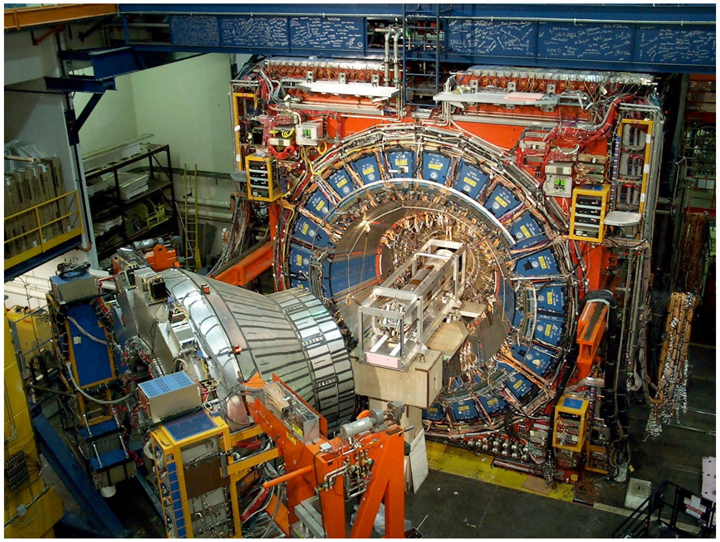
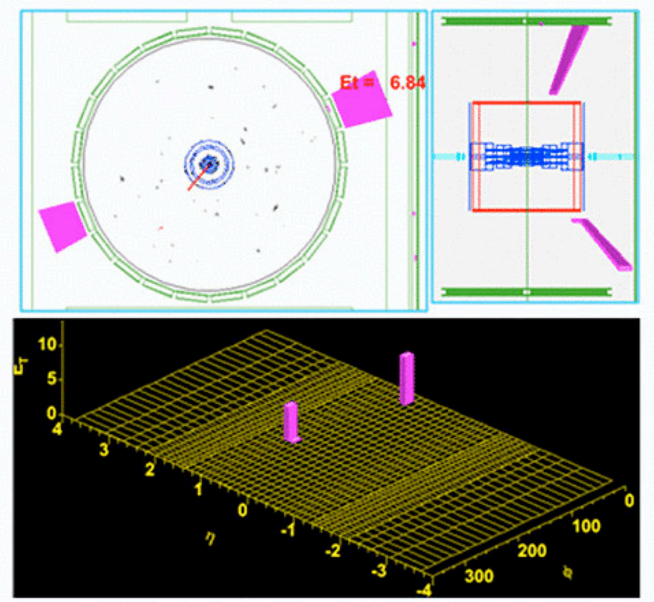
Direct Photon Results from CDF

Tingjun Yang for the CDF collaboration

Fermilab

LHCP 2013
Barcelona, Spain, May 14, 2013





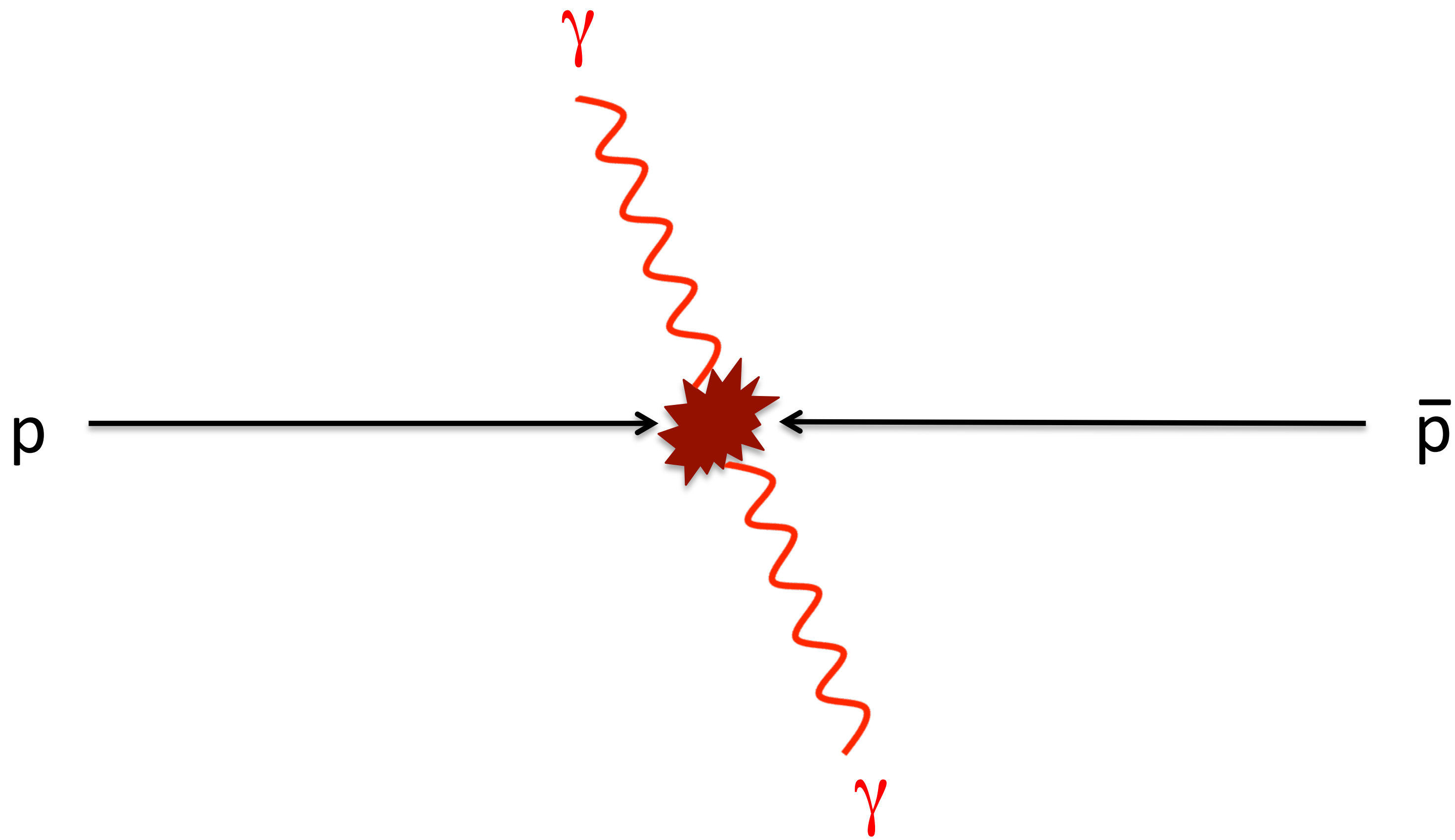
Observation of exclusive diphoton production
PRL 108, 081801 (2012)

Prompt γ production in hadron colliders

- Prompt photon production is a field of very high interest in hadron colliders.
  - The clean probe to test QCD predictions
  - Constrain background for searches with photon final state

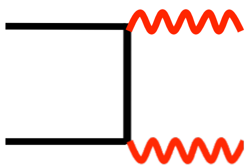
- I will present two recent photon results from CDF using the full Run II data set at sqrt(s) = 1.96 TeV
  - Diphoton cross sections: PRL 110, 101801 (2013)
  - Photon+heavy flavor (b/c) cross sections: arXiv:1303.6136

Diphoton cross sections



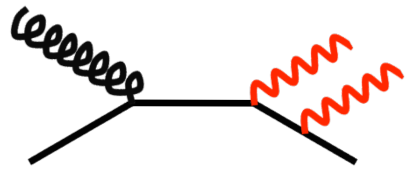
Prompt γγ production in hadron colliders

Hard QCD ("direct" γγ production):



$q\bar{q} \rightarrow \gamma\gamma$

Born: α^2

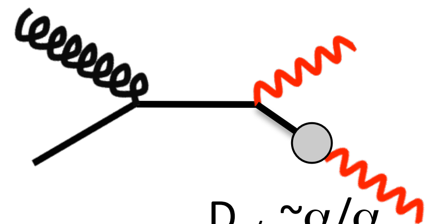


$gq \rightarrow \gamma\gamma q$

Compton+radiation

$\alpha_s\alpha^2$

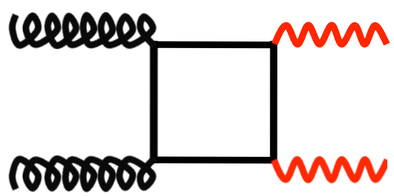
colinear singularity →



$D_{\gamma/q} \sim \alpha/\alpha_s$

Fragmentation: α^2

Suppressed by isolation cut

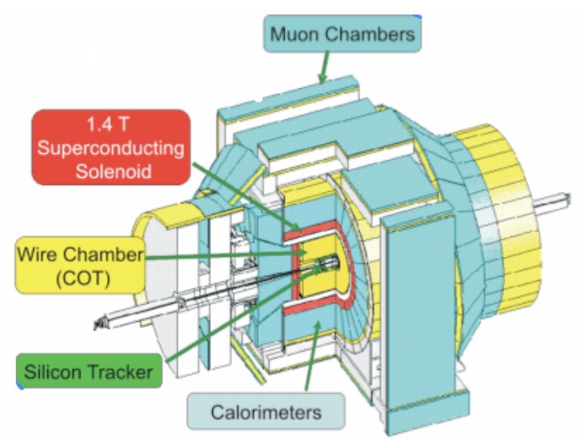


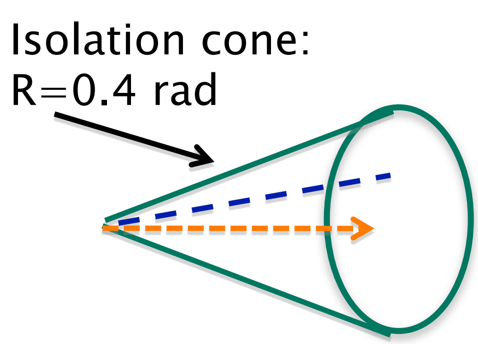
$gg \rightarrow \gamma\gamma$

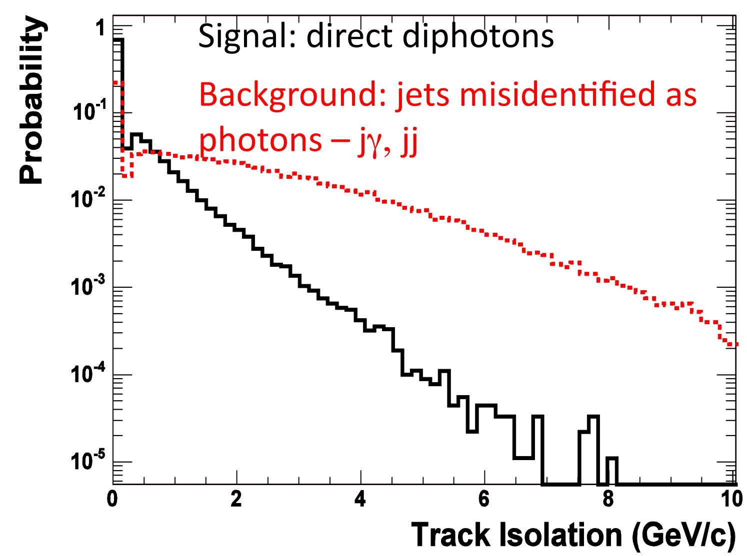
"Box": Dominant at the LHC

Diphoton selection and background subtraction

- Use the full 9.5 fb^{-1} CDF run II dataset.
- Select diphoton events in central calorimeter.
  - $|\eta|<1.1$
  - $E_T \geq 17,15$ GeV ($\gamma\gamma$ events)
  - Isolated, consistent with EM objects
- Use track isolation information to subtract background statistically.
- Pythia evaluation of efficiency/acceptance/unfolding.







