Physics with Photons at CDF

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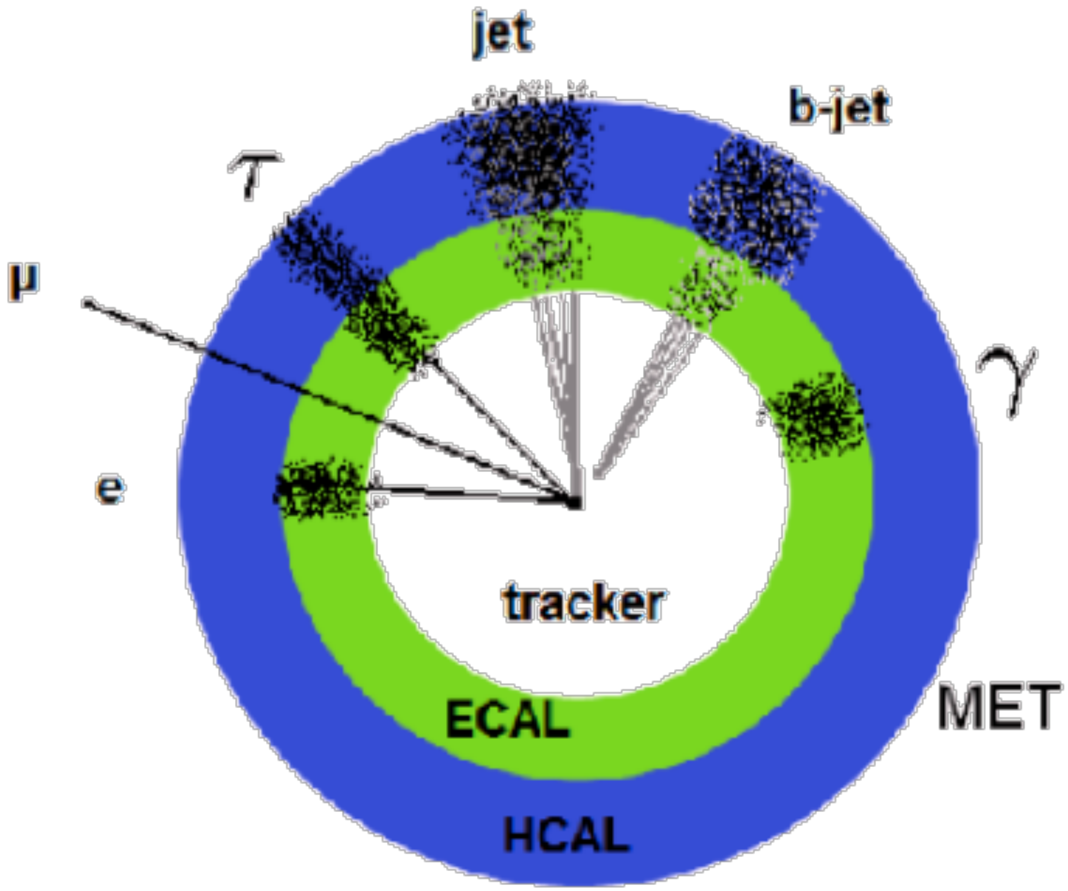
"Noble Sevenfold Path" Of High P_T Physics

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"*



① Photon is one of seven objects at colliders

② QCD > QED > EWK

- photons second most frequent objects after jets

"New" Physics with Photons

There is no deficit of models or signatures!!

- **SUSY**

$\chi^0_1 \to \gamma G$	$\gamma\gamma+ME_T$, displaced γ+X, $\gamma\gamma$+j+ME_T, l+γ+ME_T, γ+b+ME_T, γ+bj+ME_T,
$\chi^0_2 \to \gamma\chi^0_1$	γ+bc+ME_T, γ+jj+ME_T, γ+ll+ME_T, $\gamma\gamma$+ll+ME_T, γ+ME_T, jj+γ+ME_T

- **Technicolor**

$\omega_T, \rho_{T\pi T} \to \gamma\, \pi_T$	γ+bb, γ+jj, γ+tt, $\gamma\gamma\gamma$, ll+$\gamma\gamma$, ll+$\gamma\gamma$+ME_T
$\pi_T \to \gamma\gamma$	

- **Compositeness**

$f^* \to \gamma f$	ll+γ, ll+$\gamma\gamma$, jj+γ, bb+γ, jj+$\gamma\gamma$, bb+$\gamma\gamma$

- **Extra Dimensions**

LED: $G \to \gamma\gamma$	$\gamma\gamma$, γME_T
UED (6DSM)	$\gamma\gamma$+n*l+ME_T

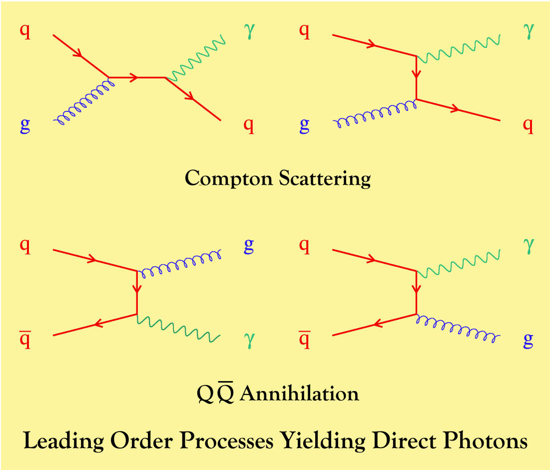
- **Higgs**

$H \to \gamma\gamma$, $A \to \gamma\gamma$	$\gamma\gamma$, , ll+γ, l+$\gamma\gamma$+ME_T, $\gamma\gamma$+ME_T, jj+$\gamma\gamma$, $\gamma\gamma$+$\gamma\gamma$

- **4th generation**

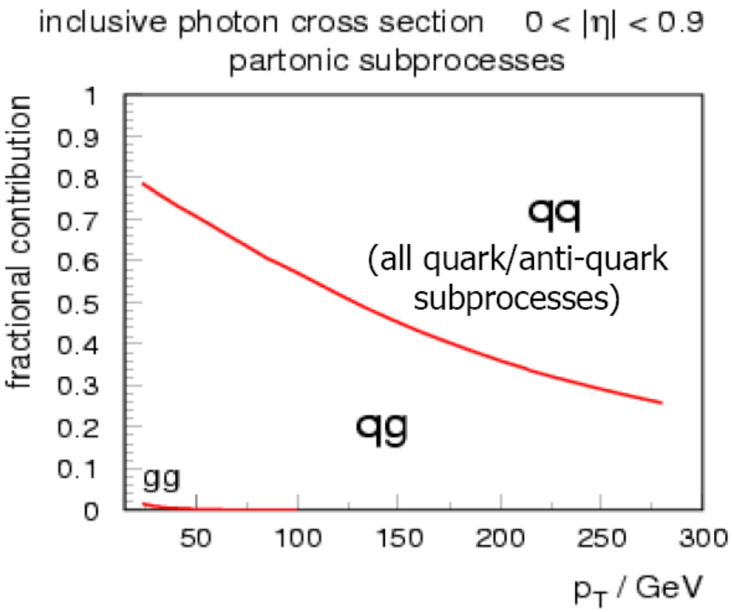
$b' \to \gamma b$	$\gamma\gamma$+bb, ll+γ+bb, jj+$\gamma\gamma$+bb

"Old" Physics with Photons

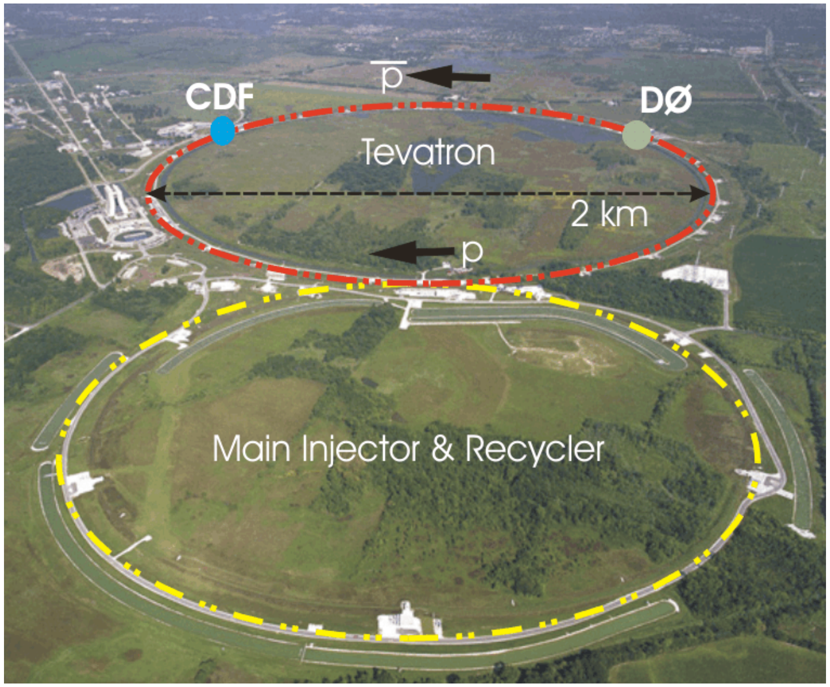


- X-section measurements
  - Inclusive photon
  - Photon+jets
  - Photon+H.F.(c/b-jet)
  - Photon+bb
  - Inclusive di-photon
  - Z/W+photon

- Prompt γ's come unaltered (by fragmentation/hadronization) from hard scattering
- Well known coupling to quarks
- Well measured (unlike jets) P_T^{γ}
- Can be used to constrain gluon PDFs
- $\sigma(\gamma)/\sigma(\text{jets}) \sim 10^{-3} \rightarrow$ challenging measurement
  - Dominant background: π^0/η from jets

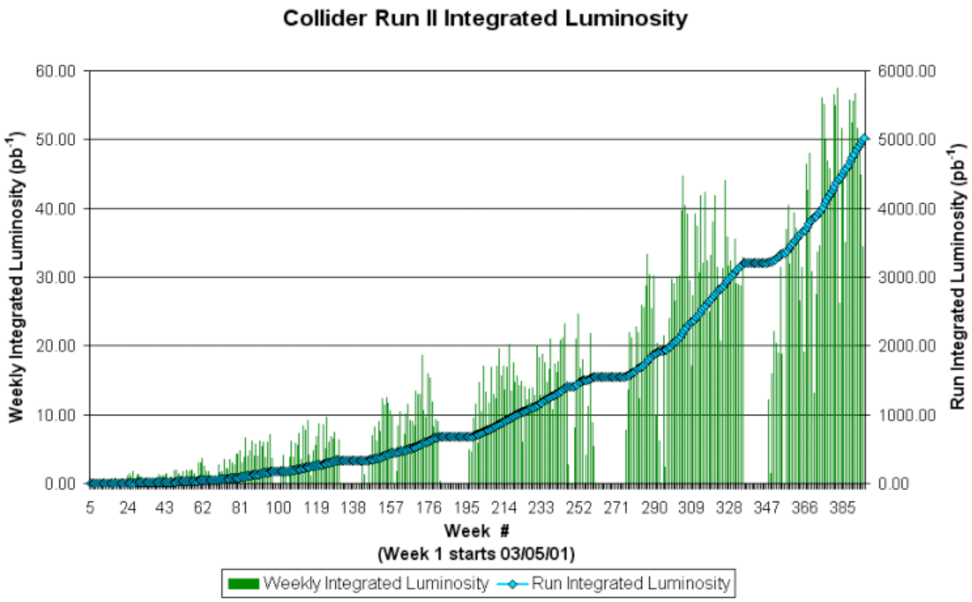


Tevatron

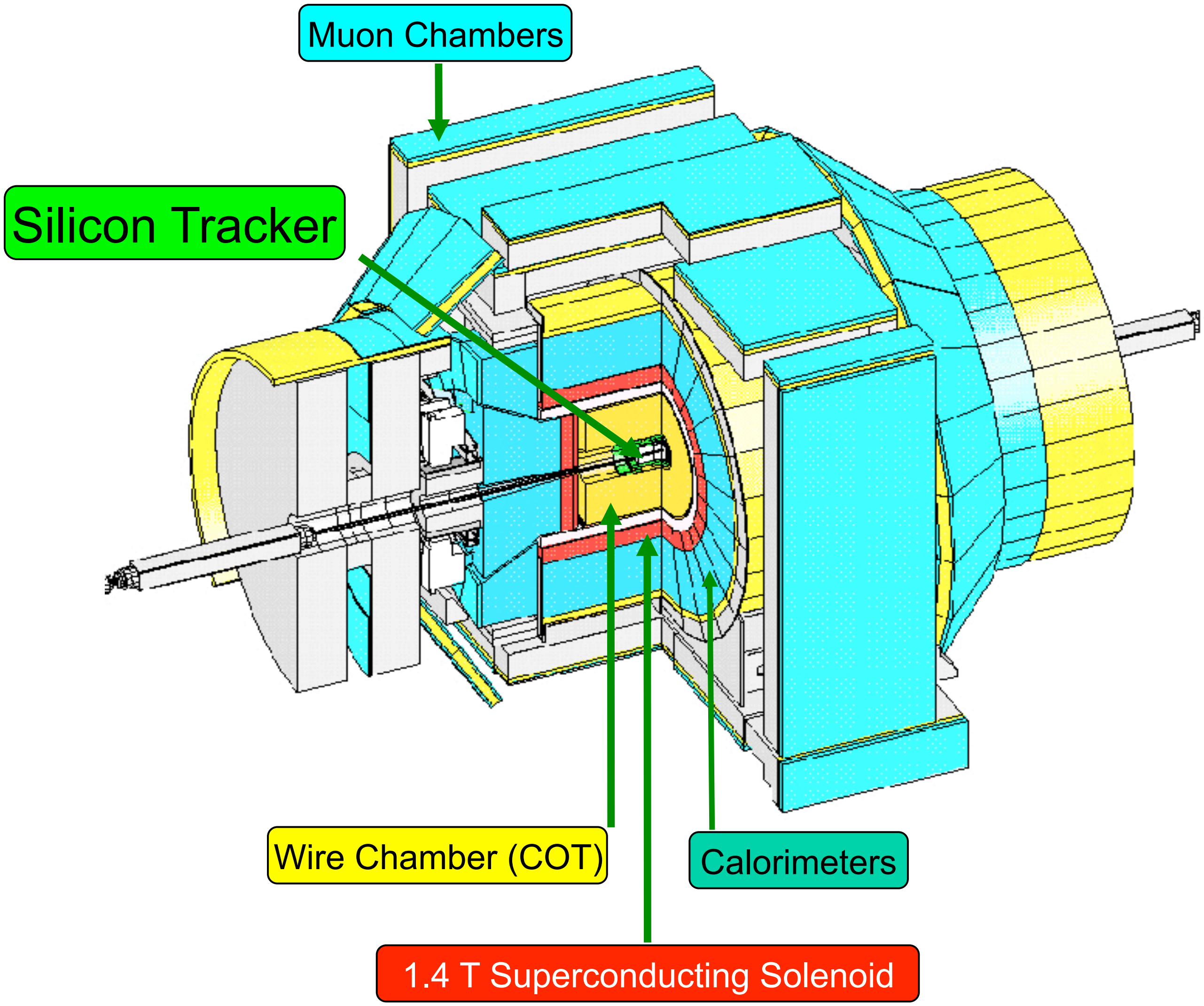


- 36×36 bunches
- Collisions every 396 ns
- Proton-antiproton collisions at $\sqrt{s}$=1.96 TeV

- Tevatron running well
  - 5 fb^{-1} per experiment
  - ~1.6 fb^{-1} in FY08
  - Current rate: ~50 pb^{-1} per week
  - Goal by 2009: 5-8 fb^{-1}
  - Running till 2010?



CDF Run II Detector



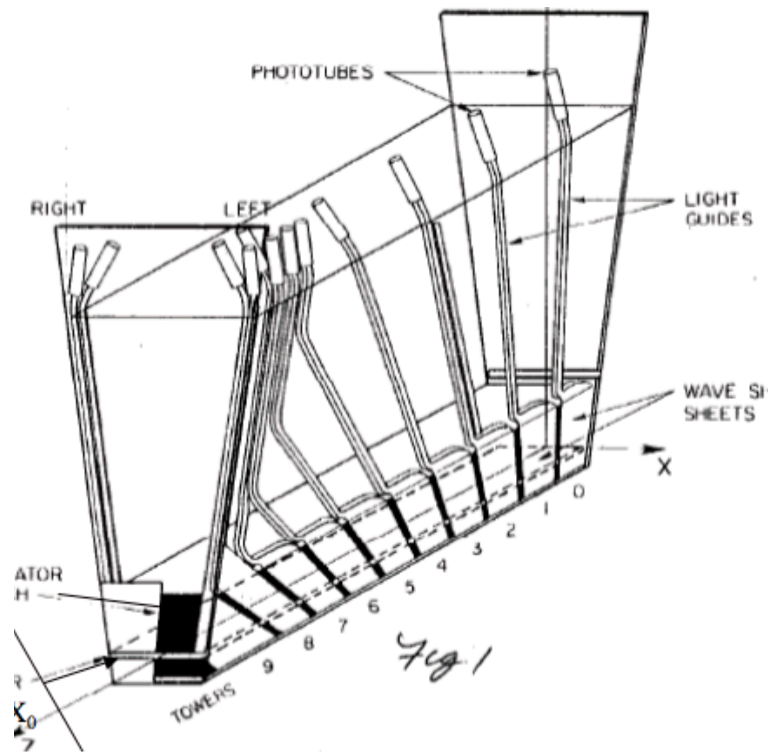
Photons in Central EM Calorimeter

Thickness	18 X_0, 1λ
Absorber	Lead
Scintillator	Polystyrene (SCSN-38)
Shower Max (CES)	R=184 cm; depth=5.9 X_0
Energy resolution	13.5%/$\sqrt{E}$
Position resolution	±2 mm

Detector	$\|\eta\|$ range	$\Delta\phi$	$\Delta\eta$
CEM	0 - 1.1	15°	~0.1

CES chamber: one per wedge

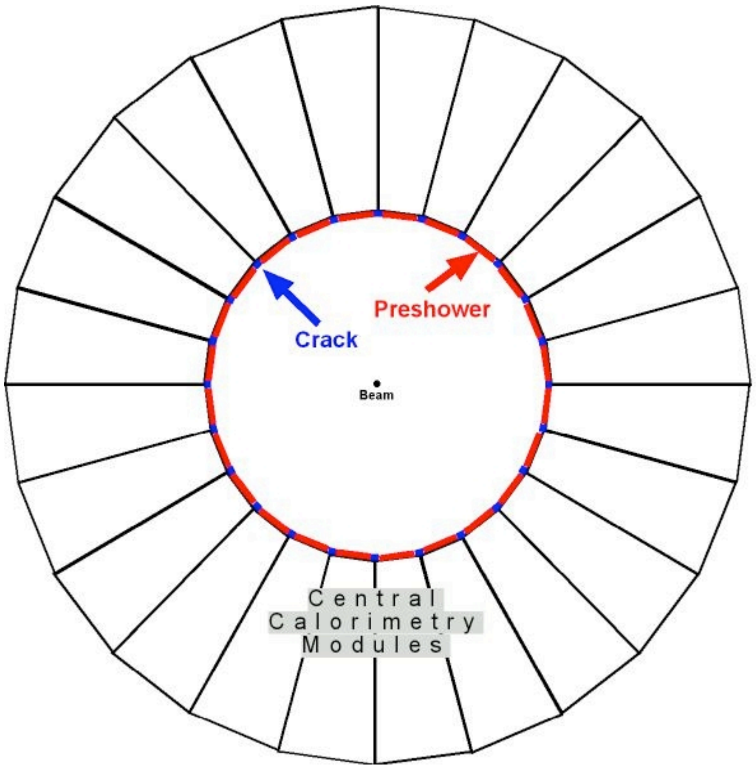
Perpendicular distance to beamline	184 cm
Chamber section 1	6.2 cm< $\|z\|$ <121.2 cm
Wire readout (ganged in pairs)	32 pairs × 1.45 cm
Strip readout	69 strips × 1.67 cm
Chamber section 2	121.2 cm< $\|z\|$ <239.6 cm
Wire readout (ganged in pairs)	32 pairs × 1.45 cm
Strip readout	59 strips × 2.01 cm

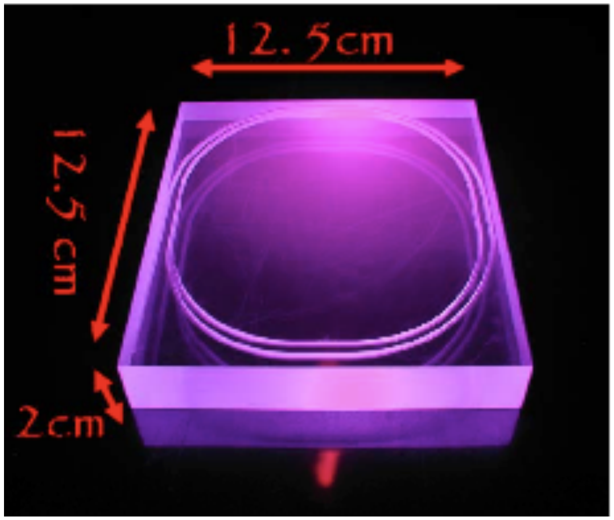


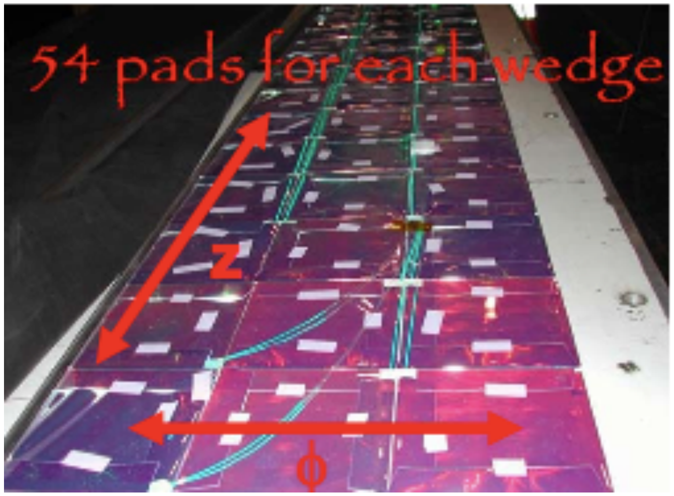
CP2 (Preshower) Detector

- CP2 replaced old CPR in 2004
  - Scintillator pads efficiently detect MIPs
  - Design optimized for higher luminosity

CP2 location: R=170.47 cm





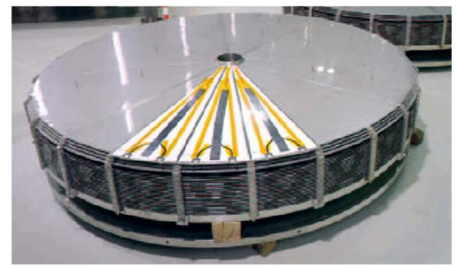


Photons in Plug EM Calorimeter

Detector	$|\eta|$ range	$\Delta\phi$	$\Delta\eta$
PEM	1.1 - 1.8	7.5°	~0.1
	1.8 - 2.1	7.5°	~0.16
	2.1 - 3.64	15°	0.2 - 0.6

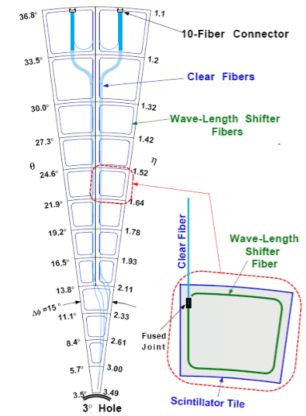
Thickness	$21\ X_0$, 1λ
Absorber	Lead
Scintillator	Polystyrene (SCSN38)
Shower Max (PES)	Z~184 cm; depth~6 X_0
Energy resolution	$16\%/\sqrt{E}$; +1% const term

Plug Electromagnetic Calorimeter (PEM)

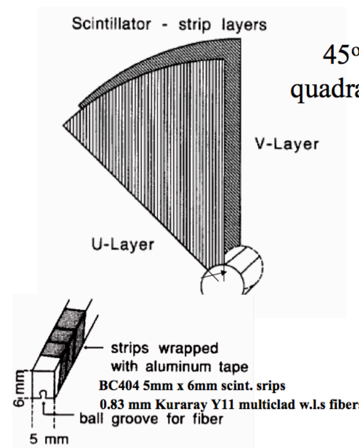


15° megatiles

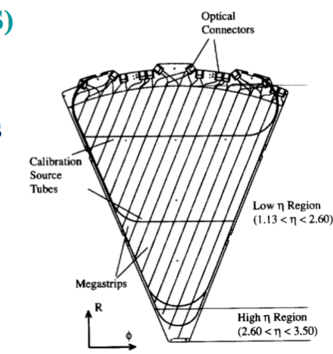
PEM megatile and plug segmentation



Plug Shower max detector (PES)



