Photon Physics at the High Energy Frontier: The Lepton's Tale

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BNL Particle Physics Seminar

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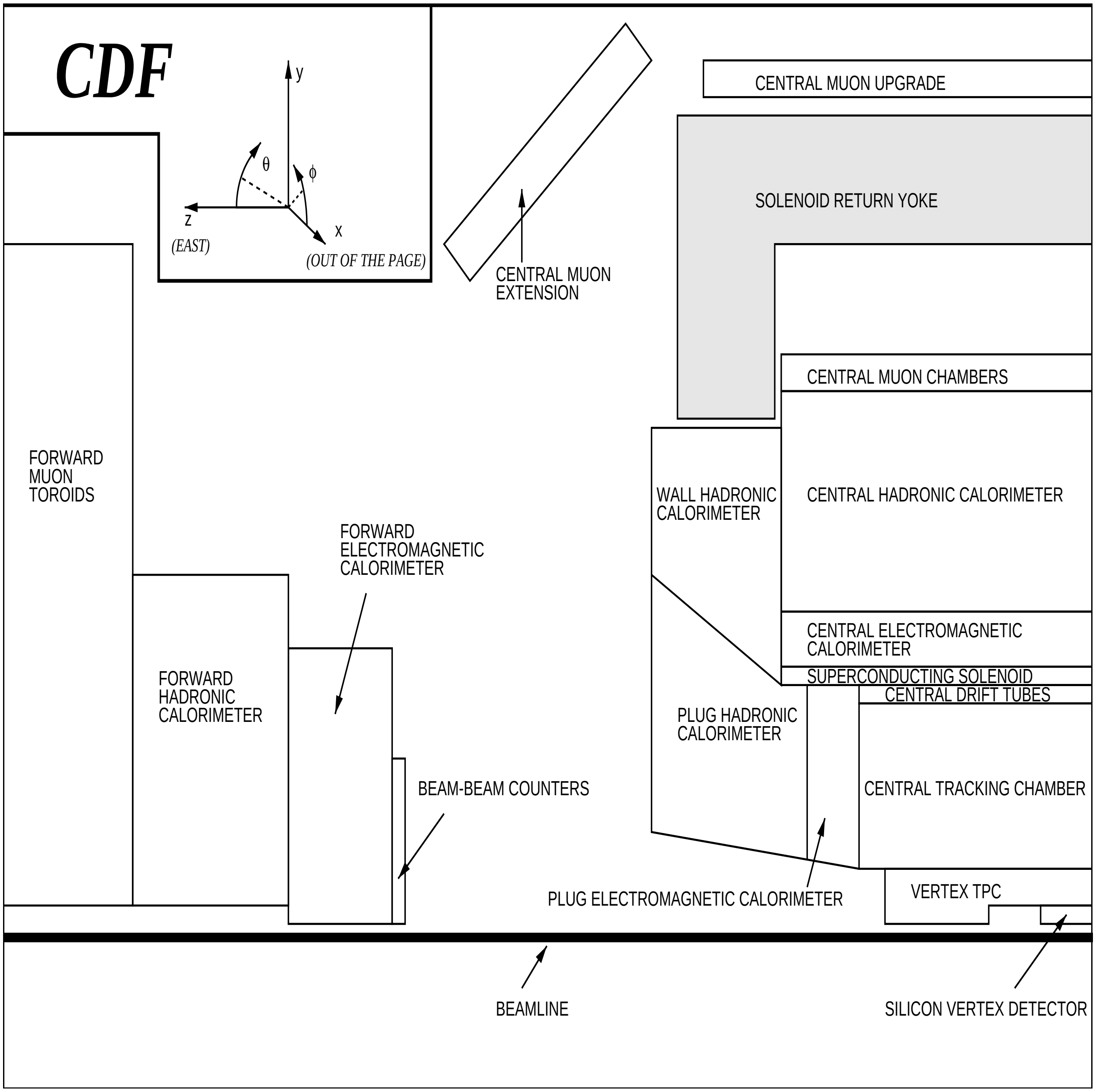
The CDF Detector



The CDF "Chinese Menu"

(Order one item from column A, one item from column B, etc. Mix, match, count and present some simple kinematic distributions.)

- **Central Electrons:** **Good high-p_T track + good high-E_T CEM cluster + good strip chamber hits.**
- **Central Photons:** **NO high-p_T track + good high-E_T CEM cluster + good strip chamber hits.**
- **Central Muons:** **Good high-p_T track + good MIP tower + good muon stub(s).**
- **Central Hadronic Taus:** **Good high-p_T 1-3 track cluster + good CHA cluster.**
- **Heavy quark jets:** **Calorimeter cluster + intersecting high-IP, high-p_T tracks.**
- **Gluon/light quark jets:** **Calorimeter cluster + NO high-IP tracks.**
- **Missing E_T:** $-(\Sigma\vec{E}_T)$ **of all menu items ordered.**

Prologue

- On April 28, 1995, the CDF detector recorded a spectacular $ee\gamma\gamma \not\!\!E_T$ candidate event:

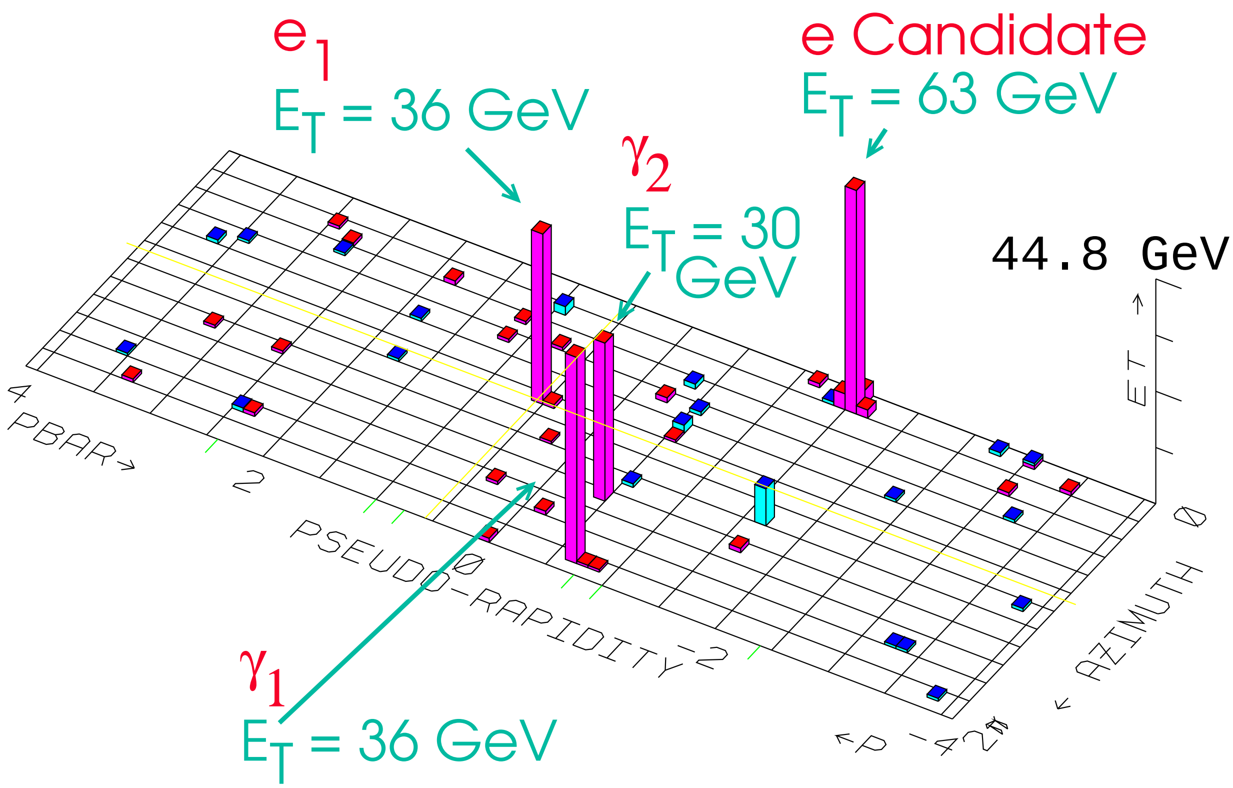
  1 CEM electron
  2 CEM photons
  1 PEM "electron"
  55 GeV $\not\!\!E_T$

- Total *a posteriori* expected rate is 10^{-6}, including possibly misidentified particles.

- The PEM electron satisfies all standard selection criteria, but examination *ex post facto* reveals it to have tracking data inconsistent with that of an electron.

- A single event in a category chosen *a posteriori* does not a discovery make, so searches were initiated in related categories chosen *a priori* in hopes of discovering new physics...

$ee\gamma\gamma\not{E}_T$ Candidate Event

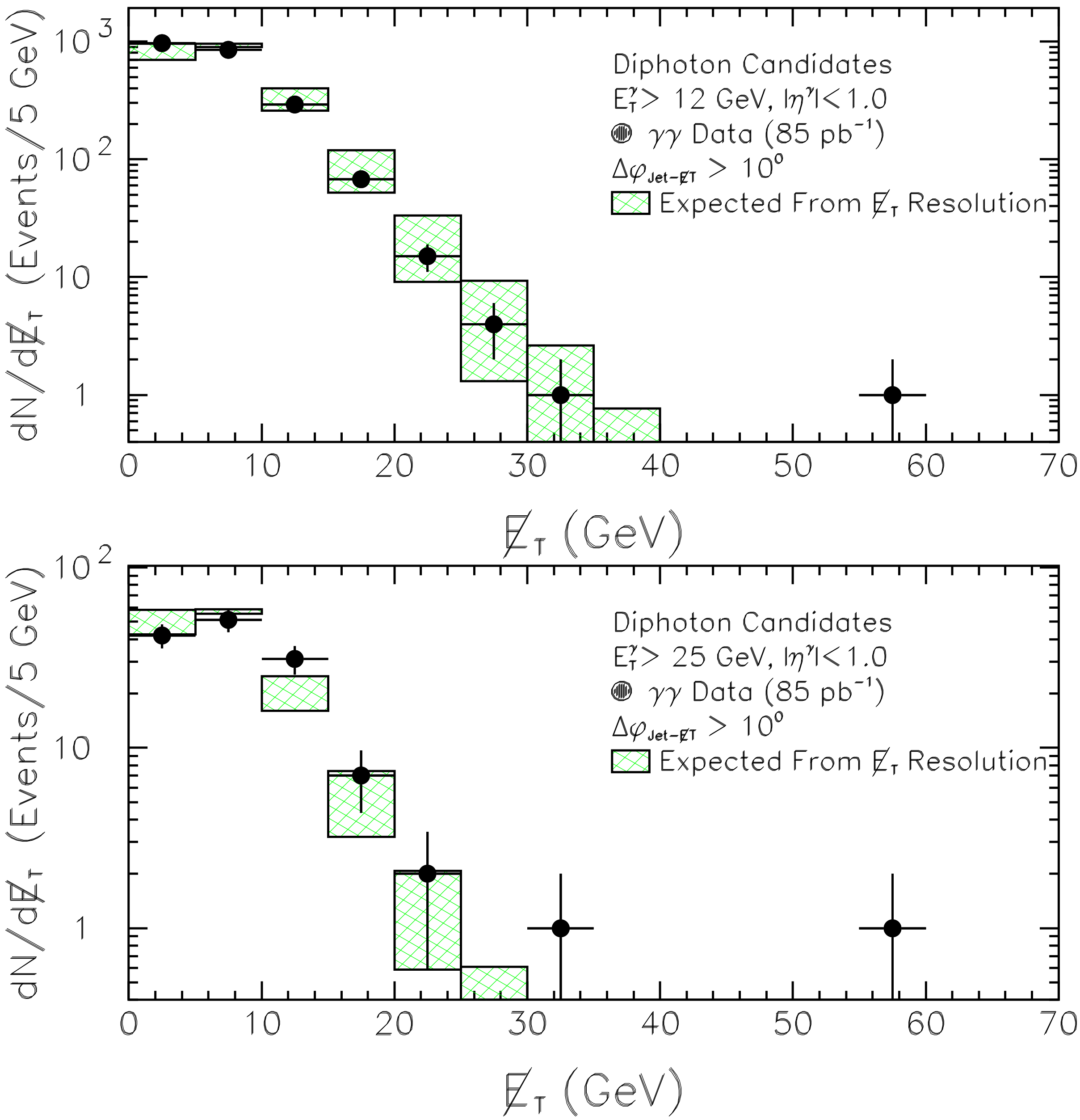


$\not{E}_T$ = 55 GeV

The Diphoton's Tale

- **Study inclusive diphoton events triggered by a pair of 12 GeV CEM photons (prescaled) or a pair of 25 GeV CEM photons, produced in association with anything identifiable.**
- $\not\!\!E_T$ **spectrum of diphoton events predicted from** $Z \rightarrow ee$ **events.**
- **Excepting the** $ee\gamma\gamma\not\!\!E_T$ **event, no anomalies were found.**

