SEARCHING FOR SUSY DECAYS OF THE HIGGS BOSON IN THE EXCLUSIVE PHOTON + MISSING TRANSVERSE ENERGY FINAL STATE AT CDF

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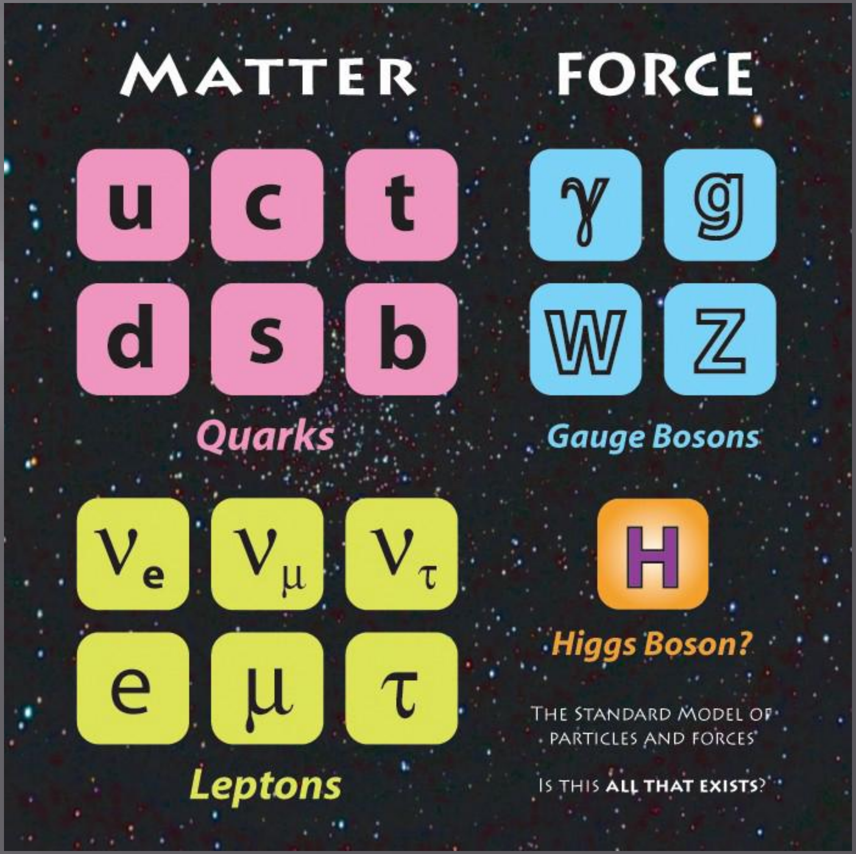
Outline

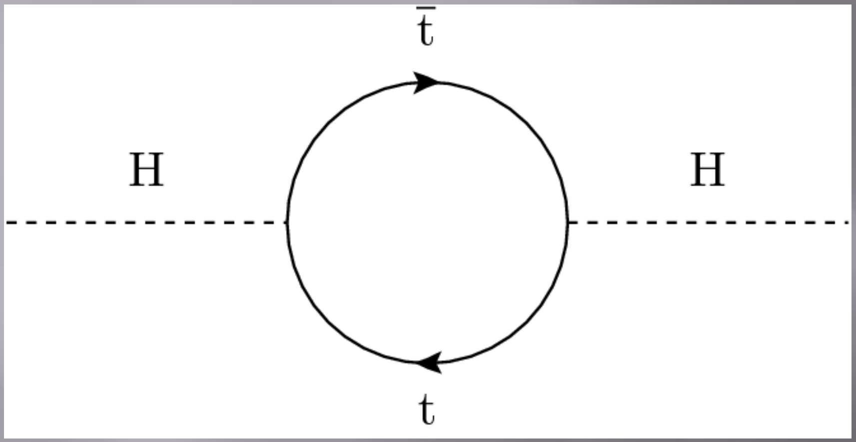
- Introduction: why new physics?
  - Standard Model
  - Higgs problem, Dark matter
  - Supersymmetry
- Exclusive Photon + MET search (first half of CDF data)
  - Outline
  - Backgrounds (Cosmics & SM collision backgrounds)
  - Estimation methods for Background
  - Results
- Going forward: what can we do next?
  - Results with updated tools
  - Half of data from CDF→ full CDF dataset
  - Simulating Higgs → neutralinos signal with Monte Carlo
  - Optimize the search for Higgs
- Conclusions

Standard Model of Particle Physics

- Describes three of the four known forces of nature
- Six quarks, six leptons, four mediator particles
- While experimentally verified for years, SM has some problems



Why new physics: Hierarchy problem



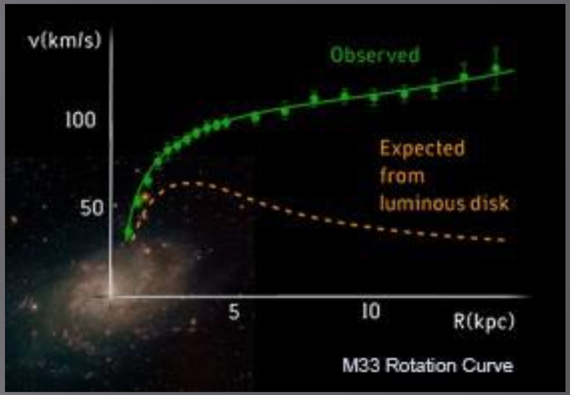
$$m_H^2 = m_{Bare}^2 + \delta m_H^2$$

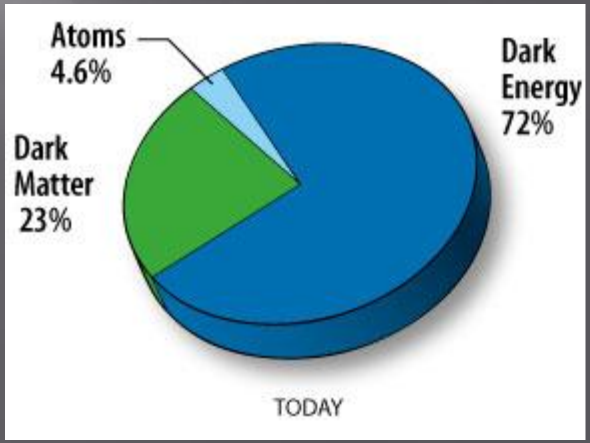
$$\delta m_H^2 \approx \frac{\lambda_f^2}{4\pi^2}(\Lambda^2 + m_f^2) + \ldots$$

- When trying to calculate Higgs mass with self interactions, it does not reach finite number!
- Need something that enables us to have a finite Higgs mass
- Tevatron and LHC both see a new particle in Higgs searches
  - Is it *a* Higgs? *The* Higgs? We still have hierarchy problem

