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

Adam Aurisano

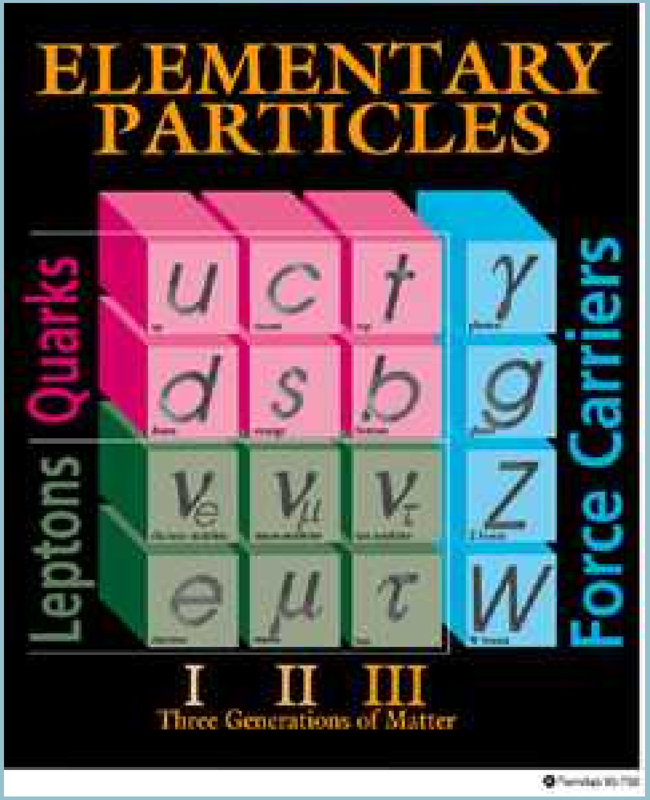
Preliminary Exam
Texas A&M University

Special thanks to: Jonathan Asaadi,
Daniel Goldin, Jason Nett, and David Toback

Outline

- Introduction
- Motivation
- Tools
- Overview of the Delayed Photon Analysis
- Sources of Large Times from SM Backgrounds
- Estimating SM Background Contributions
- Conclusions

Standard Model



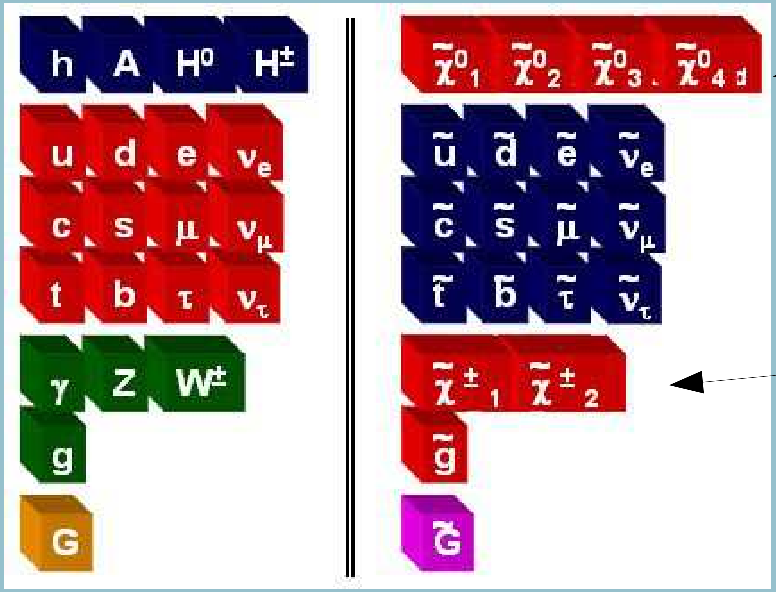
NB: The Higgs boson is also part of the Standard Model, but it has not been observed yet.

- 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.
- One problem is the “hierarchy problem” - the Higgs mass has quadratic divergences that must be canceled with fine tuning.

Supersymmetry

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

Requires five Higgs particles instead of one.



Neutral Higgses and electroweak bosons mix to make “neutralinos”

The new particles remove the quadratic divergence in the Higgs mass.

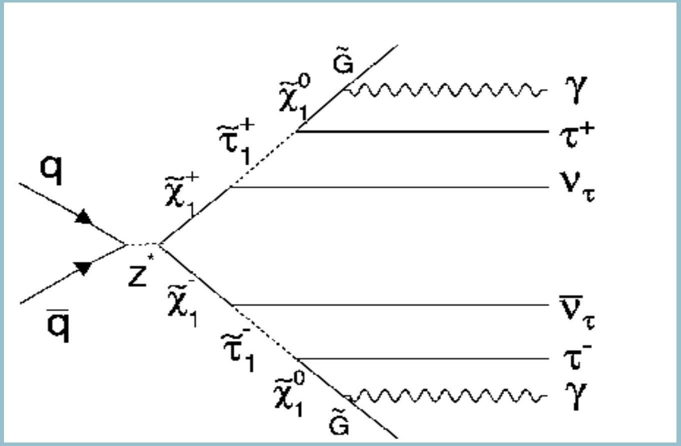
Charged Higges and electroweak bosons mix to make “charginos”

SUSY must be a broken symmetry: M(SUSY) != M(SM) or else we would have seen them already.

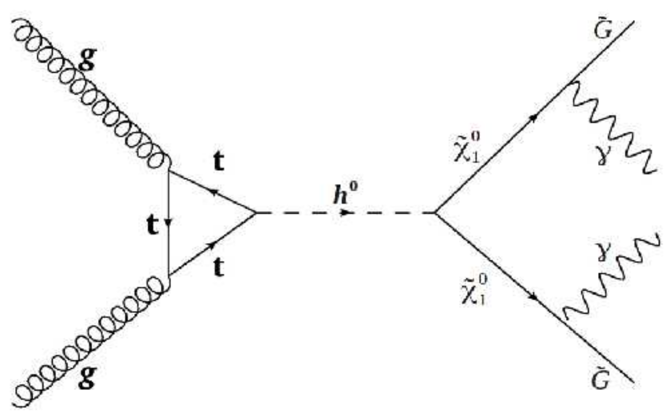
Gauge Mediated Supersymmetry Breaking (GMSB)

- GMSB is one possible way to break supersymmetry.
- Posits symmetry breaking via a hidden sector transmitted through Standard Model gauge interactions.
- GMSB scenarios typically have the SUSY partner of the graviton, the gravitino, as the lightest SUSY particle.
- In non-minimal versions of GMSB, only the gravitino and the lightest neutralino are light enough to be created in detectors.
- These scenarios are not constrained by current neutralino mass limits set my LEP, the Tevatron or the LHC → worth going after!

GMSB Search Types



Minimal GMSB models tend to produce cascade decays → look for photons + lots of extra stuff (done at CDF in 2007 and 2010)



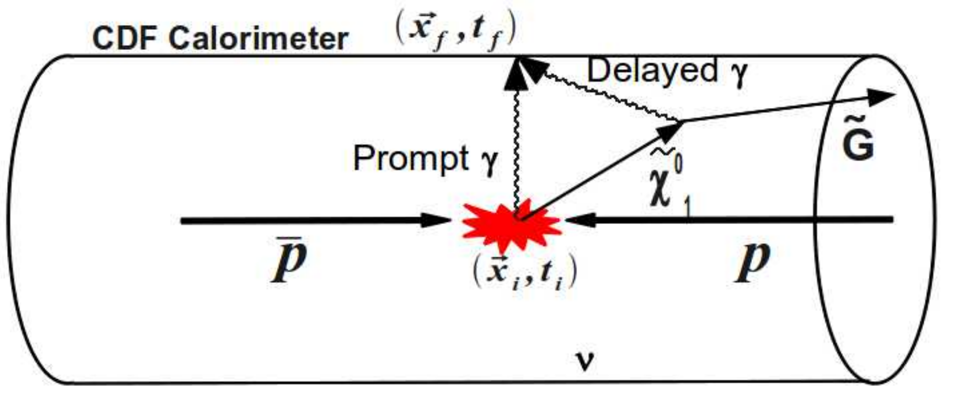
In general GMSB models, only the $\widetilde{\chi_1^0}$ and $\widetilde{G}$ are accessible → look for photons and nothing else.

These have never been done before, so we focus on this type of search. In particular, in the long lived case, one $\widetilde{\chi_1^0}$ may decay outside the detector - leaving only a single photon visible.

References:
Toback and Wagner
Phys. Rev. D 70, 114032 (2004) and
Mason and Toback
Phys. Lett. B 702, 377 (2011)

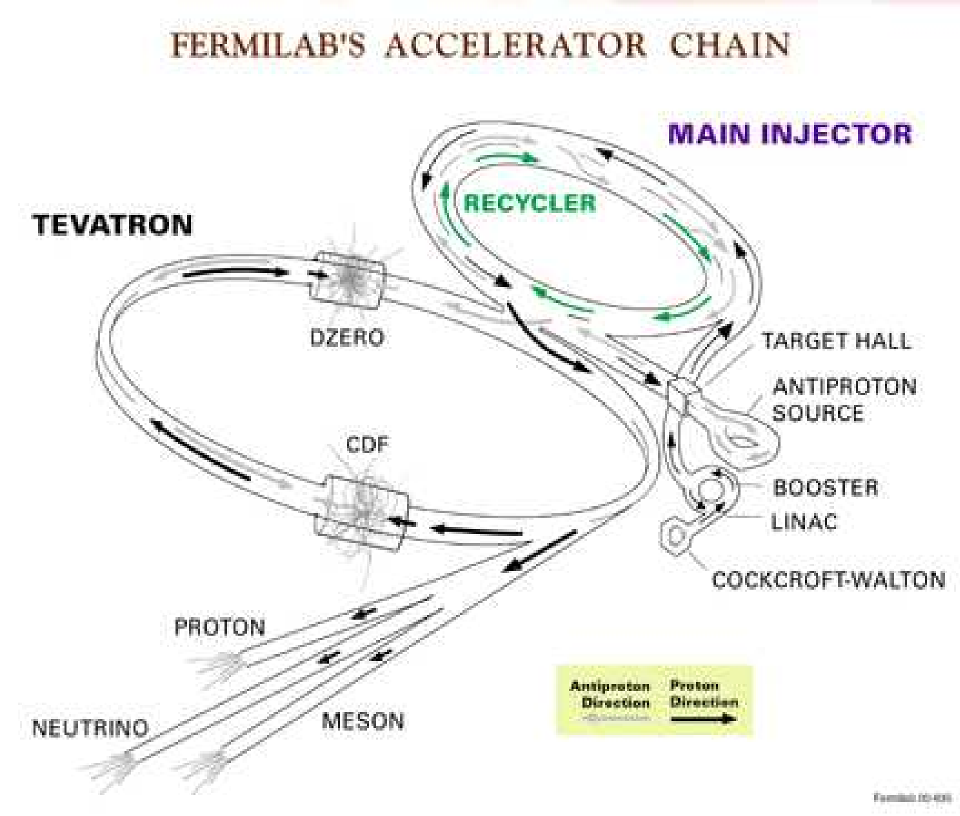
GMSB and Long Lifetimes

In some forms of GMSB, the next to lightest SUSY particle has a lifetime ~few nanoseconds before decaying to a photon and the lightest SUSY particle.



Photons arriving late relative to expectations provides a distinct search signature. This provides a non-standard way to do a Higgs search.

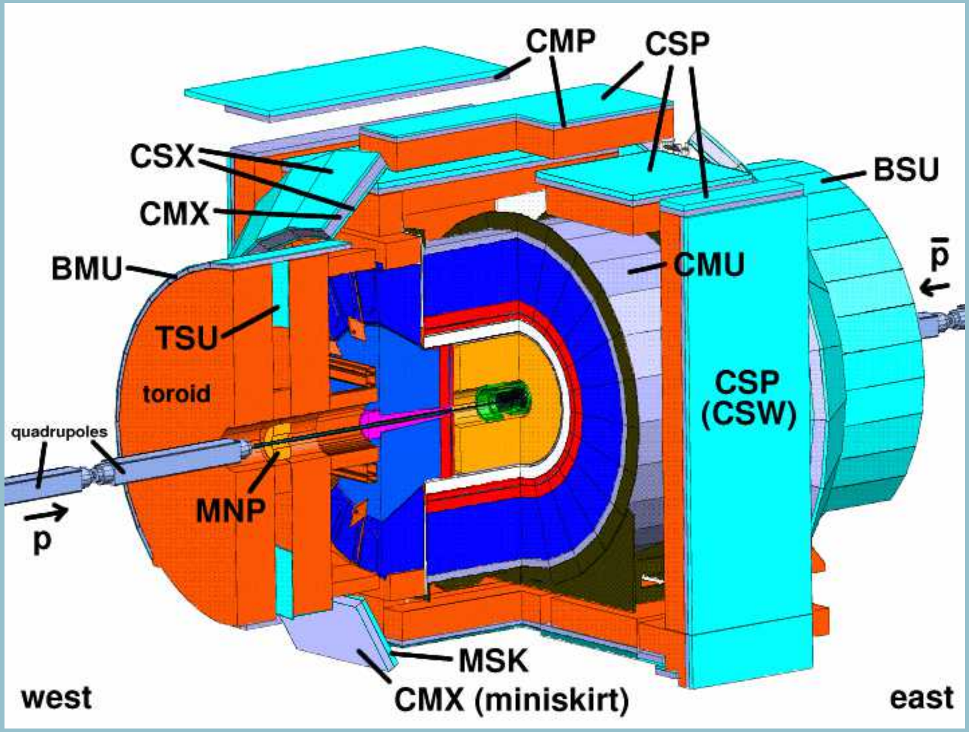
Tevatron



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

Even though the LHC is much more powerful, the Tevatron has accumulated nearly 10 fb^{-1} of data. In certain final states, the Tevatron is still more sensitive.

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.

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.

Electromagnetic calorimeter - records energy deposits from particles that interact electromagnetically.

