Search for Supersymmetry Using Diphoton Events in ppbar Collision at $\sqrt{s}$=1.96 TeV

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Outline

Motivation

Tools

Analysis

Conclusion

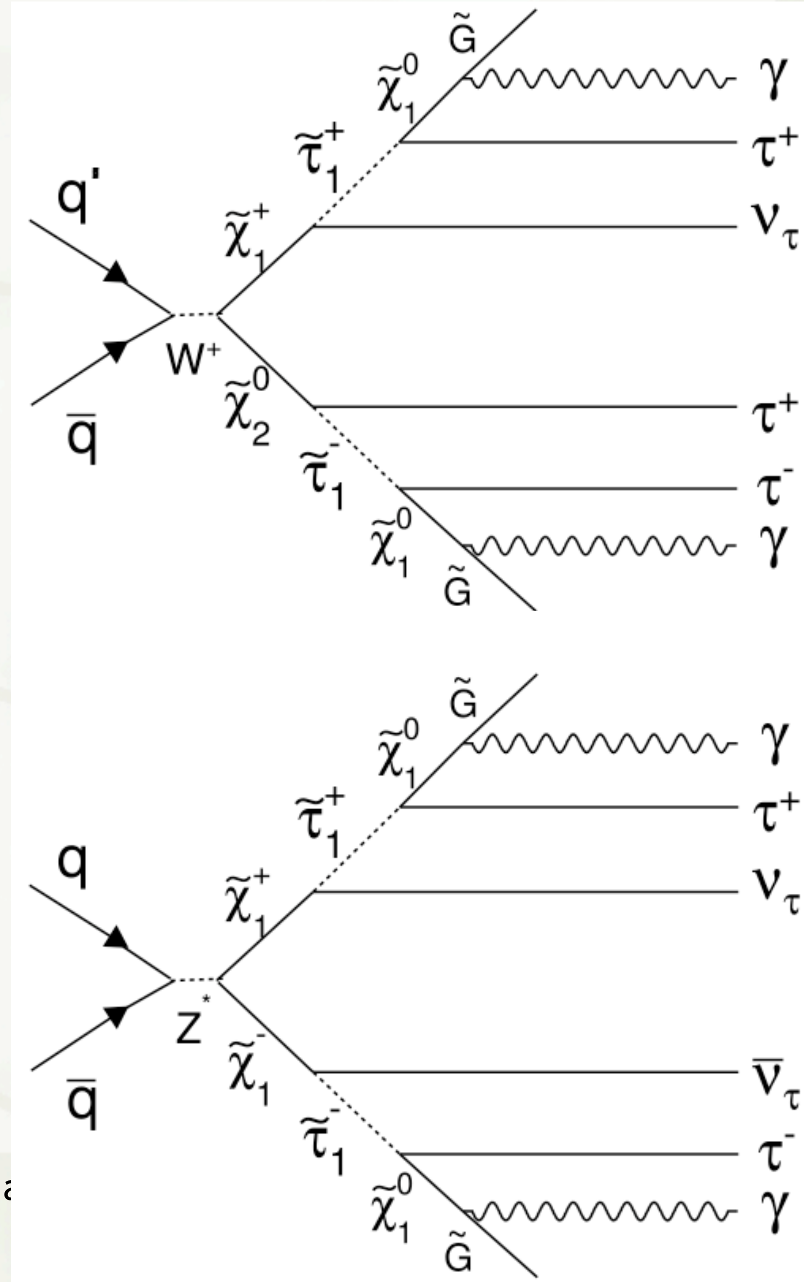
Motivation

Supersymmetry

- Supersymmetry (SUSY) is a symmetry between fermion and boson and provides an elegant solution to the naturalness problem
- In real world SUSY must be broken since no observation of SUSY particles yet
- SUSY must be an approximate symmetry of the theory above the TeV scale $\Rightarrow$ possible when SUSY is broken only softly
- These soft terms determine the mass spectrum of the new particles
- The mechanism of SUSY breaking is the key element for low-energy aspects of SUSY theories
- There are many ways of SUSY-breaking can occur

GMSB Models

- In Gauge Mediated SUSY Breaking (GMSB) Models SUSY is broken at low energy scale (TeV), with breaking transmitted by SM gauge interactions
- GMSB is quite predictive in the SUSY mass spectrum and has distinctive phenomenological features - collider experiments can put these predictions fully to test



More on GMSB

- This nominal GMSB has only 6 “free” parameters while Minimal SUSY Model has 105 free parameters
- Intrinsically suppress flavor-changing neutral currents (FCNC), which is experimentally not observed
- Consistent with cosmological constraints as all SUSY particles produced in early universe decay to the $\tilde{G}$ Lightest SUSY Particle (LSP) which can be a dark matter candidate - More on this later

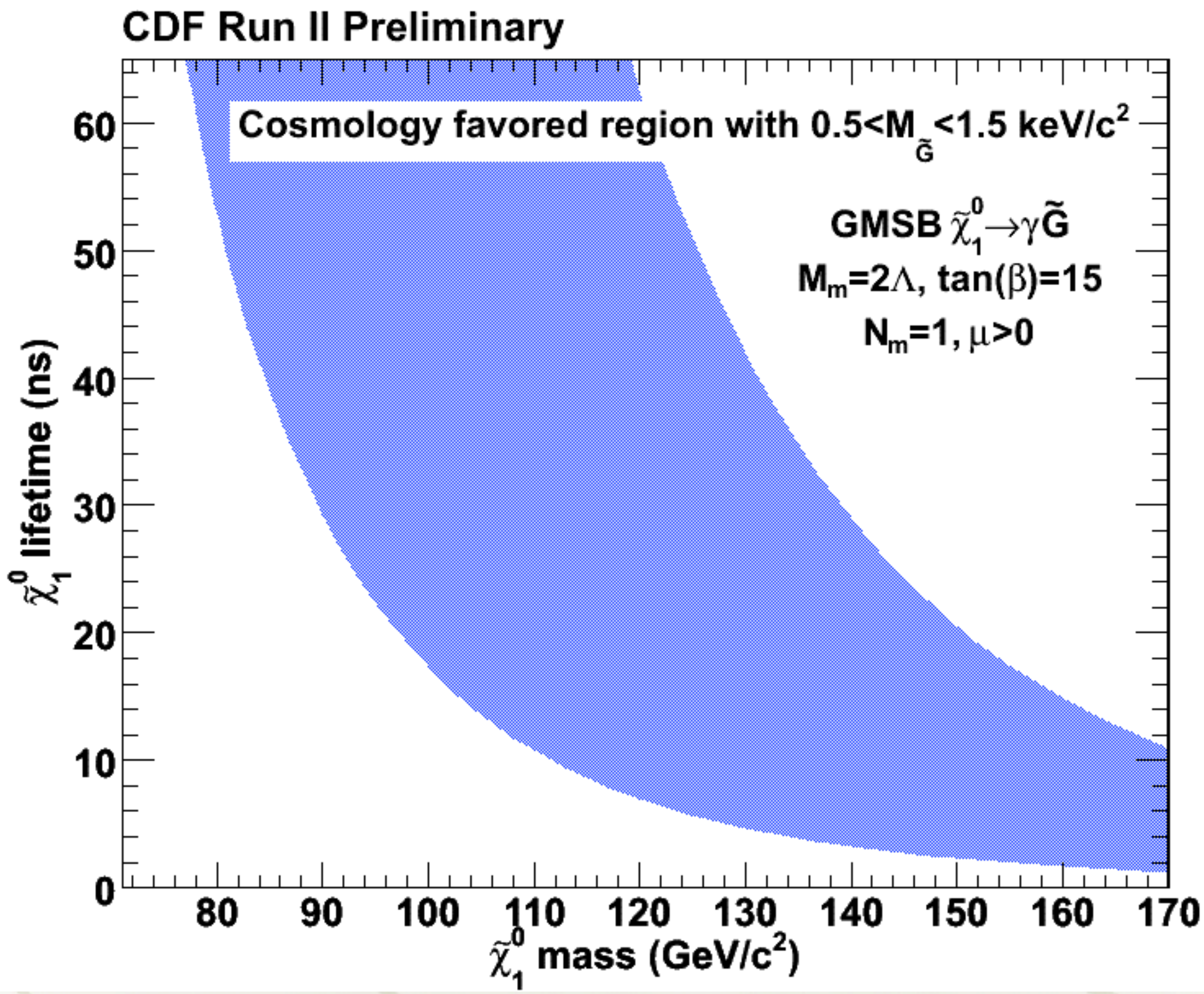
GMSB Neutralino

- For simple case GMSB predicts the lightest Neutralino ($\tilde{\chi}_1^0$) to be the Next-to-Lightest SUSY Particle with the Gravitino ($\tilde{G}$) as the Lightest SUSY Particle
- For much of the parameter space the Neutralino decays via $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$
- The final state high energy photons can be produced at collider experiments
- $\tilde{\chi}_1^0$ can travel macroscopic distance (meters) with nanosecond lifetimes - measure the arrival time of photon

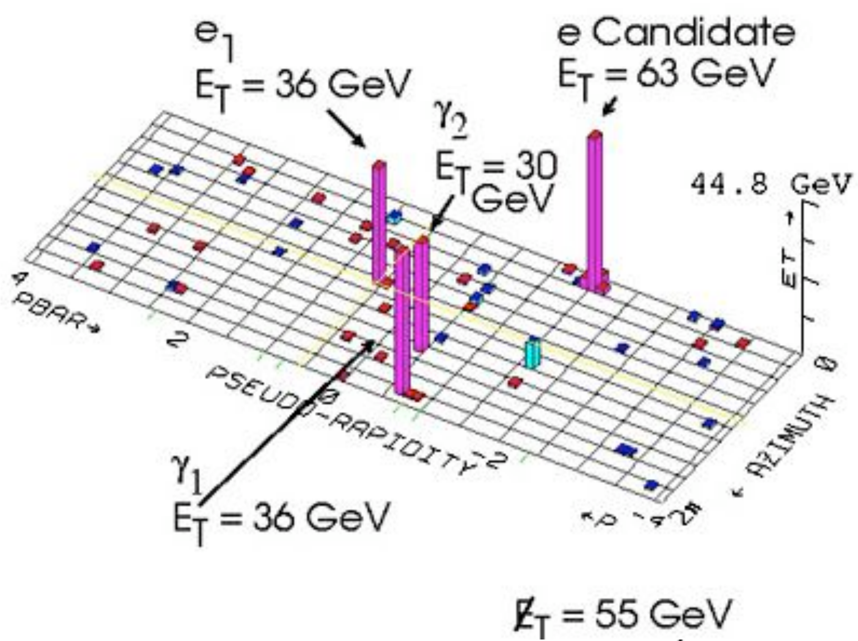
GMSB and Cosmology

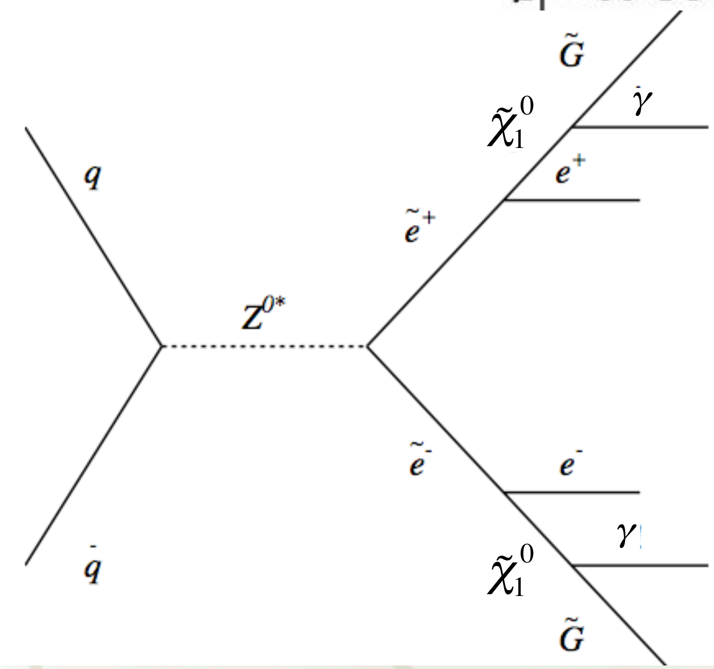
- GMSB with non-zero $\tilde{\chi}_1^0$ lifetime and ~1 keV mass $\tilde{G}$ is favored as they are consistent with astronomical observations and early universe inflation model
- If $\tilde{G}$'s too light (< 1 keV) these will not contribute significantly to the total mass density of the universe, may need another source of dark matter (i.e., QCD axion)
- If $\tilde{G}$'s too heavy (> 1 keV) their density can cause the universe to "overclose"
- This cosmology constraints (m_{Grav}~1 keV) relate mass and lifetime of $\tilde{\chi}_1^0$
  - small lifetimes (several ns) are favored for large masses (~100 GeV)

Cosmology Favored Region



- 0.5<m_{Grav}<1.5 keV
- $\tilde{G}$ can be a warm dark matter candidate in this region





Unusual Event: SUSY?

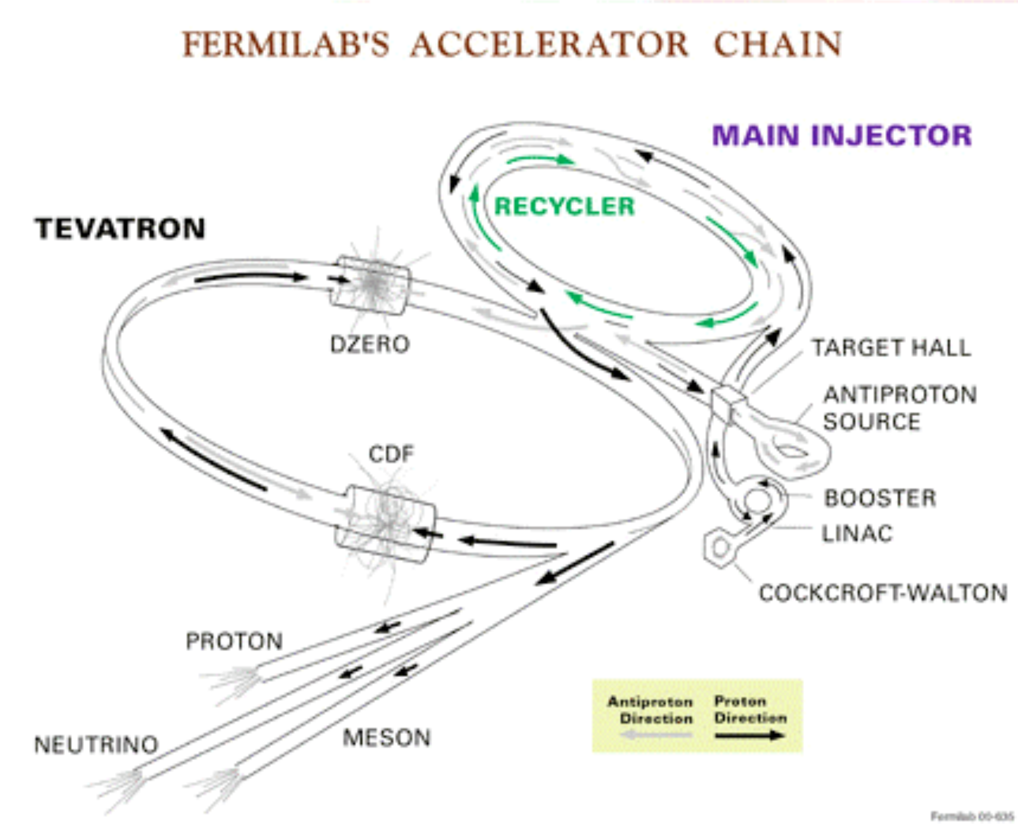
- In late 1990's an unusual $ee\gamma\gamma\not{E}_T$ candidate event was observed at the CDF detector in Fermilab
- SM prediction: ~10^{-6} events
- Is this GMSB-SUSY?

