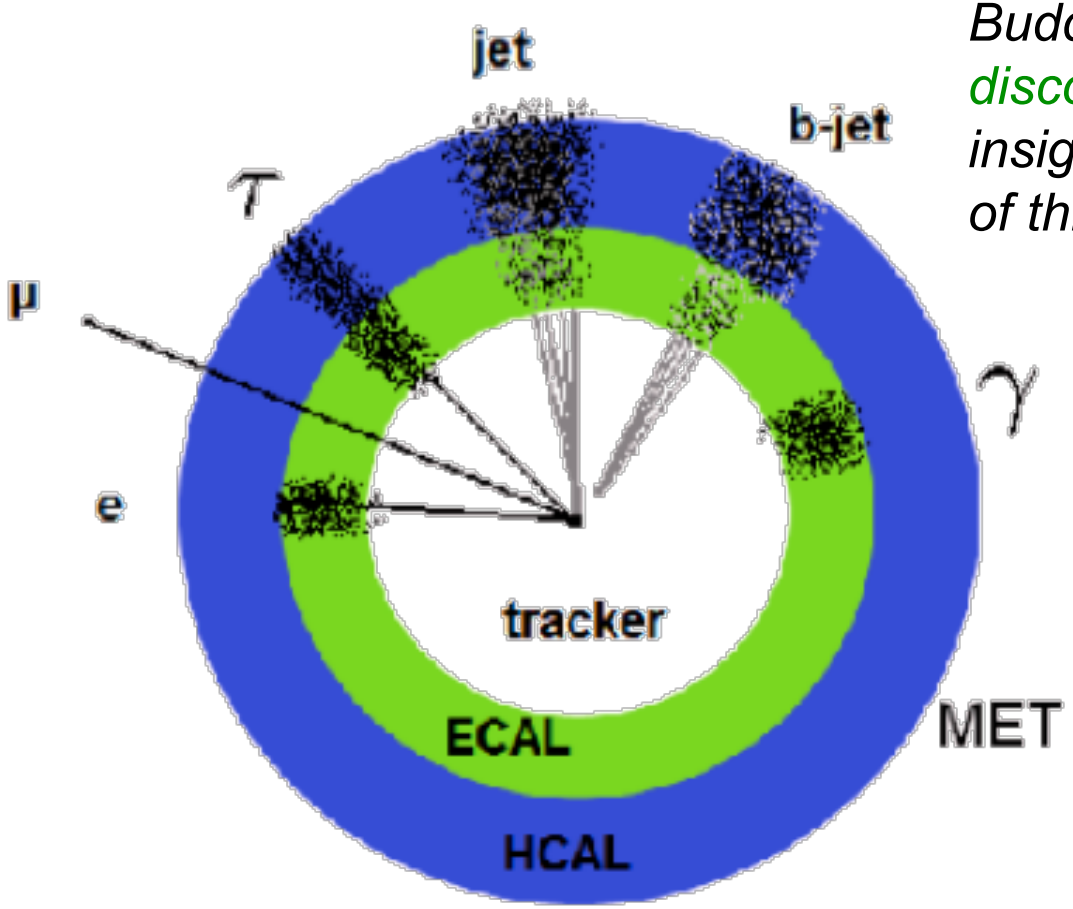
# Old and New Physics with Diphotons at CDF

Sasha Pranko

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**

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

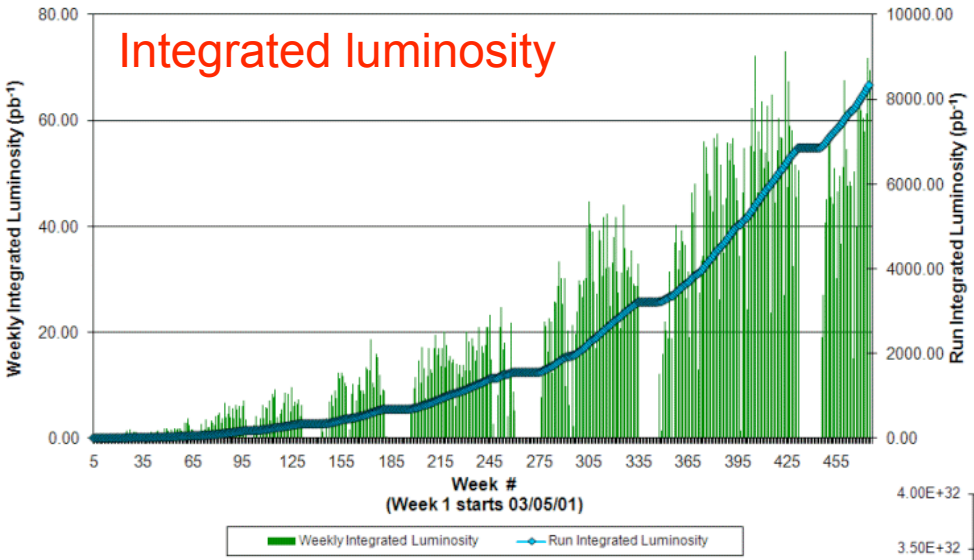
# Diphotons at CDF

This talk

- Prompt diphoton production X-section
- Search for Randall-Sundrum gravitons in $\gamma\gamma$
- Search for fermiophobic $H \rightarrow \gamma\gamma$
- Search for SM $H \rightarrow \gamma\gamma$
- Search for anomalous $\gamma\gamma$+MET
- Search for anomalous $\gamma\gamma + e/\mu/\tau$

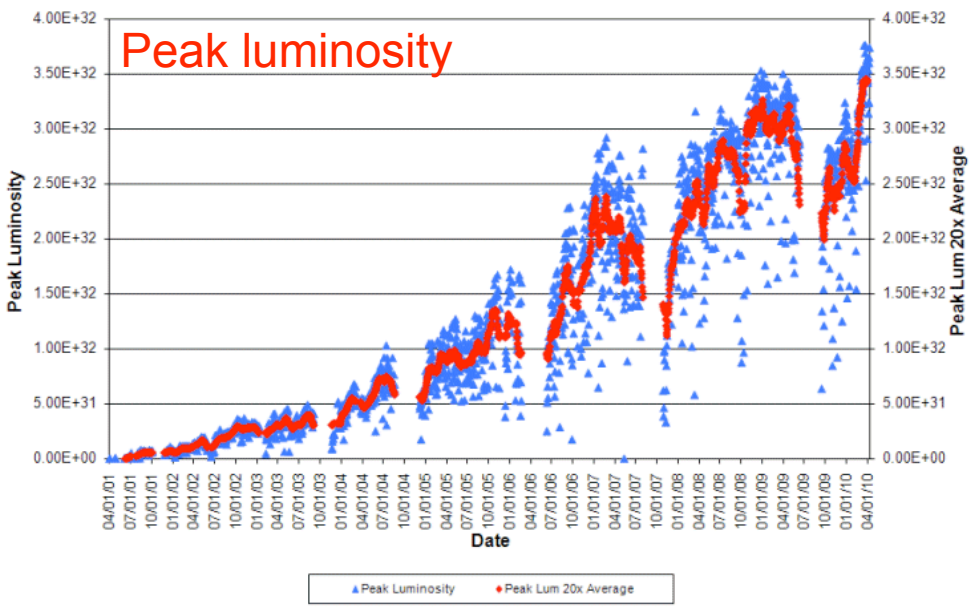
# Tevatron is Still in The Race for Higgs

## Is it a Sprint or Marathon?

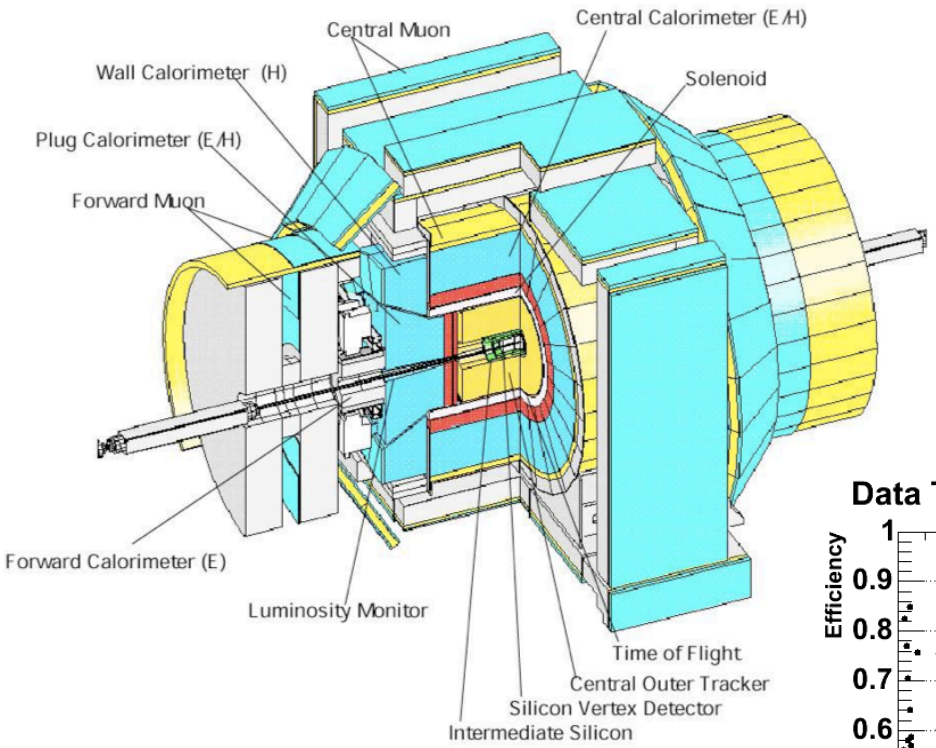



- ~8.4 $fb^{-1}$ per experiment
  - On track for ~12 $fb^{-1}$ per experiment by the end of 2011
- Investigating possibilities to run Tevatron and Nova programs
  - Run until 2014? 16-18 $fb^{-1}$?

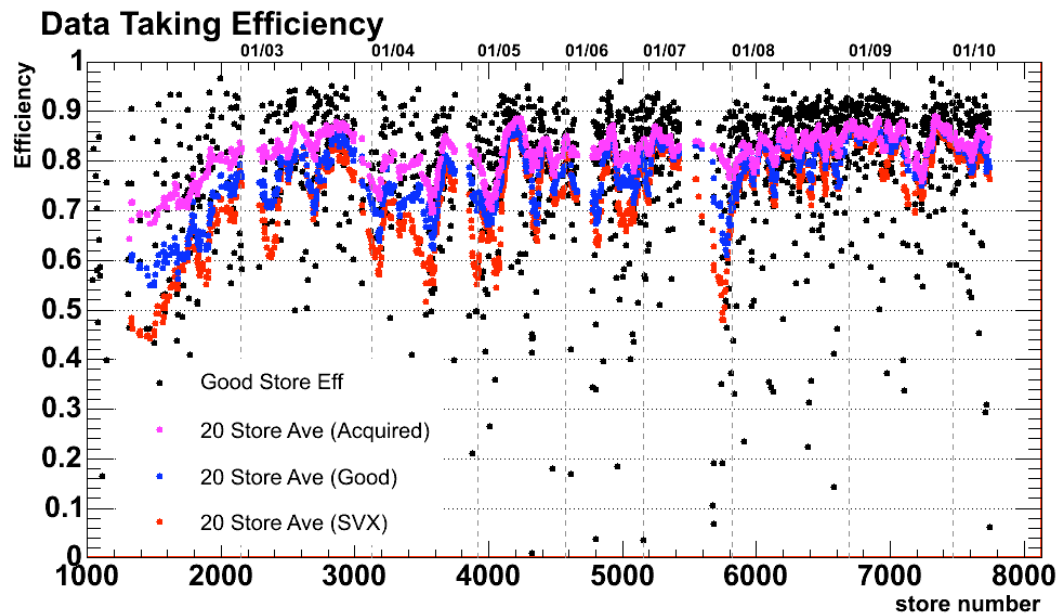
- New lumi record: 402.4E30
  - Setting record after record
  - Running consistently at >300E30



# CDF in Run II

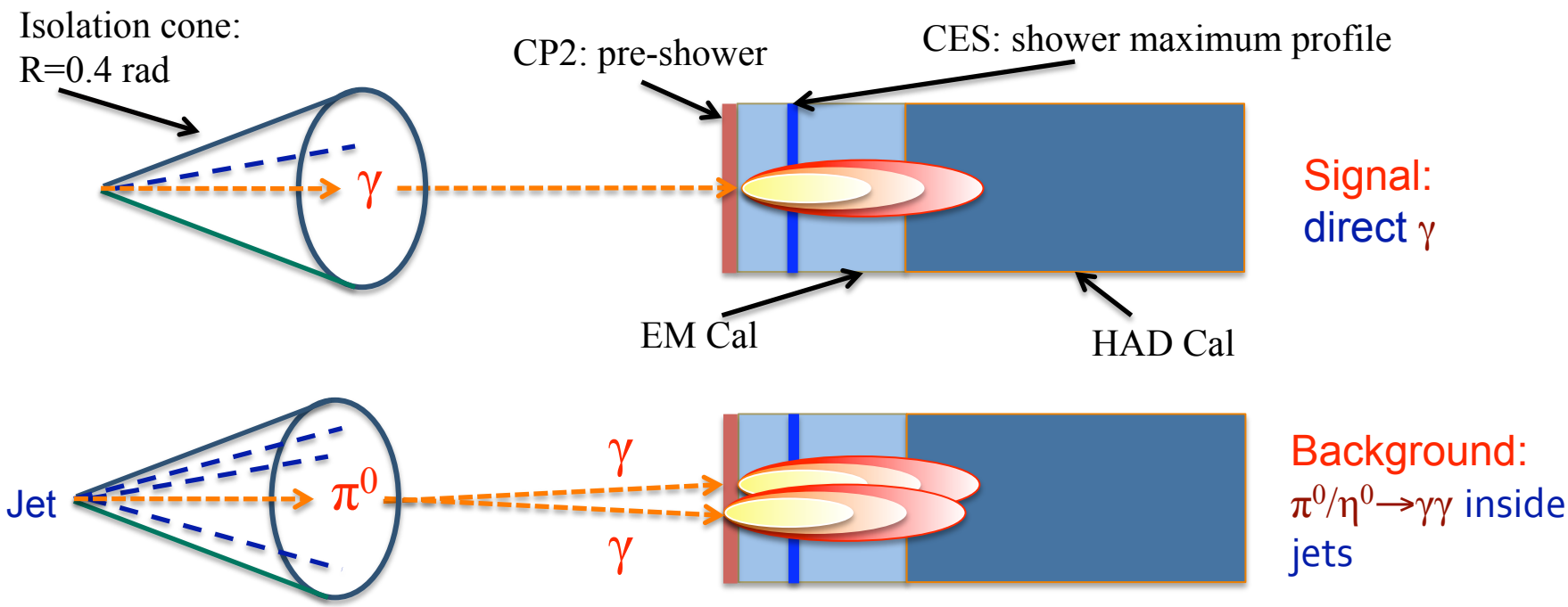



- Multipurpose, classic design
- Operating well: 80-90% efficiency
  - 7 $fb^{-1}$ on tape
- Broad program: QCD, EWK, top, B-physics, Higgs & new physics searches
  - 40 publications/year

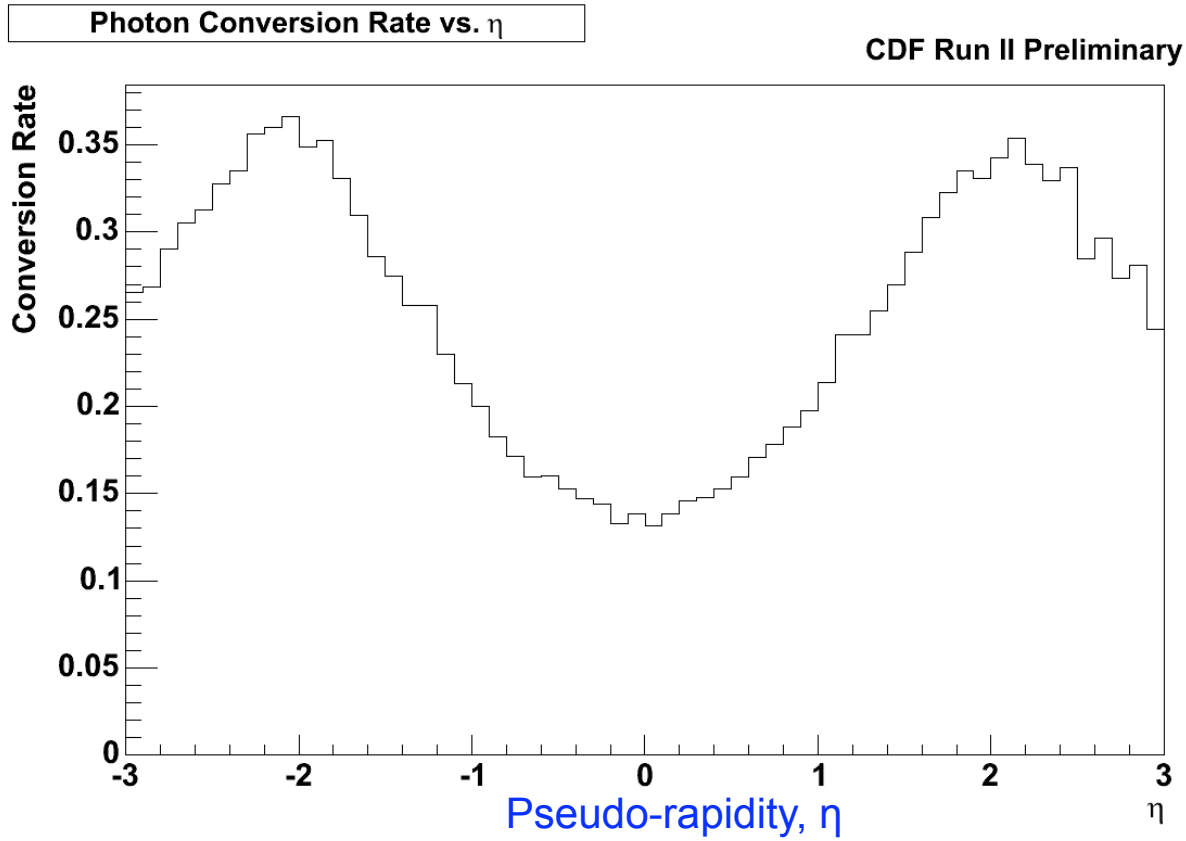


# Concept of Photon ID

- Photon detector signature
  - "Compact", isolated EM cluster: shower contained in EM CAL without much other energy around
- What fakes a photon?
  - Energetic (≈boosted) $\pi^0/\eta^0 \rightarrow \gamma\gamma$ looks like a single photon
  - Electron ≈ photon + track

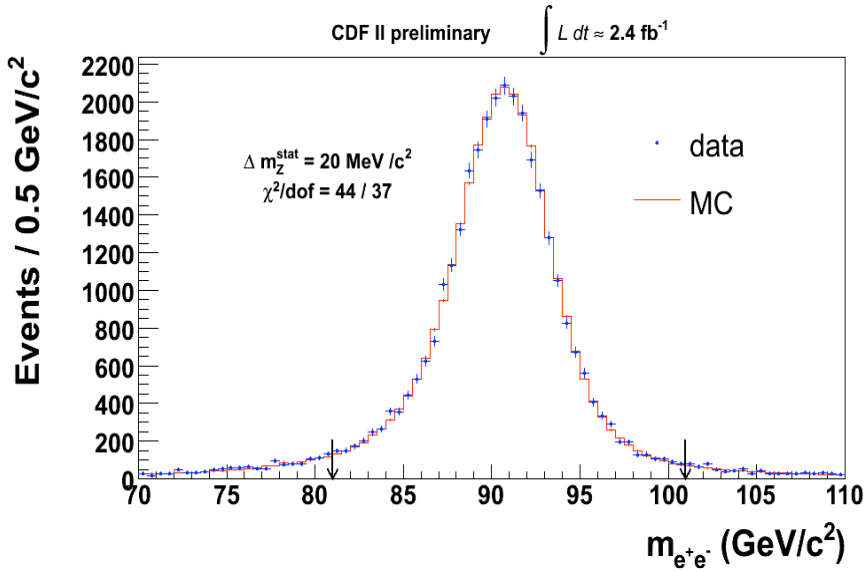


# Conversions

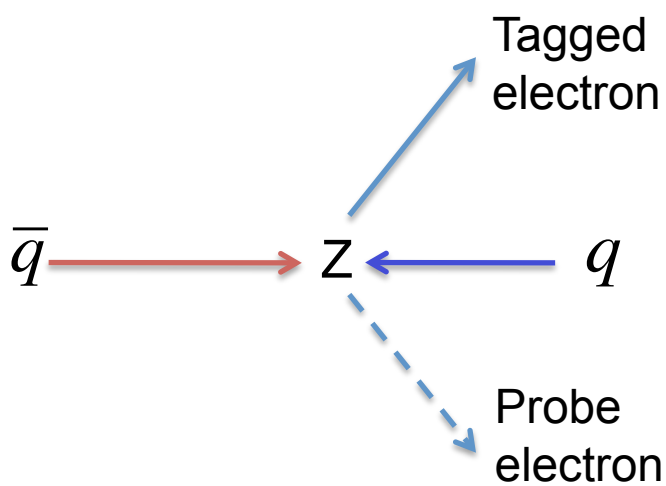



- ~15% (~30%) central (forward) photons convert to $e^+e^-$
  - Conversions are not currently used in photon analyses at CDF
  - CDF has only one Run I measurement using converted photons
    - Phys. Rev. D70, 074008 (2004)

