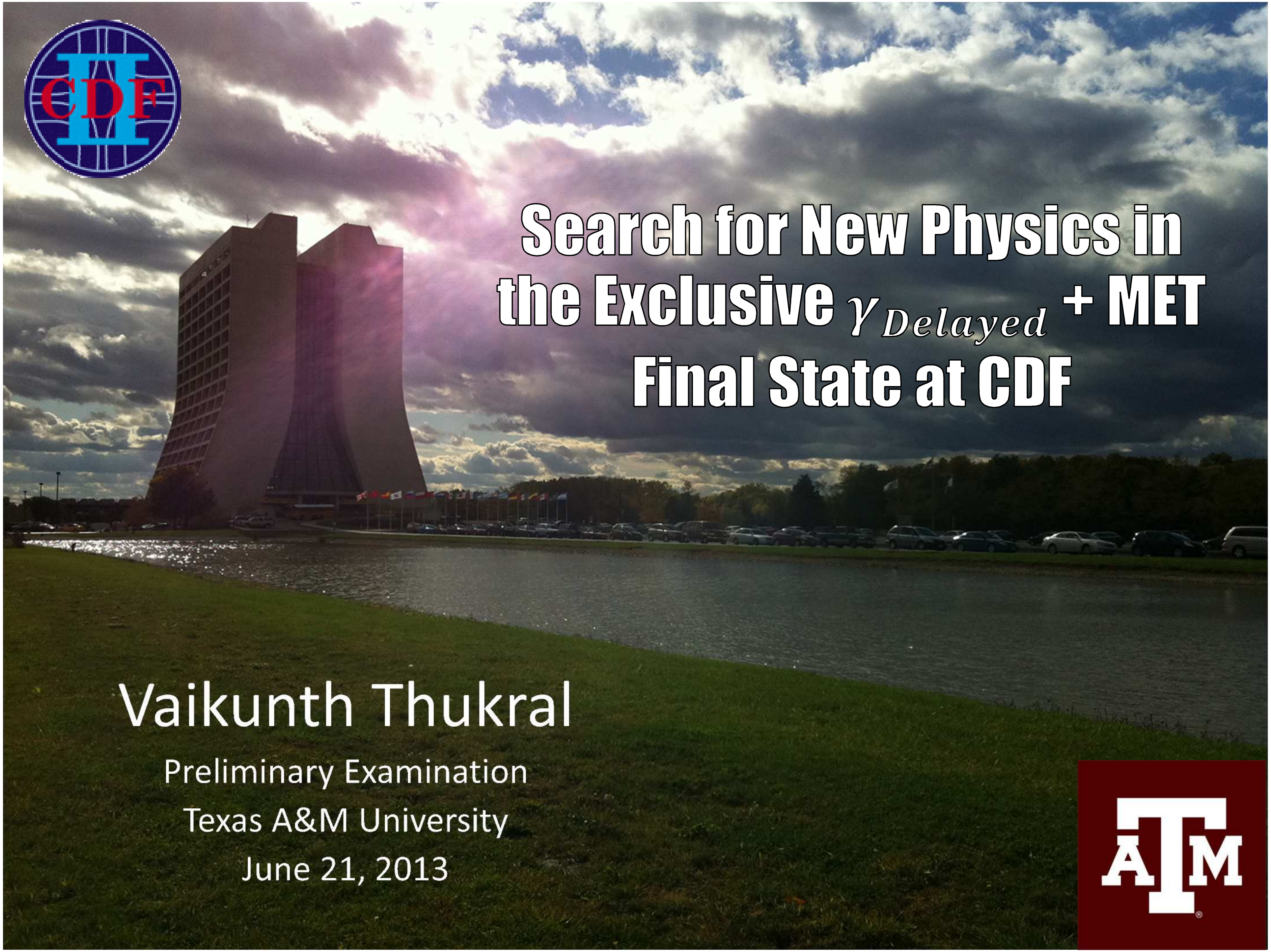

Search for New Physics in the Exclusive $\gamma_{Delayed}$ + MET Final State at CDF

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Preliminary Examination

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Outline

- Introduction
  - The Standard Model & Supersymmetry
  - Motivation for our Search
- Tools – Tevatron and the CDF Detector
- Overview of the Old Analysis & Results
- Improvements: In Progress and Future Plans
  - Improving Timing Calibrations
  - New Background Estimation
  - Future Plans with the Full Data (~9fb^{-1})
- Conclusions

Introduction – *The Standard Model*

Higgs Boson

2012 Discovery,
but is that it? Are there more particles than the Higgs, or even more Higgs'?

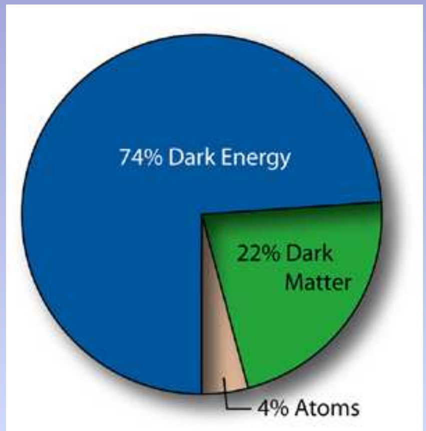
Gauge Bosons
(force carriers)

Quarks

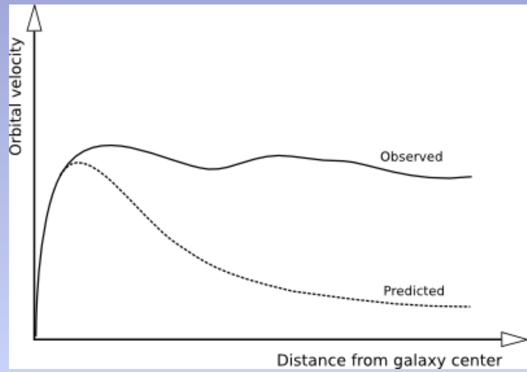
Fermions
(matter)

Leptons

The Standard Model – Not a complete description of observations



Example 1: Accelerating rate of expansion of universe → "Dark Energy"



Example 2: Rotational curves of galaxies suggest presence of more matter → "Dark Matter"

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}[\Lambda_{\mathrm{UV}}^2 + \ldots].$$

Example 3: "Hierarchy" problem – corrections to Higgs mass diverge. Adding terms to offset this can negate the divergence

All provide evidence that there may be more particles or new interactions

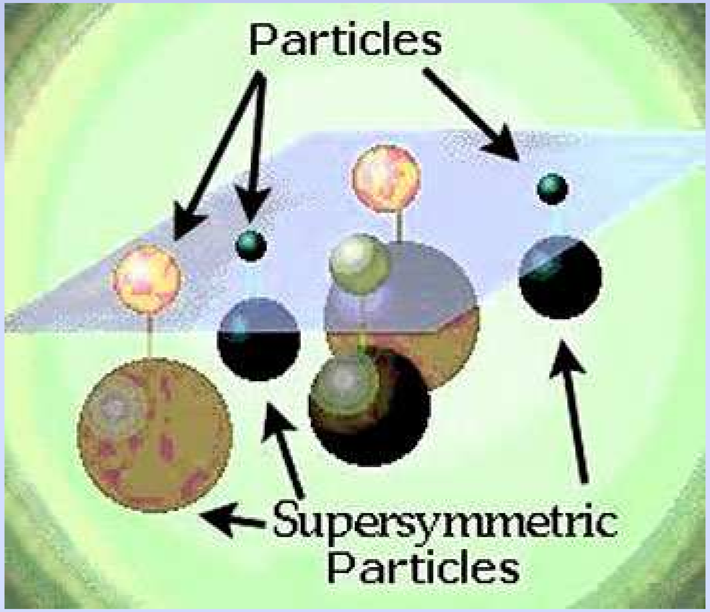
Introduction – *Supersymmetry*

- One solution to the hierarchy problem and the dark matter problem is known as Supersymmetry (SUSY)

In general, SUSY proposes a symmetry between bosons and fermions:

- SM bosons→SUSY fermions (sfermions)
- SM fermions→SUSY bosons (gauginos)

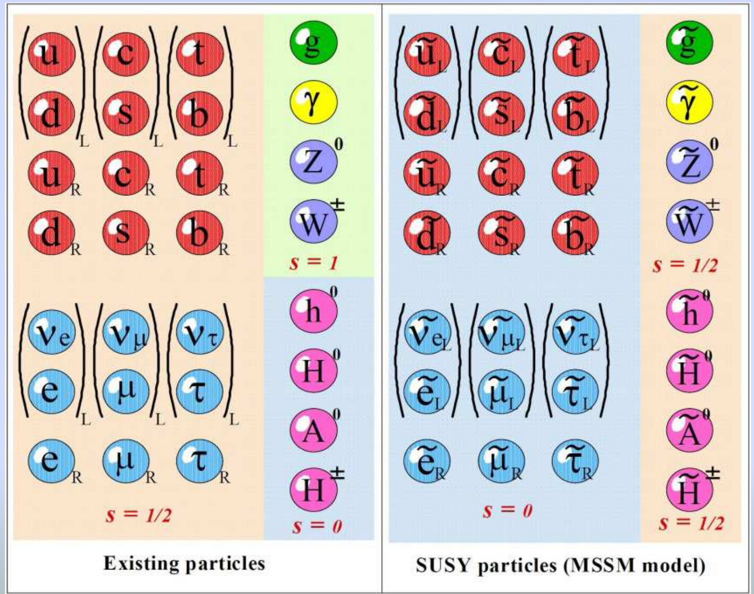
The presence of these new particles adds negative terms in the Higgs mass corrections



Supersymmetry – Cont.