Why new physics: Dark matter

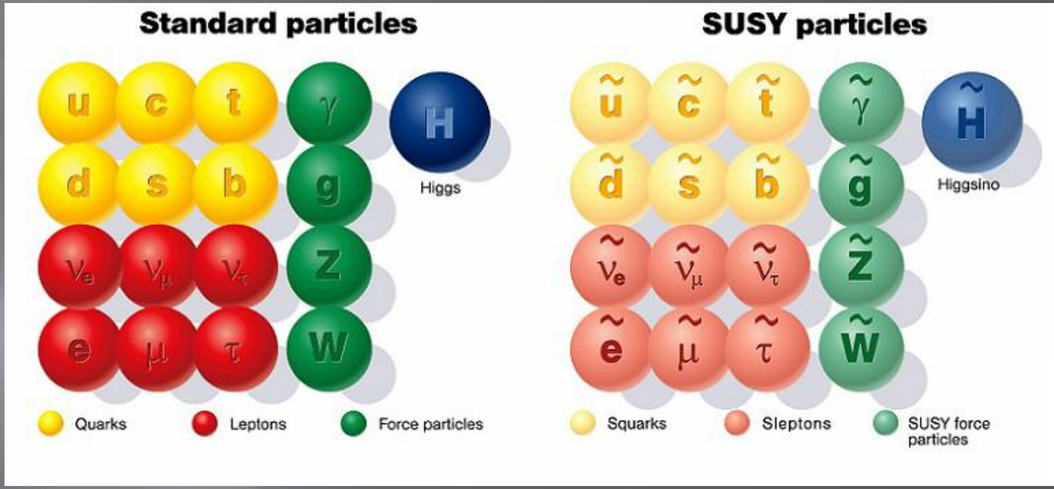
- Potentially another problem with SM
- Galaxy rotation curves tell us there is more matter present than what is currently observable
  - Also other evidence (gravitational lensing, others)
- No SM particles account for this
- Additional observations indicate visible matter (SM particles) make up ~ 5% of total mass
- There is something that could help us solve BOTH problems





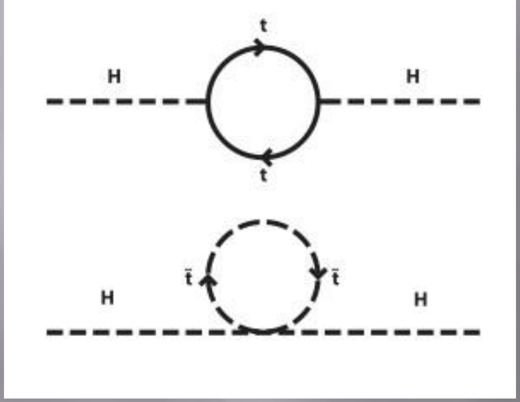
Supersymmetry

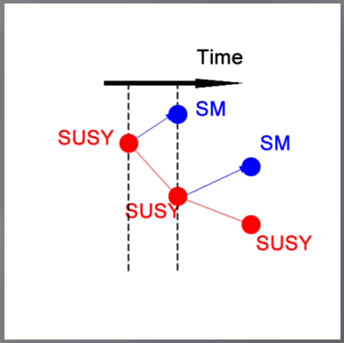
- Supersymmetry (SUSY) proposes a symmetry between fermions and bosons
- For every fermion, there is a corresponding boson (and vice-versa)
- Fermions = matter
- Bosons = mediators
- Attractive solution to both problems presented (why?...)



Supersymmetry

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





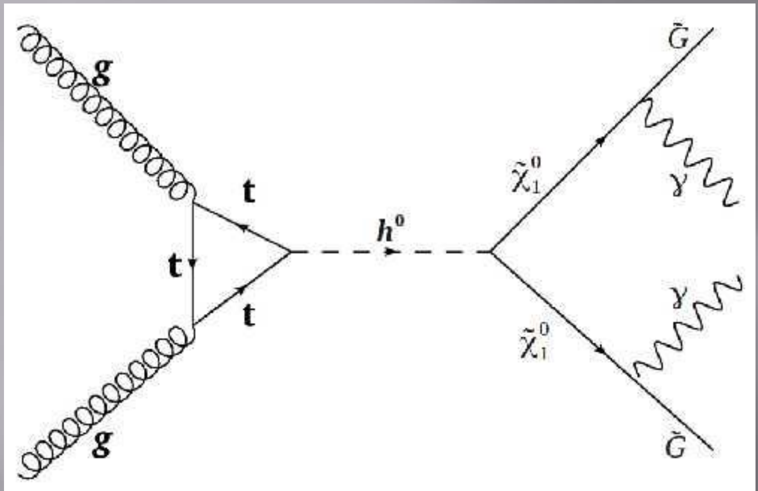
$$P_R = (-1)^{2s+3B+L}$$

- How does SUSY fix our problems?
- Higgs: sparticles introduce corrections to Higgs mass with opposite sign (stays as finite number)
- Dark matter: According to R-parity, lightest SUSY particle *cannot* decay → excellent dark matter candidate!

Why we have yet to detect Supersymmetry

- Supersymmetry must be broken (we don't see SUSY particles)
- SUSY masses > SM masses
- One possible mechanism is Gauge Mediated Supersymmetry Breaking (GMSB)
- SUSY breaking is transmitted via Standard Model gauge interactions

Outline of our search



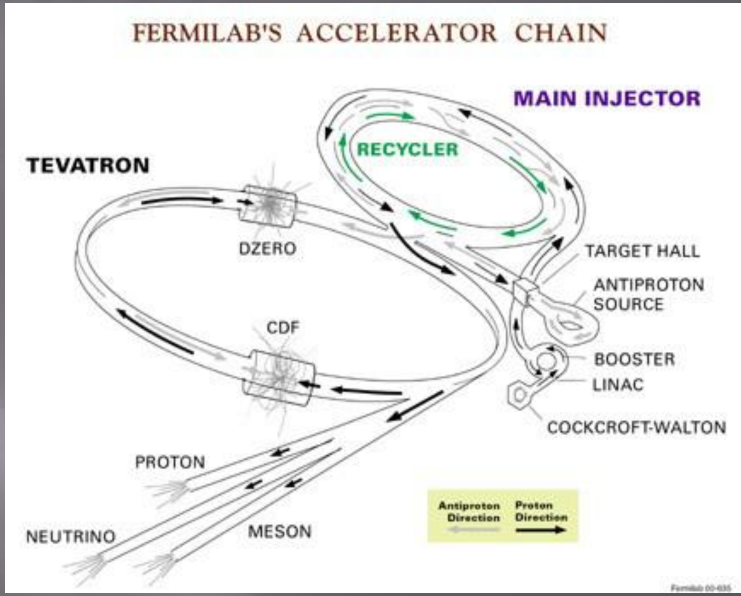
$$gg \rightarrow h^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \gamma\gamma\tilde{G}\tilde{G}$$

