Search for New Physics in the Exclusive Delayed Photon + MET Final State at CDF

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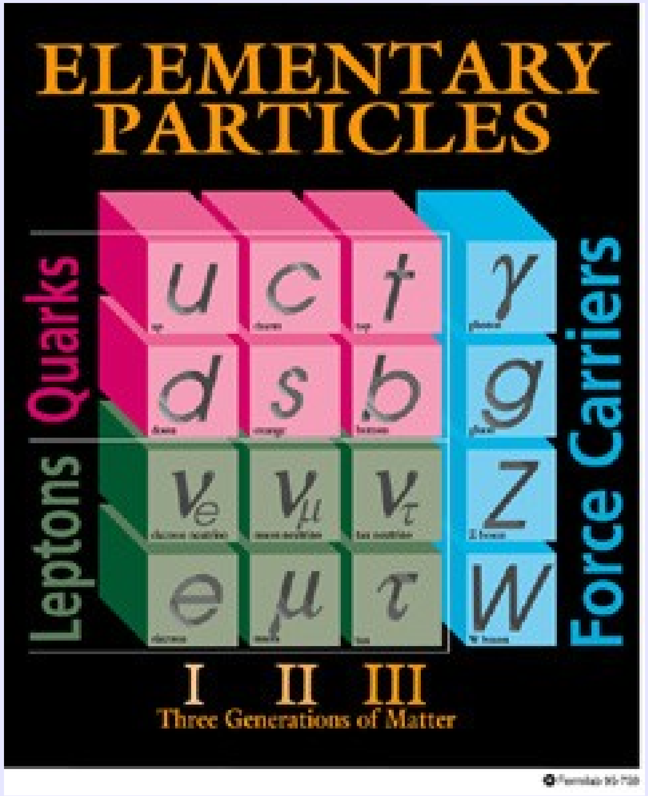
Outline

- Introduction
- Motivation
- Tools
- Overview of the Delayed Photon Analysis
- Backgrounds with Large Times and Cuts to Get Rid of Them
- Background Estimation
- Results
- Conclusions

Standard Model

- The Standard Model (SM) describes all currently known particles and interactions
- Decades of experimental verification have confirmed many of its predictions
- Despite extraordinary success, the Standard Model has problems
  - The “hierarchy problem” - the Higgs mass has divergences that must be canceled with fine tuning
  - Dark matter and dark energy make up a substantial portion of the universe



Supersymmetry

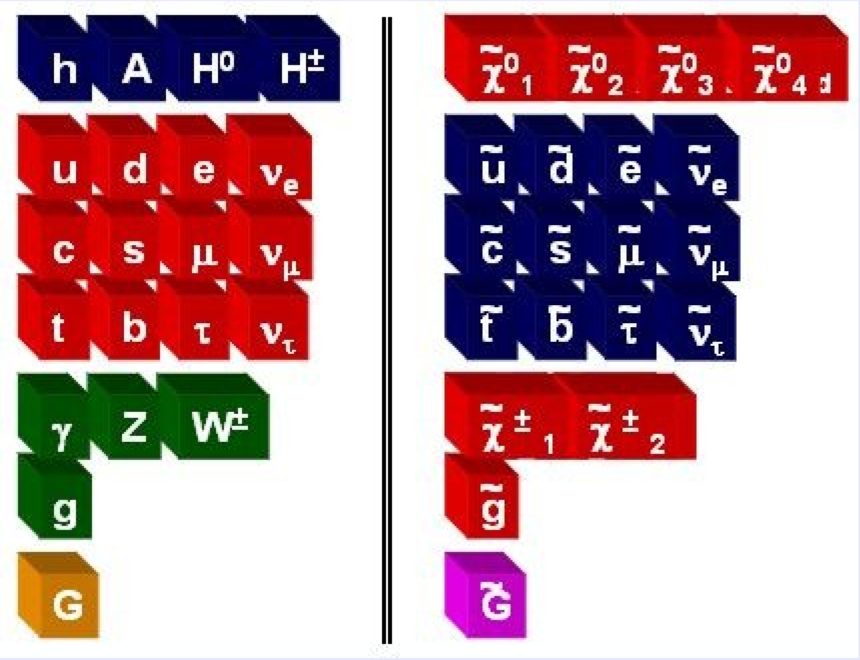
Supersymmetry (SUSY) proposes a symmetry between fermions and bosons – roughly doubles the particle count

The new particles cancel the divergence in the Higgs mass

If “R-parity” is conserved, SUSY could provide a dark matter candidate

This isn't an exact symmetry → SUSY particles must be heavy

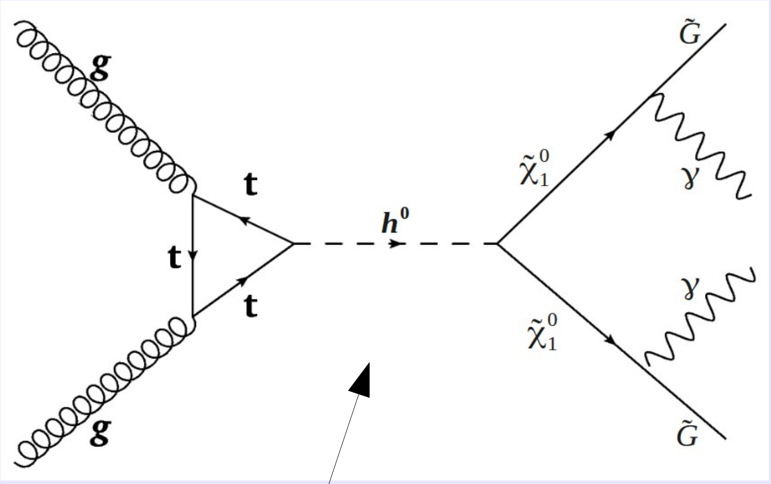
Various breaking mechanisms lead to different phenomenology



Search for SUSY decays of the Higgs in Gauge Mediated Supersymmetry Breaking Models

In GMSB, the $\widetilde{G}$, the SUSY partner of the graviton, is typically the lightest supersymmetric particle (LSP)

In general GMSB models, the light neutralino and gravitino (LNG) is possible: only the $\widetilde{\chi}_1^0$ and $\widetilde{G}$ are accessible at the Tevatron.



The NLSP, $\widetilde{\chi}_1^0$, is often long-lived. This is favored in low-scale SUSY breaking models. We look at cases where it has a lifetime of a few nanoseconds

Observation of Higgs at 125 GeV means this should be visible at the Tevatron

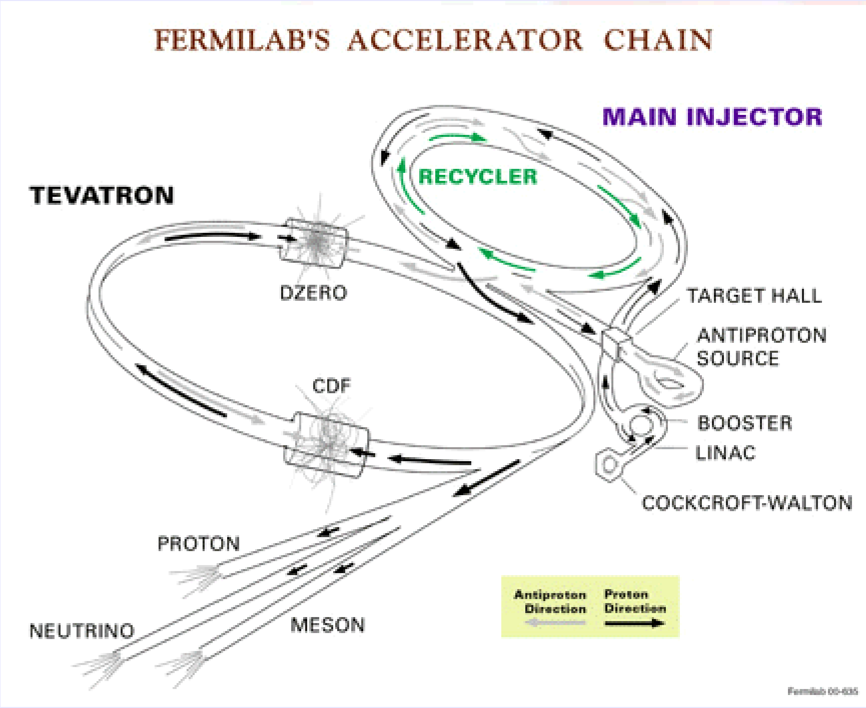
Long lifetime means only one $\widetilde{\chi}_1^0$ decays in the detector, leading to the exclusive $\gamma + \not{E}_T$ final state → never been searched for at Tevatron

Delayed photon prospects:
Phys. Rev. D 70 (2004) 114032
LNG prospects:
Phys. Lett. B 702 (2011) 377

Tevatron

The Tevatron, with a center of mass energy of 1.96 TeV, was the highest energy accelerator in the world. It collided protons with anti-protons every 396 ns.

Two detectors, CDF and D0 each collected nearly 10 fb^{-1} of data.



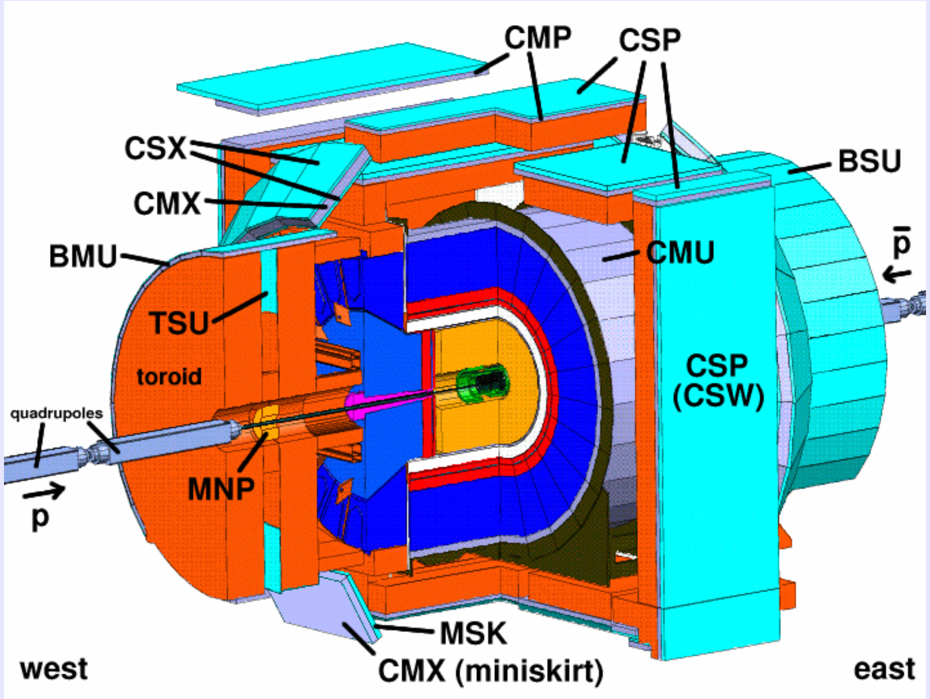
Collider Detector at Fermilab (CDF)

CDF is one of two multi-purpose detectors built to study collisions at the Tevatron.

Components heavily used in this analysis:

Central outer tracker – records the path taken by charged particles.

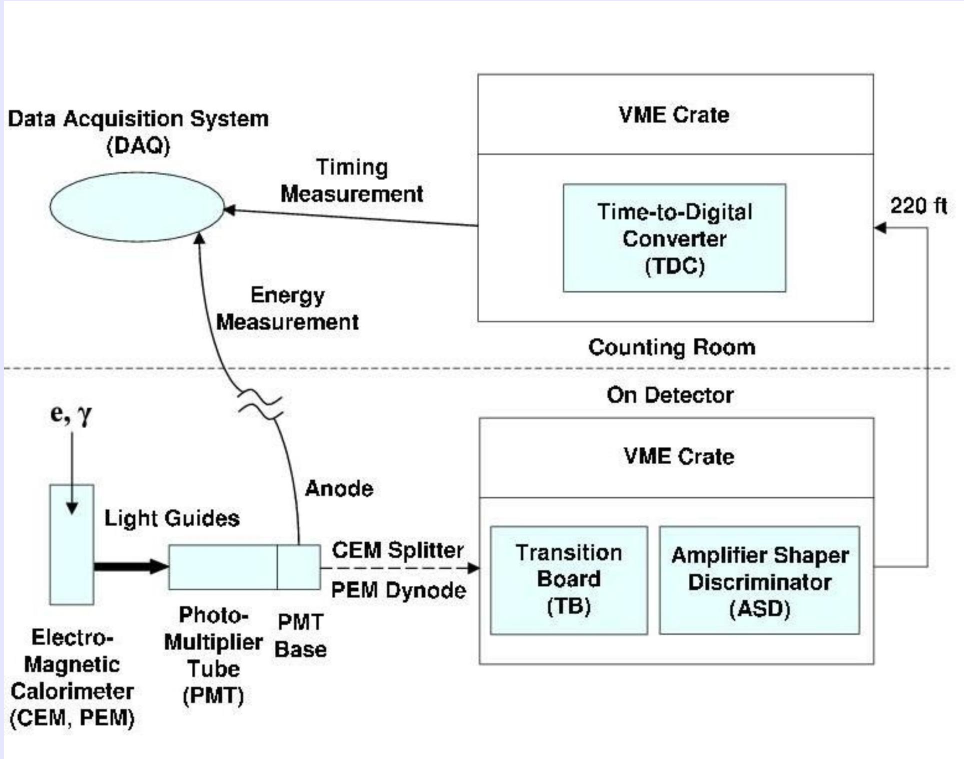
Electromagnetic calorimeter - records energy deposits from particles that interact electromagnetically



EMTiming System

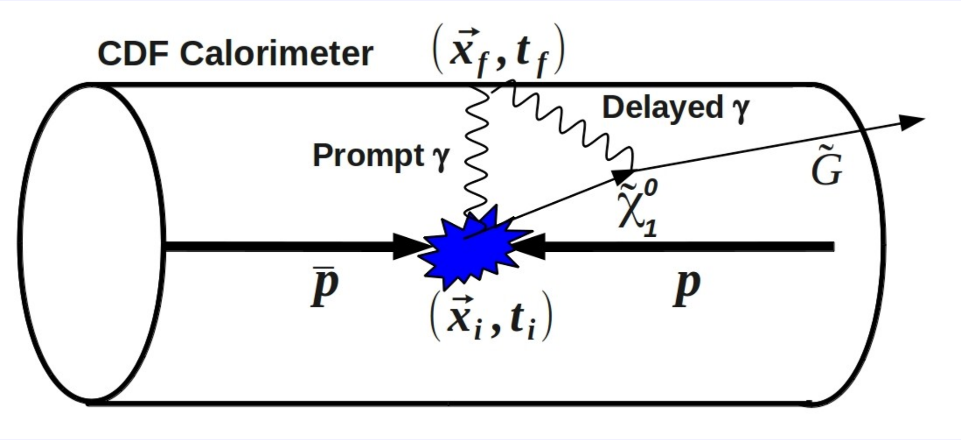
The EMTiming system converts output of the EM calorimeter into the time of arrival of the incident particle.

In the central region, it is fully efficient for energies > 6 GeV with a resolution ~ 0.6 ns.



Delayed Photons

Photons from long-lived $\widetilde{\chi}_1^0$, or any long-lived heavy neutral particle, arrive at the calorimeter late compared to expectations from prompt photons ("delayed photons").



This gives provides a distinct search signature for lifetimes between 1 and 50 ns.