Exclusive γ+MET Final State

Standard Model Collision Backgrounds

$$W \rightarrow e\,\nu \rightarrow \gamma_{\text{fake}}\,\not{E}_{\text{T}}$$

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

$$W \rightarrow \tau\,\nu \rightarrow \gamma_{\text{fake}}\,\not{E}_{\text{T}}$$

$$W\,\gamma \rightarrow \gamma\,l_{\text{lost}}\,\nu \rightarrow \gamma\,\not{E}_{\text{T}}$$

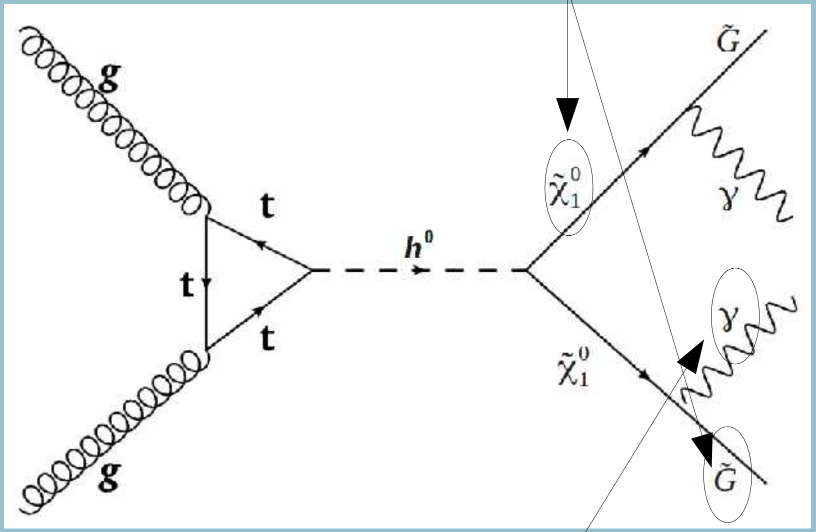
$$Z\,\gamma \rightarrow \gamma\,\nu\,\nu \rightarrow \gamma\,\not{E}_{\text{T}}$$

Other Backgrounds

γ

- Cosmic Rays
- Beam Halo
- Satellite Bunches

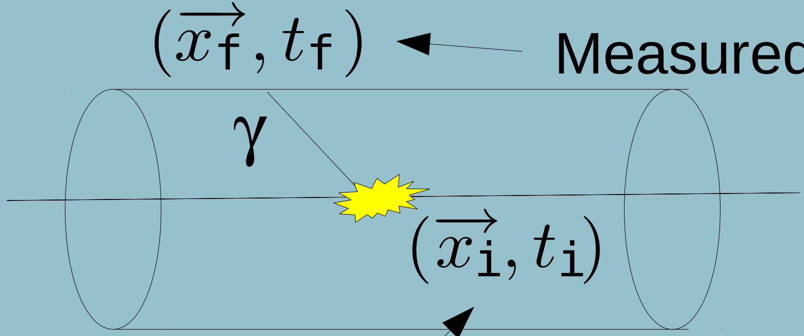
Leave detector unseen: detected as an imbalance in transverse energy (MET)



Seen as a single delayed photon + MET + nothing else.

Definition of Corrected Time

Corrected time ($t_{\mathtt{corr}}$) allows us to GMSB from background:

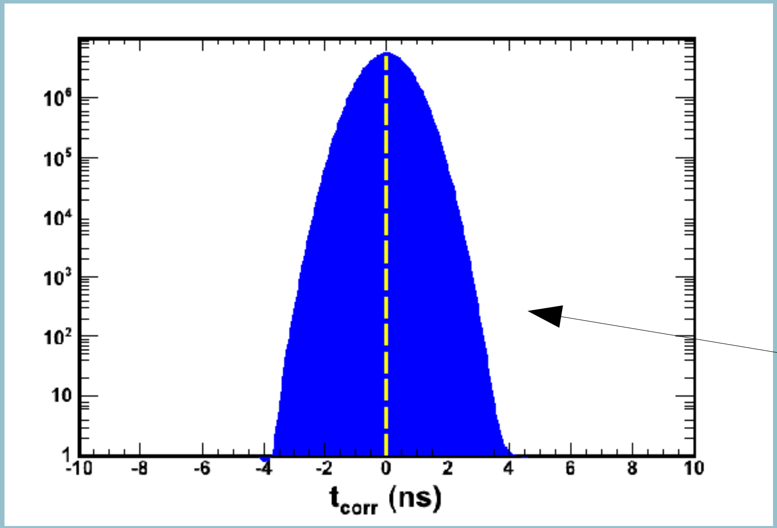


Measured by EMTiming

Measured by clustering tracks from the COT

$$t_{\mathtt{corr}} = (t_{\mathtt{f}} - t_{\mathtt{i}}) - \frac{|\overrightarrow{x_{\mathtt{f}}} - \overrightarrow{x_{\mathtt{i}}}|}{c}$$

Assumption of “prompt photon” - particle comes directly from the interaction point and travels the speed of light.

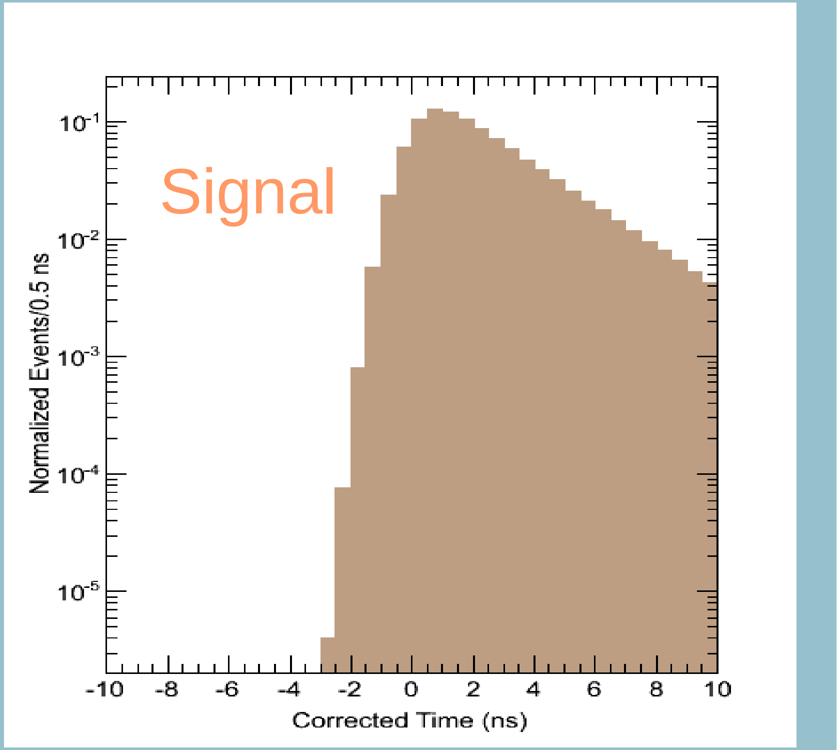


If the photon is “prompt”, and it comes from the selected interaction point, we call it a “right vertex” event.
By definition, $t_{\mathtt{corr}}$ is zero smeared by the detector resolution (~0.66 ns).

Reference:
Nucl.Instrum.Meth.A563, 543 (2006)

Signal Distribution

A GMSB delayed photon signal looks like a decaying exponential.



In our detector, it would be smeared by the ~0.66 ns resolution.

For a reference point of:

$$M_{h^0} = 135 GeV$$

$$M_{\tilde{\chi}_1^0} = 65 GeV$$

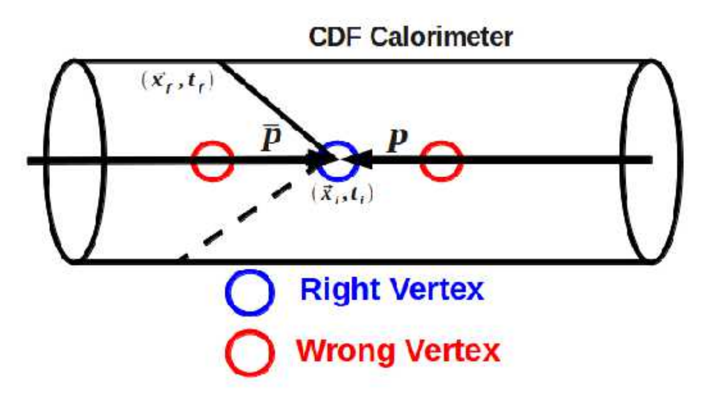
$$\tau_{\tilde{\chi}_1^0} = 5 ns$$

the decay constant is ~2.5 ns.

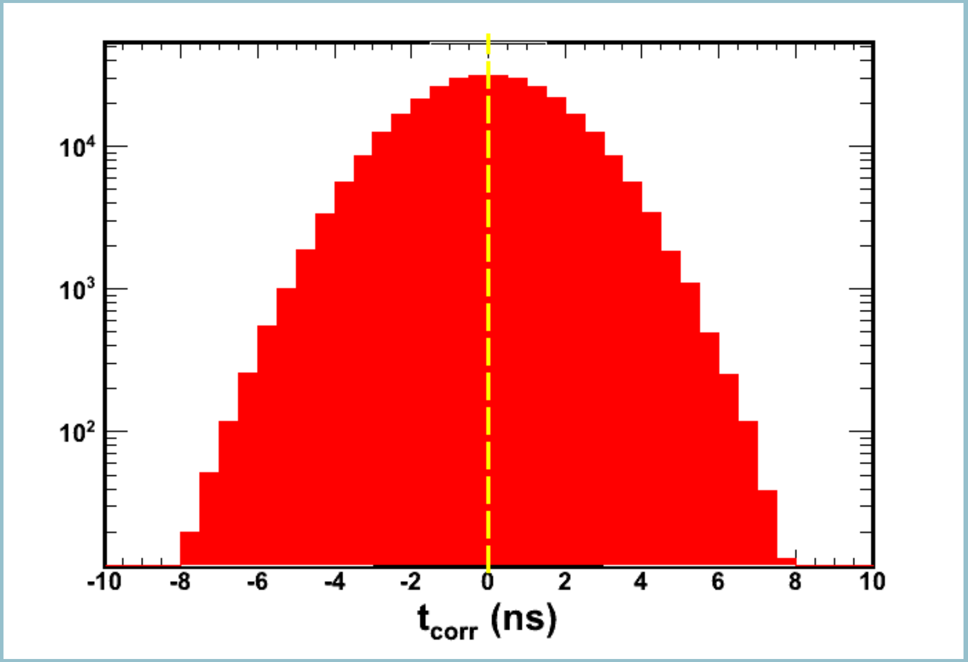
Next, we will look at the different types of background contributions.

Wrong Vertex Distribution

Sometimes SM collisions have multiple reconstructed interaction points (vertices), and sometimes, the correct one is not reconstructed.



Wrong vertex events are Gaussian σ ~ 2.05 ns.

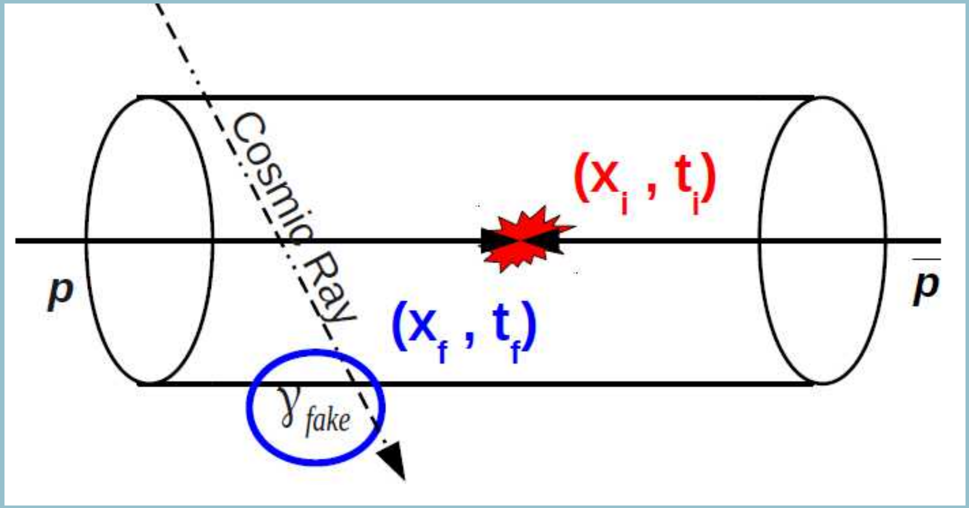


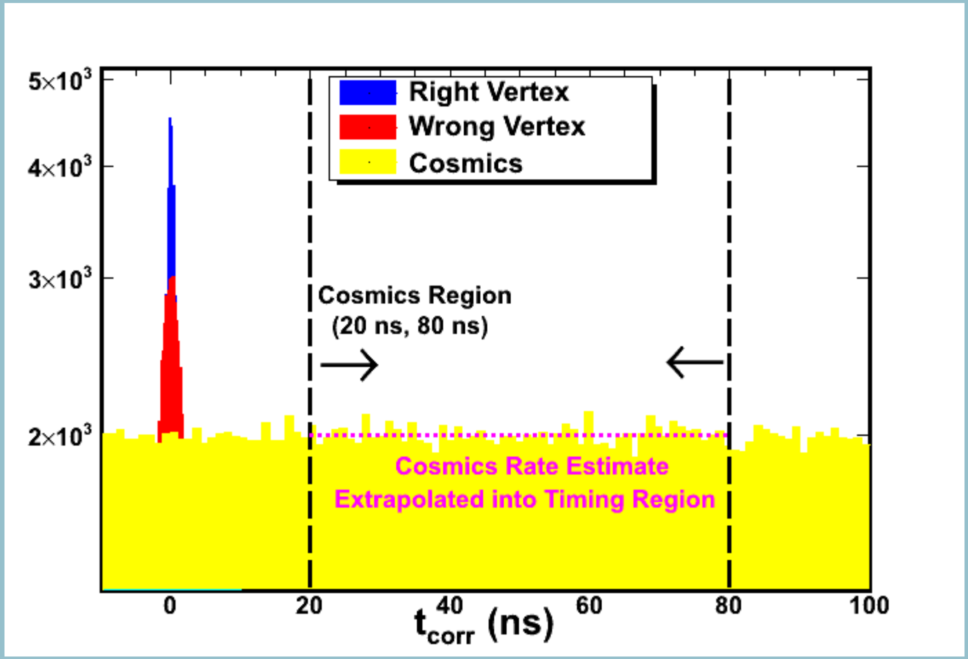
If we choose the wrong one, it is a "wrong vertex" event. This means we subtract of the wrong t_i and time of flight.

We used to assume that the wrong vertex mean = 0. Measuring this mean is the primary concern of this analysis.

Cosmic Ray Distribution

Cosmic rays can hit the calorimeter and get reconstructed as photons.





Cosmic rays are uncorrelated with the actual collisions, so their distribution is flat in time.

This is the dominant background, but it is easy to measure.

We determine the event rate/ns between 20 and 80 ns
(far from any collision physics) and extrapolate back to the collision region.

