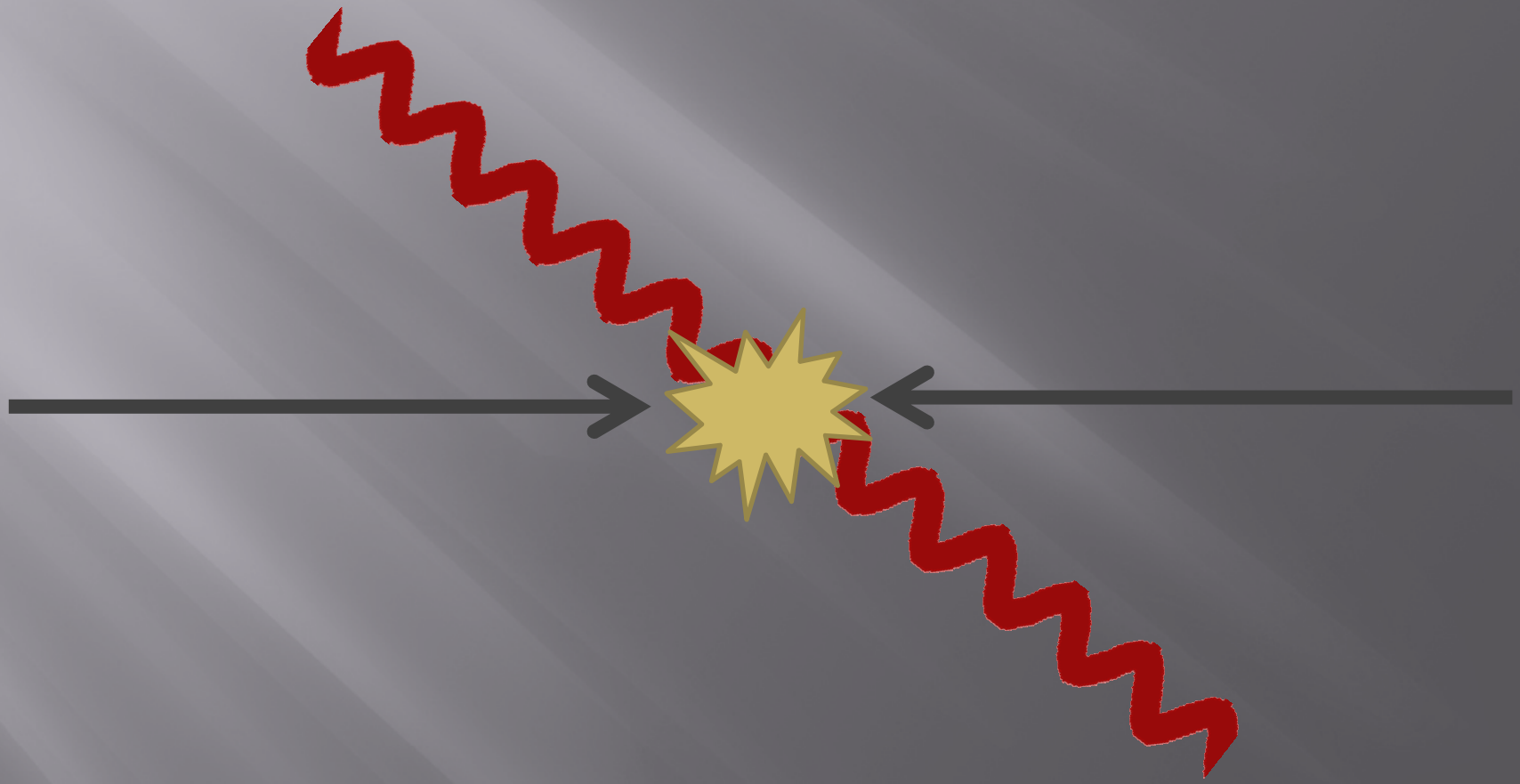
Legacy Photon Results from CDF

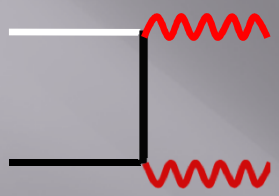
Ray Culbertson, FNAL

Diphoton Cross Section



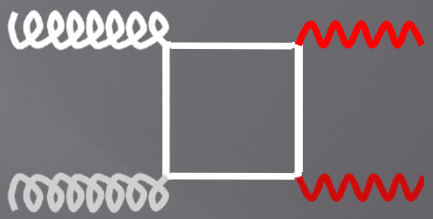
Phys Rev. Lett. 110, 101801 (2013)

Diphoton Production



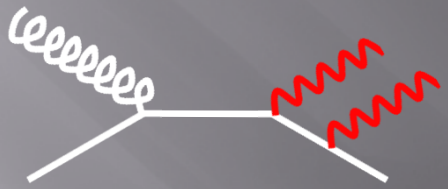
$q\bar{q} \to \gamma\gamma$

Born: α^2



$gg \to \gamma\gamma$

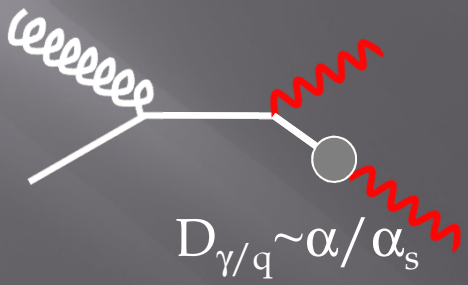
"Box": Leading at the LHC



$gq \to \gamma\gamma q$

Compton with radiation: $\alpha_s\alpha^2$

collinear singularity



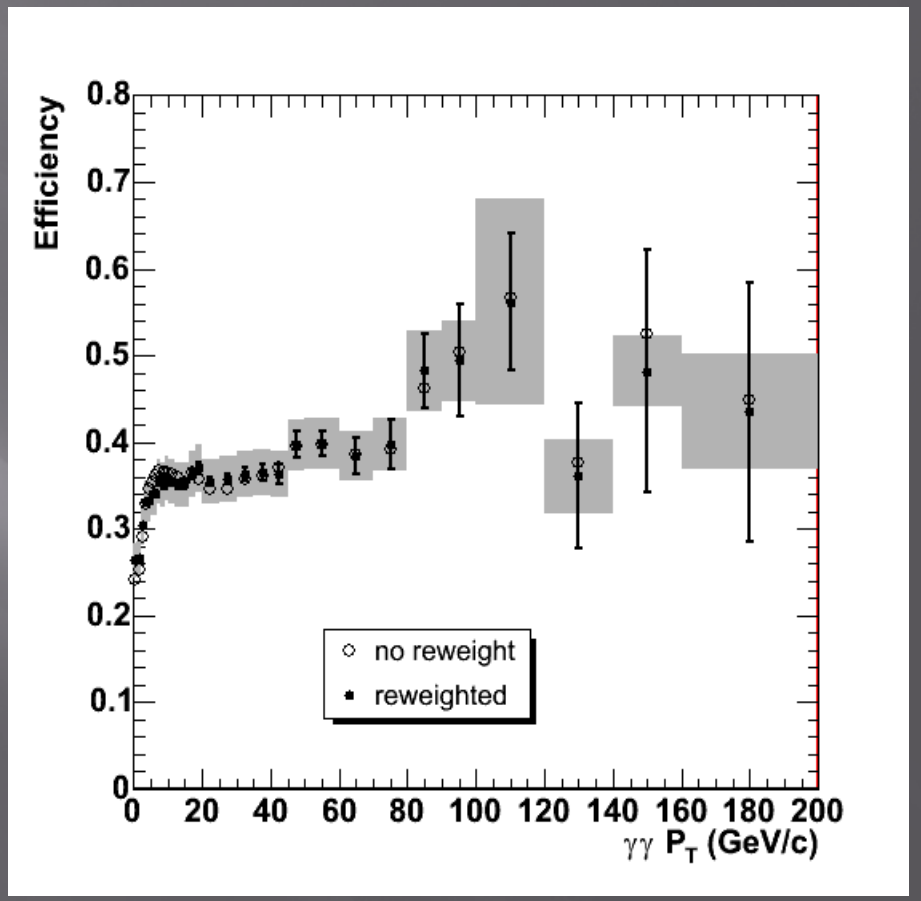
Fragmentation: α^2

Suppressed by isolation

Diphoton Selection/Efficiency

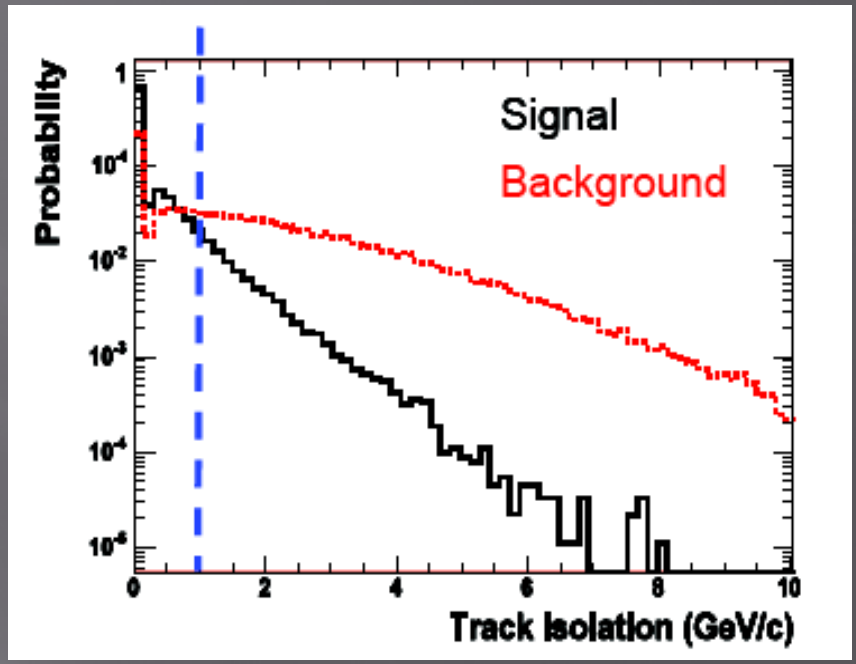
- Full Dataset
- $E_T > 15, 17$ GeV
- $|\eta| < 1$ (central)
- $\Delta R > 0.4$

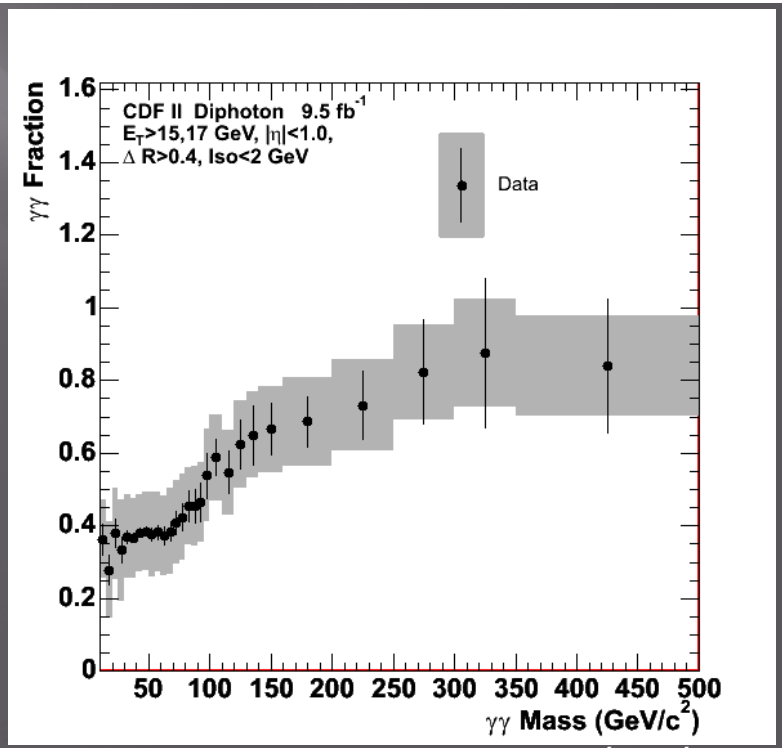
- Efficiencies
  - PYTHIA + GEANT, iterated
  - ~35%, small variations
  - largest systematic, 6%, underlying event modeling



