Search for New Physics in the Exclusive Delayed Photon + Missing Transverse Energy Final State at CDF

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Final Examination
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Special thanks to: Adam Aurisano,
Daniel Goldin, Jason Nett, and David Toback

Outline

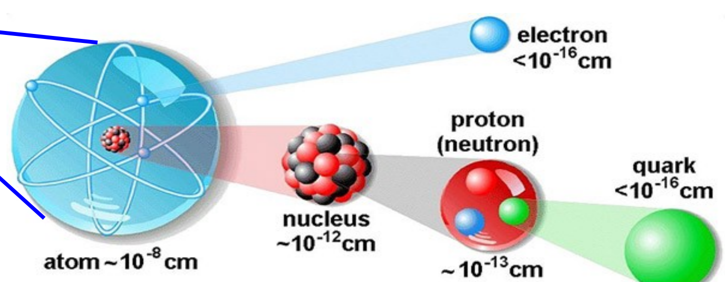
- Motivation
  - Standard Model of Particle Physics
  - Supersymmetry
- Tools
  - Tevatron & CDF Detector
  - EMTiming System
- Overview of the Delayed Photon Analysis
  - Intriguing 2008 Preliminary Result
- Exclusive γ+MET Analysis
  - Calibrations
  - Removing / Minimizing Timing Biases
  - Data Driven Background Estimation
- Results

Motivation

The Standard Model of Particle Physics

The Standard Model (SM) is a remarkably successful theory which describes the properties and interactions of the fundamental particles

05/17/12



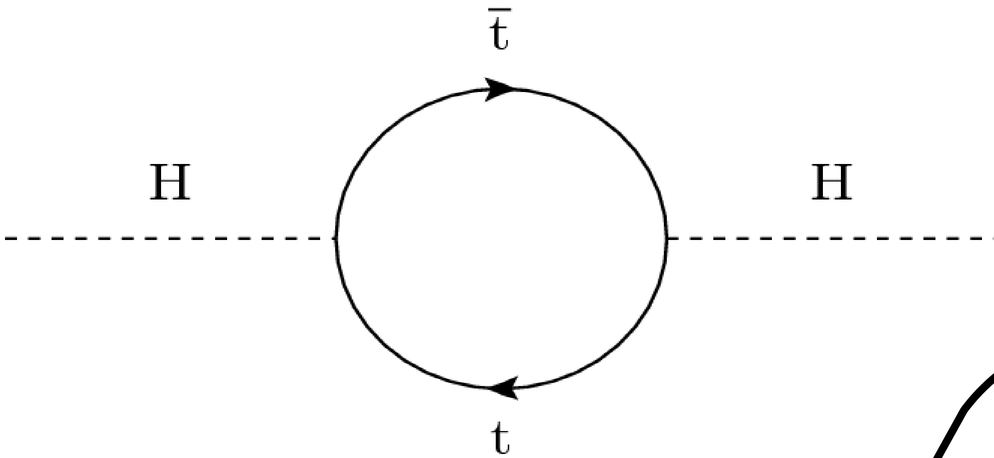
Question:

Is there evidence that the SM may not be the complete story?

Motivation

The Standard Model of Particle Physics

Problem: The Hierarchy Problem



$$m_H^2 = m_{Bare}^2 + \delta m_H^2$$

$$\delta m_H^2 \approx \frac{\lambda_f^2}{4\pi^2}(\Lambda^2 + m_f^2) + ...$$

Calculating the Higgs mass using terms and interactions with other particles, causes the Higgs mass to blow up

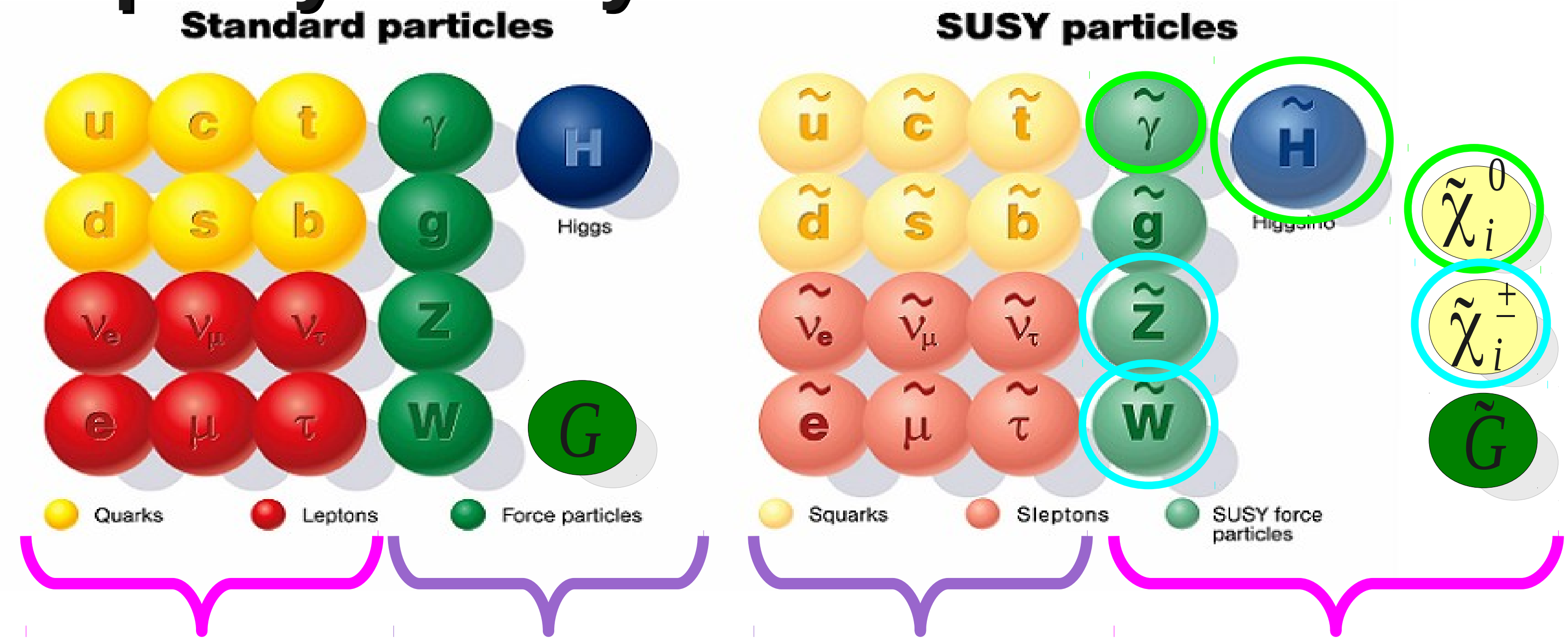
(m_H ~ 10^{15} GeV unless parameters are fine tuned)! ***(This is bad)***

This suggests that the SM may be a low energy approximation for something more

Supersymmetry to the rescue ?!

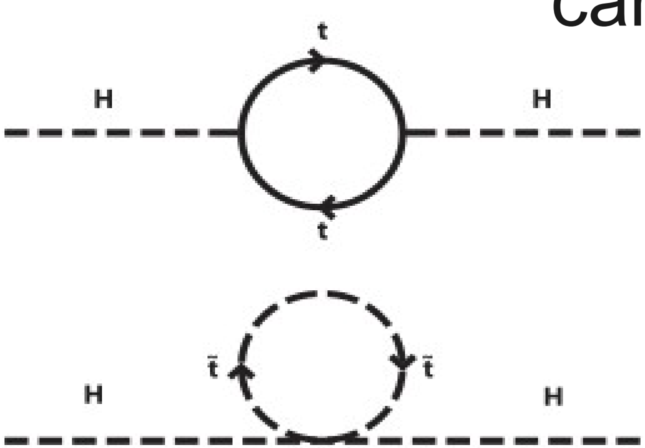
Supersymmetry (man?)

Supersymmetry



Fermions **Bosons** **SFermions** **Bosinos**

Supersymmetry (SUSY) proposes a symmetry between the particles that make up matter (fermions) and the force carrying particles (bosons)



Fixing The Hierarchy Problem

Sparticles introduce new corrections to the Higgs mass, but with an opposite sign

$$\delta m_H^2 \approx -\frac{\lambda_{\tilde{f}}^2}{4\pi^2}(\Lambda^2 + m_{\tilde{f}}^2) + \ldots$$

Saves the Higgs mass from blowing up

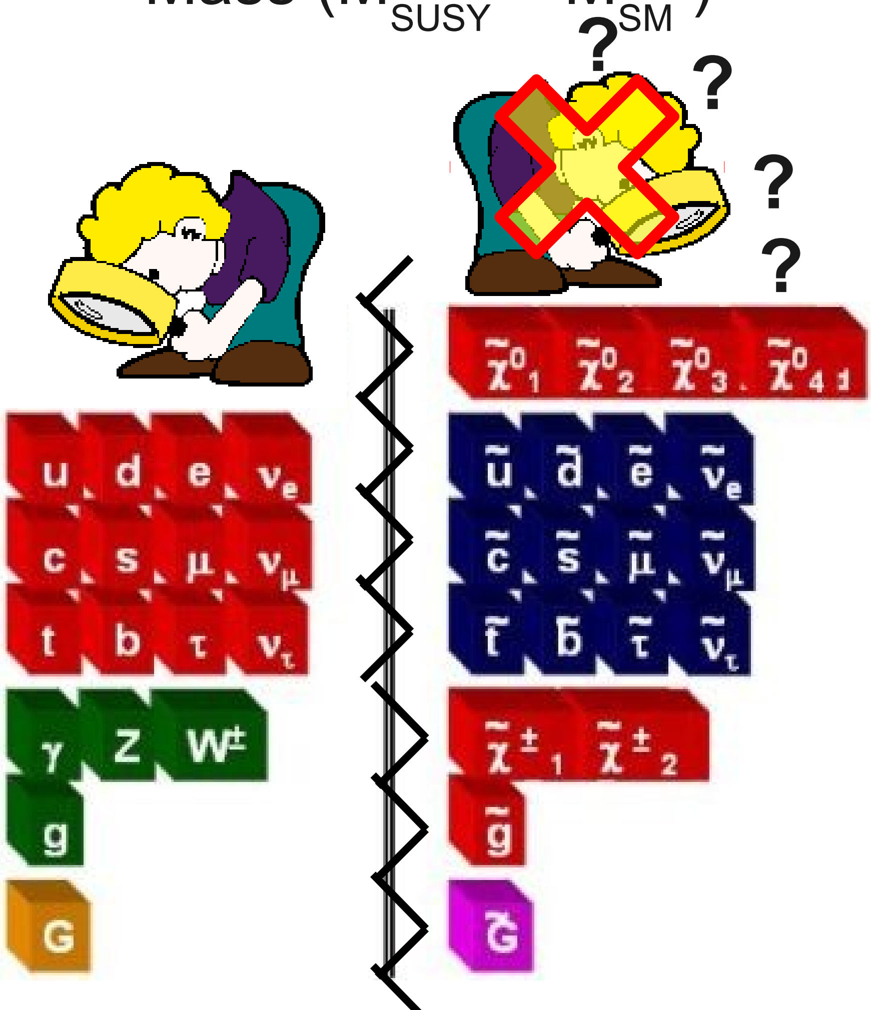
Supersymmetry

Problem:

→ We do not observe these particles at typical energies found today.

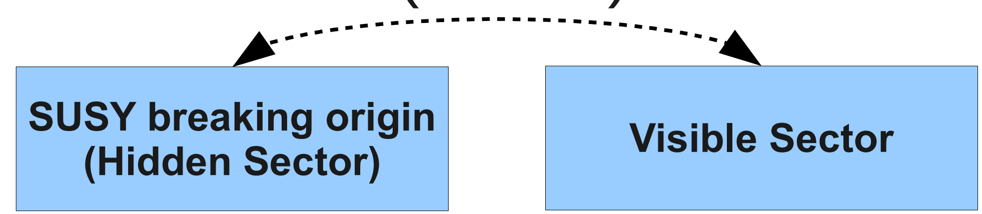
→ This symmetry is broken

→ SUSY Mass > Standard Model Mass ($M_{SUSY} > M_{SM}$)



"Particles, particles, particles."

One possible mechanisms for this symmetry breaking is known as Gauge Mediated Supersymmetry Breaking (GMSB)

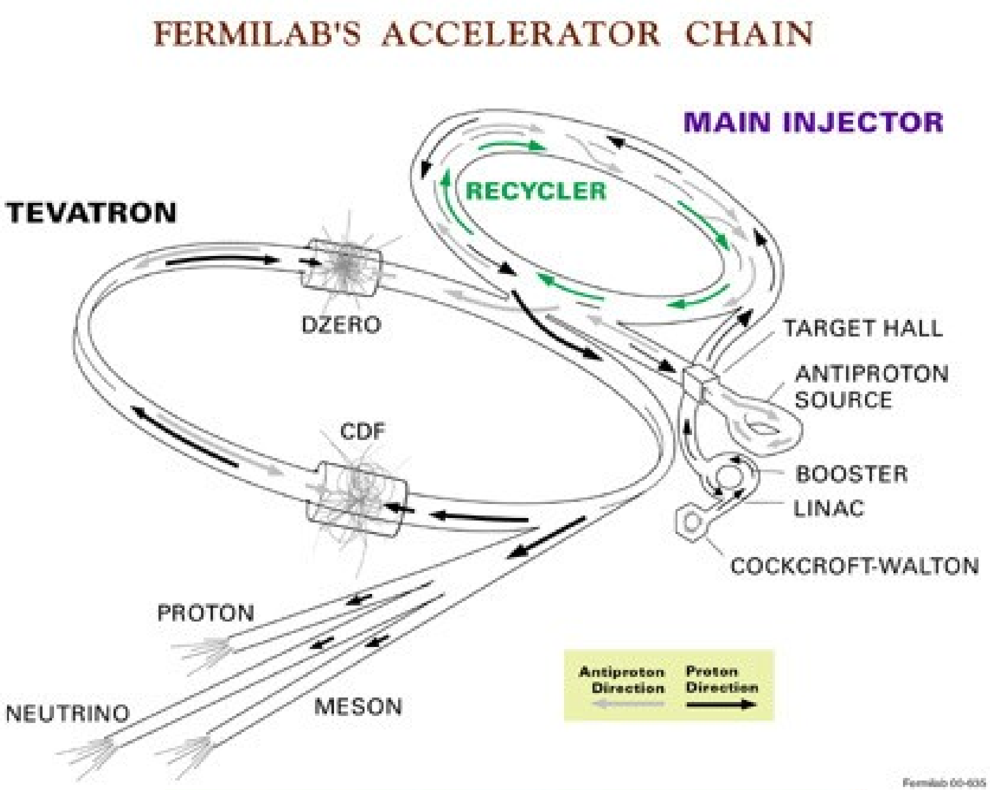


The symmetry breaking is transmitted from the hidden sector via Standard Model gauge interactions. This process is what gives mass to the SUSY particles observable in the Visible Sector

Overview of the

In the coming slides we go over the physical tools that allow us to perform these new particles. In particular, the analysis in this thesis

Tevatron



The Tevatron was the most powerful proton-antiproton accelerator in the world

Center of Mass Energy

$$\sqrt{s} = 1.96\, TeV$$

Collision Parameters

36 proton $\times$ 36 antiproton bunches
w/ Collisions every 396 ns

Integrated Luminosity

$\sim 10\,\mathrm{fb}^{-1}$ delivered in Run II
$6.3\,\mathrm{fb}^{-1}$ used in this analysis

Collider Detector at Fermilab (CDF)

Muon Chambers

Hadronic Calorimeters

ElectroMagnetic Calorimeter

Central Tracker

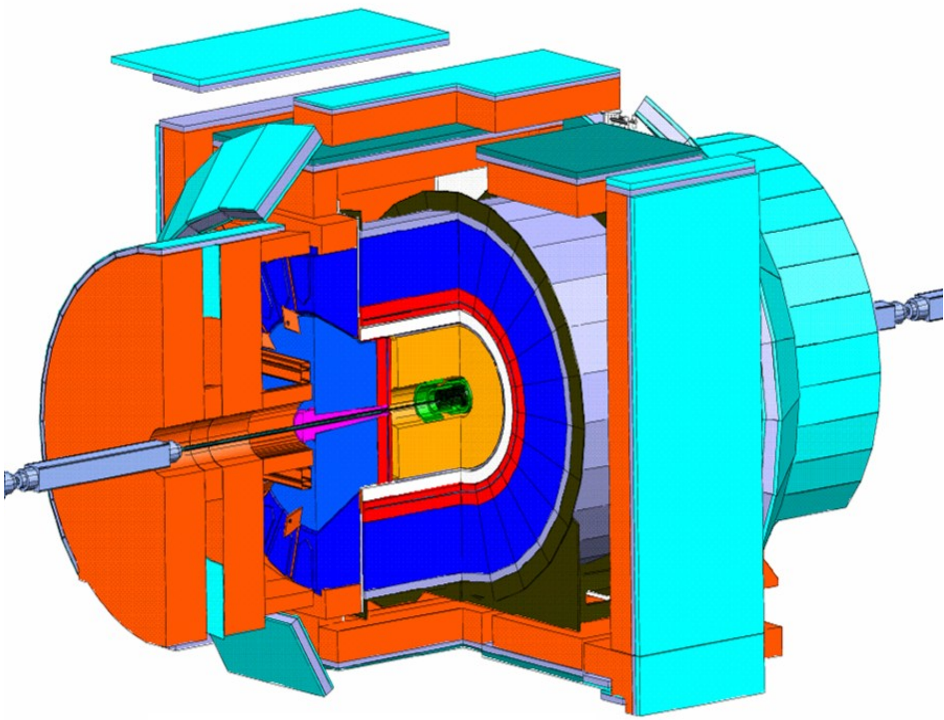
Silicon Tracker

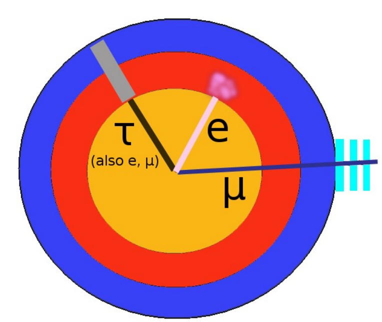
Multi-purpose detector capable of identifying Electrons, Muons, Photons, Taus, b-jets, and Missing Transverse Energy (neutrinos and SUSY particles)

Highlights of Systems used in the Delayed Photon Analysis

Central Outer Tracker: Open cell drift chamber with 96 layers of sense wire. Each wire capable of making a timing measurement on a track.

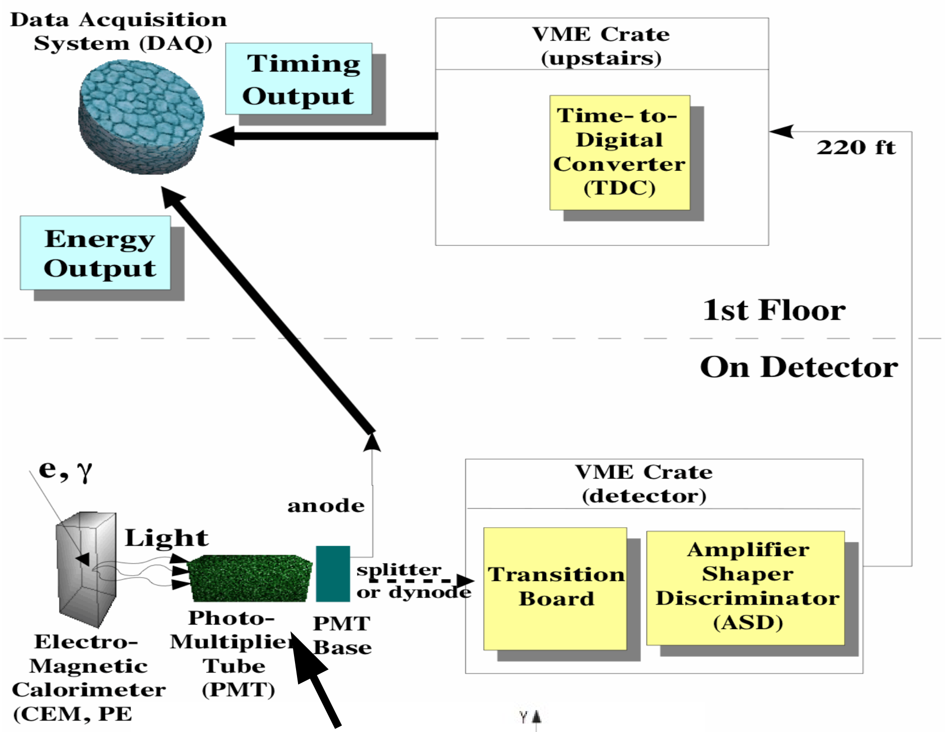
Electromagnetic Calorimeter:
Detector for energy measurement of electromagnetic events (especially photons and electrons).
Lead/scintillator sampling calorimeter

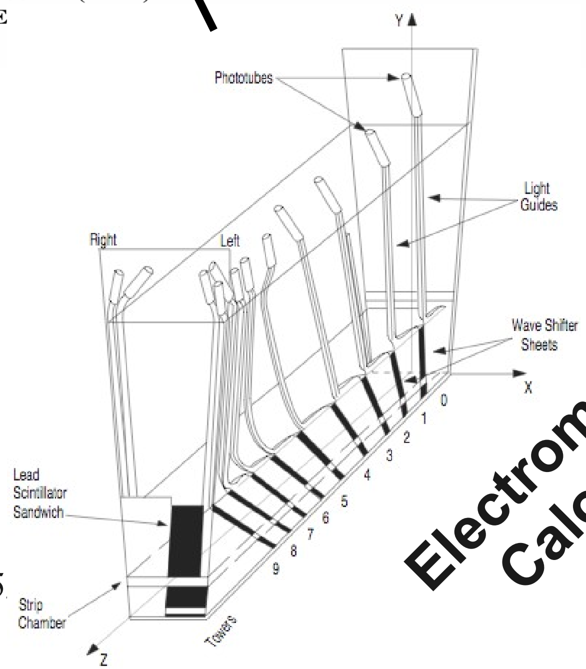




Photon Timing System (EMTiming)

CDF EM Timing Project





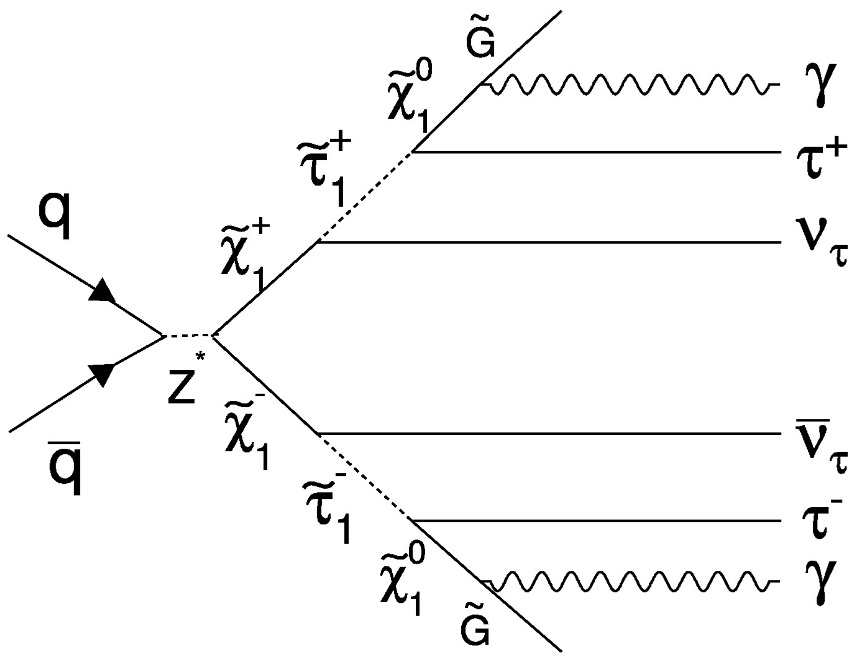
Electromagnetic Calorimeter

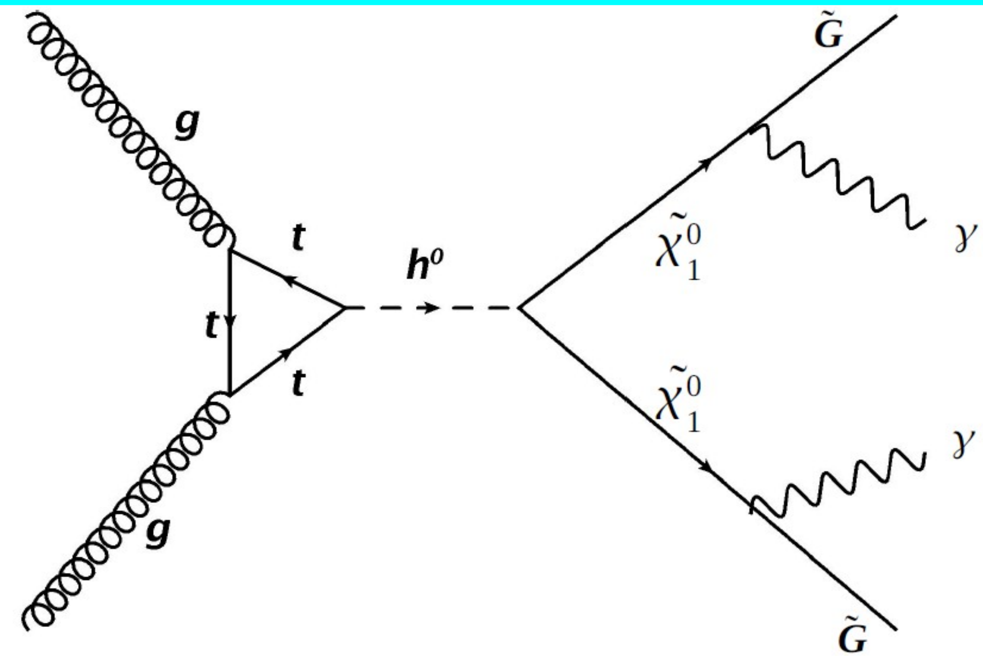
Provides timing information with a **resolution of ~ 0.5 ns**

System is ~ 100% efficient for Energies > 3 GeV

6600 Hours of Live Time ~13 million PMT-hours over its lifetime

GMSB SUSY at the Tevatron





GMSB models provide compelling motivation for looking for SUSY with long lifetime

$\gamma\gamma$+MET (short lifetime) or

γ+MET+Jet (long lifetime)

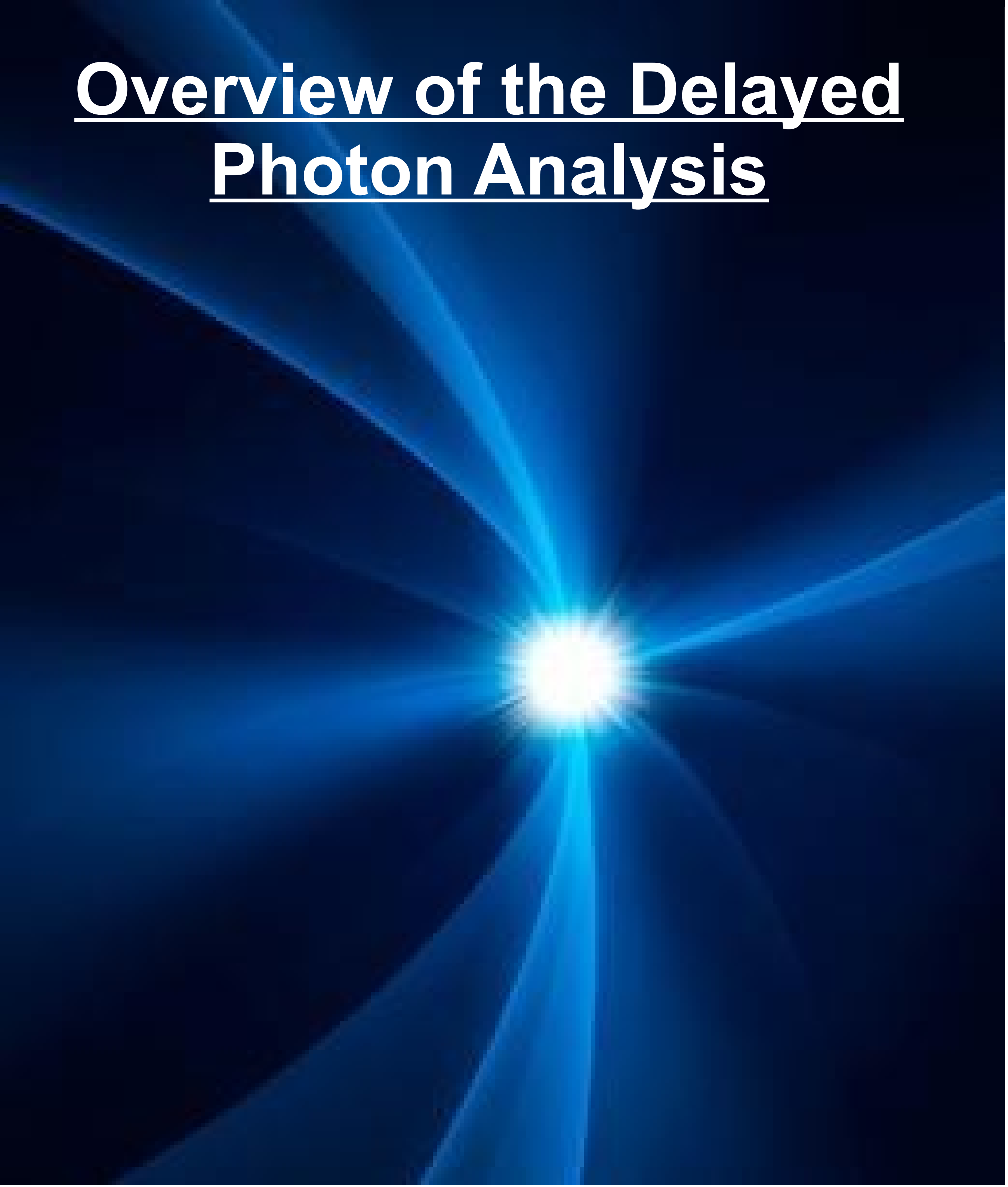
Slightly simpler but less common models provide motivation for looking at exclusive γ+MET and $\gamma\gamma$+MET

Models of this kind are previously unexplored and a new window of opportunity

BOTH THESE SEARCHES HAVE BEEN PERFORMED HERE AT CDF 2007 & 2010

Phys. Rev. D 70 (2004) 114032 &
Phys. Lett B 702 (2011) 377

Overview of the Delayed Photon Analysis

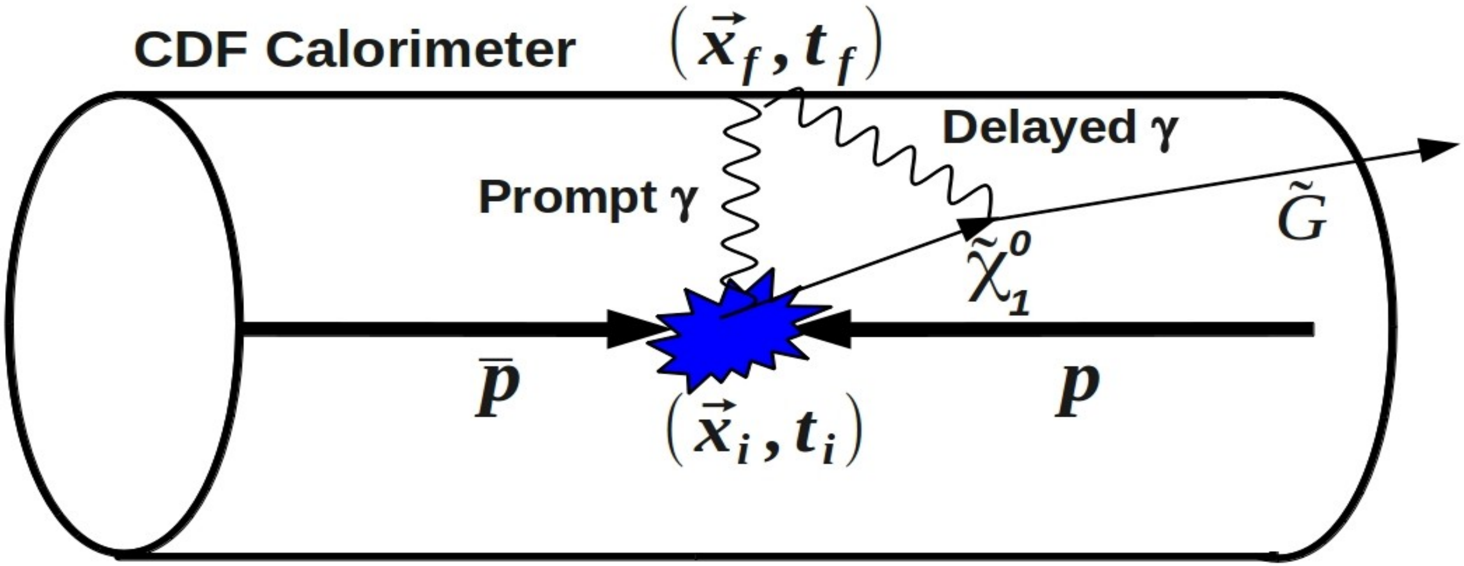


Now we shift to an explanation of how we use these tools to search for the delayed photon signature

Also, why we call it a delayed photon

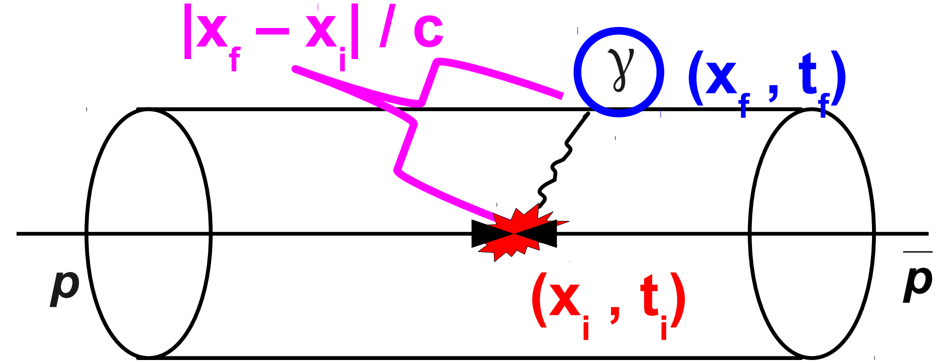
Overview of the Delayed Photon Analysis

In some forms of Gauge Mediated Supersymmetry (SUSY) the next to lightest stable particle (NLSP) is long lived (lifetime on the order of nanoseconds) before decaying to a photon and the lightest stable particle (LSP).



