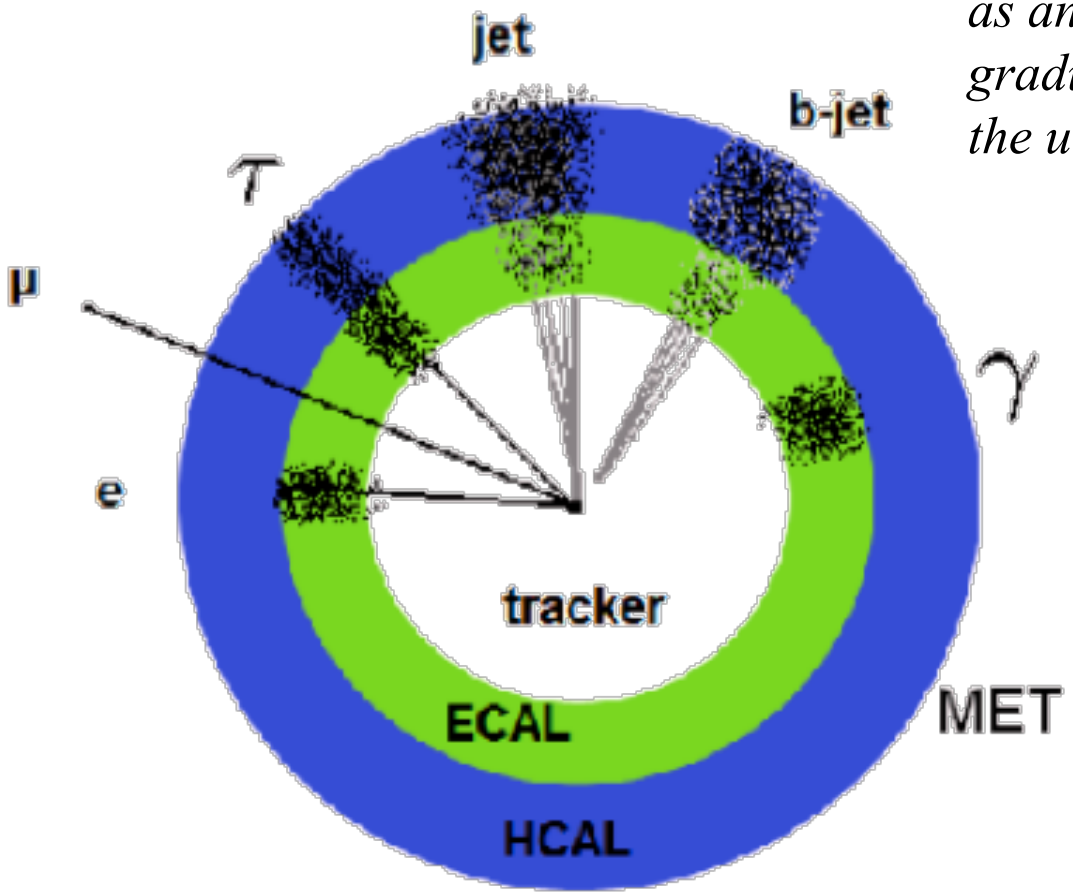
Searching for New Physics with Light at CDF

Sasha Pronko

Fermilab

"Noble Sevenfold Path" Of High P_T Physics

Wikipedia: *"The Noble Eightfold Path, in the teachings of the Buddha, is used as an instrument of discovery to gradually generate insights unveiling the ultimate truth of things"*



Photon is one of seven objects at colliders

New Physics with Photons

Compositeness

$ll+\gamma$, $ll+\gamma\gamma$, $jj+\gamma$,
$bb+\gamma$, $jj+\gamma\gamma$, $bb+\gamma\gamma$

4th generation

$\gamma\gamma+bb$, $ll+\gamma+bb$,
$jj+\gamma\gamma+bb$

Technicolor

$\gamma+bb$, $\gamma+jj$, $\gamma+tt$, $\gamma\gamma\gamma$,
$ll+\gamma\gamma$, $ll+\gamma\gamma+ME_T$

There is no deficit of models!!

SUSY

$\gamma\gamma+ME_T$, $\gamma\gamma+ll+ME_T$, $\gamma\gamma+j+ME_T$,
$l+\gamma+ME_T$, $\gamma+b+ME_T$, $\gamma+bj+ME_T$
$\gamma+bc+ME_T$, $\gamma+jj+ME_T$, $\gamma+ll+ME_T$,
displaced $\gamma+X$, $\gamma+ME_T$, $jj+\gamma+ME_T$

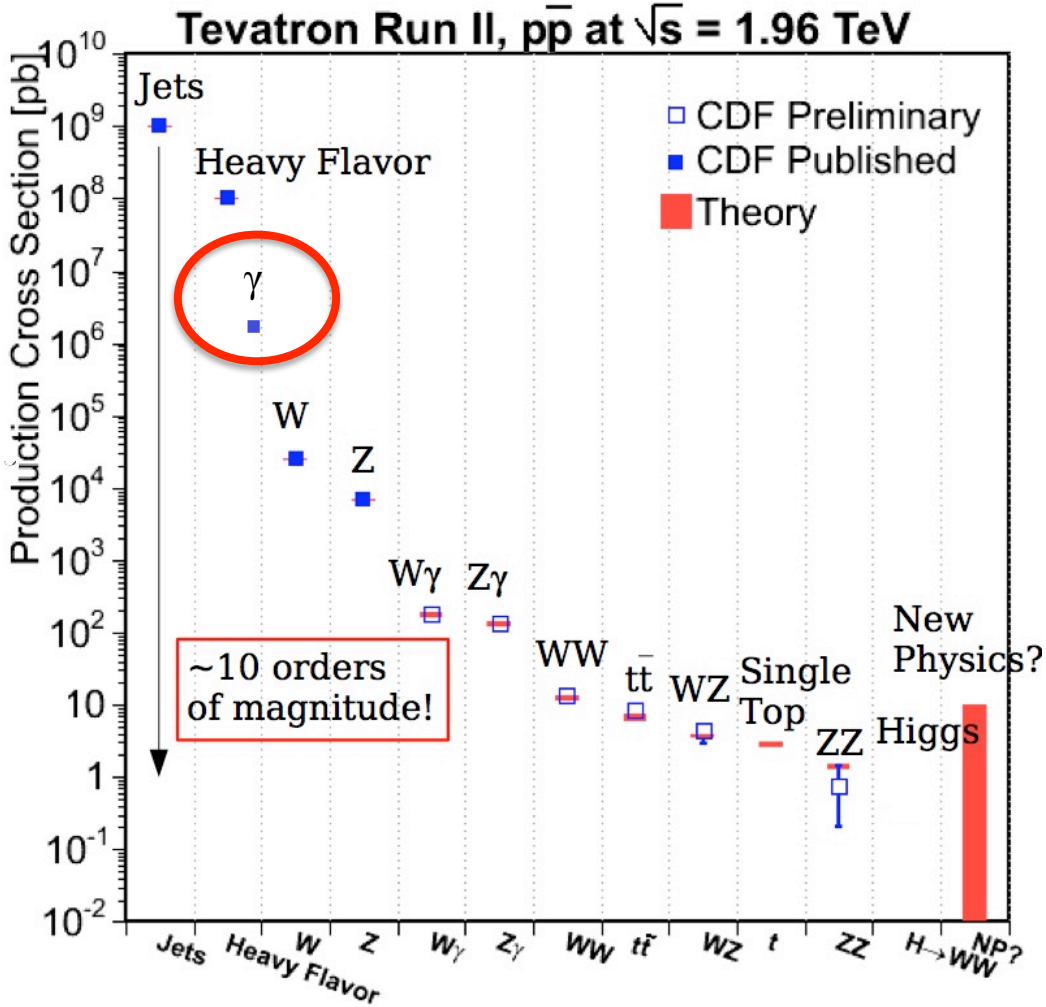
Higgs

$\gamma\gamma$, $ll+\gamma$, $l+\gamma\gamma+ME_T$,
$\gamma\gamma+ME_T$, $jj+\gamma\gamma$, $\gamma\gamma+\gamma\gamma$

Extra Dimensions

$\gamma\gamma$, γME_T
$\gamma\gamma+n*l+ME_T$

Photon Production at Tevatron

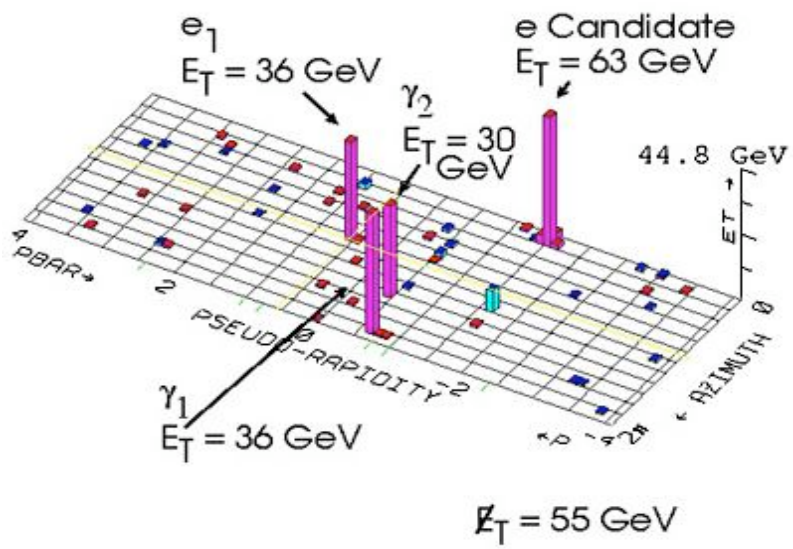


QCD > QED > EWK

- Photons are 2nd most frequent objects after jets

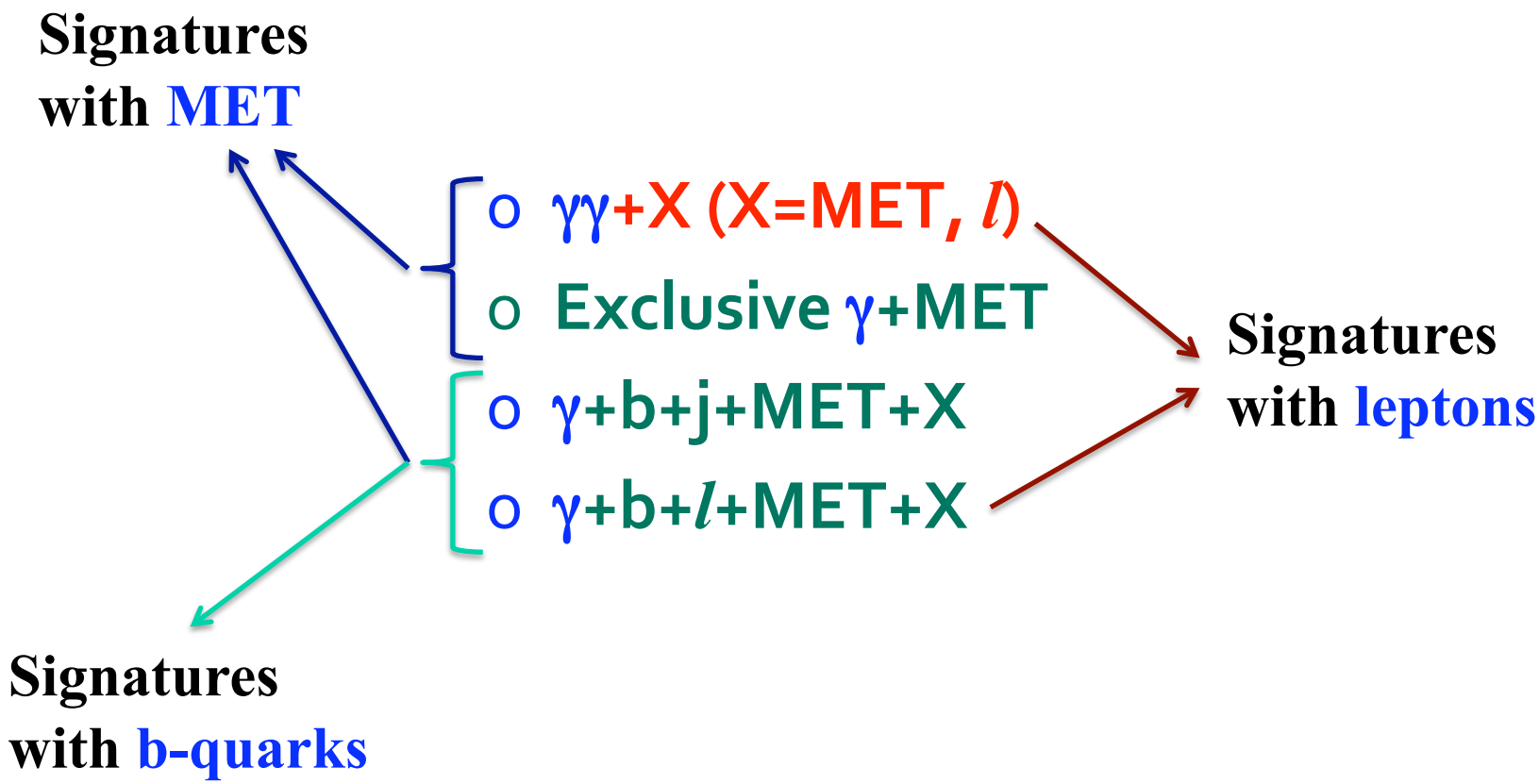
Any Surprises with Photons?

Run I $ee\gamma\gamma\not{E}_T$ (10^{-6} expected, 1 observed)

