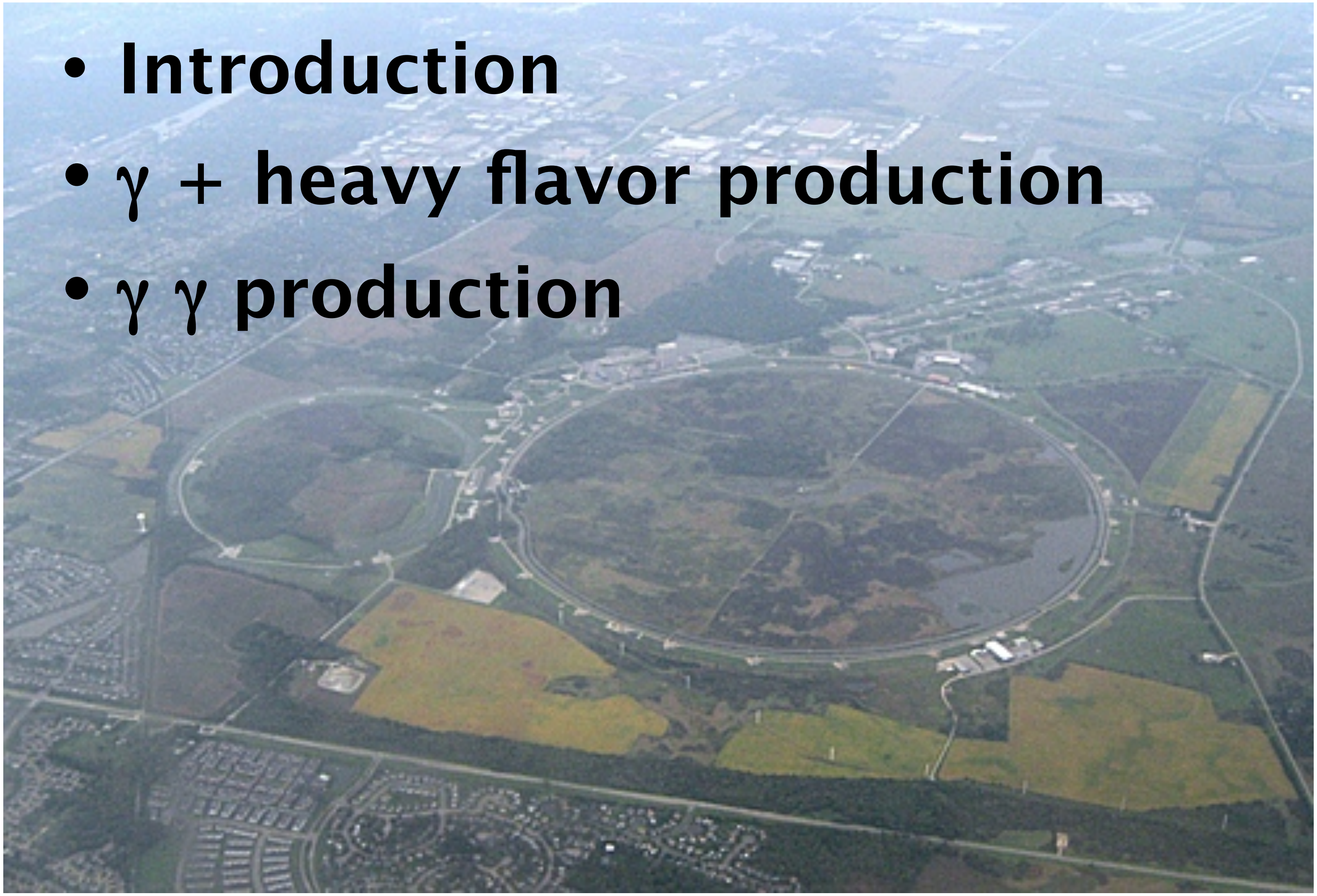
New Measurements with Photons

Rencontres de Moriond
QCD & High Energy Interactions
March 9-16, 2013

Leo Bellantoni
for CDF & D0 collaborations

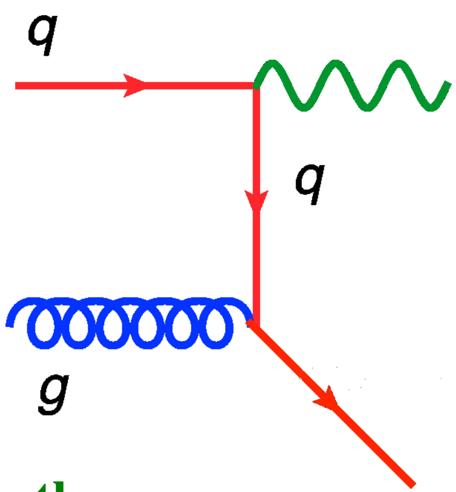
In This Talk:



- **Introduction**
- **γ + heavy flavor production**
- **γ γ production**

Introduction

Isolated, energetic photons only!

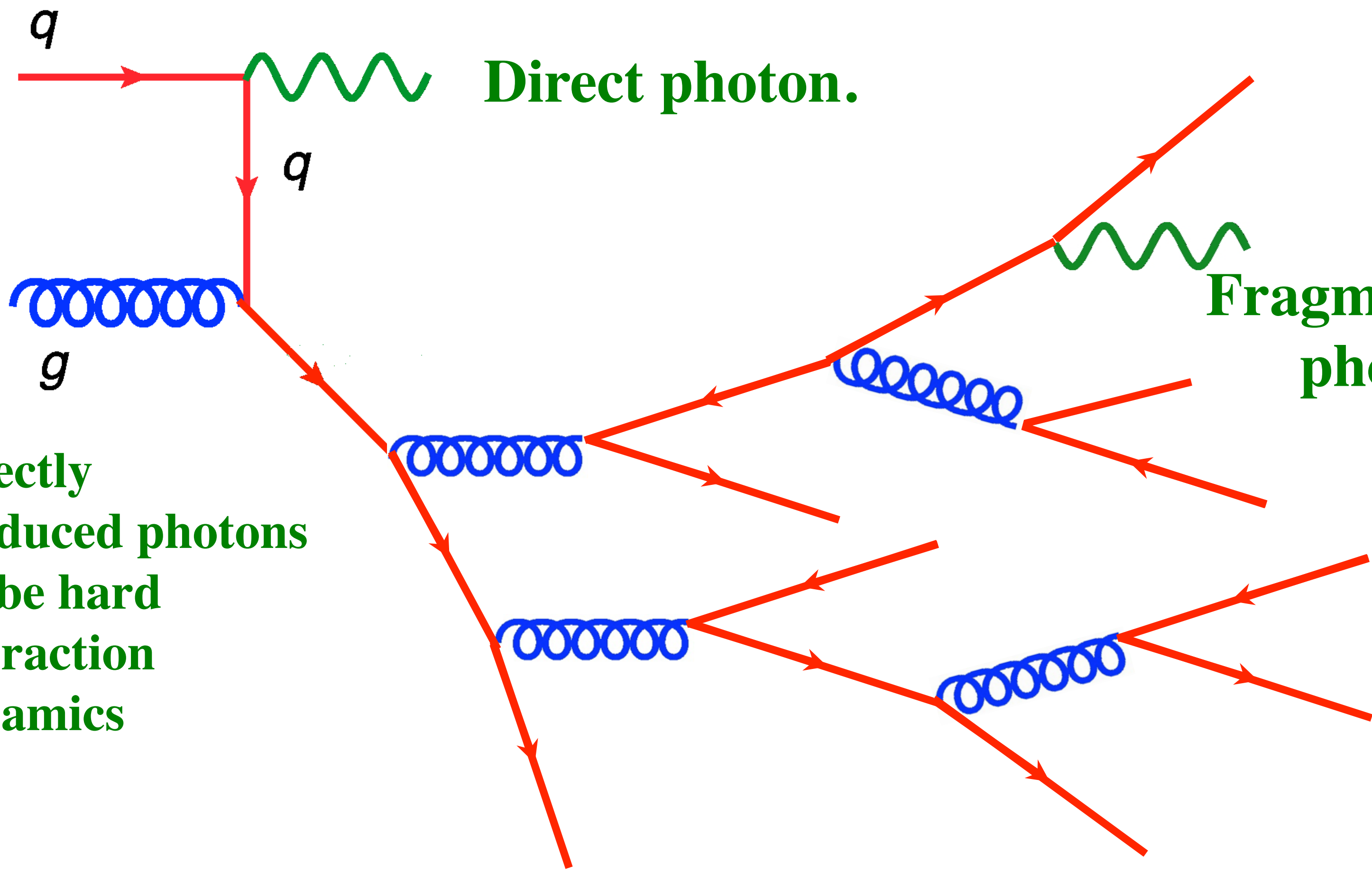


Direct photon.