# Photon ID Efficiency

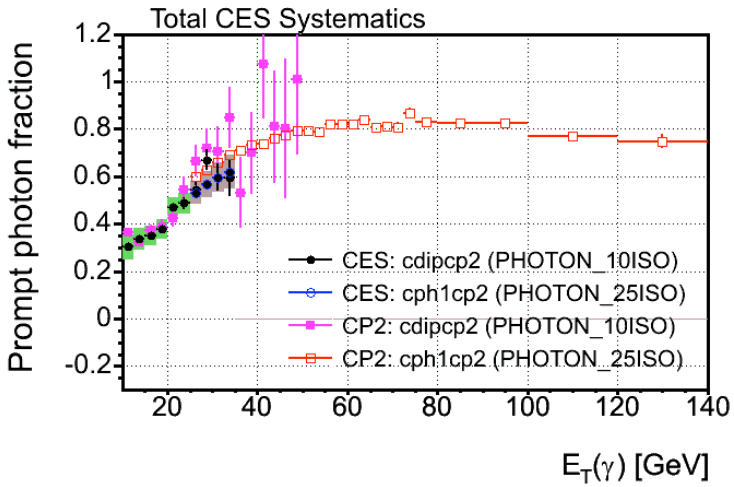


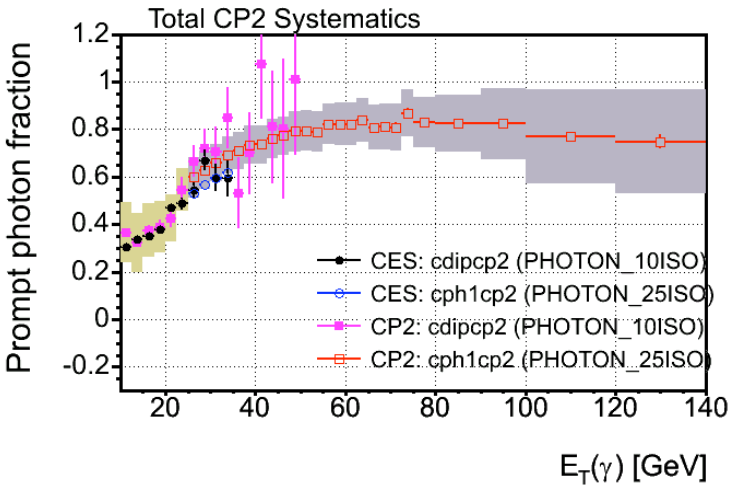

- Method
  - MC for $E_T$ dependence
  - Data/MC scale factor:
    - $Z \rightarrow e^+e^-$ in data and MC



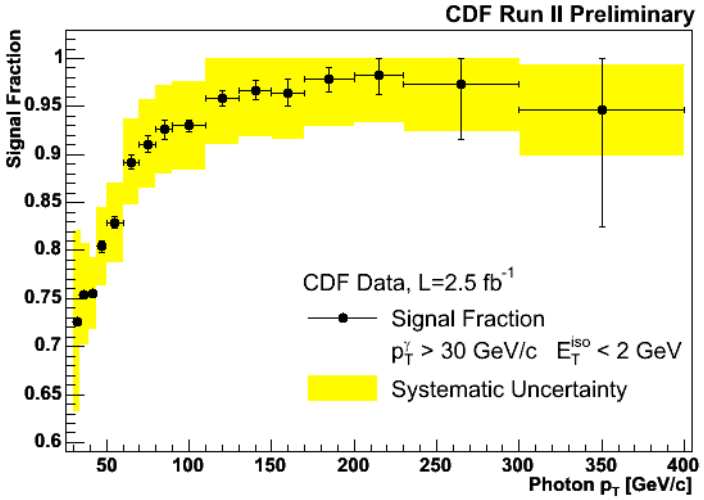

**Efficiency of photon ID**
**Central: ~86%**
**Forward: ~76%**

# Overview of Background Subtraction




- CES method
  - Based on shower profile in CES
  - Only up to $E_T$<35 GeV; 10%-17% systematics
- CPR/CP2 method
  - Count number of photon conversion in magnet
  - 10%-30% systematics (~20% at low $E_T$)
- Calorimeter Isolation method
  - Difference in cal-ISO between signal & fakes
  - ~5% systematics (up to 15% for $E_T$<35 GeV)
  - Need complex MC-based corrections



# Calorimeter & Track Isolation

callSO = U.E. + M.I. + Leakage + Fragmentation (if fake)
trkISO = U.E. + Fragmentation (if fake)
all tracks are required to point to the primary vertex

$$calISO = \sum_{towers}^{r<0.4} E_T$$

$$trkISO = \sum_{tracks}^{r<0.4} P_T$$

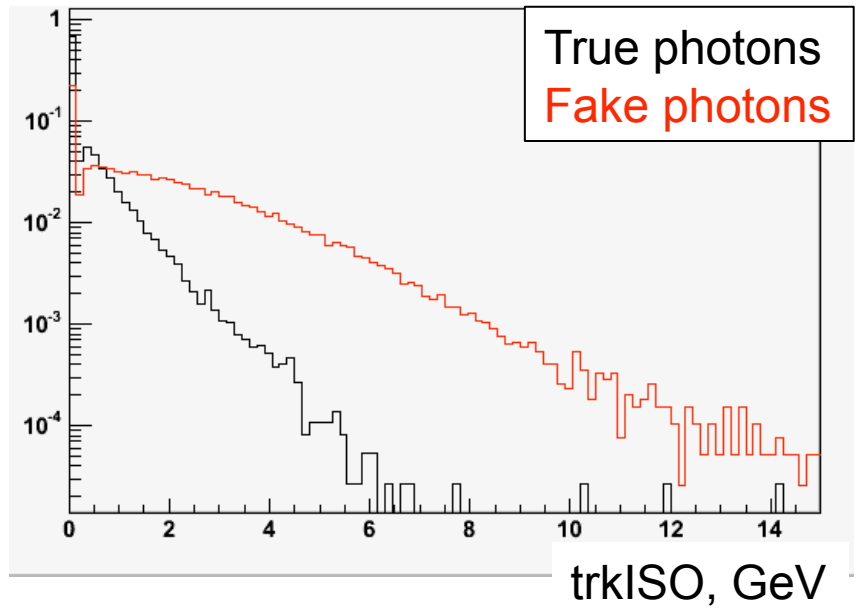
U.E. = underlying event
M.I. = pile-up
Leakage = energy leakage from photon to neighbors in φ
Fragmentation = soft particles from jet producing fake photon

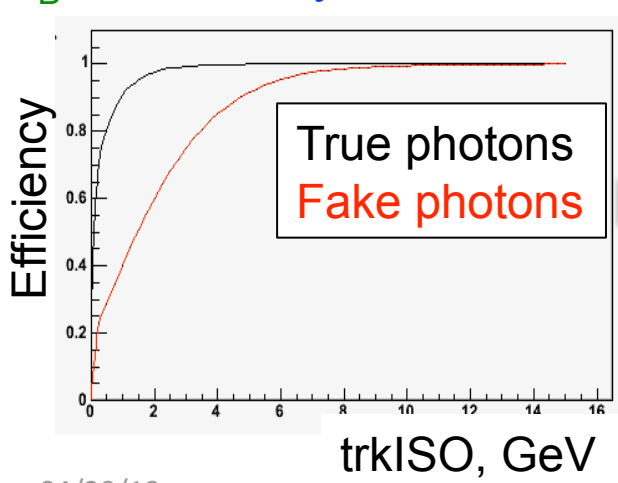
- Advantage of **callSO**
  - Measures energy of charged and neutral particles
  - Can be used for central and forward photons
- Disadvantage of **callSO**
  - Smeared by M.I. and Leakage
  - Poor energy resolution at low $E_T$
- Advantage of **trkISO**
  - Sensitive only to U.E. and fragmentation
  - Good resolution
- Disadvantage of trkISO
  - Measures energy of charged particles only

# Background Subtraction with trkISO

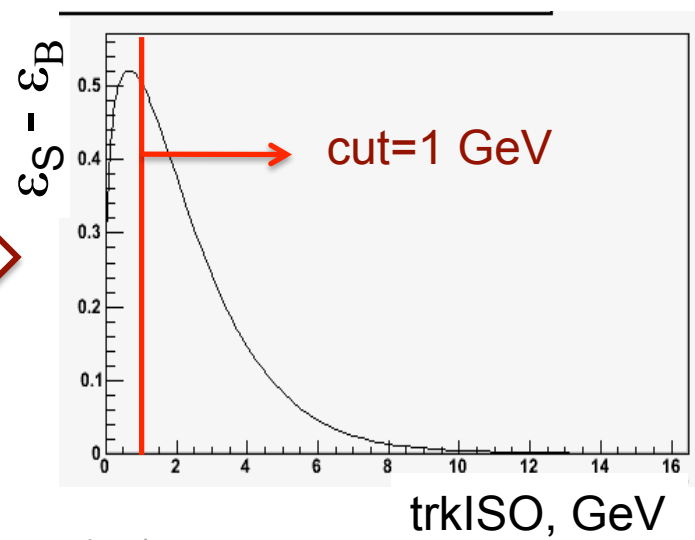
$$w = \frac{\varepsilon - \varepsilon_B}{\varepsilon_S - \varepsilon_B}$$

- $w$ – weight for each event
  - In diphoton analysis, $w$ is a 4×4 matrix
- $\varepsilon$=1 if data photon has trkISO < cut
- $\varepsilon$=0 if data photon has trkISO ≥ cut
- $\varepsilon_S$ – efficiency of trkISO < cut for signal
- $\varepsilon_B$ – efficiency of trkISO < cut for fakes

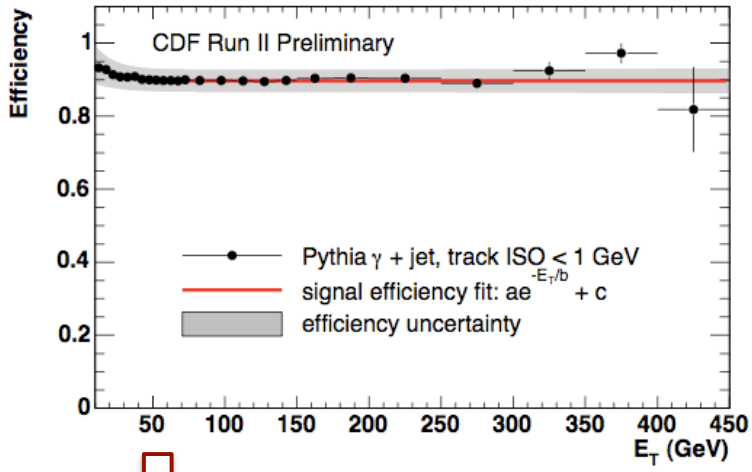


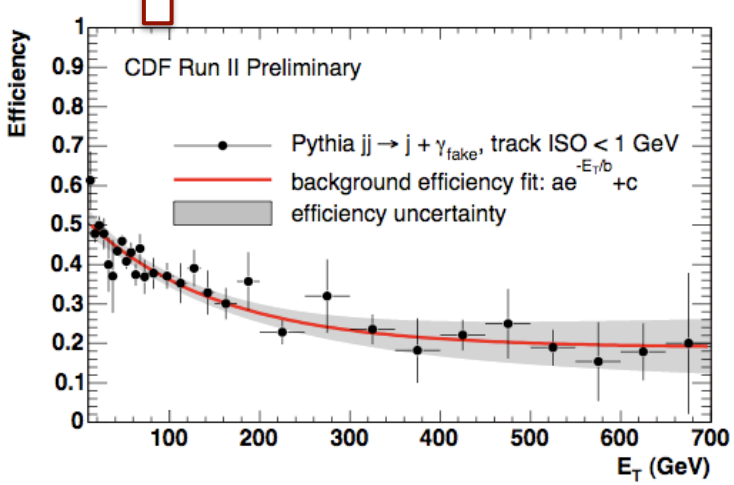

trkISO-cut optimization



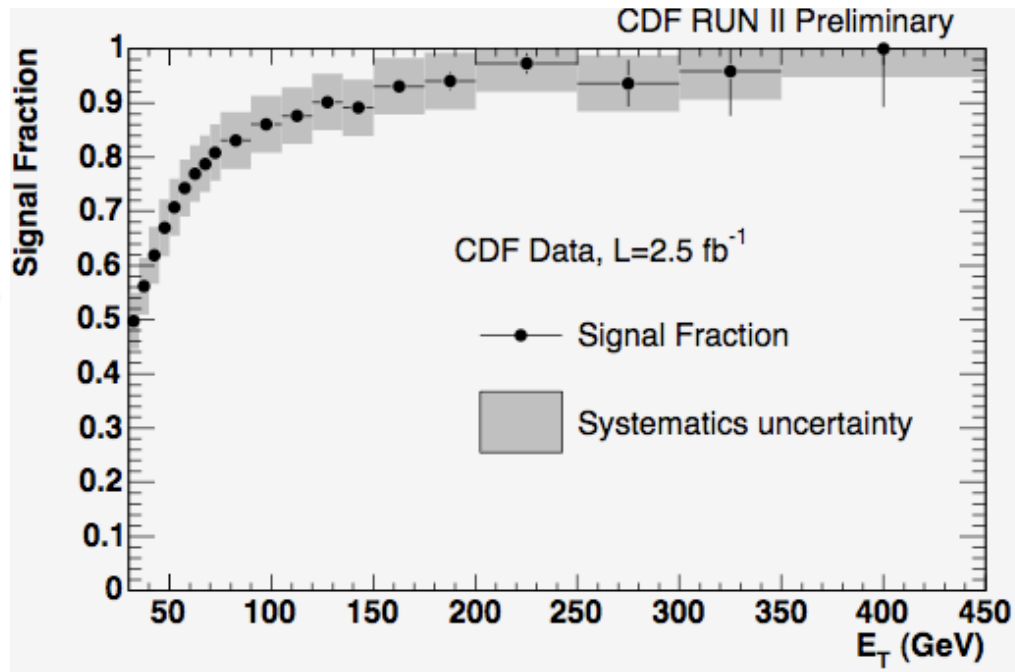
# Background Subtraction with trkISO




$$w = \frac{\varepsilon - \varepsilon_B}{\varepsilon_S - \varepsilon_B}$$



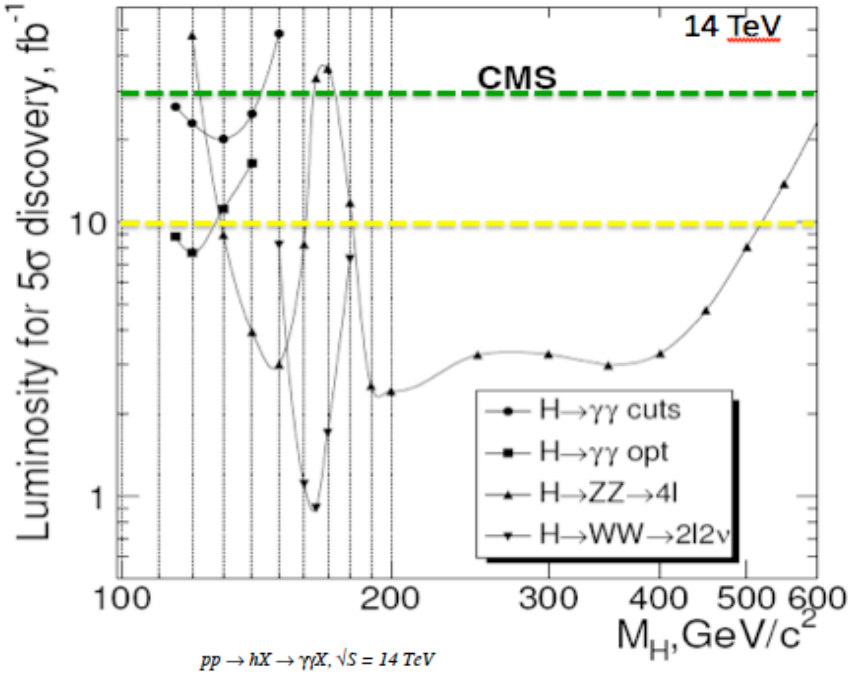

- trkISO method systematics:
  - ~10% at low $E_T$ (~10-15 GeV)
  - ~5% at large $E_T$ (>100 GeV)