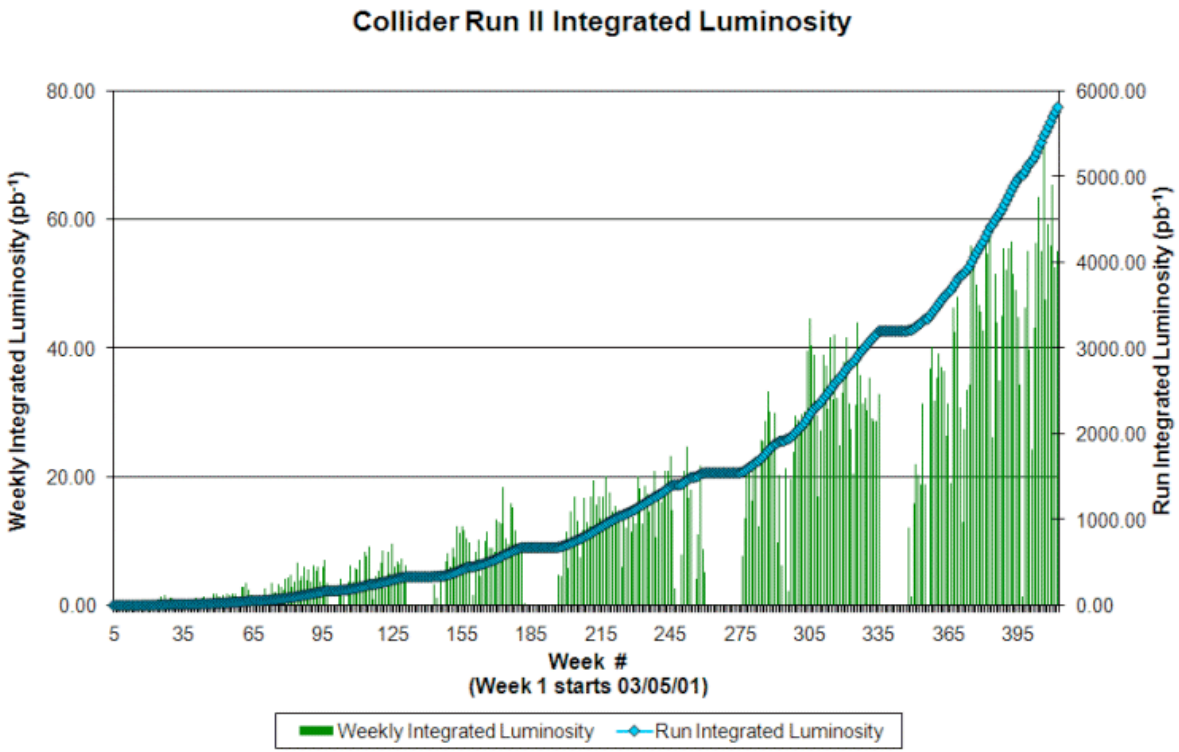


Run I $\ell\gamma\not{E}_T$: 7.6±0.7 expected, 16 observed, 2.7σ

Photon Searches in This Talk



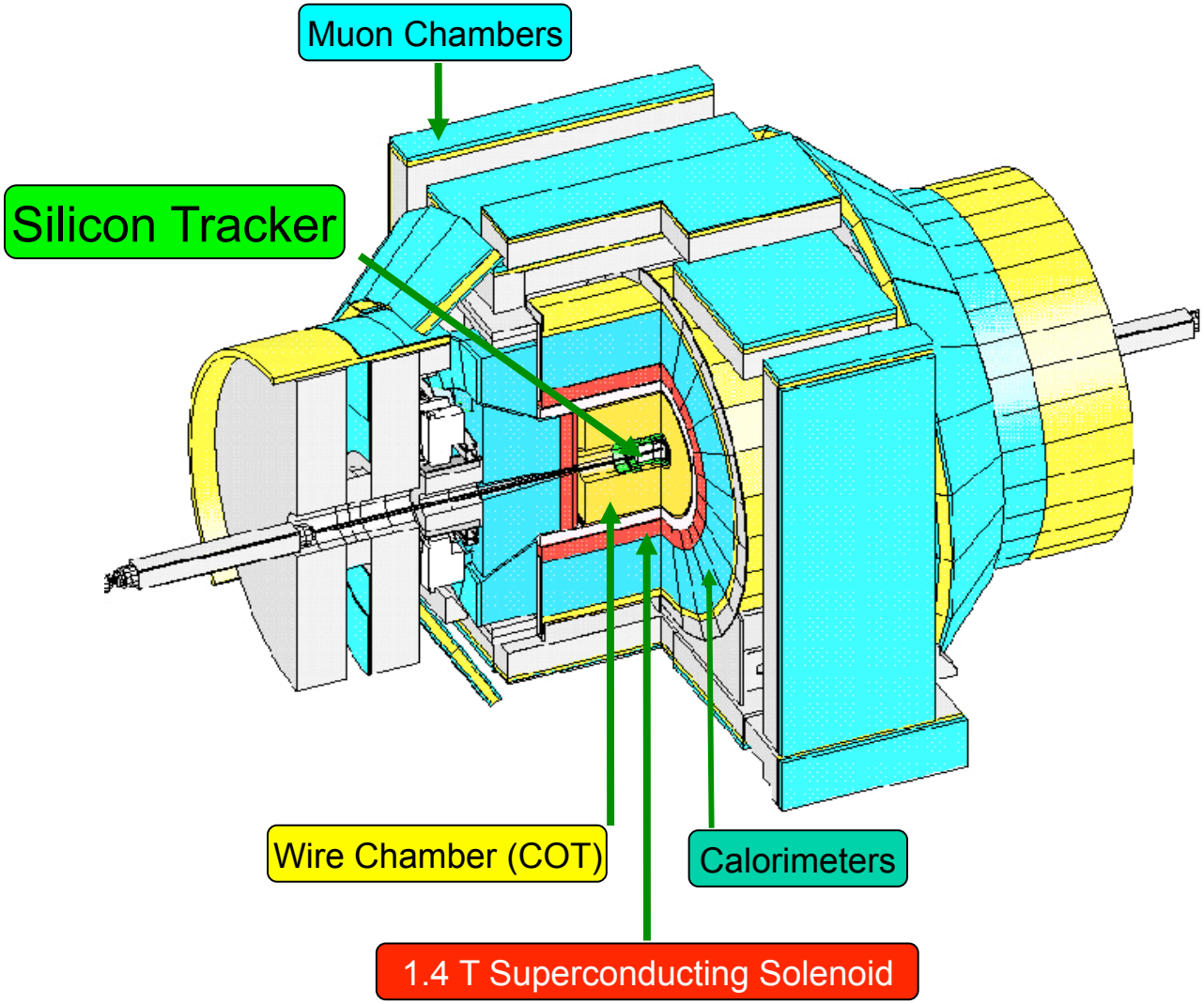
Tevatron



Results in this talk are based on 1-3 fb^{-1} of data

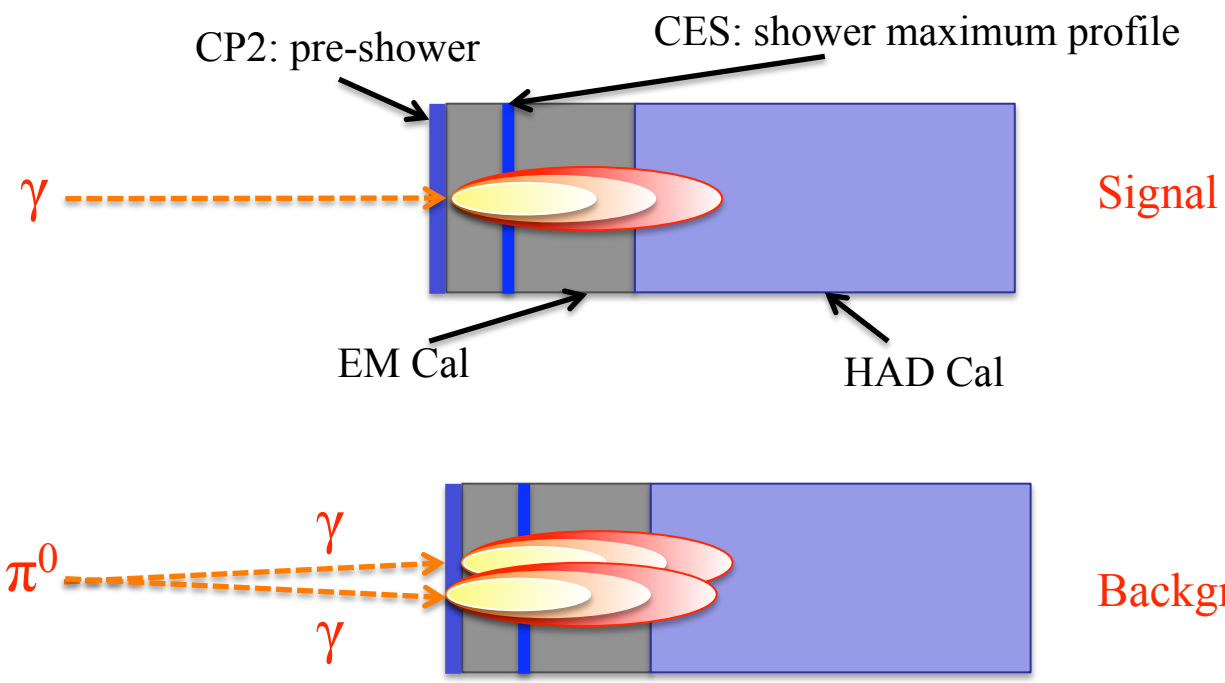
Many thanks to our colleagues from the Accelerator Division for being so luminous and providing us with data for our pursuit to shed light on the ultimate truth about laws of Nature !!

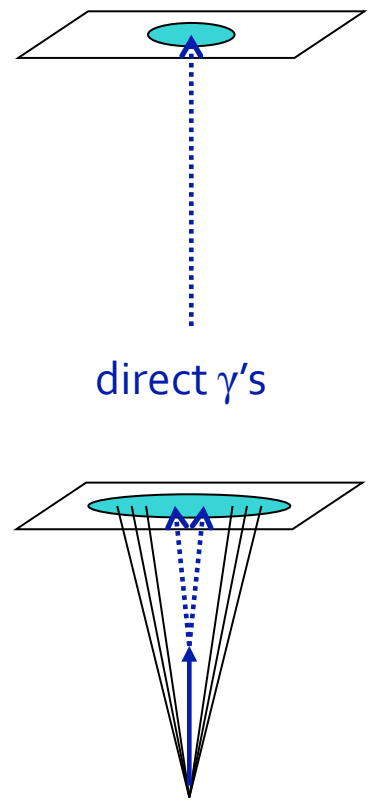
CDF Run II Detector



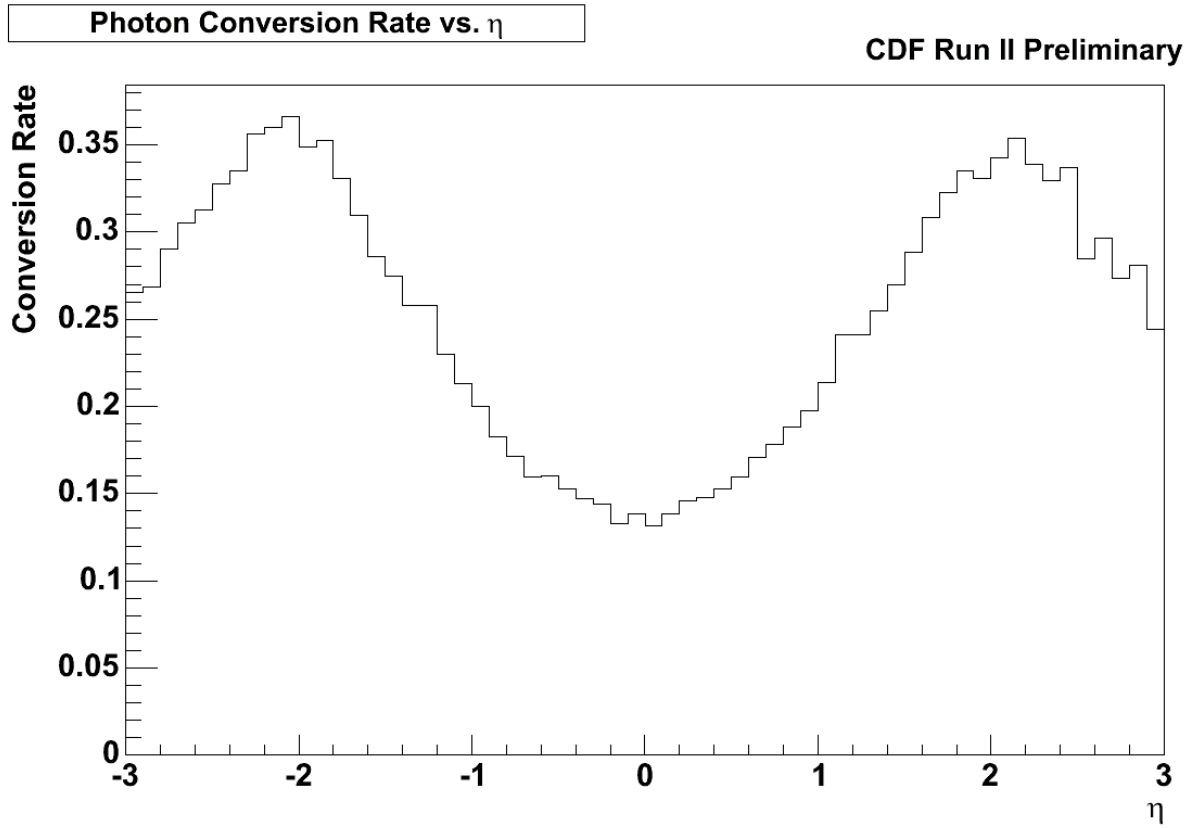
Concept of Photon ID

- 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





Conversions

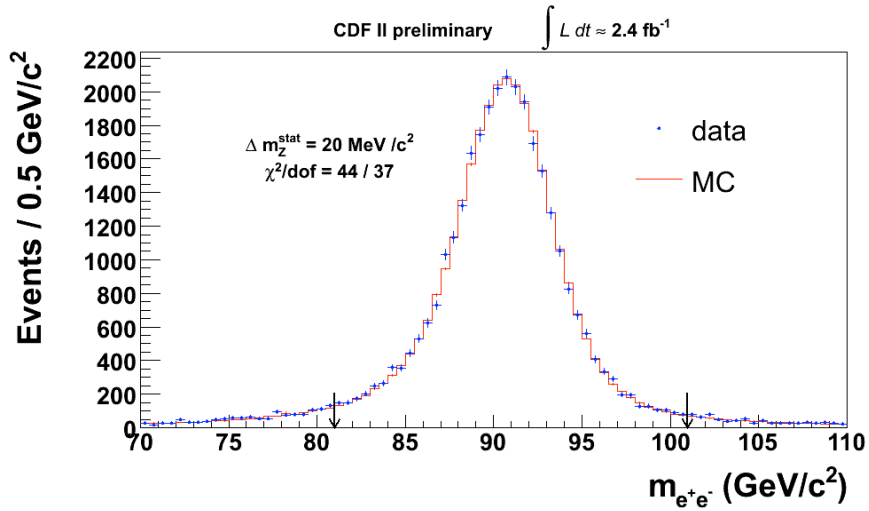


- ~15% (~30%) central (forward) photons convert to e^+e^-
  - Conversions are not currently used in photon analyses at CDF
  - CDF has only one Run I measurement using converted photons
    - Phys. Rev. D70, 074008 (2004)

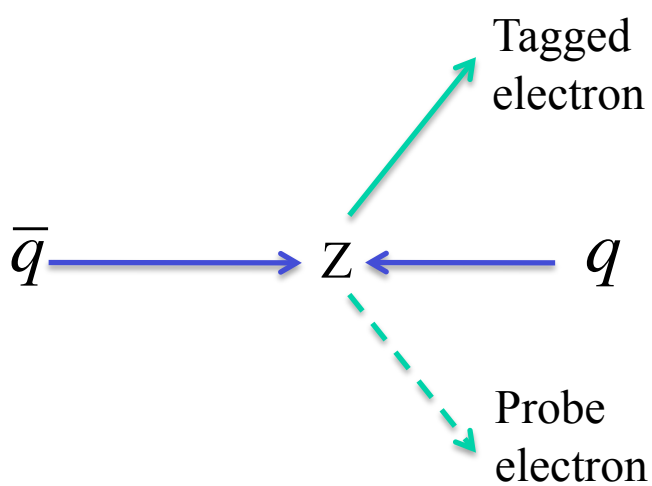
Check List For Photons

- What do you need in order to do an analysis with photons?
  - Photon ID efficiency & acceptance
  - Photon purity & background subtraction
  - Fake rates
  - Anything else?...