Diphoton Backgrounds

- Backgrounds from jets with a leading π^0
- BG subtraction by track isolation, cone R=0.4
- allow for correlations between photons
  → subtraction using a matrix of track iso efficiences
- largest systematics from modeling iso efficiencies



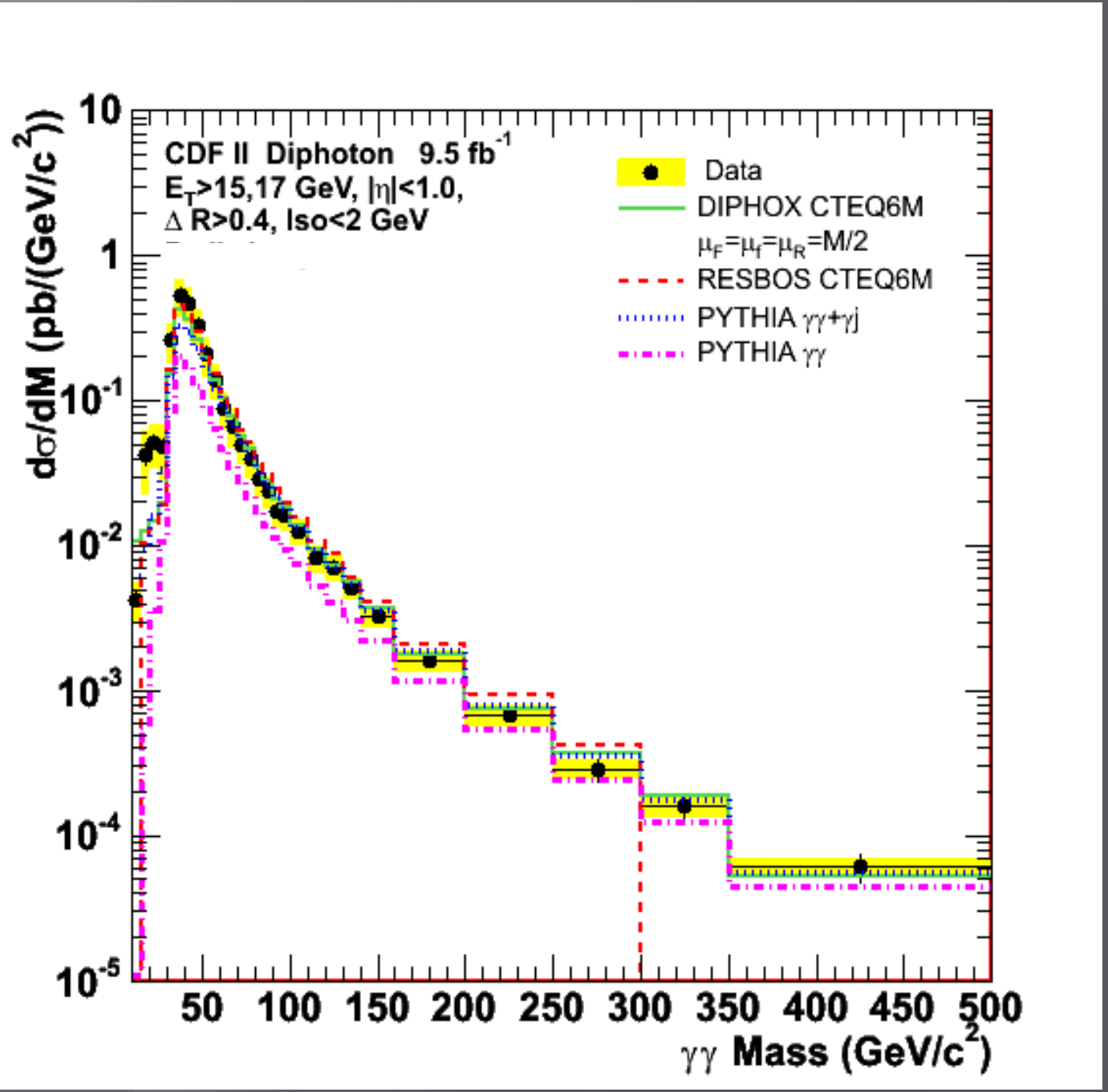


Diphoton Models

- **PYTHIA** LO parton-shower calculation – including $\gamma\gamma$ and γj with radiation [T. Sjöstrand *et al*., Comp. Phys. Comm. **135**, 238 (2001)]
- **SHERPA** LO parton-shower calculation with improved matching between hard and soft physics [T. Gleisberg *et al*., JHEP **02**, 007 (2009)]
- **MCFM** fixed-order NLO calculation including non-perturbative fragmentation at LO [J. M. Campbell *et al*., Phys. Rev. D **60**, 113006 (1999)]
- **DIPHOX** fixed-order NLO calculation including fragmentation at NLO [T. Binoth *et al*., Phys. Rev. D **63**, 114016 (2001)]
- **RESBOS** low-P_T analytically resummed calculation matched to high-P_T NLO [T. Balazs *et al*., Phys. Rev. D **76**, 013008 (2007)]
- **NNLO** calculation with q_T subtraction [L. Cieri *et al*., http://arxiv.org/abs/1110.2375 (2011)]