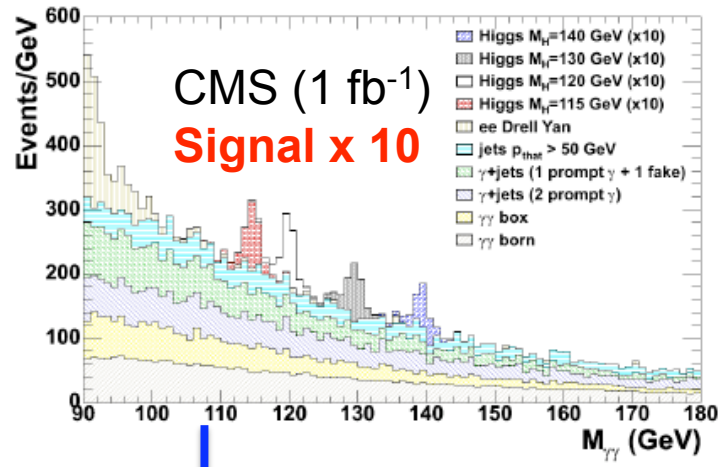


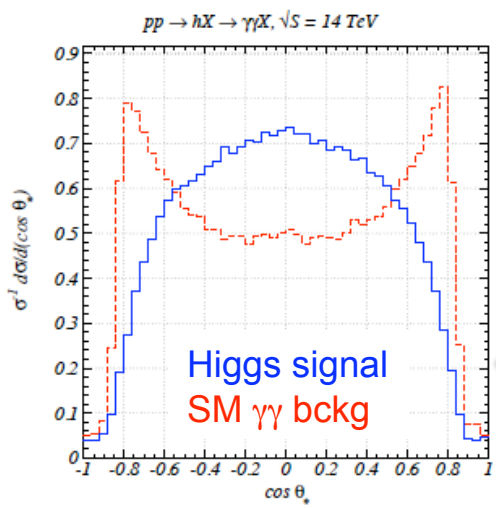
# Direct γγ Production Cross Section

THE ROAD MAP

# Search for H→γγ at LHC

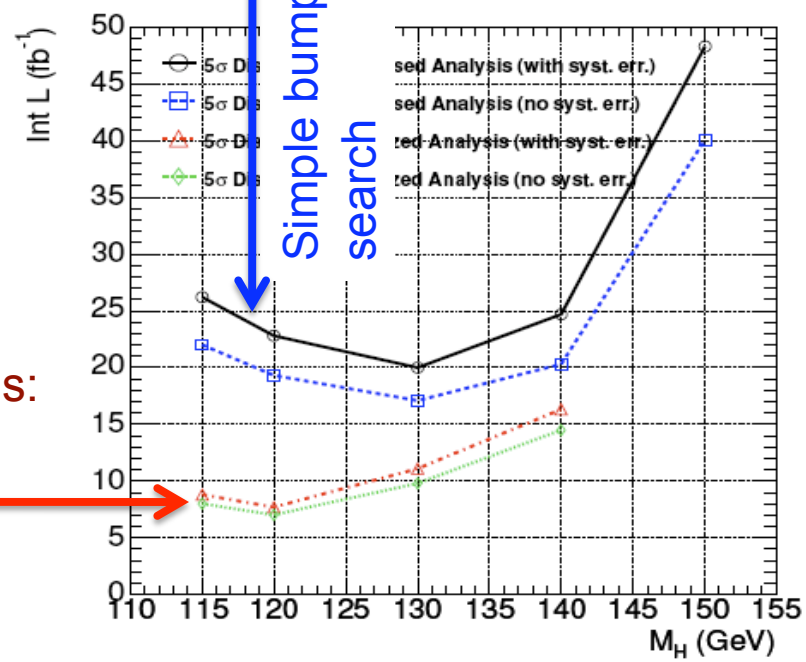


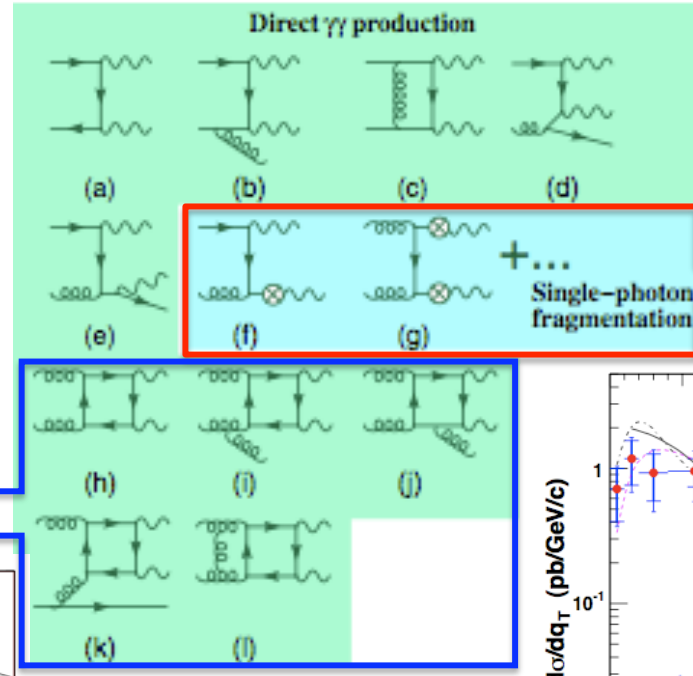

Optimized analysis:
x3 improvement

Simple bump search



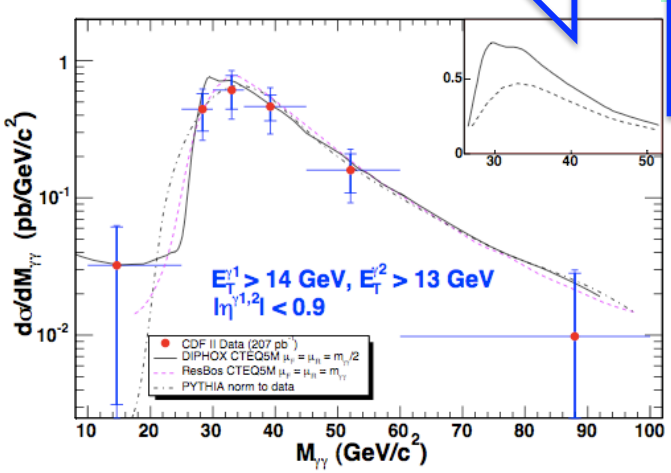
# Direct γγ Production Cross Section

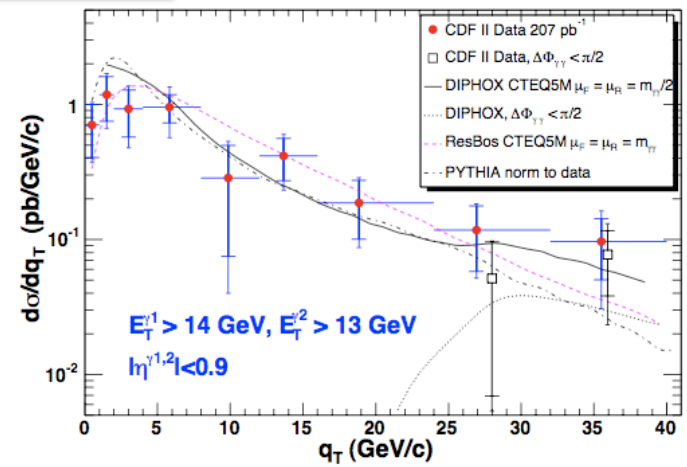
- Irreducible background for H→γγ search at LHC




**Role of "fragmentation"?**
Kink at ~30 GeV?

**Role of "box" diagrams?**
Much bigger at LHC



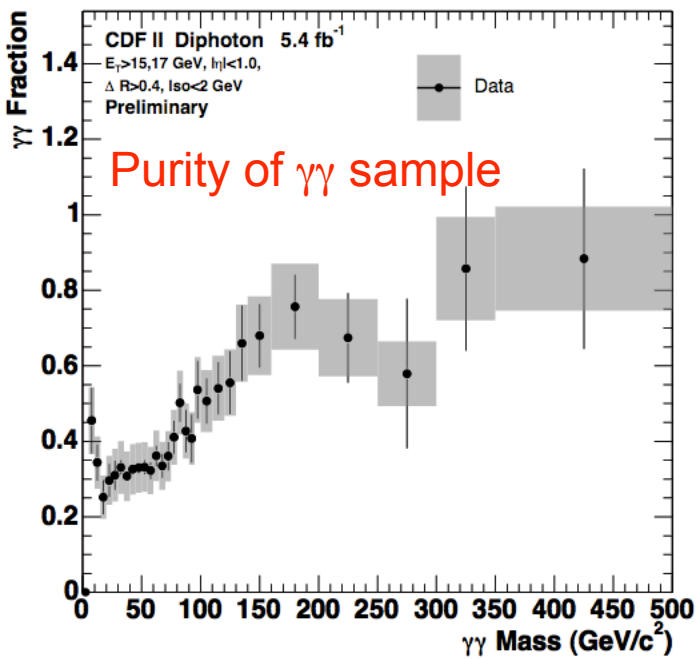



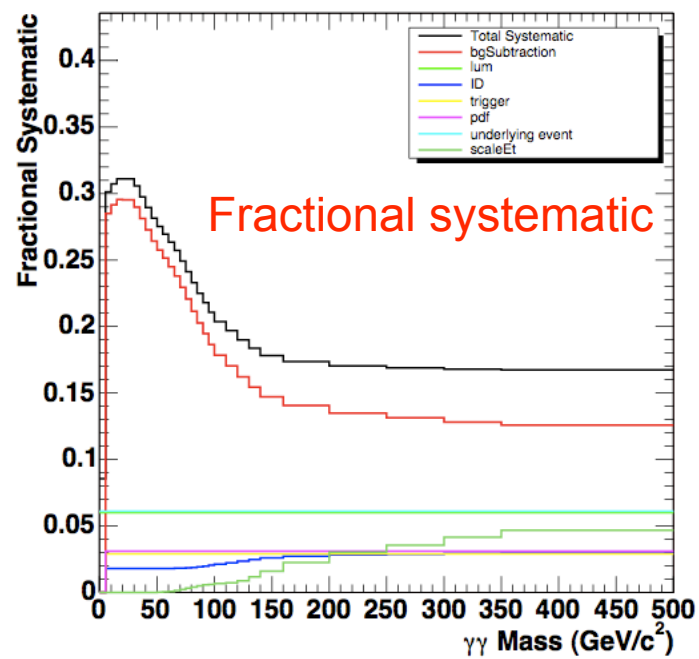

**ResBos**: NLO + NNLL re-summation; no fragmentation

**Diphox**: NLO + Fragmentation; no NLO "box" diagrams

# γγ Production Cross Section: Analysis Overview

- Event selection in 5.4 $fb^{-1}$ of data
  - 2 "tight" photons: $E_T(\gamma 1)>17$ GeV, $E_T(\gamma 2)>15$ GeV, $|\eta_{1,2}|<1.0$

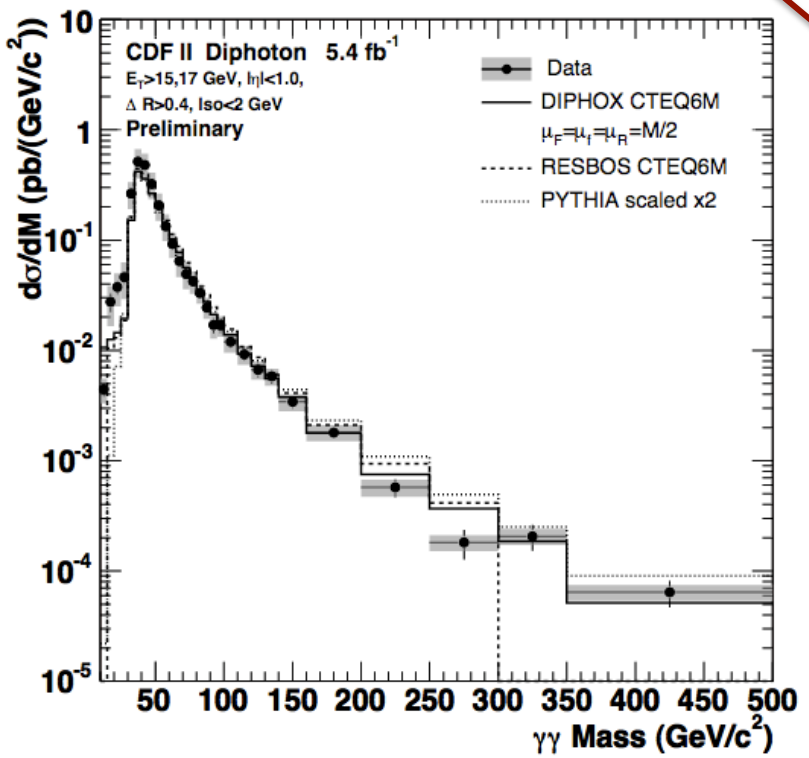


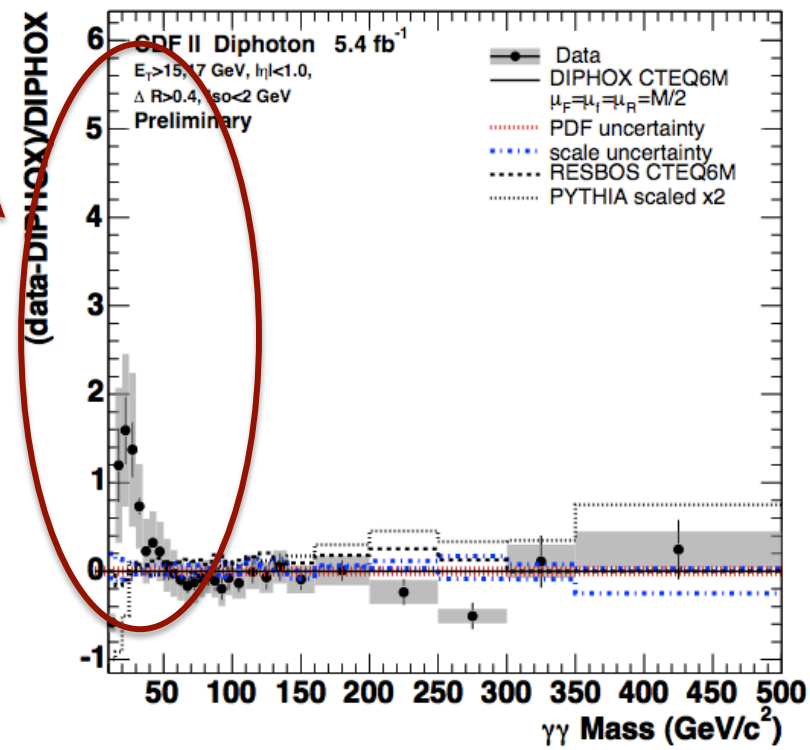




- **Systematics on background subtraction is critical**
  - Developed new background subtraction method based on track ISO
    - ~6%-12% systematics per photon

# Results for $d\sigma/dM_{\gamma\gamma}$ Cross Section

- **Effect of single/double-fragmentation or gluon radiation?**

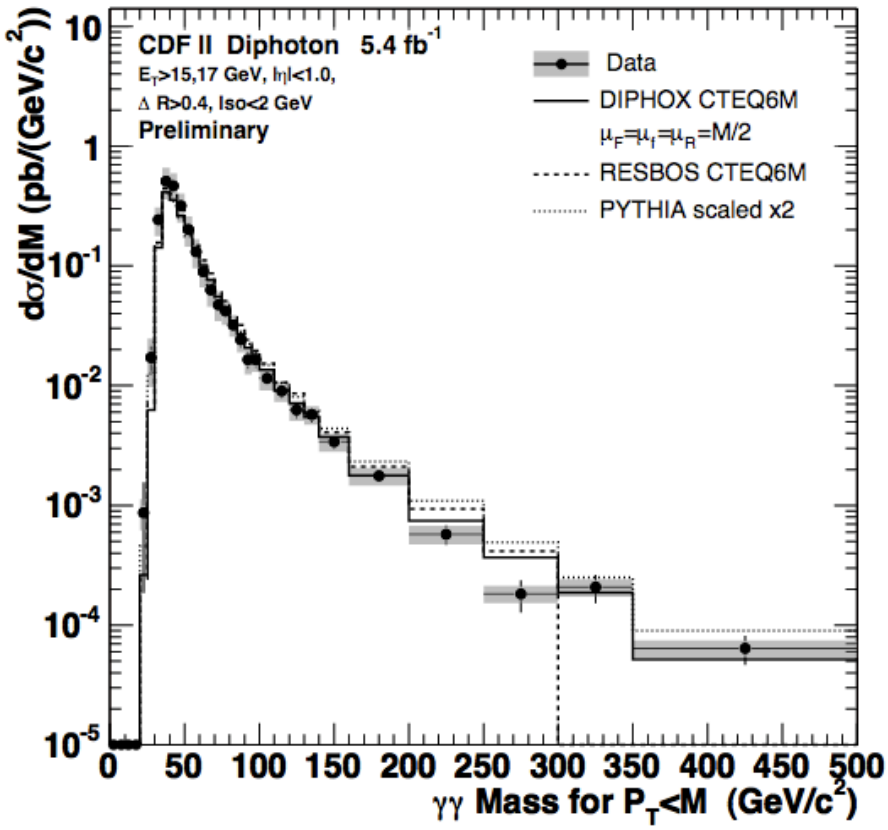


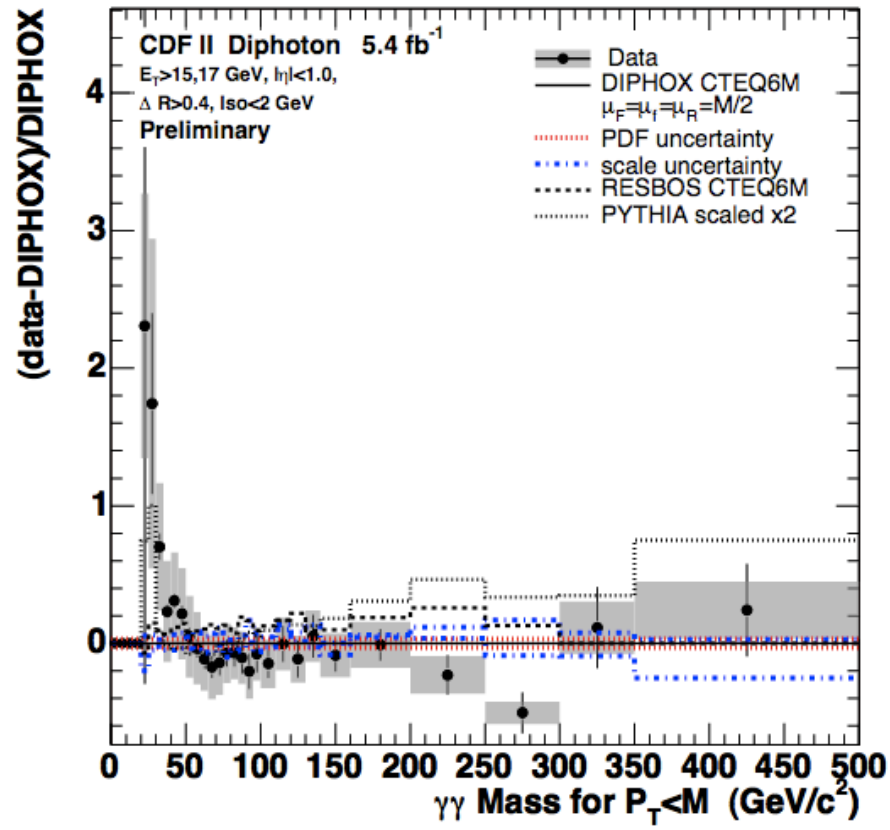




- ResBos slightly over-estimates cross-section for $M_{\gamma\gamma}$>50 GeV/c$^2$

# Results for $d\sigma/dM_{\gamma\gamma}$ if $M_{\gamma\gamma} > P_T(\gamma\gamma)$

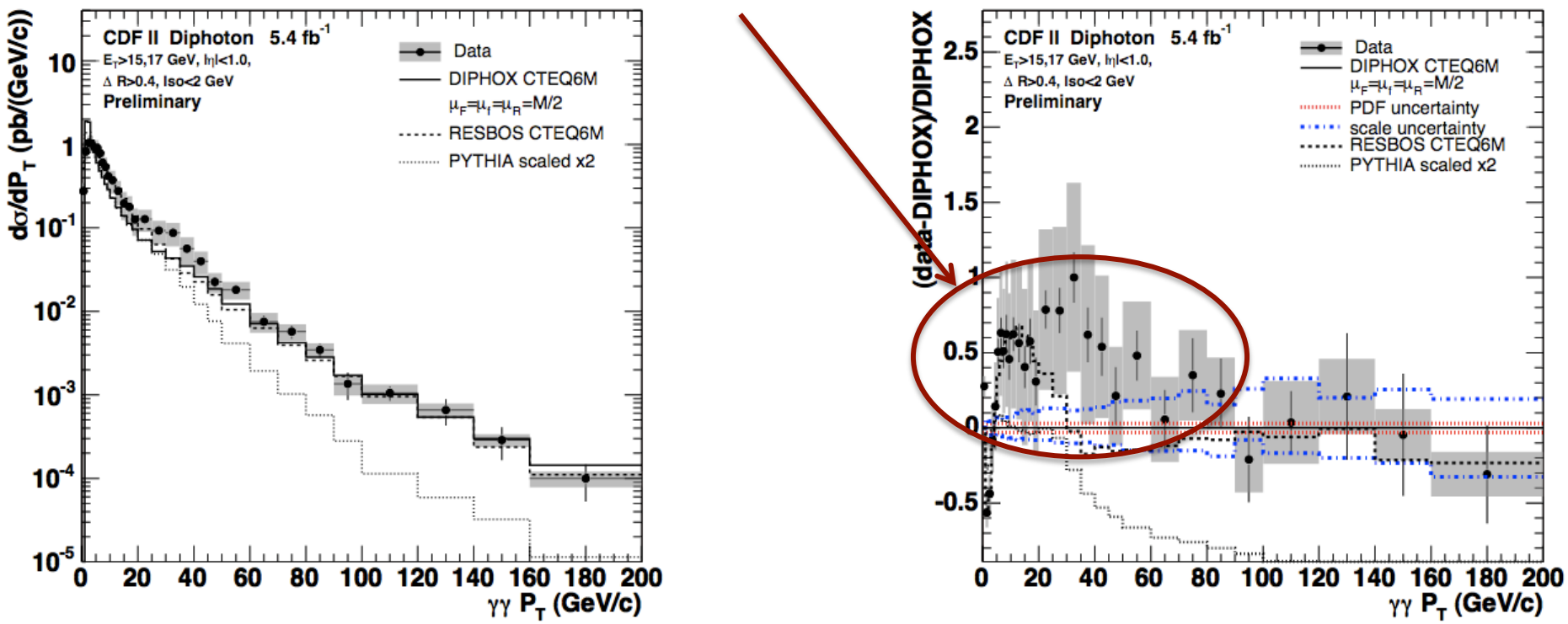
- $M_{\gamma\gamma} > P_T(\gamma\gamma)$ cut suppresses double fragmentation contribution
- Data agree with Diphox
- ResBos predicts slightly larger cross-section