Diphoton Results
$\not\!\!E_T$ Spectrum



Diphoton Results
Additional Objects

$E_T^\gamma > 12$ GeV Threshold		
Signature (Object)	Obs.	Expected
$\not\!\!E_T > 35$ GeV, $\lvert\Delta\phi_{\not E_T-\mathrm{jet}}\rvert > 10°$	1	0.5 ± 0.1
$N_{\mathrm{jet}} \geq 4$, $E_T^{\mathrm{jet}} > 10$ GeV, $\lvert\eta^{\mathrm{jet}}\rvert < 2.0$	2	1.6 ± 0.4
Central e or μ, $E_T^{e \text{ or } \mu} > 25$ GeV	3	0.3 ± 0.1
Central τ, $E_T^\tau > 25$ GeV	1	0.2 ± 0.1
b-tag, $E_T^b > 25$ GeV	2	1.3 ± 0.7
Central γ, $E_T^{\gamma 3} > 25$ GeV	0	0.1 ± 0.1
$E_T^\gamma > 25$ GeV Threshold		
Object	Obs.	Exp.
$\not\!\!E_T > 25$ GeV, $\lvert\Delta\phi_{\not E_T-\mathrm{jet}}\rvert > 10°$	2	0.5 ± 0.1
$N_{\mathrm{Jet}} \geq 3$, $E_T^{\mathrm{Jet}} > 10$ GeV, $\lvert\eta^{\mathrm{Jet}}\rvert < 2.0$	0	1.7 ± 1.5
Central e or μ, $E_T^{e \text{ or } \mu} > 25$ GeV	1	0.1 ± 0.1
Central τ, $E_T^\tau > 25$ GeV	0	0.03 ± 0.03
b-tag, $E_T^b > 25$ GeV	0	0.1 ± 0.1
Central γ, $E_T^{\gamma 3} > 25$ GeV	0	0.01 ± 0.01

Number of observed and expected $\gamma\gamma$ events with additional objects in 85 pb^{-1}

The b-Quark's Tale

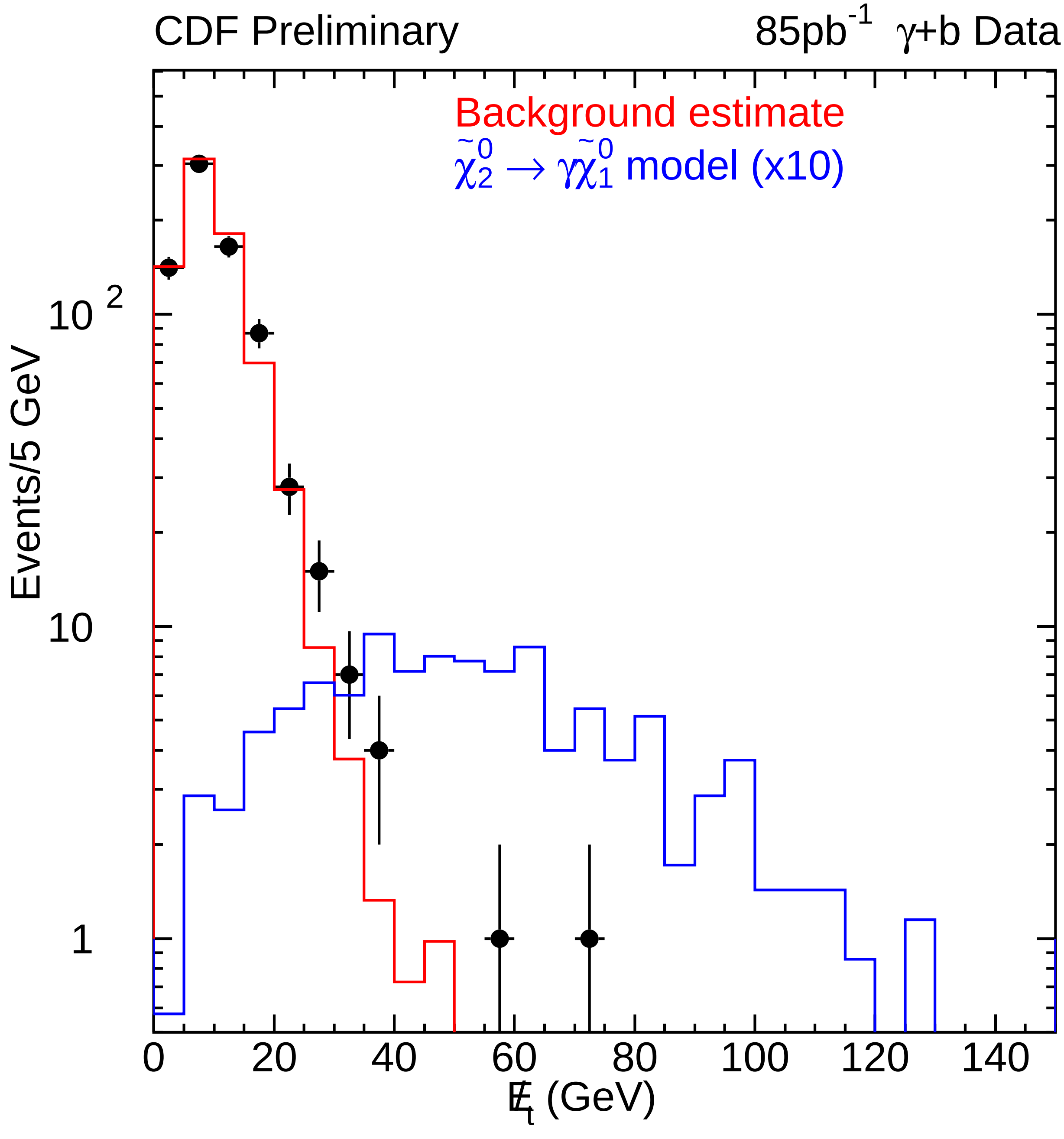
- **Study inclusive photon events triggered by 25 GeV CEM photons and measure the properties of events with a 30 GeV jet tagged as a b-quark.**
- **Total γb rate, $\not\!\!E_T$ spectrum, N_{jet} spectrum predicted and measured.**
- **No anomalies in total rates. Interesting high-mass $\gamma b \not\!\!E_T$ events were identified *a posteriori*.**

Photon-b Quark Results

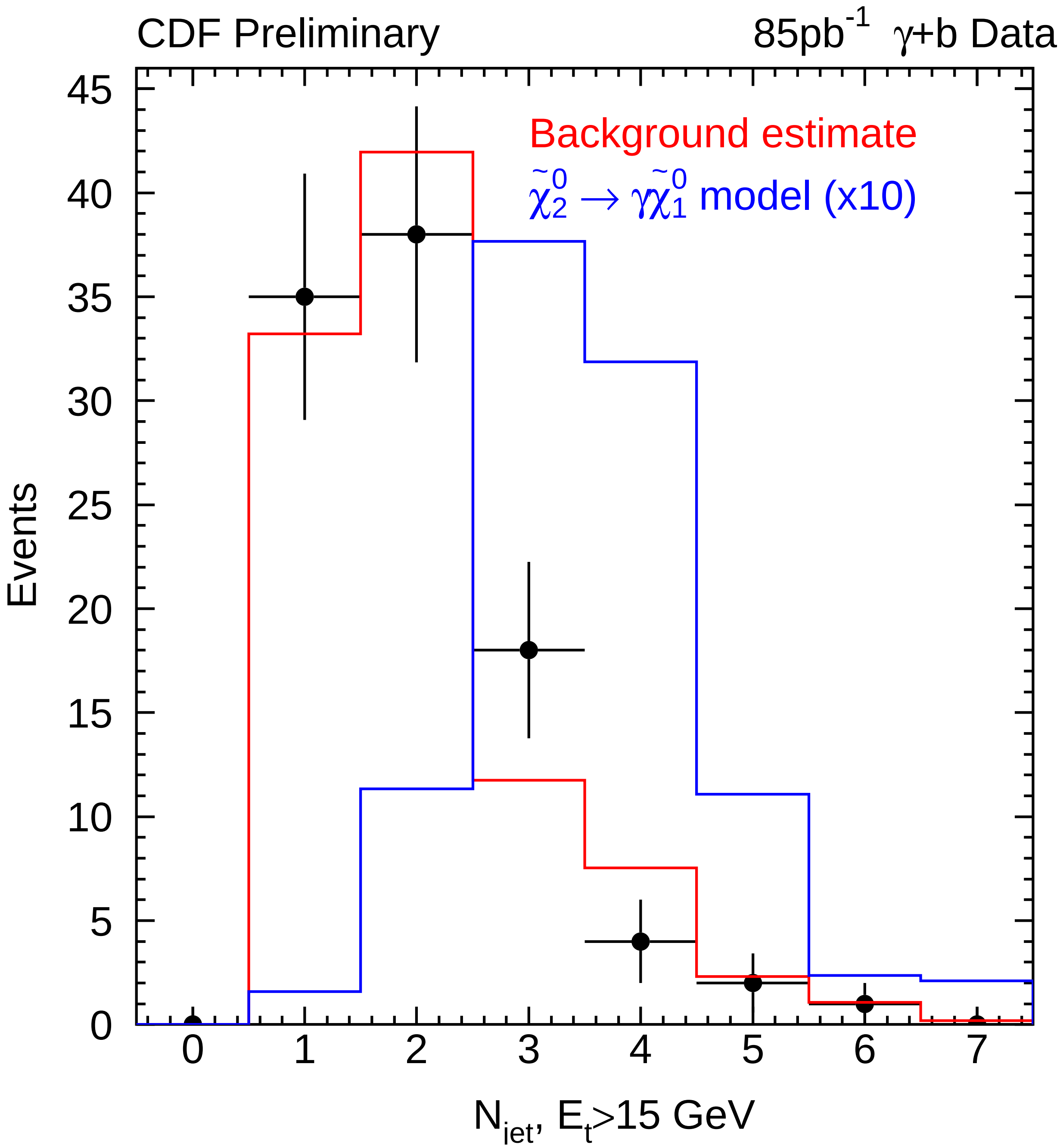
Source	Events	Events $\not\!\!E_t > 20$	Events $\not\!\!E_t > 40$, $\Delta\phi$
$\gamma b\bar{b}$	$99 \pm 5 \pm 50$	$9 \pm 1 \pm 10$	$0.4 \pm 0.3 \pm 0.4$
$\gamma c\bar{c}$	$161 \pm 9 \pm 81$	$7 \pm 2 \pm 8$	$0.0 \pm 0.5 \pm 0.5$
γ+mistag	$124 \pm 1 \pm 62$	$10.3 \pm 0.3 \pm 5.2$	$0.7 \pm 0.05 \pm 0.5$
fake γ	$648 \pm 69 \pm 94$	$49 \pm 22 \pm 7$	$1.0 \pm 1.0 \pm 0.2$
$W\gamma$	2 ± 1	$0.4 \pm 0.2 \pm 0.4$	$0 \pm 0.1 \pm 0.1$
$Z\gamma$	6 ± 4	$0.8 \pm 0.6 \pm 0.8$	$0.08 \pm 0.06 \pm 0.08$
$e \to \gamma$	0.4 ± 0.1	0.4 ± 0.1	$0.1 \pm .03$
cosmics	0 ± 16	0.3 ± 5	0
total background	$1040 \pm 72 \pm 172$	$77 \pm 23 \pm 20$	$2.3 \pm 1.2 \pm 1.1$
data	1175	98	2

Table 3: Summary of the primary background calculation. The $\gamma b\bar{b}$ and $\gamma c\bar{c}$ systematic uncertainties are considered 100% correlated. The column labeled $\not\!\!E_t > 40$ GeV also includes the requirement that $\Delta\phi(\gamma - \not\!\!E_t) < 168^\circ$. The entry for fake photons in the column labeled $\not\!\!E_t > 40$ GeV is not measured but is from the assumption that approximately 50% of photons, in most samples, are fakes and the number is assigned a 100% uncertainty.

Photon-b Quark Results
$\not\!\!E_T$ Spectrum

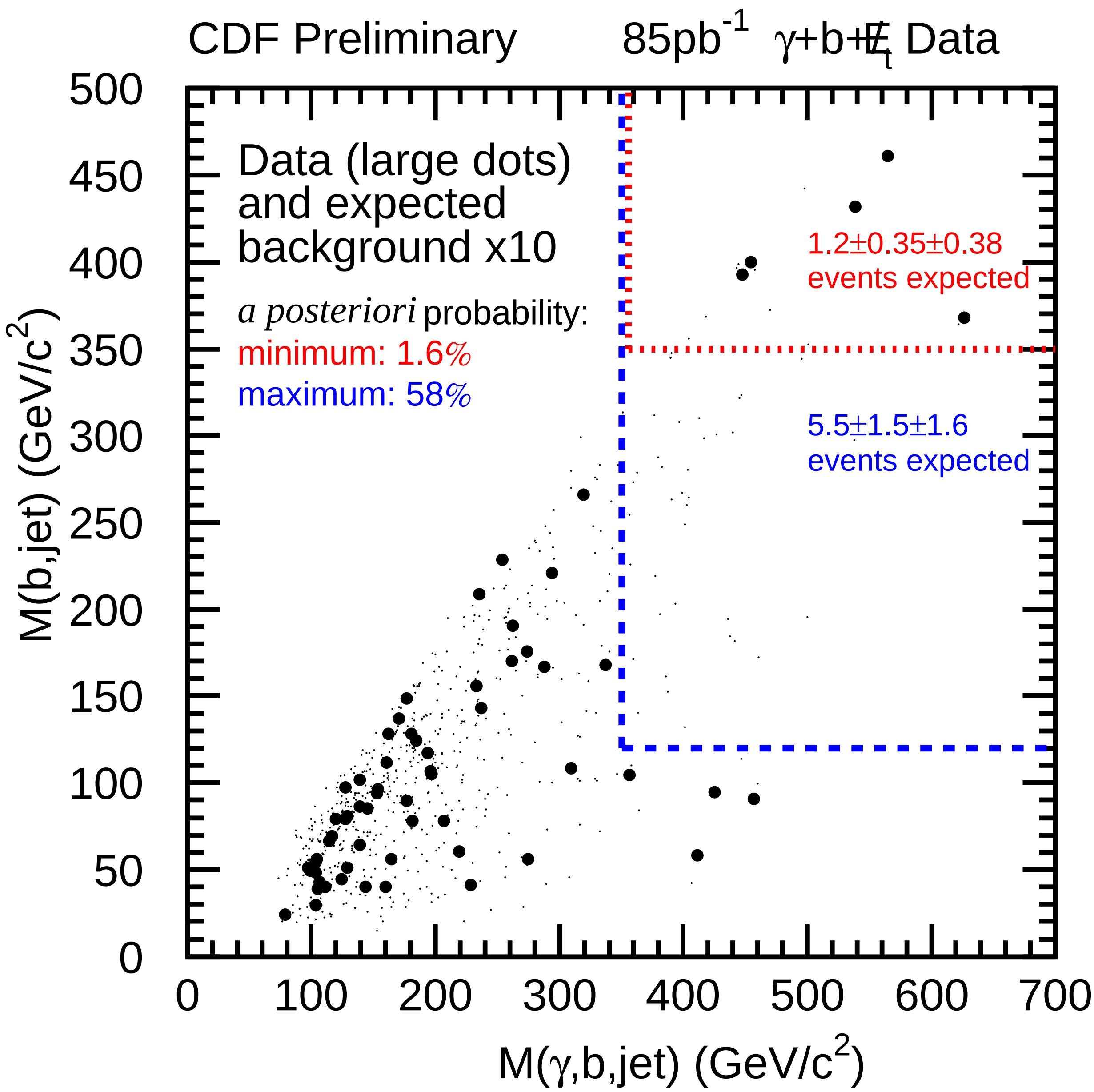


Photon-b Quark Results
N_{jet} Spectrum



Photon-b Quark Results

$M(b, jet)$ vs. $M(\gamma, b, jet)$



The Lepton's Tale

- **Collect events with inclusive lepton and inclusive photon events triggered by 18 GeV CEM electrons, 18 GeV muons, or 25 GeV CEM photons.**
- **Identify photons, leptons, $\not\!\!E_T$ using the methods of previously published analyses (photon searches, top, W, Z).**
- **Define *a priori* the categories of photon-lepton events to be analyzed, representative of the possibilities for new physics.**
- **Compare the inclusive event rates of each category with Standard Model predictions.**
- **Present simple kinematic distributions of the candidate events in each category.**