Our primary analysis variable is the time of arrival of the photon at the EM calorimeter minus the expected time of arrival.

$$t_{corr} = t_f - t_i - \frac{|\vec{x}_f - \vec{x}_i|}{c}$$

Strategy

Look for delayed photons in a model independent, but LNG inspired (no cascade decays, long-lived $\widetilde{\chi}_1^0$) way in events with a single photon and nothing else.

Final State and Backgrounds

Final State

Require

(all E_T relative to Z = 0)

-Photon with E_T > 45 GeV

-MET > 45 GeV

-At least one space-time vertex with |Z| < 60 cm

Veto

-Extra calorimeter clusters with E_T > 15 GeV

-Tracks with P_T > 10 GeV

-Tracks close to the photon

-Vertices with |Z| > 60 cm

-Additional cosmics and beam halo cuts

Backgrounds

Standard Model Sources

$$W \rightarrow e\nu \rightarrow \gamma_{fake} + \not{E}_T$$

$$\gamma + jet \rightarrow \gamma + jet_{lost} \rightarrow \gamma + \not{E}_{T\,fake}$$

$$W \rightarrow \tau\nu \rightarrow \gamma_{fake} + \not{E}_T$$

$$W\gamma \rightarrow l\nu\gamma \rightarrow \gamma + l_{lost} + \not{E}_T$$

$$Z\gamma \rightarrow \nu\nu\gamma \rightarrow \gamma + \not{E}_T$$

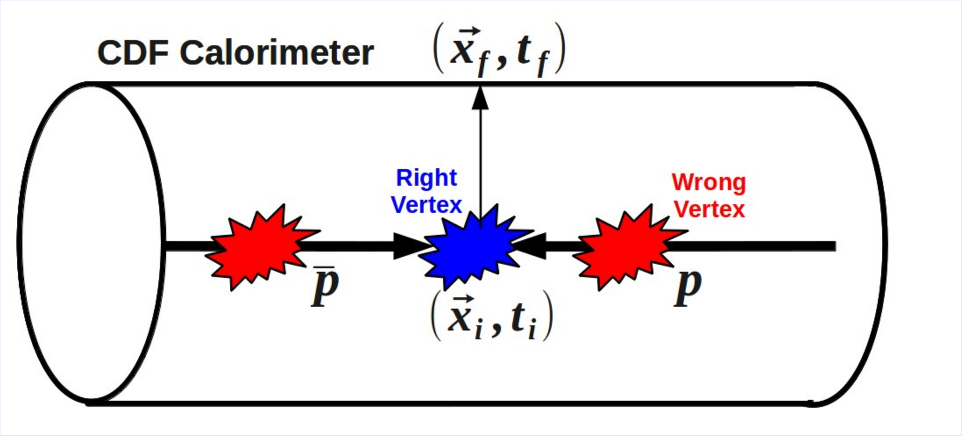
Non-Collision

-Cosmics

-Beam Halo

Collision Backgrounds

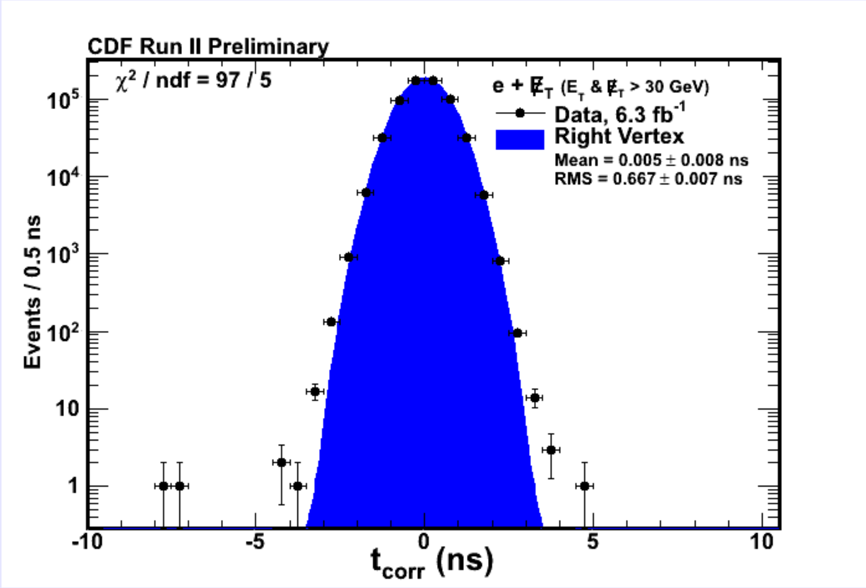
To construct the corrected time, we pick the highest ΣP_T vertex.



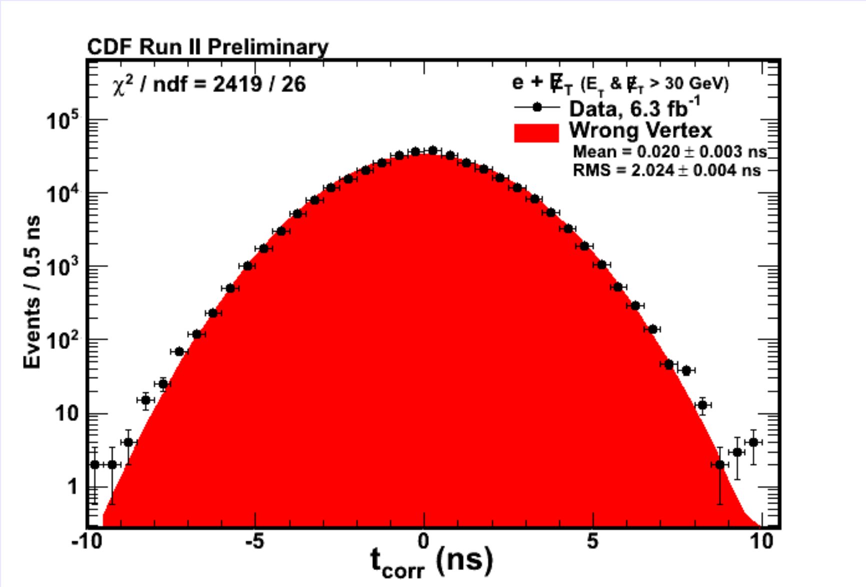
There often multiple vertices per event. Sometimes the wrong vertex has a higher ΣP_T than the right vertex, and sometimes the right vertex is not reconstructed at all. The corrected time for collision background depends crucially on whether or not the right vertex was selected.

Right and Wrong Vertices

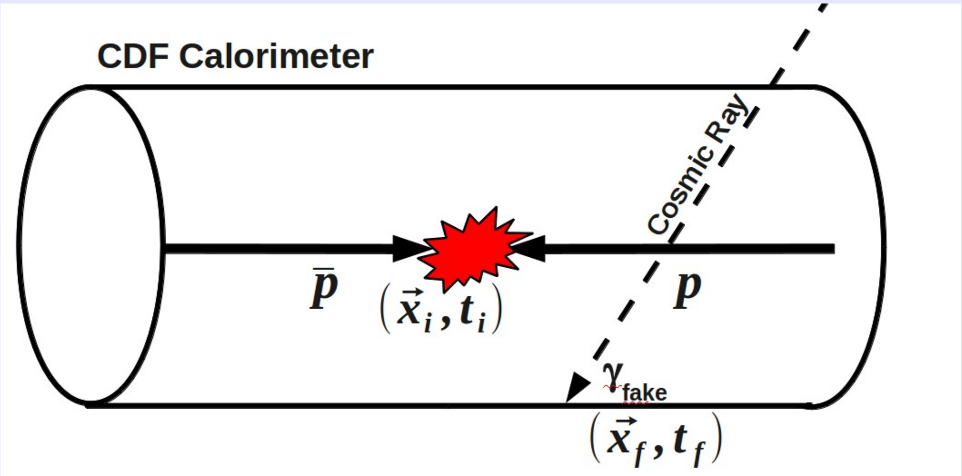
If this vertex is the origin of the particle that created the deposit in the calorimeter, it is a **Right Vertex** event - by defintion, the mean is zero but with an RMS of ~0.64 ns.



If we pick some other vertex, it is a **Wrong Vertex** event. The RMS for these events increases to ~2 ns mostly due to the timing distribution of minimum bias collisions. Generally speaking, the mean is non-zero.

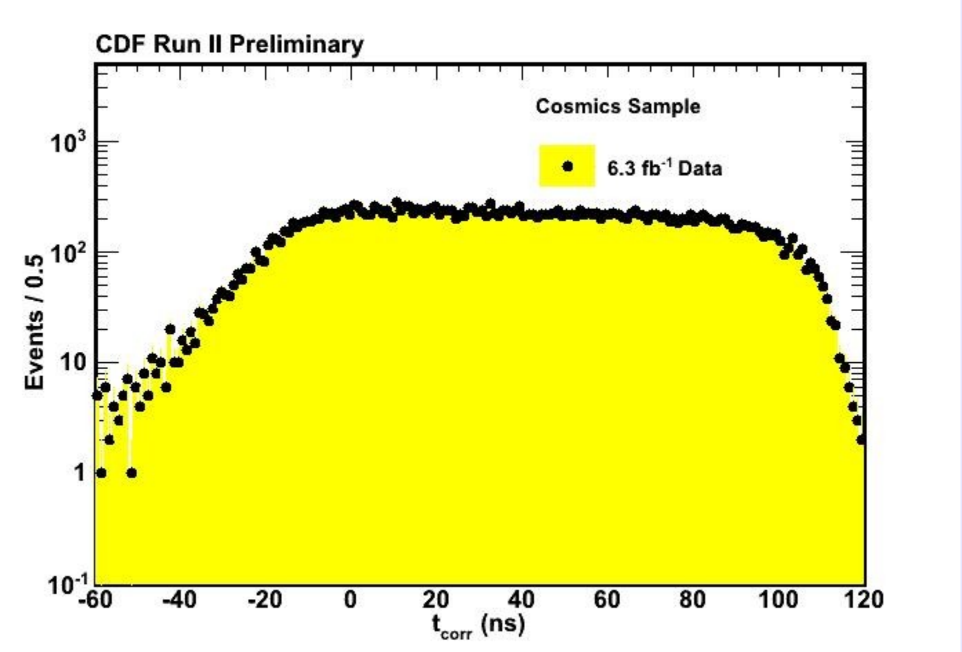


Cosmic Rays

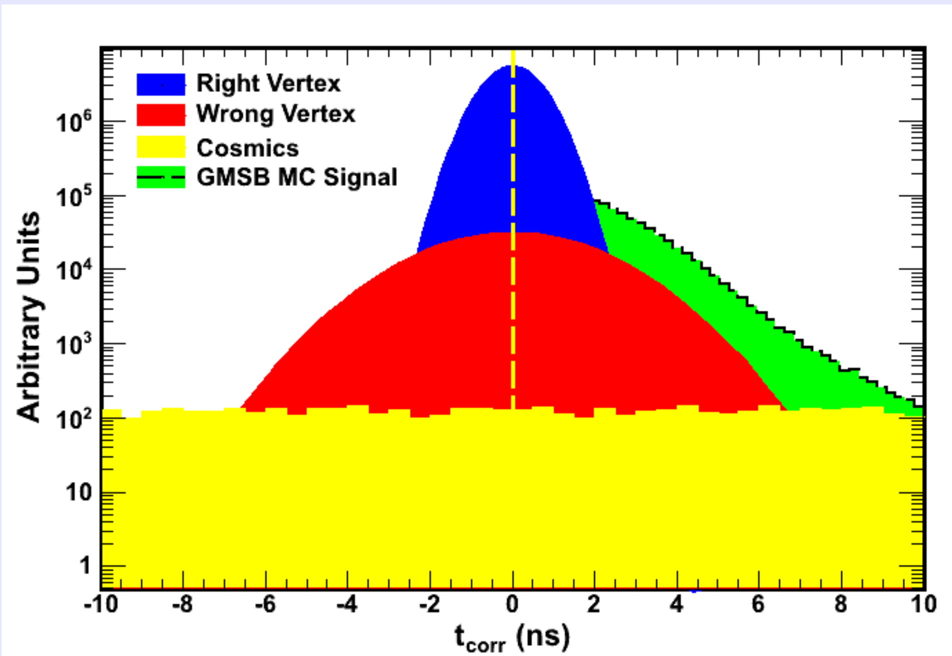


Cosmic rays occasionally reach the detector and leave an energy deposit which is reconstructed as a photon

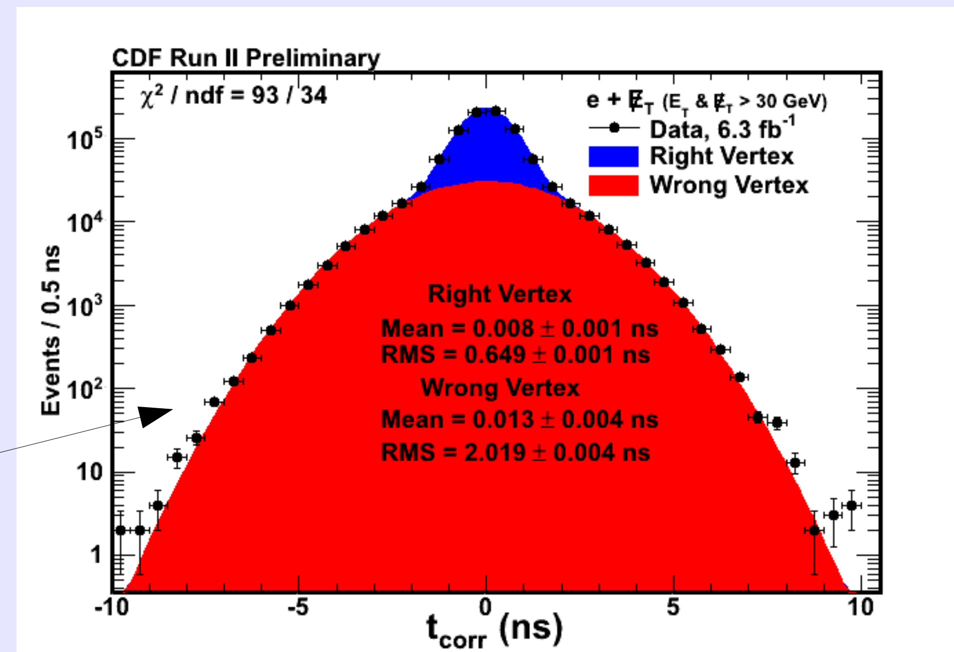
This is uncorrelated with the bunch structure of the beam, so the rate of recording such events is flat in time, except near the opening and closing of the energy integration window



Timing Distributions



The distribution of photons from GMSB decays are expected to be a decaying exponential smeared by the detector resolution



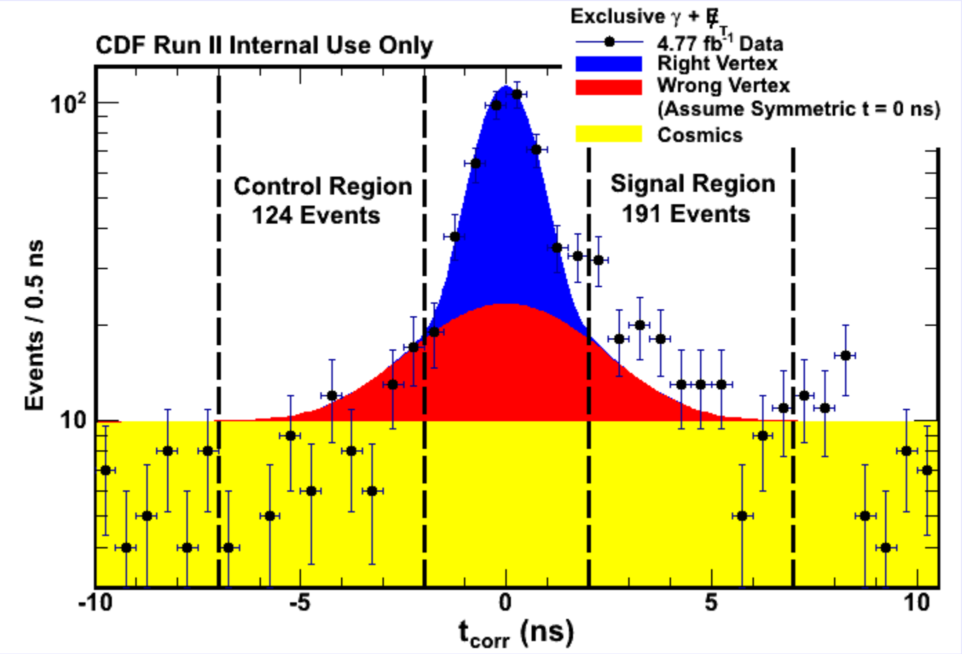
W → eν where we ignore the track for the purposes of selecting a vertex acts as a control sample for $\gamma + \not{E}_T$

Real collision data with electrons, known to have no signal and few cosmic ray events, is well modeled by a double Gaussian description.