Directly produced photons probe hard interaction dynamics

Introduction

Isolated, energetic photons only!



Directly produced photons probe hard interaction dynamics

Photons produced in fragmentation process fail the isolation & energy cuts

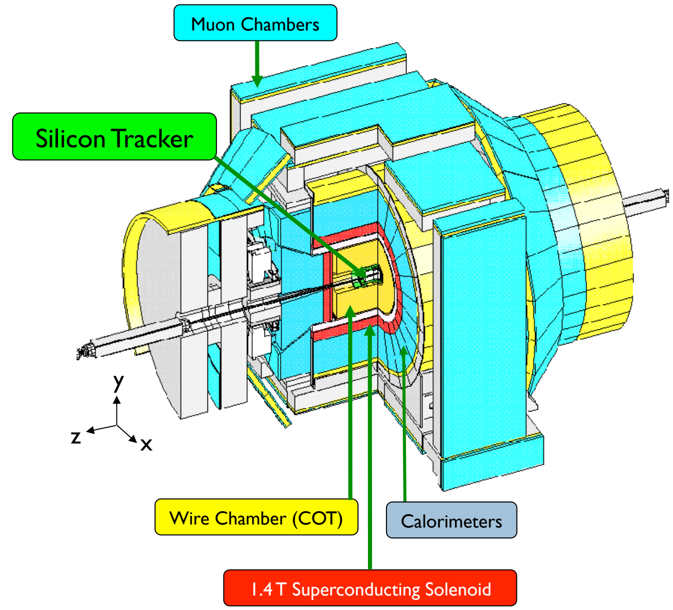
The Experimental Apparatus

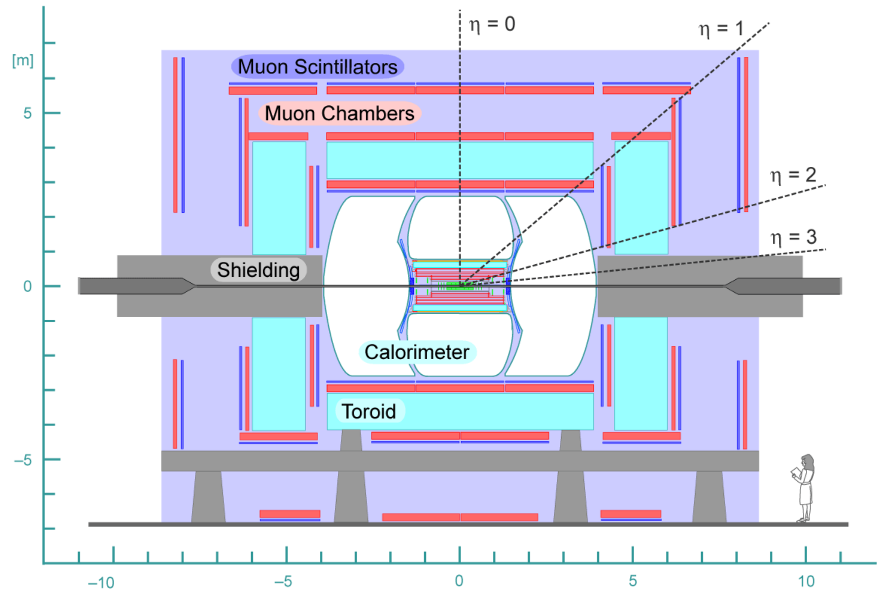
Both CDF & D0 detectors measure e, μ, γ, jets, τ well and tag b, c with vertex detectors

After so many years, these are well-understood detectors

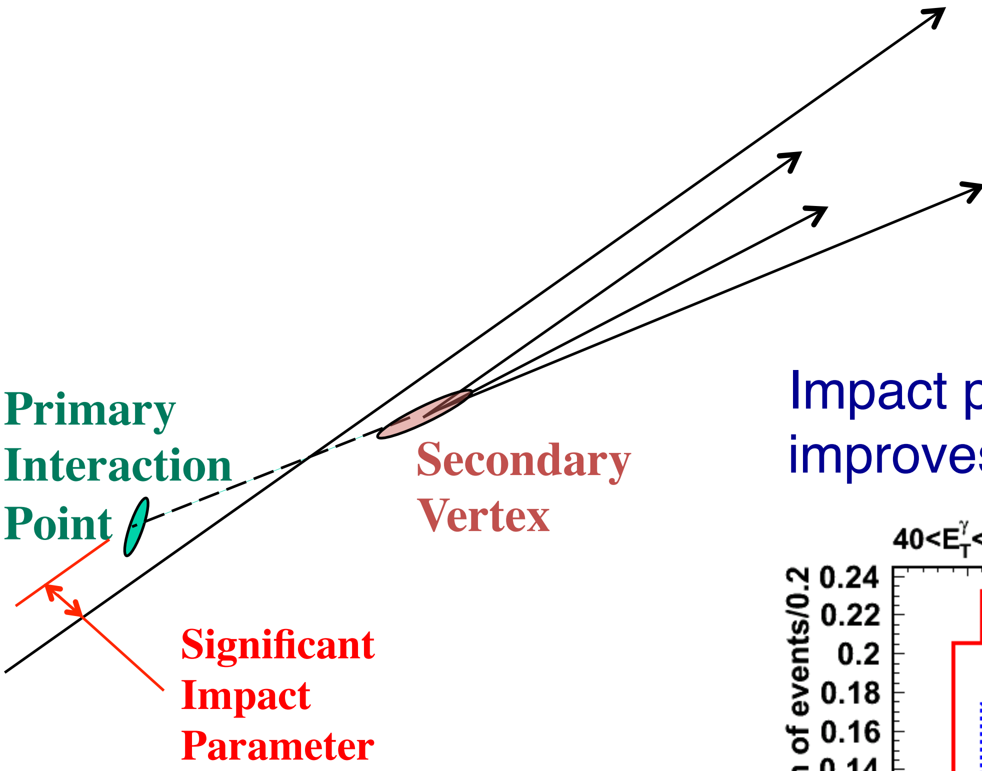
Tevatron provided
$p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

In Run II (March 2001 – Sept. 2011)
- Delivered : 11.6 fb-1
- Recorded : 10.4 fb-1 per experiment