Particle Identification

- Photons are selected with requirements from previous photon searches. A 25 GeV transverse energy threshold is adopted for efficient photon triggering.
- Leptons(= central e, central μ) are selected with requirements from top quark analyses. A 25 GeV transverse energy threshold is adopted as a clear indicator of heavy particle (W or Z) decay.
- $\not\!\!E_T$ is computed as in previous analyses, accounting for all identified leptons and photons, as well as hadronic jets. A 25 GeV transverse energy threshold is adopted as a clear indicator of heavy particle (W) decay.
- Additional leptons are selected with looser requirements from previous analyses of the Z and top quark. Additional photons are selected with the same requirements as the first photon.

Inclusive Lepton, Photon Trigger Requirements

Inclusive Photon Trigger		
CEM photon		
E_T	$>$	23 GeV
fiducial CES cluster		
$E_{3x3}^{iso} < 4$ GeV OR $E_T > 50$ GeV		
Inclusive Electron Trigger		
CEM electron		
E_T	$>$	18 GeV
p_T	$>$	13 GeV/c
HAD/EM	$<$	0.125
χ^2 (CES strips)	$<$	10
Lshr	$<$	0.2
Track-CES matching:		
$\|\Delta x_{CES}\|$	$<$	3 cm
$\|\Delta z_{CES}\|$	$<$	5 cm
Inclusive Muon Trigger		
CMNP, CMUP, or CMX muon		
p_T	$>$	18 GeV/c
HAD energy	$<$	6 GeV
Track Stub Matching:		
$\|\Delta x_{stub}\|$	$<$	5 cm (CMNP, CMUP)
$\|\Delta x_{stub}\|$	$<$	10 cm (CMX)

Primary Electron, Muon Selection Requirements

Electron candidates		
CEM fiducial electron		
Electron E_T	$>$	25 GeV
$p_T \times c$	$>$	$5/9 \times E_T$
Track-CES matching:		
$\quad|\Delta x_{CES}|$	$<$	1.5 cm
$\quad|\Delta z_{CES}|$	$<$	3 cm
Track-vertex matching:		
$\quad|\Delta z_{event}|$	$<$	5 cm
E_{HAD}/E_{EM}	$<$	0.05
χ^2_{strip}	$<$	10
$|L_{shr}|$	$<$	0.2
Photon conversion removal		
Isolation E_T	$<$	$0.1 \times E_T$
Muon candidates		
CMNP, CMUP, CMX, CMP, or CMU muon		
Track p_T	$>$	25 GeV/c
Track-stub matching:		
$\quad|\Delta x_{stub}|$	$<$	5 cm (CMP, CMX)
$\quad|\Delta x_{stub}|$	$<$	2 cm (all other)
Track-vertex matching:		
$\quad|d_0|$	$<$	0.3 cm
$\quad|\Delta z_{event}|$	$<$	5 cm
CEM energy	$<$	2 GeV
CHA energy	$<$	6 GeV
CEM+CHA energy	$>$	0.1 GeV
Isolation E_T	$<$	$0.1c \times p_T$

Table 1: The selection criteria used to identify electron and muon candidates.

Photon Selection Requirements

Photon candidates		
CEM fiducial photon		
Photon E_T	$>$	25 GeV
Tracks with $p_T > 1$ GeV/c	$=$	0
Tracks with $p_T \leq 1$ GeV/c	$\leq$	1
E_{HAD}/E_{EM}	$<$	$0.055 + 0.00045\ \mathrm{GeV}^{-1} \times E^{\gamma}$
$\chi^2_{avg} = (\chi^2_{strip} + \chi^2_{wire})/2$	$<$	20
E^{CES}_{2nd}	$<$	$2.39 + 0.01 \times E^{\gamma}$ GeV
E_T in a cone of 0.4, E^{iso}_{cone}	$<$	2 GeV
p_T of tracks in a cone of 0.4	$<$	5 GeV/c

Table 2: The selection criteria used to identify photon candidates.

Additional Electron, Muon Selection Requirements

LCEM electron		
E_T	$>$	20 GeV
$p_T \times c$	$>$	$1/2 \times E_T$
E_{HAD}/E_{EM}	$<$	0.1
Isolation E_T	$<$	$0.1 \times E_T$
PEM electron		
E_T	$>$	15 GeV
E_{HAD}/E_{EM}	$<$	0.1
$\chi^2_{3\times3}$	$<$	3.0
Isolation E_T	$<$	$0.1 \times E_T$
FEM electron		
E_T	$>$	10 GeV
E_{HAD}/E_{EM}	$<$	0.1
Isolation E_T	$<$	$0.1 \times E_T$
CMI muon		
p_T	$>$	20 GeV/c
$\lvert\eta_\mu\rvert$	$<$	1.2
Track-vertex matching:		
$\lvert d_0\rvert$	$<$	0.3 cm
$\lvert\Delta z_{event}\rvert$	$<$	5 cm
CEM energy	$<$	2 GeV
CHA energy	$<$	6 GeV
CEM+CHA energy	$>$	0.1 GeV
p_T of tracks in a cone of 0.4	$<$	$0.1 \times p_T$
Isolation E_T	$<$	$0.1c \times p_T$

Table 3: The selection criteria used to identify additional lepton candidates.

Photon-Lepton Categories

- **Two-Body Photon-Lepton: one lepton, one photon, no additional photons or leptons, with the lepton and photon nearly opposite in azimuth ($\Delta\varphi_{\ell\gamma} > 150^\circ$).**

  Characteristic of processes with a two-particle final state.

  150° **selected to contain 95% of $Z^0 \rightarrow ee$ events.**

- **Z-like Photon-Electron: Two-body topology ($\Delta\varphi_{\ell\gamma} > 150^\circ$) with $M_{e\gamma}$ within 5 GeV of M_Z. Excluded from analysis and used to estimate electron misidentification as a photon.**

Photon-Lepton Categories

- **Multi-Body Photon-Lepton: all other events with one lepton and one photon.**

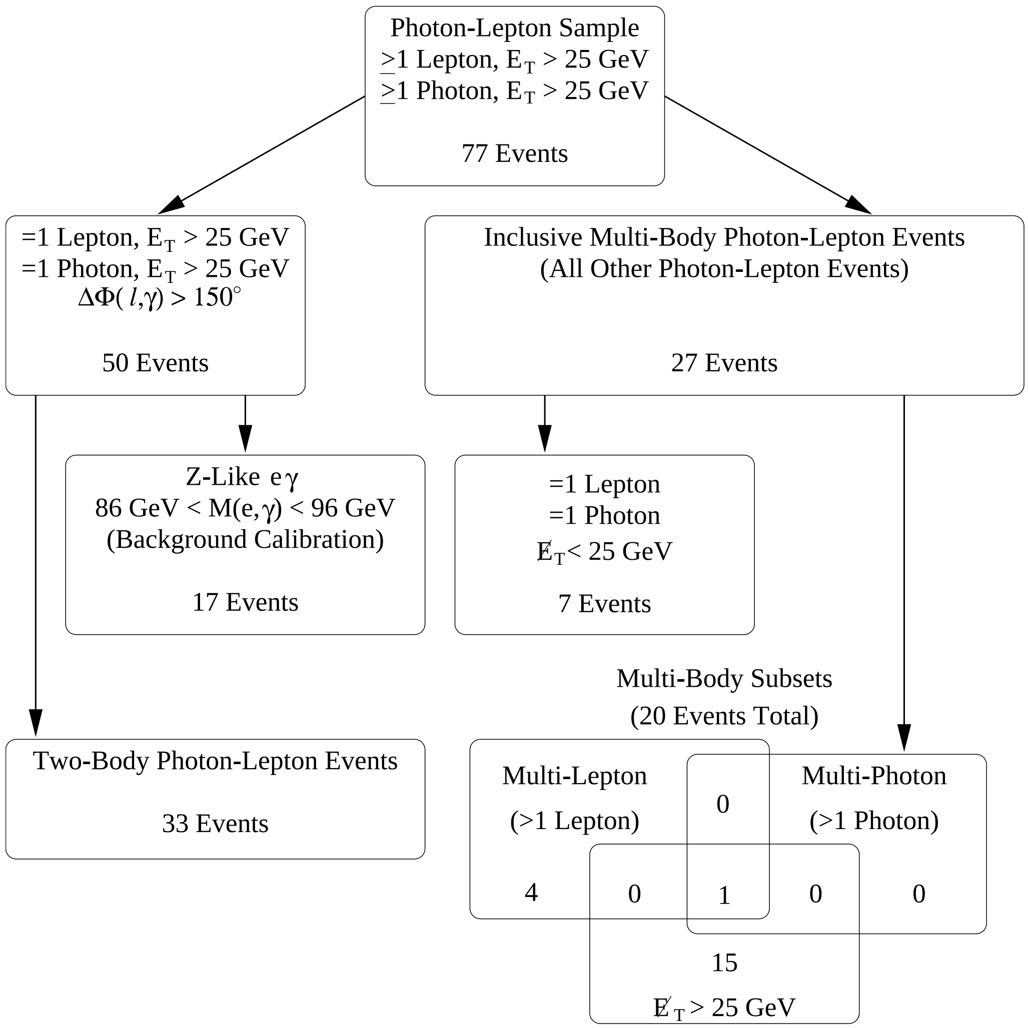
  Characteristic of processes with three or more final state particles.

SUBCATEGORIES (possibly overlapping):

- **Multi-Body $\ell\gamma\not{E}_T$: Multi-body events with $\not{E}_T >$ 25 GeV.**
- **Multi-Body Multi-Lepton: Multi-body events with additional leptons.**
- **Multi-Body Multi-Photon: Multi-body events with additional photons.**

Photon-Lepton Analysis Path

CDF Data (86 pb^{-1})



Sources of Photon-Lepton Events

- Two kinds of lepton or photon sources:

  1. Prompt sources where the particle is the direct outcome of a perturbatively calculable hard scattering process.

  2. Other sources Misidentified as prompt: hadron decay, particles mimicking lepton or photon ID.

- (Prompt Lepton)+(Prompt Photon):

  SM $W + \gamma$, $Z + \gamma$ production

- (Prompt or Misid. Lepton)+(Misid. Photon):

  $\ell + jet$ production, hadron jet misidentified as prompt γ

  $Z \rightarrow ee$ production, electron misidentified as prompt γ

- (Misid. Lepton)+(Prompt Photon):

  π, K punchthrough misidentified as prompt μ.

  π, K decay in flight misidentified as prompt μ.

  b, c decay in flight misidentified as prompt e, μ.