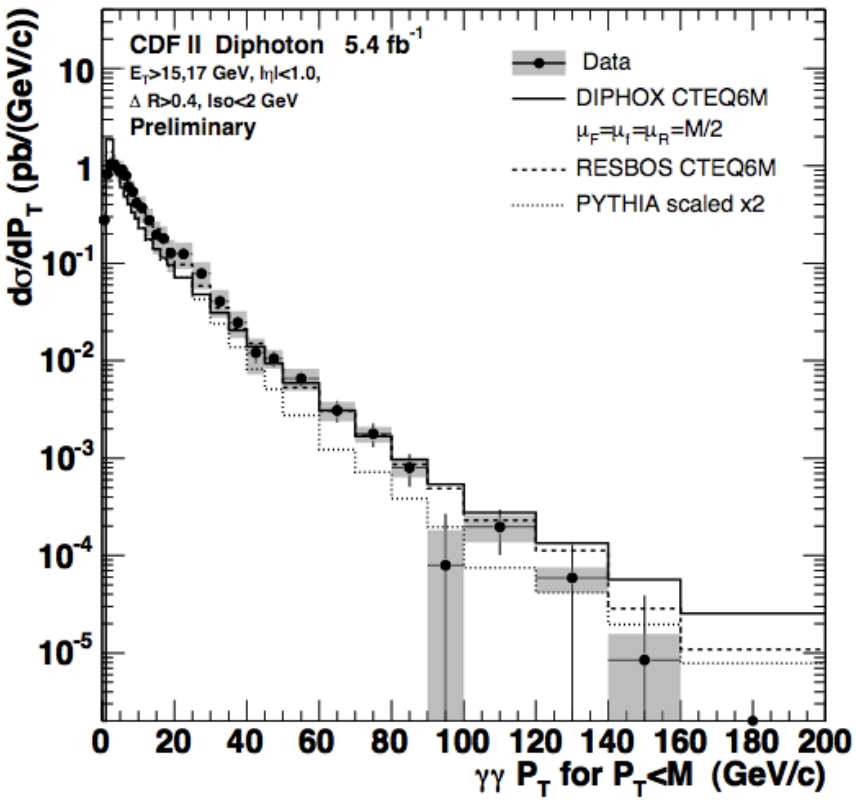
# Results for $d\sigma/dP_T(\gamma\gamma)$ Cross Section

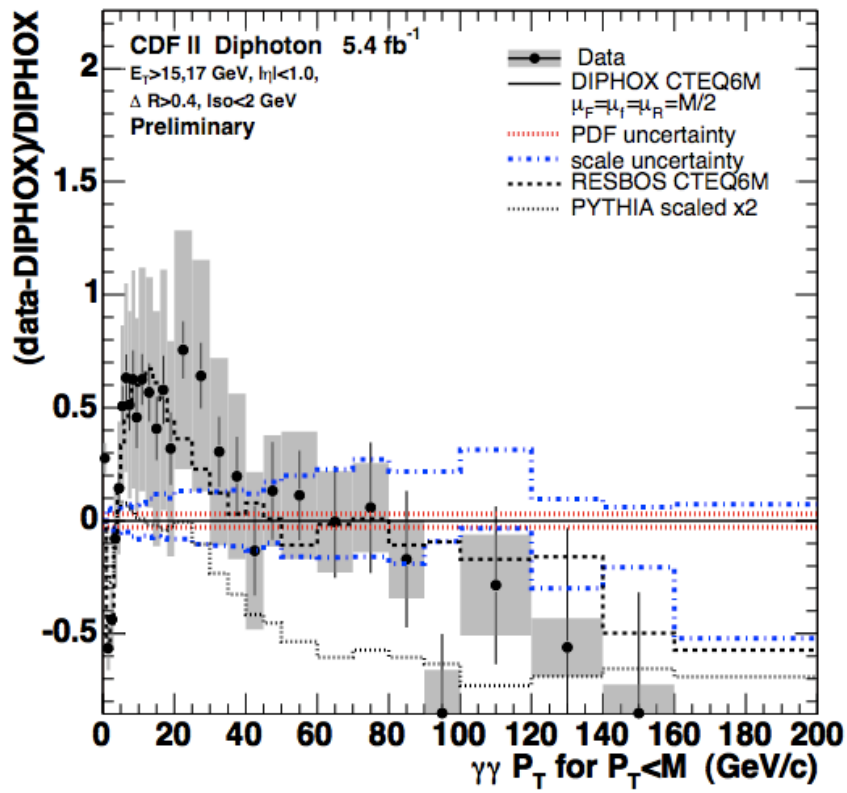
- Kink in the region of $Q_T$~30 GeV is confirmed
- **Diphox significantly off in the region <50 GeV**
  - Pythia shows its limitations (test ISR model; fragmentation not included)
  - ResBos fails to describe "kink" region, but otherwise in good agreement
    - Low $P_T$: effect of gluon re-summations



# Results for $d\sigma/dP_T(\gamma\gamma)$ if $M_{\gamma\gamma} > P_T(\gamma\gamma)$

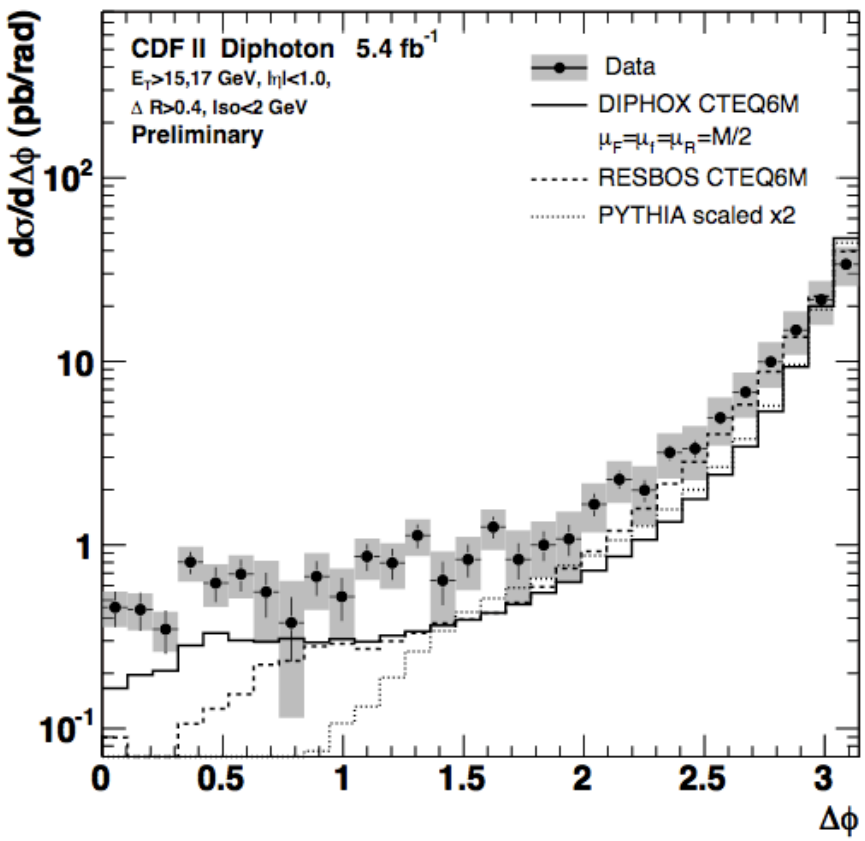
- ResBos is in good agreement with data over entire range
  - Diphox fails to describe data at $P_T(\gamma\gamma)<40$ GeV
  - Indicates importance of soft gluon re-summations
- Pythia fails to describe data over entire range

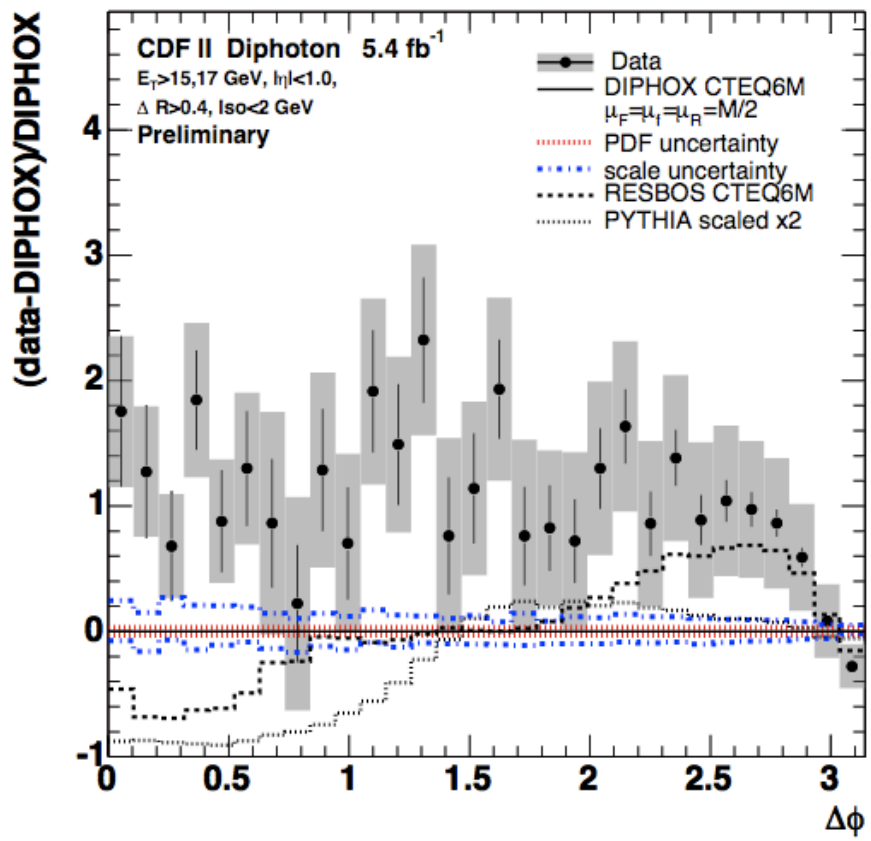


# Results for $d\sigma/d(\Delta\varphi_{\gamma\gamma})$ Cross Section

- Neither prediction agrees with data in the entire range
  - ResBos is better at $\Delta\varphi \sim \pi$
  - Diphox has similar trend, but still fails to describe data

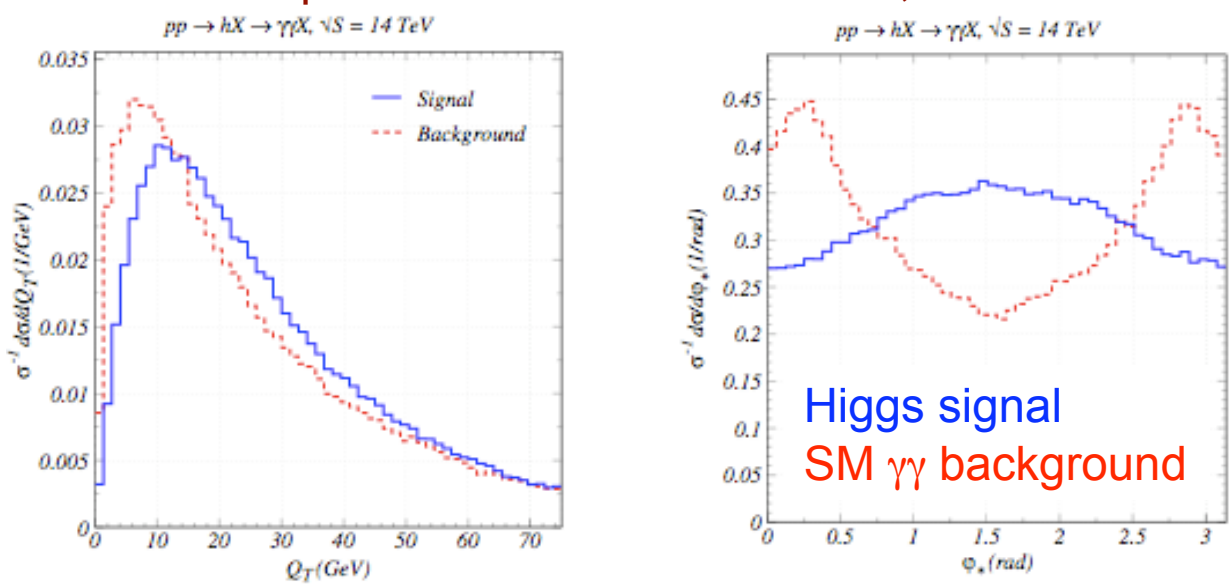


# From γγ Cross Section at CDF to H→γγ at LHC

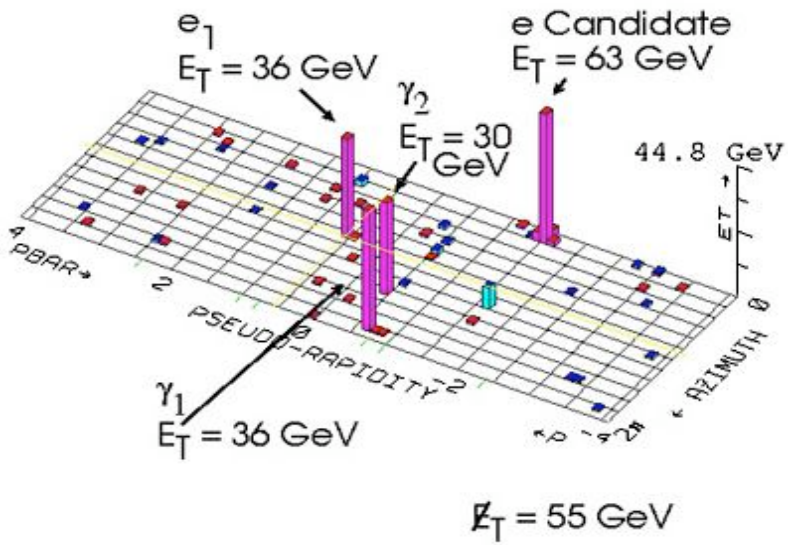
- Neither prediction describes all kinematic properties of data
  - Pythia shows its limitations
  - Comparison of data with ResBos & Diphox indicates roles of soft gluon re-summations and fragmentation contributions
  - Double fragmentation contribution and higher order corrections needed
- **Message to LHC:** VBF H→γγ+qq may be tougher than initially thought (particularly sensitive to modeling of diphoton $P_T$)

ResBos predictions for LHC: PRD 76, 013009



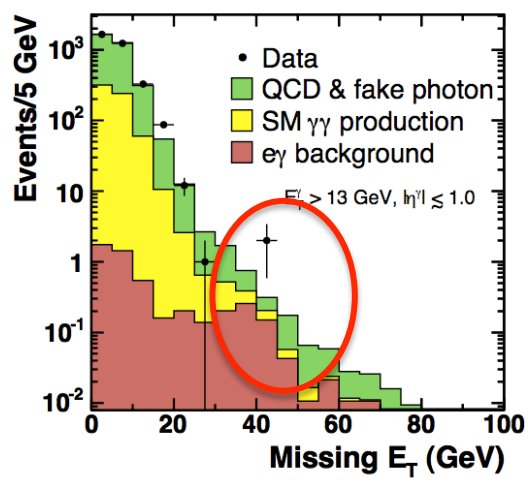
# Exploring $\gamma\gamma$+MET

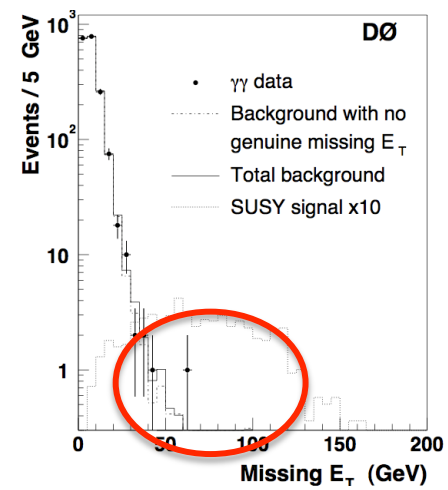
# Why γγ+MET?




- Surprise in Run-I
  - Data: *ee*+γγ+MET event
  - SM background: $10^{-6}$ expected
- Early Run-II results
  - CDF: 202 $pb^{-1}$, PRD 71, 031104
  - D0: 263 $pb^{-1}$, PRL 94, 041801
  - Events on tails of MET distribution

- Rich physics
  - Many models
  - Gauge Couplings
- Experimental know-how
  - Photon & MET techniques



# Which Model to Pick?

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

- Take "hybrid" approach:
  - Do model-independent analysis
  - Set limits on model of most impact (often subjective criteria)

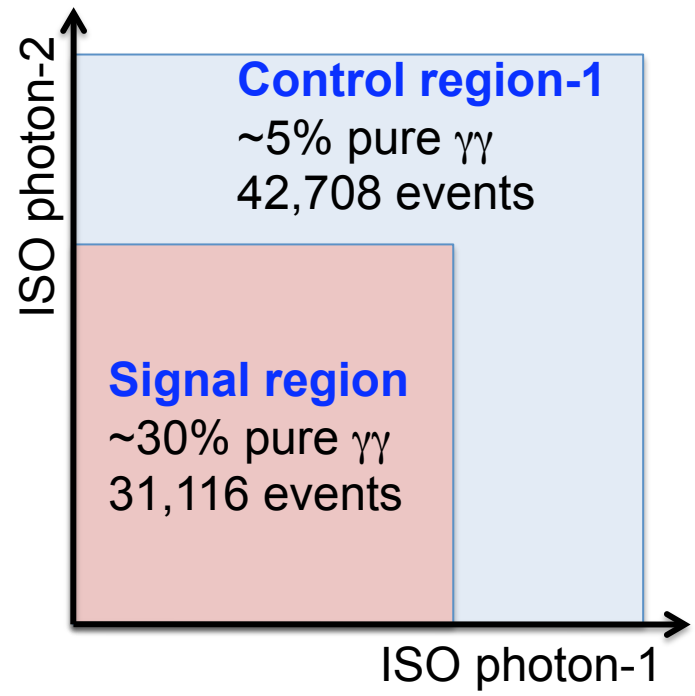
- **Typical week at arXiv: ~100 papers**
- **hep-ph daily 11 new + 3 crosses received**
- **hep-ph daily 14 new + 4 crosses received**
- **hep-ph daily 14 new + 5 crosses received**
- **hep-ph daily 33 new + 4 crosses received**
- **hep-ph daily 7 new + 3 crosses received**

# “Roadmap” for γγ+MET Analysis

- **Signal & control samples**
- **QCD background**
- **EWK background**
- **Non-collision backgrounds and QCD pathologies**
- **Model-independent results and limits on GMSB**

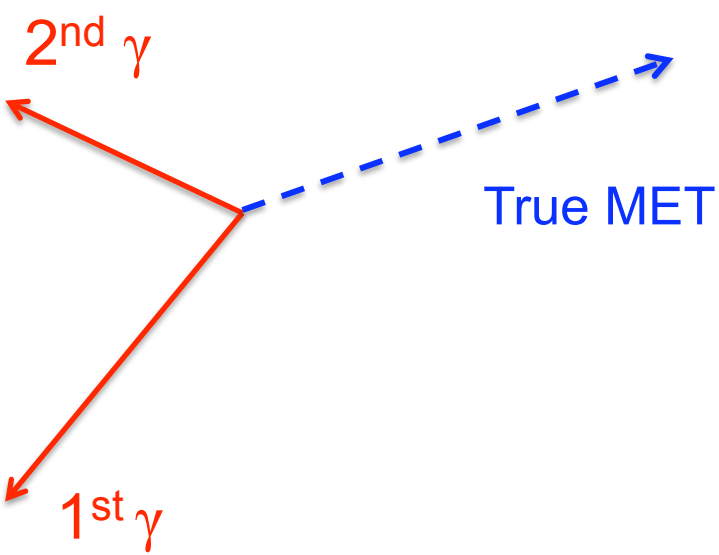
# $\gamma\gamma$+MET Analysis: Signal & Control Samples

- **Signal region: "tight" $\gamma\gamma$**
  - 2 photons: $E_T$>13 GeV, $|\eta|$<1.1
  - 2 $fb^{-1}$ of data
- Control region-1: "loose" $\gamma\gamma$
  - Same topology & backgrounds
  - Test analysis procedure
- Control region-2: "tight" $e+\gamma$ events
- Control region-3: "loose" $e+\gamma$ events
  - Same event selection
  - Check of EWK backgrounds