Preliminary 4.8 fb^{-1} Result

A preliminary study uncovered a large excess in the exclusive $\gamma + \not{E}_T$ final state

Extraordinary claims require extraordinary evidence: examine the assumptions in the background model and look for any previously unknown biases .



Rather than treat this as a focused Higgs search, we treat this as a model independent search to determine whether or not this excess is real

Understanding the Preliminary Result

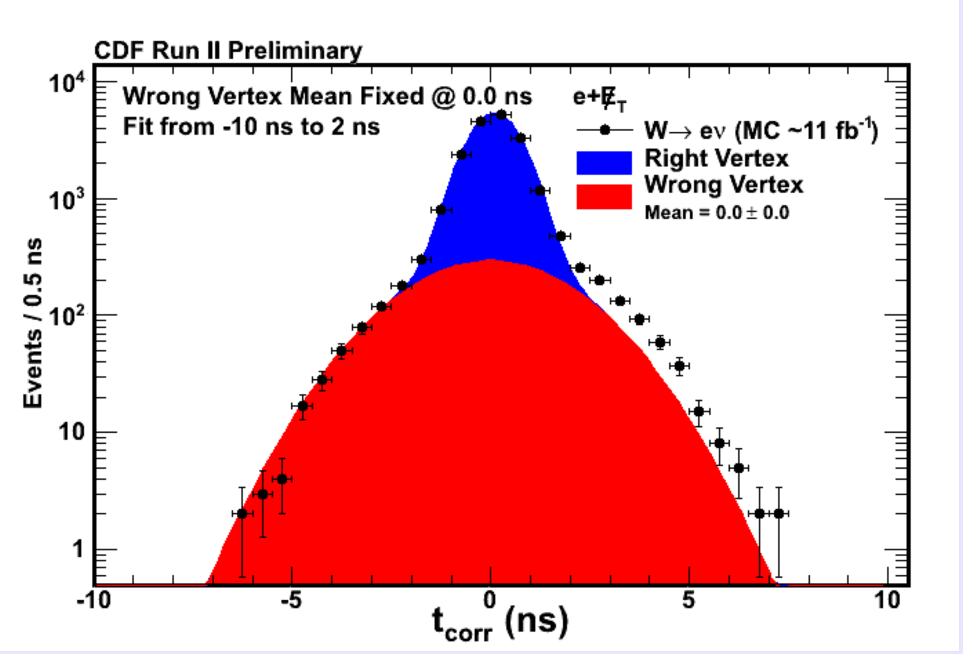
Assuming the wrong vertex mean is zero mistakenly makes it look like there is signal in this $W \rightarrow e\nu$ Monte Carlo sample

<u>Questions we need to answer:</u>

1) What biases cause the wrong-vertex mean to be shifted?

2) How can we reduce those biases?

3) How can we estimate how much bias is left?



Understanding Non-Zero Wrong-Vertex Means

The corrected time when we choose a wrong vertex:

$$t_{corr}^{WV} = t_{arrival} - TOF_{WV} - t_{WV}$$

Substituting the definition of the time of arrival:

$$t_{corr}^{WV} = t_{RV} + TOF_{RV} - TOF_{WV} - t_{WV}$$

Rearranging:

$$t_{corr}^{WV} = (t_{RV} - t_{WV}) + (TOF_{RV} - TOF_{WV})$$

Mean = 0, RMS = $\sqrt{2} * 1.28$ ns due to the beam profile in T

Physics dependent geometrical term – can have a non-zero mean.

Next, we will show three effects which cause this term to be biased.

Sources of Large Times from SM Backgrounds

The following effects can bias the timing distribution:

1) **<u>E_T Threshold Effect</u>**:
A distortion caused by events entering or leaving our sample due mis-measured E_T near the cut.

<u>Topology Biases</u>:
2) Fake photons: Fake photons tend to be biased to larger times due to being more likely at large path lengths.

3) Lost jets: Losing an object tends to happen at more extreme vertex Z positions (to allow the object to point out of the detector).

Sources of Large Time Events: 1) E_T Threshold Effect

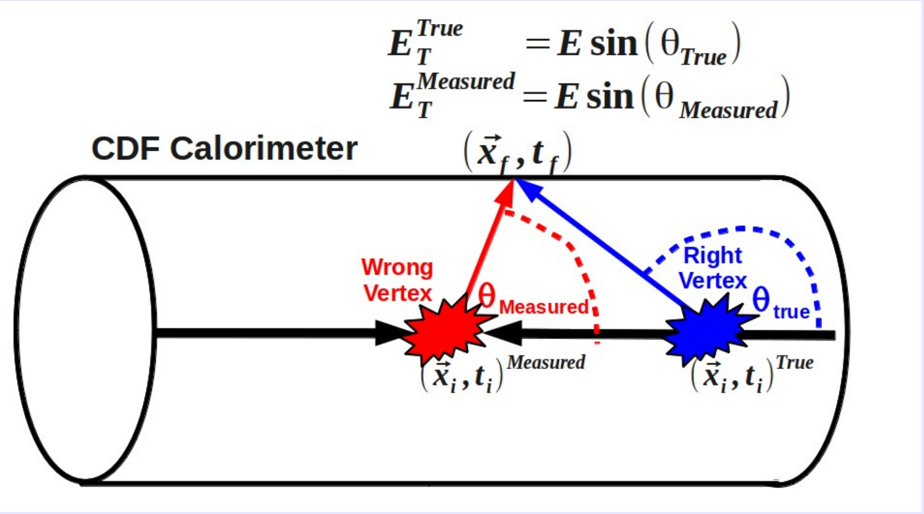
<u>Promotion Effect</u>

Wrong vertex gives shorter apparent path length

→ Longer apparent time

→ Larger measured E_T

Events below the E_T threshold enter the sample and **increase** the positive time bias.



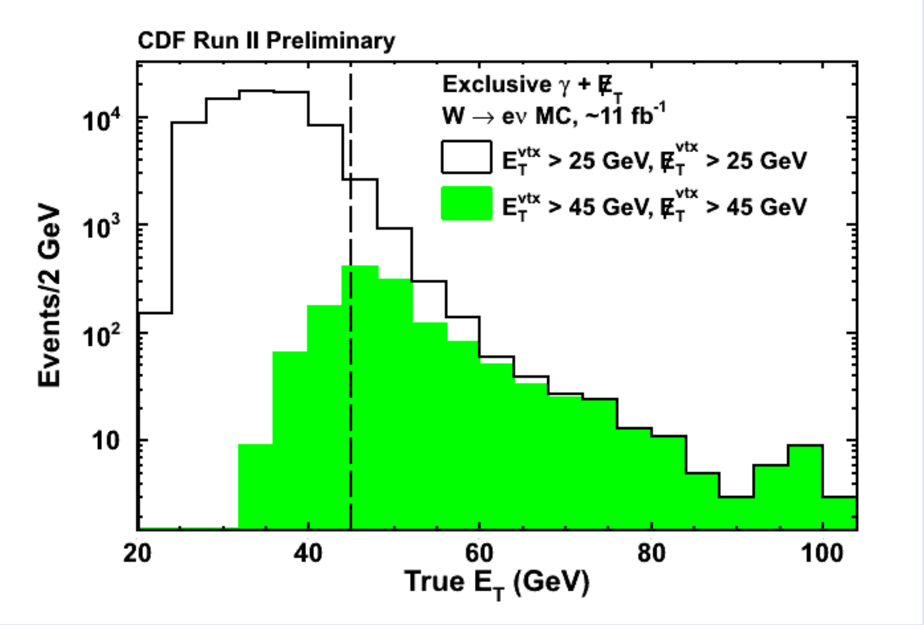
<u>Demotion Effect</u>

Wrong vertex gives larger apparent path length

→ Shorter apparent time

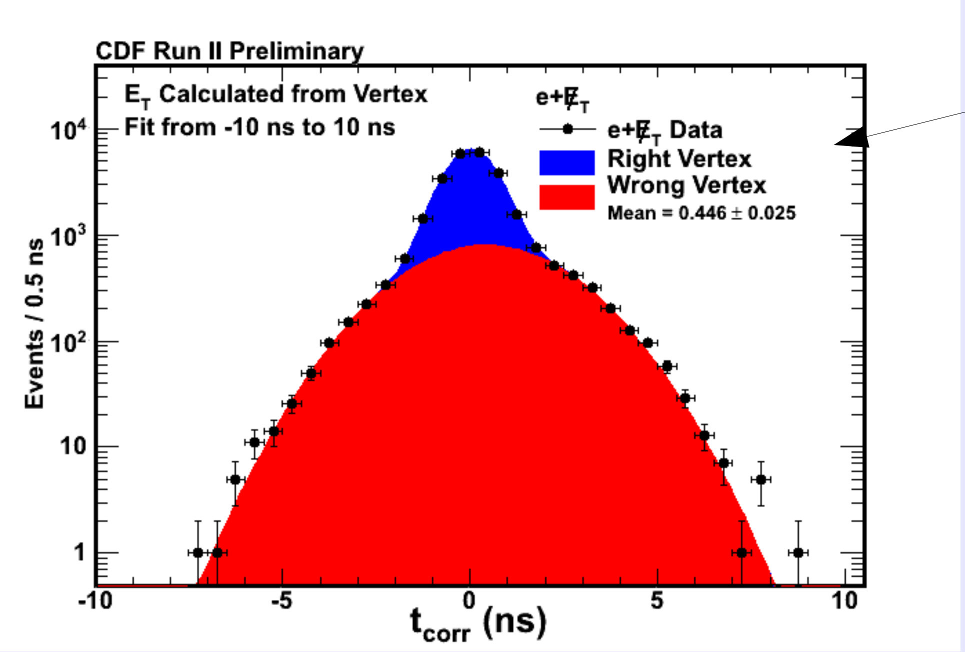
→ Smaller measured E_T

Events above the E_T threshold exit the sample and **decrease** the negative time bias.



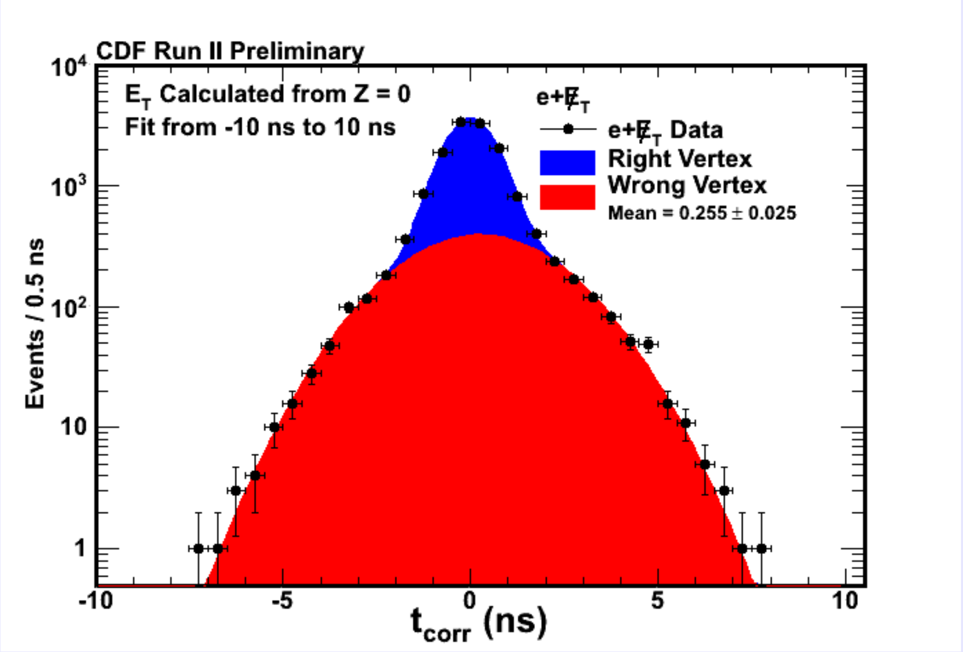
1) Solution: E_T^0 Cut

Decouple the timing measurement from the E_T measurement by calculating E_T relative to Z = 0

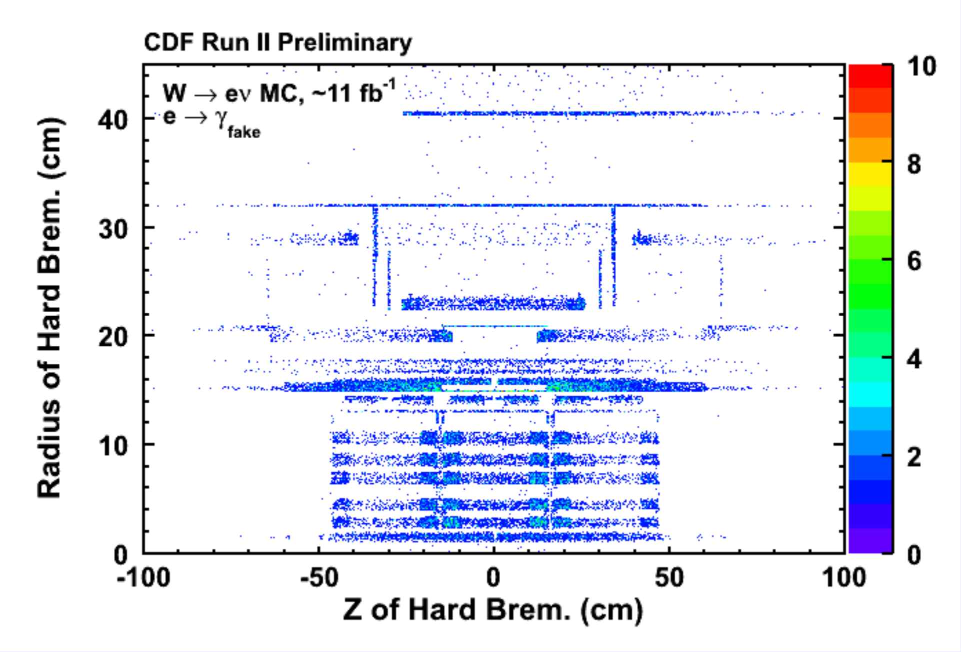


Real data with electrons using E_T relative to the selected vertex

The same data using E_T^0 → the wrong-vertex mean decreases by ~half!