Photon ID Efficiency



- Method
  - MC for E_T dependence
  - Data/MC scale factor:
    - $Z \rightarrow e^+e^-$ in data and MC



Efficiency of photon ID
Central: ~86%
Forward: ~76%

Estimating Backgrounds in Photon Searches

- Searches in γ+X+Y+Z+… or $\gamma\gamma$+X…
- "Physics" backgrounds
  - SM processes where all experimental signatures (γ,X,Y,Z…) are genuine
    - from MC (LO→NLO k-factors)
    - Normalization: σ×Lumi or data-based (control samples)
- "Instrumental" backgrounds ("fakes")
  - At least one of experimental signatures is faked by object from SM process with larger x-section: e.g., jet→γ
    - From data
    - Fake rates; photon purity
- Non-collision backgrounds
  - "Cosmics": muons from cosmic rays faking photon
  - "Beam Halo": muons produced by beam halo faking photon
    - From data

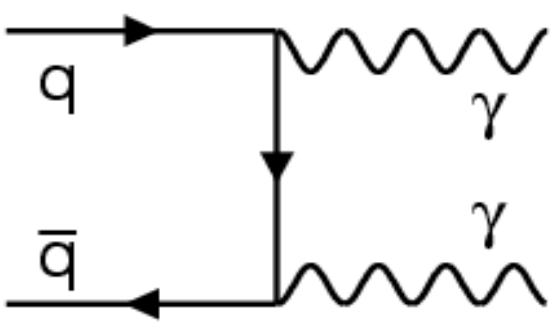
Search for Anomalous Production of $\gamma\gamma$+X

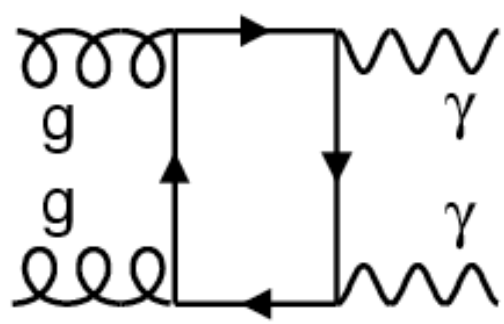
Search for Anomalous Production of γγ+X

- Why γγ+X?
- Why model-independent?

$$SUSY: \quad \gamma\gamma + \not{E}_T,\ \gamma\gamma + jets + \not{E}_T,\ \gamma\gamma + ll + \not{E}_T$$
$$Technicolor: \quad \gamma\gamma + ll, \gamma\gamma + ll + \not{E}_T$$
$$Higgs: \quad \gamma\gamma + \not{E}_T, \gamma\gamma + l + \not{E}_T$$
$$UED(6DSM): \gamma\gamma + m * l + \not{E}_T$$

- LO diagrams for SM di-photon production: leading background for many γγ+X searches





$\gamma\gamma$+X Search: Analysis Overview

Three analyses in one:

X=MET, e/μ, τ

Same backgrounds:

"QCD" ($\gamma\gamma$, γj, jj)

EWK (W/Z+γ/$\gamma\gamma$)

Non-collision (for X=MET)

Results:

Comparison of data & background predictions (event count; kinematic distributions)

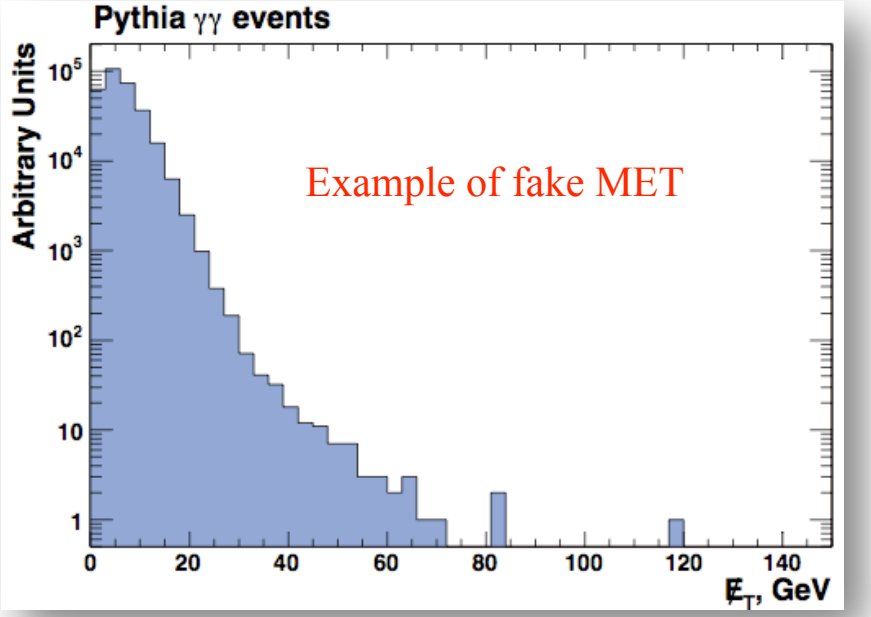
Signal region

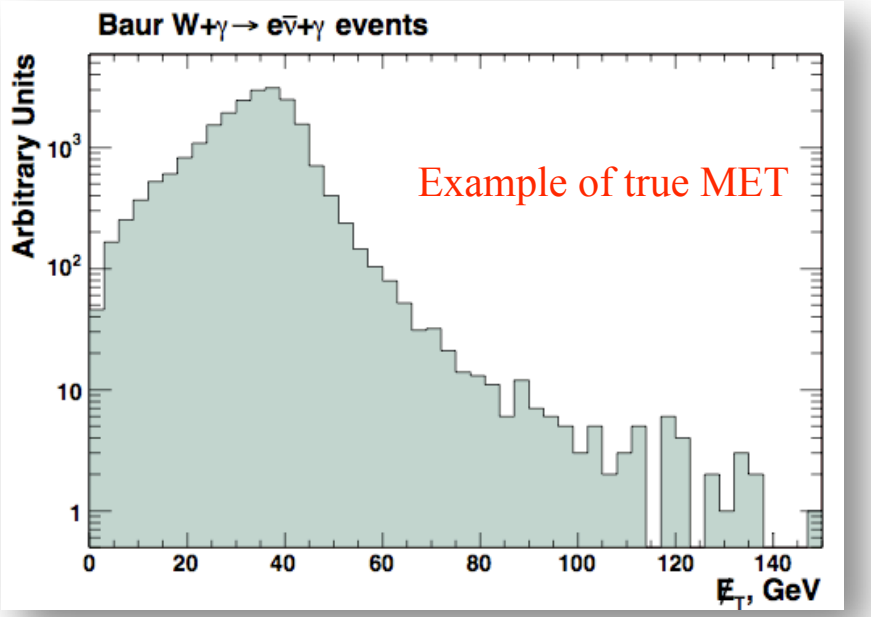
2 central photons

$E_T(\gamma)$>13 GeV

~30% pure $\gamma\gamma$

Fake MET Problem in γγ+MET Search



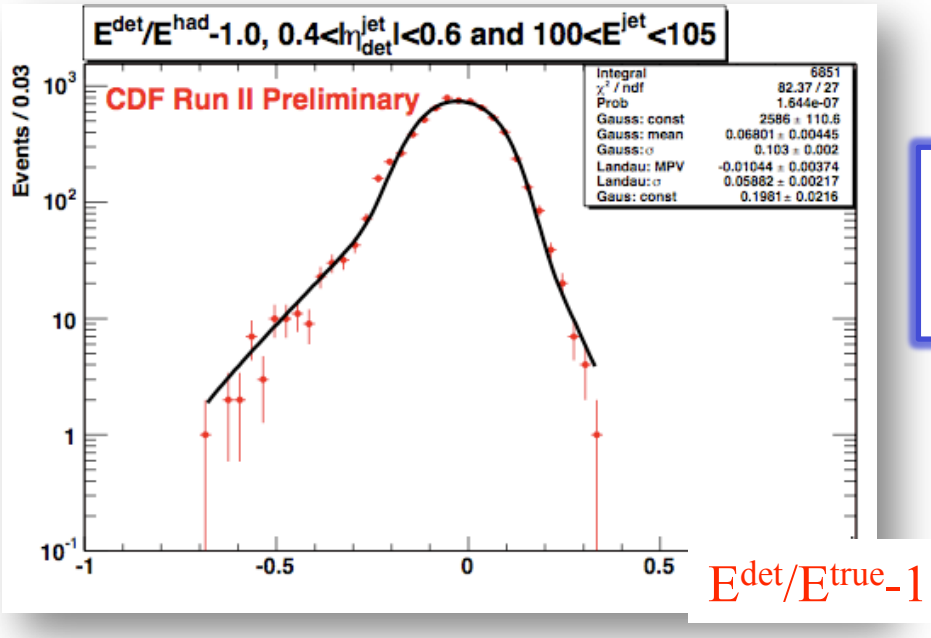


- MET distribution in γγ events is dominated by regular "QCD" events with fake MET
- MC is not reliable in modeling multi-jet events:
  - not accurate description of fake MET
- How do you distinguish events with true & fake MET?

Met Resolution Model

Example of jet energy resolution

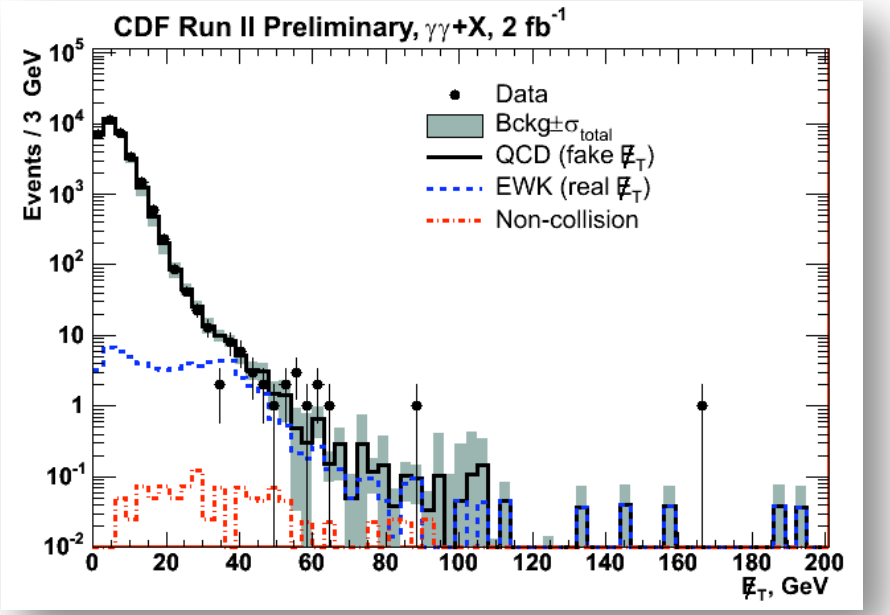
Mis-measurements in jet energy are leading source of fake MET



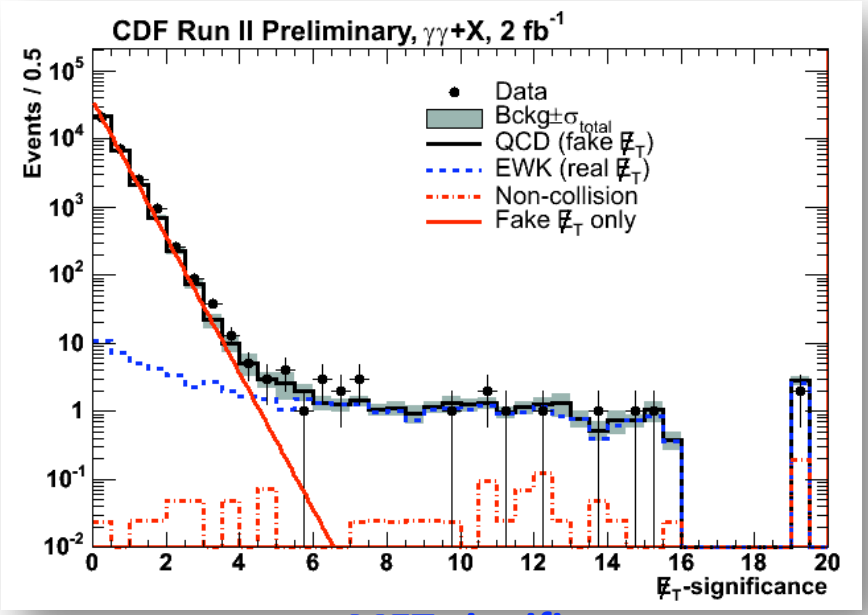
Obtain jet energy resolution as function of E^{jet} & η

- 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

MET & MET-significance in γγ events



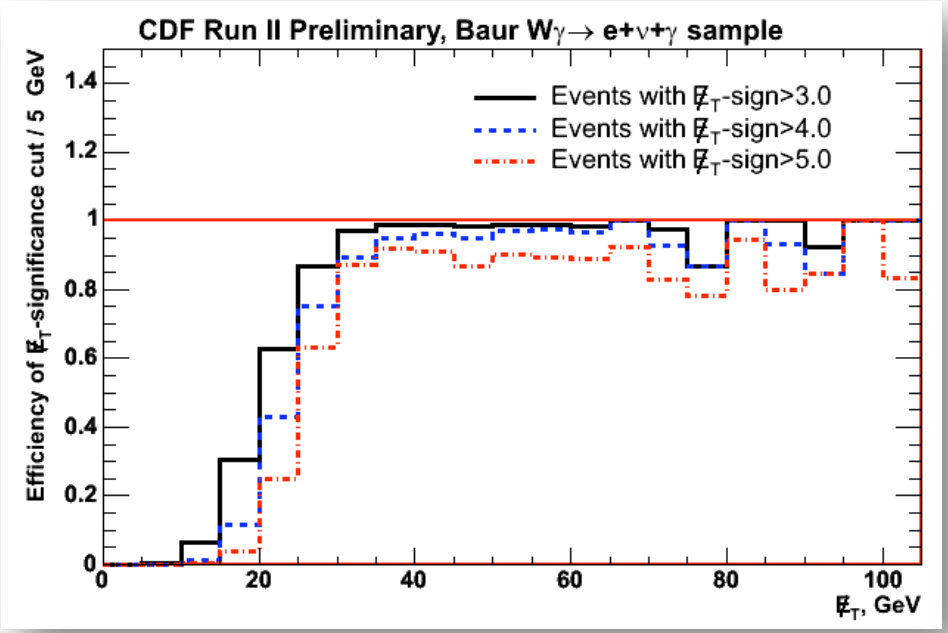
MET

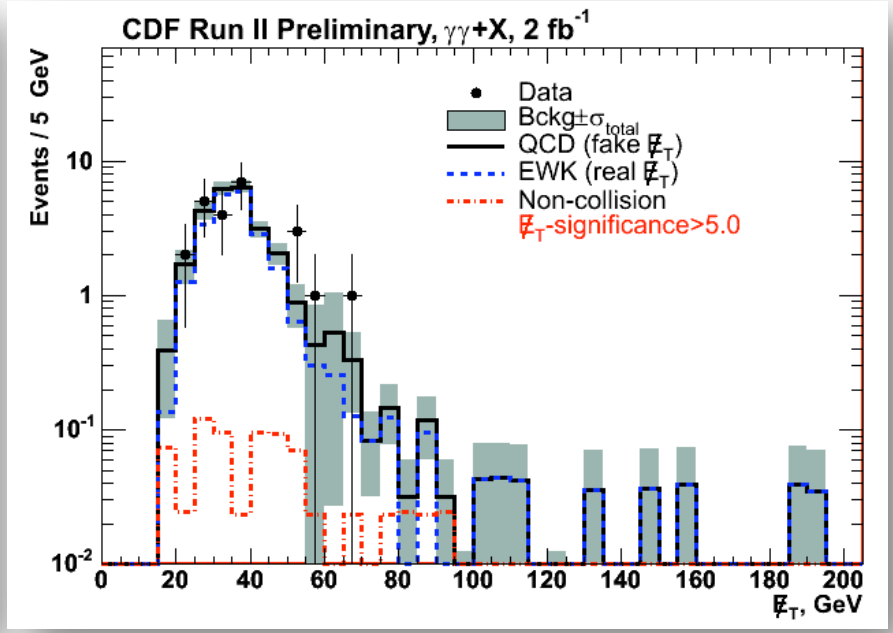


MET-significance

- Select events with MET-significance >3, 4, 5 in 2 fb^{-1} of data
  - Suppress QCD by 3, 4, 5 orders of magnitude
- Backgrounds
  - QCD with fake MET (γγ, γj, jj): from data
  - EWK with true MET (W/Z+γ, W/Z+jet, $Z \to \tau\tau \to \gamma_{fake}\gamma_{fake}$): from MC (normalized to data)
  - Non-collision (Beam Halo, Cosmics): from data (events out of time collision time)

γγ+MET: MET Distribution



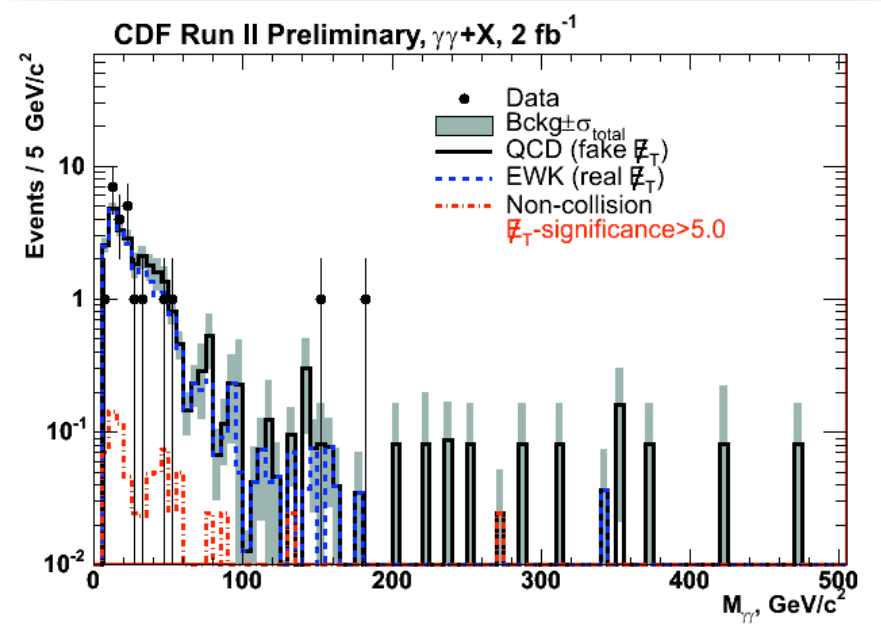


- Efficiency of MET-significance cut for events with true MET (e.g., Wγ→eνγ)