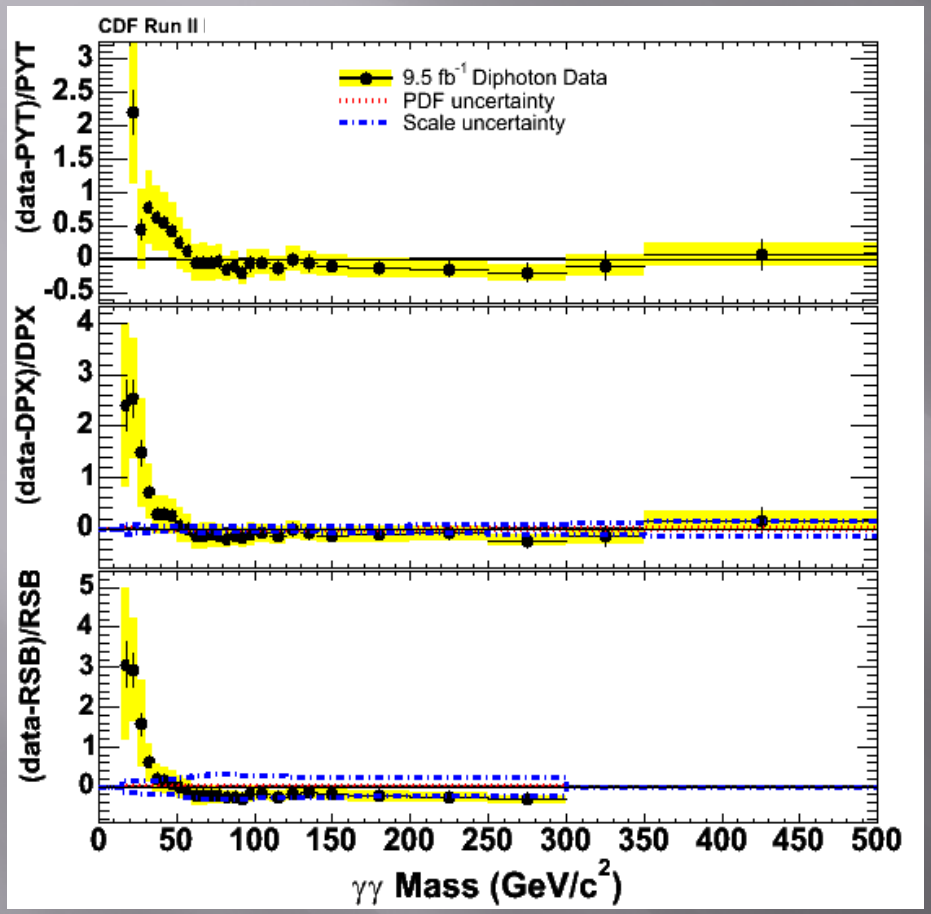
Diphoton Mass

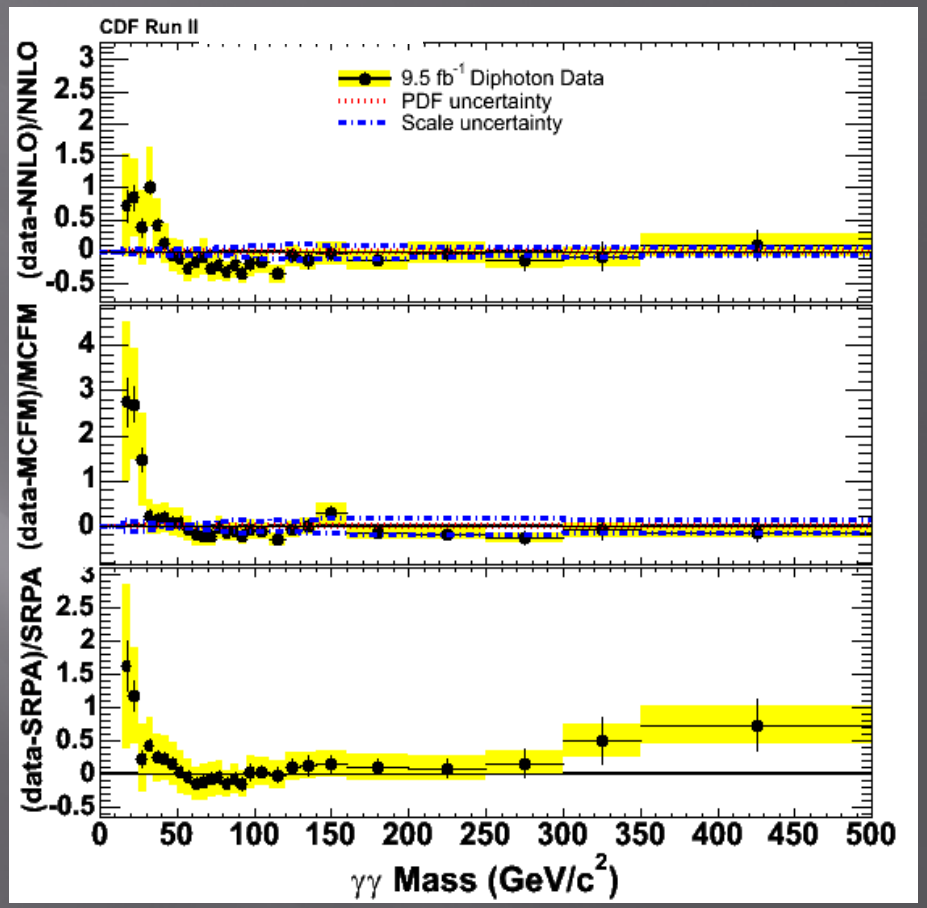
- Energy scale
- Resonances



Diphoton Mass

Vertical scales are not the same

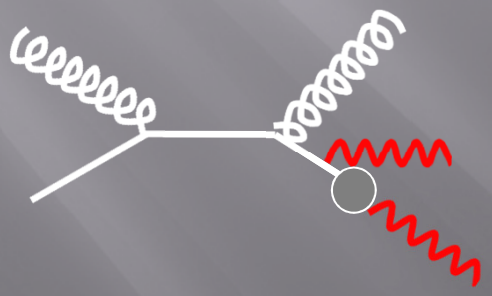


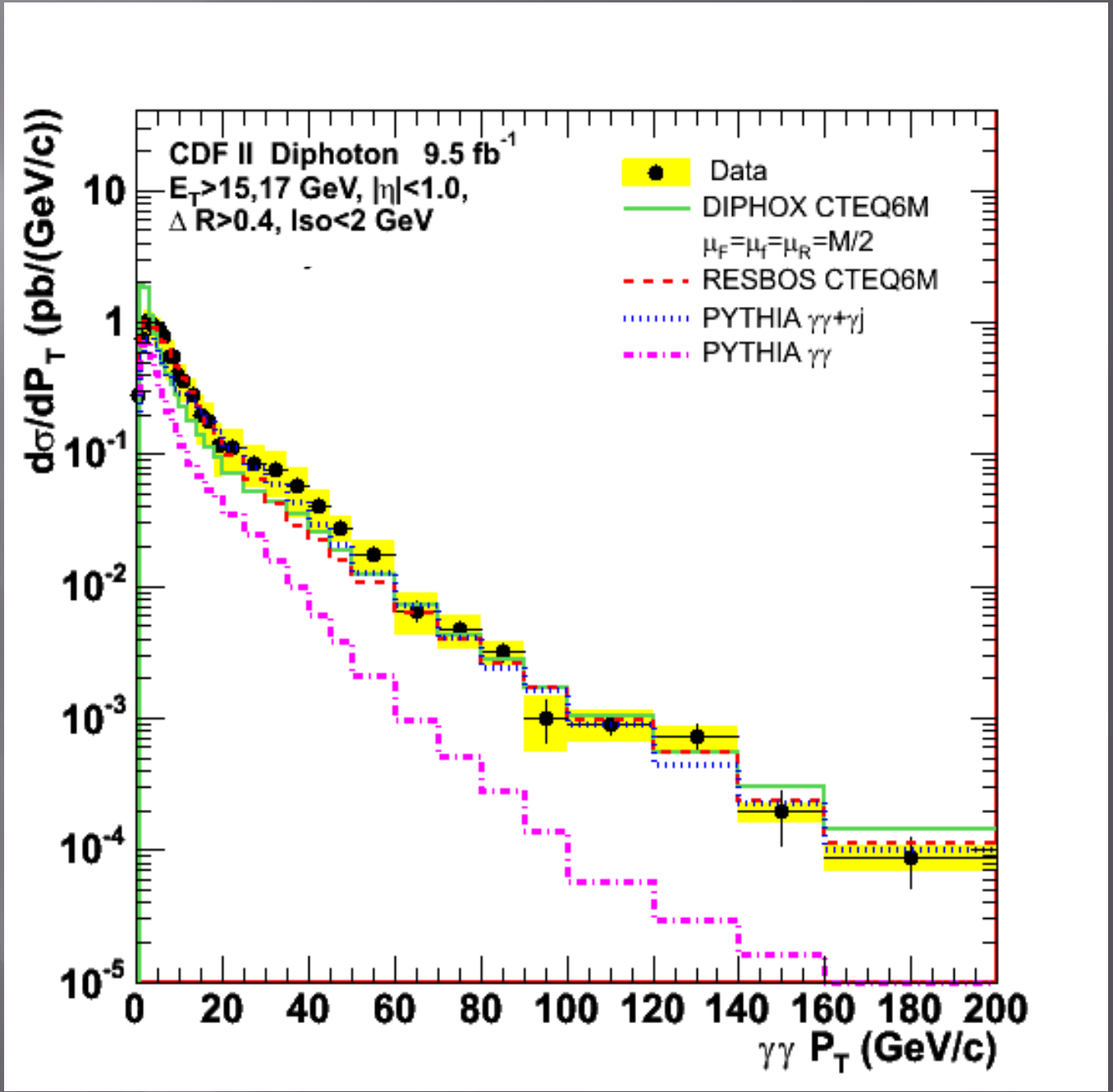


- All models don't describe extremely small masses
- All models do well at mid to high masses

Diphoton Vector Sum P_T

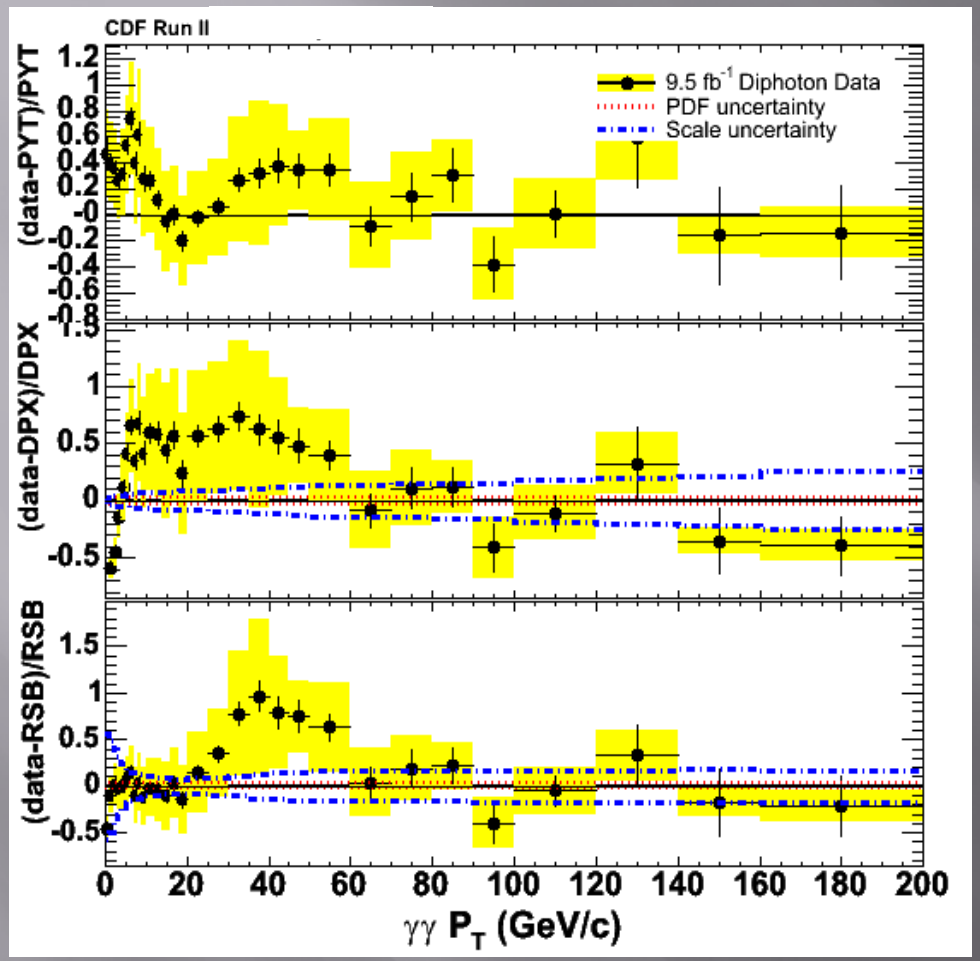
- At low P_T, sensitive to soft radiation
- Shoulder indicates higher orders