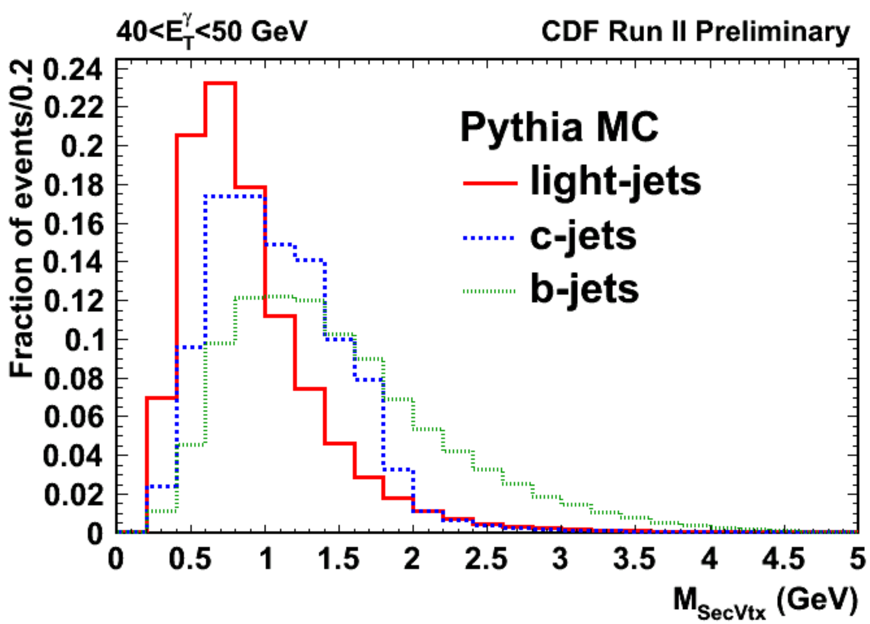


Heavy Flavor Identification



$m_c << m_b$ means m(secondary vertex) can distinguish charm from beauty –

Impact parameter based tagging improves *b*/*c* purity of jet sample



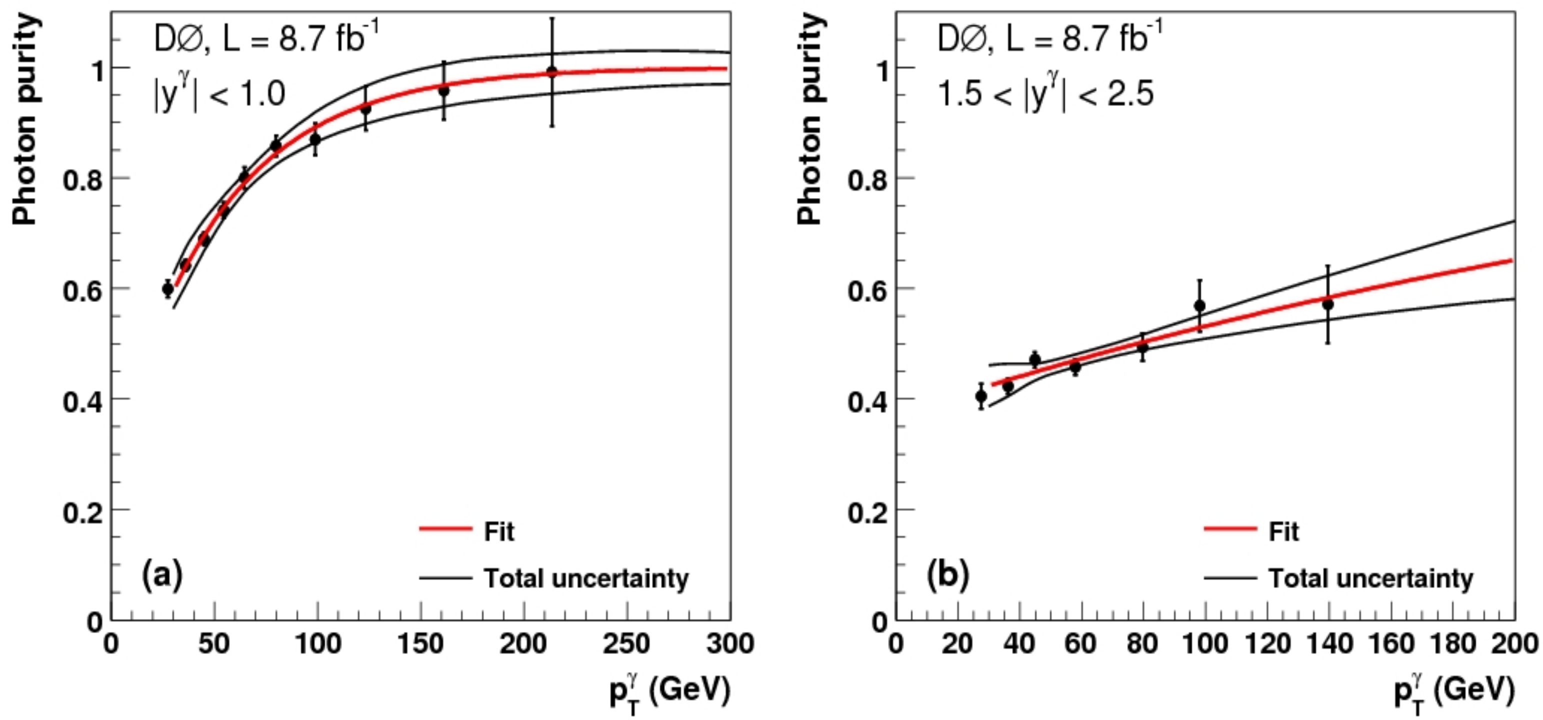
CDF:	"SecVtx" algorithm Phys. Rev. D 72, 052003 (2005)
D0:	"SVT", "JLIP" algorithms NIM A 620 490 (2010)

Photon Fiducials

	CDF	DØ
ΔR Isolation Cones	$E_{TOT}(<0.4) - E_{EM}(<0.4) \leq 2$ GeV Tracking isolation analysis dependent	$E_{TOT}(<0.4) - E_{EM}(<0.2) \leq 2.5$ GeV $P_T(<0.4) - P_T(<0.2) \leq 1.5$ GeV
Minimum momentum ⊥ to beam (calorimeter)	$E_T(\gamma) > 30$ GeV γ + HF $E_T(\gamma) > 17 / 15$ GeV γγ	$E_T(\gamma) > 30$ GeV γ + HF $E_T(\gamma) > 18 / 17$ GeV γγ
$\lvert\eta(\gamma)\rvert$	$\lvert\eta\rvert < 1.1$ γ + HF $\lvert\eta\rvert < 1.0$ γγ	$\lvert\eta\rvert < 1.0$, $1.5 < \lvert\eta\rvert < 2.5$ $\gamma + b$ $\lvert\eta\rvert < 1.0$ $\gamma + c$ $\lvert\eta\rvert < 0.9$ γγ

Photons for γ + HF

Both CDF & D0 use artificial neural networks to ID photons and estimate the purity by fitting data distributions of network output to simulation distributions for true photons and jets

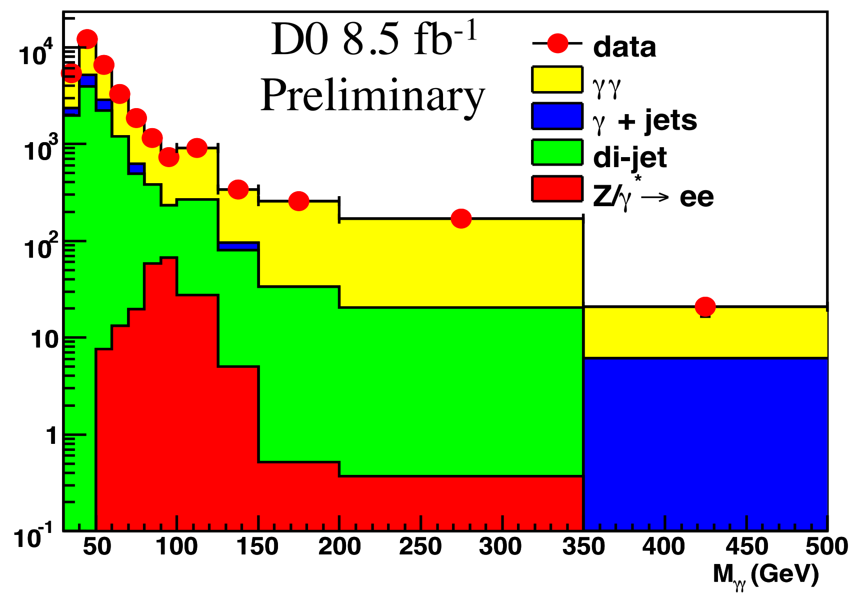


Photons for γ γ

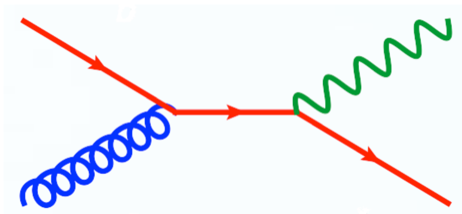
- **CDF uses a matrix formulation for background subtraction (no network for this analysis)**

$$\begin{bmatrix} N_{ff} \\ N_{fp} \\ N_{pf} \\ N_{pp} \end{bmatrix} = \begin{bmatrix} (1-\varepsilon_b)(1-\varepsilon_b) & (1-\varepsilon_b)(1-\varepsilon_s) & (1-\varepsilon_s)(1-\varepsilon_b) & (1-\varepsilon_s)(1-\varepsilon_s) \\ (1-\varepsilon_b)\varepsilon_b & (1-\varepsilon_b)\varepsilon_s & (1-\varepsilon_s)\varepsilon_b & (1-\varepsilon_s)\varepsilon_s \\ \varepsilon_b(1-\varepsilon_b) & \varepsilon_b(1-\varepsilon_s) & \varepsilon_s(1-\varepsilon_b) & \varepsilon_s(1-\varepsilon_s) \\ \varepsilon_b\varepsilon_b & \varepsilon_b\varepsilon_s & \varepsilon_s\varepsilon_b & \varepsilon_s\varepsilon_s \end{bmatrix} \begin{bmatrix} N_{bb} \\ N_{bs} \\ N_{sb} \\ N_{ss} \end{bmatrix}$$