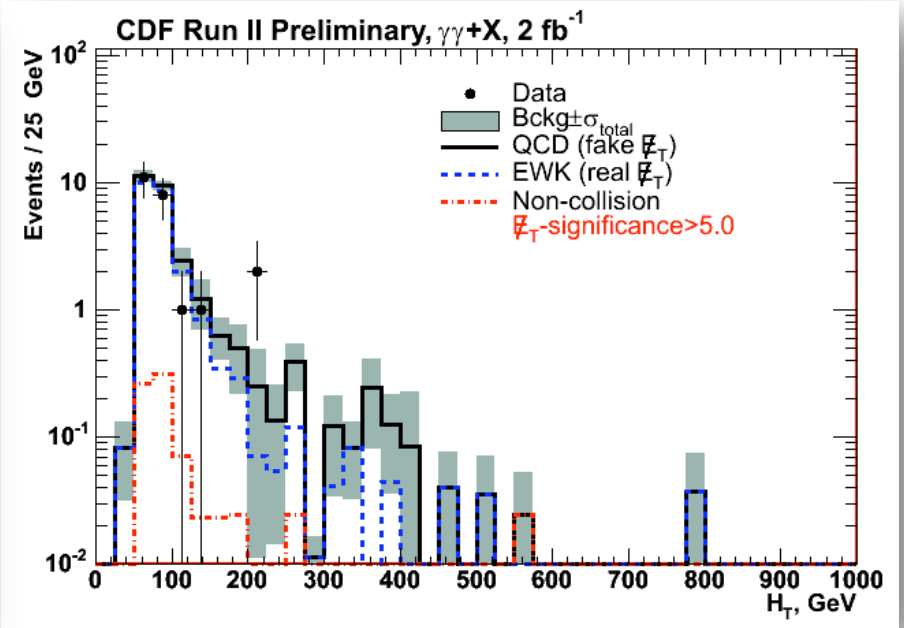
Note! Almost no QCD even at MET~20-30 GeV!

Efficiency for Wγ→eνγ	MetSig>3.0	MetSig>4.0	MetSig>5.0
	84%	74%	67%

Results for γγ+MET: Results



$M_{\gamma\gamma}$

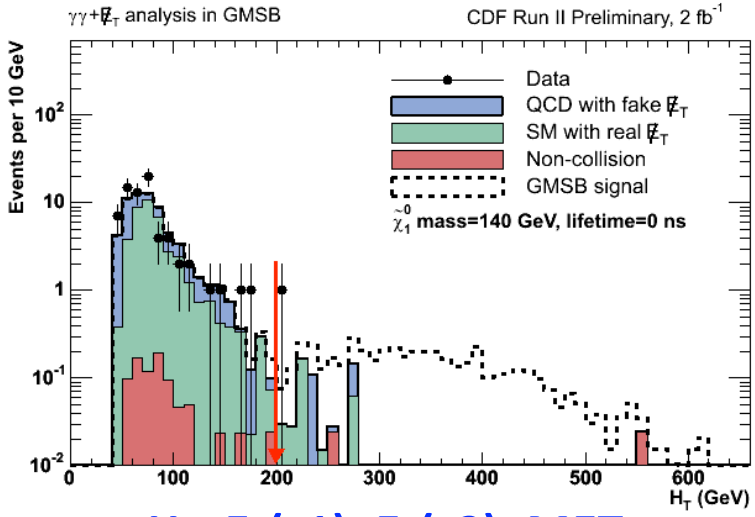


$H_T=E_T(\gamma1)+E_T(\gamma2)+MET+...$

- $M_{\gamma\gamma}$ and H_T distributions after MET-sig>5 cut

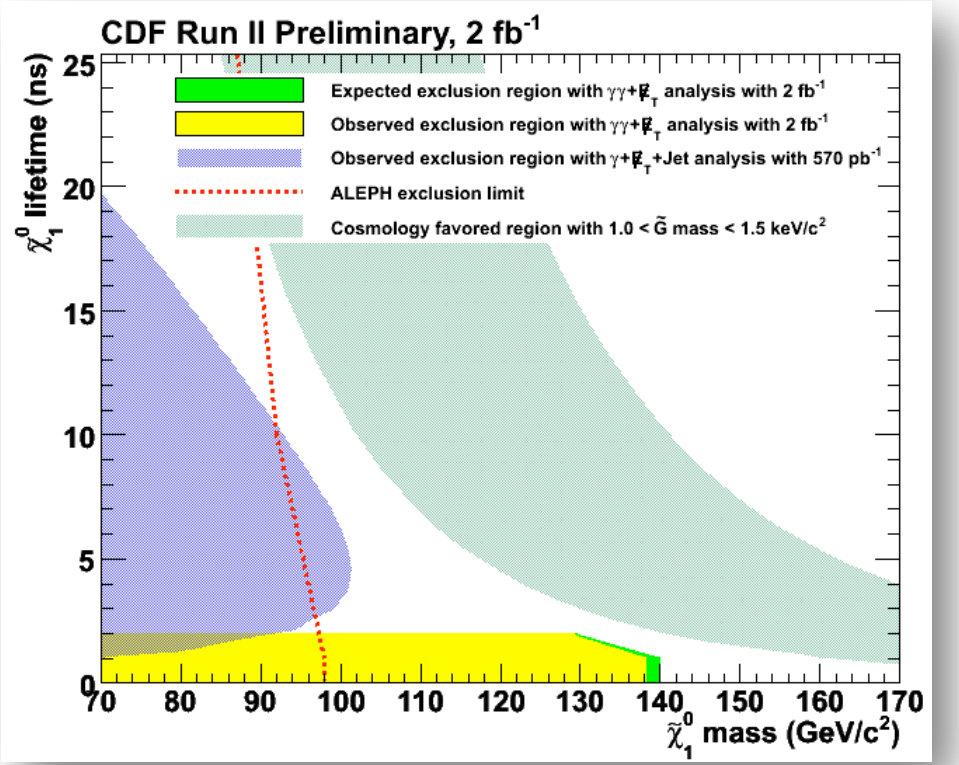
	MetSig>3.0	MetSig>4.0	MetSig>5.0
Background	67.9±7.5	35.8±3.0	27.3±2.3
Data, 2 fb^{-1}	82	31	23
EWK	47%	75%	84%

Limits on GMSB in γγ+MET



$H_T=E_T(\gamma1)+E_T(\gamma2)+MET+...$

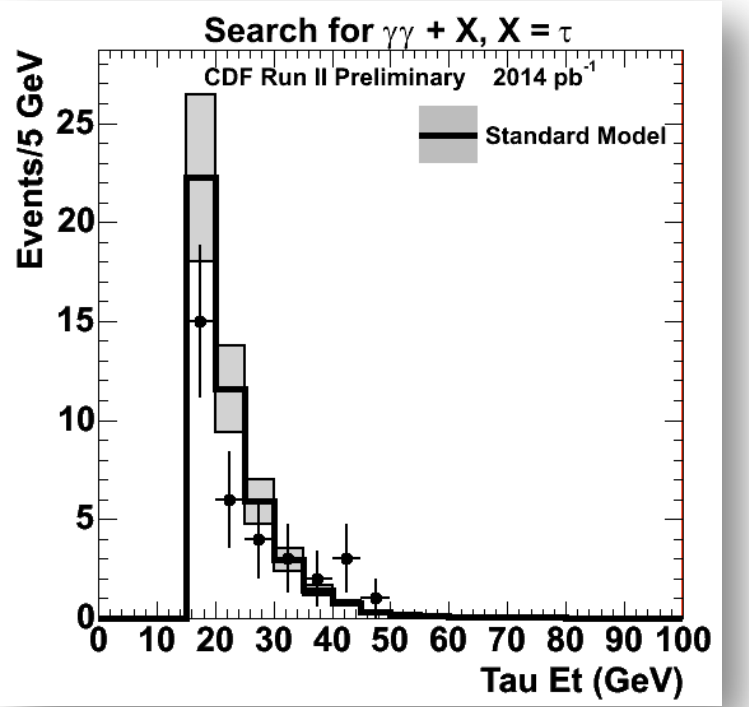
After MET-sig>3 & $\Delta\varphi_{\gamma\gamma}$<3

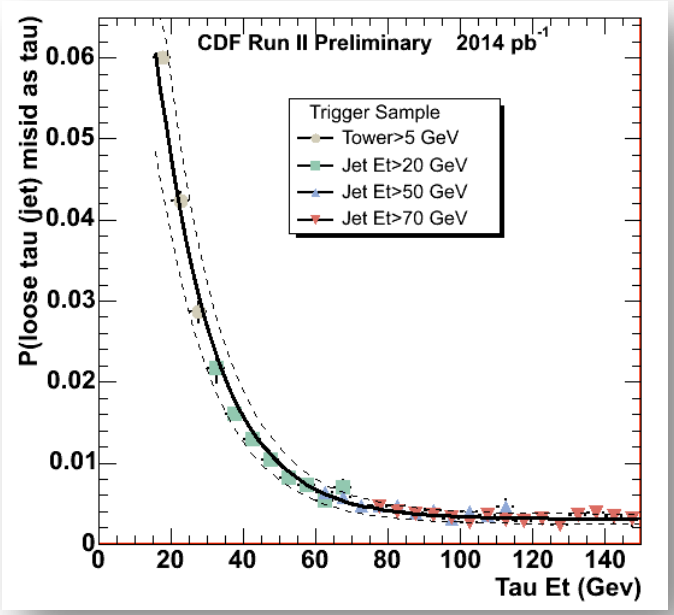


- Based on results of γγ+MET analysis
  - 3D optimization: MET-sig, H_T, $\Delta\varphi_{\gamma\gamma}$
- Gauge-Mediated SUSY Breaking
  - Snowmass Slope constraint (SPS-8)

- 95% CL limits in neutralino mass & lifetime plane
  - Neutranilo mass>138 GeV/c^2
  - Signal acceptance: 9.2%±1.7%

Search for Anomalous $\gamma\gamma+\tau$





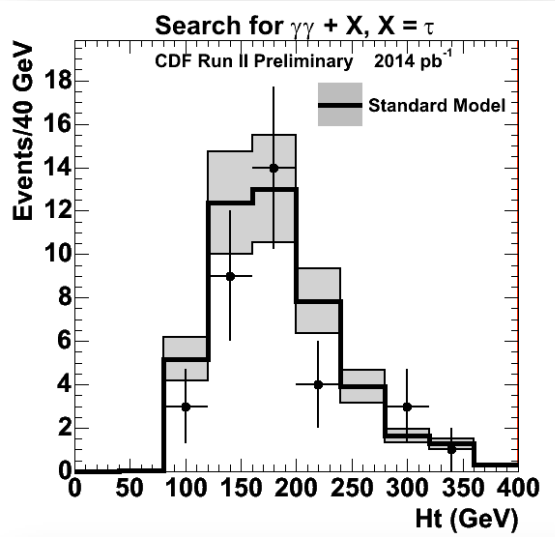
jet→τ fake rate from di-jet events

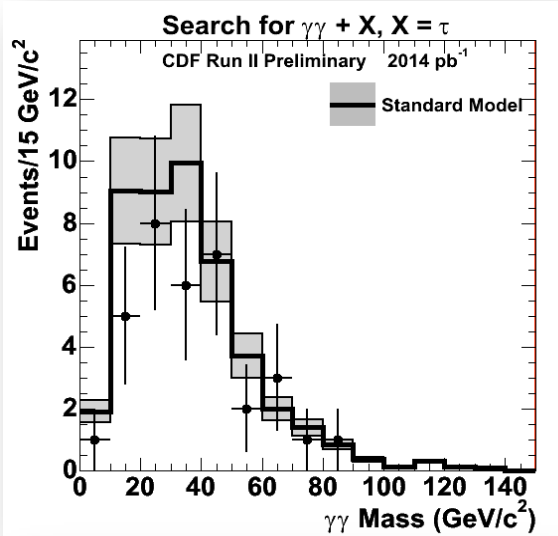
- Visible "hadronic" tau E_T>15 GeV
- Backgrounds
  - "Instrumental": $\gamma\gamma$+(jet→τ fake)
    - $\gamma\gamma$+jet × fake rate
  - "Physics": $W\gamma\gamma$ or $Z\gamma\gamma$

Data, 2 fb^{-1}	**40**
Total Bckg	**46±10**
"Instrumental"	44±10
"Physics"	2.2±1.0