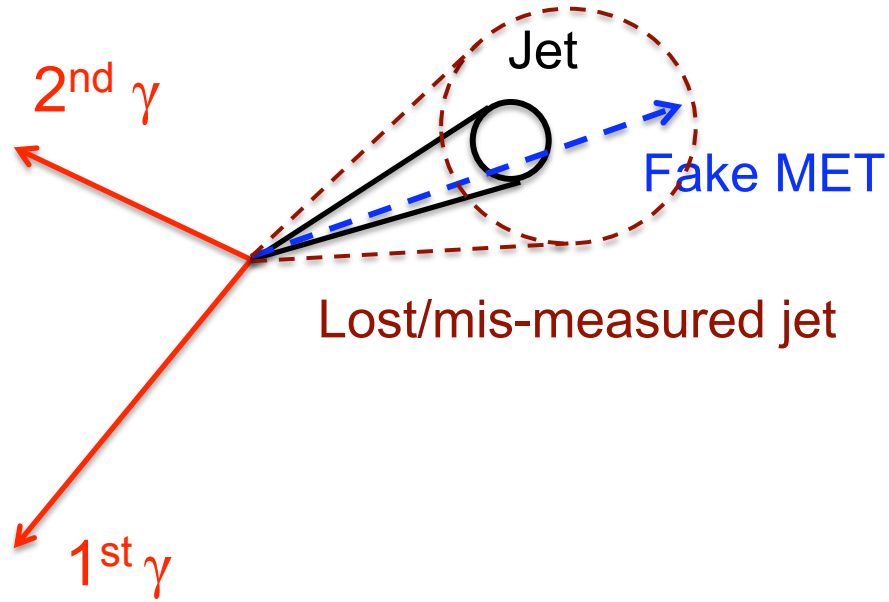


# "QCD" background: SM γγ Events with Fake MET

Signal candidate



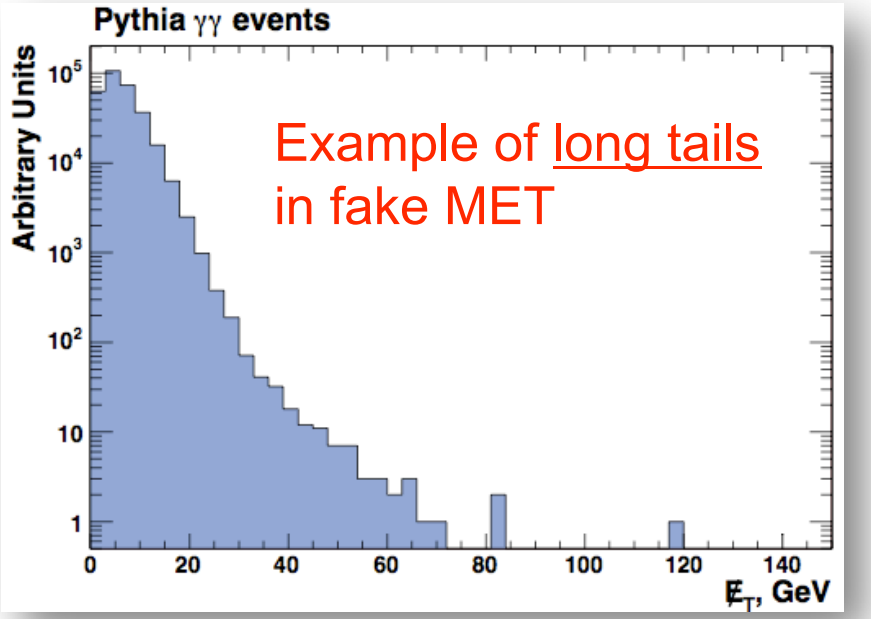

"QCD" background

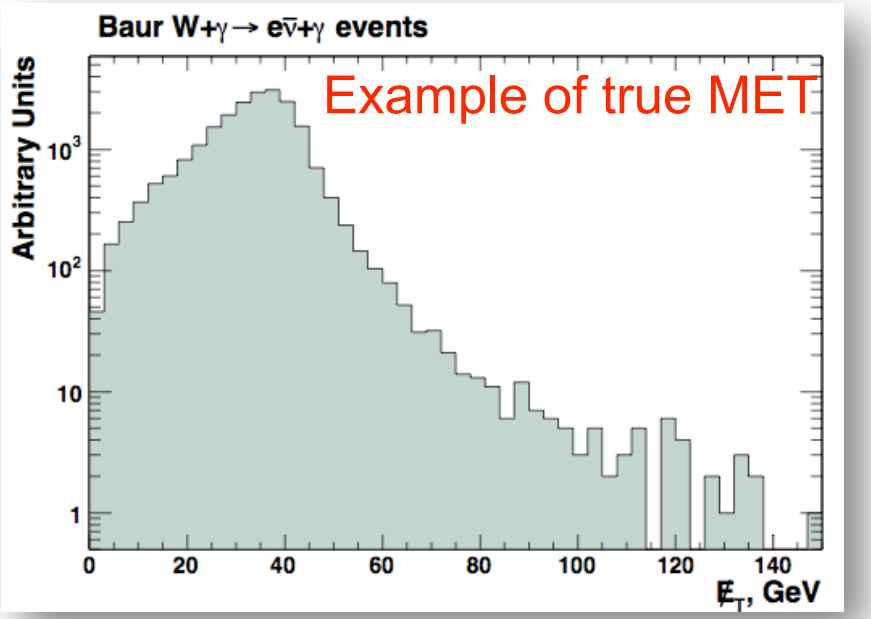



- Both photons and MET are genuine
  - MET can be due to ***neutrino*** or ***new particles*** not interacting with detector

- SM γγ+N-jet events
  - One or both photons can be fakes
  - Lost or mis-measured jet gives fake MET

# Fake MET Problem in γγ+MET Search



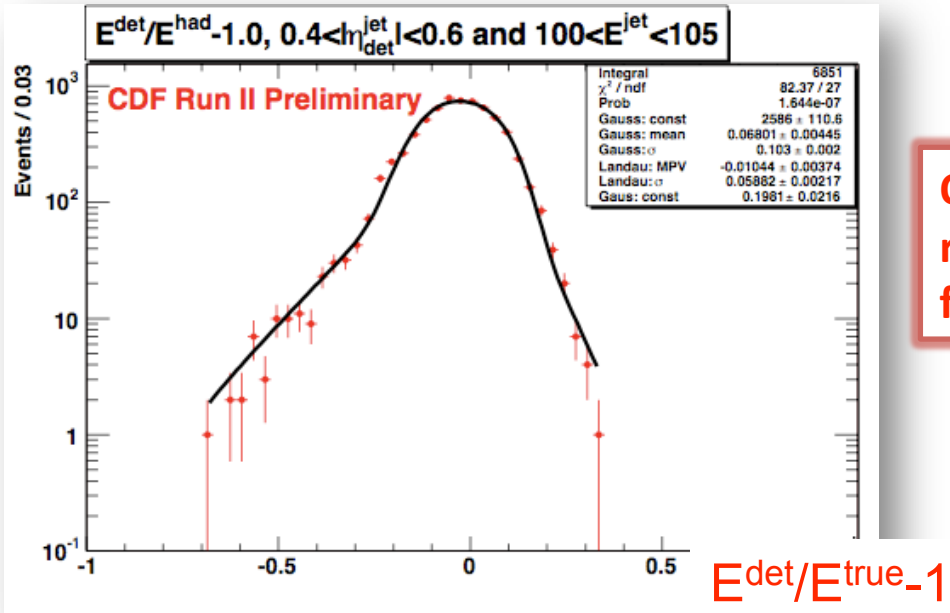




- MET distribution in γγ events is dominated by regular "QCD" events with fake MET
  - MC is not reliable in modeling multi-jet events:
    - not accurate description of fake MET
- How do you distinguish events with true & fake MET?

# Met Resolution Model (*METMODEL*)

Example of jet energy resolution

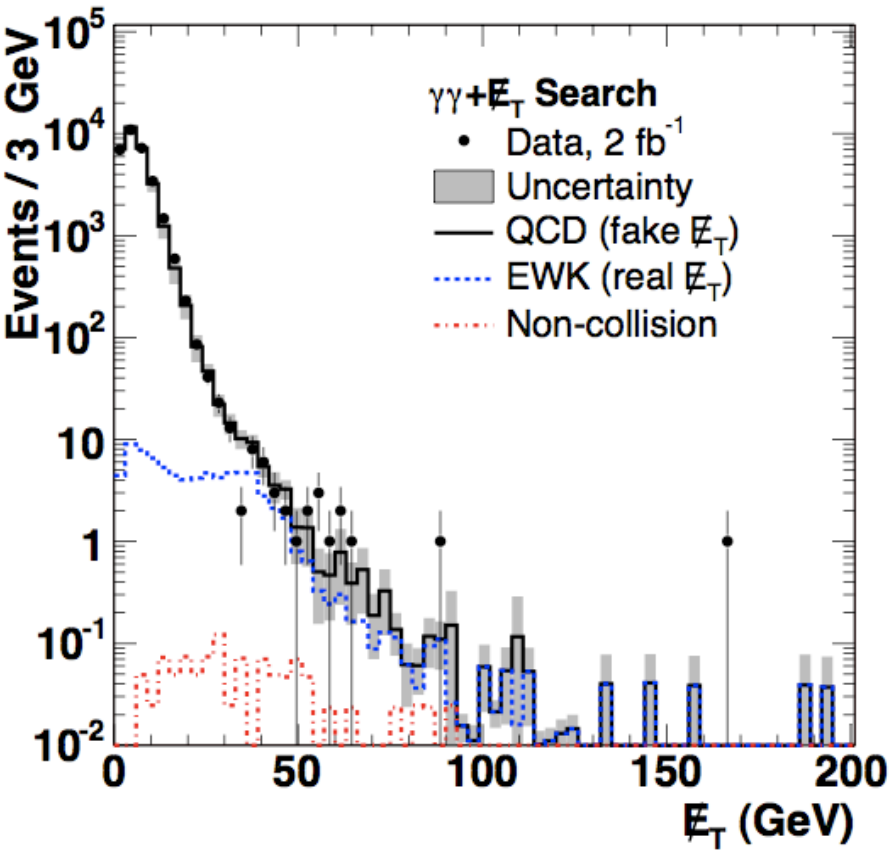
**Mis-measurements in jet energy are leading source of fake MET**

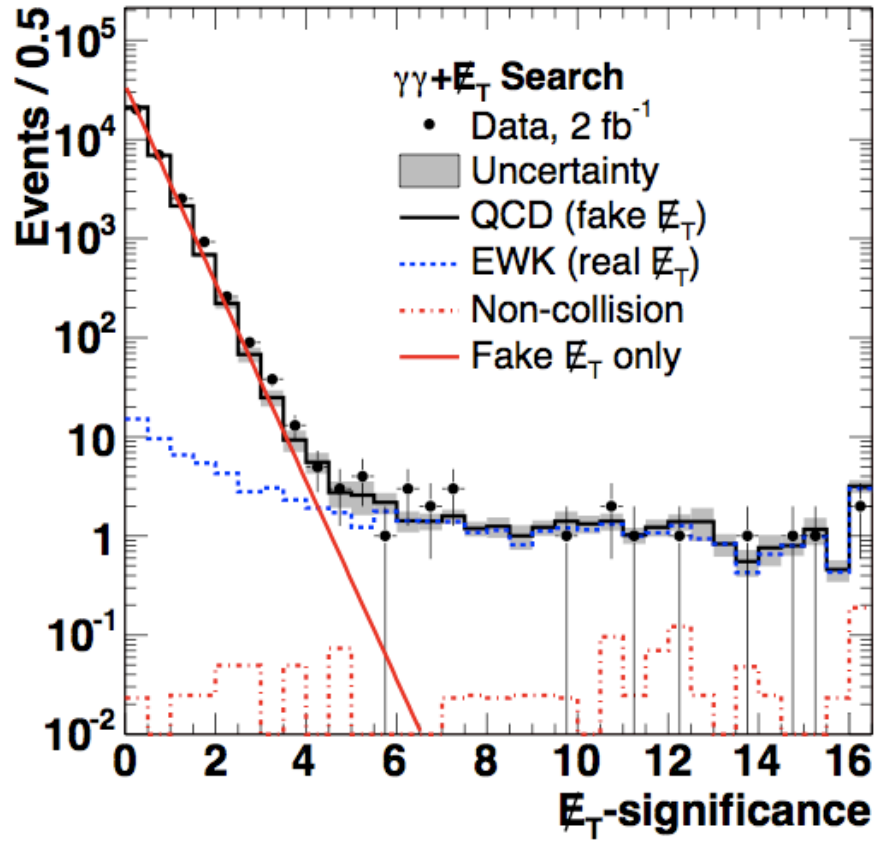



**Obtain jet energy resolution as function of $E^{jet}$ & η**

- 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

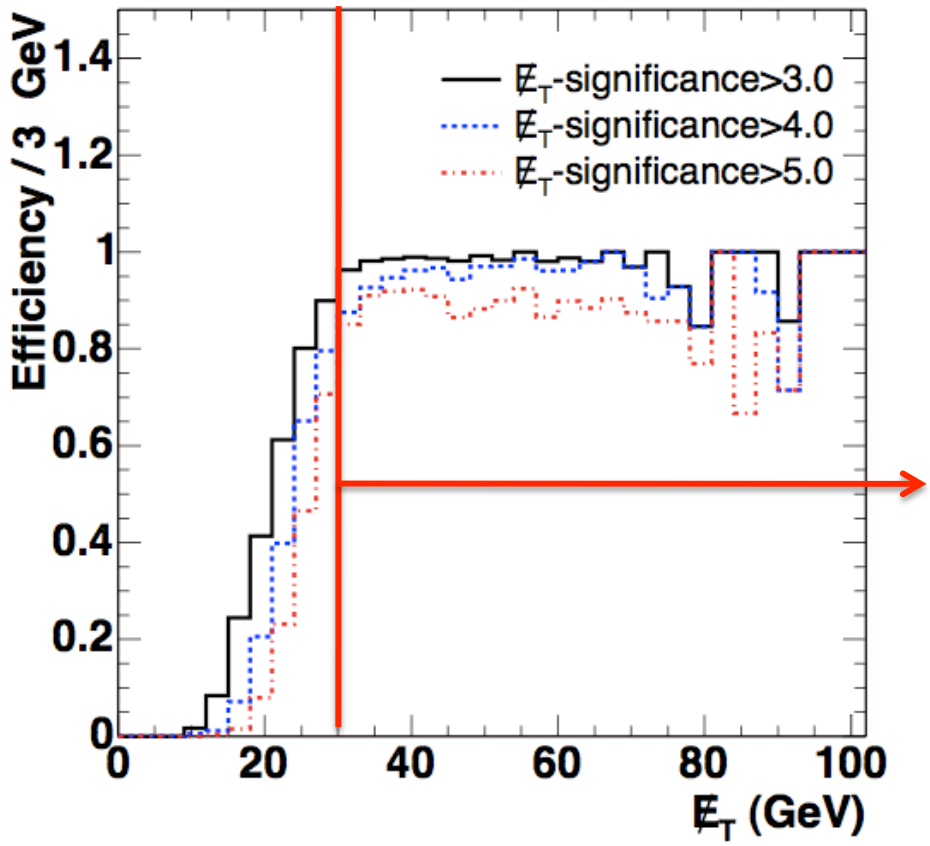
# MET-significance Effectively Separates True & Fake MET




- Select events with MET-significance >3, 4, and 5
  - Suppress QCD by 3, 4, and 5 orders of magnitude, respectively
  - METMODEL: data-based fake MET predictions

# MET-significance Very Effective for True MET




MET-sig>3 is **~100%** efficient at MET>30 GeV !!

- Efficiency of MET-significance cut for events with true MET (e.g., $W\gamma \rightarrow e\nu\gamma$)

| Efficiency for $W+\gamma \rightarrow e\nu+\gamma$ | MET-sig>3.0 | MET-sig>4.0 | MET-sig>5.0 |
|---|---|---|---|
| | 84% | 74% | 67% |

# “Roadmap” for γγ+MET Analysis

- Signal & control samples
- QCD background
- **EWK background**
- Non-collision backgrounds and QCD pathologies
- Model-independent results and limits on GMSB

# EWK Backgrounds in γγ+MET Search

| Process | MET-sig>3 | MET-sig>5 |
|---|---|---|
| **W(eν)+γ/jet** | **46%** | **50%** |
| Z/W+γγ | 35% | 35% |
| W(τν)+γ/jet | 11% | 10% |
| Z(ττ)+γ/jet | 7% | 5% |

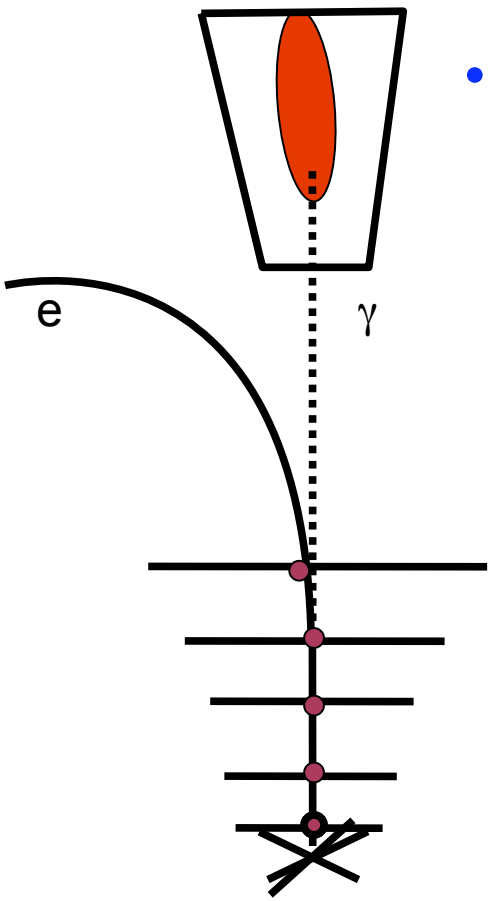
- EWK processes with genuine MET
  - Leptons faking photon: 65%
    - Fakes: e→γ or τ→γ
    - Note **τ→γ** :15% - 18% of total EWK
      - Not considered in earlier analyses
  - Real photons: 35%

- MC EWK prediction normalized to data

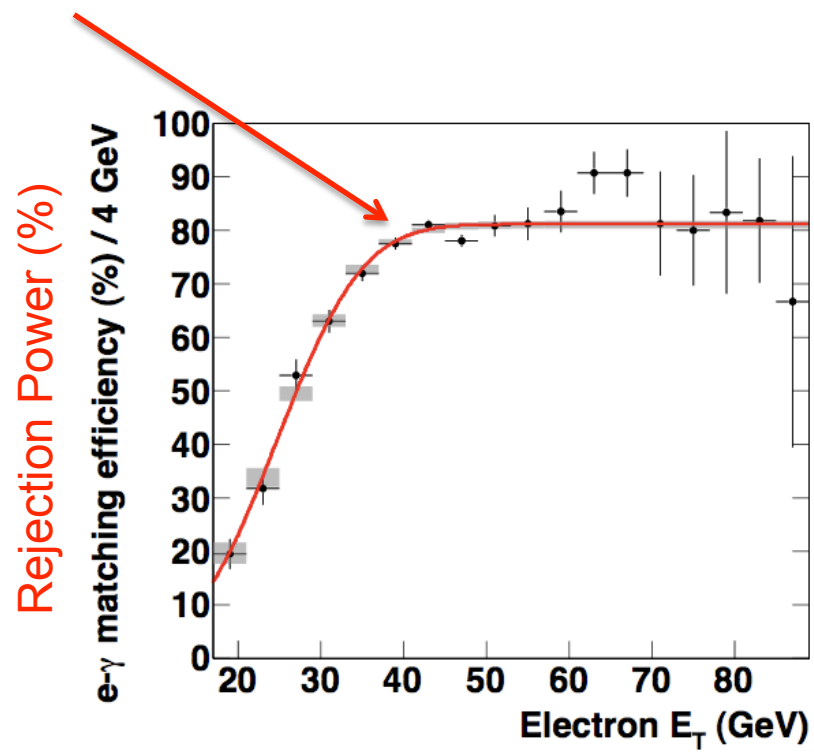
$$MC(\gamma\gamma + \not{E}_T) \times \frac{Data(e\gamma + \not{E}_T)}{MC(e\gamma + \not{E}_T)}$$

- X-check:
  - Repeat analysis with "loose" γγ events

# Reducing e→γ Fake Rate



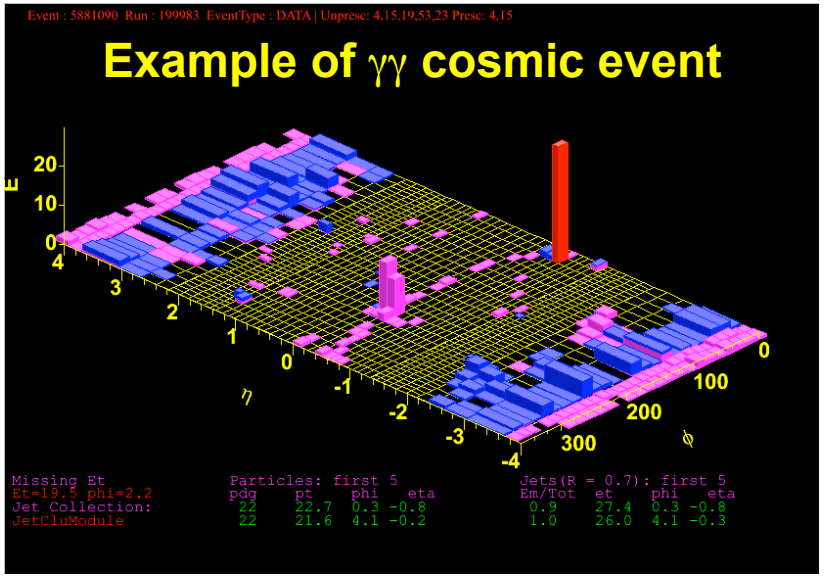

- Silicon "tracking" for photons
  - Originally developed for "forward" electrons
  - First applied in γγ+MET analysis
  - Reduce e→γ fake rate by up to 80% at $E_T$>40 GeV