This means that you could have events where the photons arrive late when compared to expectation from prompt photons ("delayed photons")

Overview of the Delayed Photon Analysis



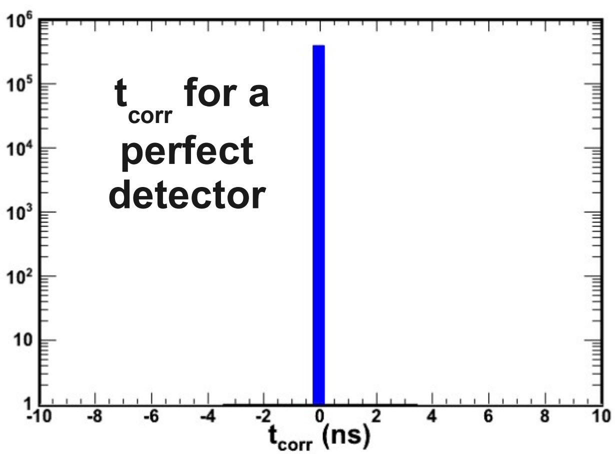
Definition of Timing Variables (t_{corr})

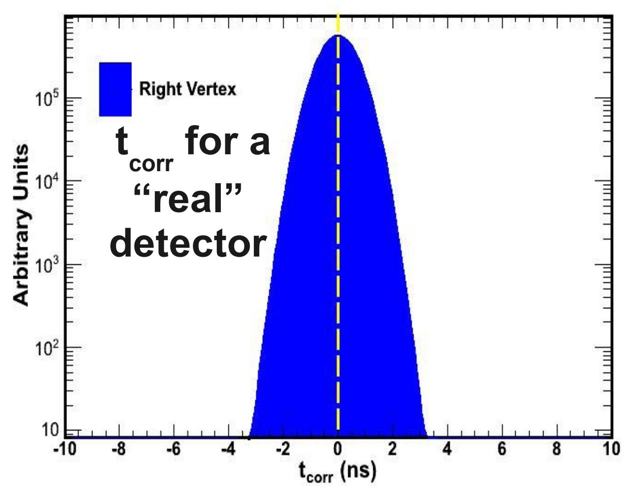
The typical variable used for photon timing is the corrected time of arrival

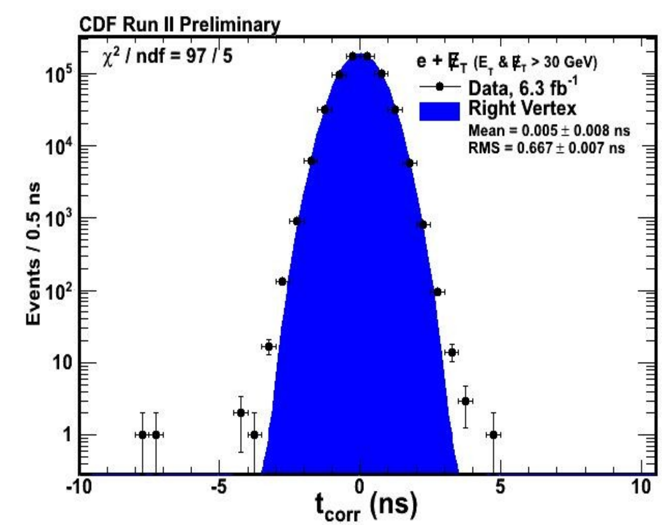
$$t_{corr} = (t_f - t_i) - \frac{|x_f - x_i|}{c}$$

Arrival Time **Initial Time** **Time of Flight**

For a perfect detector we would measure t_{corr} = 0 for all promptly produced particles.







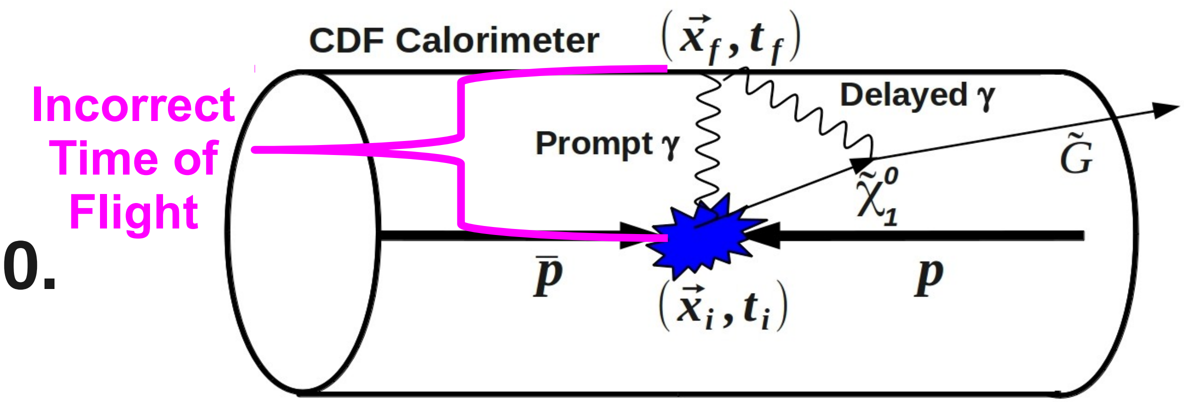
However, we don't have a perfect detector! So our measurement becomes smeared.

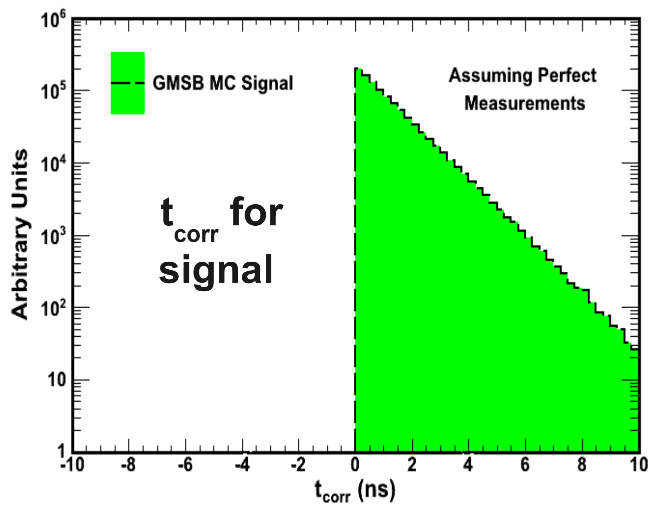
Confirmed by looking at electron data.
We call this Right Vertex Timing Distribution

Overview of the Delayed Photon Analysis

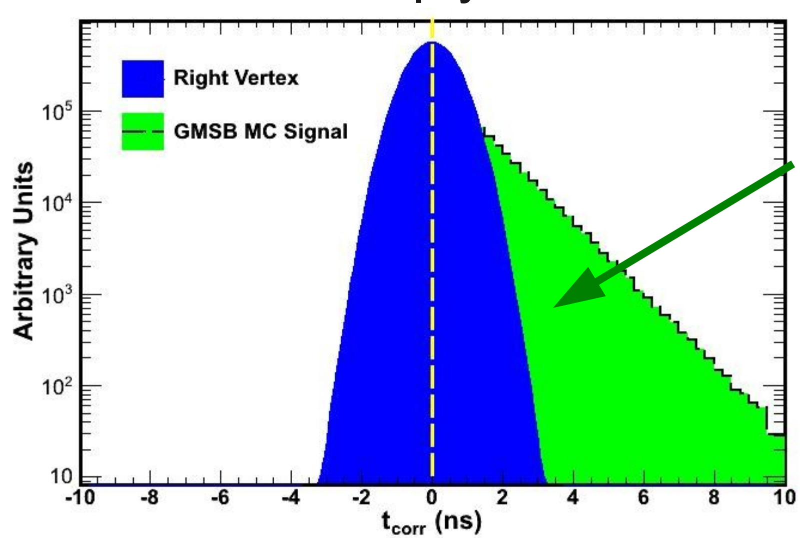
What does the timing of New Physics Look Like?

For a perfect detector photons from long-lived objects would have $t_{corr} > 0$.





t_{corr} for prompt photons plus plus delayed photons from new physics



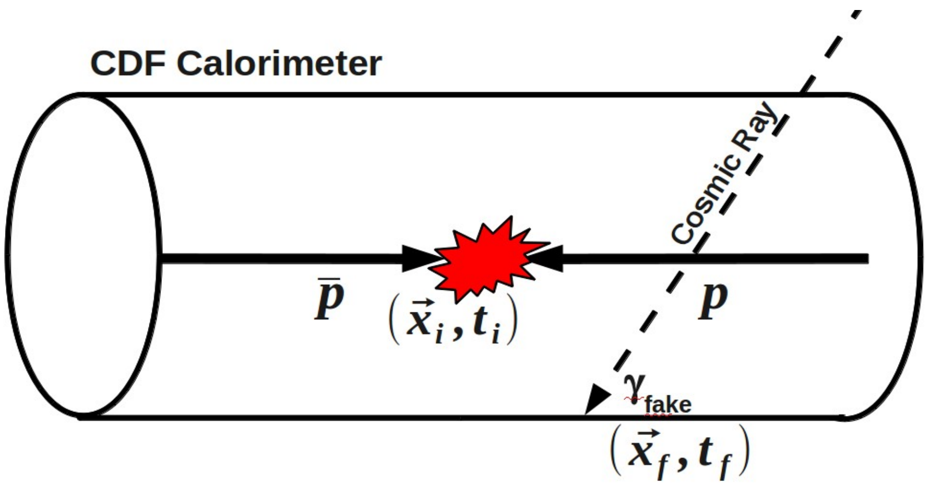
Clearly the place to look for decays coming from long lived neutral objects is $t_{corr} > 2$ ns

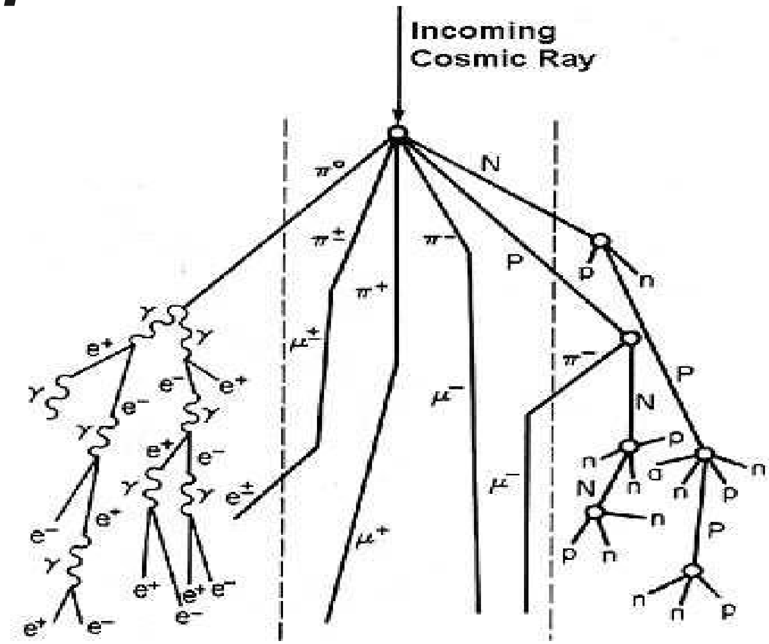
What are the dominant backgrounds in the delayed photon search?

Overview of the Delayed Photon Analysis

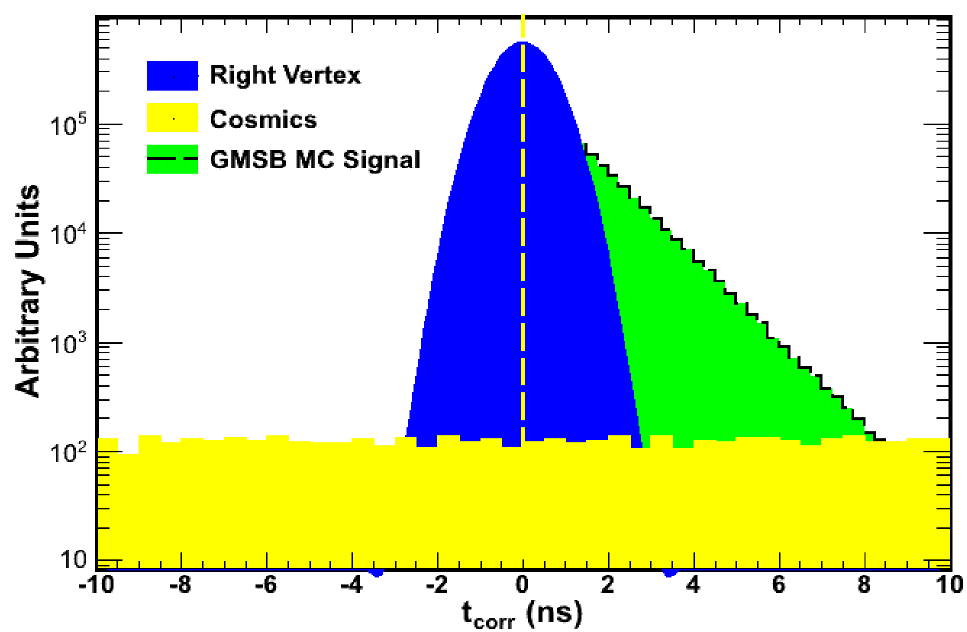
Backgrounds in the delayed photon search

Cosmic rays are charged particles that originate in outer space and interact with the earth's atmosphere producing secondary charged particles that shower down to the earth's surface



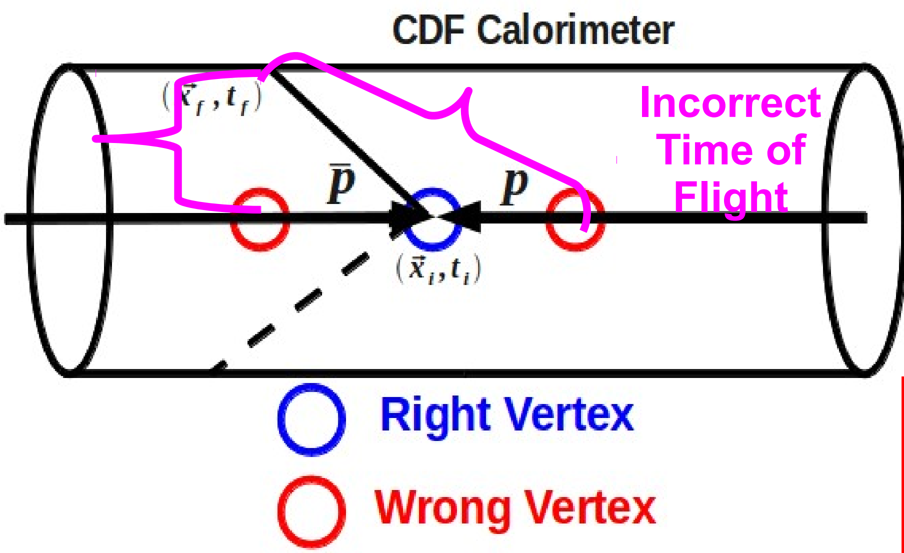


If a cosmic ray happens to hit the detector and fake a photon at the same time as a collision we may incorrectly assign that as a photon and calculate a corrected time.



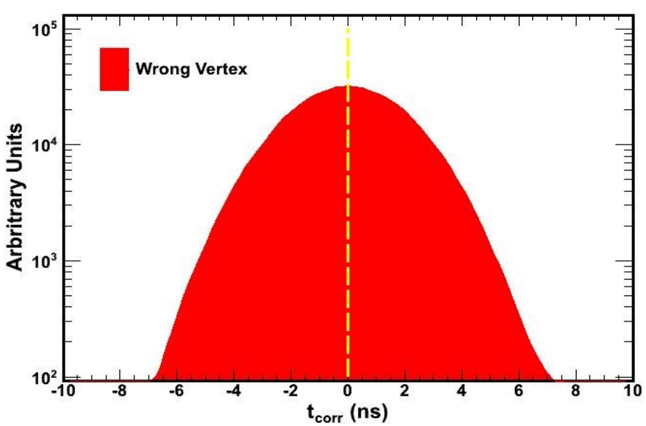
Cosmics show up roughly flat as a function of time

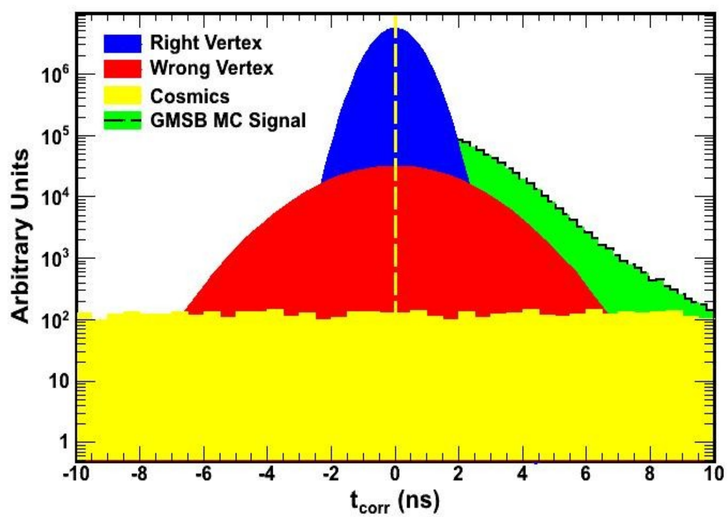
Backgrounds for the Delayed Photon Analysis

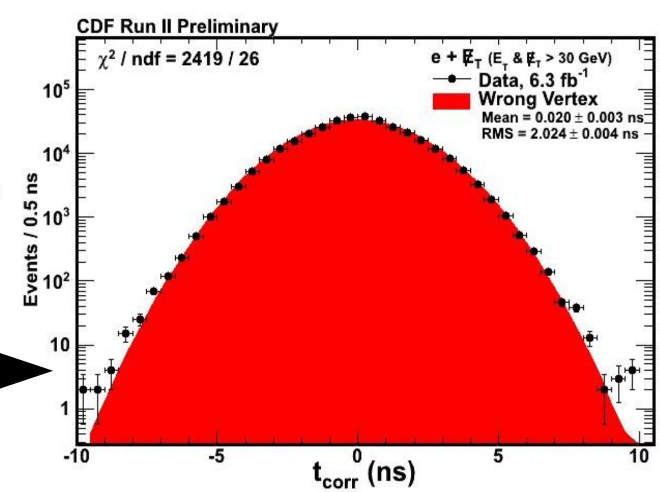


If there are secondary collisions in the detector we may incorrectly pick one of those "**Wrong Verticies**" and thus assign an incorrect time of flight and incorrect collision time.

→ These events are well described by a Gaussian with an RMS = 2 ns







This description confirmed by looking at electron data when we anti-match the electron to the vertex

We call this the Wrong Vertex Timing Distribution

Overview of the Delayed Photon Analysis

- Intriguing 2008 Preliminary Result using the old analysis tools

- Extraordinary claims require extraordinary evidence

- More data, better understanding, and new analysis techniques to see if this excess is real

Overview of Previous Delayed Photon Search

“Back in the Good 'ol Days”

Step 1

Count the number of events in the Control Region

Step 2

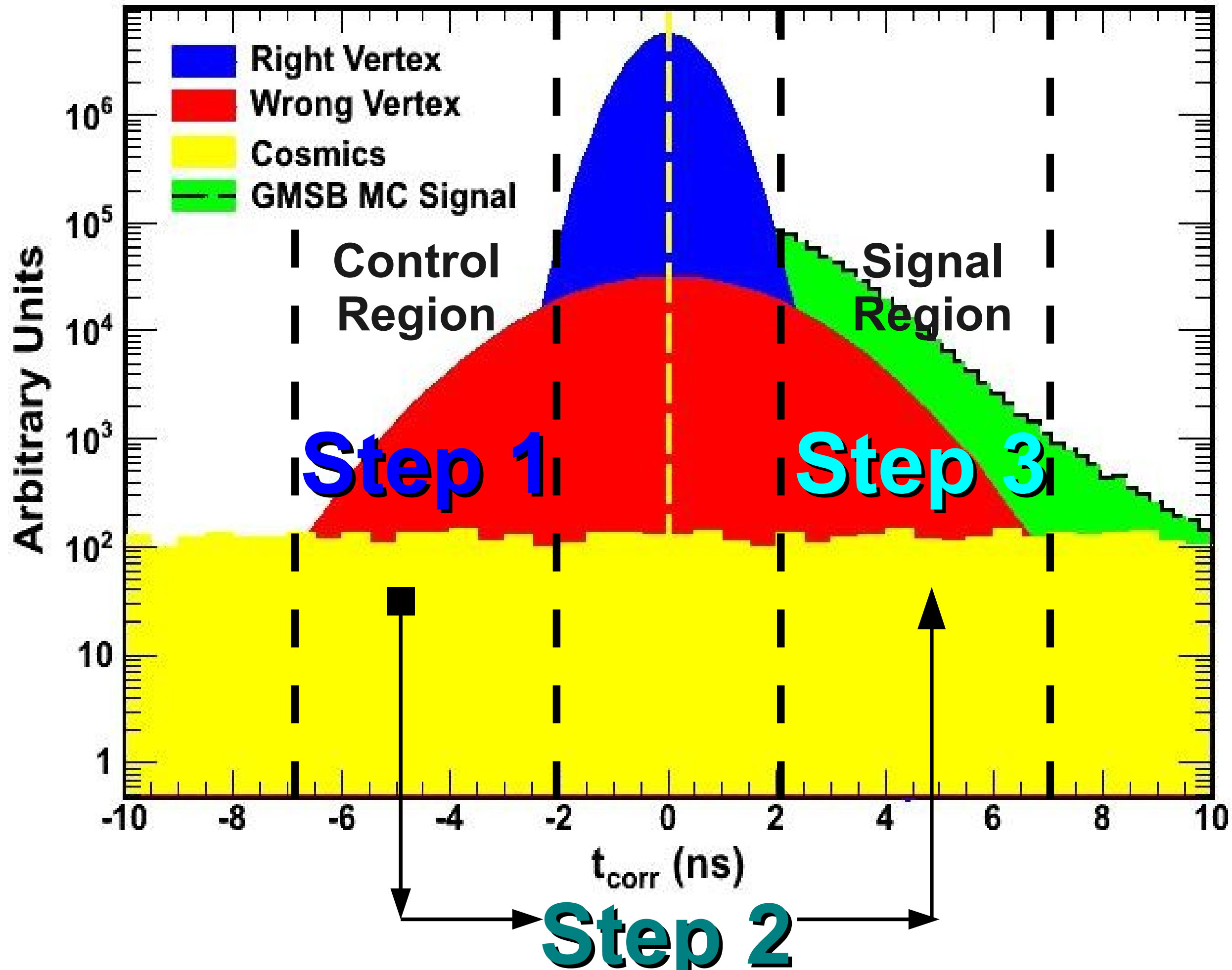
Use this number to predict the number of events in the signal region

Step 3

Observe an excess in the signal region

Step 4

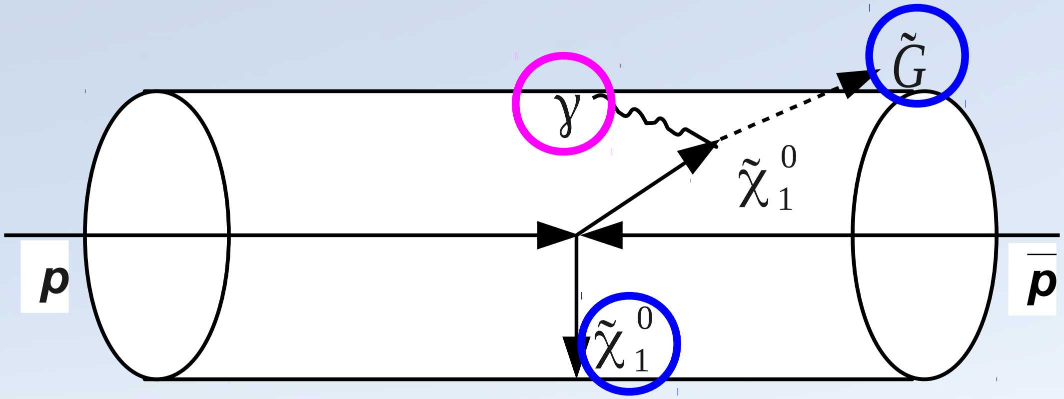
Win a Nobel Prize!!



$$N_{Signal\,Region} = N_{Control\,Region}$$

for the backgrounds

Preliminary 2008 Search



Standard Model Backgrounds:

$W \longrightarrow e\nu \longrightarrow \gamma_{fake}\nu$

$W \longrightarrow \mu\nu \longrightarrow \gamma_{fake}\nu$

$W \longrightarrow \tau\nu \longrightarrow \gamma_{fake}\nu$

$W\gamma \longrightarrow \gamma\nu$ *(lost lepton)*

$Z\gamma \longrightarrow \gamma\nu\nu \longrightarrow \gamma$ MET

$\gamma + jet_{lost} \longrightarrow \gamma$ MET

Exclusive γ+MET

Single Delayed Photon

(Photon from decay of long-lived neutral object)

+

Missing Energy

(Created from invisible particles leaving the dector)

+

Nothing Else

(Assuming Direct Pair Production)

Preliminary Analysis Cuts

γ E_T > 45 GeV & MET > 45 GeV

Veto Jet Cluster E_T > 15 GeV

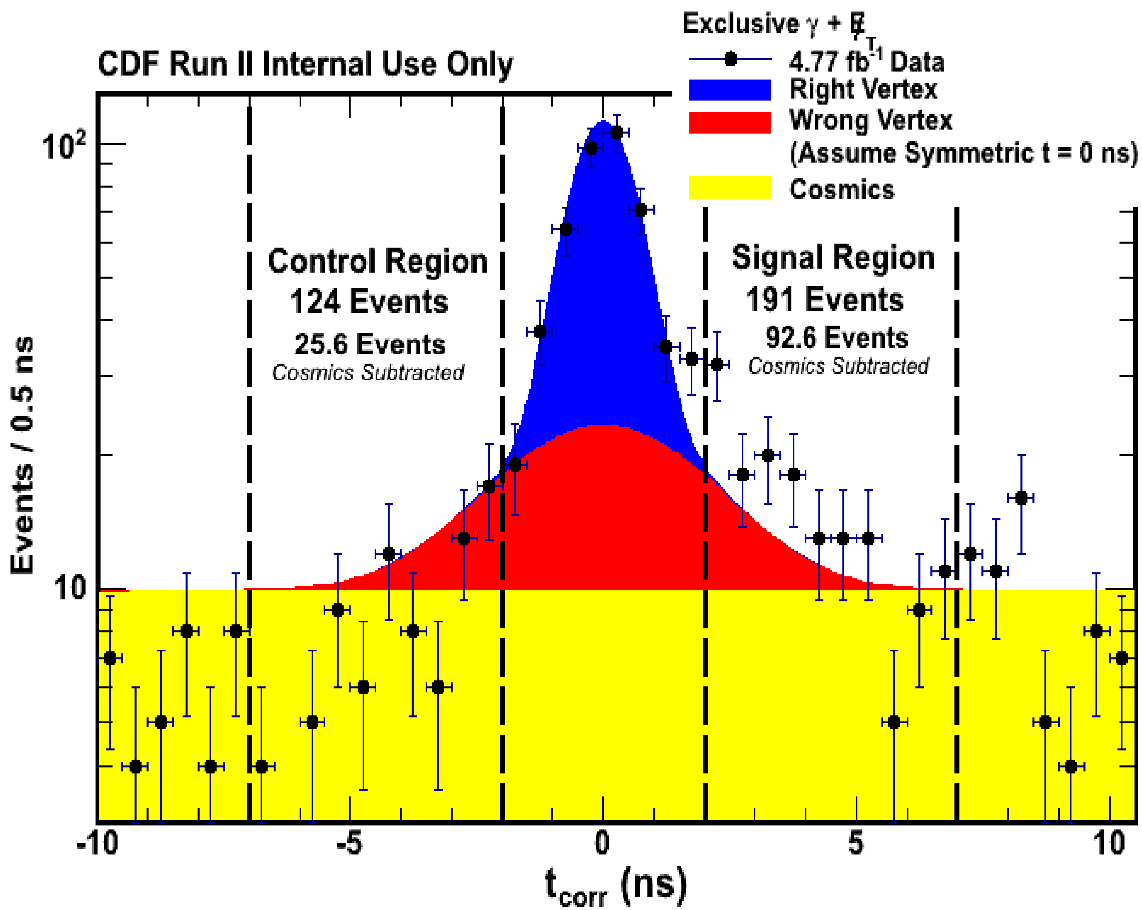
Veto Track P_T > 10 GeV

Cosmics & Beam Halo Rejection

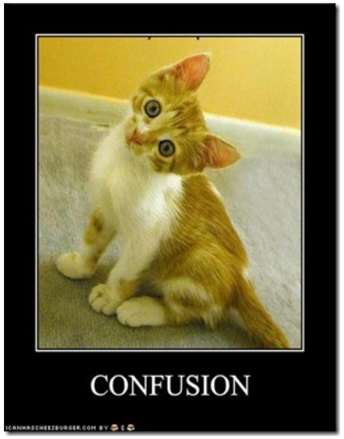
Non-Standard Model Background

Cosmics, Beam Halo, Satellite Bunches

Extraordinary Claims Require Extraordinary Evidence



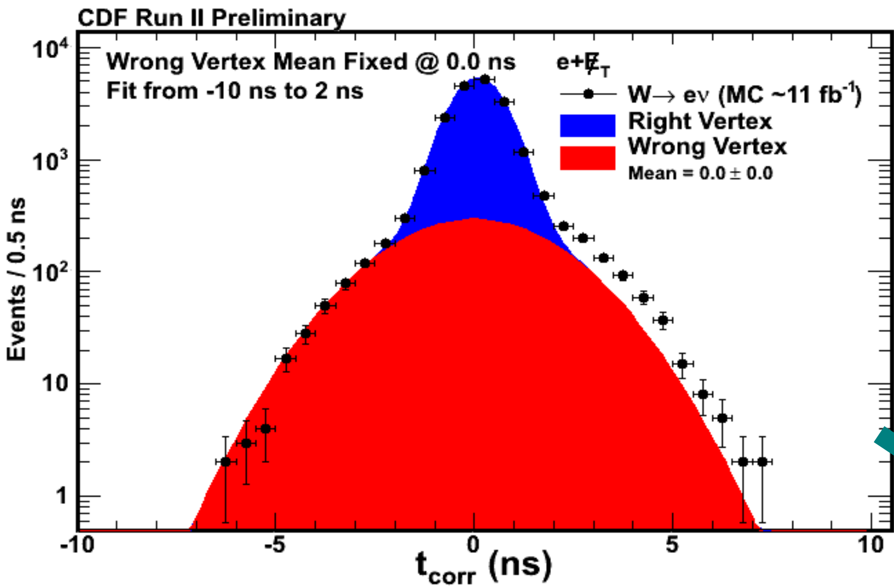
Preliminary Analysis done in 2008 and found a surprising result!