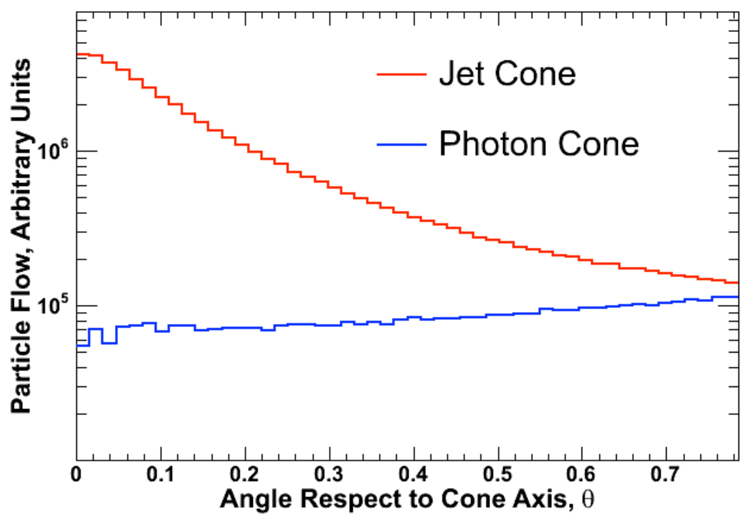
45° quadrants



PES: 5 mm pitch
V & U scintillator strips

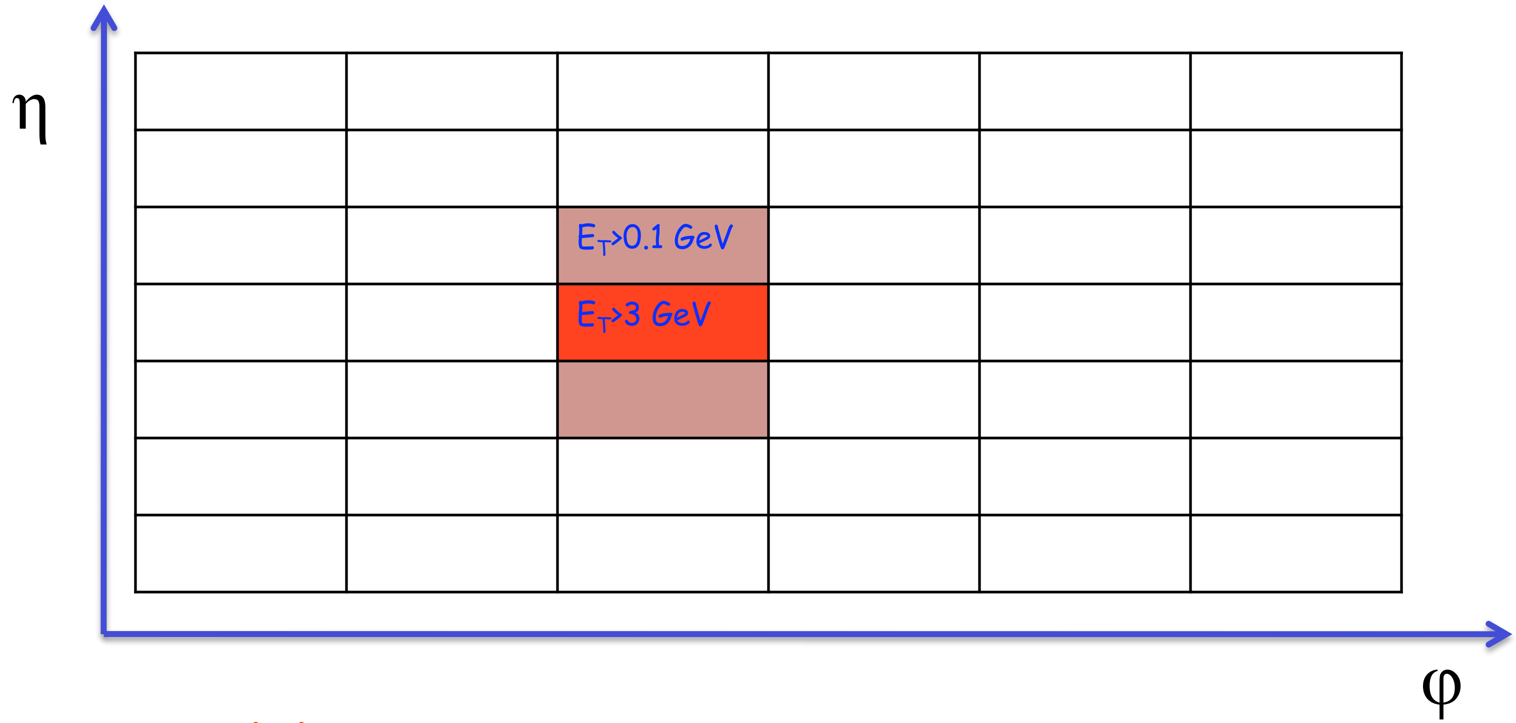
Concept of Photon ID

- Photon signature
  - No electric charge
    - no track
  - "Compact" EM cluster
    - shower contained in EM CAL
  - No color charge
    - Unlike jets, photon is isolated object



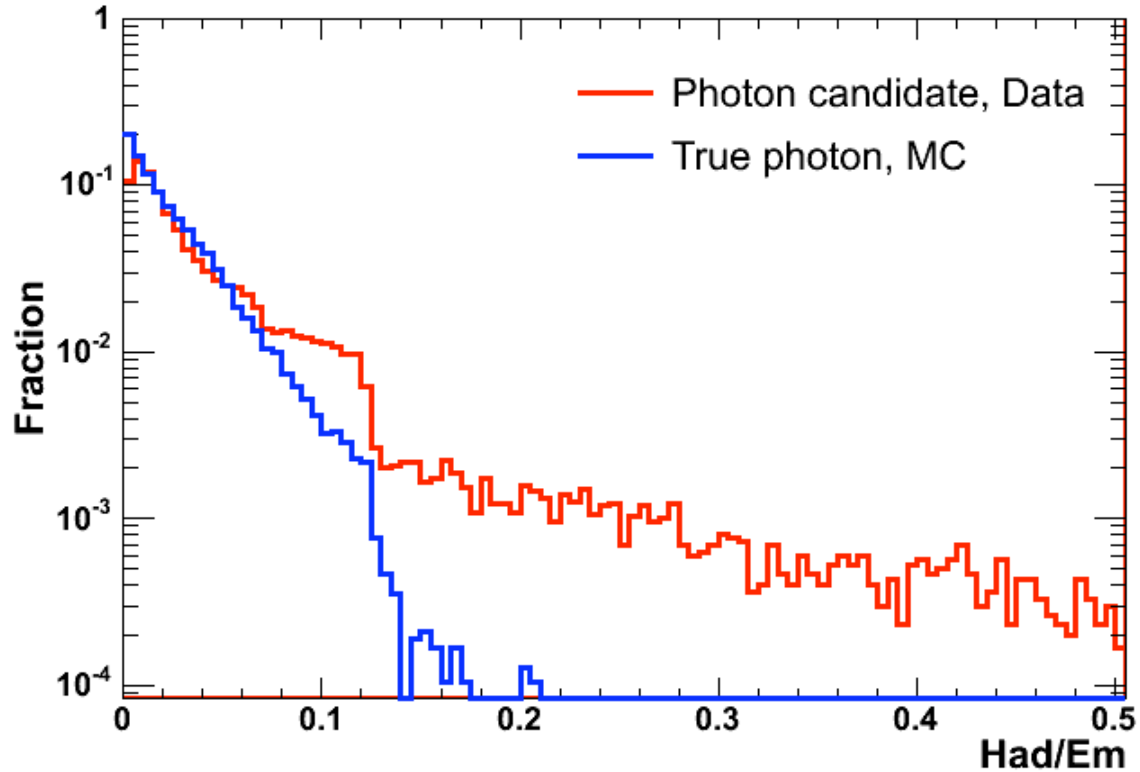
- What fakes a photon?
  - A: another photon…
  - $\pi^0/\eta^0 \rightarrow \gamma\gamma$ is two photons in one cluster
    - Copiously produced in jets
    - Surrounded by other particles
  - Electron is a "photon" with a track, and it brems in material
  - Non-collision sources…

Photon Reconstruction at CDF



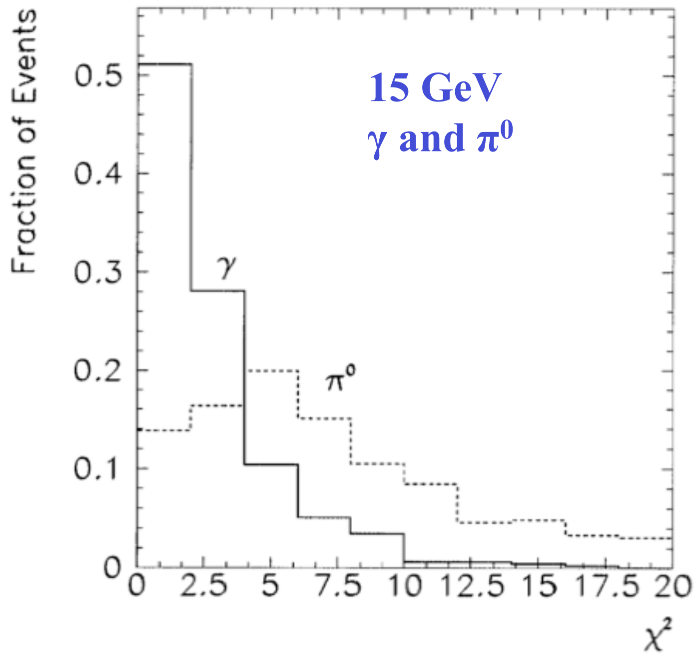
- Photon candidate
  - Up to 3 towers in η:
    - seed tower EM $E_T > 3$ GeV; shoulder tower EM $E_T > 0.1$ GeV
  - Had/Em<12.5% unless EM $E_T > 100$ GeV

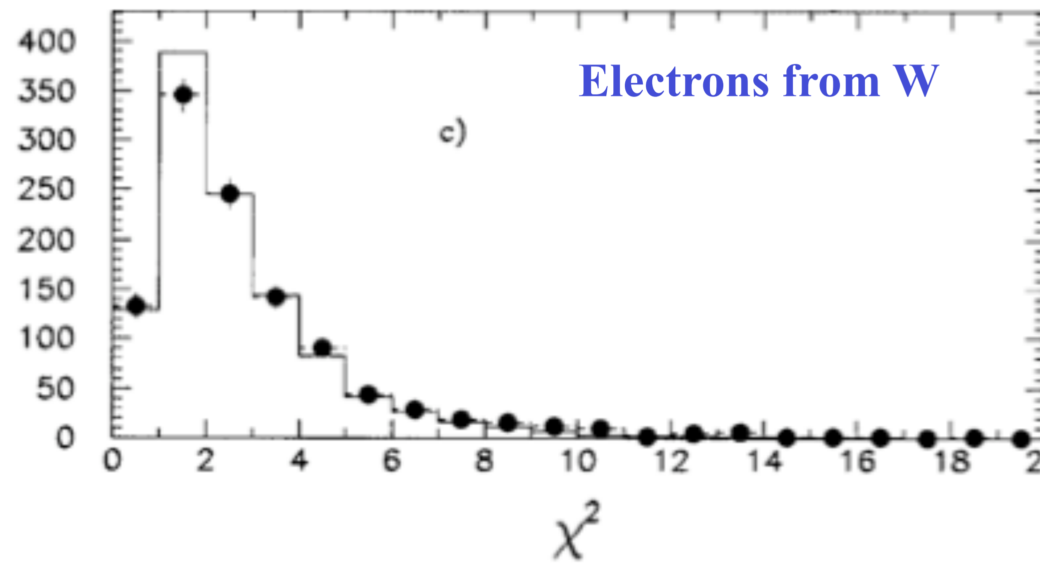
Photon ID: Had/Em



	Central	Forward
Had/Em	<0.125 or <0.055+0.00045*E	<0.05 if E≤100 GeV, <0.05+0.026*ln(E/100) if E>100 GeV

Photon ID: Shower Profile Shape (CES χ^2)





	Central Only
CES χ^2	<20

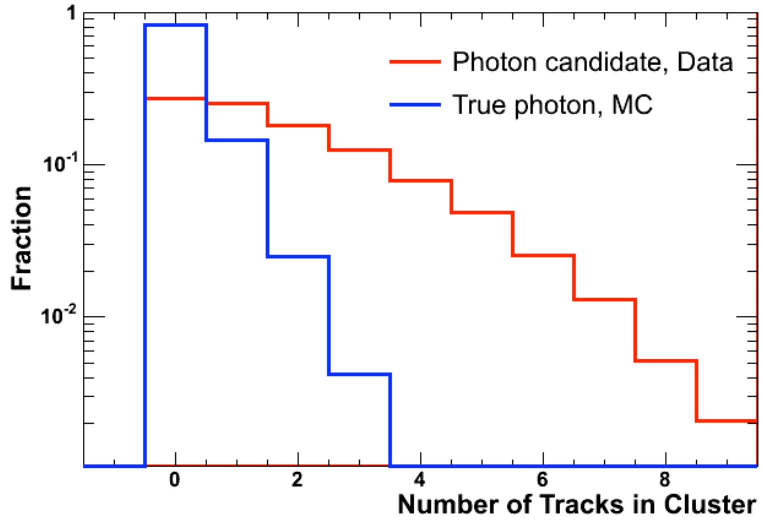
$$\chi^2 = (\chi_S^2 + \chi_W^2)/2$$

$$\chi_{S(W)}^2 = \Sigma(p_i - y_i)^2/\sigma_i^2$$

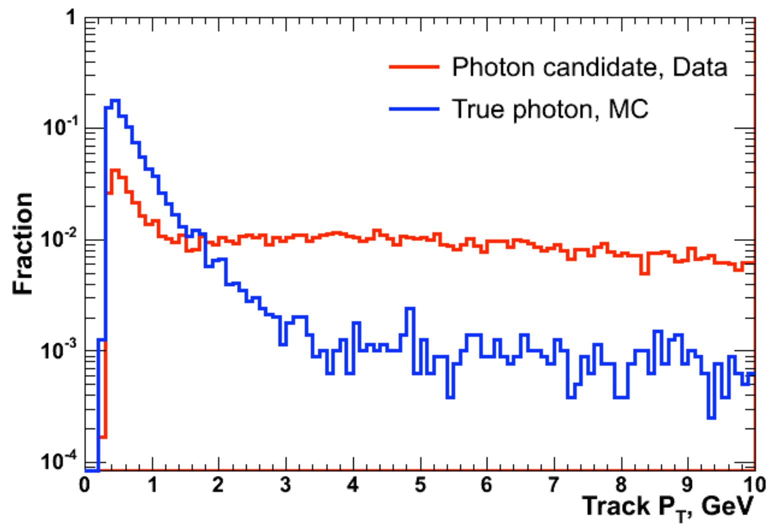
$$\sigma_i^2 = 4(0.026^2 + 0.096^2 y_i) \times \left(\frac{10\,GeV}{E}\right)^{0.747}$$

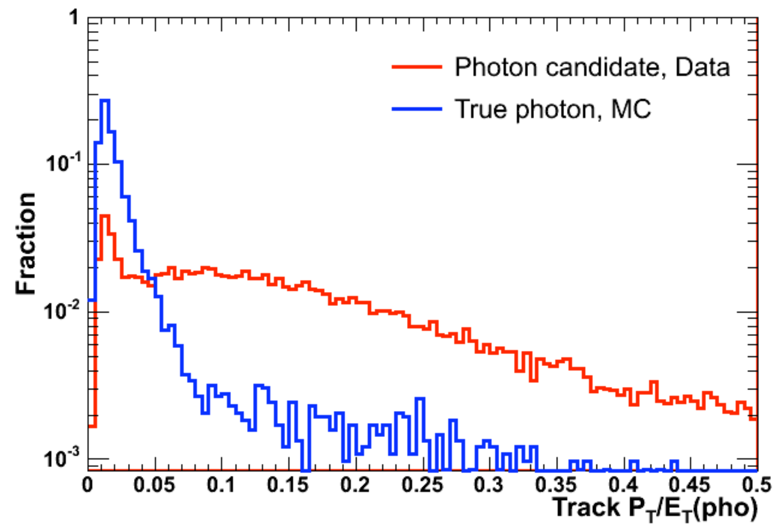
- Shower size ~3.5 cm; minimal γ separation for π^0: 50 [cm GeV]/E_T
  - Can resolve individual γ showers from π^0 for $E_T(\pi^0)<15$ GeV

Photon ID: Track in CES Cluster

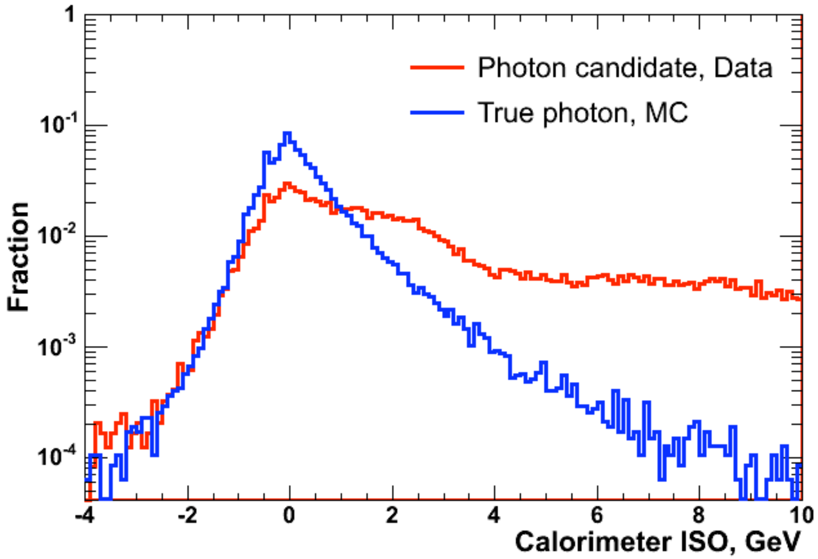


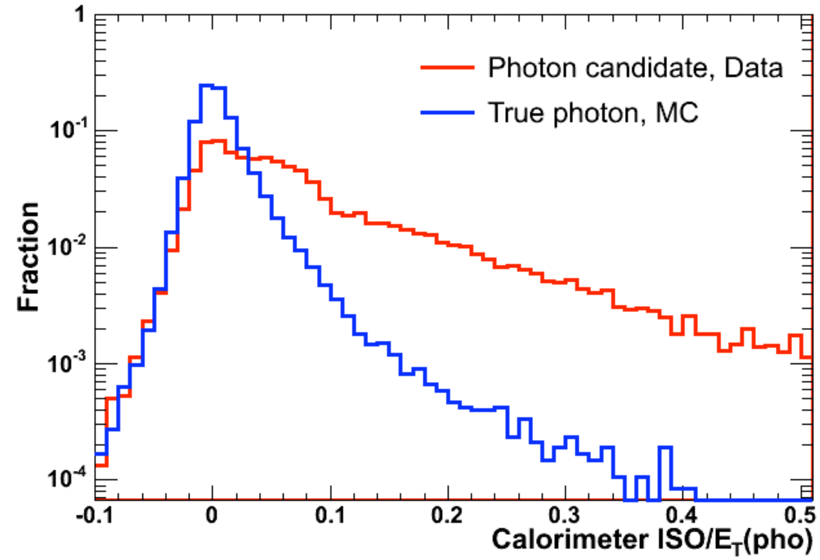
	Central Only
Number of Tracks in CES cluster	≤1
P_T of track	<1.0+0.005*E_T





Photon ID: Calorimeter Isolation

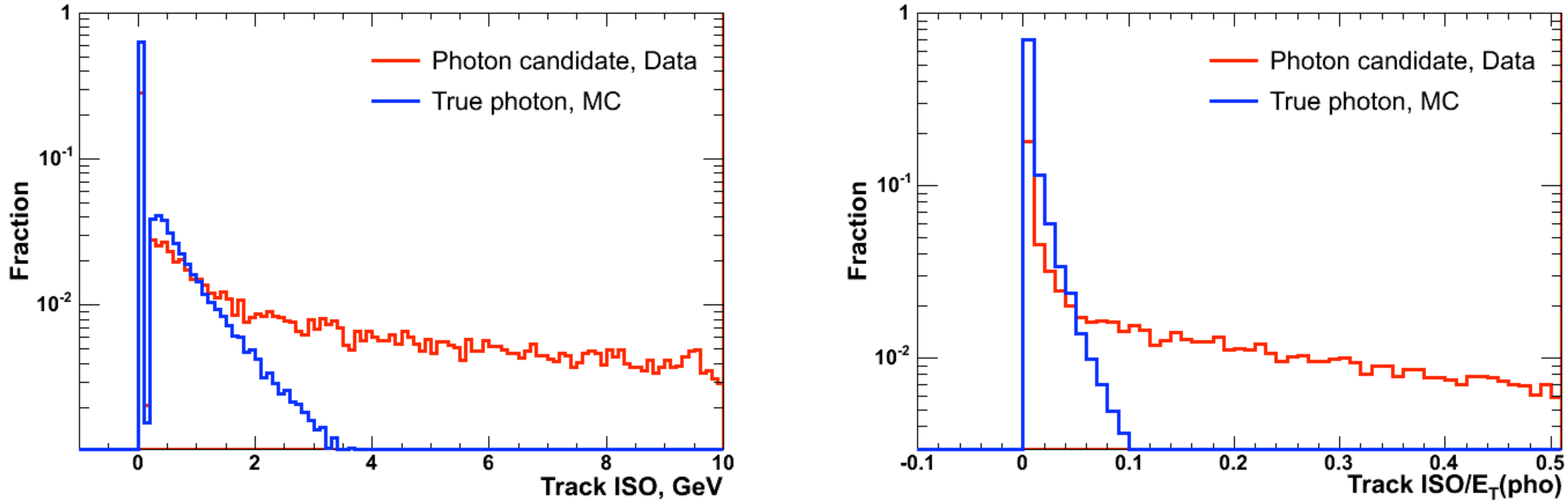




- Calorimeter ISO corrections
  - Photon towers removed;
  - Leakage in φ-direction
  - Multiple interaction

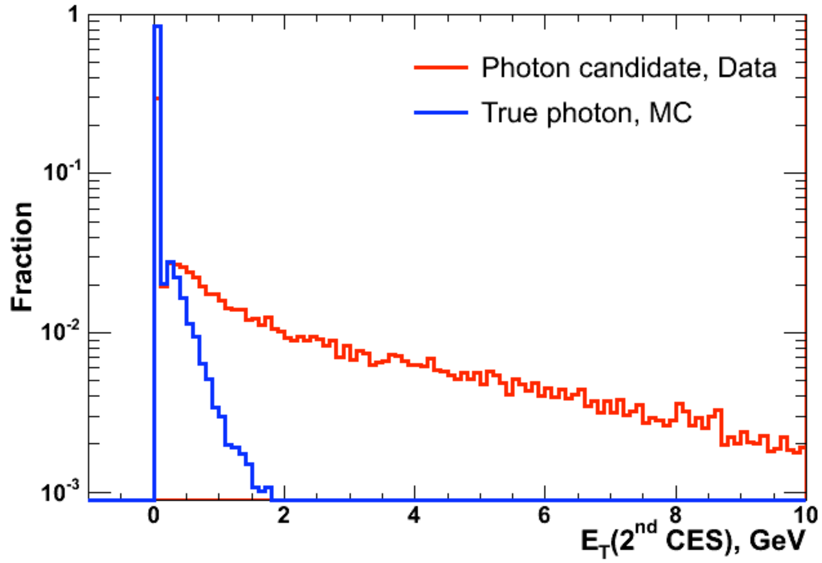
	Central & Forward
Cal ISO (cone R<0.4)	E_T<20 GeV: <0.1*E_T E_T>20 GeV: <2.0+0.02*(E_T-20.0)

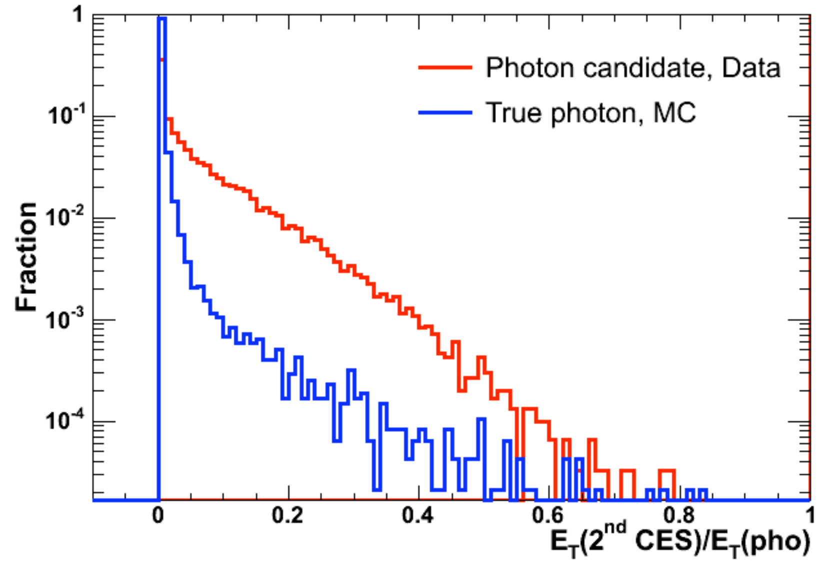
Photon ID: Track ISO



	Central & Forward
Track ISO (cone R<0.4; all tracks with |Δz|<5 cm)	$<2.0+0.005*E_T$