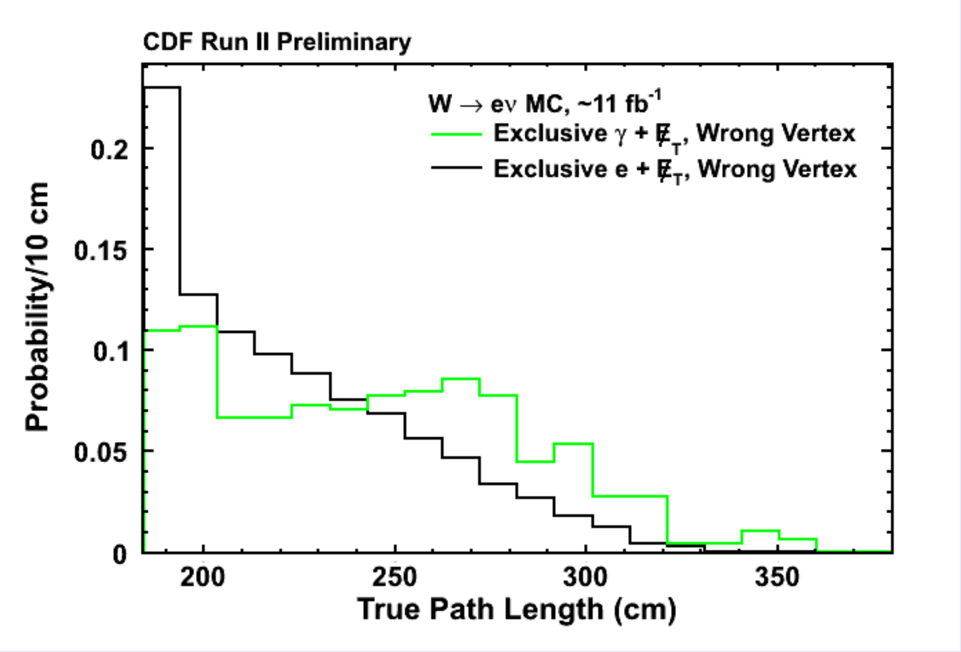


Sources of Large Time Events: 2) Fake Photons



Most electrons that fake photons are due to hard interactions with detector material

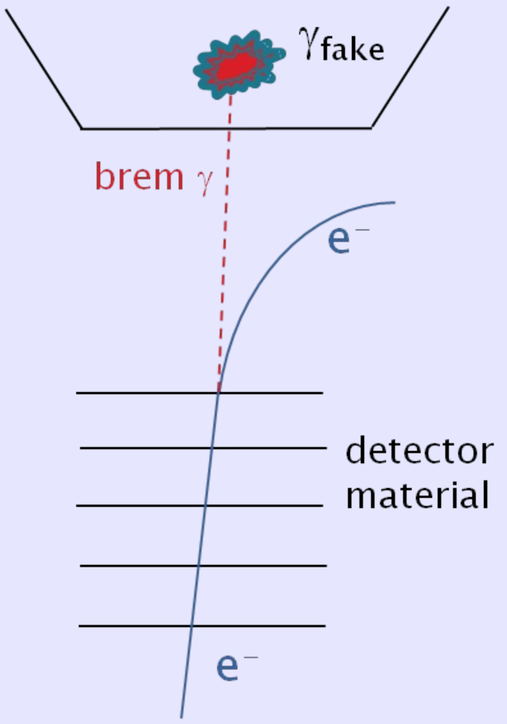
This make makes them have longer path lengths on average → larger apparent times with a wrong vertex



2) Solution: ΔR_{pull} Cut

Develop a new fake rejection technique:

Electrons faking photons start off pointing towards the calorimeter deposit, but due to the hard interaction, the path has a “kink” that ruins track extrapolation



Create a ΔR between the track and the calorimeter deposit based on standardized versions of the initial η and ϕ of the track

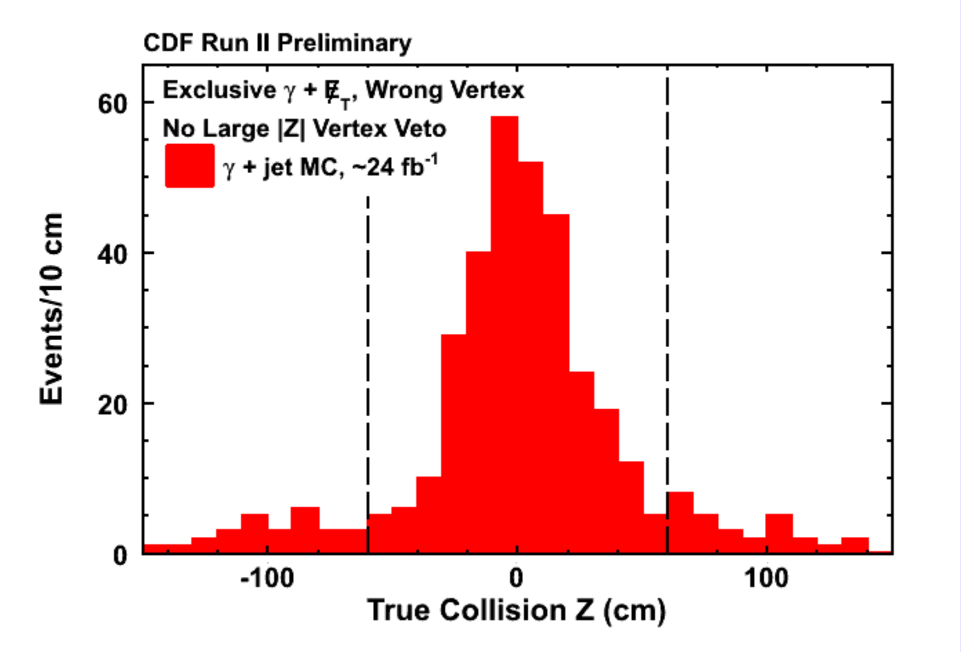
~73% rejection of fake photons
~90% efficiency

Sources of Large Time Events: 3) Large |Z| Production

Any collision at |Z| > 60 cm that produces a photon will always be reconstructed as wrong vertex

These events will always have large corrected times

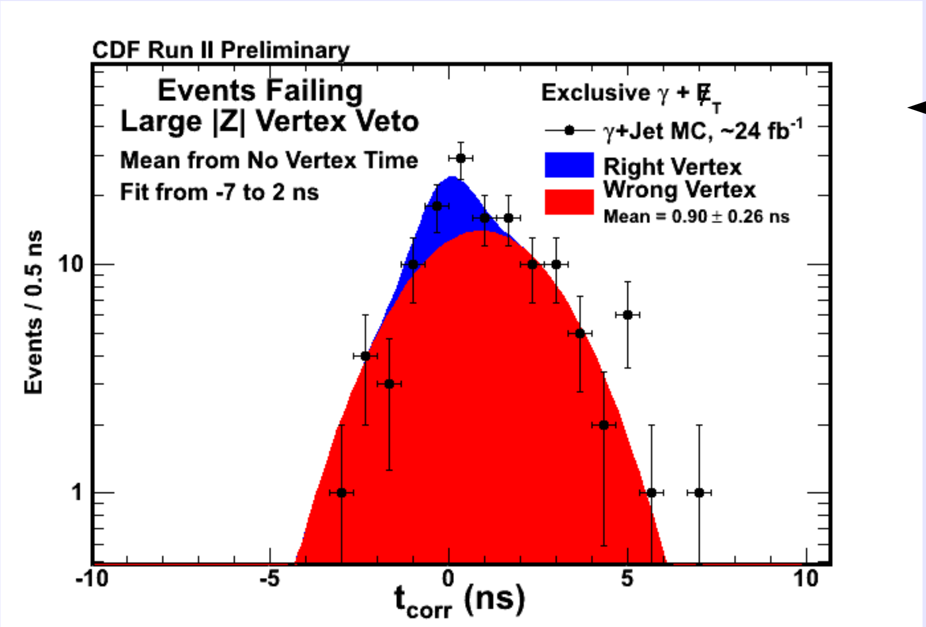
Thus, it is a good idea to reject events with evidence of a large |Z| collision.



The biggest source of these events are γ+jet since jets from large |Z| are less likely to hit the detector.

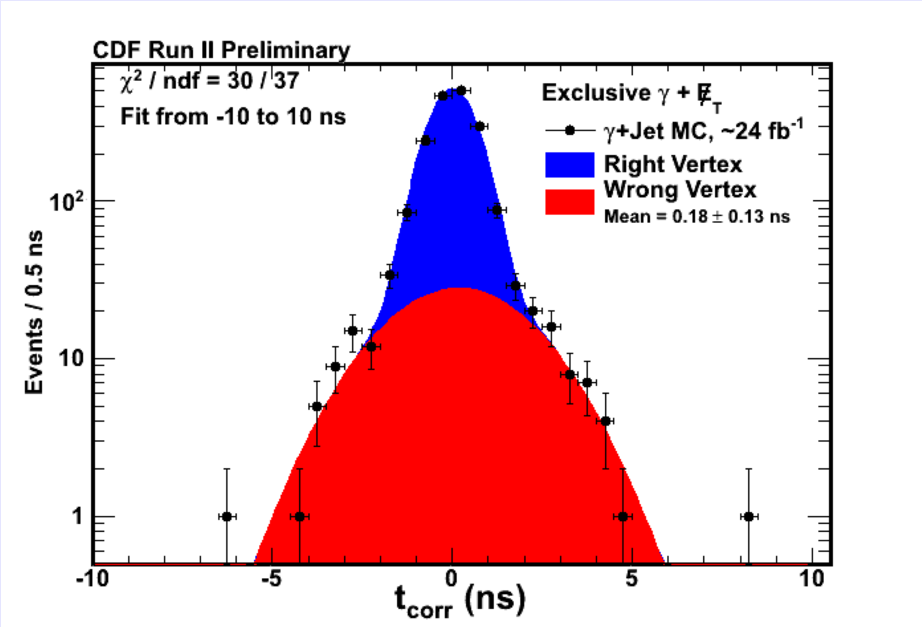
3) Solution: Large |Z| Veto

Reject any event with a vertex with 3 or more tracks and |Z| > 60 cm (~95% efficient for right vertex events)

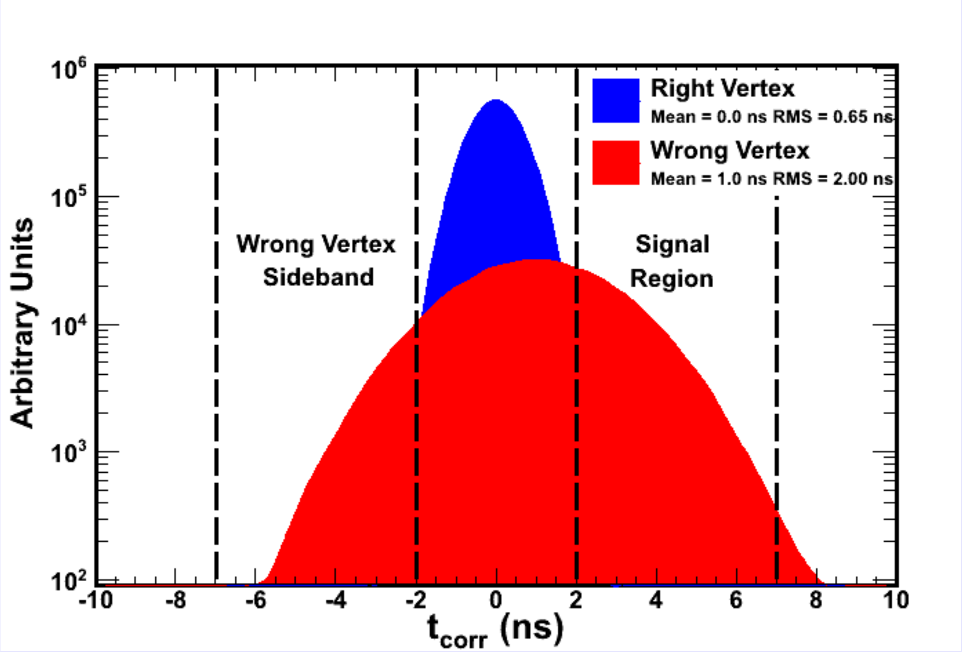


γ+jet events failing the large |Z| veto are highly shifted

After the veto, the distribution is well behaved with a small wrong-vertex mean



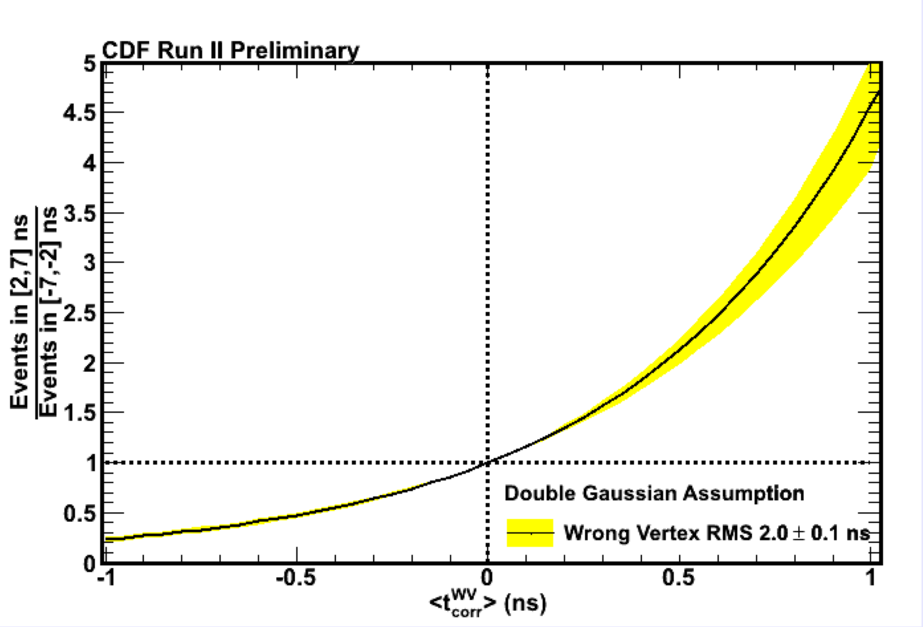
Predicting Background Events in the Signal Region From the Wrong-Vertex Mean



We want to be able to predicted the number of background events in (2,7) ns using a data-driven method

Note: right-vertex events are largely irrelevant in the signal region

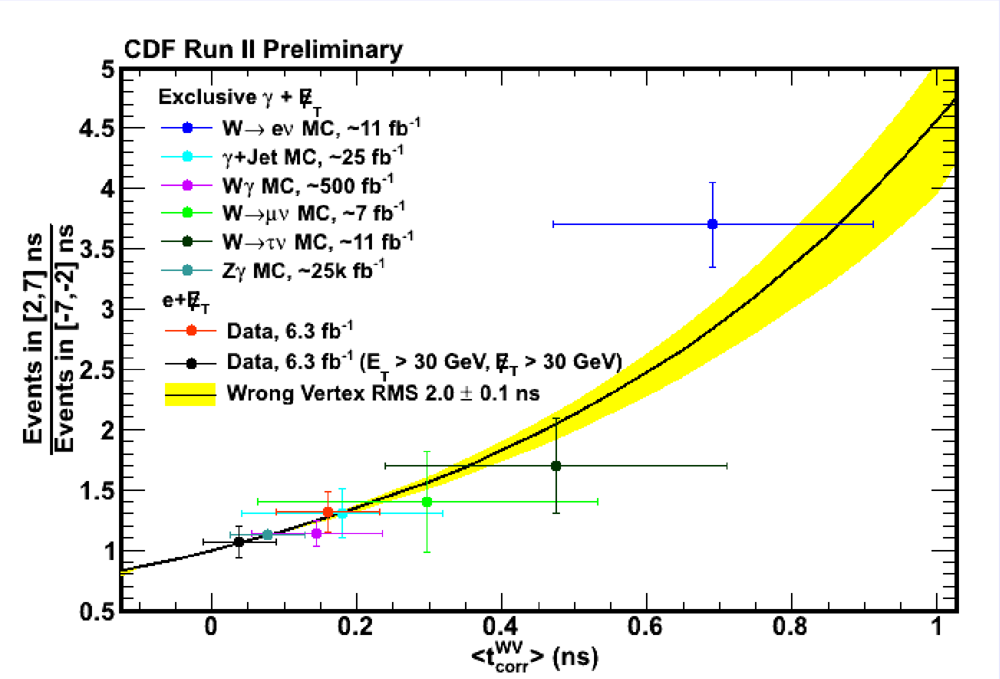
The number of wrong-vertex background events in the signal region depends directly on its normalization which we can get from (-7,-2) ns, and the wrong-vertex mean which we get from a second sample



Checking the Double Gaussian Approximation with Lots of Datasets

We isolate wrong vertex events in Monte Carlo and fit to find the wrong-vertex mean and RMS

For real data, we use electrons so we can use the electron track to identify wrong vertex events

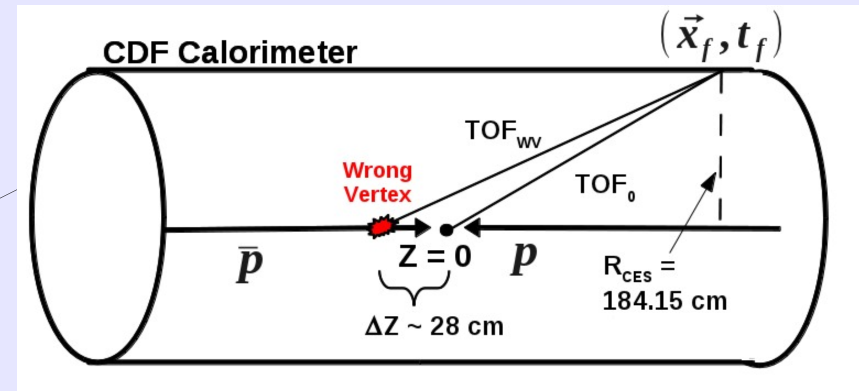


Our data after all cuts is at ~0.2 ns

The ratio of events in (2,7) ns to events in (-7,-2) ns follows our predictions according to the double Gaussian approximation. (Not a fit!)

