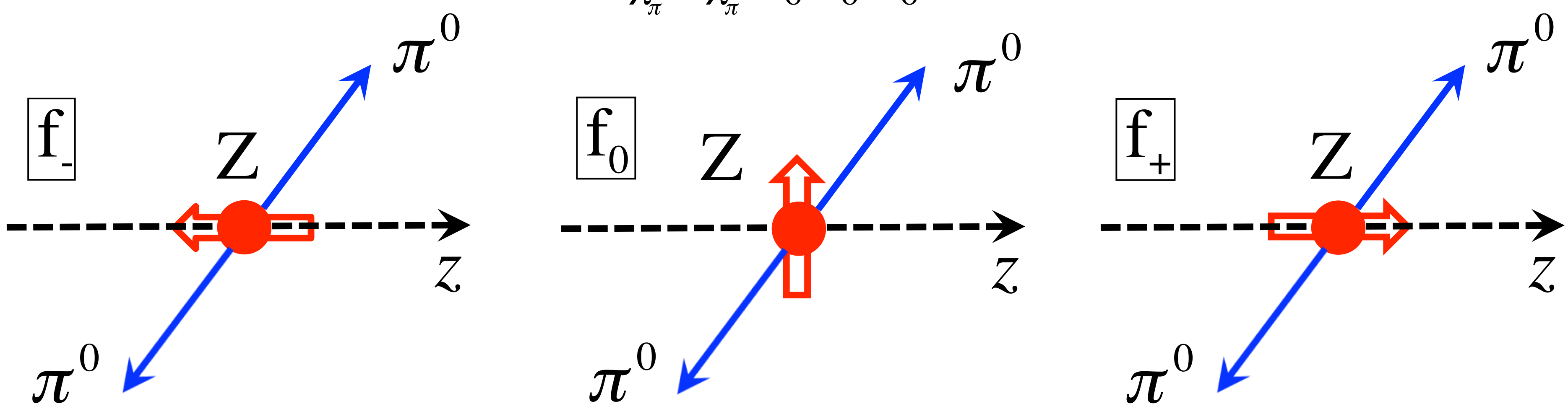
Angle-Weighted
Z → γγ decay



$Z \rightarrow \pi^0 \pi^0$ decay

λ_π can be only zero. We then have the following spin states:

$$\lambda_\pi - \lambda_\pi = 0 - 0 = 0$$



$$\left(d^1_{-1,0}\right)^2 = \left(d^1_{1,0}\right)^2 = \frac{1}{2}\sin^2\theta$$

$$\left(d^1_{0,0}\right)^2 = \cos^2\theta$$

$$\left(d^1_{1,0}\right)^2 = \frac{1}{2}\sin^2\theta$$

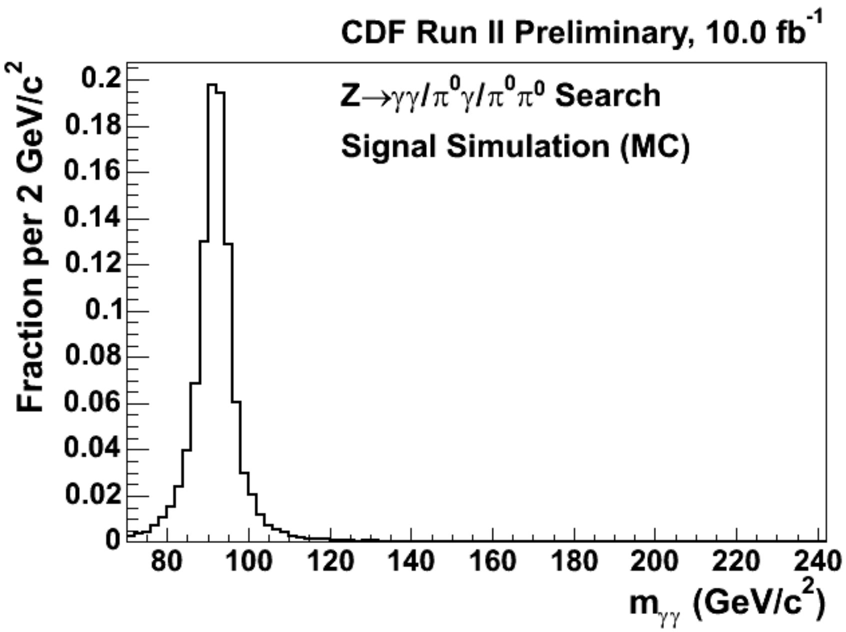
The angular distributions are the same as with the $Z \rightarrow \gamma\gamma$ decay.
We then apply the neutrino to γ reweighting function to the $Z \rightarrow \pi^0\pi^0$ decay.

Signal MC Samples: Summary

- Unweighted $Z \to \gamma\gamma$ MC Sample
  - Has angular distribution of neutrinos ~ $(\alpha+\cos^2\theta)$ with α a constant
- $Z \to \pi^0\gamma$ Model
  - Determined to have the same angular distribution as the neutrinos
  - Start with unweighted $Z \to \gamma\gamma$ MC sample then, and correct for the observed 2% difference in π^0/γ efficiency
- $Z \to \gamma\gamma$ and $Z \to \pi^0\pi^0$ Models
  - Determined to have *different* angular distribution as the neutrinos (but same as each other)
  - Start with unweighted $Z \to \gamma\gamma$ MC sample, then correct to the expected angular distribution of these decays: ~ $(\beta-\cos^2\theta)$ with β a constant
  - The $Z \to \pi^0\pi^0$ decay is furthermore corrected based on the 2% difference observed in in π^0/γ efficiency