- **D0 does a 2D fit to neural network outputs (cross-checks w/ matrix)**

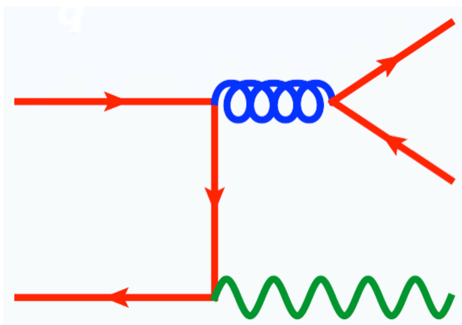


γ + HF production in $p\bar{p}$

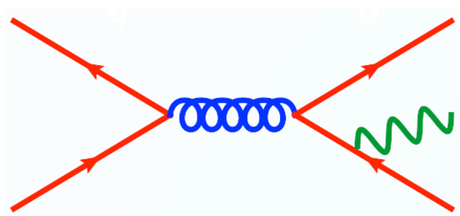


"Compton" scattering – probes HF in initial hadron

$\propto (\alpha\alpha_S)$



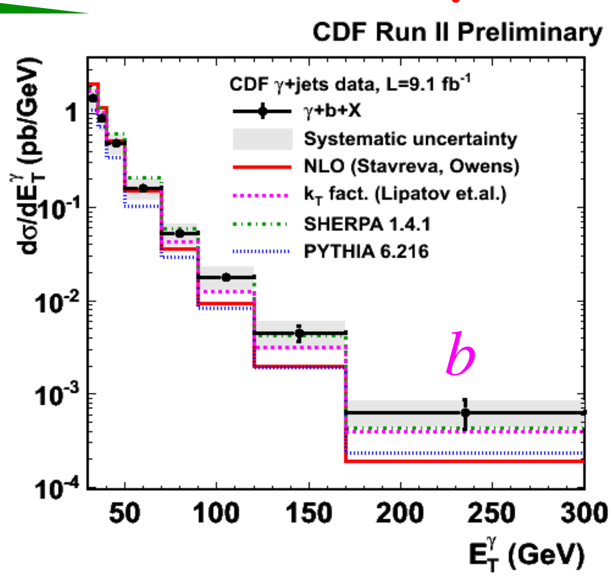
Annihilation with ISR or FSR – doesn't need HF in initial hadron, dominates at high photon E_T. FSR suppressed relative to ISR by isolation cuts.

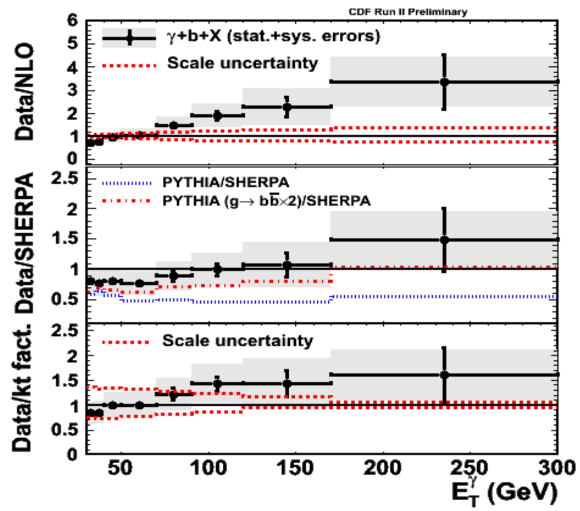


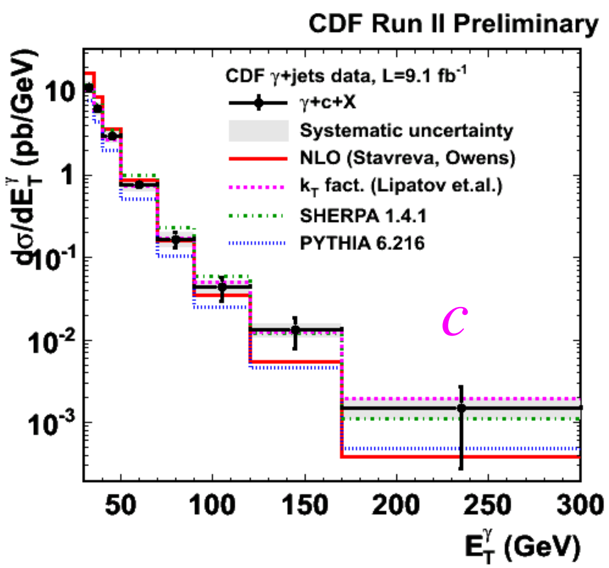
$\propto (\alpha\alpha_S^2)$

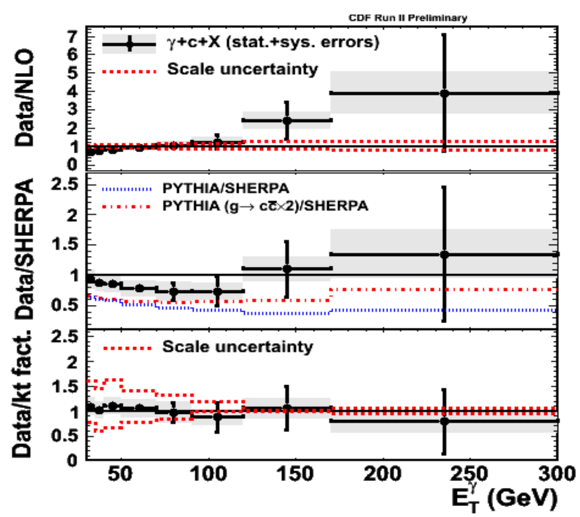
With high-$|\eta|$ γ detection, covers parton x between 0.007 and 0.4

γ + HF $d\sigma/dE_T^{\gamma}$ Results









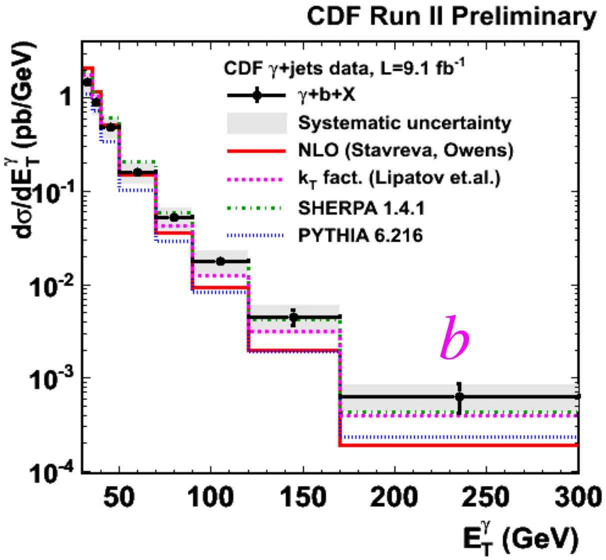
Experimental systematics ~ 16-35% and dominated by b/c jet fraction uncertainties

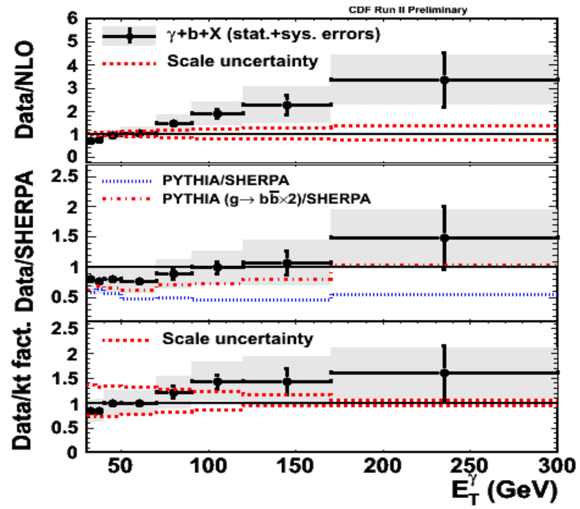
Parton → hadron correction for NLO and k_T from SHERPA