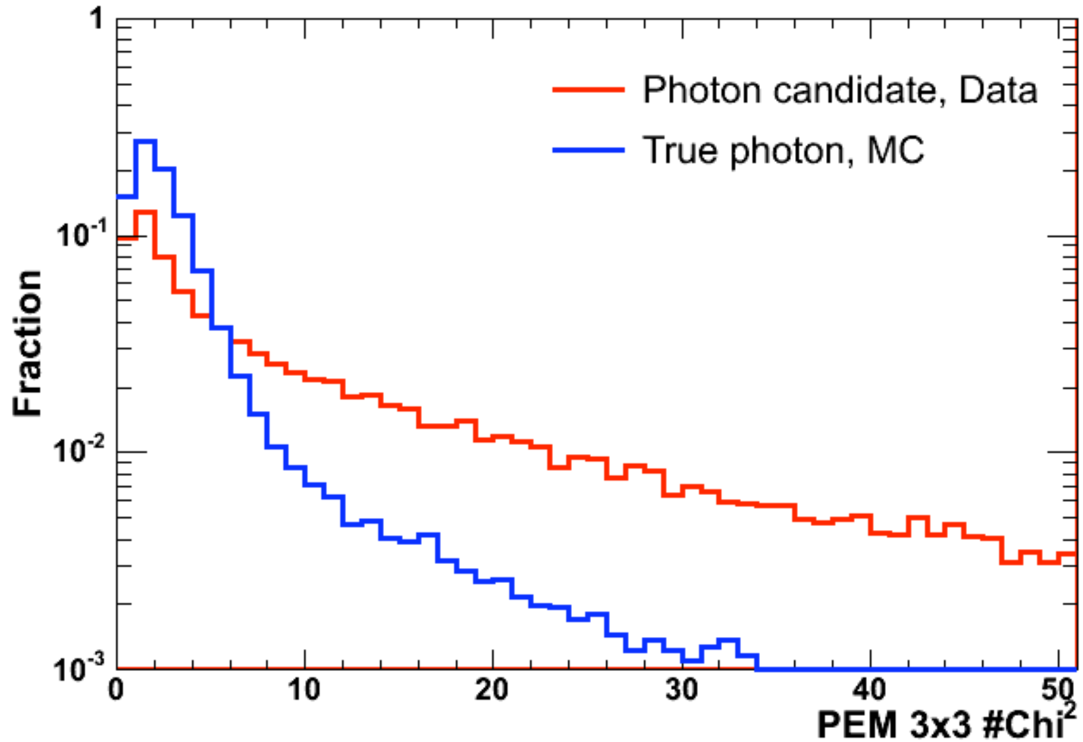
Photon ID: E_T of 2^{nd} CES Cluster





	Central Only
E_T of 2^{nd} CES cluster in same chamber	E_T<18 GeV: <$0.14*E_T$ E_T>18 GeV: <$2.4+0.01*E_T$

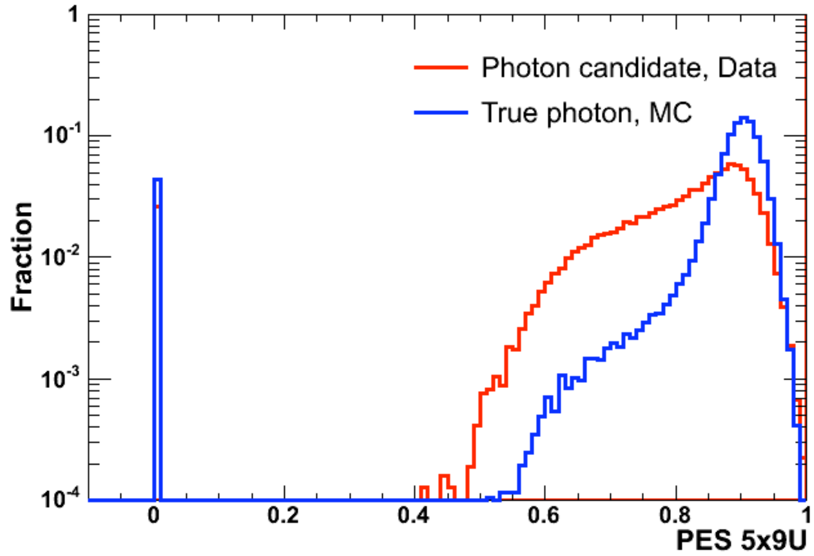
Photon ID: PEM 3x3 χ^2

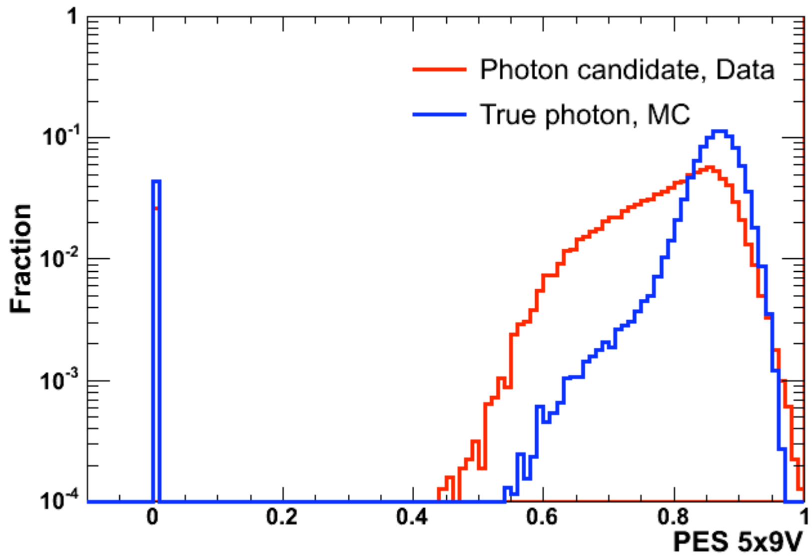


- **PEM 3x3 χ^2**
  - EM shower profile in 3x3=9 towers
  - Compared to known EM shower shape

	Forward Only
PEM 3x3 χ^2	<10

Photon ID: PES 5x9 Ratio

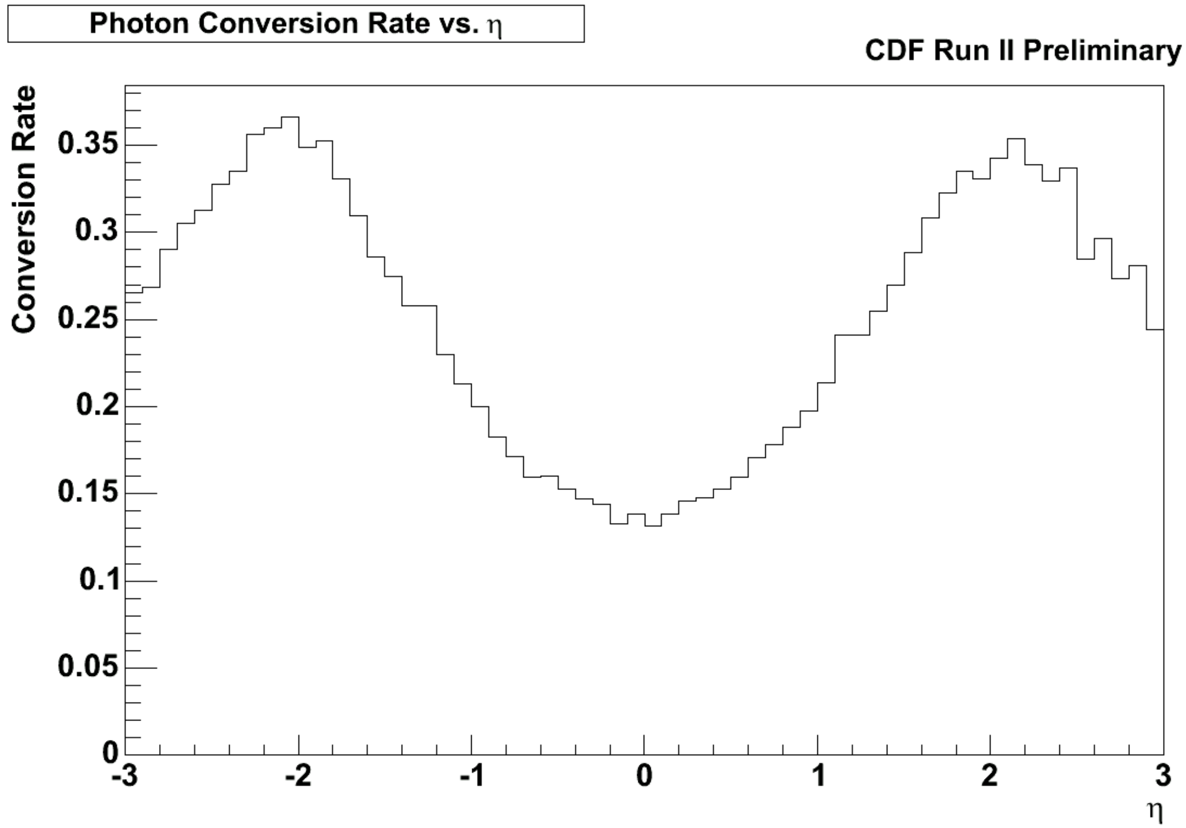




- PES 5x9 Ratio
  - Ratio of E(5 strips)/E(9 strips) centered on EM cluster
  - For U- & V-layers

	Forward Only
PES 5x9 Ratio U & V	>0.65

Conversions

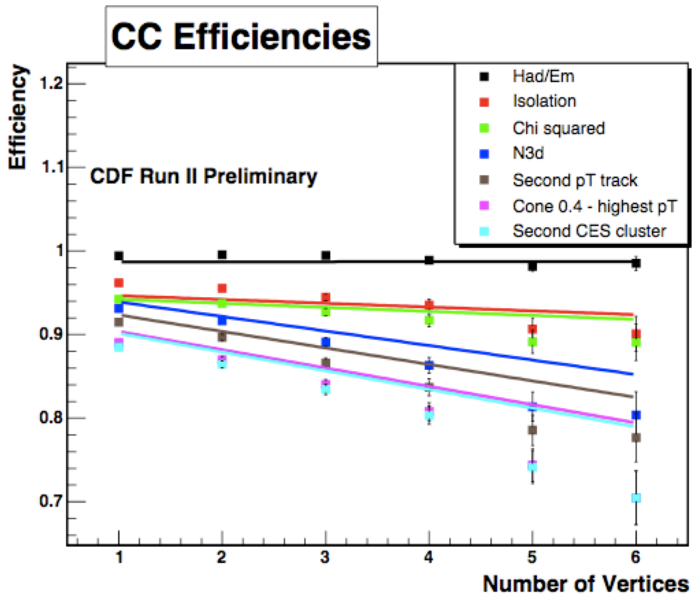


- ~15% (~30%) central (forward) photons convert to e^+e^-
  - Conversions are not used in photon analyses at CDF
  - CDF has only one measurement using converted photons
    - Phys. Rev. D70, 074008 (2004)

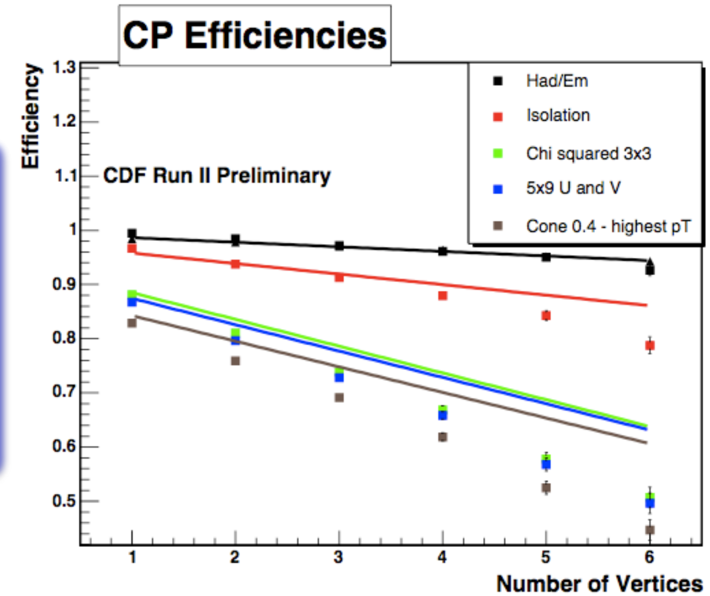
Check List For Photons

- 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

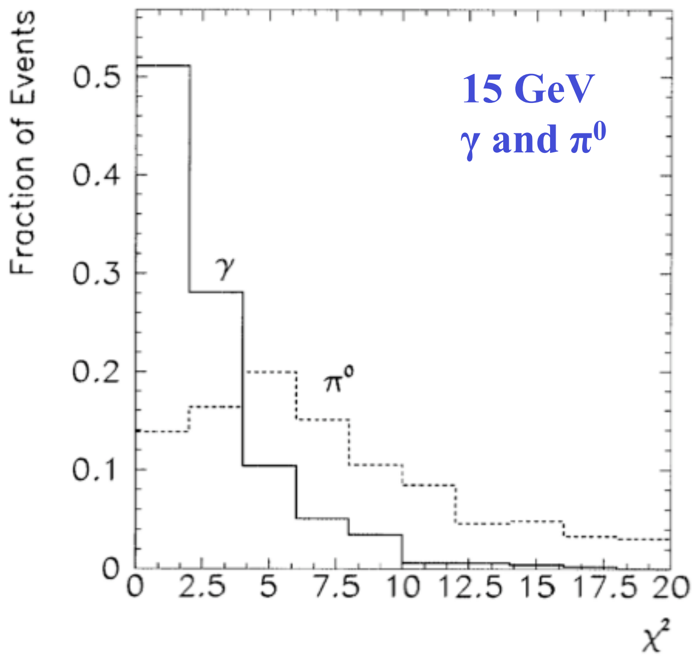


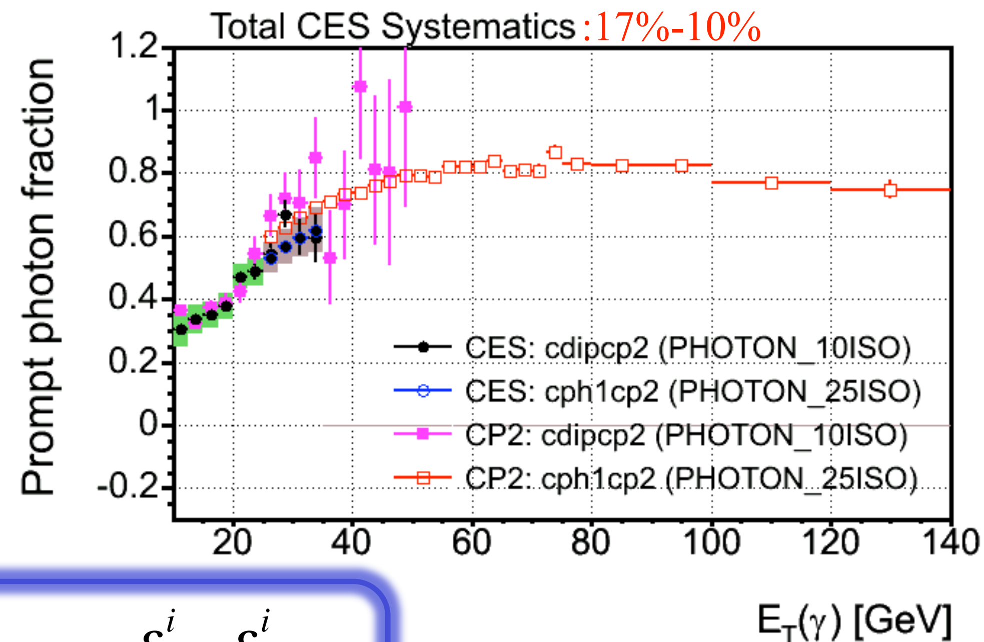
Efficiency
Central: ~86%
Forward: ~76%



- **Method**
  - Use photon MC for efficiency
  - Data/MC scale factor: **compare "unbiased" electron from Z-peak in data and MC**
- **Acceptance**
  - ~15% of central photons lost because they have no CES cluster

Photon Purity: CES Method

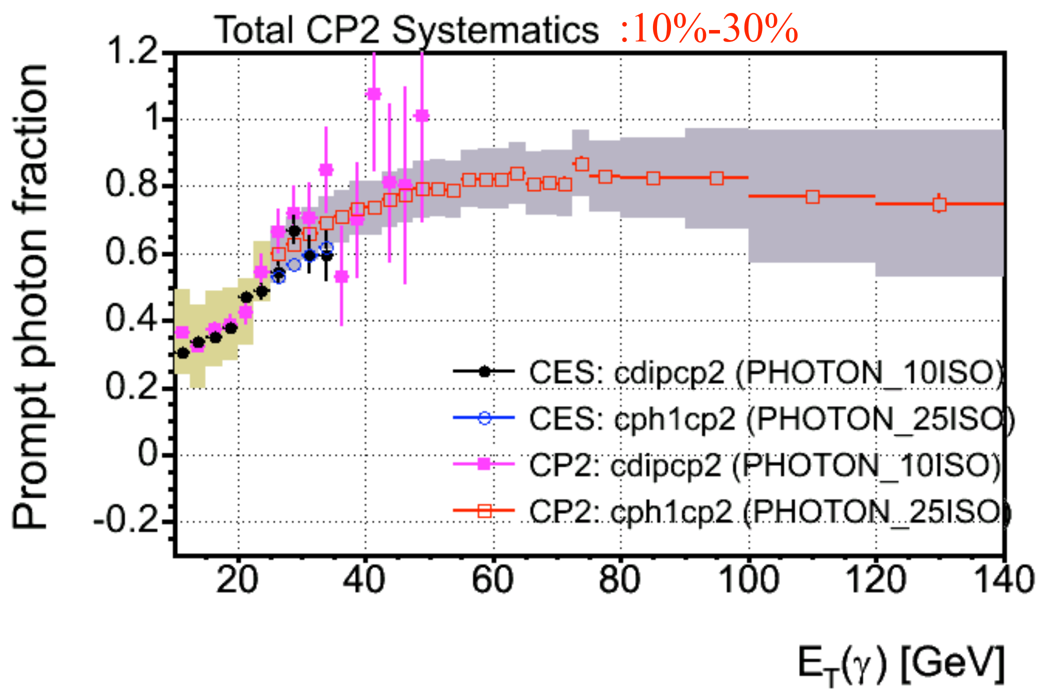




$$W_\gamma = \sum_i \frac{\varepsilon^i - \varepsilon^i_{bckg}}{\varepsilon^i_{sig} - \varepsilon^i_{bckg}}$$

- EM cluster produced by π^0/η have worse χ^2 (if E_T<35 GeV)
  - $\varepsilon=1$ if $\chi^2<4$; $\varepsilon=0$ if $\chi^2>4$
  - $\varepsilon_{sig}=N(\chi^2<4)/N(\chi^2<20) \sim 78\%$ (checked in W/Z+γ with γ FSR in Run II)
  - $\varepsilon_{bckg}=N(\chi^2<4)/N(\chi^2<20) \sim 30\text{-}40\%$ (checked with $\rho^\pm \rightarrow \pi^\pm\pi^0$ in Run I)

Photon Purity: CP2 Method



$$W_\gamma = \sum_i \frac{\varepsilon^i - \varepsilon^i_{bckg}}{\varepsilon^i_{sig} - \varepsilon^i_{bckg}}$$

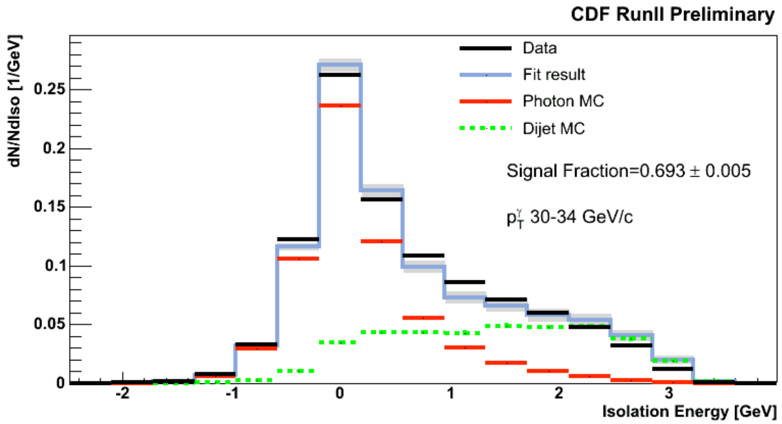
$$P = 1 - \exp\left(-\frac{7 * M * N_\gamma(E, \sin\theta)}{9 X_0 \sin\theta}\right)$$

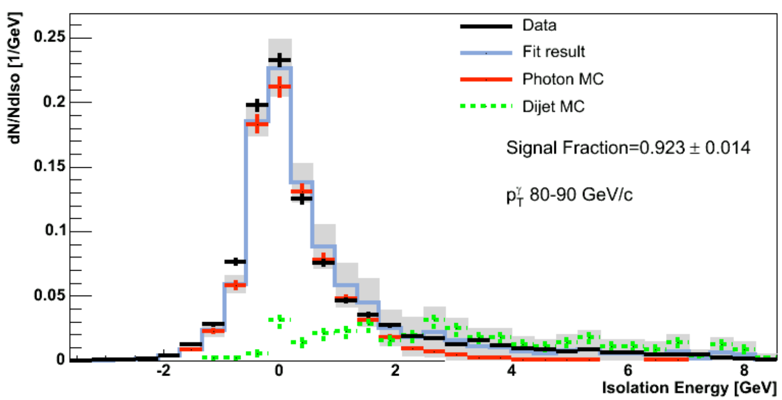
$$M = 1.105 X_0$$

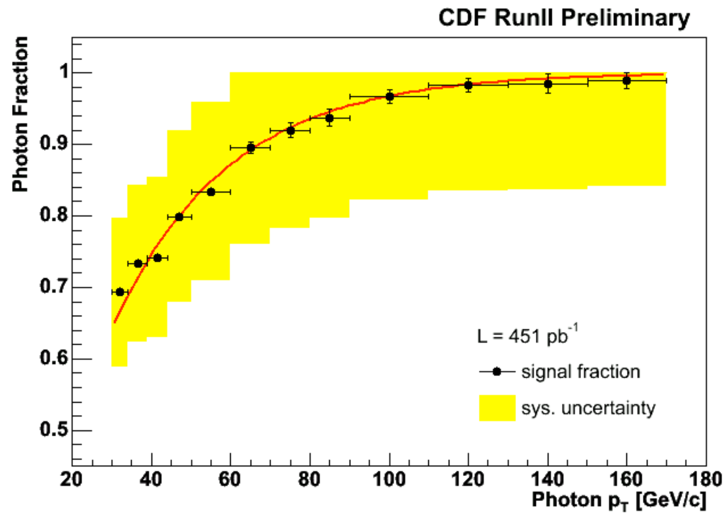
N_γ=1 for single photon
N_γ~2 for π^0

- Two photons have higher conversion probability than one photon
  - ε=1 if CP2 hit; ε=0 if no CP2 hit
  - ε_{sig}= ~ 65% (checked with W/Z+γ events with γ FSR)
  - ε_{bckg}= ~ 85%

Photon Purity: ISO Method

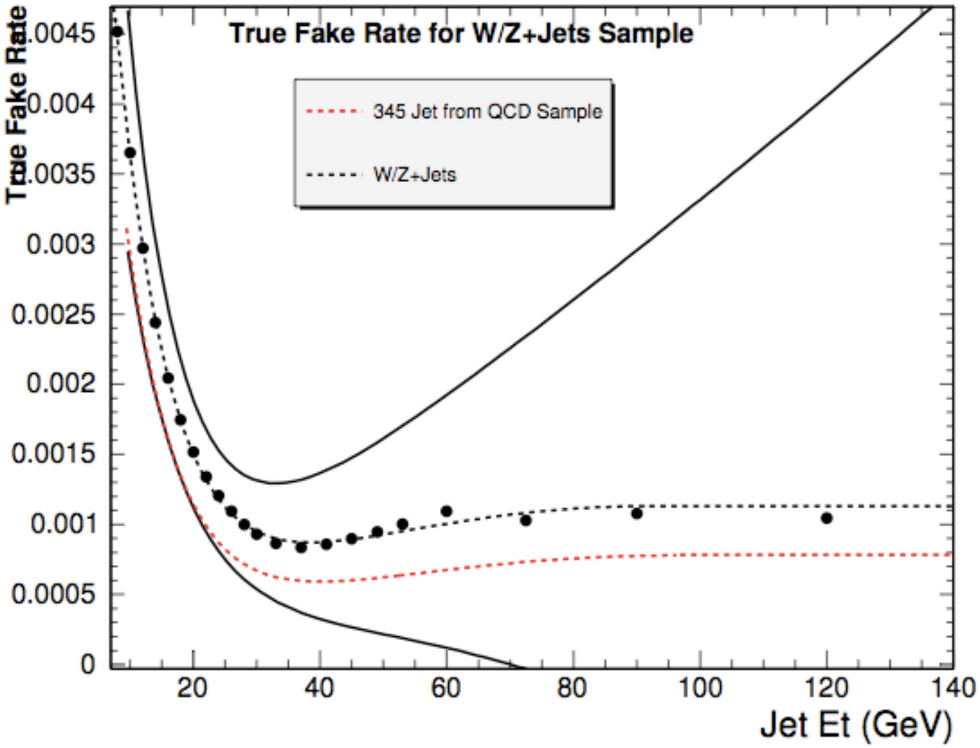


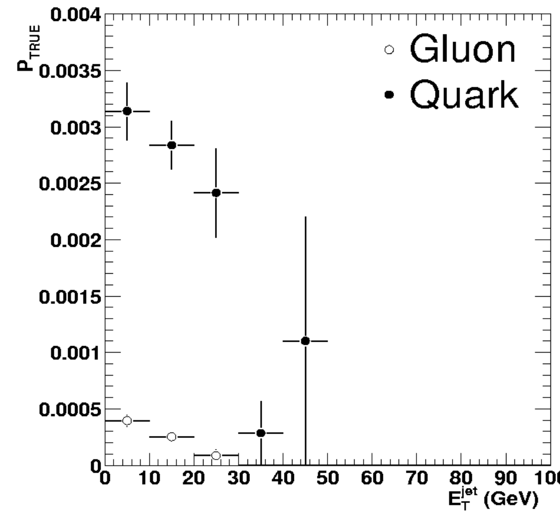




- **Method**
  - Signal template from γ+jet MC
    - Can use Z's in data and MC for validation
  - Background template from large stat. di-jet MC
    - Can use jets with leading $\pi^{\pm}$ (P_T/E_T>0.8) in data and MC for validation

Fake Rate: jet→γ



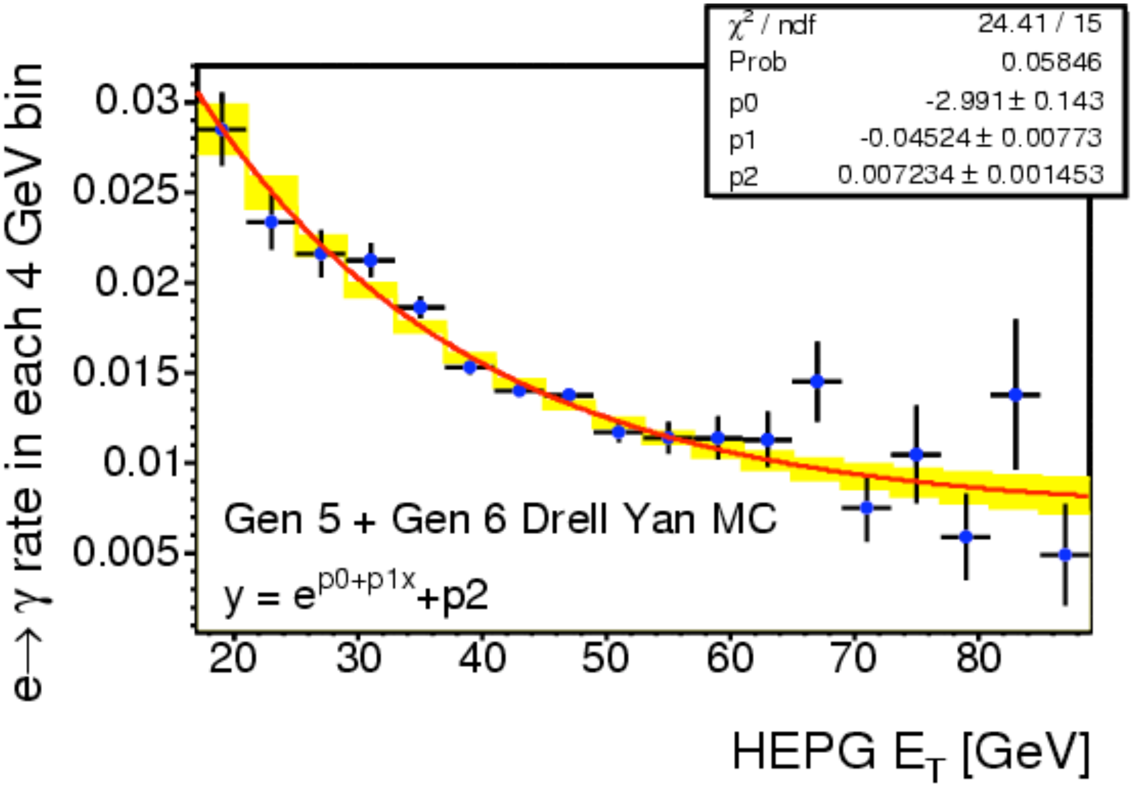


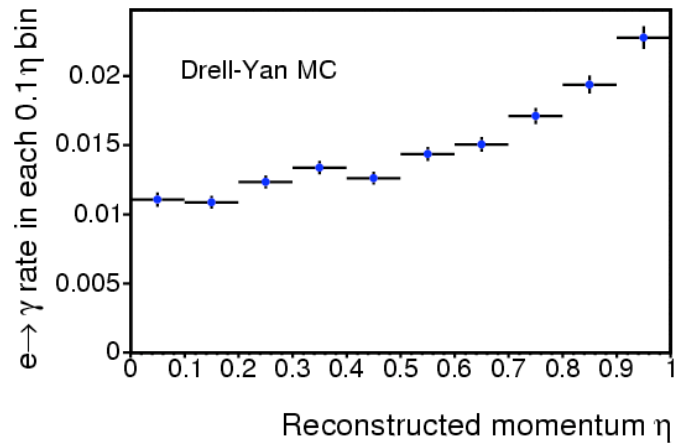
How does jet fake a photon?