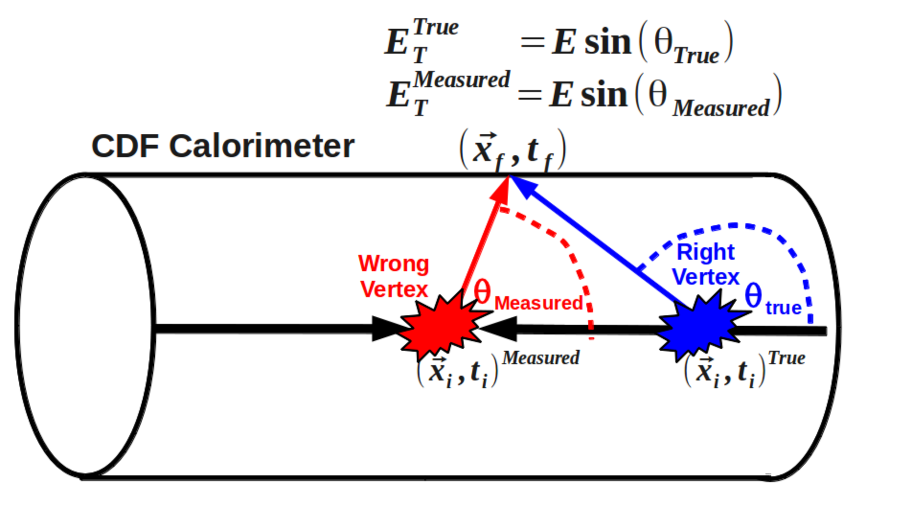
Mason and Toback
Phys. Lett. B 702, 377 (2011)

- GMSB model where sparticles are too heavy to be produced at Tevatron and LHC
  - Sparticle production at Tevatron dominated by production and decay of lightest Higgs
- Produce Higgs which decay to neutralinos (τ ~ ns) which decay to photons and gravitinos → look for gammas + missing energy!
- Neutralinos = next-to-lightest stable particle (NLSP); gravitinos = lightest stable particle (LSP)

Tevatron

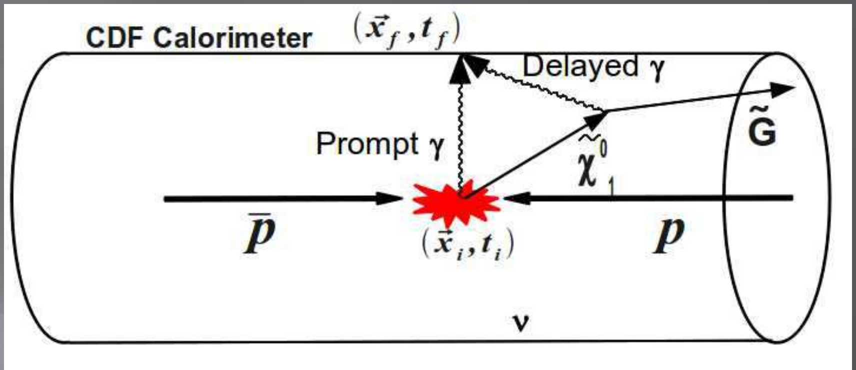
- Up until 2008, most powerful particle accelerator in the world
- Center-of-Mass energy equal to 1.96 TeV
- Collides protons and anti-protons





Final State

- In general GMSB models, NLSPs may be long-lived before they decay to LSPs and photons
- Tevatron has 0.5 ns timing resolution
  - Higgs produced with smaller boost → able to detect delayed photons
- Thus, we only look for single photons (we get a photon whose timing is "delayed" with respect to time of collision) since other neutralino will have left detector
- Our final state = photon + missing energy, *nothing* else

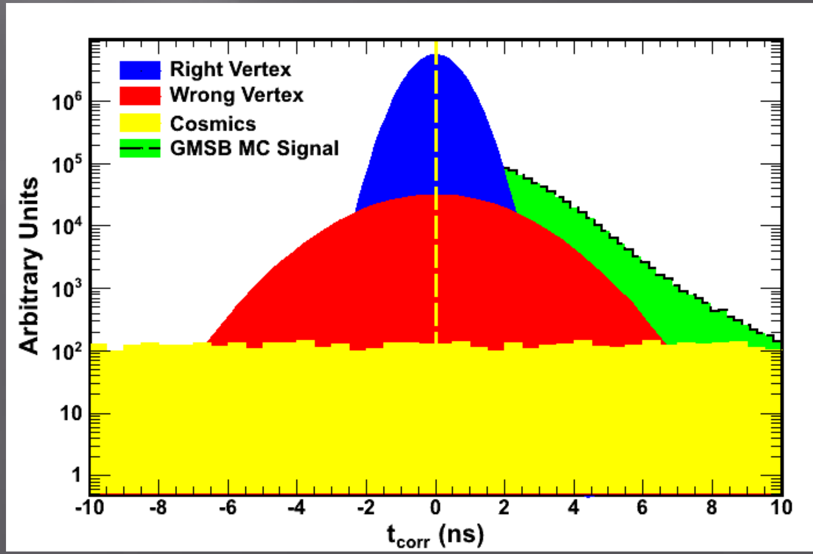


$$t_{corr} \equiv t_f - t_i - \frac{|\vec{x_f} - \vec{x_i}|}{c}$$

Backgrounds

- Backgrounds in two types: SM + non-SM
- SM backgrounds can have many vertices per collisions; sometimes right vertex is not reconstructed
- Wrong vertices mess up timing and produce fake (large) flight times → dominate SM backgrounds
- However, all SM backgrounds can be modeled as two Gaussians
- For non-SM backgrounds, cosmics are flat smearing across timing distribution

Standard Model Collision Sources
$W \to e\nu \to \gamma_{\text{fake}} + \not{E}_T$
$\gamma + \text{jet} \to \gamma + \text{jet}_{\text{lost}} \to \gamma + \not{E}_{T\,\text{fake}}$
$W \to \tau\nu \to \gamma_{\text{fake}} + \not{E}_T$
$W\gamma \to l\nu\gamma \to \gamma + l_{\text{lost}} + \not{E}_T$
$Z\gamma \to \nu\nu\gamma \to \gamma + \not{E}_T$
Non-Collision Sources
Cosmics
Beam Halo
Satellite Bunches



Key to Collision Background Estimation

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

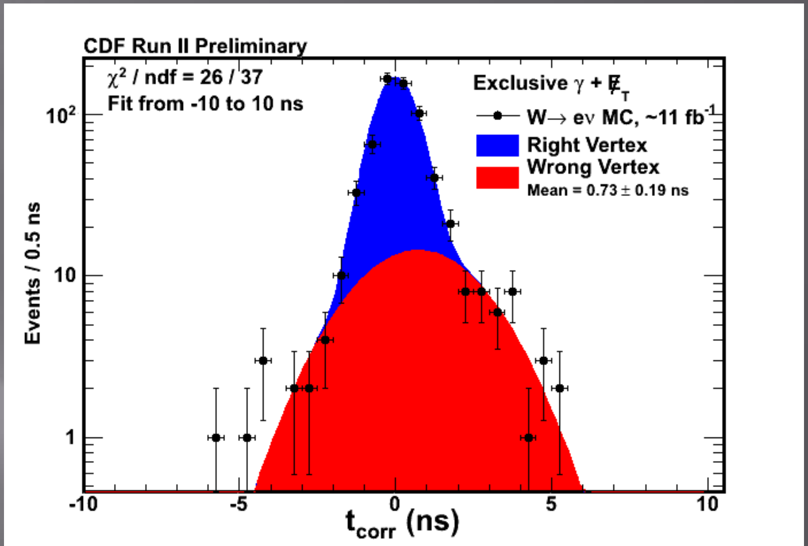
Determined by beam widths: mean of 0.0 and RMS of sqrt(2)*1.28. Primary contribution to RMS

