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

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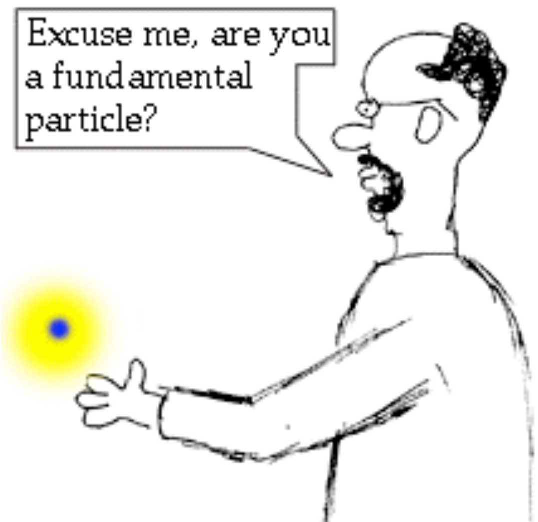
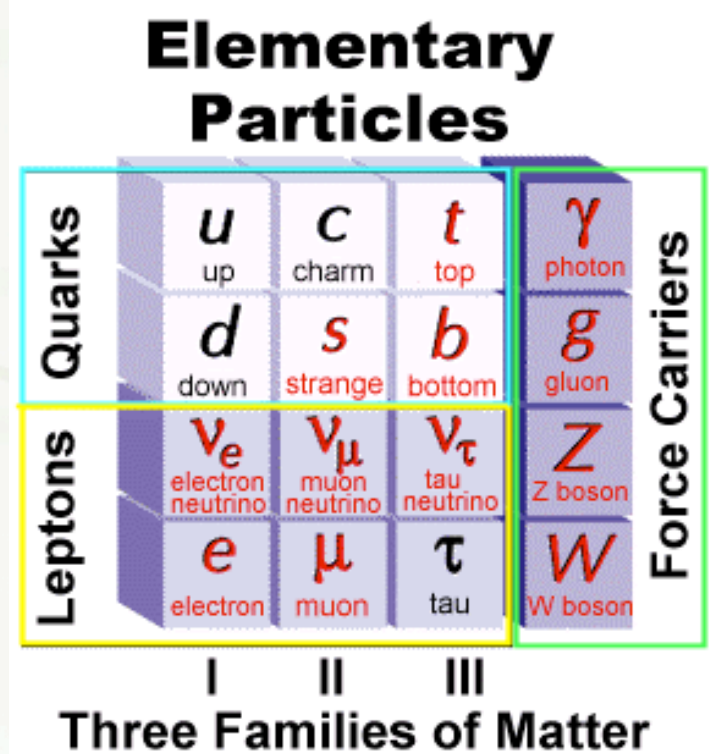
Motivation



The Standard Model

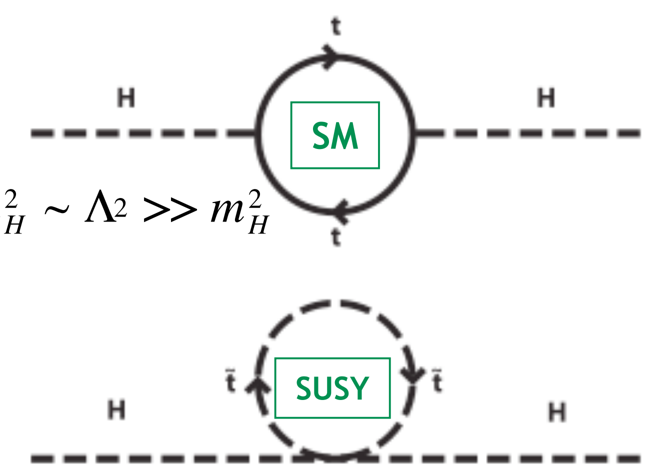
The Fundamental Question: What is the world made of?

- The SM provides a remarkably successful description of the properties of fundamental particles based on symmetry principle.
  - Fermions (matters, spin 1/2)
  - Bosons (force carriers, spin 1)
  - Particle masses acquired by Higgs boson (not found yet)
- But incomplete… e.g. hierarchy (naturalness) problem



Hierarchy Problem in SM

- Electromagnetic and weak forces are successfully unified at ~10^2 GeV scale: Electroweak theory (EWK)
- Want to unify EWK and strong force: Grand Unified Theory (GUT)
- The GUT scale (Λ) is believed to be 10^{16} GeV while Higgs mass should be EWK scale ~10^2 GeV - Difficulties arise in the SM: HIERARCHY problem
- Higgs mass driven by the GUT scale is unstable (divergent)
- Supersymmetry is designed to solve this problem

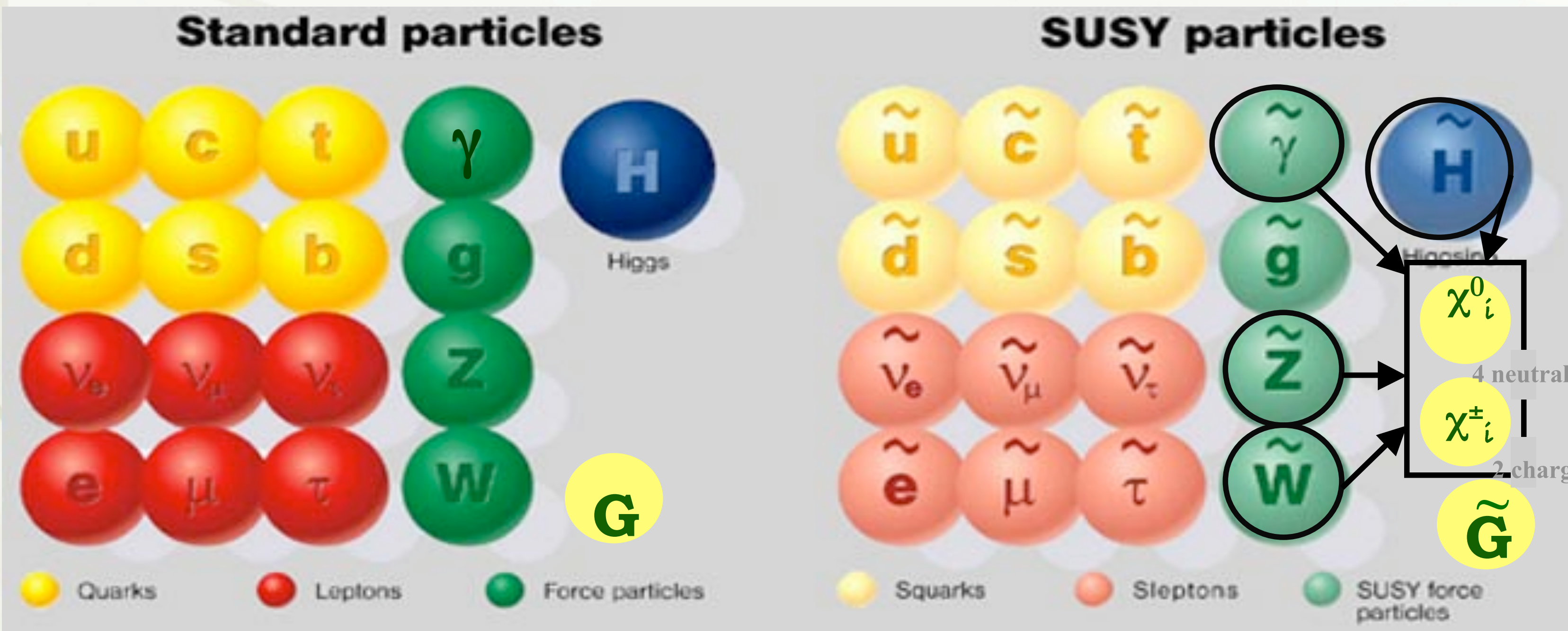


$$\delta m_H^2 \sim \Lambda^2 >> m_H^2$$

$$\delta m_H^2 \sim O(\frac{\alpha}{\pi})(m_B^2 - m_F^2) \sim TeV^2$$

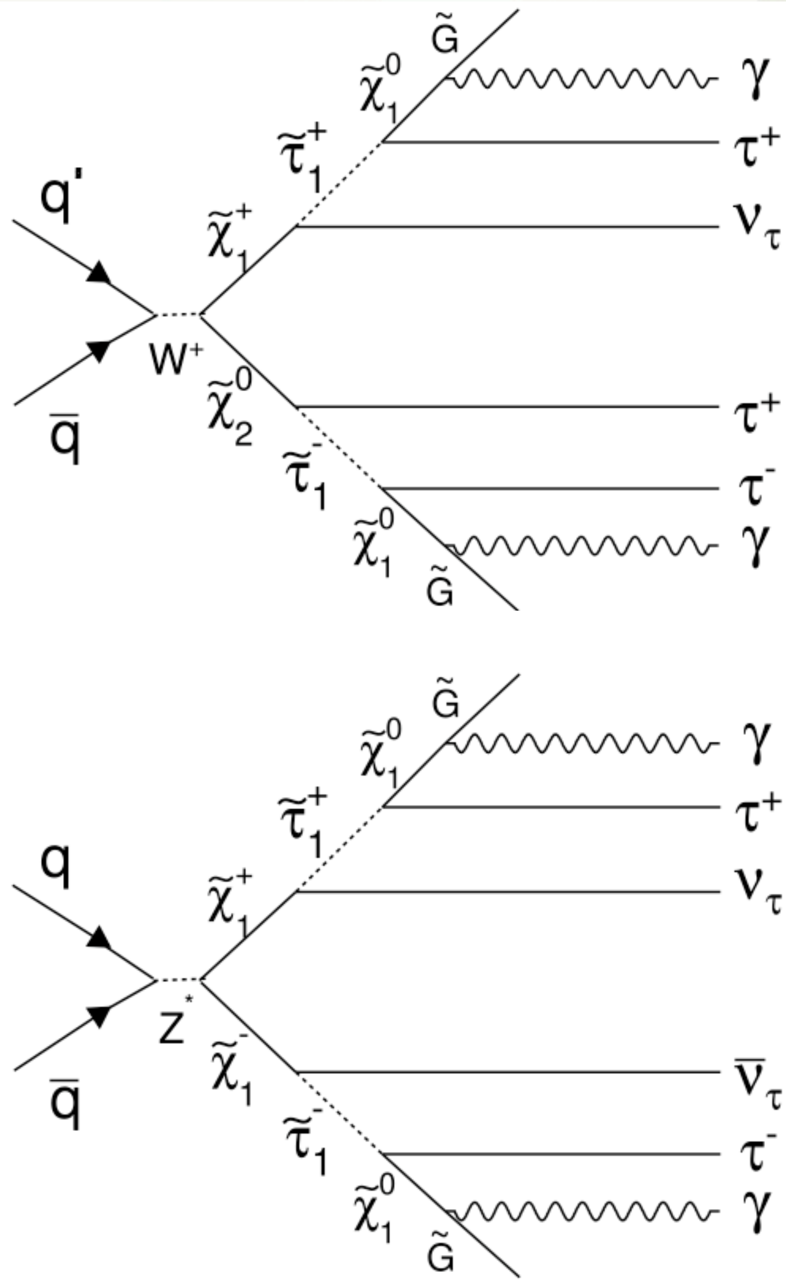
Supersymmetry

- A solution to the problem: suggest a symmetry between fermions and bosons, supersymmtry, at few TeV scale
- Protect the Higgs mass from the divergence
- SUSY particles not observed yet - they must be heavier and SUSY must be broken at higher energy (~TeV)