Theoretical predictions

- **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 non-perturbative 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)]

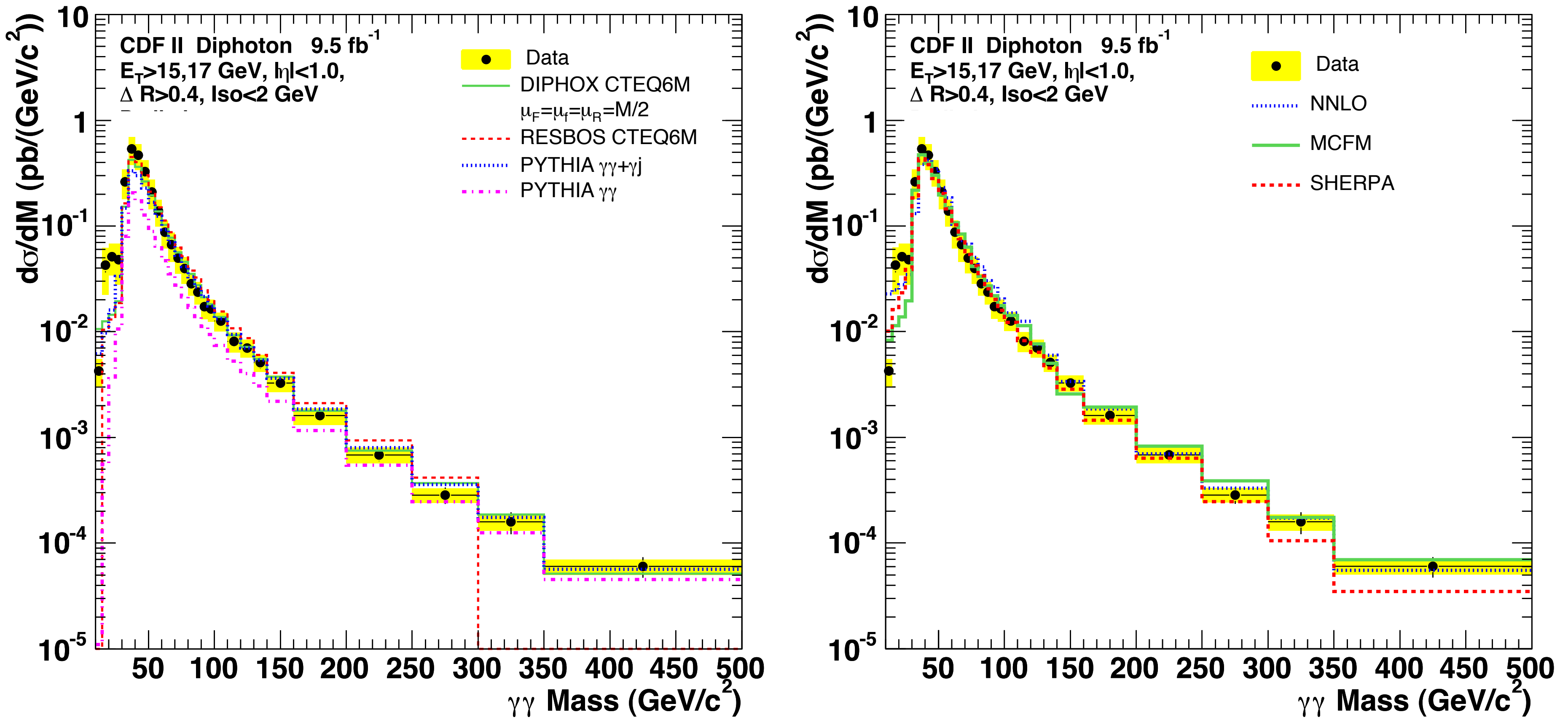
Theoretical predictions

- **PYTHIA** LO parton-shower calculation – including $\gamma\gamma$ and γj with radiation [T. Sjöstrand *et al.*, Comp. Phys. Comm. **135**, 238 (2001)]

	Integrated cross section in fiducial region (pb)
Data (CDF)	$12.3 \pm 0.2_{stat} \pm 3.5_{syst}$
RESBOS	11.3
DIPHOX	10.6
MCFM	11.5
SHERPA	12.4
PYTHIA $\gamma\gamma$+γj	9.2
NNLO	11.8

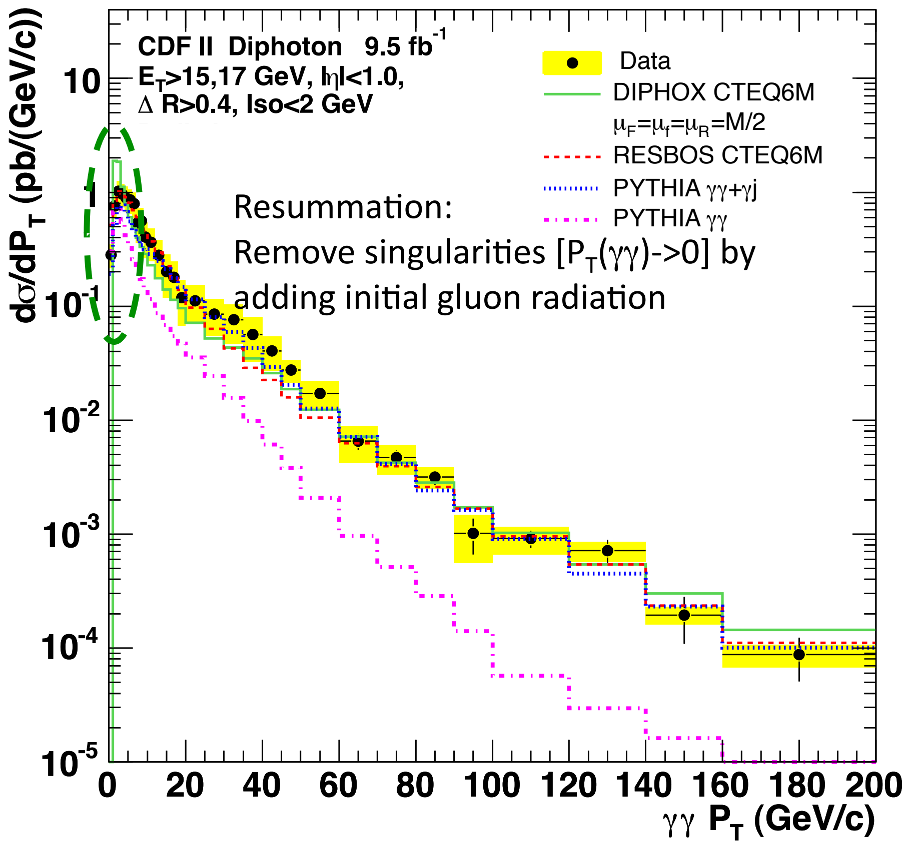
- **SHI** anc
- **MC** at L
- **DIP** at N
- **RES** [T. Balazs *et al.*, Phys. Rev. D **76**, 013008 (2007)]
- **NNLO** calculation with q_T subtraction [L. Cieri *et al.*, http://arxiv.org/abs/1110.2375 (2011)]

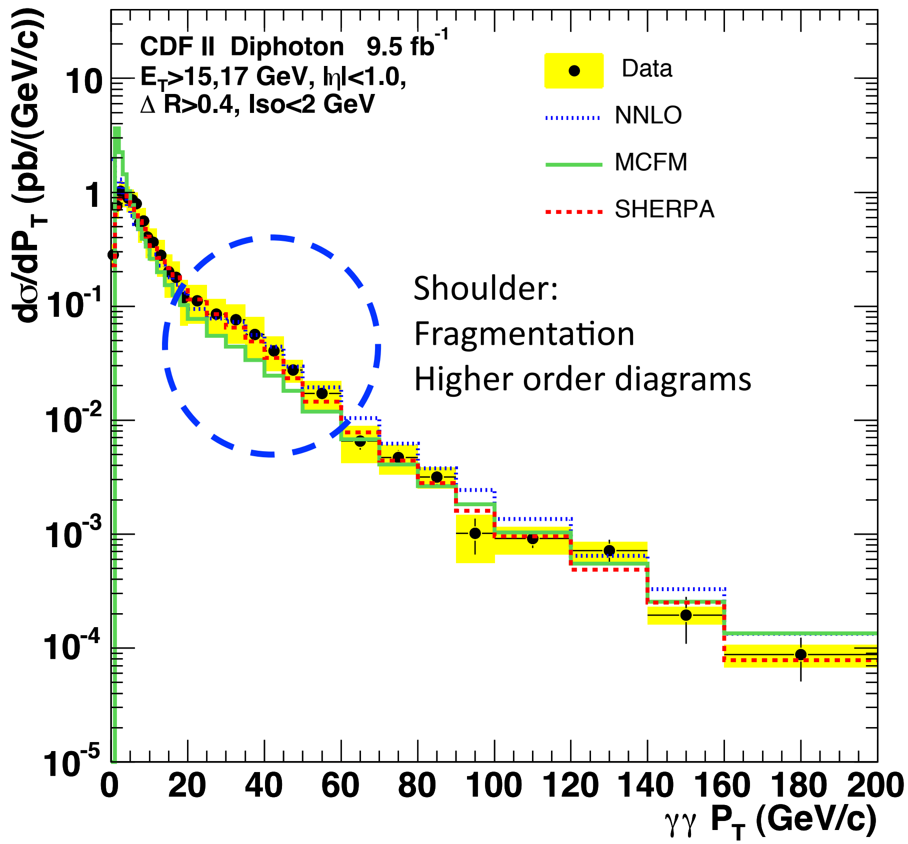
m(γγ)