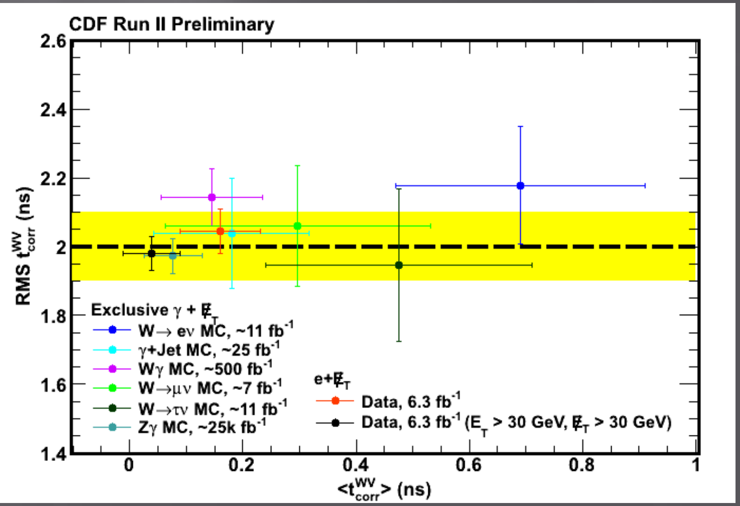
Geometric term: small RMS, with mean up to a nanosecond

Determining wrong-vertex mean and RMS is key to backgrounds

SM Backgrounds: double Gaussian

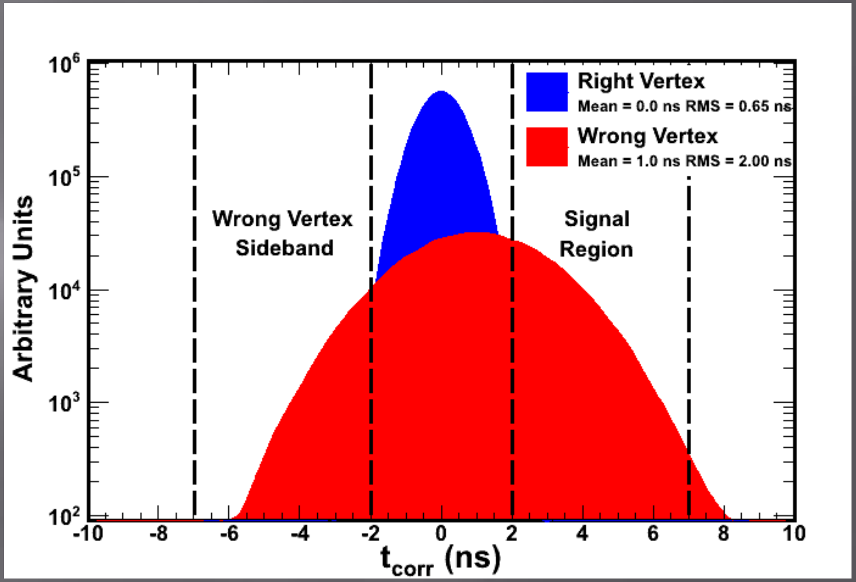
- Have to account for effects which can bias our sample
- After taken into account, we can model backgrounds as double Gaussian fits: right-vertex and wrong-vertex
- Wrong-vertex mean is non-zero, with RMS of ~2.0 ns
- RMS doesn't depend on mean





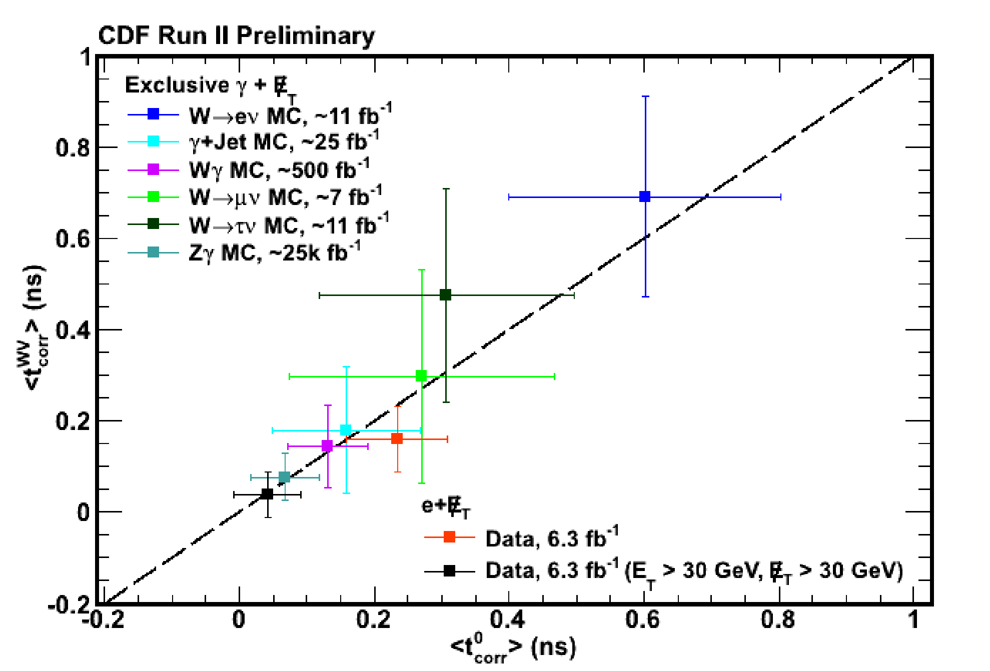
Background estimation methods

- We need to be able to predict number of events in signal region (2 ns < t_{corr} < 7 ns)
- Two things we need
  - Normalization of wrong vertex backgrounds
  - Wrong-vertex mean (RMS is independent of it)