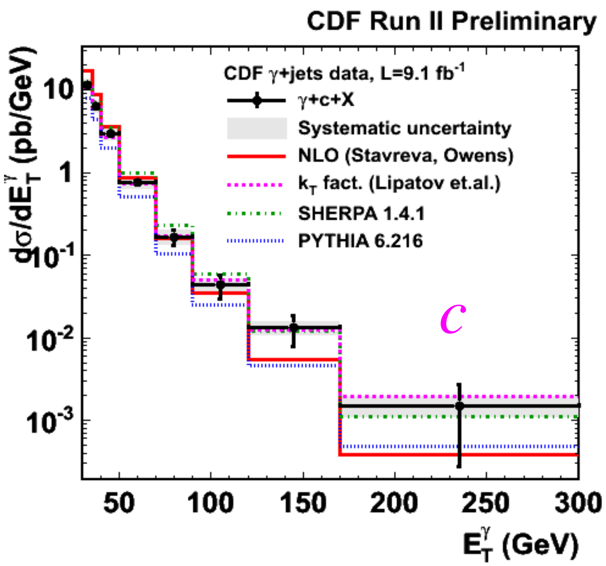
c results much more uncertain than b results

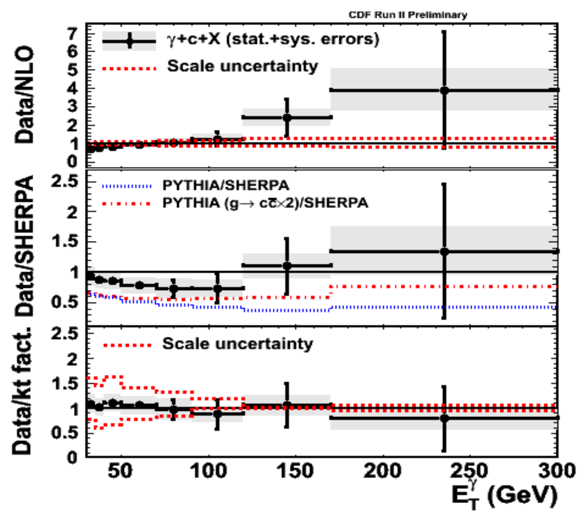
CDF/PHYS/JET/PUBLIC/10818 2 Nov 2012

γ + HF $d\sigma/dE_T^{\gamma}$ Results









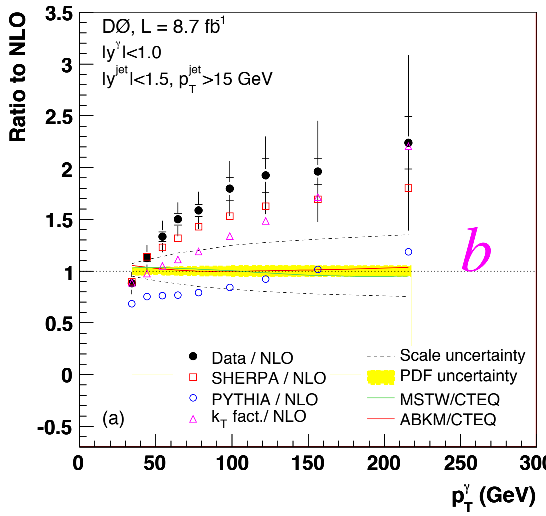
NLO predictions below data for $\gamma + b + X$ at $E_T(\gamma) > 70$ GeV

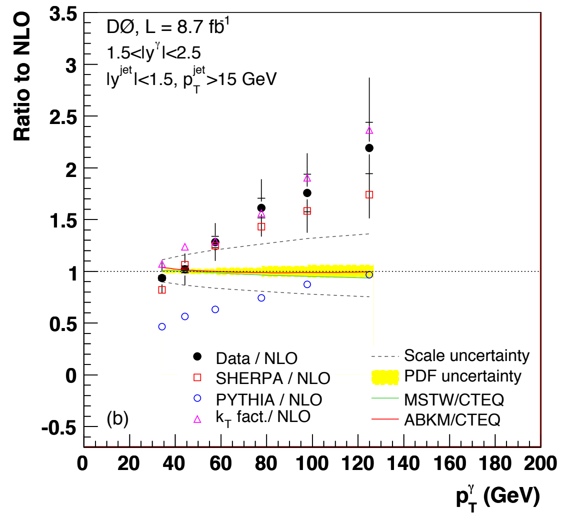
PYTHIA generally lower than data (unless 2x gluon splitting)

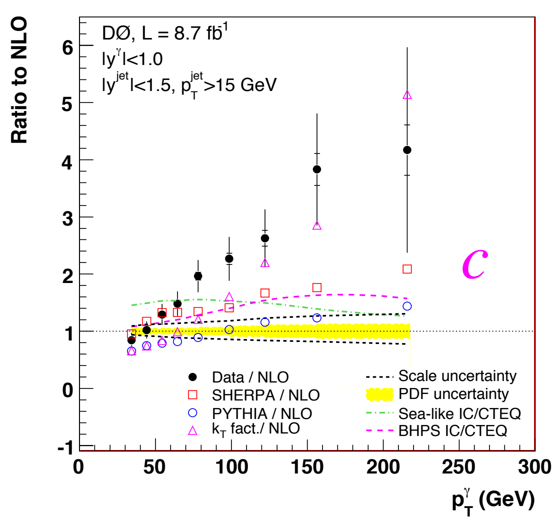
SHERPA, k_T factorization match data

CDF/PHYS/JET/PUBLIC/10818 2 Nov 2012

γ + HF $d\sigma/dE_T^\gamma$ Results







Experimental systematics ~ 10-35% and dominated by b/c jet fraction uncertainties and γ purity at lower $E_T(\gamma)$

Parton → hadron and MPI correction from PYTHIA, SHERPA

NLO predictions below data for $\gamma + b/c + X$ at higher $E_T(\gamma)$

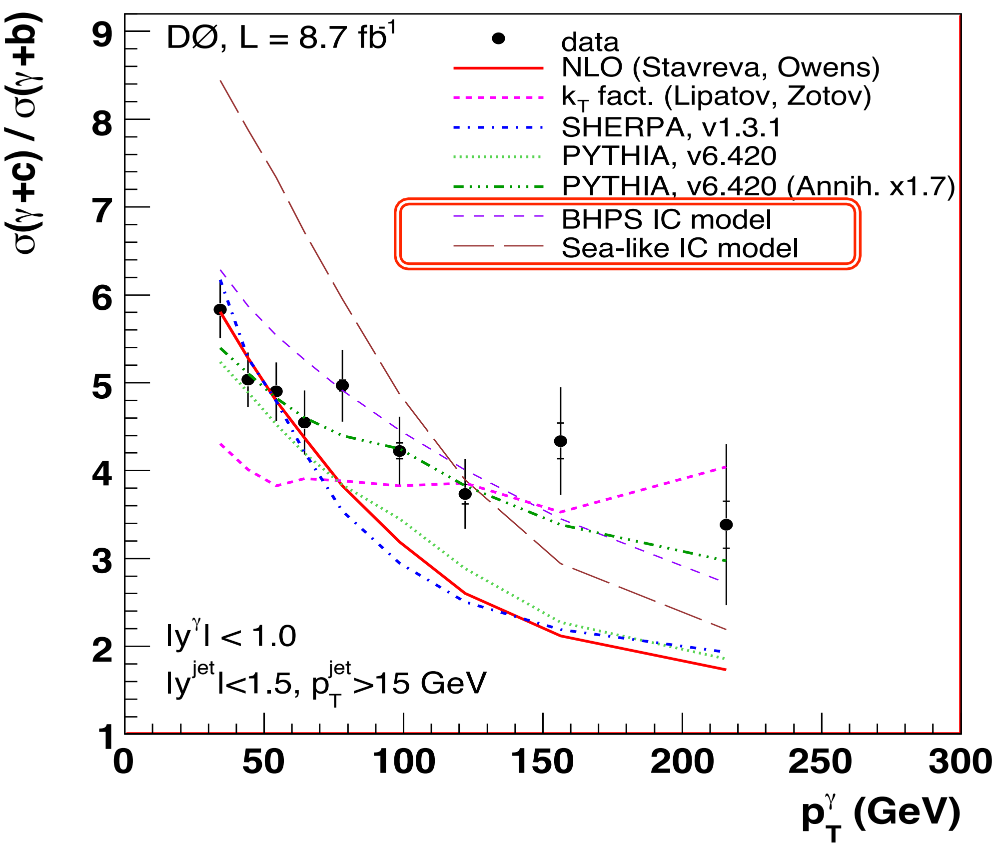
PYTHIA generally lower than data

k_T prediction lower than data at lower $E_T(\gamma)$

Phys. Lett. B 714 (2012) 32; arXiv:1210.5033

γ + HF $d\sigma/dE_T^\gamma$ Results

c/b ratio

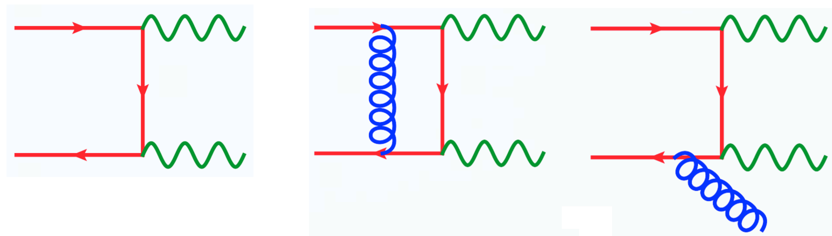


PYTHIA with $g \to bb$ increased by factor of 1.7 gets the right c/b ratio

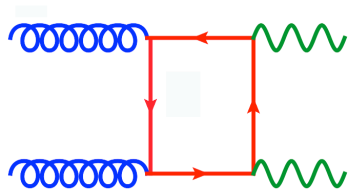
Intrinsic charm with PDF like a sea quark not close to the data