- A particular SUSY model is Minimal Supersymmetric Standard Model (MSSM)
  - Roughly doubles the particle count
  - If there is R-Parity conservation ($P_R = (-1)^{2s+3B+L}$) then the lightest SUSY particle (LSP) is stable

- Requires multiple Standard Model Higgs'
- No sparticles have been observed, hence → M(SUSY) >> M(SM), or only interact weakly



Introduction – *Motivation*

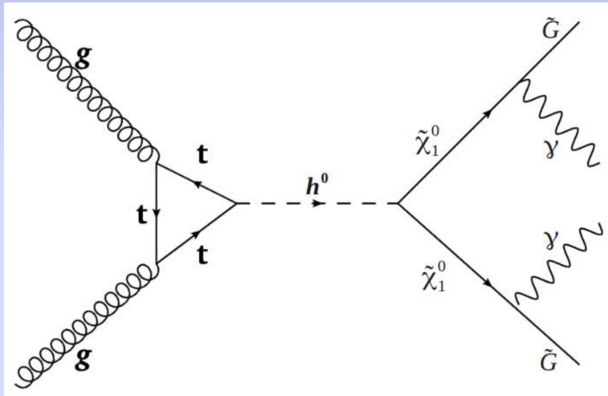
- If SUSY is correct and the sparticles have different mass than their SM counterparts, the symmetry is somehow broken!
  - One way to do that is via Gauge Mediated SUSY Breaking (GMSB) . Communicates symmetry breaking from higher energy scales into visible sector.

- Different GMSB scenarios
  - Often, the Gravitino is the Lightest SUSY particle(LSP), and Neutralino the Next to Lightest (NLSP)
  - GMSB allows Neutralino lifetimes of the order of few ns
  - Sparticle masses determine production at colliders

GMSB scenarios

Model	$\tau_{\tilde{\chi}_1^0} \lesssim 1\text{ns}$	$1 < \tau_{\tilde{\chi}_1^0} < 10$ ns
SPS-8 GMSB Production	$\gamma\gamma + \not{E}_T + H_T$	$\gamma_{\text{delayed}} + \not{E}_T +$ jets
Higgs-Type Production	Exclusive $\gamma\gamma + \not{E}_T$	Exclusive $\gamma_{\text{delayed}} + \not{E}_T$

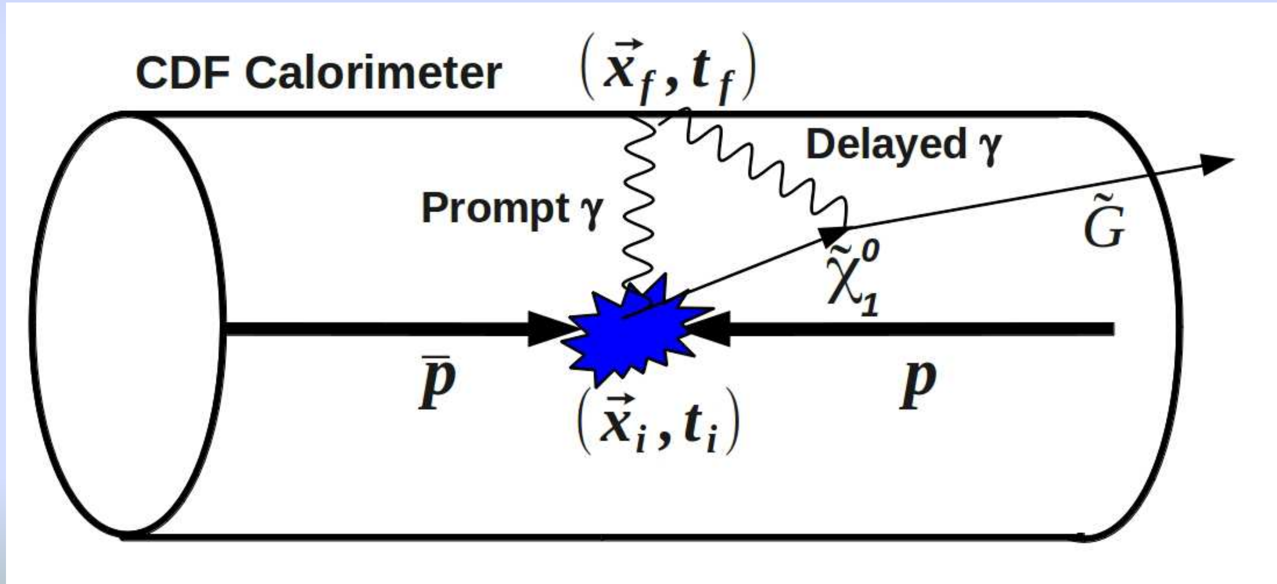
- Lots of searches at LEP, Tevatron and LHC, no evidence for sparticles
- In an allowed scenario, the Neutralino and Gravitino are the only sparticles that are kinematically accessible at collider experiments
- If true, can have large production of events through neutral scalars (like those in MSSM) in a collider experiment
- Possible to produce 2 photons and 2 gravitinos that leave the detector to give missing energy ($\not{E}_T$)



Could see 2 photons, or the neutralinos could have a long-lifetime and we only have one decay inside the detector→ exclusive ($\gamma + \not{E}_T$)

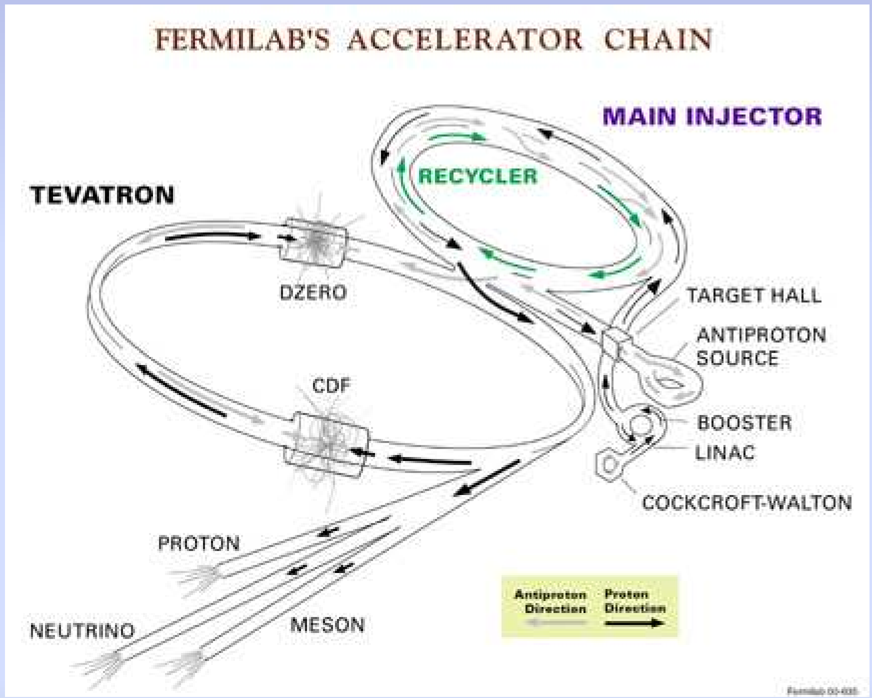
Motivation – Cont.