GMSB Models

- In Gauge Mediated Supersymmetry Breaking (GMSB) Models the ordinary gauge interactions are responsible for SUSY breaking
- SUSY broken at low energy (~ TeV)- much of parameter space predict new particles to be accessible at today's experiments
- GMSB is quite predictive in the SUSY mass spectrum and have distinctive phenomenological features - collider experiments can put these predictions fully to test



More on GMSB

- GMSB has only 6 "free" parameters while Minimal SUSY Model has 106 free parameters
- Intrinsically suppress flavor-changing neutral currents (FCNC)
- 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 warm dark matter candidate - More on this later

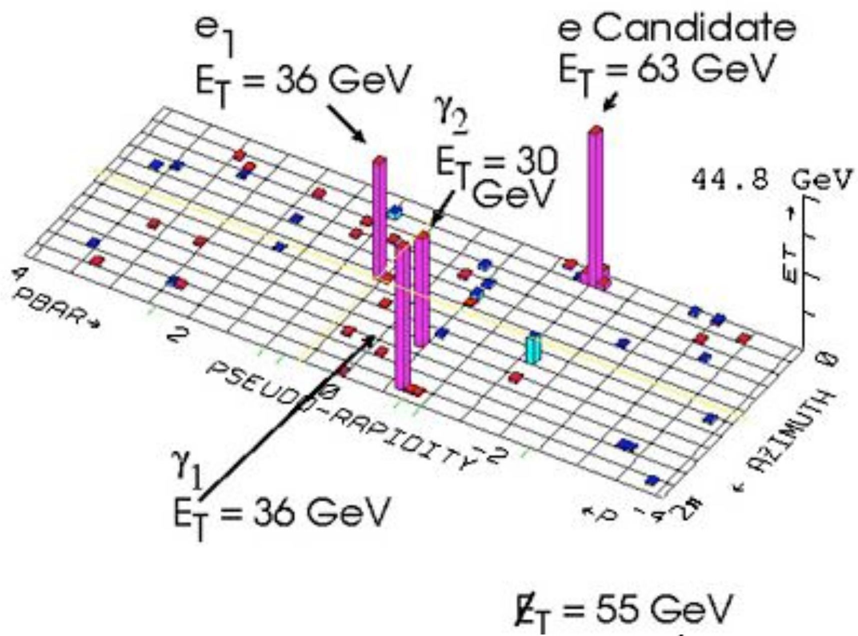
GMSB Neutralino

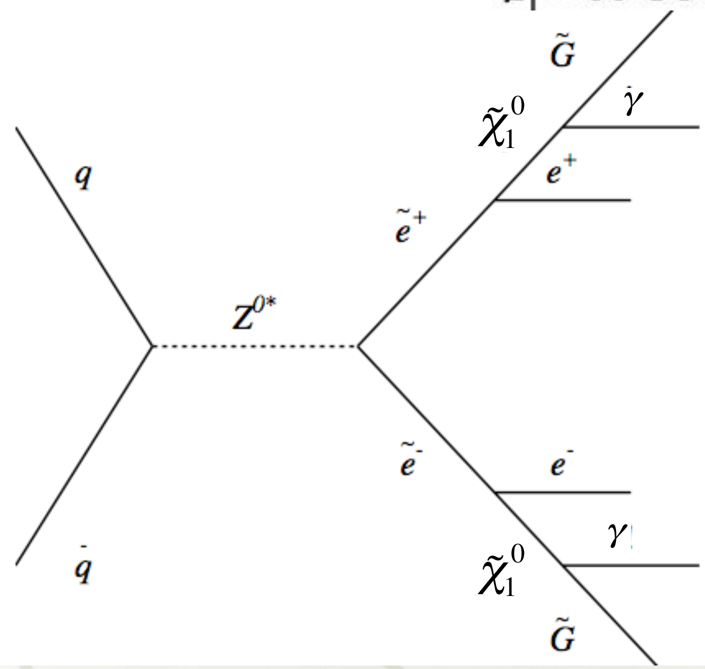
- For simple case GMSB predicts the lightest Neutralino ($\tilde{\chi}_1^0$) to be the Next-to-Lightest SUSY Particle with the Gravitino ($\tilde{G}$) as the Lightest SUSY Particle
- For much of the parameter space the Neutralino decays via $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$
- The final 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) they can destroy the nuclei produced during big bang nucleosynthesis - cosmic microwave background inconsistent with observation
- 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)





Unusual Event: SUSY?

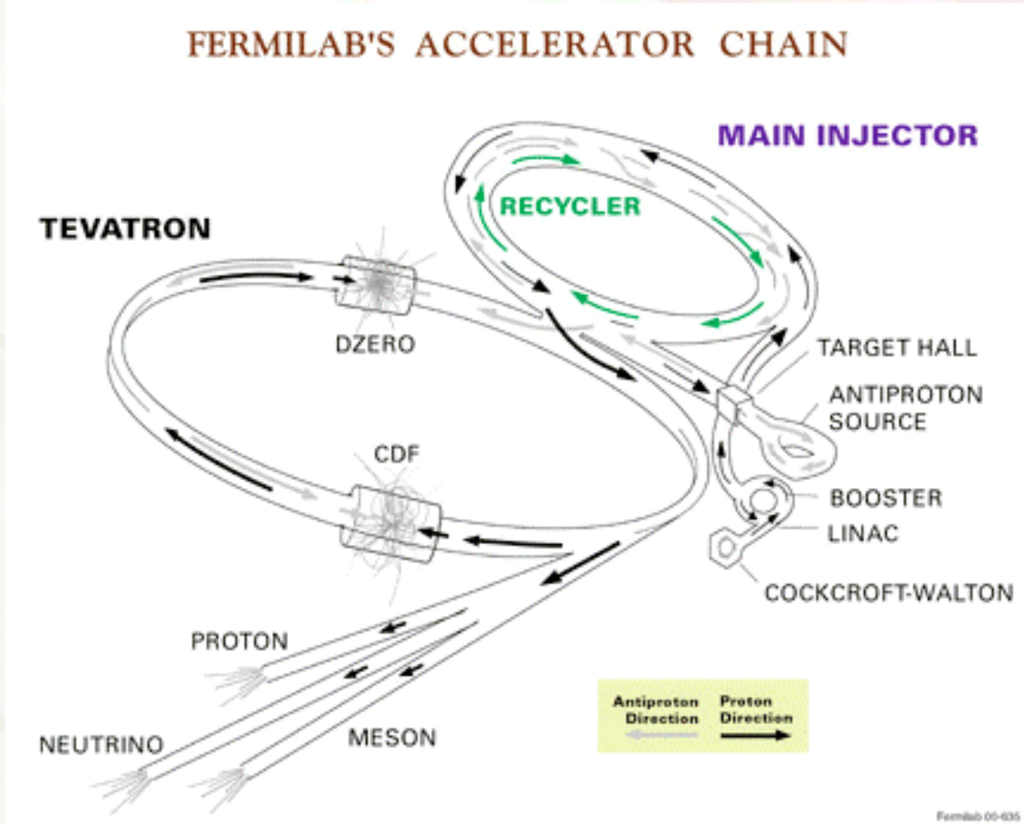
- In late 1990's an unusual $ee\gamma\gamma\not{E}_T$ candidate event was observed at the CDF detector in Fermilab
- SM prediction: ~10^{-6} events
- Is this GMSB-SUSY?