Tools

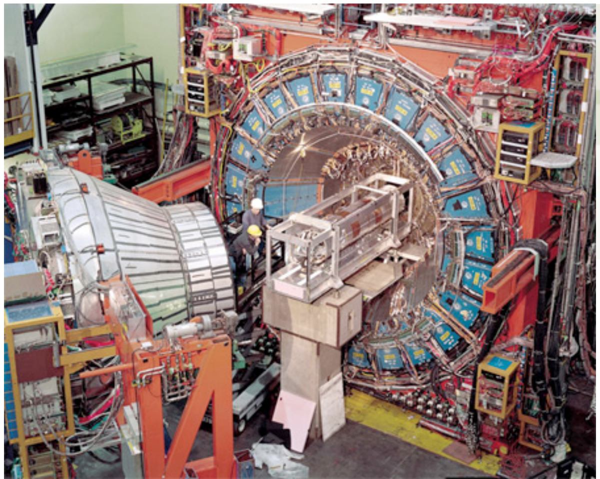
Particle Collider

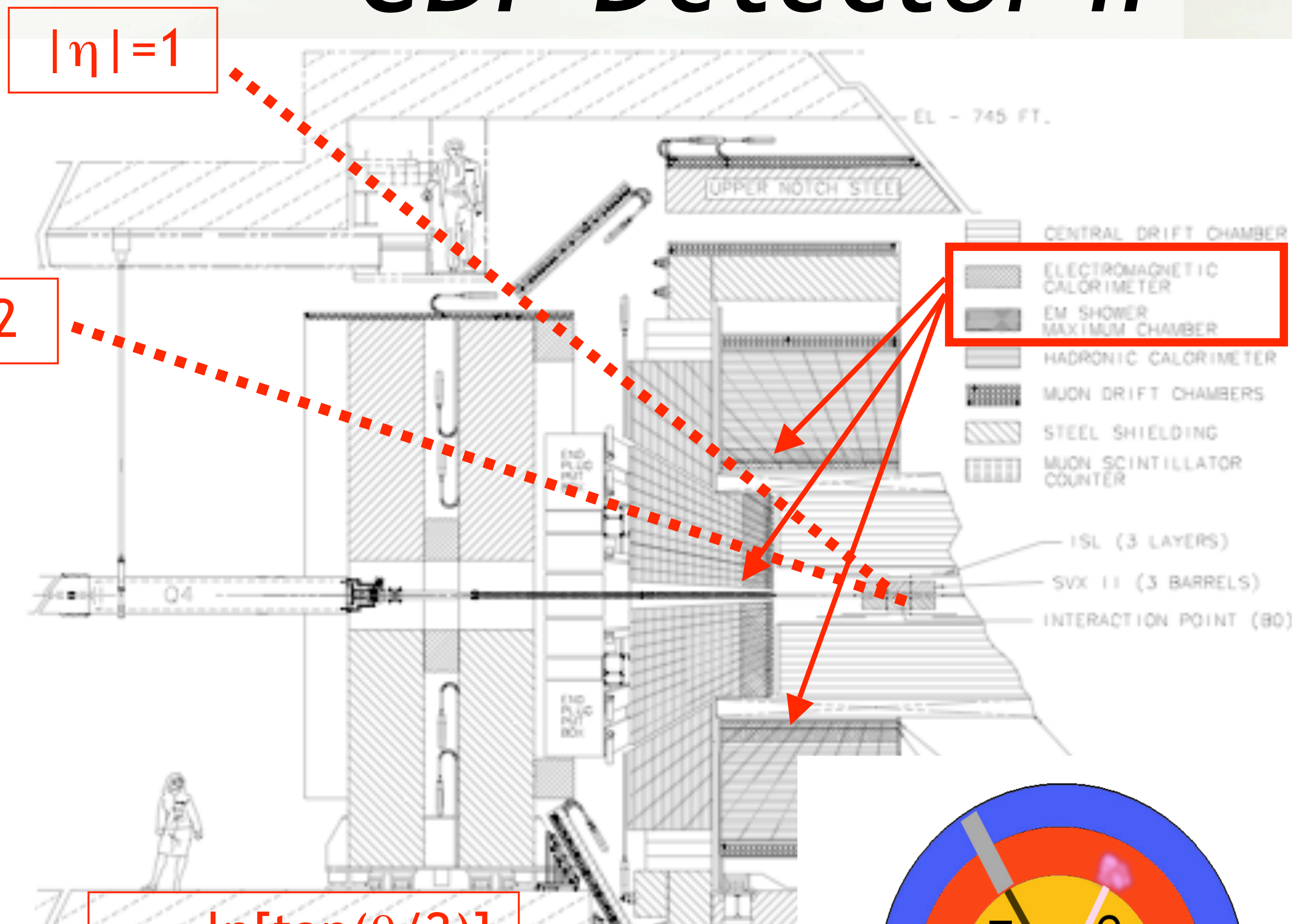
One way to search for the Neutralinos is to use particle colliders like the Tevatron at Fermilab

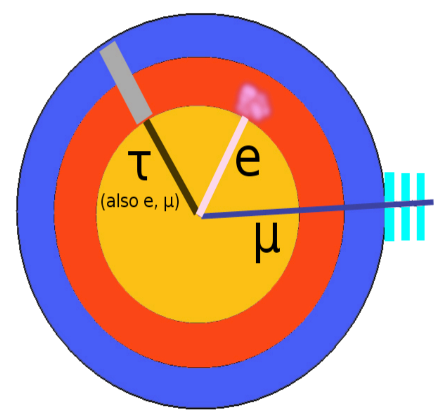
- Energy frontier for now : 1.96 TeV
- A beam crossing every 396 ns
- ~ 60 mb inelastic cross section: 6 trillion collisions per 100 pb^{-1}
- Total integrated luminosity ~5.8 fb^{-1} delivered up to now



CDF Detector II



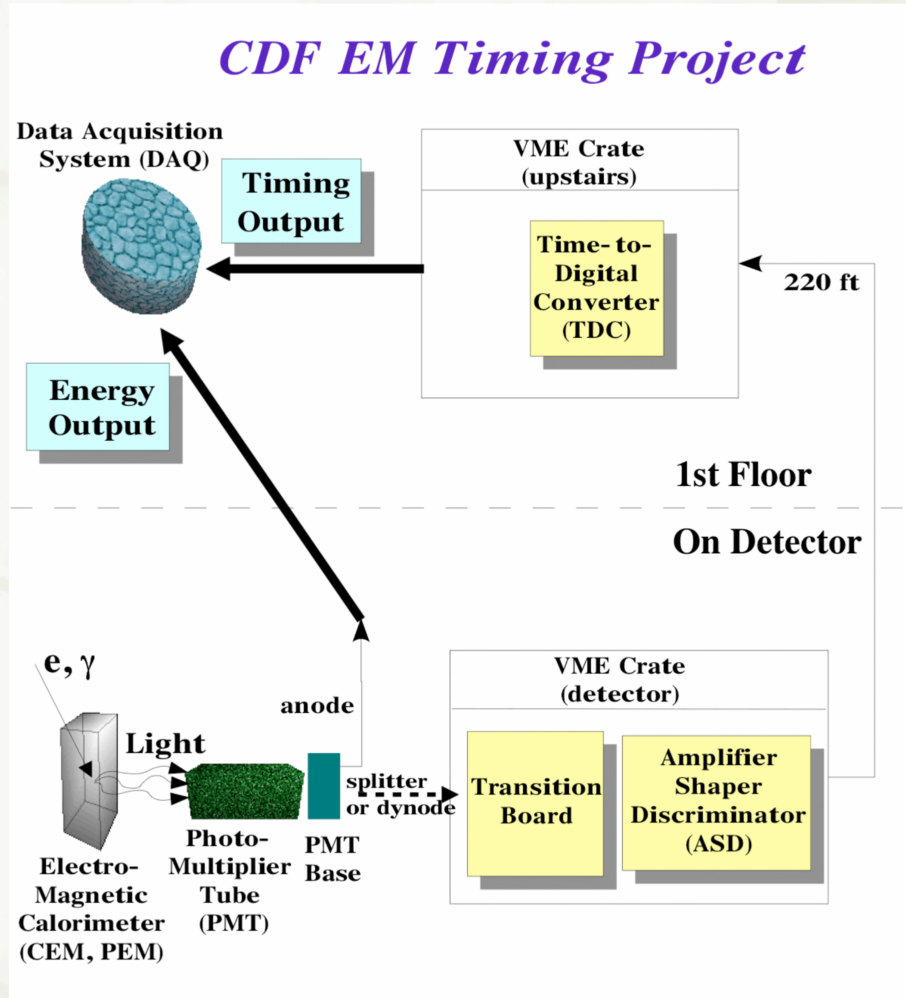




- This is a multipurpose detector with multi concentric system
- Able to identify electrons, muons, taus, jets, photons, b's and $\not{E}_T$

The EMTiming System

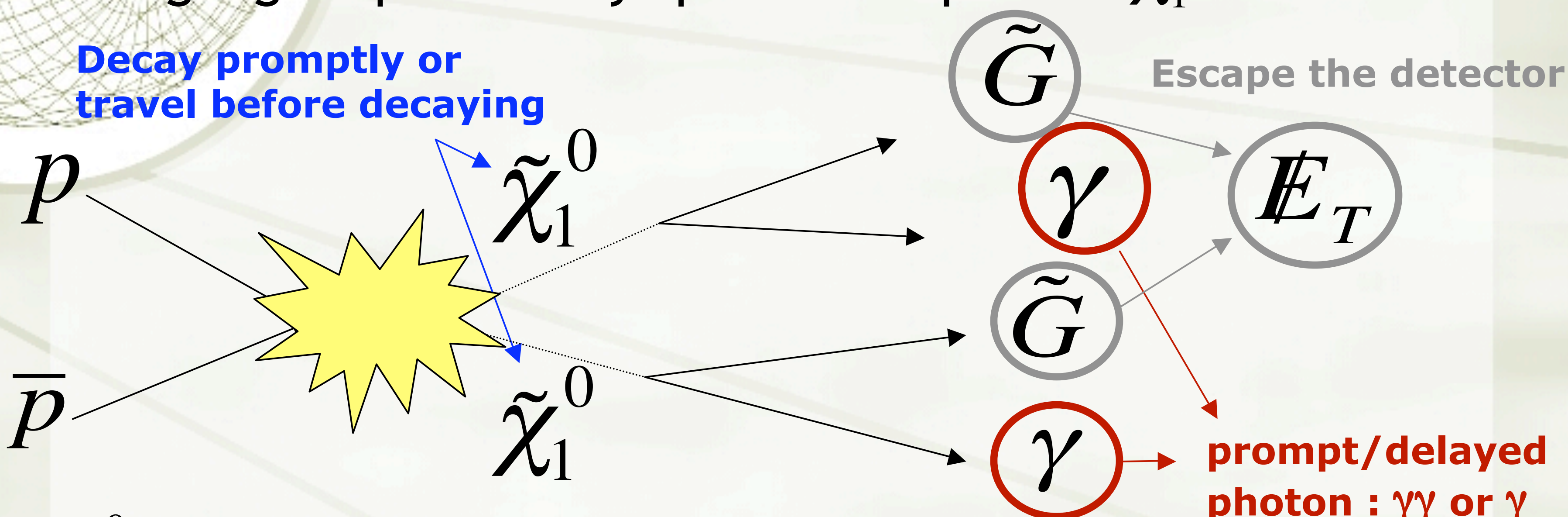
- Provides time of arrival of photons at calorimeter
- Includes both CEM and PEM ($|\eta| < 2.0$)
- Became fully operational starting in Dec 2004
- Timing resolution: ~0.5 ns
- 100% efficient for photons with $E_T > 3$ GeV



Analysis

GMSB Event Signature

- In the Tevatron ($p\bar{p}$ collision) gaugino pair-production dominates in our GMSB model
- The gaugino pair decays produce a pair of $\tilde{\chi}_1^0$'s



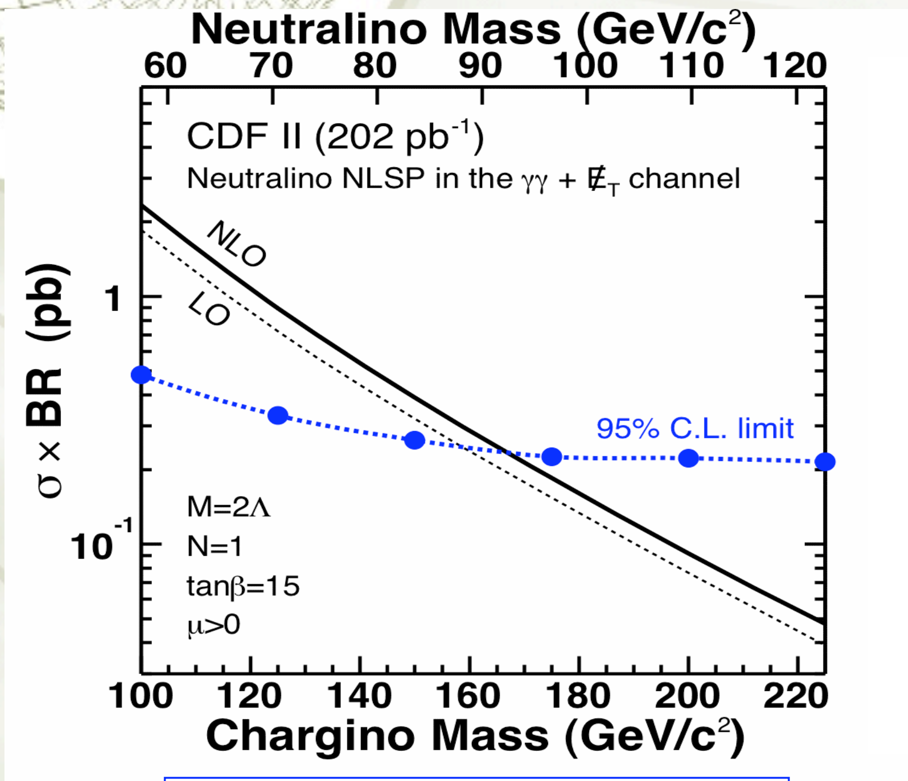
- $\tilde{\chi}_1^0$ decays into $\tilde{G}$, that gives rise to missing transverse energy ($\not{E}_T$), and a photon
- Both or either $\tilde{\chi}_1^0$ can decay in the detector

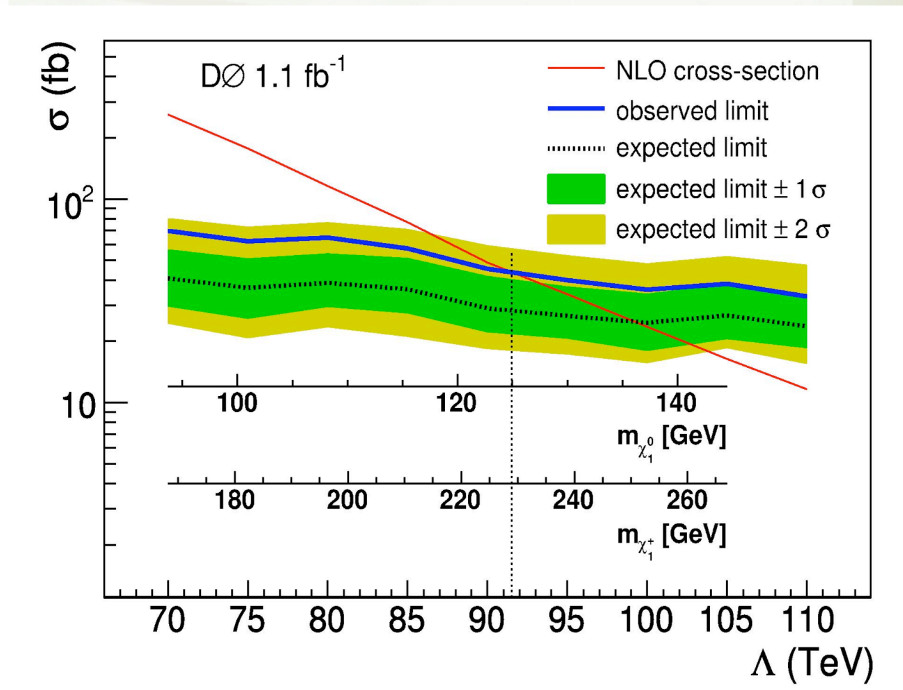
$$\gamma\gamma + \not{E}_T \text{ or } \gamma + \not{E}_T$$

Previous Diphoton Searches

$\gamma\gamma + \not{E}_T$ searches : sensitive to low lifetimes (τ < 2 ns)

(only prompt photons : $\tau = 0$ ns)





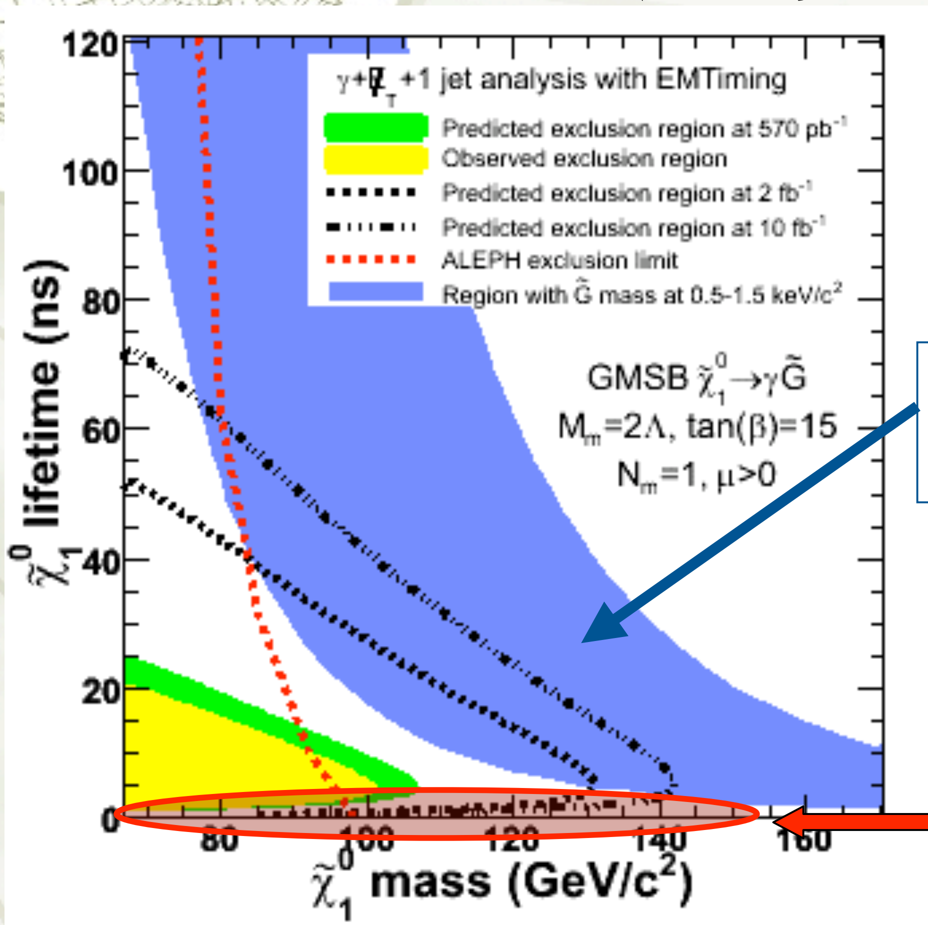
CDF (0.2 fb^{-1})
Phys.Rev.D71, 031104 (2005)

DØ (1.1 fb^{-1})
Phys.Lett.B659, 856 (2008)