- Powerful way to look for long-lived heavy particles (like neutralinos) in a collider experiment is to look for photons with a delayed time of arrival in the Timing system (PRD 70 (2004) 114032)



Tools – *Tevatron and CDF*

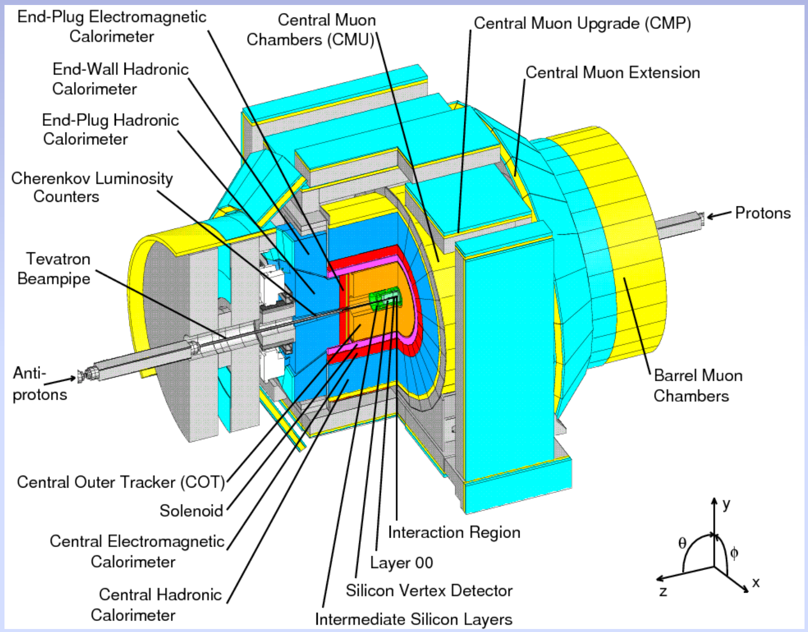
- The Tevatron at Fermilab ran from 1983-2011



- Proton-Antiproton beam
- Center of Mass Energy of collisions = 1.96 TeV since ca. 2004
- Collected ~10fb^{-1} of data (plan on using ~9fb^{-1})
- 36x36 bunch collisions at 396ns intervals (ca. 2004)
- ~10 million collisions/sec

Tools – *CDF (Tracking and Timing)*

- CDF is a multipurpose detector at one of the collision points at the Tevatron



- Tracking Chamber

- Open cell drift chamber design with 96 layers

- Records the path of charged particles

- Calorimeter Timing System

- Uses readout of EM Calorimeter (EMTiming)

- Converts to particle arrival time with a resolution of ~0.6ns

Tools – *CDF*

Turning on the CDF, one last time – Sept 30, 2011

Overview of the Search

- The $(\gamma_{delayed} + \not{E}_T)$ final state can be mimicked by two types of background event sources

Standard Model Collision Sources
$W \to e\nu \to \gamma_{\rm fake} + \not{E}_T$
$\gamma + {\rm jet} \to \gamma + {\rm jet}_{\rm lost} \to \gamma + \not{E}_{T\,{\rm fake}}$
$W\gamma \to l\nu\gamma \to \gamma + l_{\rm lost} + \not{E}_T$
$W \to \mu\nu \to \gamma_{\rm fake} + \not{E}_T$
$W \to \tau\nu \to \gamma_{\rm fake} + \not{E}_T$
$Z\gamma \to \nu\nu\gamma \to \gamma + \not{E}_T$

These come from interactions at the primary bunch collision

Non-Collision Sources
Cosmics
Beam Halo
Satellite Bunches

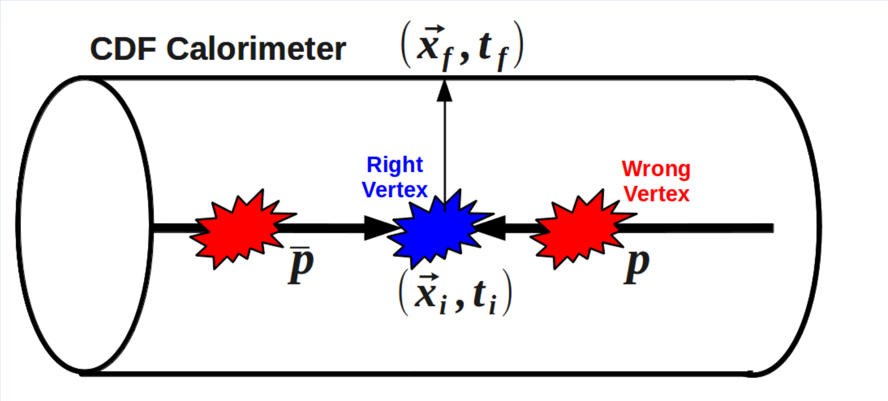
These come from external interactions, away from the primary bunch collision (Dominantly cosmics)

Backgrounds

We define the corrected time:

$$t_{corr} = t_{measured} - t_{expected}$$

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



In a perfect detector, $t_{corr} = 0$ for prompt photons (by definition)

Separating new Physics from SM backgrounds:

Each event can have multiple collisions at the same time

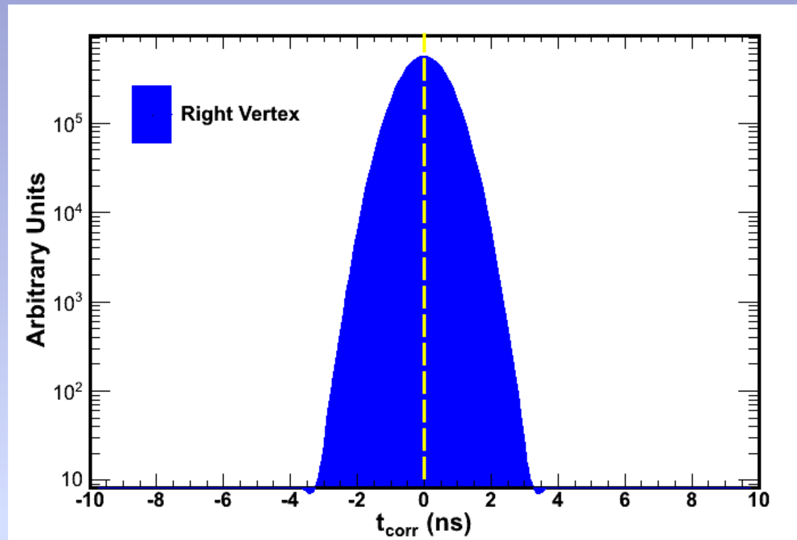
For events where we picked the correct vertex from which the photon came, we call it a **"Right Vertex"** event (RV).

For events where there we incorrectly pick the vertex, we call it a **"Wrong Vertex"** event (WV).

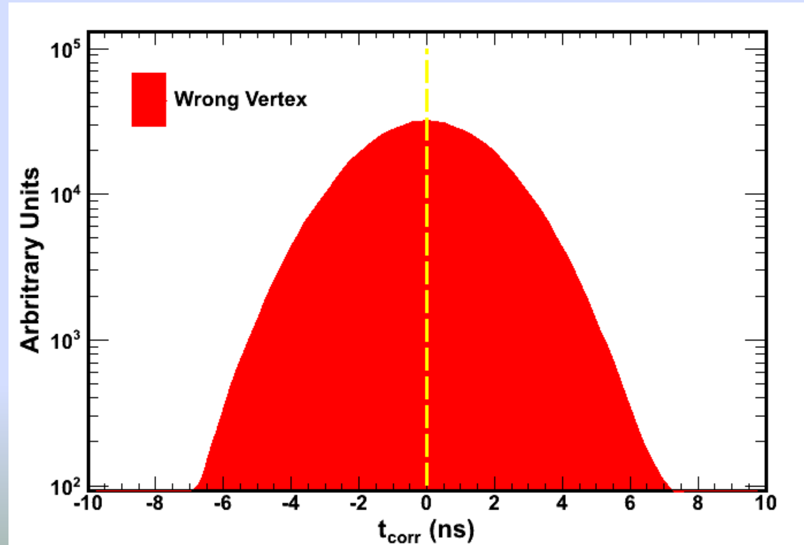
We also define a case where no vertex was picked as a "No Vertex" (NV) event. (This will be important)

Backgrounds – *Cont.*

- The "Right Vertex" timing distribution for prompt photons is a well measured Gaussian of RMS ~0.65ns, and reflects the timing resolution