Question: Is there something not well understood in this final state?

(Really just confused)

There are problems with this approach!

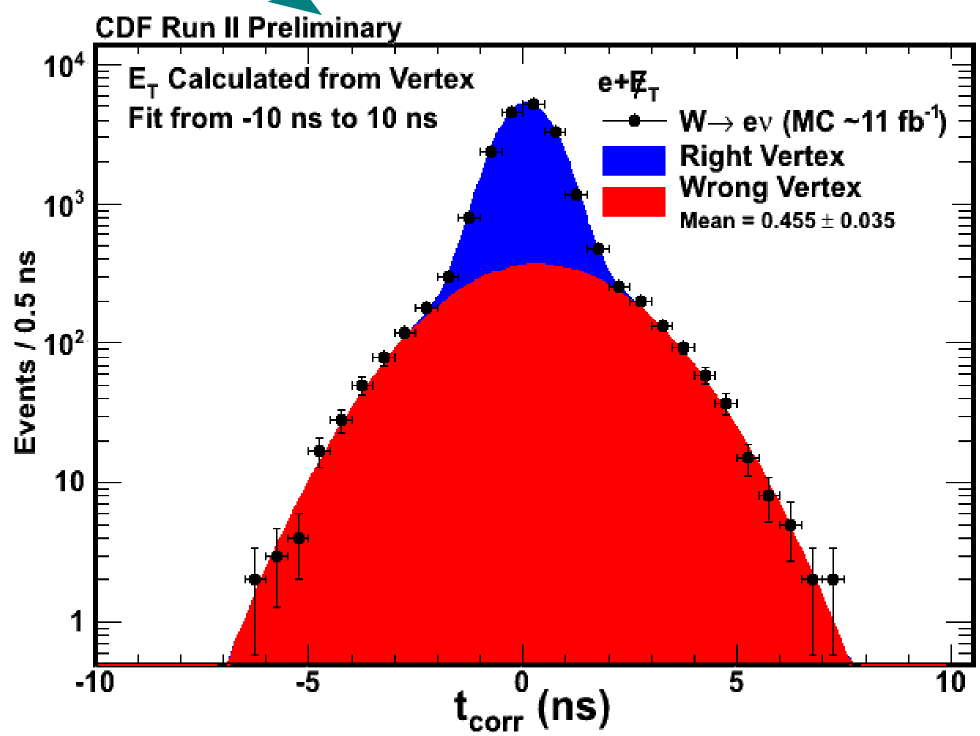


We are able to find samples where we know there is no new physics and the wrong vertex mean is shifted (Background Monte Carlo)

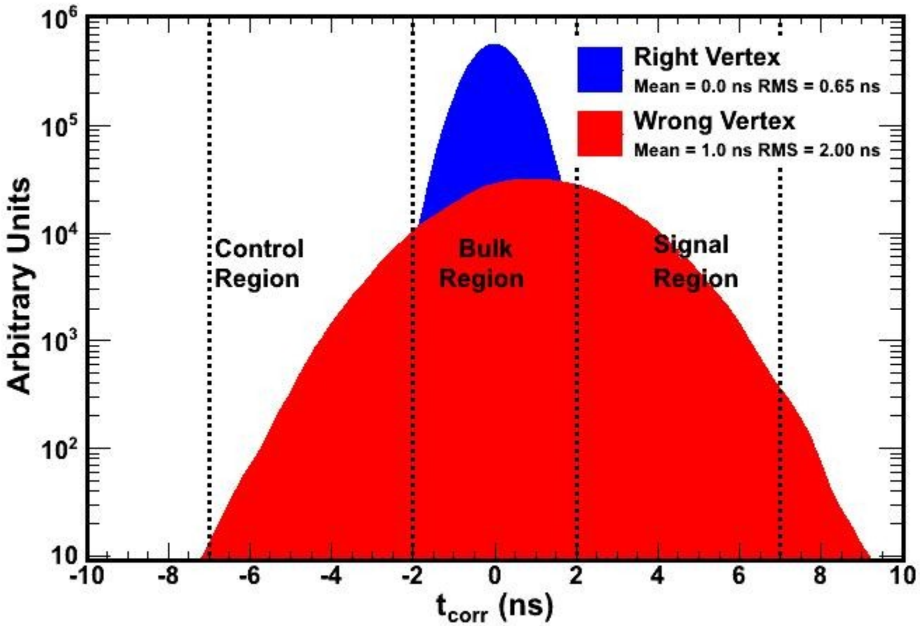
Excess can be accounted for by allowing the mean of the Wrong Vertex to shift

The mean of the Wrong Vertex background is not always centered at t = 0

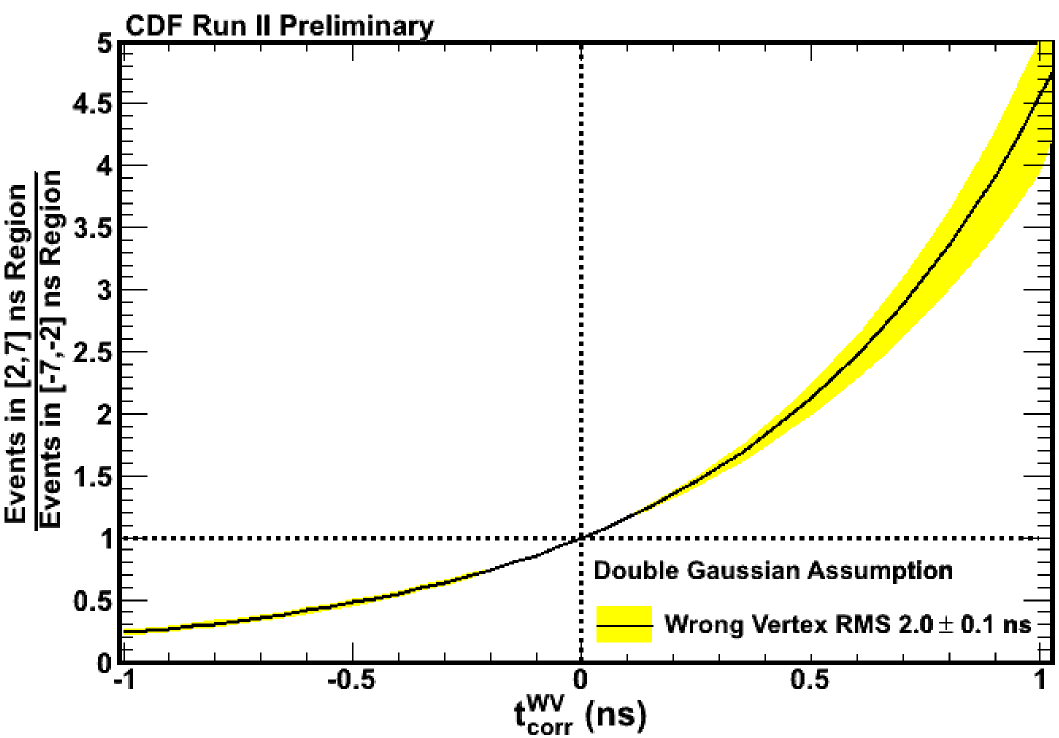
$$N_{Signal\,Region} \neq N_{Control\,Region}$$



Effects of Wrong Vertex Mean Shifts



1) A timing bias leads to events **leaving the control region AND entering the signal region** *(→ More complicated counting experiment)*



2) The Wrong Vertex is **still well described by a Gaussian** with a known RMS.
→ We can predict the number of events in the signal region if we know the mean

$$N_{Signal} = R(\mu) \times N_{Control}$$

Previously, we had assumed R = 1.

Need to pause and evaluate whether we believe there is new physics here...

Redo / cross-check the timing calibrations on all relevant detector components

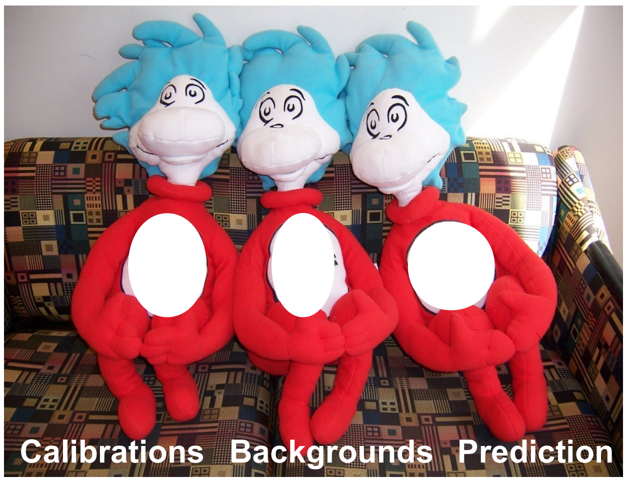
Systematic search for SM events with large times

Reject and minimize these types of events

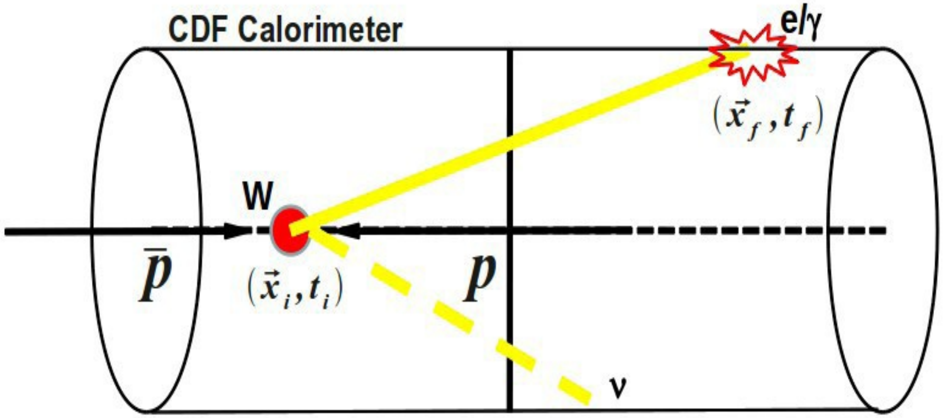
- Redefine our E_T
- New $e \rightarrow \gamma_{fake}$ rejection
- Veto events from large |Z|
- Non-standard Backgrounds

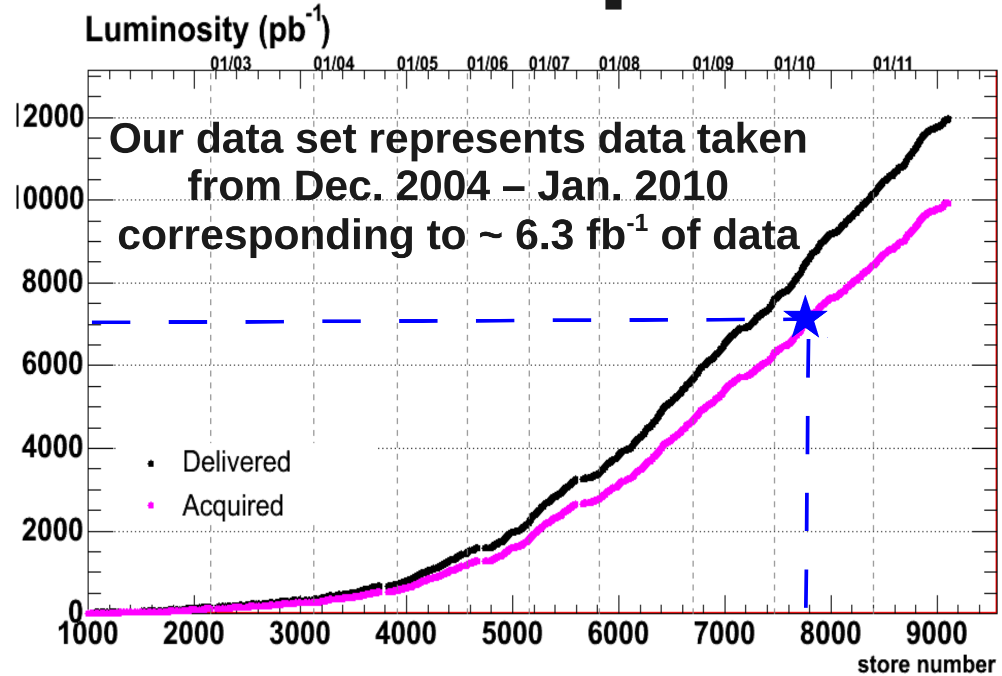
Better estimate of the SM backgrounds

- Use the data to estimate the wrong vertex mean



Calibrating the Data Sample





Calibrate EMTiming System and the COT with a well understood sample that looks mimics γ + MET in the detector:

W $\rightarrow$ eν events

These calibrations are done on top of the enormous number of offline calibrations done by the whole CDF group

- Thanks to all for the Wonderful Data!

By ignoring the electron track this becomes exclusive γ + MET final state providing a testing ground for our analysis

Outline of the Calibration Procedure for W→eν events

Aside: Take a slight detour to tell you a part of this analysis that took over a year to get right and give you some sense of the details

1) Calibrate Track Times

- Calibrate versus variables that have a timing dependence

2) Calibrate Vertex Times

- Calibrate verticies constructed from the tracks

3) Calibrate EMTiming Times

- Calibrate EMTiming times associated with electrons matched to our verticies versus variables that have a timing dependence

Event Selection
Pass Trigger and Photon Good Run List *(See Table 2.8 and Section 2.4)*
$\not{E}_T^0 > 30$ GeV
Identified Electron w/ $E_T^0 > 30$ GeV *(See Table 2.6)*
Passing Beam Halo Rejection *(See Table 4.3)*
Good Space Time Vertex *Note: Electron Track is removed from the Vertexing* *See Table 2.7*
Only one SpaceTime Vertex is Matched to the Electron

Table 2.11

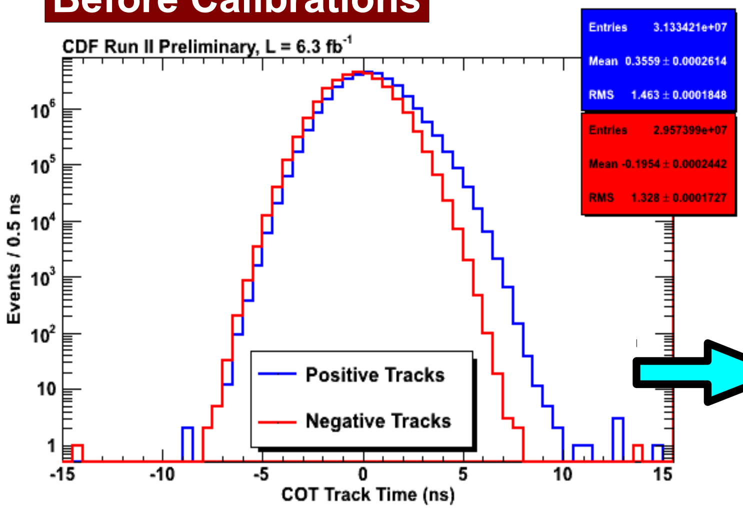
Table summarizing the cuts used to generate the $e + \not{E}_T$ timing calibration sample.

Data Sample

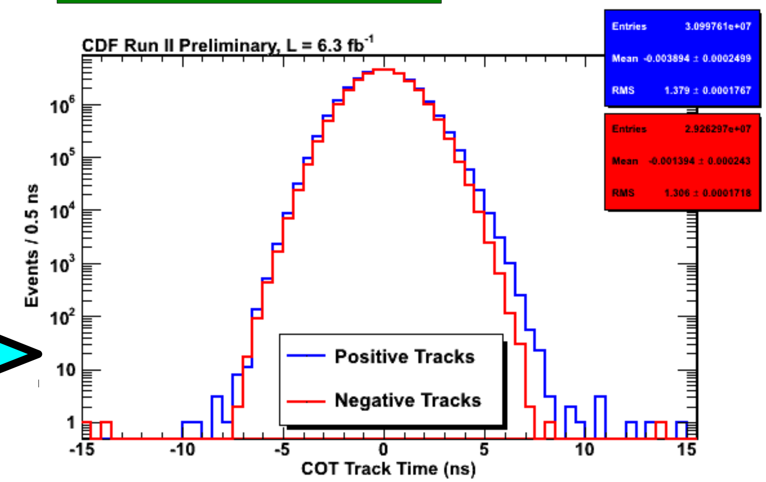
COT Tracks

RESULTS OF CALIBRATIONS

Before Calibrations



After Calibrations



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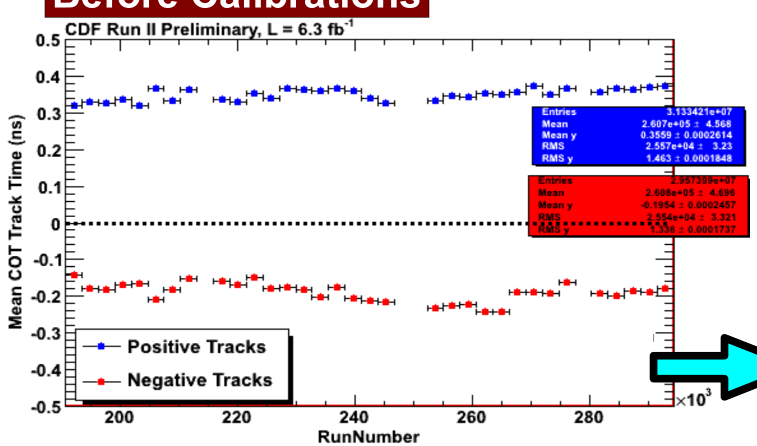
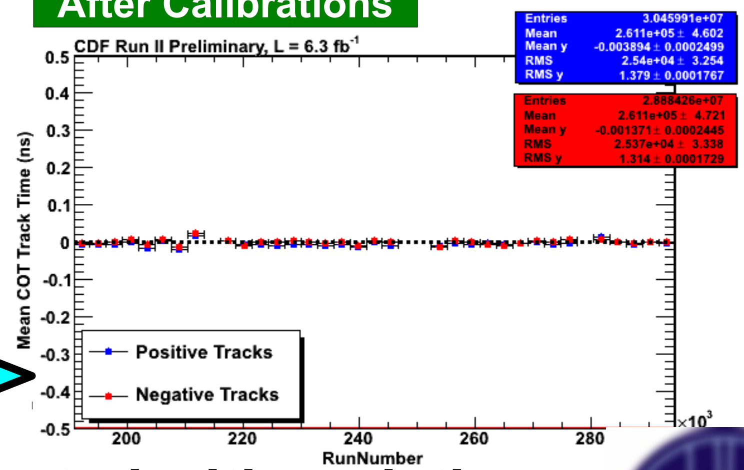


After Calibrations



Timing distributions are gaussian to many sigma as well as being centered and flat over 9 years of running!

Tracking chamber is calibrated with variations < 100 picoseconds

Similar plots are made other variables which the timing strongly depended on. Available in the back-ups

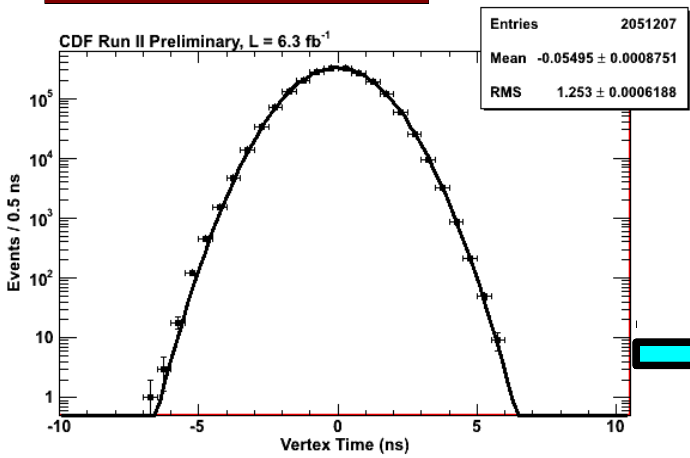
Timing Calibrations

Data Sample

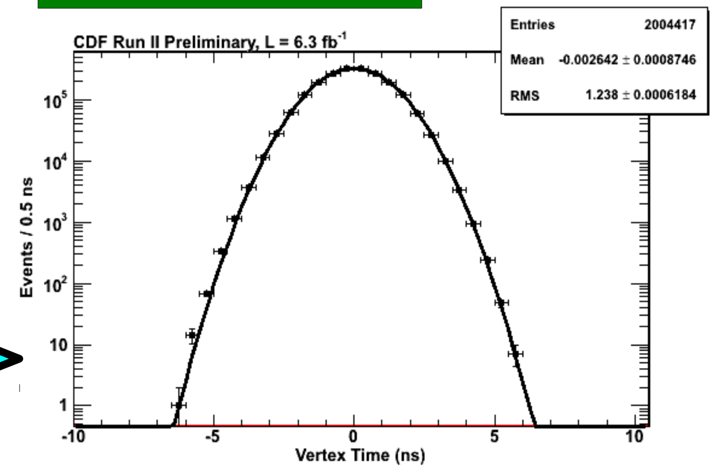
SpaceTime Vertex

RESULTS OF CALIBRATIONS

Before Calibrations



After Calibrations



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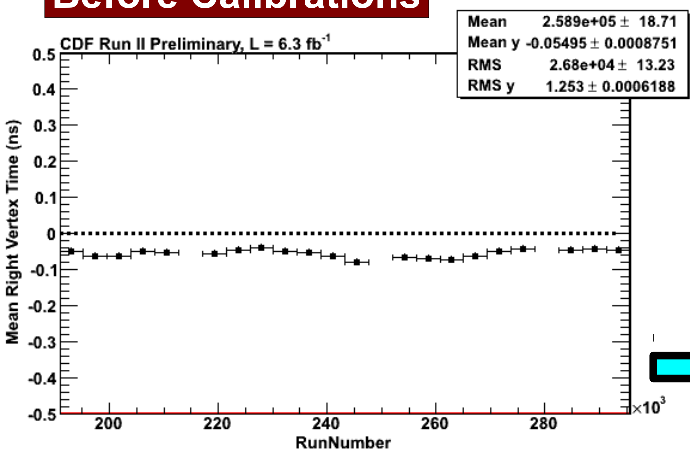
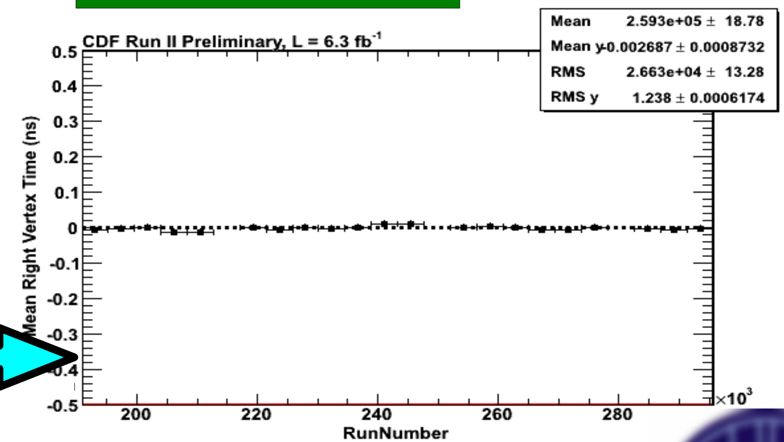


After Calibrations



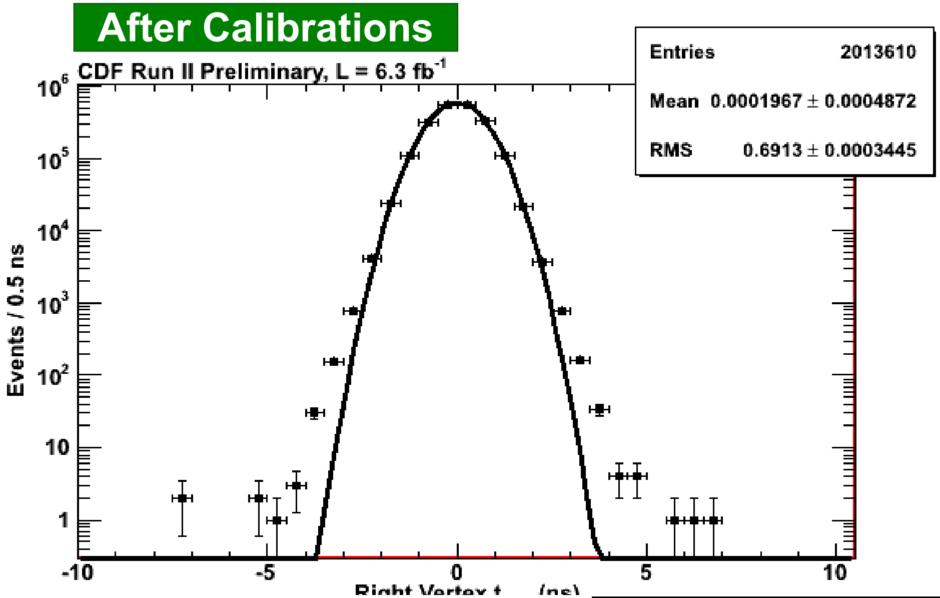
Vertexing is calibrated with variations < 50 picoseconds

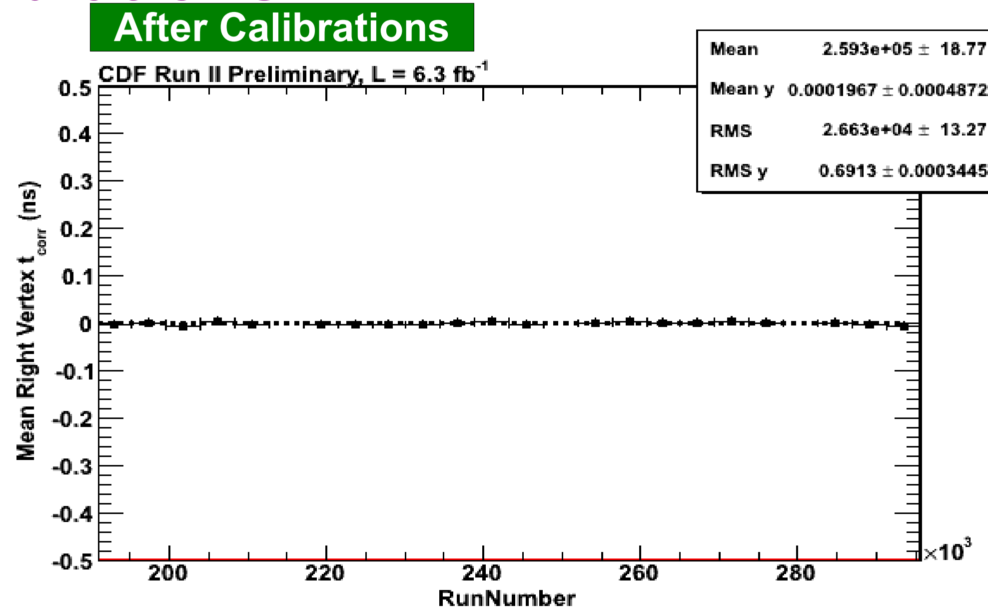
Similar plots are made other variables which the timing strongly depended on.
Available in the back-ups

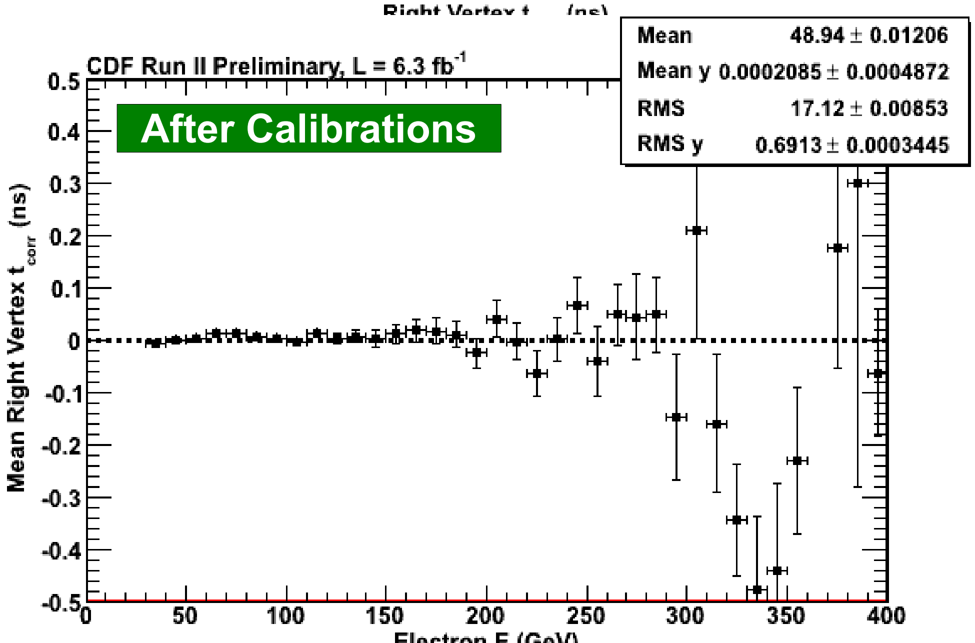
Timing Calibrations

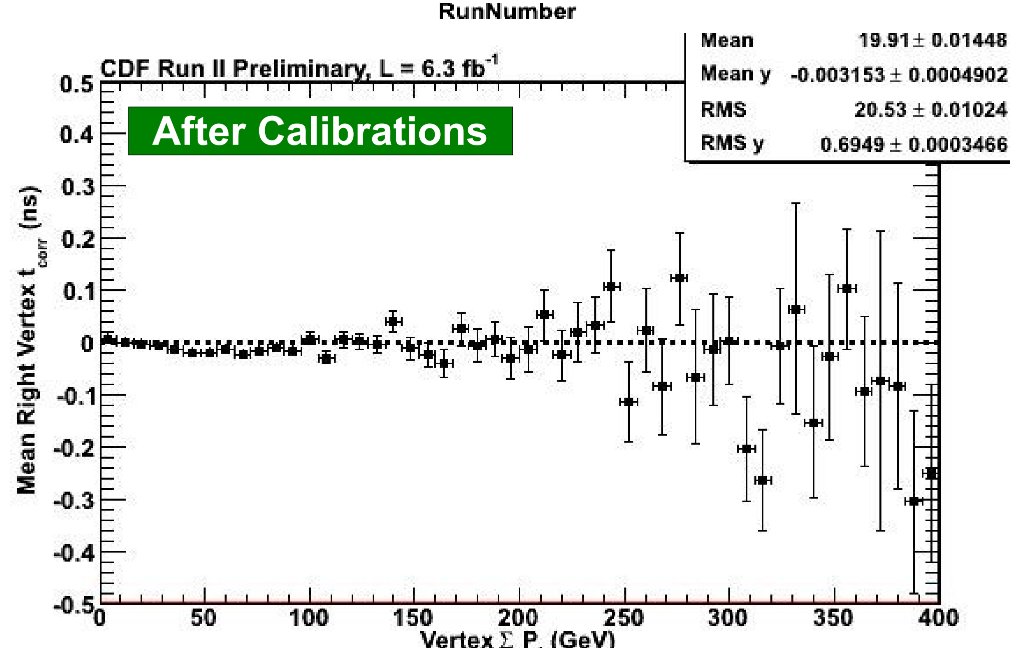
Making this all work...

Check the Data and Calibrations









Corrected Time is calibrated with variations < 100 picoseconds

Need to pause and evaluate whether we believe there is new physics here...