Signal Diphoton Mass Shapes

- After all corrections, reconstructed mass shape of each decay is obtained
- Expected to be the same for each signal decay mode
- This is because the calorimeter response for π^0 is found to be the same as that for isolated photons for π^0 with Et around 45 GeV, determined by studying energy scale



Signal Acceptance × Efficiency

- Both the angular distributions and the photon identification efficiency affect the fraction of $Z \rightarrow \pi^0\gamma$, $Z \rightarrow \gamma\gamma$ and $Z \rightarrow \pi^0\pi^0$ that pass the full diphoton event selection
- Difference in acceptance × efficiency for $Z \rightarrow \pi^0\gamma$ relative to $Z \rightarrow \gamma\gamma$ and $Z \rightarrow \pi^0\pi^0$ is almost entirely due to difference in angular distribution
- Difference in acceptance × efficiency for $Z \rightarrow \gamma\gamma$ relative to $Z \rightarrow \pi^0\pi^0$ is due to difference in π^0/γ photon ID efficiency

Signal Decay Mode	$Z \rightarrow \pi^0\gamma$	$Z \rightarrow \gamma\gamma$	$Z \rightarrow \pi^0\pi^0$
Acc * Eff ($m_{\gamma\gamma}$ = 80 – 102 GeV)	5.5%	7.6%	7.3%

Signal Yields

- In principle, could obtain signal yields from

$$N_{Z\to\gamma\gamma} = \frac{\sigma(Z\to ee)}{\mathrm{Br}(Z\to ee)}\cdot \mathrm{Br}(Z\to\gamma\gamma)\cdot L\cdot (A\epsilon)_{Z\to\gamma\gamma},$$

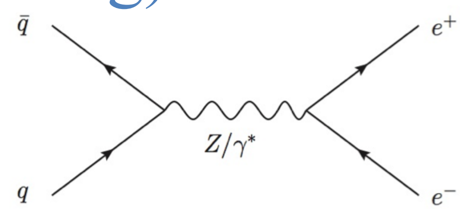
$$N_{Z\to\pi^0\gamma} = \frac{\sigma(Z\to ee)}{\mathrm{Br}(Z\to ee)}\cdot \mathrm{Br}(Z\to\pi^0\gamma)\cdot L\cdot (A\epsilon)_{Z\to\pi^0\gamma},$$

$$N_{Z\to\pi^0\pi^0} = \frac{\sigma(Z\to ee)}{\mathrm{Br}(Z\to ee)}\cdot \mathrm{Br}(Z\to\pi^0\pi^0)\cdot L\cdot (A\epsilon)_{Z\to\pi^0\pi^0},$$

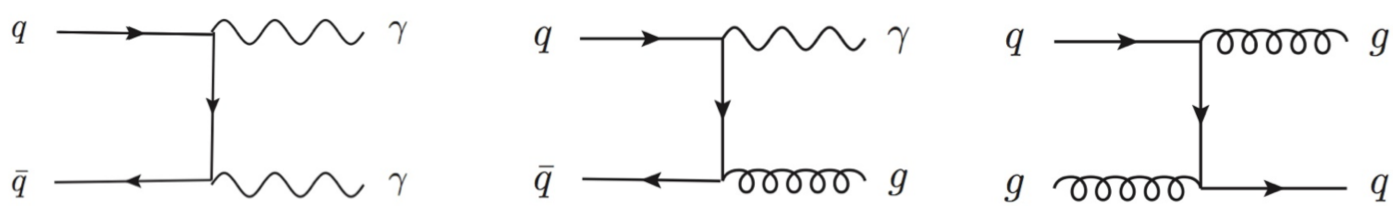
  where σ(Z→ee) is 250 pb, Br(Z→ee) = 0.034, L = 10.0 fb-1, and Aε is acceptance × efficiency values from previous slide
- We assume no theoretical branching ratio however
- Later, signal branching ratios become a parameter of 95% C.L. limit calculation

Background Model

- Resonant background (2% of total bkg)
  - Drell-Yan
  - Modeled with MC



- Smooth $m_{\gamma\gamma}$ backgrounds (~98% of total bkg)
  - Modeled from fit to $m_{\gamma\gamma}$ sideband region
  - Fit is made to Drell-Yan subtracted data
  - Composition:
    - γγ from QCD processes (~⅔ of smooth bkg); irreducible
    - γj or jj: one or two jets faking a photon (~⅓ of smooth bkg)