$\gamma\,\gamma$ production in $p\bar{p}$

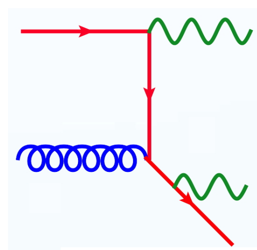
Leading contributions at Tevatron are $q\bar{q}$



gg when glue PDFs are large;
gg fusion larger at LHC

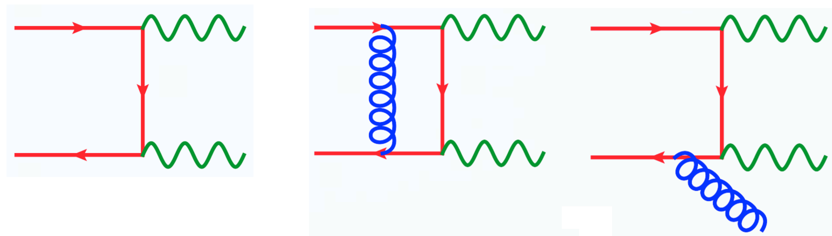


gq also large at LHC



γ γ production in $p\bar{p}$

Leading contributions at Tevatron are $q\bar{q}$



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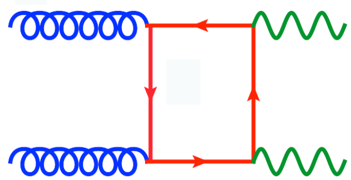

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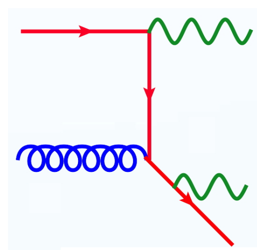
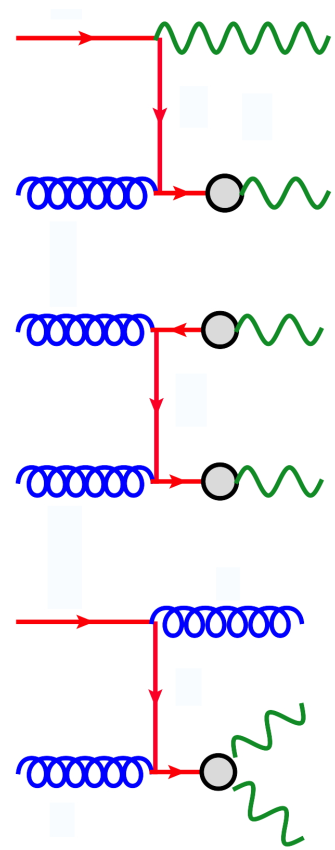


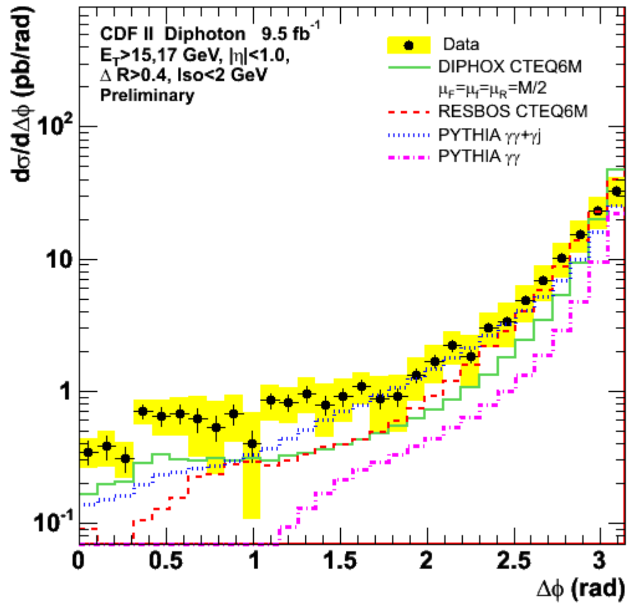


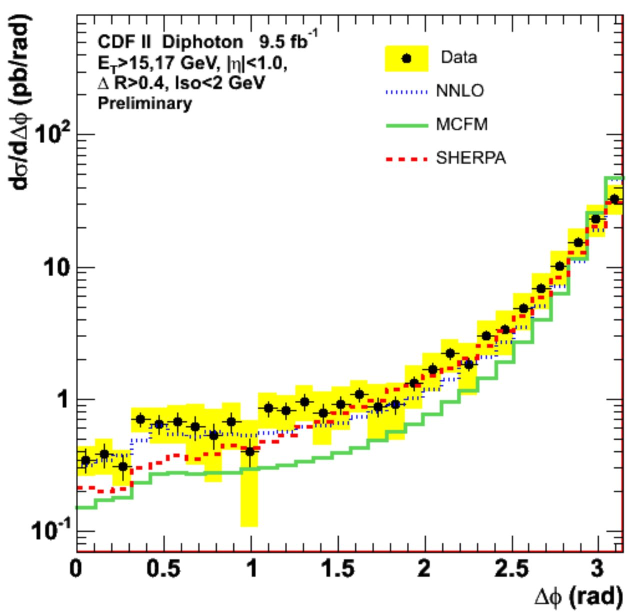
Even after isolation cuts, fragmentation contributions are still considerable

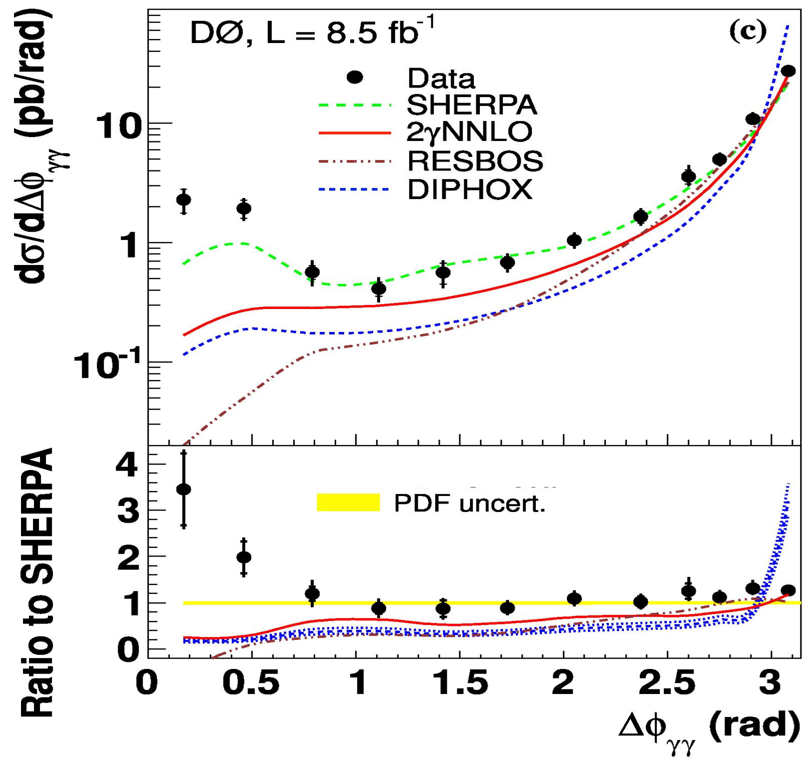
They are largest at $m(\gamma\gamma) < E_T(\gamma\gamma)$