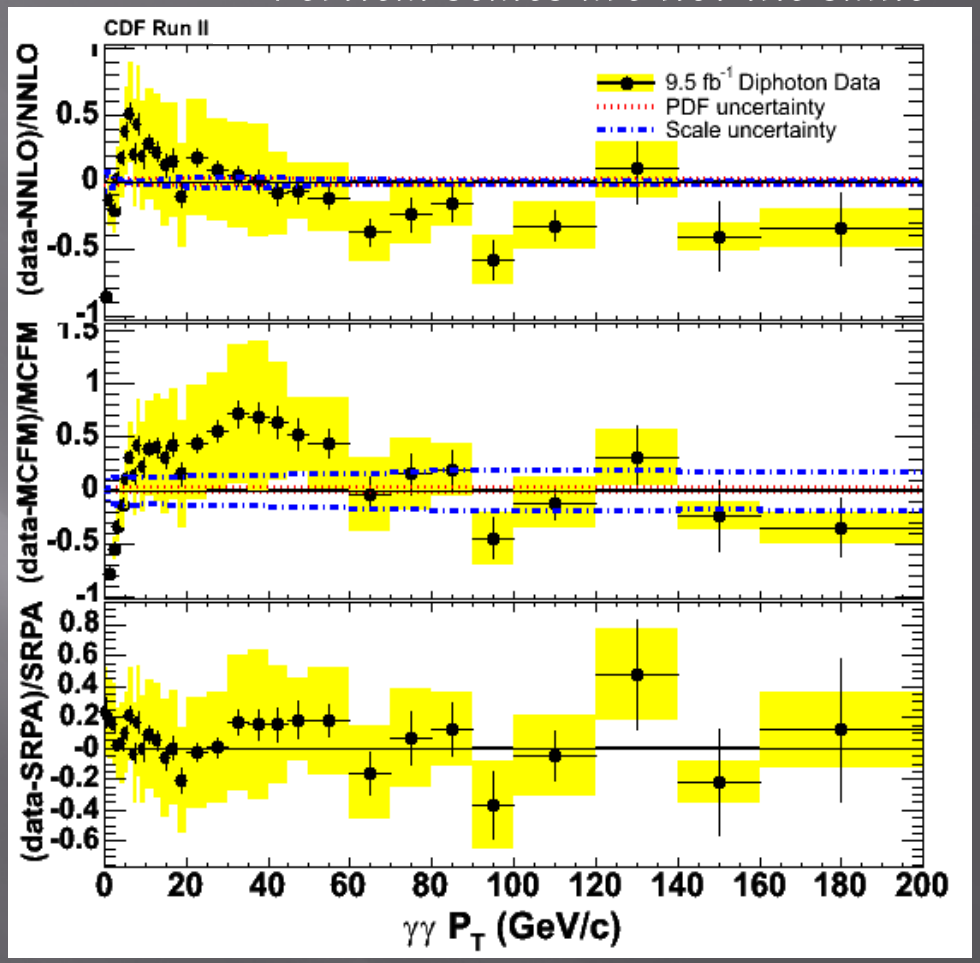




Diphoton Vector Sum P_T

Vertical scales are not the same

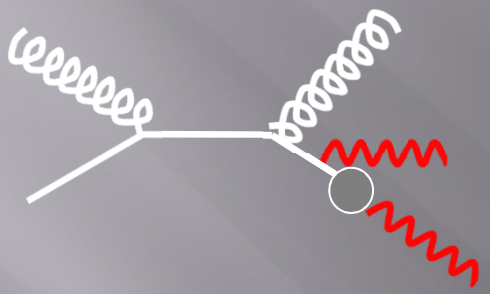




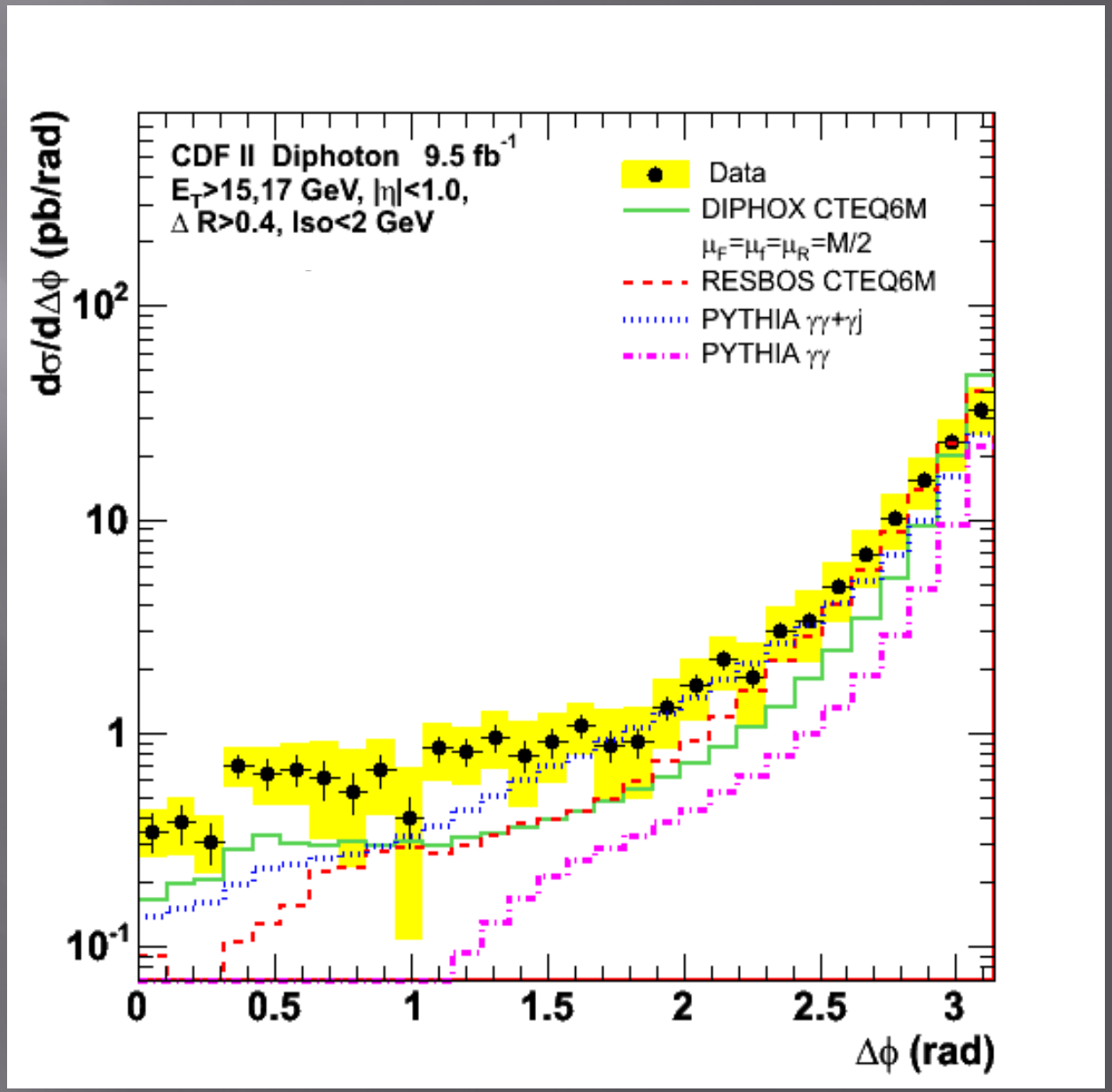
- Pythia, DIPHOX, RESBOS, MCFM tend to miss the shoulder, SHERPA and NNLO do well
- RESBOS and SHERPA do well with soft radiation

Diphoton Δϕ

- small Δϕ sensitive to higher orders

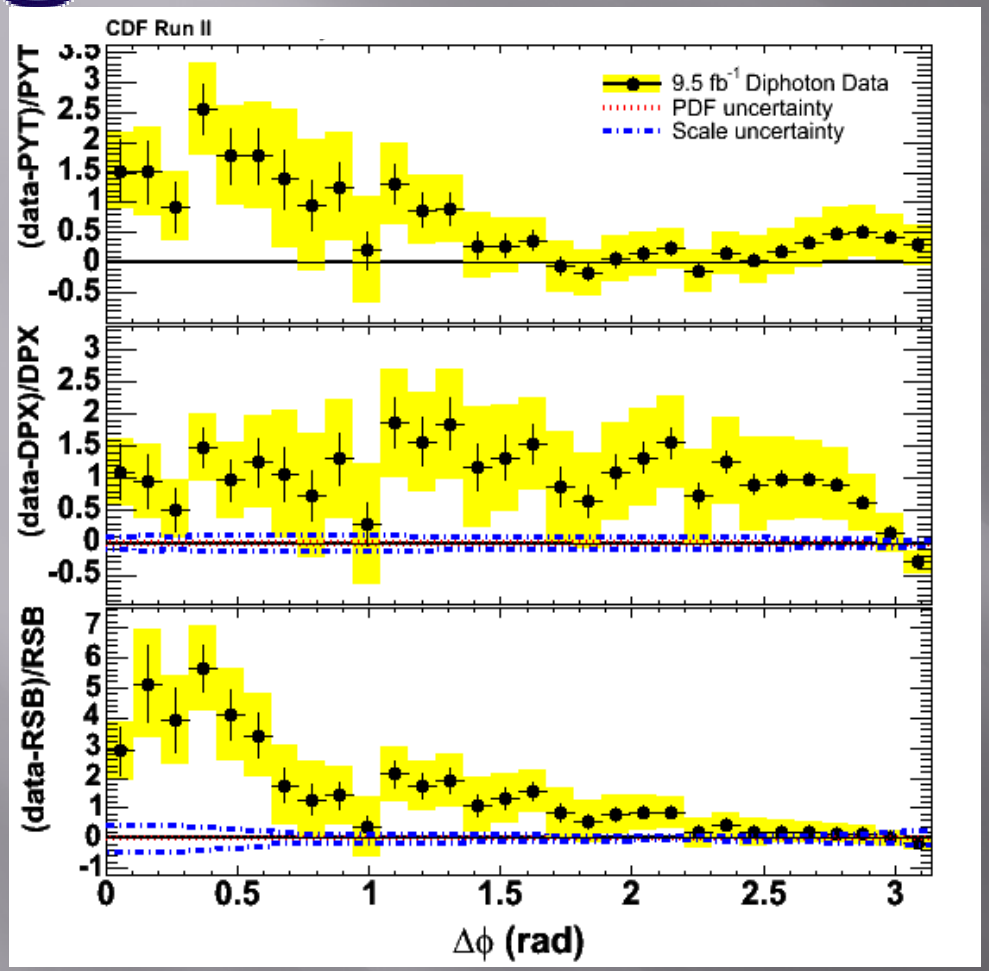


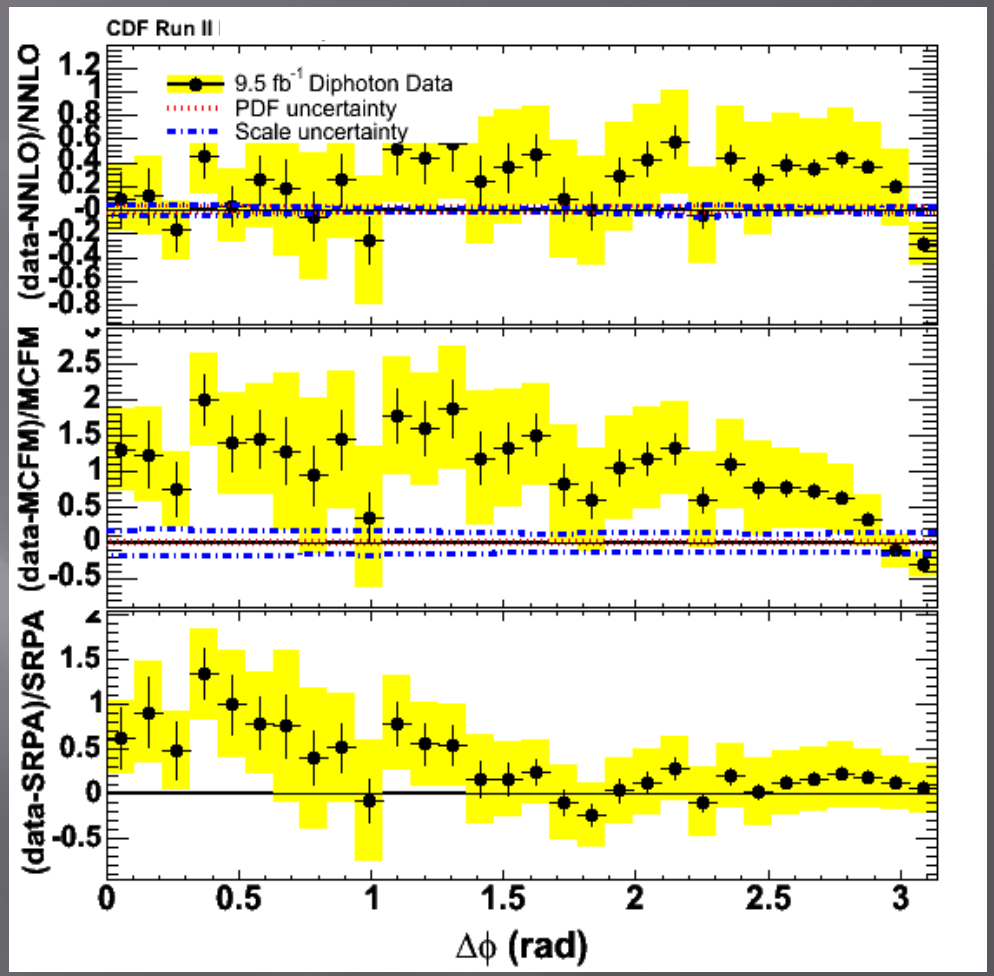
- Large Δϕ sensitive to soft radiation



Diphoton

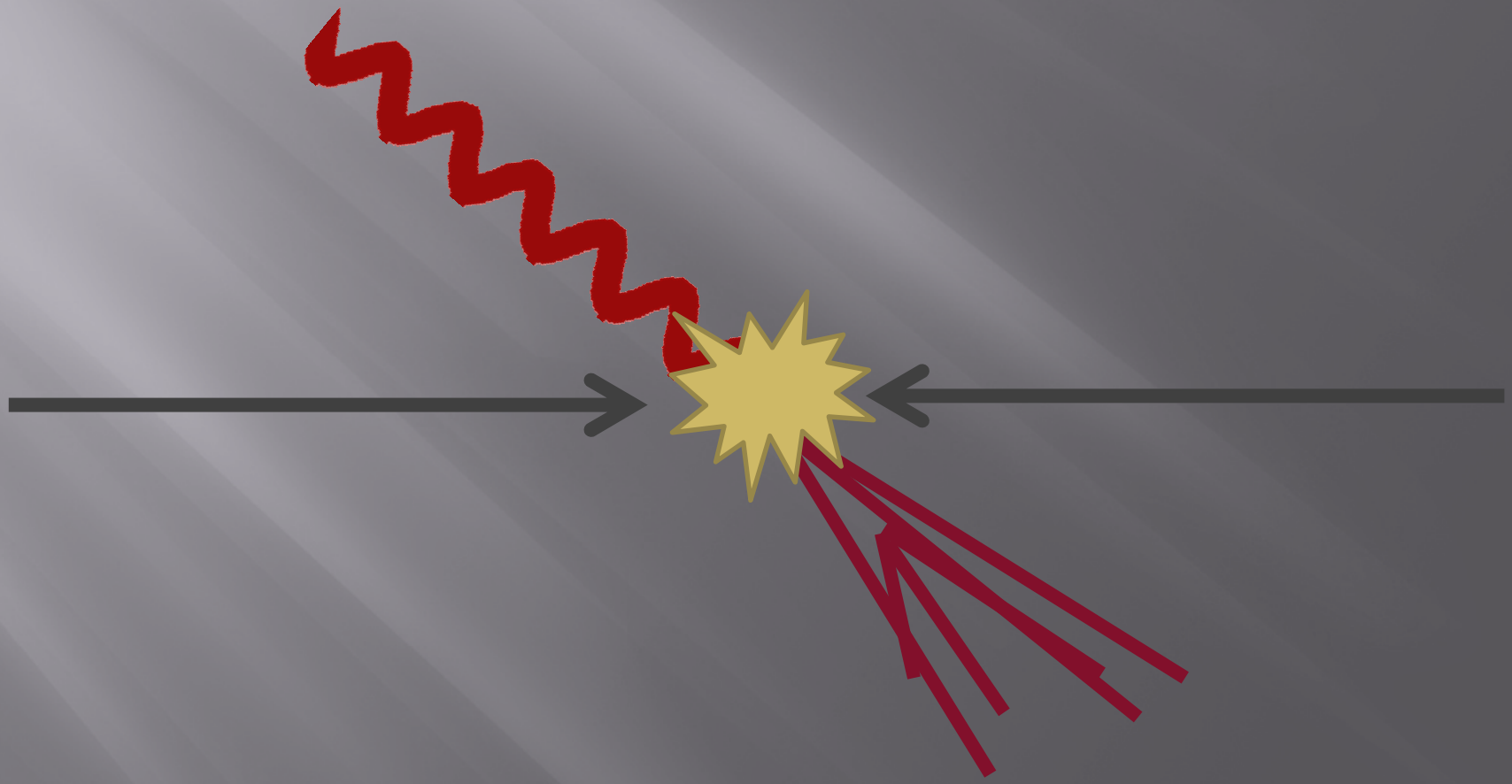
Many more available!