Redo / cross-check the timing calibrations on all relevant detector components

Remove / minimize the most pathological causes of timing biases

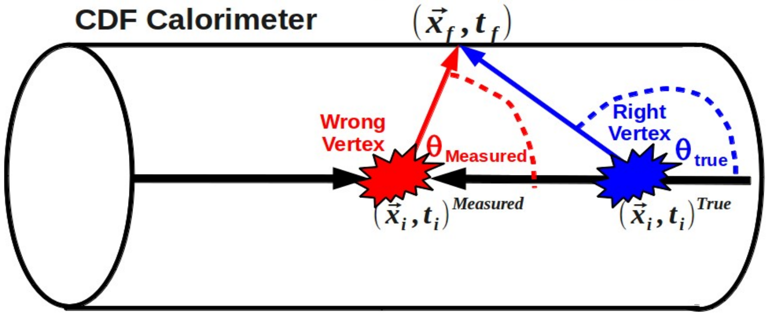
- Redefine our E_T
- New $e \rightarrow \gamma_{fake}$ rejection
- Veto events from large |Z|
- Non-standard Backgrounds

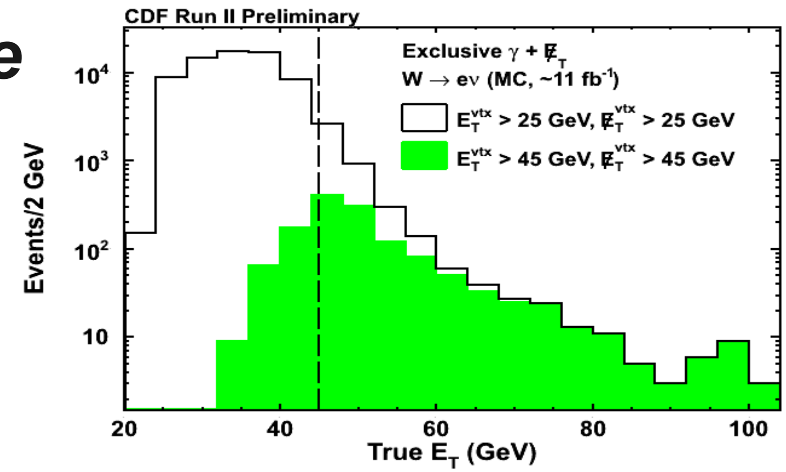
Data driven estimate of the wrong vertex mean

Redefining our E_T Variable

Threshold Effect: Events near the E_T cut become promoted into our sample

$$E_T^{True} = E\sin(\theta_{True})$$
$$E_T^{Measured} = E\sin(\theta_{Measured})$$



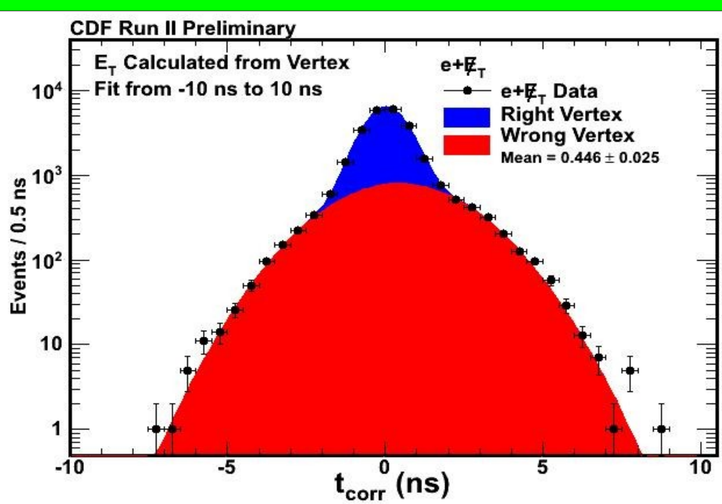


If you pick a wrong vertex with a shorter path length

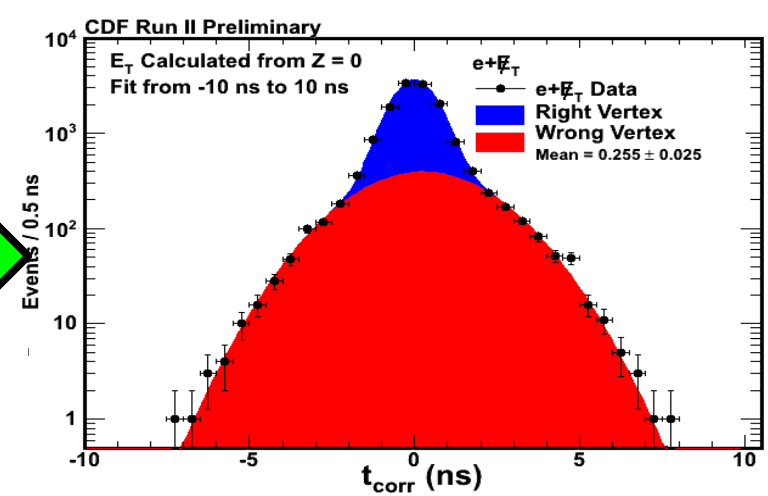
1) $E_T^{Measured} > E_T^{True}$ (More events enter our sample)
2) $t_{corr} > t_{true}$ (Causes a large time of flight)

These two effects conspire to give you a large bias time

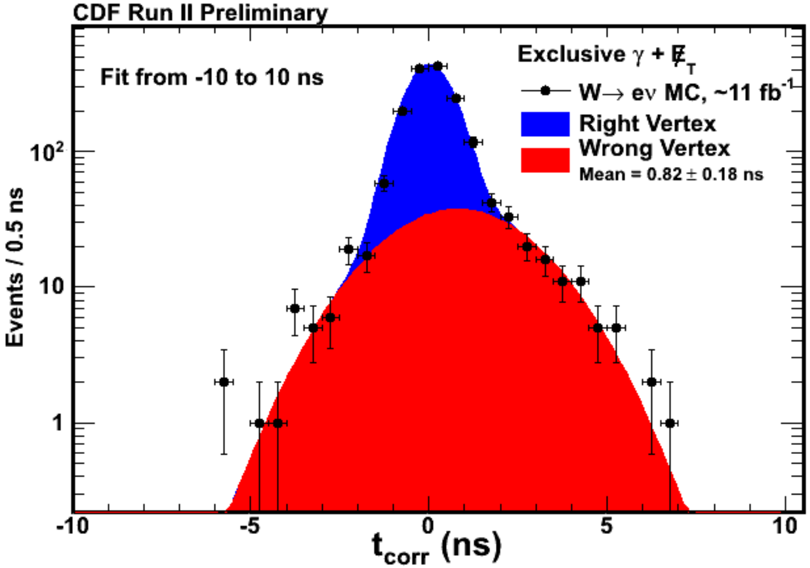
Solution: Define E_T and MET from Z = 0 instead of from the vertex



Redefine E_T



New $e \rightarrow \gamma_{fake}$ Rejection

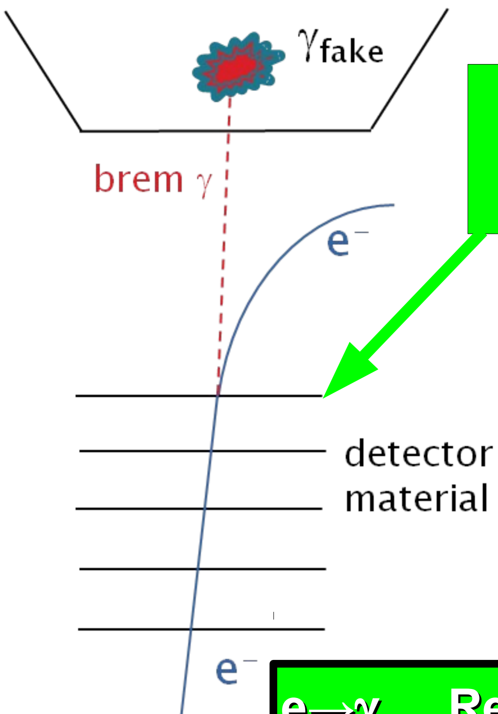


$W \rightarrow e\,\nu \rightarrow \gamma_{fake}$ + MET Background

Longer Path length→ Higher probability to brem→ Large time bias

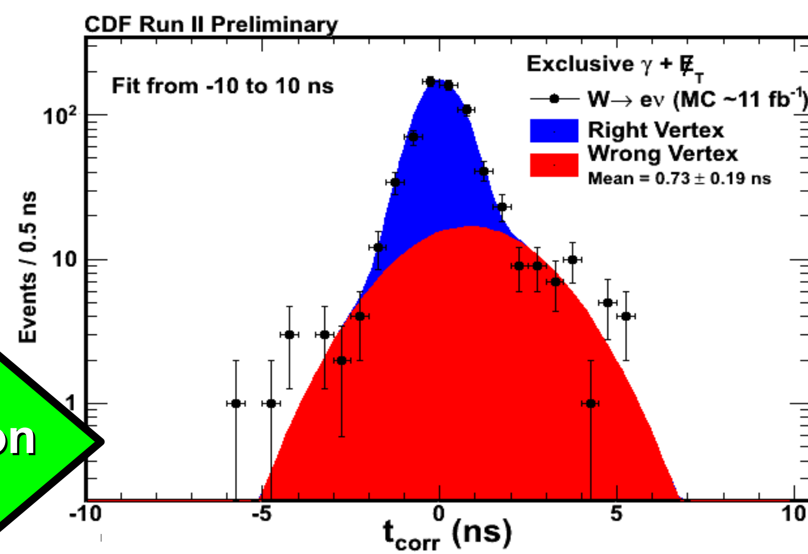
→ This background has the largest timing bias

→ ~50% of these events in Monte Carlo do not leave a vertex to reconstruct



Solution: Veto events with tracks topologically close to the photon

$e \rightarrow \gamma_{fake}$ Rejection



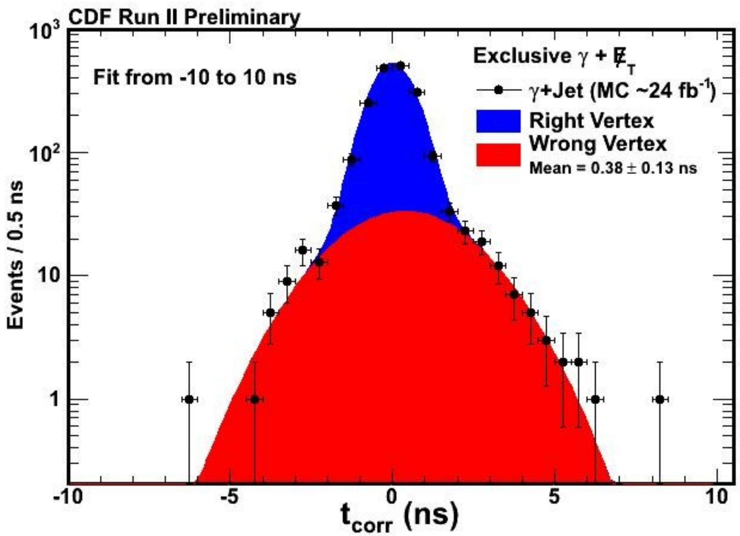
We **reject 67% of $W \rightarrow e\,\nu \rightarrow \gamma_{fake}$ + MET** with **95% efficient** for real photons

N.B. Cut doesn't change the wrong vertex mean, just the rate

Veto Events from Large |z|

Events from Large |Z| have large mean shift (Topological Effect)

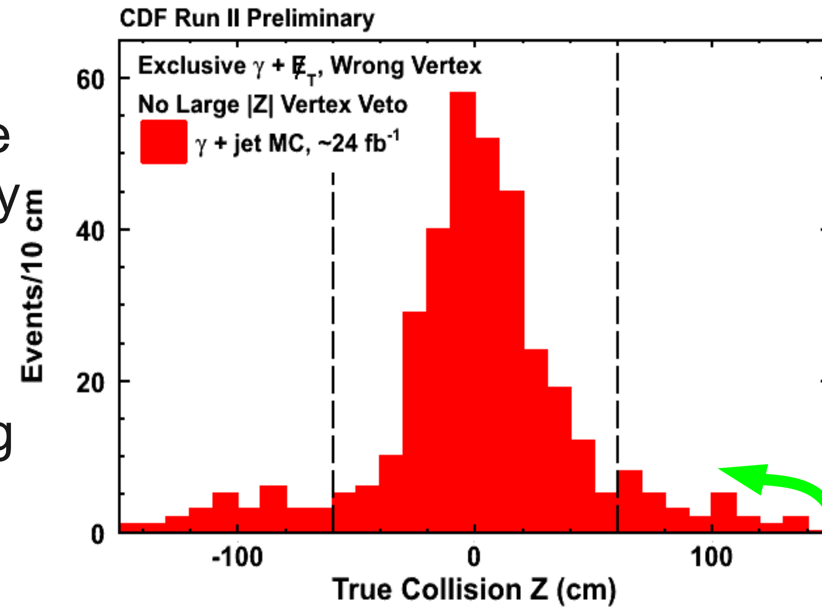
→ Most easily seen in γ+Jet→γ+MET



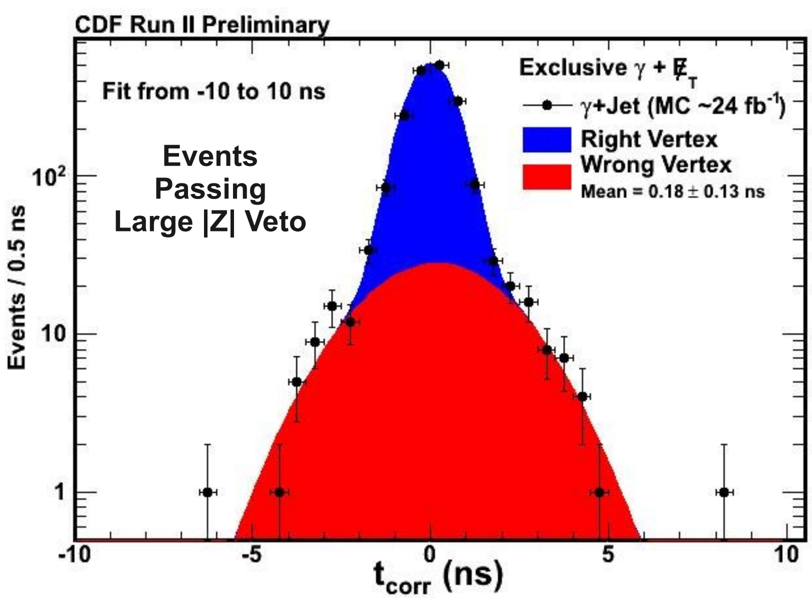
γ+Jet must have unusual topology to enter our sample

(no intrinsic MET)

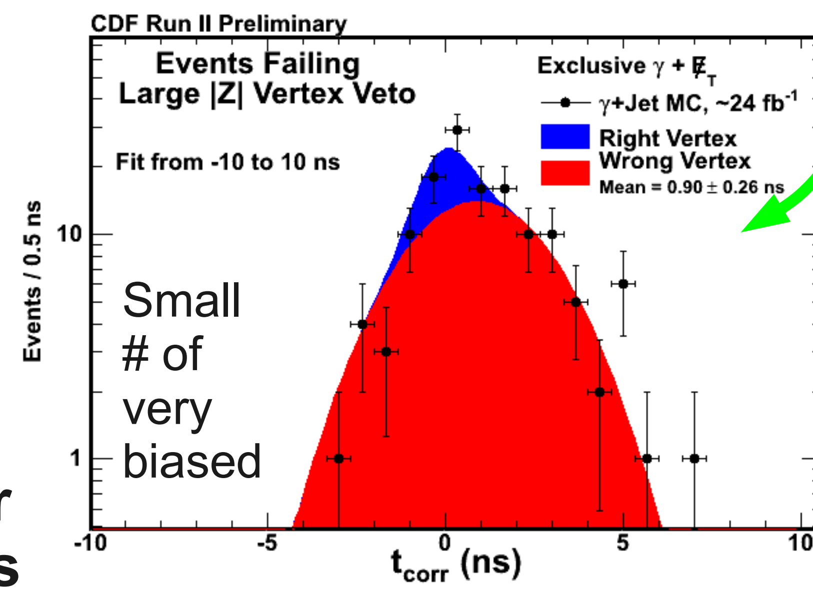
→ Biased wrong vertex distribution



Solution: Veto events w/ Standard Vertex @ |z| >60 cm and N_{track} >3

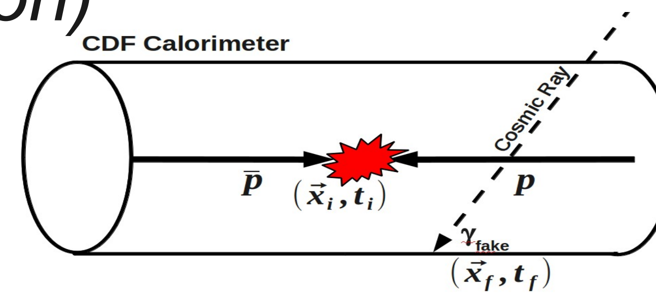


Cut is 96% efficient for real physics

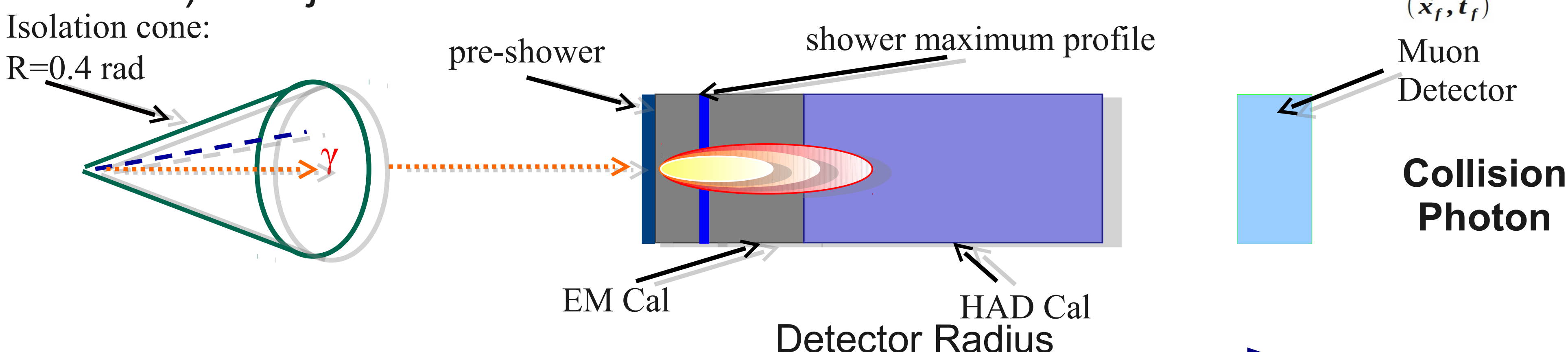


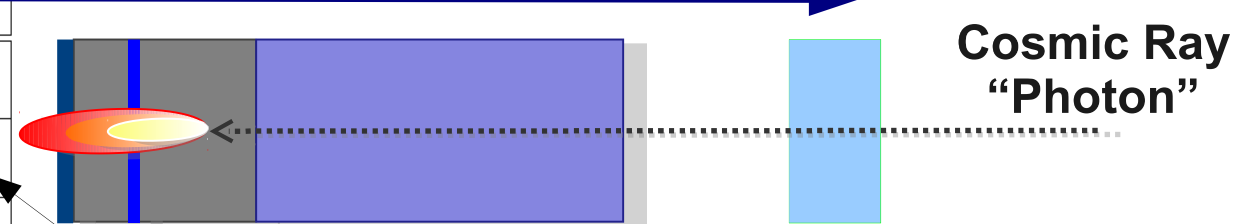
Non-Standard Background Sources

(New Cosmics Rejection)



Cosmic ray events are our dominant background
Utilizes their unique topology (coming from outside the detector) to reject them





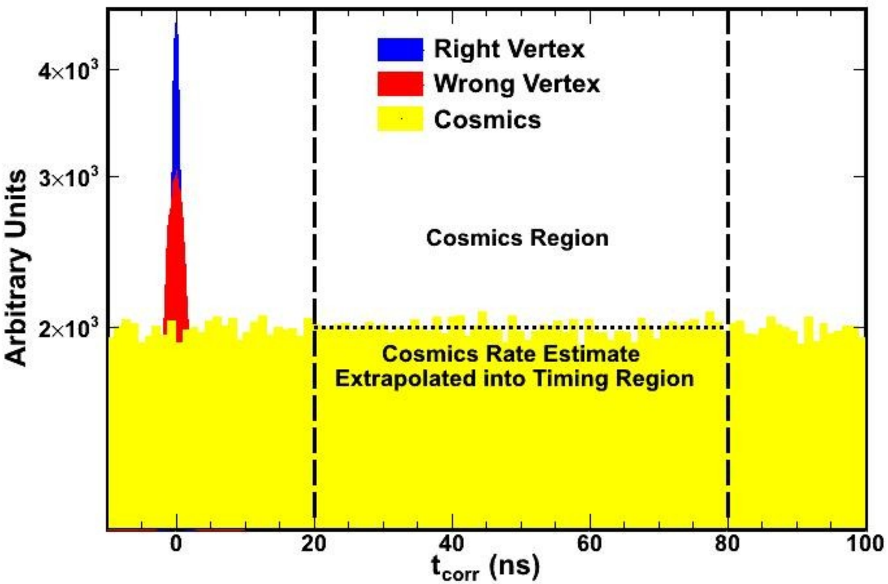
Variable	Cuts
N μStub $\Delta\phi < 30°$ *Number of Muon Stubs in $\Delta\phi < 30°$*	< 1
Had E *Hadronic Energy deposited*	$\geq -0.30 + 0.008 \cdot E_T$ Sliding cut as a function of E_T
CES(E)/Total E *Fraction of Energy Deposited in the CES over the total Energy*	≥ 0.2

Table 4.2
Summary of requirements used to veto photon candidates as originating from cosmic rays. Note, the hadronic energy cut (Had E) and the fraction of energy deposited in the CES (CES(E)/Total E) are included in the photon ID variable listed in Table 2.3. We include them here in order to explain why these non-standard cuts are present in the Photon ID used in this analysis.

New Cosmics Rejection

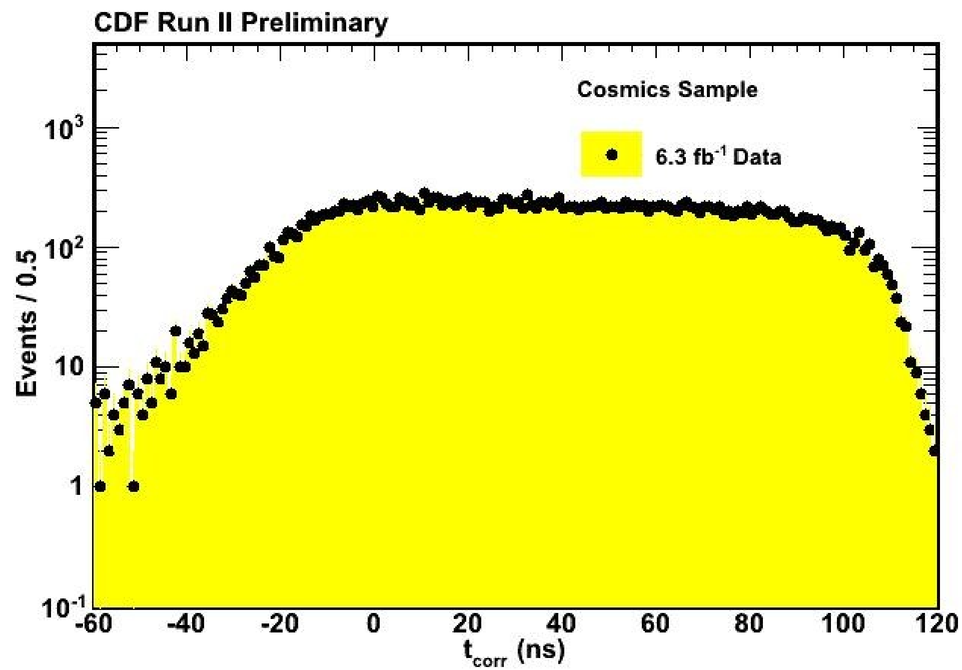
76% rejection for cosmic ray events with **92% efficiency** for collision electrons

Estimating Cosmic Ray Rate



Cosmic rays events show up roughly flat over time

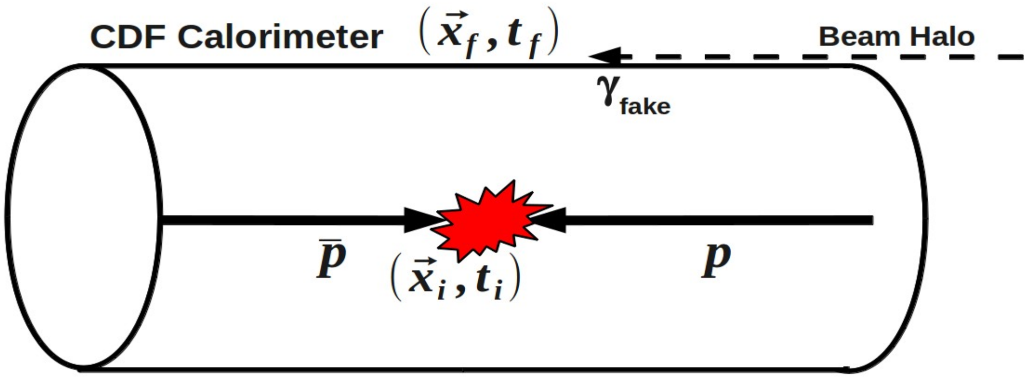
Verify this by selecting for cosmic ray events



Use the region 20 ns < tcorr < 80 ns to estimate the rate per nanosecond of cosmic rays events observe

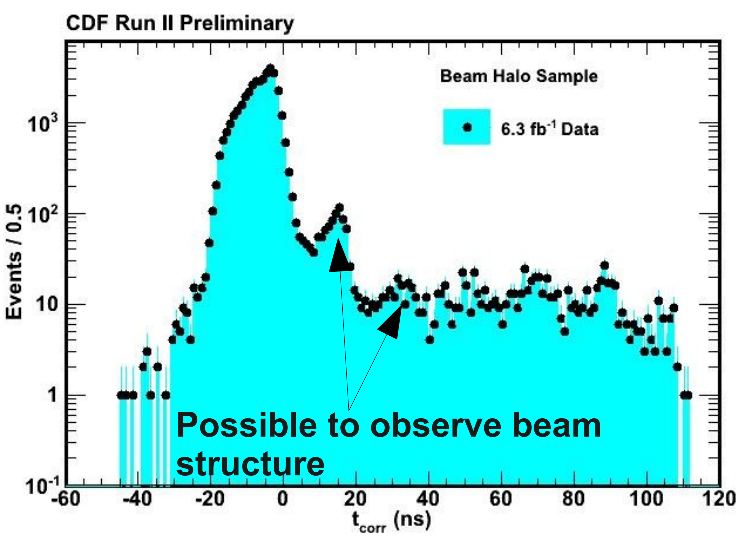
Non-Standard Background Sources

Beam Halo Rejection



Beam Halo is created when an errant proton bunch has a hard interaction upstream of the detector

Creates a muon that travels parallel to the beam and may fake a photon



Reject these events by looking for interactions in the detector parallel to the observed photon candiate

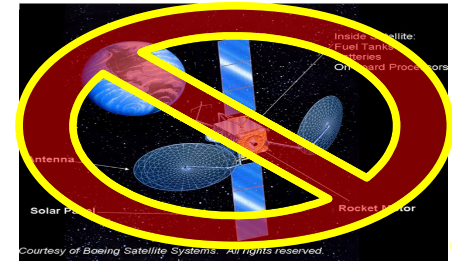
seedWedge *N Hits in the same wedge as the electron*	> 8
NHadPlug *Number of Plug Hadronic Tower Hits*	≤ 2

Table 4.3
Summary of requirements used to identify and veto photon candidates as originating from beam halo sources.

Cut is 98% efficient for real electrons

Non-Standard Background Sources

Satellite Bunches

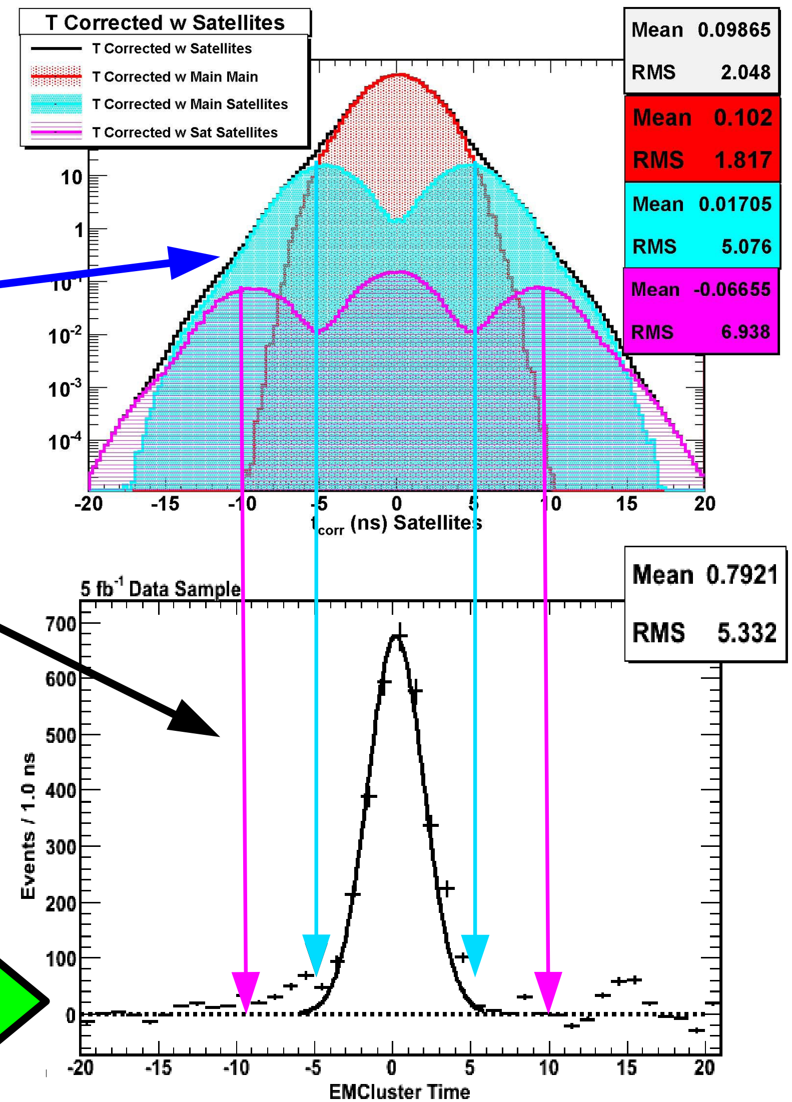


Satellite bunches are vestiges of protons and anti-protons left from the coalescing of bunches in the Main Injectors RF Cavities

These satellites are separated at multiples of ~ 18.8 ns (The RF Bucket ~ 53MhZ)

Model what these events would look like in collision data

Select for satellite bunch interactions and estimate their rate from data



No clear evidence that satellite events will be a significant background and occur <u>≤ 1 %</u> of all non-collision events

Need to pause and evaluate whether we believe there is new physics here...