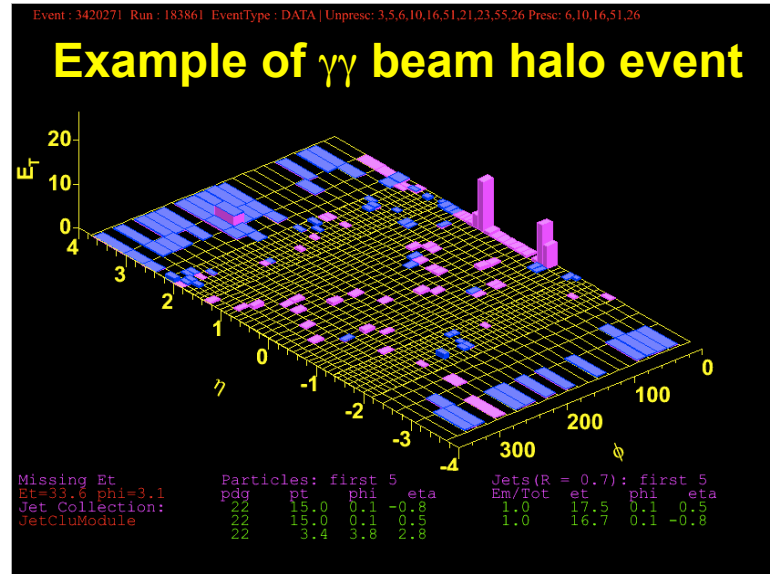
# “Roadmap” for γγ+MET Analysis

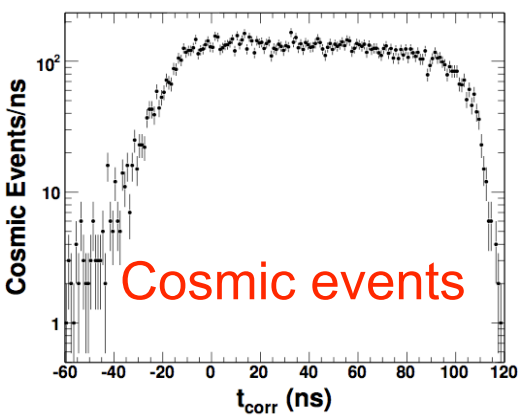
- Signal & control samples
- QCD background
- EWK background
- **Non-collision backgrounds and QCD pathologies**
- Model-independent results and limits on GMSB

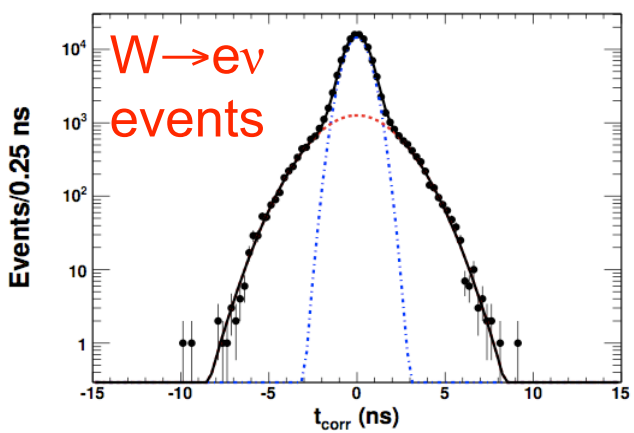
# Backgrounds for γγ+MET: Non-Collision Events

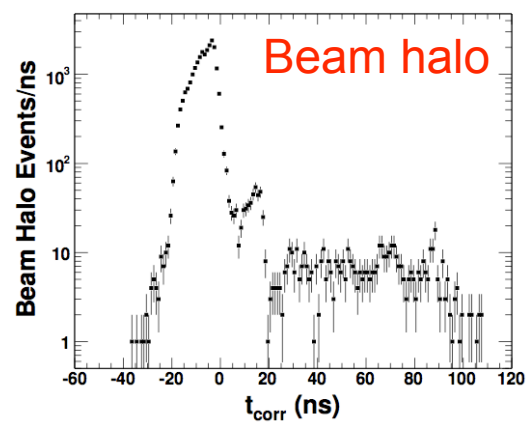



η-φ view



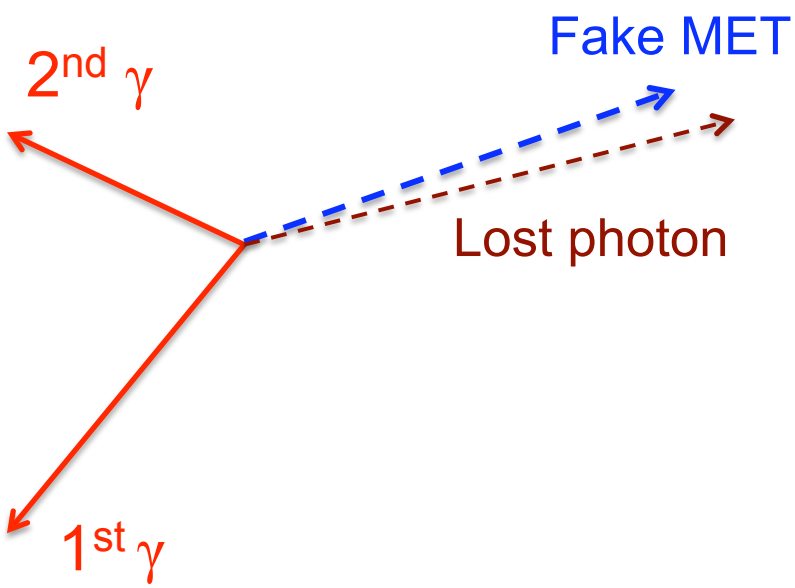




- Use timing information to reject cosmics & beam halo

# Pathological QCD γγ+"MET" Events

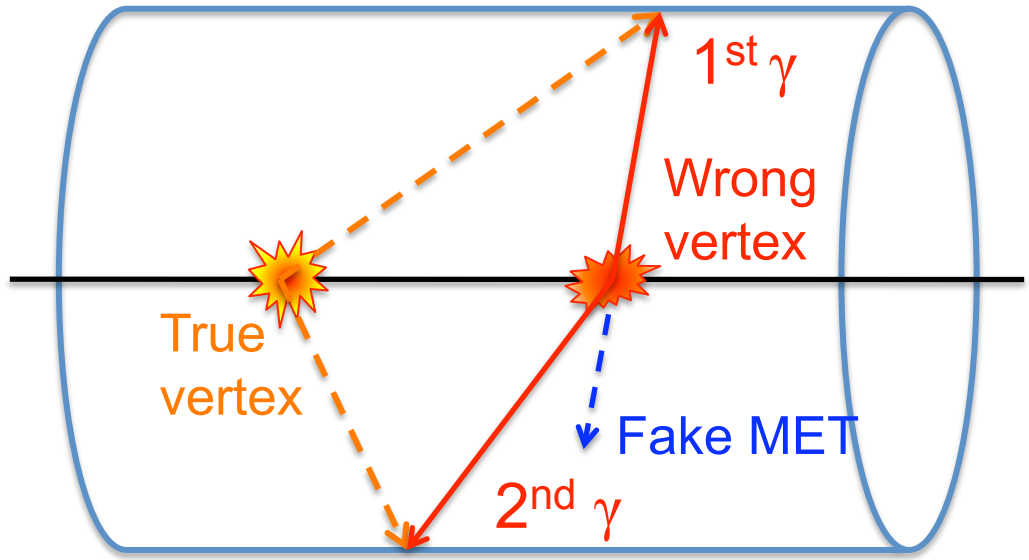
"QCD type-2" background




- Photons can be fakes
- MC prediction normalized to data

$$MC(\gamma\gamma + lost\,\gamma) \times \frac{Data(\gamma\gamma + \gamma)}{MC(\gamma\gamma + \gamma)}$$

"QCD type-3" background

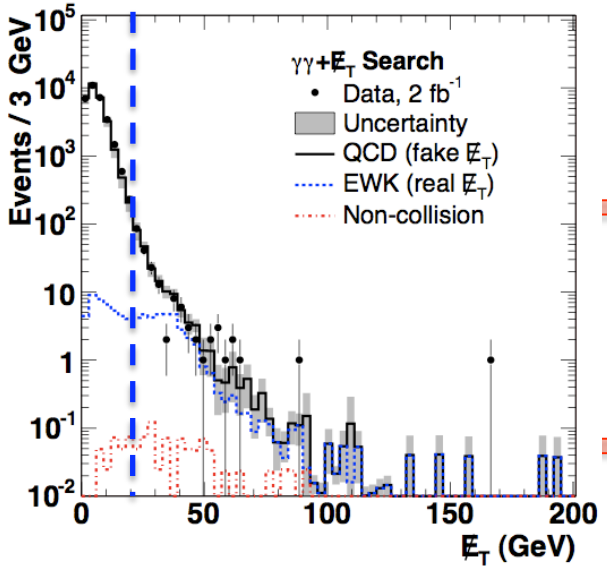



- Reconstructed true vertex
  - Re-assign vertex to minimize MET
- Lost true vertex
  - MC prediction normalized to data

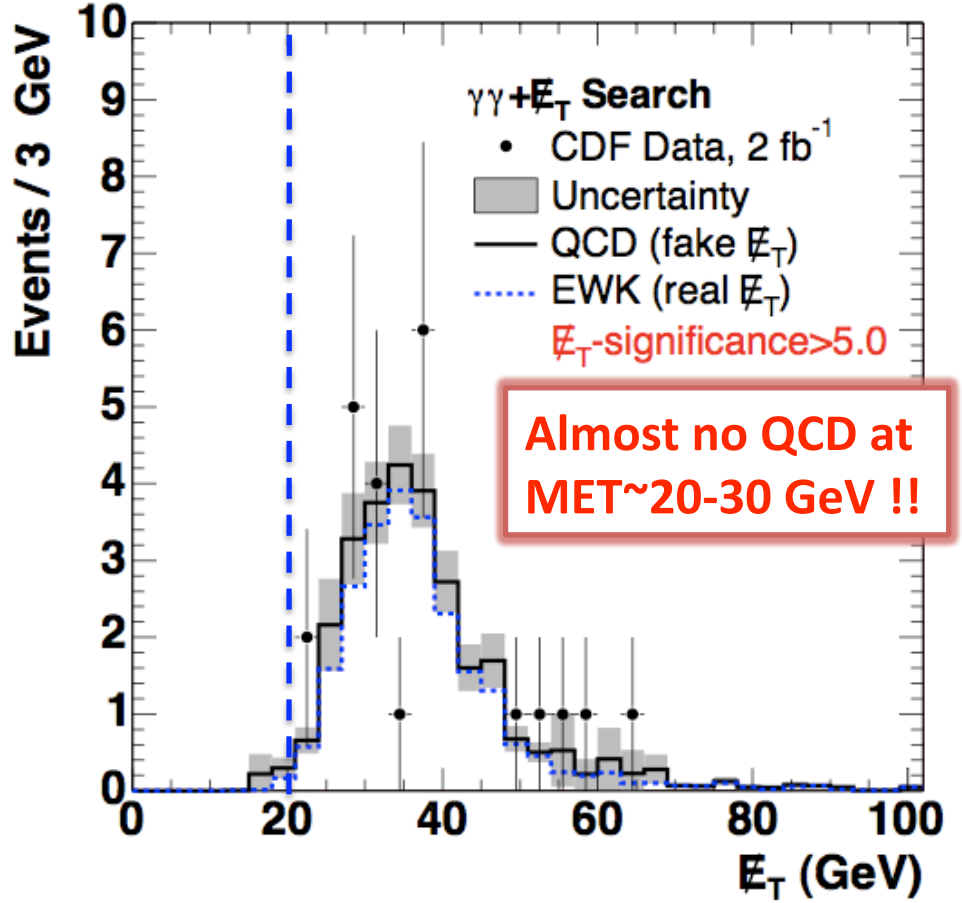
# “Roadmap” for γγ+MET Analysis

- Signal & control samples
- QCD background
- EWK background
- Non-collision backgrounds and QCD pathologies
- **Model-independent results and limits on GMSB**

# No QCD Contamination in Selected γγ+MET Events !!

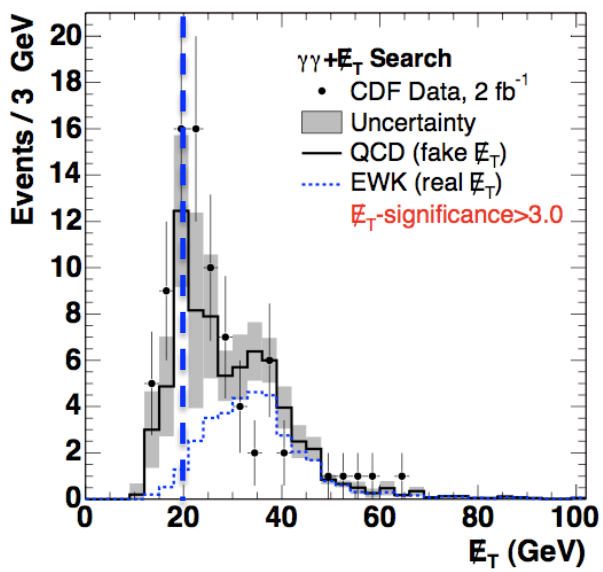



MET-sig>5



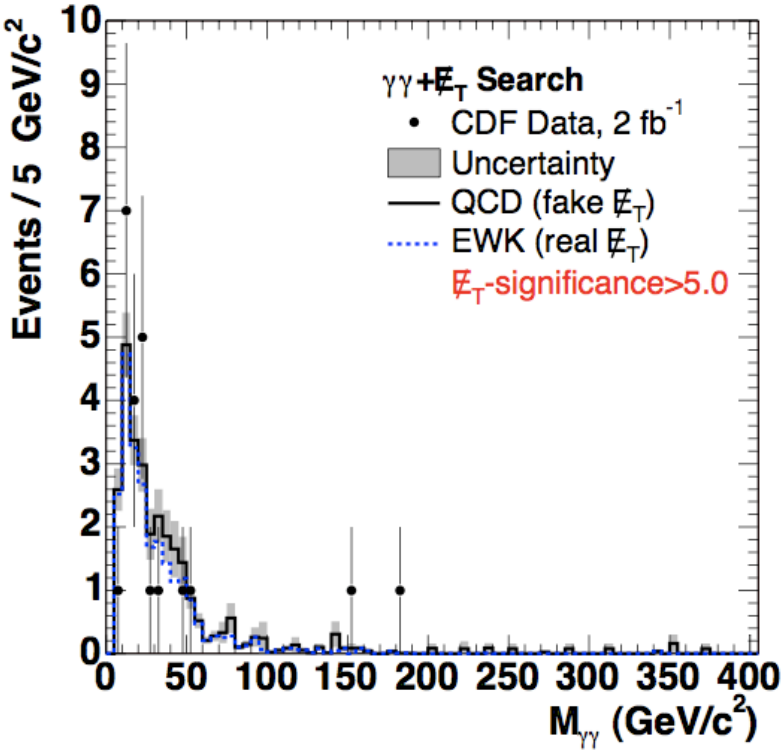

**Almost no QCD at MET~20-30 GeV !!**

MET-sig>3

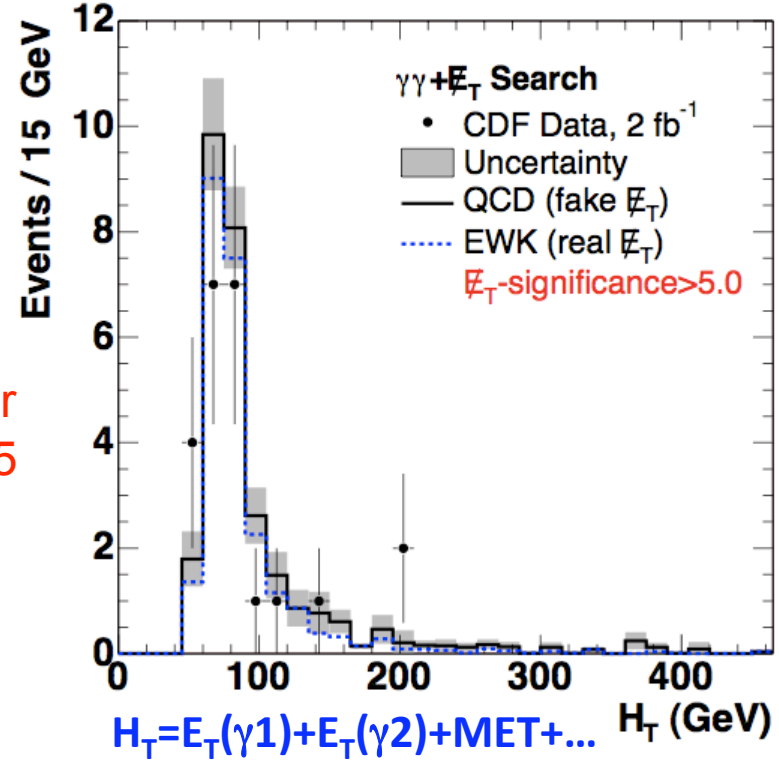



- Predictions agree with data in selected γγ+MET events

# No Signs of Anomalies in Selected γγ+MET Events



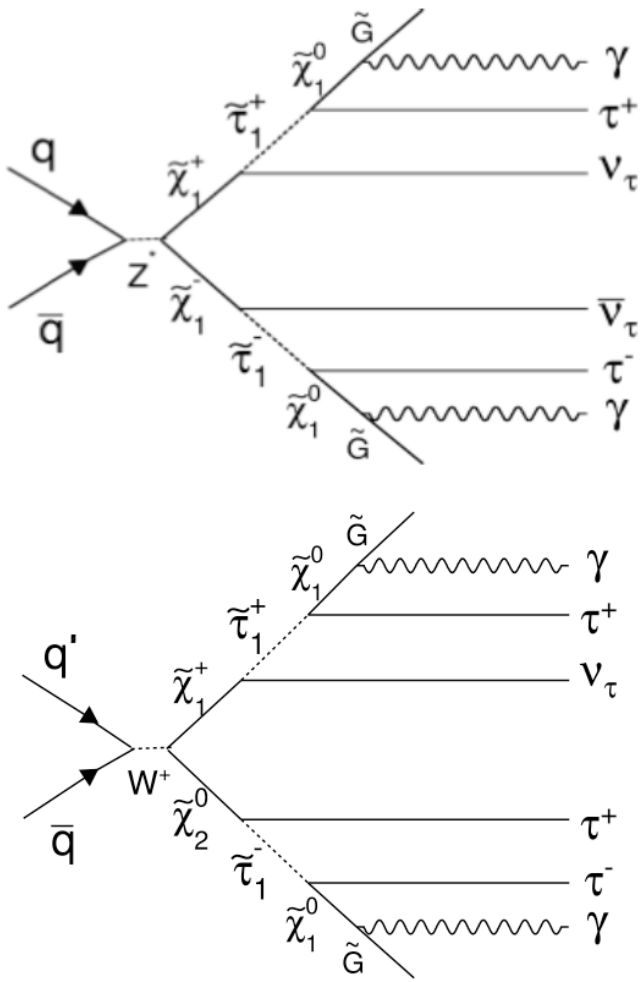

Results for MET-sig>5




- Studied many more distributions for MET-sig>3 and 5

| | MET-sig>3 | MET-sig>4 | MET-sig>5 |
|---|---|---|---|
| Background | 71.7±7.5 | 39.0±3.1 | 30.4±2.4 |
| Data, 2 fb$^{-1}$ | 82 | 31 | 23 |
| EWK | 49% | 77% | 85% |

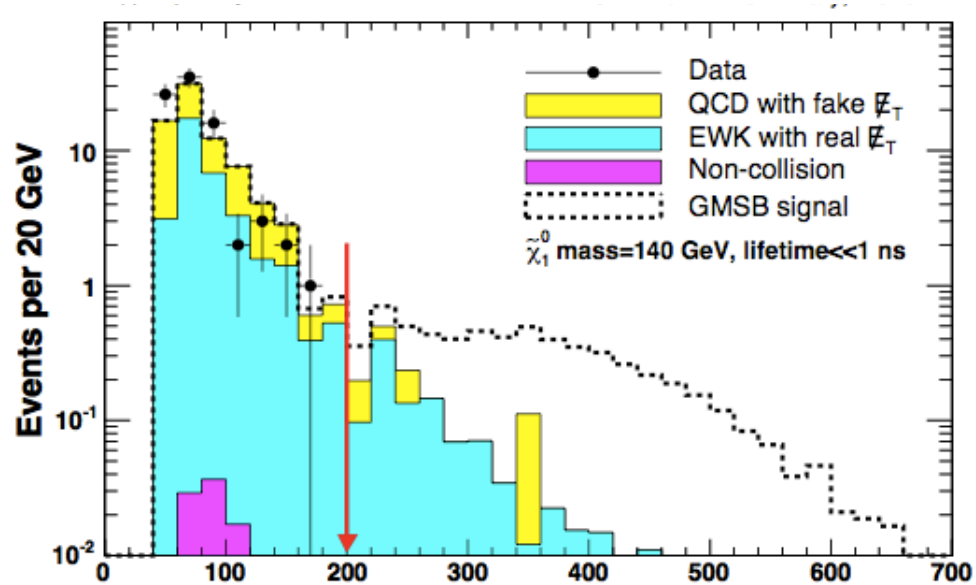
# Limits on GMSB in γγ+MET: Theory Overview