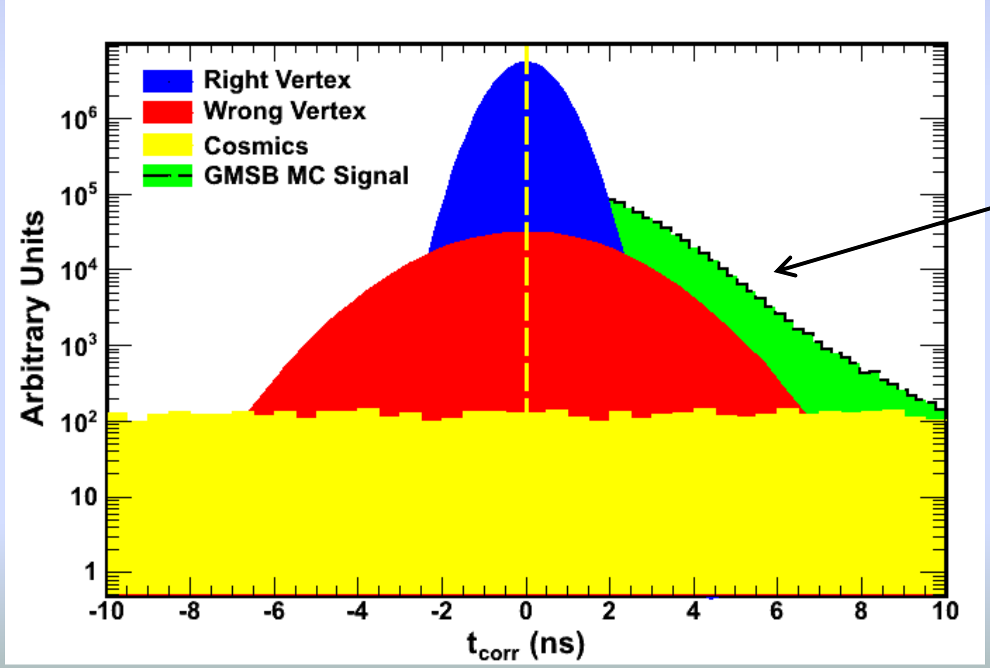


- The "Wrong Vertex" timing distribution is well described by a Gaussian of resolution ~2.0ns



Backgrounds – *Cont.*

- There are also cosmic rays that strike the detector at a steady rate, which is estimated by a flat distribution. With these, we can now put together the final timing distribution we expect from data



The green distribution is what it would look like if there was an excess in the expected number of events from total background

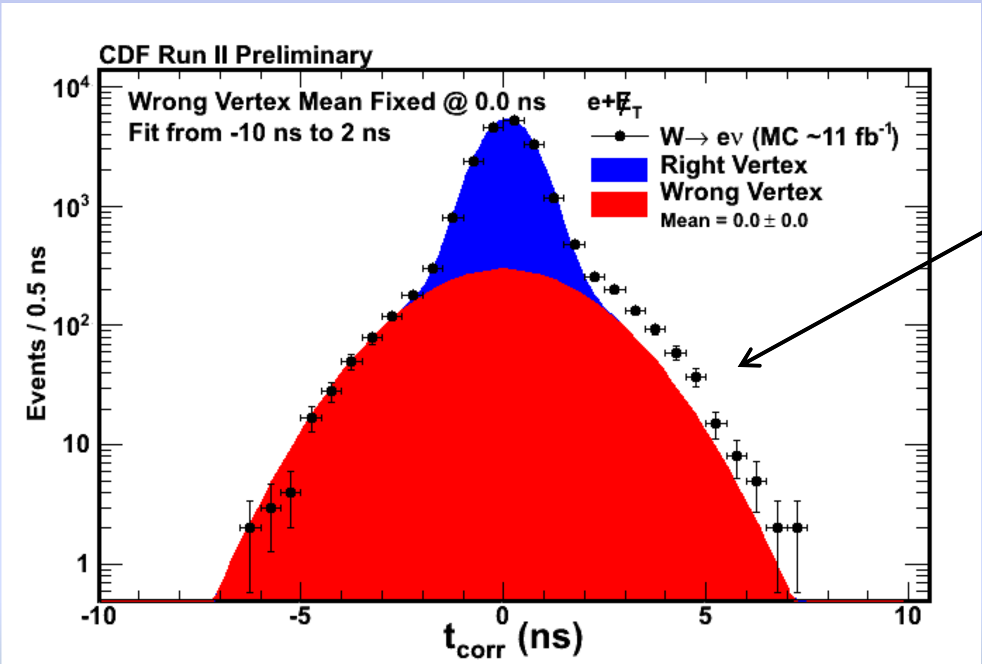
Look for an excess around this green region. Typically, from 2ns to 7ns

Overview of the History & Future of this Analysis

- 2004 (This is what we just finished discussing)
  - Phenomenology developed (PRD 70, 114032)
  - Timing System installed (NIM A 565)
- 2008
  - Simple first analysis of data ($4.8fb^{-1}$)
- 2012
  - Sophisticated analysis with better understanding of backgrounds ($6.3fb^{-1}$)
- Now and Future
  - Improved calibrations, background estimation, and full dataset ($\sim 9fb^{-1}$)

Overview – *2008*

- The very first iteration of this analysis assumed that the mean of the WV distribution was zero



This assumption produced a big "excess" in the (2, 7)ns timing region (over 3σ), and hence, strongly suggested further investigation into the methodology

This turned out to be an incorrect assumption and a better background estimation needed to be formulated

Overview – *2012*

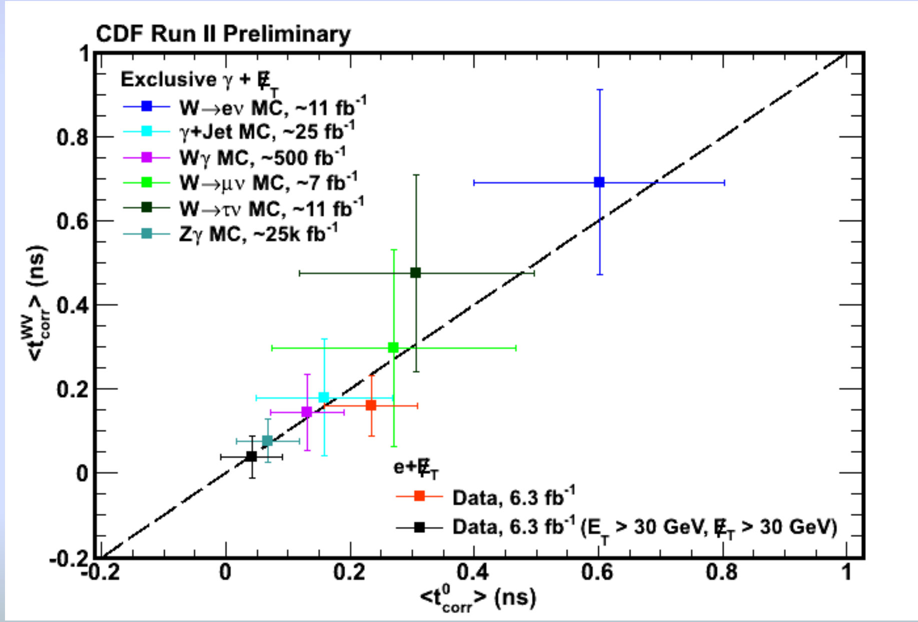
- SM Wrong Vertex backgrounds can have large mean shifts (biased positively) due to multiple effects
  - E_T threshold effect, Fake Photons & Lost Jets

- New analysis techniques and requirements reduce most pathological cases of biasing the value of the Wrong Vertex mean.

- Created new background estimation techniques to estimate the mean of the WV timing distribution

2012 Overview – *Cont.*

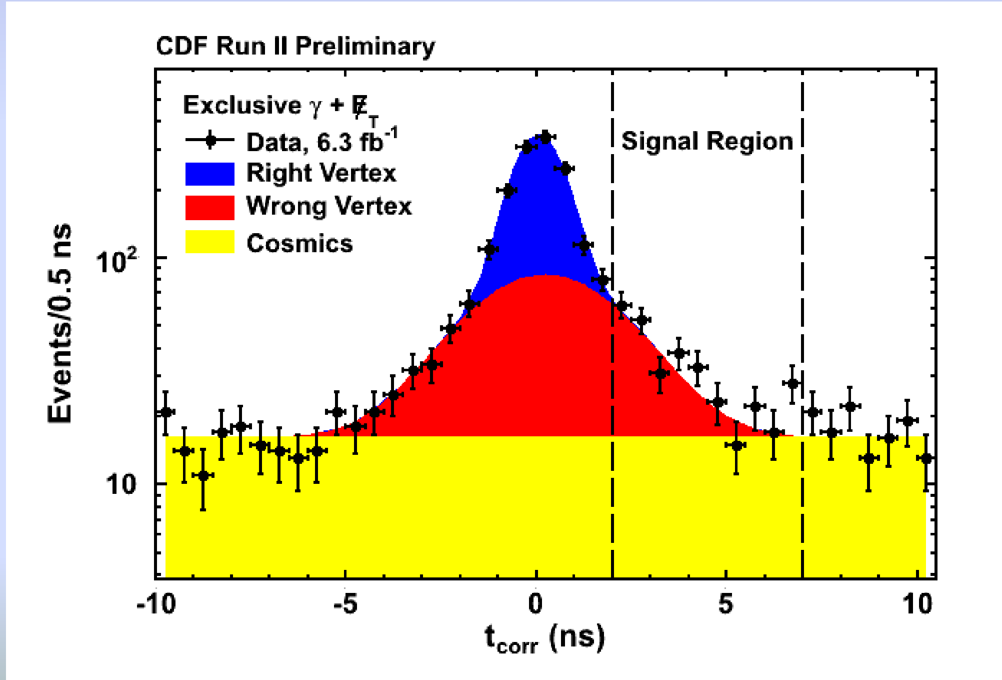
- Double Gaussian approximation with fixed parameters for the Right Vertex distribution, and floating mean for the Wrong Vertex distribution
  - Use No Vertex sample to estimate Wrong Vertex mean