- Good agreement between data and theory for $M_{\gamma\gamma}$>30 GeV/c^2 except PYTHIA γγ

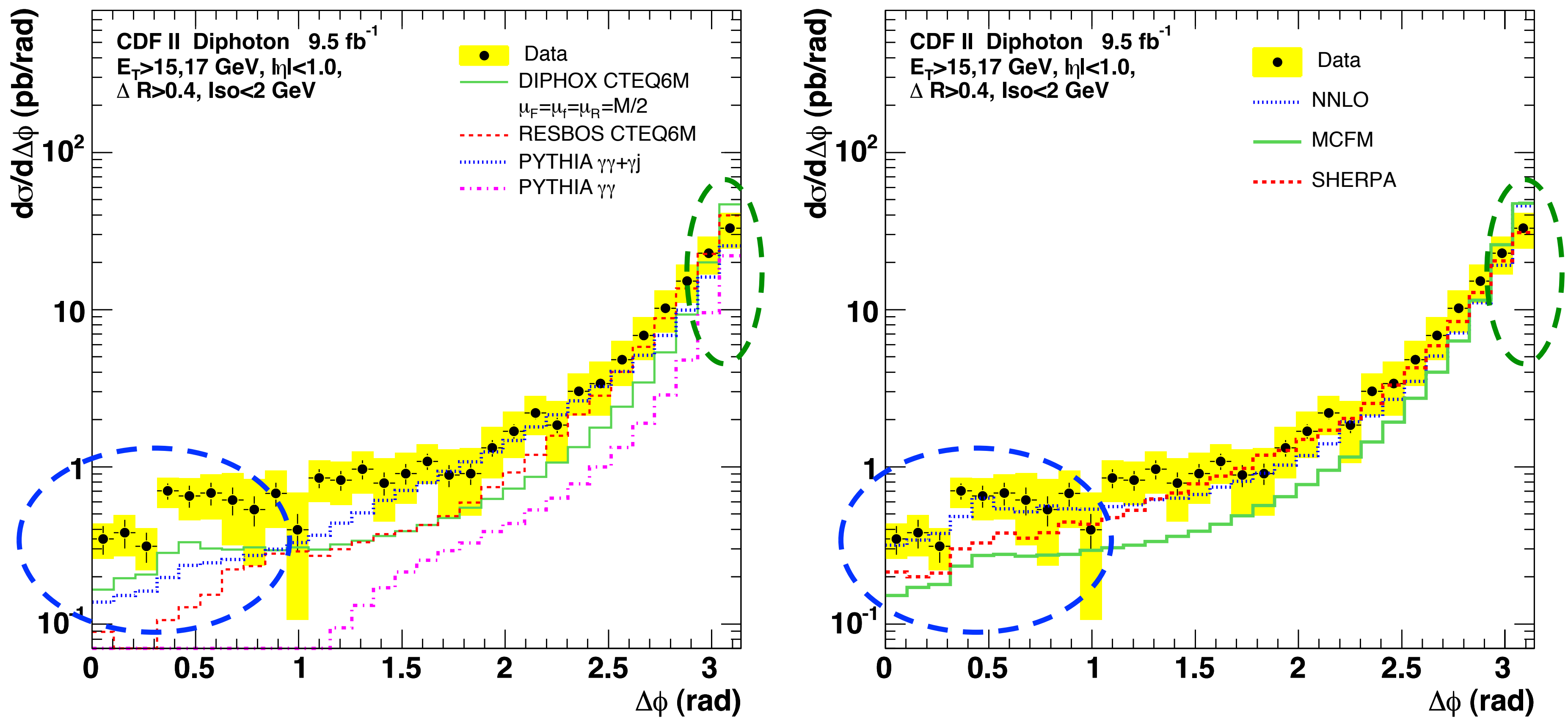
$P_T(\gamma\gamma)$





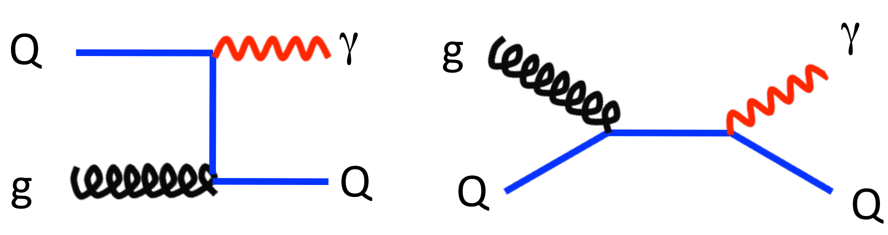
- RESBOS agrees with low $P_T(\gamma\gamma)$ data the best
- SHERPA agrees with low $P_T(\gamma\gamma)$ data well
- NNLO and SHERPA describe the “shoulder” of the data at $P_T(\gamma\gamma)$ = 20 – 50 GeV/c

$\Delta\phi(\gamma\gamma)$



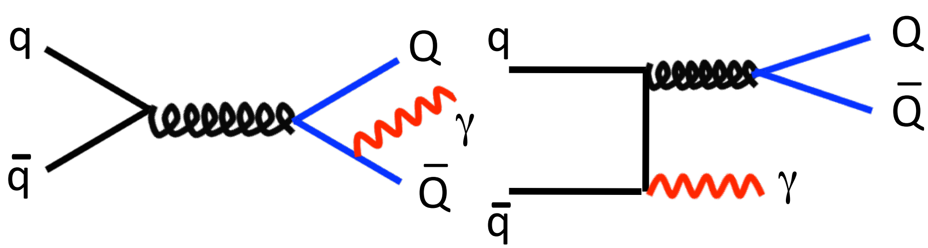
- RESBOS and SHERPA describe $\Delta\phi(\gamma\gamma) = \pi$
- Fixed order calculations do not describe $\Delta\phi(\gamma\gamma) = \pi$ as well
- NNLO describes $\Delta\phi(\gamma\gamma) = 0$

γ+*b*/*c*+X production



LO: Compton scattering ~ $\alpha\alpha_S$

$E_T^{\gamma} < 90$ GeV



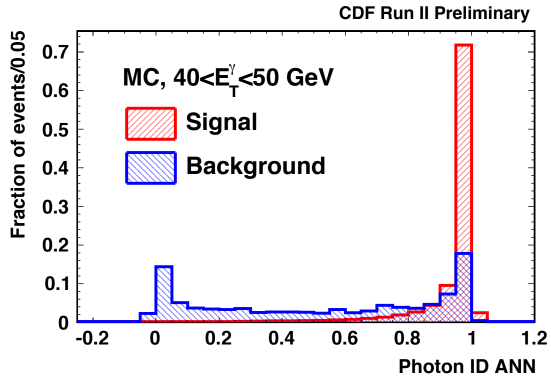
NLO: Annihilation ~ $\alpha\alpha_S^2$

$E_T^{\gamma} > 90$ GeV

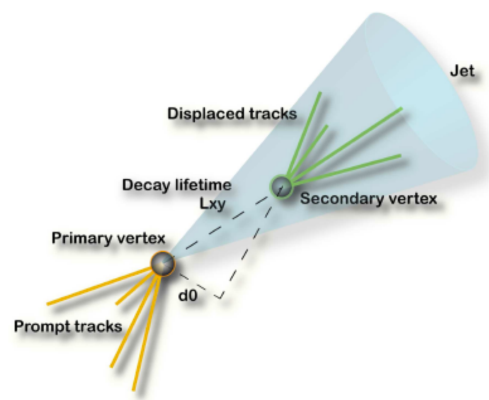
- Test heavy-flavor component in the proton
  - Gluon evolution
  - Intrinsic heavy flavor
- Test final-state gluon splitting rate to heavy flavors

Event selection

- Use the full 9.1 fb^{-1} CDF run II dataset.
- Select isolated photons in central calorimeter.
  - $|\eta|<1$
  - $30<E_T<300$ GeV
  - ANN photon ID
    - isolation,
    - shower shape
    - HAD/EM