Tools

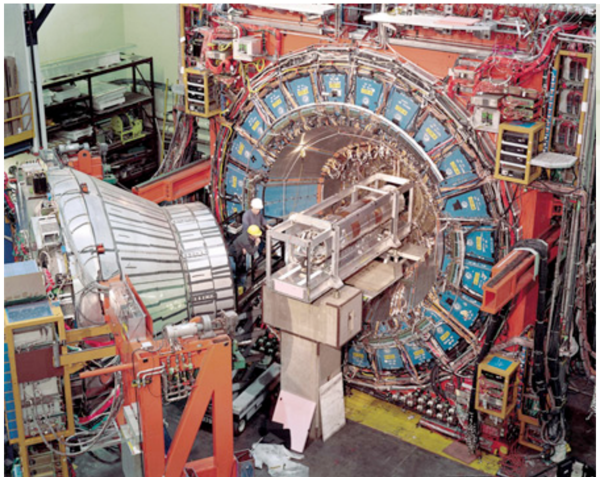
Particle Collider

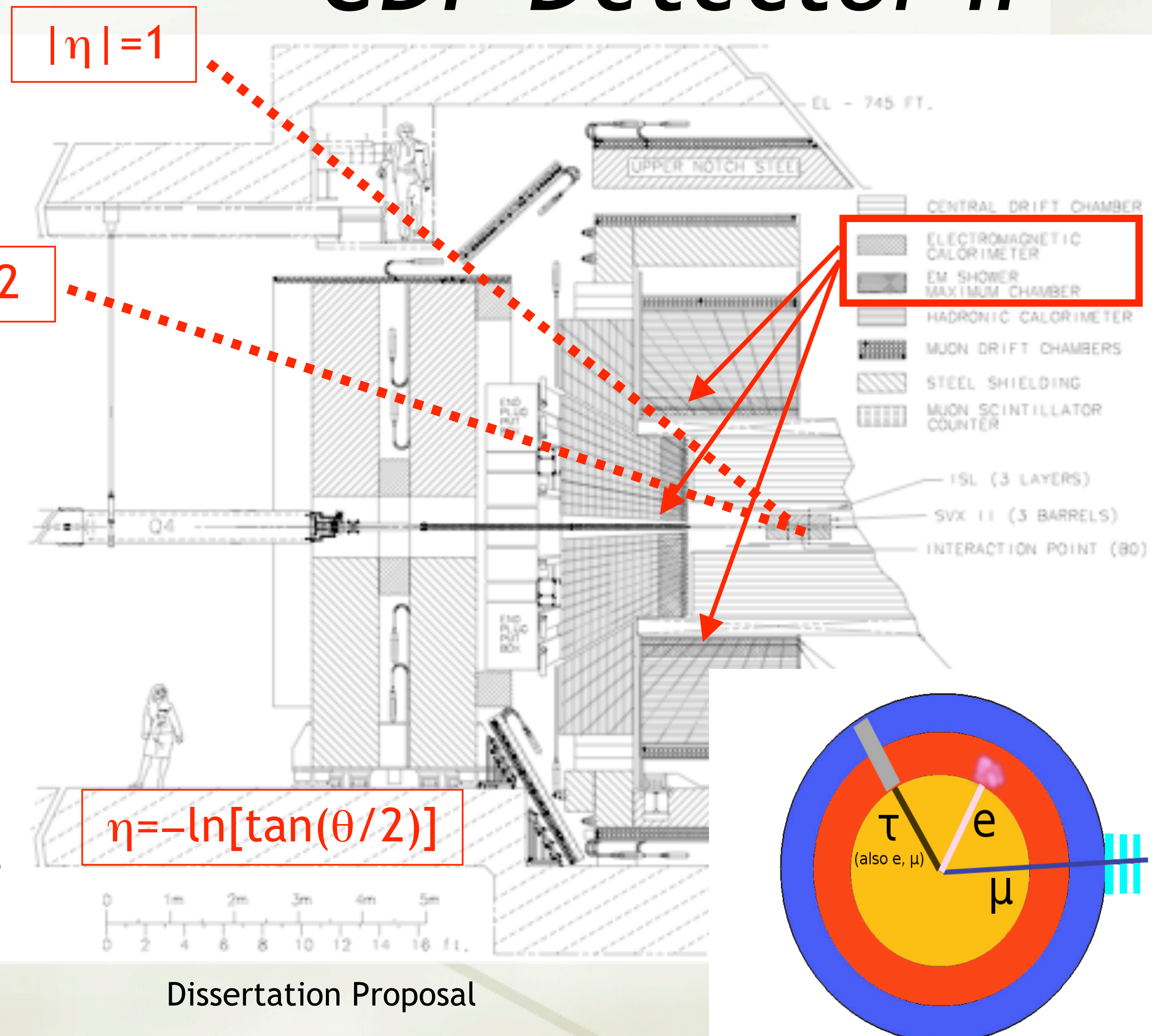
One way to search for the Neutralinos is to use particle colliders like the Tevatron at Fermilab

- 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

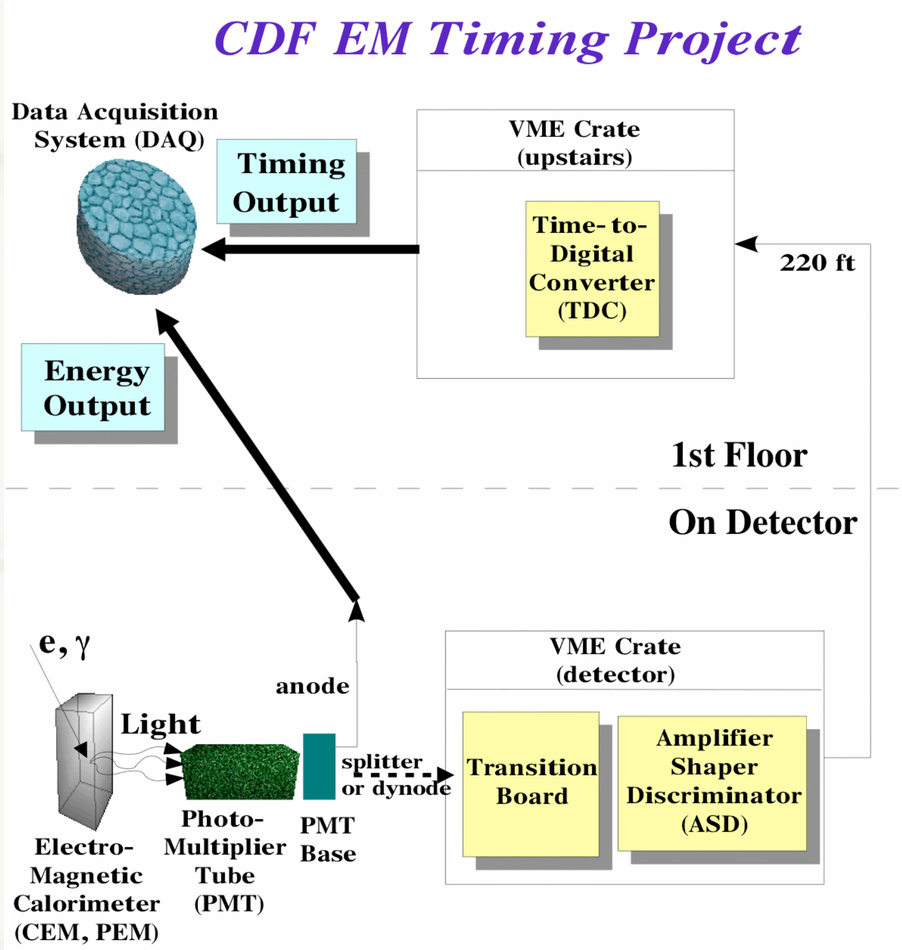




- This is a multipurpose detector with multi concentric system
- Able to identify electrons, muons, taus, jets, photons, b's and $\not{E}_T$

The EMTiming System

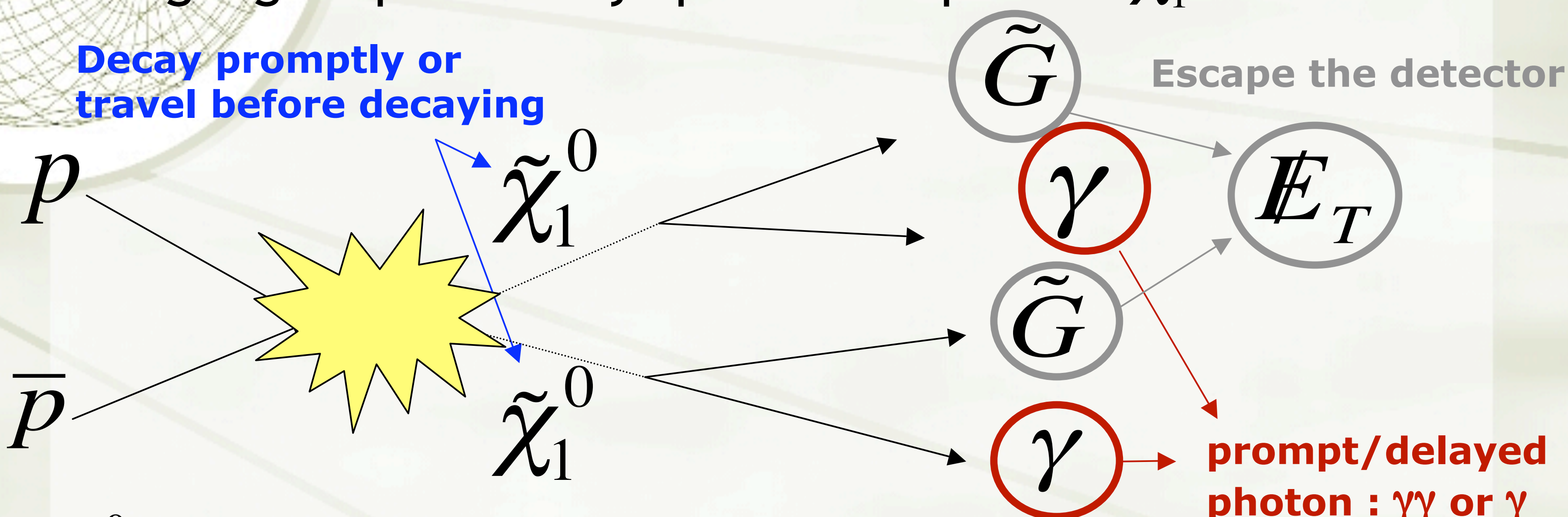
- Provides time of arrival of photons at calorimeter
- Includes both CEM and PEM ($|\eta| < 2.0$)
- Became fully operational starting in Dec 2004
- Timing resolution:~0.5 ns
- 100% efficient for photons with E_T>13 GeV



Analysis

GMSB Event Signature

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



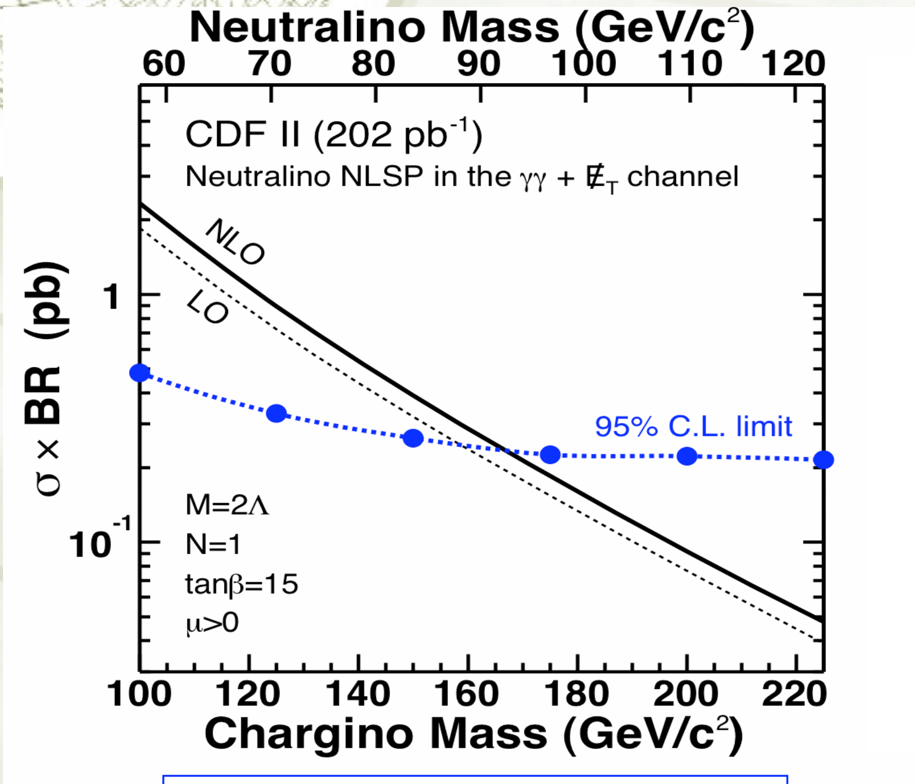
- $\tilde{\chi}_1^0$ decays into $\tilde{G}$, that gives rise to missing transverse energy ($\not{E}_T$), and a photon
- Both or either $\tilde{\chi}_1^0$ can decay in the detector