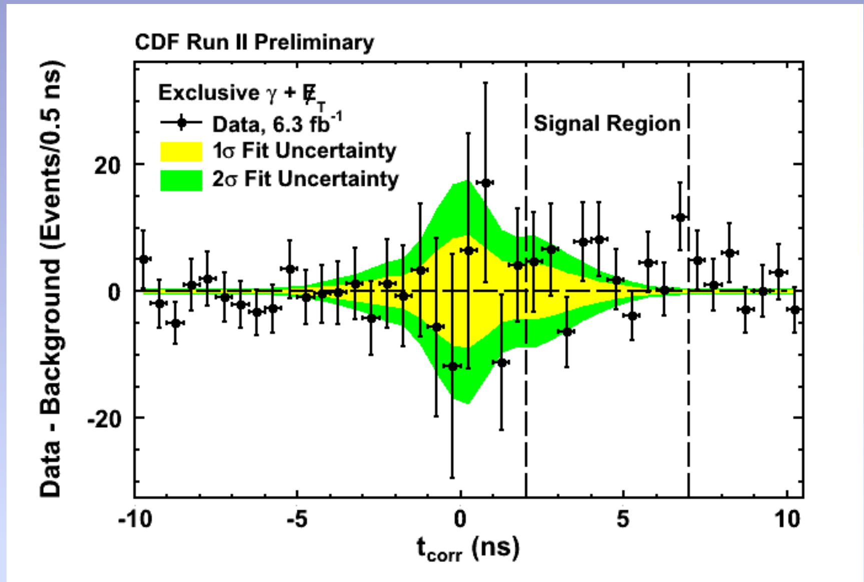
This method shows agreement for many data and MC samples

2012 Results

- Used the data to estimate the WV mean, and using a binned log likelihood fit to extrapolate in the (2, 7)ns region we expect 286±24 events



2012 Results – *Cont.*



- Observed events of 322 give a 1.2σ excess*
- This result is currently going through collaboration review
- Will be submitted to PRD-RC
  - *Note that the number of events seems to be above backgrounds for at all times for the signal region. A clue?

Overview - *Now*

- So, where do we go from here?
  - There is still room for improvement → 3 Things on the list

1. Improve timing calibrations to reduce potential tails
2. Better background estimation
3. Add more data

1. New Timing Calibrations

- Tracks
  - Calibrate on timing measurements for tracks left by charged particles
  - Usually 10's-100's of tracks per event
  - Used to reconstruct vertices → Calibrating tracks leads to better measured vertices

- Use events mimicking the signal. $W \rightarrow e\nu$ ($e + \not{E}_T$) data sample with removed electron track

1. New Timing Calibrations – *Cont.*

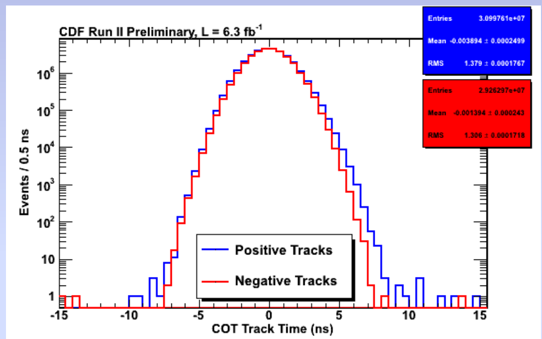
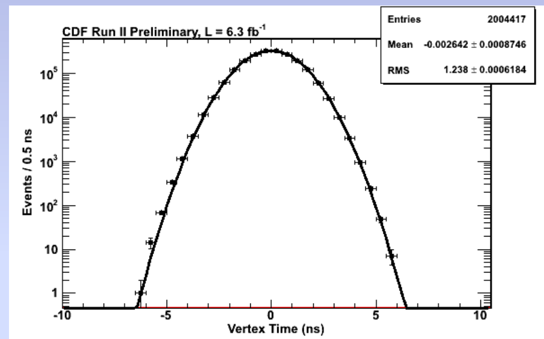
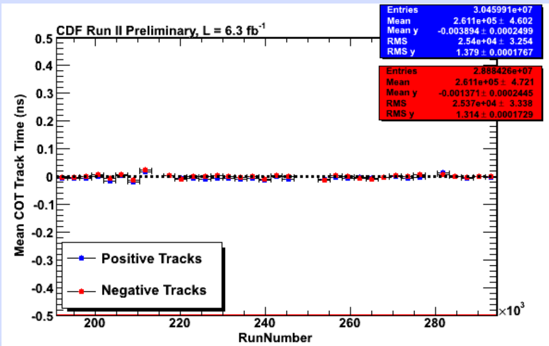
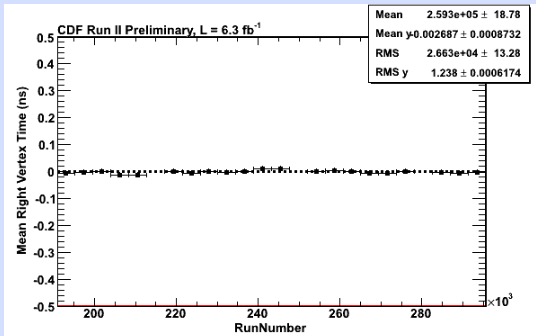
- But why calibrate tracks?
  - Needed for accurate t_{corr} calculation

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

  - Initial time (t_i) is determined by time of reconstructed vertex
  - Vertices are reconstructed using tracks
  - Calibrated tracks lead to well measured vertices

1. New Timing Calibrations – *Cont.*

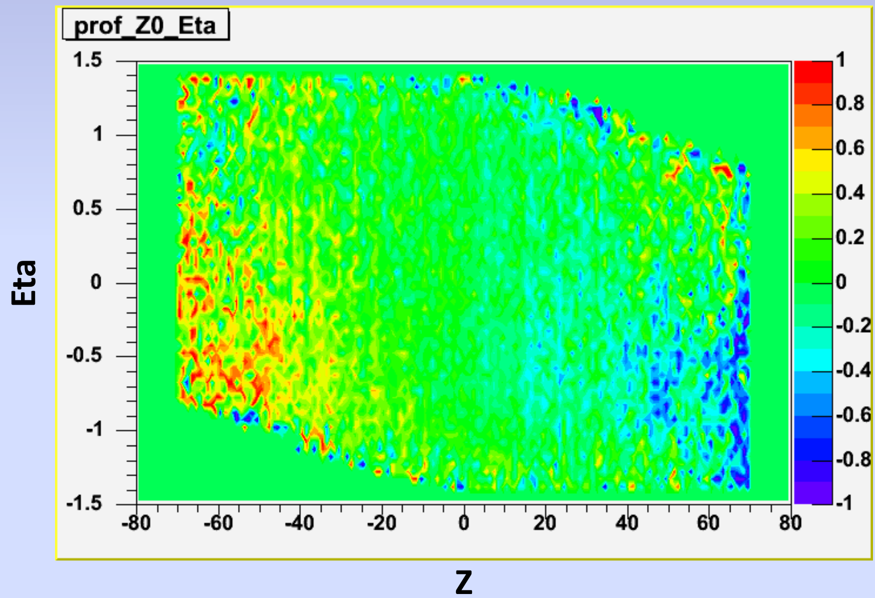
- In previous calibrations:

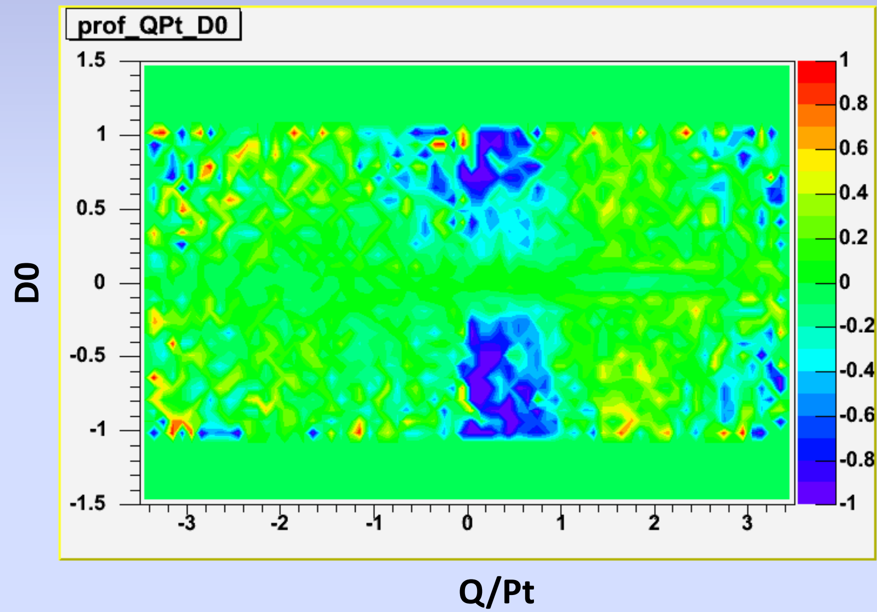
	Tracks	Vertices
Individual Times		
Mean Time		