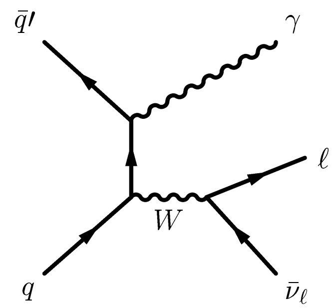
$W + \gamma$, $Z + \gamma$ Production

- A LO matrix element (full $2 \rightarrow 3$ body) $\times$ NLO K-factor, embedded in PYTHIA 6.125 (for parton frag., QCD ISR) with CTEQ5L PDF, outputting weighted events.
- Acceptance and efficiency calculated with full detector simulation.
- Predicted rate given by

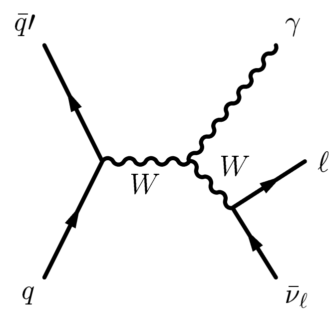
$$N_{\ell\gamma} \;=\; K_{NLO} \times \sigma_{LO} \times (\sum w_{pass})/(\sum w_{tot}) \times \epsilon_{trig} \times C_{sim.} \times \int L_{IB},$$

- Systematic uncertainty is approx. 12% per channel (equal parts NLO scale dependence, detector simulation, luminosity)

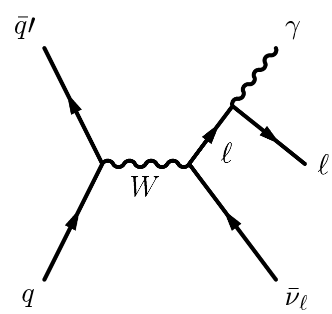
Leading-Order $W\gamma$ Production



a) Initial state photon radiation

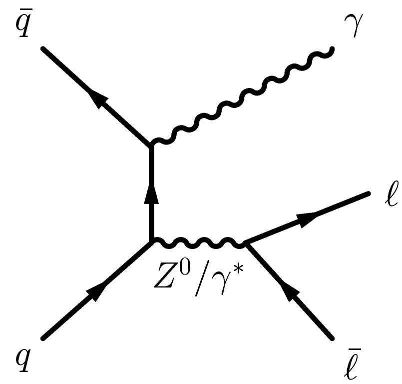


b) W final state photon radiation

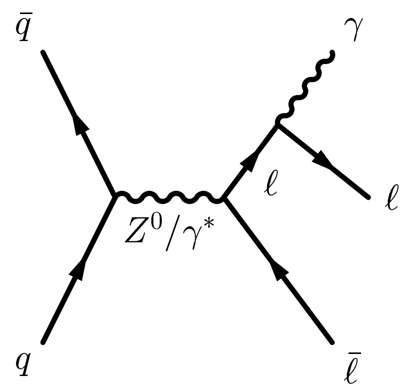


c) Lepton final state photon radiation

Leading-Order $Z\gamma$ Production



a) Initial state photon radiation



b) Lepton final state photon radiation

Sample Calculation of Simulated Event Rate

CDF Data (86 pb^{-1})

Item	Value	Relative Uncertainty
K_{NLO}	1.30 ± 0.10	7.7%
σ_{LO}	105.0 ± 5.3 pb	5.0%
$\sum w_{pass} / \sum w_{tot}$	$(2.57 \pm 0.12) \times 10^{-4}$	4.7%
ϵ_{trig}	0.985 ± 0.015	1.5%
C_{sim}	0.792 ± 0.052	6.6%
$\int Ldt$	86.34 ± 3.52 pb^{-1}	4.1%
$\bar{N}_{e\gamma}$	2.36 ± 0.31	13.1%

Diboson Simulation
Two-Body Photon-Lepton Events
CDF Data (86 pb^{-1})

	Two-Body Events	
Process	$e\gamma X$	$\mu\gamma X$
$\gamma + W$ production		
$\gamma + W \to \ell\nu$	1.1 ± 0.1	1.4 ± 0.2
$\gamma + W \to \tau\nu$	0.08 ± 0.02	0.09 ± 0.02
Subtotal	1.2 ± 0.2	1.5 ± 0.2
$\gamma + Z^0$ production		
$\gamma + Z^0 \to \ell\ell$	5.1 ± 0.5	6.5 ± 0.8
$\gamma + Z^0 \to \tau\tau$	0.3 ± 0.1	0.5 ± 0.1
Subtotal	5.4 ± 0.6	7.1 ± 0.8
Total	6.6 ± 0.7	8.6 ± 1.0

Diboson Simulation
Multi-Body Photon-Lepton Events
CDF Data (86 pb^{-1})

Process	Multi-Body Events $e\gamma X$	$\mu\gamma X$	$e\gamma \not\!\!E_T$	$\mu\gamma \not\!\!E_T$
$\gamma + W$ production				
$\gamma + W \rightarrow \ell\nu$	2.4 ± 0.3	2.5 ± 0.3	1.9 ± 0.3	1.9 ± 0.3
$\gamma + W \rightarrow \tau\nu$	0.08 ± 0.02	0.06 ± 0.01	0.04 ± 0.01	0.05 ± 0.01
Subtotal	2.4 ± 0.3	2.5 ± 0.3	1.9 ± 0.3	2.0 ± 0.3
$\gamma + Z^0$ production				
$\gamma + Z^0 \rightarrow \ell\ell$	4.9 ± 0.5	4.5 ± 0.5	0.3 ± 0.1	0.9 ± 0.1
$\gamma + Z^0 \rightarrow \tau\tau$	0.13 ± 0.03	0.10 ± 0.02	0.03 ± 0.01	0.05 ± 0.01
Subtotal	5.0 ± 0.5	4.6 ± 0.5	0.3 ± 0.1	1.0 ± 0.2
Total	7.5 ± 0.8	7.1 ± 0.8	2.3 ± 0.3	3.0 ± 0.4

Diboson Simulation
Multi-Body, Multi-Lepton Events
CDF Data (86 pb^{-1})

	Multi-Body Events		
Process	$ee\gamma X$	$\mu\mu\gamma X$	$e\mu\gamma X$
$\gamma + W$ production			
$\gamma + W \to \ell\nu$	—	—	—
$\gamma + W \to \tau\nu$	—	—	—
Subtotal	—	—	—
$\gamma + Z^0$ production			
$\gamma + Z^0 \to \ell\ell$	3.3 ± 0.4	2.2 ± 0.3	—
$\gamma + Z^0 \to \tau\tau$	—	—	0.05 ± 0.01
Subtotal	3.3 ± 0.4	2.2 ± 0.3	0.05 ± 0.01
Total	3.3 ± 0.4	2.2 ± 0.3	0.05 ± 0.01

Diboson Simulation
Multi-Body, Multi-Photon Events
CDF Data (86 pb^{-1})

Process	Multi-Body Events $e\gamma\gamma$	$\mu\gamma\gamma$
$\gamma + W$ production		
$\gamma + W \to \ell\nu$	—	—
$\gamma + W \to \tau\nu$	—	—
Subtotal	—	—
$\gamma + Z^0$ production		
$\gamma + Z^0 \to \ell\ell$	0.012 ± 0.012	0.004 ± 0.004
$\gamma + Z^0 \to \tau\tau$	—	—
Subtotal	0.012 ± 0.012	0.004 ± 0.004
Total	0.012 ± 0.012	0.004 ± 0.004

Lepton + jet, jet fakes photon

- **Estimated from lepton + jets events in CDF data. For $N_{\ell jet}$ jets in lepton+ ≥ 1 jet events, and a jet misidentification probability per jet P_{γ}^{jet},**

$$N_{\ell\gamma} = N_{\ell jet} \times P_{\gamma}^{jet}.$$

- $N_{\ell jet}$ **is estimated from the number of CDF events with at least one lepton and at least one hadron jet.**
- P_{γ}^{jet} **is estimated by examining the ratio of:**
  lepton trigger + 1 non-isolated photon to
  lepton trigger + 1 jet events in CDF data.

Jet Counting

- Using photon fake rate per jet, normalize backgrounds to lepton+jet samples representative of the various signal regions.
- Lepton+Jets:

  ≥ 1 tight lepton

  ≥ 1 central jet, $E_T > 25$ GeV

  Electrons are selected with an inclusive electron trigger path (91% efficient).

  Muons are selected with (possibly prescaled) inclusive muon path (CMUP,CMNP,CMX only)
- Raw jet count must be augmented by a ratio of lepton-photon to lepton-jet trigger efficiencies.
- 14% is added to the muon+jet total as an acceptance correction for omitting CMP muons.

Jet Misidentification Rate

- **Fit the distribution of photon E^{iso}_{cone} to a sum of a peaked distribution from Z electrons and a linear tail of QCD background. Intercept of linear tail is an estimate of QCD background.**

$$\frac{1}{N_{jet}} \times dN(E^{iso}_{cone})/dE^{iso}_{cone} = A_1 \times \frac{1}{N_Z} \times dN_Z(E^{iso}_{cone})/dE^{iso}_{cone} + A_2 \times E^{iso}_{cone} + A_3 \tag{1}$$

$$A_1 \equiv \textbf{prompt photon rate}$$

$$A_3 - A_2 \equiv P_\gamma^{jet}$$

Data Samples

- **Lepton Trigger+Jet:**

  $=$ 1 Stream A triggerable lepton, $E_T > 18$ GeV

  $=$ 1 central jet, corrected $E_T > 25$ GeV

  e+jet from Level 2 incl. electron trigger

  μ+jet from Level 2 incl. μ trigger (prescaled)

  59k events, 46k e+jet, 13k μ+jet

- **Lepton Trigger+Photon**

  (38$\mu\gamma$+121$e\gamma$ events)

  All photon cuts *except:*

  E_{cone}^{iso}

  $\mathrm{P_T}$ *of tracks in a cone of* $0.4 < 5.0 GeV$

  e+γ from Level 2 incl. electron trigger

  $\mu+\gamma$ from Level 2 μ+jet trigger (unprescaled)

Data Samples

- **Lepton Trigger+π^0**

  (11$\mu\pi^0$+38$e\pi^0$ events)

  $\chi^2_{Avg} = \left(\frac{\chi^2_{Strip}+\chi^2_{Wire}}{2}\right) > 20.0$

  All other photon cuts *except:*

  E^{iso}_{cone}

  $\mathrm{P_T}$ *of tracks in a cone of* $0.4 < 5.0\,GeV$

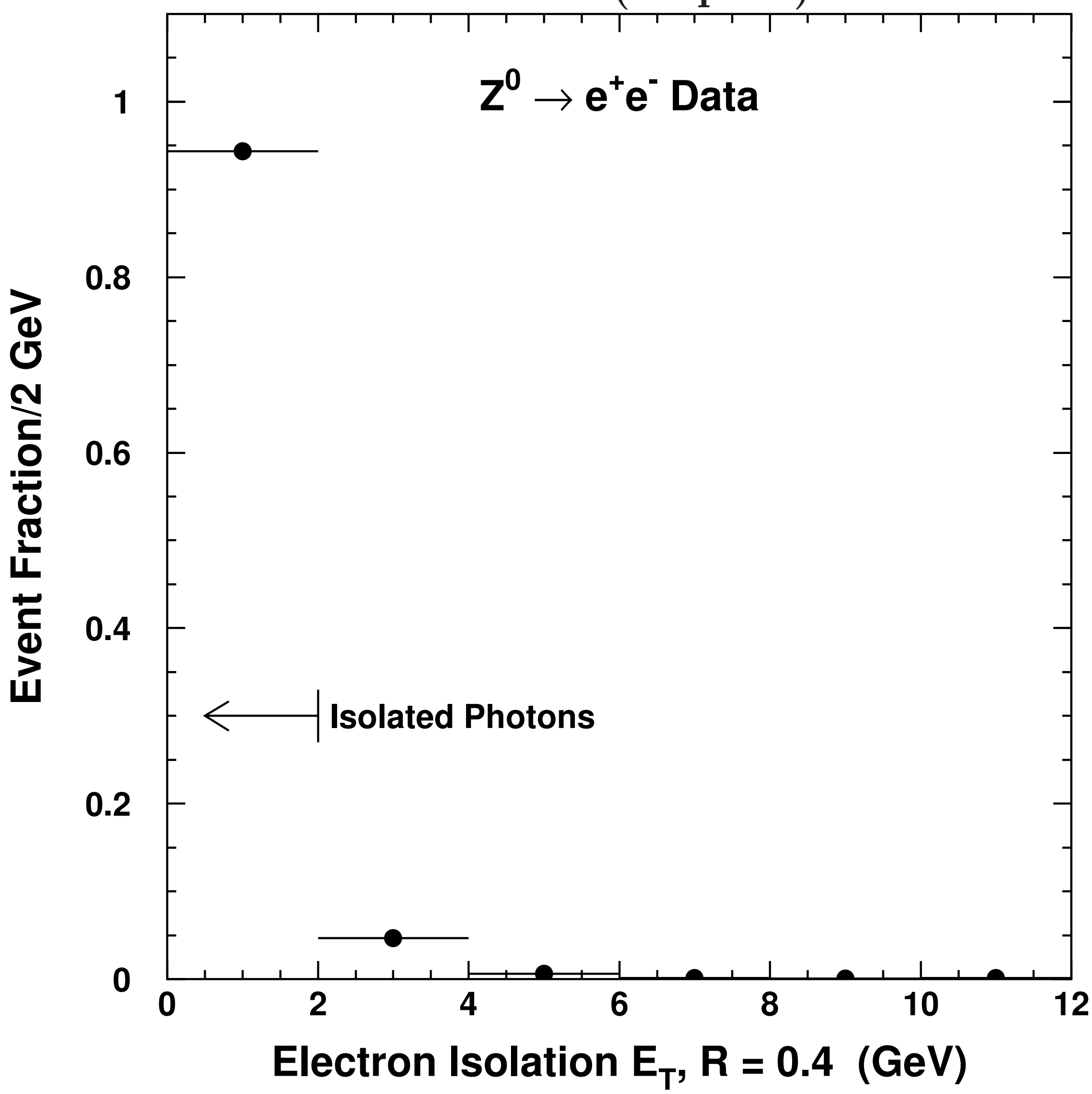
  $\mathrm{E}^{\mathrm{cluster}}_{\mathit{2nd\ strip\ or\ wire}} < 2.39 + 0.01 \times E^{\gamma}$ GeV