Previous Delayed Photon Search

$\gamma + \not{E}_T + jet$: sensitive to high lifetimes

(delayed photons : $\tau > 2$ ns)



CDF (0.6 fb^{-1})
Phys.Rev.Lett 99, 121801 (2007)
Phys.Rev.D78, 032015 (2008)
P. Geffert, M. Goncharov, **EUNSIN LEE**, D. Toback, V. Krutelyov and P. Wagner

Cosmology Favored Region (shown in previous slide)

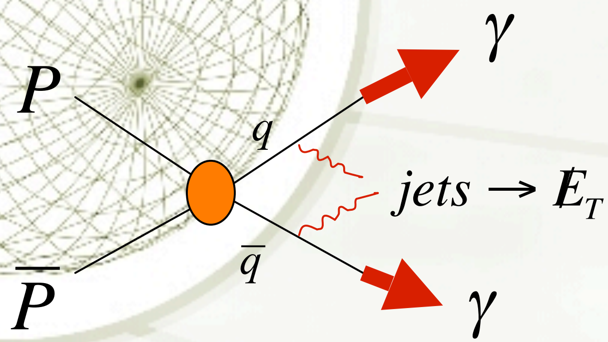
Our new search is first $\gamma\gamma$ search for non-zero low lifetime region (τ<2 ns):

Trying to understand here

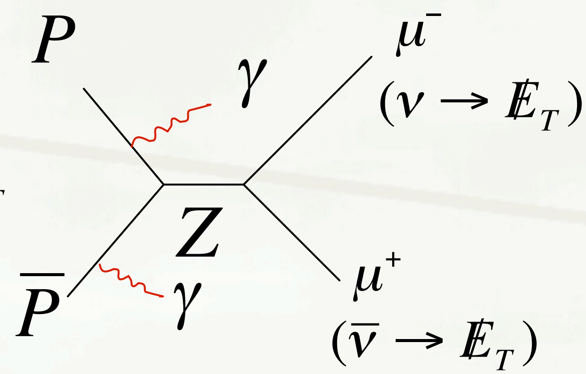
Overview of This Analysis

- An *a priori* analysis where we look at all events that have two photons, regardless of what else is in the sample (inclusive diphoton sample)
- Estimate the backgrounds for this sample as a function of various cuts
- Optimize with background predictions and signal acceptance
- Open the box

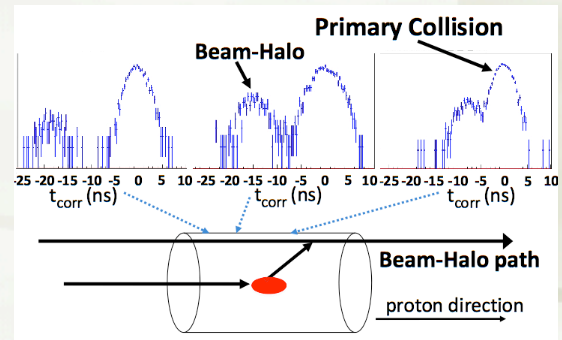
Backgrounds



QCD Background



EWK Background



Non-Collision Background : Cosmic and Beam Halo

- QCD Events ($\gamma\gamma, \gamma - jet \rightarrow \gamma\gamma_{fake}$ and $jet - jet \rightarrow \gamma_{fake}\gamma_{fake}$) with fake $\not\!\!E_T$ due to energy mis-mearsurement and event reconstruction pathologies such as wrong vertex and tri-photon events
- EWK Events (*W*'s and *Z*'s) with real $\not\!\!E_T$
- Non-Collision Backgrounds (cosmic rays and beam halo)

More on each later!

Dataset and Event Selection

- Luminosity = 2.6 fb^{-1}
- Photon of E_T > 13 GeV, $|\eta|<1.1$
- Standard CDF Photon ID requirements
- $N_{vx} \geq 1$, Highest ΣP_T Vertex, $|Z_{vx}| < 60$ cm
- Cosmic rays and Beam related background removal cuts

What's new?

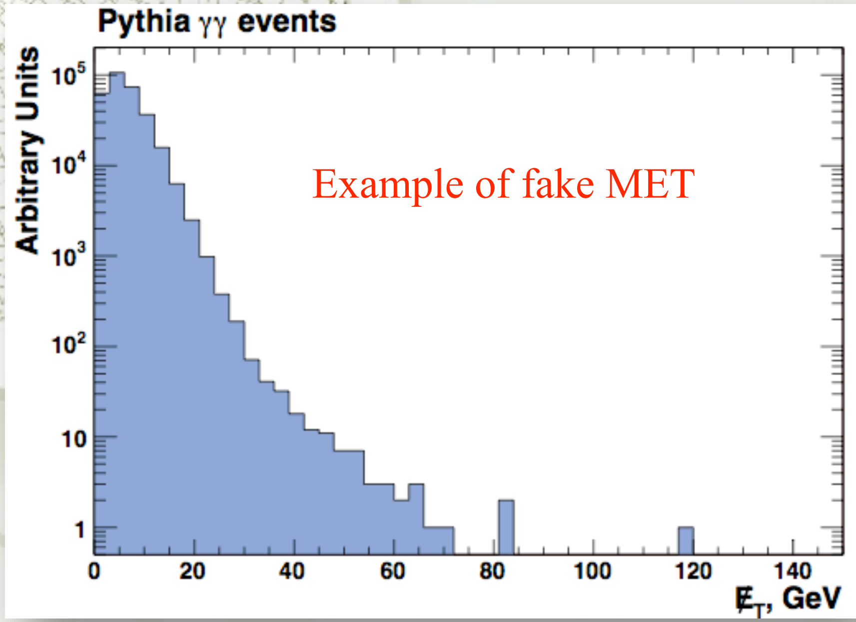
- New METMODEL to improve QCD rejection
- The EMTiming system to reject cosmics and beam related backgrounds
- Simplify and re-optimize the analysis due to more direct ways of rejecting backgrounds
- Use 13 times more data (0.2 $fb^{-1} \Rightarrow 2.6\ fb^{-1}$)
- Estimate the sensitivity to non-zero lifetimes

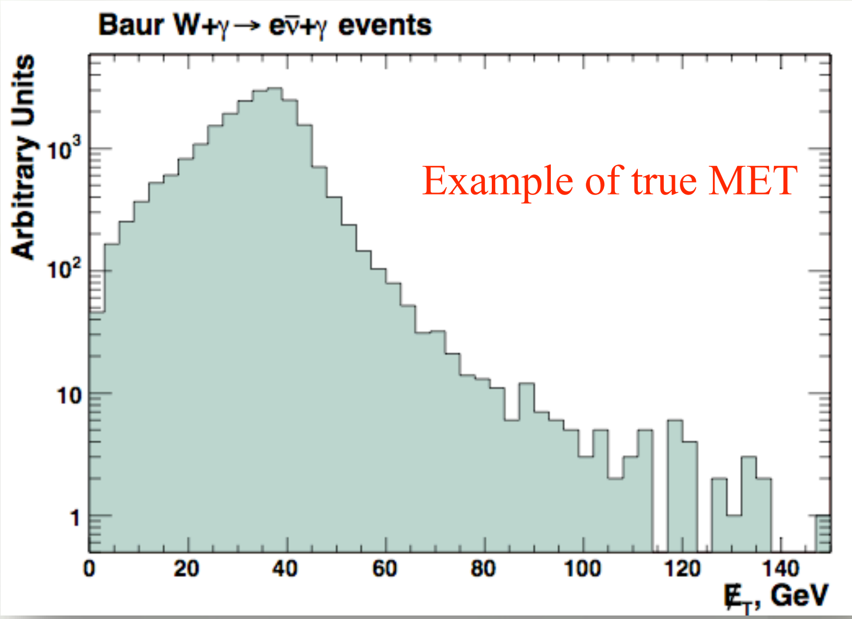
(The EMTiming Simulation in GMSB signal MC)

$\not{E}_T$ *Resolution Model*

- Missing Transverse Energy ($\not{E}_T$): Transverse momentum of particles that escape a detector ⇒ real $\not{E}_T$
- Detectors not perfect: fake $\not{E}_T$ can arise due to energy measurement fluctuations
- $\not{E}_T$ Resolution Model (*METMODEL*) is designed to measure the significance of the $\not{E}_T$ and predict the expected $\not{E}_T$ significance distribution for a sample of events

Fake MET Problem in $\gamma\gamma$+MET



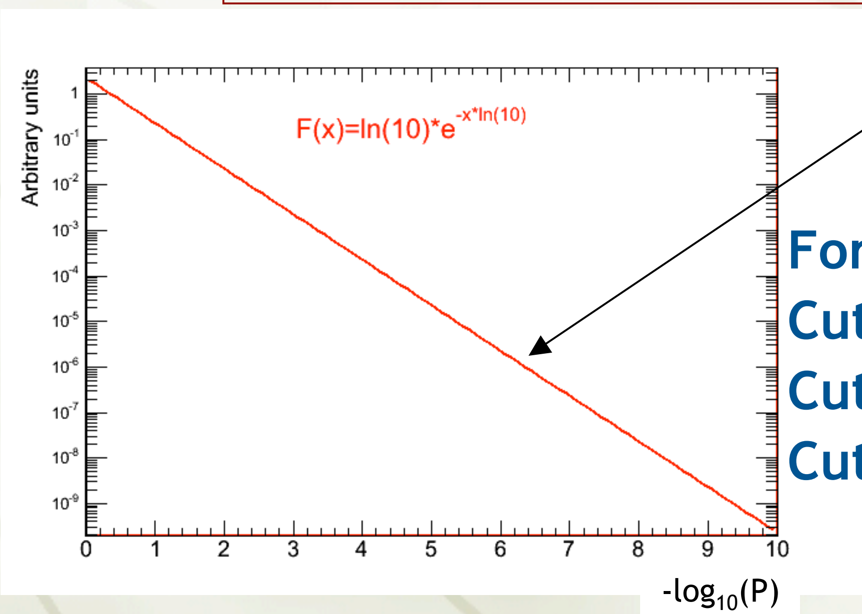


- MET distribution in $\gamma\gamma$ events is dominated by regular "QCD" events with fake MET
- MC is not reliable in modeling multi-jet events:
  - not accurate description of fake MET
- How do you distinguish events with true & fake MET?

$\not{E}_T$-significance

- METMODEL runs large number of pseudo experiments to produce $P(\not{E}_T)$ of all possible values of the fake $\not{E}_T$ by smearing clustered (jets) and unclustered energy
- Want to know how significant measured $\not{E}_T$ is
- New definition:

$$\not{E}_T\text{ - significance} = -\log_{10} P(\not{E}_T^{fluc} \geq \not{E}_T^{meas})$$



If there is no real $\not{E}_T$

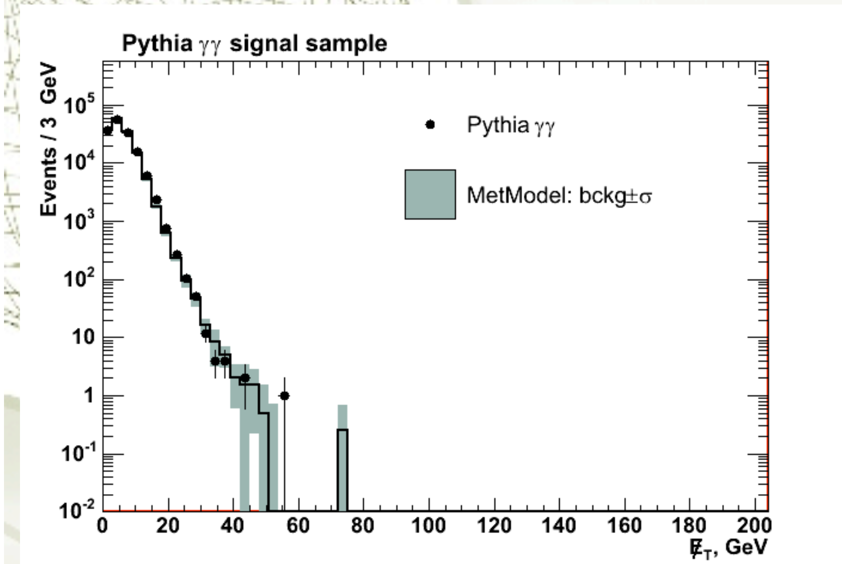
For 10,000 events

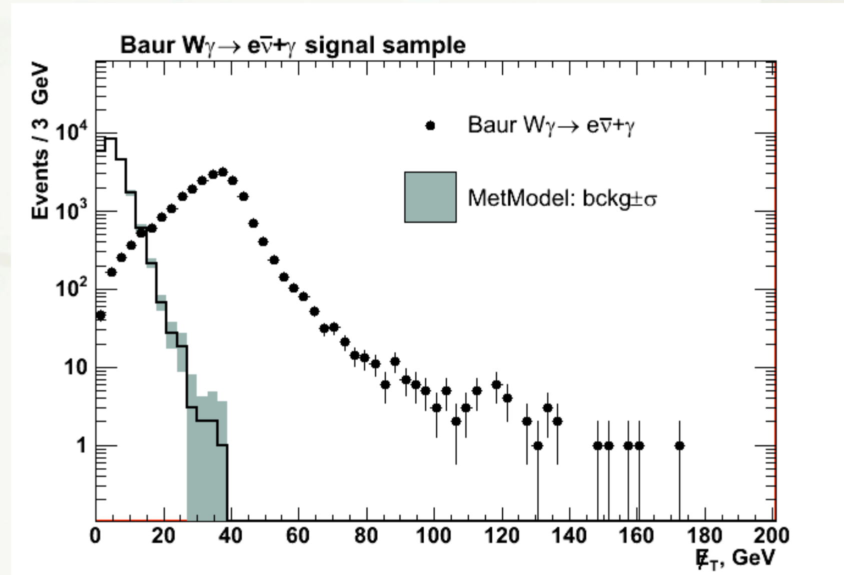
Cut on MetSig>1: ~1,000 events pass (10%)

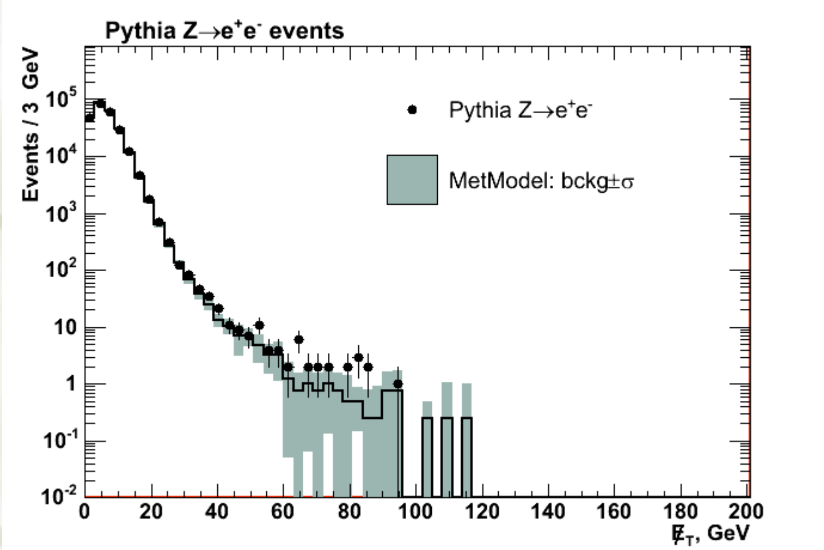
Cut on MetSig>2: ~100 events pass (1%)

Cut on MetSig>3: ~10 events pass (0.1%)

How Well METMODEL Works







- Met Model successfully describes MET in Pythia $\gamma\gamma$ and Z events where there is no real MET
- Just as expected, it doesn’t describe MET in Baur Wγ events with real MET

QCD Backgrounds with Fake $\not\!\!E_T$

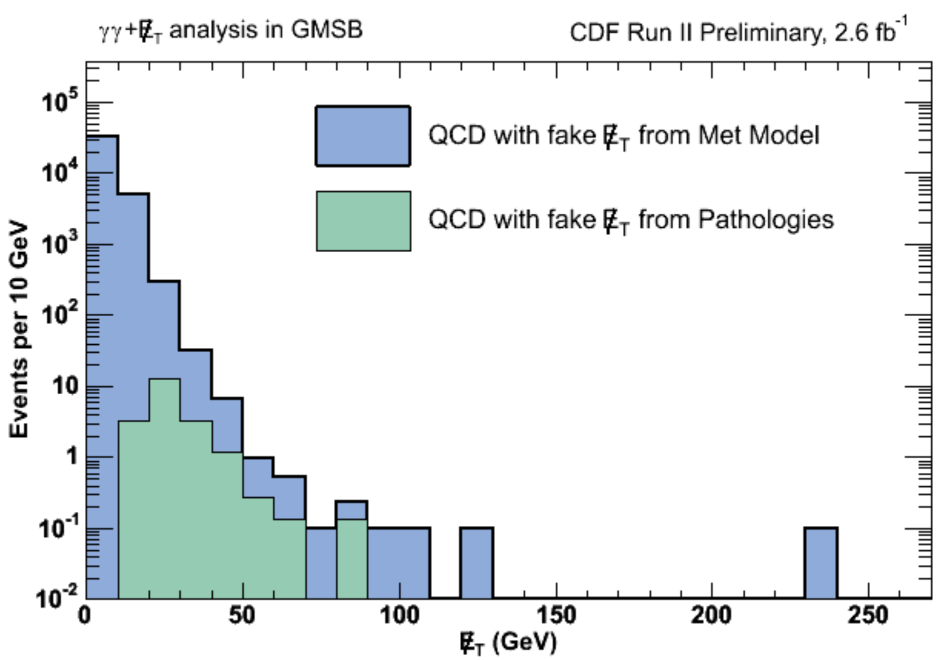
- $\gamma\,\gamma$, γ *jet* $\rightarrow \gamma\,\gamma_{fake}$, *jet jet* $\rightarrow \gamma_{fake}\,\gamma_{fake}$