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

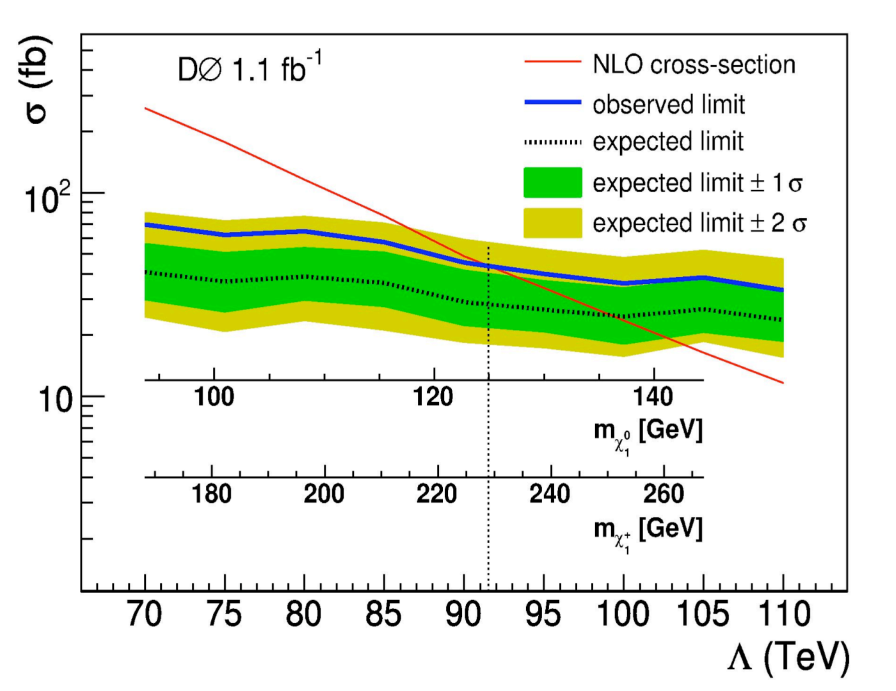
Previous Diphoton Searches

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

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



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

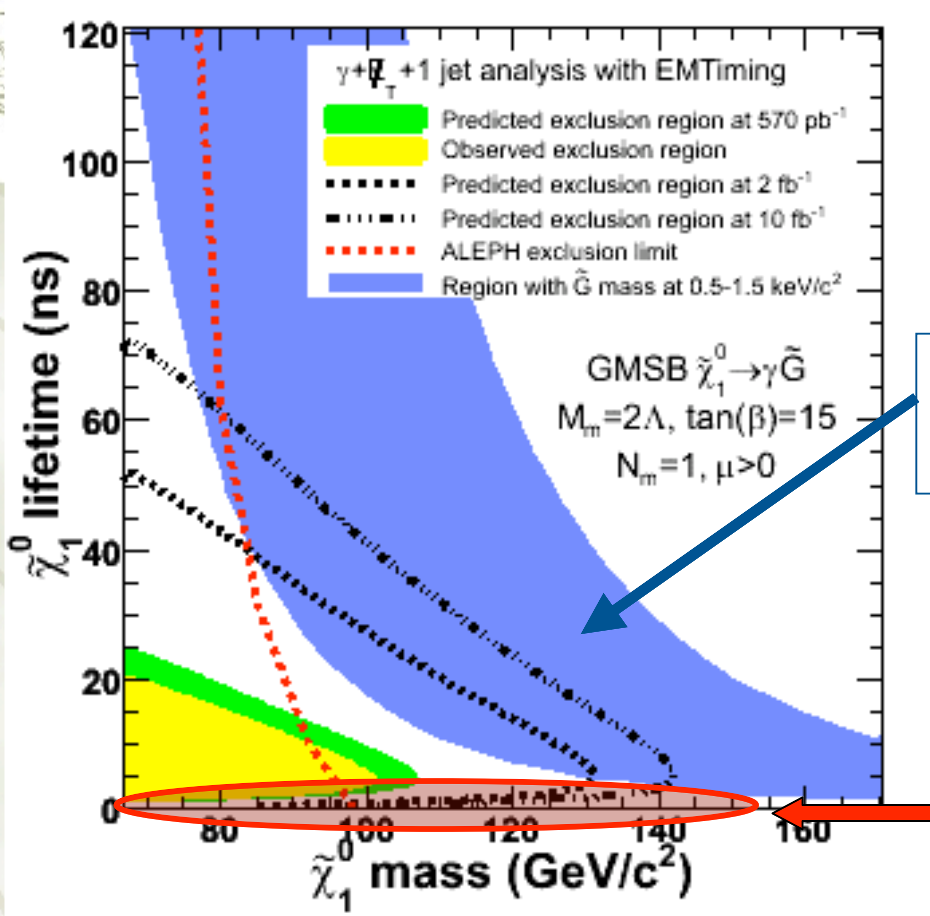


DØ (1.1 fb^{-1})
Phys.Lett.B659, 856 (2008)

Single 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)

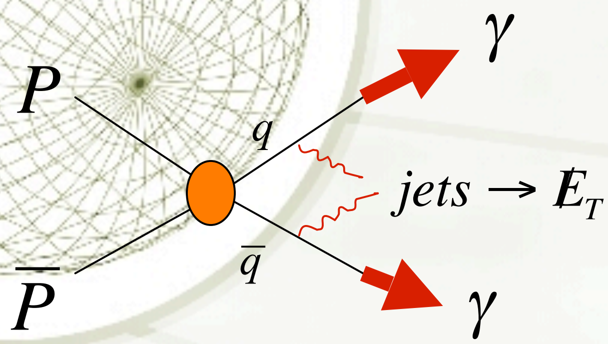
Our new search is first γγ search for non-zero low lifetime region (τ<2 ns):

Trying to understand here

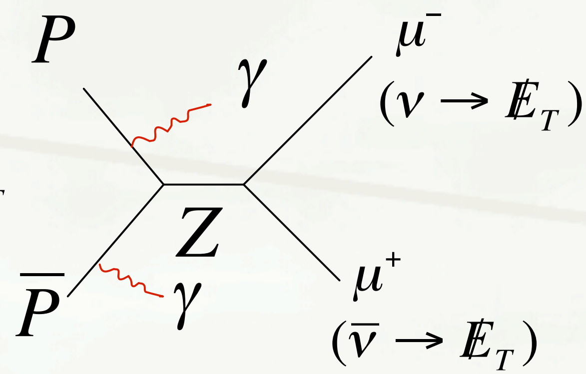
Analysis Overview

- 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

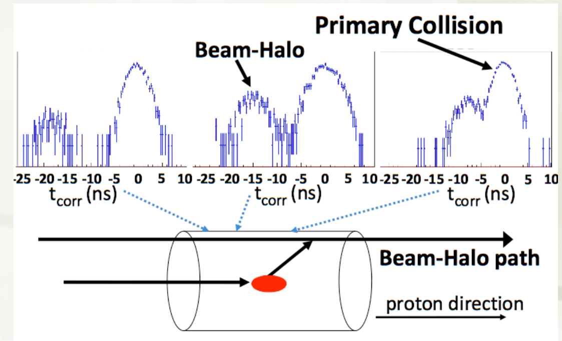
Backgrounds



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 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)

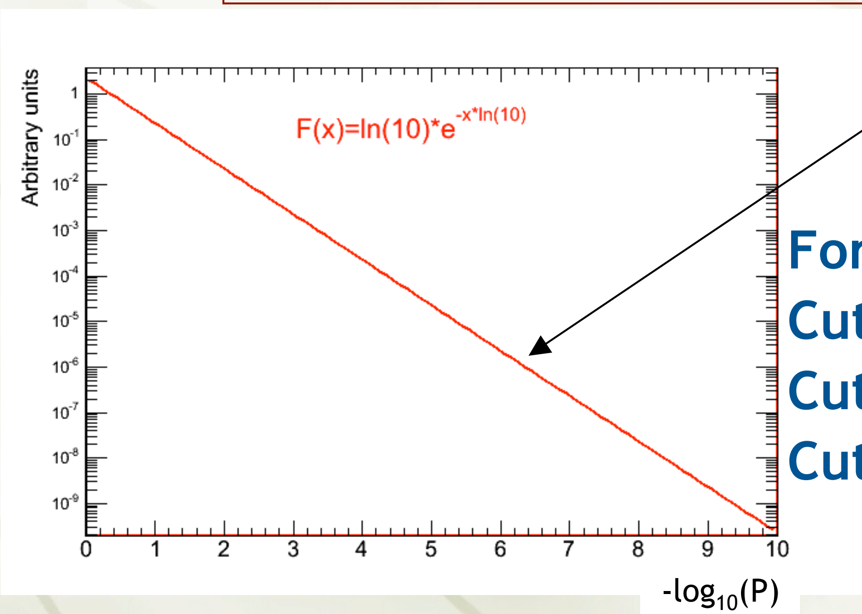
$\not{E}_T$ Resolution Model

- 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

$\not\!\!E_T$-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%)

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

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

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

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

Non-Collision Backgrounds

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

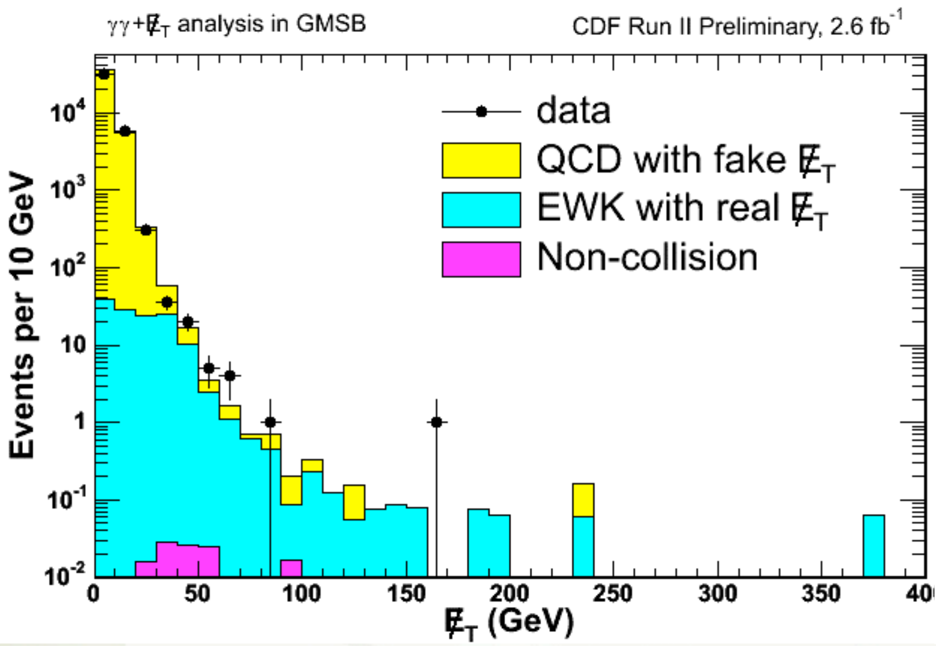
  - Distinctive energy deposition pattern of BH muons traveling along the beam pipe