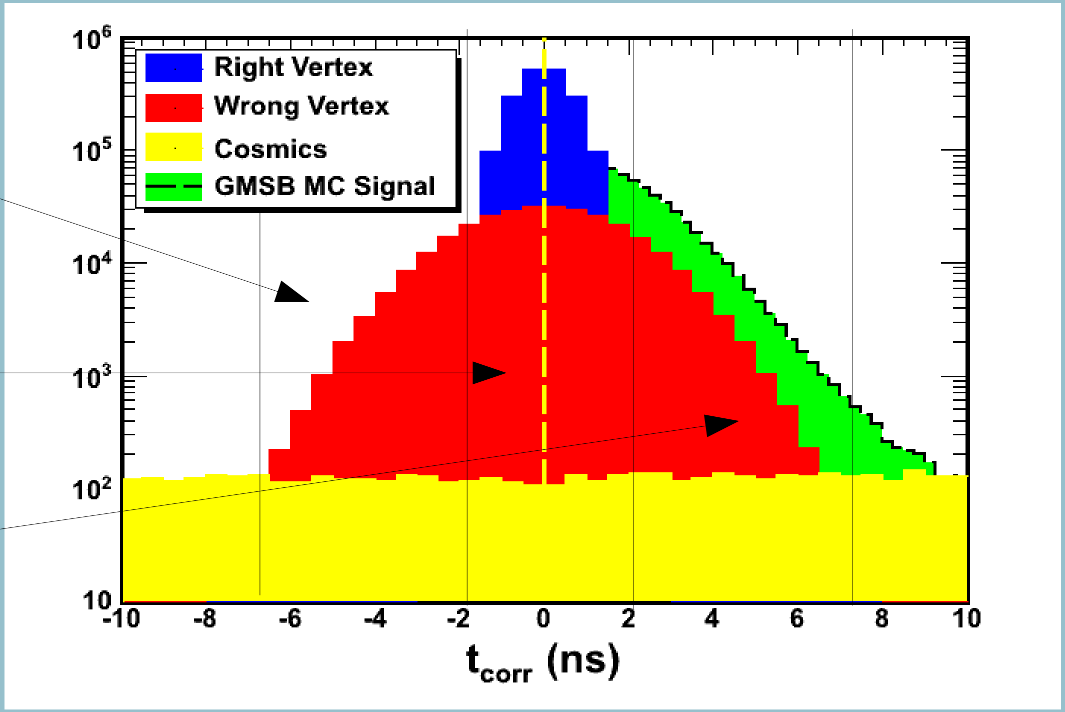
Timing Regions for Measuring SM Backgrounds

Timing Regions:

Control Region (CR)
-7 ns < t_{corr} < -2 ns

Bulk Region (BR)
-2 ns < t_{corr} < 2 ns

Signal Region (SR)
2 ns < t_{corr} < 7 ns



For SM Backgrounds:

CR = Mostly wrong vertex
BR = Mostly right vertex
SR = Mostly wrong vertex

The signal region is picked to allow as much signal (if any) as possible while minimizing right vertex and cosmic ray contamination.

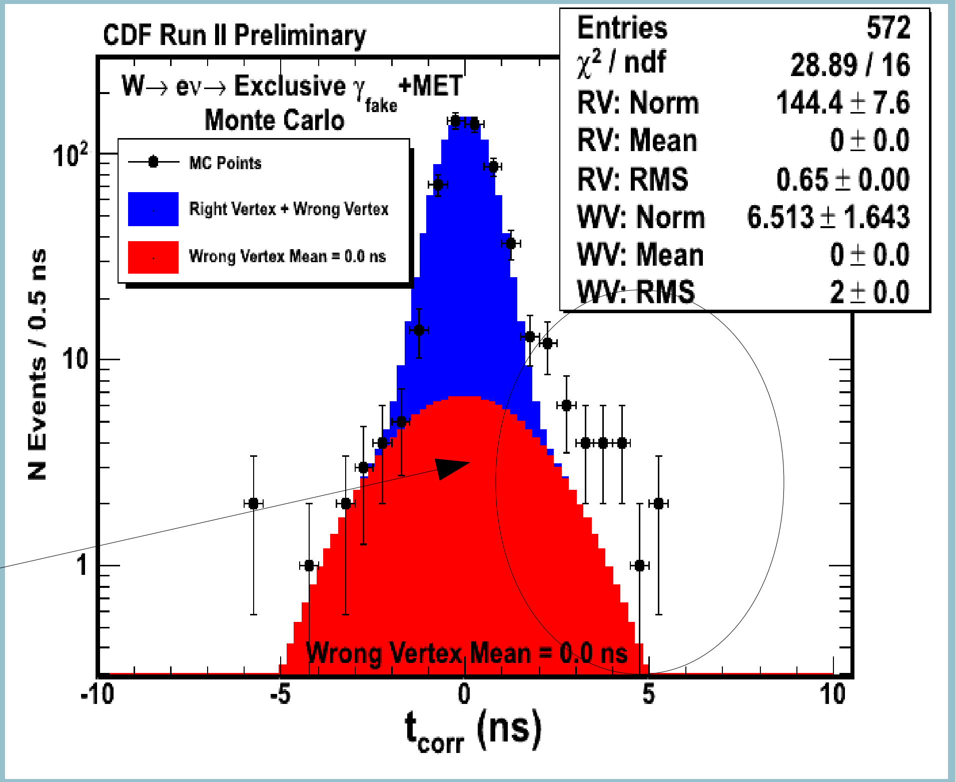
Goal – Estimate N_{SR} from background.

Wrong Vertex Mean

Is taking the wrong vertex mean = 0 a good assumption?

Fit the corrected timing distribution of $W \rightarrow e\nu \rightarrow \gamma_{fake}$ +MET Monte Carlo from (-7,2) ns assuming the wrong vertex mean is zero.

Very bad assumption! This SM background would appear to have a significant excess using the old method.



We need a method that can handle a non-zero wrong vertex mean.

Dealing with Shifted Wrong Vertex Distributions

- Goal: look for an excess in the signal region of (2,7) ns using a data driven background estimation approach.
- Assuming a wrong vertex mean of zero is biased.
- We need to:
  - Understand what causes events to have larger than zero average times
  - Determine strategies for removing or minimizing pathological cases
  - Measure the remaining bias to help estimate the amount of background in the signal region

Sources of Large Times from SM Backgrounds

A number of effects can cause SM wrong vertex backgrounds to have large mean shifts.

1) **E_T Threshold Effect**:

A distortion caused by events entering or leaving our sample due mis-measured E_T near the cut.

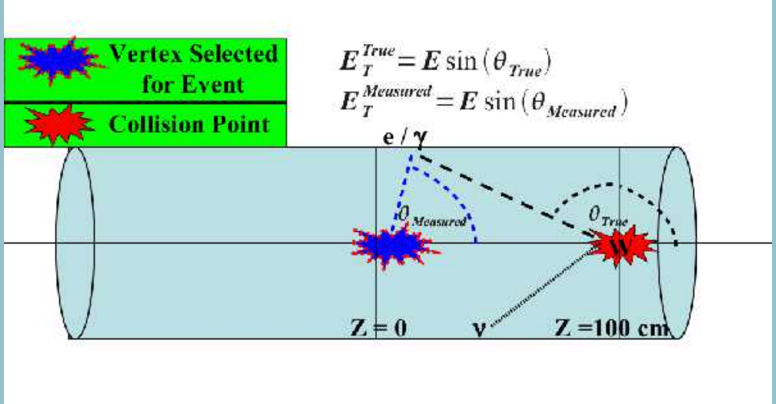
Topology Biases:

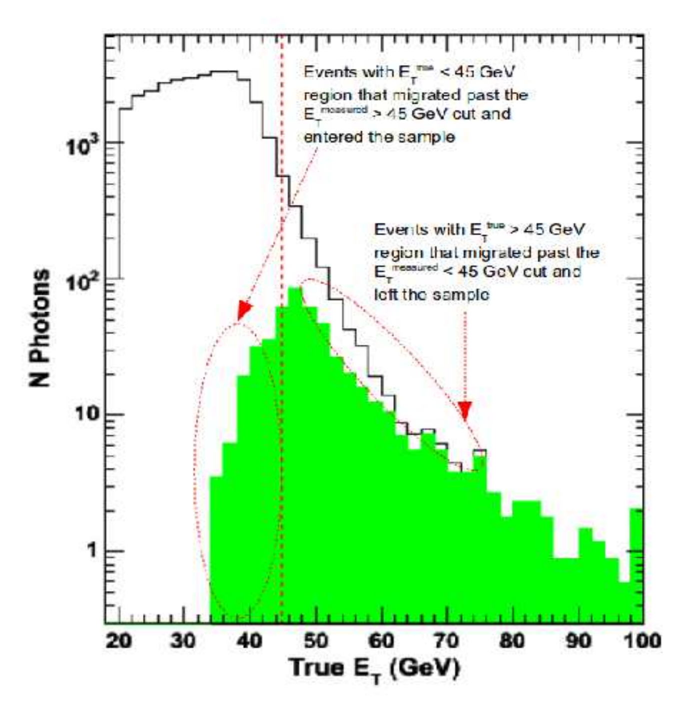
2) Fake photons: Fake photons from electrons tend to be biased to larger times due to being more likely at large path lengths.

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

Next: examine these effect and show how to mitigate them

Effect 1: E_T Threshold





Promotion Effect

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.

Demotion Effect

Wrong vertex gives larger apparent path length

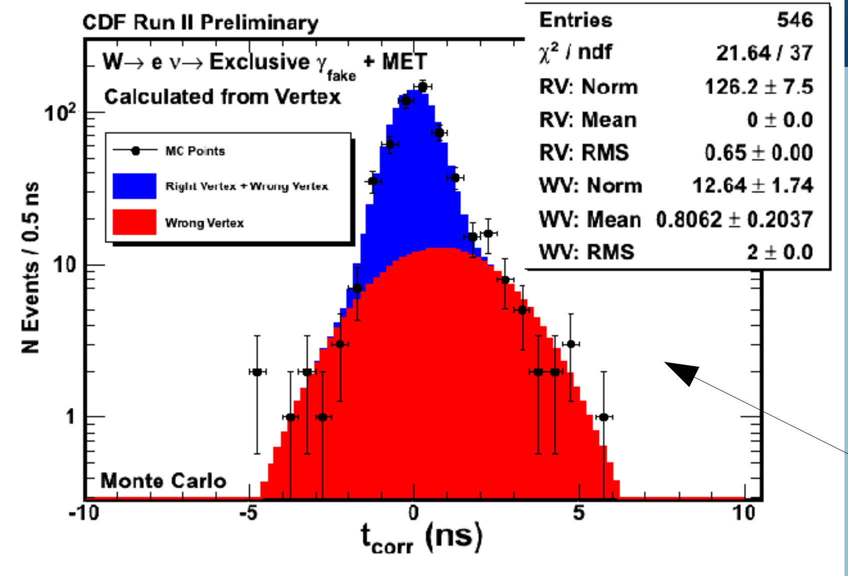
→ Shorter apparent time

→ Smaller measured E_T

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

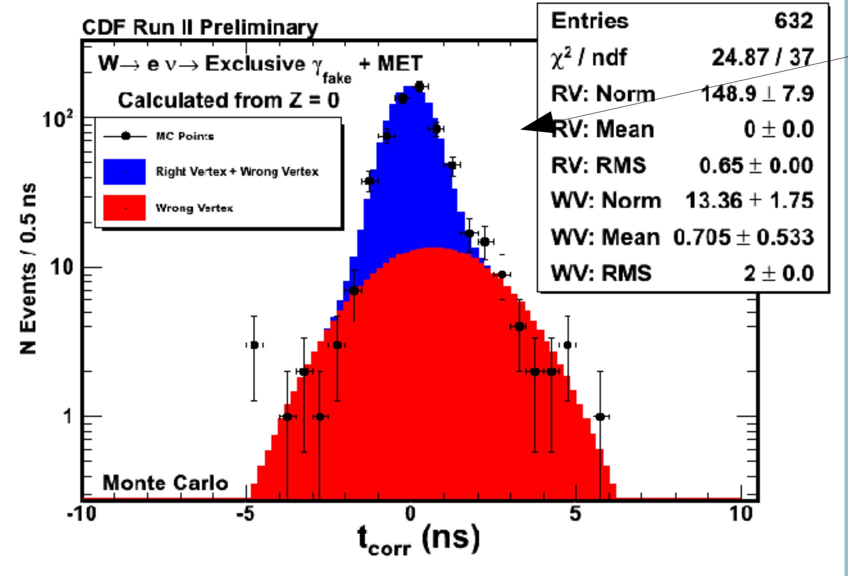
E_T^0 Cut

If we cut on E_T calculated relative to Z = 0, we limit how wrong we can be. The measured time and E_T are no longer completely coupled.