- Low P_T and high $\Delta\phi$ show the same pattern for low energy radiation
- P_T shoulder and small $\Delta\phi$ show the same pattern for higher orders

Photon and Heavy Flavor Cross Section



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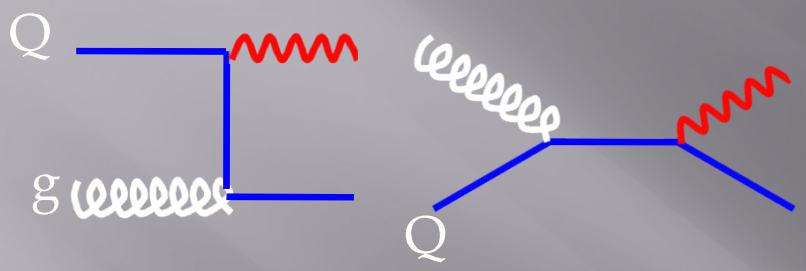
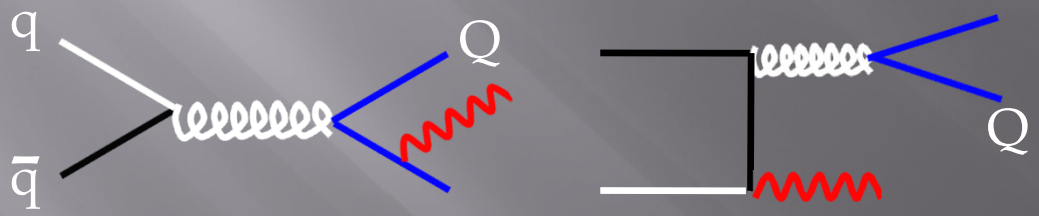
Photon and Heavy Flavor



Compton scattering ~ $\alpha\alpha_S$

- Probes the heavy flavor content in the proton
  - gluon evolution
  - intrinsic H.F.
  - important at low E_T



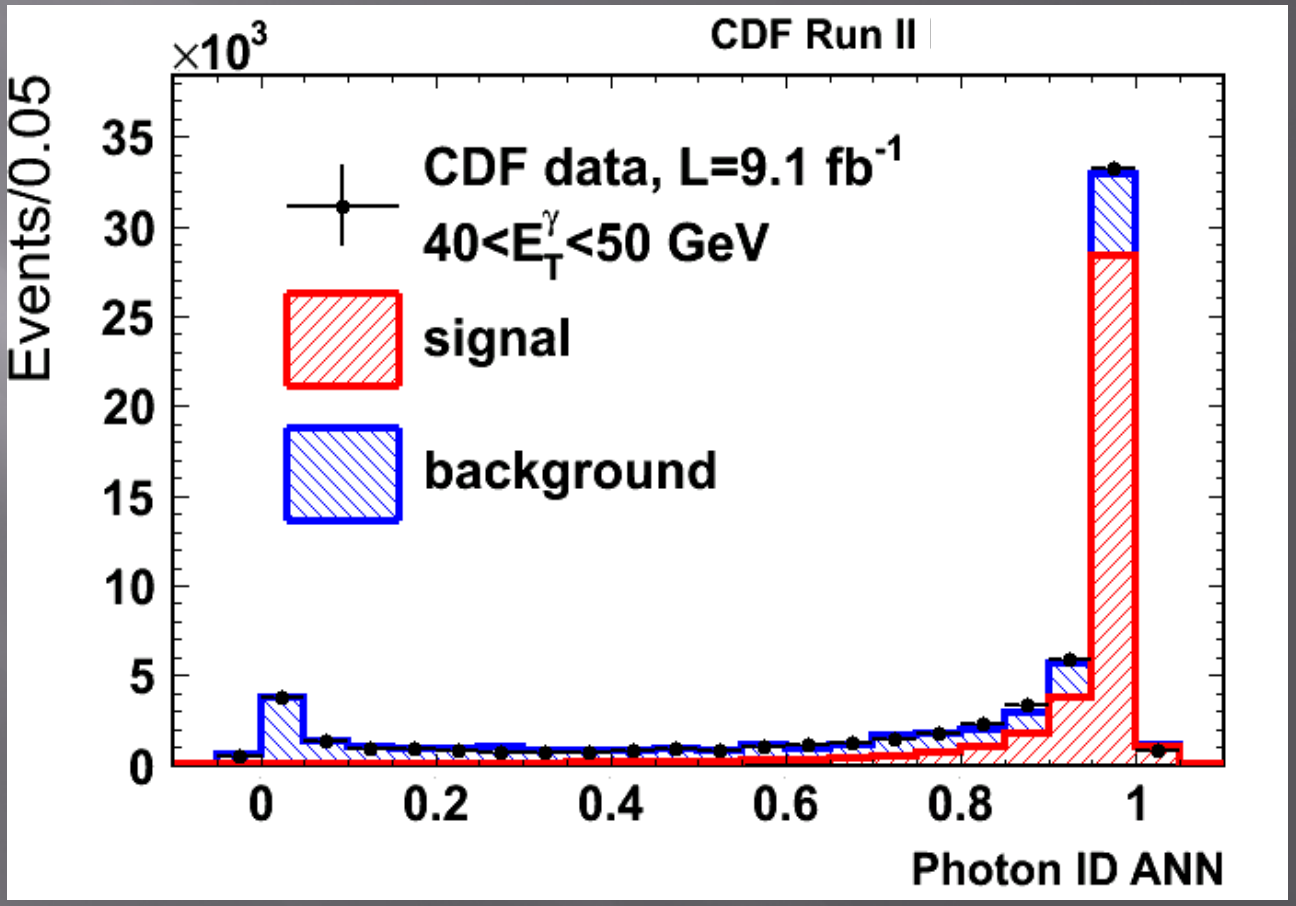
Annihilation ~ $\alpha\alpha_S^2$

- Tests final state gluon splitting to heavy flavors
  - important at high E_T

Photon+H.F., Photon Selection

- Full dataset

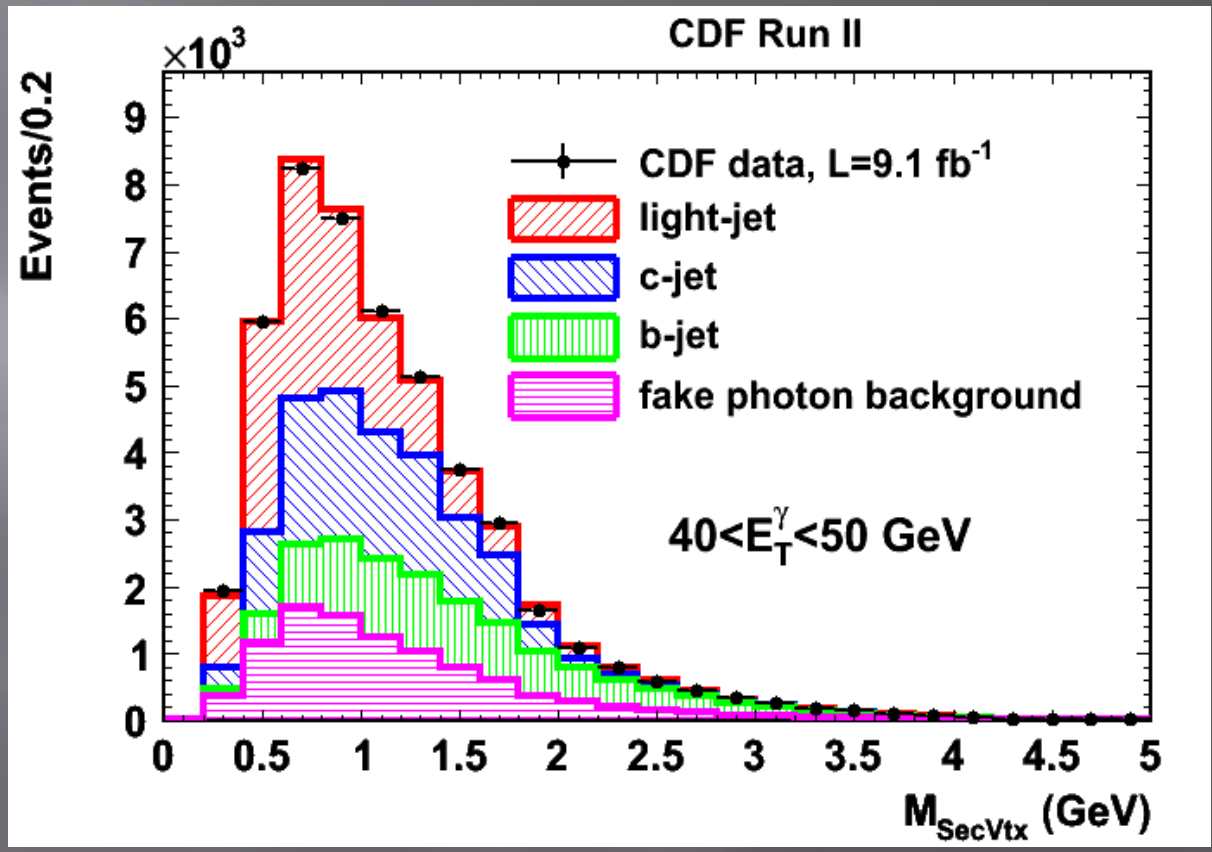
- E_T > 30 GeV
- $|\eta|$ < 1 (central)
- ANN photon ID
  - isolation
  - shower shape
  - Had/EM
- fit ANN to measure jets faking photons background



- 2-5% uncertainty due to modeling of isolation energy in templates

Photon+H.F., Jet Selection

- $E_T > 20$ GeV
- $|\eta| < 1.5$
- JetClu cone 0.4
- Secondary vertex tag
- Background subtraction by fitting secondary vertex mass to MC templates
- efficiency ~20% (b) and ~6% (c)