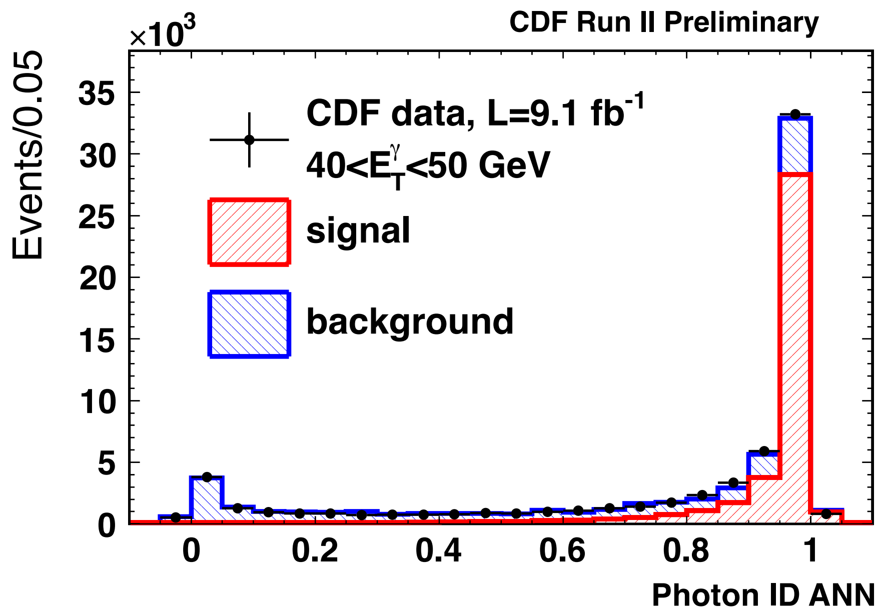


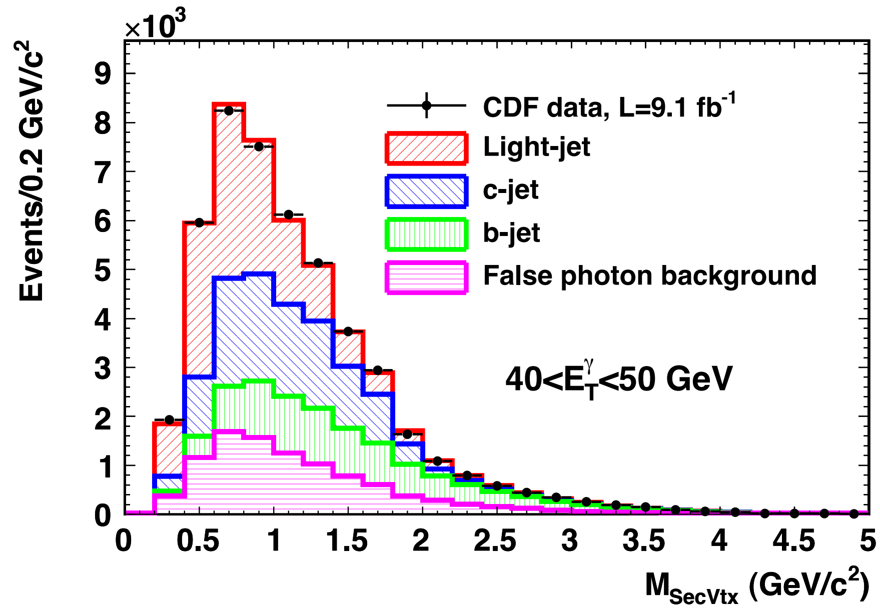
- Select heavy-flavor jets.
  - JetClu cone 0.4
  - $|\eta|<1.5$
  - $E_T>20$ GeV
  - SecVtx btag
    - Secondary vertex



- Sherpa evaluation of efficiency/acceptance/unfolding.

Background subtraction





- Fit photon ID ANN to signal and background templates to get real photon fraction
- Fit mass associated with secondary vertex to templates to get b/c-jet fraction

4 theoretical predictions

- NLO – direct-photon subprocesses and fragmentation subprocesses at $O(\alpha\alpha_s^2)$, CTEQ6.6M PDFs [T.P. Stavreva and J.F. Owens, PRD **79**, 054017 (2009)].

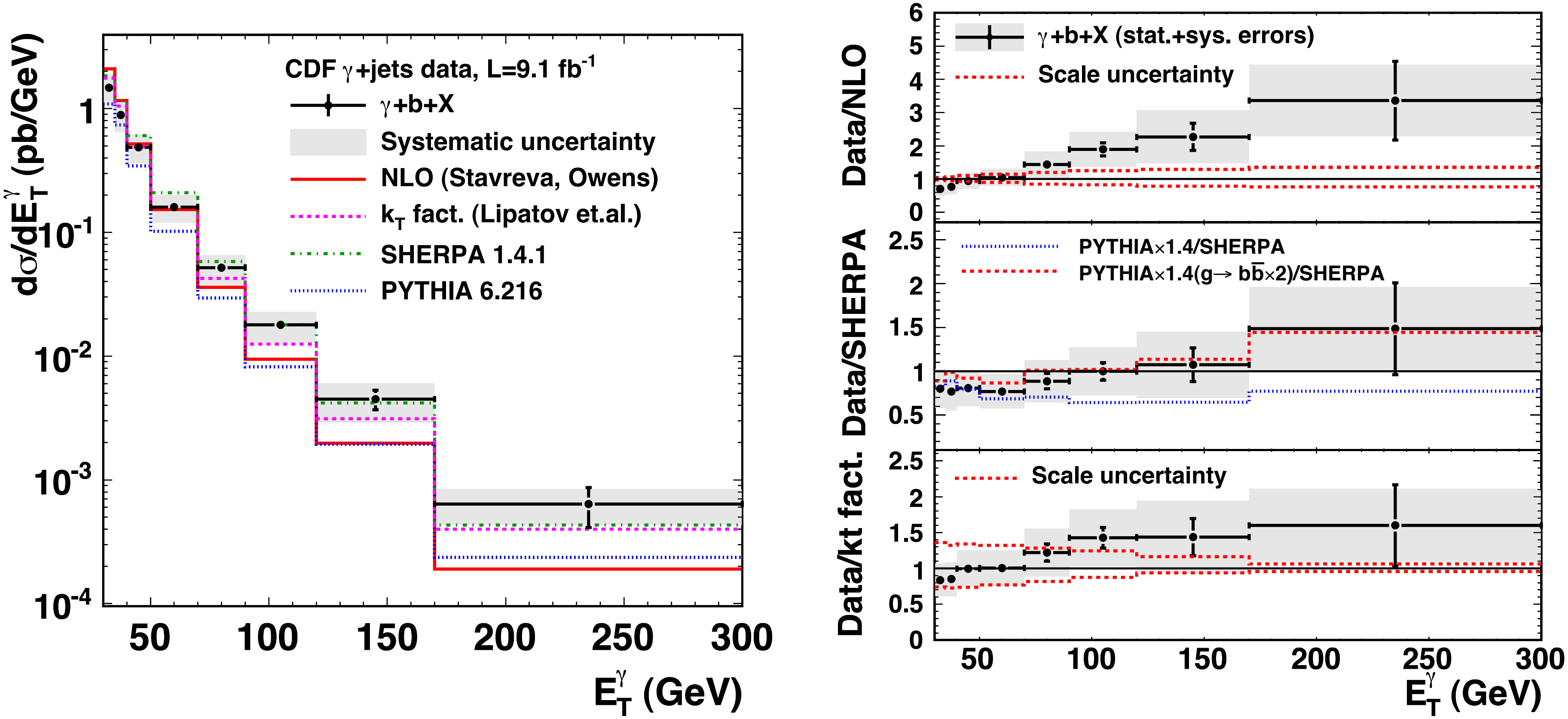
- k_T-factorization – off-shell amplitudes integrated over k_T-dependent parton distributions, MSTW2008 PDFs [A.V. Lipatov *et al.*, JHEP **05**, 104 (2012)].

- Sherpa 1.4.1 – tree-level matrix element (ME) diagrams with one photon and up to three jets, merged with parton shower, CT10 PDFs [T. Gleisberg *et al*., JHEP **02**, 007 (2009)].

- Pythia 6.216 – ME subprocesses: $gQ \rightarrow \gamma Q$, $qq \rightarrow \gamma g$ followed by gluon splitting: $g \rightarrow QQ$, CTEQ5L PDFs [T. Sjöstrand et al., JHEP **05**, 026 (2006)].

γ+b+X cross sections

NB: Vertical axis scales are not the same



- NLO fails to describe data at large photon Et – perhaps because gluon splitting is treated at LO.
- k_T-factorization and Sherpa agree with data reasonably well.
- Pythia with doubled gluon splitting rate to heavy flavor describes the shape.

γ+c+X cross sections

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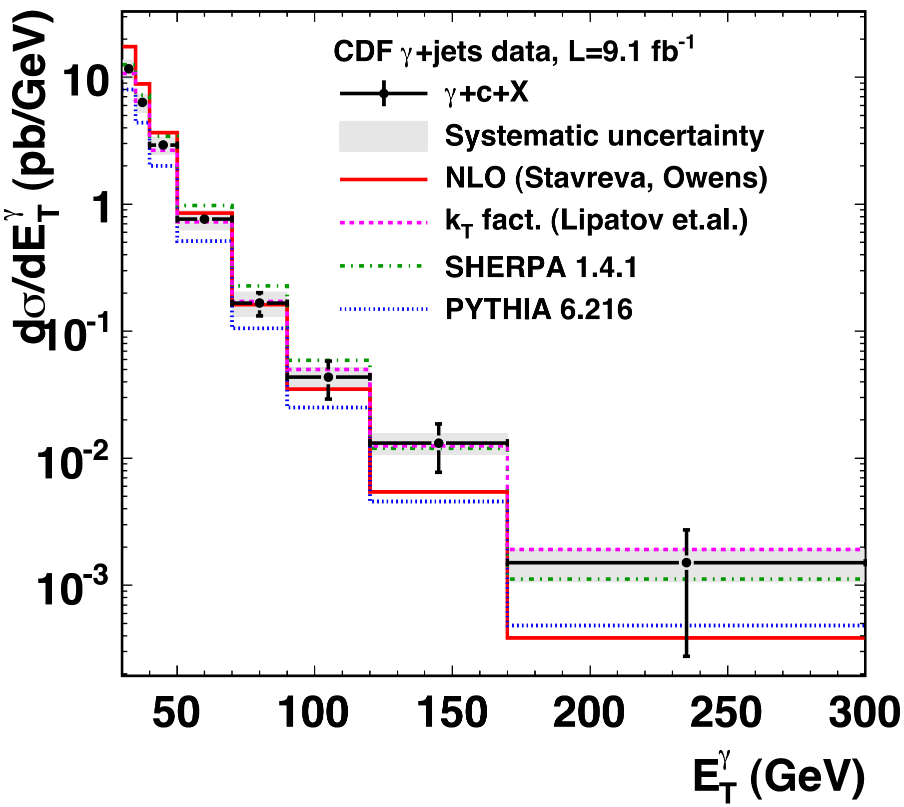