Well centered about zero, Gaussian, and little run-by-run variations

1. New Timing Calibrations – *Cont.*

- However, previous calibrations left some correlation in the reconstructed tracks that we should remove





Plots showing the mean track time against 2 calibration parameters

"Heat" (blueness and redness) indicate some variation in time for tracks with certain parameters

Observed in most combinations of the 6 calibration parameters

1. New Timing Calibrations – *Cont.*

- Conclusion → This procedure sets the average track times to zero, but leaves room to calibrate out the correlations between the calibration parameters
- Better sensitivity requires better calibrations

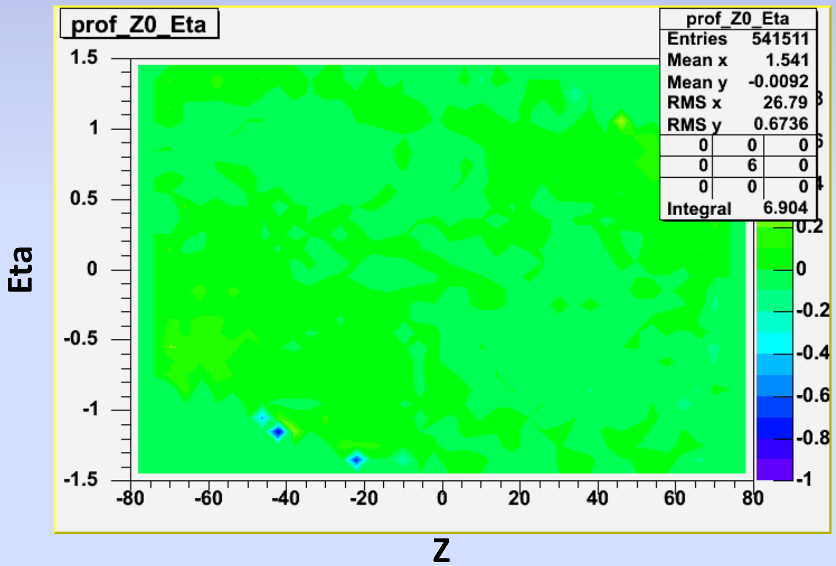
Old Procedure	New Procedure
→ Calibrate Track Times → Calibrate Vertices → Calibrate EMTiming Time	→ Coarse Calibration of Track Times → Calibrate time between tracks and associated vertices (Delta T) → Corrections to set mean Collision Time to 0 at Z=0 → Calibrate EMTiming Time

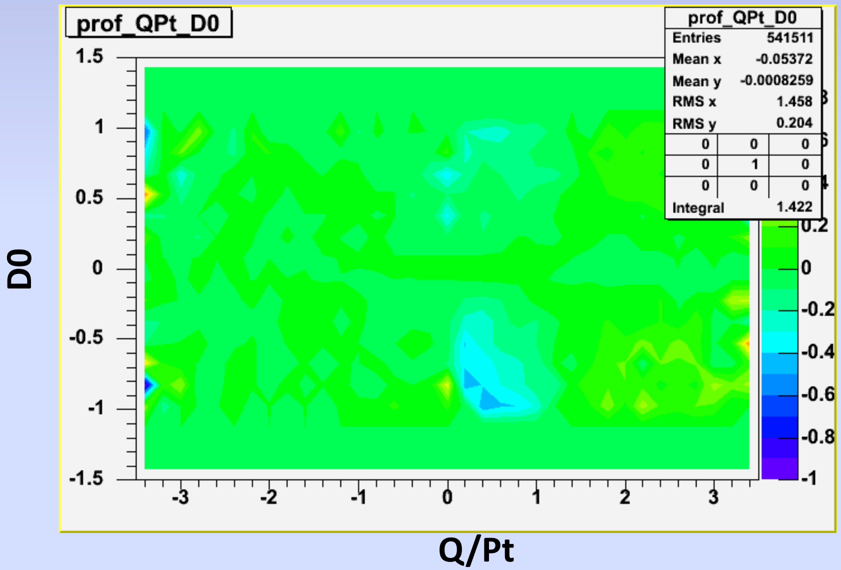
1. New Timing Calibrations – *Cont.*

- Calibrate Track Times relative to the average of all collision times (t=0)
  - Exactly the same as before, use as 0^{th} order correction
- Calibrate track times relative to their best-guess collision time event by event
  - Associate tracks with a vertex (collection of tracks) and use this as the best estimate of what the track time should be.
  - By calibrating w.r.t vertex time instead of "zeroing," potentially no need to calibrate vertices anymore
- Corrections from Z offset
  - Take into account that mean collision time is not always zero but varies depending on where the collision occurs in the detector.

1. New Timing Calibrations – *Delta T*

- Calibration parameter correlations for Delta T corrections show improvement





More motivation that DeltaT corrections will help improve sensitivity

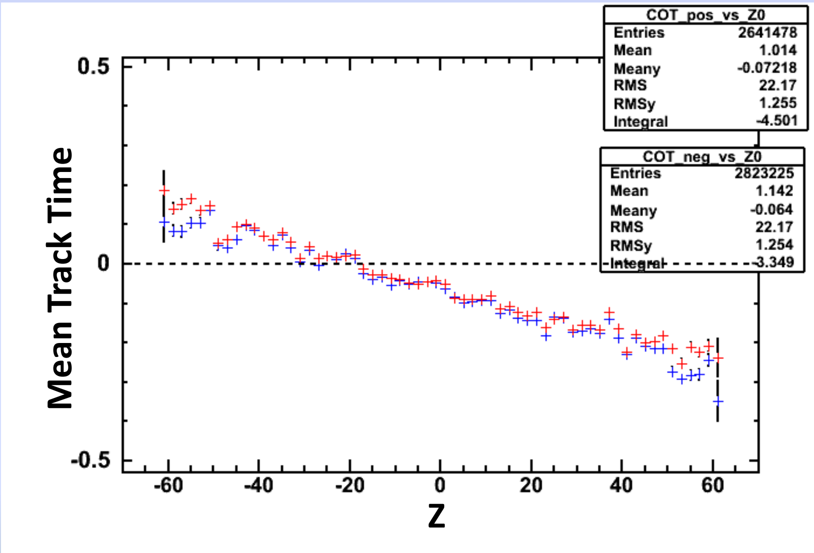
1. New Timing Calibrations – *Z "offset"*

- Proton and Anti-Proton bunches have different widths
  - Leads to a correlation between the mean track time and the collision Z position.
  - (More information in CDFNote 9812)
  - Take into account this correlation→ Set T=0 at Z=0

This slope is seen in both track times and vertex times (vertices follow tracks nearly identically)

Measure offset run-by-run, all runs may not have same slope and offset

→ Processing as we speak!