Estimating the Wrong-Vertex Mean From the No-Vertex Sample

Create orthogonal sample of events passing all cuts but good vertex requirement. Create the corrected time relative to the center of the detector: $t^{0}_{corr} = t_{arrival} - 0 - TOF_0$

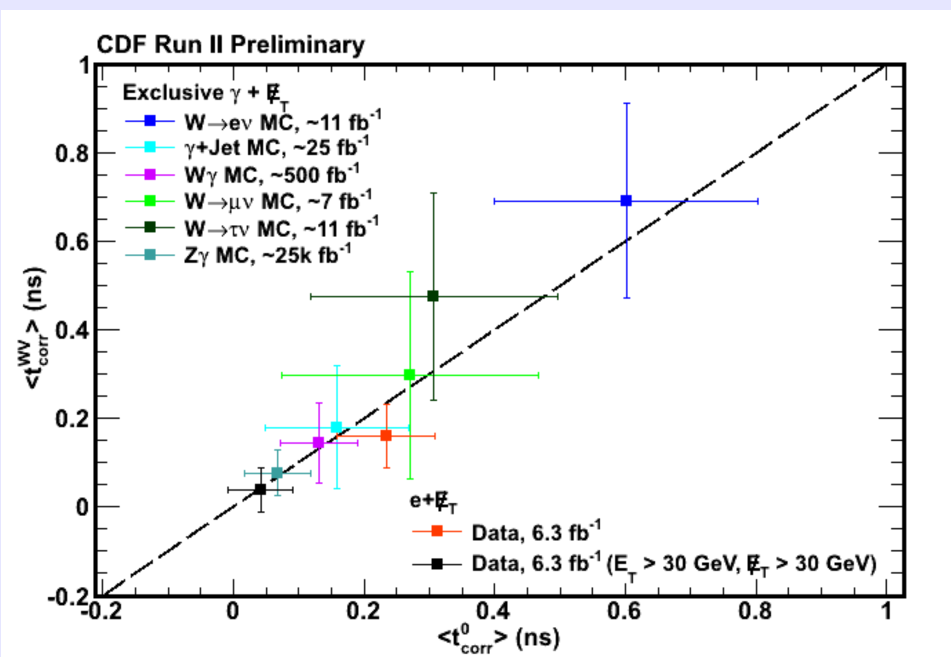


Substituting into wrong-vertex time:

$$t^{WV}_{corr} = t^{0}_{corr} - t_{WV} + (TOF_0 - TOF_{WV})$$

Zero on average

Typical ΔZ << than radius of detector → average ~ zero



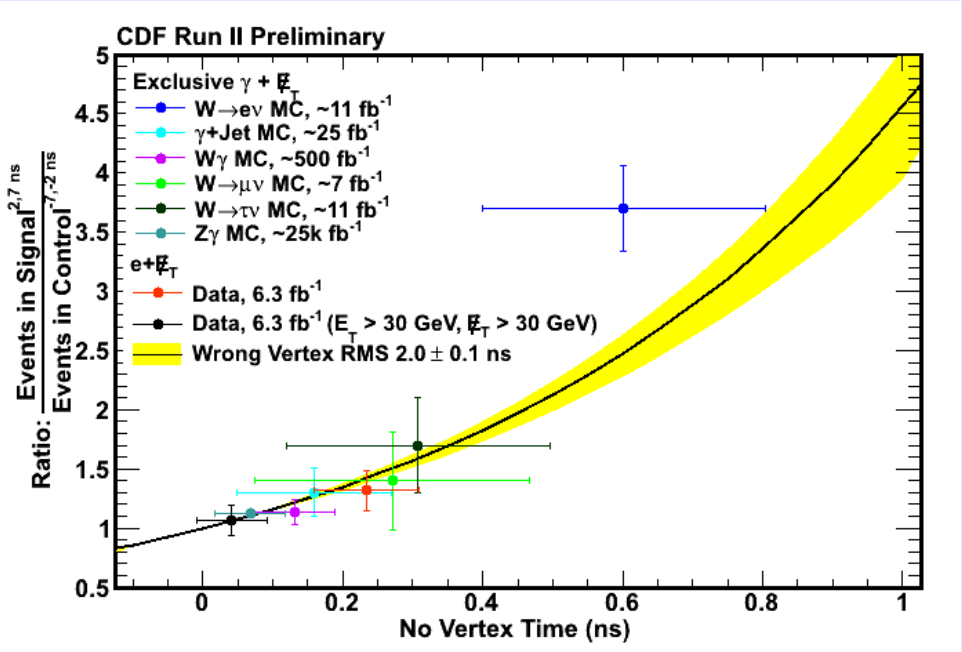
The mean no-vertex time is approximately equal to the mean wrong-vertex time for all control samples!

Predicting the Signal Region From the No-Vertex Mean

We isolate no vertex events in Monte Carlo and electron data and fit to find the no vertex mean.

The ratio of the signal region to the wrong-vertex sideband follows the prediction from the no-vertex mean just as well as for the wrong-vertex mean!

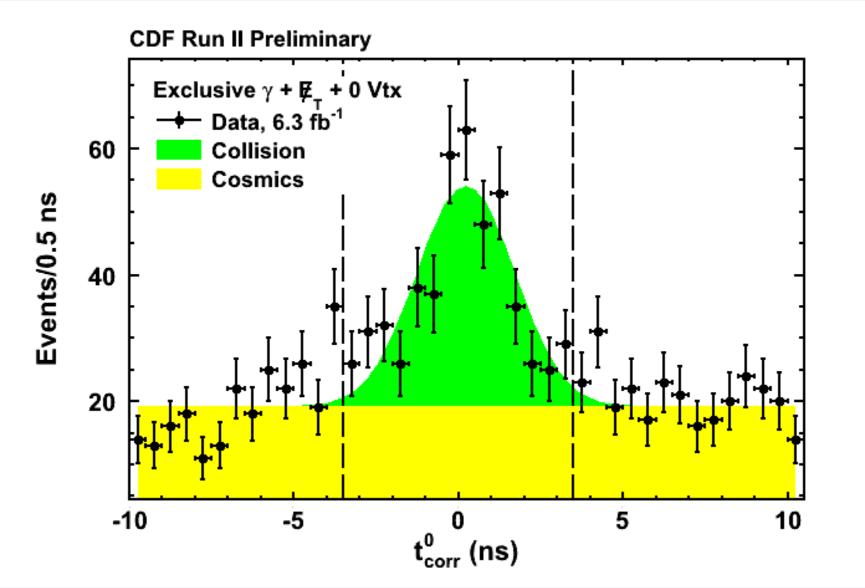
Thus, we can use the no-vertex mean as proxy for the wrong-vertex mean.



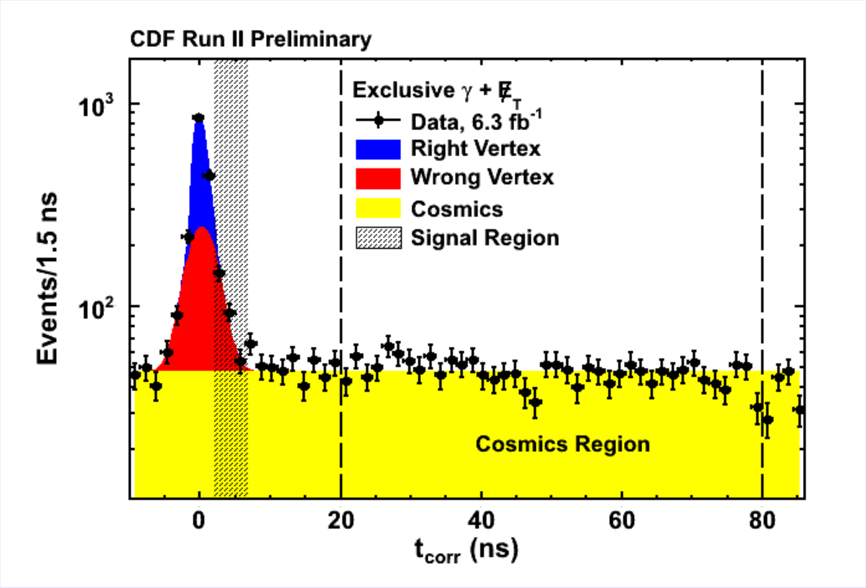
Putting It All Together: Likelihood Fit

- Estimate the number of background events in the signal region using a combined likelihood fit to the sideband regions extrapolated to the signal region
  - Good vertex: (-7,2) ns and (20,80) ns
  - No vertex: (-3.5, 3.5) ns and (20,80) ns
- Include systematic uncertainties as constraint terms:
  - Right-vertex mean = 0.0 $\pm$ 0.05 ns
  - Right-vertex RMS = 0.64 $\pm$ 0.05 ns
  - Wrong-vertex mean = No-vertex mean $\pm$ 0.08 ns
  - Wrong-vertex RMS = 2.0 $\pm$ 0.1 ns

Sideband Regions



No Vertex:
Collision Events = 260 $\pm$ 30
Collision Mean = 0.2 $\pm$ 0.1
Cosmics/ns = 38.1 $\pm$ 0.8



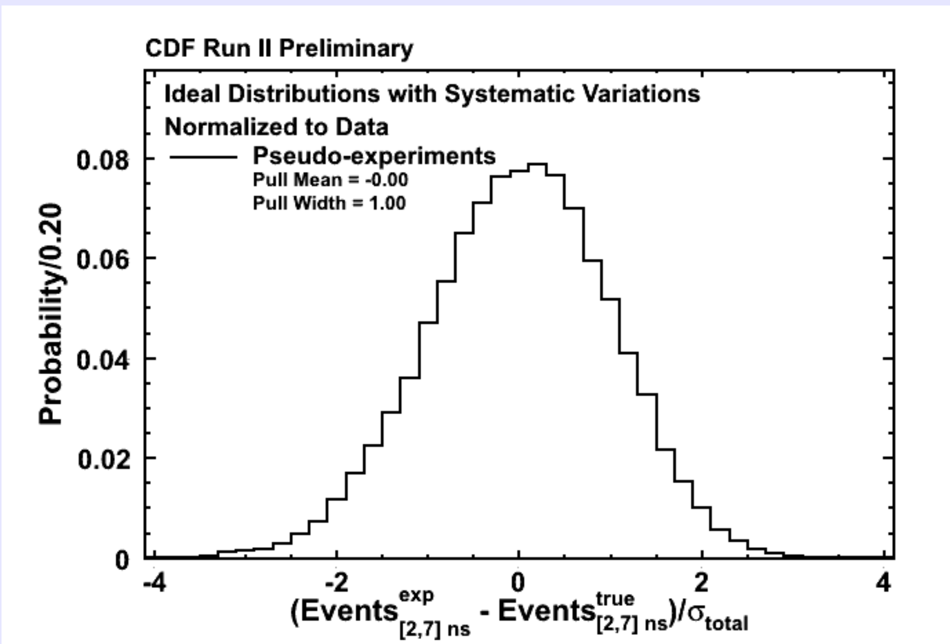
Good Vertex:
Right-Vertex Events = 870 $\pm$ 70
Wrong-Vertex Events = 680 $\pm$ 80
Cosmics/ns = 31.9 $\pm$ 0.7

Next: use the numbers to validate the fit

Validating the Likelihood Fit

- Generate ideal pseudo-experiments varying parameters within their systematic uncertainties
- Generate more realistic pseudo-experiments from full MC of the three largest SM backgrounds
- Sample at the statistics level seen in data
- Add the expected level of cosmics to the good and no vertex distributions

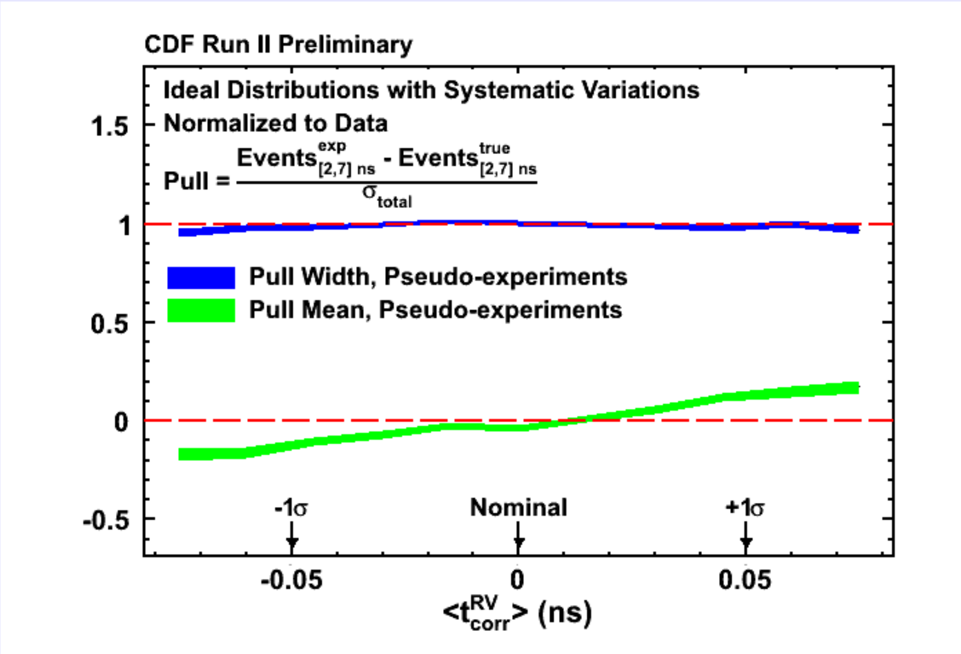
Ideal Distributions: How Well Do We Do?