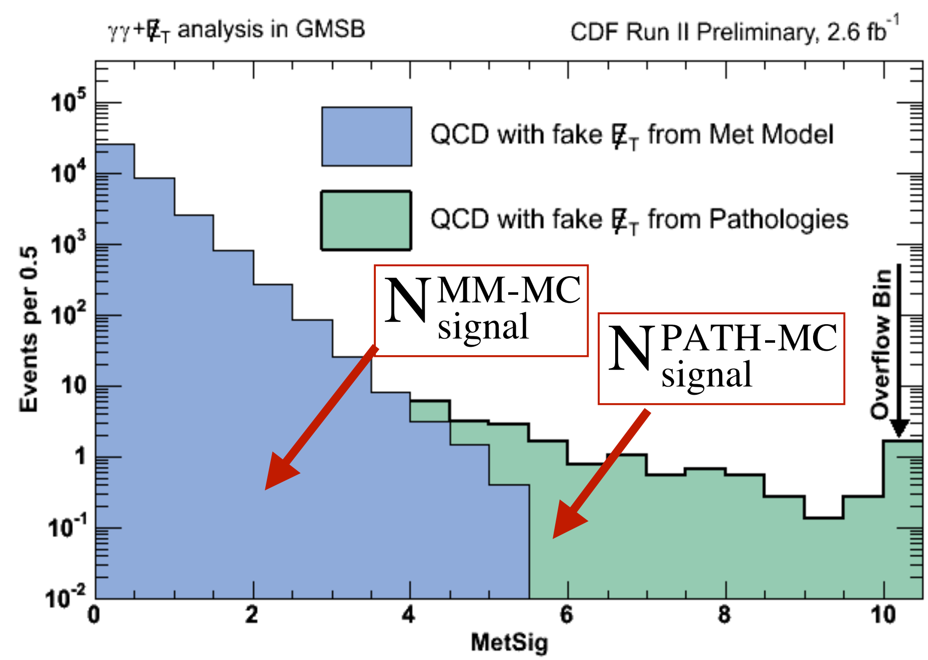
- Energy Measurement Fluctuations
  - Measure the significance of the $\not\!\!E_T$ and predict the expected significance distribution for a sample of events by means of METMODEL

- Large Fake $\not\!\!E_T$ from event reconstruction pathologies such as tri-photon events where a photon is lost
  - Normalize diphoton MC sample to the inclusive diphoton sample, taking into account jet backgrounds

- Total QCD Prediction: $N^{QCD}_{signal} = N^{MetModel}_{signal} + N^{PATH}_{signal}$

Total QCD Backgrounds





EWK Backgrounds with Real $\not{E}_T$

- *W*'s and *Z*'s with real $\not{E}_T$ in Leptonic Channels :

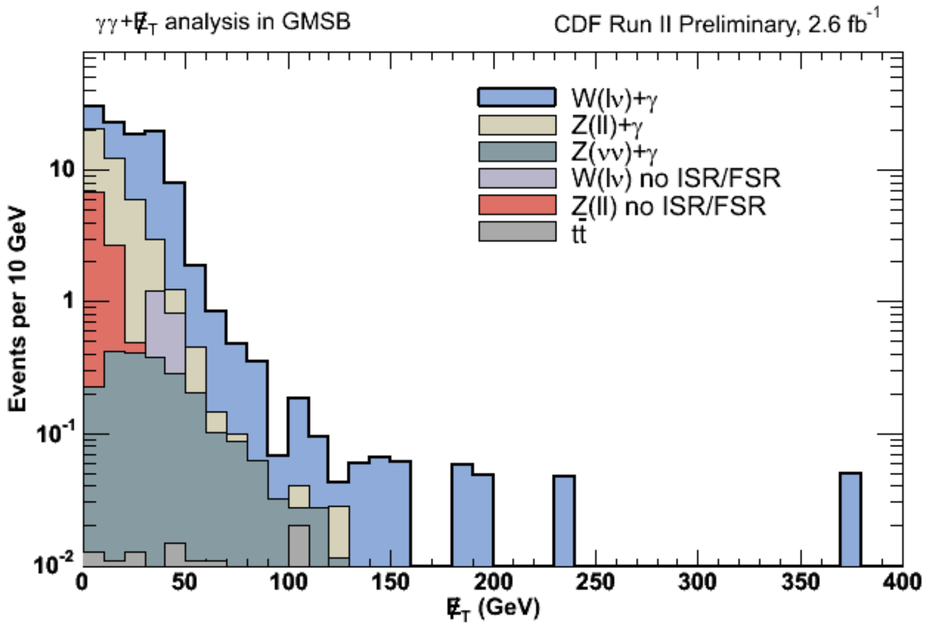
1) $W\gamma\gamma$ and $Z\gamma\gamma$
2) $W\gamma\gamma_{fake}$ and $Z\gamma\gamma_{fake}$
3) $W\gamma_{fake}\gamma_{fake}$ and $Z\gamma_{fake}\gamma_{fake}$

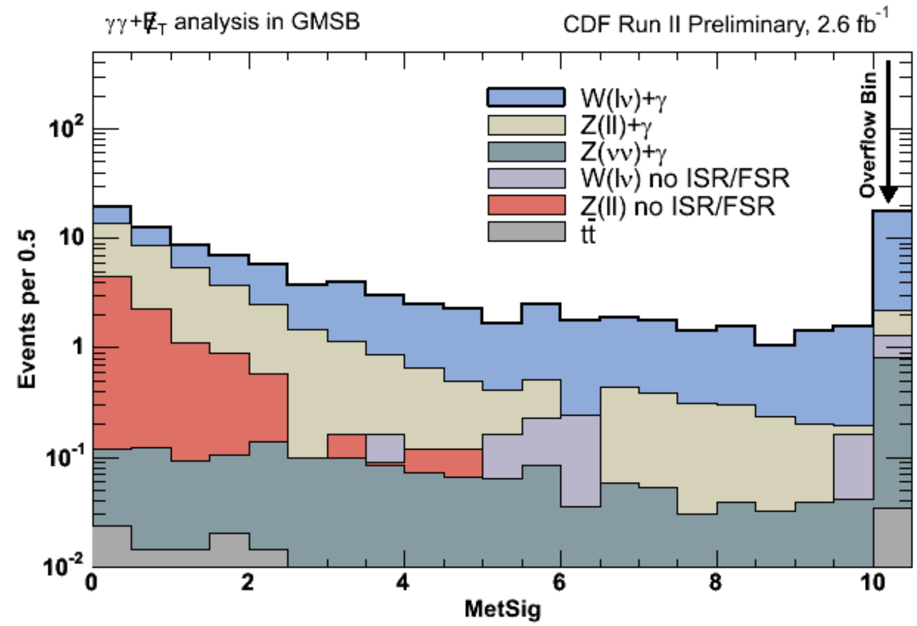
- Using MC samples with production cross section, normalize to $e\gamma$ data

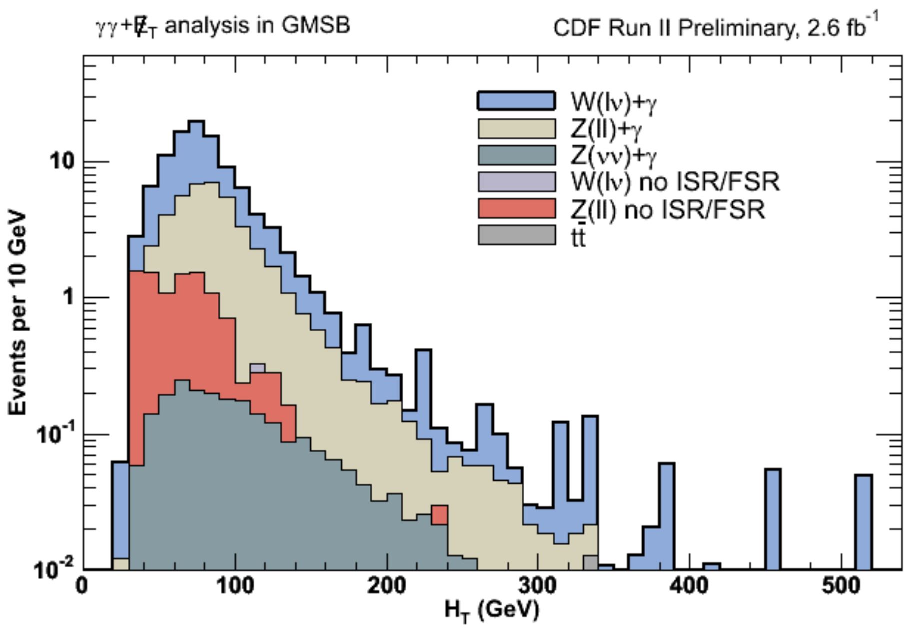
$$\mathrm{N}^{\mathrm{EWK}}_{\mathrm{signal}} = \sum_{i=\mathrm{sources}} \mathrm{N}^{\mathrm{EWK-MC}}_{\mathrm{signal},i} \cdot \mathrm{SF}_i \frac{\mathrm{Data}(e\gamma)}{\mathrm{MC}(e\gamma)}$$

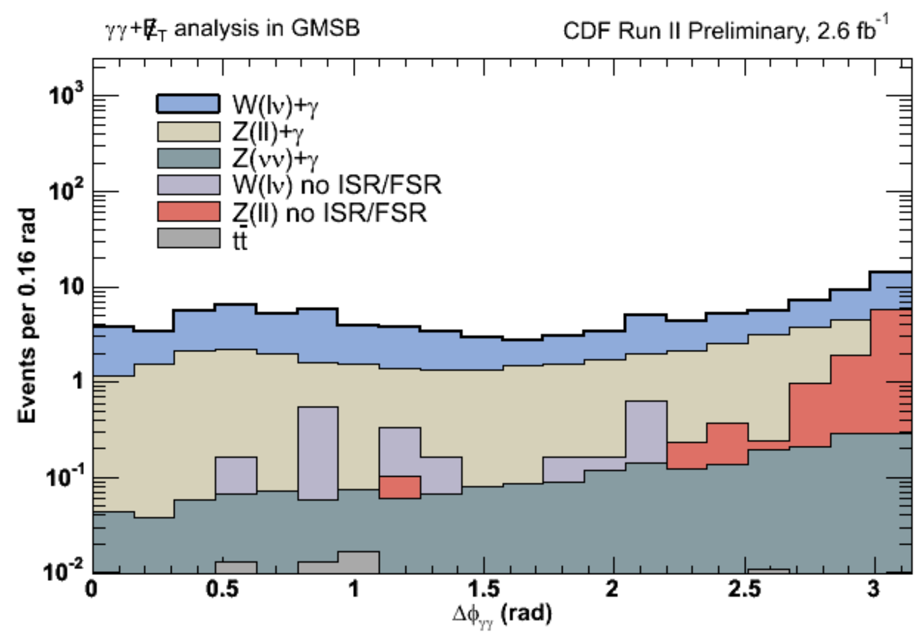
where $\mathrm{SF}_i = \dfrac{\sigma_i \cdot \mathrm{k}_i \cdot \mathcal{L}}{\mathrm{N}^{\mathrm{EWK}}_{\mathrm{sample},i}}$ is scale factors to get proper ratio of each EWK background for $\gamma\gamma + \not{E}_T$

EWK Backgrounds Distributions









Non-Collision Backgrounds

- Beam Halo (BH): Estimate based the number of identified BH events

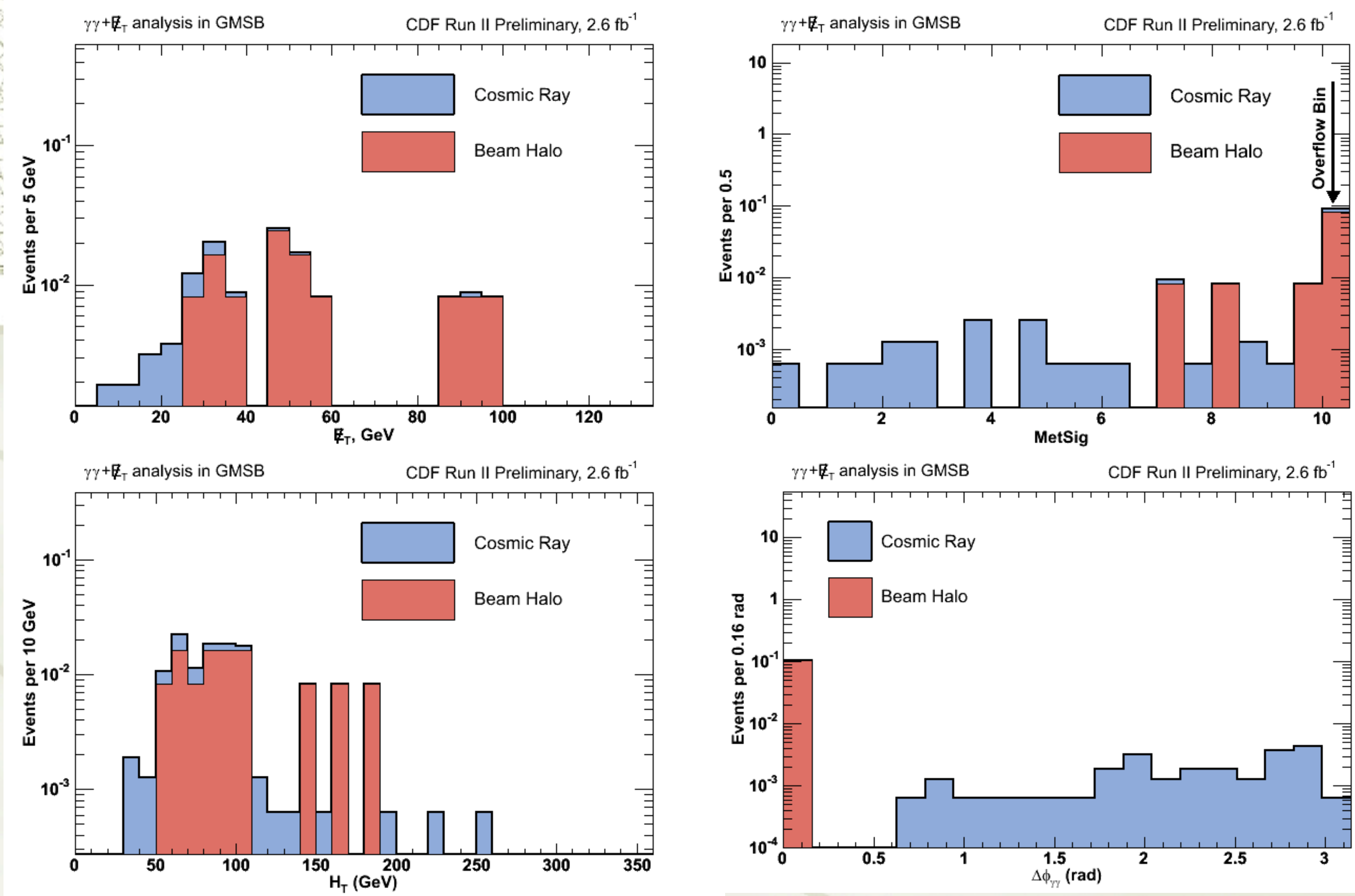
  - Distinctive energy deposition pattern of BH muons traveling along the beam pipe

- Cosmic Rays: Use the EMTiming system

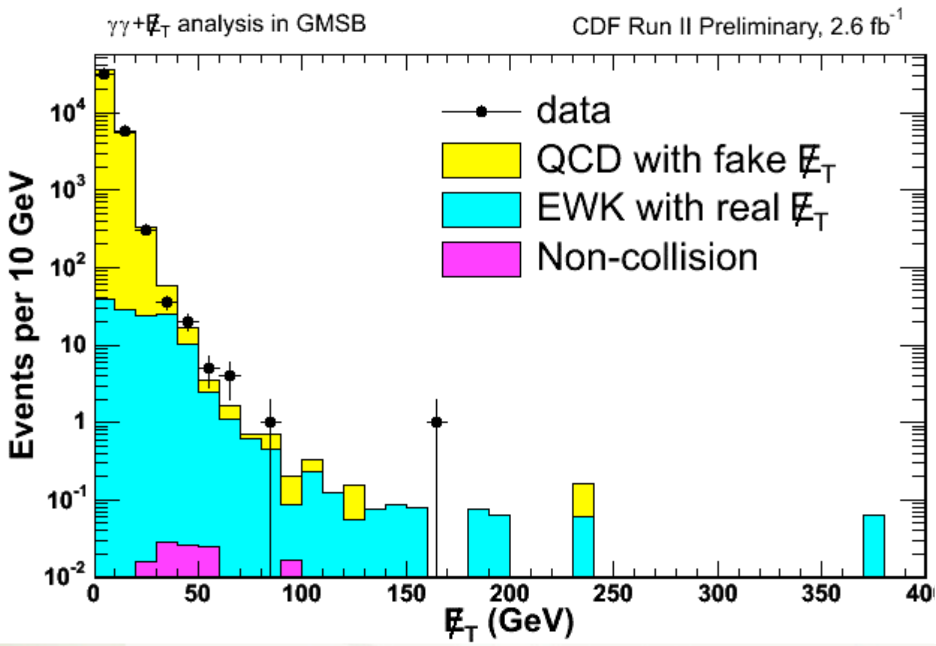
  - not correlated in time with collisions and their timing distribution roughly flat