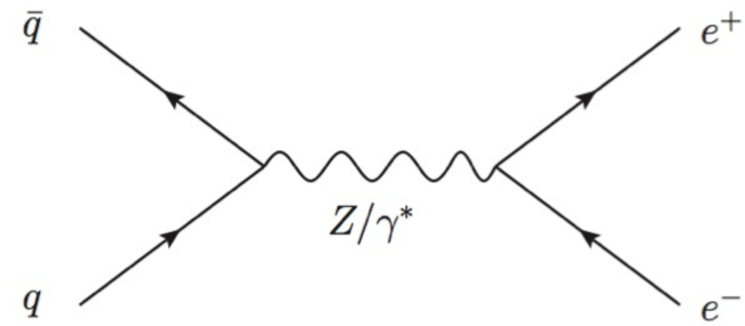


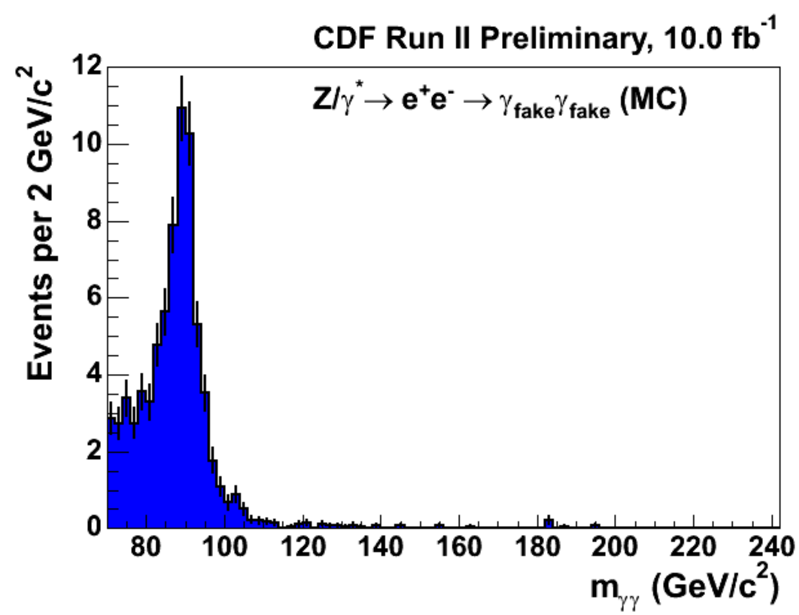
Drell-Yan Background

- Drell-Yan background arises from electrons faking photons
- Use inclusive Z→e+e- Pythia MC sample

  σ = 355 pb and a k-factor = 1.4
- L = 10.0/fb
- Acceptance × diphoton efficiency, $A\varepsilon_{\gamma\gamma}$, for full mass range: 0.0031%
- N expected = $\sigma \bullet k \bullet L \bullet A\varepsilon_{\gamma\gamma}$
  = 154 events

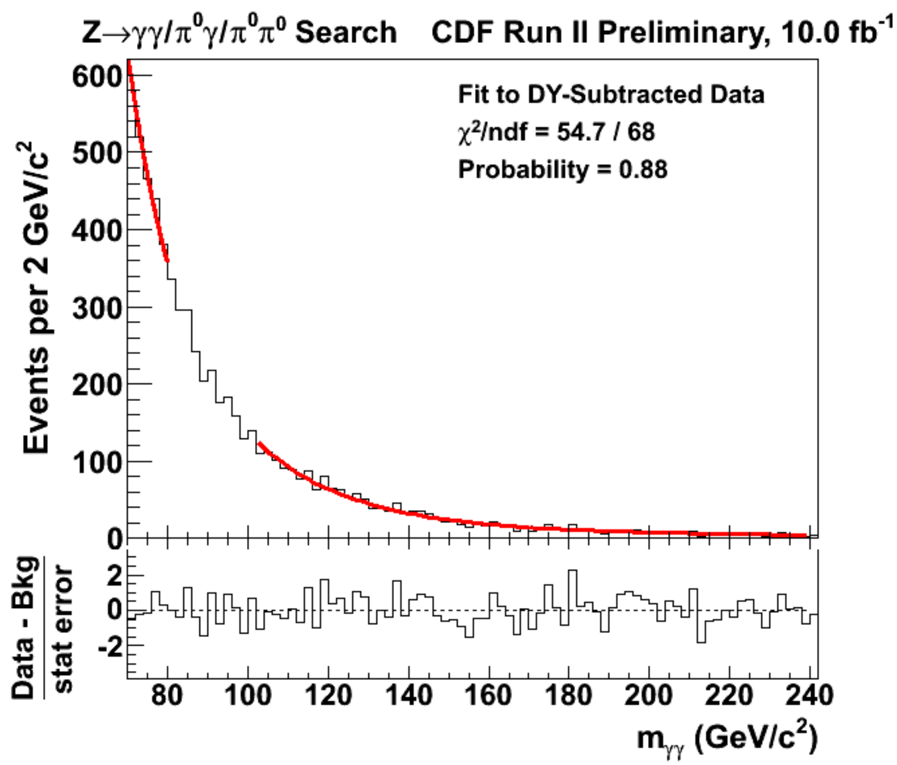
  for entire mass range
- 54 of these events expected in signal region, $m_{\gamma\gamma}$ = 80 – 102 GeV





Non-Resonant Backgrounds

- We do not model the prompt diphoton and jet faking photons background separately
- Instead use mass sidebands to determine shape and yield in signal region
- First subtract Drell-Yan component from data
- Then fit to sideband regions of DY-subtracted data
- Fit is interpolated into signal region



Fit to DY-subtracted data
(linear scale)