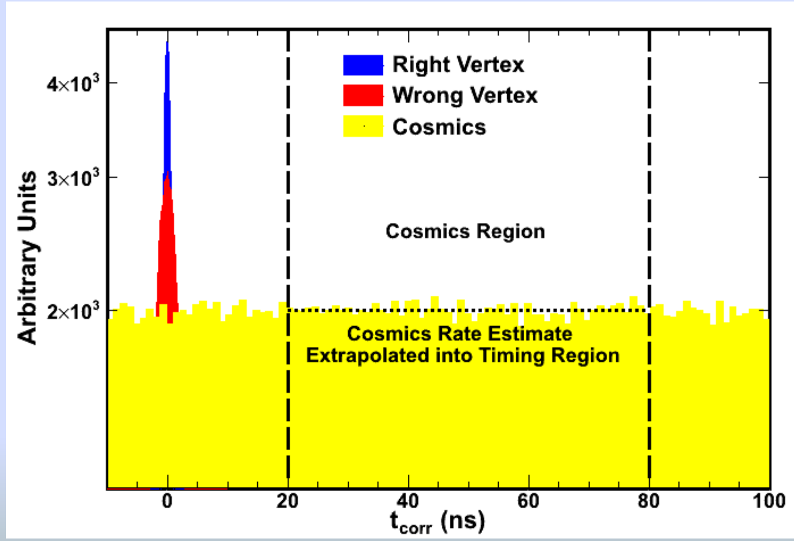


N.B: Plot is before this last correction

2. New Background Estimation

- Cosmics rate in the (2 ,7)ns region estimation previously done by assuming they have a flat rate, measuring their rate far away from the collision time and then extrapolating into the signal region

- Assumed flat rate of cosmics since they arrive flat in time

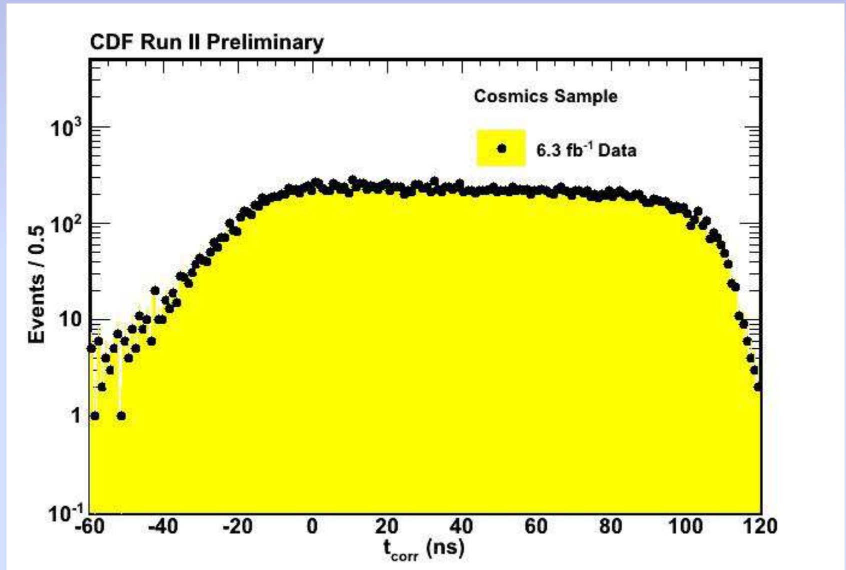


2. New Background Estimation – *Cont.*

- Measured cosmics rate not flat as a function of time

Not all cosmics will pass the requirement, lose some due to detector measurement biases.

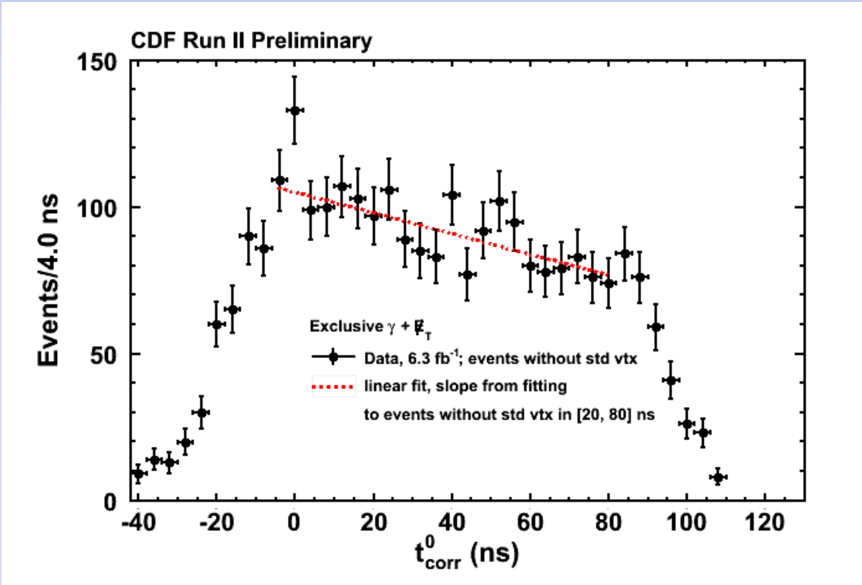
Previous measurements assumed that the losses only occured at the edges.



- With more statistics, we see a small slope in the region around the mean collision time

2. New Background Estimation – *Cont.*

- With the full dataset, we can measure the shape better from [20,80] ns instead of the previous average rate estimate



- Non-zero slope means more background events enter the (2, 7) ns region than previous estimates

- Recalculate new estimate of cosmic events in the (2, 7) ns region

N.B: Sample with $\Sigma P_t = 0$ and no vertex at all was used. Reduces to mostly cosmics

2. New Background Estimation – *Cont.*

- Refitting the 2012 data we find a new prediction of 187$\pm$8 cosmic events, compared to 159$\pm$4
- Using this new cosmics estimate gives a new result:

Quantity (*Events*)	Prediction (*Events*)	
Number of Events from Cosmic Rays expected in the Signal Region	159 $\pm$ 4	→ 187$\pm$8
Number of Events from Wrong Vertex expected in the Signal Region	126 $\pm$ 24	→ 122$\pm$24
Total Number of Events Observed in the Signal Region	322	New Expected Total = 310$\pm$24

- This now gets rid of the entire excess!
- New significance is 0.4σ

3. Future Plans with Full Data

- Last result used 6.3fb^{-1} of data
- Tevatron delivered about ~10fb^{-1}
- For our analysis, use anywhere between 8.8fb^{-1} to 9.6fb^{-1} (some runs may be removed)
- Compile final answer with full dataset and possibly set limits on new physics production cross section

    (If time)

Conclusion

- Plan is to update this important analysis using full data:
  – Performing better timing calibrations that can improve the sensitivity
  – Use new background estimation with slope fit
- Tools in place to cross the T’s and dot the I’s on the last iteration of this analysis
- Nominally in position to finish December 2014

Backups

Selection Cuts

Quantity	Selection Cut
EM cluster E_T	1 cluster with $E_T > 30$ GeV
Fiducial	$\|X_{\rm CES}\| < 21$ cm and $9 < \|Z_{\rm CES}\| < 230$ cm
Hadronic fraction	$E_{\rm HAD}/E_{\rm EM} < 0.125$ HadE $> -0.3 + 0.008 \cdot E_{\rm T}^{0}$ [13]*
Energy isolation	$E^{\rm iso}_{\rm cone\ 0.4} < 2.0 + 0.02 \cdot (E_T - 20.0)$ CES E/E > 0.2 [13]*
1st CES cluster energy ($E_{\rm CES}$ cut)	$E^{\rm 1st}_{\rm strip} + E^{\rm 1st}_{\rm wire} > 10$ GeV
2nd CES cluster energy	The bigger quantity of the CES 2nd cluster strip or wire energies required to be smaller than one of the two corresponding sliding cuts: (1) $E^{\rm 2nd}_{\rm CES} < 0.14 E_T$ (2) $E^{\rm 2nd}_{\rm CES} < 2.4 + 0.01 \cdot E_T$
PMT spike rejection*	$A_{\rm PMT} = \frac{\|E_{\rm PMT1} - E_{\rm PMT2}\|}{E_{\rm PMT1} + E_{\rm PMT2}} < 0.6$
Track Multiplicity	Number of N3D tracks either 0 or 1
Track P_T	If $N3D = 1 \rightarrow P_T < 1.0 + 0.005 \cdot E_T$

TABLE IV: The good photon selection cuts. Note that these are standard photon ID cuts for high E_T photons [17], with the following exceptions (marked with a * on the above table) described in CDF note 9625 [18]: the standard $\chi^2_{\rm CES}$ cut is removed, and the PMT asymmetry cut to reject PMT spikes, and two new cuts on Hadronic E and CES E/E to reject cosmics.