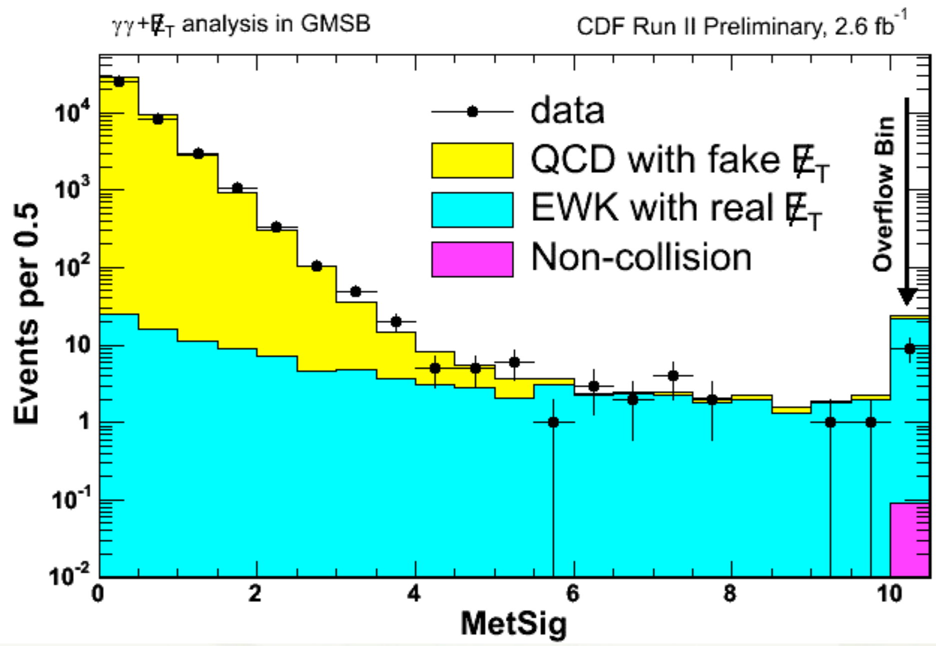
- Cosmic Rays: Use the EMTiming system

  - 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

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 $W\rightarrow e\nu$ and QCD with large H_T have high E_T back-to-back diphotons or wrong vertex)

Optimization Results

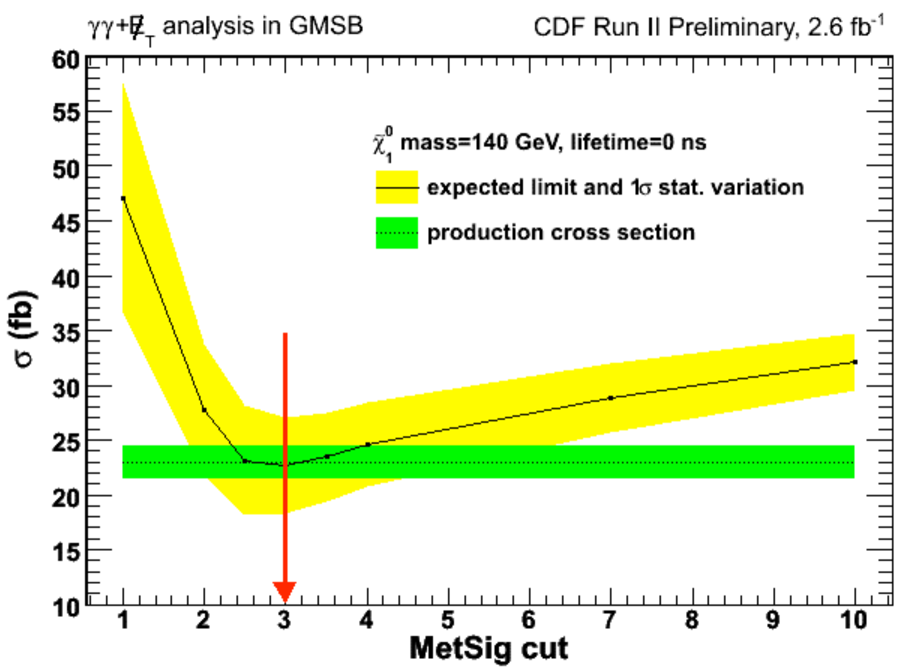
H_T > 200 GeV
$\Delta\phi(\gamma_1,\gamma_2) < \pi - 0.35$ rad
MetSig > 3

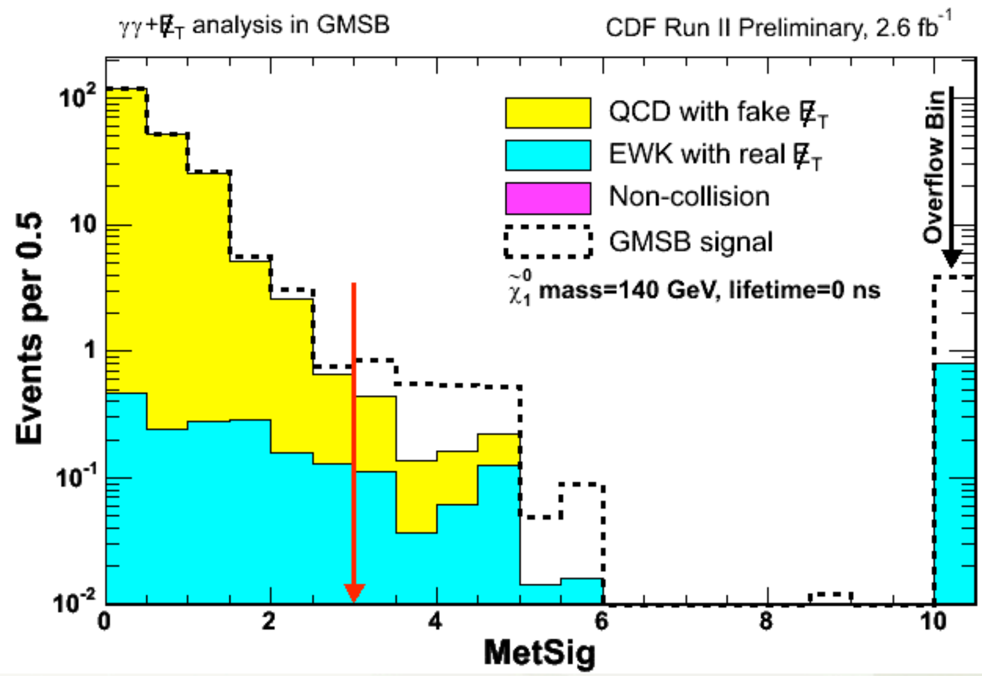
- Example point:
  $m(\chi^0{}_1)$=140 GeV, $\tau(\chi^0{}_1)$=0 ns
- Acceptance: 7.80 ± 0.54 (%)
- Luminosity: 2.6 ± 0.2 fb^{-1}

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

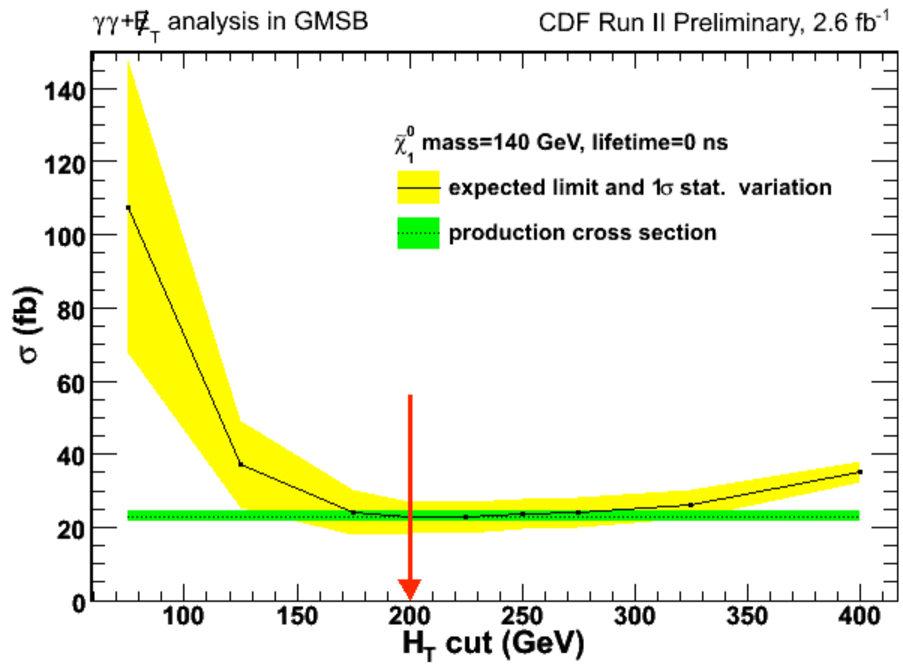
95% C.L. Cross Section Limits and N-1 Plot: MetSig

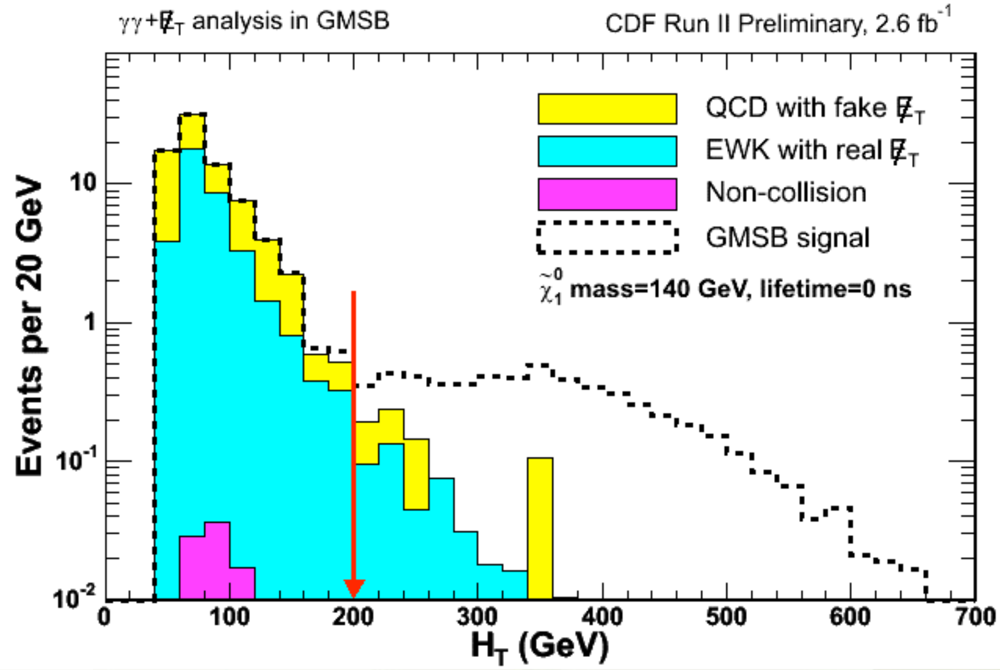




- While varying a cut all others held at optimal cuts: Minimal at Metsig=3
- N-1 Plot for background distributions along with GMSB signal: Good separation!