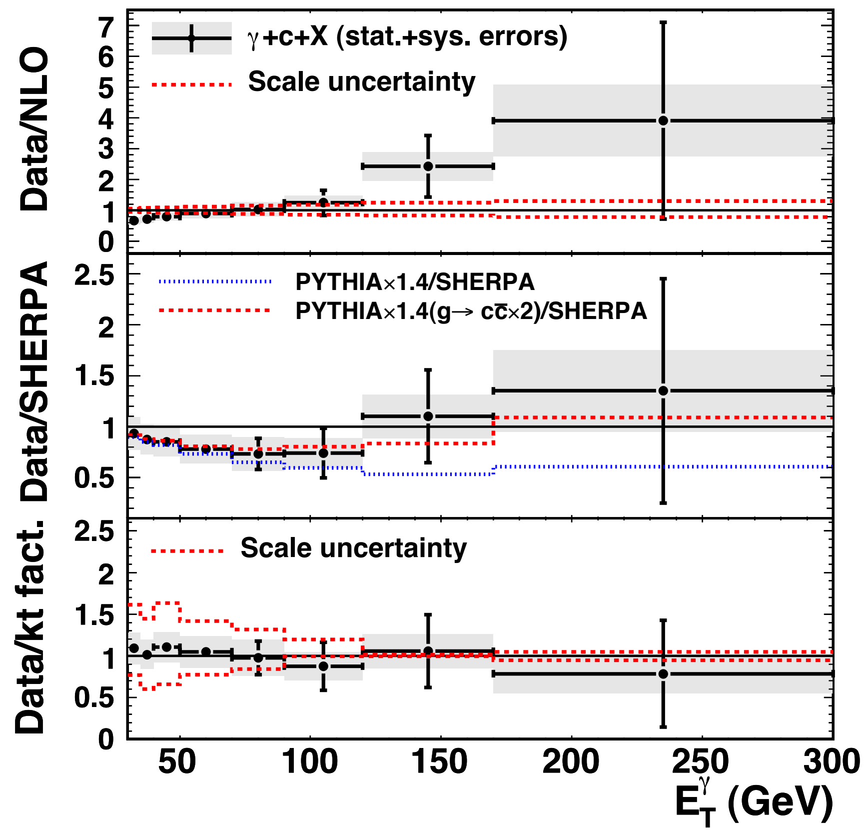

- NLO fails to describe data at large photon Et – perhaps because gluon splitting is treated at LO.
- k_T-factorization and Sherpa agree with data reasonably well.
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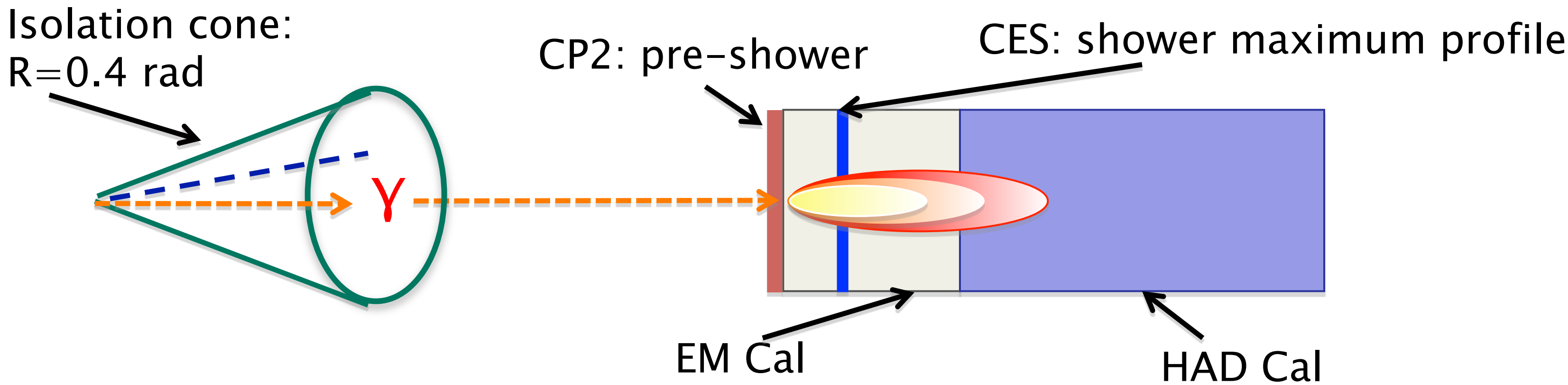
Conclusions

- High precision diphoton and photon+heavy flavor cross sections are measured using the full CDF Run II dataset.
- The data are compared with a variety of theoretical calculations.
- It is important to understand the **resummation**, **$q \rightarrow \gamma$ fragmentation** and **parton-shower** in the modeling of diphoton cross sections.
- It is important to understand the **intrinsic heavy quarks** and **gluon splitting rates** to heavy quarks in the modeling of photon+heavy flavor cross sections.

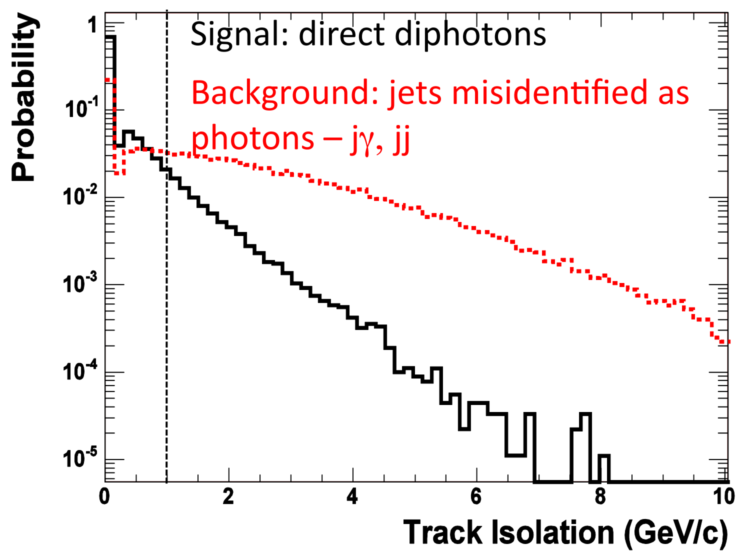
Photon identification and event selection



- Used dedicated diphoton triggers with optimized efficiency
- Photons were selected offline from EM clusters, reconstructed in a cone of radius R=0.4 in the $\eta-\phi$ plane, and requiring:
  - Fiducial to the central calorimeter: $|\eta|<1.1$
  - $E_T \geq 17,15$ GeV ($\gamma\gamma$ events)
  - Isolated in the calorimeter: $I_{cal} = E_{tot}(R=0.4) - E_{EM}(R=0.4) \leq 2$ GeV
  - Low HAD fraction: $E_{HAD}/E_{EM} \leq 0.055 + 0.00045 \times E_{tot}/\text{GeV}$
  - At most one track in cluster with $p_T^{trk} \leq 1$ GeV/c $+ 0.005 \times E_T^{\gamma}/c$
  - Shower profile consistent with predefined patterns: $\chi^2_{CES} \leq 20$
  - Only one high energy CES cluster: E_T of 2nd CES cluster ≤ 2.4 GeV $+ 0.01 \times E_T$

Imply that $\Delta R(\gamma,\gamma)$ or $\Delta R(\gamma,j) \geq 0.4$ (applies to the E_T and isolation requirements)

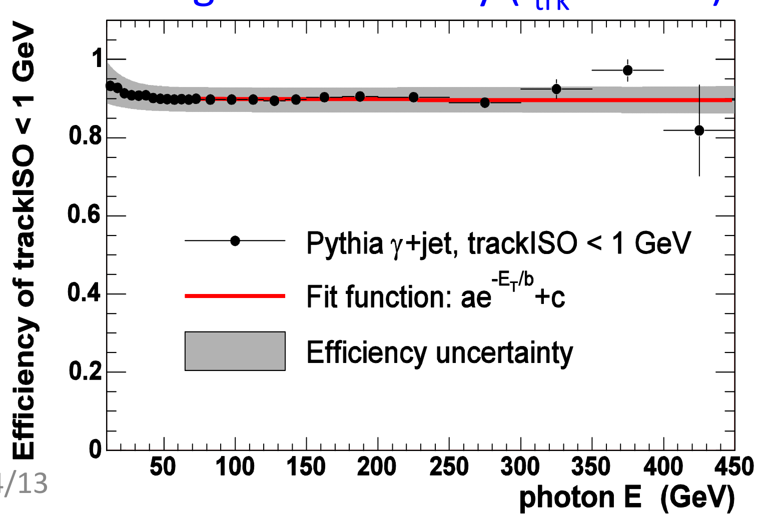
Background subtraction using track isolation



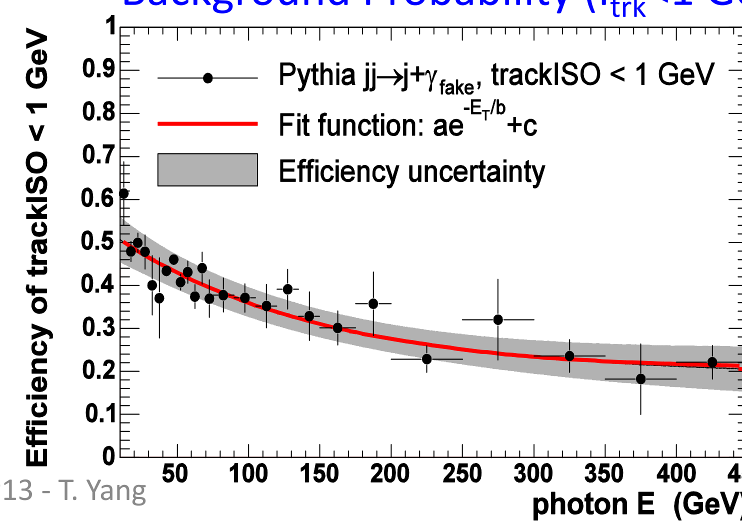
$$I_{trk} = \sum_{tracks\ \ in\ \ R<0.4}^{|z_{vtx}-z_{trk}|<5cm} p_T^{trk}$$

- Sensitive only to underlying event and jet fragmentation (for fake γ)
- Immune to multiple interactions (due to z-cut) and calorimeter leakage
- Good resolution in low-E_T region, where background is most important
- Uses charged particles only

Signal Probability (I_{trk}<1 GeV)