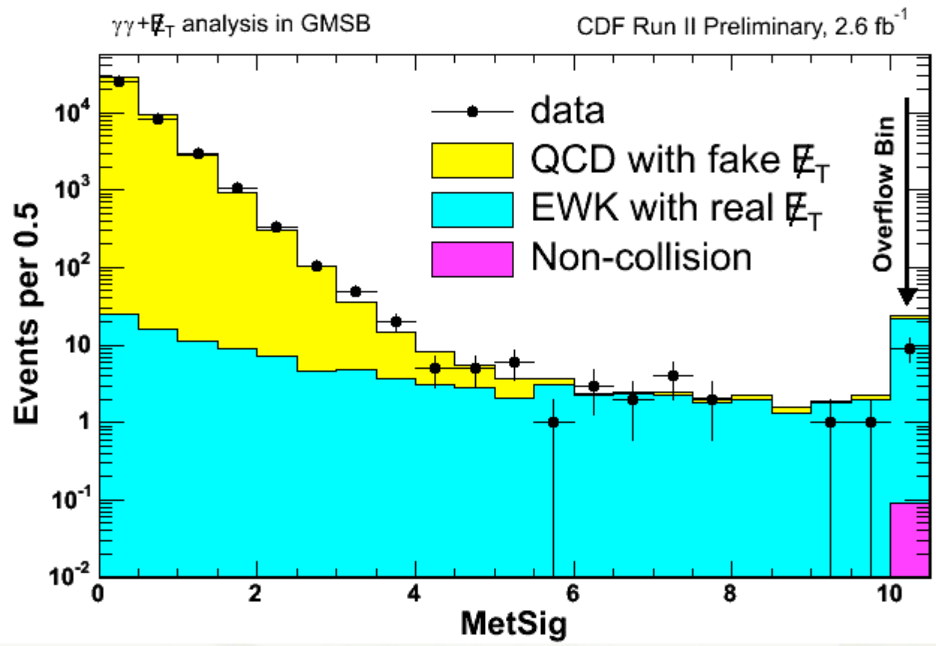
These non-collision backgrounds are almost negligible compared to QCD and EWK backgrounds

Non-Collision Background Distributions



Backgrounds for the inclusive diphoton sample





- A total of 38,053 events pass the inclusive diphoton selection requirements
- Backgrounds are well modeled
- $\not{E}_T$ - significance shows a good separation between QCD with fake $\not{E}_T$ and EWK with real $\not{E}_T$

GMSB MC Simulation

- Use MC simulation to produce the GMSB signal with detector simulation
- The EMTiming system is also simulated to search for neutralino’s non-zero lifetime region
- Generate 133K events for different mass (70 GeV - 150 GeV) and lifetime (0 ns - 2 ns) points

Optimization Strategy

- Take the inclusive diphoton sample and then do an optimization
- Pick a GMSB parameter point (mass=140 GeV, lifetime=0 ns)
- Find the optimal cuts by calculating the lowest 95% C.L. expected cross section limit
- Pick a single set of optimization variable cuts (next slide)
- Map out the sensitivity as a function of neutralino mass and lifetime

Optimization Cuts

- MetSig
  - Get rid of QCD with fake $\not{E}_T$
- H_T (Scalar sum of E_T for photon, jet and $\not{E}_T$)
  - GMSB signal gets cascade decays from heavy gaugino pairs so GMSB has large H_T compared to SM
- $\Delta\phi(\gamma_1,\gamma_2)$
  - Get rid of back-to-back photons and wrong vertex (EWK backgrounds with large H_T have a high E_T photon recoiling against $W \to e\nu$ and QCD with large H_T have high E_T back-to-back diphotons or wrong vertex)

Optimization Results

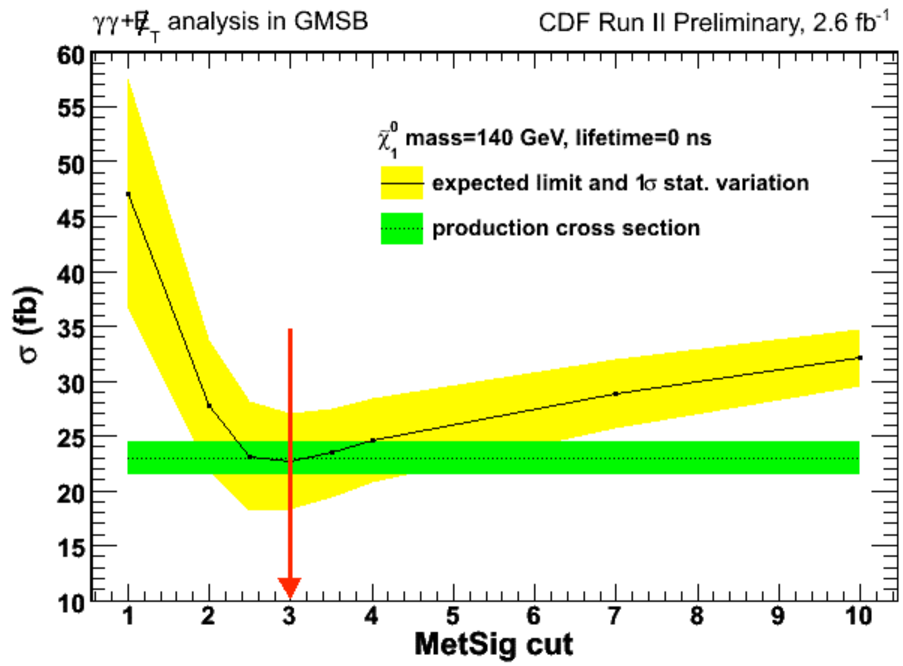
$H_T > 200$ GeV
$\Delta\phi(\gamma_1,\gamma_2) < \pi - 0.35$ rad
MetSig > 3

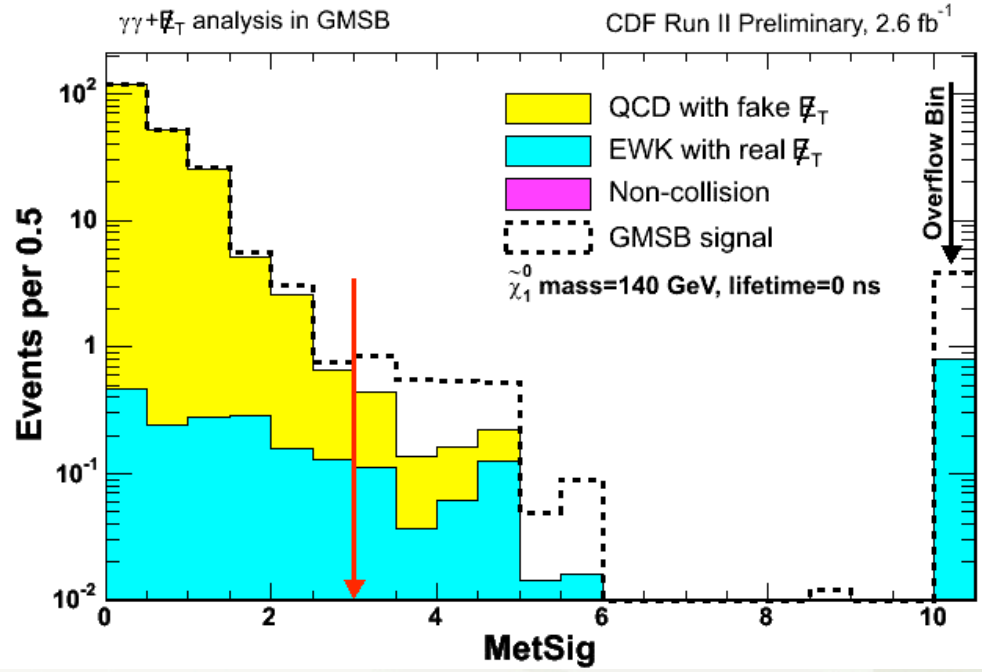
- Example point: $m(\chi^0{}_1)$=140 GeV, $\tau(\chi^0{}_1)$=0 ns
- Acceptance: 7.80 ± 0.54 (%)
- Luminosity: 2.6 ± 0.2 fb^{-1}

σ_{exp} = 22.62 fb
σ_{prd} = 22.97 fb

Background Estimations	
EWK	0.92 ± 0.21 ± 0.30
QCD	0.46 ± 0.22 ± 0.10
Non-Collision	0.001 + 0.008 - 0.001
Total	1.38 ± 0.30 ± 0.32

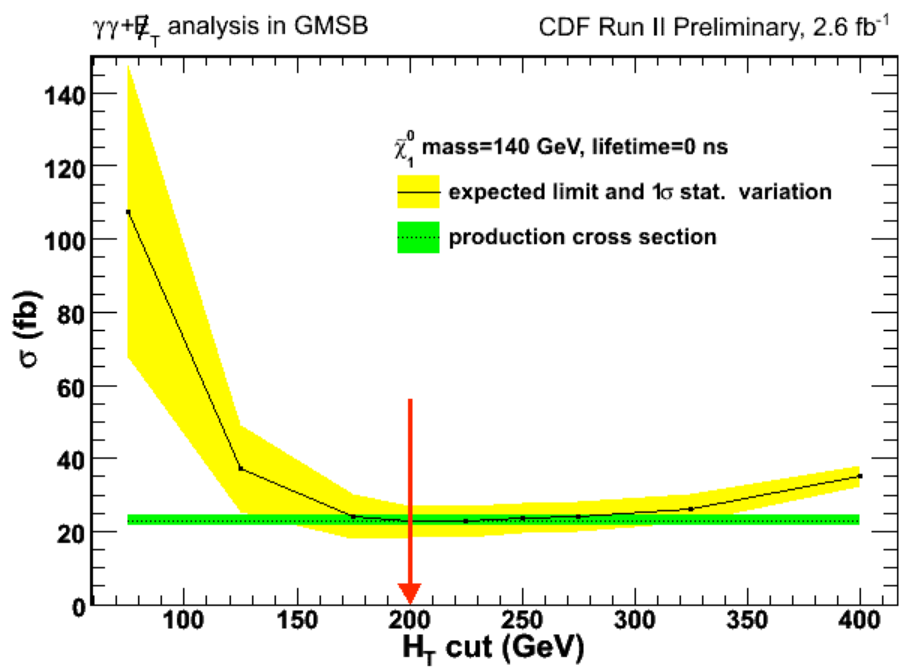
95% C.L. Cross Section Limits and N-1 Plot: MetSig

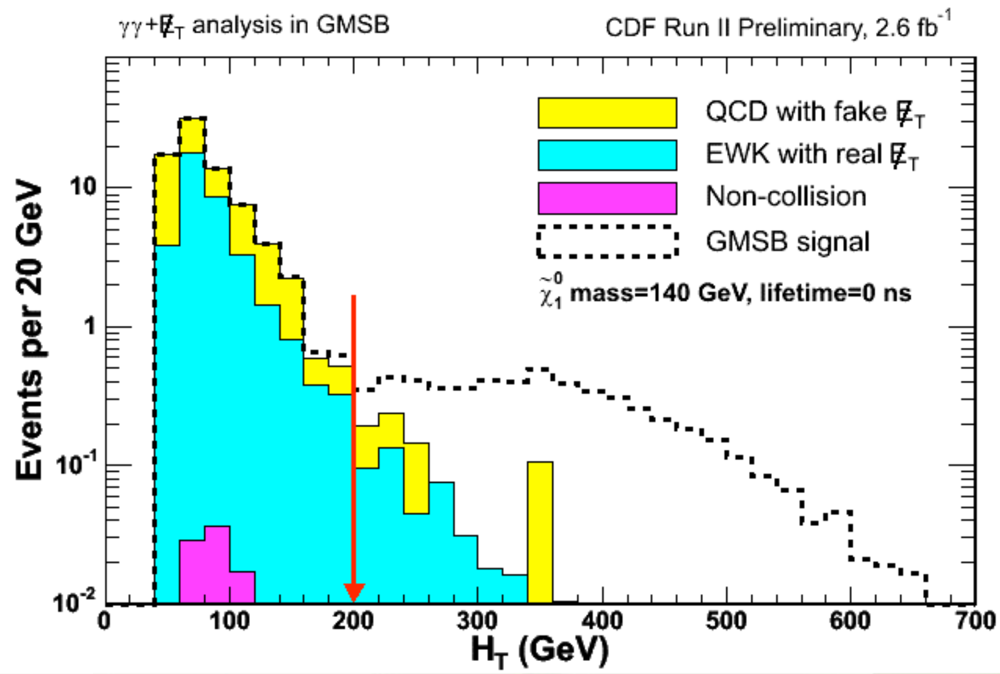




- While varying a cut all others held at optimal cuts: Minimal at Metsig=3
- N-1 Plot for background distributions along with GMSB signal: Good separation!

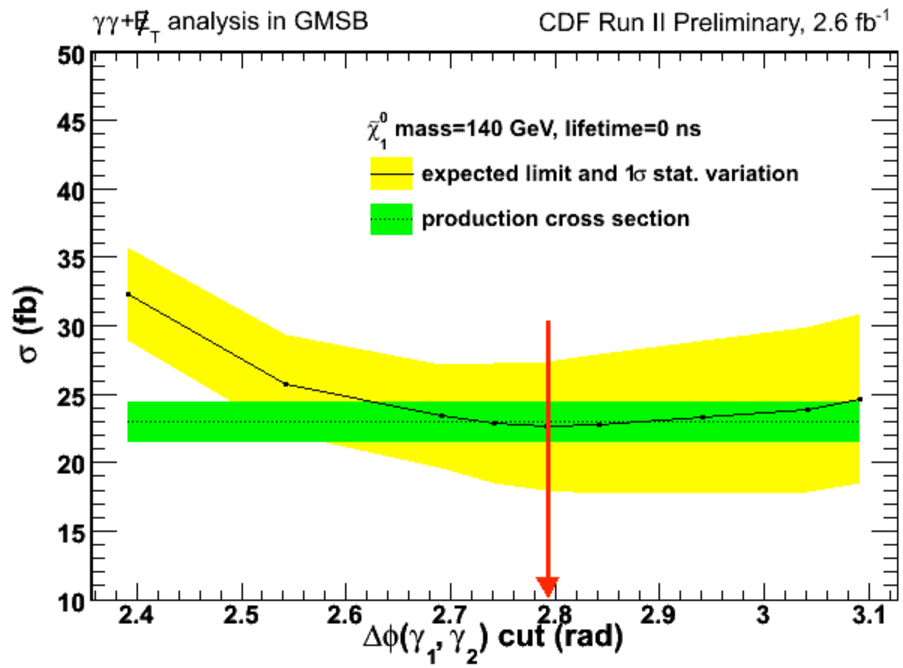
95% C.L. Cross Section Limits and N-1 Plot: H_T

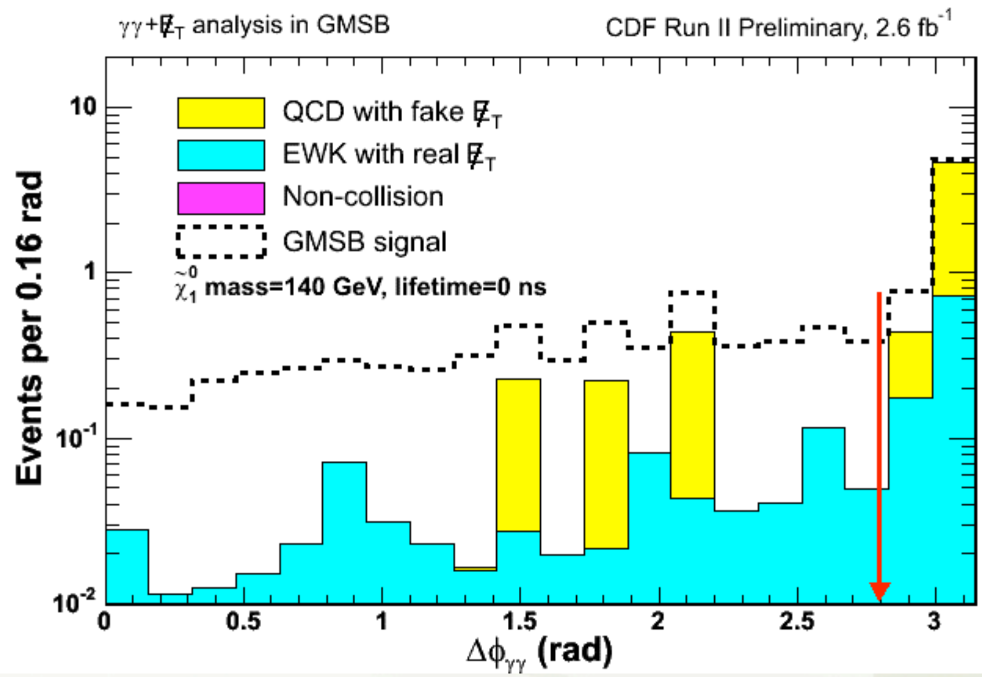




- While varying a cut all others held at optimal cuts : Minimal at H_T=200 GeV
- N-1 Plot for background distributions along with GMSB signal: Good separation!