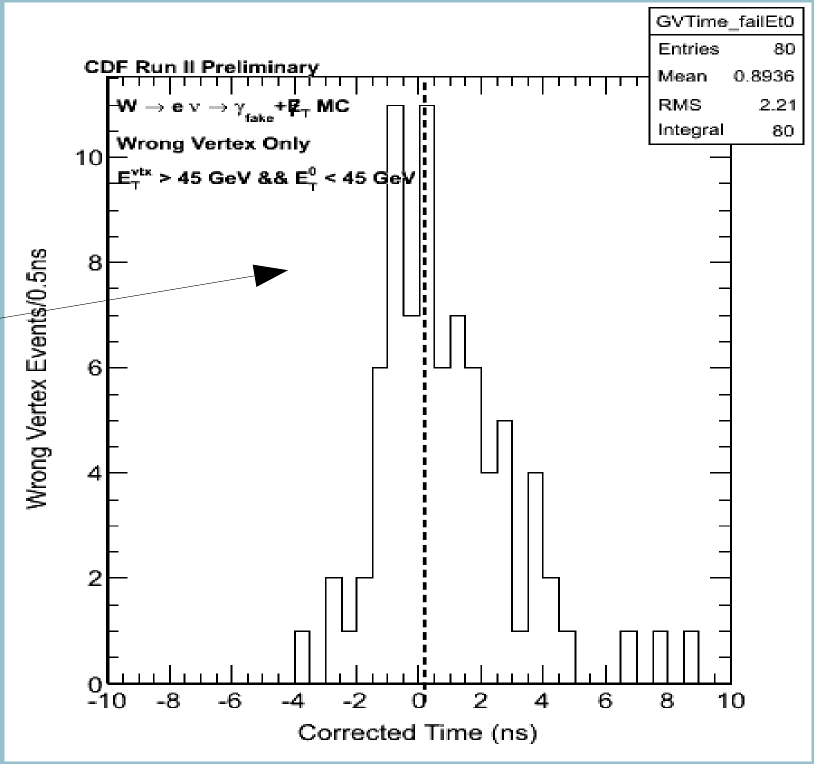


Before

After

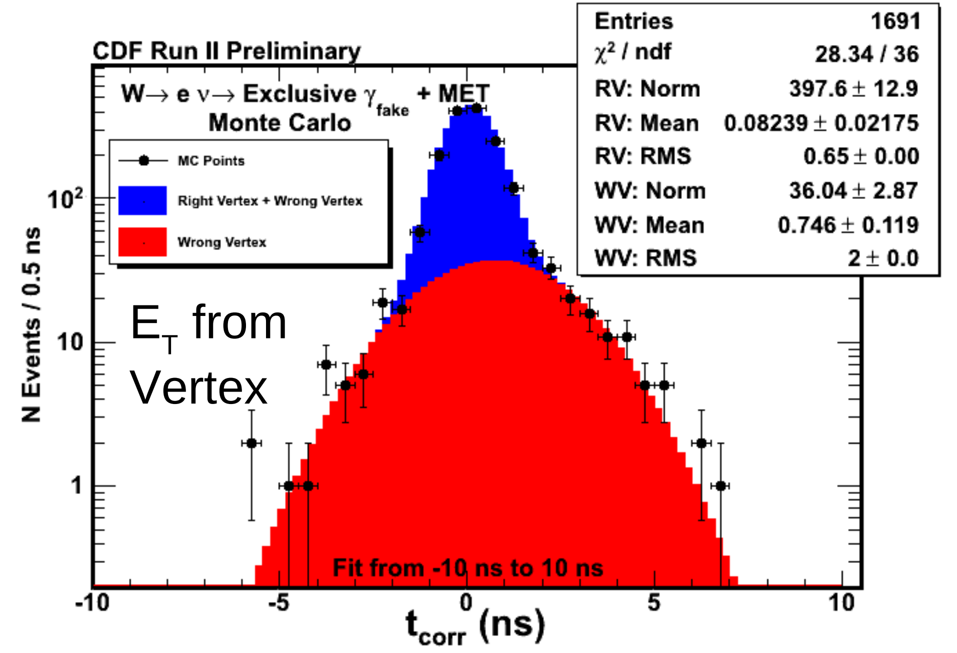


Rejected events have a very large mean (~0.9 ns)

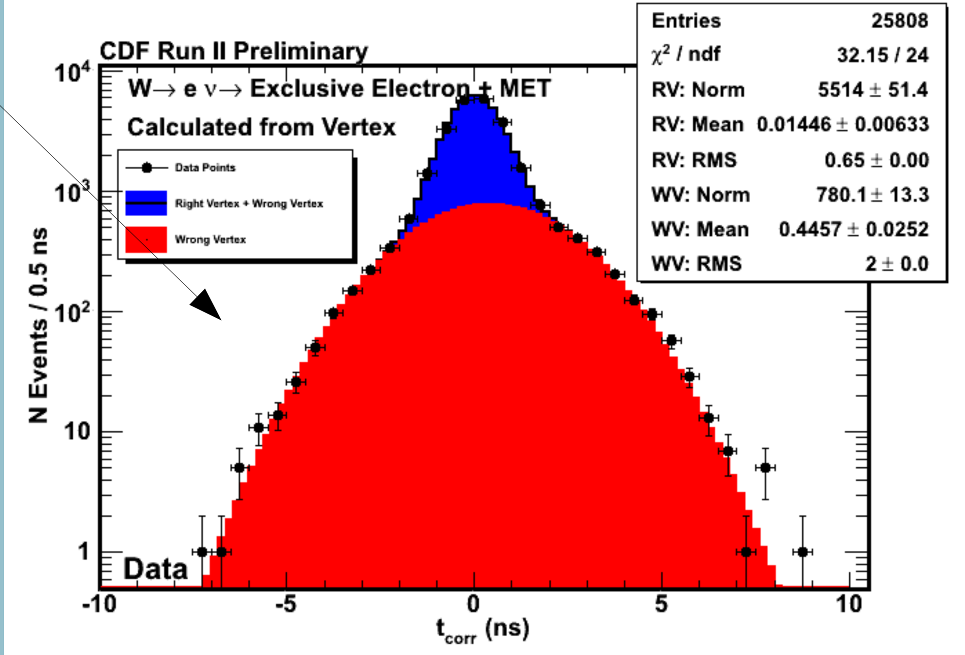


Effect 2: Fake Photons

$W \rightarrow e\nu \rightarrow \gamma_{fake}$ + MET has ~2x the mean shift that
$W \rightarrow e\nu \rightarrow e$ + MET has from the E_T threshold effect.



E_T from Vertex

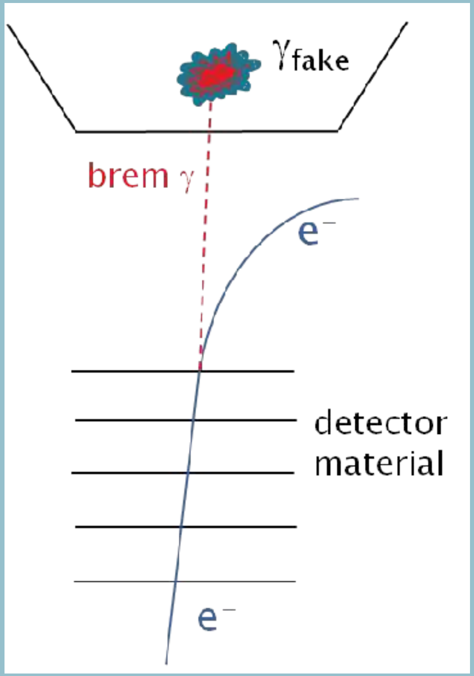


Electrons are more likely to have a hard interaction and not have a reconstructed track the more material they travel through.

Longer path lengths also correspond to larger times.

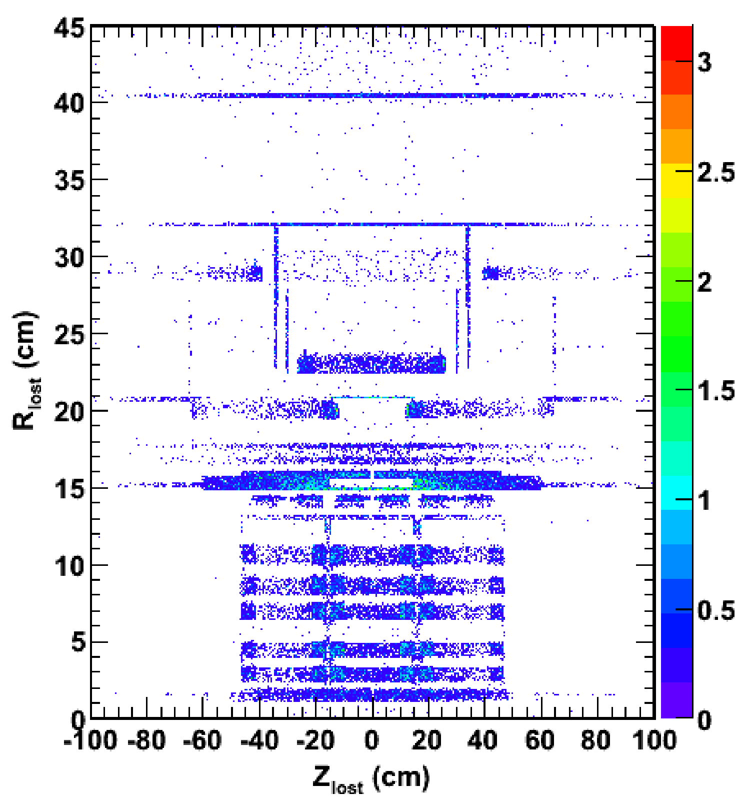
Fake Reduction

How can we reduce the number of fake photons?



-Fakes are overwhelmingly due to hard interactions which are most likely in dense regions (SVX, bulkheads, port cards, etc)

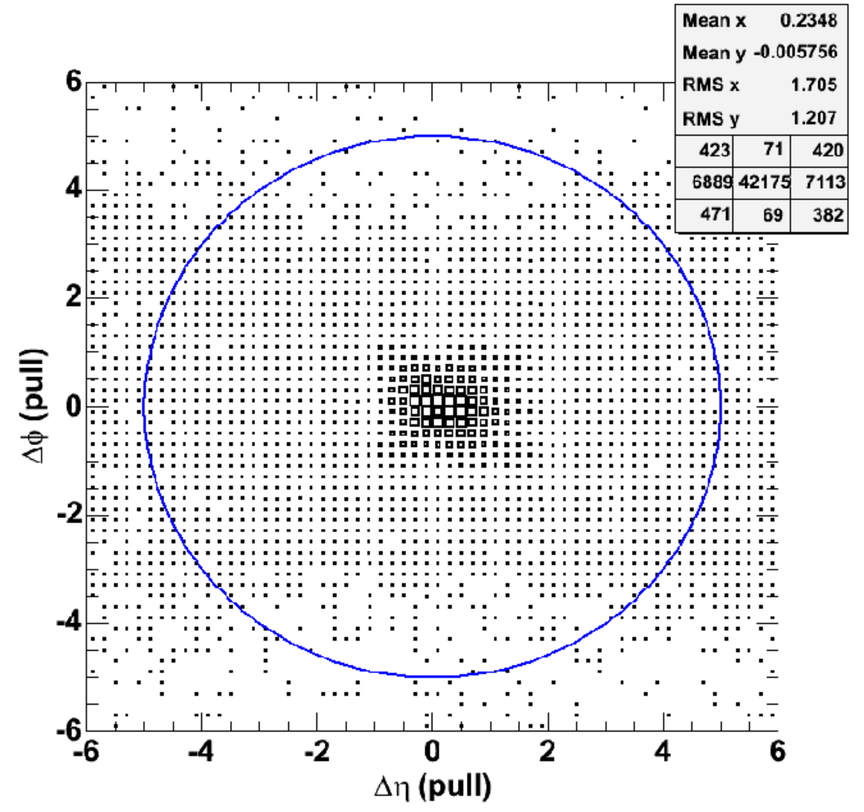
-The electron that gave rise to the fake photon should have started life pointing towards the calorimeter deposit.



Look for tracks with initial direction close to the reconstructed photon.

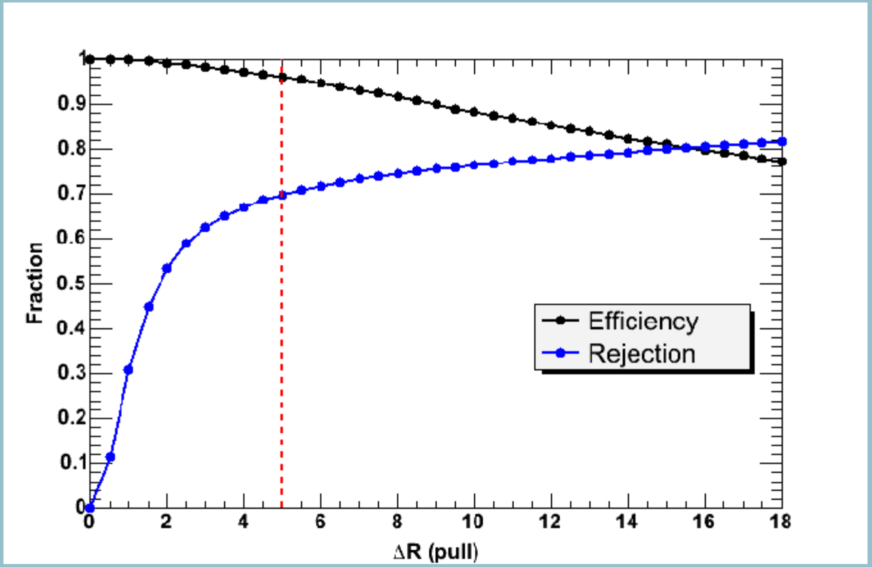
W → eν MC "xray" of locations where the electron "turns into" a photon.

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.



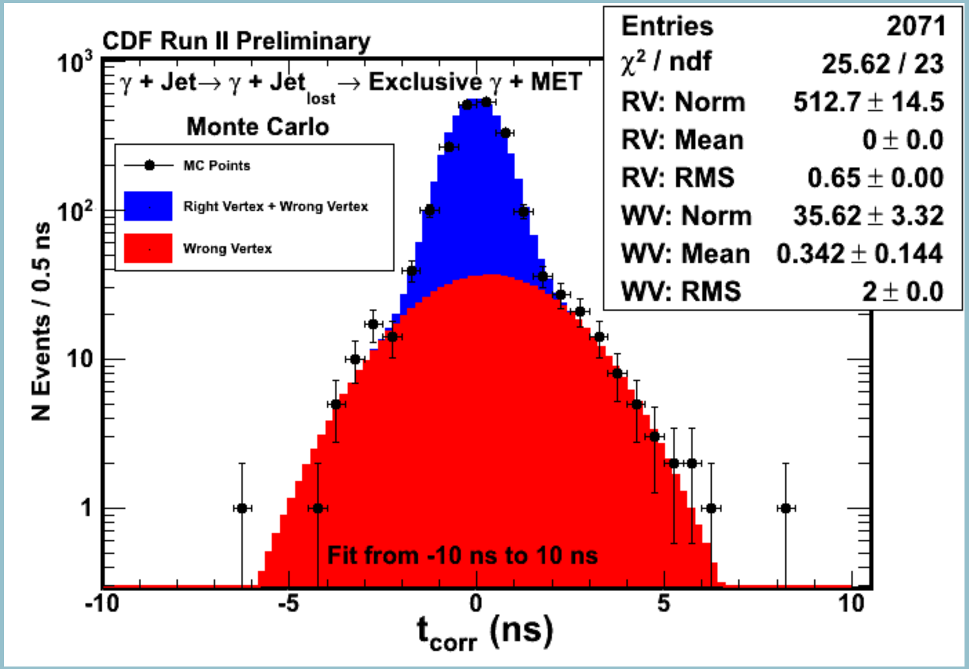
Vetoing reconstructed photons with a track with ΔR(pull) < 5 removes 67% of fake photons while accepting 95% of real photons.