Non-Resonant Backgrounds

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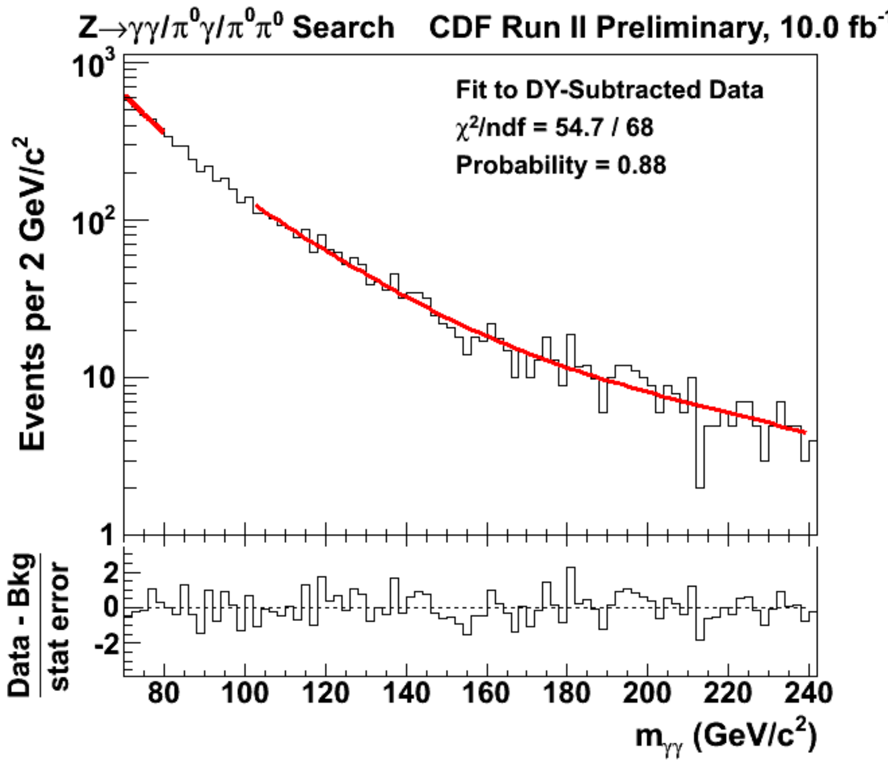
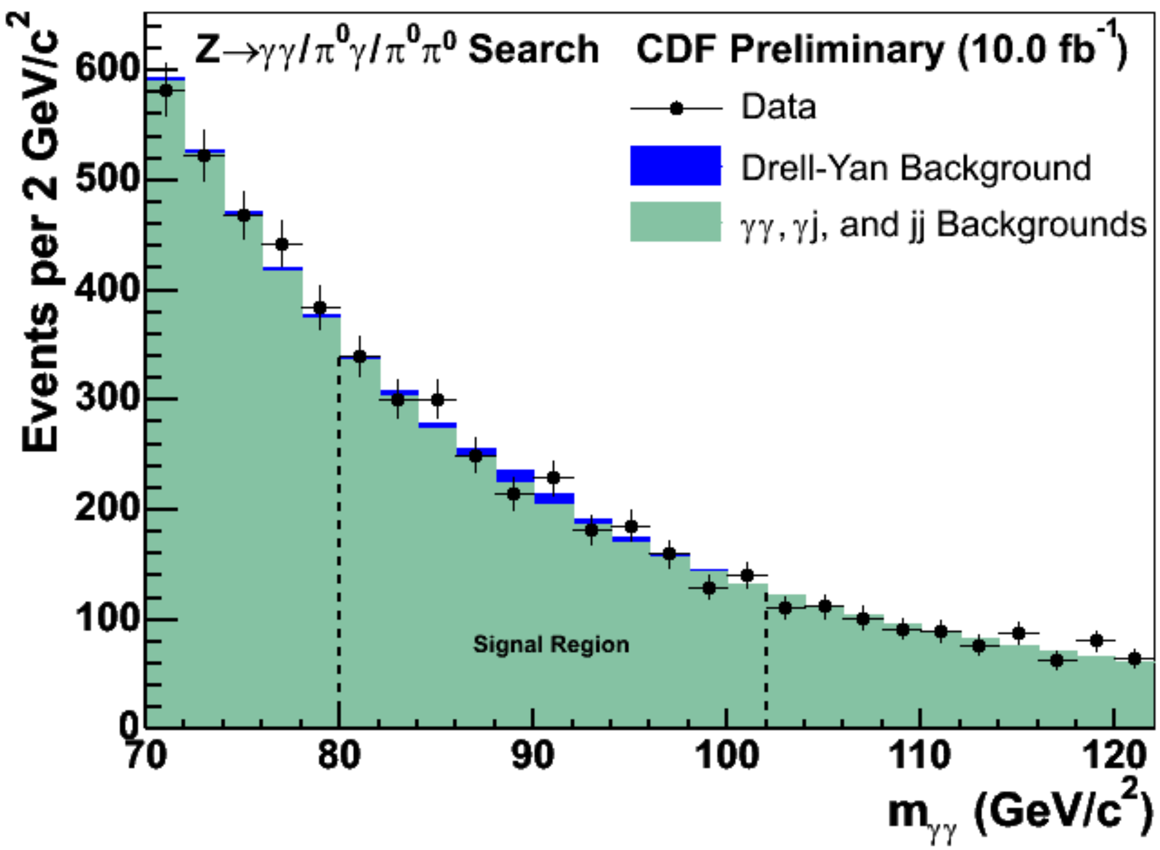


Fit to DY-subtracted data
(log scale)