Jet → leading $\pi^0/\eta^0 \rightarrow \gamma\gamma \rightarrow \gamma_{fake}$

- **Method:**
  - Start from a collection of jets
  - Count "photons" in jet collection
  - Subtract number of true photons (based on statistical methods)

Fake Rate: $e \to \gamma$





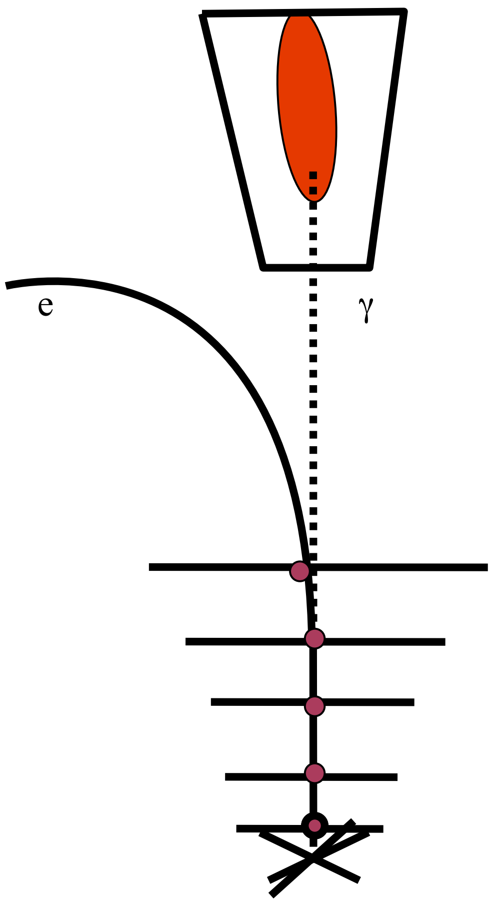
How does electron fake a photon?

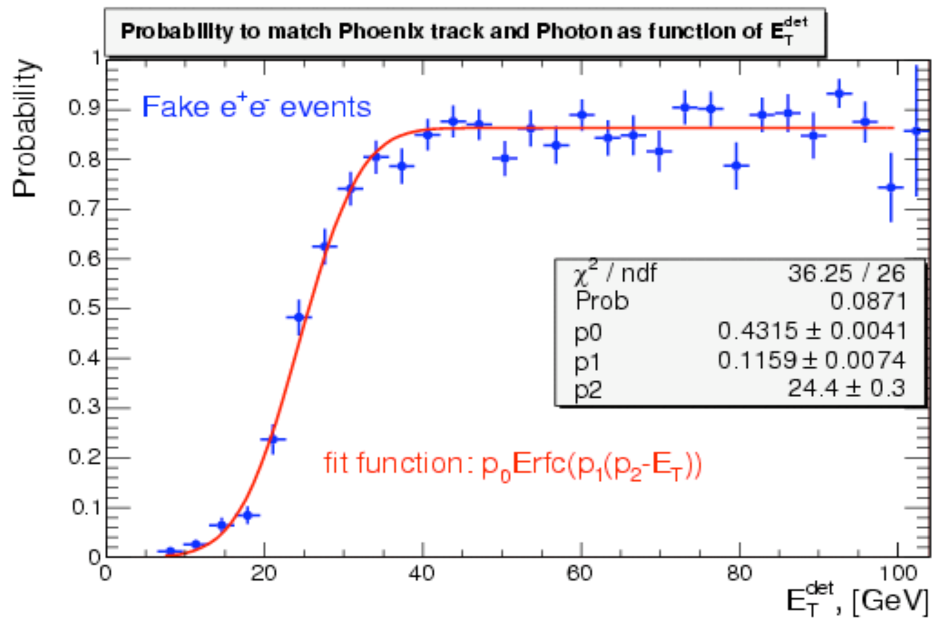
Brem in material, track loss, and collinear FSR

- **Method:**
  - Use MC (W, Drell-Yan) to get E_T and η dependences
  - Compare $e+\gamma$ and e^+e^- events from Z-peak in data and MC to get MC-to-Data normalization

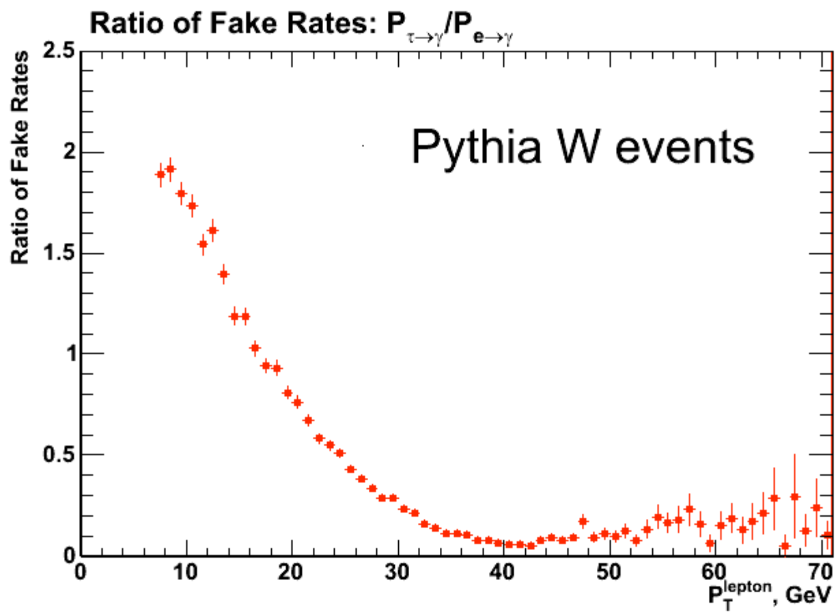
Reducing e→γ Fake Rate

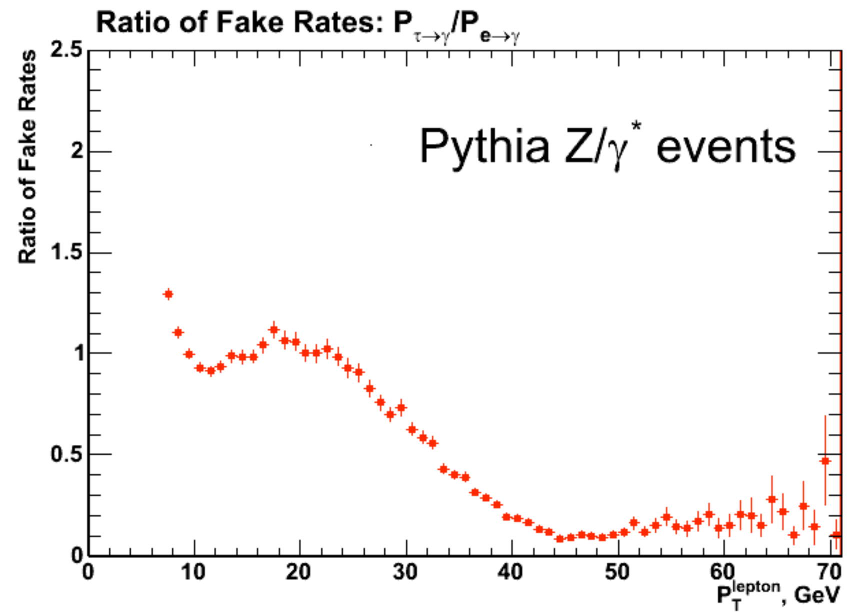
- "Phoenix" tracking
  - Seed track from CAL cluster and event vertex
  - Look for Silicon hits along the expected arc
  - Originally developed for "forward" electrons
  - Also used for rejecting fake photons due to electron bremsstrahlung





Fake Rate: $\tau \rightarrow \gamma$





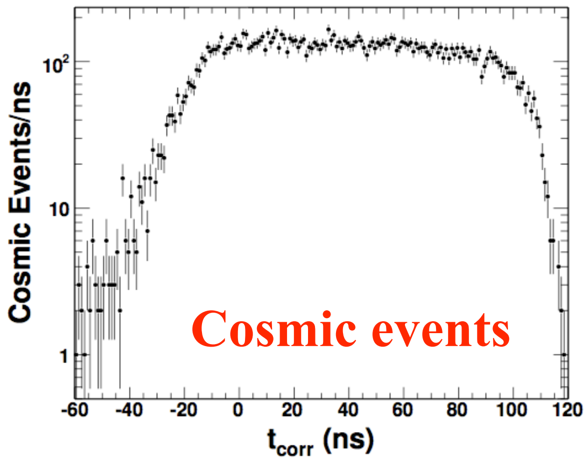
How does tau fake a photon?

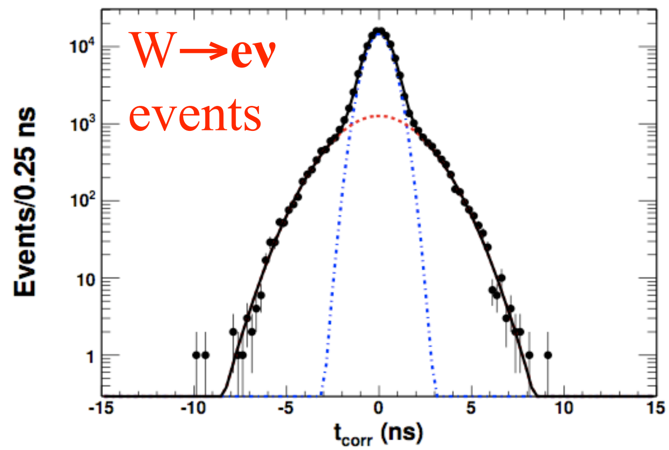
Dominant: $\tau \rightarrow \rho \rightarrow \pi^+\pi^0 \rightarrow \gamma\gamma \rightarrow \gamma_{fake}$

$$Ratio = \frac{N_{\tau\rightarrow\gamma}(P_T)/N_\tau(P_T)}{N_{e\rightarrow\gamma}(P_T)/N_e(P_T)}$$

- Hard to define and measure the fake rate; need to rely on MC
- Not the same as jet$\rightarrow\gamma_{fake}$
- Can use reconstructed $Z\rightarrow\tau\tau$ in data & MC for normalization

Cosmics & EM timing





EM timing resolution:

True vertex:

σ~0.7 ns

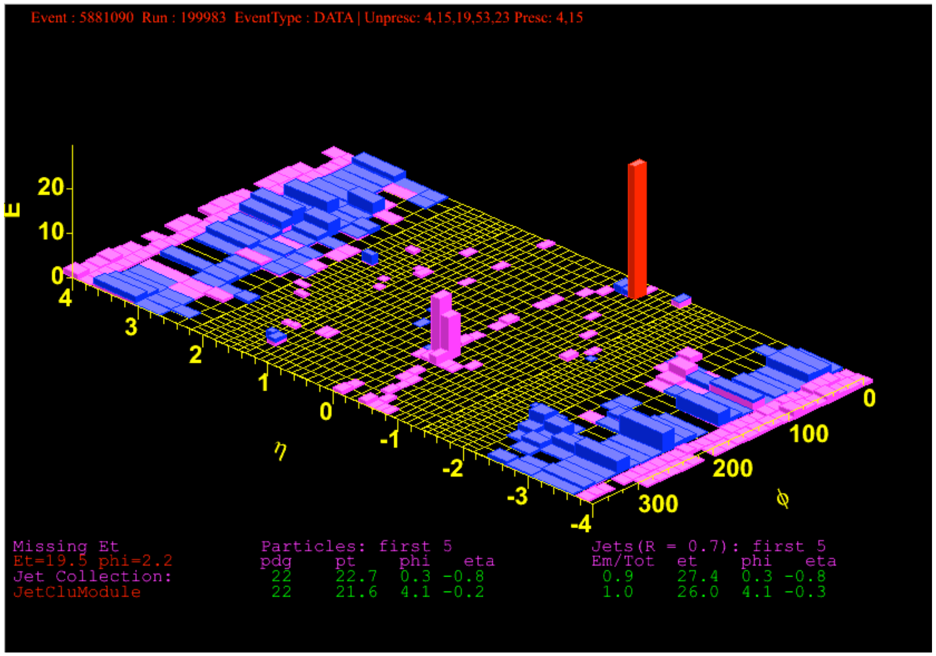
Wrong vertex:

σ~1.9 ns

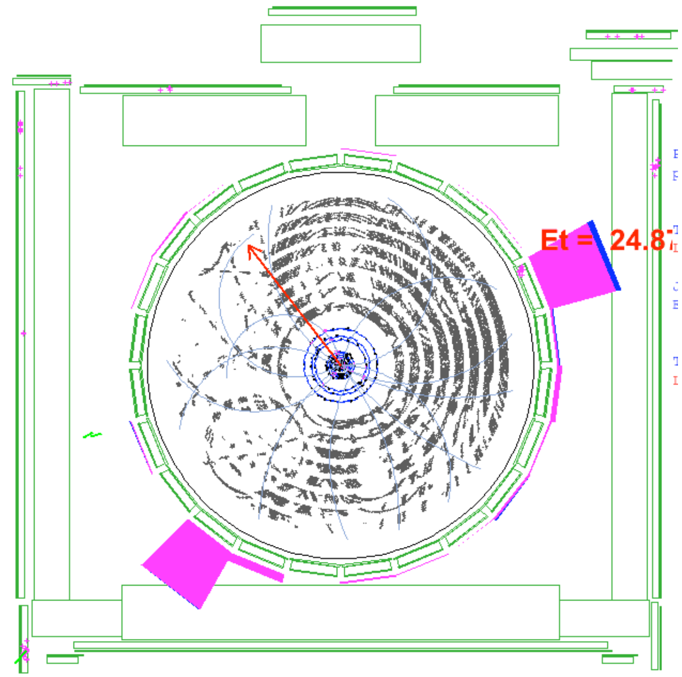
- Cosmics
  - Significant background for γ+MET and "delayed" photon searches
  - Arrives independently of collision time
  - Cosmic samples:
    - "γ+MET" candidate events without reconstructed vertex and tracks
    - "γ+MET" candidate events from special "no beam" runs
- Use W→eν events to study EM timing in true collision events

Example of Cosmic Event

Calorimet η-φ view

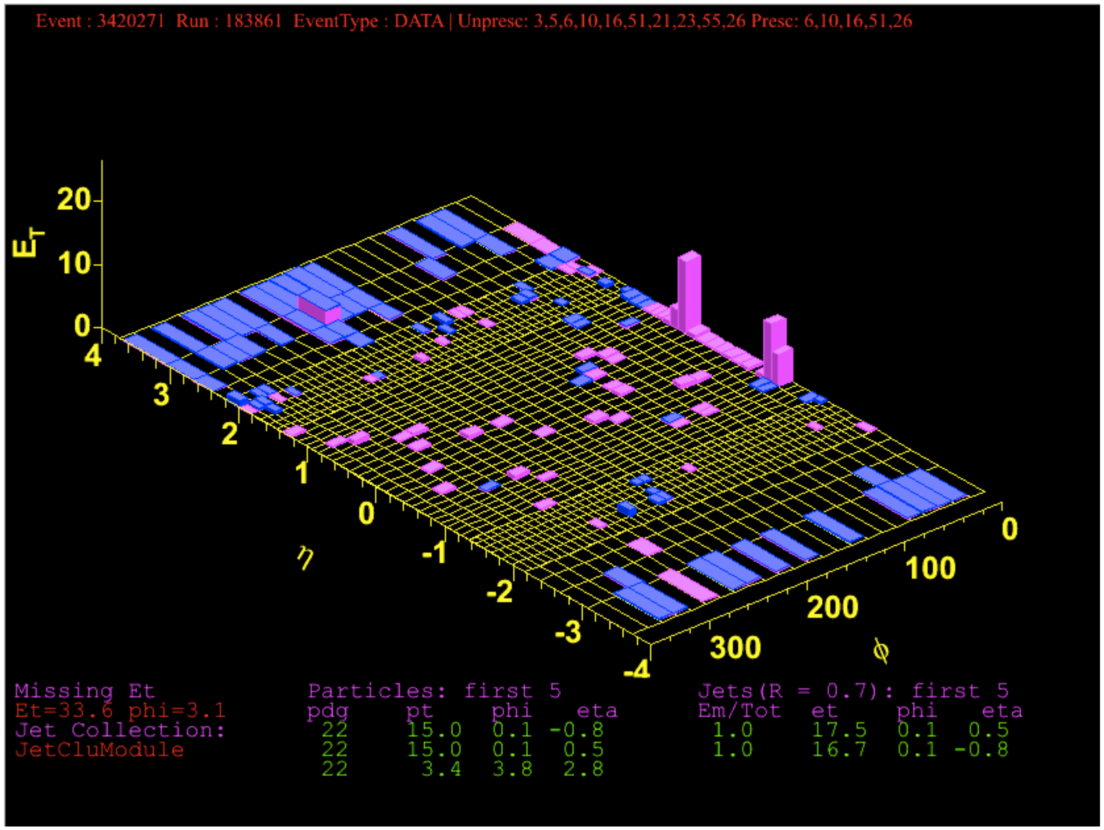


Detector r-φ view



- Cosmics can also produce di-photon signature
  - Can use ΔT_{12} cut to remove such events
    - True collision $\sigma_{\Delta T}$~1 ns
    - Cosmics: ΔT~5-10 ns

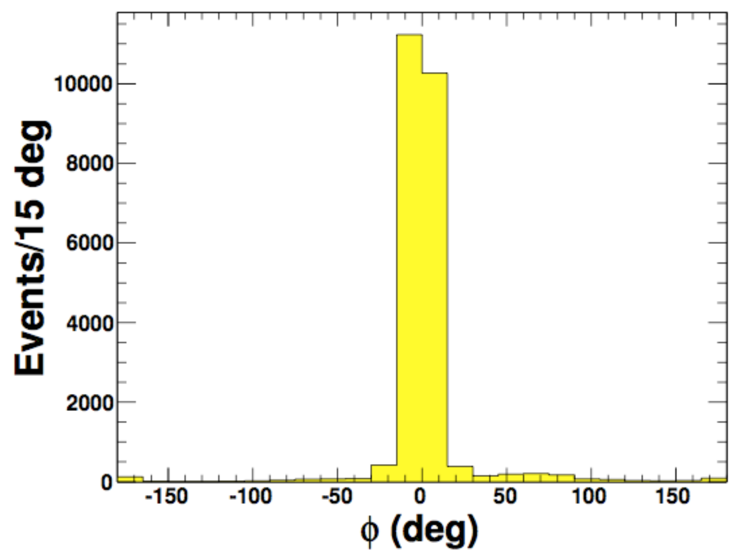
Beam Halo



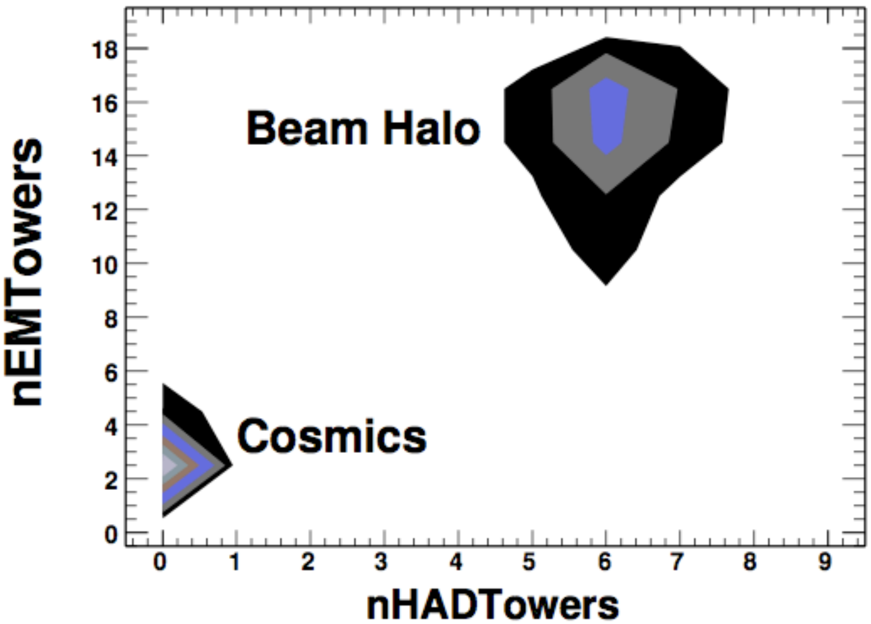
Calorimet η-φ view.
Example of "di-photon" beam halo event.