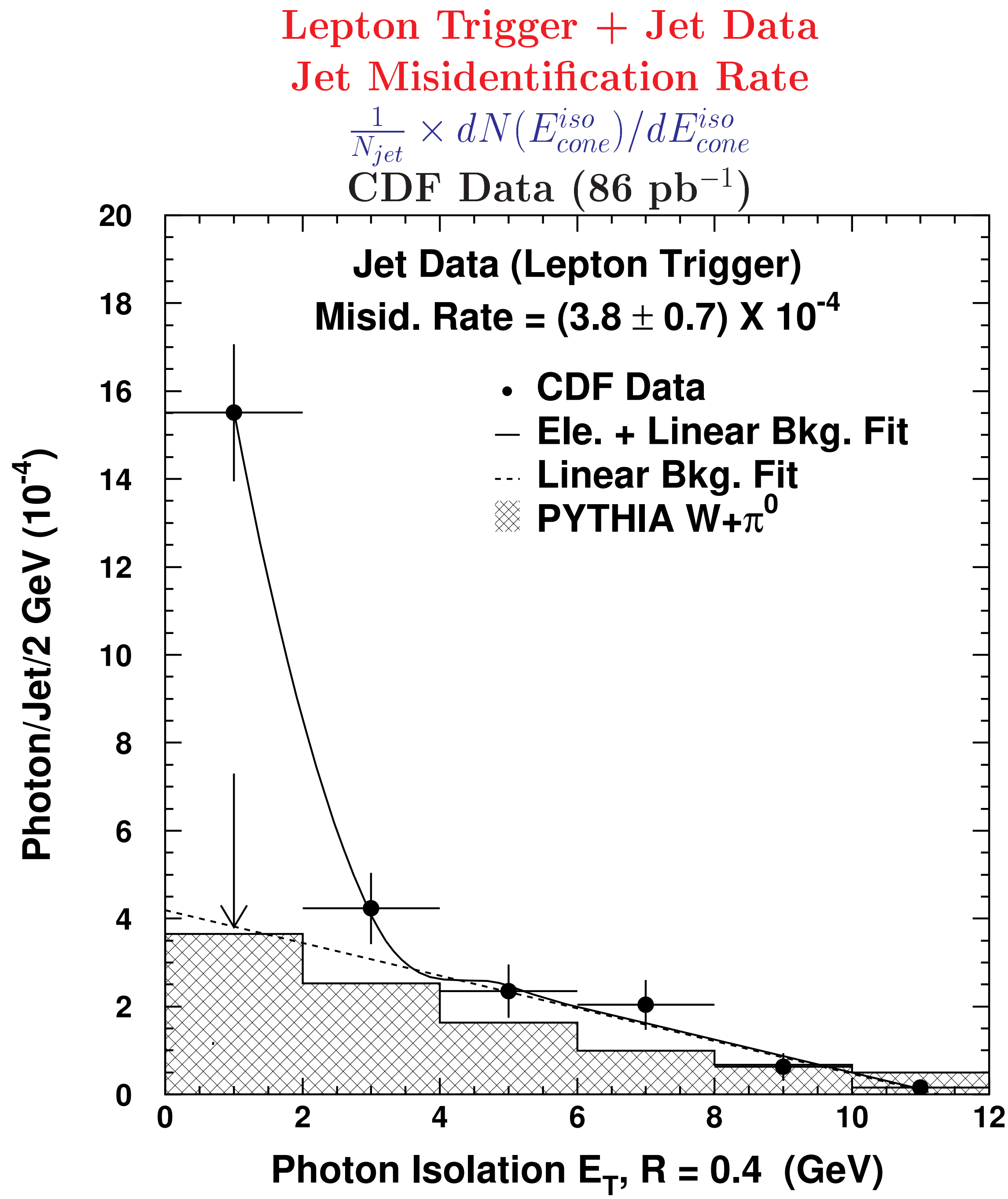
$Z^0 \rightarrow e^+e^-$ **Data**

Electron Isolation Energy Distribution

$\frac{1}{N_Z} \times dN_Z(E^{iso}_{cone})/dE^{iso}_{cone}$

CDF Data (86 pb^{-1})





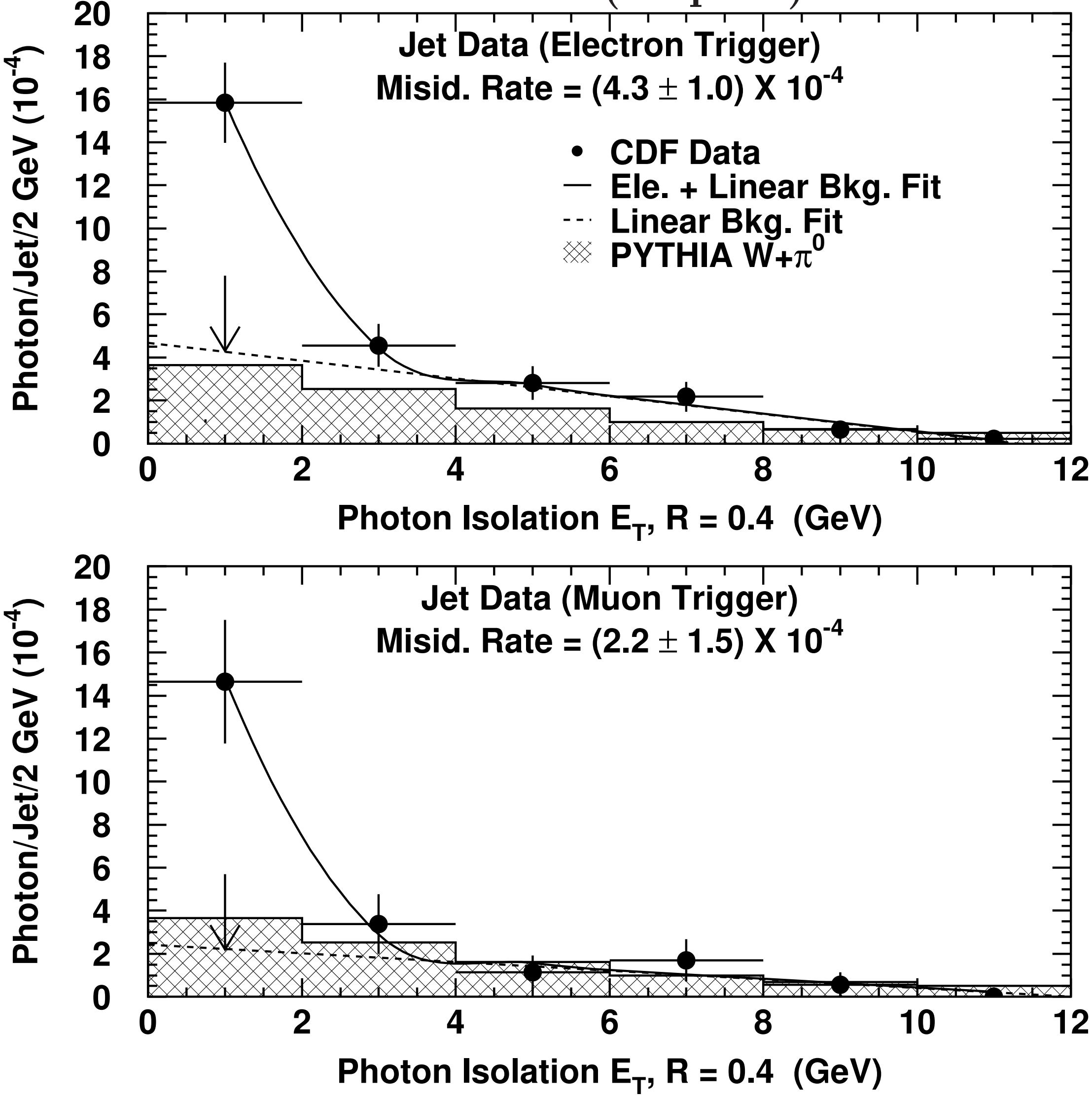
Lepton Trigger + Jet Data
Jet Misidentification Rate
$\frac{1}{N_{jet}} \times dN(E^{iso}_{cone})/dE^{iso}_{cone}$
CDF Data (86 pb^{-1})
Jet Data (Lepton Trigger)
Misid. Rate = $(3.8 \pm 0.7) \times 10^{-4}$
CDF Data
Ele. + Linear Bkg. Fit
Linear Bkg. Fit
PYTHIA $W+\pi^0$
Photon/Jet/2 GeV (10^{-4})
Photon Isolation E_T, R = 0.4 (GeV)
0
2
4
6
8
10
12
14
16
18
20
0
2
4
6
8
10
12

Lepton Trigger + Jet Data

Jet Misidentification Rate

$\frac{1}{N_{jet}} \times dN(E^{iso}_{cone})/dE^{iso}_{cone}$

CDF Data (86 pb^{-1})



Jet Misidentification Rate Fit Results

CDF Data (86 pb^{-1})

	Lepton-Jet Samples		
	ej	μj	ℓj
Photons	121	38	159
Jets	46091	17745	63836
$A_1(10^{-4})$	13 ± 2	14 ± 4	13 ± 2
$A_2(10^{-4})$	-0.4 ± 0.1	-0.2 ± 0.2	-0.4 ± 0.1
$A_3(10^{-4})$	4.7 ± 0.9	2.4 ± 1.5	4.2 ± 0.7
$P_\gamma^{jet}(10^{-4})$	4.3 ± 1.0	2.2 ± 1.5	3.8 ± 0.7
χ^2/d.o.f.	0.38	0.44	0.42

Jets Misidentified as Photons
Photon-Lepton Contributions
CDF Data (86 pb^{-1})

	N_{raw}	$N_{\ell jet}$	$N_{\ell\gamma}$
	Two-Body Events		
$e\gamma X$	4530	4909	1.9 ± 0.3
$\mu\gamma X$	1983	3844	1.5 ± 0.3
	Multi-Body Events		
$e\gamma X$	4235	4565	1.7 ± 0.3
$\mu\gamma X$	2024	3855	1.5 ± 0.3
$e\gamma \not\!\!E_T X$	2584	2798	1.1 ± 0.2
$\mu\gamma \not\!\!E_T X$	1369	2633	1.0 ± 0.2
$ee\gamma X$	479	496	0.19 ± 0.03
$\mu\mu\gamma X$	226	346	0.13 ± 0.02
$e\mu\gamma X$	16	19	—
$e\gamma\gamma X$	3	3	—
$\mu\gamma\gamma X$	3	4	—

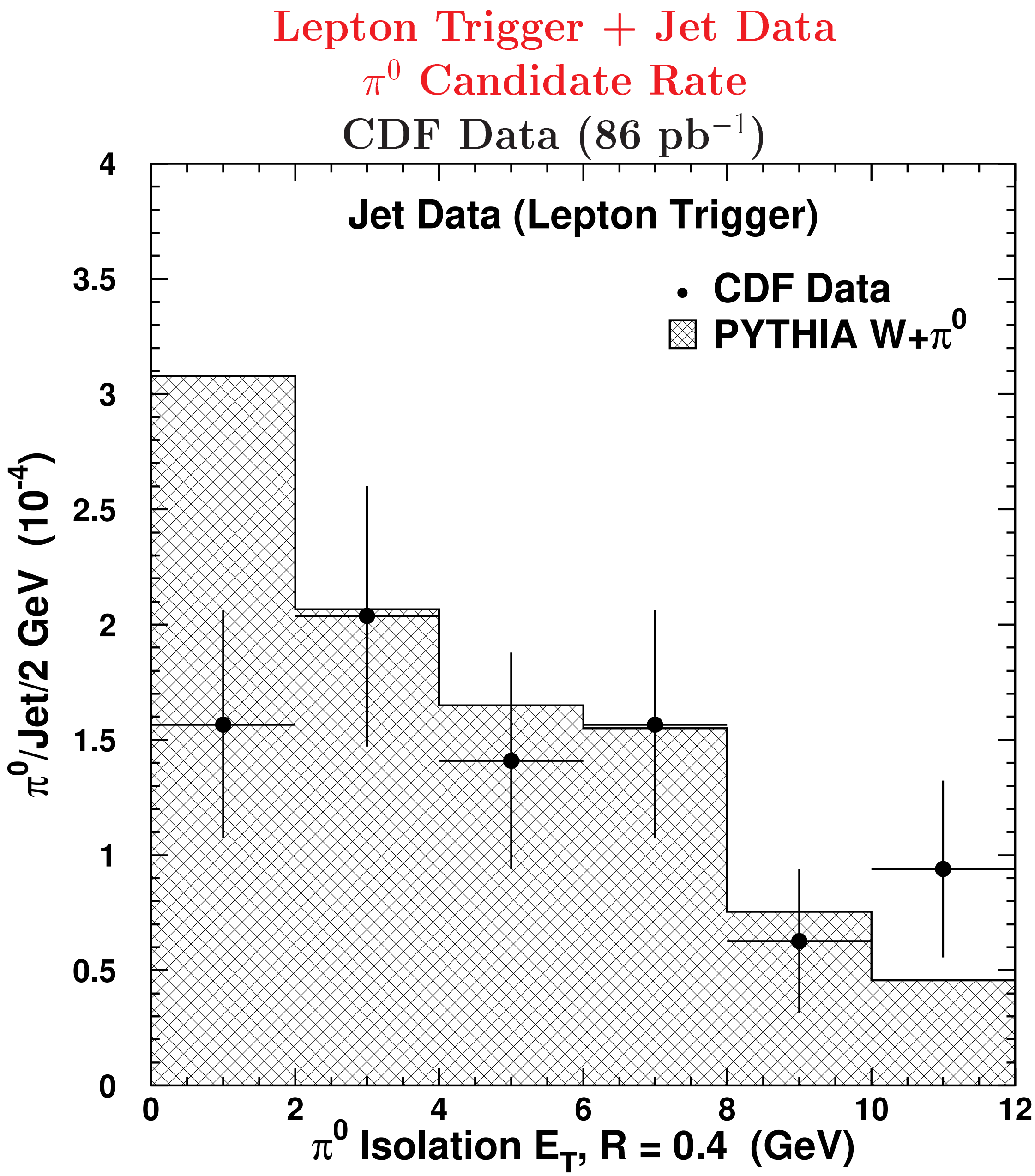
Cross Checks of P_{γ}^{jet}

- **Lepton Trigger+π^0:**

  Both PYTHIA and CDF data exhibit a flat/linear E_{cone}^{iso} distribution, with consistent rates per jet produced.