Background Model versus Data

Sideband and Signal Region

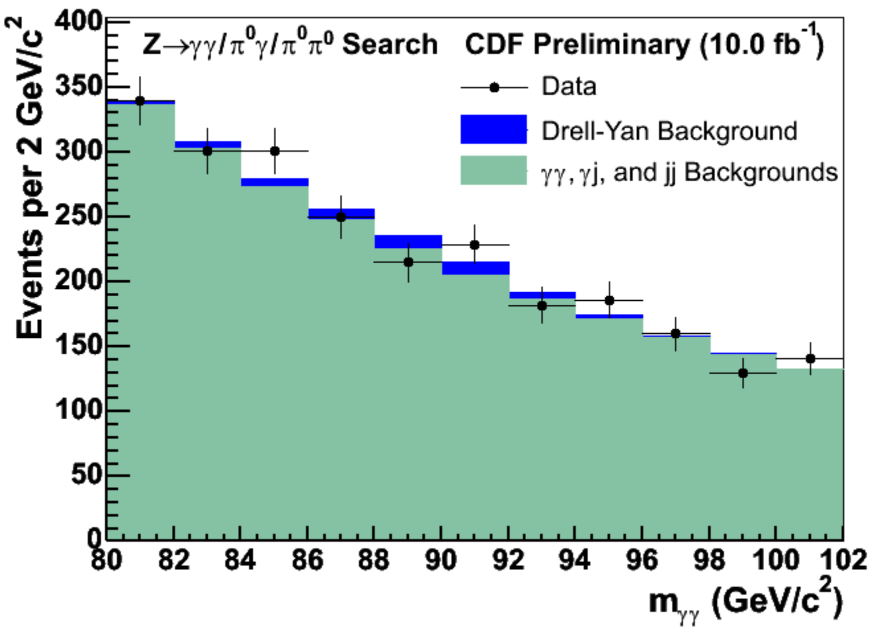


Background Model versus Data

Signal Region

$Z \to \gamma\gamma/\pi^0\gamma/\pi^0\pi^0$ Search — CDF Run II Preliminary, 10.0 fb^{-1}

Process	Number of Events for $80 < m_{\gamma\gamma} < 102$ GeV
Drell-Yan	54 ± 5
$\gamma\gamma$, γj, and jj	2251 ± 61
Total background	2305 ± 61
Data	2294



- No evidence for resonance in diphoton mass distribution
- So we set 95% C.L. limits on the branching ratios of the signal
- The mass shapes and event yields shown here are inputs to this calculation

Limit Calculation

- Binned mass shapes given as inputs
- Use mclimit software to set a Bayesian 95% C.L. upper limit on signal Br
- The binned likelihood as a function of f = Br(Z→$\pi^0\gamma$), Br(Z→$\gamma\gamma$), or Br(Z→$\pi^0\pi^0$):

$$L(f) = \prod_{i=1}^{N_{\mathrm{bins}}} \frac{\mu(f)_i^{n_i} e^{-\mu(f)_i}}{n_i!}$$

$$\mu_i(f) = f s_i + b_i$$

- n_i = number of data (pseudodata) events for observed (expected) limit
- s_i is $\sigma L A \varepsilon$ of signal
- b_i is sum of backgrounds
- 95% confidence limit obtained by finding the value of f_{95} for which:

$$0.95 = \int_0^{f_{95}} L(f)df$$

- Truncated Gaussian priors for systematic uncertainties integrated out before this

Limit Calculation

CDF Run II Preliminary						$\int \mathcal{L} = 10.0\ \text{fb}^{-1}$
		Signal			Background	
Systematic Uncertainties (%)		$Z \to \gamma\gamma$	$Z \to \pi^0\gamma$	$Z \to \pi^0\pi^0$	Drell-Yan	Non-Resonant
Luminosity	6	✓	✓	✓	✓	
Z Cross Section	6	✓	✓	✓	✓	
PDF	5	✓	✓	✓		
ISR/FSR	3	✓	✓	✓		
Energy Scale	0.2	✓	✓	✓		
Trigger Efficiency	1	✓	✓	✓	✓	
z-Vertex	0.2	✓	✓	✓	✓	
Photon ID Efficiency	4	✓	✓	✓		
π^0/γ Efficiency	2 per π^0		✓	✓		
Electron Fake Rate	2				✓	
Sideband Fit	2.7					✓

- Drell-Yan: also bin-by-bin statistical uncertainties
- Dominant uncertainty is that for the non-resonant background