- ✓ Redo / cross-check the timing calibrations on all relevant detector components
- ✓ Remove / minimize the most pathological causes of timing biases
  - Redefine our E_T
  - New $e \rightarrow \gamma_{fake}$ rejection
  - Veto events from large |Z|
  - Non-standard Backgrounds

Data driven estimate of the wrong vertex mean

Analysis

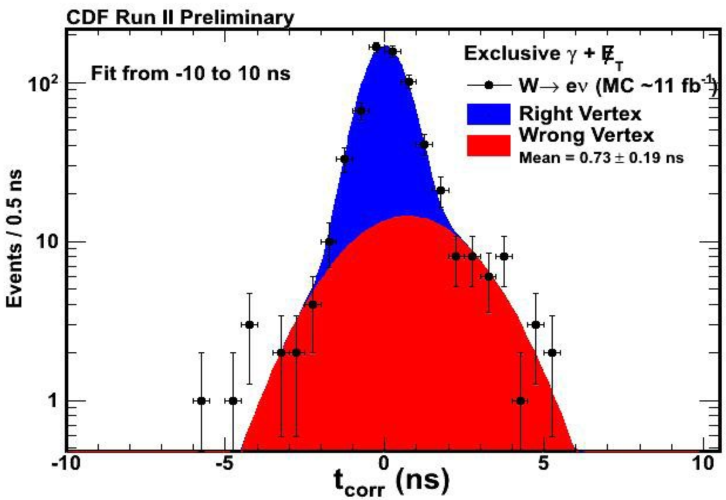
Exclusive γ+MET Final State

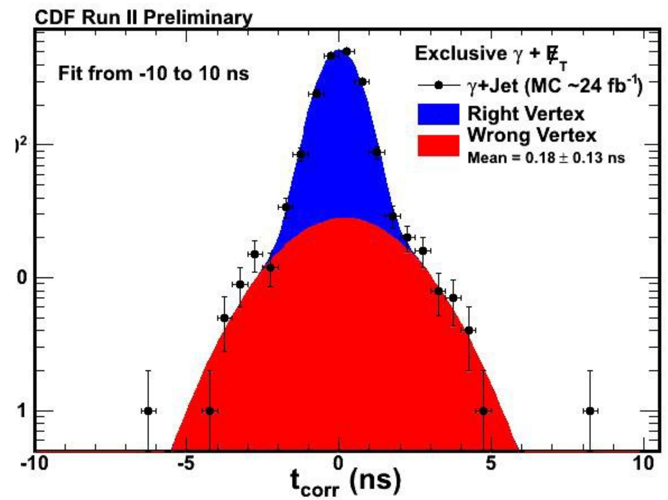
Pass Trigger and Photon Good Run List *(See Table 2.8 and Section 2.4)*
Pass Tight Photon requirements w/ $E_T^0 > 45$ GeV and $\not{E}_T^0 > 45$ GeV *(See Table 2.5 and Section 2.4.1)*
Pass Beam Halo Rejection *(See Table 4.3)*
Pass Cosmics Rejection *(See Table 4.2)*
Pass Track Veto for Tracks with $P_T > 10$ GeV *(See Table 2.4.1)*
Pass Jet Veto for Jets with $E_T^0 > 15$ GeV *(See Table 2.2)*
Pass Large $\|Z\|$ Vertex Veto *(See Section 5.3.3)*
Pass $e \to \gamma_{fake}$ Veto *(See Table 5.1 and Section 5.3.2)*
Require a Good SpaceTime Vertex *(See Table 2.7)*

Table 5.2

Exclusive $\gamma_{delayed} + \not{E}_T$ complete table of event selection requirements

Understanding Bias Backgrounds





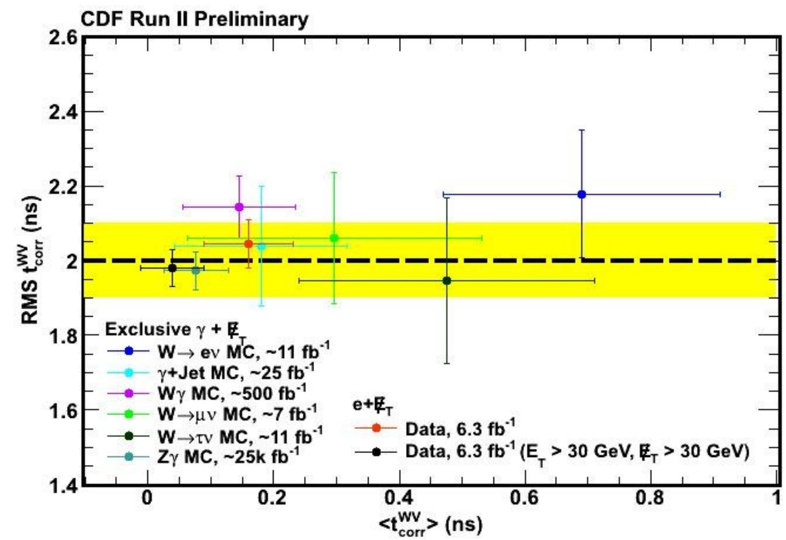
After all cuts, each background is well described by a double Gaussian shape

e.g. W→eν & γ+Jet (more examples in the back-ups)

Monte Carlo Sample	Wrong Vertex Mean (ns)	Wrong Vertex RMS (ns)
$W\rightarrow e\nu$	0.69 ± 0.22 ns	2.18 ± 0.17 ns
γ+Jet	0.18 ± 0.13 ns	2.04 ± 0.16 ns
$Z\gamma$	0.08 ± 0.05 ns	1.97 ± 0.05 ns
$W\rightarrow \mu\nu$	0.30 ± 0.23 ns	2.06 ± 0.18 ns
$W\rightarrow \tau\nu$	0.48 ± 0.22 ns	1.97 ± 0.22 ns
$W\gamma$	0.14 ± 0.09 ns	2.14 ± 0.08 ns
$e+\not\!\!E_T$ data	0.16 ± 0.07 ns	2.05 ± 0.07 ns
$e+\not\!\!E_T$ data (E_T&$\not\!\!E_T > 30$ GeV	0.04 ± 0.05 ns	1.98 ± 0.05 ns

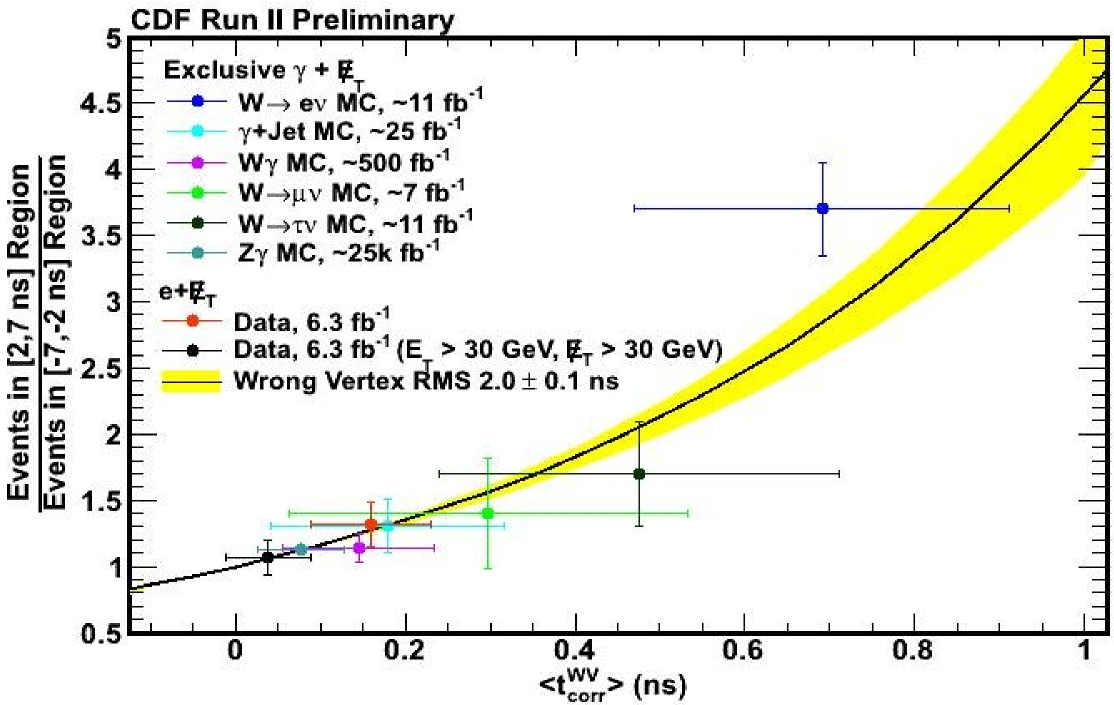
Table 5.4

Summary of Figure 5.15 Monte Carlo Backgrounds applying the exclusive $\gamma_{delayed}+\not\!\!E_T$ event selection requirements defined in Table 5.2 and the exclusive $e+\not\!\!E_T$ data samples defined in Table 2.12 when we allow their Wrong Vertex Mean and RMS to vary and fit a double Gaussian to their t_{corr} timing distribution.



For all of our various backgrounds the double Gaussian assumption with the wrong vertex RMS +/- 5% is an accurate description.

Understanding Bias Backgrounds



The ratio of events in the signal region to the control region is a function of the Wrong Vertex Mean

Monte Carlo Sample	Observed Wrong Vertex Mean (ns)	Predicted Ratio	Observed Ratio
W→ $e\nu$	0.73 ± 0.19 ns	2.92 ± 1.01	3.70 ± 0.36
γ+Jet	0.18 ± 0.13 ns	1.30 ± 0.26	1.30 ± 0.20
Wγ	0.14 ± 0.07 ns	1.22 ± 0.14	1.14 ± 0.11
Zγ	0.12 ± 0.01 ns	1.20 ± 0.01	1.12 ± 0.02
W→ $\mu\nu$	0.29 ± 0.26 ns	1.50 ± 0.70	1.40 ± 0.41
W→ $\tau\nu$	0.43 ± 0.26 ns	1.90 ± 0.90	1.70 ± 0.40
$e+\not{E}_T$ Data	0.16 ± 0.05 ns	1.26 ± 0.16	1.32 ± 0.17
$e+\not{E}_T$ Data (E_T > 30 GeV and $\not{E}_T$ > 30 GeV)	0.04 ± 0.05 ns	1.03 ± 0.07	1.06 ± 0.13

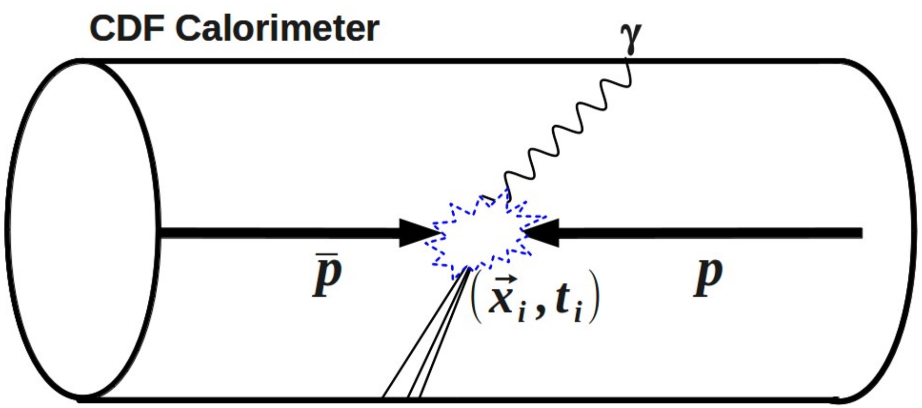
Table 6.1

Summary of Monte Carlo backgrounds and $e+\not{E}_T$ data wrong vertex mean, the predicted and observed ratio of the number of events in the signal region (2 ns to 7 ns) to the number of events in the control region (-2 ns to -7 ns) after applying the exclusive $\gamma_{delayed}+\not{E}_T$ event selection defined in Table 5.2.

Determine the <u>wrong vertex mean</u> from <u>an independent sample</u>

→ *No Vertex Sample*

New Timing Based Background Estimation Method



Mean Shifts ↔ **Event Geometry**

Mean No Vertex Time ↔ **Mean Wrong Vertex Time**

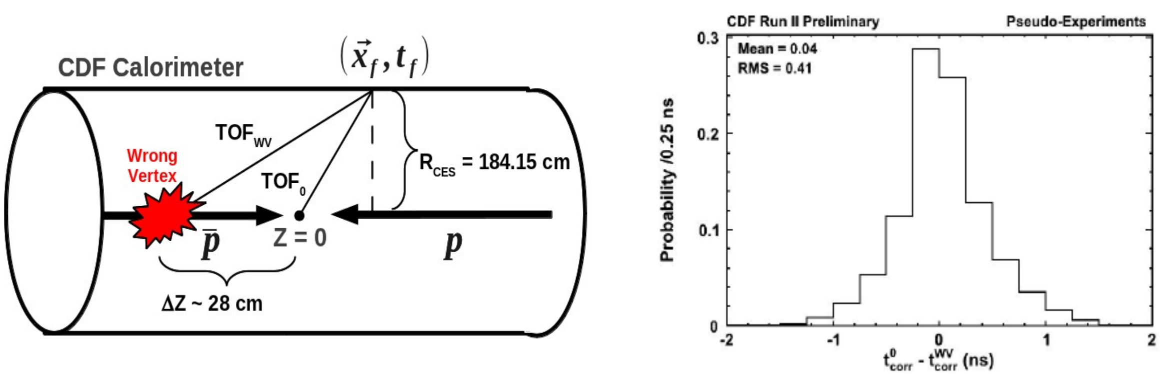


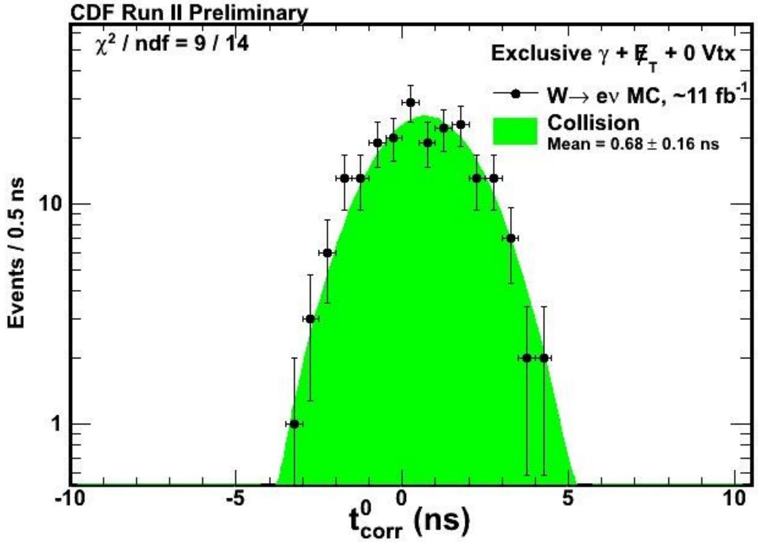
Fig. 6.4. (LHS) An illustration showing the various components of the Time of Flight components of the t_{corr} coming from the difference relative to the center of the detector ($TOF_{(z=0)}$) and the time of flight difference relative to the chosen vertex (TOF_{Vtx}) (RHS) The results of pseudo-experiments where verticies are generated according to the z and t parameters of the Tevatron and the mean of the corrected time calculated from a wrong vertex is subtracted from the mean of the corrected time assuming $z = 0$ and $t = 0$ just as we would in the no vertex case demonstrating that the expected mean of the two distributions should be very similar.

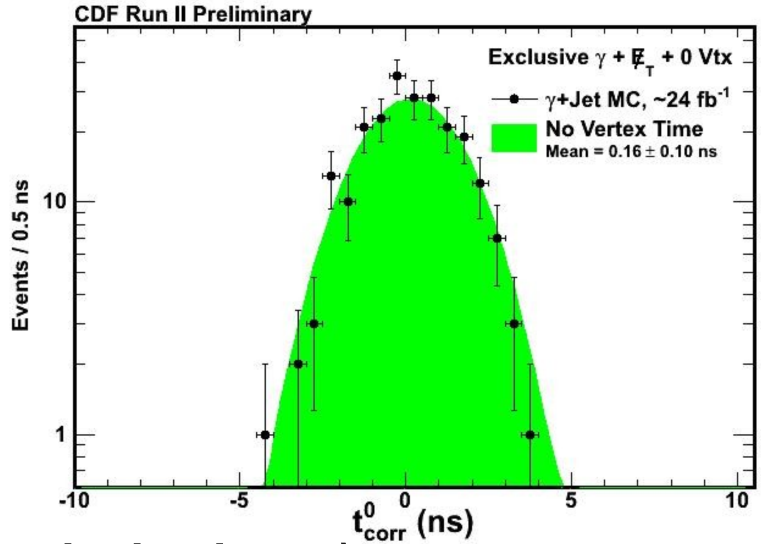
Events that pass all selection requirements but fail to reconstruct a vertex, we construct a pseudo-corrected time t^0_{corr}

(assume $t_0 = 0$ and $z_0 = 0$)

→ **Use this to measure the mean of the wrong vertex!**

New Timing Based Background Estimation Method





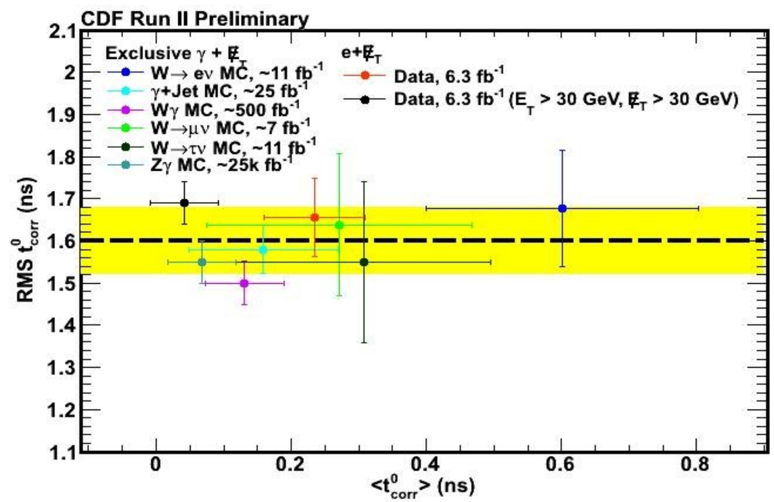
No vertex corrected time given by a Gaussian with RMS 1.6ns +/- 5%

e.g. W→eν & γ+Jet (more examples in the back-ups)

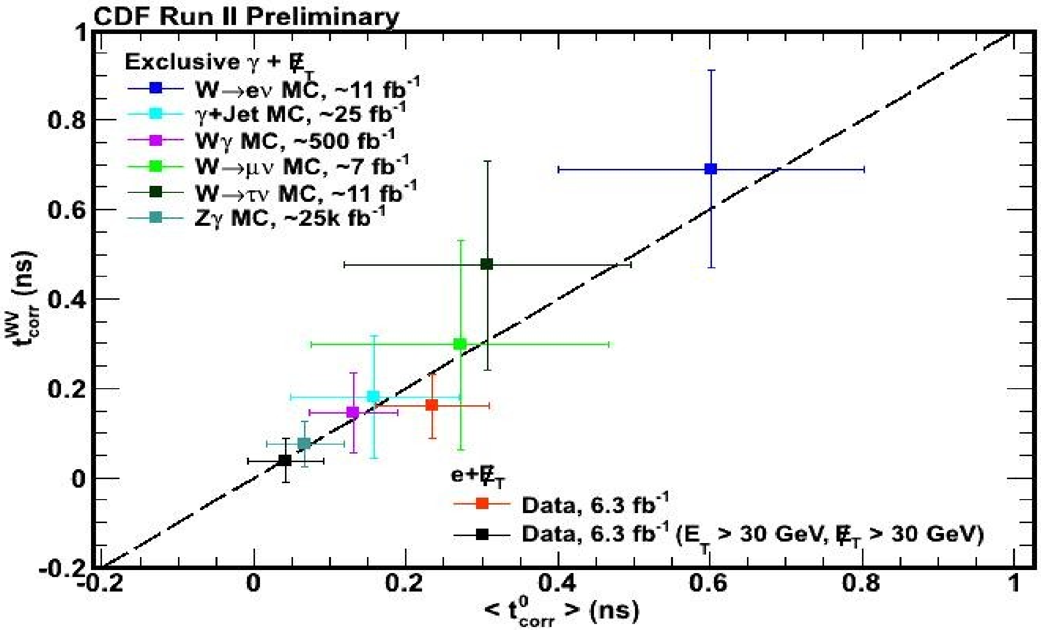
Monte Carlo Sample	No Vertex Mean (ns)	No Vertex RMS (ns)
W→ $e\nu$	0.61 ± 0.20 ns	1.68 ± 0.14 ns
γ+Jet	0.16 ± 0.11 ns	1.58 ± 0.06 ns
$Z\gamma$	0.07 ± 0.05 ns	1.55 ± 0.05 ns
W→ $\mu\nu$	0.27 ± 0.20 ns	1.64 ± 0.17 ns
W→ $\tau\nu$	0.31 ± 0.19 ns	1.56 ± 0.19 ns
$W\gamma$	0.13 ± 0.06 ns	1.50 ± 0.05 ns
$e+\not\!\!E_T$ data	0.23 ± 0.08 ns	1.66 ± 0.09 ns
$e+\not\!\!E_T$ data (E_T&$\not\!\!E_T$ > 30 GeV	0.04 ± 0.05 ns	1.69 ± 0.05 ns

Table 6.2

Summary of Figure 6.5 Monte Carlo backgrounds applying the exclusive $\gamma_{delayed}+\not\!\!E_T$ event selection requirements defined in Table 5.2 and the exclusive $e+\not\!\!E_T$ data samples defined in Table 2.12 but failing the good SpaceTime vertex requirement. The no vertex mean and RMS is found by fitting the no vertex corrected time (t^0_{corr}) distribution with a single Gaussian from -5 ns to 3 ns where the Gaussian RMS and mean are allowed to vary to find the best fit.



New Timing Based Background Estimation Method



<WV Time> ~ <No Vtx Time>

Questions: When we look at our 6 MC samples and 2 data samples how well does this method work?

Answer: Amazingly well!

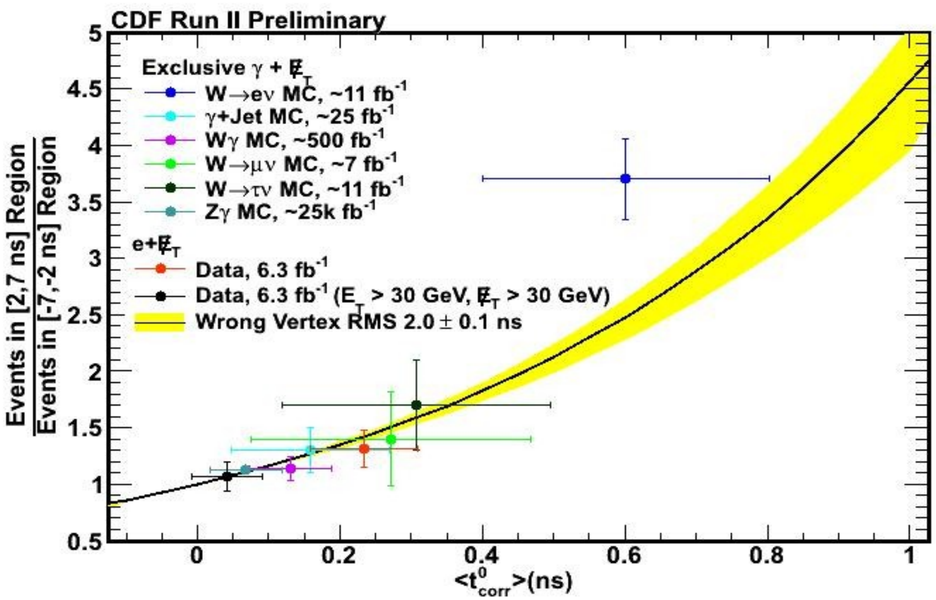
Monte Carlo Sample	Wrong Vertex Mean (ns)	No Vertex Mean (ns)
W→ $e\nu$	0.73 ± 0.19 ns	0.68 ± 0.16
γ+Jet	0.18 ± 0.13 ns	0.16 ± 0.10
Wγ	0.14 ± 0.07 ns	0.14 ± 0.03
Zγ	0.12 ± 0.01 ns	0.06 ± 0.01
W→ $\mu\nu$	0.29 ± 0.26 ns	0.25 ± 0.19
W→ $\tau\nu$	0.43 ± 0.26 ns	0.38 ± 0.17
$e+\not{E}_T$ Data	0.16 ± 0.05 ns	0.23 ± 0.05
$e+\not{E}_T$ Data (E_T > 30 GeV and $\not{E}_T$ > 30 GeV)	0.04 ± 0.05 ns	0.02 ± 0.01

Table 6.3

Summary of Monte Carlo backgrounds selected using the exclusive $\gamma_{delayed}$ + $\not{E}_T$ selection defined in Table 5.2 and the $e+$ $\not{E}_T$ data selected using the sample defined in Table 2.12. Here we obtain the wrong vertex mean by fitting the corrected time (t_{corr}) distribution with a double Gaussian function from -10 ns to 10 ns where the right vertex Gaussian mean = 0.0 ns and RMS = 0.65 ns and the wrong vertex Gaussian RMS = 2.0 ns and the mean is allowed to vary to find the best fit. The no vertex mean is found by fitting the no vertex corrected time (t^0_{corr}) distribution with a single Gaussian from -5 ns to 3 ns where the Gaussian RMS = 1.6 ns and the mean is allowed to vary to find the best fit.

Putting it all together

1) Select events for the exclusive $\gamma_{delayed}$+MET final state
2) Estimate the cosmic ray event rate
3) Measure the mean of the “no vertex” timing distribution
4) Predict the number of events in the signal region



Monte Carlo Sample	Observed No Vertex Mean (ns)	Predicted Ratio	Observed Ratio
W→ $e\nu$	0.68 ± 0.16 ns	2.74 ± 0.76	3.70 ± 0.36
γ+Jet	0.16 ± 0.10 ns	1.27 ± 0.20	1.30 ± 0.20
Wγ	0.14 ± 0.03 ns	1.23 ± 0.05	1.14 ± 0.11
Zγ	0.06 ± 0.01 ns	1.09 ± 0.02	1.12 ± 0.02
W→ $\mu\nu$	0.25 ± 0.19 ns	1.46 ± 0.48	1.40 ± 0.41
W→ $\tau\nu$	0.38 ± 0.17 ns	1.77 ± 0.51	1.70 ± 0.40
$e+\not{E}_T$ Data	0.23 ± 0.05 ns	1.39 ± 0.31	1.32 ± 0.17
$e+\not{E}_T$ Data (E_T > 30 GeV and $\not{E}_T$ > 30 GeV)	0.02 ± 0.01 ns	1.03 ± 0.07	1.06 ± 0.13

Table 6.4

Summary of Monte Carlo backgrounds and $e+\not{E}_T$ data no vertex mean and the predicted ratio using that measured mean as well as the observed ratio of the number of events in the signal region (2 ns to 7 ns) to the number of events in the control region (-2 ns to -7 ns) after applying the exclusive $\gamma_{delayed}+\not{E}_T$ event selection defined in Table 5.2.

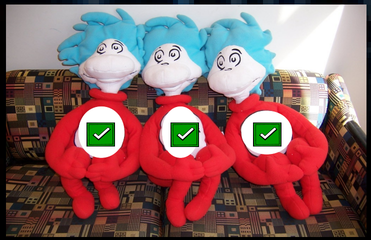
Quick Summary

1) Observed an excess in the data

2) Found ways to identify and reject our most insidious backgrounds

3) Developed a method to estimate the remaining background

4) Time to re-open the box to see what remains



Results: Exclusive γ+MET

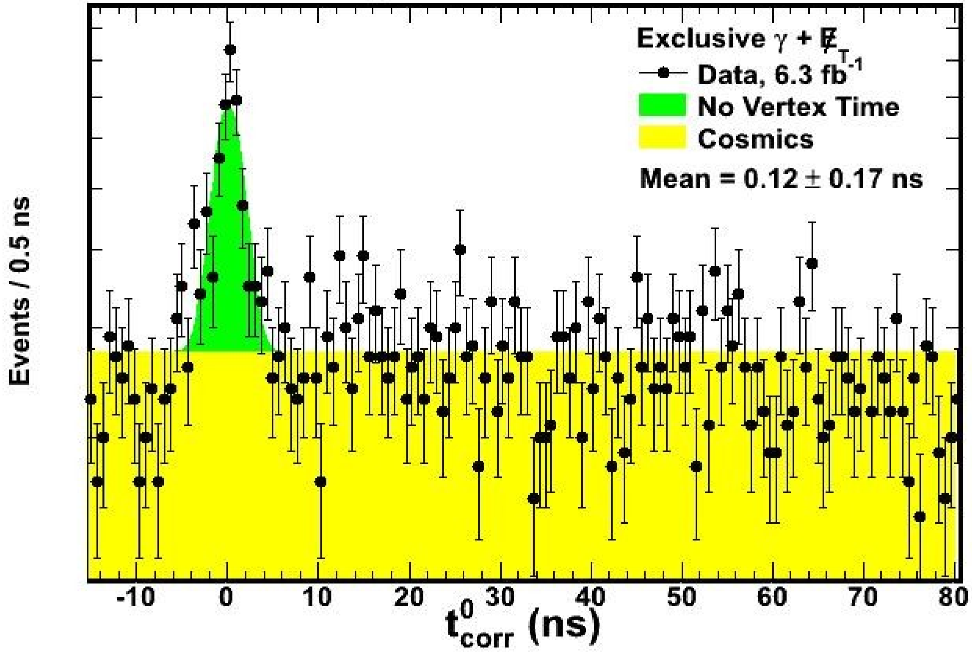
Results: Exclusive γ+MET

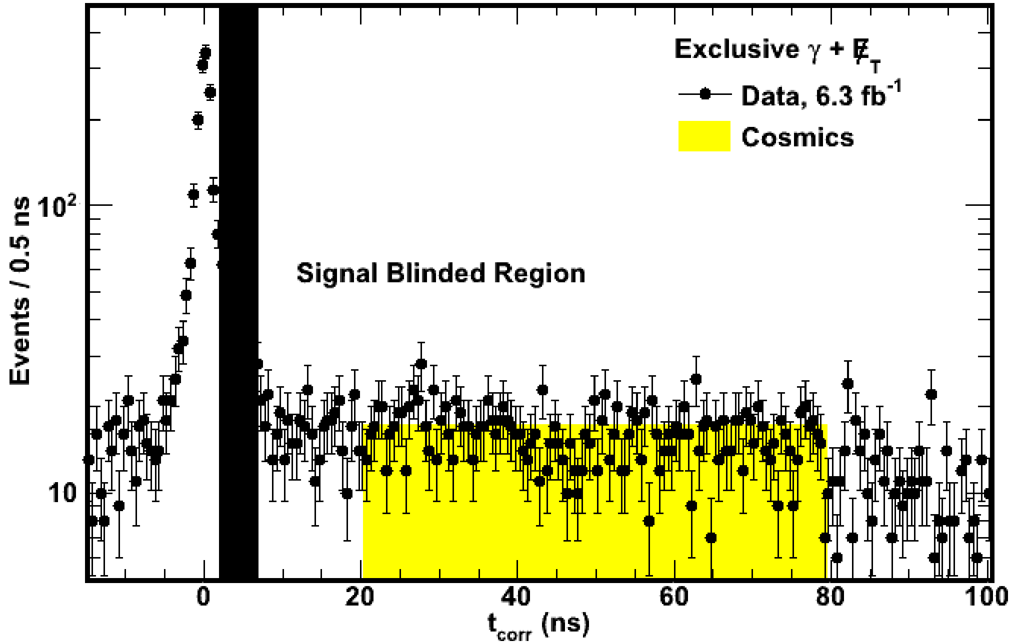
Event Selection	Number of Events
Pass Online/Offline Trigger selection with an identified photon w/ $E_T \geq 45$ GeV and $\not{E}_T \geq 45$ GeV	38,291
Pass Beam Halo Veto	36,764
Pass Cosmics Veto	24,462
Pass Track Veto for Tracks with $P_t > 10$ GeV	16,831
Pass Jet Cluster Veto for Jets with $E_T^0 > 15$ GeV	12,708
Pass Large $\|Z\|$ Vertex Veto	11,702
Pass $e \to \gamma_{fake}$ Veto	10,363
Events with Good SpaceTime Vertex / No Reconstructed Vertex ***"Good Vertex Sample" / "No Vertex Sample"***	5,421 / 4,942

Table 7.1

Event reduction table for the exclusive $\gamma_{delayed}+\not{E}_T$ search. The last selection requirement is broken into two samples: 1) Events that do have a reconstructed vertex and 2) Events that do not have a reconstructed vertex ("no vertex sample"). The sample of events that do have a reconstructed vertex are the events in which we perform our search for $\gamma_{delayed} + \not{E}_T$ while the "no vertex sample is used to estimate the mean of the wrong vertex as described in Section 6.3.

Results: Exclusive γ+MET





Quantity	Measured Value	Error
No Vertex Mean	0.12 (ns)	± 0.17 (ns)
Cosmics per Nanosecond	32 (Events)	± 0.2 (Events)
Wrong Vertex Mean	0.12 (ns)	± 0.20 (ns)

Table 7.2

Summary of the data driven background measurements used for the exclusive $\gamma_{delayed} + \not\!\!E_T$ sample prediction.

Timing Region	Number of Events Observed (Events)
Cosmics Region *20 ns to 80 ns*	1919
Control Region *-7 ns to -2 ns*	241
Bulk Region *-2 ns to 2 ns*	1463

Table 7.3

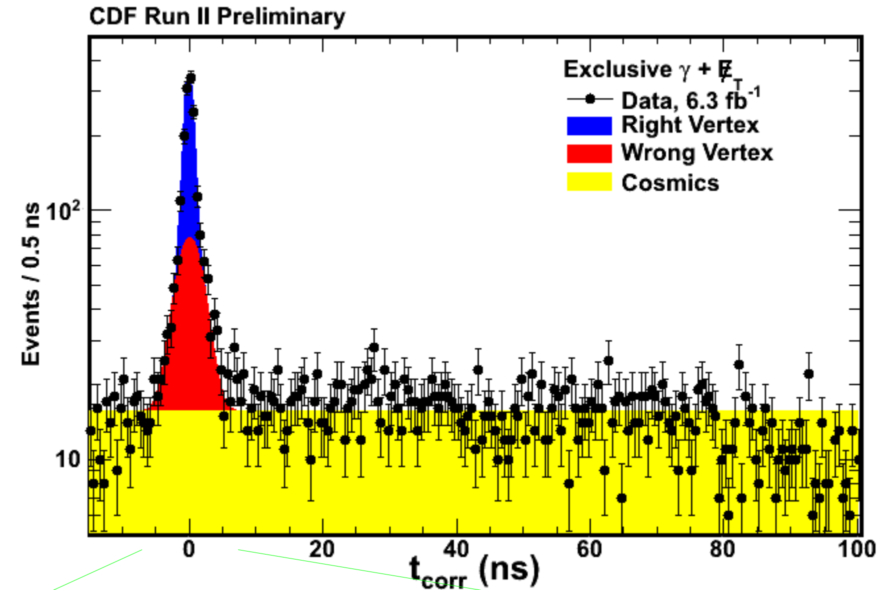
Breakdown of the number of observed events in the Cosmics, Control, and Bulk regions for the exclusive $\gamma_{delayed} + \not\!\!E_T$ sample.