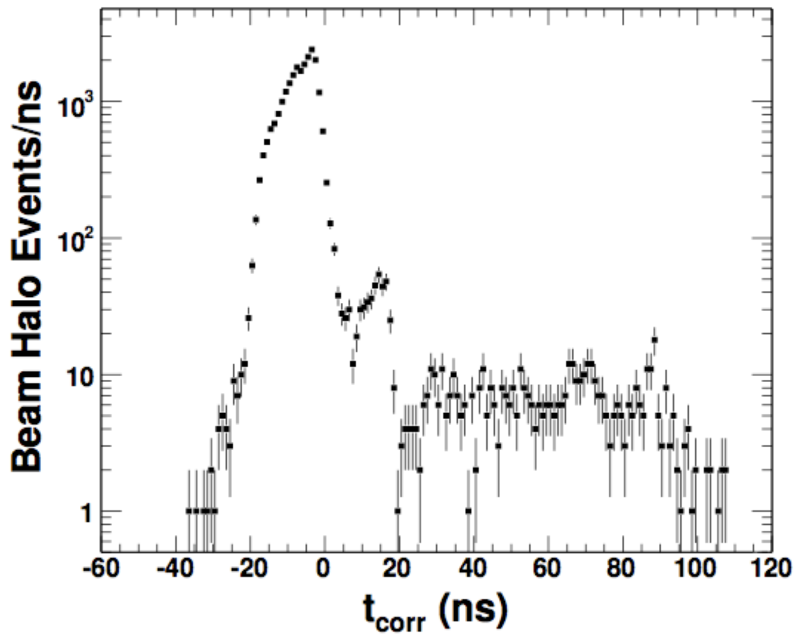
Beam Halo events can produce γ+MET or even γγ+MET signature

φ-distribution of beam halo "photons"



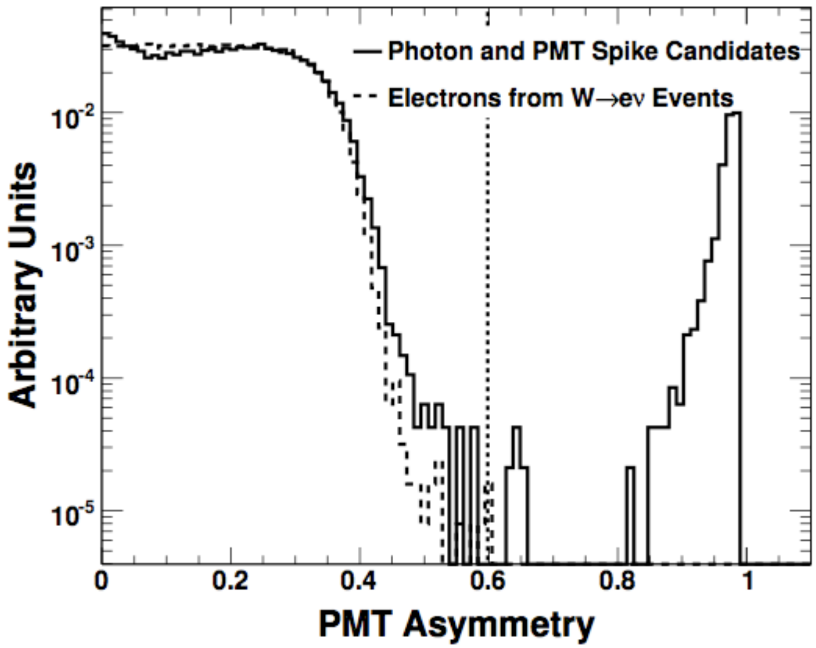
Beam Halo, Continued

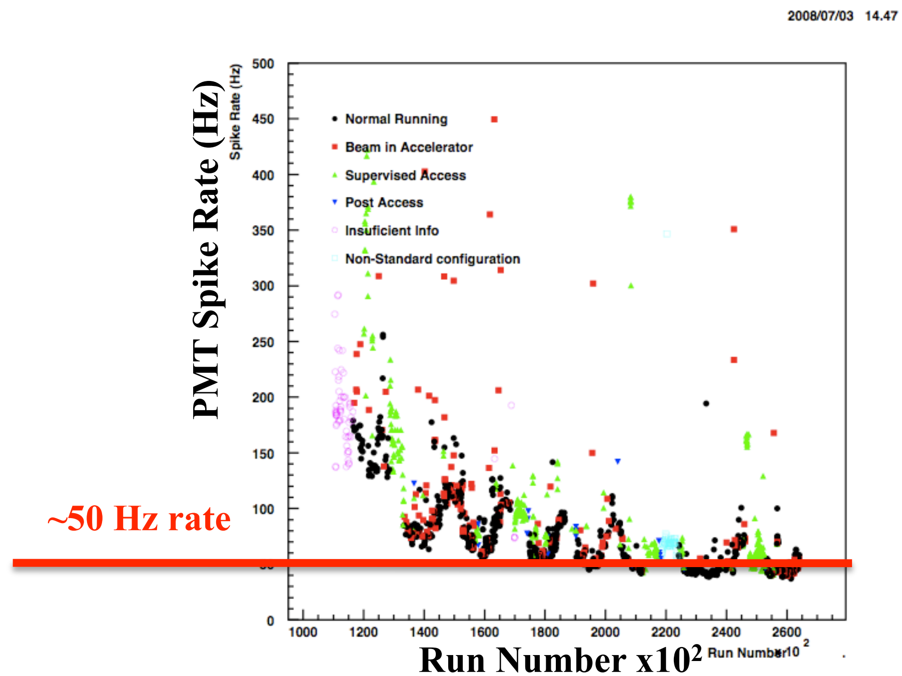




- Beam Halo samples
  - "γ+MET" candidate events without reconstructed vertex and tracks
- Beam Halo rejection
  - Topological cuts and EM timing

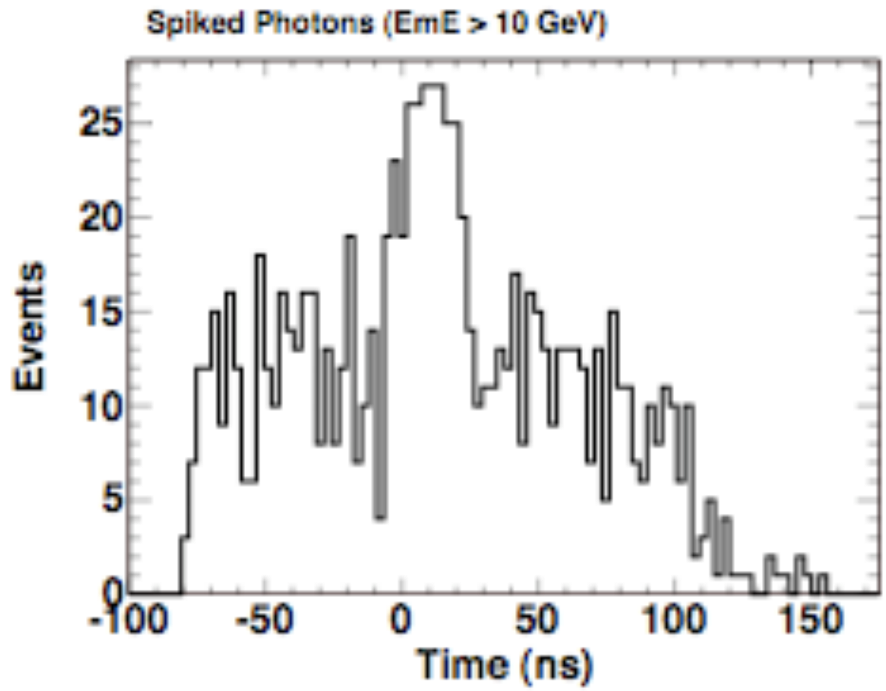
PMT Spikes





- **Central EM CAL:**
  - Spike overlaps with low E_T particle from regular collision and gives fake γ+MET
  - 2 PMTs per tower; high PMT spike rate
  - removed by PMT asymmetry cut and EM timing cut

PMT Spikes, Continued

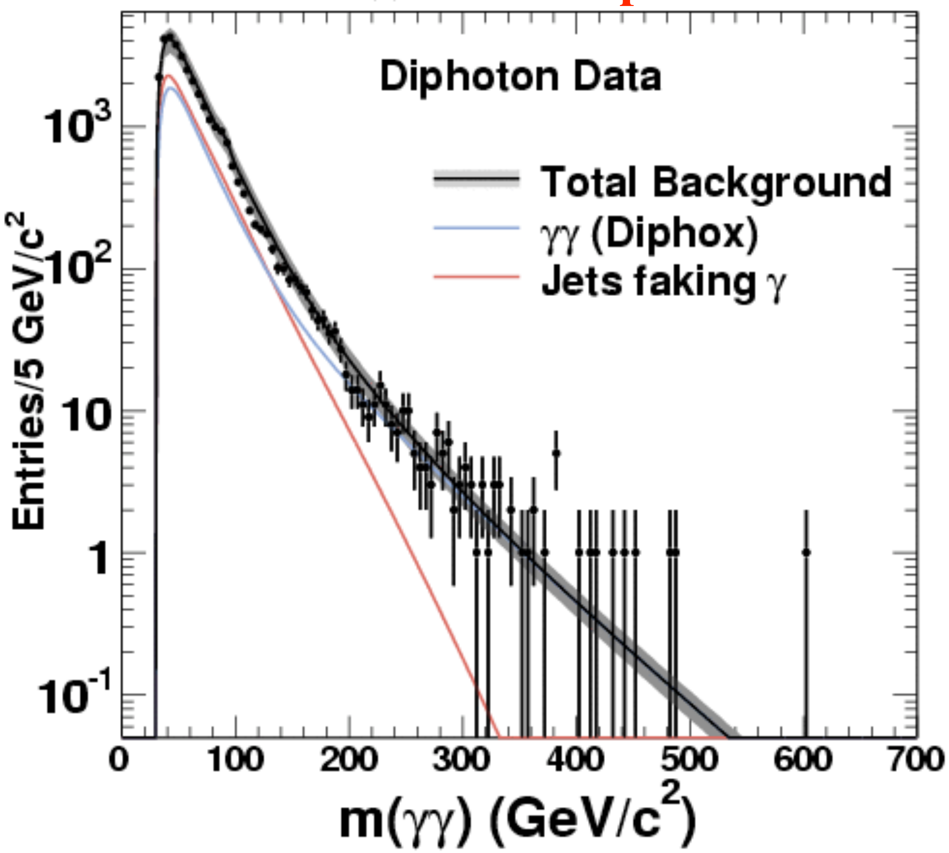


- Forward EM CAL:
  - 1 PMT per tower, but much lower PMT spike rate
  - Rejected based on EM timing

Moving on to Physics

Search for Di-Photon Peaks

1155 pb^{-1} of Data

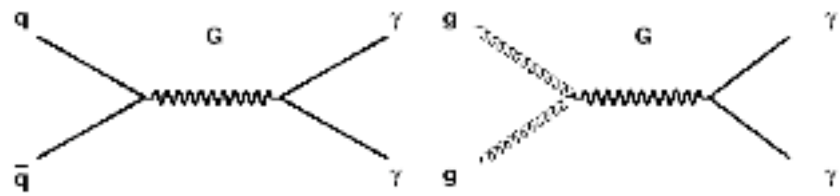


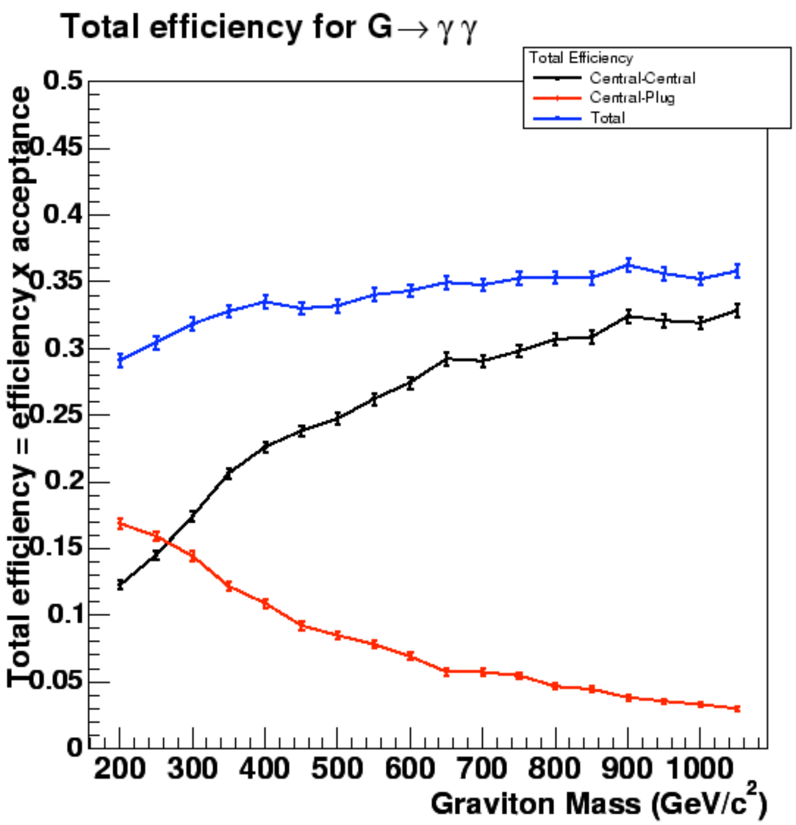
- Two central-central or central-forward photons
  - E_T(photon)>15 GeV
  - "tight" photon ID
- Backgrounds
  - SM γγ production
    - DIPHOX MC
  - Fakes: γ-jet, jet-jet events
    - **"Loose" γγ events:** at least one γ fails "tight" photon ID

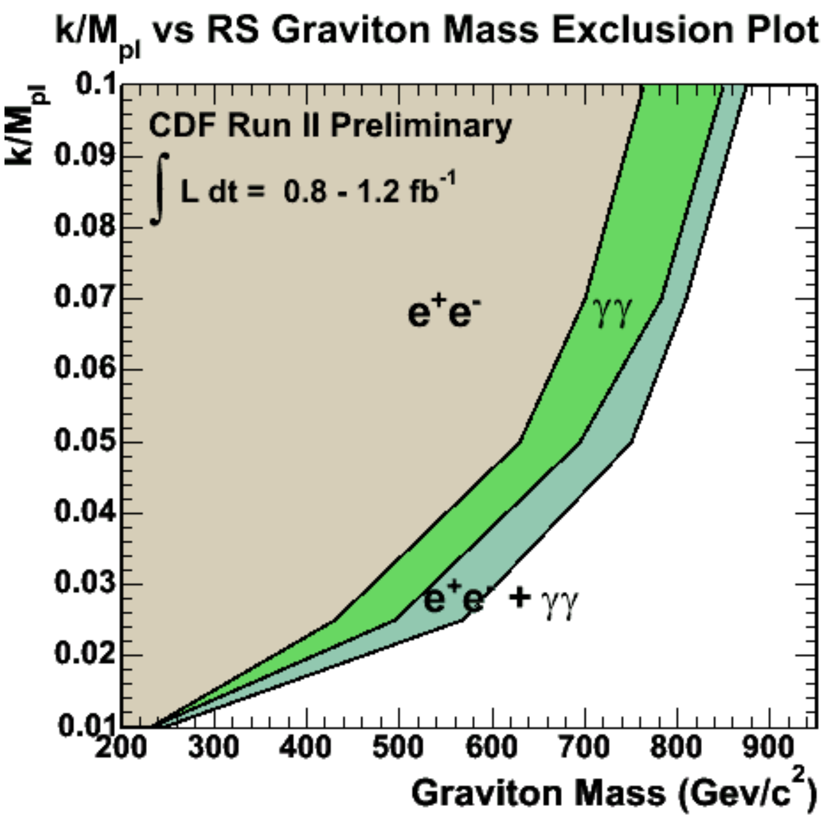
Fit function: $y = \left(x^{0.1} + \alpha_5 x^{\alpha_6}\right)\left(e^{x/\alpha_0} + \alpha_1 e^{x/\alpha_2} + \alpha_3 e^{x/\alpha_4}\right), \quad x = M_{\gamma\gamma} - 30$

Di-Photon Peaks: Randall-Sundrum Gravitons

- Limit for $k/M_{pl}=0.1$
  - Di-photons: M(G)>850 GeV
  - Combined with e^+e^-: M(G)>875 GeV

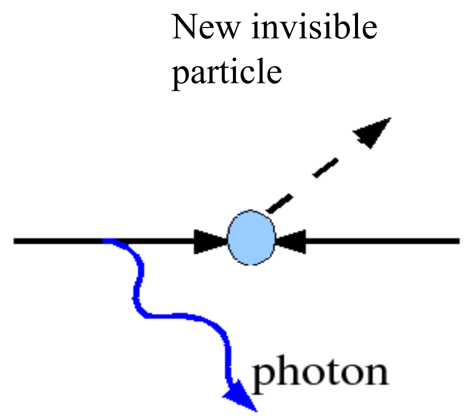


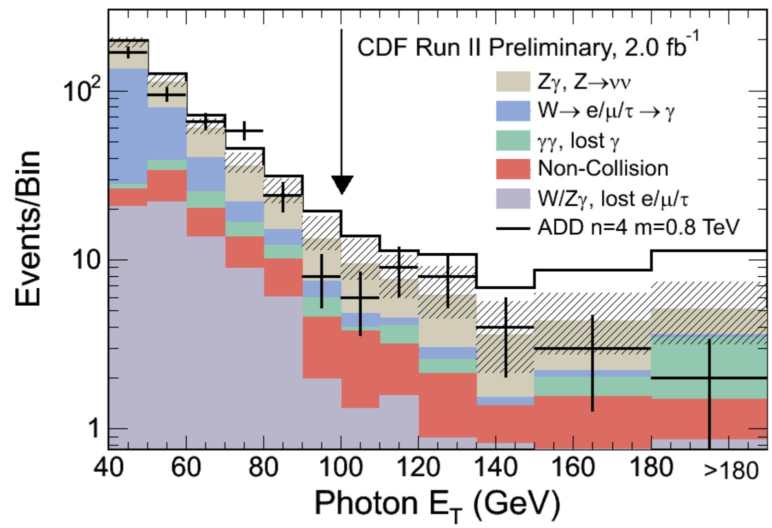




Exclusive γ+MET

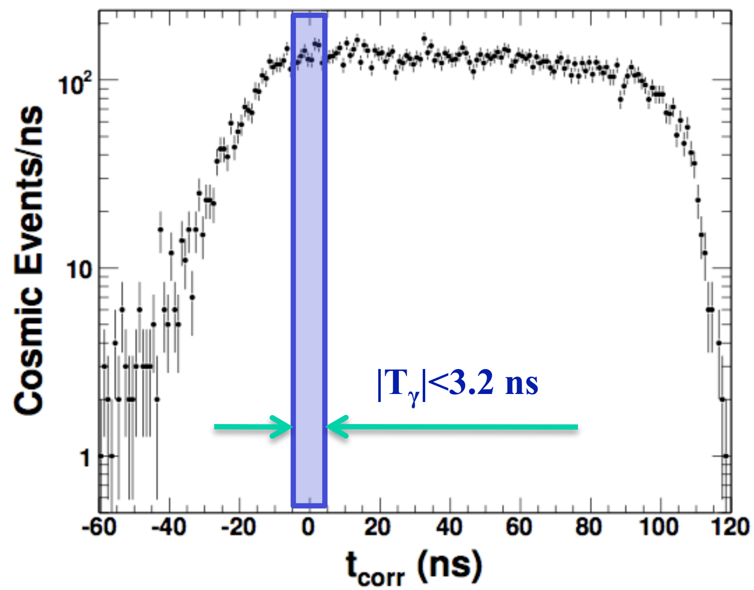
- **Models with exclusive γ+MET signature**
  - Large Extra Dimensions: $q + \overline{q} \rightarrow G + \gamma$
  - Anomalous Zγ coupling
  - Heavy right-handed neutrinos
- **Analysis**
  - $E_T(\gamma)$>50 GeV & MET>50 GeV;
  - veto E_T(jet)>15 GeV & P_T(track)>10 GeV
  - Require at least 3 tracks





Exclusive γ+MET: Analysis Technique

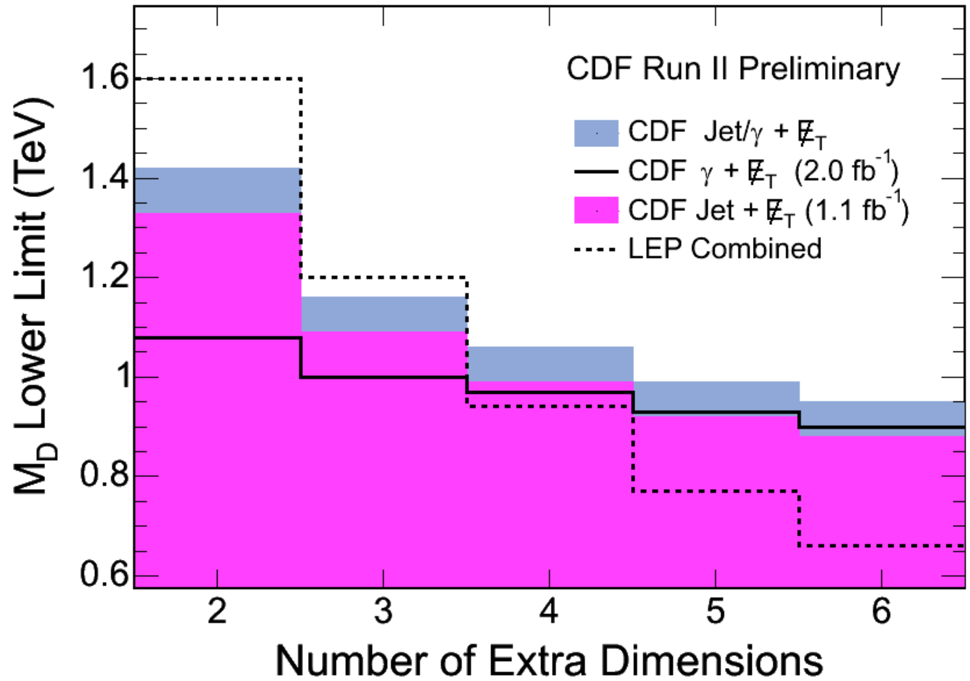
	$E_T^\gamma > 50$ GeV	$E_T^\gamma > 90$ GeV
$W(e/\tau \rightarrow \gamma)$	**24.7%**	**7.7%**
$W\gamma$	**21%**	**11%**
$\gamma\gamma \rightarrow \gamma$ (lost γ)	6.6%	4.9%
cosmics	13%	21%
$Z\gamma \rightarrow \nu\nu\gamma$	**35.6%**	**54%**
Total Bckg	280.5±15.7	46.3±3.0
Data	280	40



- Non-collision background rejection is critical
  - EM timing: $|T_\gamma|<3.2$ ns
  - Track requirements
  - Relevance Vector Machine: train on γ+jet and out-of-time cosmic events
  - Cosmic rejection: x600
- EWK backgrounds
  - Fake rates; data based

Exclusive γ+MET: Limits on LED

	$\gamma + \not\!\!E_T$		Jet $+ \not\!\!E_T$		Combined
n	α	M_D^{obs}	α	M_D^{obs}	M_D^{obs}
2	7.2	1080	9.9	1310	1400
3	7.2	1000	11.1	1080	1150
4	7.6	970	12.6	980	1040
5	7.3	930	12.1	910	980
6	7.2	900	12.3	880	940



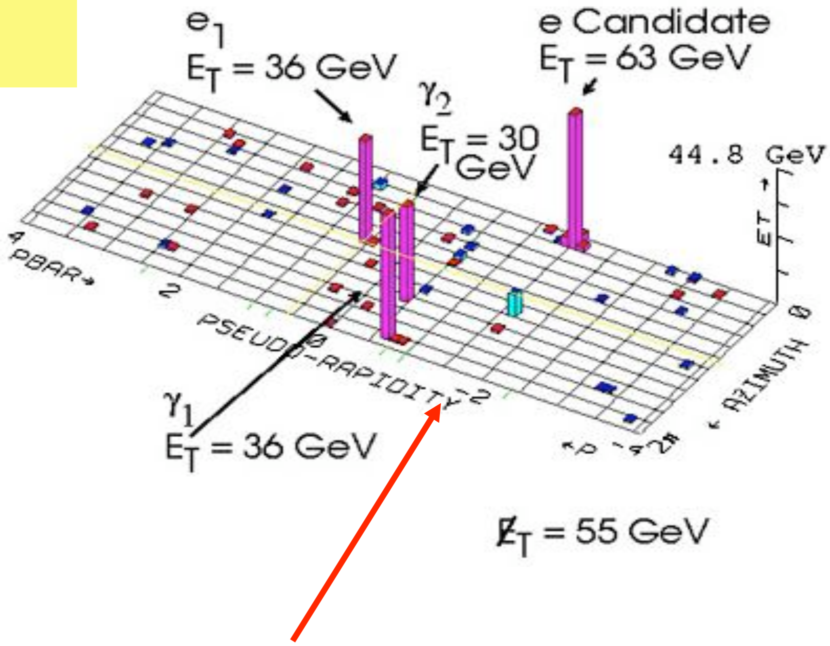
- Optimization for LED: $E_T(\gamma)$>90 GeV
  - Signal acceptance: 2.7%

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

- Why $\gamma\gamma$+X? Why model-independent

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

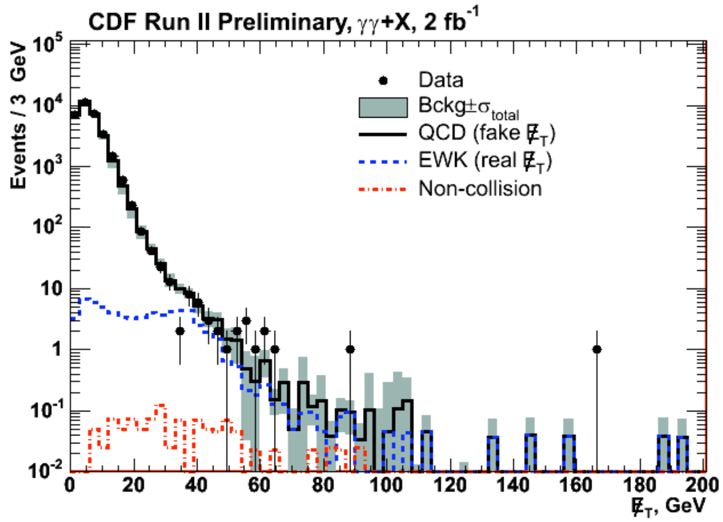
- Rare $\gamma\gamma$+X events at Tevatron
  - Infamous CDF Run I "ee$\gamma\gamma$+MET" event
    - Dominant SM: WW$\gamma\gamma$ ⇒ 8×10^{-7} events
    - Total: $\sim10^{-6}$ events
  - CDF & D0 Run II "e$\gamma\gamma$+MET" event