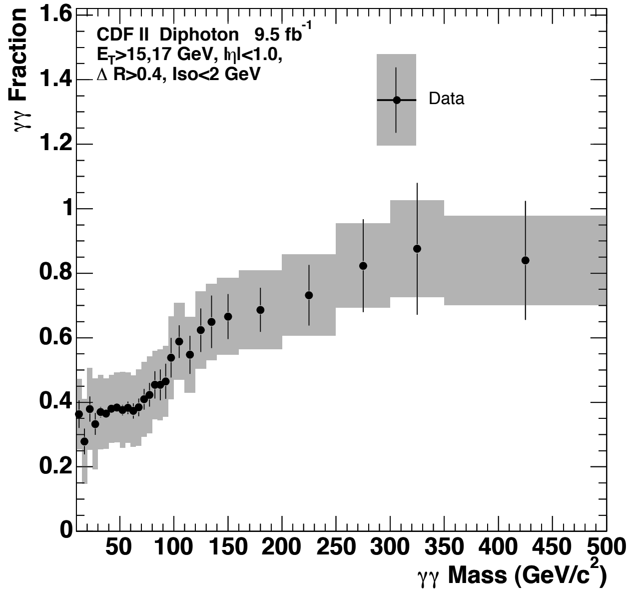


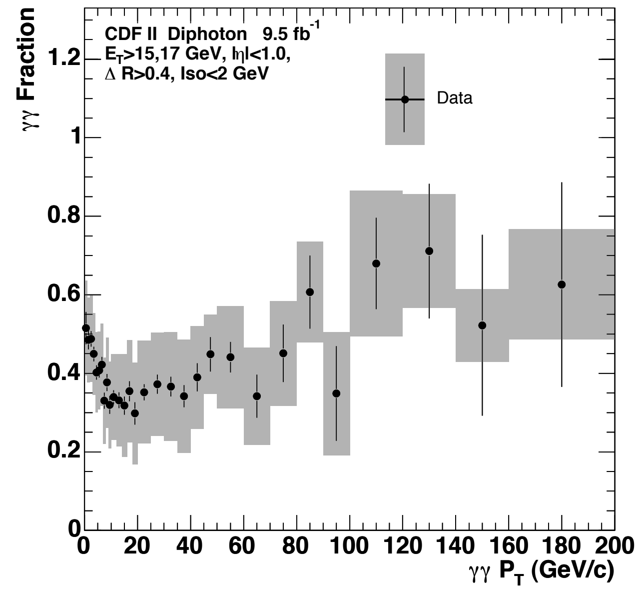
Background Probability (I_{trk}<1 GeV)

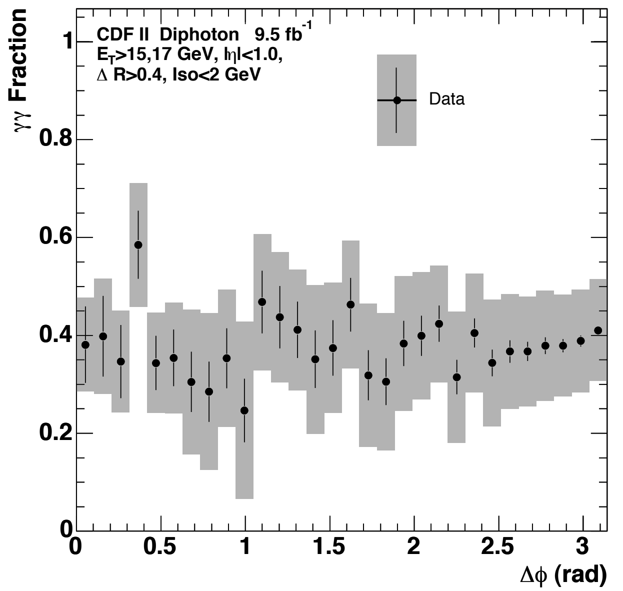


Signal fractions

$$Signal\ fraction = \frac{N_{\gamma\gamma}}{N_{data}}$$







- Average ~40%
- Better at high mass:
  - 60-80% for m(γγ) ~80-150 GeV/c^2
  - ~80% for m(γγ)>150 GeV/c^2
- Better at high P_T(γγ):
  - ~70% for P_T(γγ) >100 GeV/c
- 15-30% sys. errors

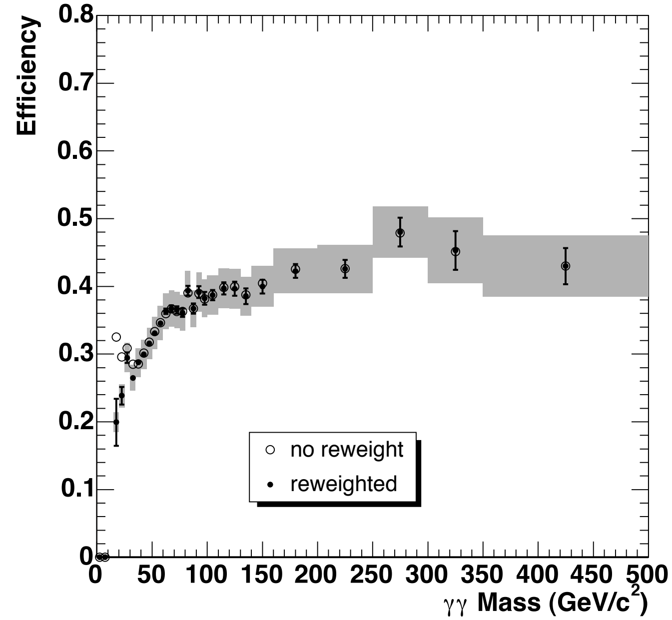
Efficiency×Acceptance

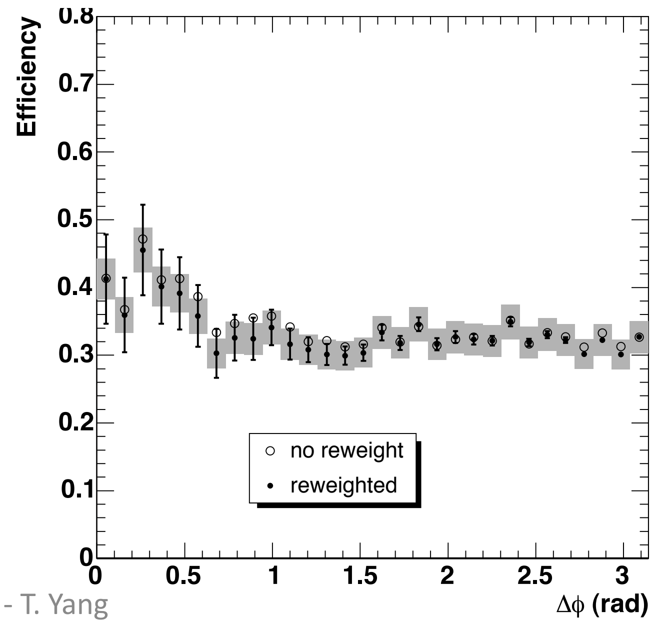
- Estimated using detector- and trigger-simulated and reconstructed PYTHIA events

- Procedure iterated to match PYTHIA kinematics to the data

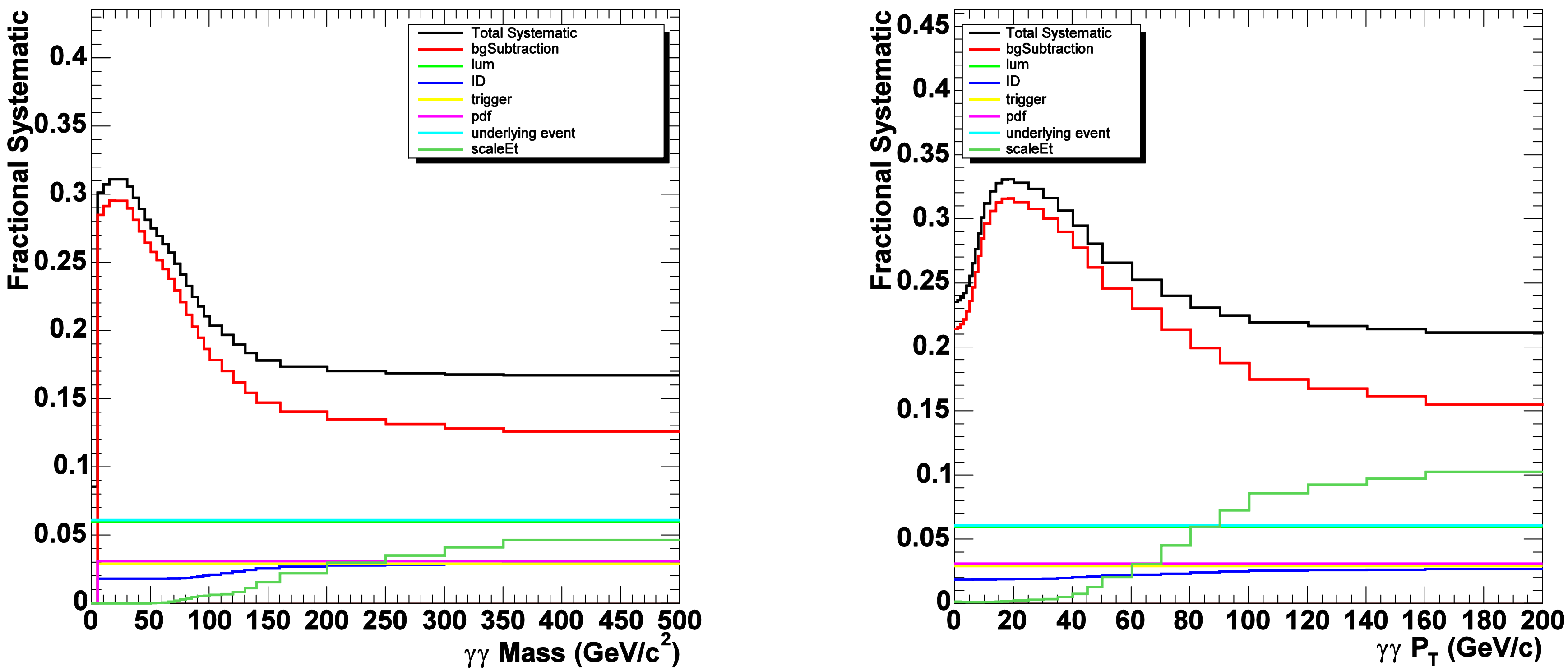
Uncertainties in the efficiency estimation:

- 3% from material uncertainty
- 1.5% from the EM energy scale
- 3% from trigger efficiency uncertainty
- 6% (3% per photon) from underlying event (UE) correction
- Total systematic uncertainty: ~7-15%