Overview – *2012*

WV Mean Shift Effects

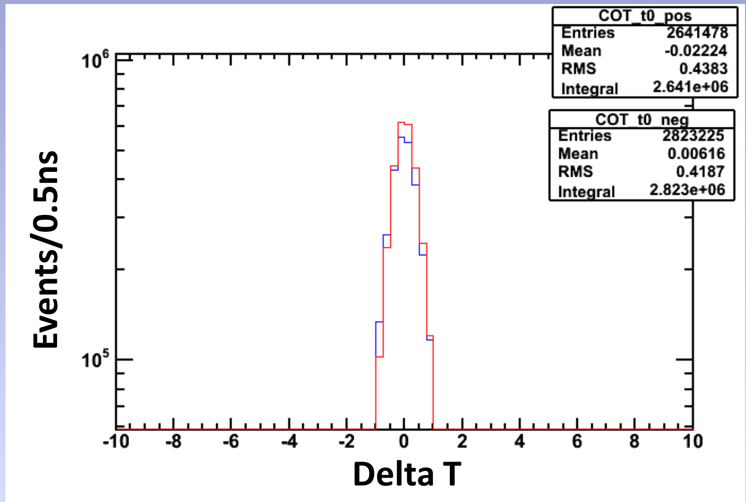
- E_T threshold effect – Events around the E_T cut of 45 GeV get simultaneously promoted into and demoted out of the event sample due to t_{corr} being calculated incorrectly by the choice of a Wrong Vertex
  - Mitigated by measuring E_T from the center of the detector instead of where the picked vertex is along the beam.
- Fake Photons – Events like $W \rightarrow e\nu$ that fake photons after detector material interaction (Brehmstrahlung) also cause shifts in the mean as they traverse through
  - This effect can be reduced by rejecting events that have a track within a $\Delta R < 5$ of the reconstructed photon

2012 Overview – *Cont.*

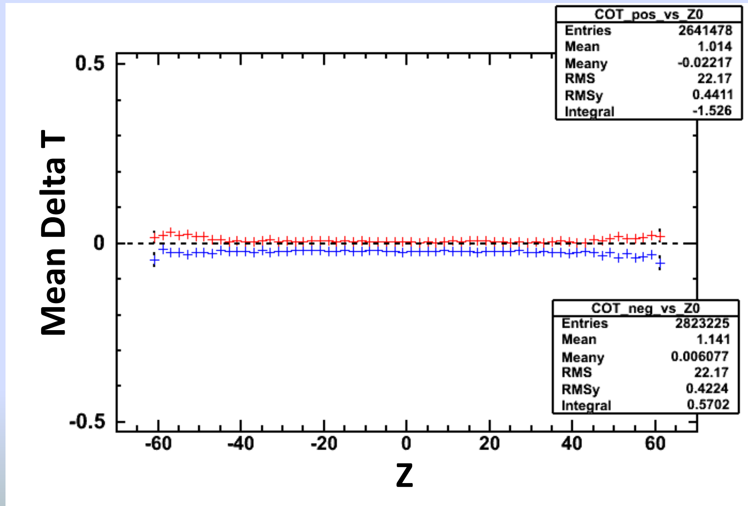
- Lost Jets – For QCD γj events, vertices tend towards larger |Z| positions even if they are the right vertex. This leads to jets that are shallow and can leave the detector by pointing outside of it, and hence, appear as missing energy
  - By requiring that events at |Z| > 60cm not be allowed into the final sample, this cut reduces the contribution of this effect considerably

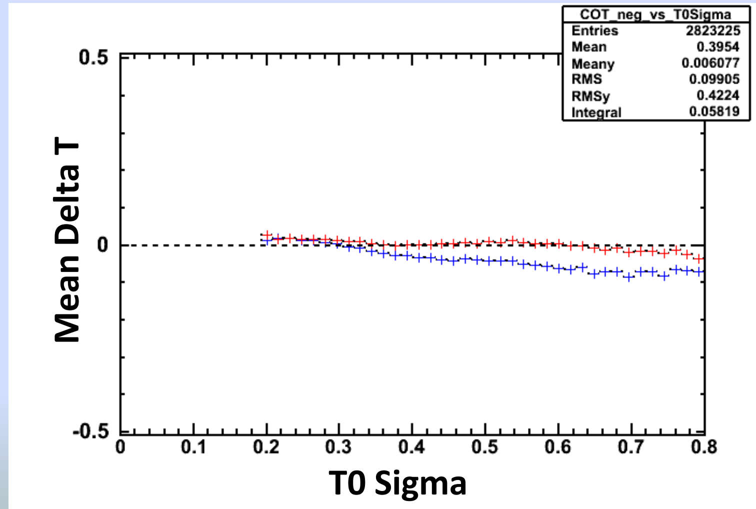
- All the aforementioned effects reduce most pathological cases of biasing the value of the Wrong Vertex mean. However, an estimation of the actual mean still remains

1. New Timing Calibrations – *Delta T*



Looking at the distribution of Delta T and its mean behavior indicates that calibrating over it will provide better resolution





1. New Timing Calibrations – *Z offset*

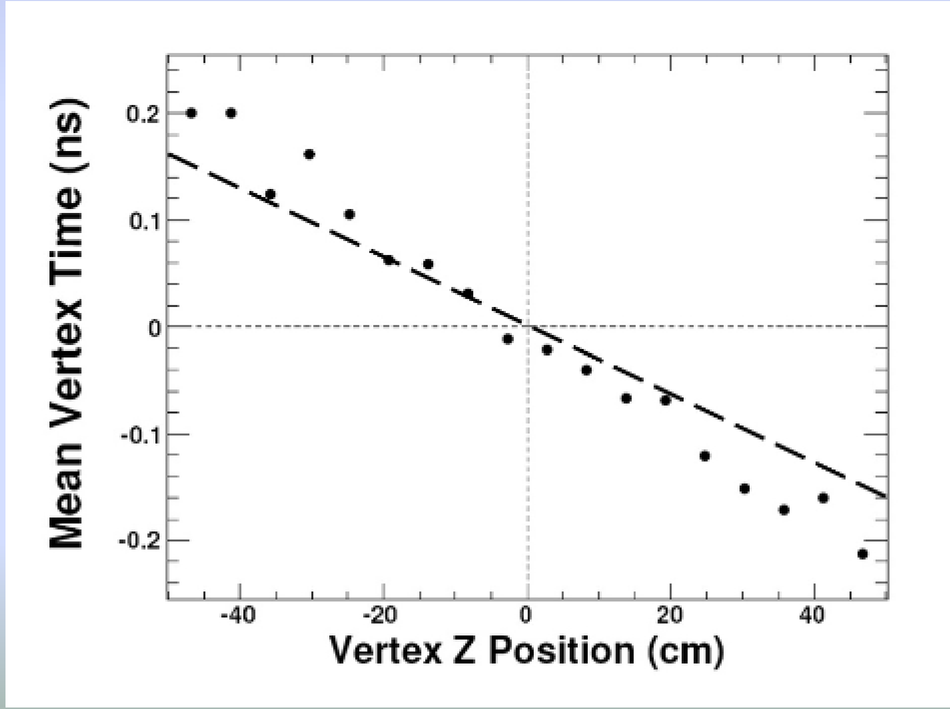
- The Proton-Antiproton bunches have a different RMS
  - $\sigma_{Proton} > \sigma_{Antiproton}$

$$\frac{\partial}{\partial t} PDF = exp^{(\frac{-(z-c\bar{t})^2}{2\sigma_{\bar{p}}^2} - \frac{(z+c\bar{t})^2}{2\sigma_{\bar{p}}^2})} (\frac{-zc + c^2\bar{t}}{\sigma_p^2} - \frac{zc + c^2\bar{t}}{\sigma_{\bar{p}}^2}) = 0.$$

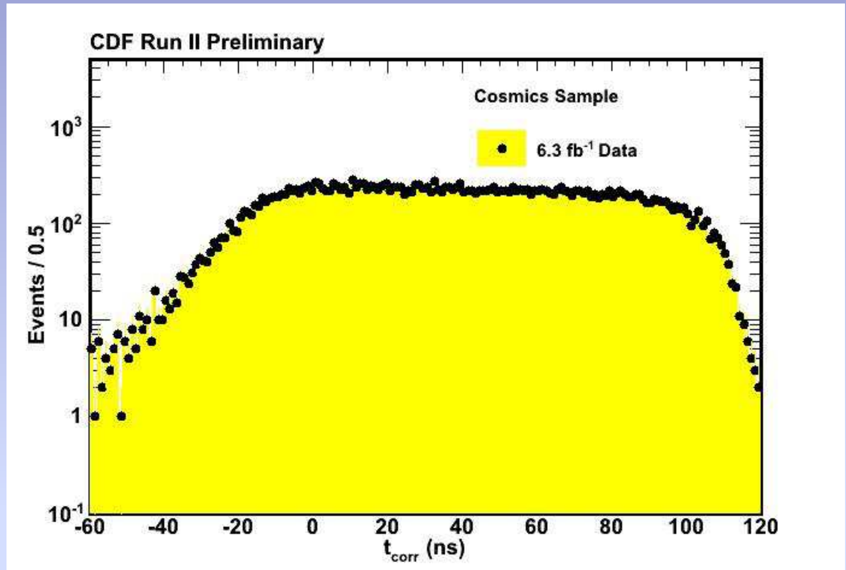
N.B: PDF = Probability Distribution Function

$$c\bar{t} = -z(\frac{\sigma_p^2 - \sigma_{\bar{p}}^2}{\sigma_{\bar{p}}^2 + \sigma_p^2}).$$

Solving for time gives a slope



2. New Background Estimation – *Cont.*



- As the cosmic arrival-time is further away from the expected collision time, we don't do as well at collecting the full energy of the cosmic. Only integrate the energy for 132 ns around the collision time.
- This causes the sharp edges at both sides.
- Had assumed it was flat in the central region, especially near the signal region.