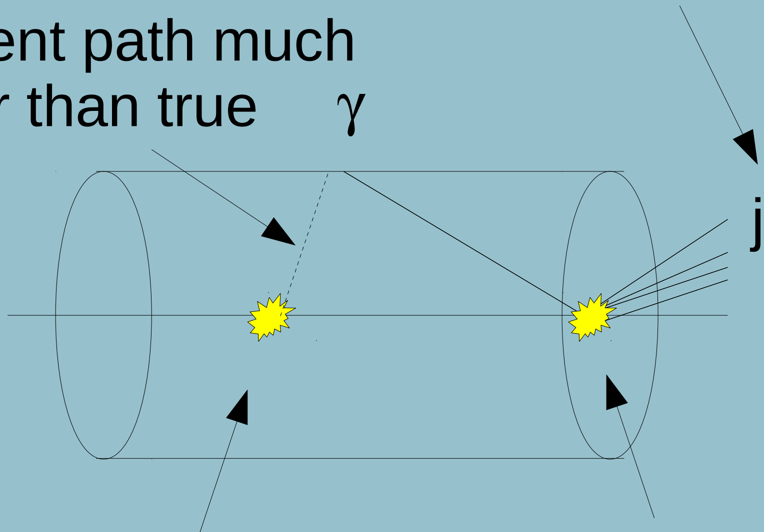
For more:
Goldin
SUSY meeting
September 21, 2011

Effect 3: Lost Jets

In the QCD γj sample, the wrong vertex mean is quite shifted despite virtually all photons being real.

This is due to the right vertex preferentially being at large |Z|.





Jet is lost due pointing out of the detector

Apparent path much shorter than true path

γ

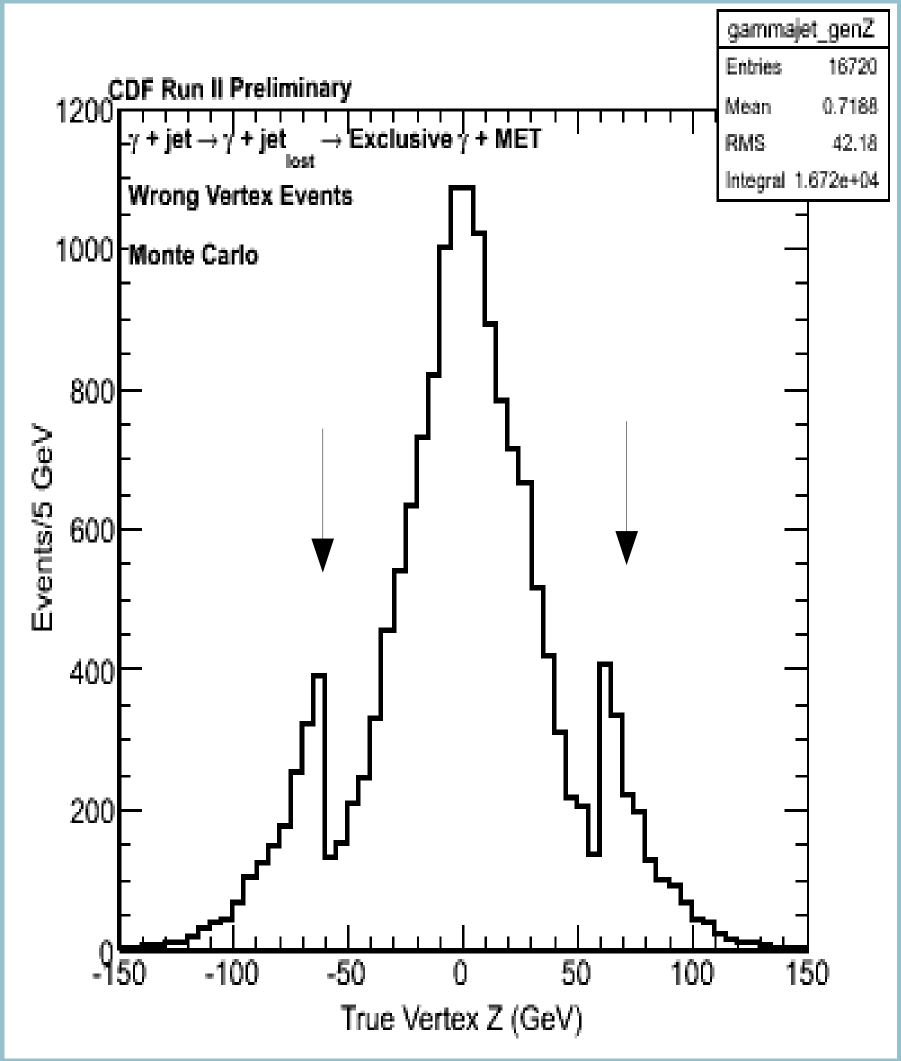
jet

Wrong vertex

Right vertex

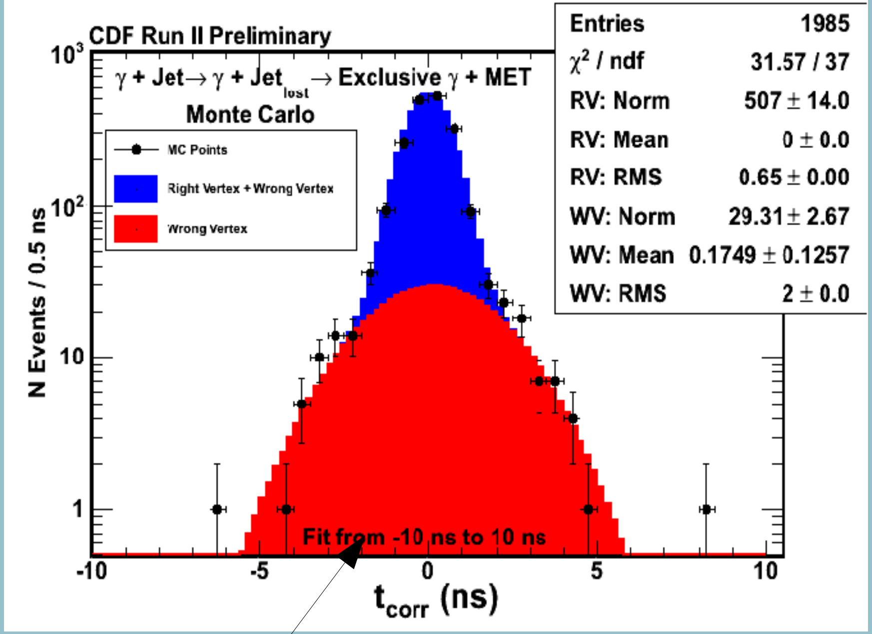
Large |Z|

- There are an unusual number of events at very large vertex |Z| positions.
- This leads to large biases, even for events that do not promote over threshold.
- To lose a real jet, either it has to be pointed into a crack, or the vertex |Z| has to be large enough for the jet to be able to point out of the detector.

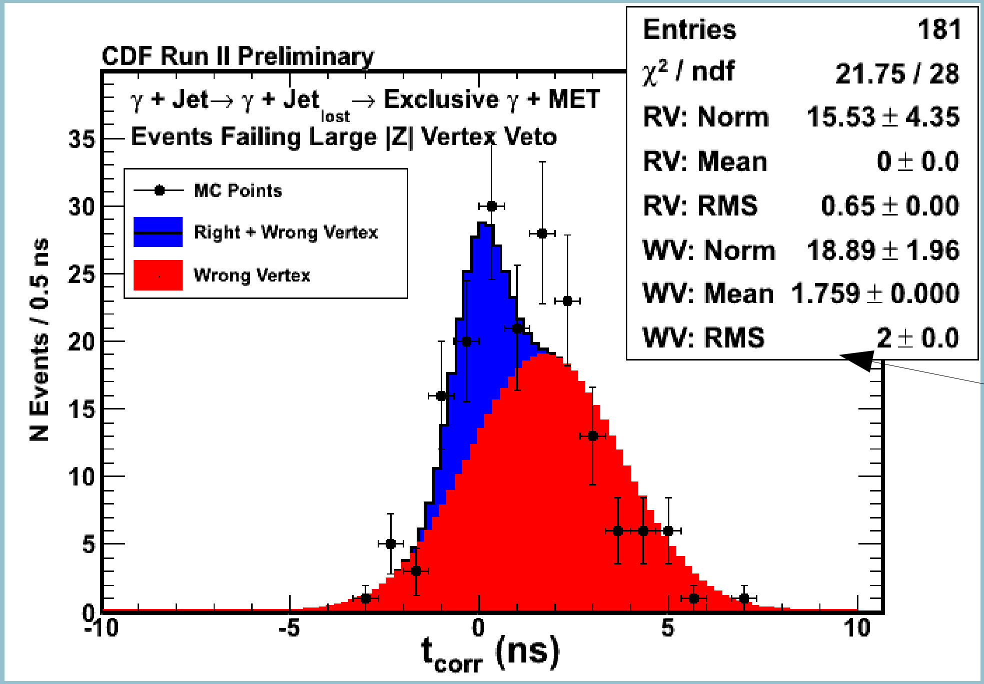


Large |Z| Veto

- Veto any event with a standard vertex with |Z| > 60 cm if it contains at least 3 tracks.
- This almost halves the γ+j wrong vertex mean.
- Using cosmics, we find this cut 96% efficient.



Passing Z Veto



Failing Z Veto
Rejected wrong vertex events are very highly shifted.

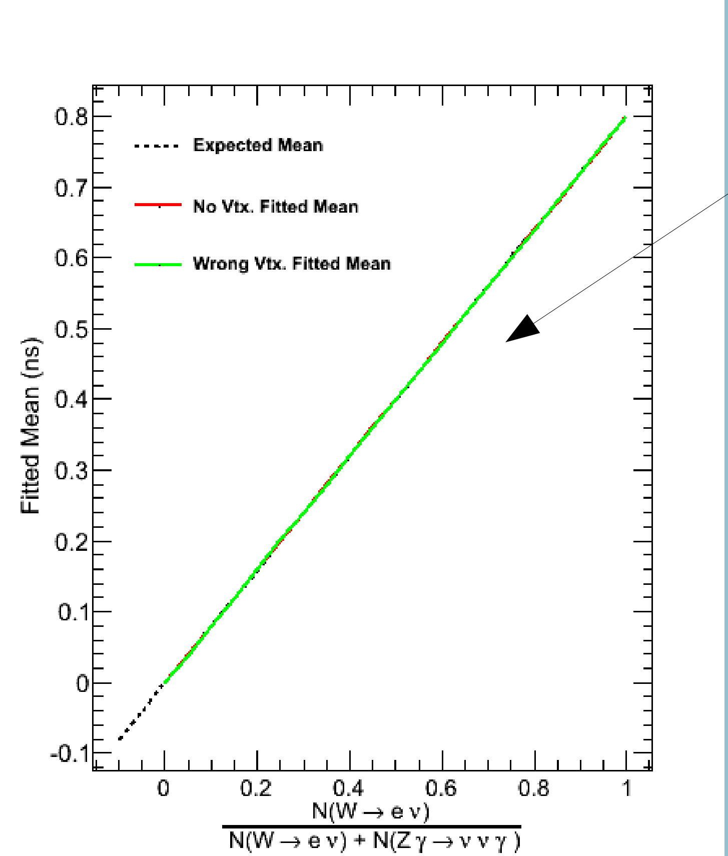
Estimating SM Background Contributions

- We've minimized the SM mean shifts and rates, but we still need to be to predict their contributions to the signal region.
- Data driven approach: use what we've learned from Monte Carlo, but get the actual estimate from fitting our control regions.
- Two approximations are necessary:
  - The corrected time distribution for all SM backgrounds combined can be approximated by a single right vertex component and a single wrong vertex component.
  - The wrong vertex mean shift can be estimated from the sample with no reconstructed vertex.

Double Gaussian Approximation

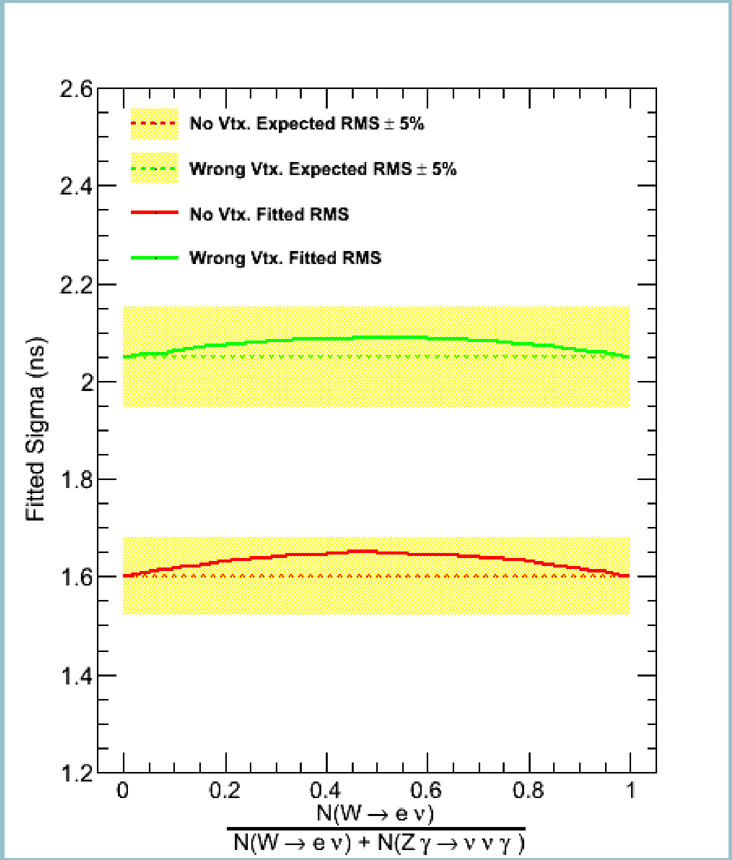
- All right vertex components have a mean of zero and an RMS of ~0.65 ns.
- All wrong vertex components have an RMS of ~2.05 ns, but their means vary.
- If we combine the most extreme cases in various fractions, can we approximate the two wrong vertex distributions as a single Gaussian?
- We can test in a toy Monte Carlo: combine:
  - $W \rightarrow e\nu$ with $\mu = 0.8$ and $\sigma = 2.05$
  - $Z\gamma \rightarrow \nu\nu\gamma$ with $\mu = 0$ and $\sigma = 2.05$

Double Gaussian Approximation



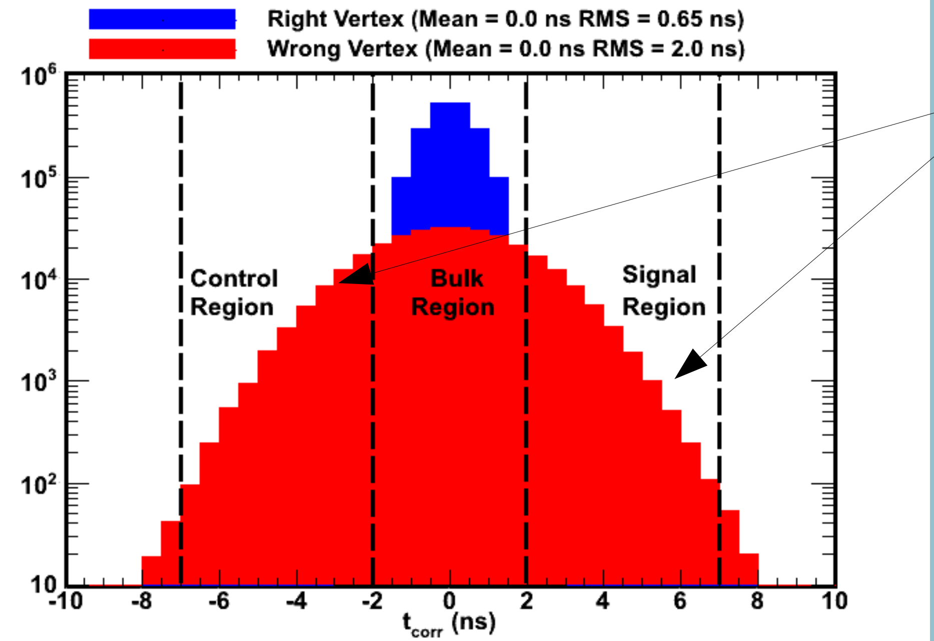
Fitted mean behaves like a weighted average of means of the combined samples

Fitted RMS deviates the most from the one sample RMS when the samples are 50% each.