95% C.L. Cross Section Limits and N-1 Plot: $\Delta\phi(\gamma_1,\gamma_2)$

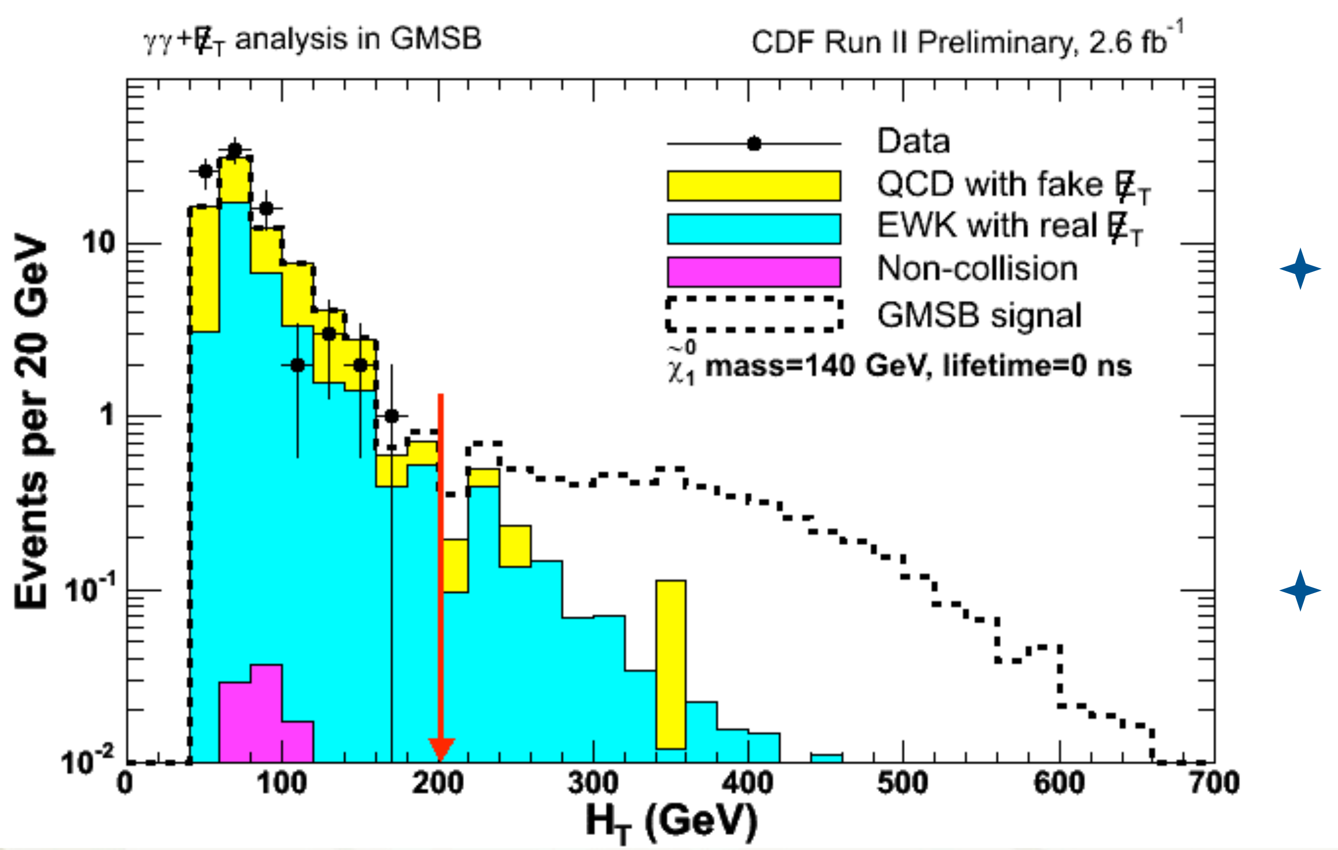




- While varying a cut all others held at optimal cuts : Minimal at $\Delta\phi(\gamma_1,\gamma_2)=\pi-0.35$ rad
- N-1 Plot for background distributions along with GMSB signal: Good separation!

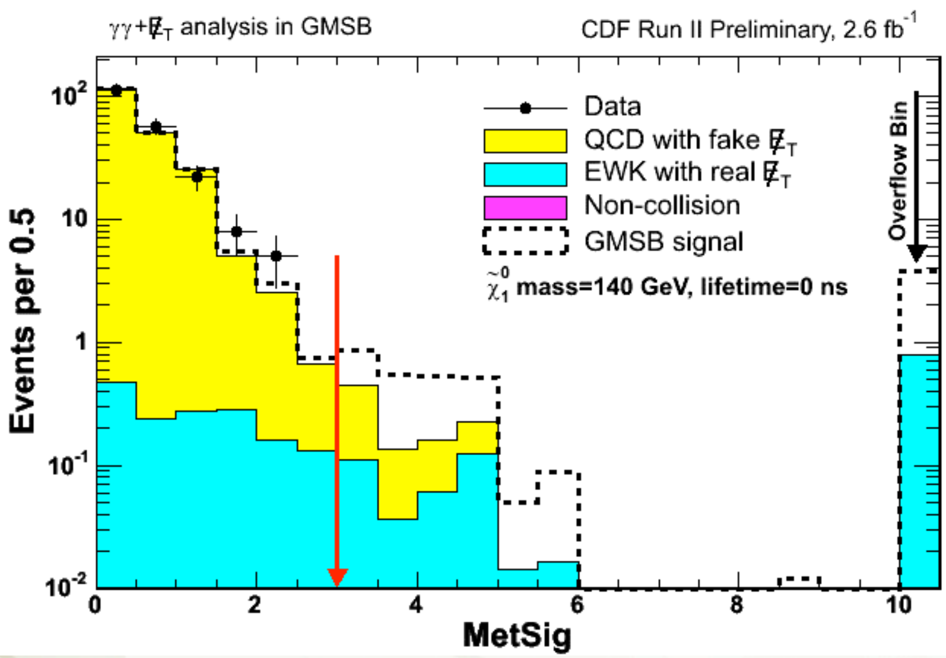
Data and N-1 Plot: H_T

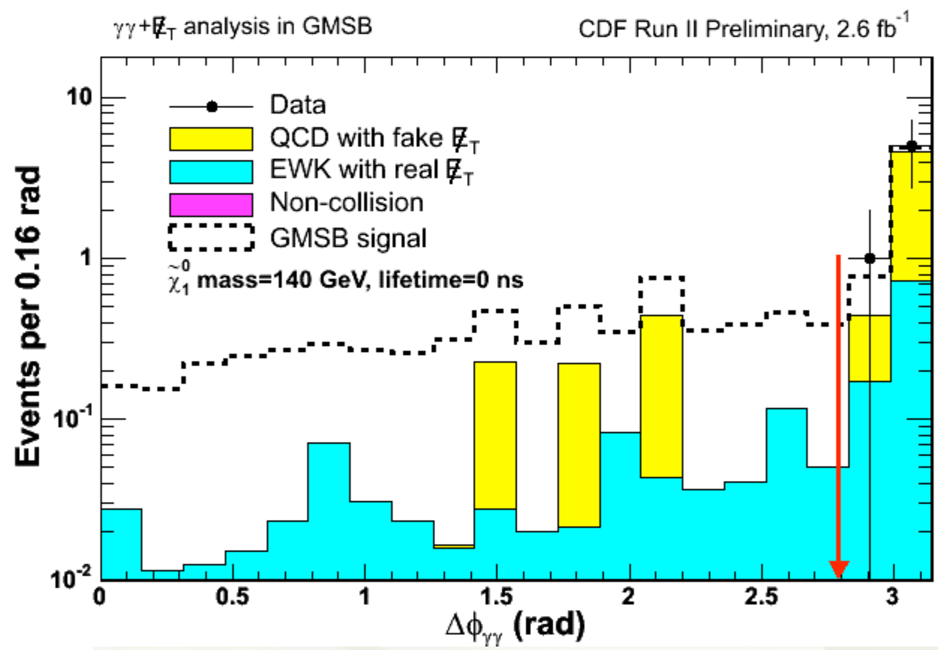
We open the box: 0 events observed



- For a distribution all other variables held at optimal cuts
- Everything is well modeled

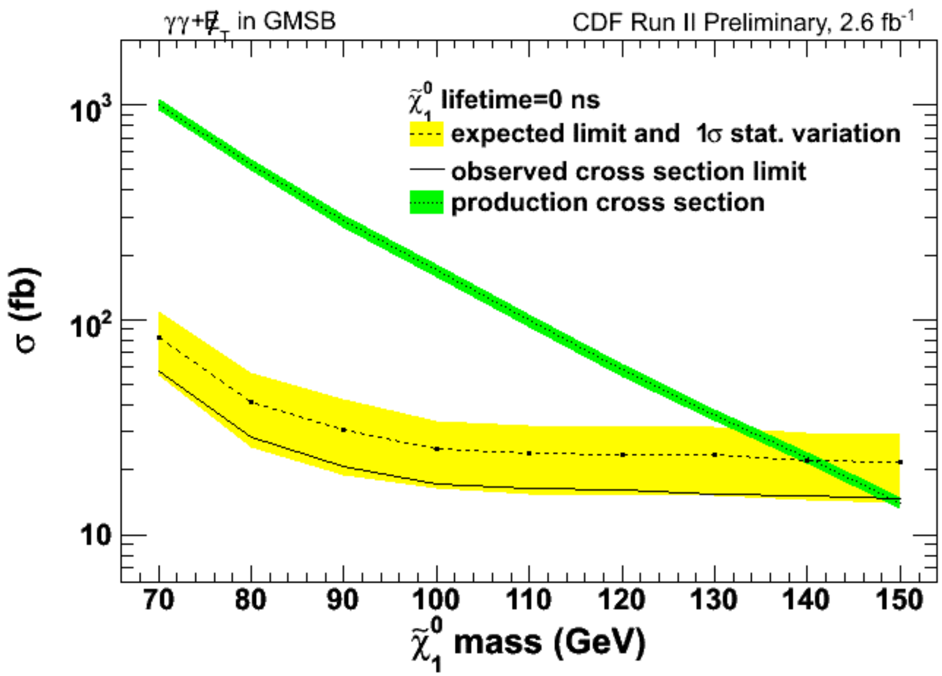
Other N-1 Plots with Data

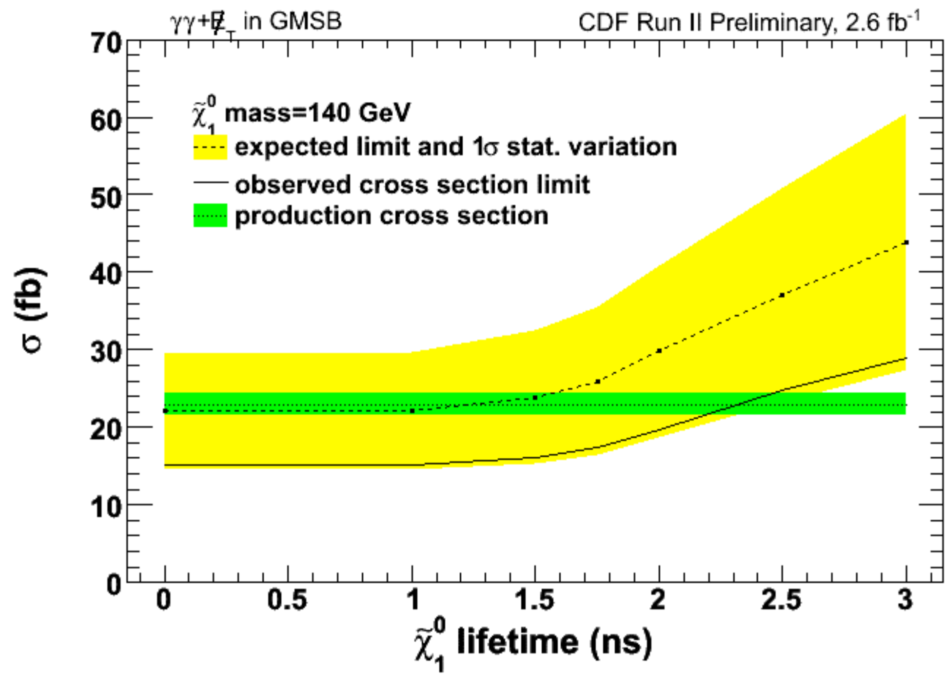




- For a distribution all other variables held at optimal cuts
- Again everything is well modeled

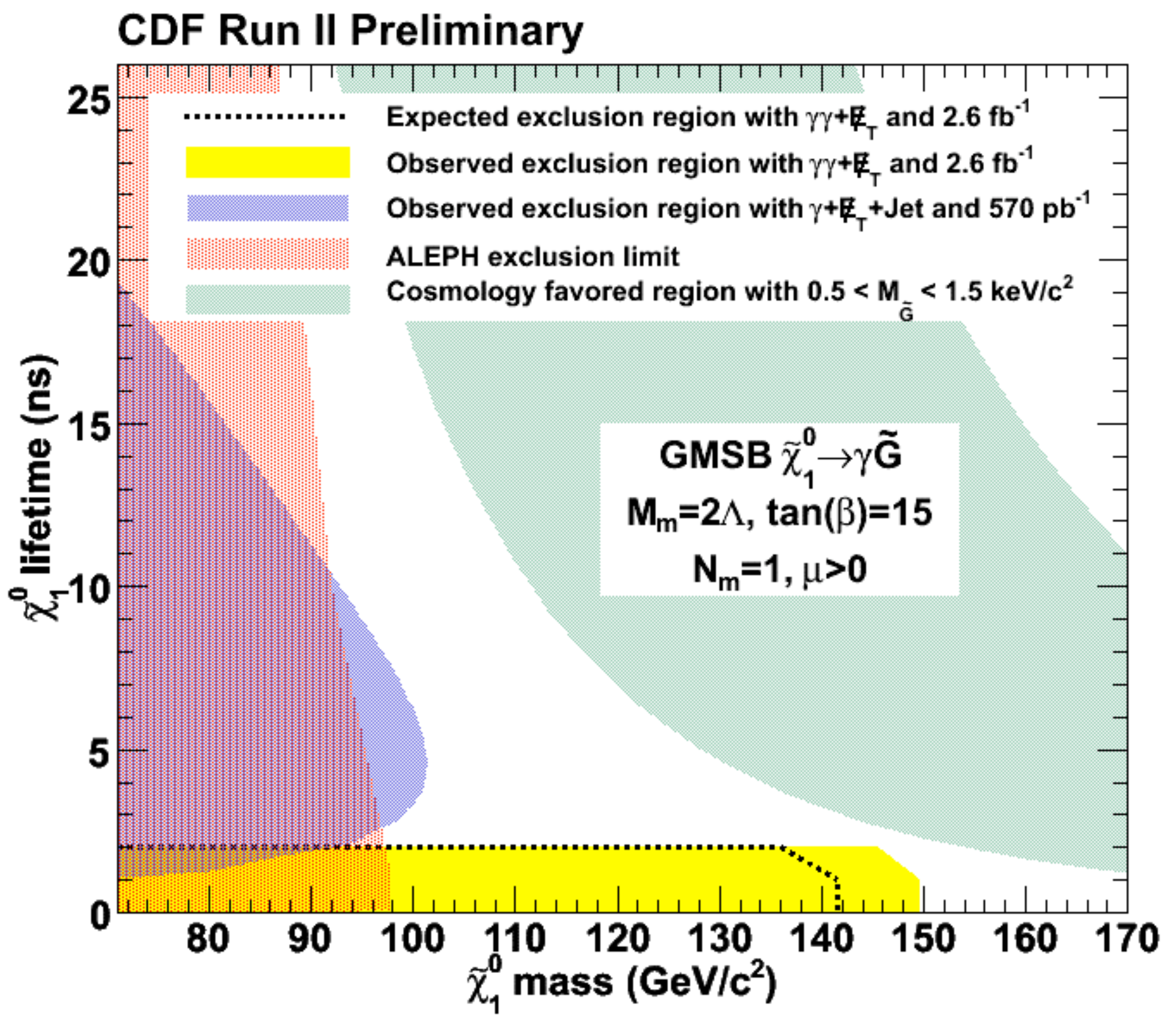
Cross Section Limits vs. Neutralino mass and lifetime





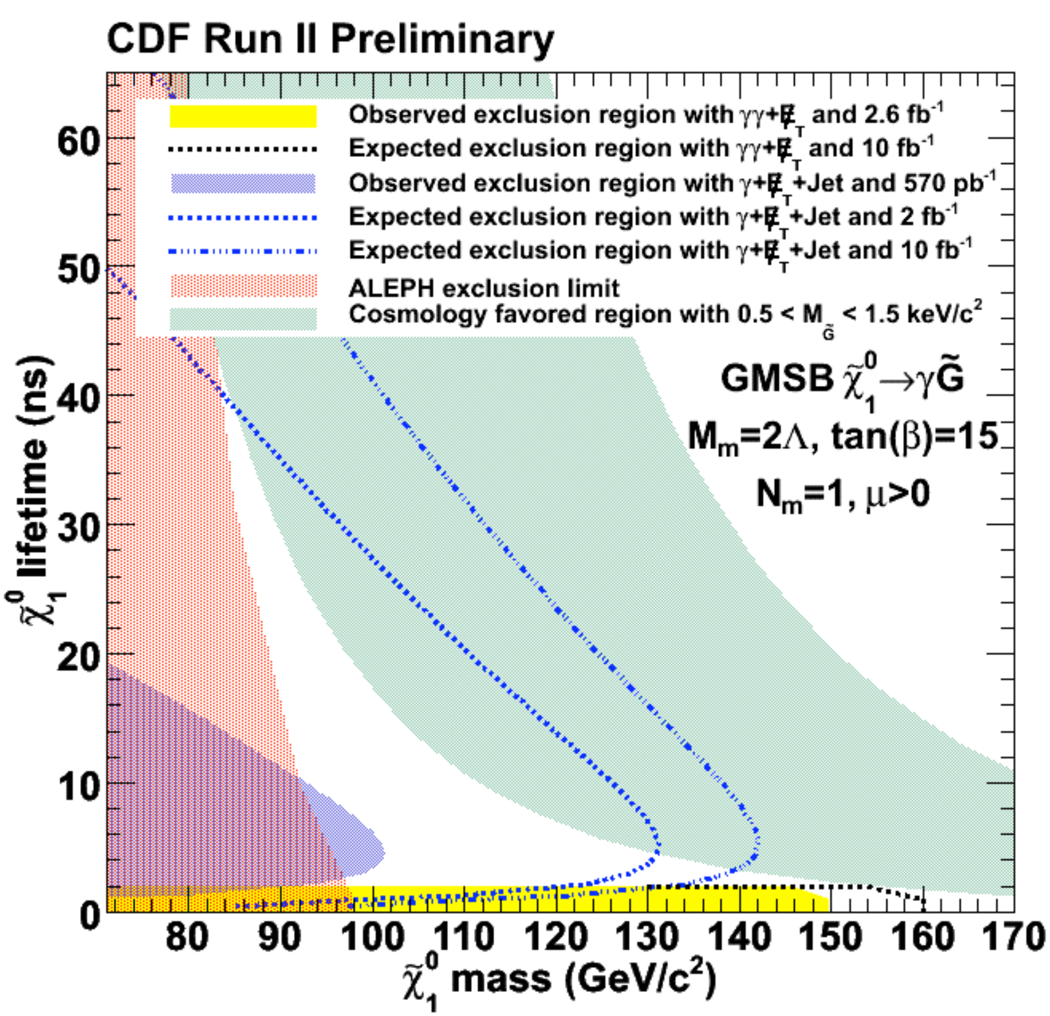
- Using the optimal cuts: H_T > 200 GeV $\Delta\phi(\gamma_1,\gamma_2) < \pi-0.35$ rad MetSig >3
- Expected (Observed) neutralino mass limit 141 GeV (149 GeV) for τ=0 ns
- Exclude neutralino lifetime up to ~2.3 ns for m=140 GeV