- Gauge-Mediated SUSY Breaking
  - One of the SUSY breaking scenarios
    - Only 6 free parameters
  - Gravitino LSP (<<MeV)
  - Neutralino or slepton (mostly stau) NLSP
  - Heavy squarks and gluinos
    - Not produced at Tevatron
  - If $\chi^0$ NLSP: $\chi^0 \rightarrow \gamma G$ (Br=100%)
    - Primary model for γγ+MET

# Limits on GMSB in γγ+MET: Analysis Overview

- 3D optimization:
  - **MET-significance, $H_T$, $\Delta\varphi_{\gamma\gamma}$**
- Signal acceptance:
  - 7.80% ± 0.54% at $M_\chi$=140 GeV
- Leading backgrounds:
  - Zγγ, QCD, Wγ



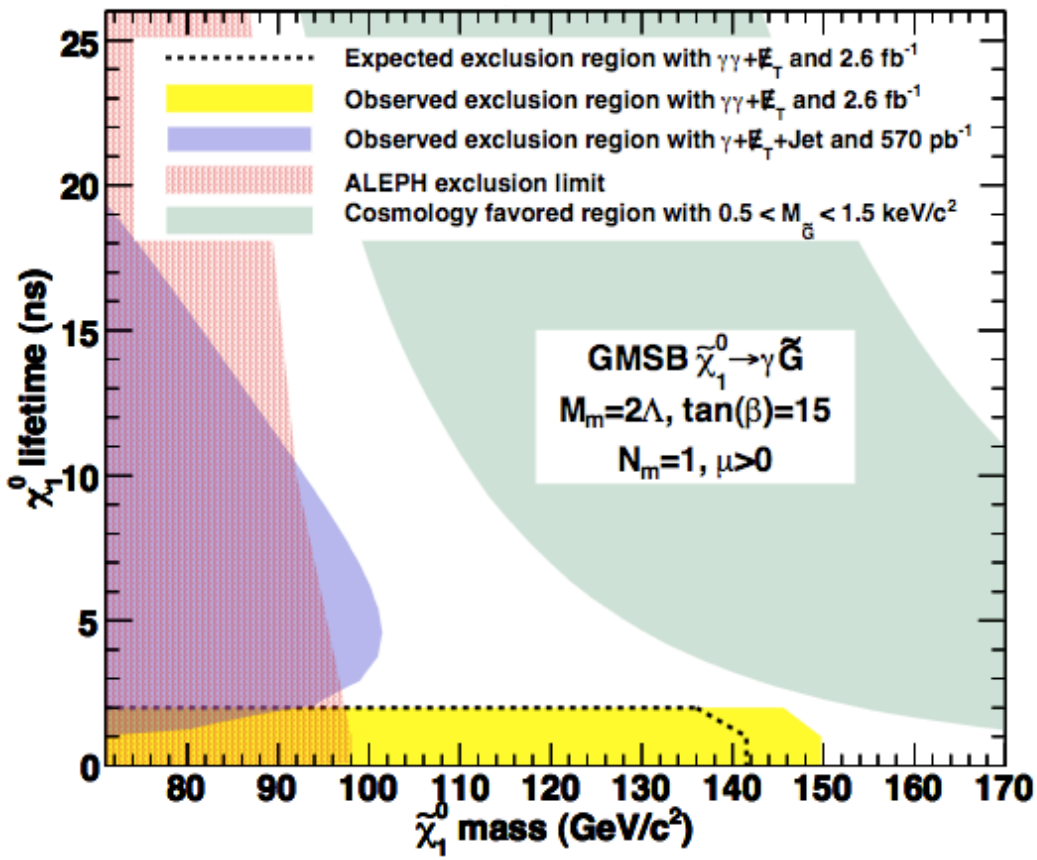

**$H_T=E_T(\gamma1)+E_T(\gamma2)+MET+...$**

After MET-sig>3 & $\Delta\varphi_{\gamma\gamma}<\pi-0.35$

**Data: no events observed in 2.6 $fb^{-1}$**

| | |
|---|---|
| **EWK** | **0.92 ± 0.21 (stat) ± 0.30 (syst)** |
| **QCD** | **0.46 ± 0.22 (stat) ± 0.10 (syst)** |
| Non-Collision | negligible |
| **Total background** | **1.38 ± 0.30 (stat) ± 0.32 (syst)** |

# World's Best Limit on GMSB with Neutralino NLSP



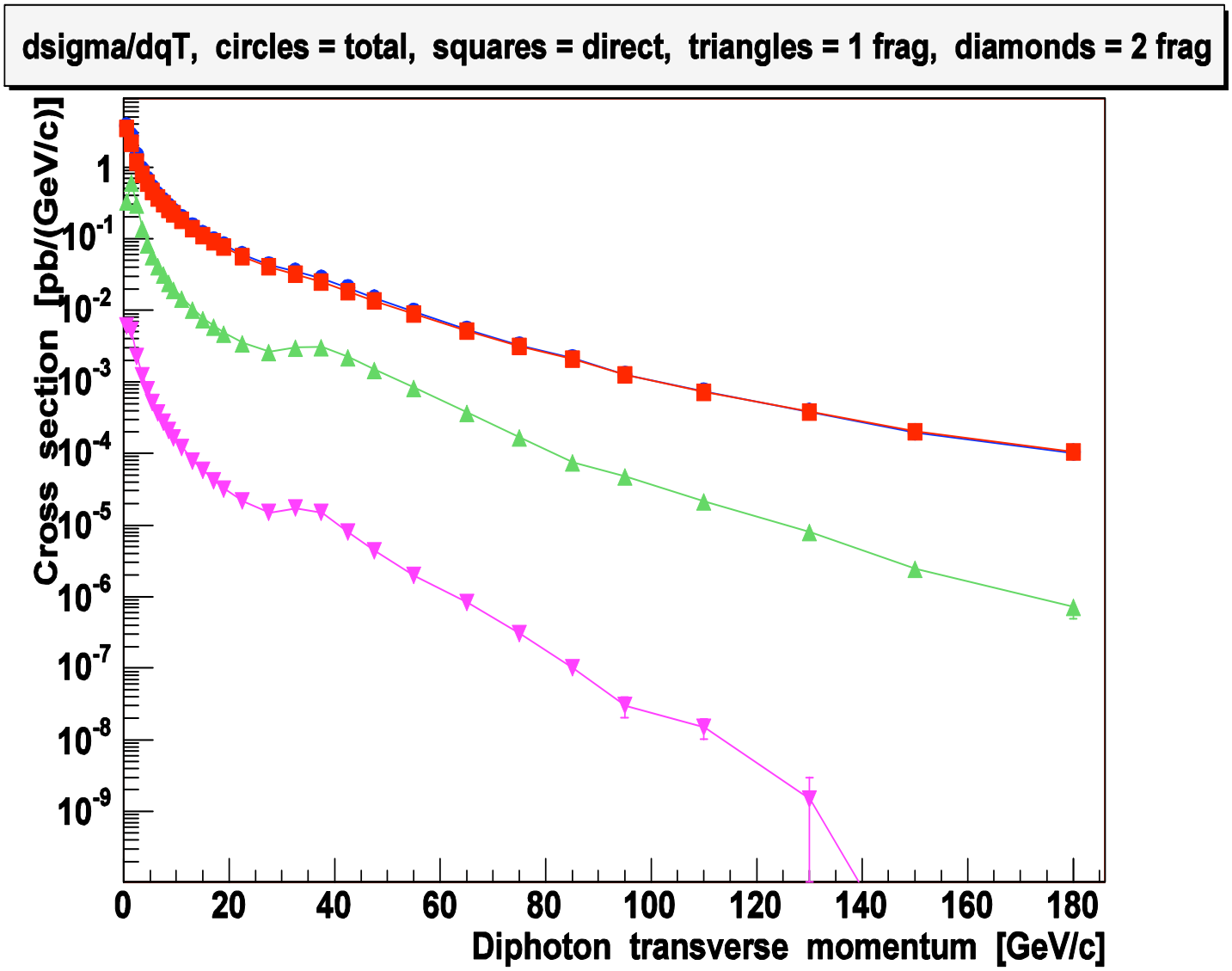

- 95% CL limits in neutralino mass & lifetime plane
  - Exclude neutralino mass<149 GeV/$c^2$ for $\tau$<<1 ns
    - GMSB analysis: PRL 104, 011801 (2010)
    - Model-independent analysis: arXiv:0910.5170 (submitted to PRD)

# Summary & Comclusion

- Measurement of prompt $\gamma\gamma$ x-section
  - Precise study of many differential distributions
  - Neither prediction (Pythia, Diphox, or ResBos) fully describes data
  - Comparison with Diphox and ResBos indicates importance of soft gluon re-summations and fragmentation contributions
  - Data calls for double fragmentation contribution and higher order corrections
  - Will help develop better search strategies for $H \rightarrow \gamma\gamma$ at LHC
- Search for anomalous $\gamma\gamma$+MET events
  - No signs of new physics $\Rightarrow$ world's best limit on GMSB
  - Developed ***Metmodel***
  - PRL & PRD publications

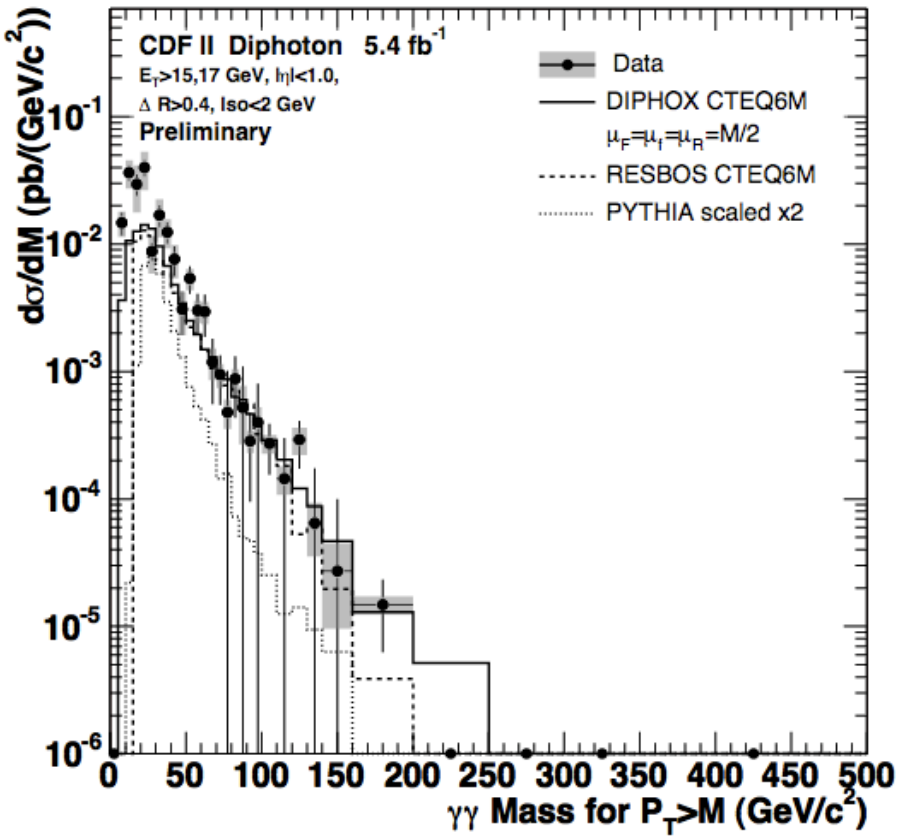
# Backup Slides

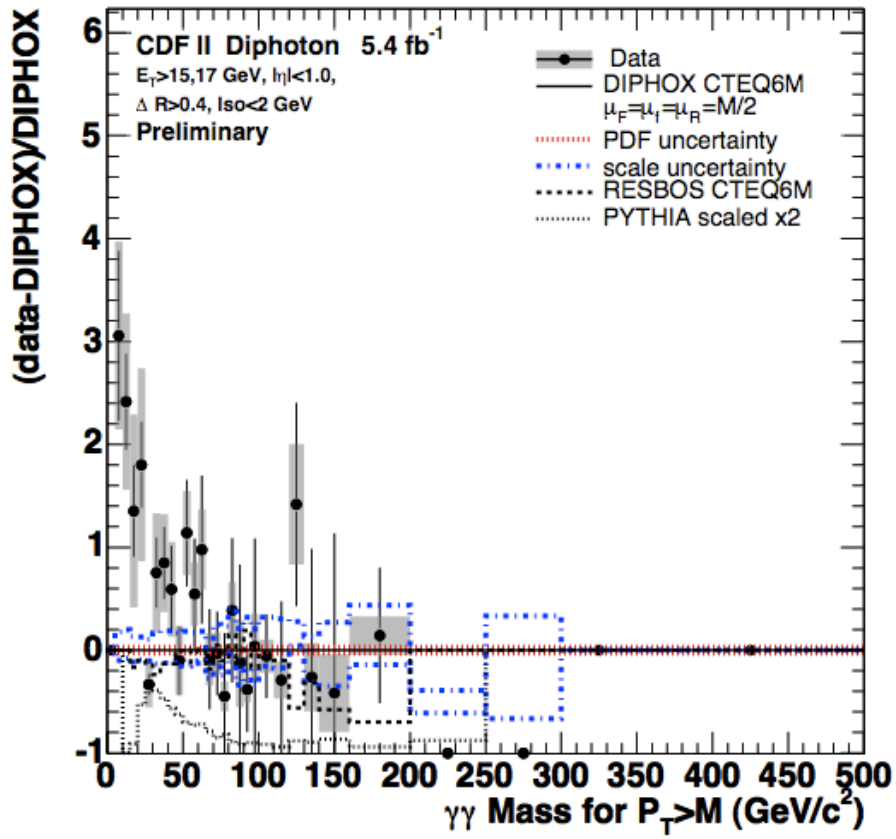
# Diphoton momentum in Diphox



# Results for $d\sigma/dM_{\gamma\gamma}$ if $M_{\gamma\gamma} < P_T(\gamma\gamma)$

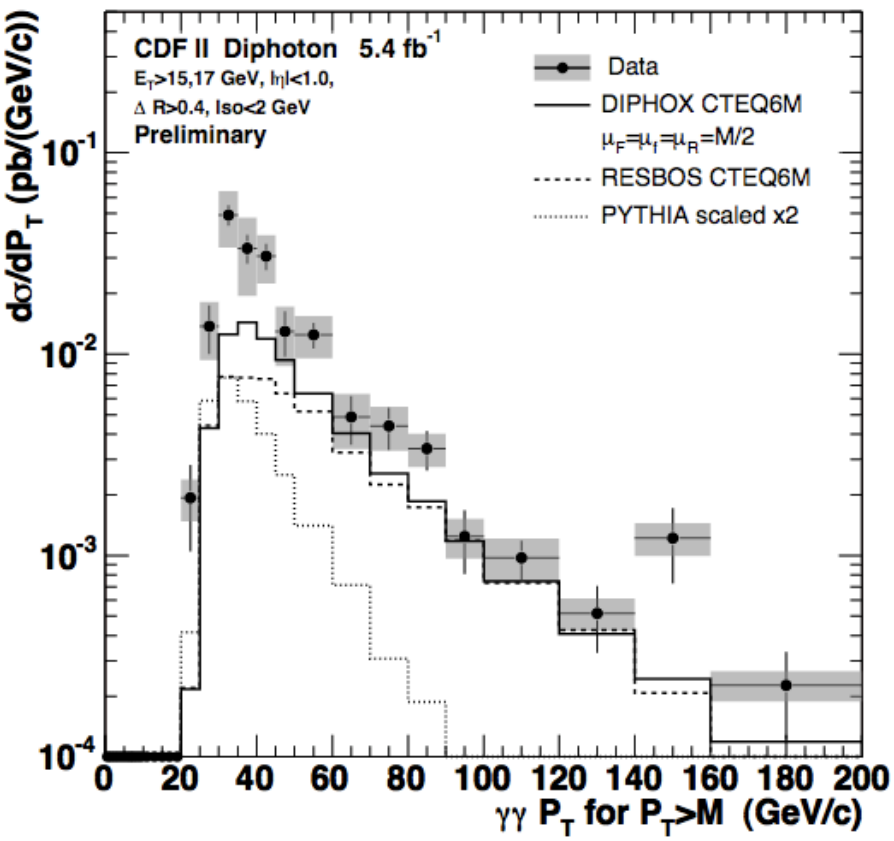
- $M_{\gamma\gamma} < P_T(\gamma\gamma)$ cut enhances double fragmentation contribution
- Diphox describes data at $M_{\gamma\gamma}$>50 GeV, but fails at small masses
- ResBos & Pythia fail in the entire range

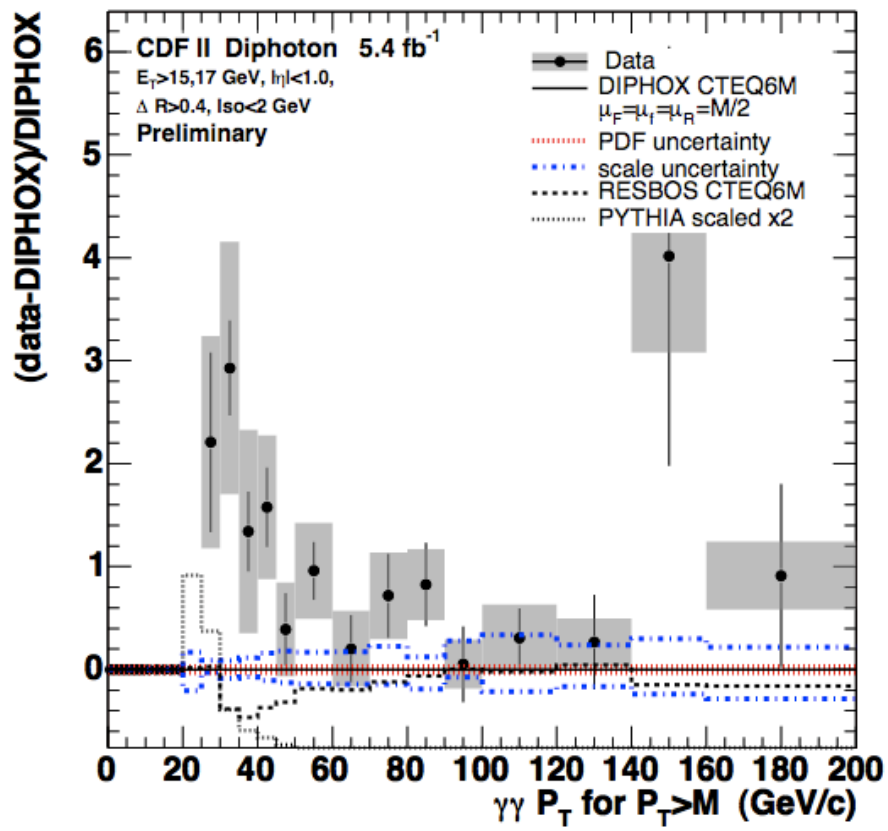


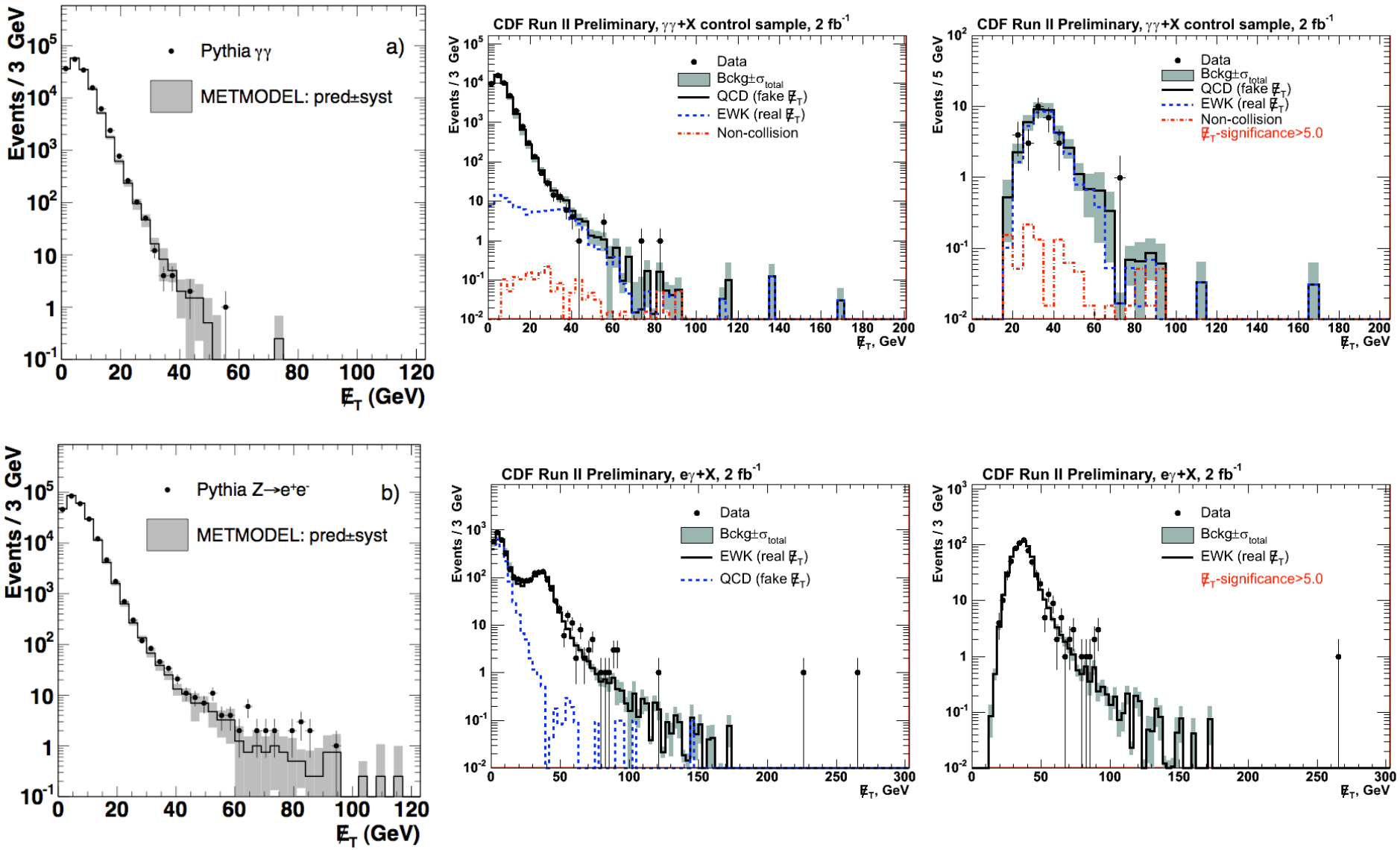
# Results for $d\sigma/dP_T(\gamma\gamma)$ if $M_{\gamma\gamma} < P_T(\gamma\gamma)$

- Pythia, Diphox, and ResBos fail to describe data
  - Role of double fragmentation?