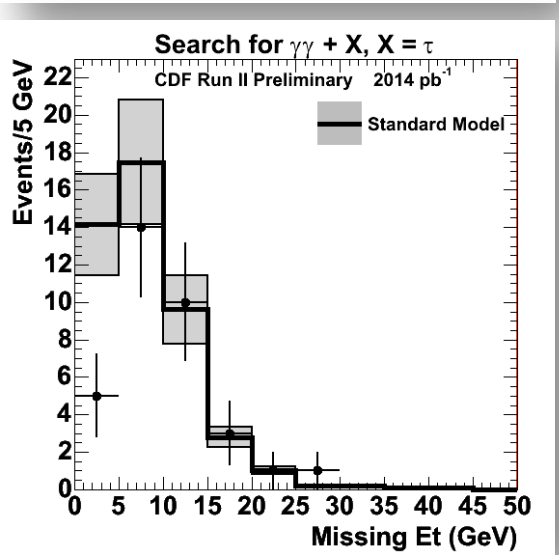
Search for Anomalous γγ+τ: Kinematics

H_T

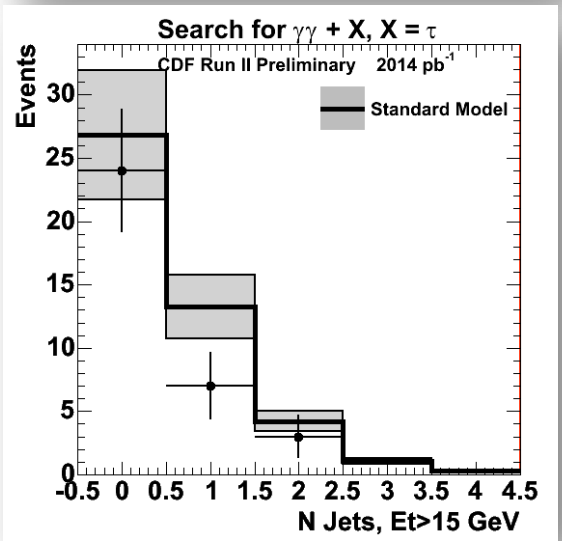




$M_{\gamma\gamma}$



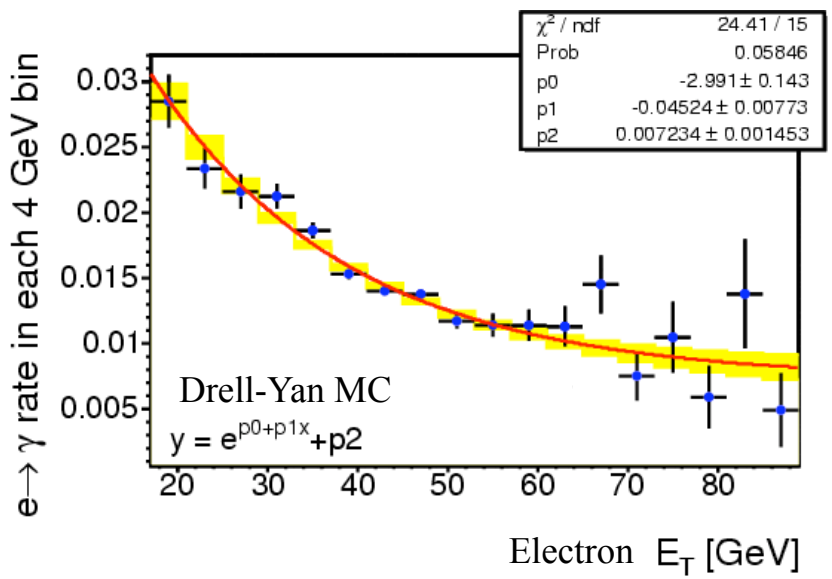
MET



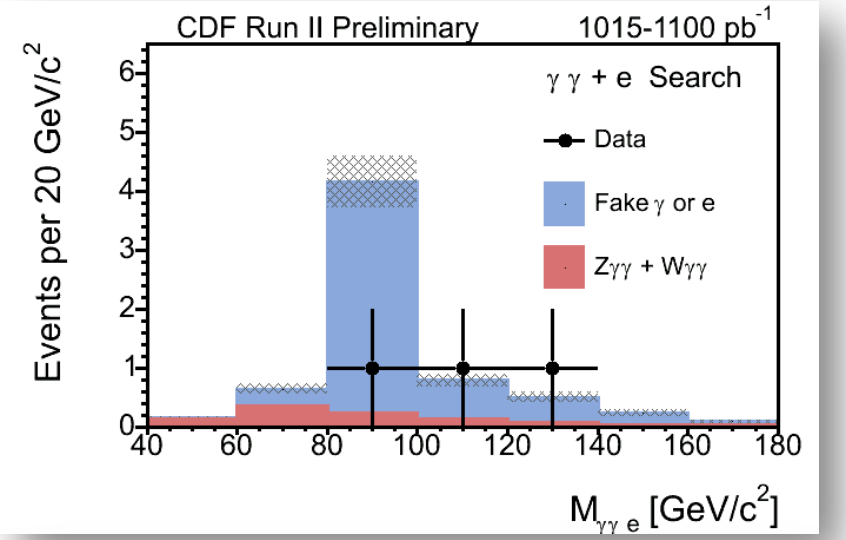
$N_{jet}(E_T>15\ GeV)$

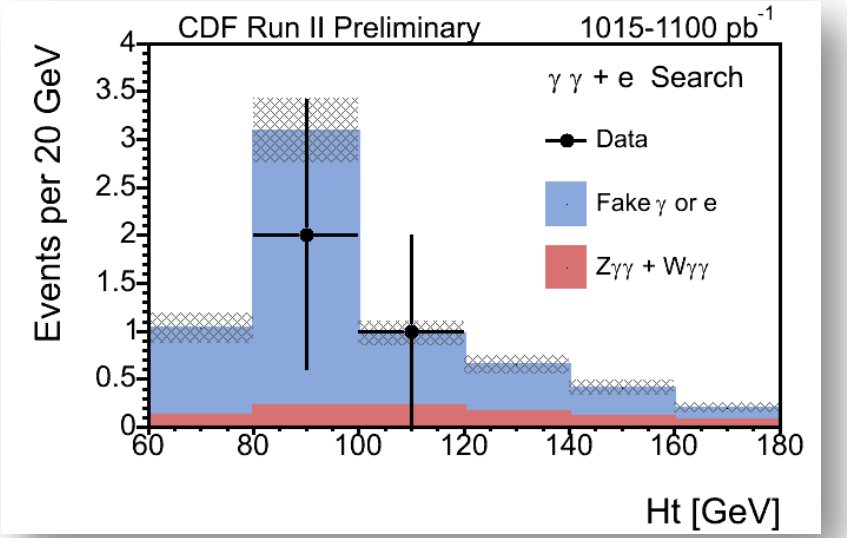
Search for Anomalous $\gamma\gamma$+e/μ in 1 fb^{-1} of Data

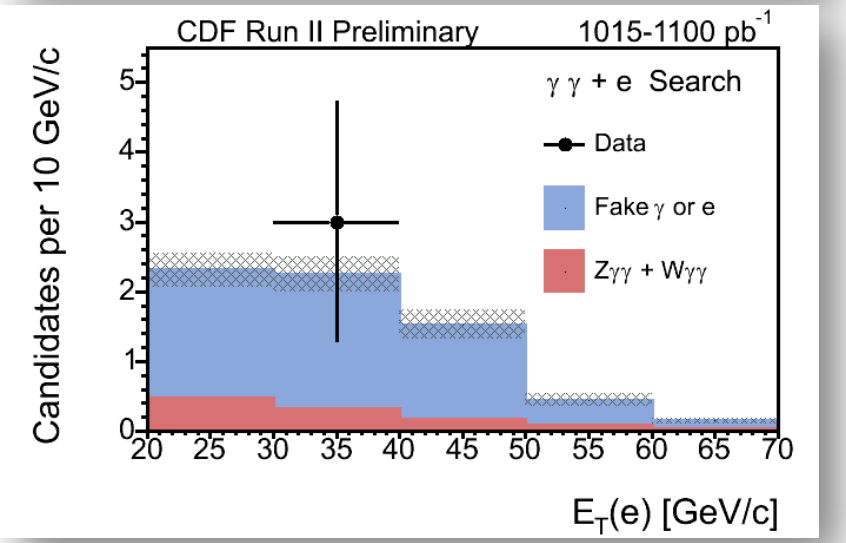
- Central or forward electron with E_T>20 GeV
- Central muon with P_T>20 GeV
- Backgrounds
  - "Physics": $W\gamma\gamma+Z\gamma\gamma$
  - "Instrumental"
    - **γ+lepton+(ele→fake γ) : dominant for $\gamma\gamma$+e**
    - $\gamma\gamma$+fake lepton
    - γ+lepton+jet→fake γ
- **Fake rate** e→γ
  - **MC for E_T and η dependences**
  - **MC-to-Data normalization from Z's (e+γ and e^+e^- events)**



Search for Anomalous γγ+e/μ: Results





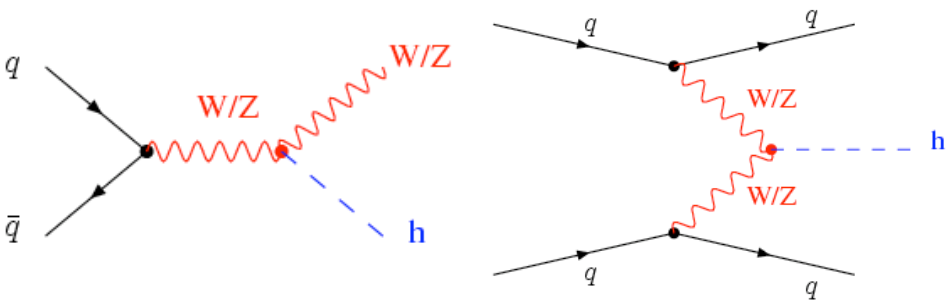


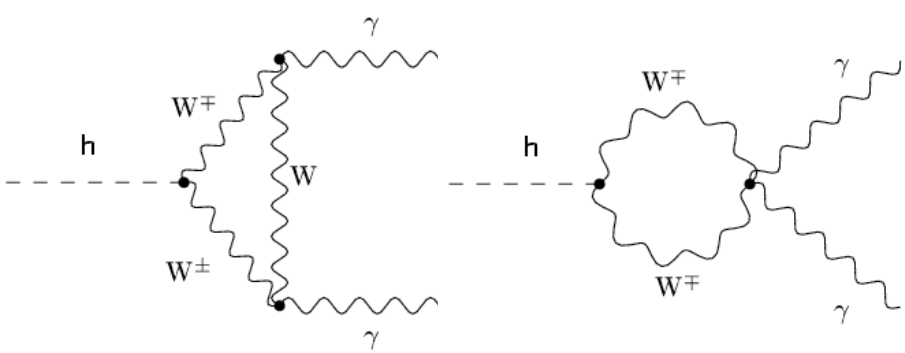
	γγ+e	γγ+μ
Data, 1 fb^{-1}	3	0
Total Bckg	6.82±0.75	0.79±0.11
"Physics"	16%	81%
γ+l+(e→γ)	75%	2%

Search for Fermiophobic Higgs in $\gamma\gamma$+X

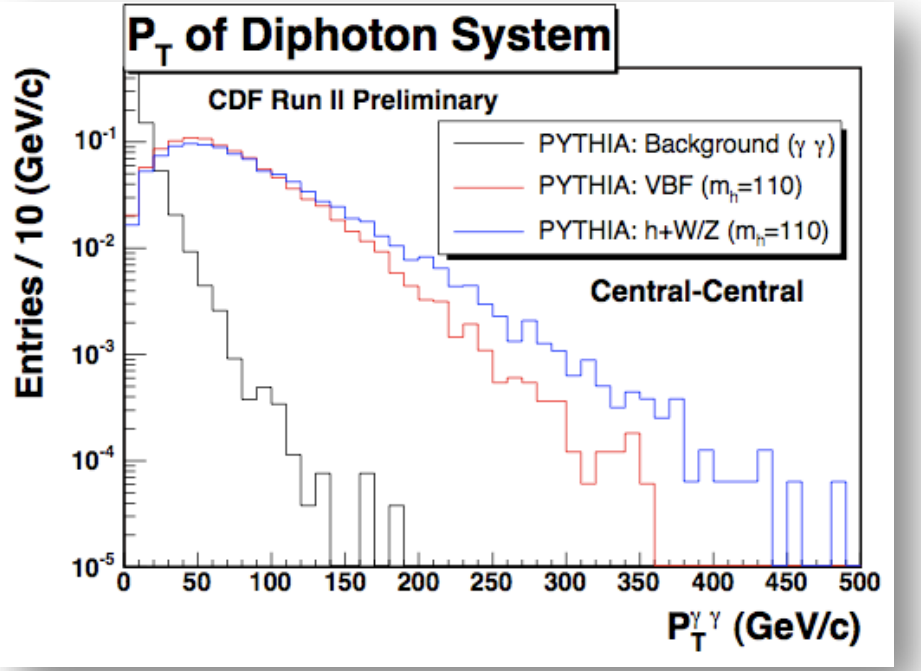
Search for Fermiophobic Higgs in $H \rightarrow \gamma\gamma + X$

- Fermiophobic Higgs
  - Top-color models
  - LED theories

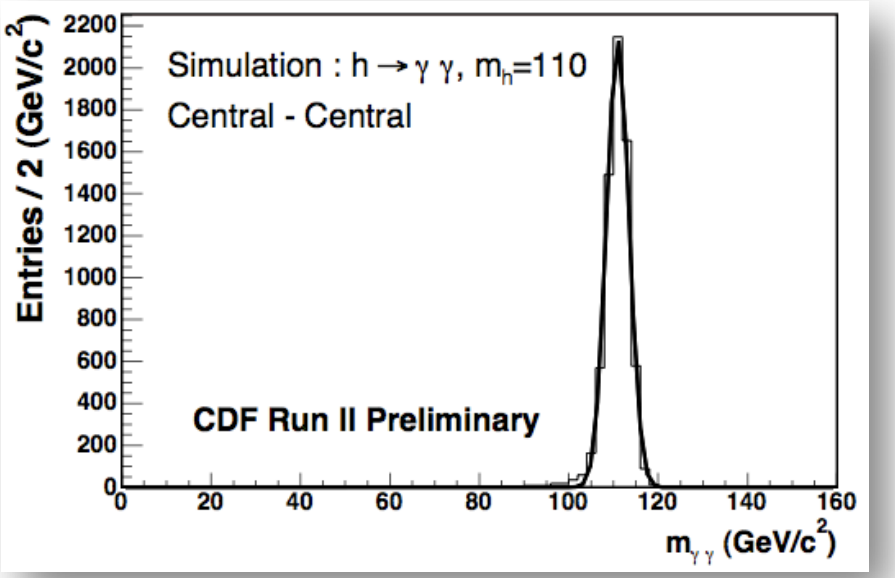


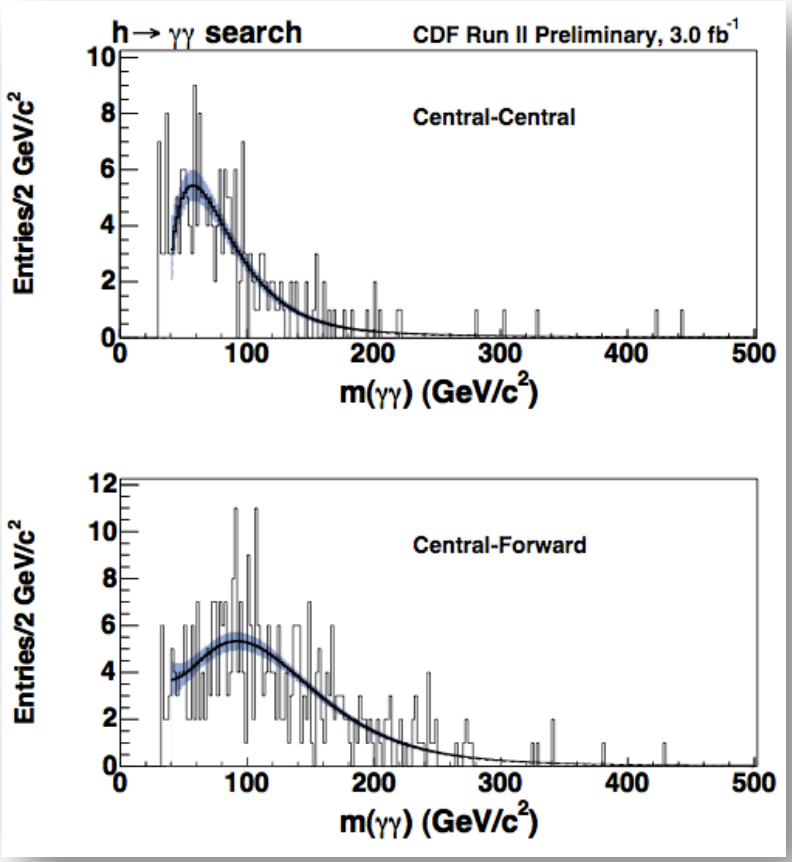


- Analysis Overview: 3 fb^{-1} of data
  - Two isolated central-central (CC) or central-forward (CF) photons
  - Photon E_T>15 GeV; $M_{\gamma\gamma}$>30 GeV
  - Optimization: $P_T(\gamma\gamma)$>75 GeV



Higgs in H→γγ+X: Di-photon Invariant Mass



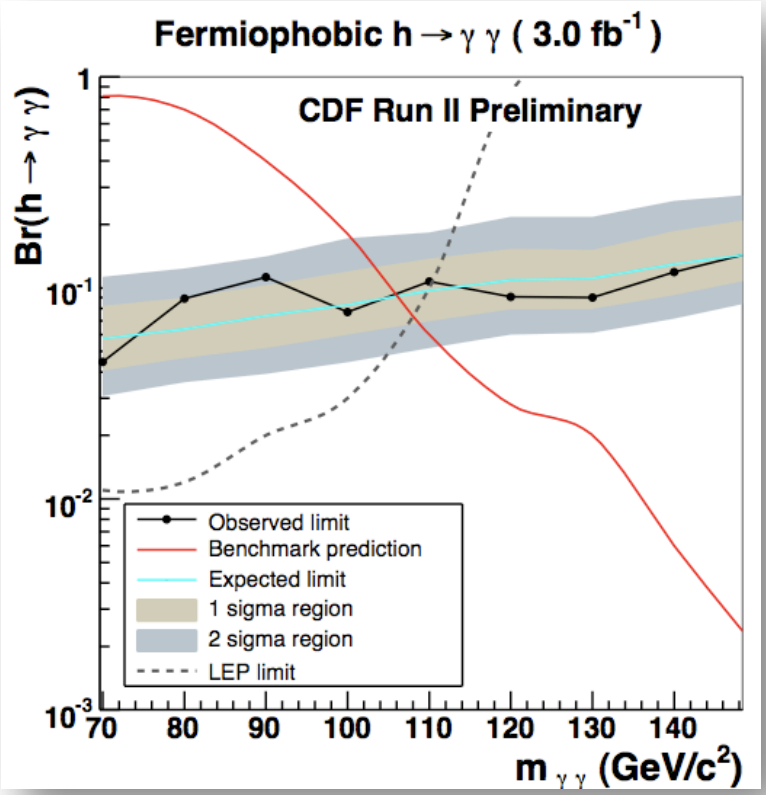


Signal signature: narrow peak

3% resolution for M_{Hf}=110 GeV/c^2

- $M_{\gamma\gamma}$ distributions in data:
  - No narrow peaks observed
  - Fit $M_{\gamma\gamma}$ with smooth function