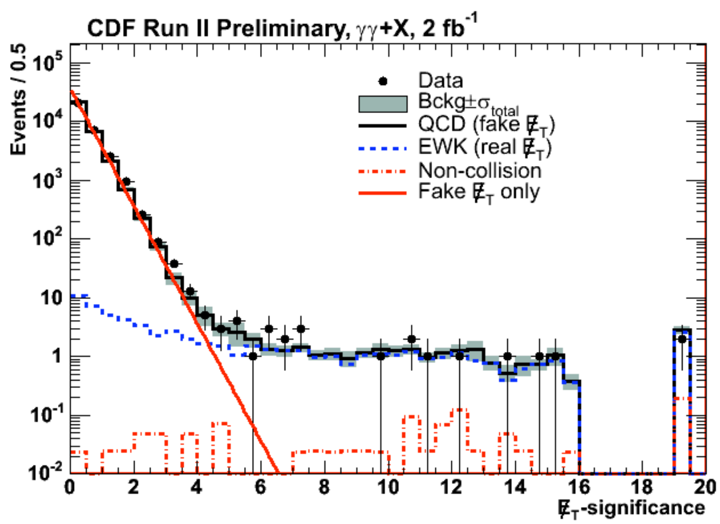


Search for Anomalous Production of $\gamma\gamma$+X

- Three $\gamma\gamma$+X analyses: X=MET, τ, e/μ
- Signal region
  - Two "tight" central photons
  - Photon candidate E_T>13 GeV
  - ~25% $\gamma\gamma$ pure events
- Control region
  - Two "loose" central photons, at least one photon must fail "tight" photon ID
  - Photon candidate E_T>13 GeV
  - ~5% $\gamma\gamma$ pure events
  - Same backgrounds as in signal region
- Results
  - Event count; background predictions; kinematic distributions

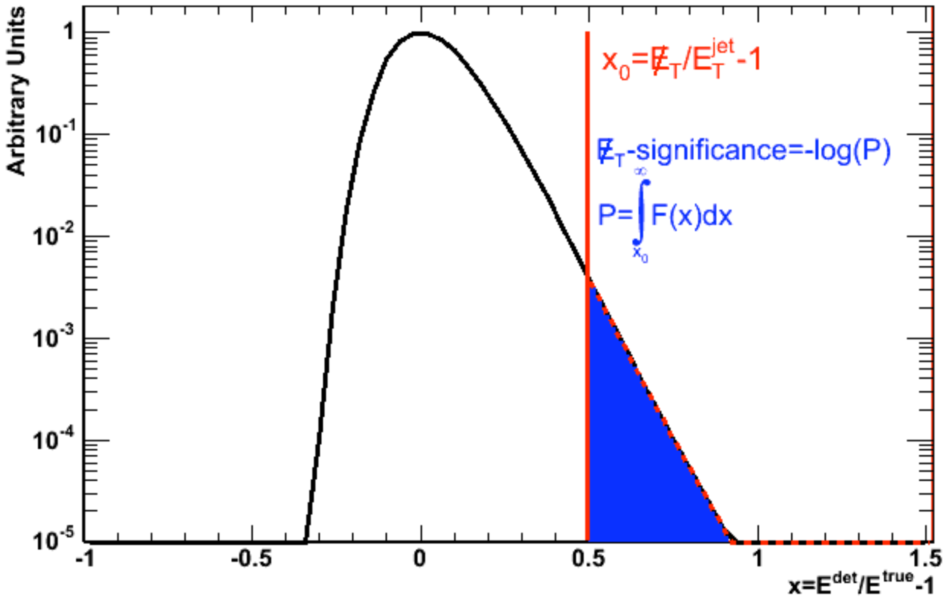
Search for Anomalous $\gamma\gamma$+MET





- Two photons in time with collision
- Select events with MET-sig>3,4,5
- Backgrounds
  - QCD with fake MET ($\gamma\gamma$, γj, jj)
    - MET Resolution Model
      - ✓ fake MET p.d.f for each event based on energy resolution (for jets and soft unclustered energy)
  - EWK with true MET
    - W/Z+γ, W/Z+jet, $Z\rightarrow\tau\tau\rightarrow\gamma_{fake}\gamma_{fake}$
    - shapes from MC; normalized to data e+γ
  - Non-collision
    - Beam Halo, Cosmics, PMT spikes
    - EM timing, topological cuts

MET Resolution & Significance Model



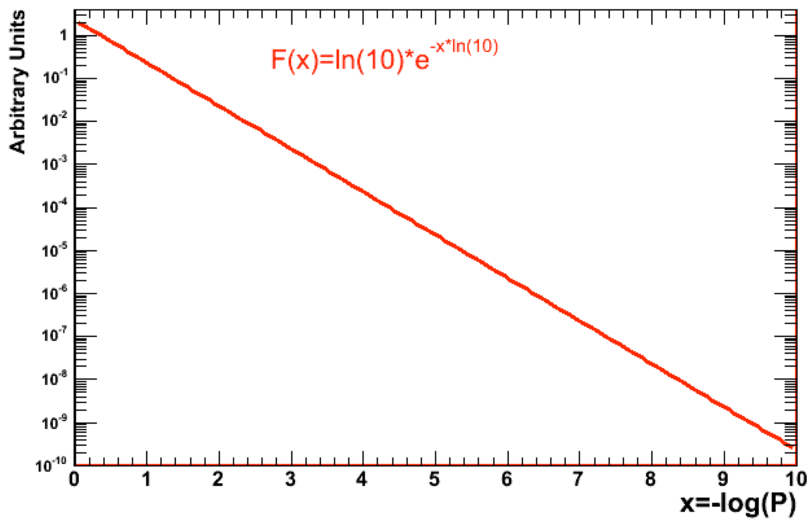
- Takes into account individual jet resolution
- Accounts for relative direction of MET and jet
- Eliminates need for Δφ(MET-jet) cuts

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

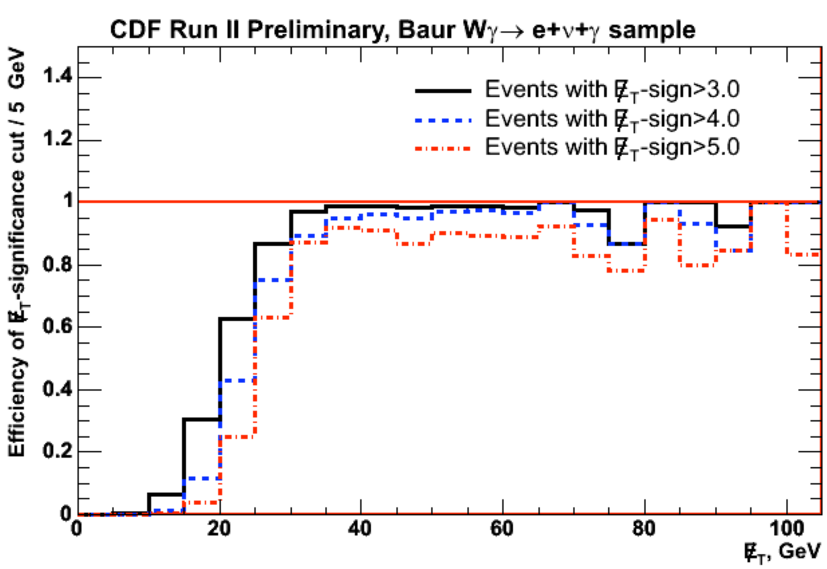
Simple shape for any distribution F(x)

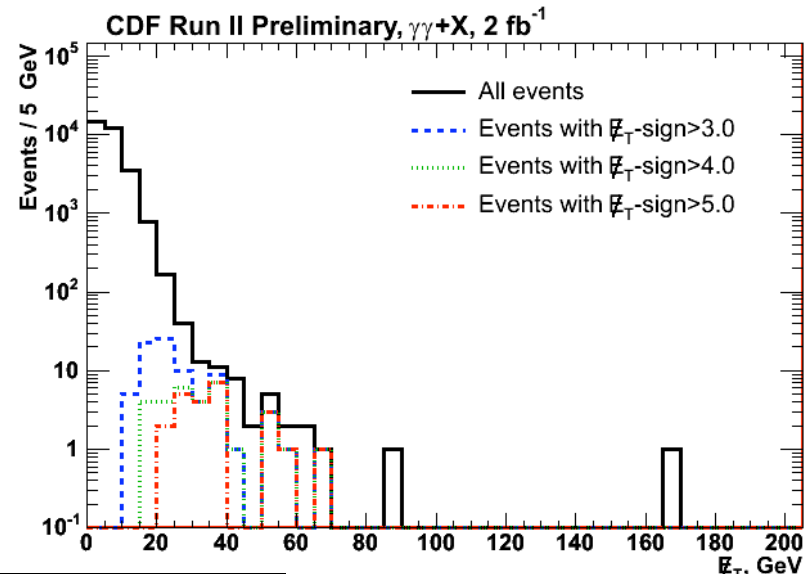
For 10,000 events:

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



γγ+MET: Results



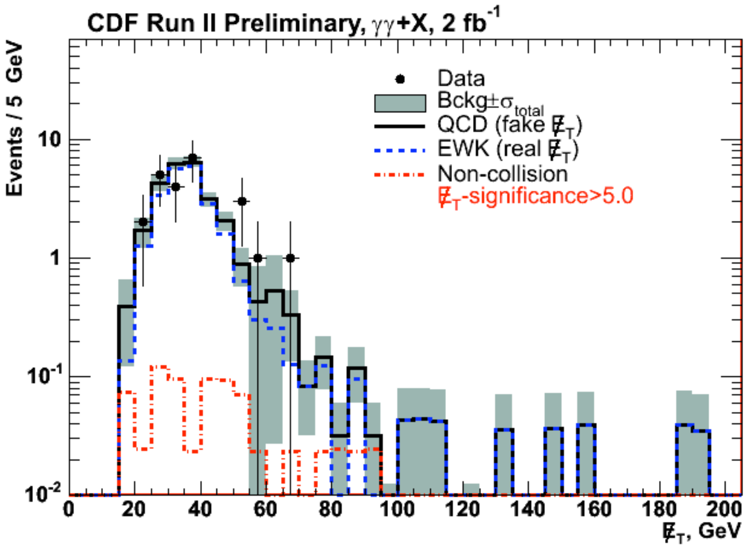


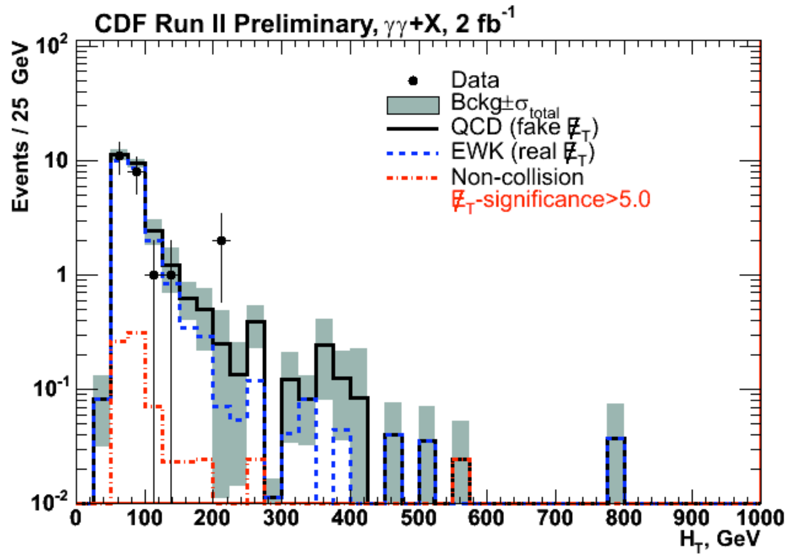
Efficiency for Wγ→eνγ	MetSig>3.0	MetSig>4.0	MetSig>5.0
	84%	74%	67%

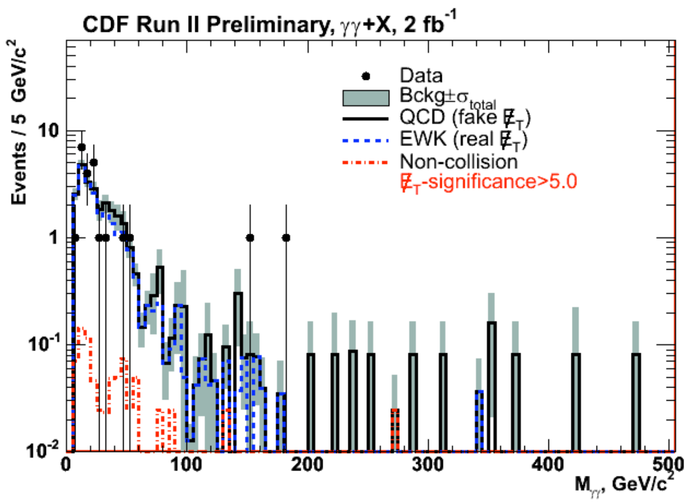
- Total number of γγ events: 31,116

	MetSig>3.0	MetSig>4.0	MetSig>5.0
EWK	47%	75%	84%
Background	67.9±7.5	35.8±3.0	27.3±2.3
Data	82	31	23

Results for γγ+MET: After Metsig>5 Cut

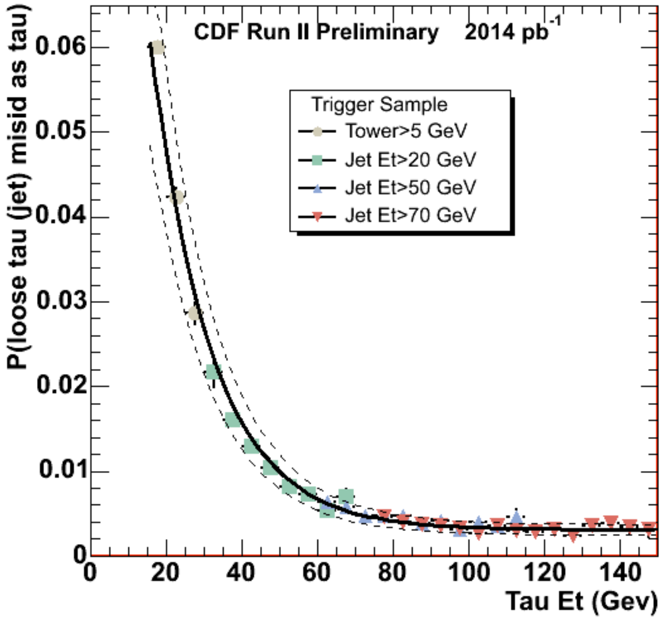




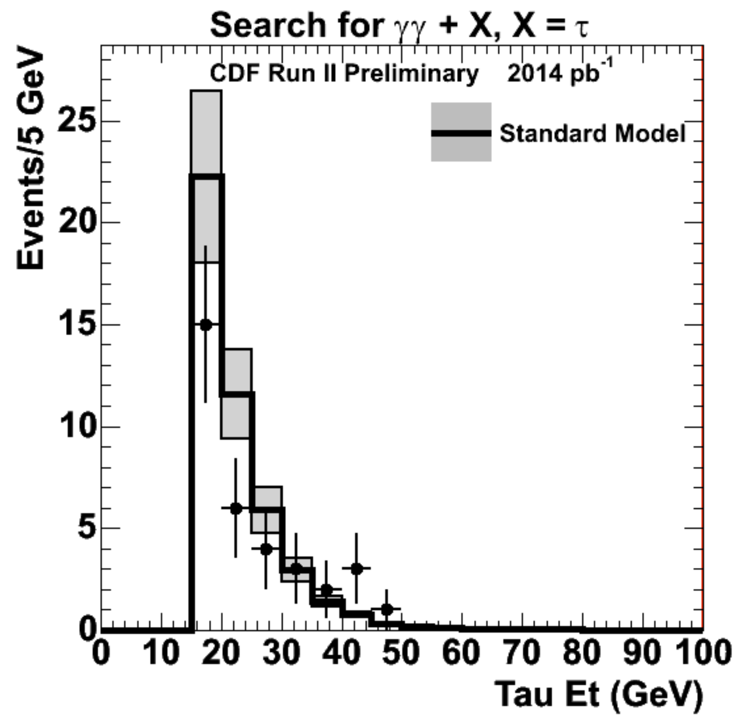


- Top left: MET
- Top right: H_T
- Bottom: $M_{\gamma\gamma}$

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



Data	40
Bckg	46±10
Fakes	44±10
Wγ	1.2±0.7
Zγ	1.0±0.7



- Visible "hadronic" tau E_T>15 GeV
  - jet→τ fake rate from di-jet events
  - γγ+jet × fake rate
  - Test technique in control sample

- Backgrounds
  - Dominant: γγ+jet fake
  - Real τ from Wγ or Zγ
    - From MC

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

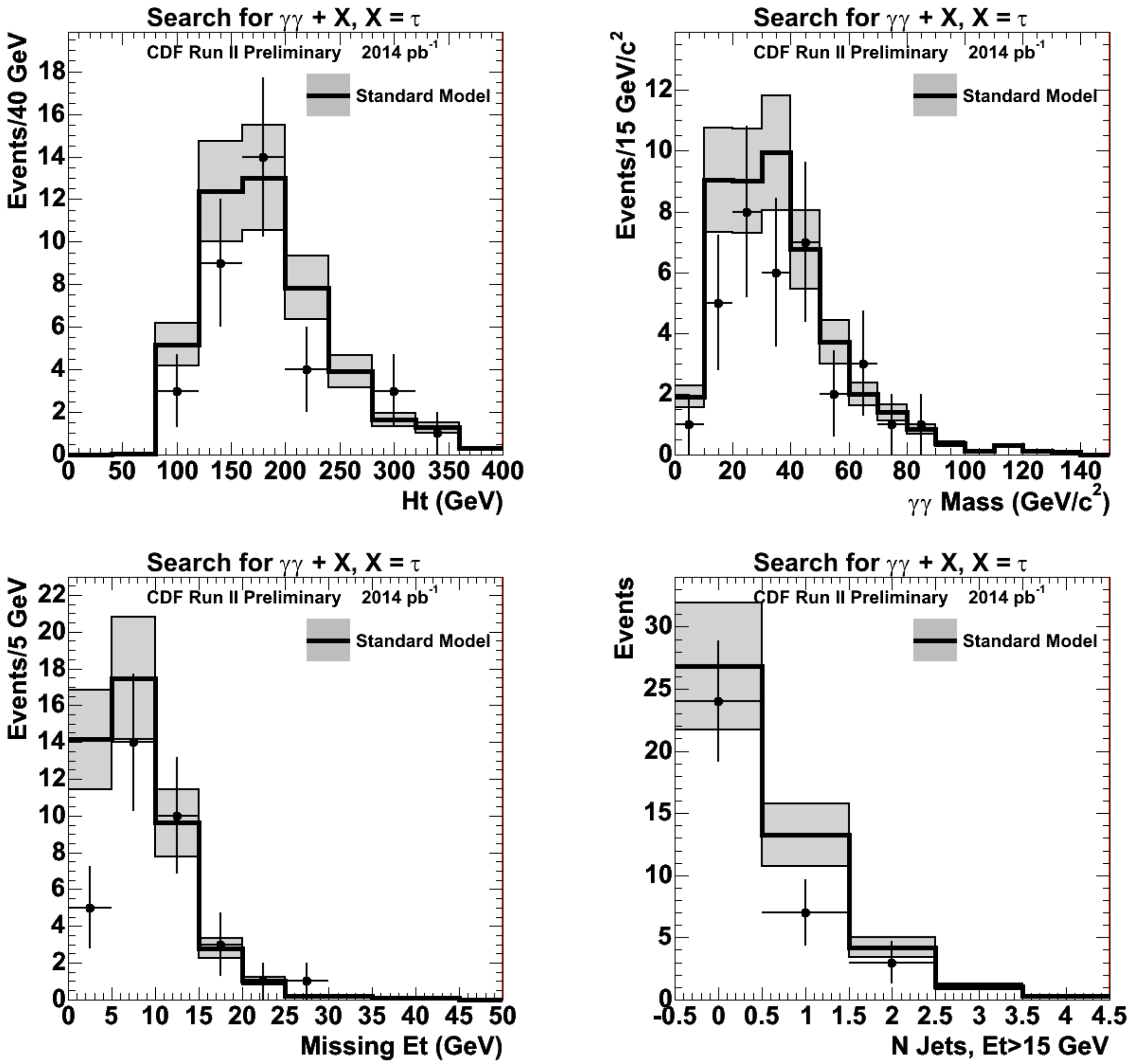
H_T

$M_{\gamma\gamma}$

MET

N_{jet}

Jet E_T>15 GeV



Search for Anomalous $\gamma\gamma$+e/μ

- Central or forward electron with E_T>20 GeV
- Central muon with P_T>20 GeV
- Backgrounds
  - W$\gamma\gamma$+Z$\gamma\gamma$ (from MC)
  - γ+lepton+ele→fake γ (dominant for $\gamma\gamma$e)
  - $\gamma\gamma$+fake lepton
  - γ+lepton+jet→fake γ

From data
Using fake rates

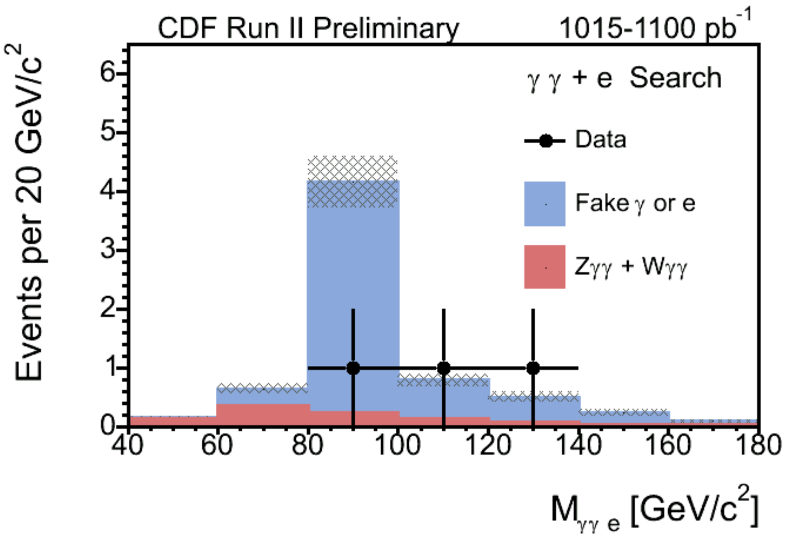
Before Phoenix rejection

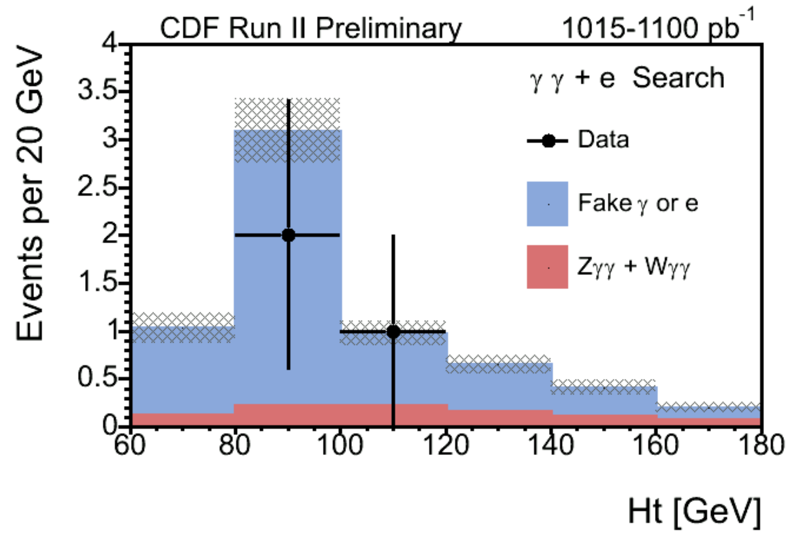
	$\gamma\gamma$+e	$\gamma\gamma$+μ
Data, 1 fb^{-1}	3	0
Bckg	6.82±0.75	0.79±0.11
W$\gamma\gamma$+Z$\gamma\gamma$	16%	81%
γl+e→γ	75%	2%

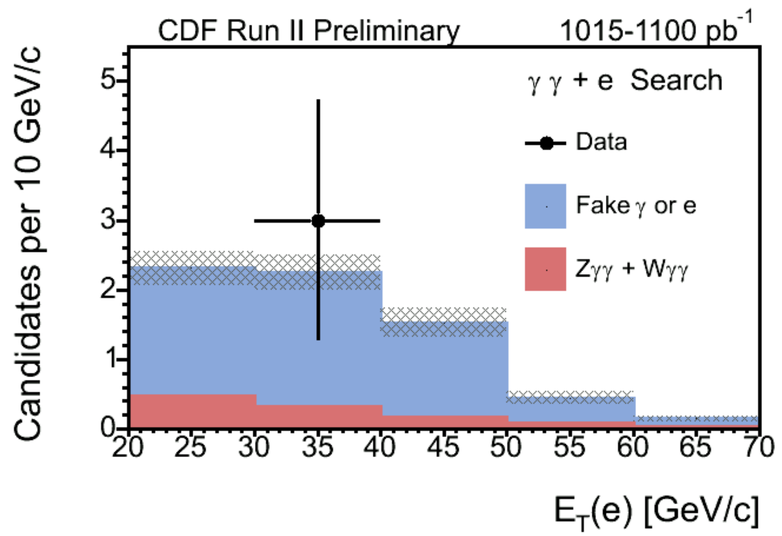
After Phoenix rejection

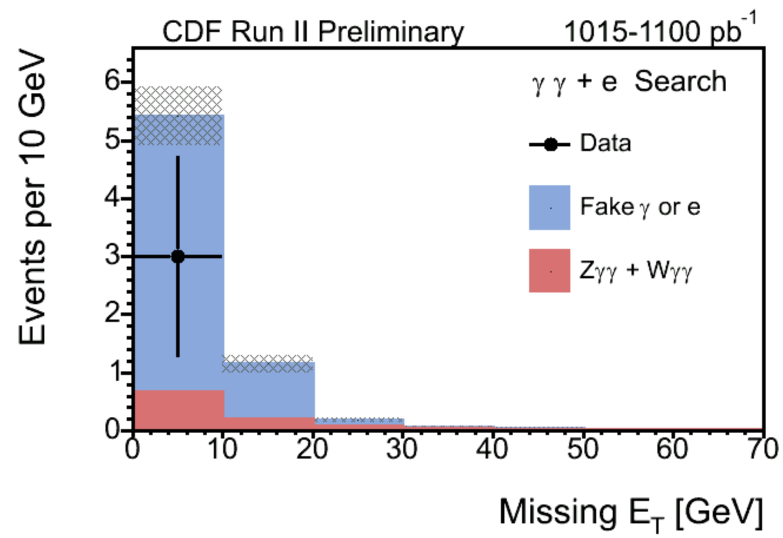
	$\gamma\gamma$+e	$\gamma\gamma$+μ
Data, 1 fb^{-1}	1	0
Bckg	3.79±0.54	0.71±0.10
W$\gamma\gamma$+Z$\gamma\gamma$	26%	81%
γl+e→γ	60%	<1%