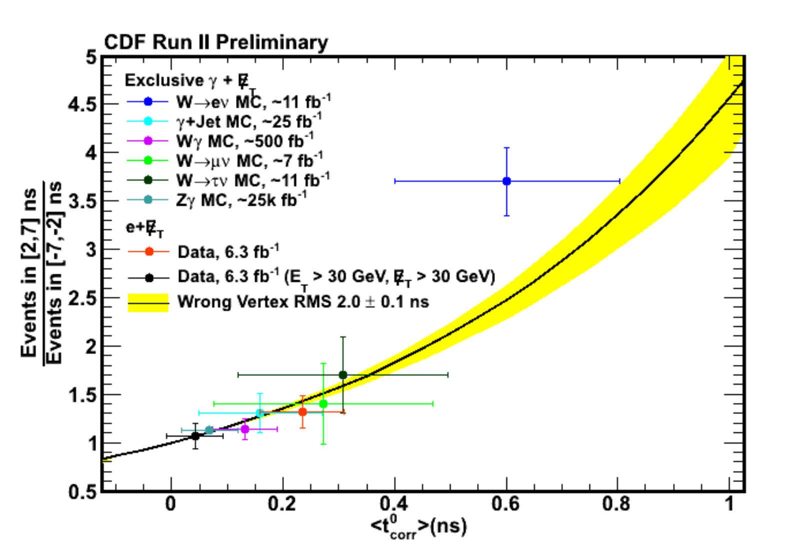
Wrong-Vertex Mean from No-Vertex Sample

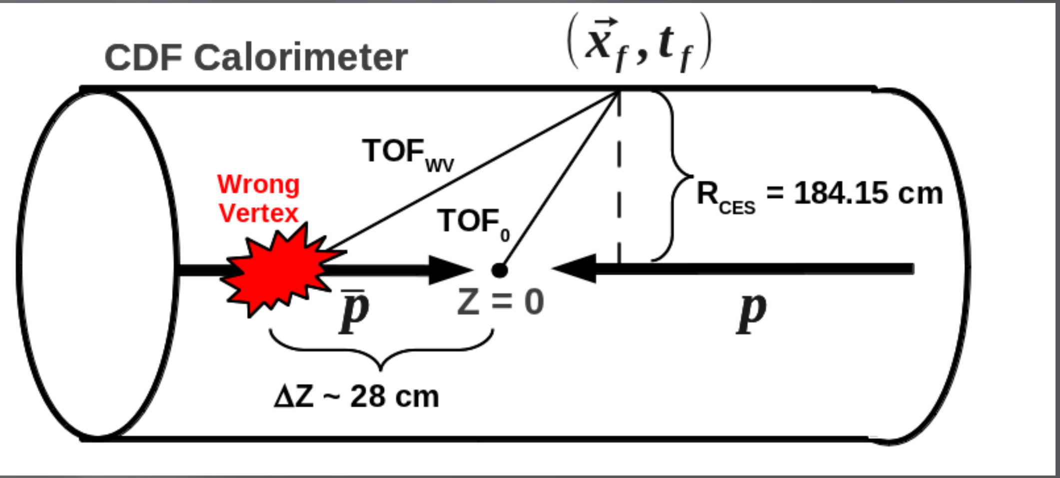
$$t^{WV}_{corr} = t^{0}_{corr} - t^{WV}_{i} + (TOF_0 - TOF_{WV})$$



- Mean of NV and WV approximately equal, since t_i^{WV} has mean of 0, and TOF_0 and TOF_{WV} are roughly equal since deviations are small compared to detector radius
- Agreement using many different data and MC control samples

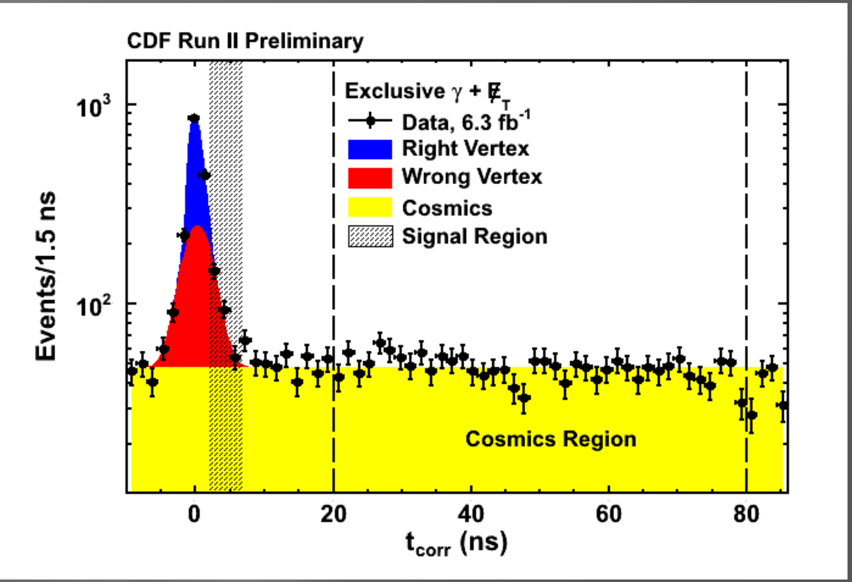
Wrong-Vertex Mean from No-Vertex Sample





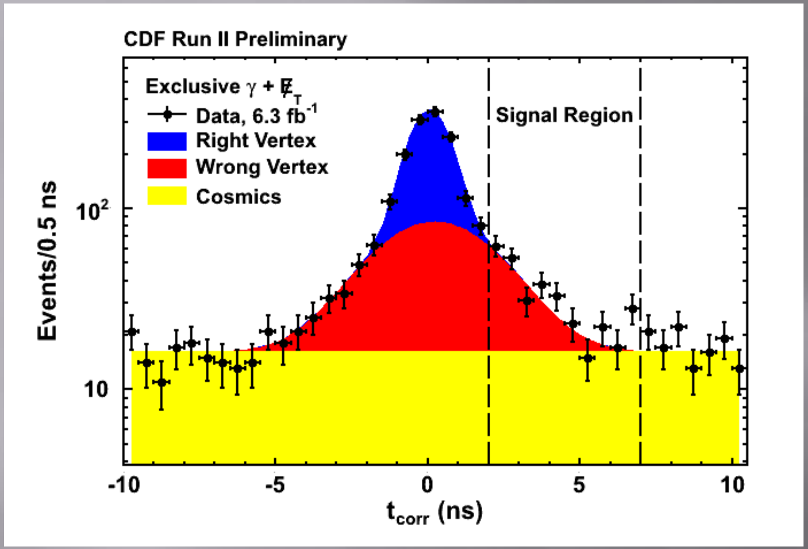
Study with 6.3 fb^{-1}

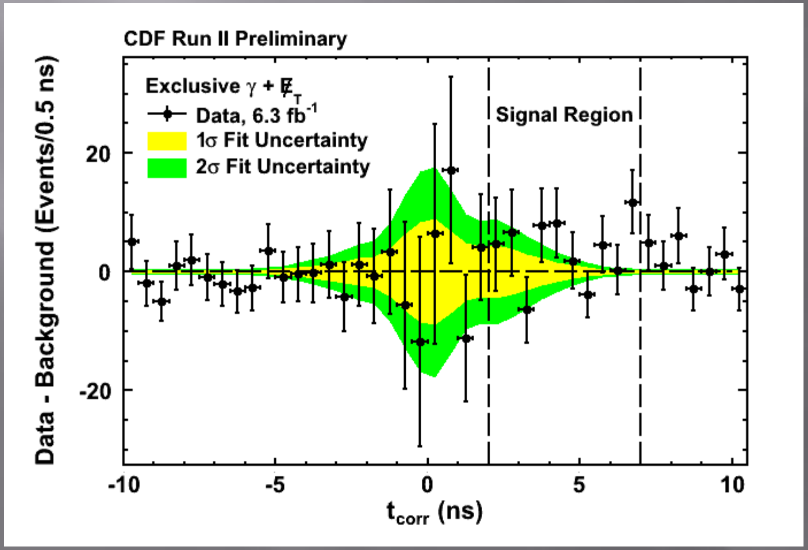
Cut	# Events
γ w/ E_T > 45 GeV & MET > 45 GeV	38,291
Reject beam halo	36,764
Reject cosmics	24,462
Track veto	16,831
Jet veto	12,708
Large |Z| vertex veto	11,702
ΔR_{Pull}	10,363
Good vertex events/No vertex events	5,421/4,942



Likelihood fit on sideband to estimate events in signal region

Results





- $N(SR)_{obs}$ = 322
- $N(SR)_{exp}$ = 286 ± 24
- Significance = 1.2σ
- For such a modest excess, all events are above expectation
- Impetus for doing study again with full dataset

Going forward: what can we do next?