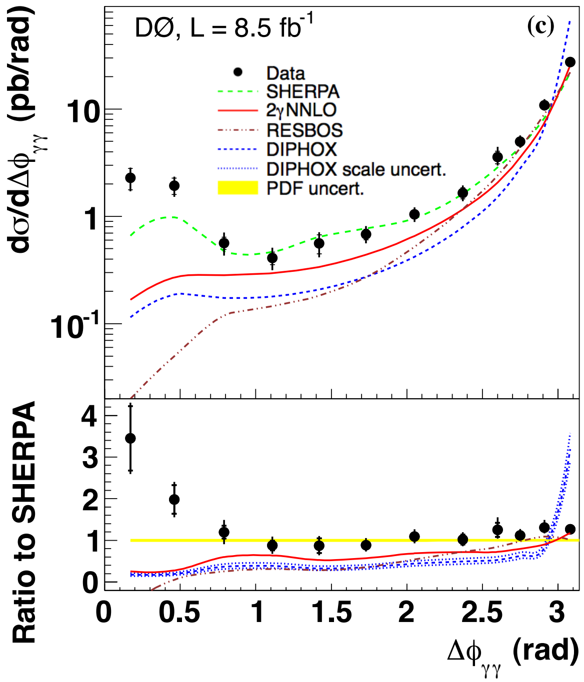


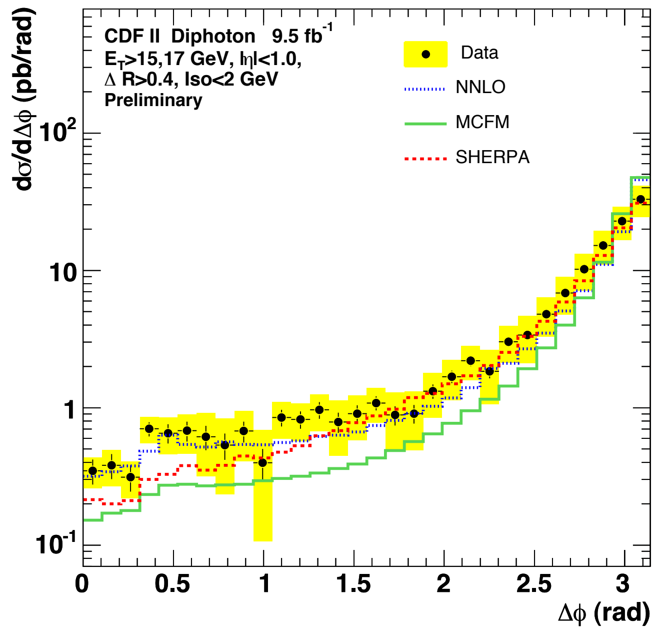
Experimental systematic uncertainties

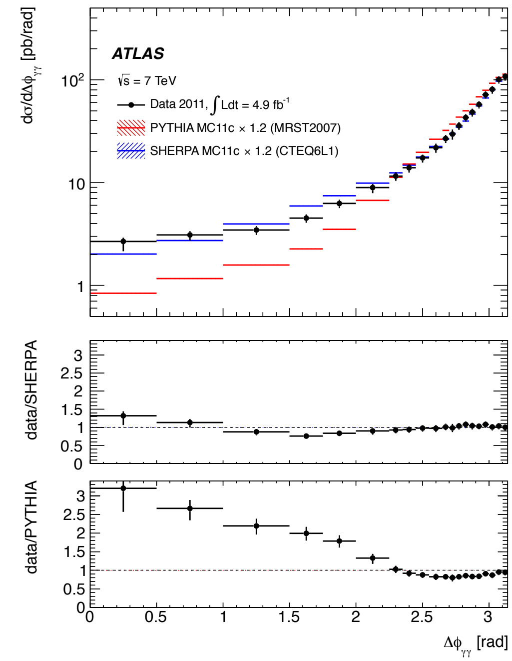


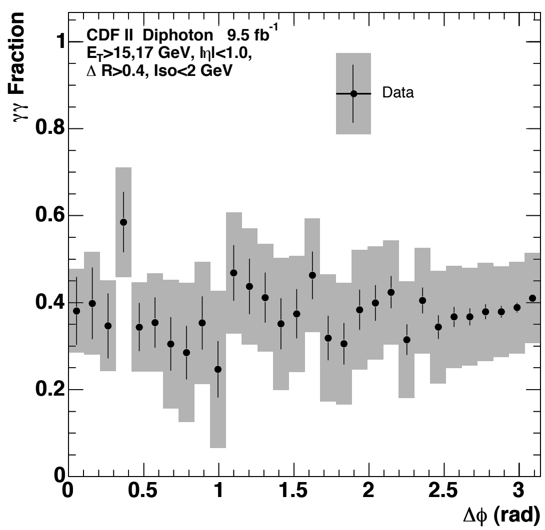
- Total systematic uncertainty ~15-30%, smoothly varying with the kinematic variables considered
- Main source is background subtraction, followed by overall normalization (efficiencies: 7%; integrated luminosity: 6%; UE correction: 6%)

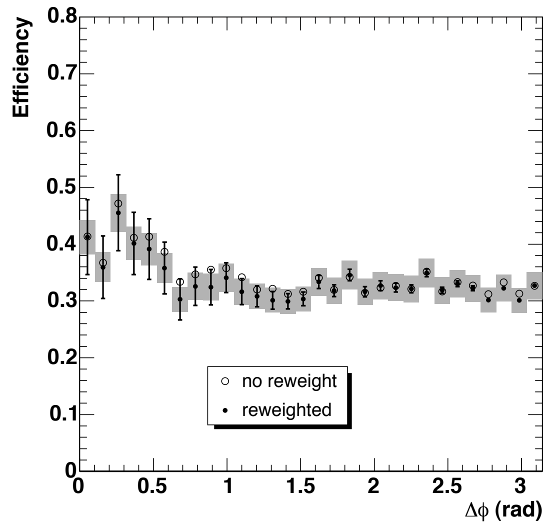
Comparison with D0







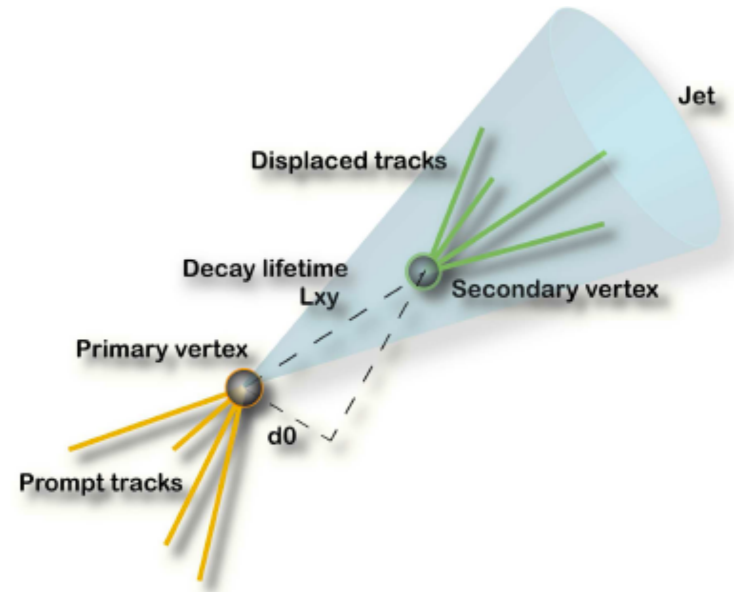


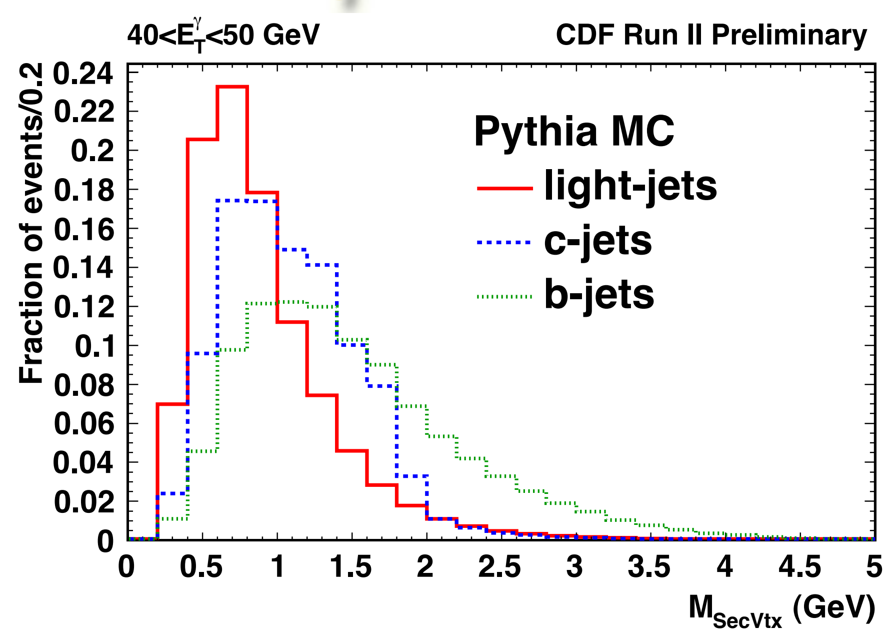


$$\frac{d\sigma}{dX} = \frac{N_{\gamma\gamma}}{\varepsilon \cdot A \cdot L \cdot \Delta}$$