Limits on Fermiophobic Higgs in H→γγ+X



- CDF 95% CL limit: M_{Hf}>106 GeV/c^2
  - Signal acceptance for M_{Hf}=100 GeV/c^2: ~5%(4%) for CC(CF) events
  - Dominant uncertainties: 6% lumi; 4% ISR/FSR; 4% modeling of $P_T(\gamma\gamma)$

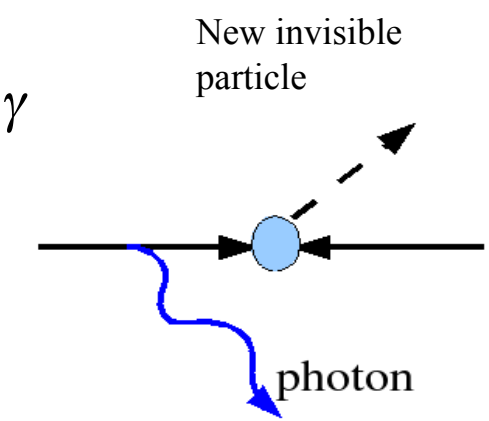
Summary of $\gamma\gamma$+X

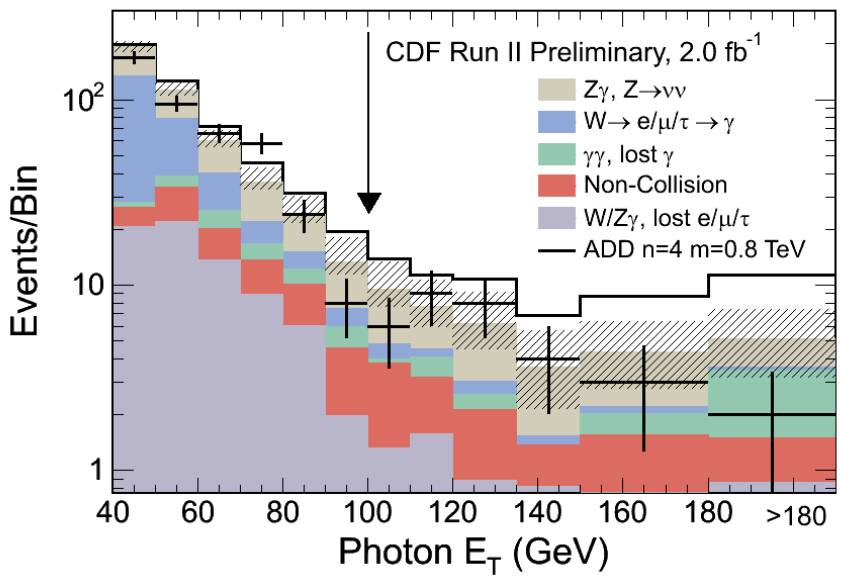
- $\gamma\gamma$+MET analysis:
  - Data agree with SM predictions
  - Met Resolution Model is effective tool for rejecting fake MET events
  - Best limits on GMSB for short lived lightest neutralinos: M_{χ}>138 GeV
- $\gamma\gamma+\tau$ & $\gamma\gamma+e/\mu$ analysis:
  - Data agree with SM predictions
- Fermiophobic Higgs
  - 95% CL limit: M_{Hf}>106 GeV/c^2
- No anomalies are observed with up to 3 fb^{-1} of data
  - No new $\gamma\gamma$+ee+MET type events

Search for Anomalous Production of Exclusive γ+MET

Exclusive γ+MET

- Models with exclusive γ+MET signature
  - Large Extra Dimensions (ADD): $q + \bar{q} \rightarrow G + \gamma$
  - Anomalous Zγ coupling
  - Heavy right-handed neutrinos

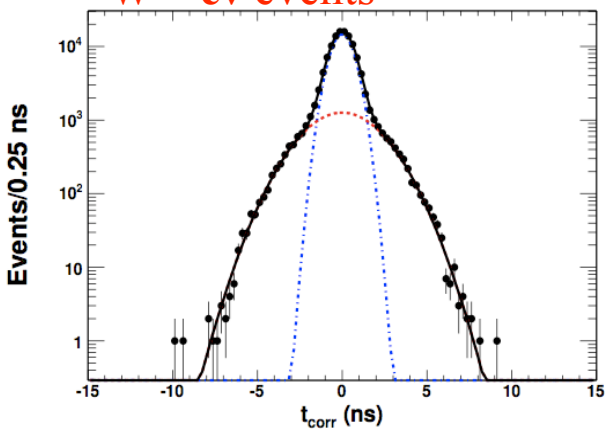




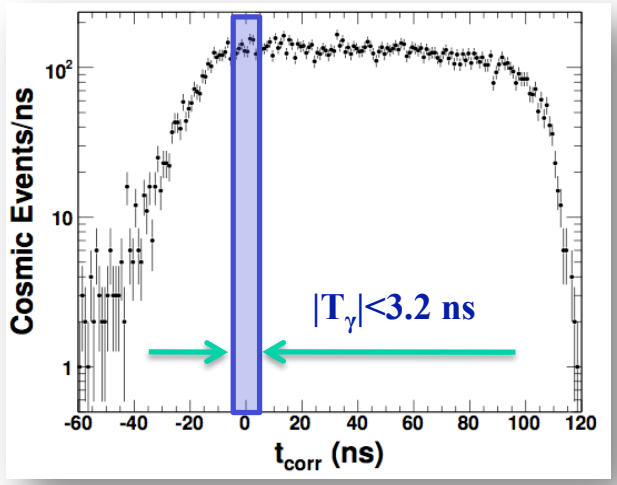
- Analysis in 2 fb^{-1}
  - $E_T(\gamma)$>50 GeV; MET>50 GeV;
  - Veto jet E_T>15 GeV
  - Veto track P_T>10 GeV
  - Require at least 3 tracks
  - Optimize for LED: $E_T(\gamma)$>90 GeV

Exclusive γ+MET: Removing Non-Collision

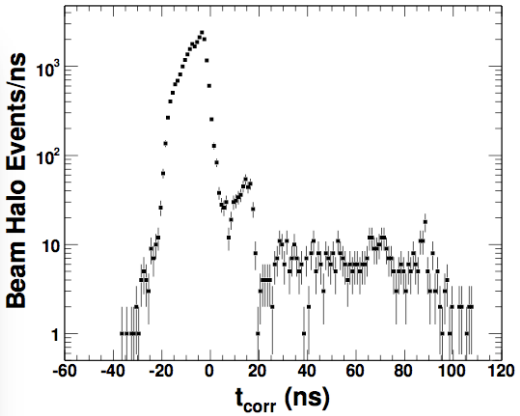
W→eν events



Cosmic events



Beam Halo



EM timing resolution:

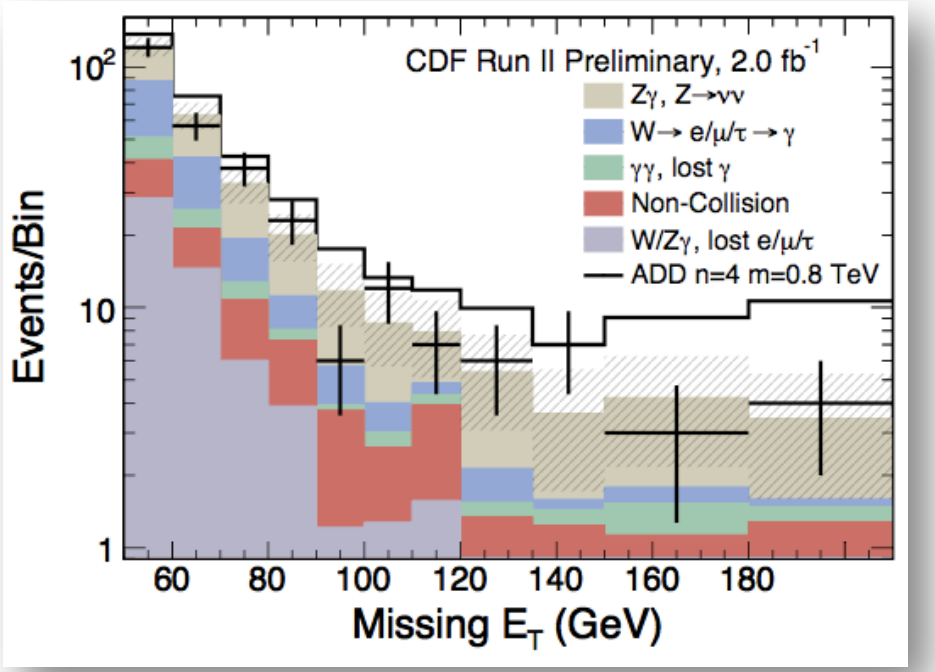
True vertex: σ~0.7 ns

Wrong vertex: σ~1.9 ns

- New EM-timing system (installed in 2004) is critical for effective non-collision background rejection !!
  - $|T_\gamma|<3.2$ ns; track requirements
  - Multivariate discriminator: train on γ+jet and out-of-time cosmic events
  - Cosmic rejection: x600

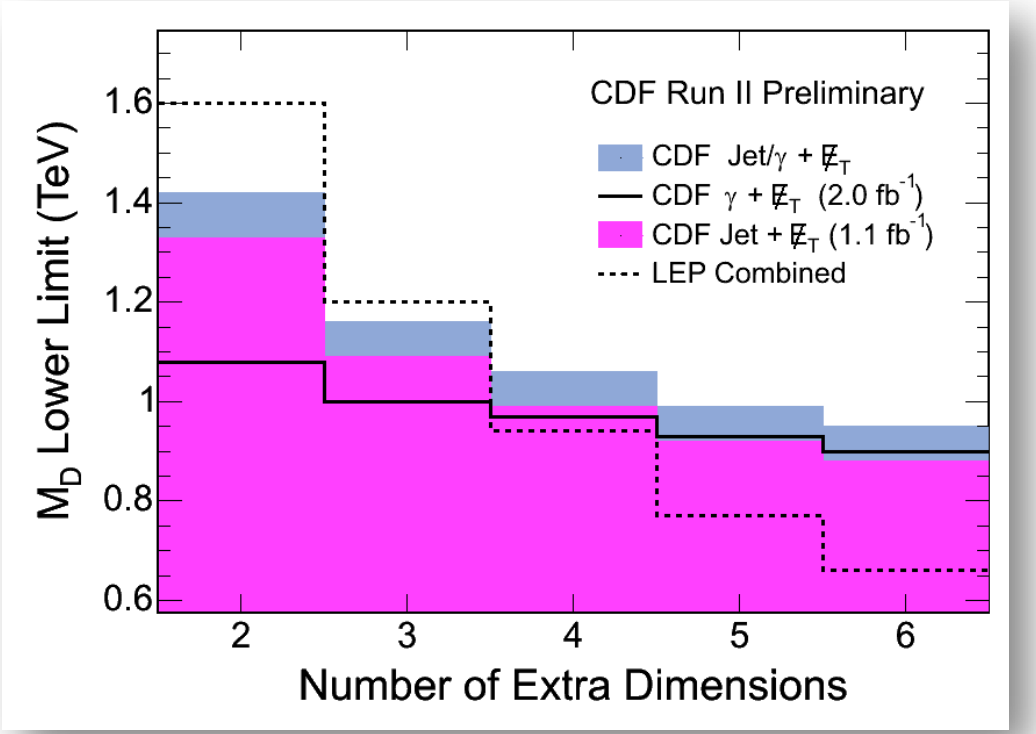
Exclusive γ+MET: Results

	E_T^{γ}>50 GeV	E_T^{γ}>90 GeV
Data	**280**	**40**
Total Bckg	**280.5±15.7**	**46.3±3.0**
$Z\gamma \rightarrow \nu\nu\gamma$	35.6%	54%
$W(e/\tau \rightarrow \gamma)$	24.7%	7.7%
$W\gamma$ (lost e/μ)	21%	11%
cosmics	13%	21%
$\gamma\gamma \rightarrow \gamma$ (lost γ)	6.6%	4.9%



- Estimation of EWK backgrounds
  - "Physics": $Z\gamma \rightarrow \nu\nu\gamma$; $W\gamma$ (lost e/μ); $\gamma\gamma \rightarrow \gamma$ (lost γ)
    - $W\gamma$ & $\gamma\gamma$ backgrounds normalized to data
  - "Instrumental": $W(e/\tau \rightarrow \gamma)$: $e \rightarrow \gamma$ fake rate

Exclusive γ+MET: Limits on LED



- Combined with exclusive jet+MET analysis to set limits on LED:
  - Published in PRL 101, 181602 (2008)
  - Signal acceptance for γ+MET analysis: ~7.3%
  - Leading systematics for γ+MET analysis: 5.7% from signal acceptance

Search for Anomalous Production of γ+b+j+MET

γ+jet+b+MET: Analysis Overview

- Gauge-Mediated SUSY models
  - Renewed interest motivated by Run I ee+γγ+MET event

$$\tilde{\chi}_1^+\tilde{\chi}_2^0 \rightarrow \left(\gamma\tilde{\chi}_1^0\right)\left(\tilde{t}\bar{b}\right) \rightarrow \left(\gamma\tilde{\chi}_1^0\right)\left(\bar{b}c\tilde{\chi}_1^0\right) \rightarrow \left(\gamma\bar{b}c\not{E}_T\right)$$

- Technicolor models, but without MET
- SM processes (e.g., ttγ) with true γ+j+b+MET signature are highly suppressed

- Event selection in 2 fb^{-1}
  - Central photon E_T>25 GeV
  - 2 jets: E_T>15 GeV & |η|<2
  - MET>25 GeV
  - Δφ(jet,MET)>0.3
  - At least 1 b-tag (SecVtx)

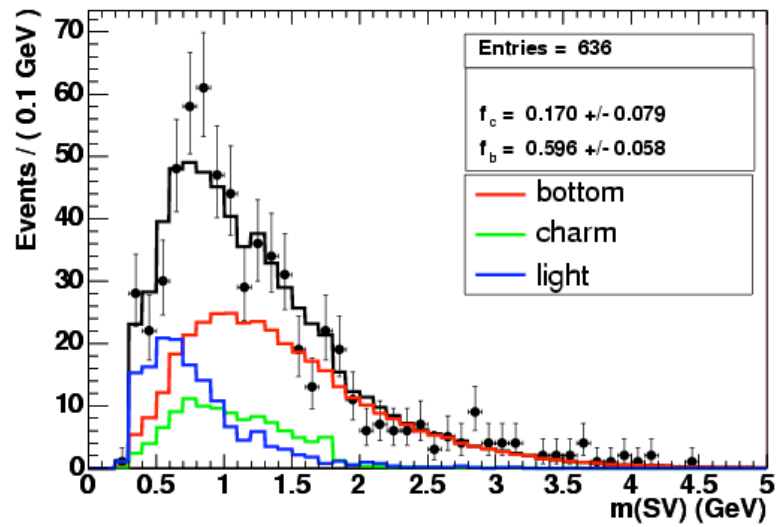
Background categories

	Real γ	Fake γ
Real b-tag	A	B
Fake b-tag	C	D

γ+jet+b+MET: Backgrounds

Background A:

- MadGraph MC: γ+b+jets, γ+c+jets
- Normalized based on photon purity & heavy flavor (c,b-quarks) fractions