A 5% uncertainty in the wrong vertex and no vertex distribution RMSs covers the variation due to treating the combine as a single background.

Double Gaussian Approximation: N(SR)/N(CR)

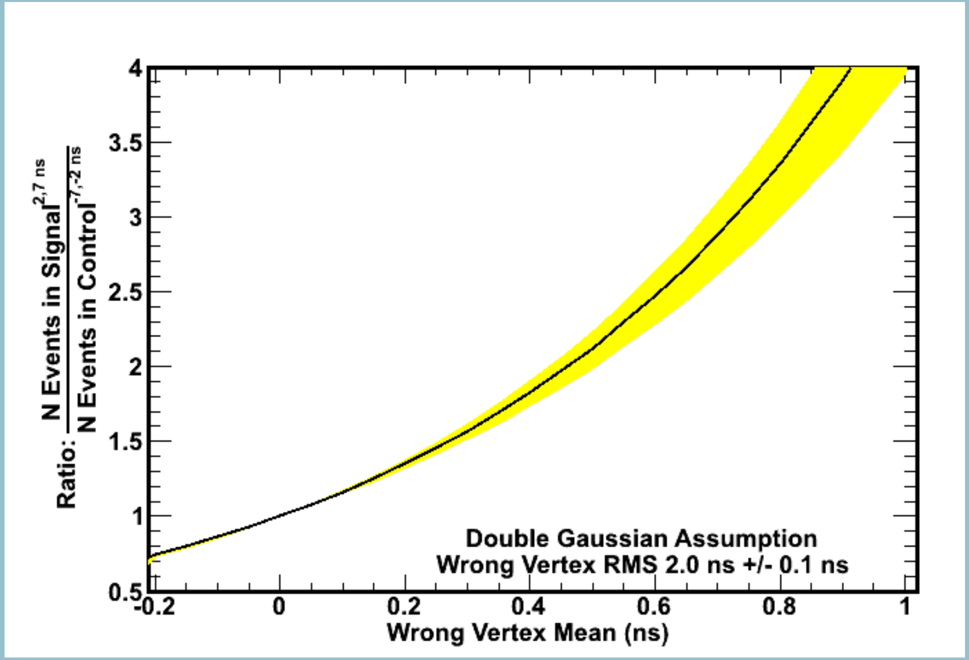


CR and SR are almost exclusively wrong vertex.

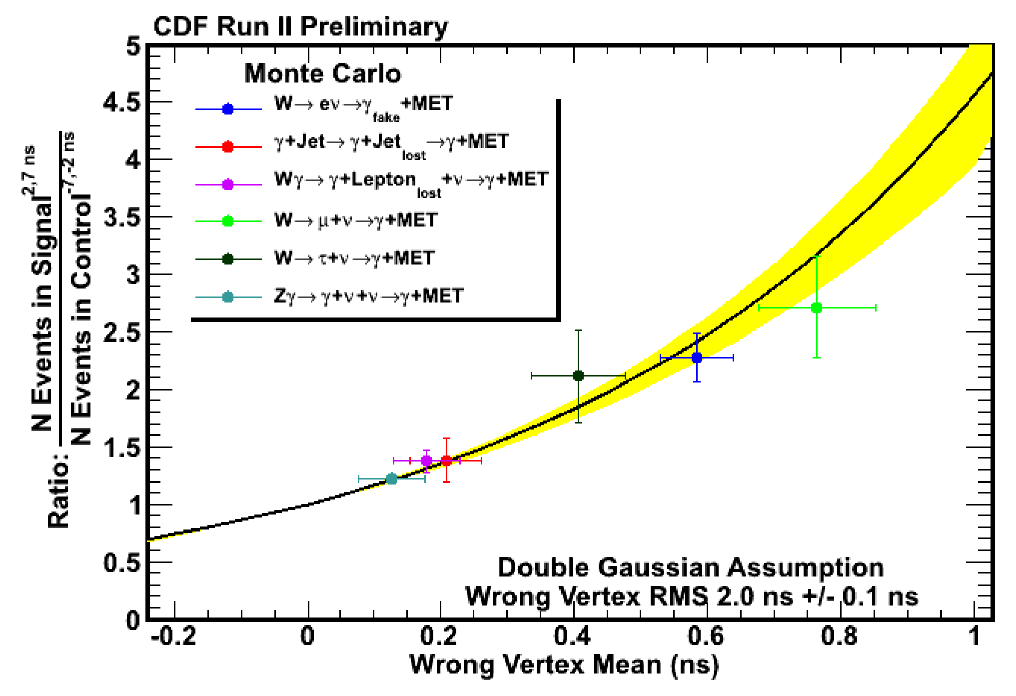
To predict N(SR), we only need:
1) Normalization of the wrong vertex distribution
2) Wrong vertex mean.
(RMS is constant with a 5% uncertainty)

Ingredients:
-Normalization from N(CR)
-Wrong vertex mean from the no vertex sample

-As wrong vertex mean increases, events leave the CR and others enter the SR.



N(SR)/N(CR) vs. Wrong Vertex Mean



In Monte Carlo samples, we separate out wrong vertex events by requiring an anti-match between the highest sum P_T reconstructed vertex and the primary generated collision.

In electron data, we anti-match the electron track Z_0 and the highest sum P_T reconstructed vertex.

When we know the wrong vertex mean, the double Gaussian assumption works very well.

Estimating Wrong Vertex Mean Using the Sample with No Reconstructed Vertex

In photon data, we cannot isolate wrong vertex events.

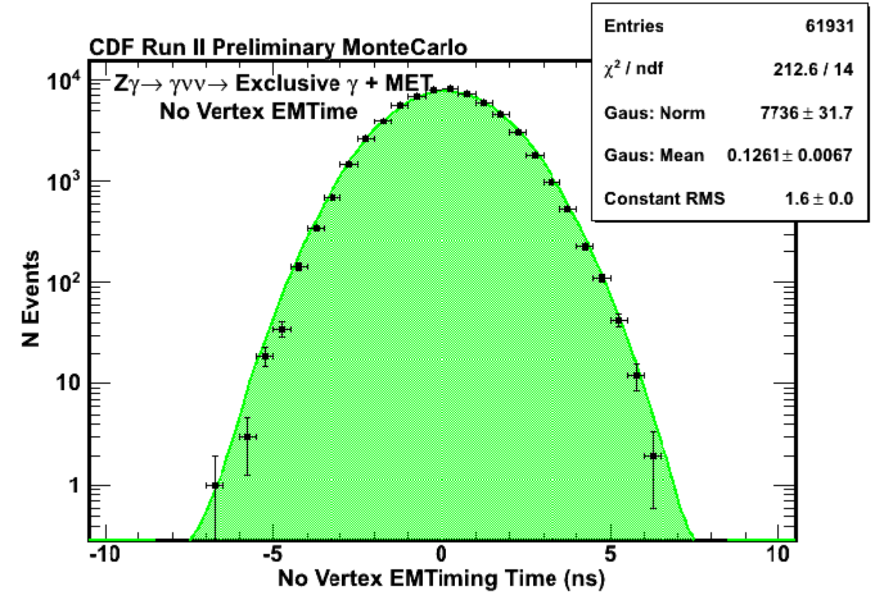
In principle, we could fit in the control region to estimate the wrong vertex mean as well as the normalizations.

In practice, very few events remain in the control region, and the higher the mean is shifted, the worse the situation is.

We need an independent handle.

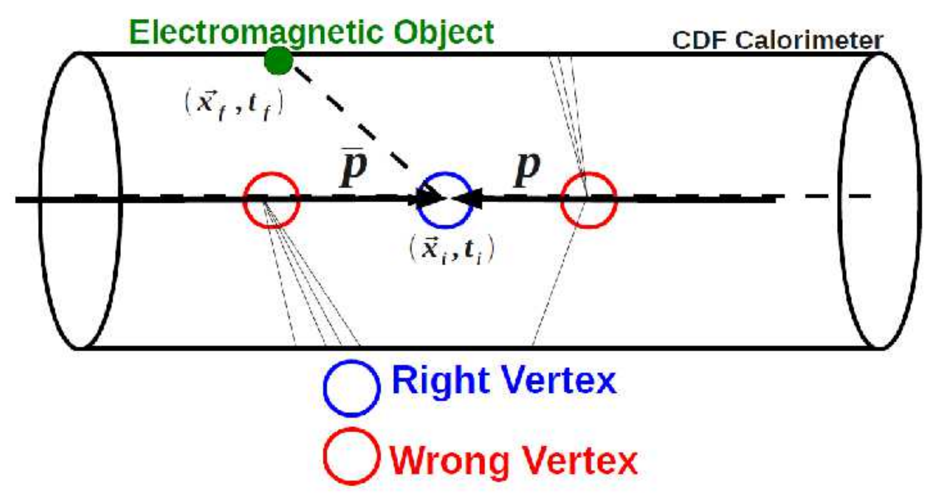
The sample of events with no reconstructed vertex can provide an estimate.

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



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

Comparing No Vertex and Wrong Vertex Components

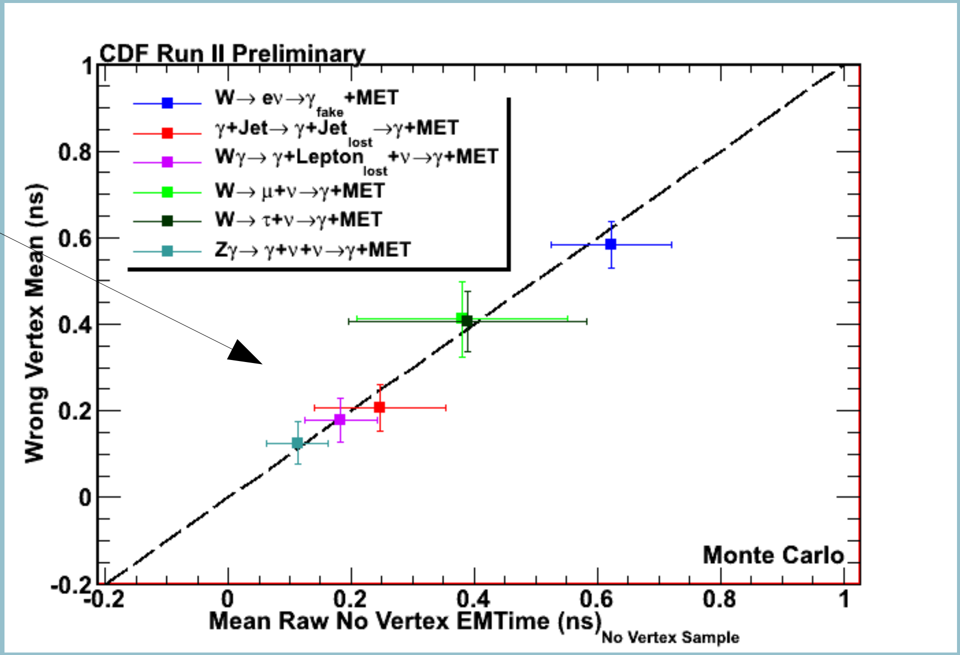


Wrong vertices are Gaussian distributed with a mean ~ 0 cm and and RMS ~ 28 cm.

The wrong vertex time is, on average, close to the no vertex raw time → picking a wrong vertex is mostly a smearing, not a shift.

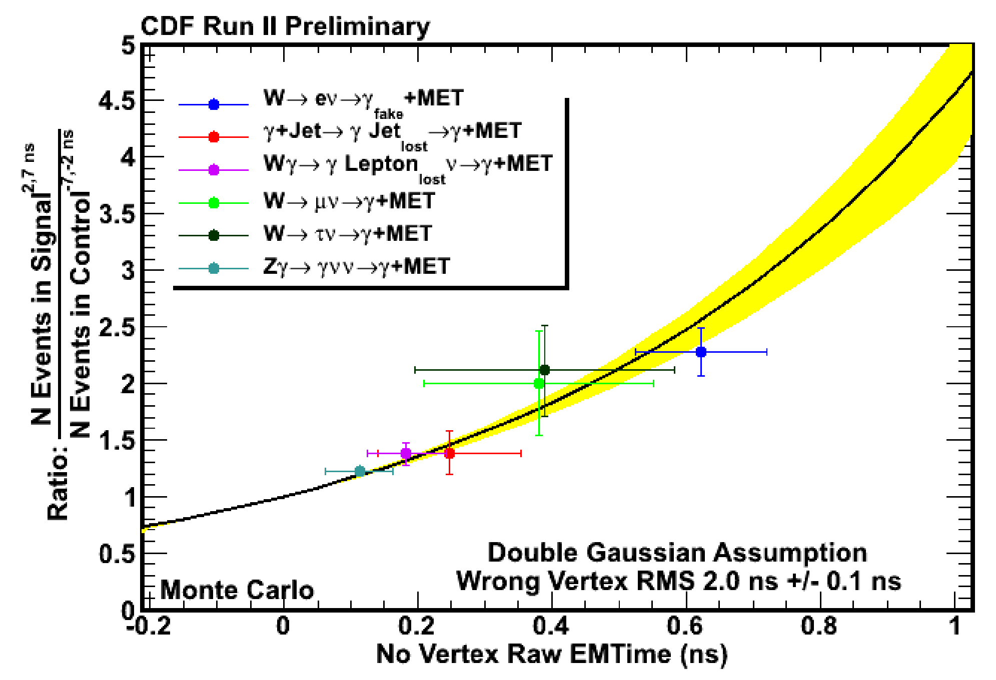
MC samples show good agreement.