Exclusion Region



- Exclude up to ~ 149 GeV for $\tau < 2$ ns (World-Best Limit)
- New Limits extend the sensitivity in both mass and lifetime. (goes above the Delayed Photon Analysis)
- We are nearing the cosmology favored region (green band)

Prospects for the Future



- For high luminosity we calculate the cross section limits assuming:
  - all backgrounds scale linearly with luminosity
  - their uncertainty fractions remain constant
- γγ+ $\not\!\!E_T$: will extend mass limits up to 160 GeV with 10 fb^{-1}
- The next generation delayed photon analysis will cover up high lifetime region

Conclusion

Summary

- First γγ search for neutralinos with non-zero lifetimes
- World's most sensitive search for low lifetime GMSB in $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$
- Observed 0 events consistent with 1.4 ±0.4 of background predictions
- Exclude neutralino mass up to 149 GeV for lifetime < 2 ns
- Results approved by collaboration for presentation at conferences
- In preparation for publication for Phys. Rev. Lett. (Almost done with first reading by collaboration, approved by God Parents)

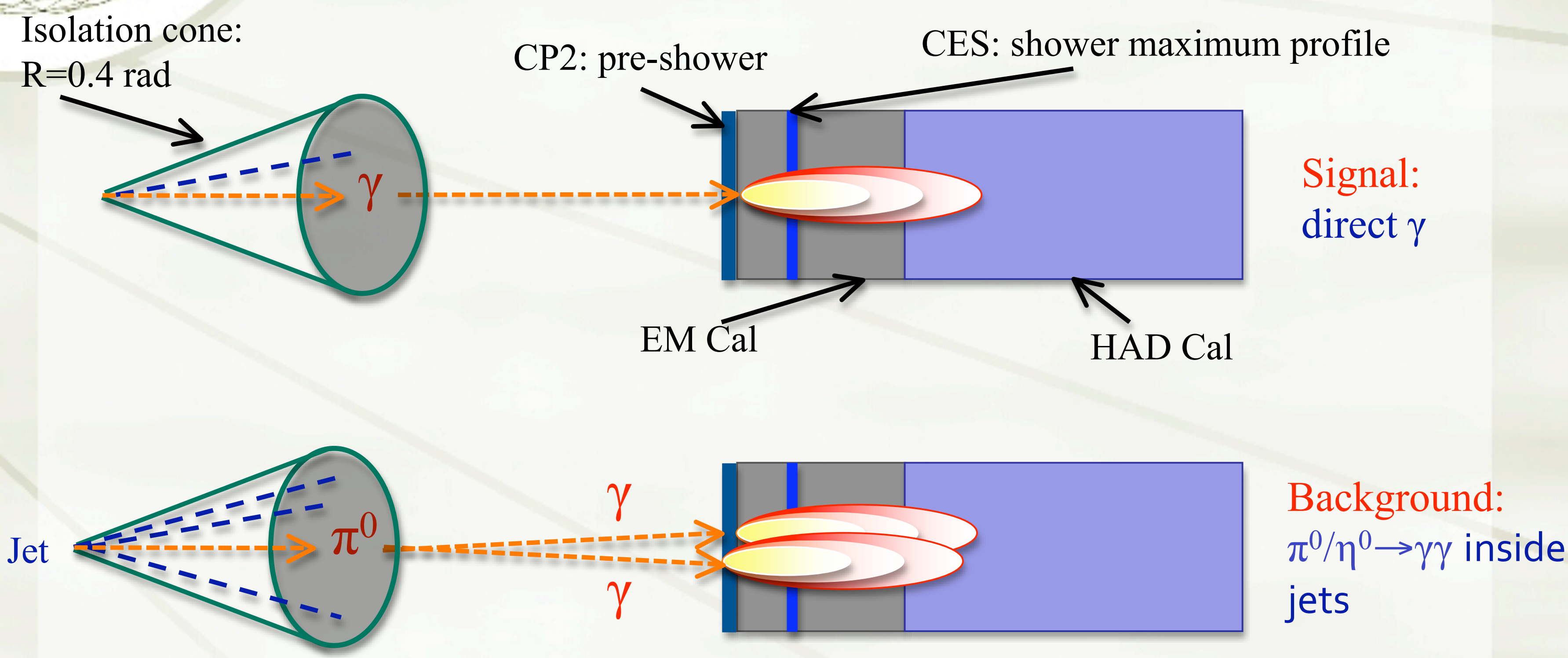
Back Up

Good Runs, Triggers, Data Sets and Pre-Selection Cuts

- Data Stntuples: cdfpstn: cdipa(d,h,i,j) , cdfpstn: bhelb(d,h,i,j)
- Triggers : DIPHOTON_12 (iso), DIPHOTON_18 (no iso),
  PHO_50 (no iso), PHO_70 (no HadEm)
- Goodrun list: The good run list v.23 (up to and including period 17)
- Luminosity = 2.59 fb^{-1} with 6% uncertainty
- Code Release: cdfsoft 6.1.4, Stntuple dev_243
- Data Samples : $\gamma\gamma$ sample, $W \rightarrow e\nu$ sample (study EWK with real $\not{E}_T$),
  $Z \rightarrow e^+e^-$ sample (study QCD with fake $\not{E}_T$)
- Pre-Selection Cuts:
- $N_{vx12} \geq 1$, Highest ΣP_T Vertex, $|Z_{vx}| < 60$ cm
- Two Central Photons ($E_T > 13$ GeV)
- Standard Photon ID cuts and Phoenix rejection cut
- PMT Spikes, Cosmics and Beam Halo removal cuts
- Vertex Swap Procedure and Met Cleanup cuts

Concept of Photon ID

- Photon signature
  - "Compact" EM cluster: shower contained in EM CAL
  - No electric charge: no track (unlike electron)
  - No color charge: unlike π^0 in jets, photon is isolated object



Standard Central Photon ID Cuts

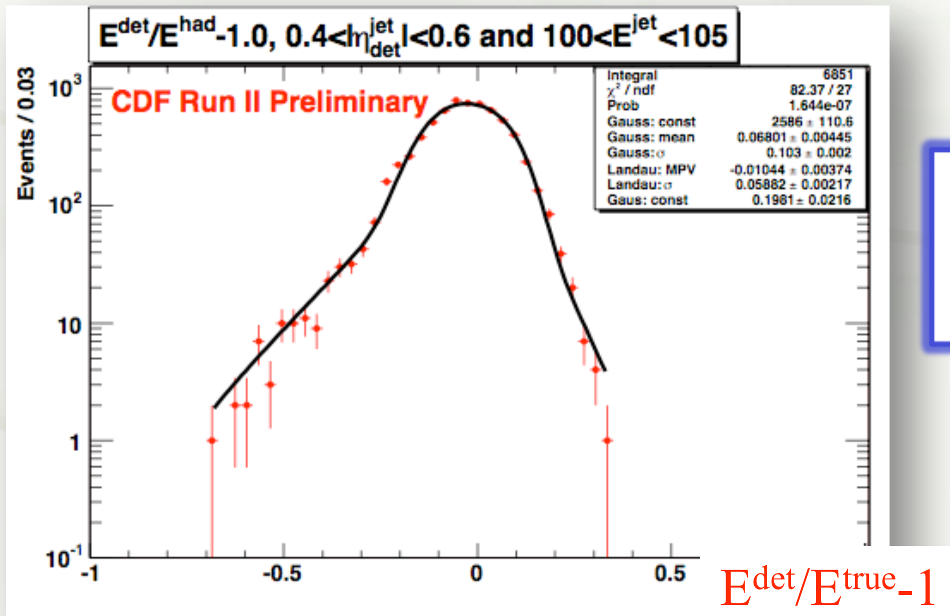
cuts	Tight cuts
Calorimeter fiduciality	central
Photon E_T	>13 GeV (7 GeV for pre-selection)
CES fiduciality	$\|X_{CES}\|$<21.0 cm; 9.0 cm<$\|Z_{CES}\|$<230.0 cm
Average CES χ^2	<20
Had/Em	<0.055+0.00045*E_T
Corrected CalISO	<2.0+0.02(E_T-20) or <0.1*E_T if E_T<20.0 GeV
TrkISO	<2.0+0.005*E_T
N3D	N3D=0,1
Trk P_T (if N3D=1)	<1.0+0.005*E_T
2^{nd} CES (wire or strip)	<0.14*E_T if E_T<18 GeV or <2.4+0.01*E_T if E_T>18 GeV

Phoenix rejection	No photons matched to phoenix track
PMT spike rejection	|pmt1-pmt2|/(pmt1+pmt2)<0.65

Met Resolution Model

Mis-measurements in jet energy are leading source of fake MET

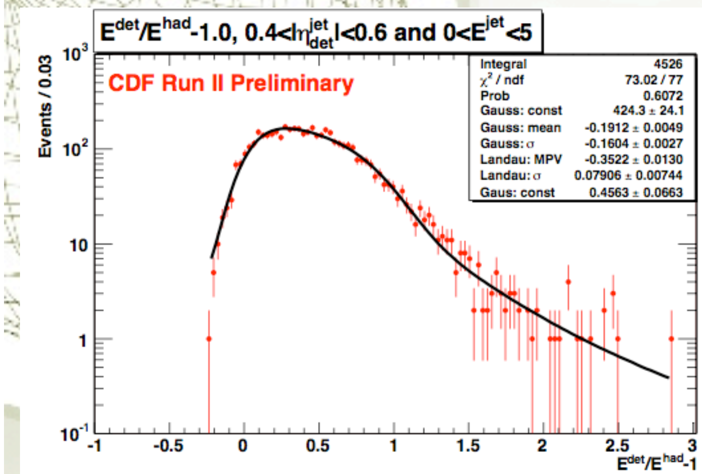
Example of jet energy resolution



Obtain jet energy resolution as function of E^{jet} & η

- Predicting fake MET
  - Smear jets & soft particles in γγ events according to energy resolution
- Select events with true MET
  - Use MET-significance to select with true MET
  - Calculate MET-significance based on event configuration & known energy resolution

J.E.R.- Key Part of METMODEL

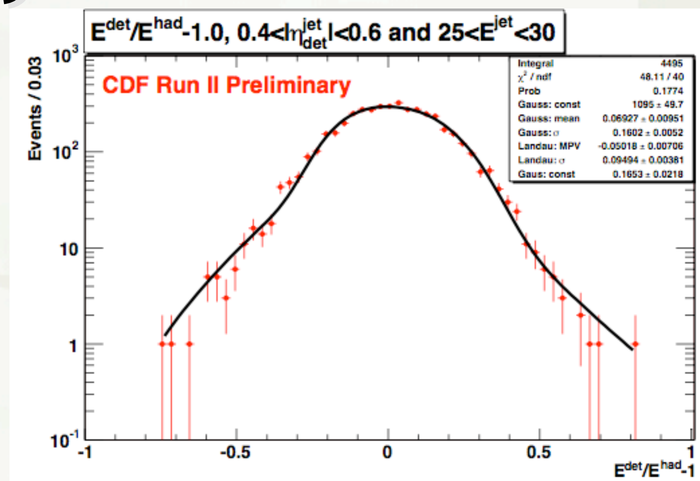


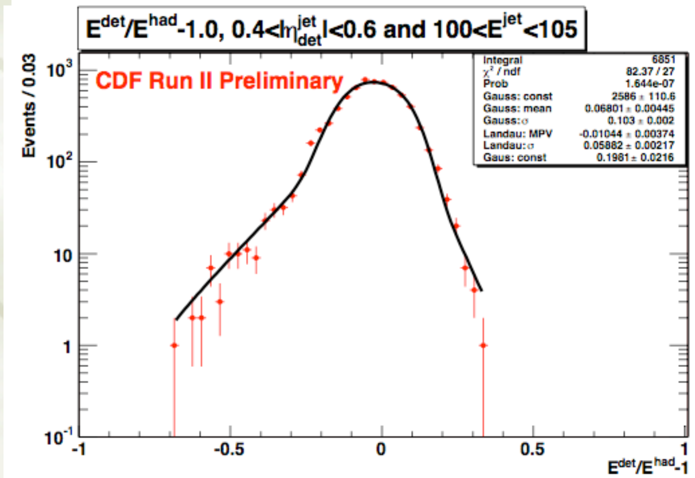
Gauss+Landau fits JER well at any E_{jet} and η

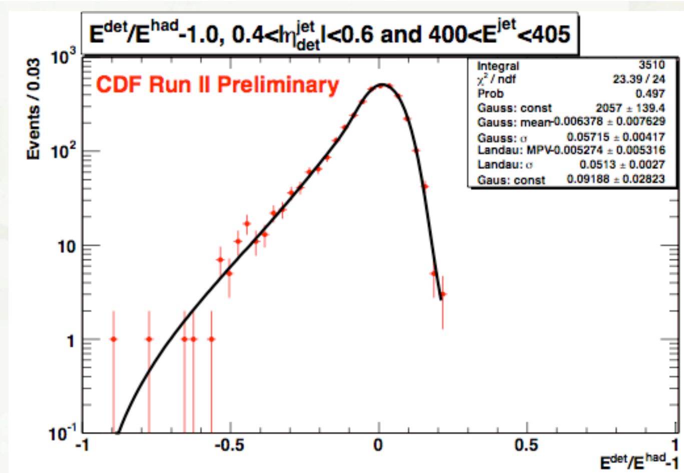
$$\frac{C * G(y) + L(y)}{1 + C},$$

$$where\ y = \frac{-x}{1+x},$$

$$x = \frac{E^{had}}{E^{det}} - 1$$

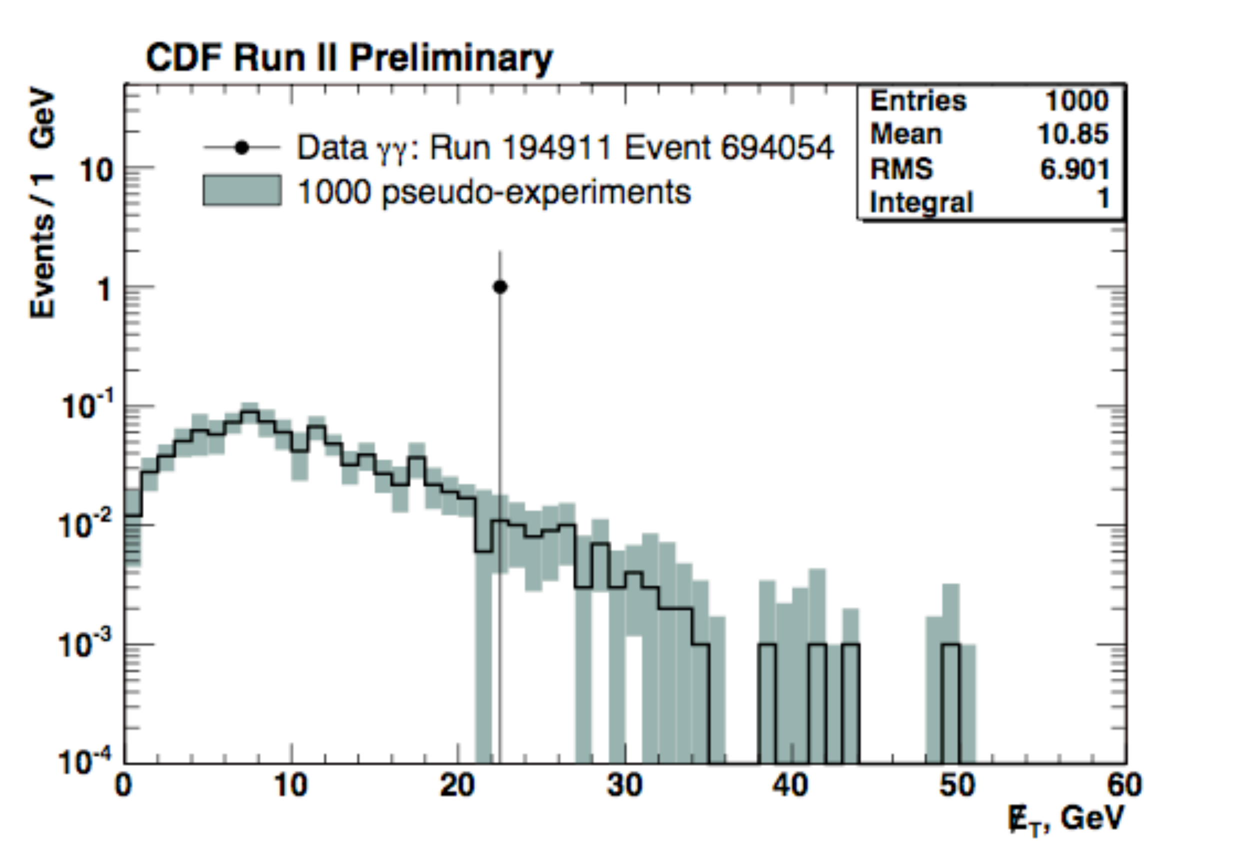






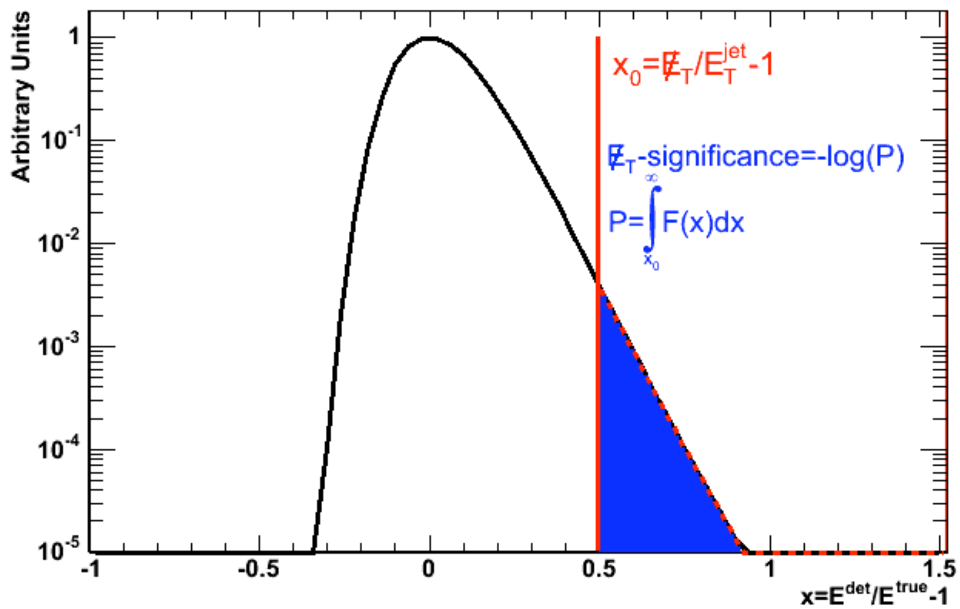
- ✓ Smooth parameterization of JER as a function of E_{jet} in bins of η_{det} (bin size of 0.2)