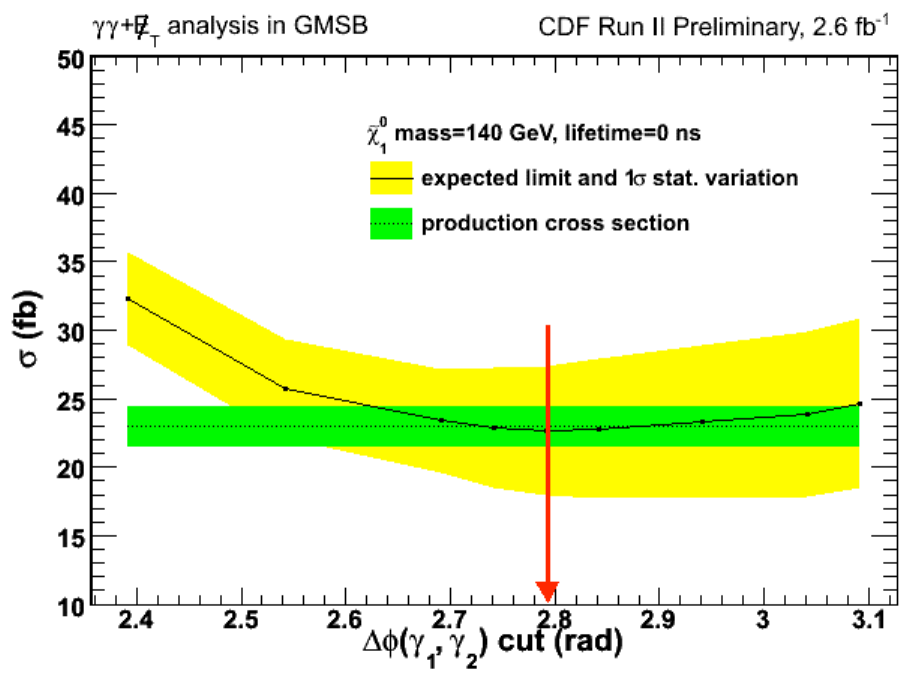
95% C.L. Cross Section Limits and N-1 Plot: H_T

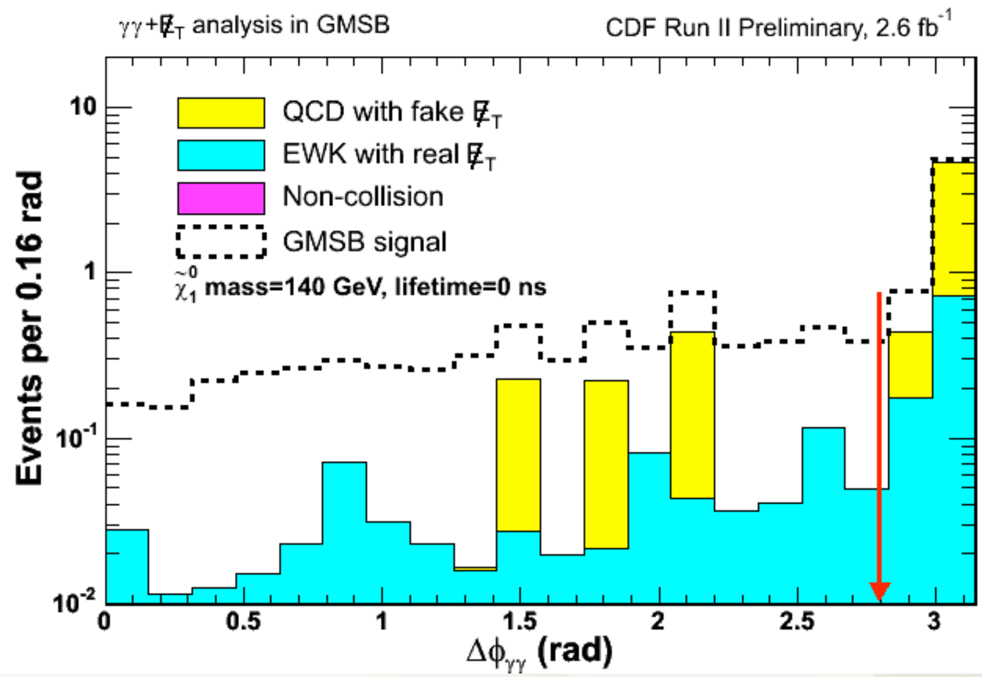




- While varying a cut all others held at optimal cuts : Minimal at H_T=200 GeV
- N-1 Plot for background distributions along with GMSB signal: Good separation!

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

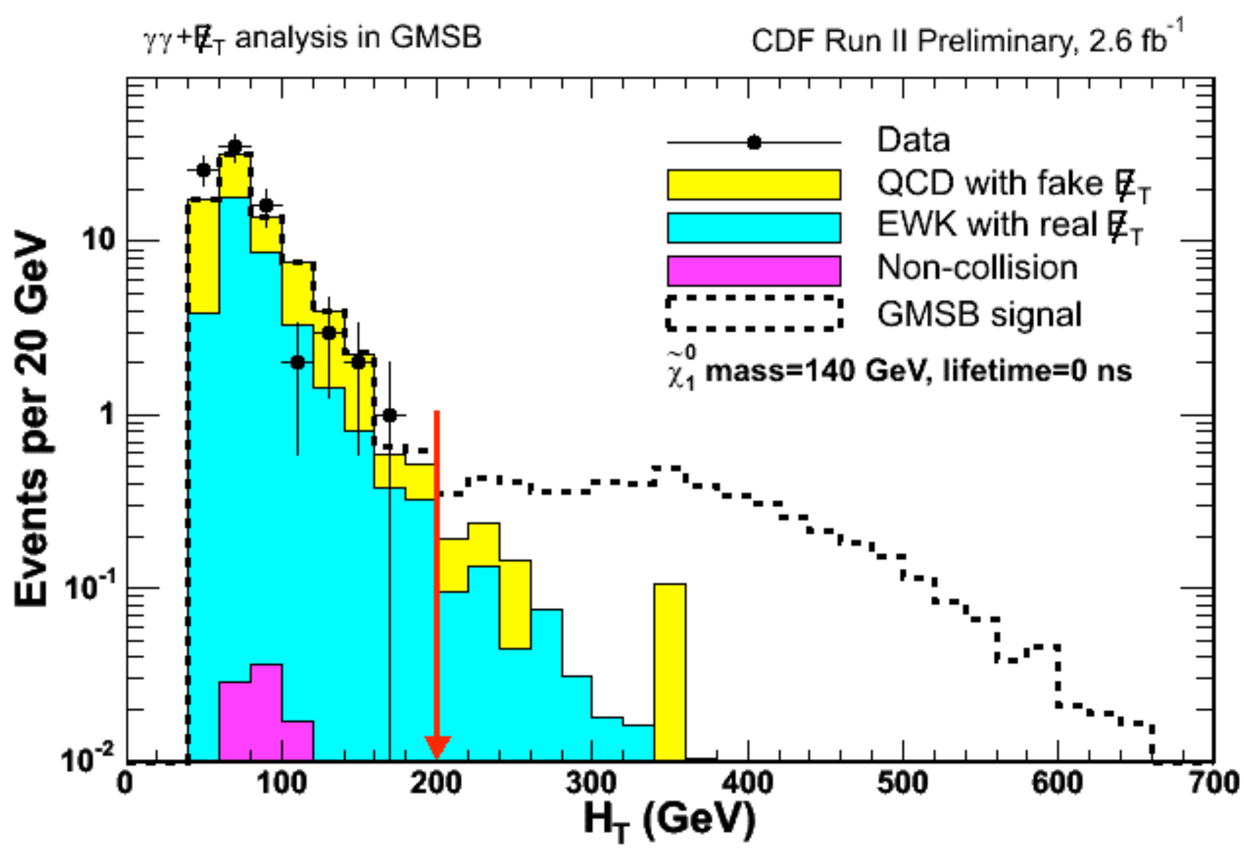




- While varying a cut all others held at optimal cuts : Minimal at $\Delta\phi(\gamma_1,\gamma_2)=\pi-0.35$ rad
- N-1 Plot for background distributions along with GMSB signal: Good separation!