We take the wrong vertex mean to be the no vertex mean with a 100 ps systematic uncertainty.



Using the No Vertex Component to Predict the Signal Region

- N(SR)/N(CR) has the same relationship to the no vertex mean raw time as to the wrong vertex mean corrected time.
- We now have all the ingredients to predict the signal region!

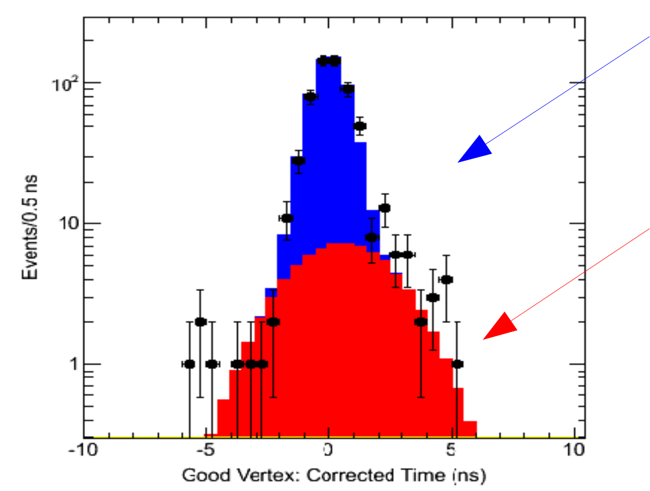


Putting It All Together

- Estimate N_{SR} for background using a fit method.
- Create a joint binned likelihood for:
  - Good vertex (-7,2) ns
  - Good vertex (20,80) ns
  - No vertex (-7,3) ns
  - No vertex (20,80) ns
- Add constraint terms to incorporate systematic uncertainties
  - RV mean = 0.0 +/- 0.05 ns, RV RMS = 0.66 +/- 0.05 ns
  - WV mean = NV mean +/- 0.1 ns
  - NV RMS = 1.6 +/- 5%
  - WV RMS = 2.05 +/- 5%
- Maximize the likelihood function – extrapolate result into SR.
- Vary the parameters using Monte Carlo methods to extract a prediction for N(SR).

Next: Show this method for each SM backgrounds
full available Monte Carlo sample.
N.B. - these distributions are not scaled to theory.