- **PYTHIA W+Jet:**

  Both PYTHIA and CDF data exhibit a flat/linear E_{cone}^{iso} distribution for $E_{cone}^{iso} > 4$ GeV, with PYTHIA π^0 production proceeding linearly below 4 GeV. Rates per jet are consistent above 4 GeV.


Lepton Trigger + Jet Data
π^0 Candidate Rate
CDF Data (86 pb^{-1})
Jet Data (Lepton Trigger)
CDF Data
PYTHIA W+π^0
π^0/Jet/2 GeV (10^{-4})
π^0 Isolation E_T, R = 0.4 (GeV)
0
0.5
1
1.5
2
2.5
3
3.5
4
0
2
4
6
8
10
12

$Z \to e^+e^-, e \to \gamma$

- **Estimated from Dielectron events from CDF data. For N_{ee} dielectron events, and an electron misidentification probability per electron P^e_γ,**

$$N_{e\gamma} = N_{ee} \times P^e_\gamma$$

- P^e_γ **is estimated from the ratio of Z-like** $e\gamma$ **events to** $Z \to e^+e^-$ **events,**

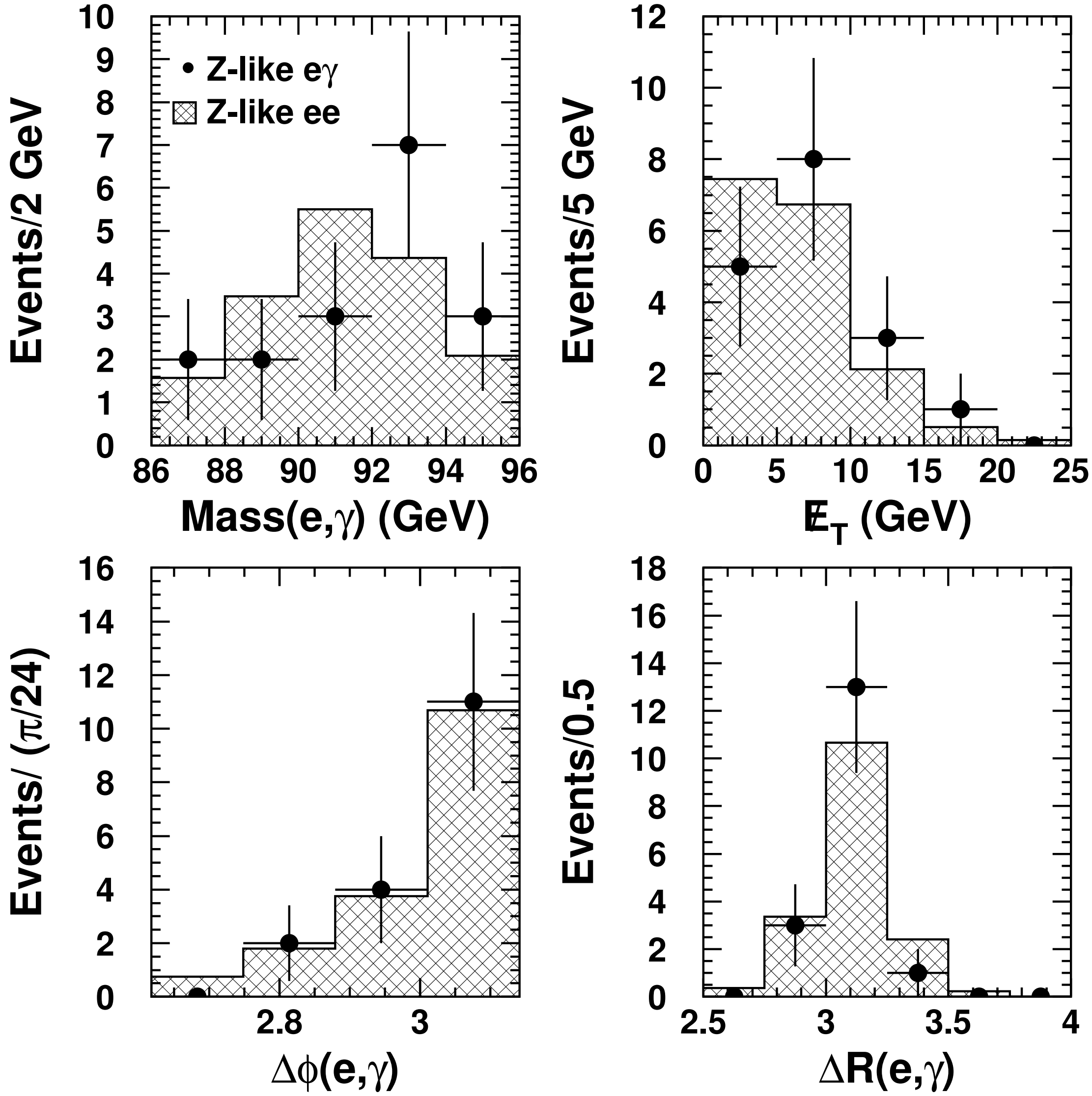
$$P^e_\gamma = \frac{N(Z \to e\gamma)}{N(Z \to ee)}$$

- $W\gamma, Z\gamma, e + jet$ **background (1.2 events) is subtracted from 17** $Z \to e\gamma$ **events.**

$$\begin{aligned} N^{mult}_{e\gamma} &= 132 \times [(15.8 \pm 4.3)/1235] \\ &= 1.7 \pm 0.5 \textbf{ events.} \end{aligned}$$

Z^0-Like Photon-Electron Data

CDF Data (86 pb^{-1})



Electrons Misidentified as Photons
Photon-Lepton Contributions
CDF Data (86 pb^{-1})

	N_{ee}	$N_{e\gamma}$
Two-Body $e\gamma X$	321	4.1 ± 1.1
Multi-Body $e\gamma X$	132	1.7 ± 0.5
Multi-Body $e\gamma \not{E}_T X$	8	0.10 ± 0.04

π, K Punchthrough/Decay-in-flight

- **Estimated from Photon+isolated track events from CDF data. Summing over all t tracks in the sample, add the muon misidentification probability P^t_μ for the hadron track, weighted by the trigger efficiency ratio of $\gamma\mu$ to γt events, $R_{\gamma t}$**

$$N_{\mu\gamma} \;=\; \sum_t R_{\gamma t} \times P^t_\mu.$$

- **Punchthrough probability estimated from the amount of intervening material in $\pi - p$, $K - p$ interaction lengths (typically ≥ 5)**

$$\begin{aligned} P^t_{PT\mu} &= F_\pi \times exp(-\lambda_\pi(E_t)/\sin\theta_t) \\ &\quad + F_K \times exp(-\lambda_K(E_t)/\sin\theta_t) \end{aligned}$$

- **Central value for $N_{\mu\gamma}$ from the empirical value $F_K = 0.33$; systematic uncertainty bounded above and below by $F_K = 1$ and $F_K = 0$, respectively.**

Hadrons Misidentified as Muons
Photon-Lepton Contributions
CDF Data (86 pb^{-1})
Punchthrough Hadrons

Stub Type	Two-Body	Multi-Body	Multi-Body
	$\mu\gamma X$	$\mu\gamma X$	$\mu\gamma \not{E}_T X$
CMUP	—	—	—
CMNP	0.37	0.12	0.07
CMX	0.15	0.08	0.03
CMP	—	—	—
CMU	0.90	0.25	0.09
Total	1.42 ± 0.74	0.45 ± 0.25	0.18 ± 0.11

π, K Punchthrough/Decay-in-flight

- **Decay in flight probability estimated from the survival probability of π/K for up to 2 meters ($\sim 0.7\%$ for K), as a function of track p_T:**

$$\begin{aligned} P^t_{DIF\mu} &= F_\pi \times \mathbf{B}R(\pi^\pm \rightarrow \mu\nu) \\ &\quad \times(1 - exp(-(2/c\tau_\pi)(m_\pi/cp_T))) \\ &\quad +F_K \times \mathbf{B}R(K^\pm \rightarrow \mu\nu) \\ &\quad \times(1 - exp(-(2/c\tau_K)(m_K/cp_T))), \end{aligned}$$

Hadrons Misidentified as Muons
Photon-Lepton Contributions
CDF Data (86 pb^{-1})
Decay-in-Flight Hadrons

Stub Type	Two-Body $\mu\gamma X$	Multi-Body $\mu\gamma X$	Multi-Body $\mu\gamma \not\!\!E_T X$
CMUP	0.35	0.10	0.03
CMNP	0.15	0.04	0.02
CMX	0.21	0.11	0.03
CMP	0.08	0.04	0.01
CMU	—	—	—
Total	0.80 ± 0.89	0.28 ± 0.31	0.10 ± 0.11

b, c Decay Misidentified as Prompt Leptons

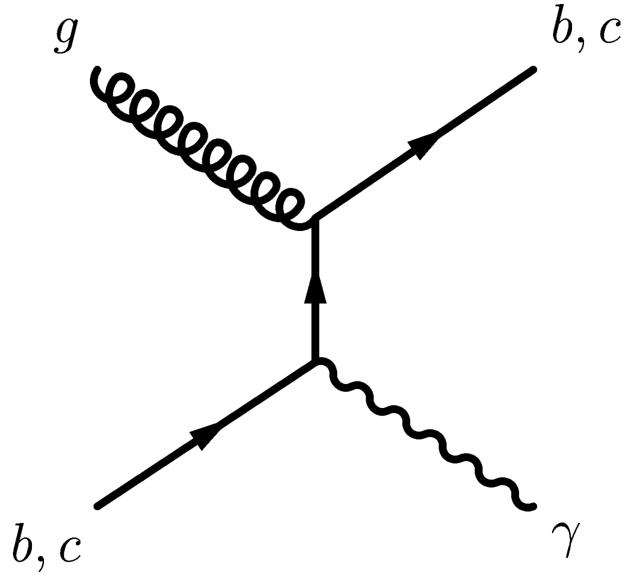
- A LO matrix element $\times$ NLO K-factor for photon + charm/bottom production, using PYTHIA 6.125 with CTEQ5L PDF and CLEO hadron decay.
- Acceptance and efficiency calculated with full detector simulation.
- Predicted rate given by

$$N_{\ell\gamma} \;=\; K_{NLO} \times \sigma_{LO} \times (\sum w_{pass})/(\sum w_{tot}) \times \epsilon_{trig} \times C_{sim.} \times \int L_{IB},$$

- Small contribution to two-body photon-lepton events;

  no contribution to multi-body photon-lepton events.

Leading-Order $b, c + \gamma$ Production



Photon-Lepton Results

- **Mean rate expected, μ_{SM} is the total of the previously estimated contributions. Uncertainty in the mean computed with correlated systematics ($\int L$, P_γ^{jet}, etc.) accounted for.**
- **Number of events observed N_0 in CDF data.**
- **Probability $P(N \geq N_0|\mu_{SM})$ that $\geq N_0$ events are observed given that the mean rate is μ_{SM}.**
- **Kinematic distributions:**
  Energies: Photon E_T, Lepton E_T, $\not\!\!E_T$, H_T
  Masses: $M_{\ell\gamma}$, $M_T(\ell \not\!\!E_T)$, $M_T(\gamma \not\!\!E_T)$, $M_T(\ell\gamma \not\!\!E_T)$
  Angles: $\Delta\varphi(\ell \not\!\!E_T)$, $\Delta\varphi(\gamma \not\!\!E_T)$, $\Delta\varphi(\ell\gamma)$, $\Delta R(\ell\gamma)$

Photon-Lepton Results

CDF Data (86 pb^{-1})

Category	μ_{SM}	N_0	$P(N \geq N_0 \mid \mu_{SM})$ %
All $\ell\gamma X$	—	77	—
Z-like $e\gamma$	—	17	—
Two-Body $\ell\gamma X$	24.9 ± 2.4	33	9.3
Multi-Body $\ell\gamma X$	20.2 ± 1.7	27	10.0
Multi-Body $\ell\ell\gamma X$	5.8 ± 0.6	5	68.0
Multi-Body $\ell\gamma\gamma X$	0.02 ± 0.02	1	1.5
Multi-Body $\ell\gamma \not\!\!E_T X$	7.6 ± 0.7	16	0.7