Search for Anomalous γγ+e

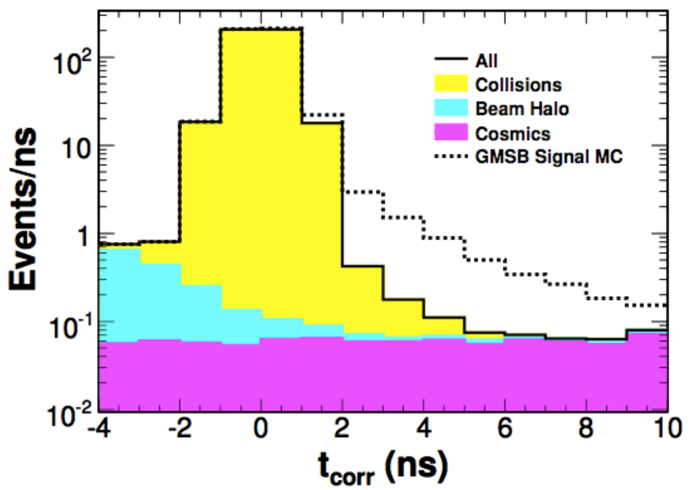


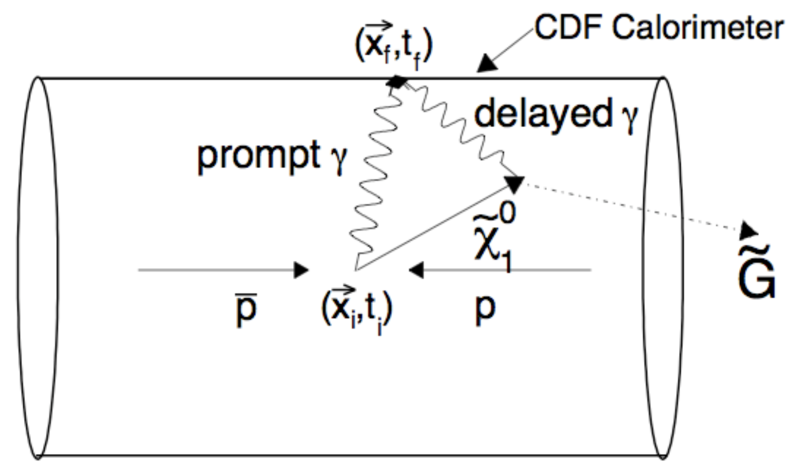




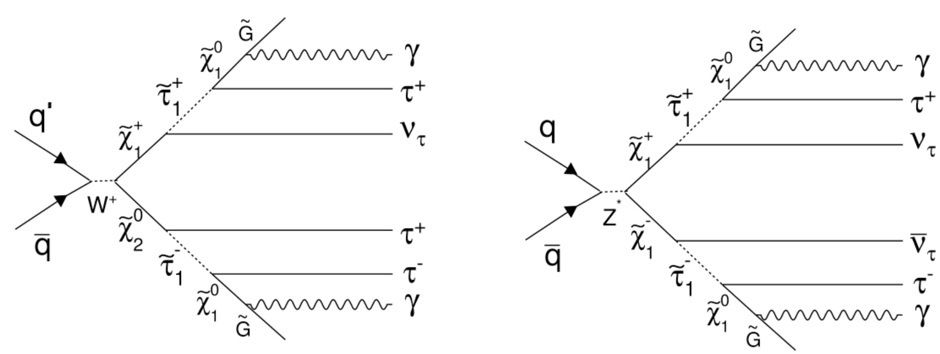


"Delayed" Photons

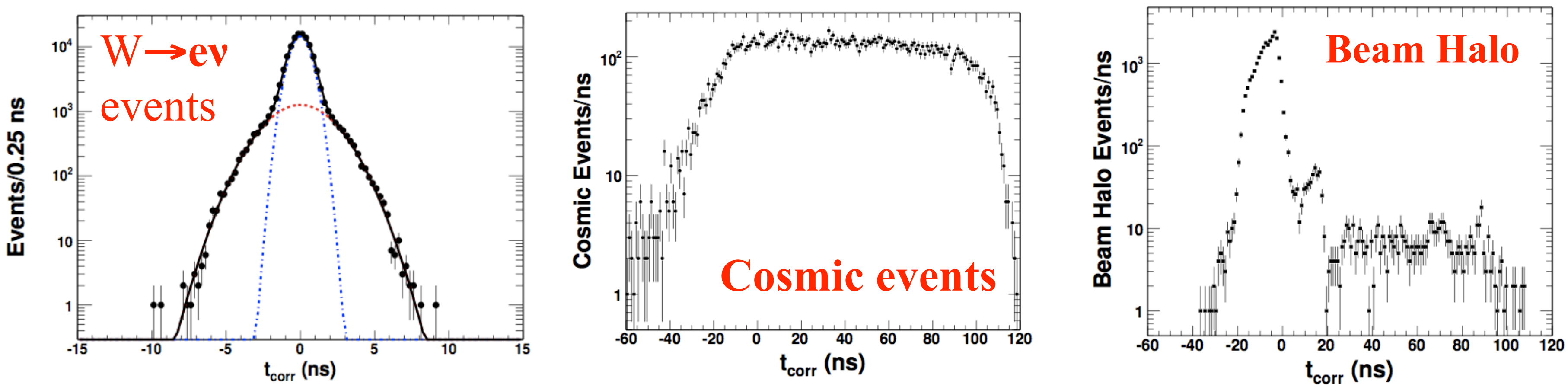




- **Gauge-Mediated SUSY**
  - $\chi^0 \rightarrow \gamma + G$ decays can occur with finite lifetime
  - Signature: at least one "delayed" photon, MET, jet (from τ's)



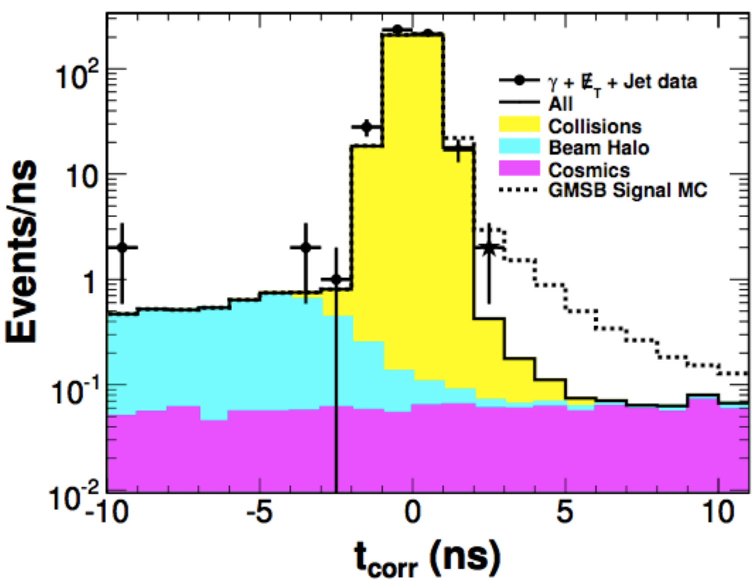
"Delayed" Photons: Analysis Technique

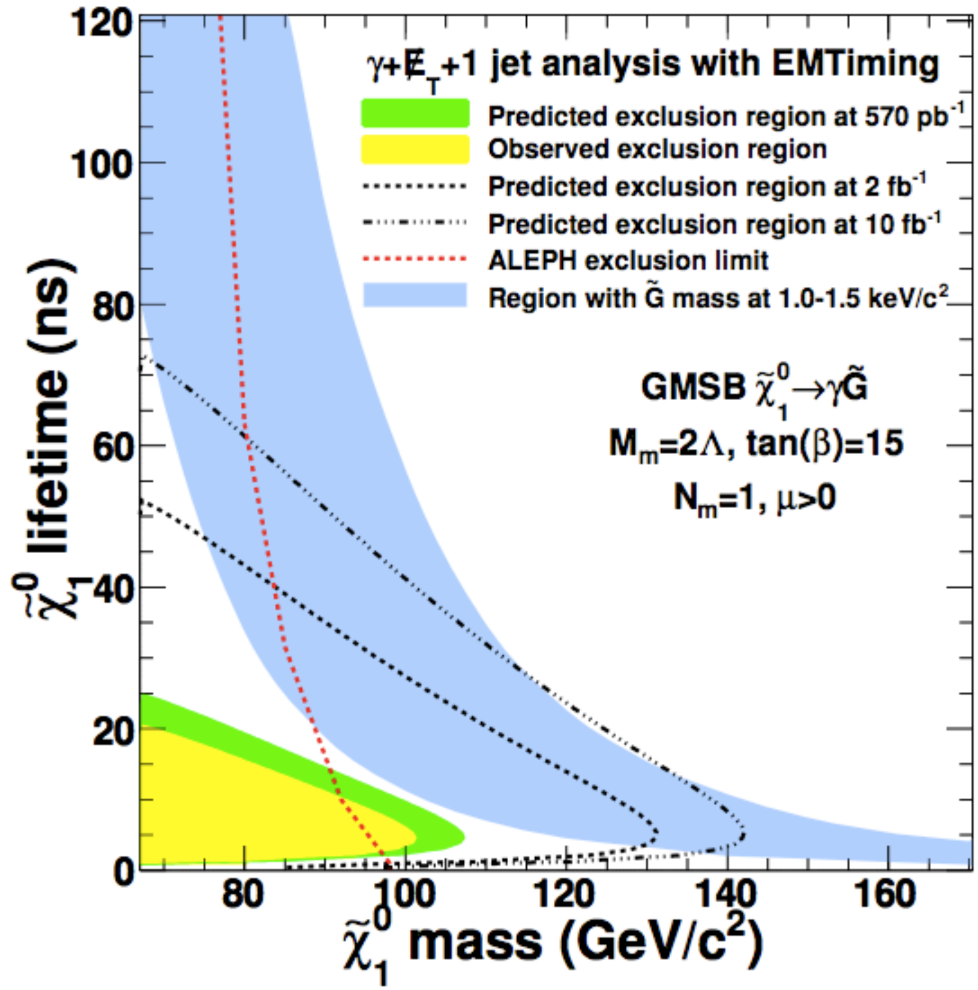


It is all about timing distribution shapes !!

- **Selection**
  - $E_T(\gamma)$>30 GeV; MET>40 GeV; E_T(jet)>35 GeV; $\Delta\varphi$(MET-jet)>1.0 rad
  - Signal region: 2 ns<T_γ<10 ns
- **Analysis feature**
  - All backgrounds estimated from purely data
  - Don't need to consider different sources of SM backgrounds

"Delayed" Pho+Jet+MET





- **Result**
  - Data: 2 events
  - Background: 1.3±0.7;
    - SM=0.71;
    - Cosmics=0.46;
    - Beam Halo=0.07

γ+jet+b+MET

- Follow up on Gauge-Mediated SUSY models
  - Renewed interest motivated by Run I ee+$\gamma\gamma$+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

- Event selection
  - Central photon E_T>25 GeV
  - 2 jets: E_T>15 GeV & $|\eta|$<2
  - MET>25 GeV
  - $\Delta\varphi$(jet,MET)>0.3
  - At least 1 b-tag (SecVtx)

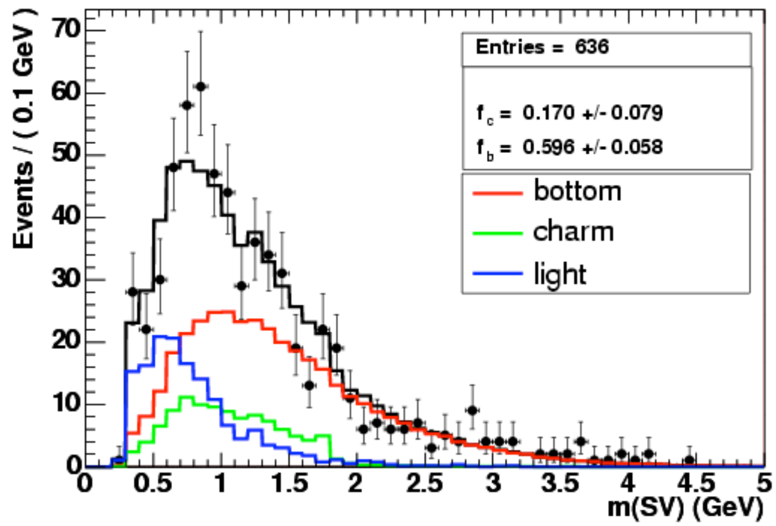
Background categories

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

γ+jet+b+MET: Backgrounds

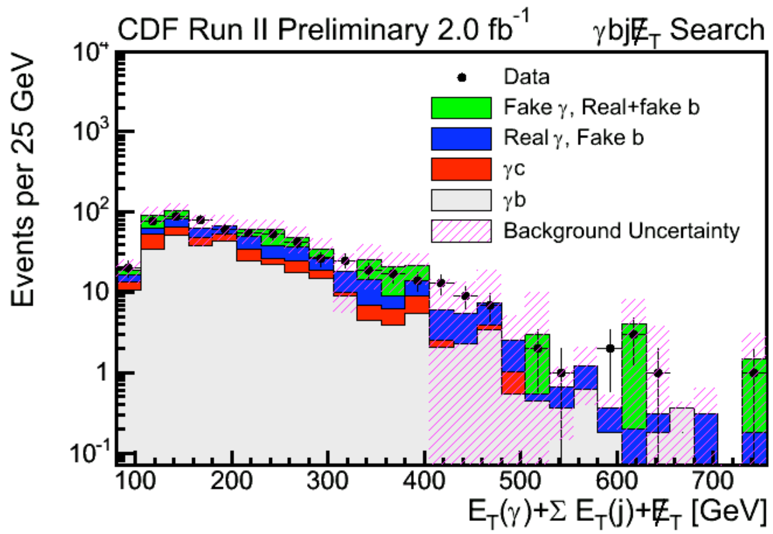
	Real γ	Fake γ
Real b-tag	A	B
Fake b-tag	C	D

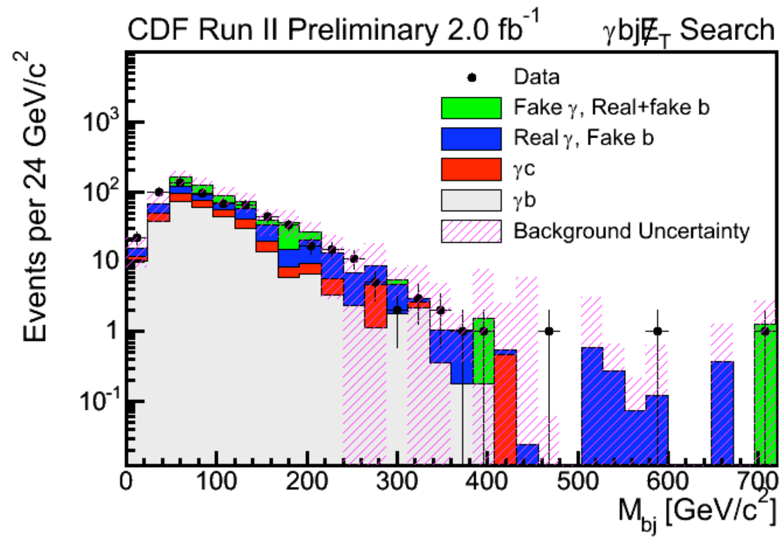
- **Background A:**
  - MadGraph MC: γ+b+jets, γ+c+jets
  - Normalized based on photon purity & H.F. fractions
- **Backgrounds B & D:**
  - Fake photon subtraction based on CES/CP2 method
  - Photon purity: 81%±12%
- **Background C:**
  - γ+jet+jet × mis-tag rate
  - CES/CP2 method to subtract fake photon contribution

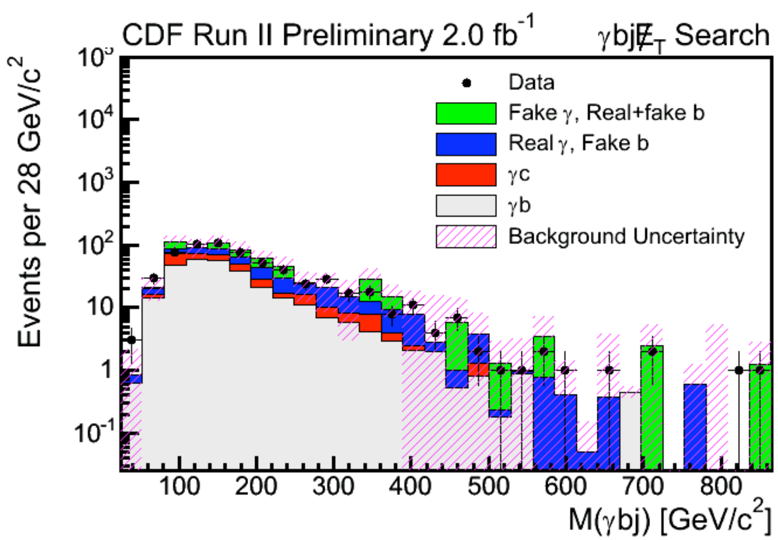


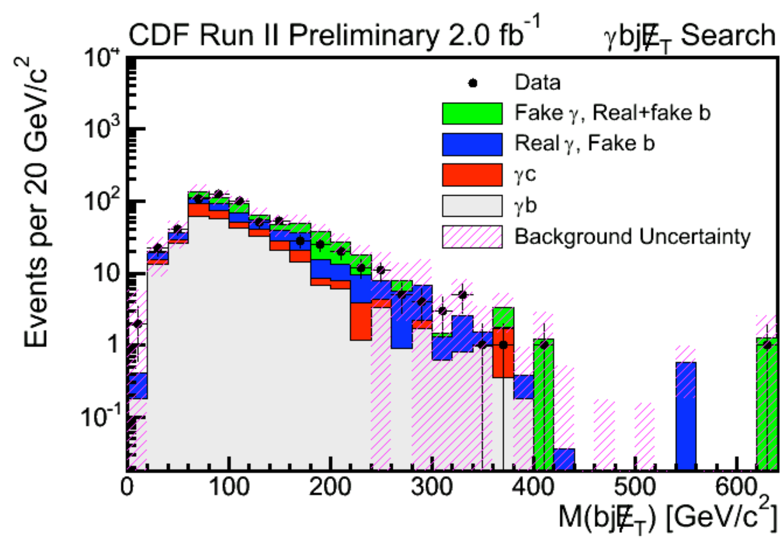
Data: 617
Background: 637±139

γ+jet+b+MET: Kinematic Distributions









γ+lepton+b+MET

Search for New Physics in $\ell\gamma \not{E}_T b$ Events and $\sigma_{t\bar{t}\gamma}$ measurement

Motivation

- Extension of $\ell\gamma \not{E}_T$
- Signature with b and t, W and γ
- $t\bar{t}\gamma$: control sample for $t\bar{t}H$ (LHC), Q(top)

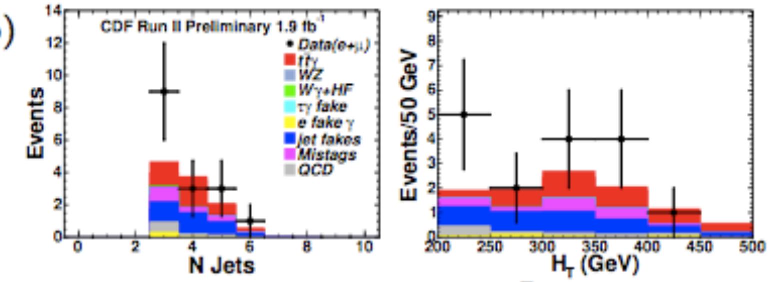
Results

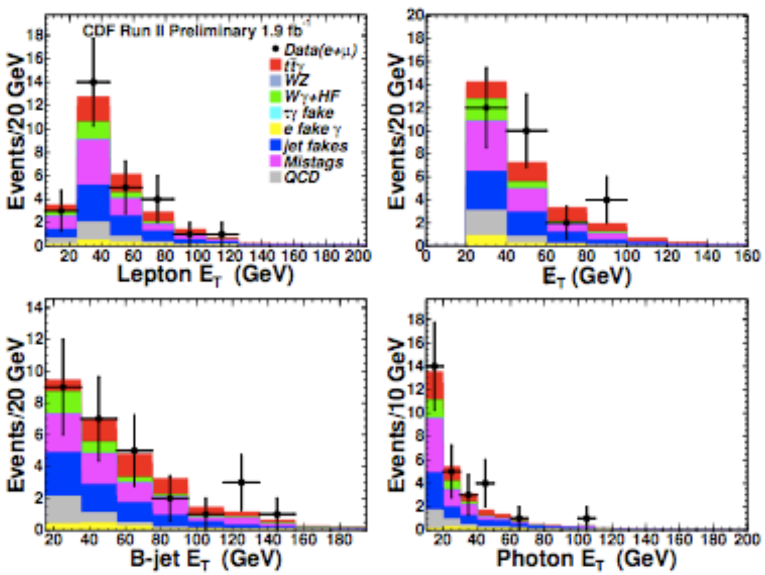
CDF Run II Preliminary, 1.9fb^{-1}

$\ell\gamma\not{E}_T b$	$e\gamma\not{E}_T b$	$\mu\gamma\not{E}_T b$	$(e+\mu)\gamma\not{E}_T b$
Expected	16.8 ± 2.2	$11.1^{+1.7}_{-1.4}$	$27.9^{+3.6}_{-3.5}$
Observed	16	12	28

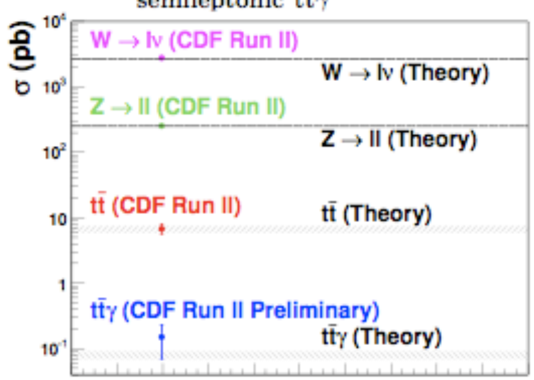
CDF Run II Preliminary, 1.9fb^{-1}

$t\bar{t}\gamma$	$t\bar{t}\gamma(e)$	$t\bar{t}\gamma(\mu)$	$t\bar{t}\gamma(e+\mu)$
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





The probability, assuming no true $t\bar{t}\gamma$ Standard Model (SM) signal, for the background alone to produce at least as many events (16) as observed in data, is 1% (2.3 σ). Assuming SM $t\bar{t}\gamma$ production, we calculate the $t\bar{t}\gamma$ cross-section to be $\sigma_{\text{semileptonic } t\bar{t}\gamma} = \mathbf{0.15 \pm 0.08}$ pb. SM prediction is $\sigma^{SM}_{\text{semileptonic } t\bar{t}\gamma} = \mathbf{0.080 \pm 0.011}$ **pb.**

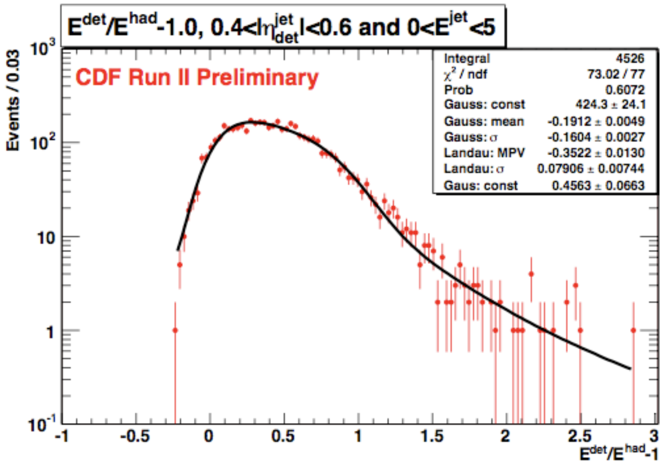


Summary

- CDF has very reach program of searches for new physics in final states with photons
  - Many channels: photon+ leptons, jets, b-jets, MET
  - 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
- Most interesting times are still ahead !!