Limit Results

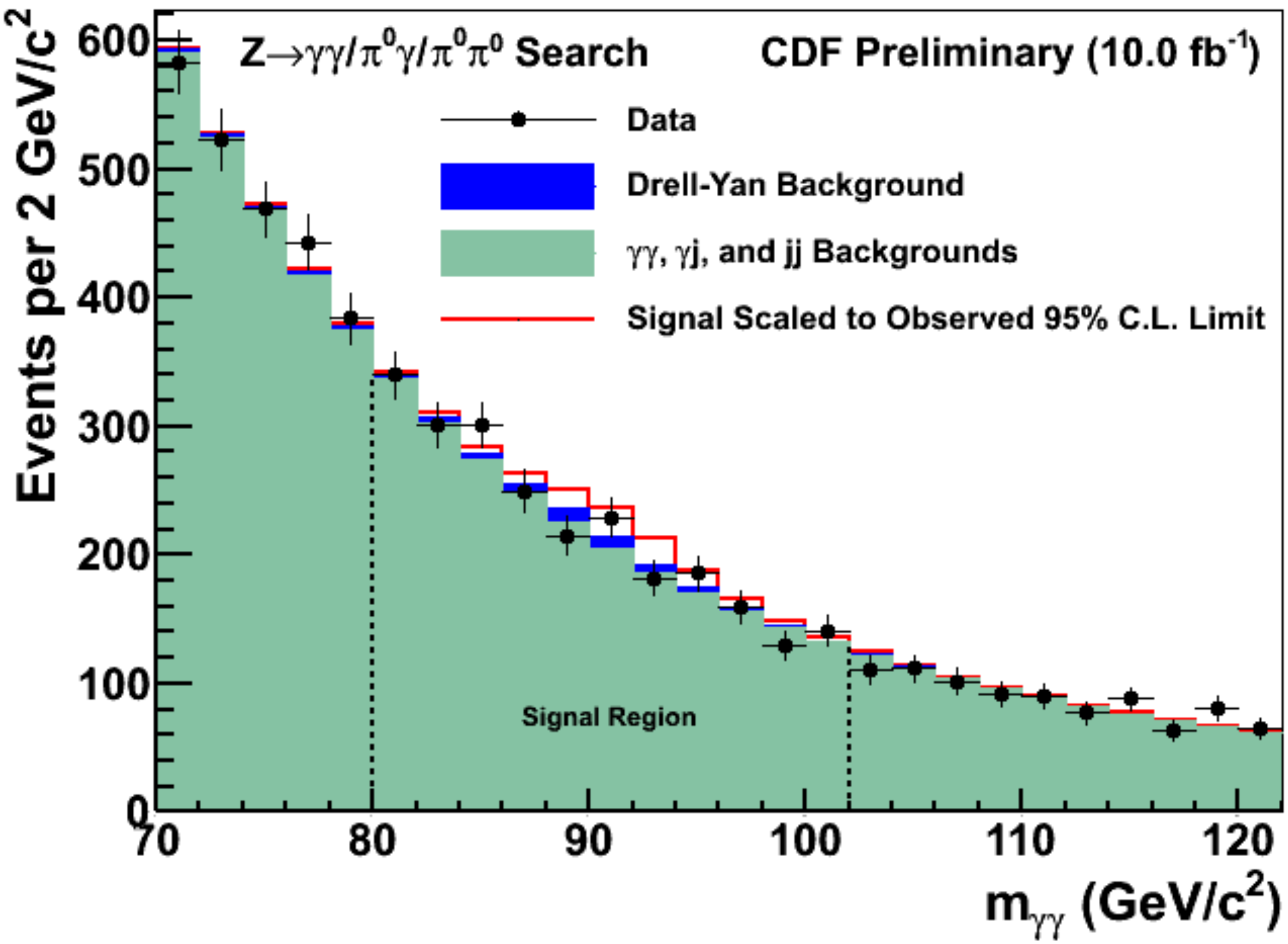
- We cannot distinguish the isolated photon from the isolated neutral pion
- We then calculate 95% C.L. limits on one at a time, assuming the other signals are not present

CDF Run II Preliminary $\int \mathcal{L} = 10.0\ \text{fb}^{-1}$

Signal Process	95% C.L. Limits: Expected ($\times 10^{-5}$) -2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	Observed ($\times 10^{-5}$)
$\text{Br}(Z \to \gamma\gamma)$	0.88	1.19	1.66	2.34	3.20	1.66
$\text{Br}(Z \to \pi^0\gamma)$	1.21	1.63	2.28	3.21	4.37	2.28
$\text{Br}(Z \to \pi^0\pi^0)$	0.93	1.23	1.72	2.41	3.29	1.73

- $\text{Br}(Z \rightarrow \pi^0\gamma)$ and $\text{Br}(Z \rightarrow \gamma\gamma)$ limits are more sensitive by factors of 3.1 and 2.3 over the previous limits
- The $\text{Br}(Z \rightarrow \pi^0\pi^0)$ limit is the first reported in this decay mode

Limit Results



Summary and Conclusions

- We report the most sensitive search to date for forbidden and exotic decays of the Z boson to a pair of photons, a pair of neutral mesons, or a neutral meson and a photon.
- 10 fb^{-1} of diphoton data used in this search
- Observed 95% C.L. upper limits are:
  - $Br(Z \rightarrow \pi^0\gamma) < 2.28\times10^{-5}$
  - $Br(Z \rightarrow \gamma\gamma) < 1.66\times10^{-5}$
  - $Br(Z \rightarrow \pi^0\pi^0) < 1.73\times10^{-5}$
- The $Br(Z \rightarrow \pi^0\gamma)$ and $Br(Z \rightarrow \gamma\gamma)$ limits are, respectively, 2.3 and 3.1 × better than the previous limits
- The $Br(Z \rightarrow \pi^0\pi^0)$ limit is the first reported in this decay mode

- Future plans: consider rare Z decays involving eta mesons

Backup

Landau-Yang Theorem

- To construct a spin 1 Z from two spin 1 photons, the total J = 1 spin function for the Z would be constructed from antisymmetric spin functions.
- For example, the |1,1> Z state would come from |1,1>|1,0> - |1,0>|1,1> photon states.
- Then, assuming that the photons conserve linear momentum in the rest frame of the Z, the spatial part of their wave function is symmetric, giving an overall antisymmetric wavefunction.
- Which is not allowed for a total J = 1 state, which should be symmetric.

Summary of H→γγ Techniques

- Event Selection:
  - Isolated photon trigger (25 GeV cut)
  - Identify two 15 GeV CEM photons using central NN selection
- Signal Model:
  - Shape and acceptance from Pythia MC
  - Isolated photon trigger and photon ID efficiency validated in Z→e+e- data
- Background Model:
  - Exploit resonant feature of H decay into photons
  - Use sideband regions of diphoton mass to determine background shape and rate in signal region