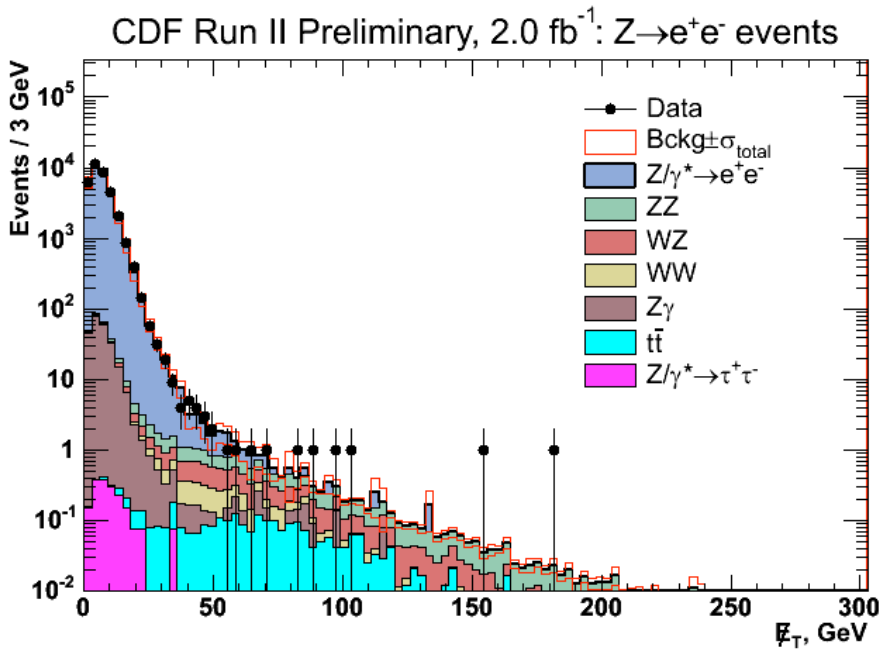


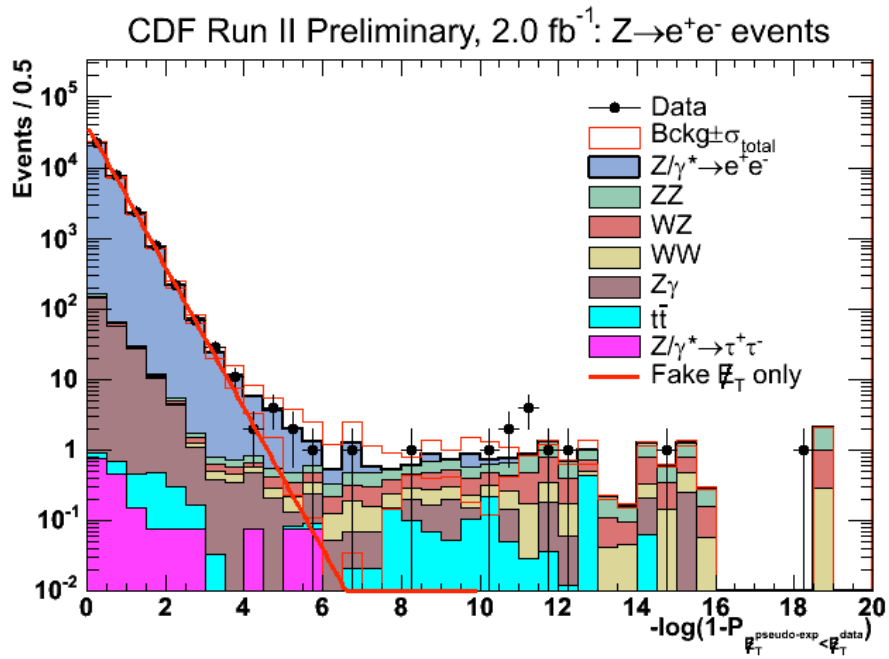



# Tests of METMODEL

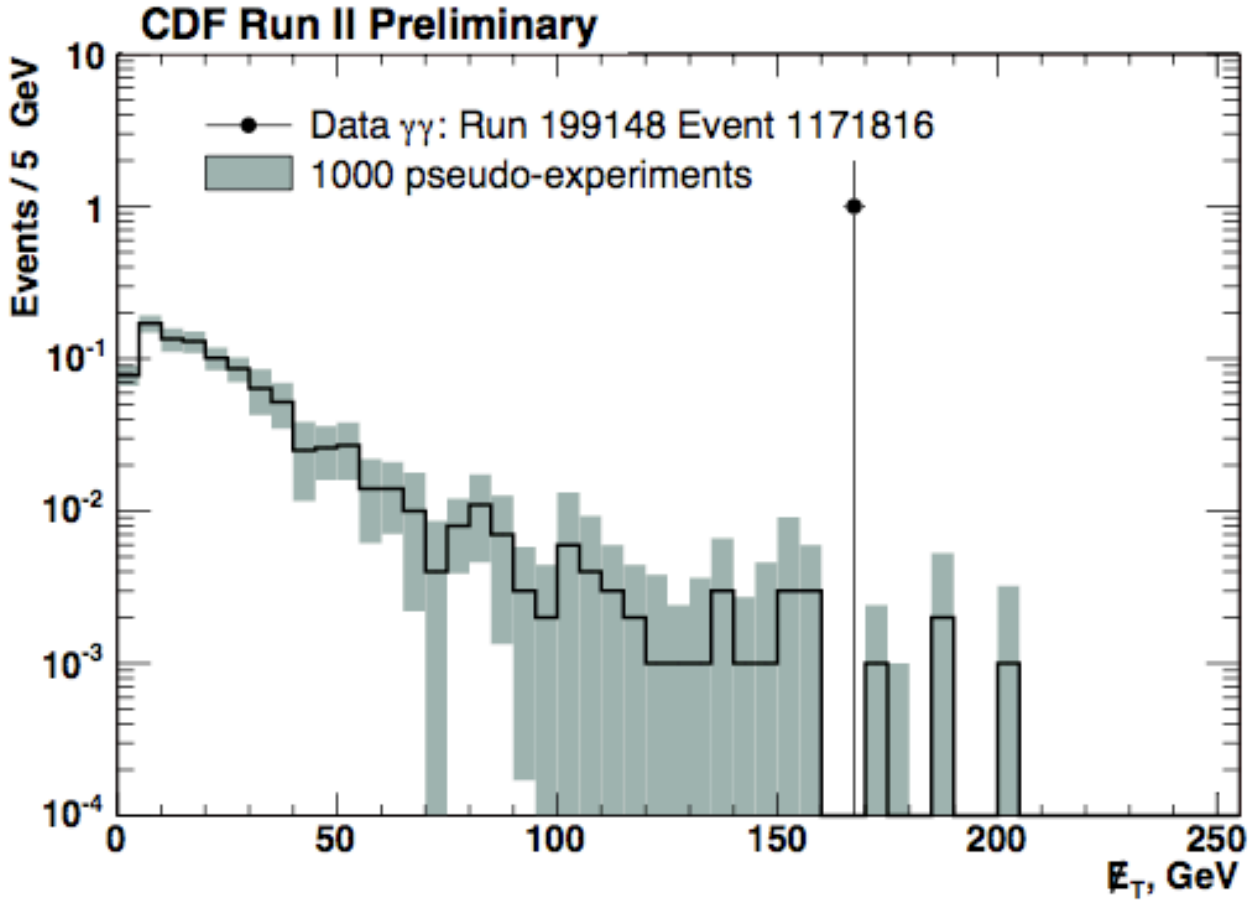


# METMODEL in Z→ee Events



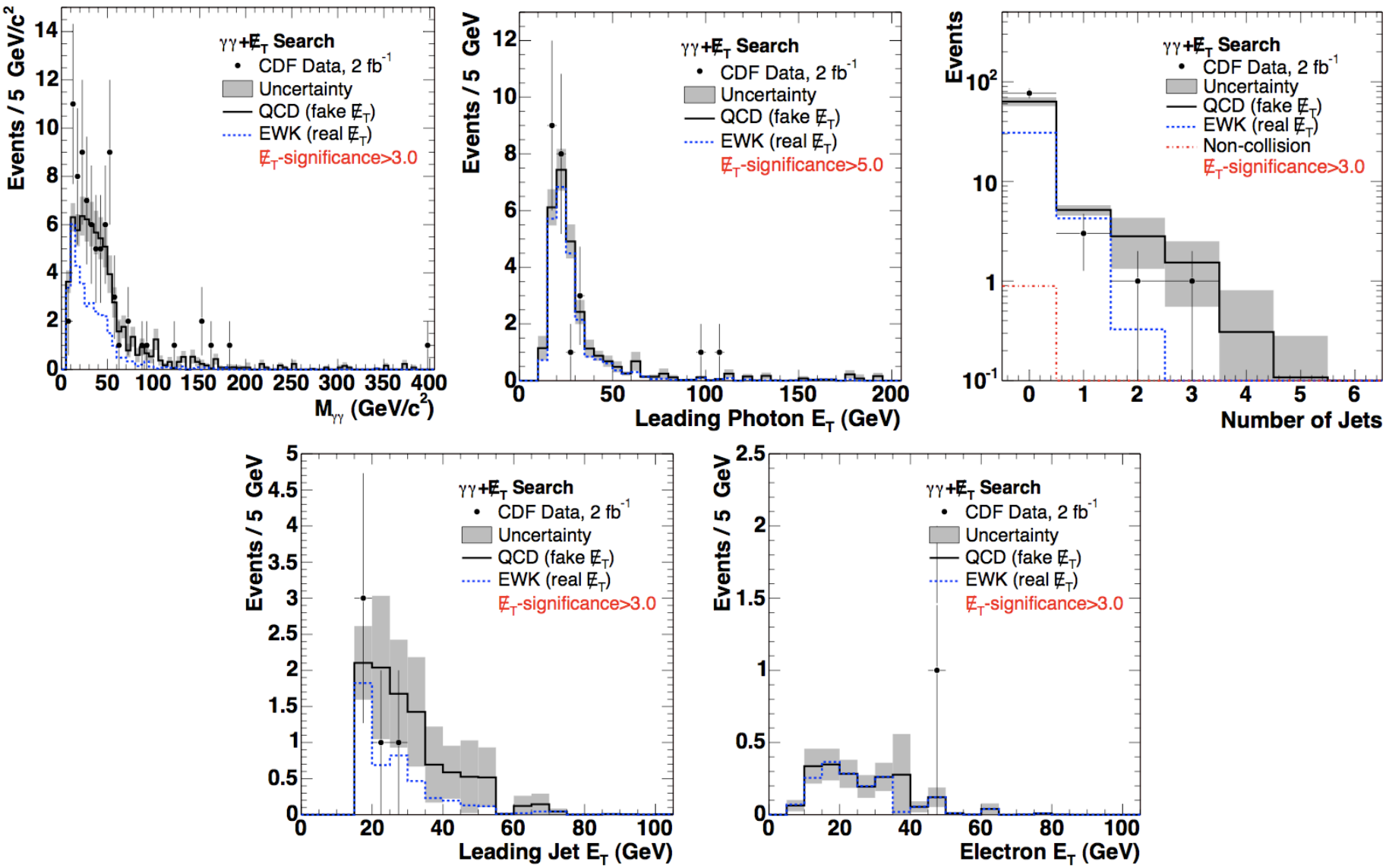



# Largest MET Event in γγ+MET Search

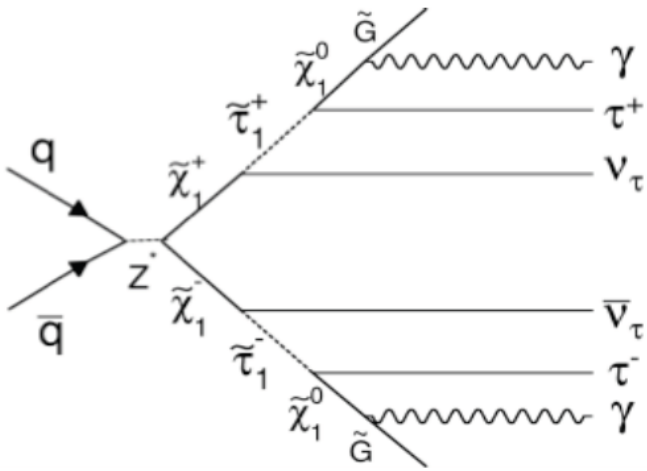


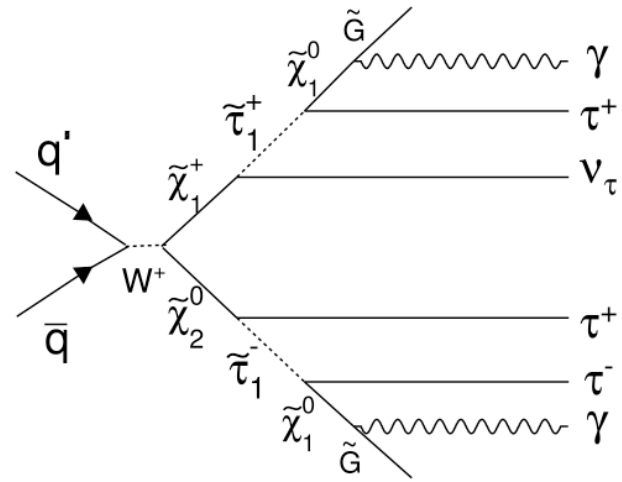

- MET=165.1 GeV
- MET-significance<2.4

# Results for γγ+MET Search



# Limits on GMSB in γγ+MET: Theory Overview



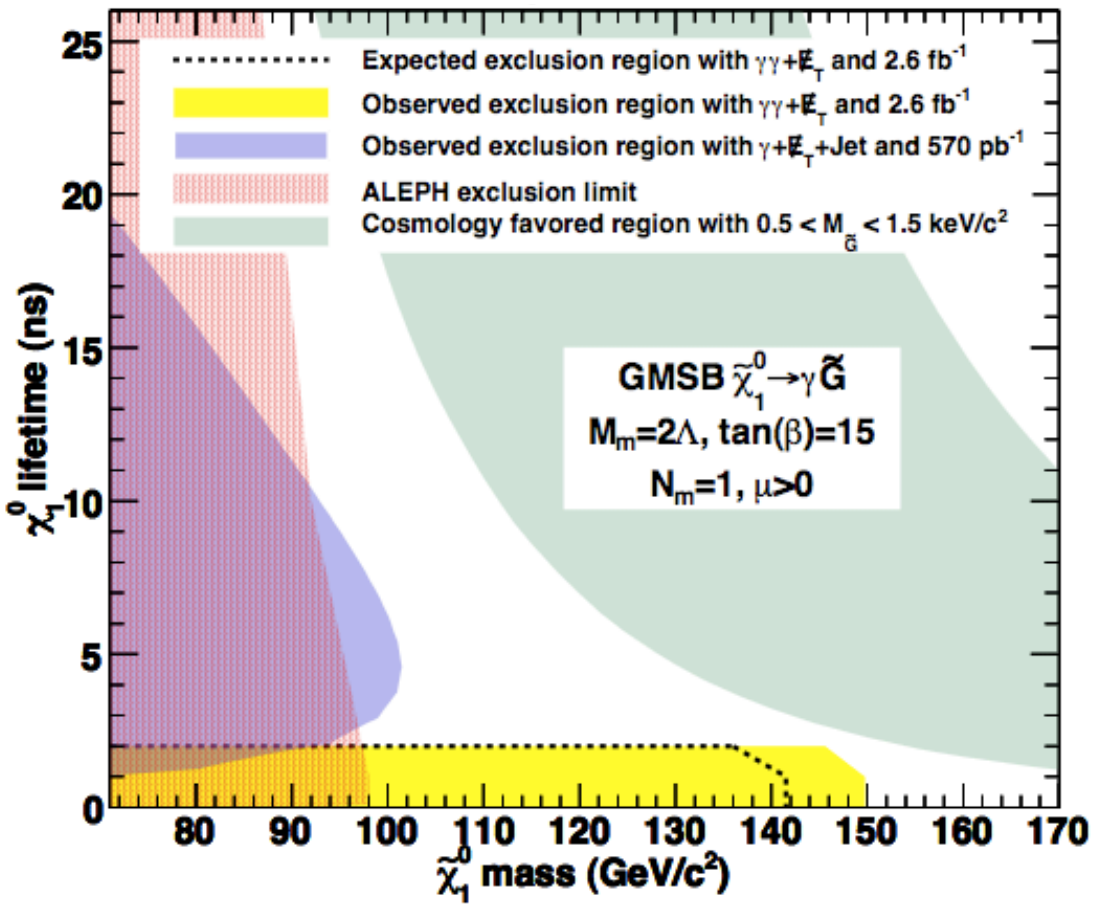




- Gauge-Mediated SUSY Breaking
  - Only 6 free parameters
    - Vs 105 parameters of MSSM
  - Natural solution to FCNC problem
  - SUSY breaking scale:10-100 TeV
  - Heavy squarks, gluinos, sleptons
  - Gravitino LSP (<<MeV)
  - Neutralino or slepton NLSP
  - If $\chi^0$ NLSP: $\chi^0 \rightarrow \gamma G$ (Br=100%)

- GMSB parameters
  - $\Lambda$ – SUSY breaking scale
  - $M_m$ – messenger mass scale
  - $N_m$ – number of messenger fields
  - $\tan\beta = \langle\phi_1\rangle / \langle\phi_2\rangle$
  - sign $\mu = \pm 1$ – sign of higgsino mass term
  - $C_{grav}$ – determines NLSP lifetime

# World's Best Limit on GMSB Neutralino NLSP

- 95% CL limits in neutralino mass & lifetime plane
  - Neutralino mass>149 GeV/$c^2$ for $\tau$<<1 ns
    - World's best limit
  - Leading uncertainties
    - Backgrounds: 32%
    - Acceptance: 7%
    - X-section: 7% (PDFs)



# “Shopping” 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?...

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