All parameters with systematic uncertainties are allowed to vary within those uncertainties.

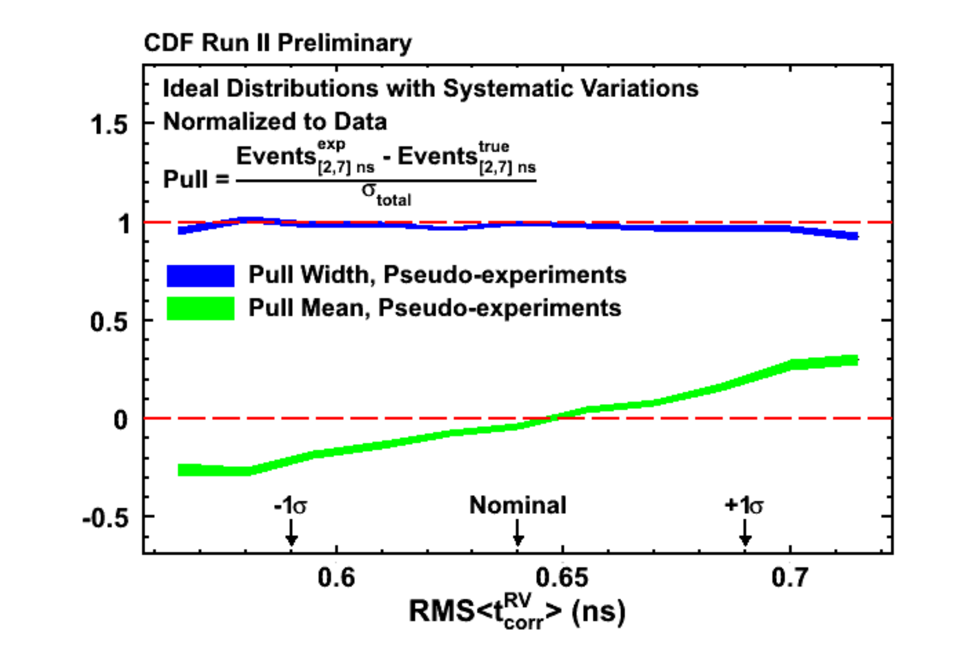
The pull distribution shows that with full variation of the systematics, the fit is unbiased (mean ~ 0) and the errors are well estimated (RMS ~ 1).

Ideal Distributions: Pulls vs. Systematic parameters



Figures range from -1.5σ to 1.5σ in systematic uncertainty

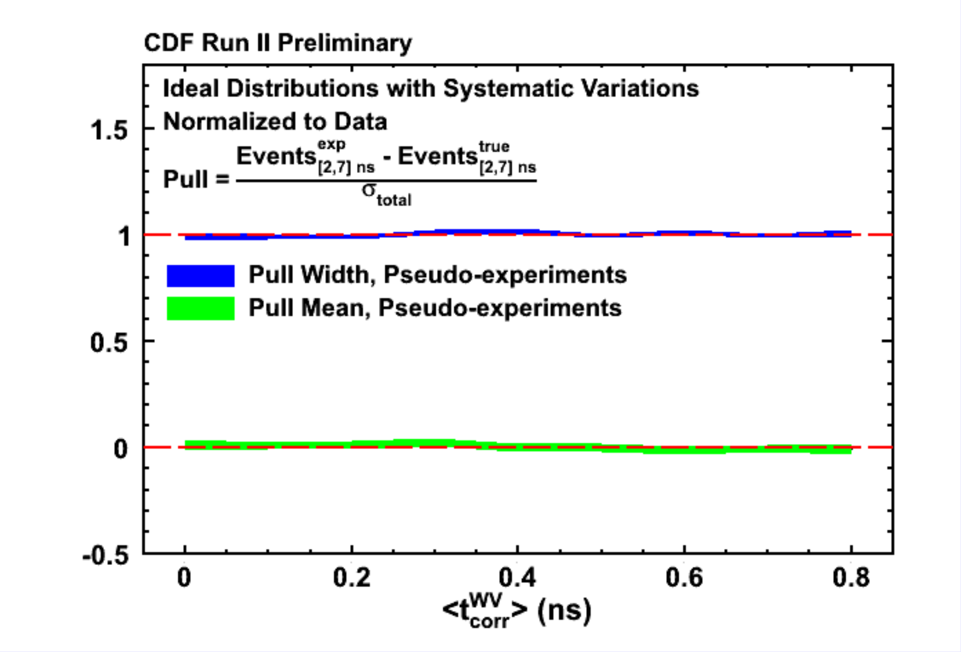
The fit remains largely unbiased over this range



In both cases, the pull width indicates that the uncertainties are well estimated over the entire range

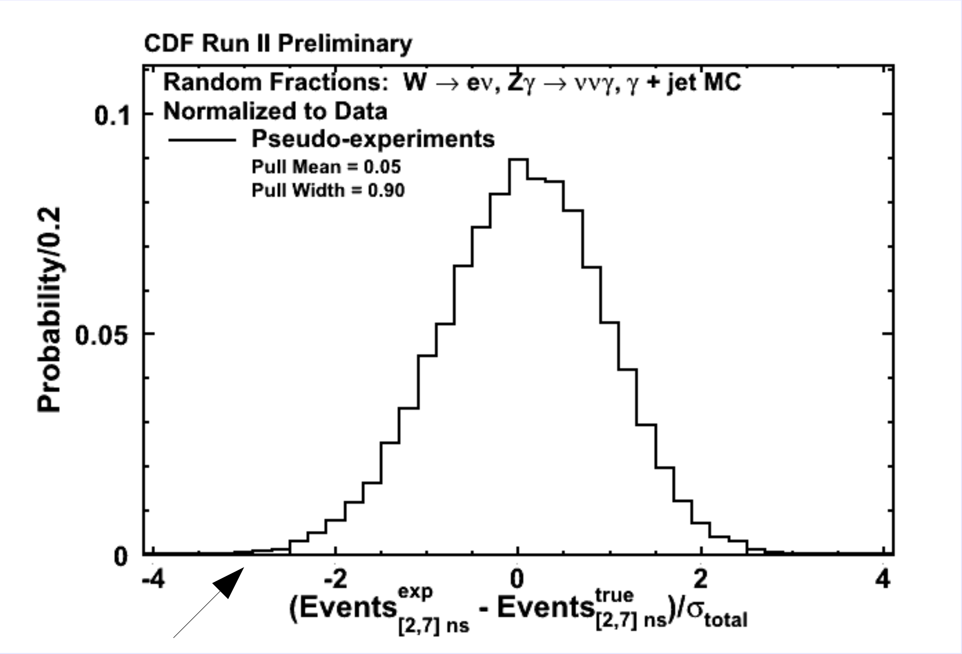
How well does the fitter do for different wrong vertex means?

The wrong-vertex mean is not known a priori.
We vary wrong-vertex mean between 0.0 ns and 0.8 ns to see how well the fitter responds.

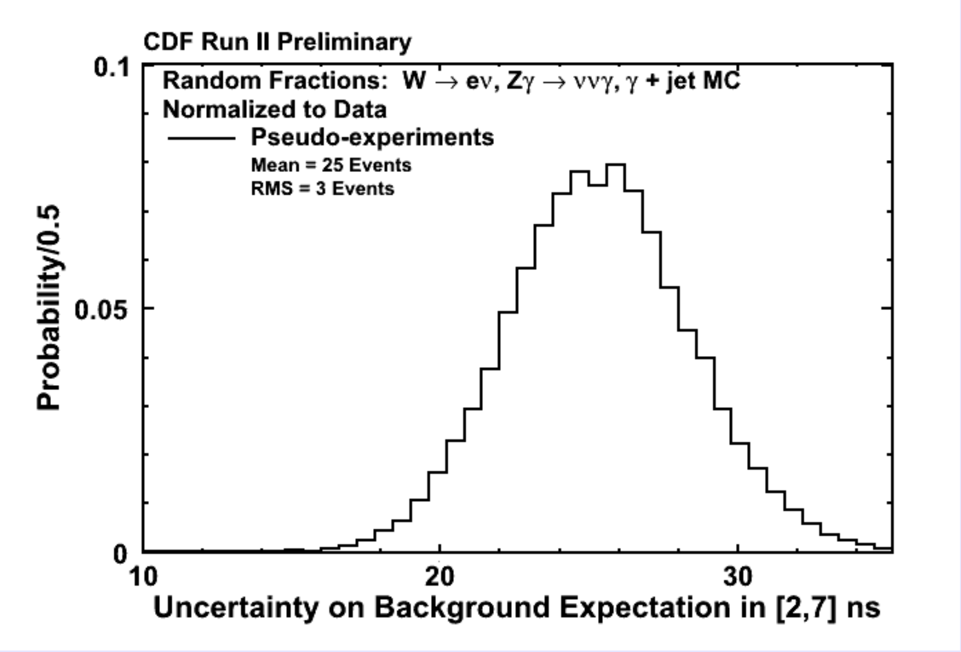


The quality of the estimation of number of events in the signal region is largely not affected by the particular wrong vertex mean chosen.

How well do we do when we combine fully simulated MC samples?



We take Zγ, W → eν, and γ+jet MC in random fractions.

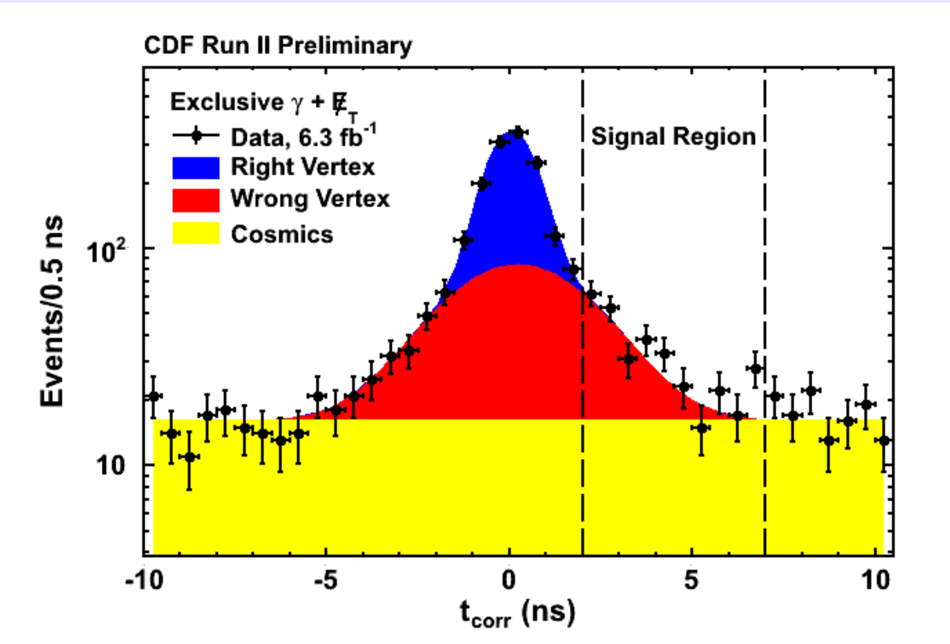


Pull distribution: largely unbiased and the errors well estimated.

Double Gaussian approximation is very successful, even under worse case combinations.

Fit uncertainty ~25 counts.

Results

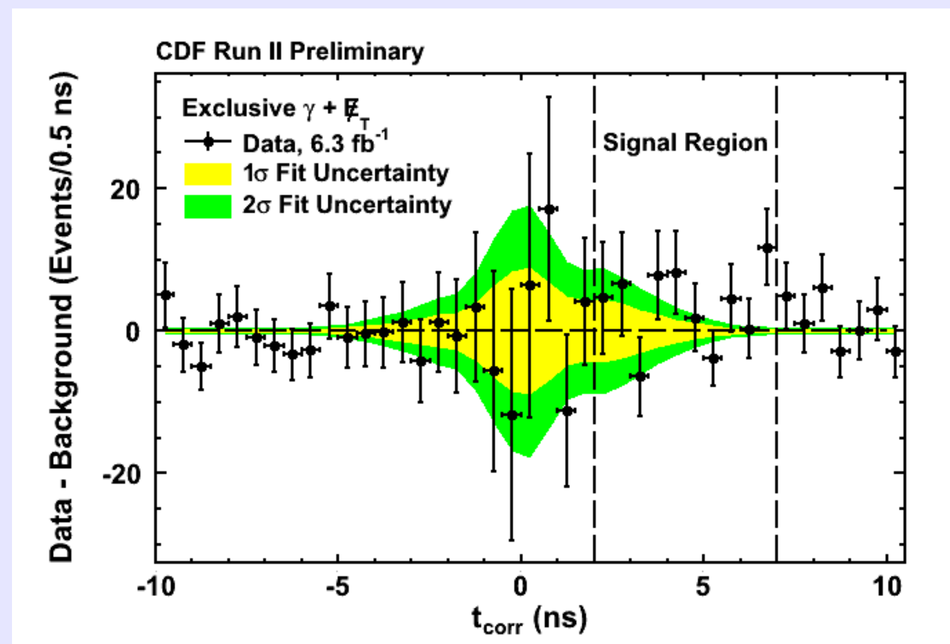


N(SR) expected = 286 $\pm$ 24
N(SR) observed = 322

Using pseudo-experiments, we determine the counting significance is 1.2σ.

Almost all bins in the signal region are high, as expected for a signal, but to be conservative, we present a simple counting experiment.

Future versions will add more data and do a shape analysis.