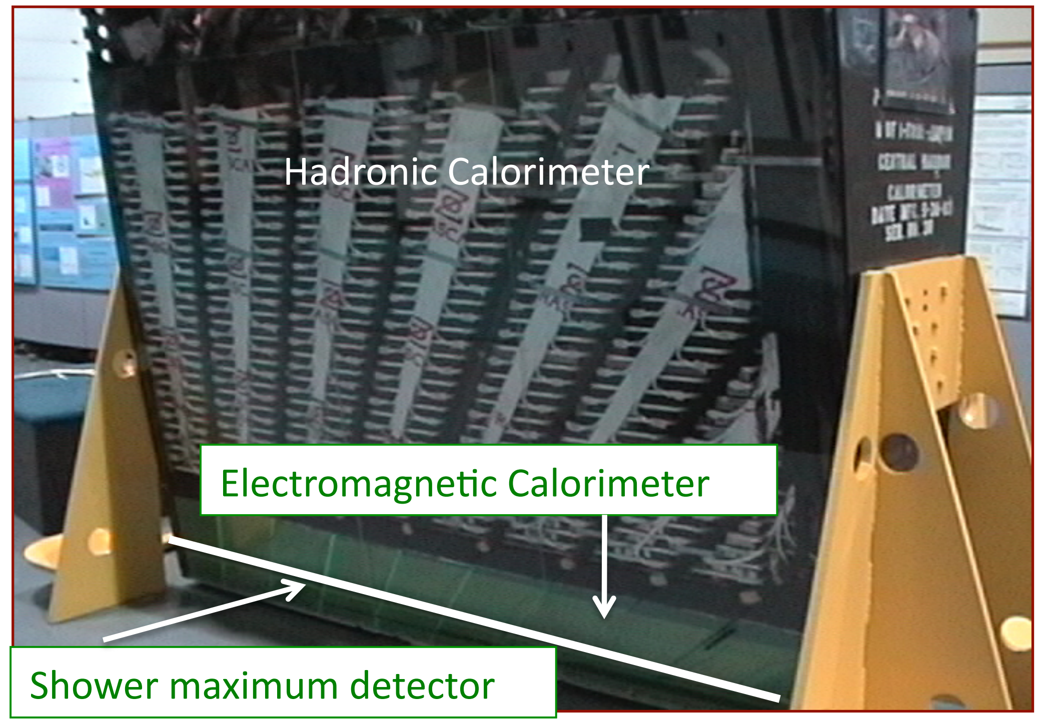
Modifications for Z→γγ/π^0γ Analysis

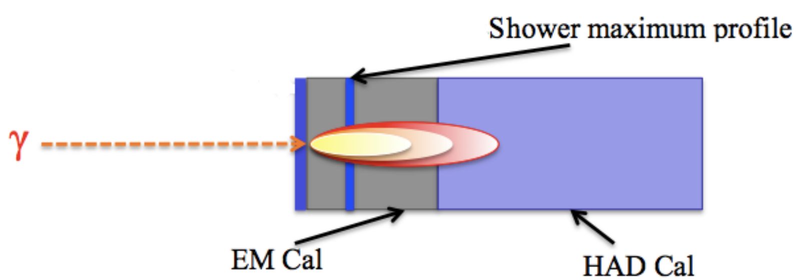
- Event Selection:
  - Isolated photon trigger (25 GeV cut)
  - Identify two 15 GeV CEM photons using central NN selection
- Signal Model:
  - Shape and acceptance from a modified (angle- or π^0 efficiency-weighted) Pythia MC
  - Isolated photon trigger and photon ID efficiency validated in Z→e+e- data
- Background Model:
  - Exploit resonant feature of Z decay into photons
  - Use sideband regions of diphoton mass to determine background shape and rate in signal region
  - Model Z→e+e- from Pythia MC

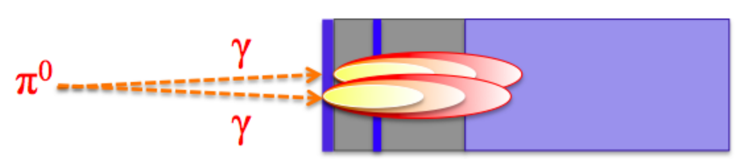
Blue indicates what has dominated our time for transition to the Z→γγ/π^0γ analysis

Photon Identification

- EM calorimeter segmentation:
  - $\Delta\eta \times \Delta\varphi \sim 0.1 \times 15°$ ($|\eta|<1$)
  - Not fine enough to distinguish π^0/η and photon showers
- Shower max detector
  - ~6 radiation lengths into EM calorimeter
  - Finely segmented: Position resolution ~1mm
  - Gives resolution to better distinguish $\pi^0/\eta \rightarrow \gamma\gamma$ from γ at low Et
  - For π^0 with sufficiently high Et, collinear photons like single γ