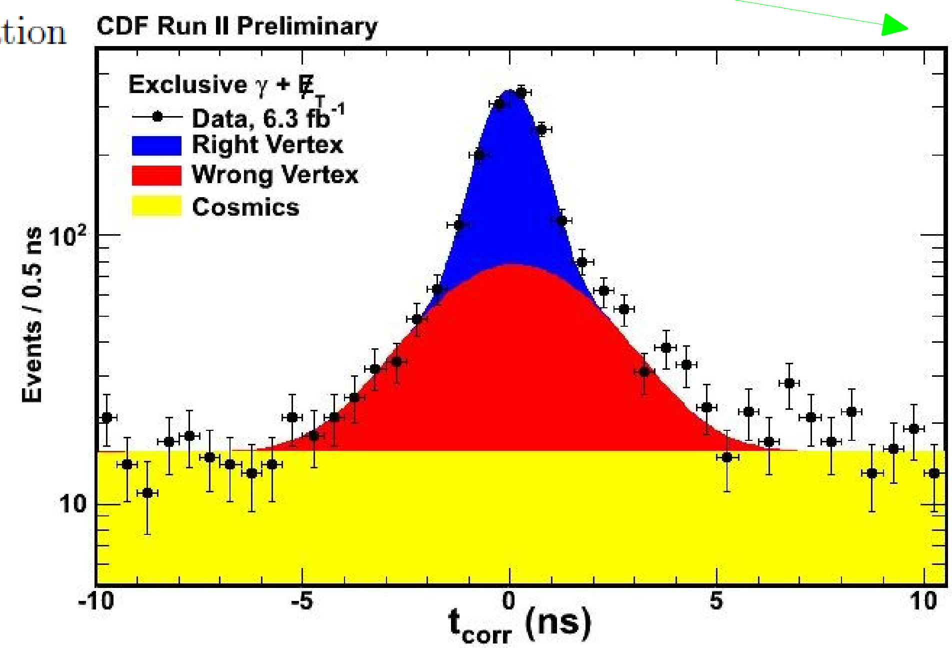
Results: Exclusive γ+MET

Quantity	Prediction *(Events)*	Error *(Events)*
Number of Events from Cosmic Rays expected in the Signal Region	160	$\pm$ 1
Number of Events from Wrong Vertex expected in the Signal Region	96	$\pm$ 35
Total Number of Events Predicted in the Signal Region	256	$\pm$ 35
Total Number of Events Observed in the Signal Region	322	*(N/A)*

Table 7.4

Summary of the data driven background prediction and observation for the exclusive $\gamma_{delayed} + \not{E}_T$ sample.

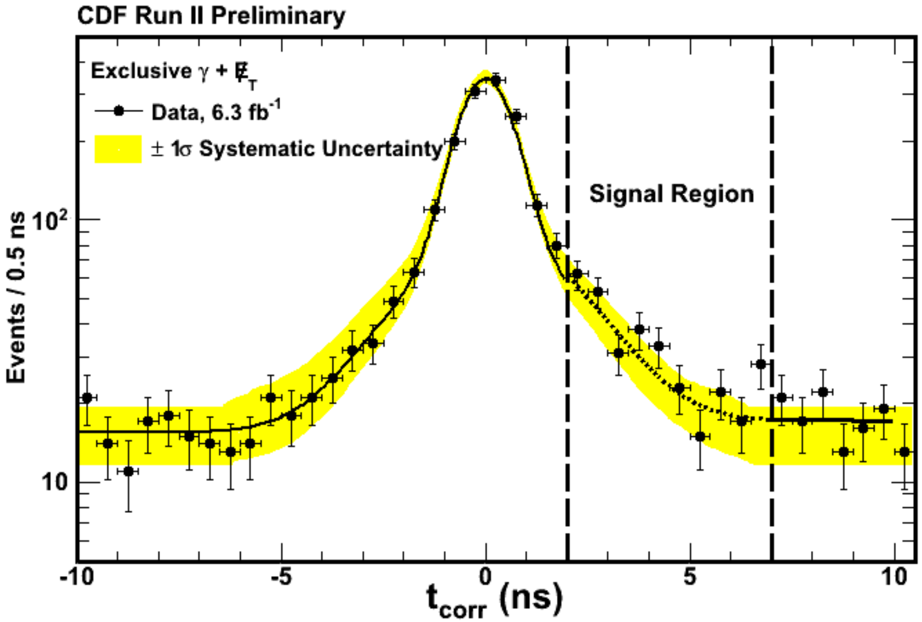


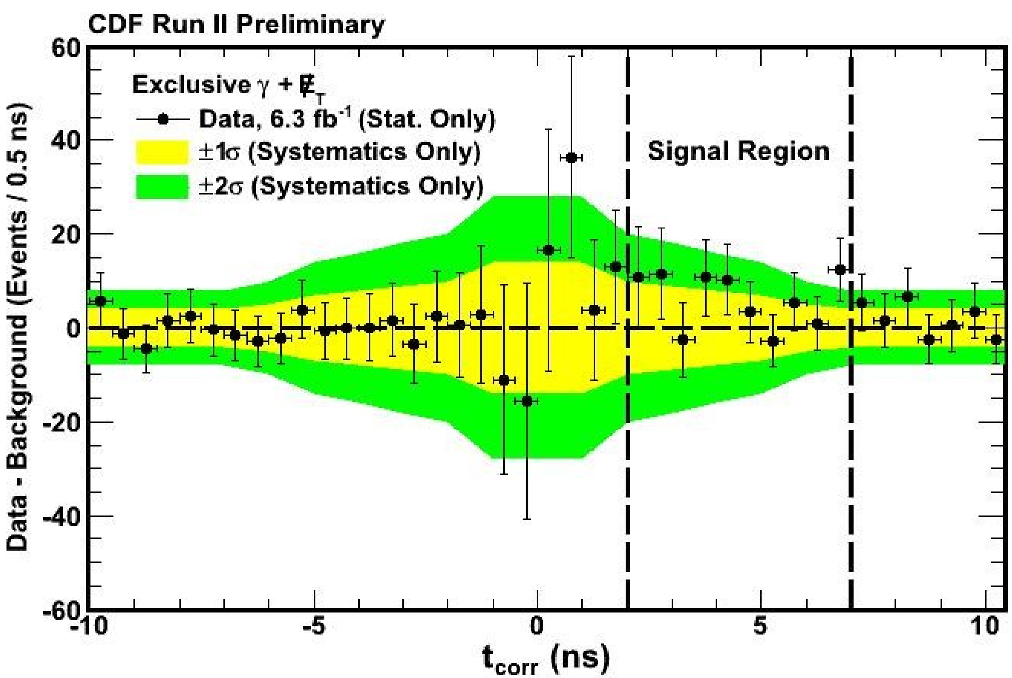


$$N^{Backgrounds}_{Signal\ Region} = N^{SM}_{Signal\ Region} + N^{Cosmics}_{Signal\ Region}$$

Note: Fits shown here not used in background calculation...simply to help guide the eye

Results: Exclusive γ+MET





$$N_\sigma = \frac{N_{Observed} - N_{Predicted}}{\sqrt{\sigma^2_{N_{Pred}} + \sigma^2_{N_{Obs}}}}$$

$$N_\sigma = \frac{322 - 257}{\sqrt{35^2 + 322}}$$

$$N_\sigma = 1.65$$

Conclusions

• **Performed a search for new physics in the Exclusive Delayed Photon + Missing Energy Final State**

• **Followed up on an exciting hint in the data**

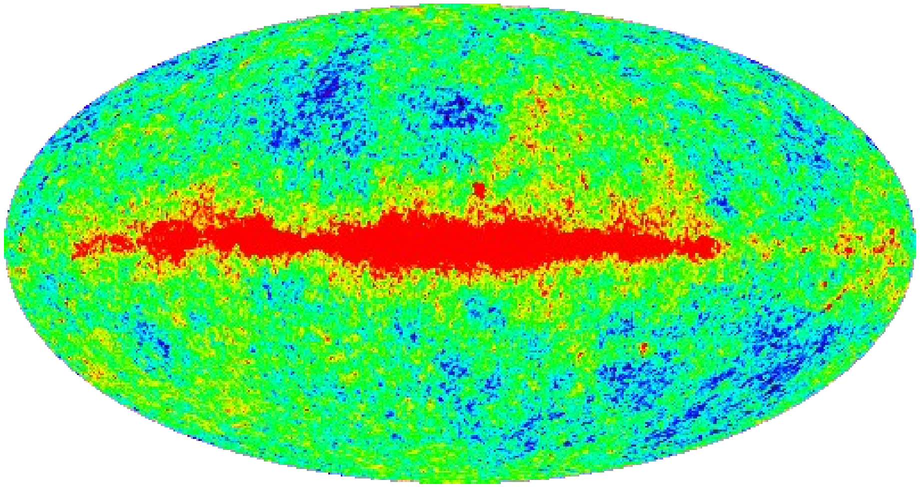
• **Developed methods for minimize timing biases from standard model sources & new background estimation methods**

• **When we remove previously unaccounted for backgrounds and perform a proper background estimation a modest 1.65σ excess remains in the signal region**

• **Looking forward to the next generation of students adding more data, optimizing, and seeing what the LHC can do**

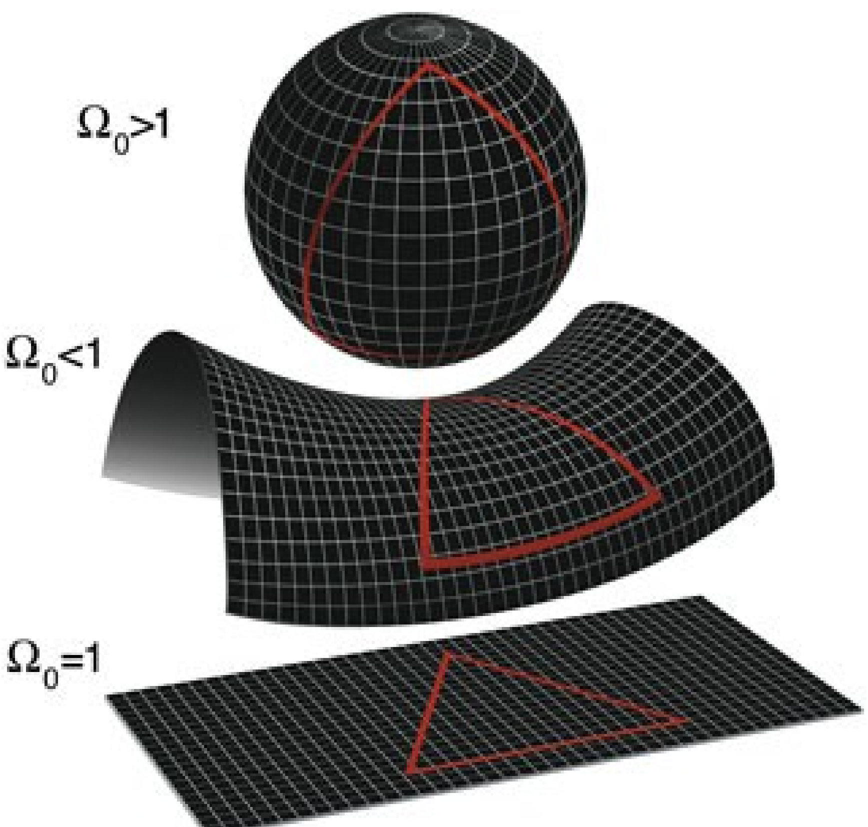
Thank You!

Back-up Slides



The WMAP spacecraft can measure the basic parameters of the Big Bang theory including the geometry of the universe. If the universe were flat, the brightest microwave background fluctuations (or "spots") would be about one degree across. If the universe were open, the spots would be less than one degree across. If the universe were closed, the brightest spots would be greater than one degree across.

Recent measurements (c. 2001) by a number of ground-based and balloon-based experiments, including MAT/TOCO, Boomerang, Maxima, and DASI, have shown that the brightest spots are about 1 degree across. Thus the universe was known to be flat to within about 15% accuracy prior to the WMAP results. WMAP has confirmed this result with very high accuracy and precision. We now know that the universe is flat with only a 0.5% margin of error. This suggests that the Universe is infinite in extent; however, since the Universe has a finite age, we can only observe a finite volume of the Universe. All we can truly conclude is that the Universe is much larger than the volume we can directly observe.



The density of the universe also determines its geometry. If the density of the universe exceeds the critical density, then the geometry of space is closed and positively curved like the surface of a sphere. This implies that initially parallel photon paths converge slowly, eventually cross, and return back to their starting point (if the universe lasts long enough). If the density of the universe is less than the critical density, then the geometry of space is open, negatively curved like the surface of a saddle. If the density of the universe exactly equals the critical density, then the geometry of the universe is flat like a sheet of paper. Thus, there is a direct link between the geometry of the universe and its fate.

ABOUT THIS IMAGE:

This NASA Hubble Space Telescope image of the rich galaxy cluster, Abell 2218, is a spectacular example of gravitational lensing. The arc-like pattern spread across the picture like a spider web is an illusion caused by the gravitational field of the cluster.

The cluster is so massive and compact that light rays passing through it are deflected by its enormous gravitational field, much as an optical lens bends light to form an image. The process magnifies, brightens and distorts images of objects that lie far beyond the cluster. This provides a powerful "zoom lens" for viewing galaxies that are so far away they could not normally be observed with the largest available telescopes.

Hubble's high resolution reveals numerous arcs which are difficult to detect with ground-based telescopes because they appear to be so thin. The arcs are the distorted images of a very distant galaxy population extending 5-10 times farther than the lensing cluster. This population existed when the universe was just one quarter of its present age. The arcs provide a direct glimpse of how star forming regions are distributed in remote galaxies, and other clues to the early evoution of galaxies.

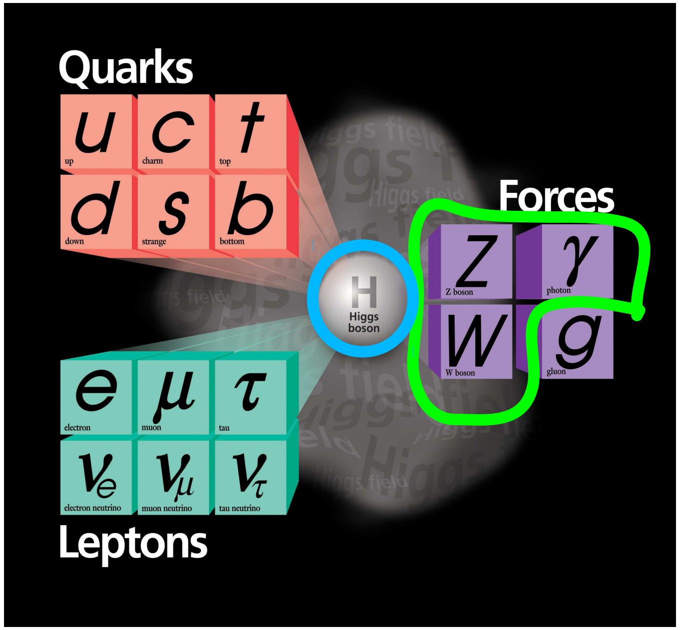
Hubble also reveals multiple imaging, a rarer lensing event that happens when the distortion is large enough to produce more than one image of the same galaxy. Abell 2218 has an unprecedented total of seven multiple systems.

The abundance of lensing features in Abell 2218 has been used to make a detailed map of the distribution of matter in the cluster's center. From this, distances can be calculated for a sample of 120 faint arclets found on the Hubble image. These arclets represent galaxies that are 50 times fainter than objects that can be seen with ground-based telescopes.

Studies of remote galaxies viewed through well-studied lenses like Abell 2218 promise to reveal the nature of normal galaxies at much earlier epochs than was previously possible. The technique is a powerful combination of Hubble's superlative capabilities and the "natural" focusing properties of massive clusters like Abell 2218.

Motivation

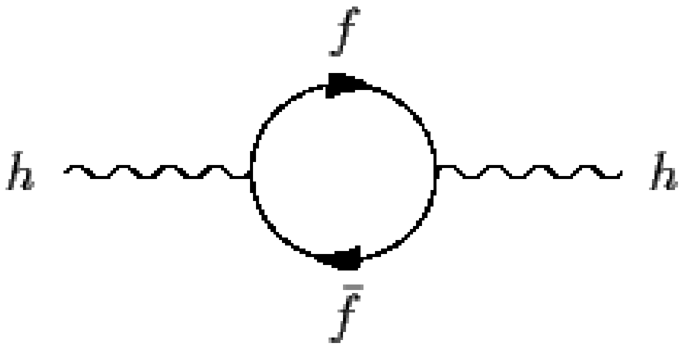
Beyond the Standard Model



Electromagnetic and Weak forces are successfully unified at ~10^2 GeV scale: Electroweak Theory (EWK)

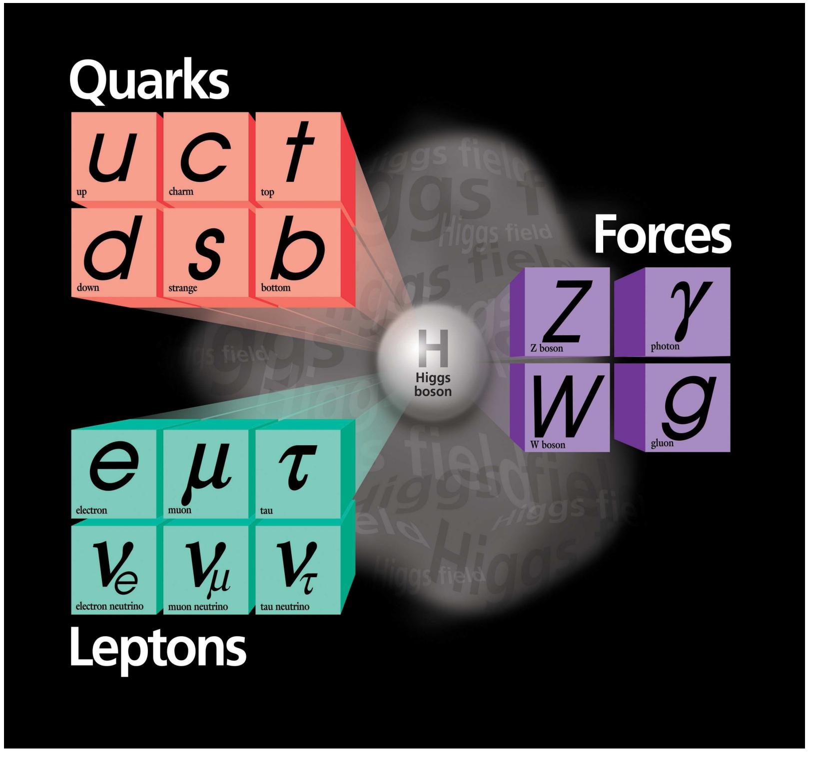
Electroweak Symmetry breaking as well the mechanism by which the various SM particles aquire their mass is known as the Higgs Field (…Higgs Boson...)

→ The Higgs mass should be around the EWK scale (~10^2 GeV).



However, SM calculations of the Higgs mass → m_H ~ 10^{15} GeV unless parameters are fine tuned

Motivation



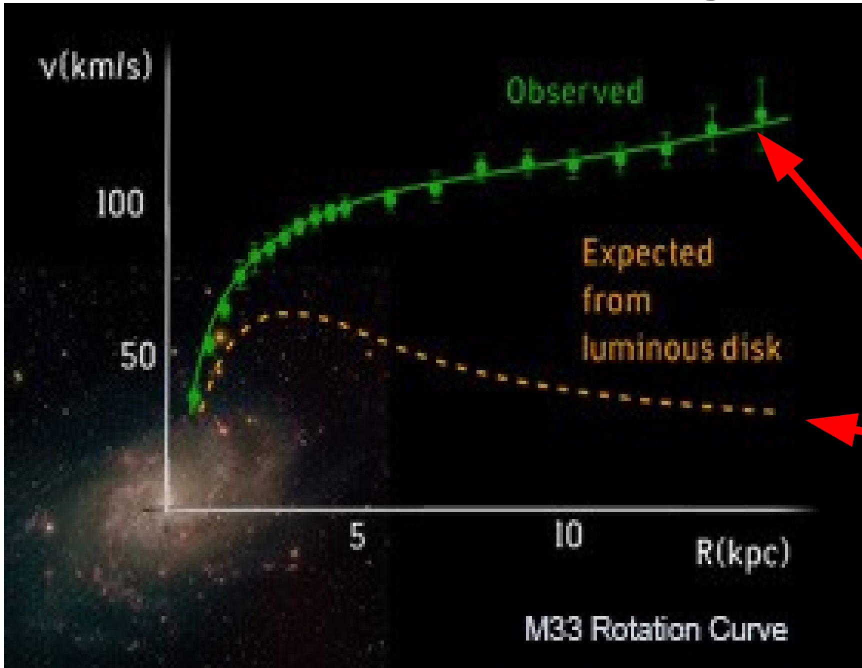
Symmetry based theory which describes the various fundamental forces *(Strong and Weak nuclear force as well as the Electromagnetic force)* as well as the building blocks of matter

The symmetries of the Standard Model are broken *(e.g. the various particles have widely varying masses)*

The mechanism by which the particles acquire their masses is known as the Higgs Mechanism and the corresponding force particle *(Higgs Boson...as yet undiscovered)*

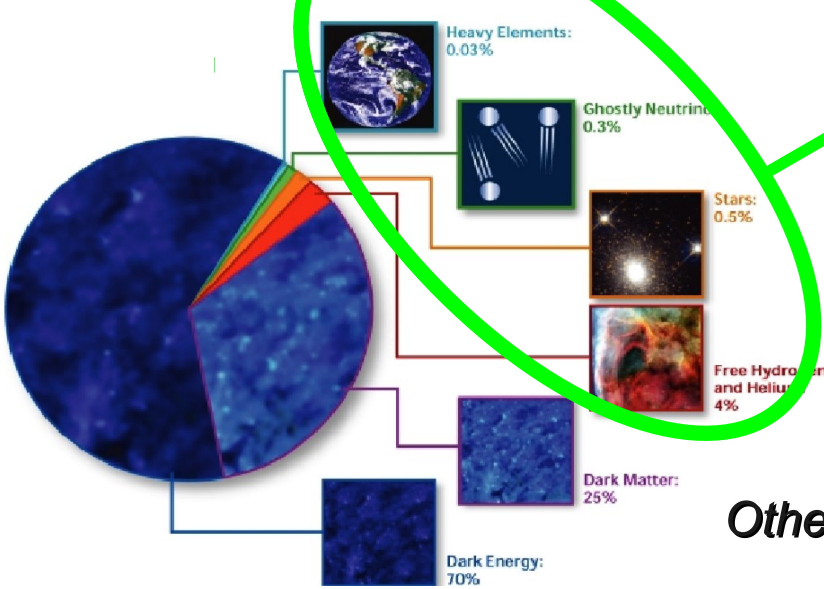
Motivation

Beyond the Standard Model



Rotation curves from galaxies indicate there is more mass present within the galaxy than is accounted for by the luminous matter

No Standard Model particle to account for this discrepancy



Additional astronomical observations indicate that the visible matter in the universe (...stuff from the SM...) seems to only account for ~5% of the total mass

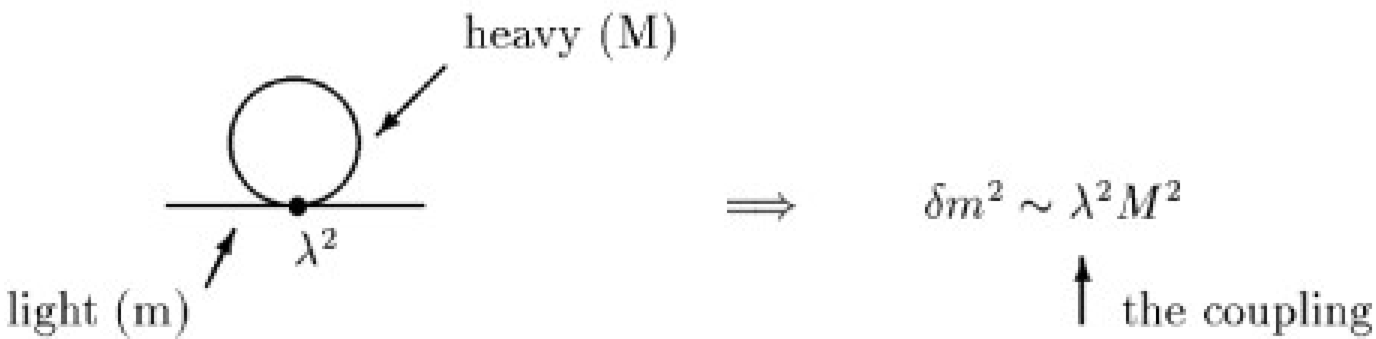
Other problems exists too...(hierarchy problem, Grand Unification, etc...)...I highlight only one

Motivation

The Standard Model of Particle Physics

Problem 1: The Hierarchy Problem

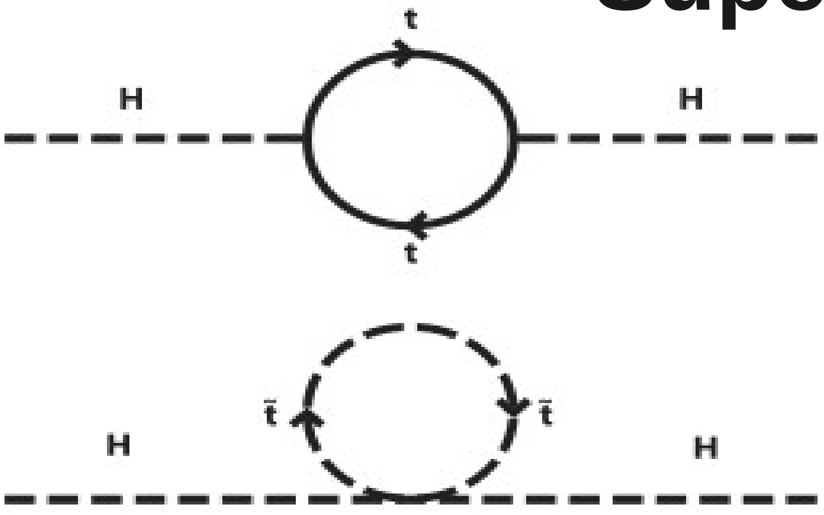
In the standard model fermions obtain their mass through interactions with the Higgs field. The mass of a fermion then is just proportional to the strength of its coupling to the Higgs field.



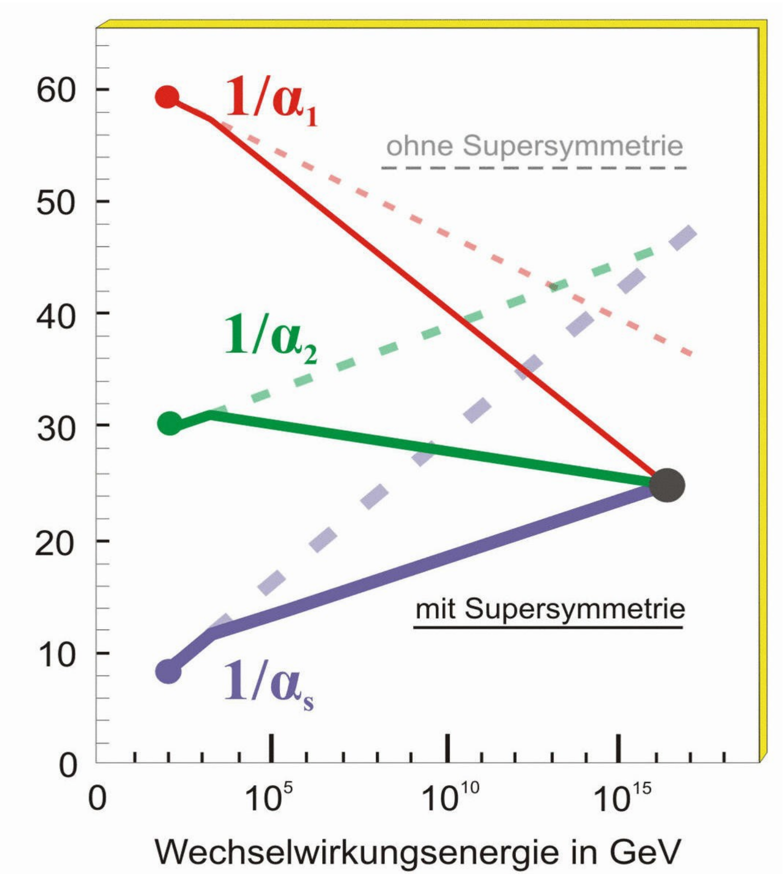
The Higgs also develops a mass through terms and interactions with other particles, leading to radiative corrections that cause the Higgs mass to become divergent ($m_H \sim 10^{15}$ GeV unless parameters are fine tuned)! ***(This is bad)***

This suggests that the SM may be a low energy approximation for something more

Supersymmetry



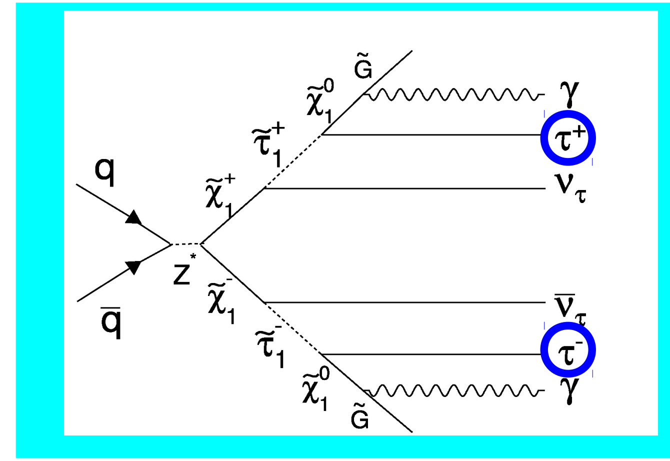
The contribution of each supersymmetric partner cancels off the contribution of each SM particle, thus protecting the Higgs mass from divergence.