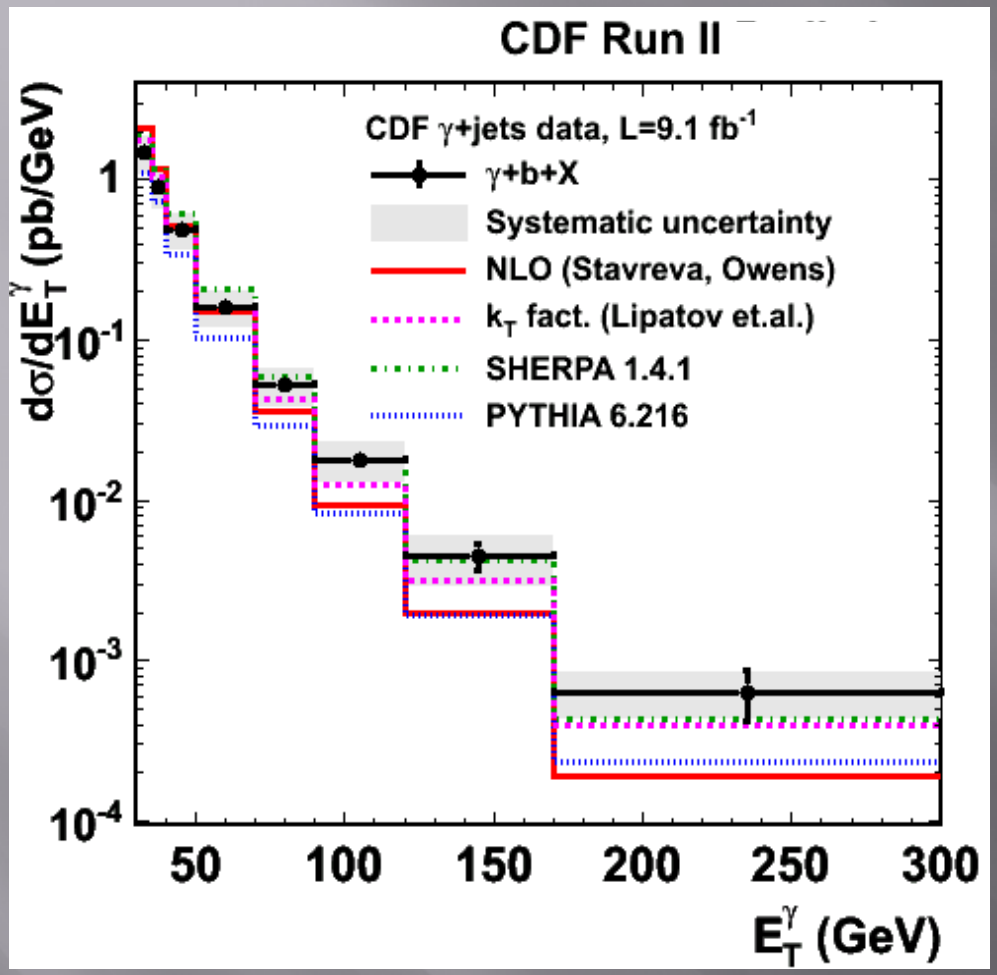
- 20% systematic uncertainty on track efficiencies, varies the template shapes

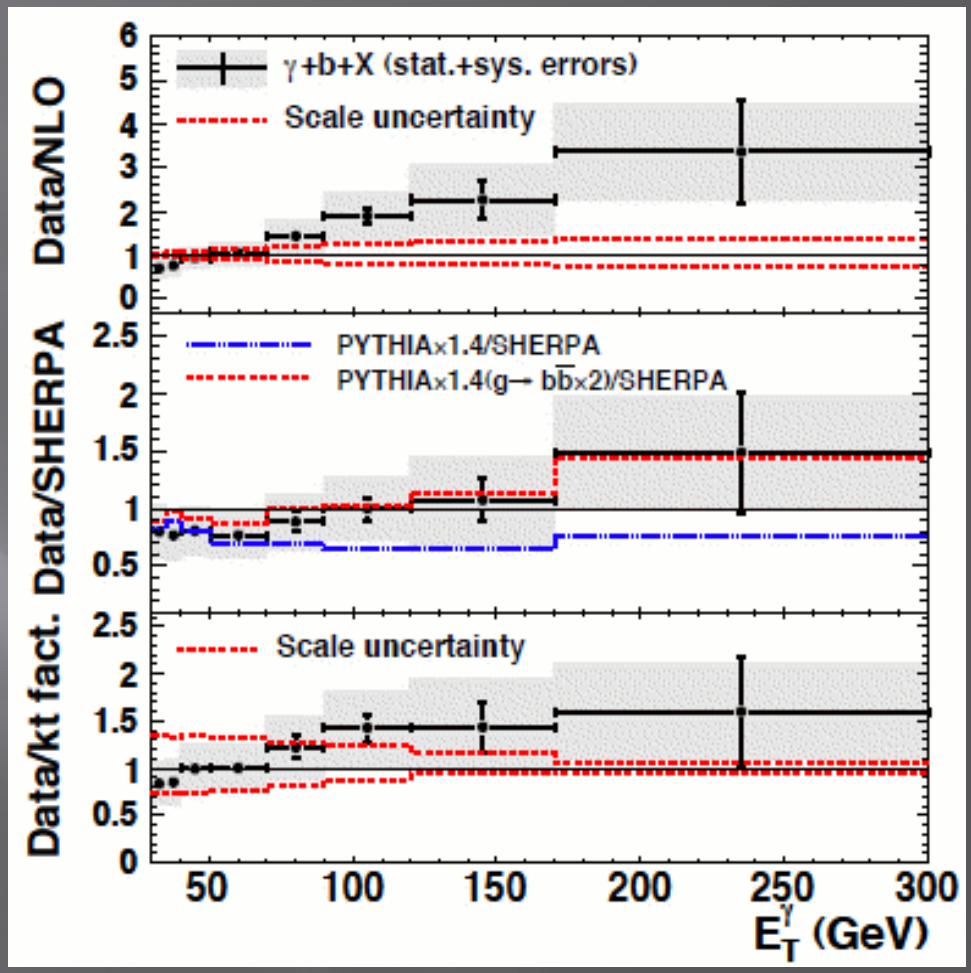
Photon and H.F. Models

- **NLO** – direct-photon and fragmentation subprocesses at $O(\alpha\alpha_s^2)$, CTEQ6.6M PDFs [T.P. Stavreva and J.F. Owens, PRD **79**, 054017 (2009)]
- **k_T-factorization** – off-shell amplitudes integrated over k_T-dependent parton distributions, MSTW2008 PDFs [A.V. Lipatov *et al.*, JHEP **05**, 104 (2012)]
- **SHERPA 1.4.1** – tree-level matrix element (ME) with one photon and up to three jets, merged with parton shower, CT10 PDFs [T. Gleisberg *et al*., JHEP **02**, 007 (2009)]
- **PYTHIA** – ME subprocesses: $gQ \rightarrow gQ$, $qq \rightarrow gg$, with gluon splitting: $g \rightarrow QQ$, CTEQ5L PDFs [T. Sjöstrand et al., JHEP **05**, 026 (2006)]