Met Model Example-1



- Met Model gives a PDF of possible MET values due to energy mis-measurements (also available in XY)
  - This is done by smearing un-clustered and each jet energy according to their resolution

METMODEL & Significance



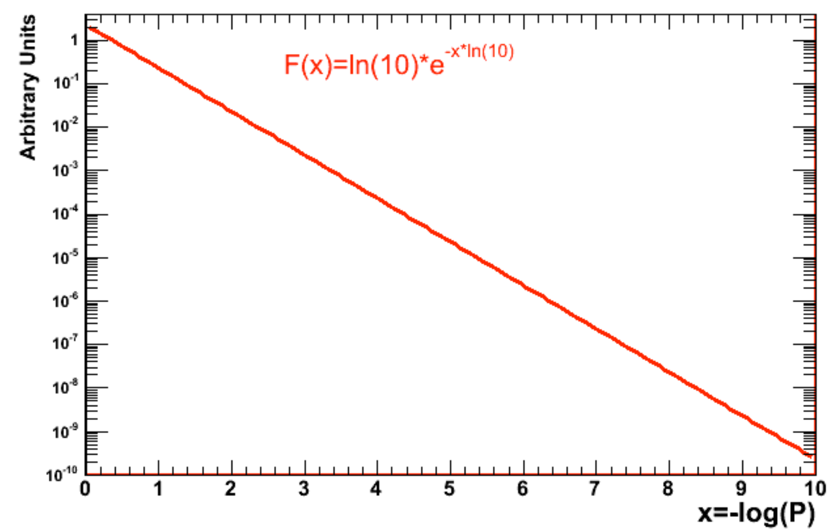
- Takes into account individual jet resolution
- Accounts for relative direction of MET and jet
- Eliminates need for $\Delta\varphi$ (MET-jet) cuts

New MET-sig=-log(P) for fake MET:

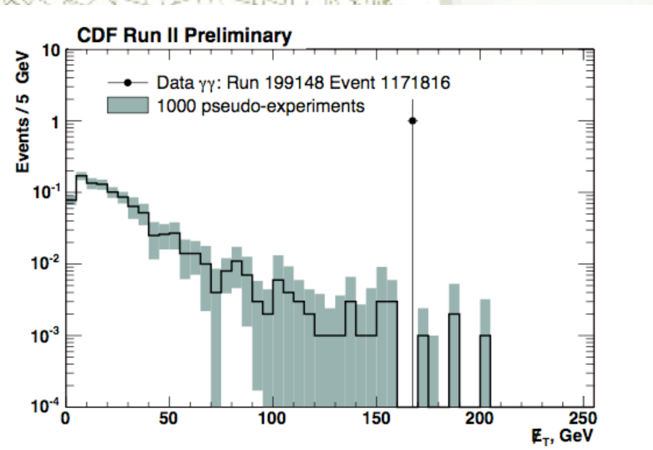
Simple shape for any distribution F(x)

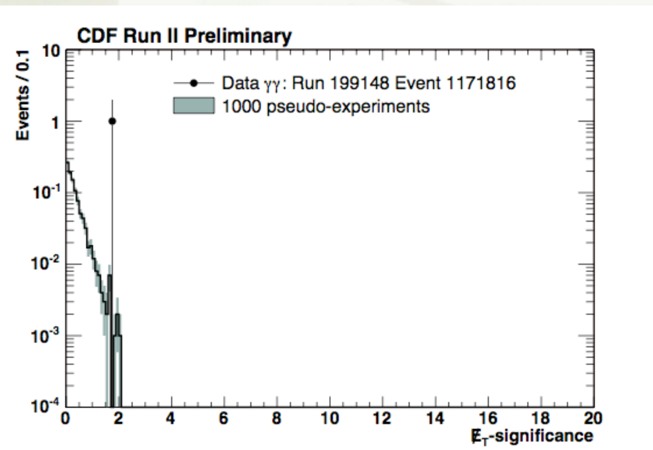
For 10,000 events:

Cut on Sig>1 ⇒ ~1,000 events pass
Cut on Sig>2 ⇒ ~100 events pass
Cut on Sig>3 ⇒ ~10 events pass
Cut on Sig>4 ⇒ ~1 event pass

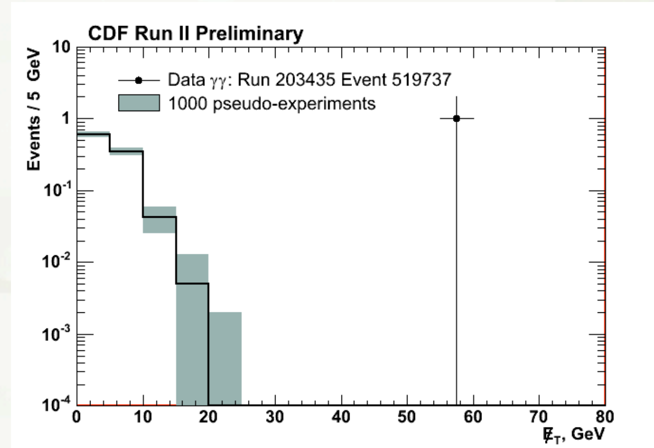


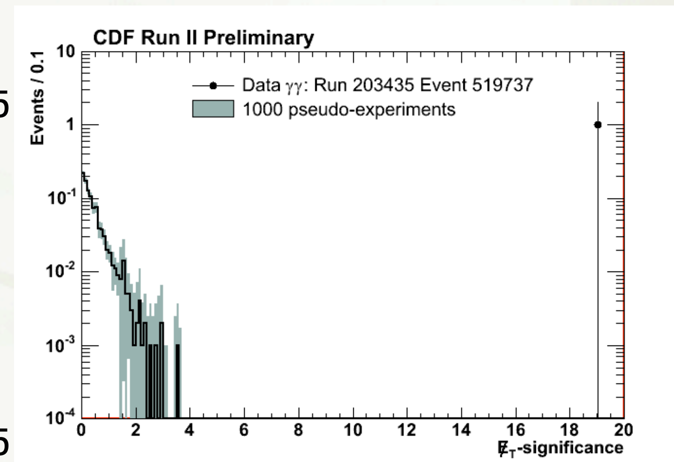
“New” MET Significance



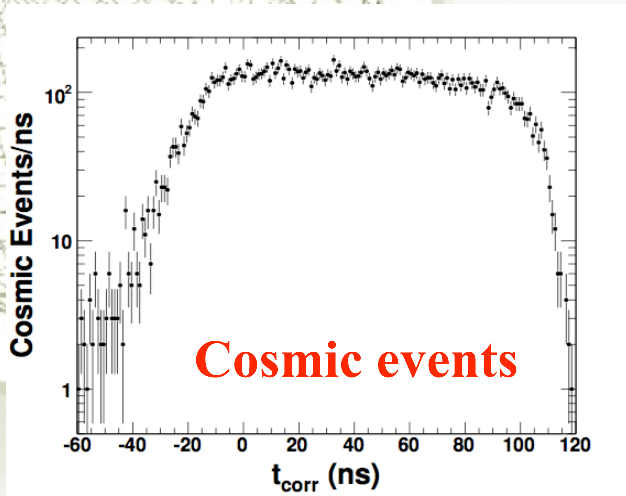


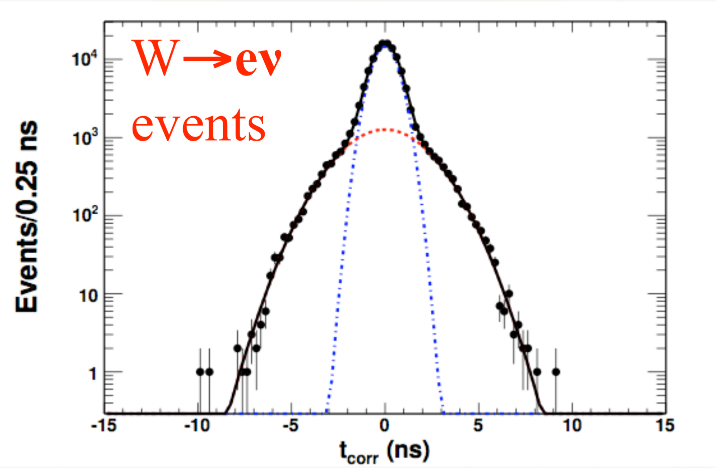
- “Old” Metsig
  - Sig=MET/∑E
- Event-1
  - largest MET
  - MET=165.1 GeV
  - METsig
    - METMODEL: 1.76
    - “Old” Metsig: 7.65
- Event-2
  - MET=57.1 GeV
  - METsig
    - METMODEL: >18.0
    - “Old” Metsig: 5.45





Cosmics & EMTiming





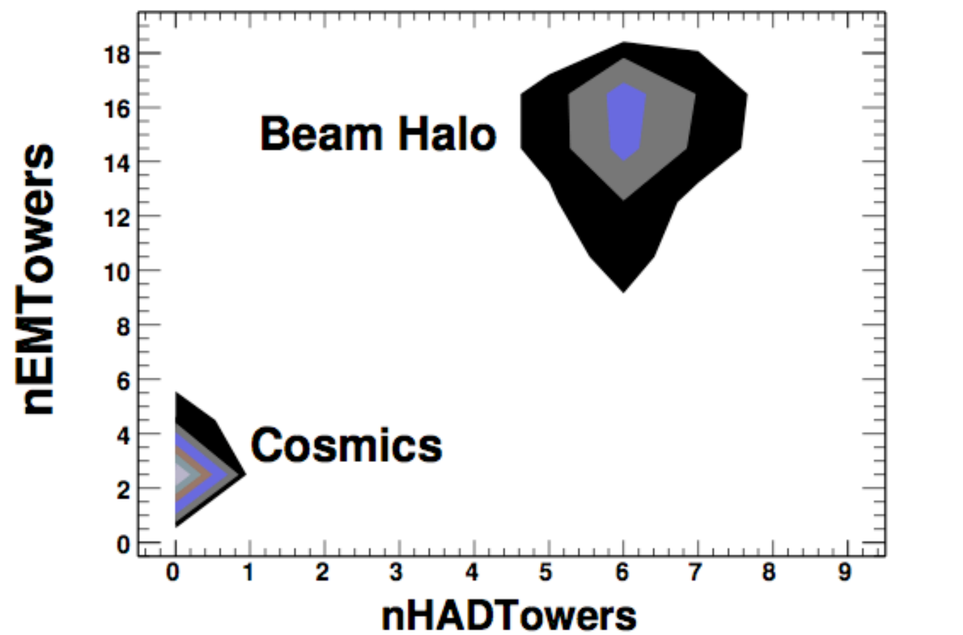
EM timing resolution:

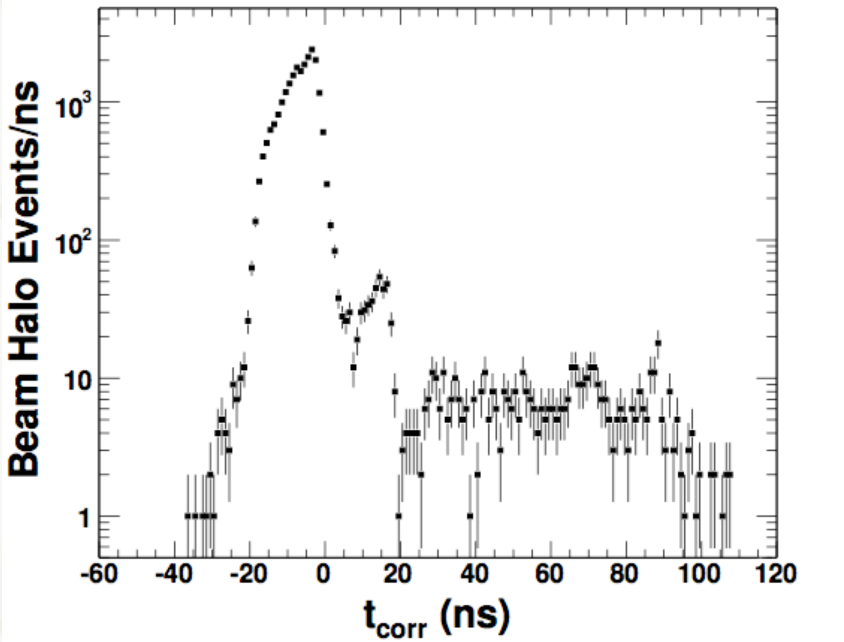
True vertex: σ~0.7 ns

Wrong vertex: σ~1.9 ns

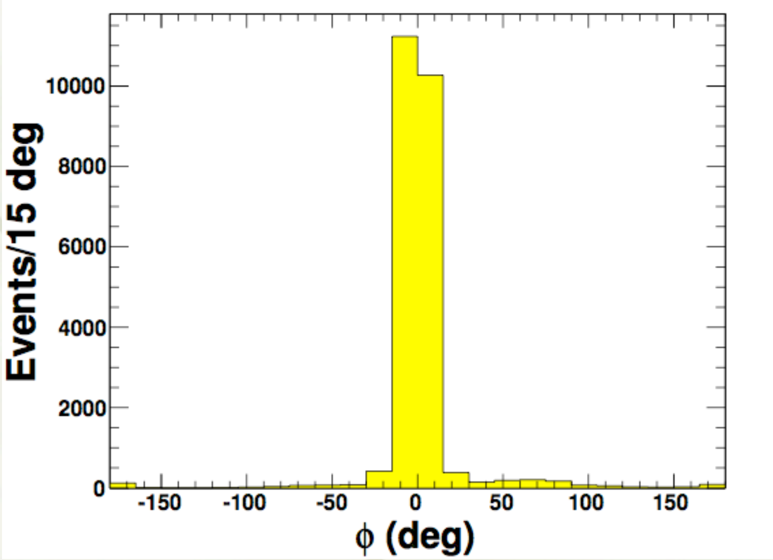
- Cosmics
  - Significant background for γ+MET and "delayed" photon searches
  - Arrives independently of collision time
  - Use W→eν events to study EM timing in true collision events

Beam Halo





φ-distribution of beam halo "photons"



- Beam Halo rejection
  - Topological cuts and EM timing

Diphoton Events after Pre-selection

Requirements	Events passed
Trigger, Goodrun, and Standard Photon ID with E_T>13 GeV	45,275
Phoenix Rejection	41,418
PMT Spikes Rejection	41,412
Vertex requirements	41,402
E_T(swap)>13 GeV after vertex swap	39,719
Beam Halo Rejection	39,713
Cosmic Rejection	39,663
Met Cleanup Cuts	38,053

- 38,053 events pass these pre-selection cuts

Uncertainties (bkg)

- QCD with fake MET
  - METMODEL: syst. from METMODEL parameterizations
    stat. from pseudo-experiment (dominant)
  - PATHOLOGIES: syst. from SF, MC-data differences in METMODEL paramterization, JES
    stat. from MC (dominant)
- EWK with real MET
  - stat. from MC
  - MC-to-data normalization uncertainies (dominant): include stat. from eγ data and MC, syst. from differences in MC modeling (E/p)
- Non-collision
  - dominant in stat.

Systematic Uncertainties (signal)

- Acceptance
  - Diphoton ID and Isolation: 5.4%
  - ISR/FSR: 4.0%
  - JES: 1.5%
  - MetSig parameterization: 0.7%
  - PDFs: 0.6%
- Cross Section
  - PDFs: 7.5%
  - Q^2: 2.6%
- **Total (combined in quadrature): 10.6%**