and azimuthal opening angle $\Delta\phi(\gamma\gamma) < \pi/2$

Δϕ(γγ) Results





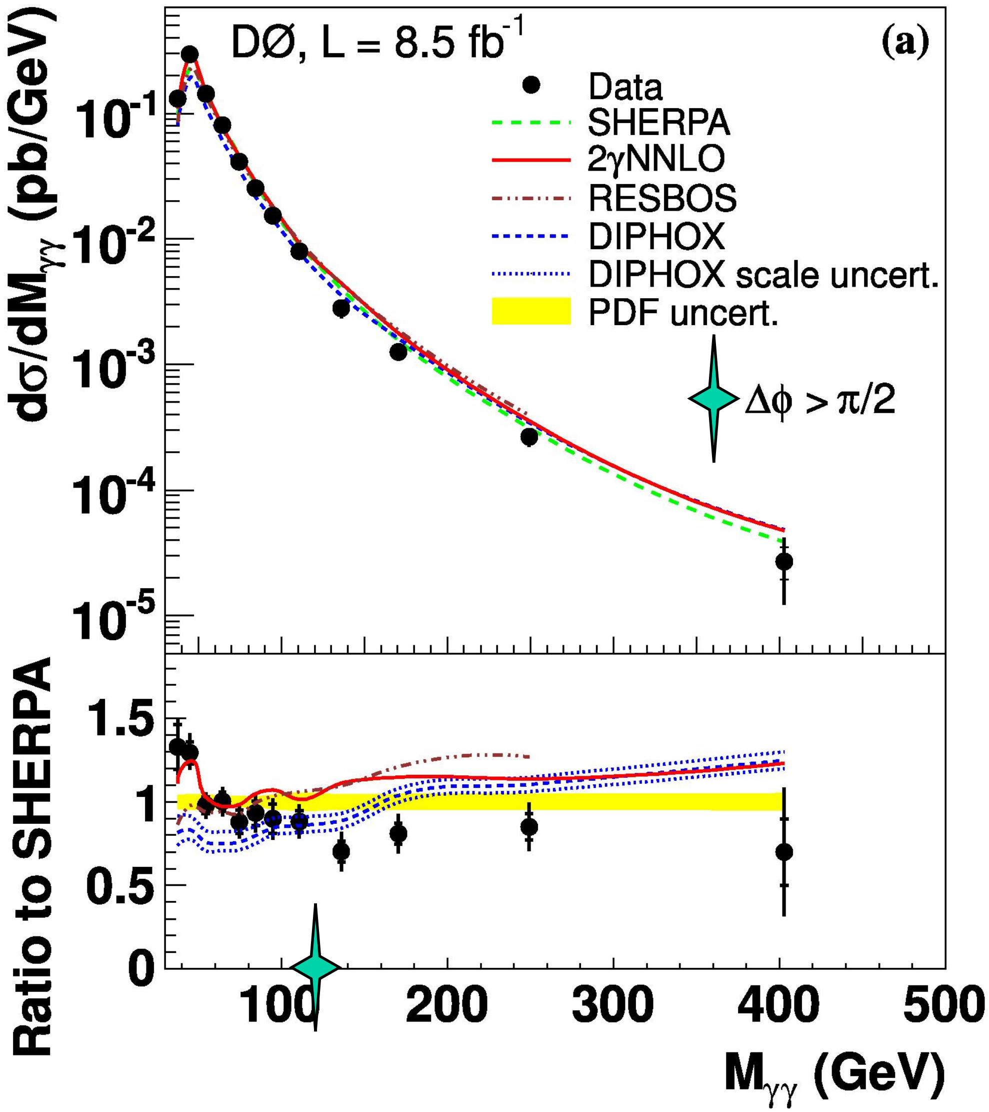


NNLO is Catani *etal* PRL **108**, 072011 (2012)
2γNNLO is Catani & Grazzini, PRL 98, 222002 (2007)

PYTHIA needs preselected *g + jet*

CDF used SHERPA v1.3.1; D0 used v1.2.2; both with CTEQ6.6M

$m(\gamma\gamma)$ Results



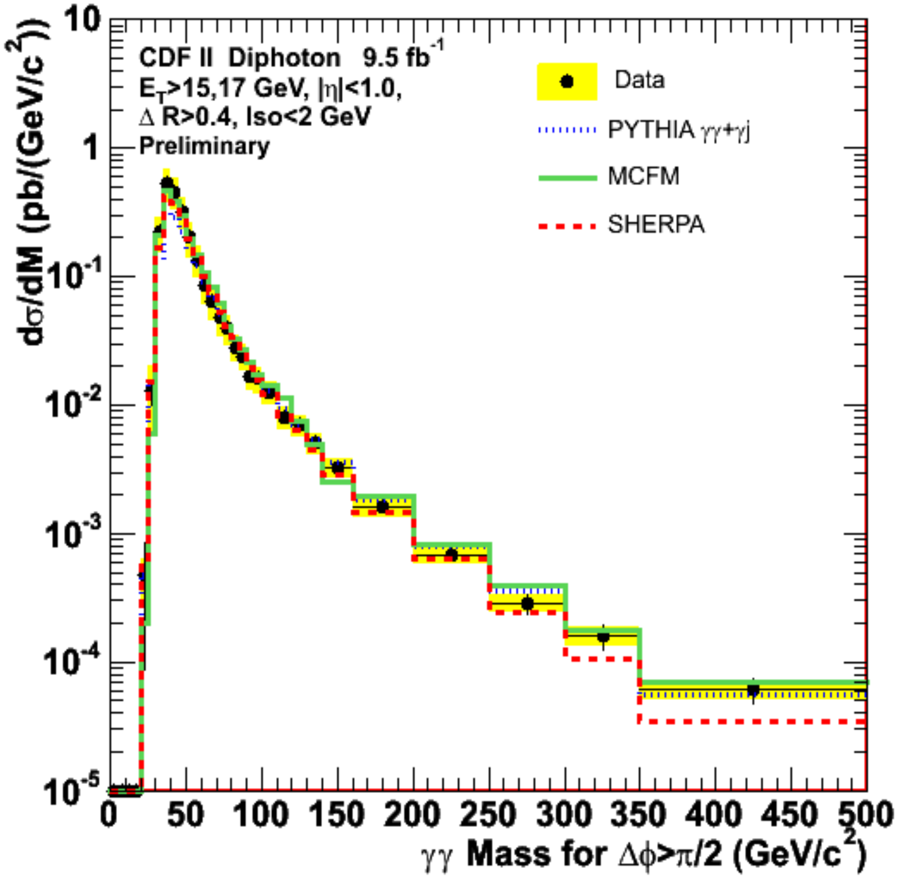
For both CDF & D0, dominant uncertainty (15-30%) & (10-20%) from *g* ID and purity

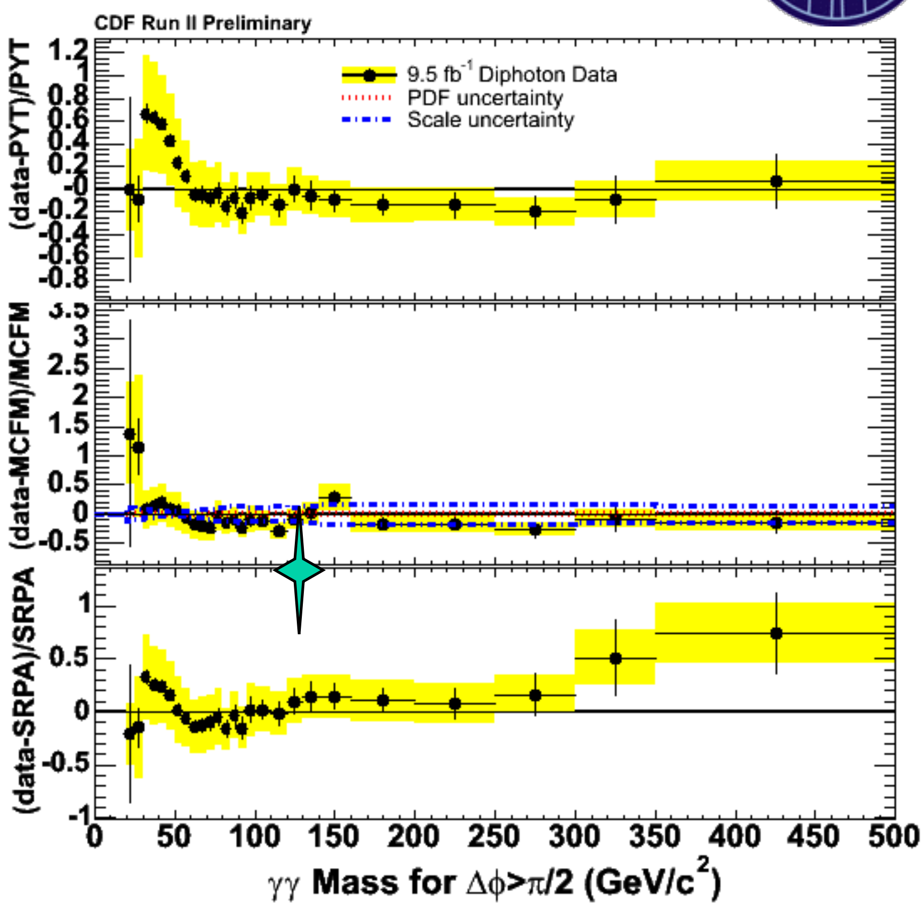
PDF and scale uncertainty evaluated with DIPHOX