Photon and b quark

Vertical scales are not the same

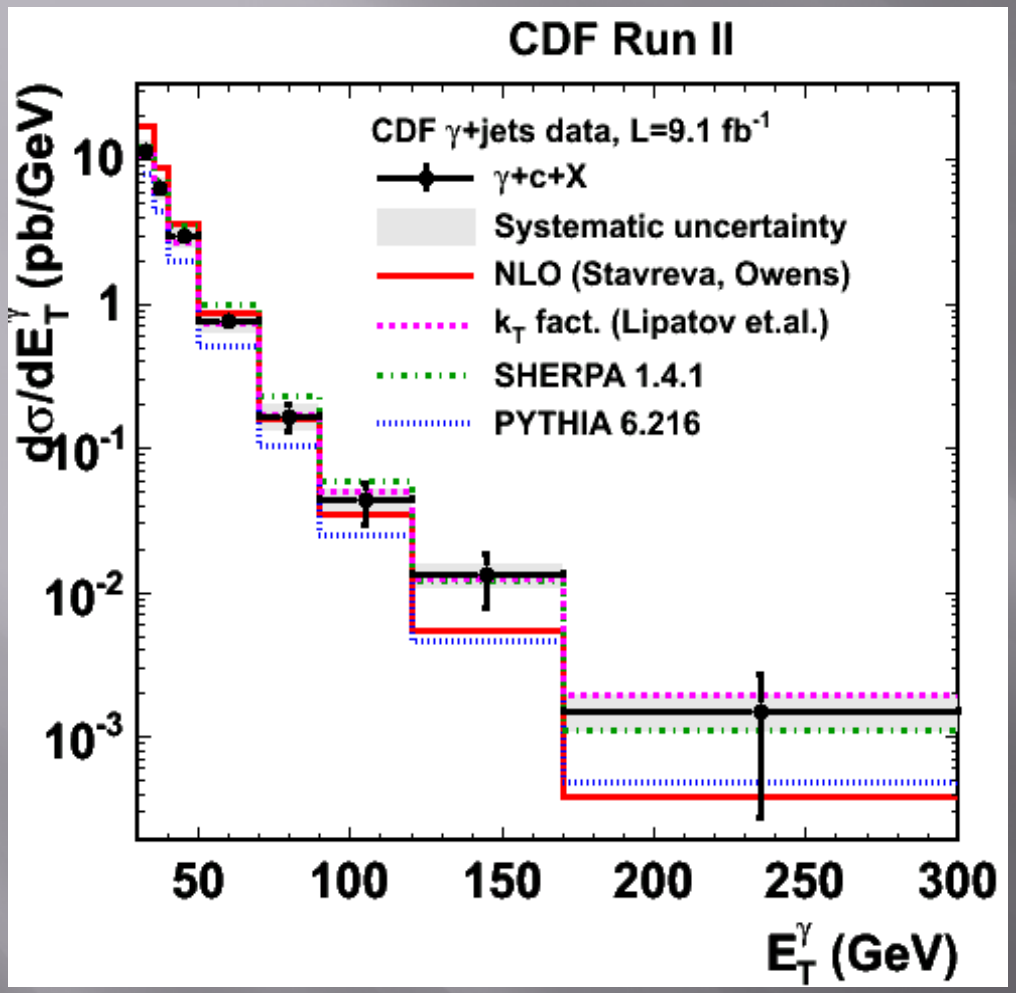


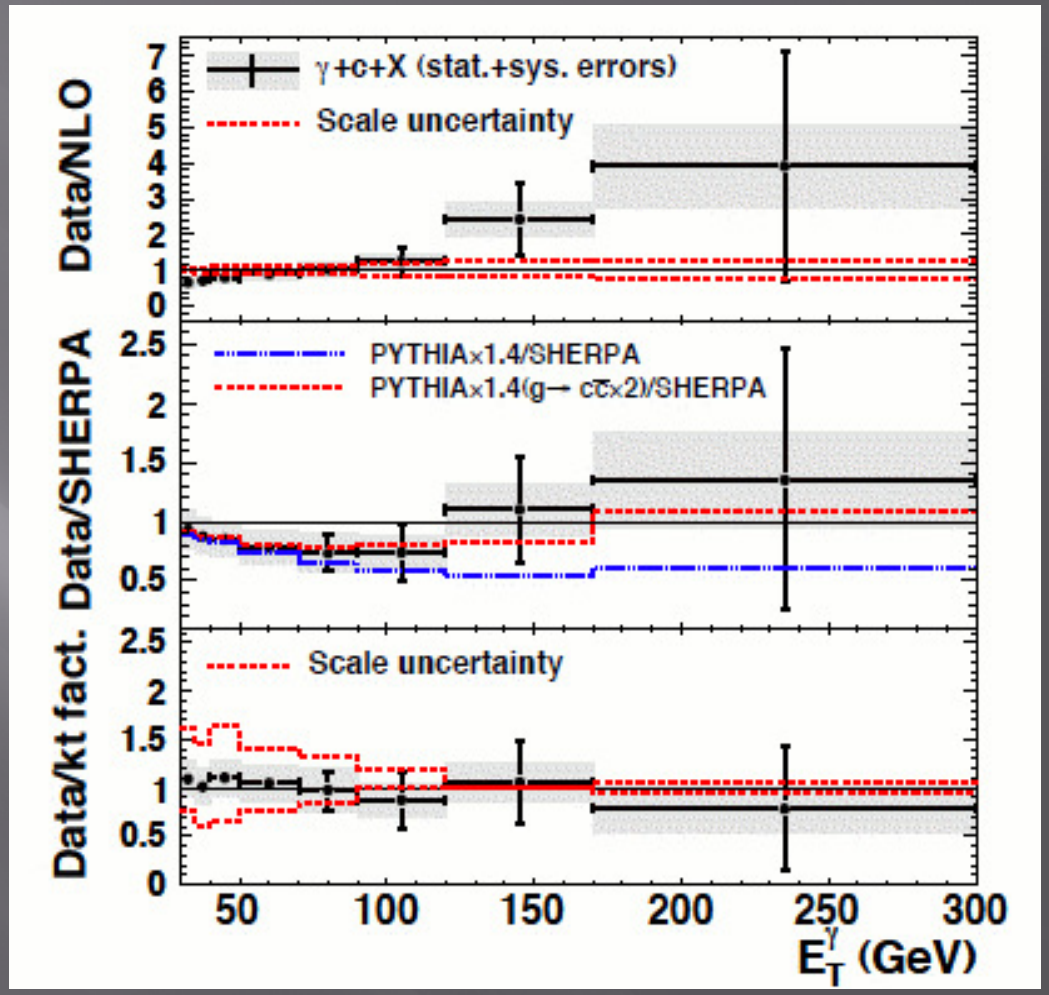


- NLO low at high E_T - gluon splitting at tree-level
- k_T and SHERPA have moderate agreement
- PYTHIA with gluon splitting rate scaled matches shape

Photon and c Quark

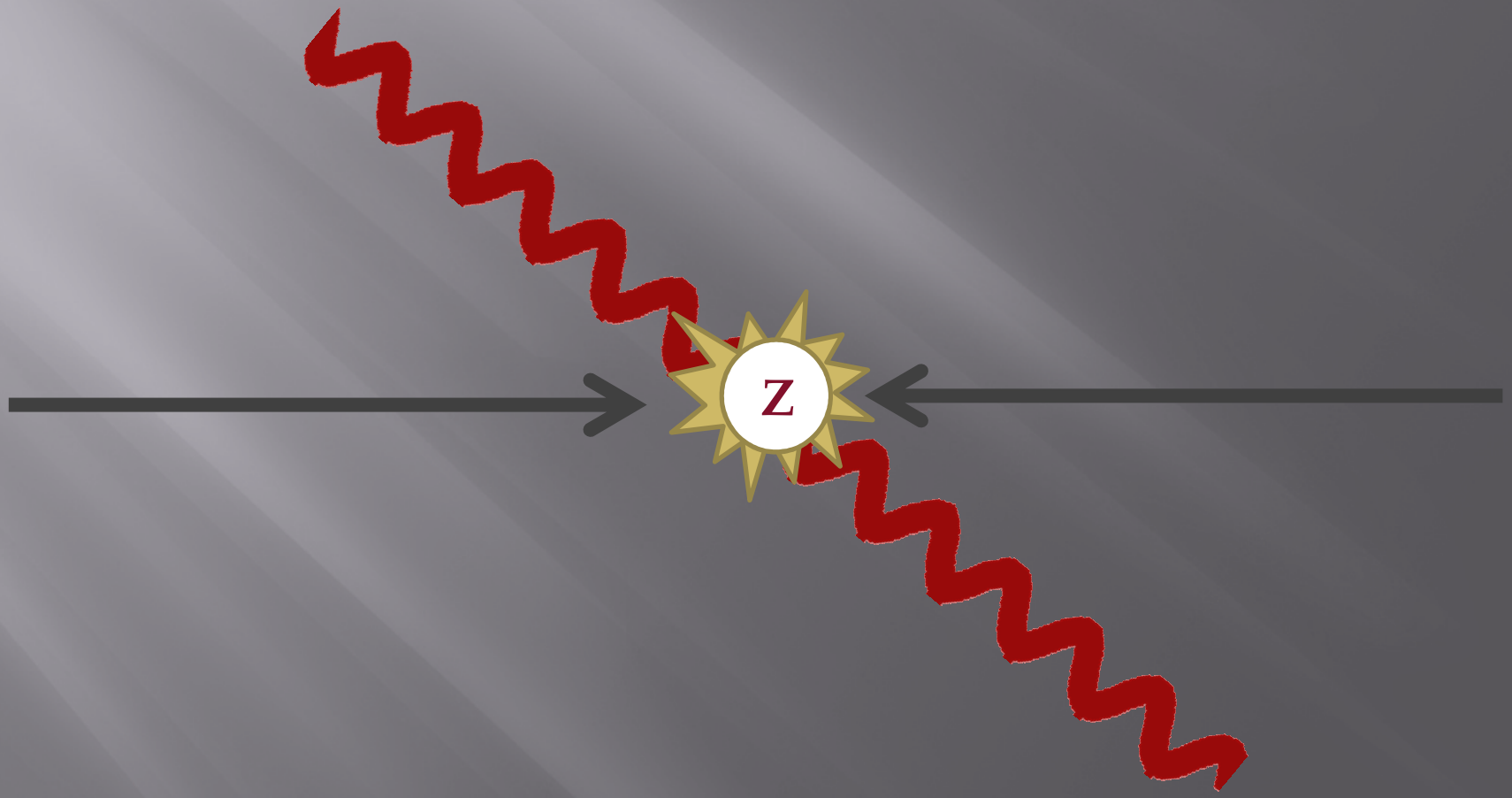
Vertical scales are not the same



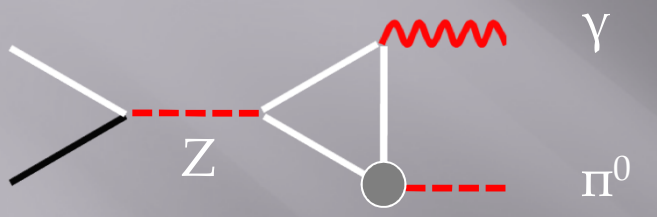


- NLO low at high E_T - gluon splitting at tree-level
- k_T agrees well, SHERPA has moderate agreement
- PYTHIA with gluon splitting rate scaled matches shape

Z Decays to Photons and Neutral Pions



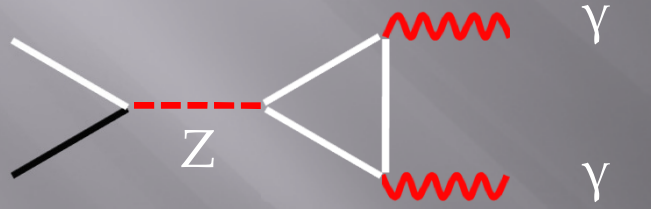
Rare and Forbidden Z decays



Small in the SM, Similar to $W^+ \rightarrow \pi^+\gamma$

Tests:

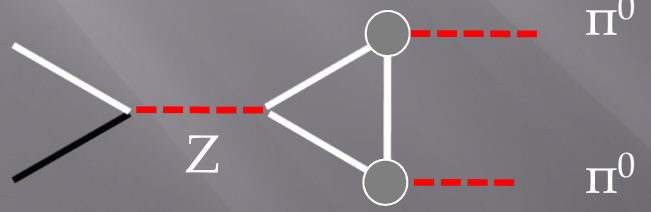
- Pion form factor
- Physics beyond the SM…



Not allowed in SM - Landau-Yang theorem, Bose-Einstein statistics

Tests:

- Commutativity of gauge theory
- Physics beyond the SM…

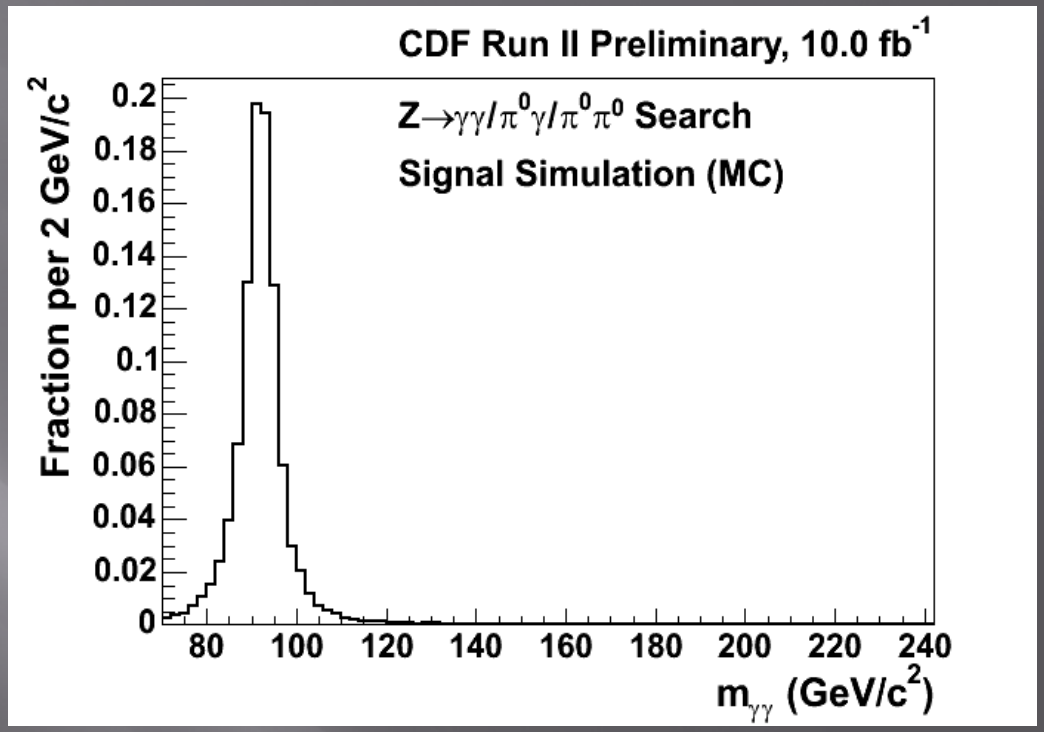


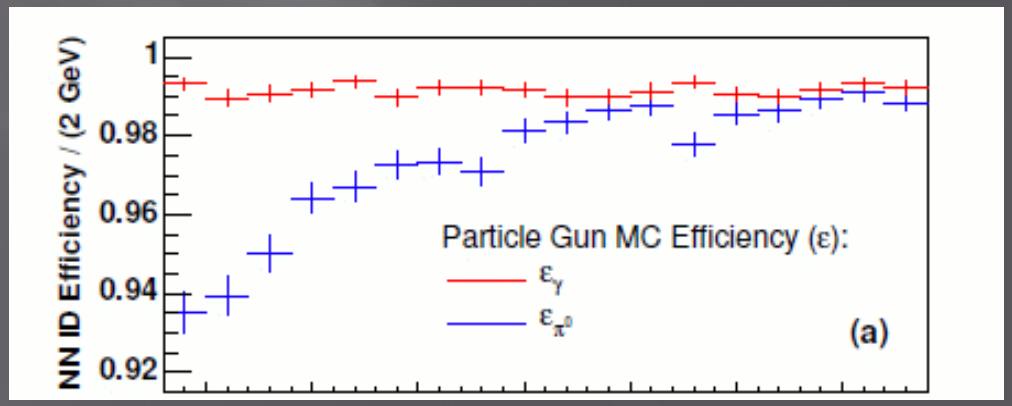
Selection, Efficiency

- Full dataset

- 2 γ, E_T > 15 GeV
- |η| < 1 (central)
- ANN selection

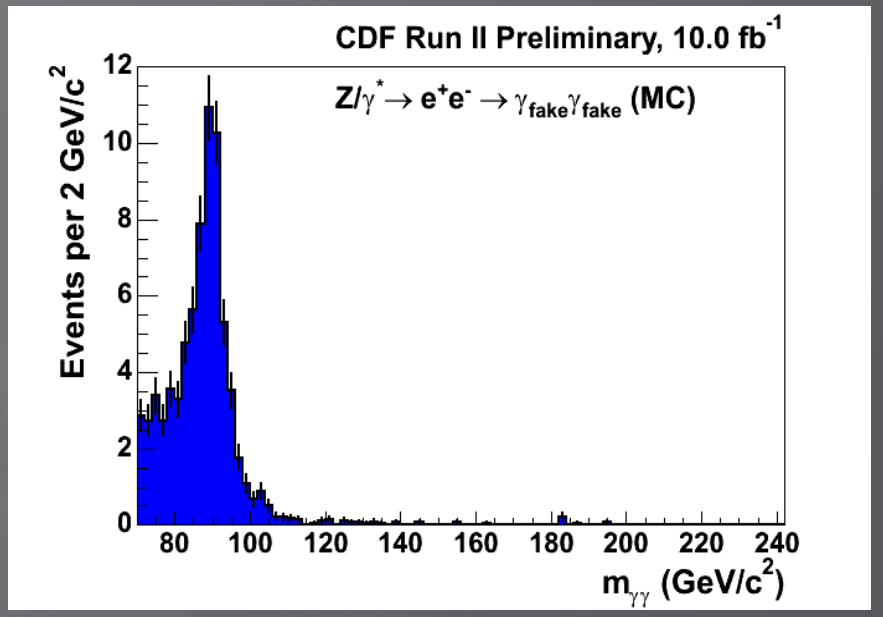
- In this energy range π^0's have an efficiency 5% smaller than a photon
- Signal Monte Carlo created by reweighting angular distribution in a Z decay

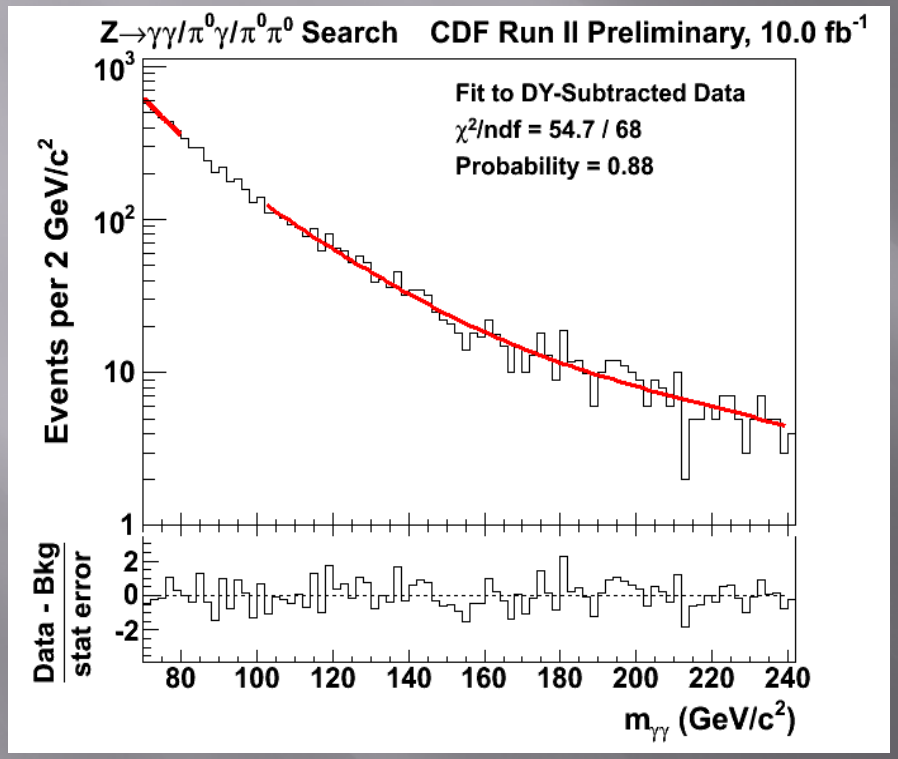




Background

- Subtract simulated Drell-Yan contamination



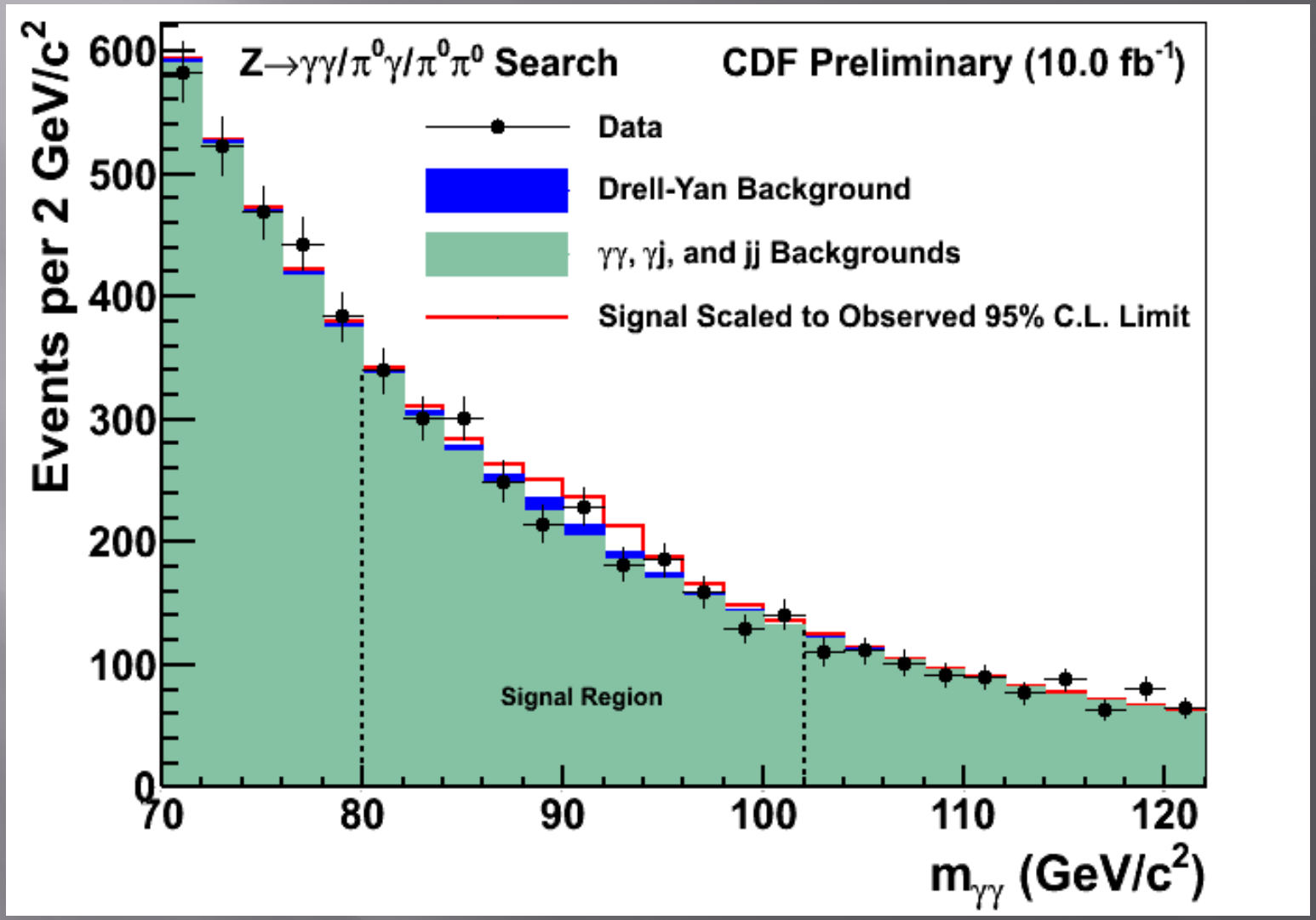


- fit the D-Y subtracted mass spectrum to an exponential and 2nd degree polynomial

$Z \rightarrow \gamma\gamma/\pi^0\gamma/\pi^0\pi^0$ Search	CDF Run II Preliminary, 10.0 fb^{-1}
Process	Number of Events for $80 < m_{\gamma\gamma} < 102$ GeV
Drell-Yan	54 ± 5
$\gamma\gamma$, γj, and jj	2251 ± 61
Total background	2305 ± 61
Data	2294

Setting Limits

- Final limit process includes signal line shape



Limits

- Final result reported as BR
- Leading systematics
  - 6% luminosity

CDF Run II Preliminary $\int \mathcal{L} = 10.0\ \text{fb}^{-1}$

Signal Process	95% C.L. Limits Expected ($\times 10^{-5}$) -2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	Observed ($\times 10^{-5}$)
$\text{Br}(Z \to \gamma\gamma)$	0.88	1.19	1.66	2.34	3.20	1.66
$\text{Br}(Z \to \pi^0\gamma)$	1.21	1.63	2.28	3.21	4.37	2.28
$\text{Br}(Z \to \pi^0\pi^0)$	0.93	1.23	1.72	2.41	3.29	1.73

- 3.1 times smaller than world's best
- 2.3 times smaller than world's best
- first reported

- SM expectations for BR($Z \to \pi^0\gamma$): $10^{-9} - 10^{-12}$

Last Slide

CDF continues to report many legacy measurements

- Diphoton Cross Section
  - most complete kinematics and comparisons
- Photon and Heavy Flavor Cross Section
  - high statistics, new model
- Z Decays to Two Reconstructed Photons
  - new world's best limits

Many more legacy measurements to come…

Photon + H.F. Total Cross Section

	Integrated cross section (pb)	
	γ+b+X	γ+c+X
Data	$19.7 \pm 0.7_{stat}$ $(+5.0-4.2)_{syst}$	$132.2 \pm 4.6_{stat}$ $(+13.2-19.2)_{syst}$
PYTHIA	19.5	106.0
SHERPA	29.4	173.9
NLO	$27.3 + 2.3 - 1.5$	$152.6 + 12.2 - 9.6$
k_T factorization	25.2	106.4

Diphoton Total Cross Section

	Integrated cross section (pb)
Data (CDF)	$12.3 \pm 0.2_{stat} \pm 3.5_{syst}$
RESBOS	11.3 ± 2.4
DIPHOX	10.6 ± 0.6
MCFM	11.5 ± 0.3
SHERPA	12.4 ± 4.4
PYTHIA $\gamma\gamma$+γj	9.2
NNLO	$11.8 + 1.7 - 0.6$

Z Rare Decay Systematics

CDF Run II Preliminary $\int \mathcal{L} = 10.0\ \text{fb}^{-1}$

		Signal			Background	
Systematic Uncertainties (%)		$Z \to \gamma\gamma$	$Z \to \pi^0\gamma$	$Z \to \pi^0\pi^0$	Drell-Yan	Non-Resonant
Luminosity	6	✓	✓	✓	✓	
Z Cross Section	6	✓	✓	✓	✓	
PDF	5	✓	✓	✓		
ISR/FSR	3	✓	✓	✓		
Energy Scale	0.2	✓	✓	✓		
Trigger Efficiency	1	✓	✓	✓	✓	
z-Vertex	0.2	✓	✓	✓	✓	
Photon ID Efficiency	4	✓	✓	✓		
π^0/γ Efficiency	2 per π^0		✓	✓		
Electron Fake Rate	2				✓	
Sideband Fit	2.7					✓