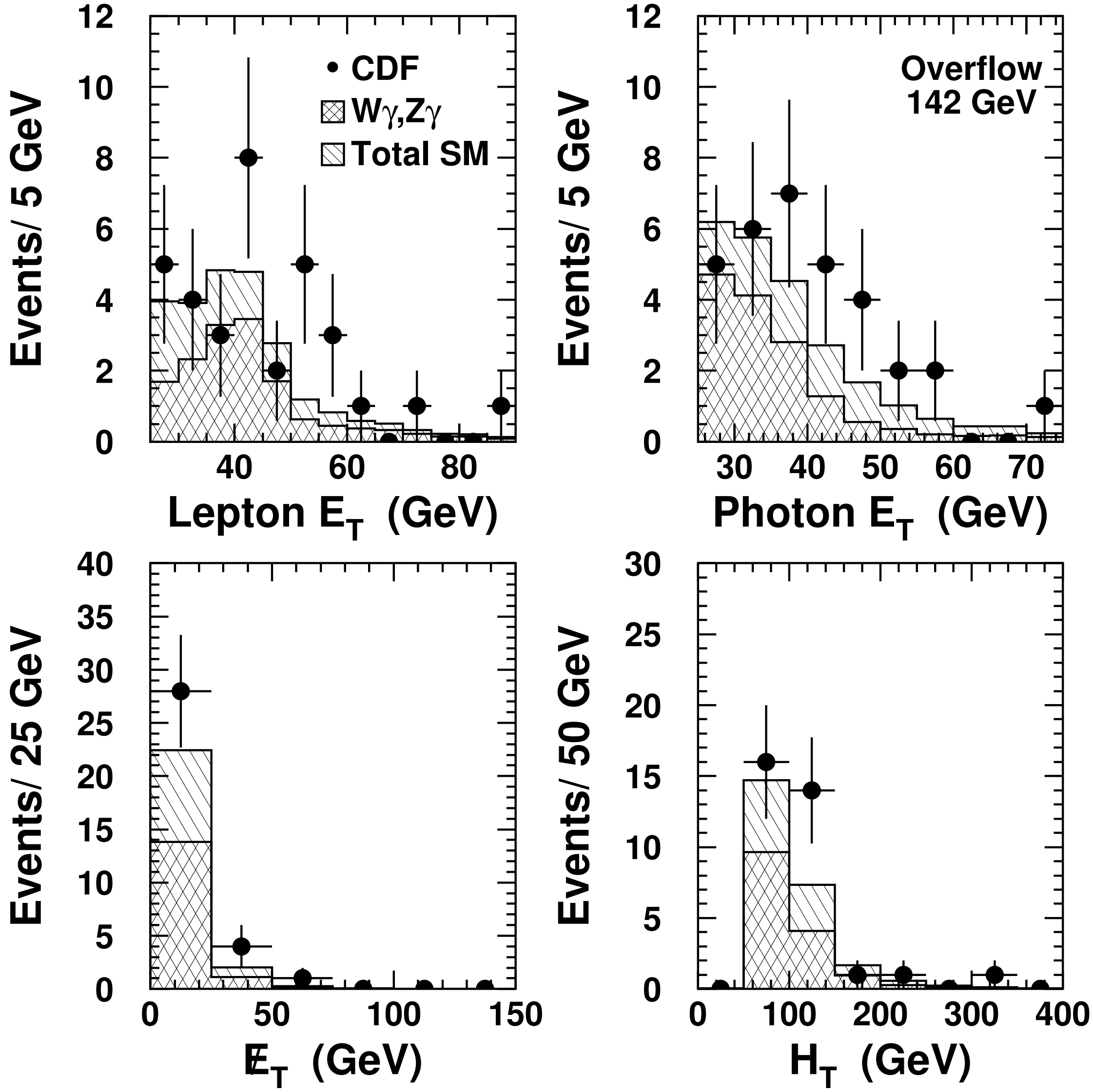
Photon-Lepton Results
Two-Body Photon-Lepton Events
CDF Data (86 pb^{-1})

Process	$e\gamma X$	$\mu\gamma X$	$\ell\gamma X$
W+γ	1.2 ± 0.2	1.5 ± 0.2	2.7 ± 0.3
Z+γ	5.4 ± 0.6	7.1 ± 0.8	12.5 ± 1.2
ℓ+jet, jet $\to \gamma$	1.9 ± 0.3	1.5 ± 0.3	3.3 ± 0.7
$Z \to ee, e \to \gamma$	4.1 ± 1.1	—	4.1 ± 1.1
Hadron+γ	—	1.4 ± 0.7	1.4 ± 0.7
π/K Decay+γ	—	0.8 ± 0.9	0.8 ± 0.9
b/c Decay+γ	0.07 ± 0.02	0.03 ± 0.01	0.10 ± 0.03
Predicted μ_{SM}	12.6 ± 1.4	12.3 ± 1.8	24.9 ± 2.4
Observed N_0	20	13	33
$P(N \geq N_0 \mid \mu_{SM})$	0.043	0.46	0.093

Photon-Lepton Results
Inclusive Multi-Body Photon-Lepton Events
CDF Data (86 pb^{-1})

Process	$e\gamma X$	$\mu\gamma X$	$\ell\gamma X$
W+γ	2.4 ± 0.3	2.5 ± 0.3	5.0 ± 0.6
Z+γ	5.0 ± 0.5	4.6 ± 0.5	9.6 ± 0.9
ℓ+jet, jet $\rightarrow \gamma$	1.7 ± 0.3	1.5 ± 0.3	3.2 ± 0.6
$Z \rightarrow ee, e \rightarrow \gamma$	1.7 ± 0.5	—	1.7 ± 0.5
Hadron+γ	—	0.5 ± 0.3	0.5 ± 0.3
π/K Decay+γ	—	0.3 ± 0.3	0.3 ± 0.3
b/c Decay+γ	< 0.01	< 0.01	< 0.01
Predicted μ_{SM}	10.9 ± 1.0	9.3 ± 1.0	20.2 ± 1.7
Observed N_0	11	16	27
$P(N \geq N_0 \mid \mu_{SM})$	0.52	0.037	0.10

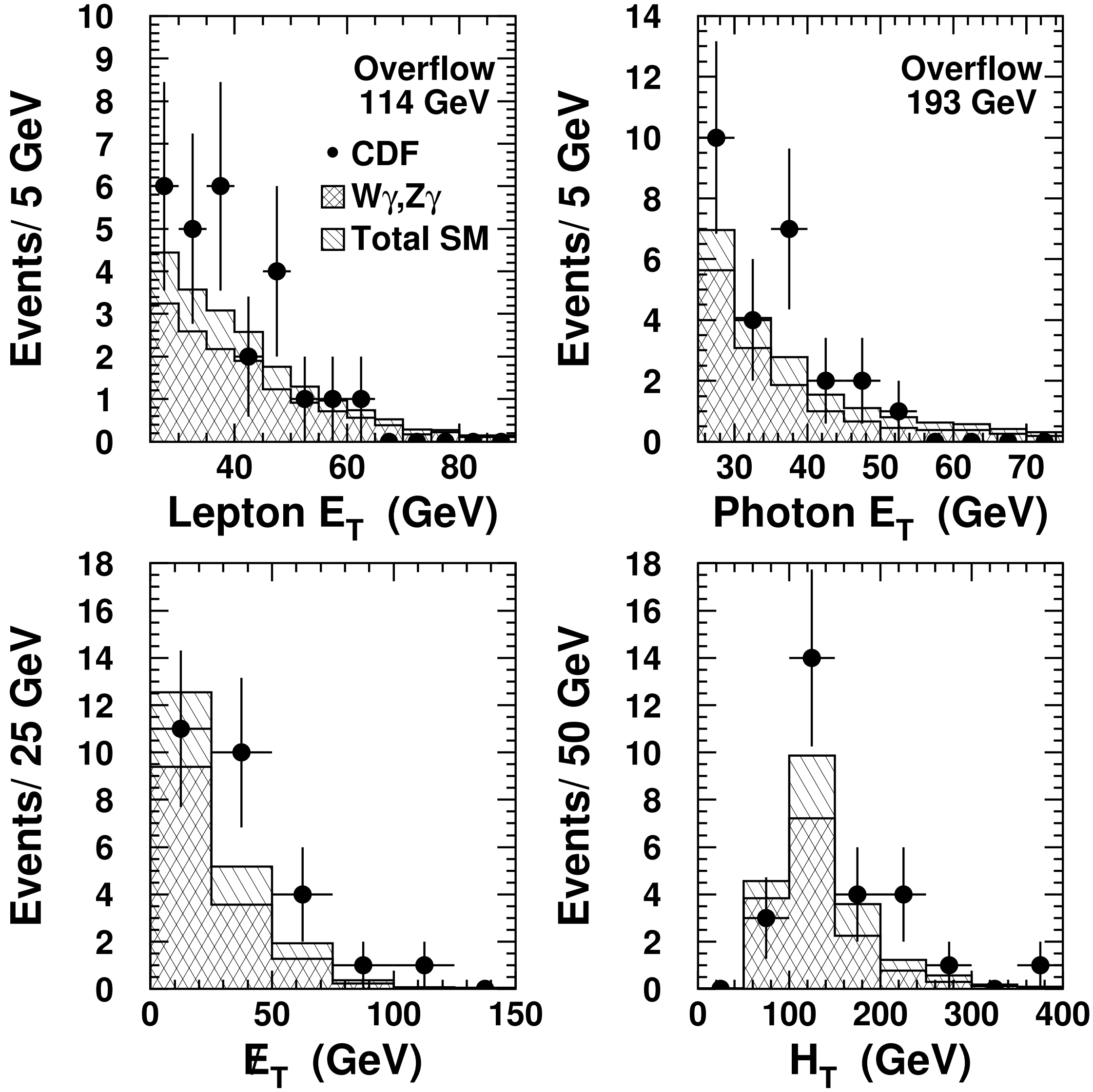
Photon-Lepton Results
Two-Body Photon-Lepton Events
CDF Data (86 pb^{-1})



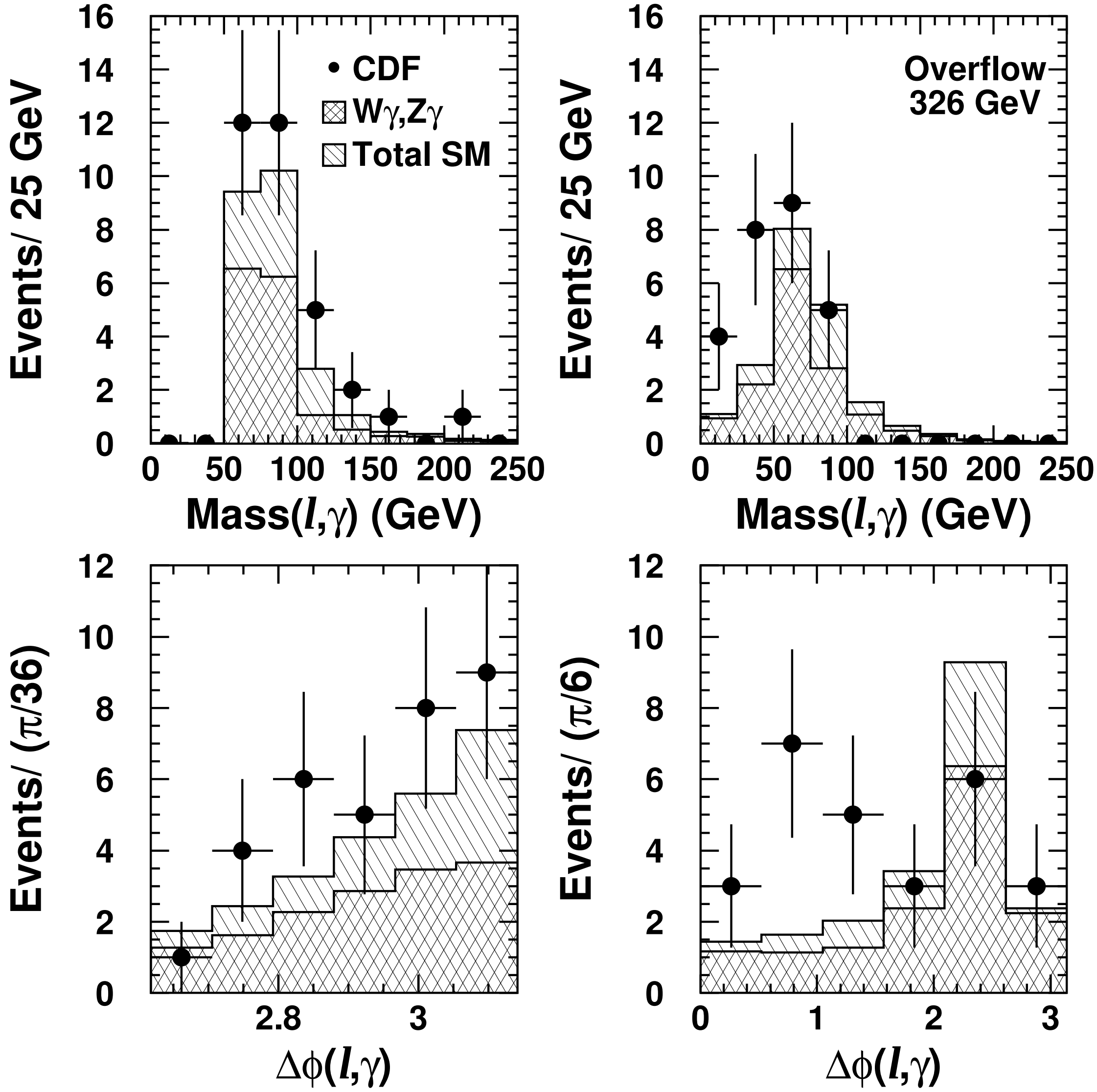
Photon-Lepton Results

Inclusive Multi-Body Photon-Lepton Events

CDF Data (86 pb^{-1})



Photon-Lepton Results
Two-Body (left), Multi-Body (right) Events
CDF Data (86 pb^{-1})