Conclusions

- First attempt at understanding this final state
- Uncovered previously unknown timing biases
- Created new requirements to minimize those biases in an efficient way for signal
- Developed a data driven method to estimate background contributions
- Found a modest but interesting excess → if real, could be the first observation of the Higgs in a SUSY mode

Backups

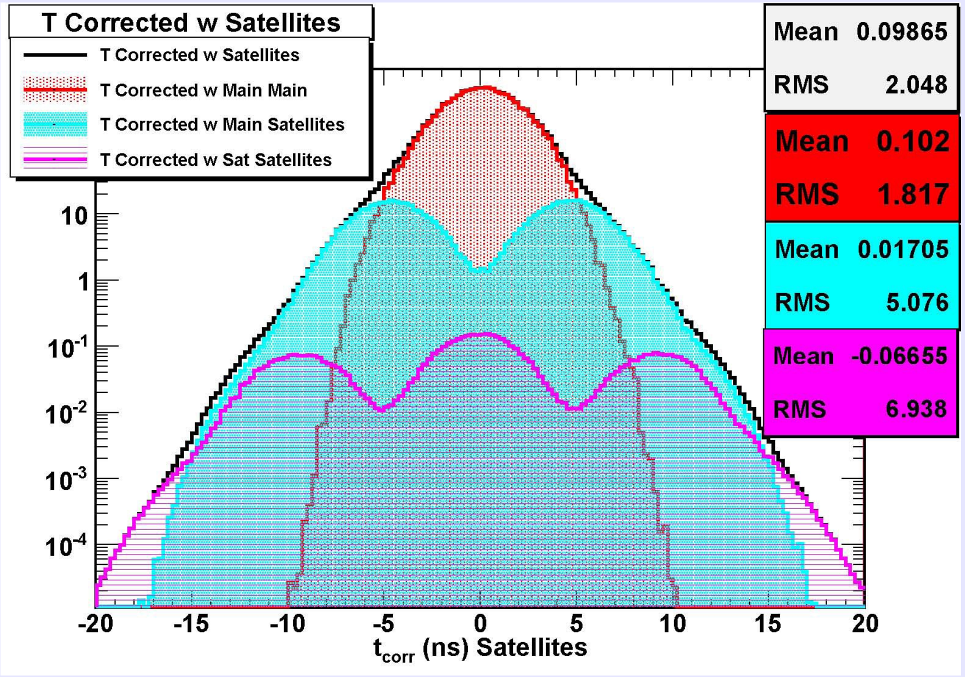
Overview of the Delayed Photon Analysis: Satellite Bunches

Satellite bunches occur 18.8 ns before and after the primary bunches

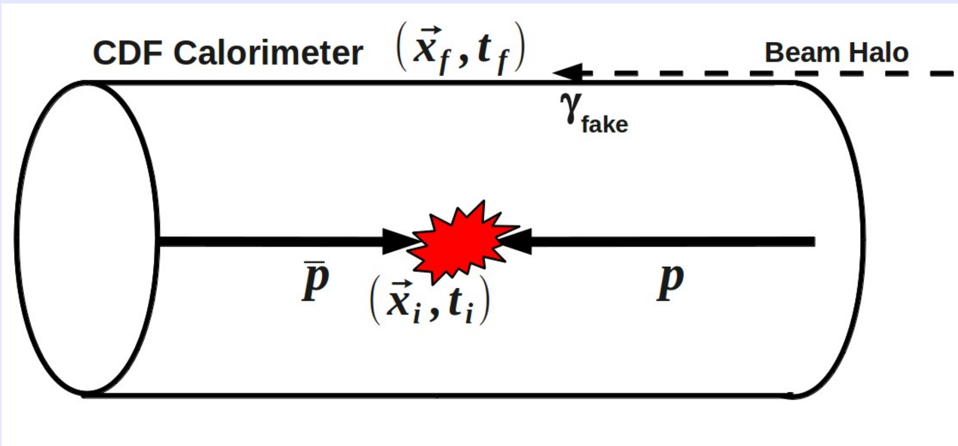
Satellite bunches contain ~1% as many particles as the main bunches do

Satellite-satellite and satellite-main collisions contribute heavily suppressed peaks to the corrected time distribution

These contributions are negligible in this analysis

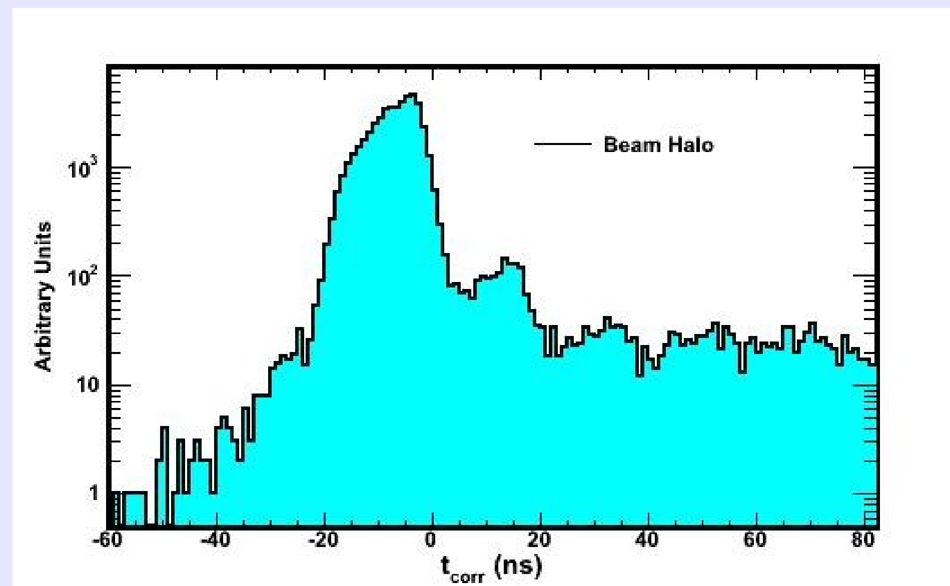


Overview of the Delayed Photon Analysis: Beam Halo



Beam halo particles are typically muons produced beam interactions upstream of the detector

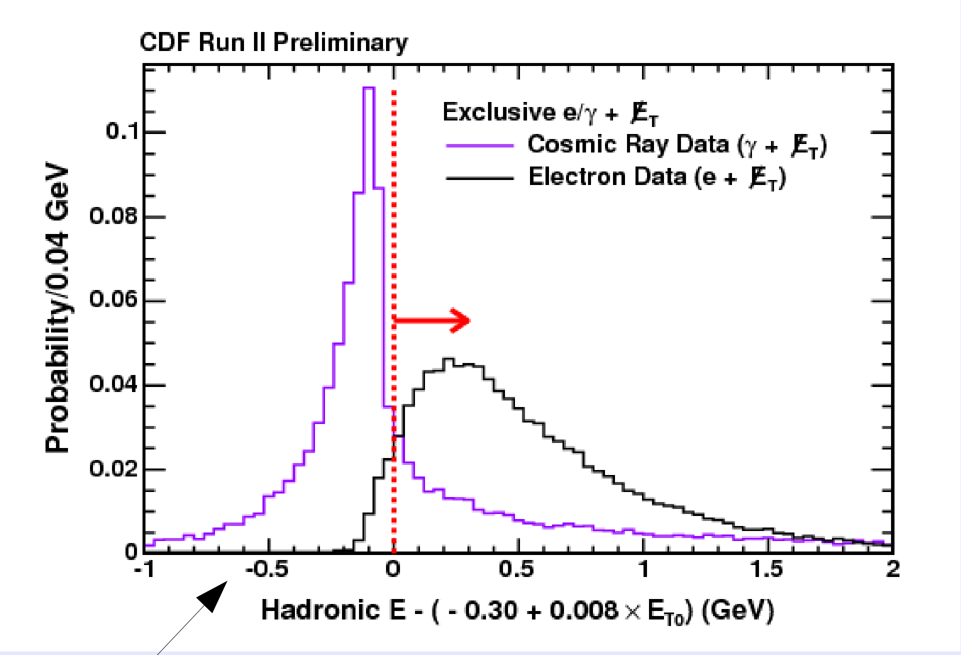
These particles travel parallel to the beam. If they interact in the calorimeter, they predominantly appear as photons arriving earlier than expected.



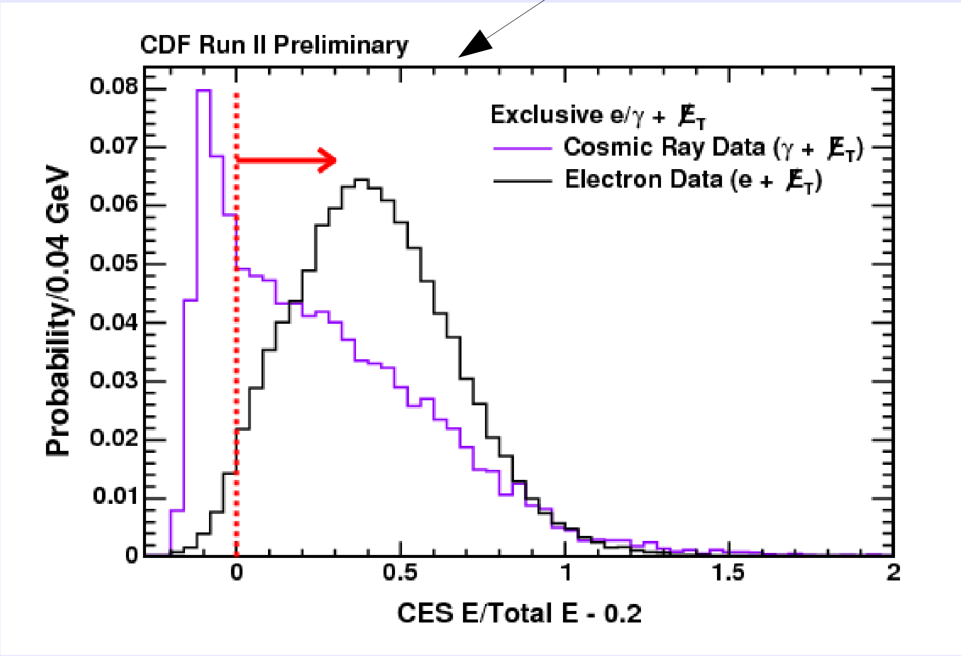
Our cuts are efficient at removing beam halo

Cosmic Ray Rejection

Since cosmic rays are muons and typically travel from outside the detector to the inside, look for evidence of abnormal showering:



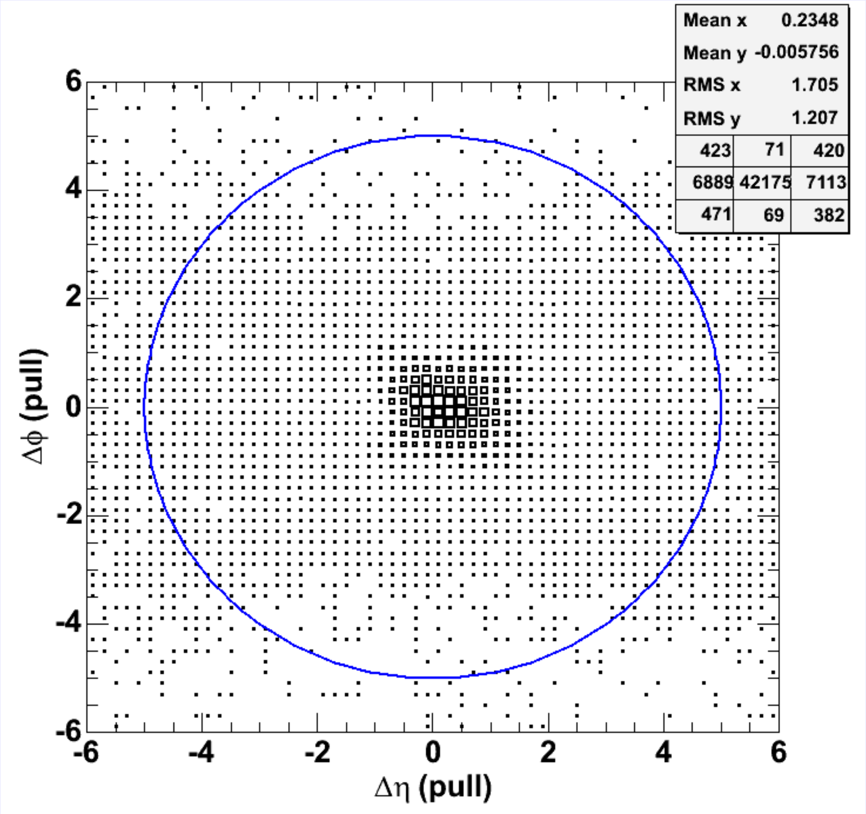
97% efficient
36% rejection



95% efficient
66% rejection

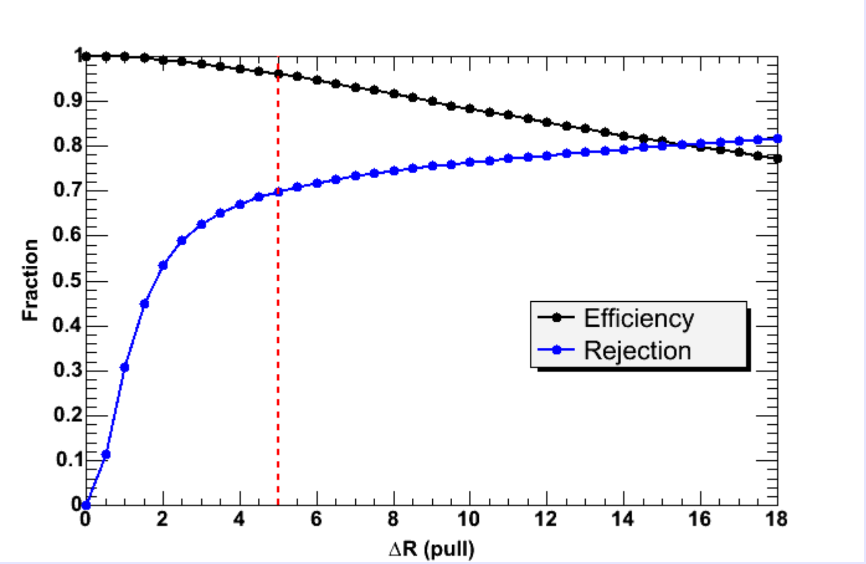
Combined: 92% efficient, 76% rejection

ΔR(pull)



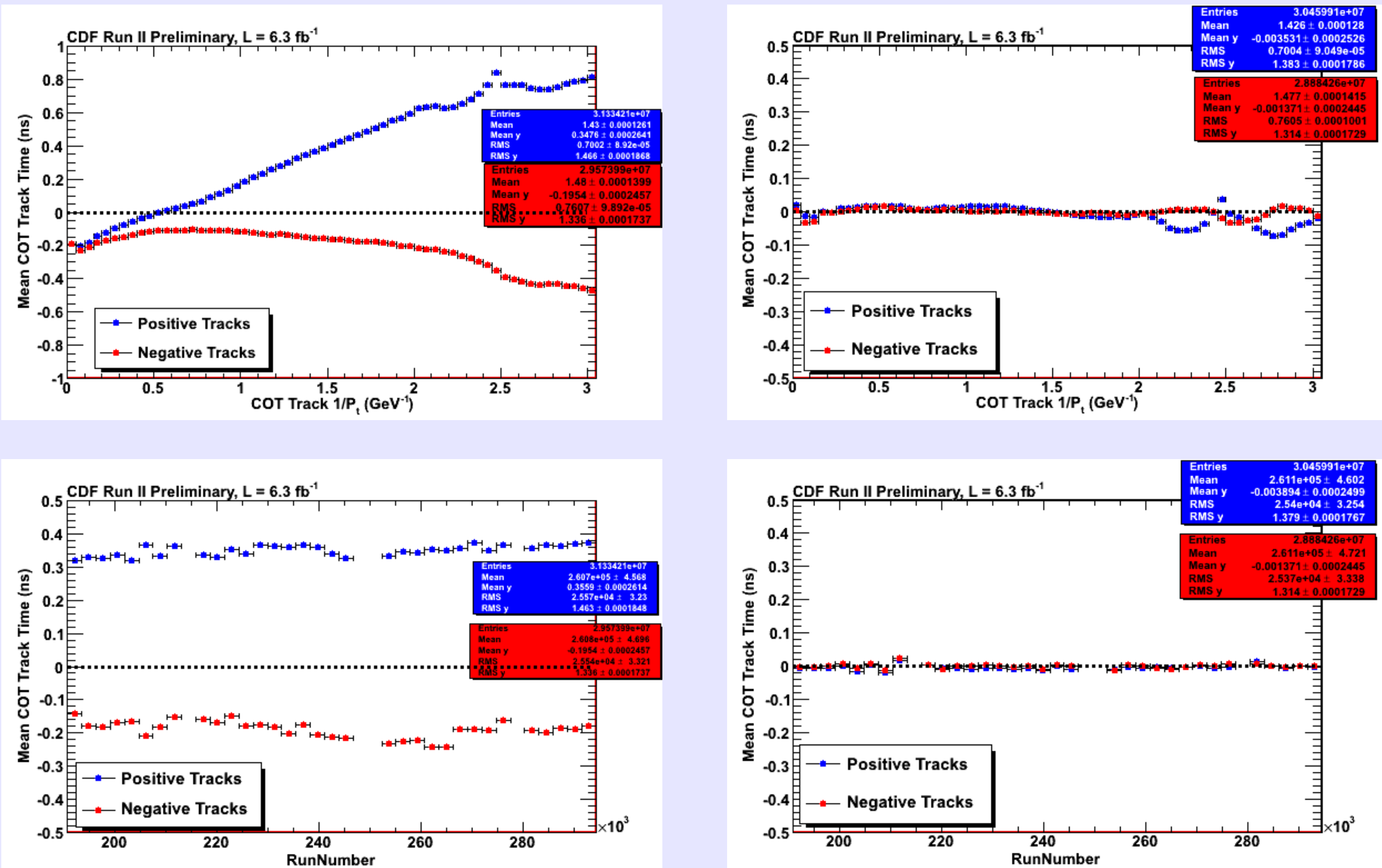
-Find the track with Φ_o and η closest to the reconstructed photon.