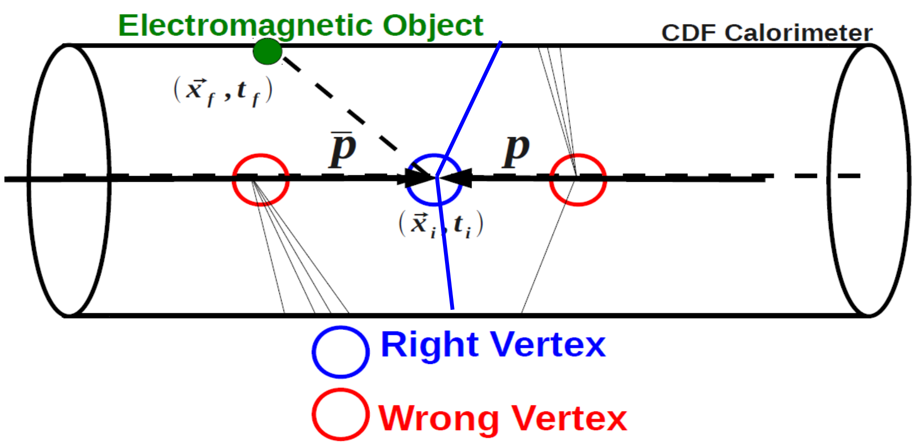


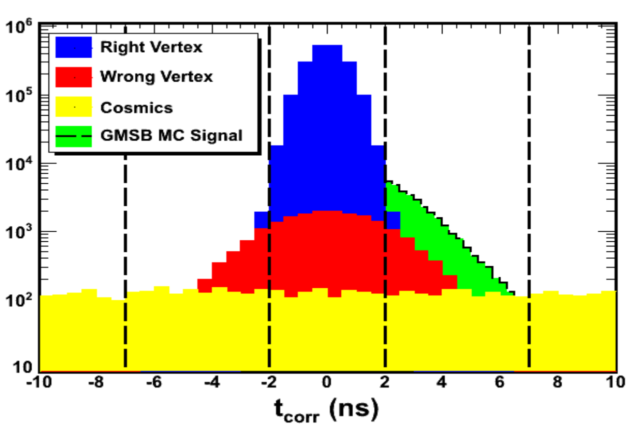
Overview of the Delayed Photon Analysis

"Why previous analysis didn't see this"

"Performing a GMSB search is a straight forward counting experiment since I have these leptons and jets to identify the right vertex with"
- Previous Physicists



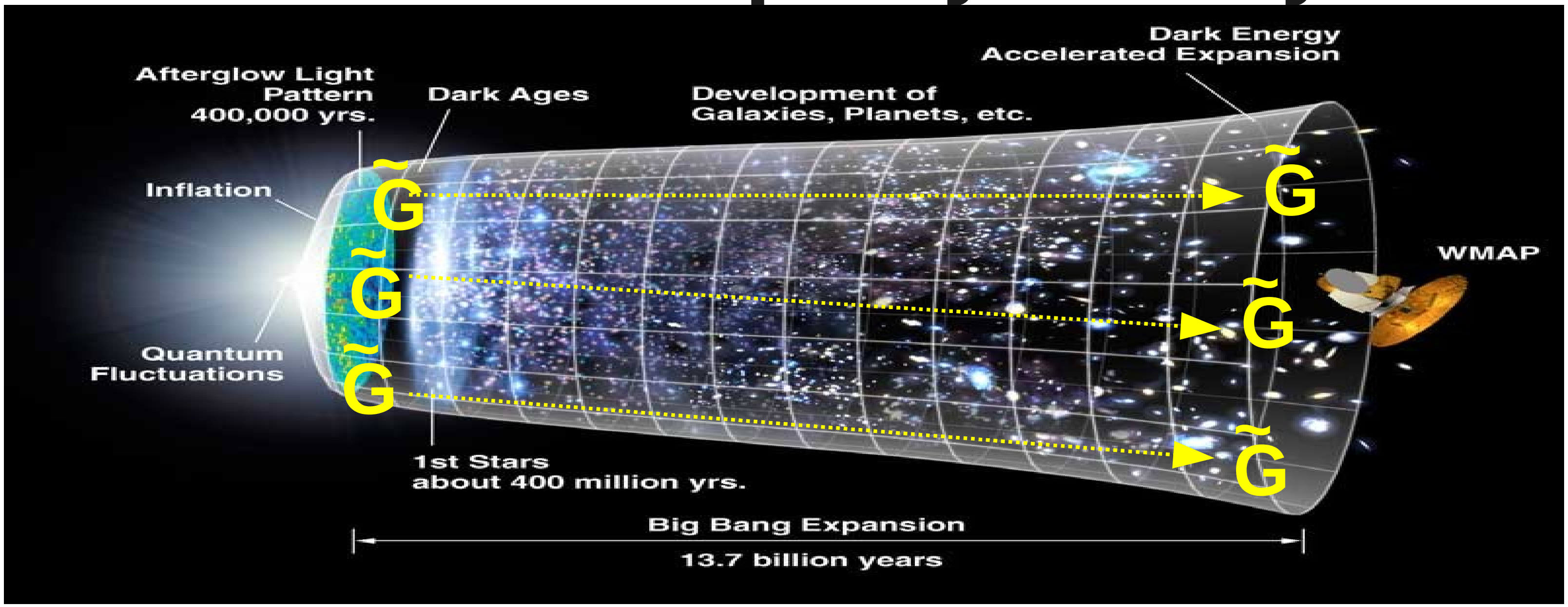




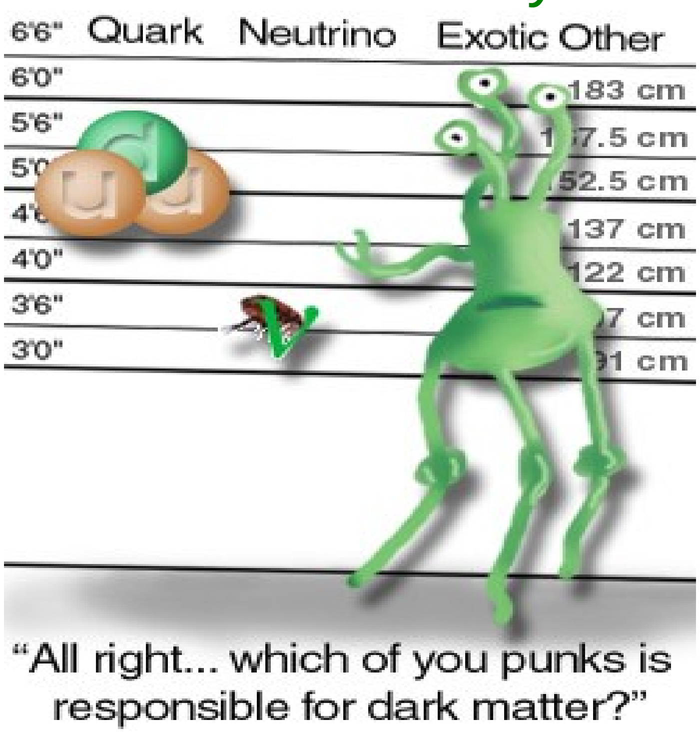
Previous GMSB searches observed symmetric description of the timing of collision and non-collision events.

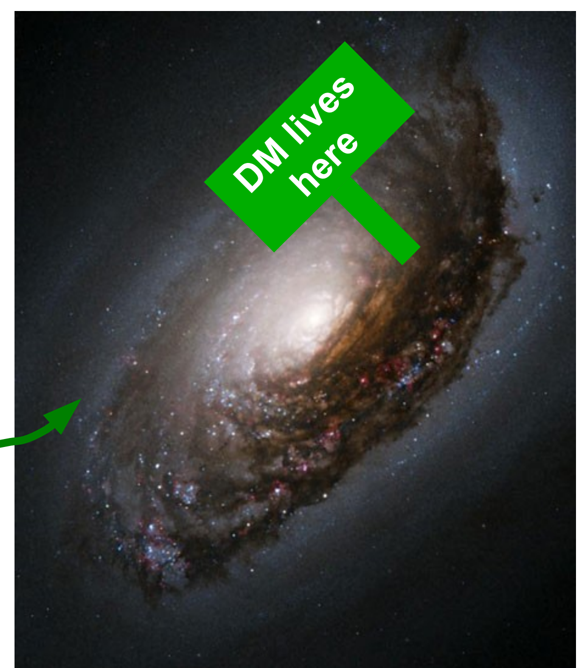
This was possible because you expected to have additional charged particles created along with the delayed object. Thus making the Wrong Vertex rate small and you were not very sensitive to these mean shifts.

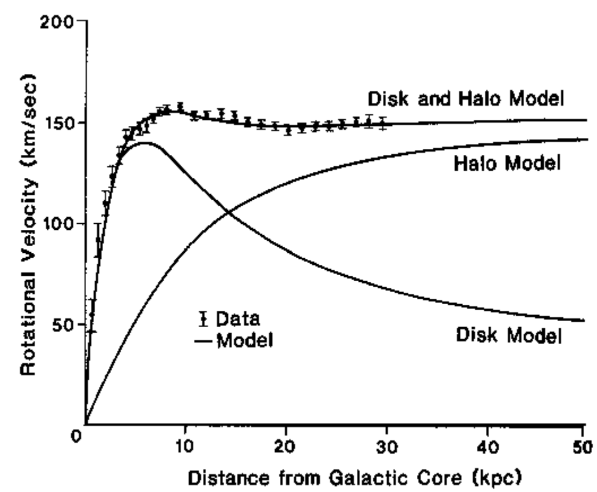
Supersymmetry



SUSY theories provide stable neutral particles that could have been created in the early universe and would be found today as dark matter







Could provide an explanation to the rotation curves

Collider Detection at Fermilab (CDF)

Muon Chambers

Hadronic Calorimeters

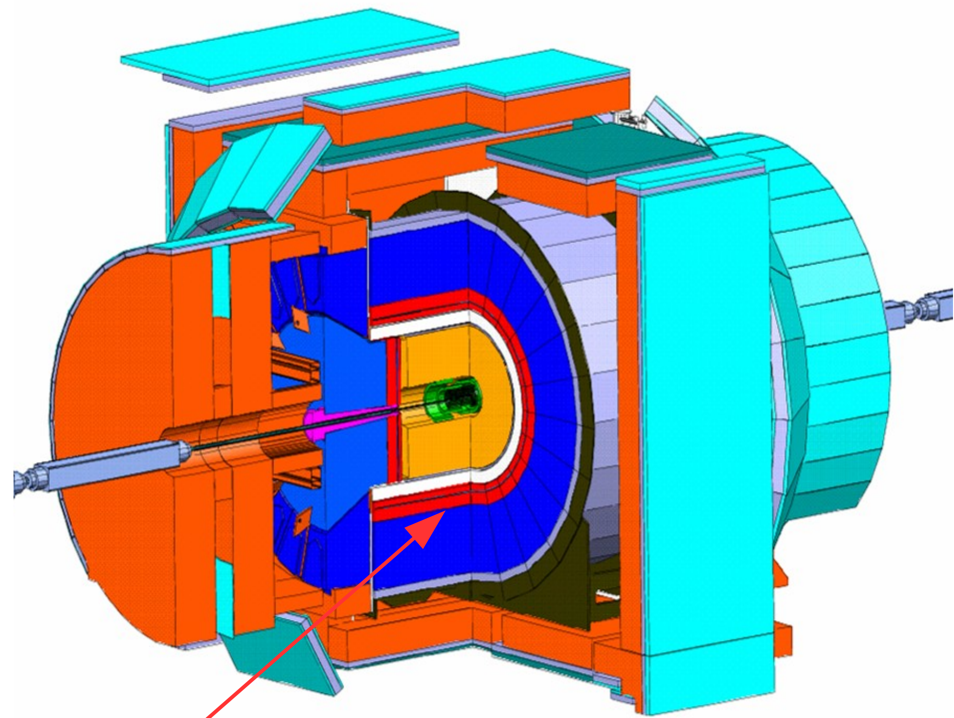
ElectroMagnetic Calorimeters

Central Tracker

Silicon Tracker

CDF is a multi-purpose detector with concentric identification system

Capable of identifying Electrons, Muons, Photons, Taus, b-jets, and Missing Energy



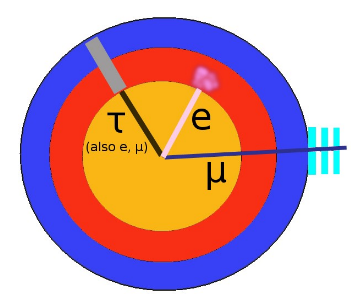
Highlights of Systems used in the Delayed Photon Analysis

Central Outer Tracker: Open cell drift chamber with 96 layers of sense wire. Each wire capable of making a timing measurement on a track. Track $\sigma_Z \sim 0.22$cm

Track $\sigma_{T0} \sim 0.27$ ns

Electromagnetic Calorimeter: Detector for energy measurement of electromagnetic events (especially photons and electrons). Lead/scintillator sampling calorimeter, segmented into 10 towers in η and 24 wedges in ϕ

EMTiming System



New Timing Based Background Estimation Method

The Number of Events in the Control Region (C) is determined by:

$$C = N_w \beta_{WV}^{Control} + N_{RV} \beta_{RV}^{Control}$$

where

$$N_{WV} = \text{Number of Events from Wrong Vertex}$$

$$N_{RV} = \text{Number of Events from Right Vertex}$$

$$\beta_{WV}^{Control}(Mean_{WV}, RMS_{WV}) = Erf\left(\frac{\sigma_{0,-7ns}^{WV}}{2}\right) - Erf\left(\frac{\sigma_{0,-2ns}^{WV}}{2}\right)$$

$$\beta_{RV}^{Control}(Mean_{RV}, RMS_{RV}) = Erf\left(\frac{\sigma_{0,-7ns}^{RV}}{2}\right) - Erf\left(\frac{\sigma_{0,-2ns}^{RV}}{2}\right)$$

2 Equations

(N_{events} for Control & Bulk)

2 Unkowns

(N_{WV} , N_{RV})

Similarly, the number of Events in the Bulk Region (B) is determined by:

$$B = N_w \beta_{WV}^{Bulk} + N_{RV} \beta_{RV}^{Bulk}$$

Note: Erf(x) is the standard Gauss Error Function defined as

$$erf(x) = \frac{2}{\pi} \int_0^x e^{\frac{-(t-\mu)^2}{\sigma_{rms}}}$$

It is through this function that our predictions become a function of the wrong vertex Mean and RMS

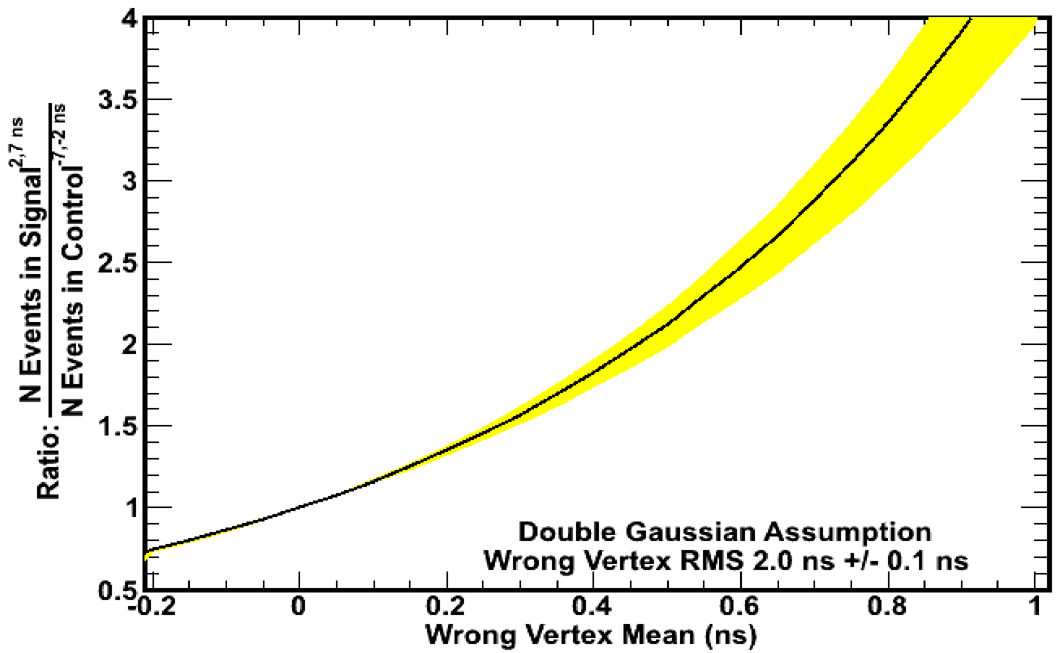
New Timing Based Background Estimation Method

The Number of events in the Signal Region (S) is also described by these equations:

$$S = N_w \beta_{WV}^{Signal} + N_{RV} \beta_{RV}^{Signal}$$

Therefore, if we know the number of events in the Bulk Region and the Number of events in the Control Region we can solve the equation for number of events in the Signal Region:

$$Ratio = R = S/C = \frac{N_w \beta_{WV}^{Signal} + N_{RV} \beta_{RV}^{Signal}}{N_w \beta_{WV}^{Control} + N_{RV} \beta_{RV}^{Control}}$$



Here, we assume the Right Vertex is described by a Gaussian with Mean = 0.0 ns and an RMS = 0.65 ns and the Wrong Vertex is described by a Gaussian with RMS = 2.0 +/- 0.1 ns and we allow the Mean to float

Triggers

Object Type	Trigger		
	Level 1	**Level 2**	**Level 3**
Electromagnetic Cluster	≥ 1 Central EM Cluster $E_T > 8$ GeV $\frac{E_{Had}}{E_{EM}} < 0.125$	$\lvert\eta\rvert < 1.1$ $E_T > 20$ GeV $E_T^{SeedTower} > 8$ GeV	≥ 1 EM Cluster $E_T > 25$ GeV $\frac{E_{Had}}{E_{EM}} < 0.125$
Missing Energy	$\not{E}_T > 15$ GeV $\Sigma E_T > 1$ GeV		$\not{E}_T > 25$ GeV

Table 2.8
Online Event Selection for the WNOTRACK Trigger.

Object Type	Trigger		
	Level 1	**Level 2**	**Level 3**
ZNOTRACK			
Electromagnetic Cluster	≥ 1 Central EM Cluster $E_T > 8$ GeV $\frac{E_{Had}}{E_{EM}} < 0.125$	≥ 2 EM Cluster $\lvert\eta\rvert < 1.1$ Both w/ $E_T > 16$ GeV Both w/ $E_T^{SeedTower} > 8$ GeV	≥ 2 EM Cluster Both w/ $E_T > 16$ GeV $\frac{E_{Had}}{E_{EM}} < 0.125$
SUPERPHOTON70			
Electromagnetic Cluster	≥ 1 Central EM Cluster $E_T > 10$ GeV	$\lvert\eta\rvert < 1.1$ $E_T > 70$ GeV $E_T^{SeedTower} > 8$ GeV	≥ 1 EM Cluster $E_T > 70$ GeV $\frac{E_{Had}}{E_{EM}} < 0.2$
PHOTON25ISO			
Electromagnetic Cluster	≥ 1 Central EM Cluster $E_T > 8$ GeV $\frac{E_{Had}}{E_{EM}} < 0.125$	$\lvert\eta\rvert < 1.1$ $E_T > 21$ GeV $E_T^{SeedTower} > 8$ GeV $E_T^{ISO} < 3$ GeV $\frac{E_{Had}}{E_{EM}} < 0.125$	≥ 1 EM Cluster $E_T > 25$ GeV $\text{Iso}^{Total} < 2.0$ $\chi^2 < 20$ $\frac{E_{Had}}{E_{EM}} < 0.055$

Table 2.9
List of additional triggers accepted on the logical *or* of the WNOTRACK trigger.

Object Id

Variable	Cuts
$\|\eta\|$	< 1.0 (Central)
Photon E_T *(Measured from Z = 0)*	$\geq$ 30 GeV
Fiducial (Ces $\|X\|$ <21 cm, 9< Ces $\|Z\|$ <230 cm) Tower 9 excluded	= 1
$\frac{HadronicEnergy}{ElectromagneticEnergy}$	< 0.125
Energy Isolation $E_T^0 \geq 20$ GeV	$E_{cal}^{iso} < 2.0 + (0.02 \cdot (E_T^0\text{-}20))$
Track Isolation	$\leq 2.0 + (0.005 \cdot E_T^0)$
N3D Track Rejection If N3D Track = 1	≤ 1 Track $P_t \leq 1.0 + (0.005 \cdot E_T^0)$
2^{nd} CES Cluster Energy $E_T^0 < 18$ GeV $E_T^0 \geq 18$ GeV	 $E^{2nd}CES \leq 0.14 \cdot E_T^0$ $E^{2nd}CES \leq 2.4 + (0.01 \cdot E_T^0)$
$\|PMTAysmmetry\|$	< 0.6
$\|EMTime\|$	< 900
Had E *Hadronic Energy deposited*	$\geq$ -0.30 + 0.008 $\cdot E_T$
CES(E) *Total Energy in the CES*	$\geq$ 10 GeV
CES(E)/Total E *Fraction of Energy Deposited in the CES over the total Energy*	$\geq$ 0.2

Table 2.5

Standard central photon identification requirements used to identify photon candidates in the delayed photon analysis. Note, these cuts are the standard CDF definition for photons in addition to requiring PMT Aysmmetry, EMTiming variables, total CES Energy, a sliding CES Energy fraction and additional hadronic energy requirement as well as removing CES χ^2. These variables are defined in more detail in Appendix A.

Variable	Cuts
Electron E_T *(Measured from Z = 0)*	>30 GeV
$\frac{\text{HadronicEnergy}}{\text{ElectromagneticEnergy}}$	$< 0.055 + 0.00045 \cdot E$
P_T	> 10 GeV
$\|\Delta Z\|$ CES	<5 cm
$\|\Delta X\|$ CES	<3 cm
Isolation	$< 0.1 \cdot E_T$
E/P_T	< 2 *For P_t < 50 GeV*
L_{shr}	< 2
Fiducial (Ces $\|X\|$ <21 cm, 9< Ces $\|Z\|$ <230 cm) Tower 9 excluded	= 1
$\|Z\|$	< 60 cm
$\|PMTAysmmetry\|$	< 0.6
$\|EMTime\|$	< 900

Table 2.6

Table of standard central electron identification variables. Note, in addition to the standard CDF variables PMT Aysmmetry and EM-Timing requirements have been added to ensure a good timing measurement is made. These variables are defined in more detail in Appendix A.

Object Id

Variable	Cuts
P_T	≥ 0.3 GeV
$\|\eta\|$	< 1.6
$COTStereoSeg(5)$	≥ 2
$COTAxialSeg(5)$	≥ 2
$\|Z\|$	≤ 70 cm
$\|d_0\|$	≤ 1.0 cm
$T_0\ \sigma$	$0.2 < T_0\ \sigma < 0.8$ ns

Table 2.3

Standard good timing track identification variables. Note, these cuts are used in order to ensure a good timing measurement on the track in addition to a good position measurement. These variables are defined in more detail in Appendix A.

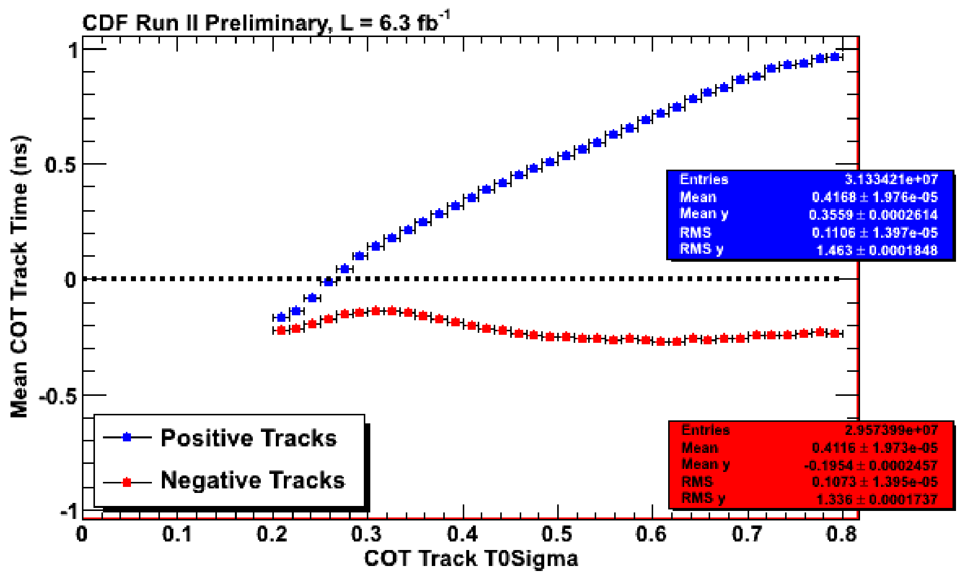
Variable	Cuts
P_T	≥ 10 GeV
$COTAxialHits$	≥ 2
$nCOTHits$	$>$ 60% of last layer of the COT

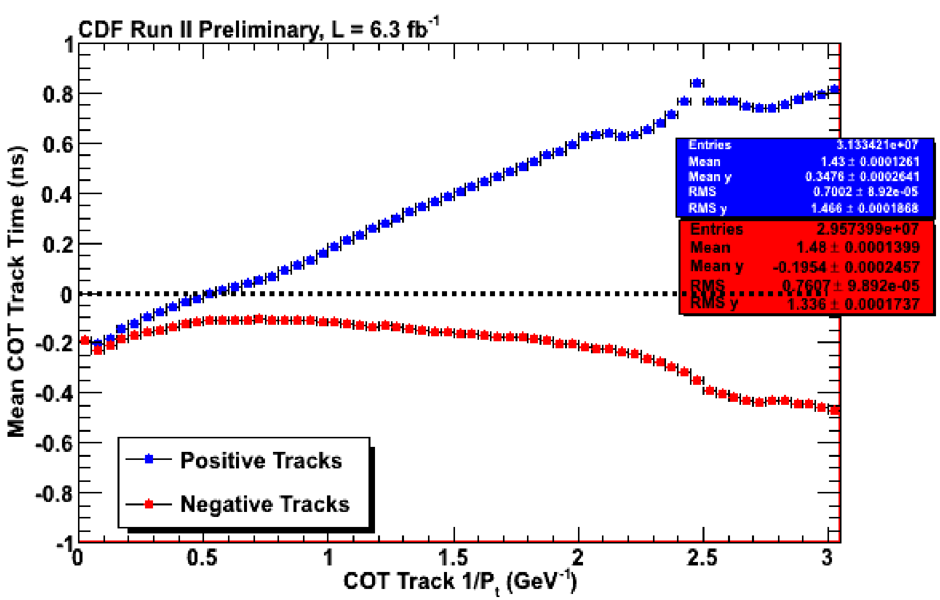
Table 2.4

Table outlining the definition of tracks that we veto against in the exclusive $\gamma + \not\!\!E_T$ final state.