	Real γ	Fake γ
Real b-tag	A	B
Fake b-tag	C	D

Background C:

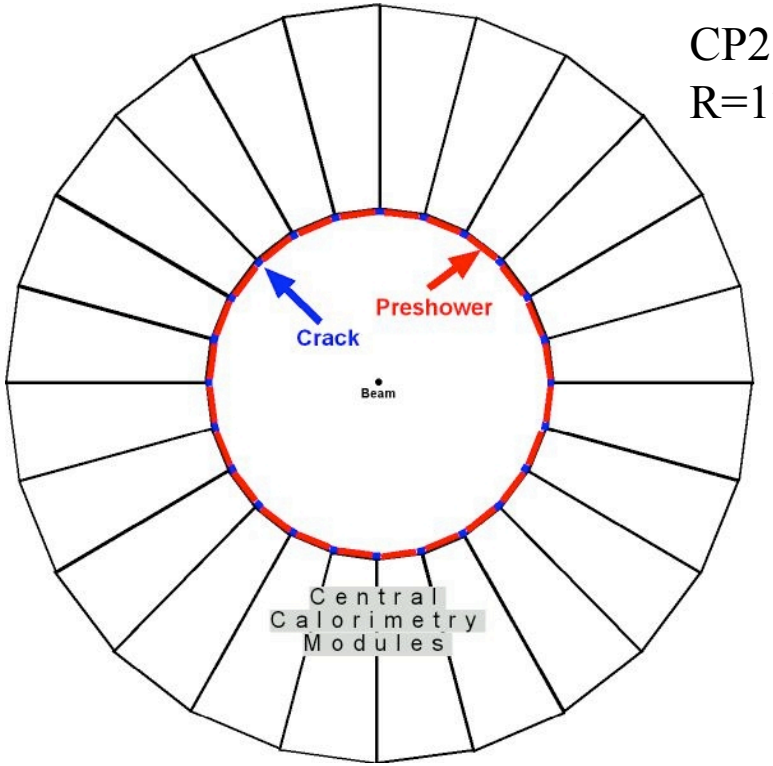
- γ+jet+jet × mis-tag rate
- Subtract fake photon contribution

Backgrounds B & D:

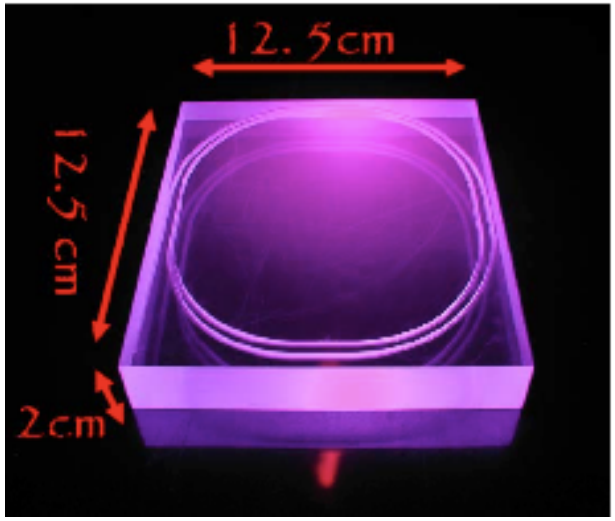
- Fake photon subtraction
- Photon purity: 81%±12%

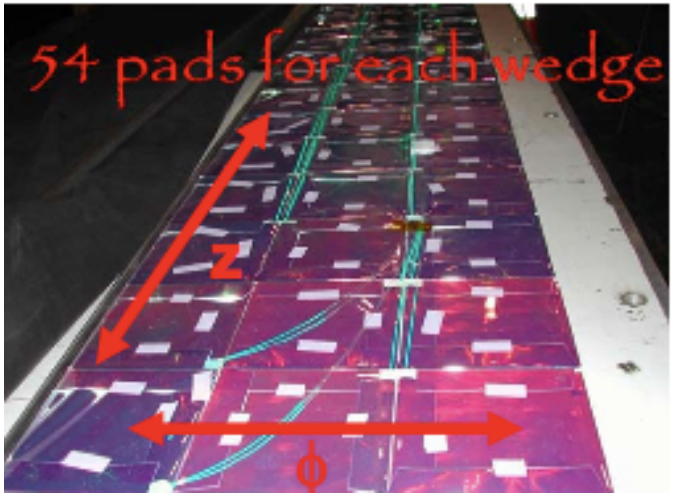
CP2 (Preshower) Detector

- CP2 upgraded old CPR-detector in 2004
  - Scintillator pads efficiently detect MIPs
    - Used to count photon conversions
  - Design optimized for higher luminosity

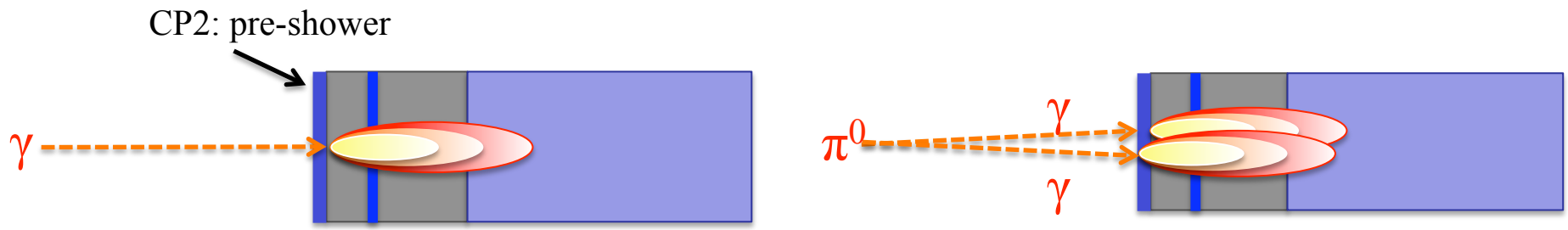


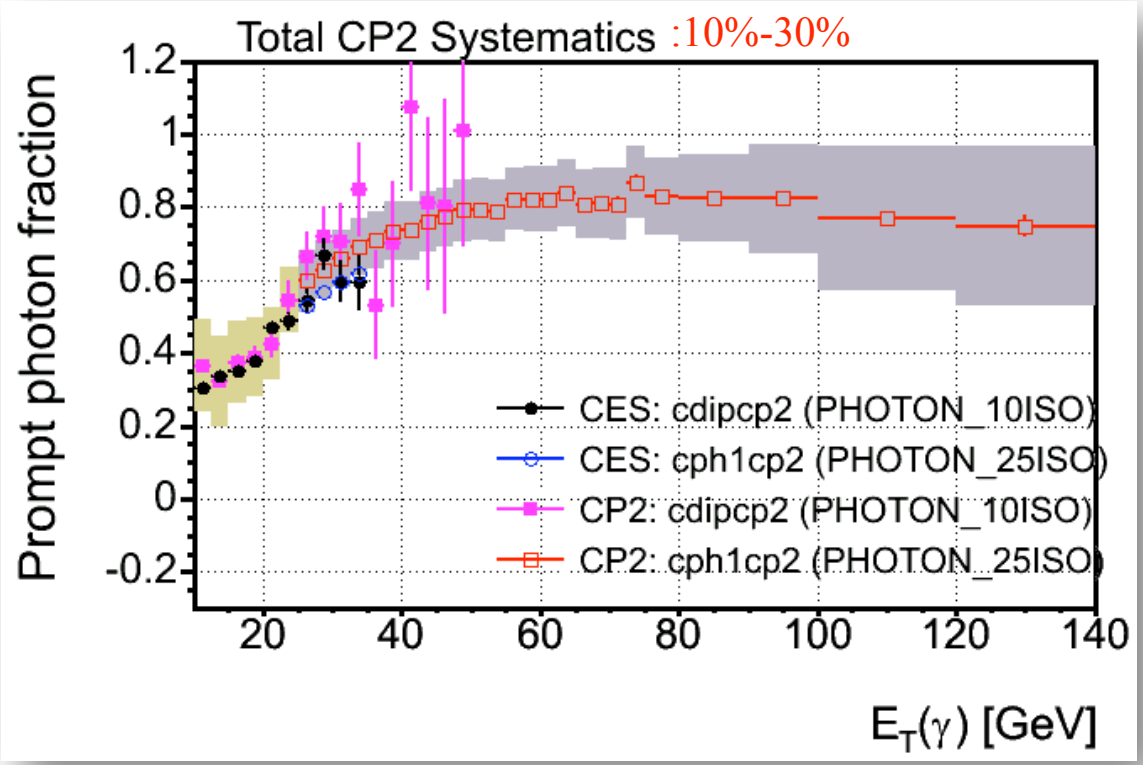
CP2 location:
R=170.47 cm





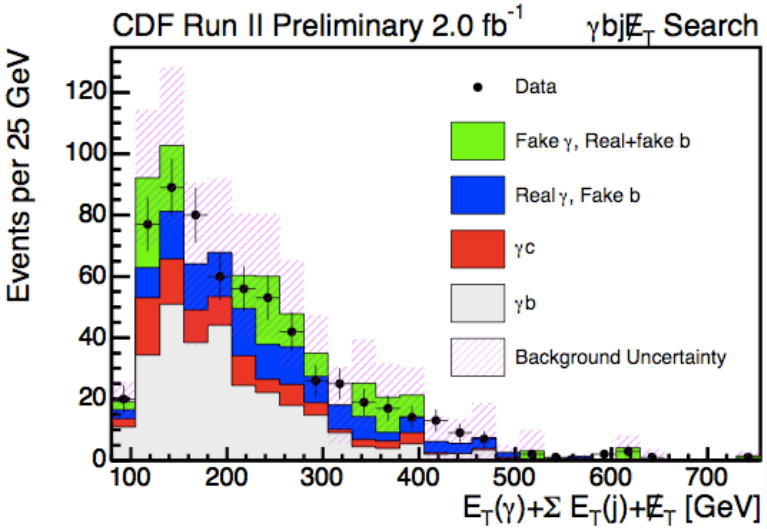
Photon Purity

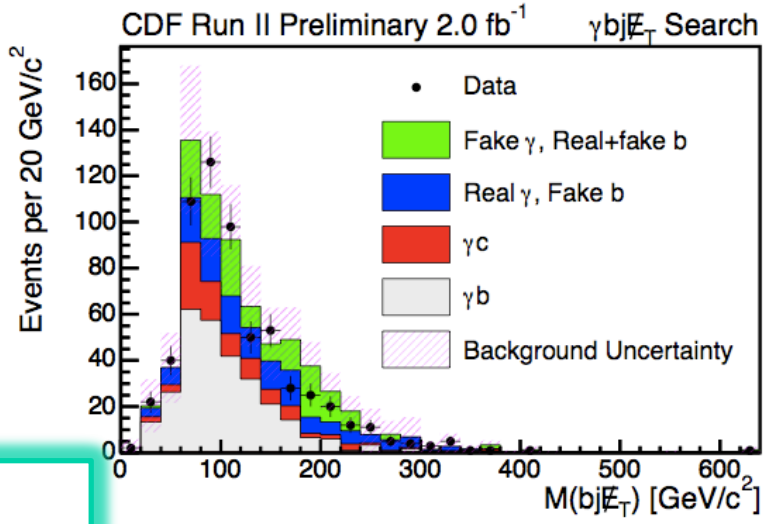




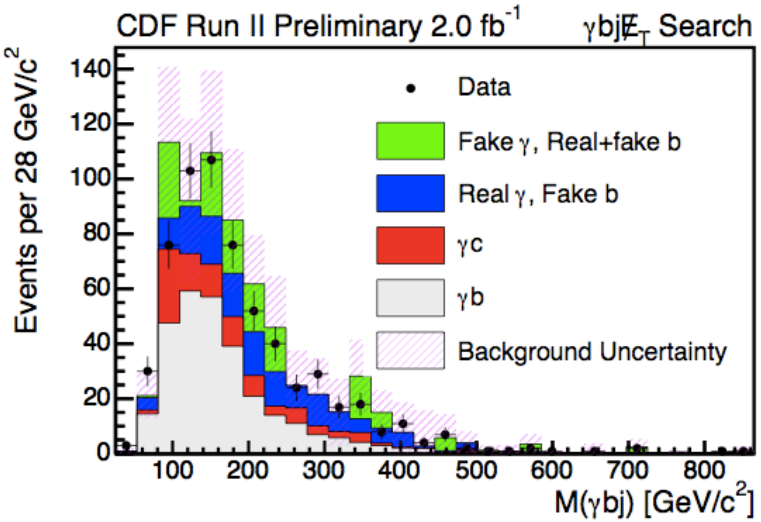
- Two photons have higher conversion probability than one photon
  - Signal: $\varepsilon_{sig} \sim 65\%$;
  - Background: $\varepsilon_{bckg} \sim 85\%$

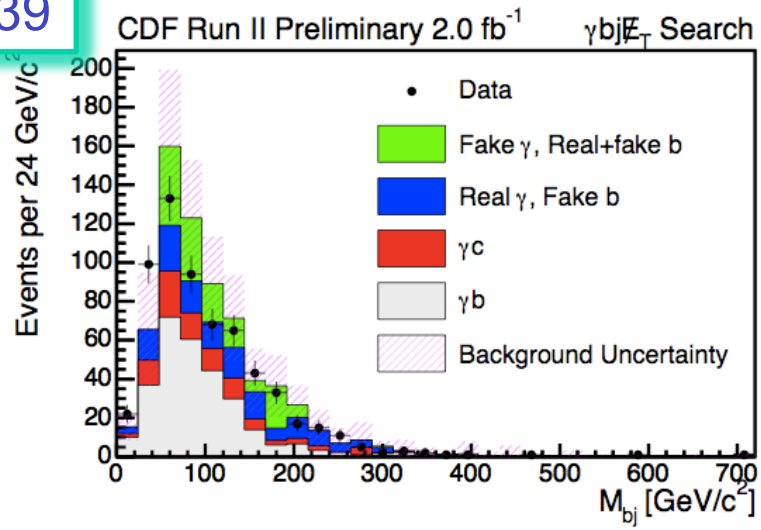
γ+jet+b+MET: Kinematic Distributions





Data: 617
Bckg: 637±139





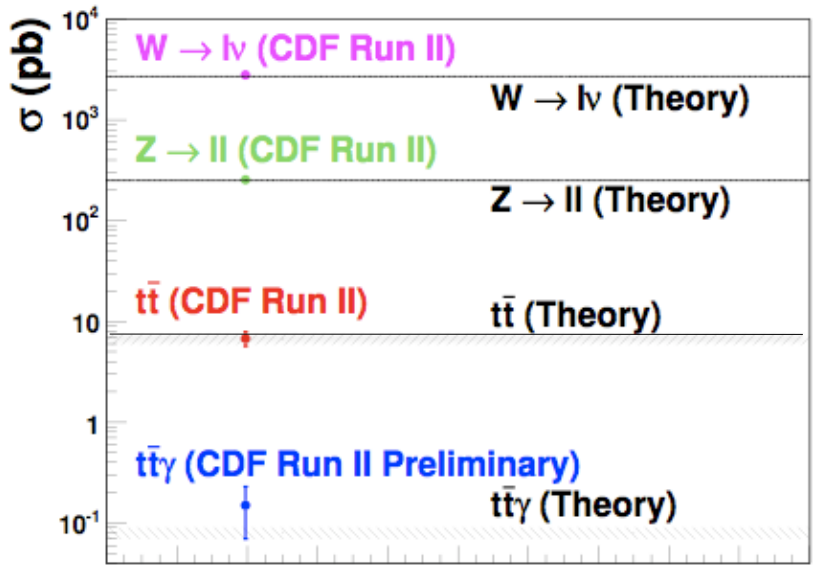
Search for Anomalous Production of γ+l+b+MET And SM tt+γ

γ+l+b+MET+X: Analysis Overview

- Why is it interesting?
  - Extension of γ+l+MET+X search: PRD 75, 112001 (2007)
  - Signature with b- & t-quarks, and two gauge bosons: γ & W
  - ttγ: control sample for ttH (at LHC)