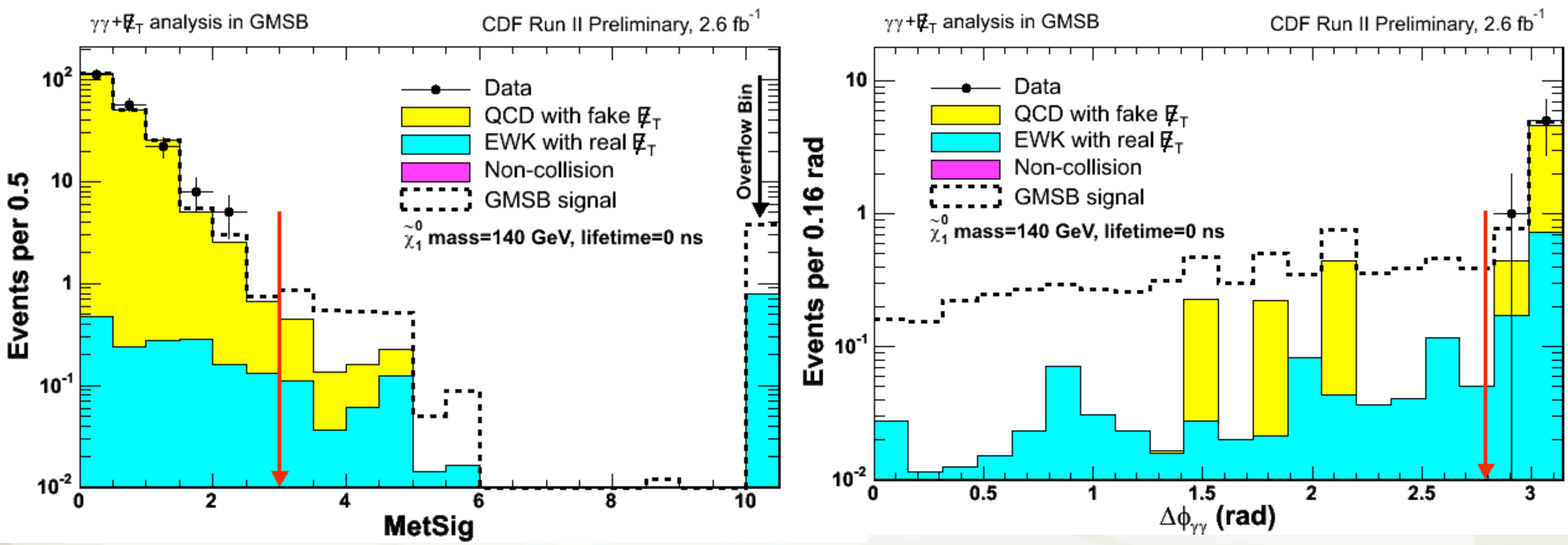
Data and N-1 Plot: H_T

We open the box: 0 events observed



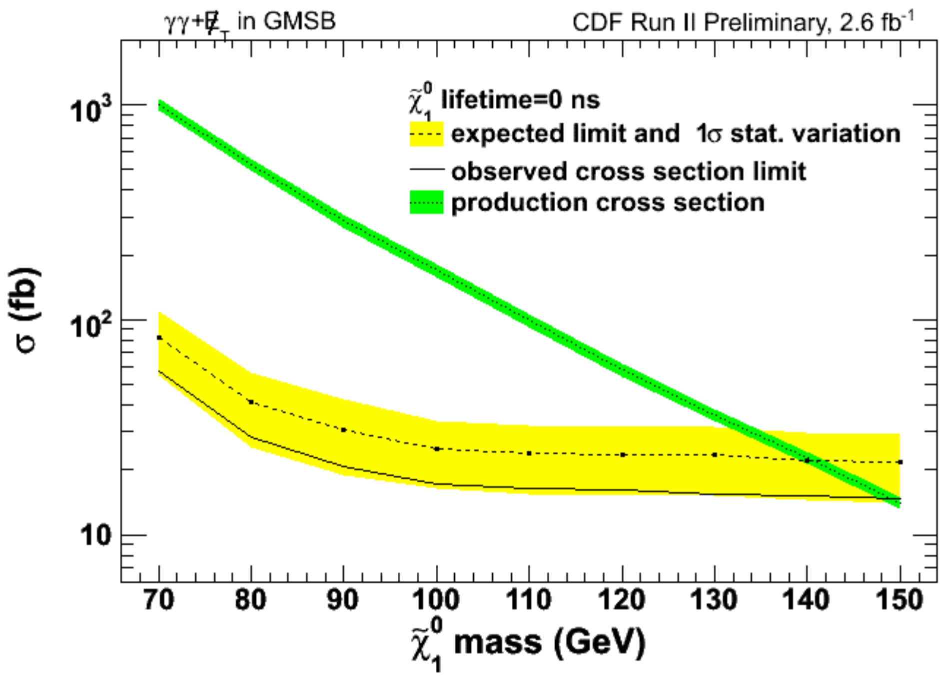
- For a distribution all other variables held at optimal cuts
- Everything is well modeled

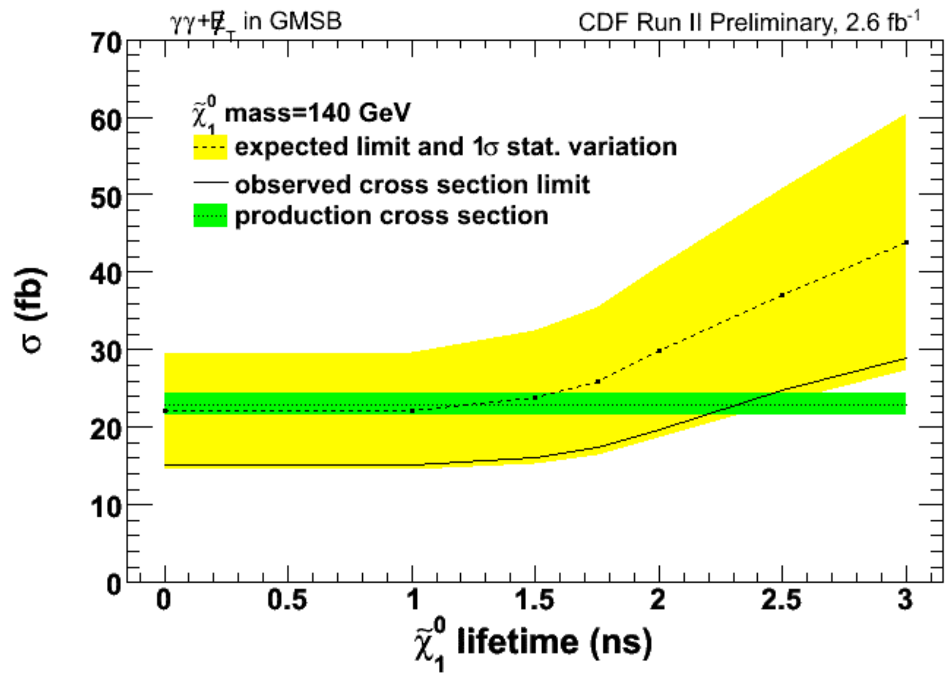
Other N-1 Plots with Data



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

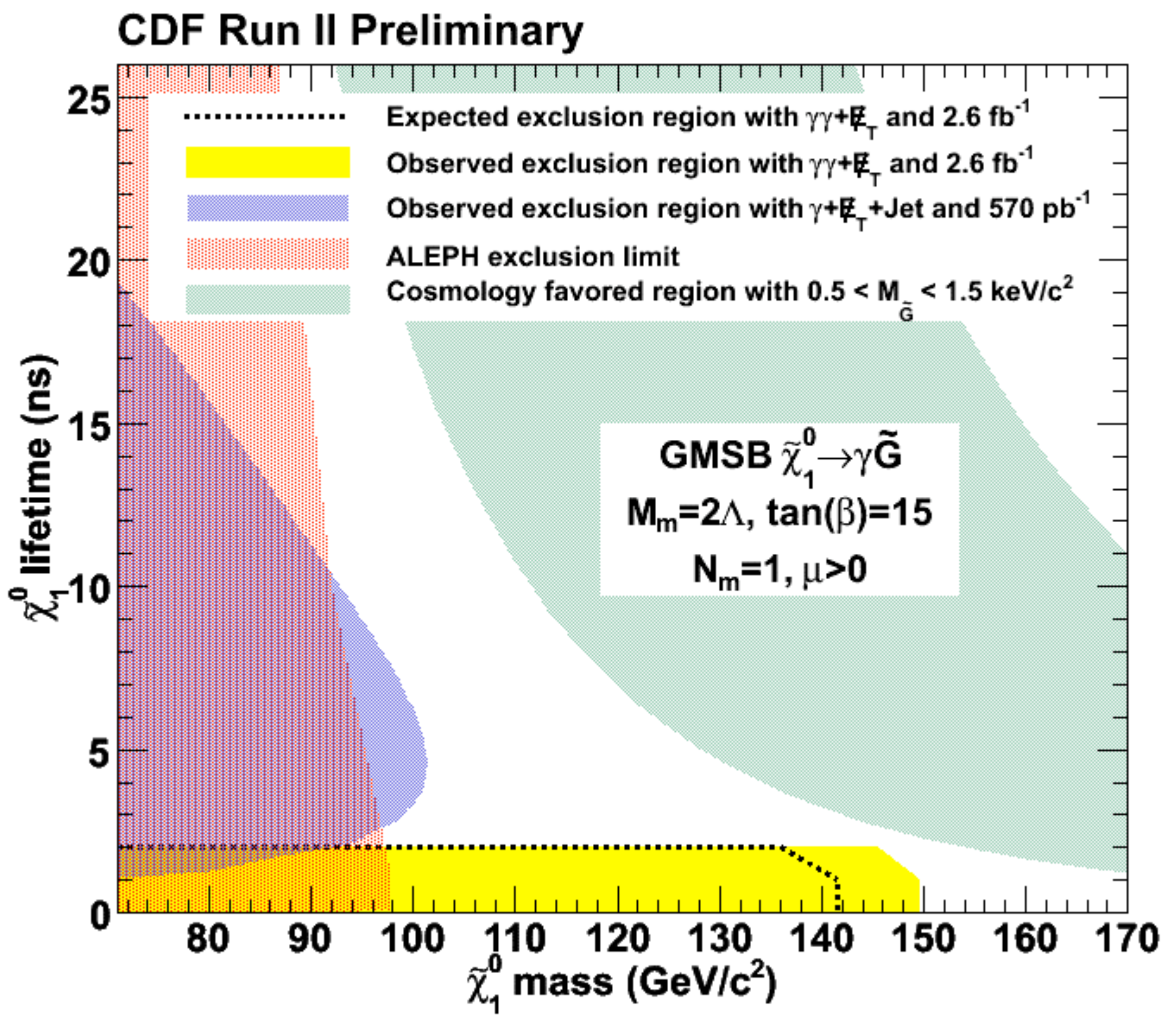
Cross Section Limits vs. Neutralino mass and lifetime