W → eν Fit

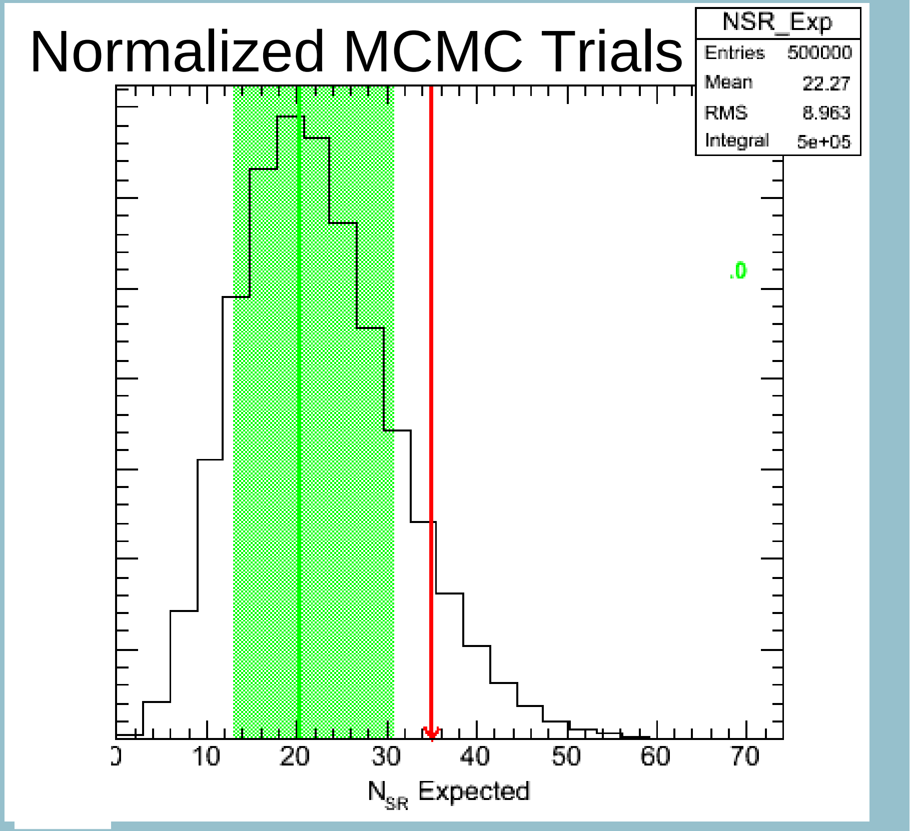


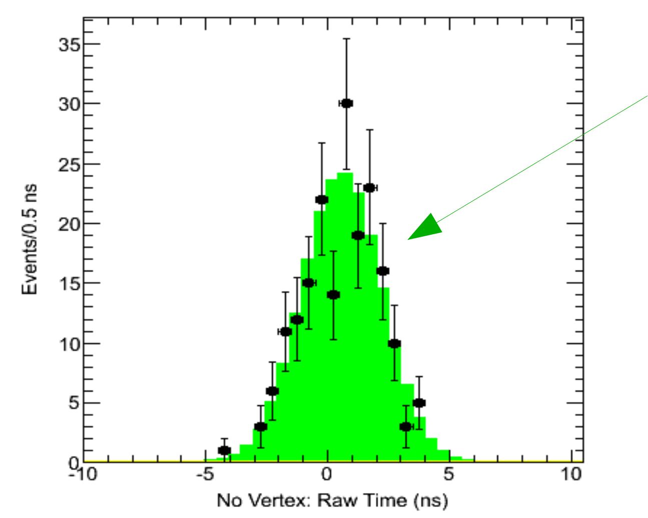
Right Vertex

Wrong Vertex

N_{SR} Obs = 35.0

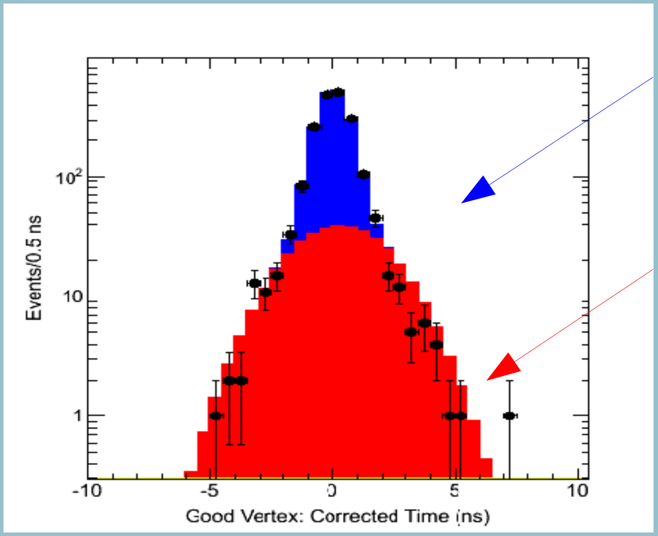
N_{SR} Exp = 20.3 +/- 9.0





No Vertex

γj Fit

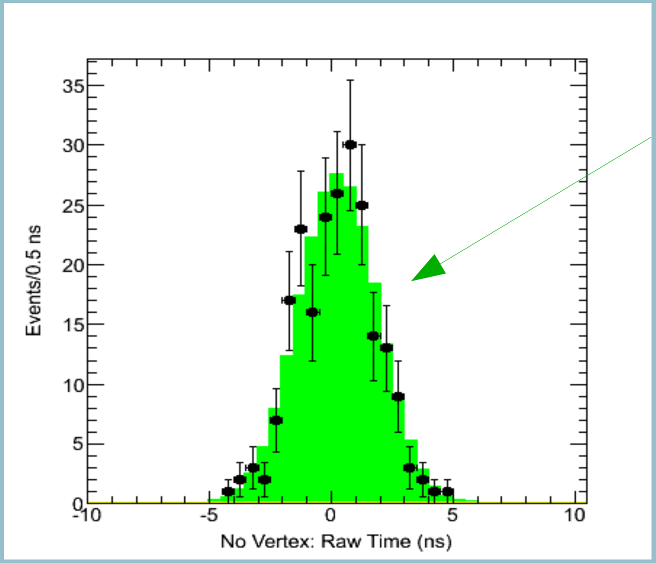


Right Vertex

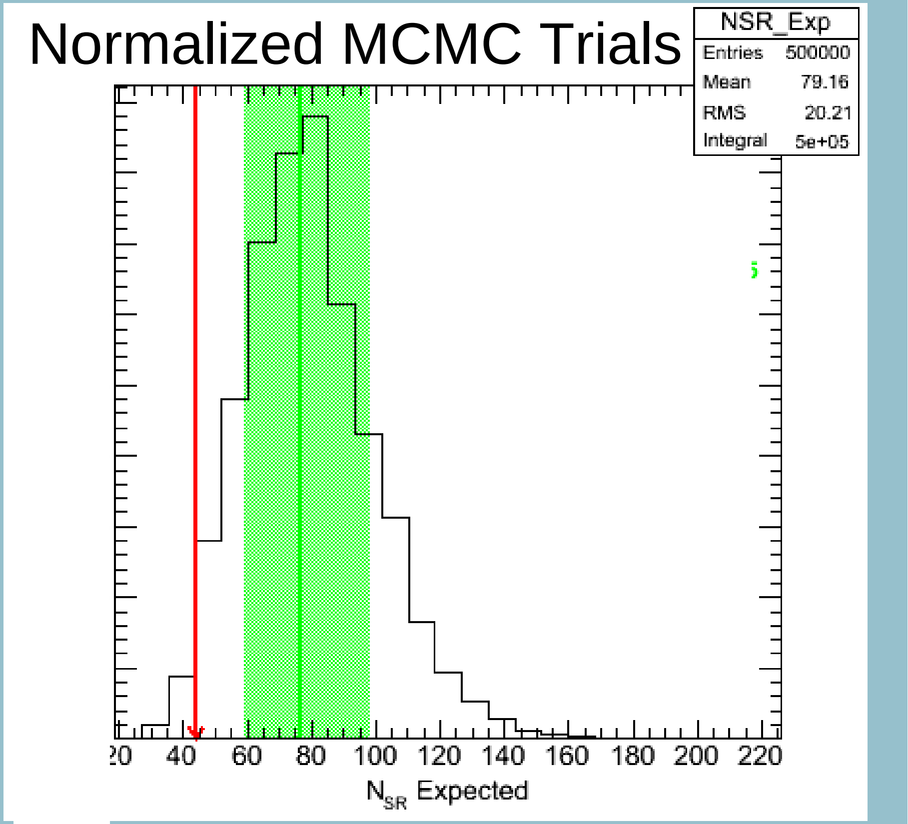
Wrong Vertex

N_{SR} Obs = 44

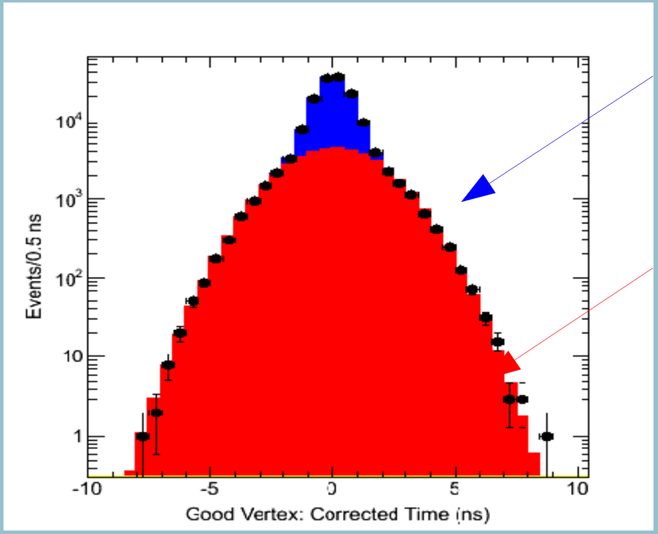
N_{SR} Exp = 76.8 +/- 19.5



No Vertex


Normalized MCMC Trials

Zγ Fit

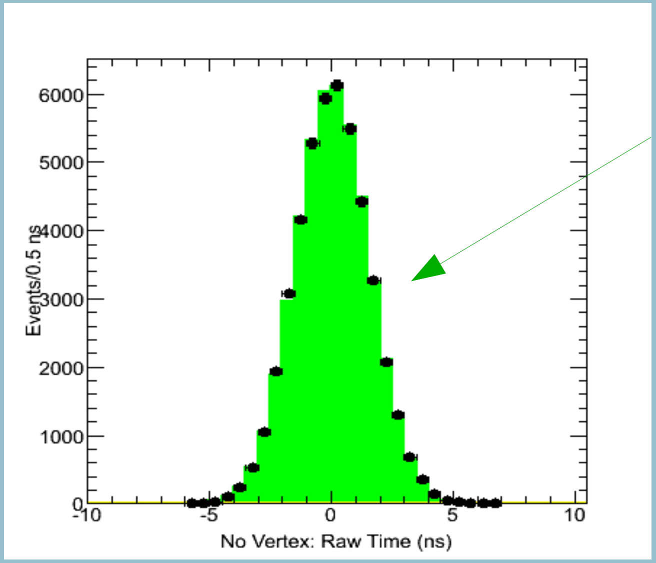


Right Vertex

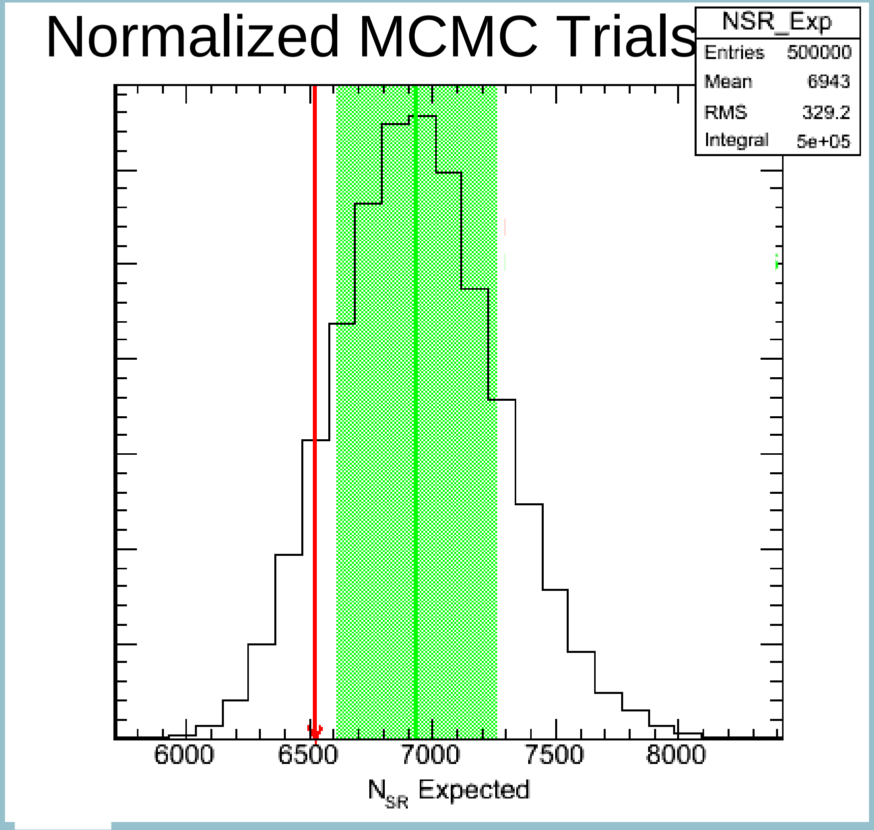
Wrong Vertex

N_{SR} Obs = 6523

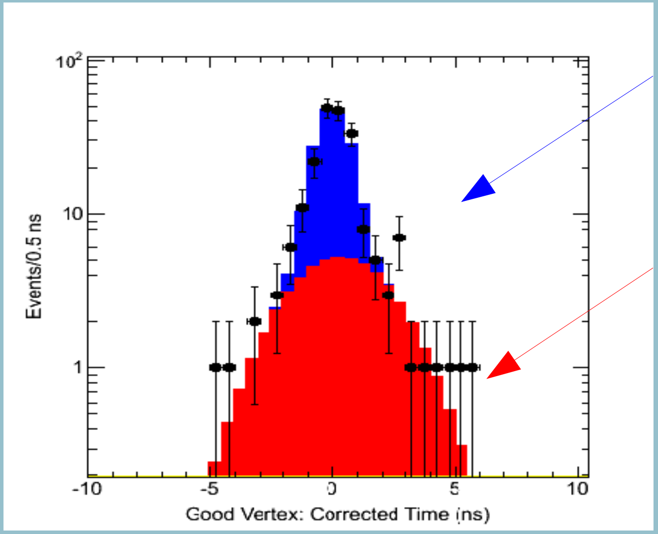
N_{SR} Exp = 6932.5 +/- 327.5



No Vertex

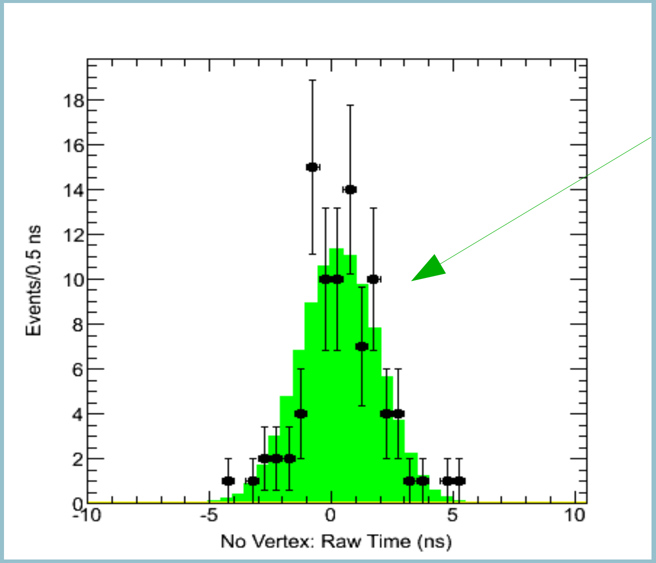

Normalized MCMC Trials

$W \to \mu\nu$ Fit



Right Vertex

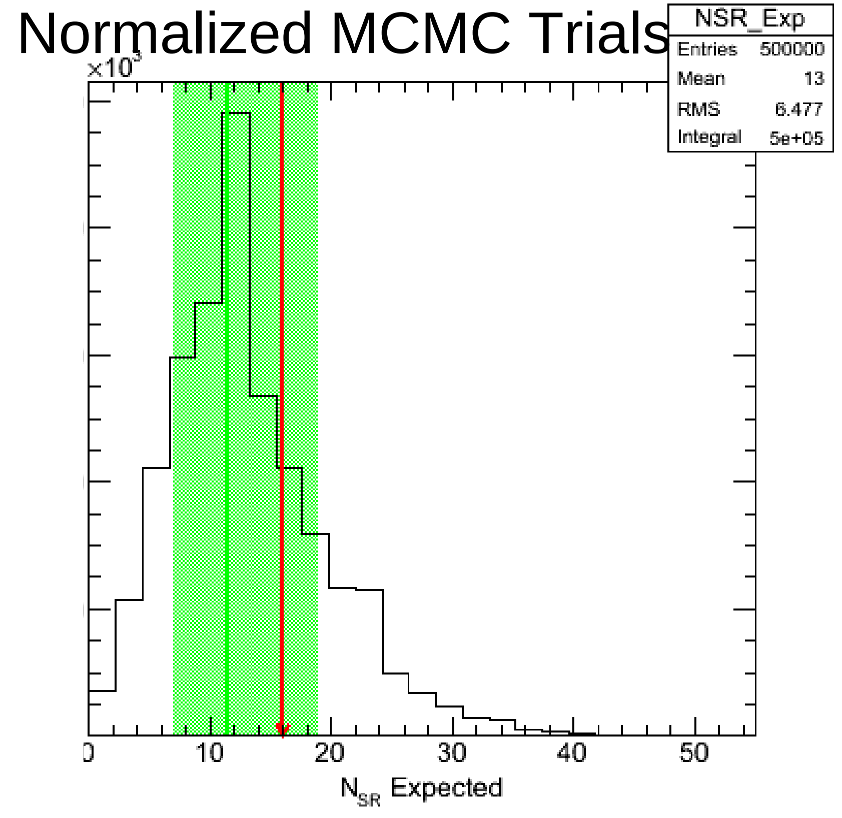
Wrong Vertex



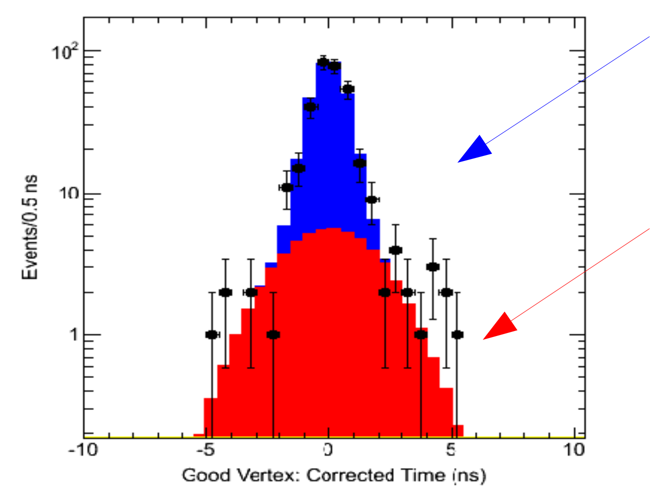
No Vertex

N_{SR} Obs = 16

N_{SR} Exp = 11.4 +/- 6.0



W → τν Fit

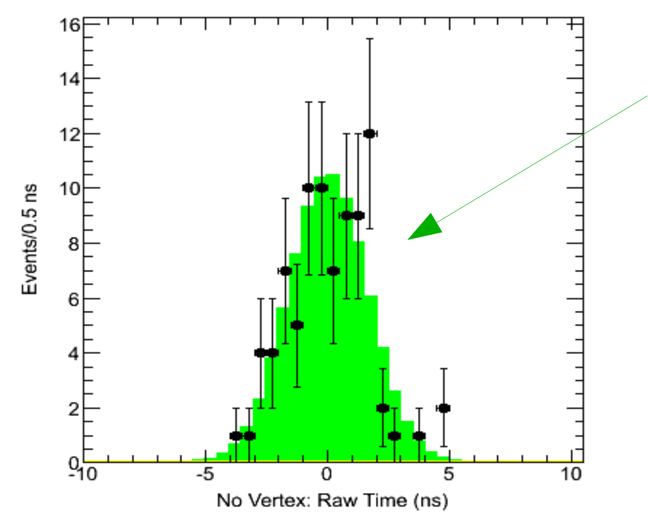


Right Vertex

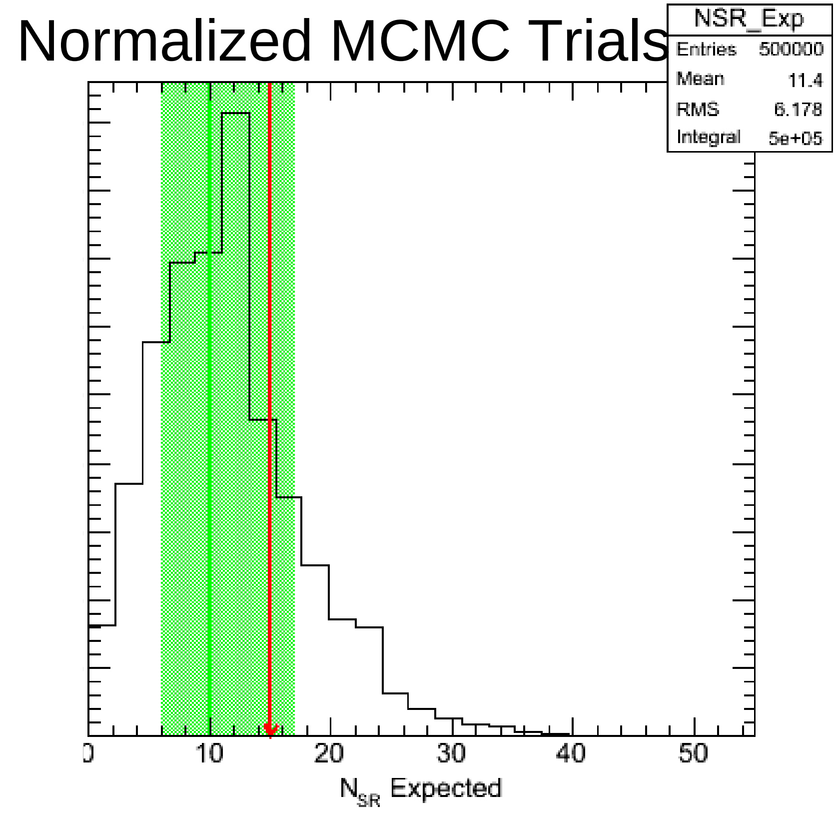
Wrong Vertex

N_{SR} Obs = 15

N_{SR} Exp = 10.1 +/- 5.5



No Vertex

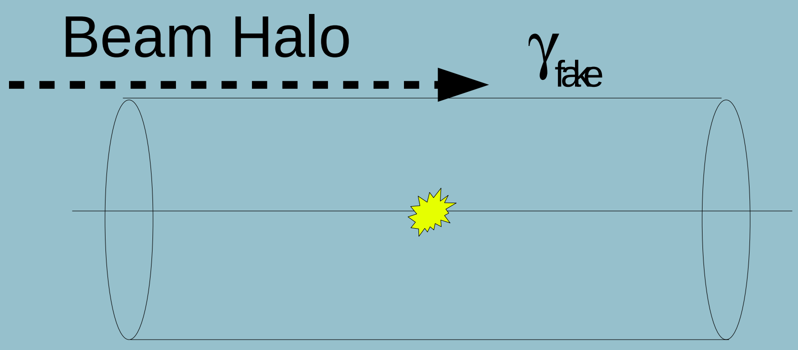


Conclusions

- We have studied all backgrounds for the delayed photon analysis.
- We have formulated ways to reduce highly biased SM backgrounds.
- We have developed a data driven method to estimate the Standard Model backgrounds in the signal region.
- Using standard methods, we can estimate cosmics contributions to the signal region.
- All the ingredients are now in place to open the box!

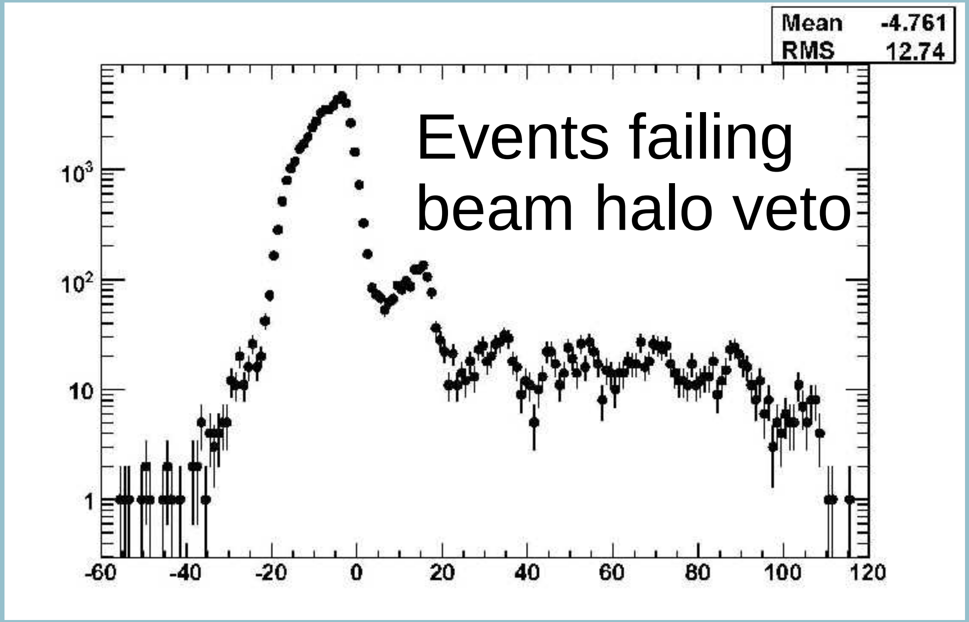
Backups

Beam Halo



Beam halo are muons created by beam interactions upstream of the detector.

They travel parallel to the beam and can be reconstructed as a photon.



Events failing beam halo veto

Reject events that have evidence of parallel moving particles (several deposits in the calorimeter at the same azimuthal angle).

This removes almost all beam halo & any remnants would be visible at negative times (we are interested in positive times).

Satellite Bunches

Satellite bunches remnants of the bunch coalescing in the Main Injector RF cavities. Satellite bunches occur at multiples of ~18.8 ns.

Model what the events would look like in collision data.

Select events in data that are likely non-collision (no reconstructed vertex).

The satellite component is < 1% of all non-collision events.

No additional cut is required.