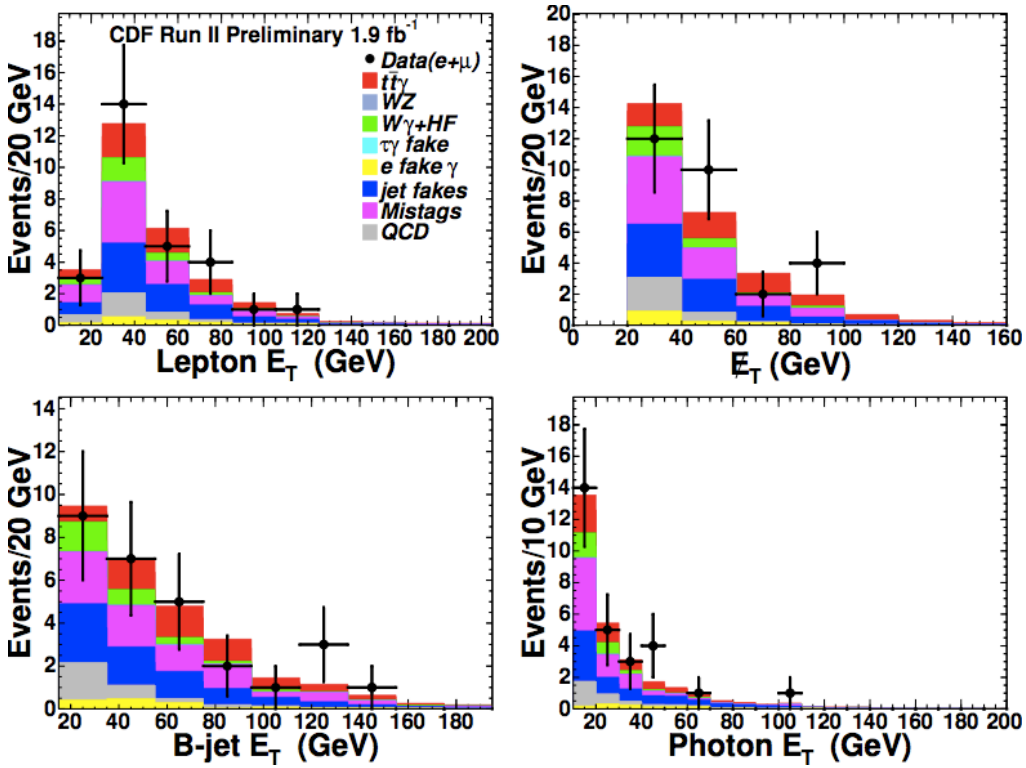
Event Selection for 1.9 fb^{-1}

- γ+l+b+MET
  - Central photon: $E_T(\gamma)$>10 GeV
  - Central lepton (l=e,μ): $E_T(l)$>20 GeV
  - b-tagged jet: $E_T(jet)$>15 GeV
  - MET>20 GeV
- ttγ: γ+l+b+MET+H_T+3j
  - H_T>200 GeV
  - At least 3 more jets $E_T(jet)$>15 GeV



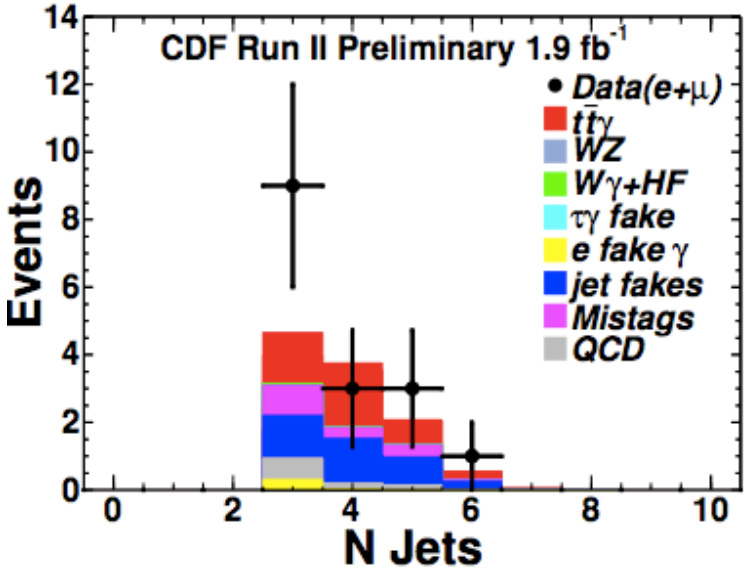
γ+l+b+MET: Results

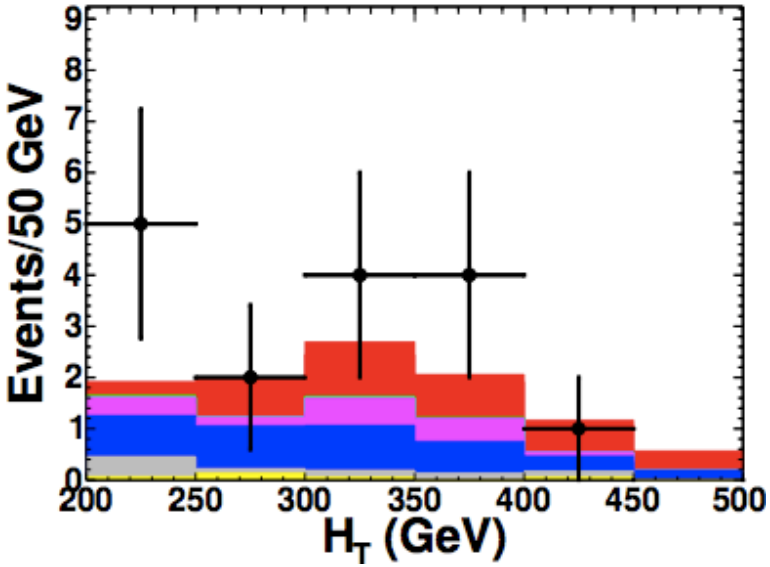
	e+γ+b+MET	μ+γ+b+MET	(e+μ)+γ+b+MET
Total bckg	16.8±2.2	11.1±1.7	27.9±1.7
Data	16	12	28



	(e+μ)+γ+b+MET
tt+γ	21%
"Physics"	11%
"Instrumental"	68%

tt+γ: Results

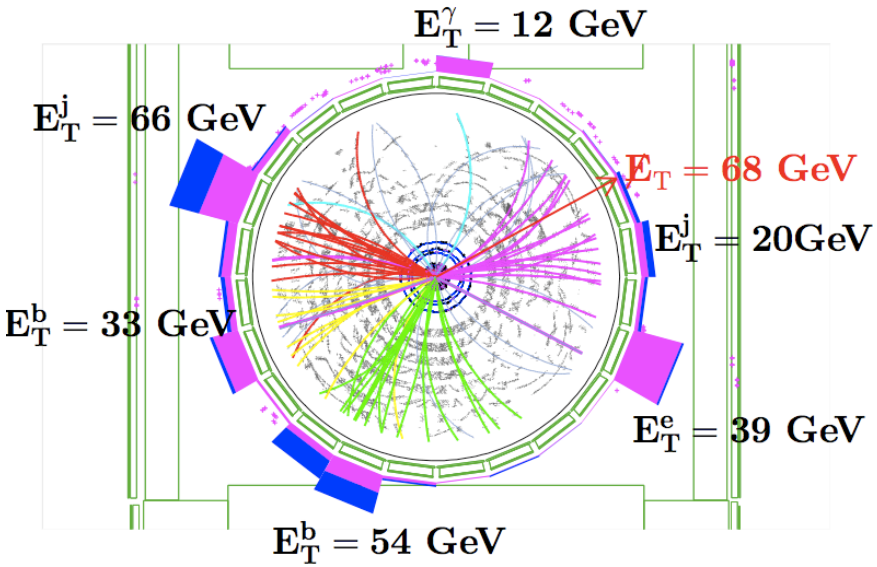




CDF Run II Preliminary, 1.9fb^{-1}			
$t\bar{t}\gamma$	$t\bar{t}\gamma(e)$	$t\bar{t}\gamma(\mu)$	$t\bar{t}\gamma(e+\mu)$
Predicted	$6.7 \pm 1.4(tot)$	$4.4^{+1.3}_{-0.8}(tot)$	$11.1^{+2.3}_{-2.1}(tot)$
Observed	8	8	16

- SM tt+γ: σ=0.080±0.011 pb
- Measured tt+γ: σ=0.15±0.08 pb
- If no SM tt+γ:
  - 1% (2.3σ) to observe 16 events

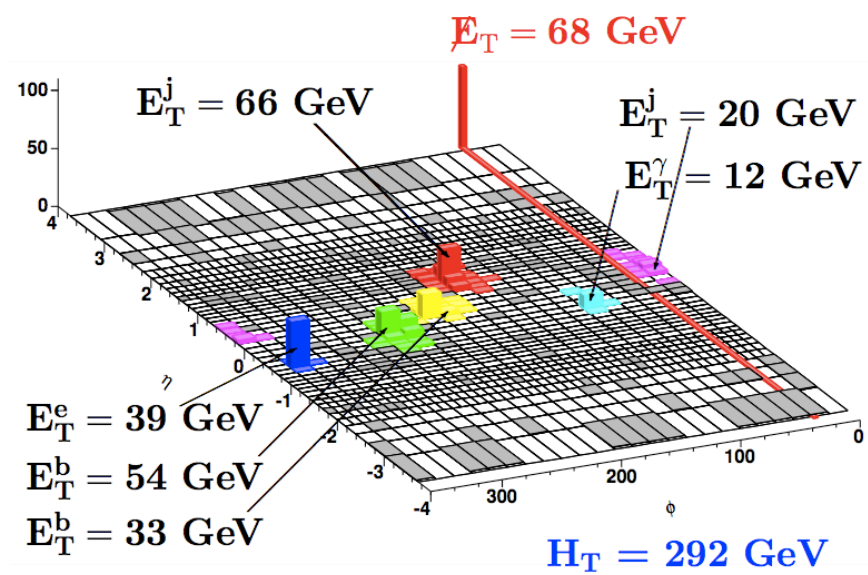
tt+γ Candidate



Run 193396 Event 1050006, $H_T = 292$GeV

R-φ view

"Lego" η-φ view



Run 193396 Event 1050006

Summary of Photon Searches at CDF

Compositeness
$ll+\gamma$, $ll+\gamma\gamma$, $jj+\gamma$,
$bb+\gamma$, $jj+\gamma\gamma$, $bb+\gamma\gamma$

4th generation
$\gamma\gamma+bb$, $ll+\gamma+bb$,
$jj+\gamma\gamma+bb$

Technicolor
$\gamma+bb$, $\gamma+jj$, $\gamma+tt$, $\gamma\gamma\gamma$,
$ll+\gamma\gamma$, $ll+\gamma\gamma+ME_T$

- **Five analyses probed many models**
  - $\gamma\gamma+X$ (X=MET, l)
  - fermiophobic Higgs
  - Exclusive γ+MET
  - $\gamma+b+j+MET+X$
  - $\gamma+b+l+MET+X$
- **No anomalies are observed with up to 3 fb^{-1} of data**

SUSY
$\gamma\gamma+ME_T$, $\gamma\gamma+ll+ME_T$, $\gamma\gamma+j+ME_T$,
$l+\gamma+ME_T$, $\gamma+b+ME_T$, $\gamma+bj+ME_T$
$\gamma+bc+ME_T$, $\gamma+jj+ME_T$, $\gamma+ll+ME_T$,
displaced $\gamma+X$, $\gamma+ME_T$, $jj+\gamma+ME_T$

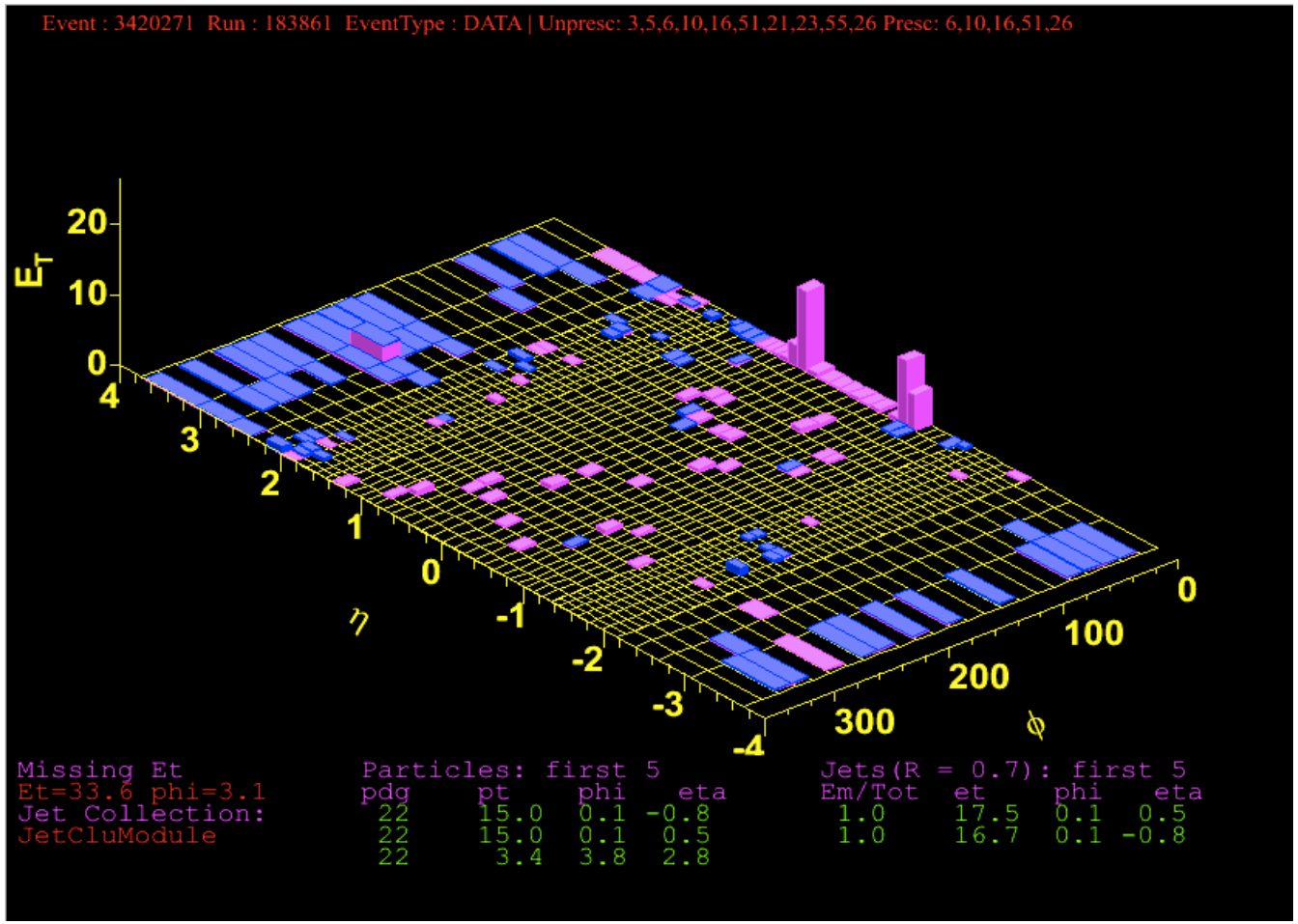
Higgs
$\gamma\gamma$, $ll+\gamma$, $l+\gamma\gamma+ME_T$,
$\gamma\gamma+ME_T$, $jj+\gamma\gamma$, $\gamma\gamma+\gamma\gamma$

Extra Dimensions
$\gamma\gamma$, γME_T
$\gamma\gamma+n*l+ME_T$

Conclusion

- CDF has very rich program of searches for new physics in final states with photons
  - Many signatures and models are investigated
  - New techniques developed and applied
  - Unfortunately, no signs of new physics… just yet
- Physics with photons is both fun and challenging
  - LHC experiments should be prepared for surprises
- More interesting times are still ahead !!

First LHC "Discovery" in γγ+MET



Typical Beam Halo event mimicking γγ+MET signature