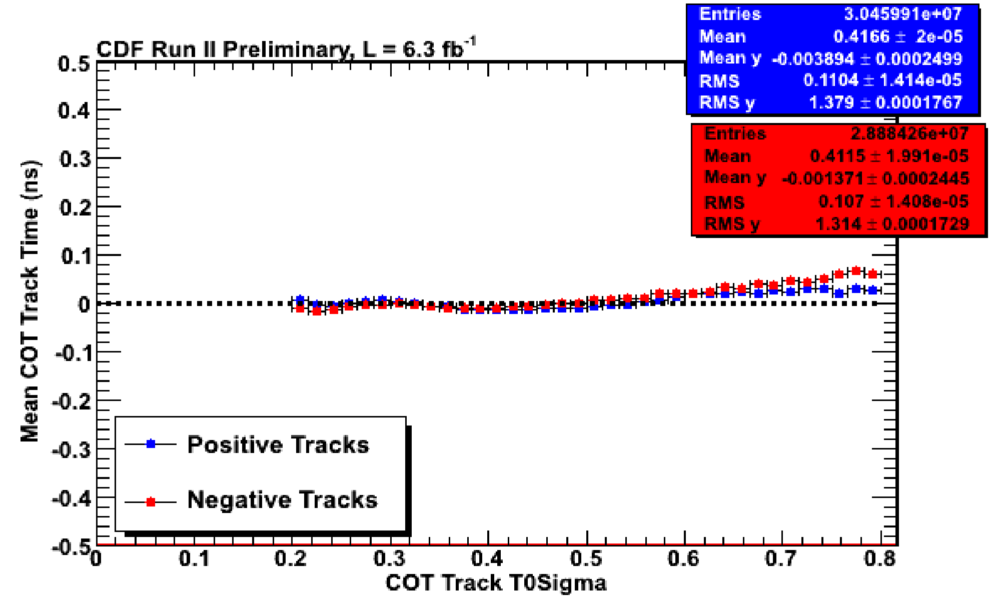
Track Calibrations

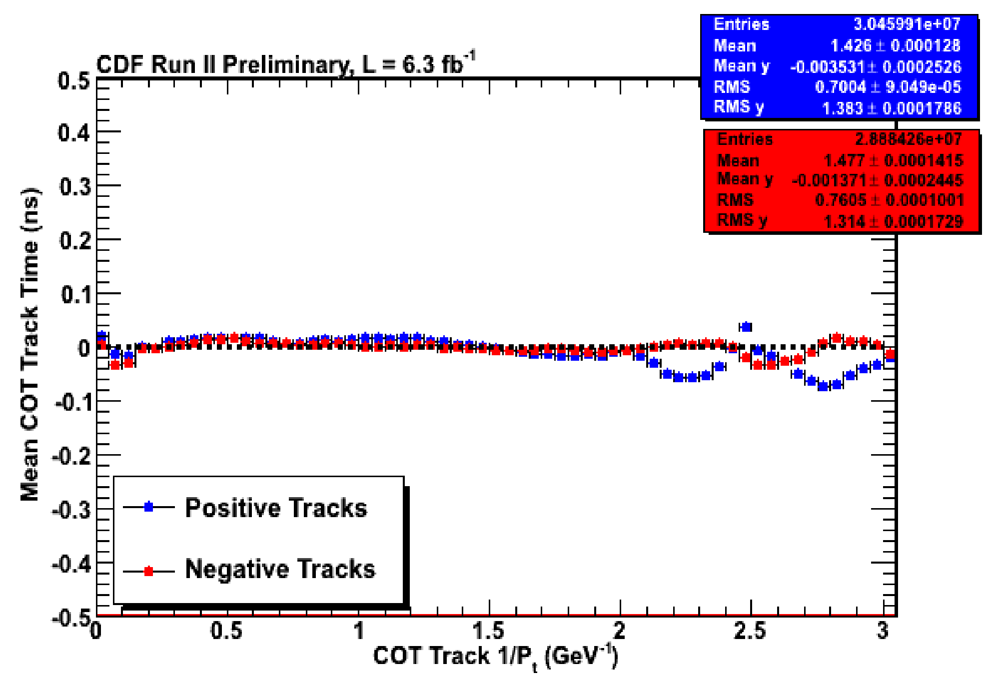
Before Calibrations





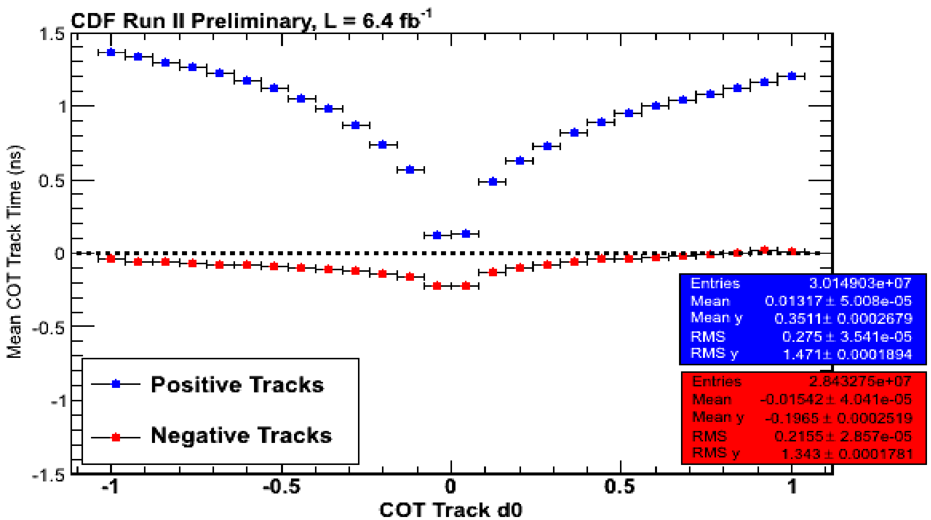
After Calibrations

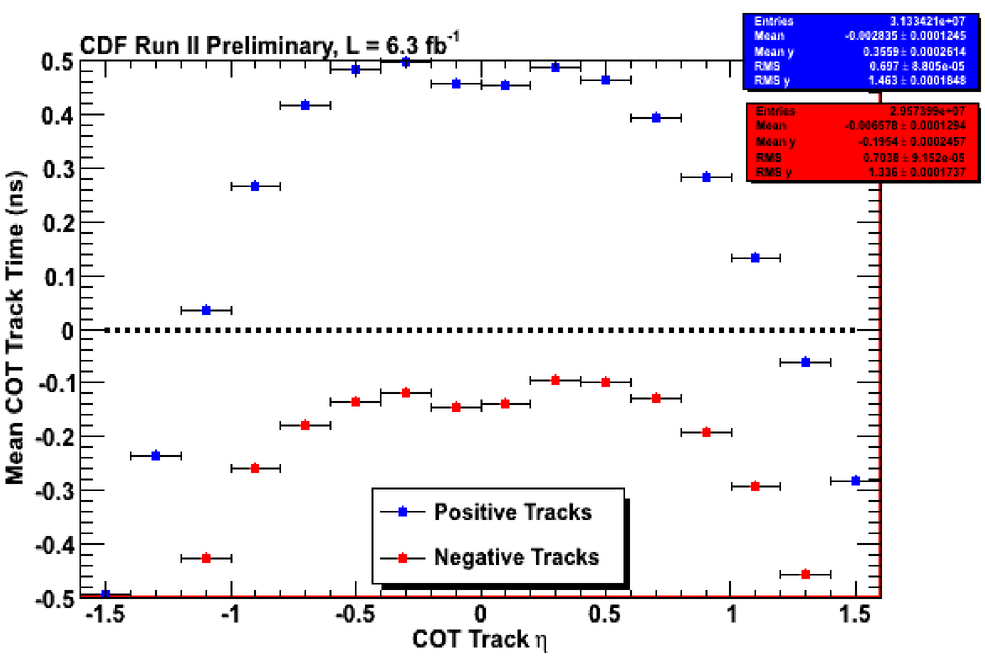




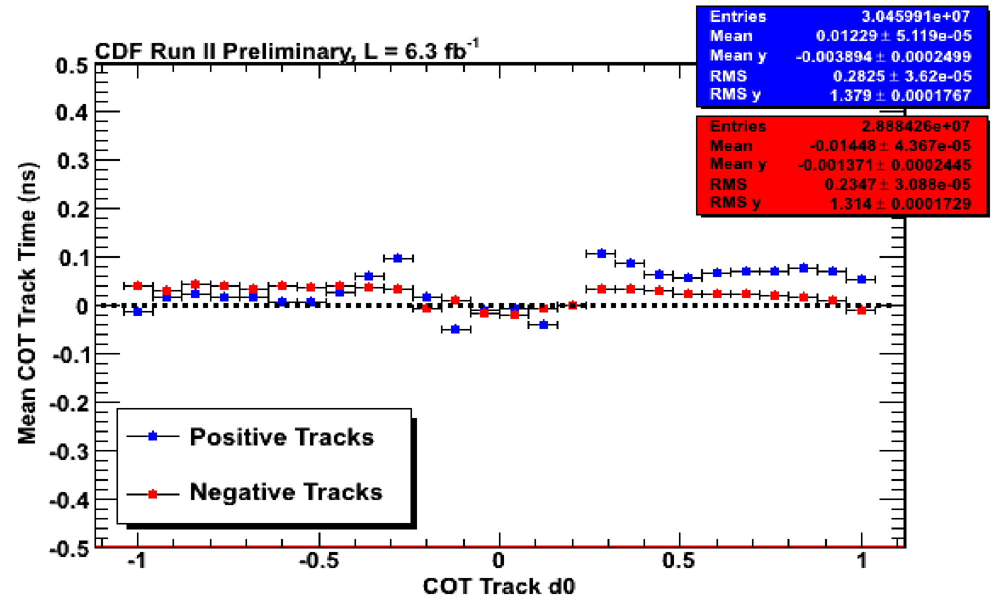
Track Calibrations

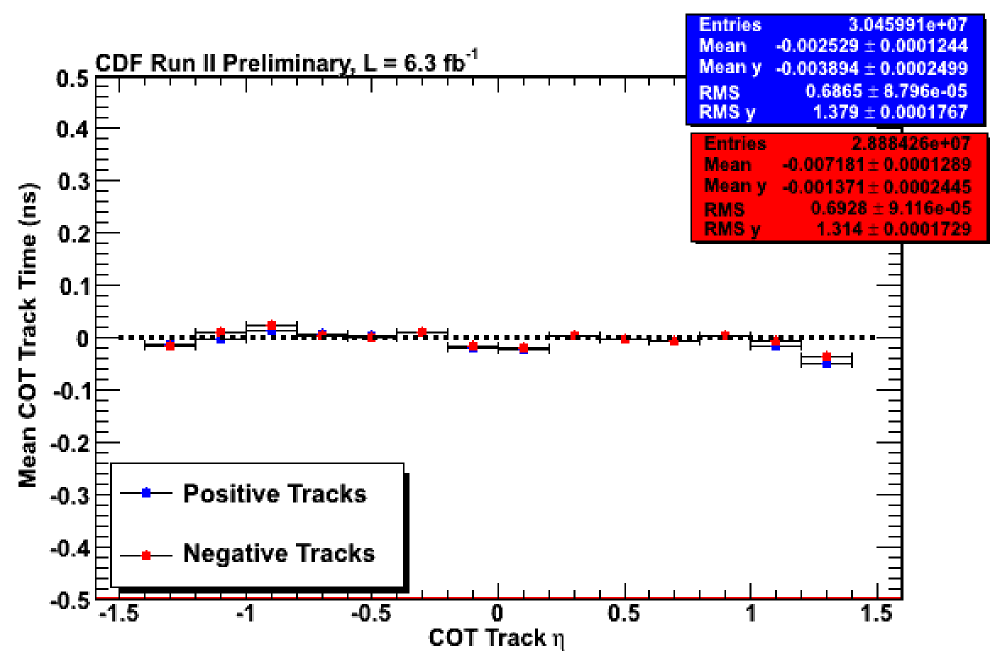
Before Calibrations





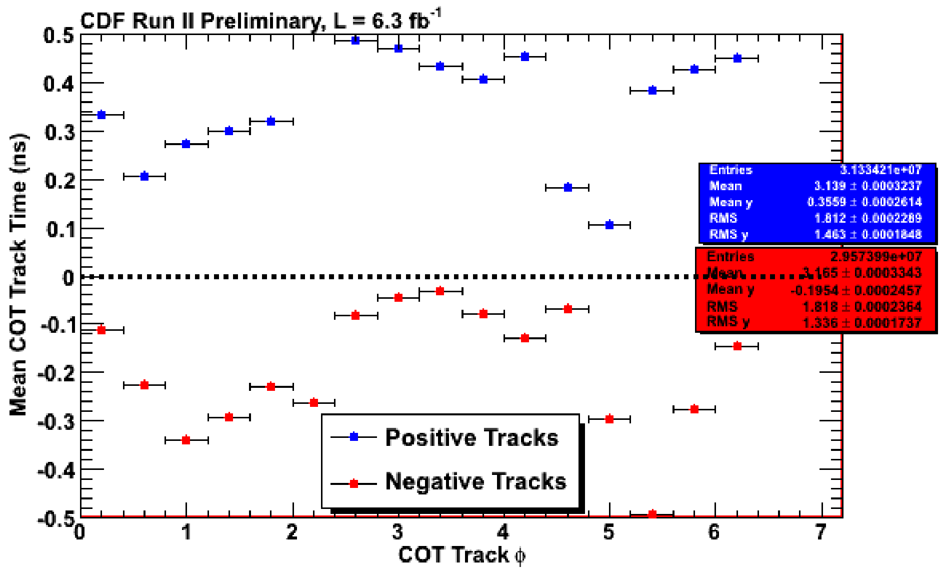
After Calibrations

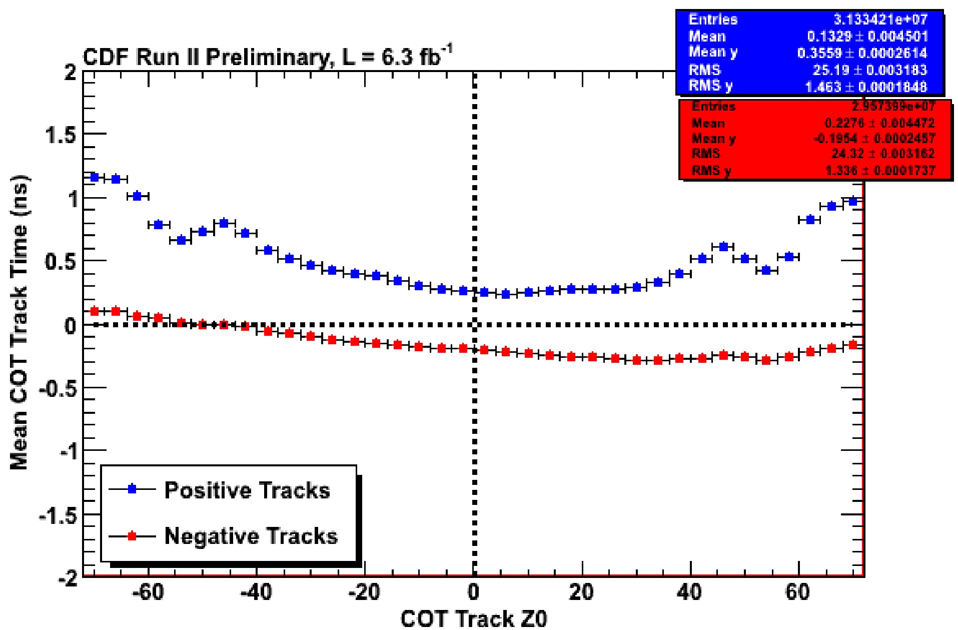




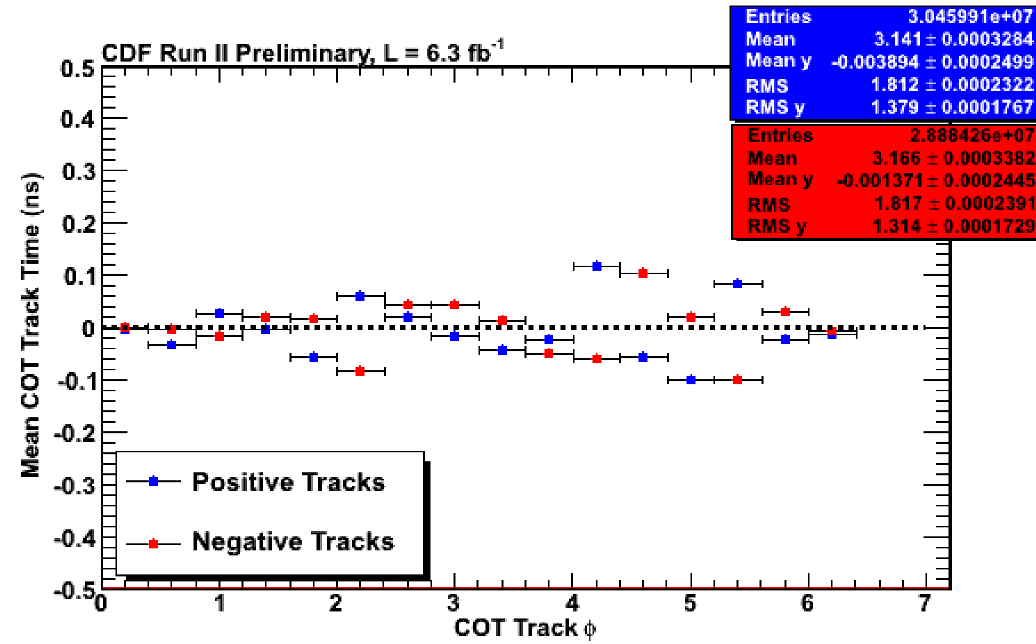
Track Calibrations

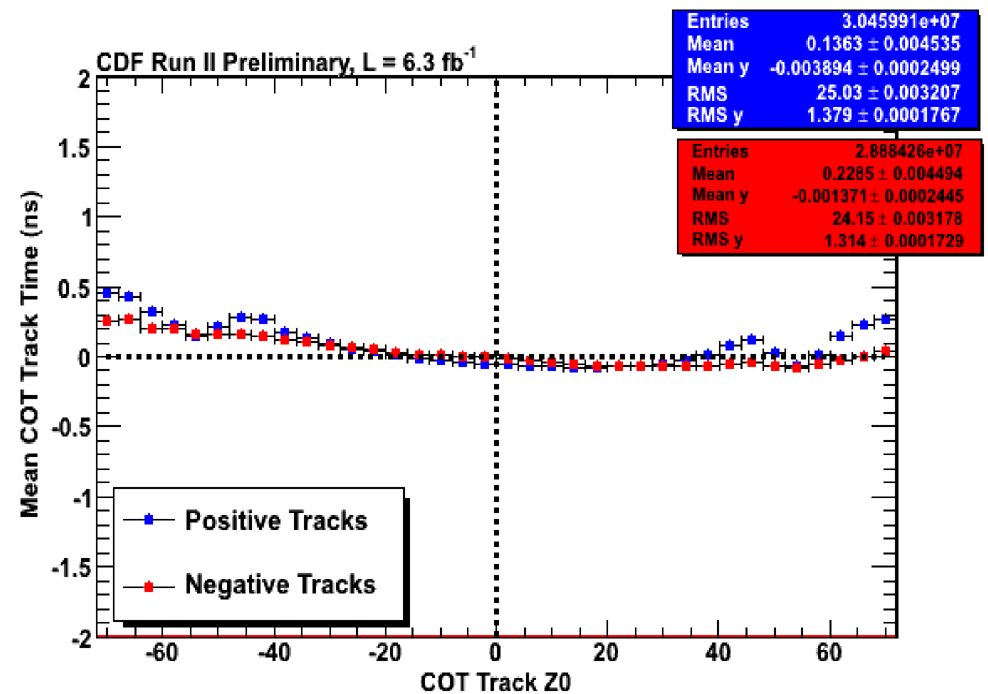
Before Calibrations





After Calibrations

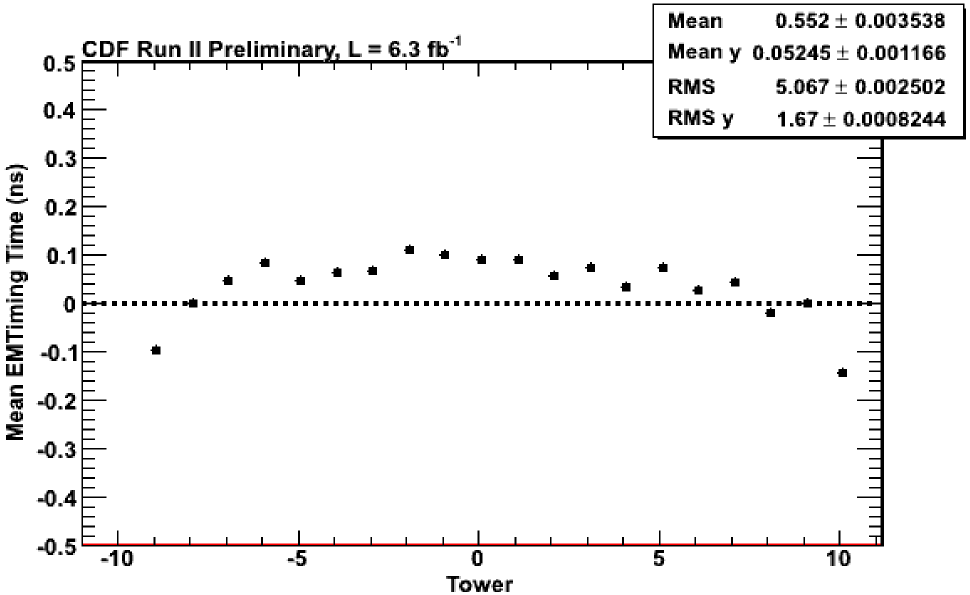


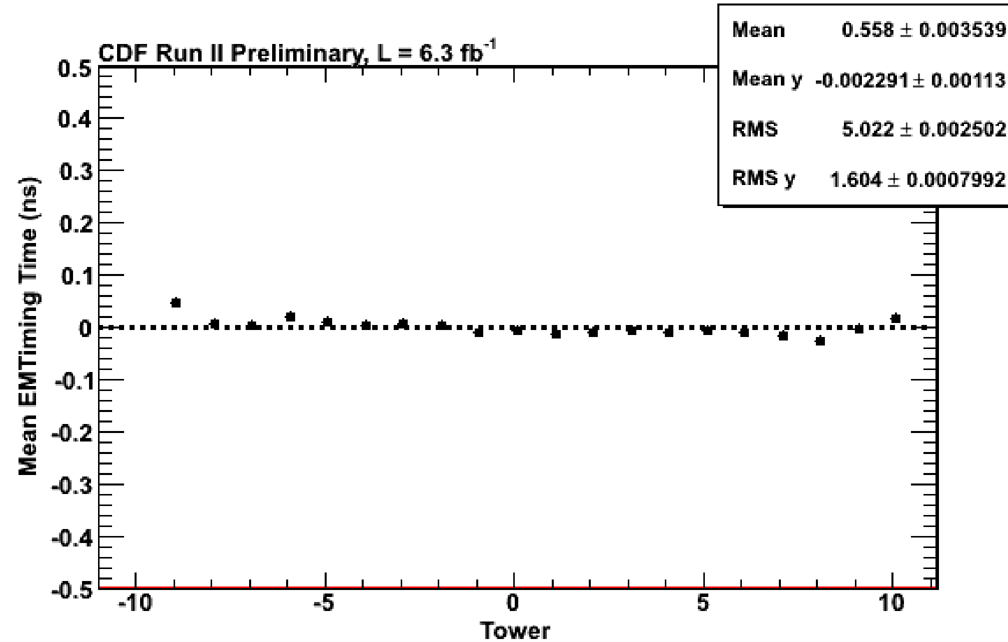


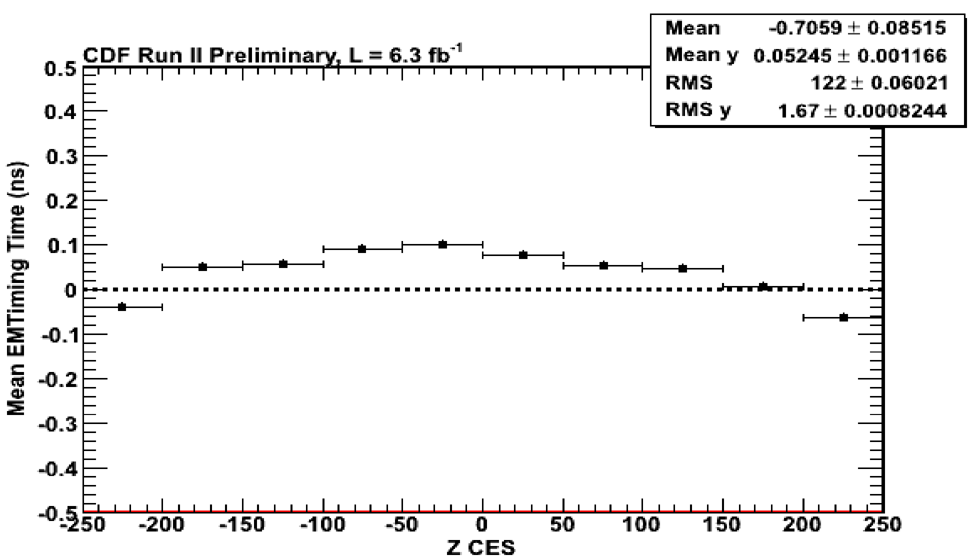
EMTiming Calibrations

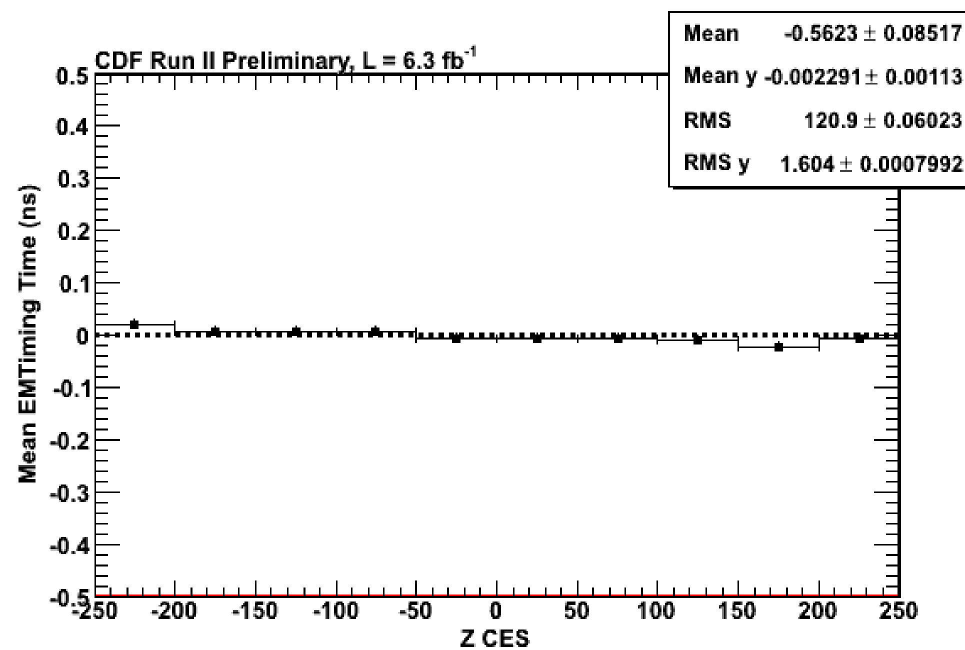
Before Calibrations

After Calibrations



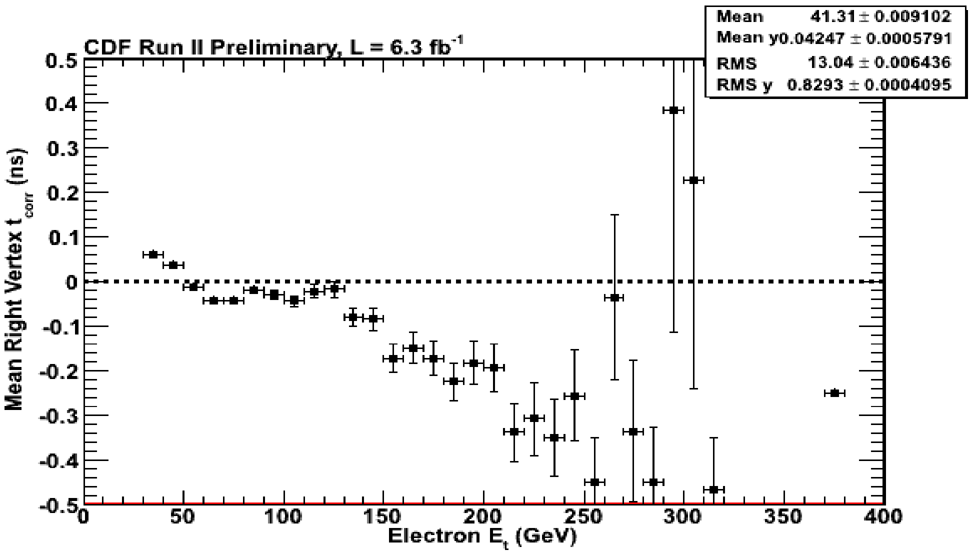


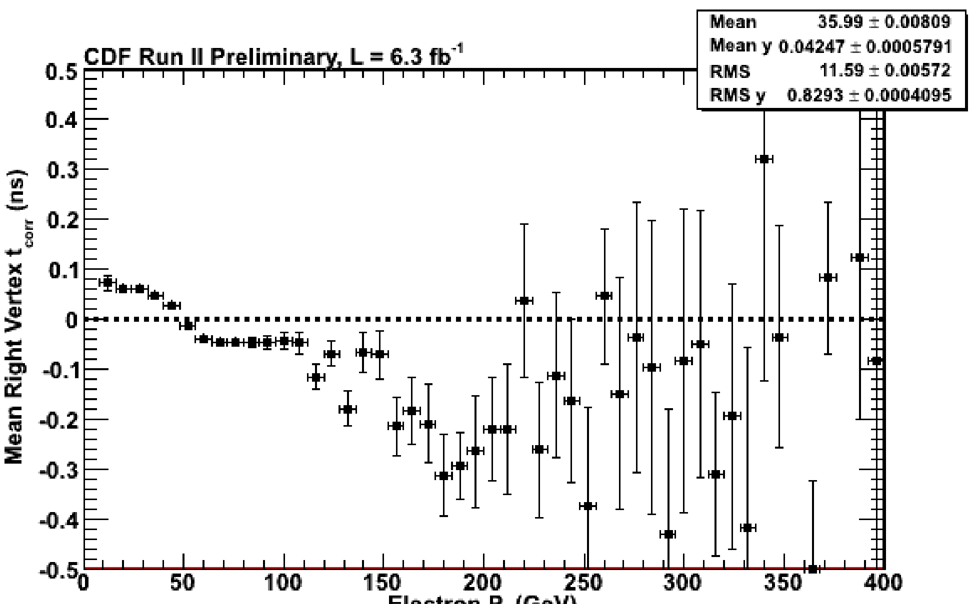




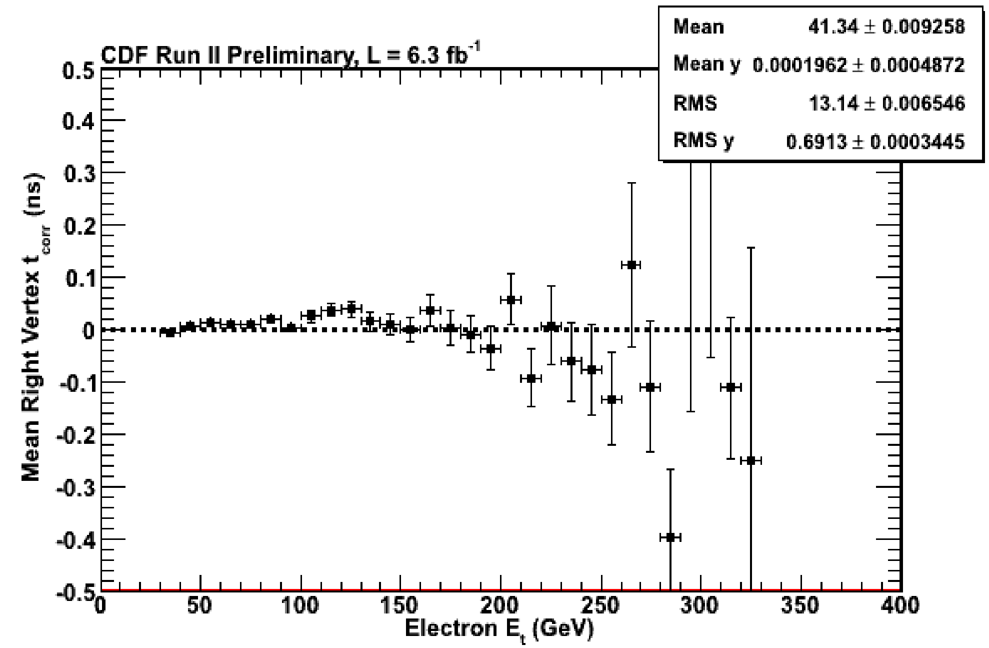
TCorr Calibrations

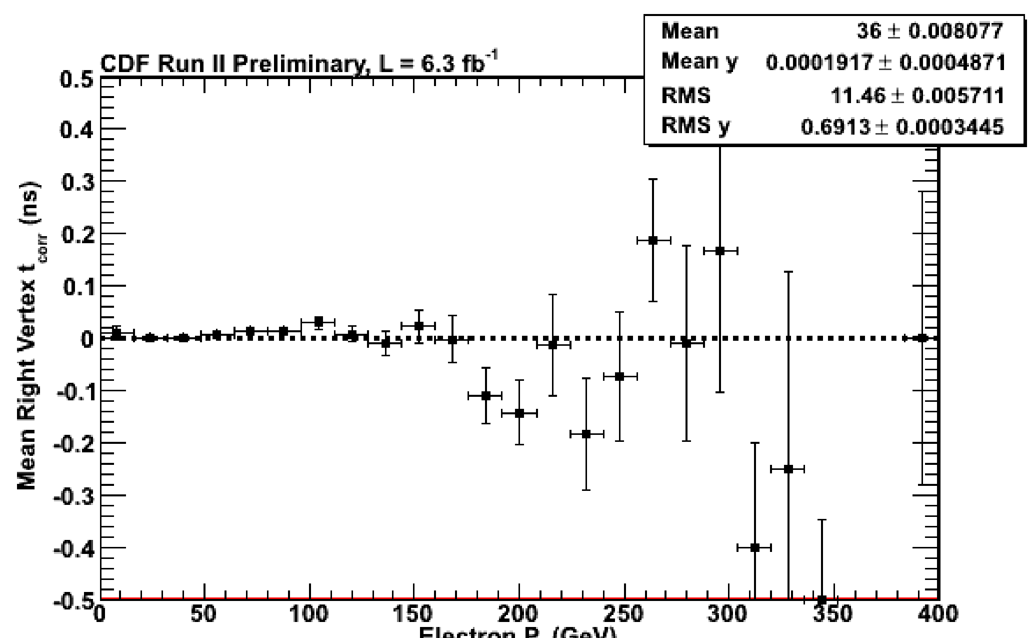
Before Calibrations





After Calibrations



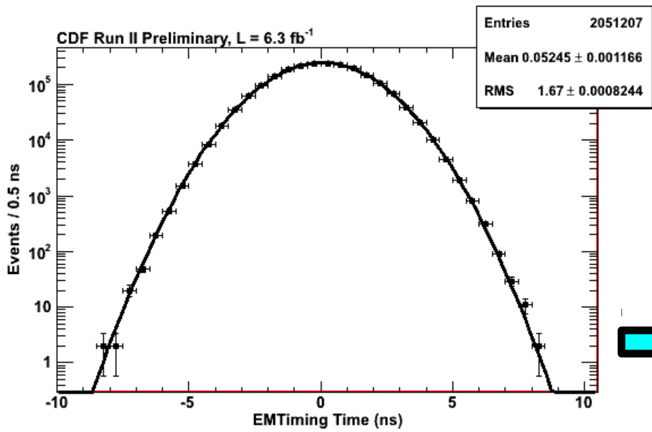


Data Sample

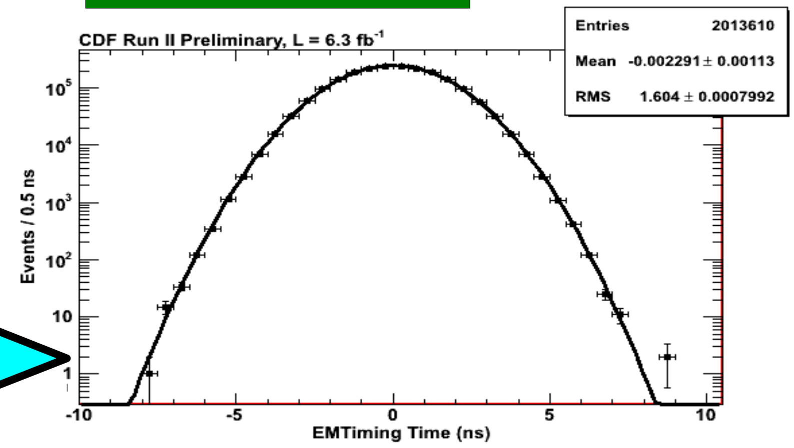
EMTiming Time

RESULTS OF CALIBRATIONS

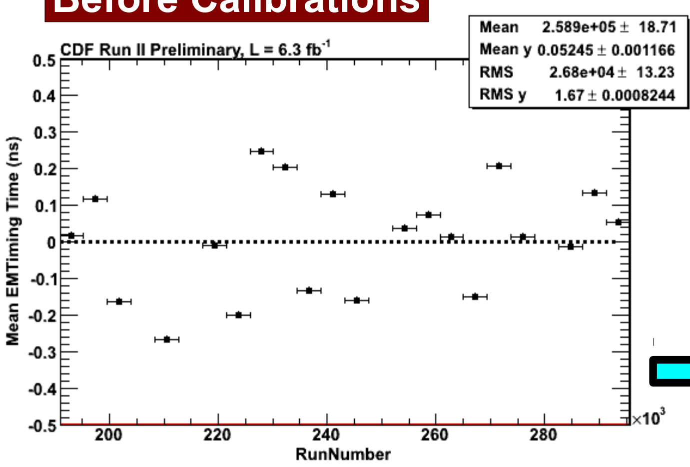
Before Calibrations



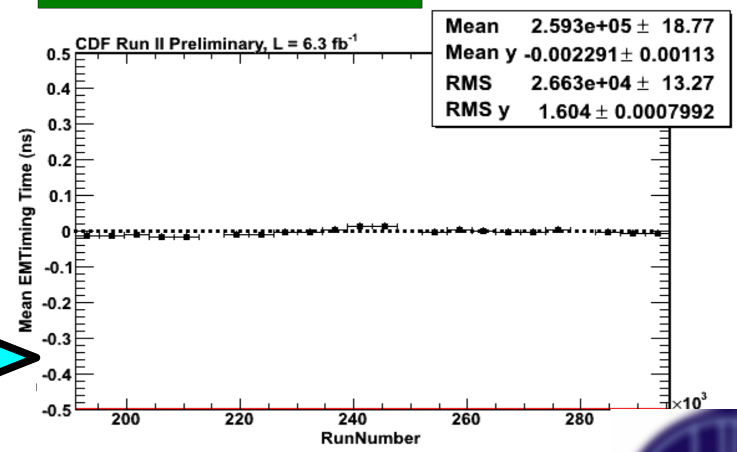
After Calibrations



Before Calibrations



After Calibrations



Timing distributions are Gaussian to many sigma as well as being centered and flat over 9 years of running!

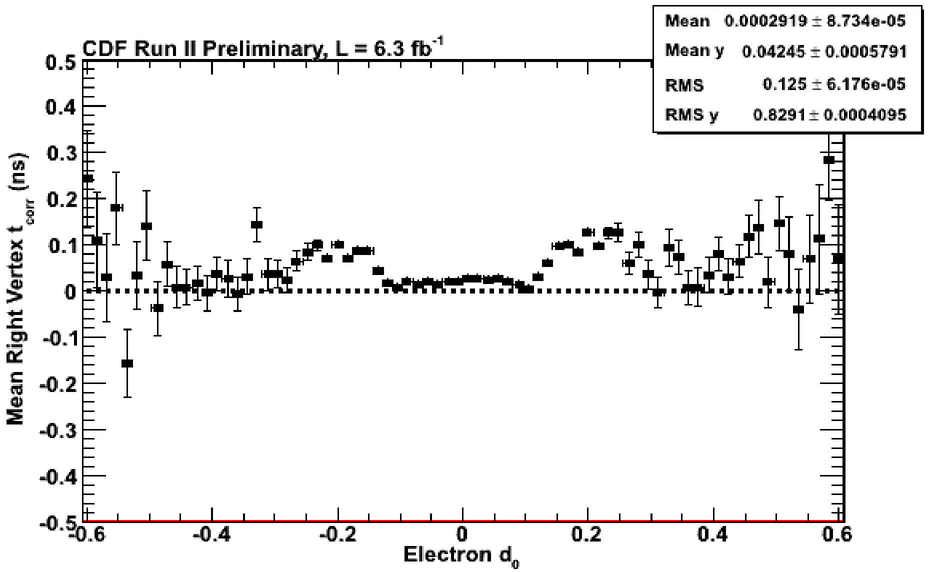
EMTiming is calibrated with variations < 100 picoseconds

Similar plots are made other variables which the timing strongly depended on.
Available in the back-ups

Timing Calibrations

TCorr Calibrations

Before Calibrations



After Calibrations