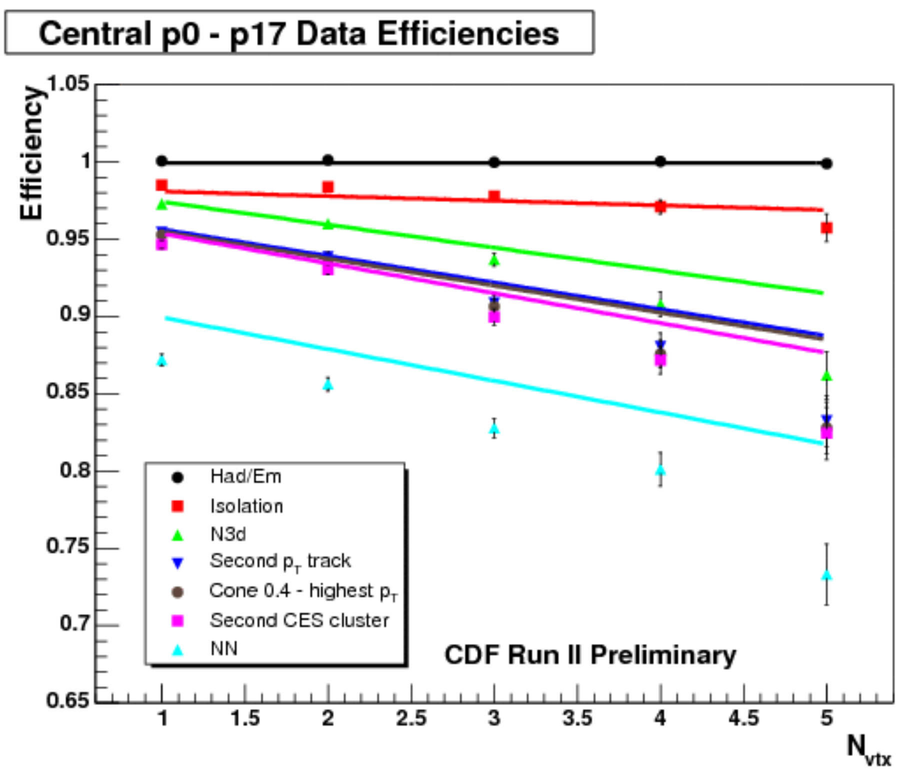


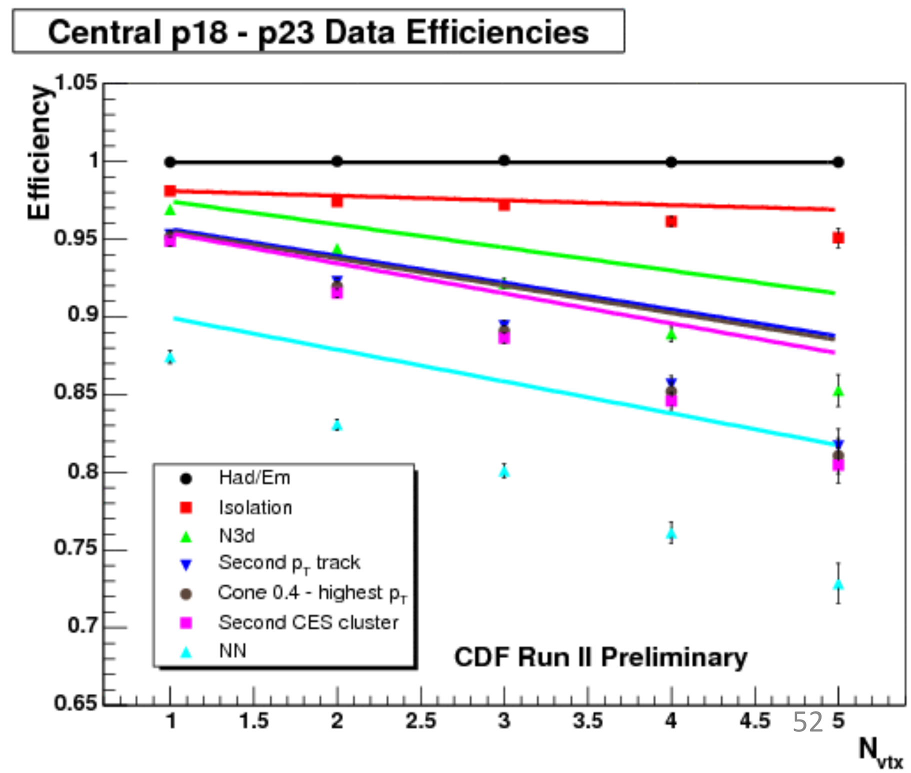




Photon ID Efficiency Scale Factors

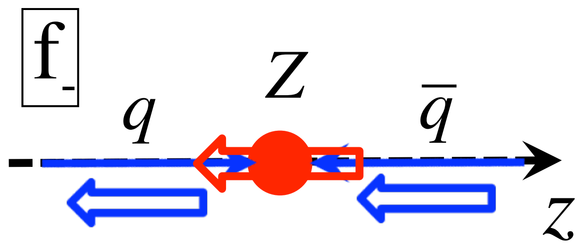
- Photon ID efficiency calibrated with Z→e+e-
- Data (MC) efficiency indicated with points (lines)

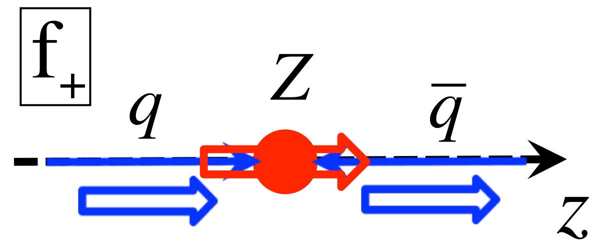




Revisiting the Z polarization from Drell-Yan

We considered all polarization states. In the limiting case (where the collision is of head-on (massless) quarks) only the two states here would be considered:





In this limit f_0 = 0, and then the angular distributions in the Z rest frame for Z→νν and Z→γγ events becomes

$$F_{\nu\bar{\nu}}(\theta) = f_+\left(d^1_{1,1}\right)^2 + f_-\left(d^1_{1,-1}\right)^2 = f_+\left(1+\cos^2\theta\right)$$

$$F_{\gamma\gamma}(\theta) = f_+\left(d^1_{1,0}\right)^2 + f_-\left(d^1_{1,0}\right)^2 = f_+\left(1-\cos^2\theta\right)$$

The corresponding weight function would then be:

$$w_{\gamma\gamma}(\theta) = \frac{F_{\nu\bar{\nu}}(\theta)}{F_{\gamma\gamma}(\theta)} = \frac{1-\cos^2\theta}{1+\cos^2\theta}$$