- Have code set-up for next analysis
- Moving to the full 10 fb^{-1} dataset taken by CDF
- Simulate Higgs → neutralinos with full CDF detector simulation tools
- Can we make our search more sophisticated and more optimized?

Code for next analysis

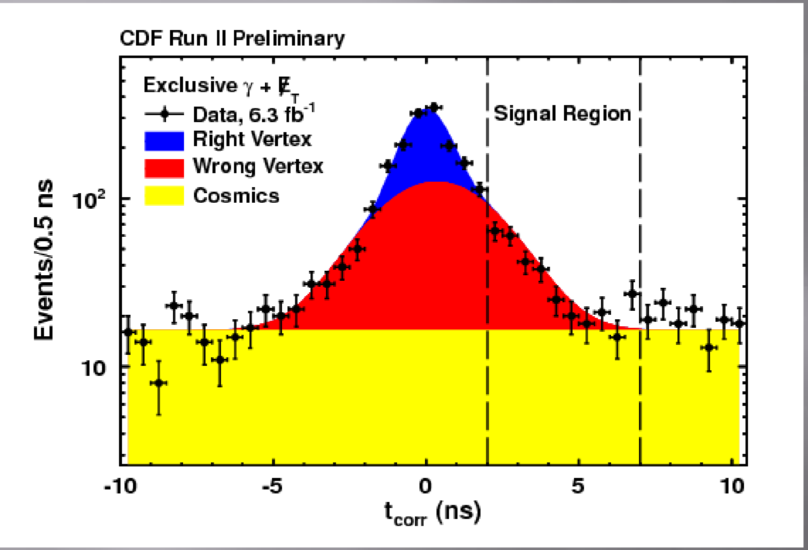
- Cleaned up some of the cuts
- Made photon cuts more regimented (now all aspects measured from z = 0)
- Looking to add new track isolation cut
- Merged background fit calculator software with our current framework

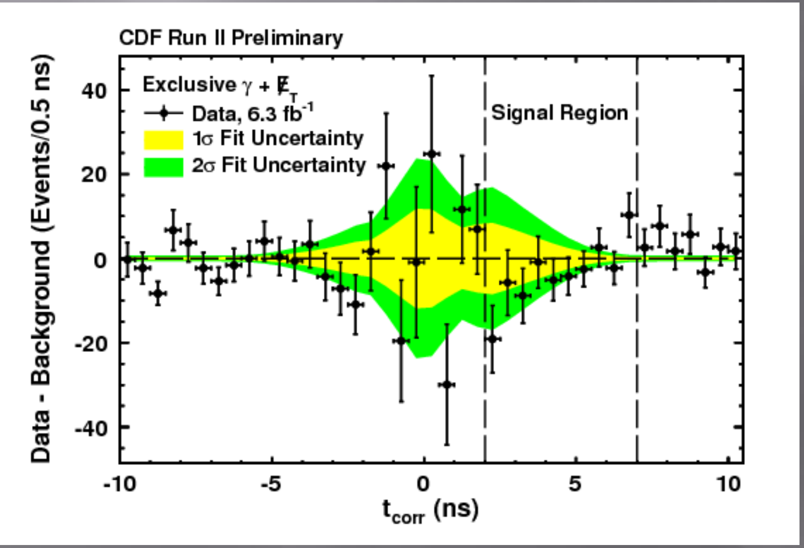
Results with new cuts

Cut	# Events
γ w/ E_T > 45 GeV & MET > 45 GeV	68,139
Reject beam halo	64,363
Reject cosmics	43,214
Track veto	24,193
Jet veto	13,269
Large |Z| vertex veto	12,183
ΔR_{Pull}	10,558

- This is comparing to the OLD way of doing the analysis (does not reflect on upcoming analysis)
- Working on understanding the results

Results with new cuts





- $N(SR)_{obs} = 330$
- $N(SR)_{exp} = 366 \pm 34$
- Significance = -0.9σ
- Still work to do in fully reproducing old results

Full 10 fb^{-1} dataset

- Tevatron shut down in September 2011
- In the totality of Run II, CDF collected 10 fb^{-1} of data
- Ready to add 4.7 fb^{-1} to our existing 6.3 fb^{-1}
- Have to calibrate the rest of the dataset (easier said than done!)

Simulating Higgs signal with MC

- Have started doing simulation work
- Need to do full simulation with CDF software
- Transitioning from GMSB to direct Higgs search

More sophisticated search

- As of this moment, we have a simple counting experiment
- Looking to do a full fit in the signal region
- Will let us know whether data looks like signal or looks like backgrounds
- Optimizing for Higgs search
  - Lower E_T thresholds
  - Raising ΣP_T of vertex

Conclusions

- With 6.3 fb^{-1} study complete, ready to move forward
- Tools are in place to move up to 10 fb^{-1}
  - Calibrate the new data
- With new tools, can optimize search for Higgs and Supersymmetry
- Looking to refine how we do our analysis