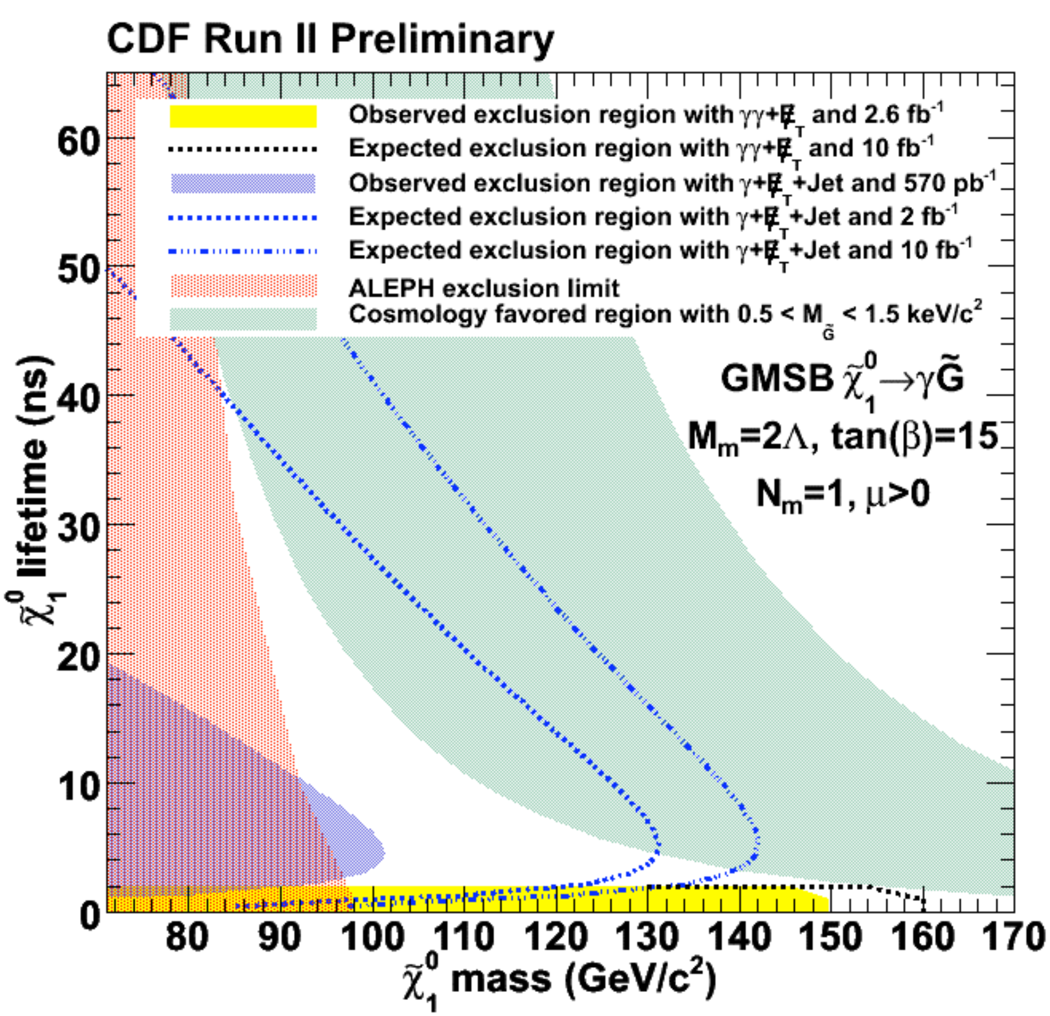
- Using the optimal cuts: $H_T > 200$ GeV $\Delta\phi(\gamma_1,\gamma_2) < \pi - 0.35$ rad MetSig >3
- Expected (Observed) neutralino mass limit 141 GeV (149 GeV) for τ=0 ns
- Exclude neutralino lifetime up to ~2.3 ns for m=140 GeV

Exclusion Region



- Exclude up to ~ 149 GeV for τ < 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
- $\gamma\gamma+\not{E}_T$: will extend mass limits up to 160 GeV with 10 fb^{-1}
- The next generation delayed photon analysis will cover up high lifetime region

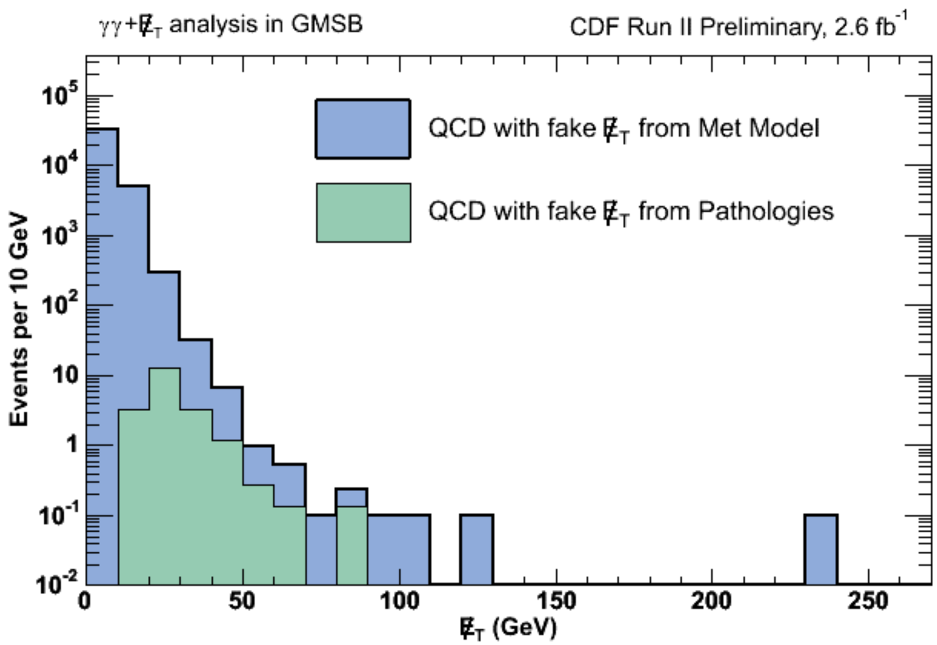
Conclusion

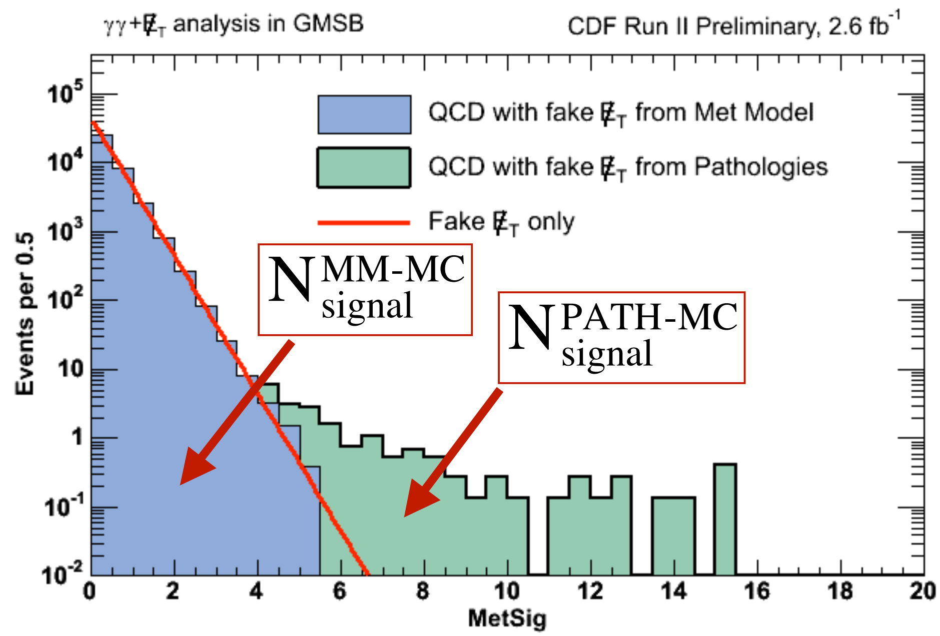
Summary

- First $\gamma\gamma$ 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. (Currently in first reading by collaboration, approved by God Parents)

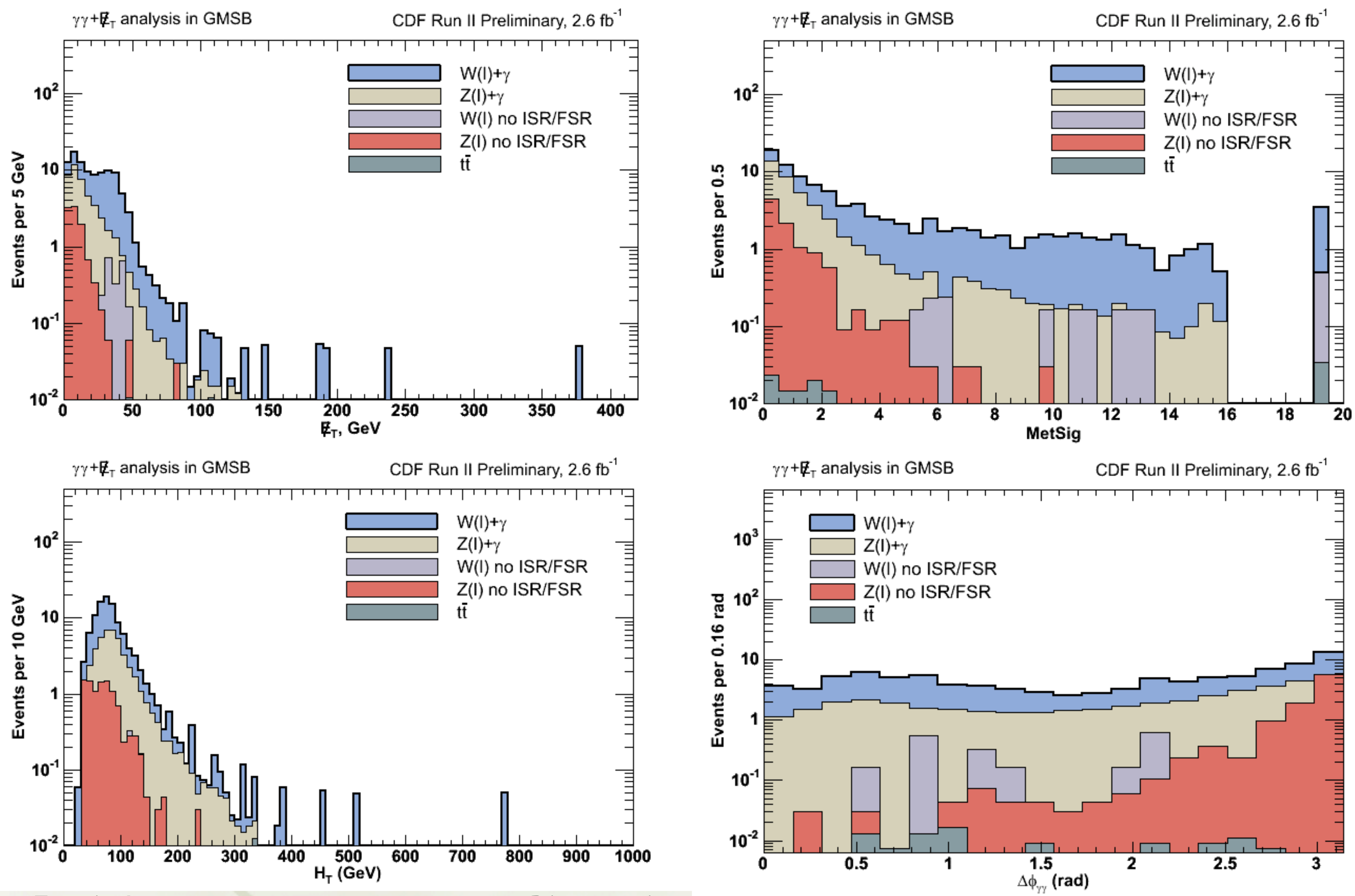
Back Up

Total QCD Backgrounds





EWK Backgrounds Distributions



Non-Collision Background Distributions