Backup Slides

J.E.R.- Key Part of MET Resolution Model

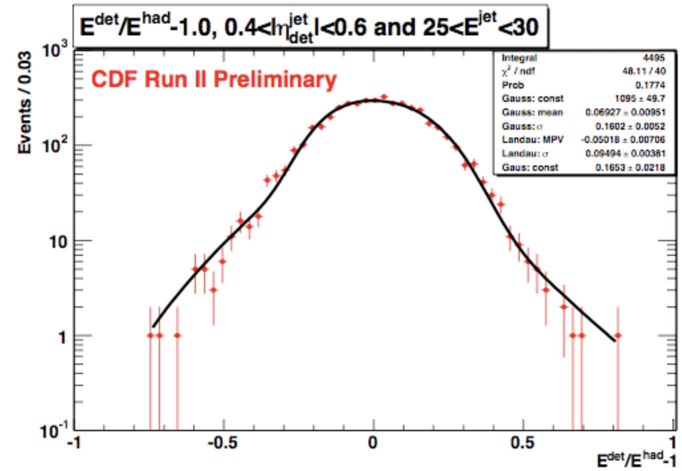


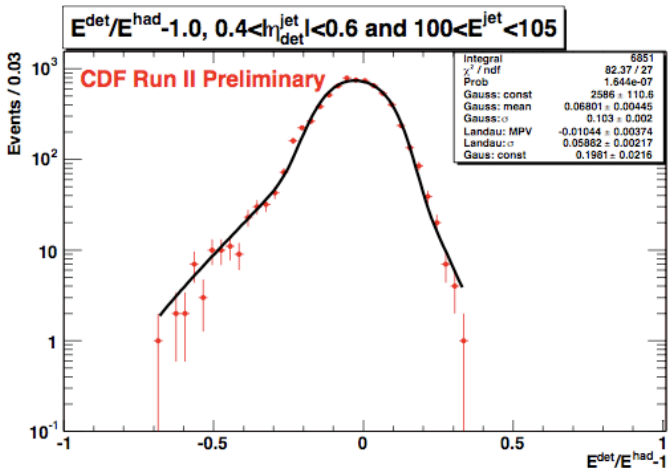
Gauss+Landau fits JER well at any E_{jet} and η

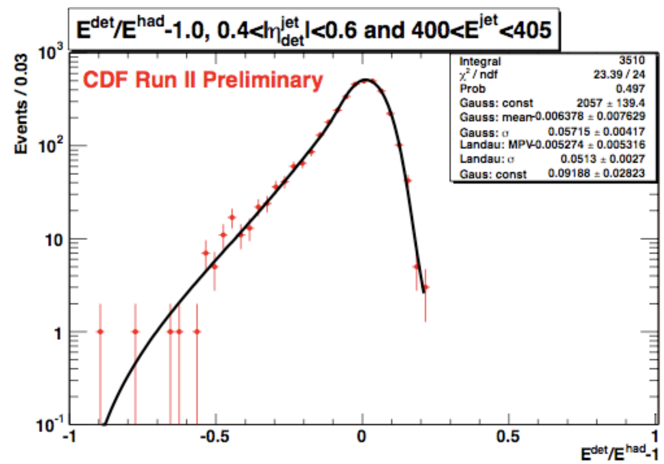
$$\frac{C*G(y)+L(y)}{1+C},$$

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

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

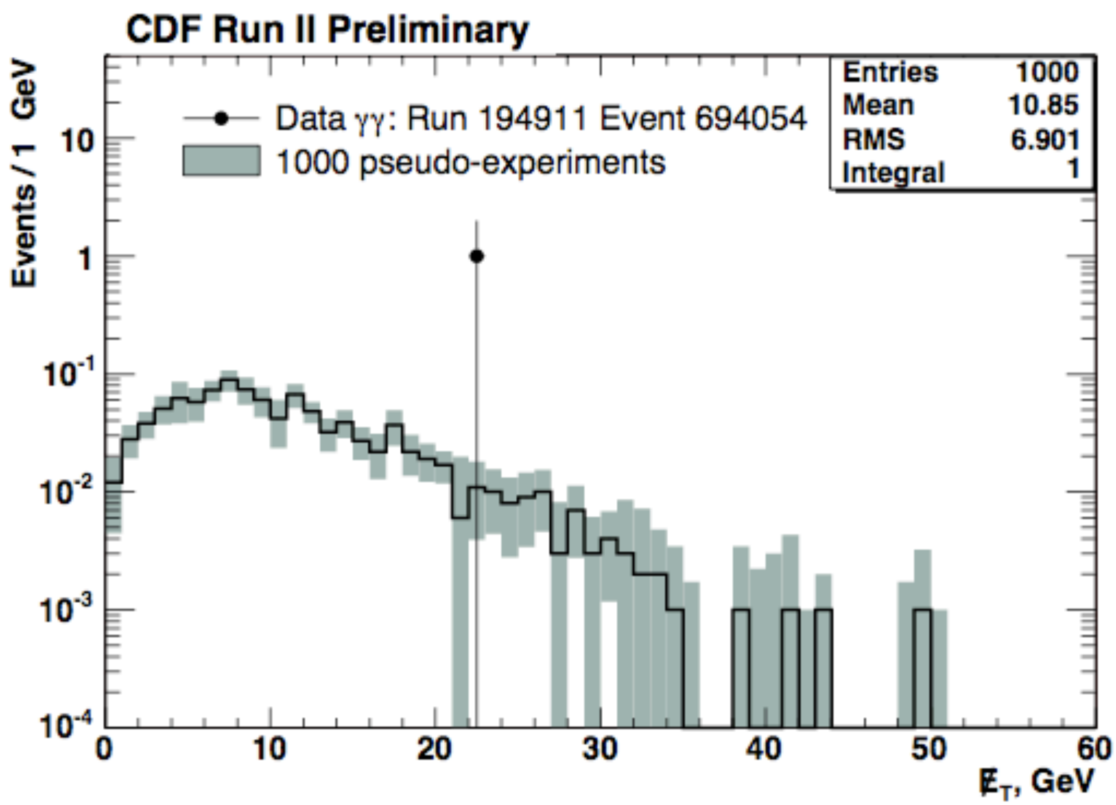






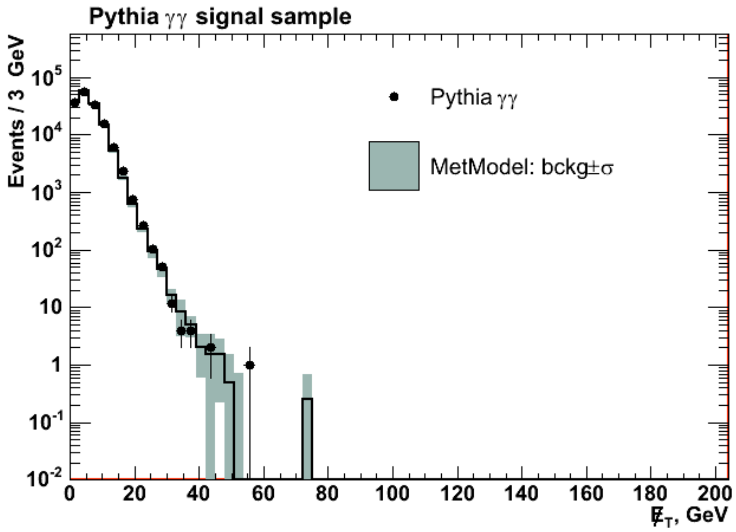
- ✓ Smooth parameterization of JER as a function of E_{jet} in bins of η_{det} (bin size of 0.2)

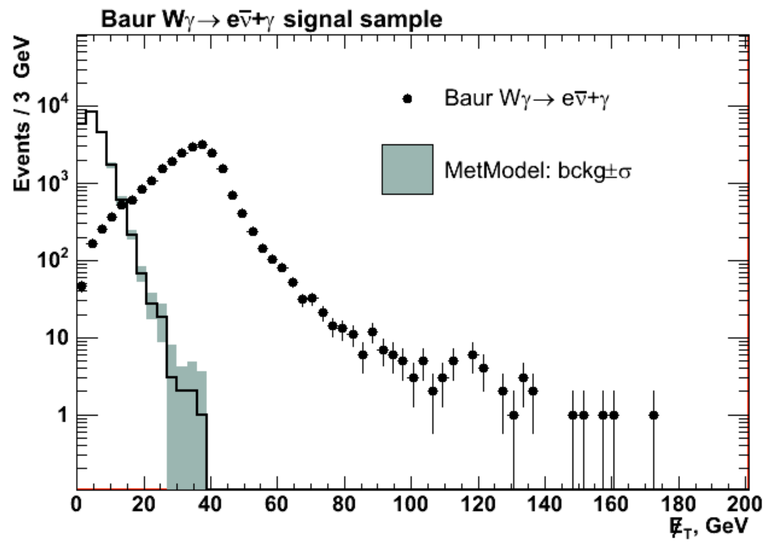
Met Model Example-1

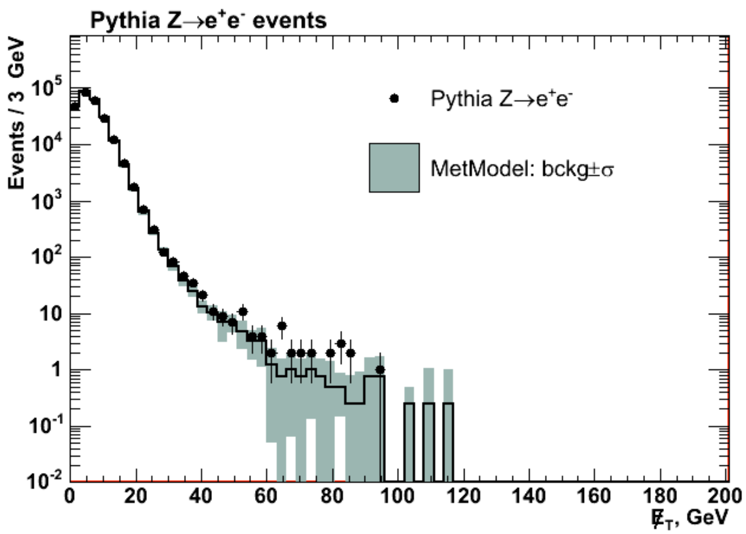


- Met Model gives a PDF of possible MET values due to energy mis-measurements (also available in XY)
  - This is done by smearing un-clustered and each jet energy according to their resolution

Met Model Example-2

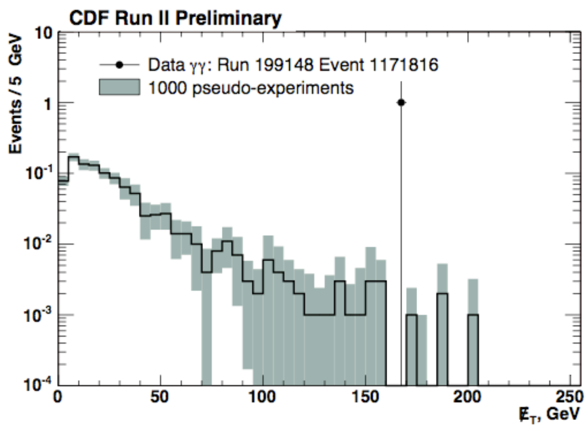


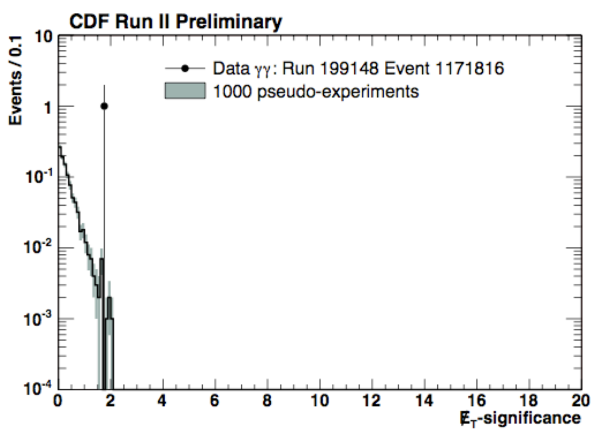




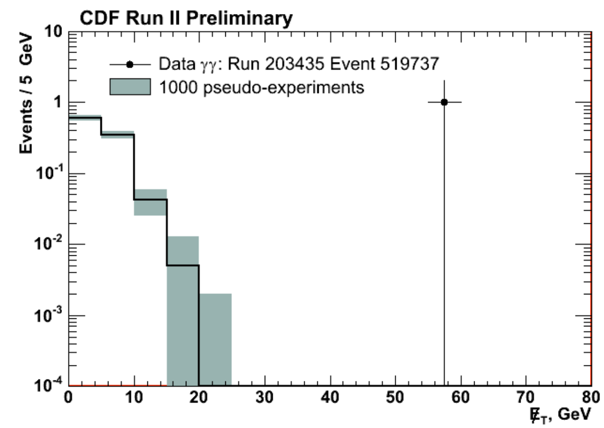
- Met Model successfully describes MET in Pythia γγ and Z events where there is no real MET
- Just as expected, it doesn't describe MET in Baur Wγ events with real MET

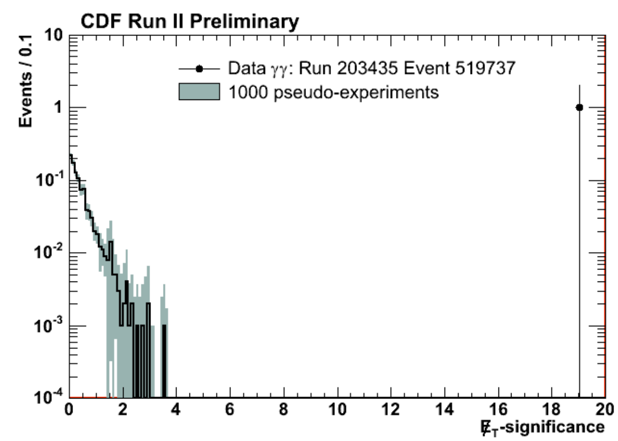
"New" MET Significance Example



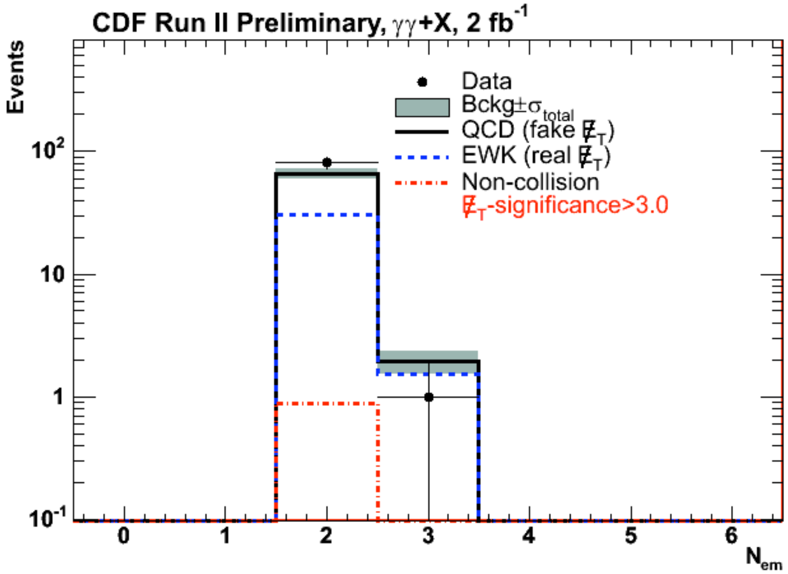


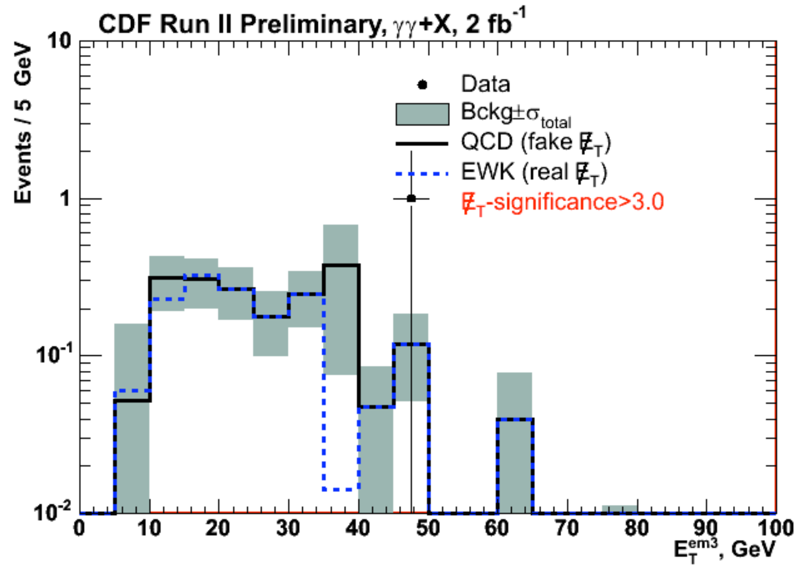
- "Old" Metsig
  - Sig=MET/∑E
- Event-1
  - largest MET
  - MET=165.1 GeV
  - METsig
    - Met Model: 1.76
    - "Old" Metsig: 7.65
- Event-2
  - MET=57.1 GeV
  - METsig
    - Metmodel: >18.0
    - "Old" Metsig: 5.45





γγ+e+MET





Object	E_T, GeV	φ	η
Pho-1	85.2	5.93	-0.303
Pho-2	24.7	2.22	-0.845
Electron	49.6	3.20	1.07
MET	15.1	2.56	N/A
H_T	174.6	N/A	

Results for $\gamma\gamma$+MET: Signal Sample

- Signal sample
  - two "tight" photons;
  - ~25% true $\gamma\gamma$ events
- $\gamma\gamma$ events before MetSig cut: 31,116

	MetSig>3.0	MetSig>4.0	MetSig>5.0
Non-collision	0.89 ± 0.32	0.84 ± 0.30	0.77 ± 0.27
"No $\gamma\gamma$ Vertex"	4.4 ± 2.0	2.5 ± 1.0	1.5 ± 0.7
$\gamma\gamma\gamma$ (lost γ)	2.9 ± 1.0	2.2 ± 1.0	1.6 ± 1.0
Fake Met (MetModel)	**28.1 ± 6.8**	**3.6 ± 1.8**	**0.60 ± 0.83**
EWK real MET	**31.6 ± 2.0**	**26.7 ± 1.9**	**22.8 ± 1.7**
Total	**67.9 ± 7.5**	**35.8 ± 3.0**	**27.3 ± 2.3**
Observed	82	31	23

Results for $\gamma\gamma$+MET: Control Sample

- Control sample
  - Two "loose" photons; at least one photon fails "tight" ID cuts;
  - ~5% true $\gamma\gamma$ events
- $\gamma\gamma$ events before MetSig cut: 42,708

	MetSig>3.0	MetSig>4.0	MetSig>5.0
Non-collision	1.29 ± 0.47	1.18 ± 0.42	1.03 ± 0.36
"No $\gamma\gamma$ Vertex"	1.35 ± 0.62	0.78 ± 0.30	0.45 ± 0.22
$\gamma\gamma\gamma$ (lost γ)	4.4 ± 1.5	3.2 ± 1.4	2.4 ± 1.4
Fake Met (MetModel)	**38.5 ± 11.0**	**5.7 ± 1.3**	**0.80 ± 0.36**
EWK real MET	**43.7 ± 5.4**	**35.4 ± 4.7**	**32.2 ± 7.8**
Total	89.2 ± 12.4	46.2 ± 5.1	36.9 ± 8.0
Observed	103	50	28

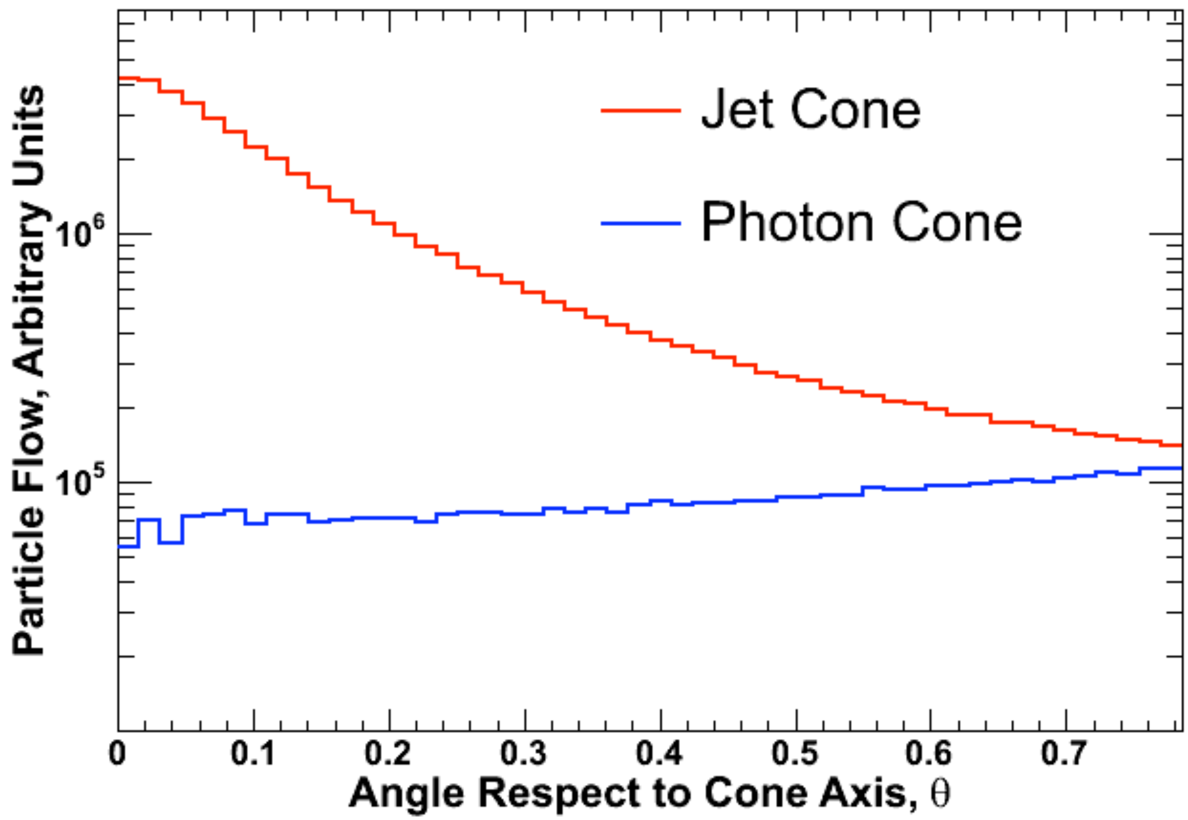
γ+lepton+b+MET

CDF Run II Preliminary, 1.9fb^{-1}			
Lepton + Photon + $\not\!\!E_T$ + b Events, Isolated Leptons			
Standard Model Source	$e\gamma b\not\!\!E_T$	$\mu\gamma b\not\!\!E_T$	$(e+\mu)\gamma b\not\!\!E_T$
$t\bar{t}\gamma$semileptonic	2.06 ± 0.38	1.52 ± 0.28	3.58 ± 0.65
$t\bar{t}\gamma$ dileptonic	1.30 ± 0.23	1.02 ± 0.18	2.32 ± 0.41
$W^{\pm}c\gamma$	0.75 ± 0.16	0.72 ± 0.15	1.47 ± 0.26
$W^{\pm}c\bar{c}\gamma$	0.08 ± 0.04	0.22 ± 0.06	0.30 ± 0.08
$W^{\pm}b\bar{b}\gamma$	0.62 ± 0.11	0.42 ± 0.08	1.04 ± 0.17
$Z(\tau\tau)\gamma$	0.13 ± 0.09	0.11 ± 0.08	0.24 ± 0.12
WZ	0.08 ± 0.04	0.01 ± 0.01	0.09 ± 0.04
$\tau \to \gamma$ fake	0.12 ± 0.01	0.10 ± 0.01	0.22 ± 0.01
Jet faking γ $(ej\not\!\!E_T b, j\to\gamma)$	4.56 ± 1.92	3.02 ± 1.19	7.58 ± 3.11
MisTags	4.11 ± 0.41	3.54 ± 0.37	7.65 ± 0.70
QCD(Jets faking ℓ and $\not\!\!E_T$)	1.49 ± 0.77	0 ± 1	1.49 ± 1.30
$ee\not\!\!E_T b$, $e\to\gamma$	1.50 ± 0.28	–	1.50 ± 0.28
$\mu e\not\!\!E_T b$, $e\to\gamma$	–	0.45 ± 0.10	0.45 ± 0.10
Total SM Prediction	$16.8 \pm 2.2(tot)$	$11.1 \pm 1.7(tot)$	$27.9 \pm 3.6(tot)$
Observed in Data	16	12	28

CDF Run II Preliminary, 1.9fb^{-1}			
$t\bar{t}\gamma$, Isolated Leptons			
Standard Model Source	$e\gamma b\not\!\!E_T$	$\mu\gamma b\not\!\!E_T$	$(e+\mu)\gamma b\not\!\!E_T$
$t\bar{t}\gamma(semileptonic)$	1.97 ± 0.36	1.47 ± 0.27	3.44 ± 0.62
$t\bar{t}\gamma(dileptonic)$	0.52 ± 0.10	0.43 ± 0.08	0.95 ± 0.17
$W^{\pm}c\gamma$	0.0 ± 0.02	0.0 ± 0.02	0 ± 0.03
$W^{\pm}c\bar{c}\gamma$	0.0 ± 0.02	0.01 ± 0.01	0.01 ± 0.02
$W^{\pm}b\bar{b}\gamma$	0.06 ± 0.03	0.01 ± 0.01	0.07 ± 0.03
WZ	0.02 ± 0.02	0.0 ± 0.02	0.02 ± 0.02
$\tau \to \gamma$ fake	0.08 ± 0.01	0.02 ± 0.01	0.10 ± 0.01
Jet faking γ $(ej\not\!\!E_T b, j\to\gamma)$	2.37 ± 1.22	1.42 ± 0.70	3.79 ± 1.92
MisTags	0.78 ± 0.20	0.83 ± 0.22	1.61 ± 0.31
QCD(Jets faking ℓ and $\not\!\!E_T$)	0.53 ± 0.46	0 ± 1	0.53 ± 1.10
$ee\not\!\!E_T b$, $e\to\gamma$	0.34 ± 0.11	–	0.34 ± 0.11
$\mu e\not\!\!E_T b$, $e\to\gamma$	–	0.20 ± 0.06	0.20 ± 0.06
Total SM Prediction	$6.7 \pm 1.4(tot)$	$4.4 \pm 1.3(tot)$	$11.1 \pm 2.3(tot)$
Observed in Data	8	8	16

- Central photon: E_T>10 GeV
- Lepton: E_T>20 GeV
- B-jet: E_T>15 GeV
- MET>20 GeV
- ttγ: H_T>200 GeV

ISO ideas



Jet Cone
Photon Cone
10^6
10^5
Particle Flow, Arbitrary Units
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Angle Respect to Cone Axis, θ

Photons in Central EM Calorimeter