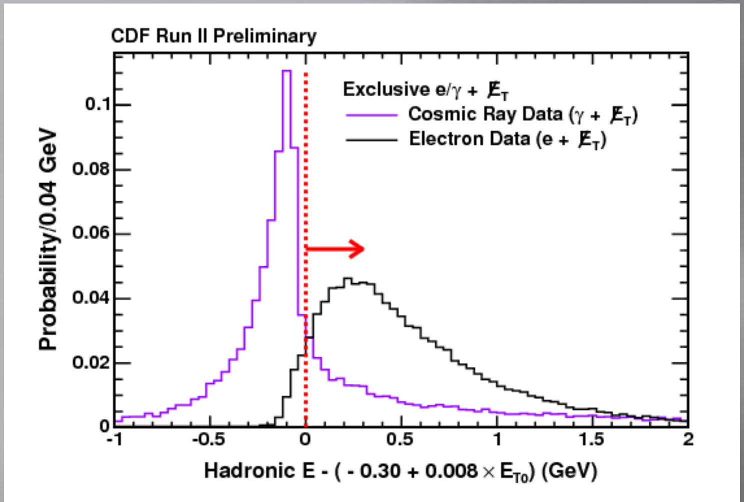
Backups

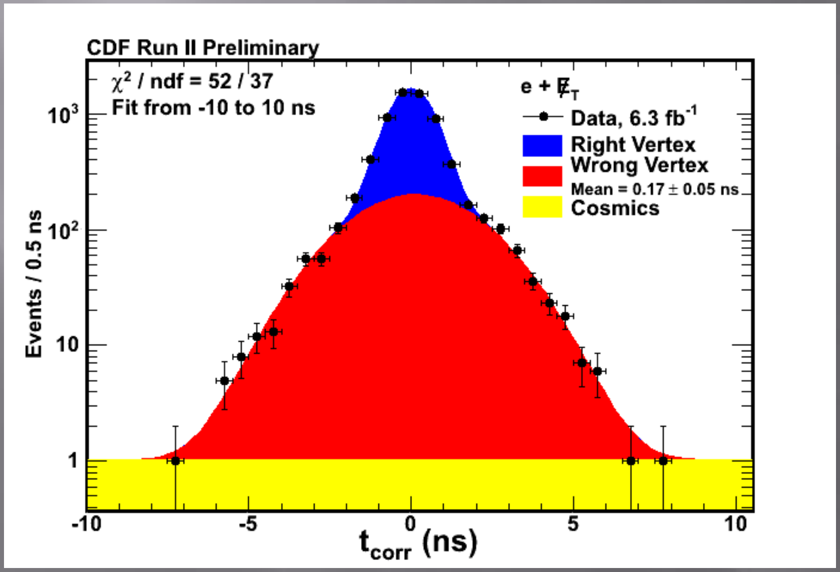
Good photon selection

Quantity	Selection Cut
EM cluster E_T	1 cluster with $E_T > 30$ GeV
Fiducial	$\lvert X_{\mathrm{CES}} \rvert < 21$ cm and $9 < \lvert Z_{\mathrm{CES}} \rvert < 230$ cm
Hadronic fraction	$E_{\mathrm{HAD}}/E_{\mathrm{EM}} < 0.125$ HadE $> -0.3 + 0.008 \cdot E_{\mathrm{T}}^{0}$ [13]*
Energy isolation	$E_{\mathrm{cone}\ 0.4}^{\mathrm{iso}} < 2.0 + 0.02 \cdot (E_T - 20.0)$ CES E/E > 0.2 [13]*
1st CES cluster energy (E_{CES} cut)	$E_{\mathrm{strip}}^{\mathrm{1st}} + E_{\mathrm{wire}}^{\mathrm{1st}} > 10$ 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) $E_{\mathrm{CES}}^{\mathrm{2nd}} < 0.14 E_T$ (2) $E_{\mathrm{CES}}^{\mathrm{2nd}} < 2.4 + 0.01 \cdot E_T$
PMT spike rejection*	$A_{\mathrm{PMT}} = \frac{\lvert E_{\mathrm{PMT1}} - E_{\mathrm{PMT2}} \rvert}{E_{\mathrm{PMT1}} + E_{\mathrm{PMT2}}} < 0.6$
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 χ^2_{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.

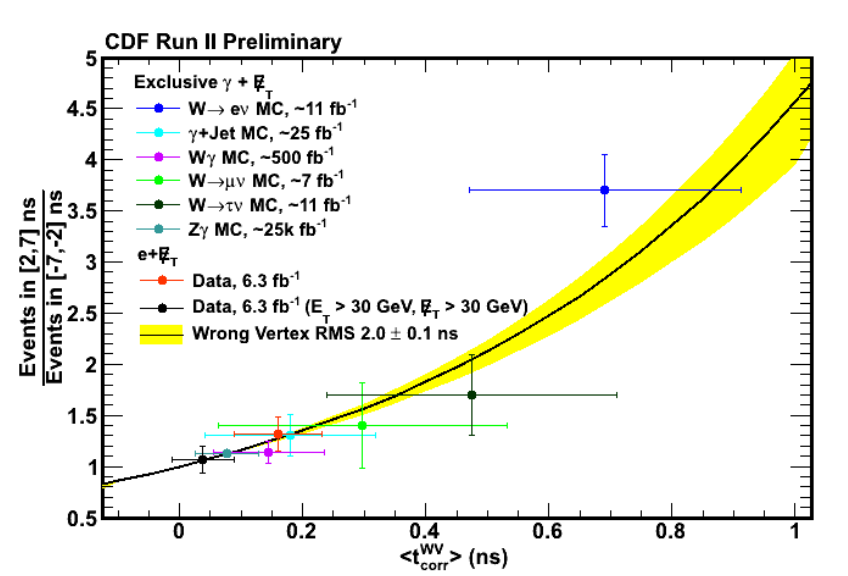
Non-SM Backgrounds: Cosmics





- Flat distribution across time
- To avoid swamping our signal, require some energy in CES and hadronic calorimeters
- Reduces cosmics rate significantly (no need to worry about other non-collision backgrounds)

Normalization of WV backgrounds



- Normalize wrong-vertex backgrounds from the (-2,-7) region
- Follows well predictions from double Gaussian approximation

Photon Timing

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

- t_f = arrival time measured by EMTiming
- t_i = initial time measured by space-time vertexing
- x_f = final position measured in the CES
- x_i = initial position measured in the space-time vertexing

- Our primary analysis variable is the time of arrival of the photon at the EM calorimeter minus the expected time of arrival.
- We calculate the expected time of arrival assuming the photon originated at the event vertex and is prompt.

Likelihood fit

$$-\ln \mathcal{L} \equiv -\ln \mathcal{L}_{GV} - \ln \mathcal{L}_{NV} - \sum_{constraints} \frac{(\alpha_k - \hat{\alpha_k})^2}{2\sigma_k^2}$$

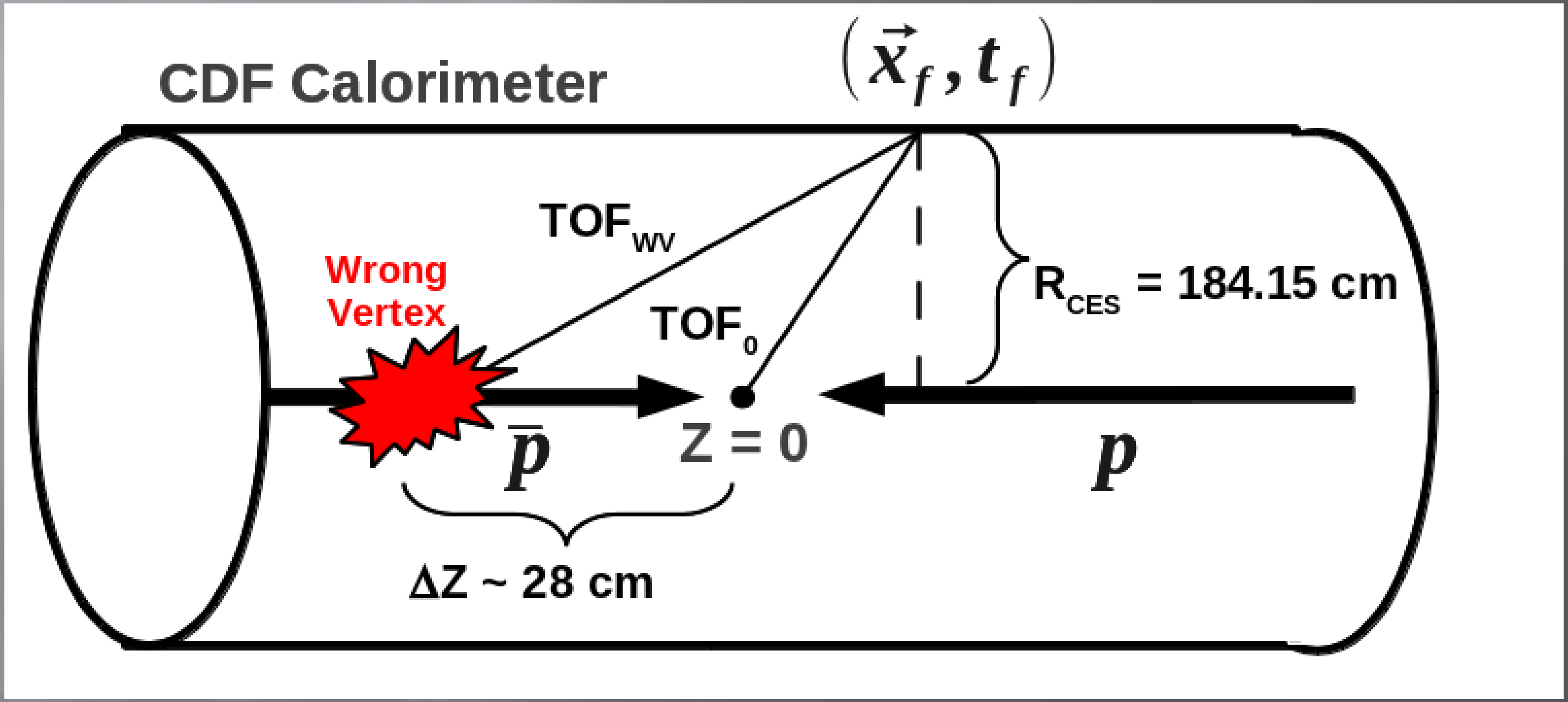
- n_i = observed events
- v_i = expected events
- α_k = parameter being constrained
- $\hat{\alpha}_k$ = nominal value of parameter being constrained
- σ_k = systematic uncertainty on α_k