-Standardize the variables to account for worse resolution in Φ_0 due to the "kink" in the track from the hard interaction.

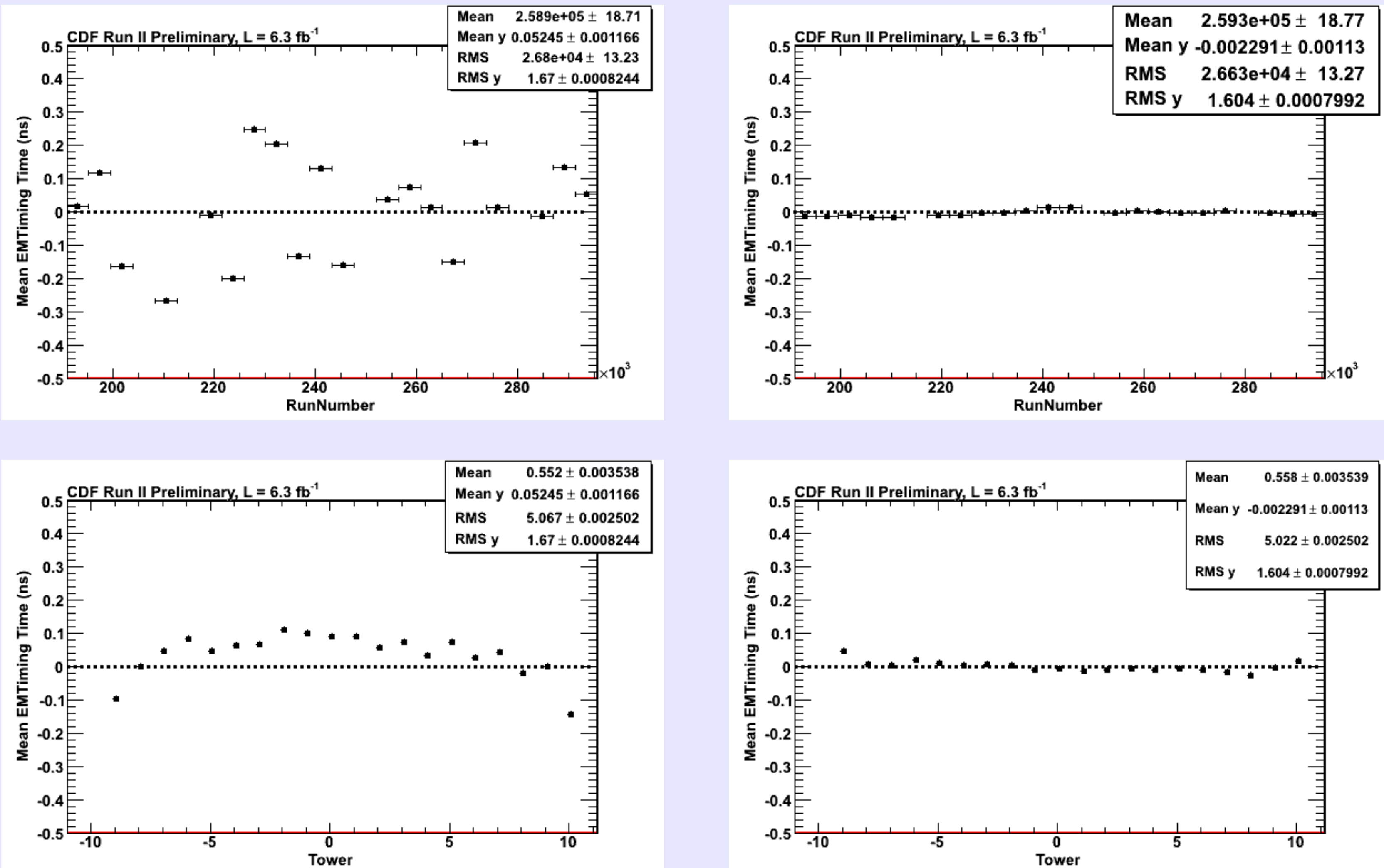


Vetoing reconstructed photons with a track with ΔR(pull) < 5 removes 73% of fake photons while accepting 95% of real photons.

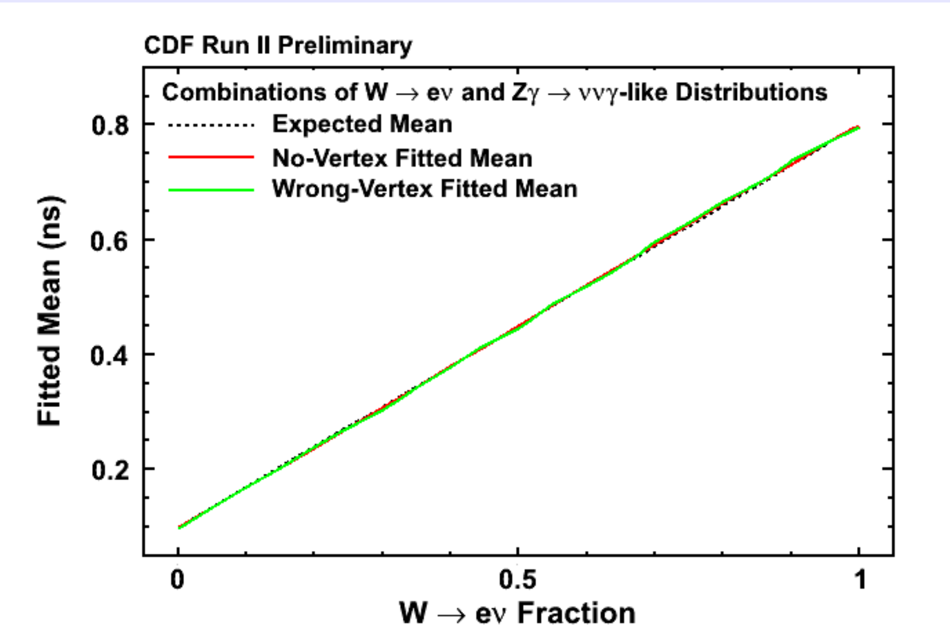
COT Track t_0 Corrections



EMTiming Corrections



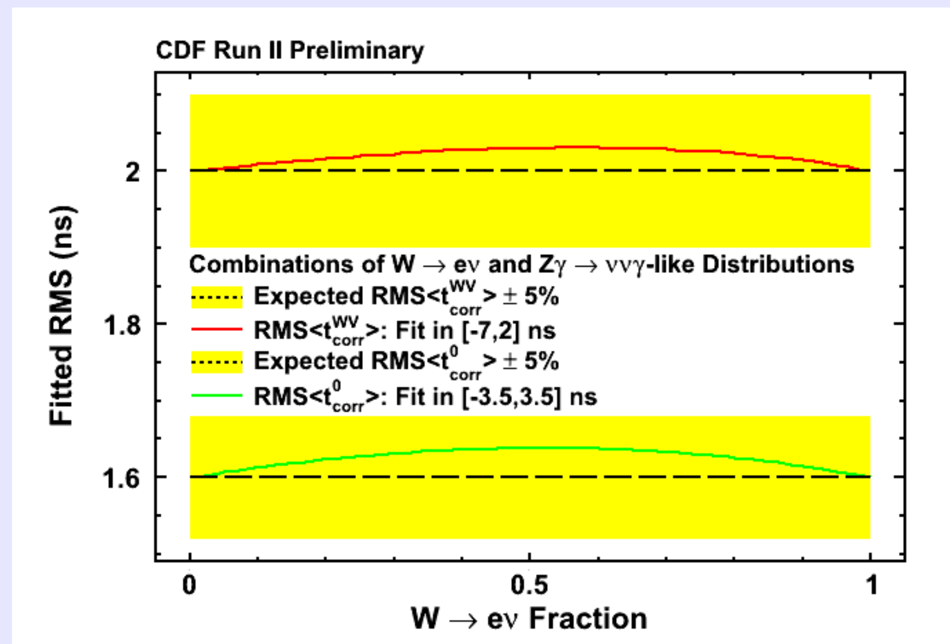
Effect of Combining Collision Background Sources



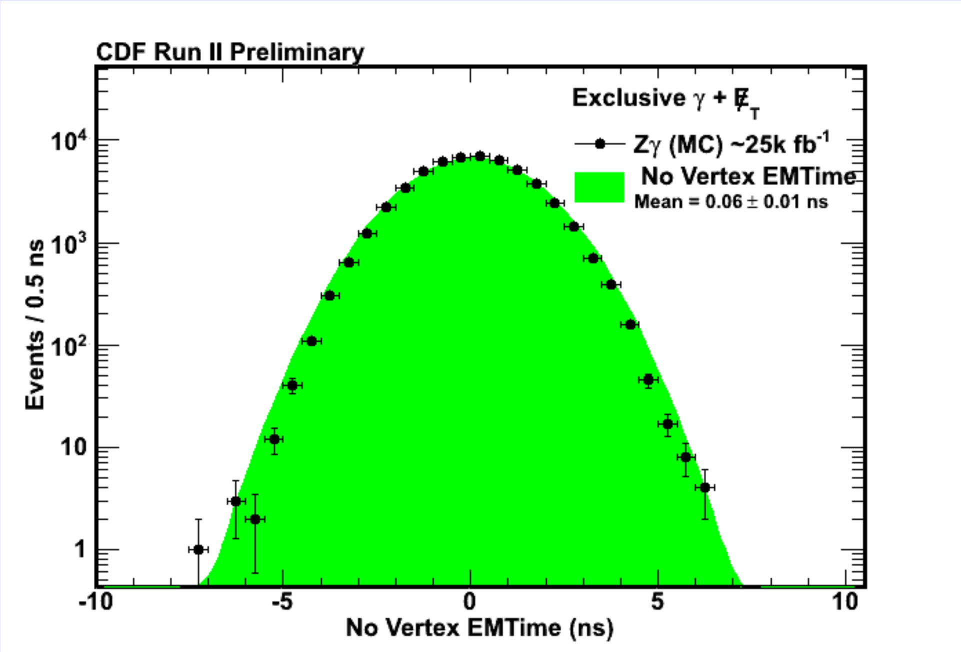
Up to this point, we considered single Standard Model sources. Does the double Gaussian description apply with combinations of sources?

We generate Gaussians with means of 0.1 ns and 0.7 ns. We combine them in various fractions.

The fitted RMS increases slightly as we approach a 50% combination. We cover this with a 5% systematic.



No Vertex Distribution



If no good vertex reconstructed, we can still construct the raw time variable: the corrected time, around a vertex with Z = 0 and T = 0.

The raw time distribution is Gaussian with RMS ~1.6 ns.

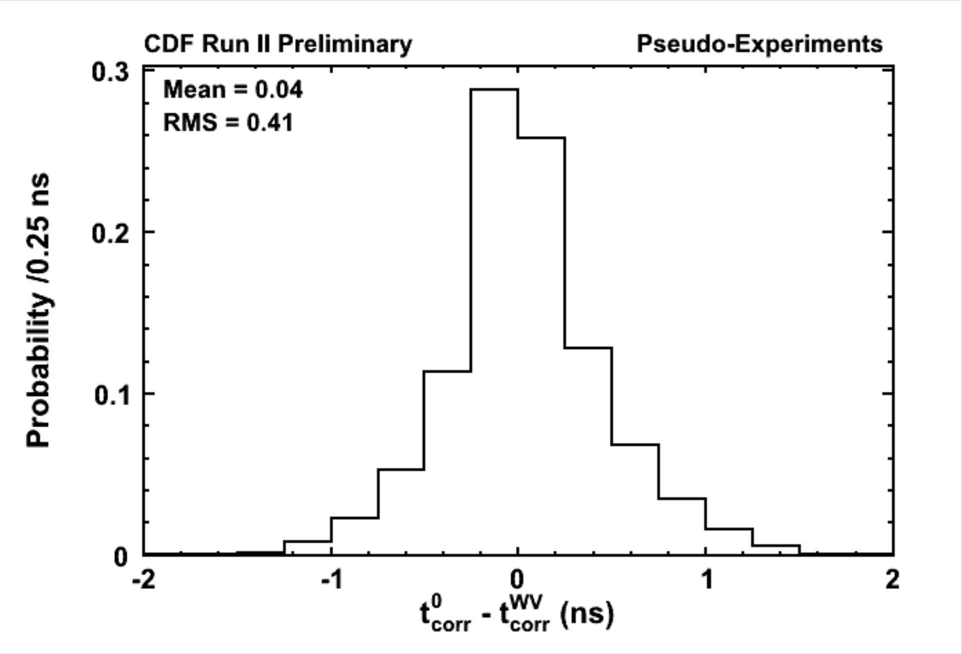
We will show that the mean of the no vertex distribution is always close to that of the wrong vertex distribution.

No-Vertex Time and Wrong-Vertex Time Toy MC

Consider pseudo-experiments where vertices are generated according to the Z and T profiles of the beam spot (Z RMS ~ 28 cm, T RMS ~ 1.28 ns).

Assume spherically symmetric production to determine CES Z.

Shows that if the process dependent geometric time of flight difference is the same for no-vertex and wrong-vertex events, the means of the two distributions will be very close.



Combined Likelihood Function

$$\text{-}\ln L = \sum_{i}^{Nbins(GV)} \nu_i^{GV} - n_i^{GV} \ln \nu_i^{GV} + \sum_{j}^{Nbins(NV)} \nu_j^{NV} - n_j^{NV} \ln \nu_j^{NV} + \sum_{k}^{Nconstraints} \frac{(\theta_k - \theta_k^0)^2}{2\sigma_k^2}$$

Good vertex portion includes bins between (-7,2) ns and (20,80) ns
No vertex portion includes bins between (-3.5, 3.5) ns and (20,80) ns
ν is the number of expected events in a bin
n is the number of observed events in a bin
θ_k is the parameter being constrained
θ_k^0 is the nominal value of the constrained parameter
σ_k is the systematic uncertainty on θ_k

Event Reduction Table for 6.3 fb^{-1}

Cut	# of Events
Preselect a sample with a Photon w/ E_T > 45 GeV & MET > 45 GeV	38,291
Reject Beam Halo Events	36,764
Reject Cosmic Events	24,462
Track Veto	16,831
Jet Veto	12,708
Large |Z| Vertex Veto	11,702
$e \rightarrow \gamma_{fake}$ Rejection	10,363
Good Vertex Events/No Vertex Events	5,421/4,942

Fit Results

CDF Run II Preliminary			$\int \mathcal{L} = 6.3\ \mathrm{fb}^{-1}$
	Signal $2 < t_{\mathrm{corr}} < 7$ ns	**RV Sideband** $-2 < t_{\mathrm{corr}} < 2$ ns	**WV Sideband** $-7 < t_{\mathrm{corr}} < -2$ ns
Right Vertex	1.0 ± 0.6	873 ± 65	0.6 ± 0.4
Wrong Vertex	126 ± 24	460 ± 60	89 ± 11
Cosmics	159 ± 4	128 ± 3	159 ± 4
Total Estimation	286 ± 24	1461 ± 38	249 ± 11
Data	322	1463	241

The number of events predicted and observed in our three regions of interest. The total event expectations in the signal region is 286 ± 24; we observe 322 events in the data. This gives a modest 1.2σ excess. Note that the two sideband regions are determined using the fit, but are included here for completeness.