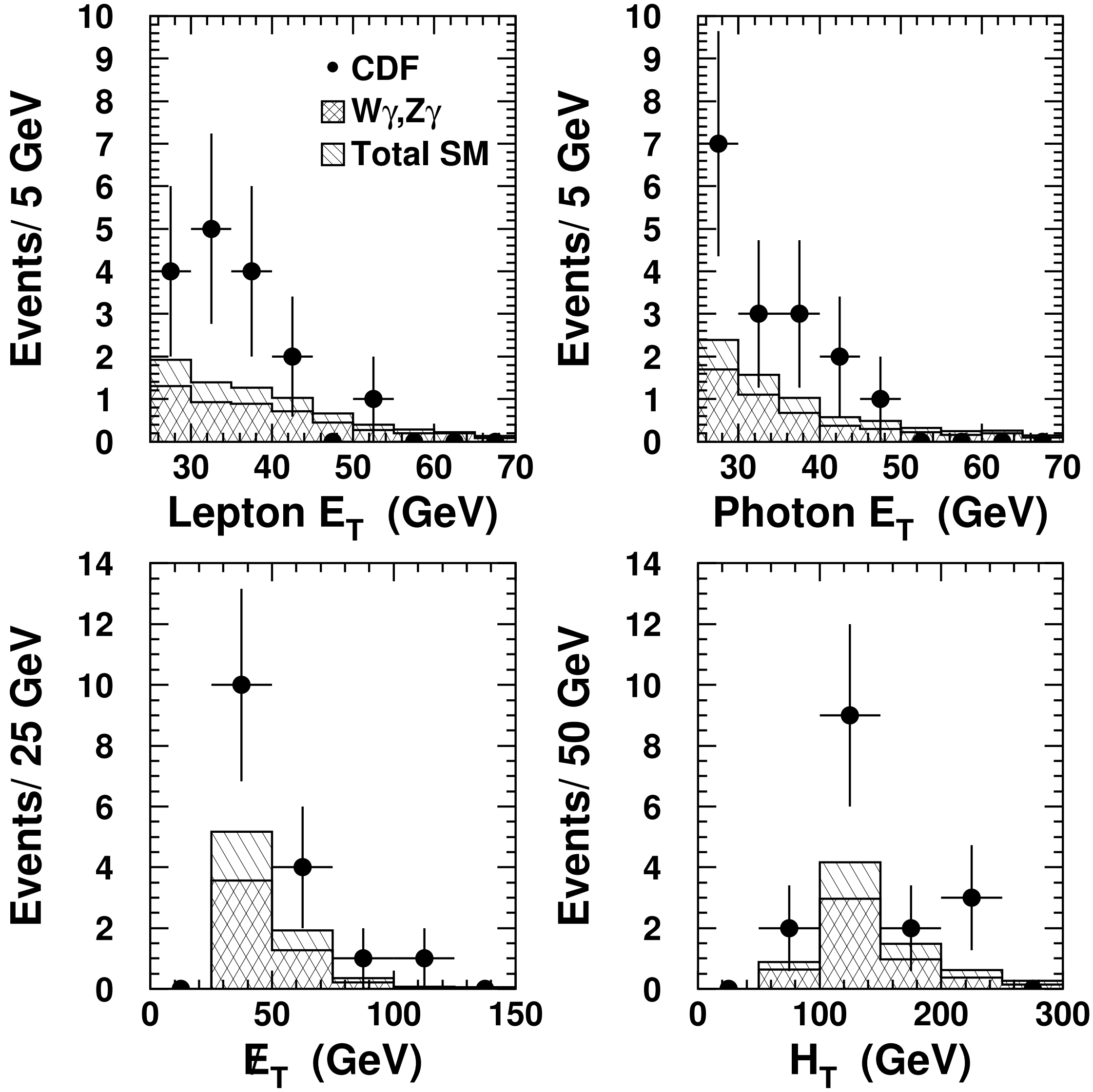
Photon-Lepton Results
Multi-Body $\ell\gamma \not{E}_T$ Events
CDF Data (86 pb^{-1})

Process	$e\gamma \not{E}_T X$	$\mu\gamma \not{E}_T X$	$\ell\gamma \not{E}_T X$
W+γ	1.9 ± 0.3	2.0 ± 0.3	3.9 ± 0.5
Z+γ	0.3 ± 0.1	1.0 ± 0.2	1.3 ± 0.2
ℓ+jet, jet $\rightarrow \gamma$	1.1 ± 0.2	1.0 ± 0.2	2.1 ± 0.4
$Z \rightarrow ee, e \rightarrow \gamma$	0.10 ± 0.04	-	0.10 ± 0.04
Hadron+γ	-	0.2 ± 0.1	0.2 ± 0.1
π/K Decay+γ	-	0.1 ± 0.1	0.1 ± 0.1
b/c Decay+γ	< 0.01	< 0.01	< 0.01
Predicted μ_{SM}	3.4 ± 0.3	4.2 ± 0.5	7.6 ± 0.7
Observed N_0	5	11	16
$P(N \geq N_0 \vert \mu_{SM})$	0.26	0.0054	0.0072

Photon-Lepton Results

Multi-Body $\ell\gamma\not{E}_T$ Events

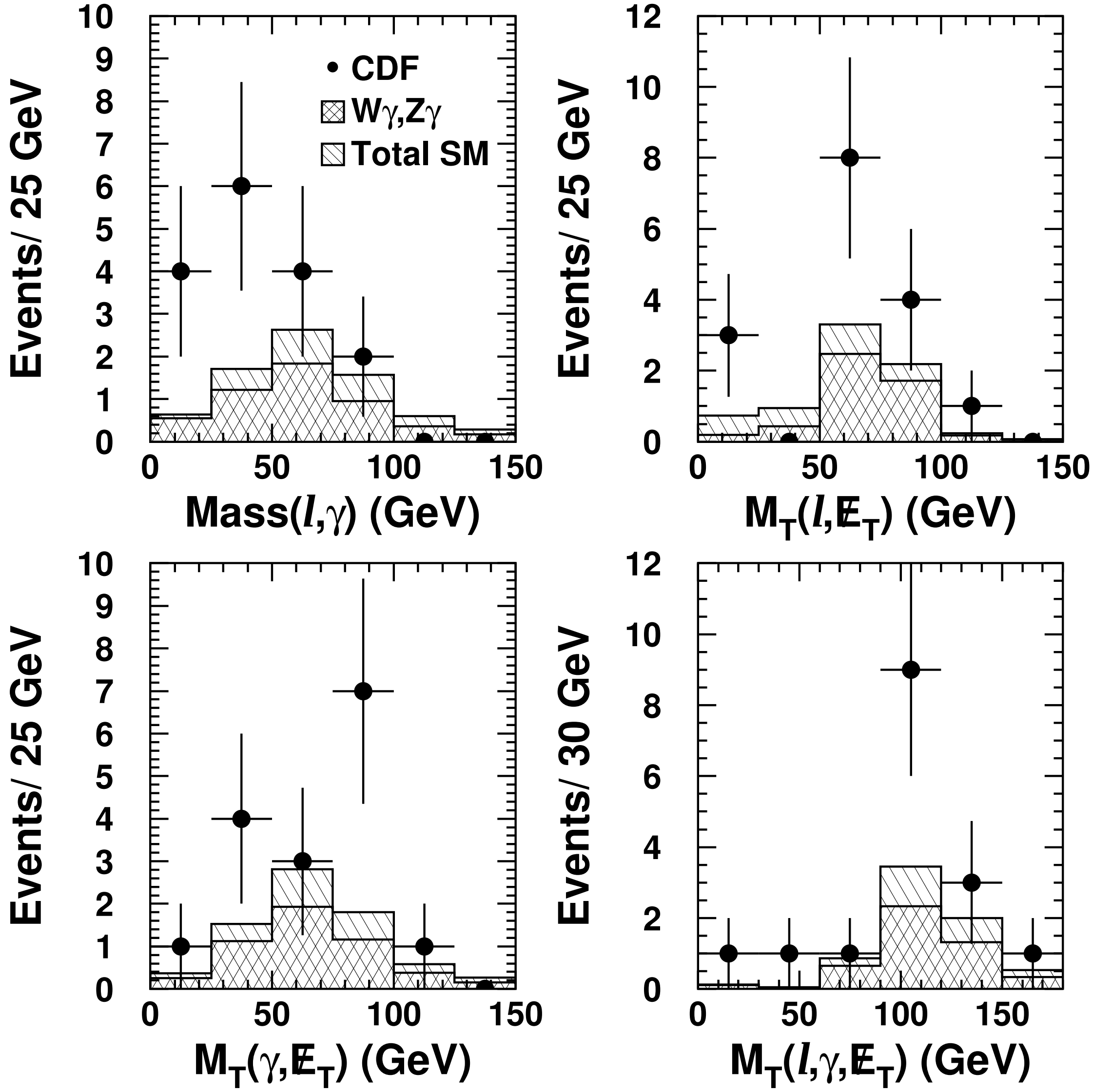
CDF Data (86 pb^{-1})



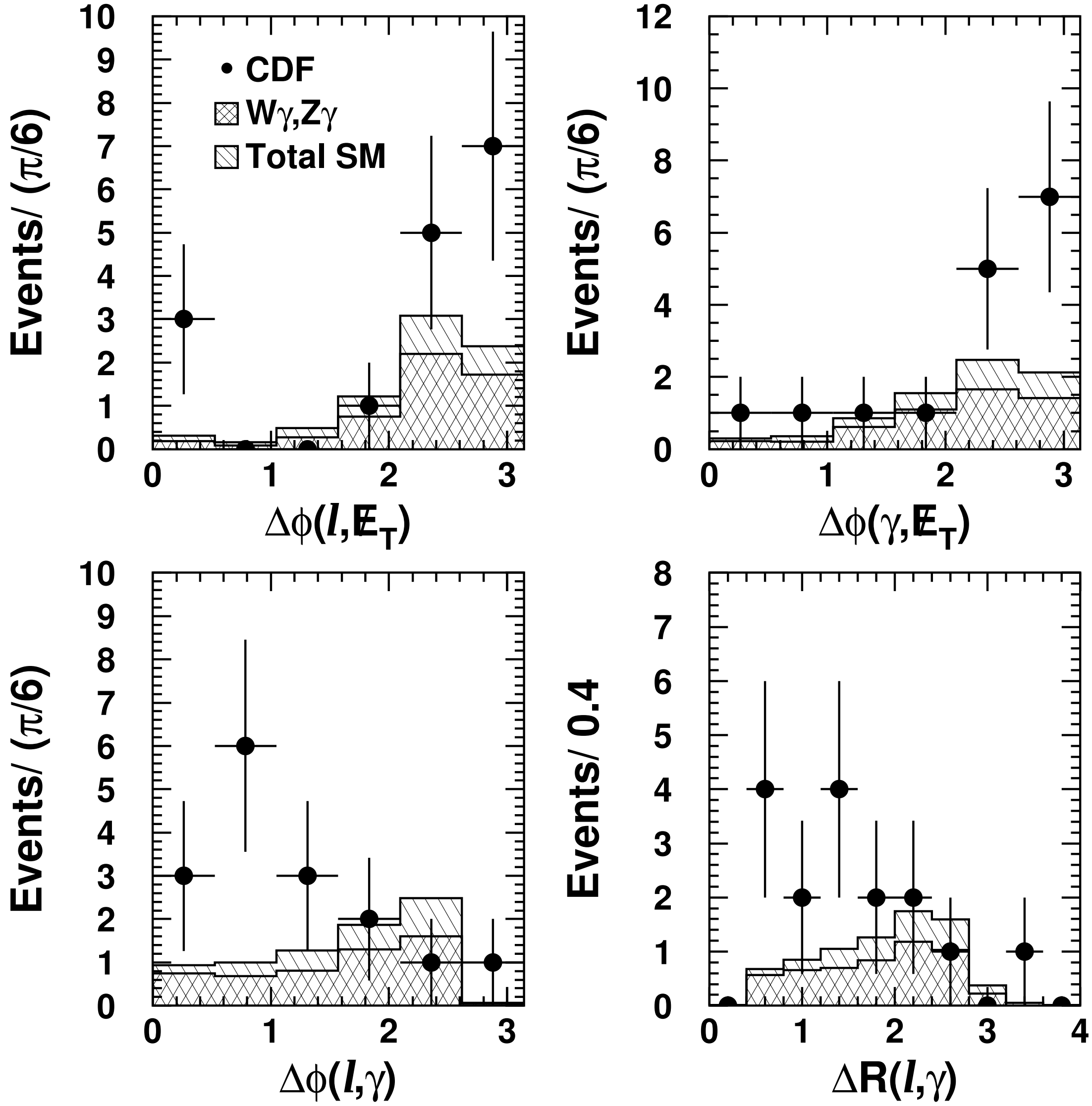
Photon-Lepton Results

Multi-Body $\ell\gamma \not{E}_T$ Events

CDF Data (86 pb^{-1})



Photon-Lepton Results
Multi-Body $\ell\gamma\not{E}_T$ Events
CDF Data (86 pb^{-1})



Photon-Lepton Results
Multi-Body, Multi-Photon and Multi-Lepton Events
CDF Data (86 pb^{-1})

Process	$ee\gamma X$	$\mu\mu\gamma X$	$\ell\ell\gamma X$	$e\mu\gamma X$
Z+γ	3.3 ± 0.4	2.2 ± 0.3	5.5 ± 0.6	0.05 ± 0.01
ℓ+jet, jet $\rightarrow \gamma$	0.19 ± 0.04	0.13 ± 0.03	0.32 ± 0.07	—
Predicted μ_{SM}	3.5 ± 0.4	2.3 ± 0.3	5.8 ± 0.6	0.05 ± 0.01
Observed N_0	4	1	5	0
$P(N \geq N_0 \| \mu_{SM})$	0.45	0.90	0.68	0.95

Process	$e\gamma\gamma$	$\mu\gamma\gamma$	$\ell\gamma\gamma$
Z+γ	0.012 ± 0.012	0.004 ± 0.004	0.016 ± 0.016
ℓ+jet, jet $\rightarrow \gamma$	—	—	—
Predicted μ_{SM}	0.012 ± 0.012	0.004 ± 0.004	0.016 ± 0.016
Observed N_0	1	0	1
$P(N \geq N_0 \| \mu_{SM})$	0.013	1.0	0.015

Conclusions

- **Inspired by the unexplained $ee\gamma\gamma\not\!\!E_T$ event, the highest-E_T photon-lepton $(+\ell, \gamma, \not\!\!E_T)$ data have been inclusively compared with Standard Model expectations.**

- **There is no conclusive evidence for new physics in the categories analyzed.**

- **This analysis will be repeated with Run II CDF data, $(> 20\times$ Run I data) which will decisively confirm or contradict the discrepancies between observed and predicted $\ell\gamma\not\!\!E_T$ and $\ell\gamma\gamma$ rates.**

- **Chinese menu physics leaves us hungry for more data!**