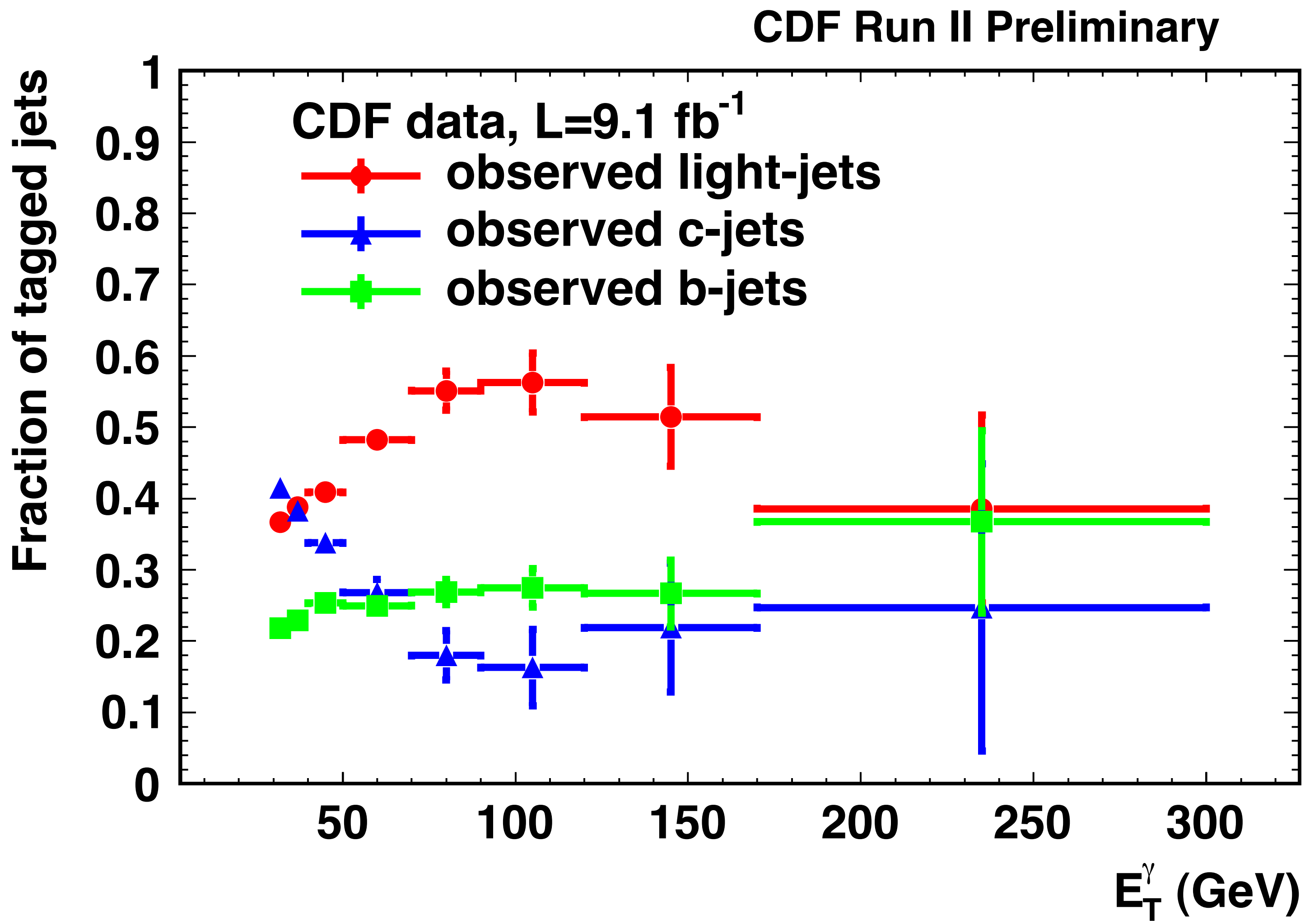
Standard b-jet identification

- B-hadrons are long-lived – search for displaced vertices
- Fit displaced tracks and cut on L_{xy} significance (σ ~ 200 μm)
- Charm hadrons have similar tag behavior but lower efficiency
- Use "tag mass" to deduce the flavor composition of a sample of tagged jets
  - Mass of the tracks forming the secondary vertex
  - B-hadrons are heavy: will have higher m_{tag} spectrum than charm or light jet fakes



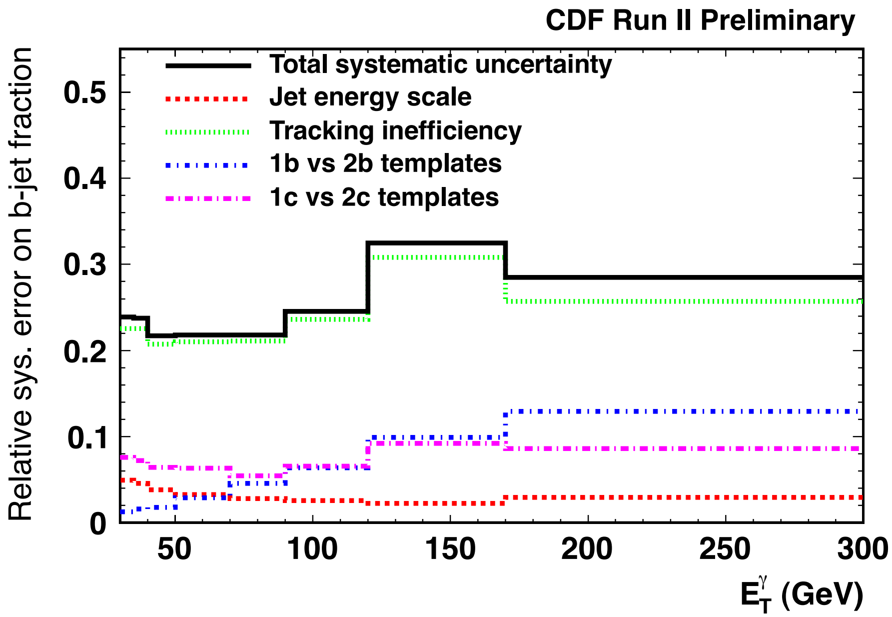


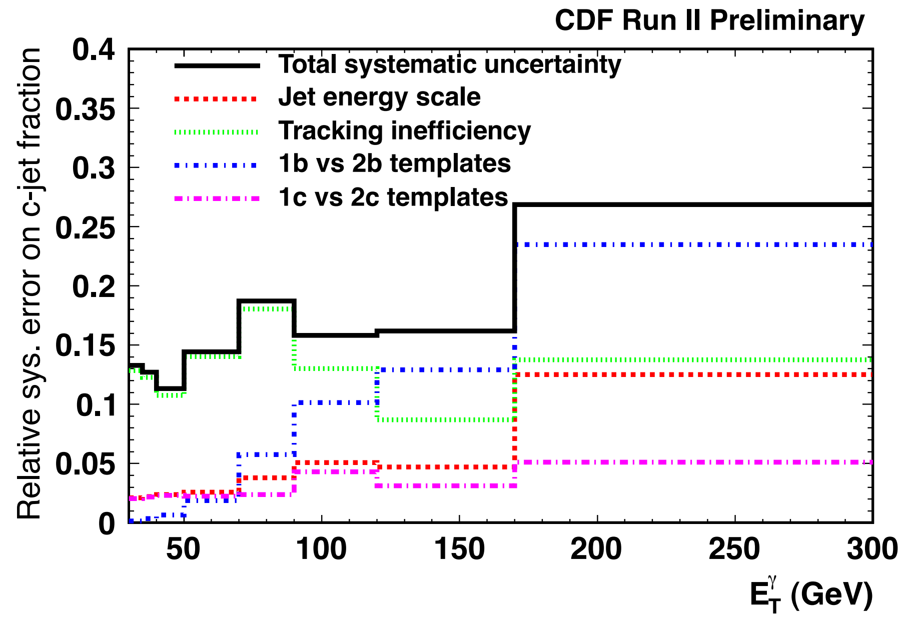
Light/*c*/*b*-jet fractions (continued)



Results from fitter.

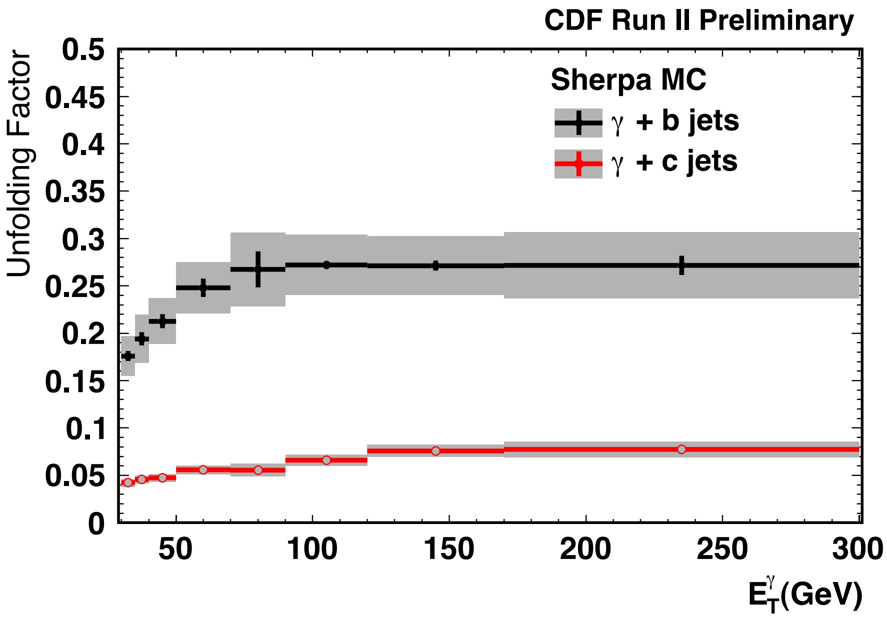
Systematics on b/c-jet fractions

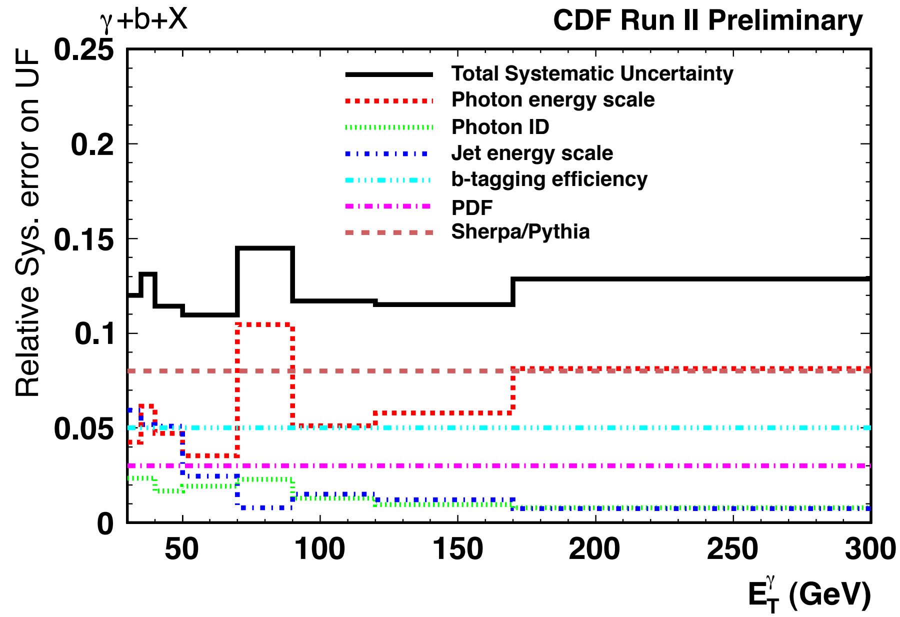




- Jet energy scale: affects acceptance
- Uncertainty in tracking efficiency: scale secondary vertex mass templates by ±3%
  - Dominant systematic effect
- Difference between single-quark and di-quark jets
- Total systematic error is ~20%

Efficiency×Acceptance





- Use Sherpa MC to unfold photon ID efficiency, b-tagging efficiency, detector acceptance and smearing effects.
- Systematic effects evaluated
  - photon energy scale and ID
  - jet energy scale
  - b-tagging efficiency
  - Generator
  - PDF