$$-\ln \mathcal{L} \equiv \sum_i -n_i \ln \nu_i + \nu_i$$

Parameters and nominal values

Parameter	Nominal Value	Systematic Uncertainty
$\langle t_{corr}^{RV} \rangle$	0 ns	0.05 ns
$RMS\langle t_{corr}^{RV} \rangle$	0.64 ns	0.05 ns
$\langle t_{corr}^{WV} \rangle$	$\langle t_{corr}^{0} \rangle$	0.08 ns
$RMS\langle t_{corr}^{WV} \rangle$	2.0 ns	0.1 ns

Wrong-Vertex Mean from No-Vertex Sample



Relating Wrong-Vertex Time to No-Vertex Time

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

Add and subtract time-of-flight from zero

$$t_{corr}^{WV} = (t_i^{RV} - t_i^{WV}) + (TOF_{RV} - TOF_0) + (TOF_0 - TOF_{WV})$$

And note that:

$$t_{corr}^{0} = t_i^{RV} + TOF_{RV} - TOF_0$$

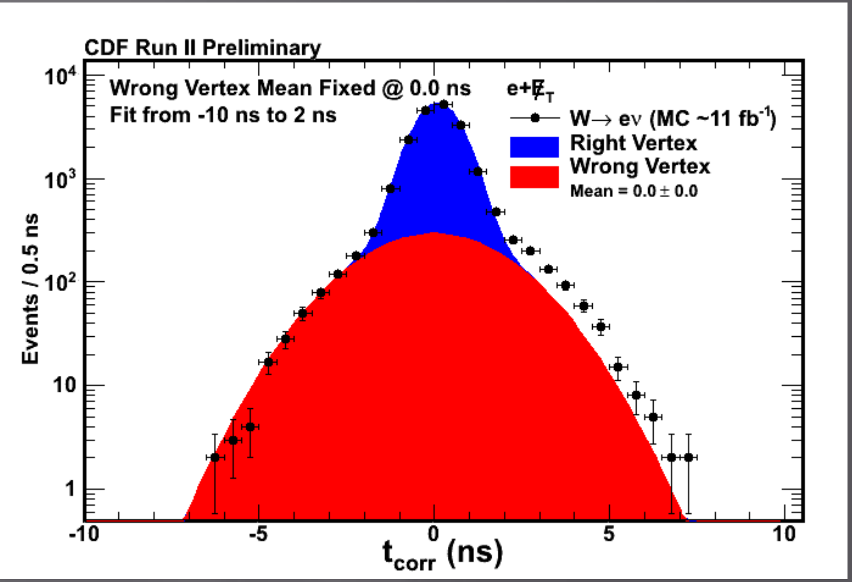
$$t_{corr}^{WV} = t_{corr}^{0} - t_i^{WV} + (TOF_0 - TOF_{WV})$$

Why LHC and not Tevatron?

- Observed excess at Tevatron (CDF), *not* LHC
- Slower times are favored at Tevatron
  - Easier to do delayed photon at CDF

WV Mean = 0 BAD ASSUMPTION

- SM background would look like it has excess even when we know there's no new physics
- Wrong Vertex mean = 0 fails to account for biases towards large flight times
- WV Mean = 0.20 ± 0.13 ns



Fake Large Flight Times

- Three main causes
  - E_T threshold effect
  - Fake photons from electrons
  - Lost jets

E_T Threshold

- Picking wrong vertex can give shorter *AND* longer apparent path lengths
- To solve, we cut on E_T from $z = 0$; this limits how wrong we can be

Fake photons

- Electrons can give rise to fake photons via hard interactions with the material
- We look for track close to reconstructed photon (since this photon began life as an electron)
- This method removes 67% of fake photons while accepting 95% of real photons

Lost jets

- Events with jets happen at very large |Z|
- Our jets can point outside the detector
- Solution: veto events with |Z| > 60 cm, if it contains three tracks
- Cut 96% efficient

Dominant backgrounds

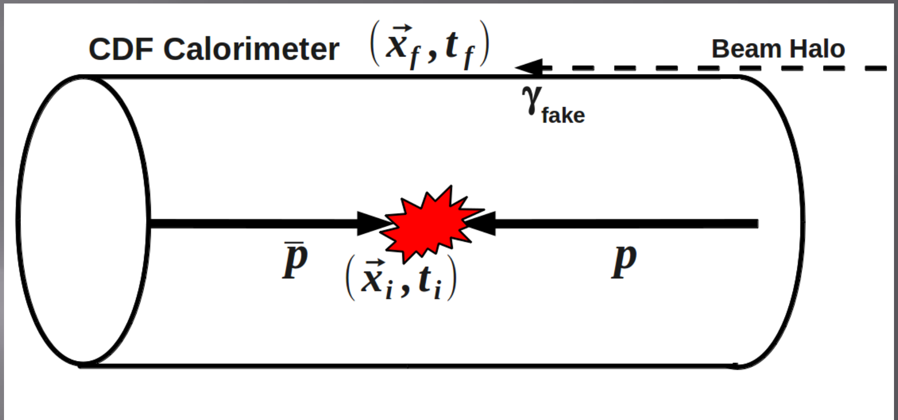
- $W \rightarrow e\nu$ is the dominant background
- Mean of 0.69 ± 0.22 ns

Systematics

- Because of the entirely data-driven nature of the background expectation model, free from usual systematics
- Dominant systematic uncertainty = uncertainty on the estimated mean of the vertex

Beam Halo

- Produced by interactions between beam and accelerator material
- End up as muons flying parallel to beam, with larger radius
- Leave identifying signal on calorimeters



Satellite bunches

- Packets within beam line that are not intended to include particles, but which do
- Interact with particles from main bunch at an offset of ~18 ns at very large |Z|