$\mu_{FACT} = \mu_{FRAG} = \mu_{RENORM} = m(\gamma\gamma)$

arXiv:1301.4536
Submitted to PLB

$m(\gamma\gamma)$ Results





	Integrated cross section (pb)
Data	$12.3 \pm 0.2_{STAT} \pm 3.5_{SYST}$
SHERPA	12.4 ± 4.4
MCFM	11.5 ± 0.3
NNLO	$11.8^{+1.7}_{-0.6}$

Many distributions available in the papers-

arXiv:1212.4204

Conclusions

γ + HF and $\gamma\gamma$ production measured with full Tevatron dataset

NLO predictions below data for γ + HF at $E_T(\gamma) > 70$ GeV

PYTHIA also low for γ + HF, but SHERPA and k_T factorization are better

Fragmentation contribution to $\gamma\gamma$ difficult to model well

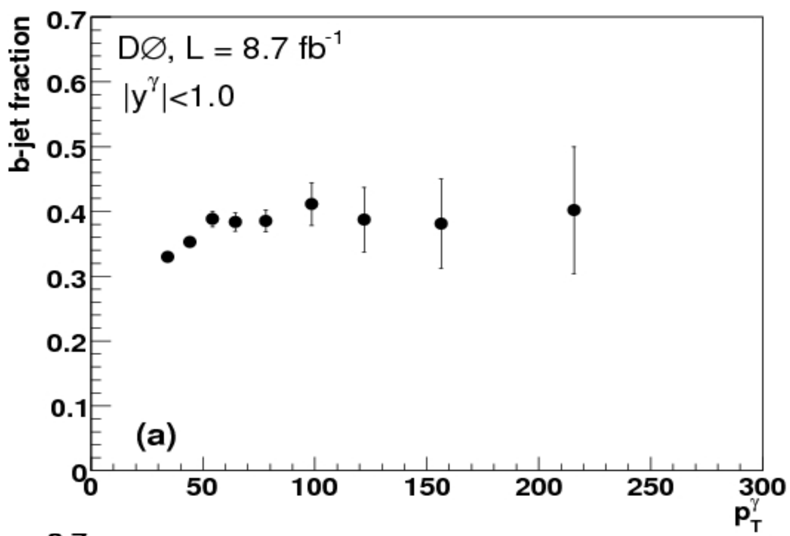
$m(\gamma\gamma)$ near 125GeV at $\Delta\phi > \pi/2$ "OK" with DIPHOX, SHERPA and PYTHIA (if you include γ+*jet* with $\gamma\gamma$)

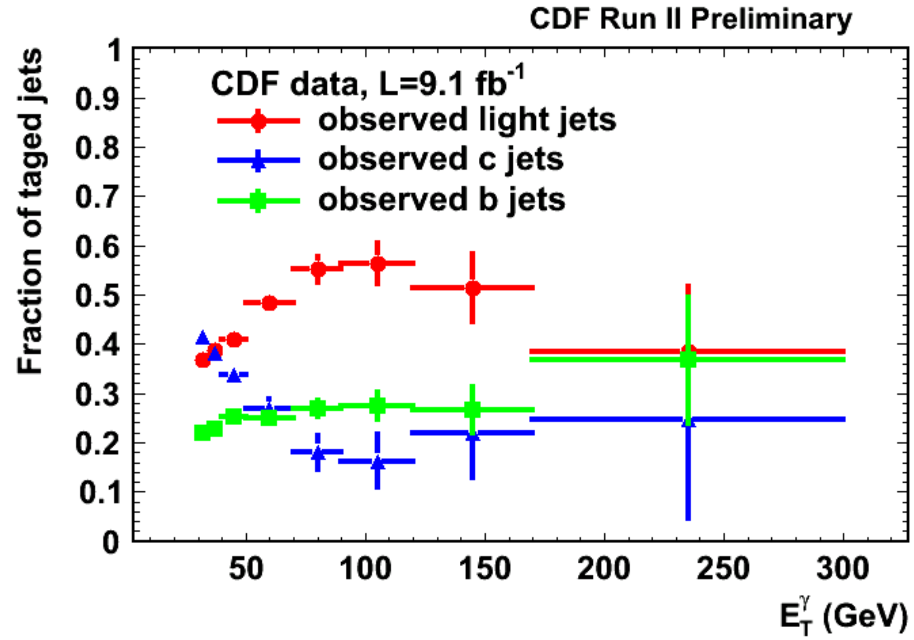
Find more at

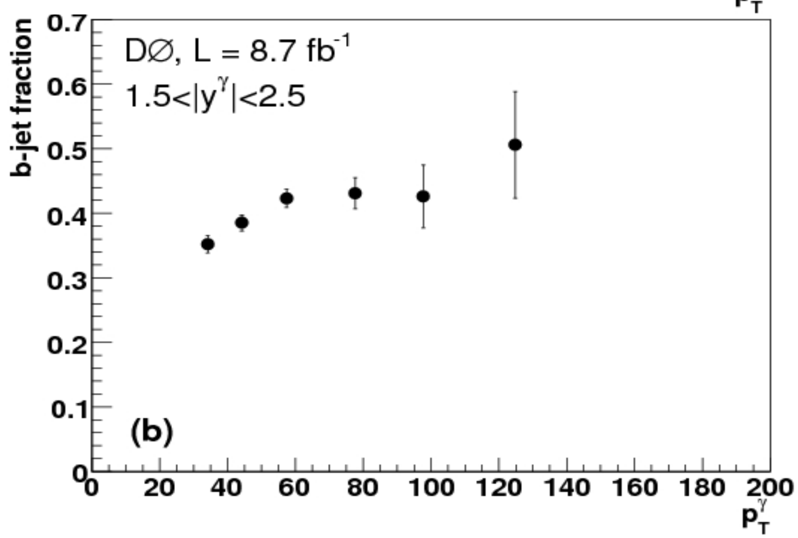
http://www-d0.fnal.gov/Run2Physics/WWW/results/qcd.htm
http://www-cdf.fnal.gov/physics/new/qcd/QCD.html

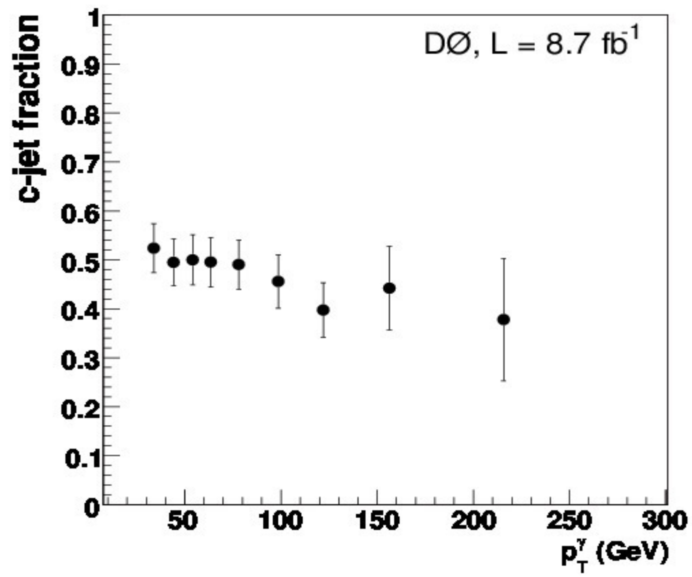
Additional information

b – jet fractions









Re. models for γ + HF

- **NLO pQCD (Stavreva, Owens) done at $\mu_{FACT} = \mu_{FRAG} = \mu_{RENORM} = E_T^{\gamma}$, with CTEQ6.6M**

- **k_T factorization (Lipatov Zotov) has contributions beyond NLO from resumming gluon radiation with transverse momentum over probing scale μ; uses MSTW2008**

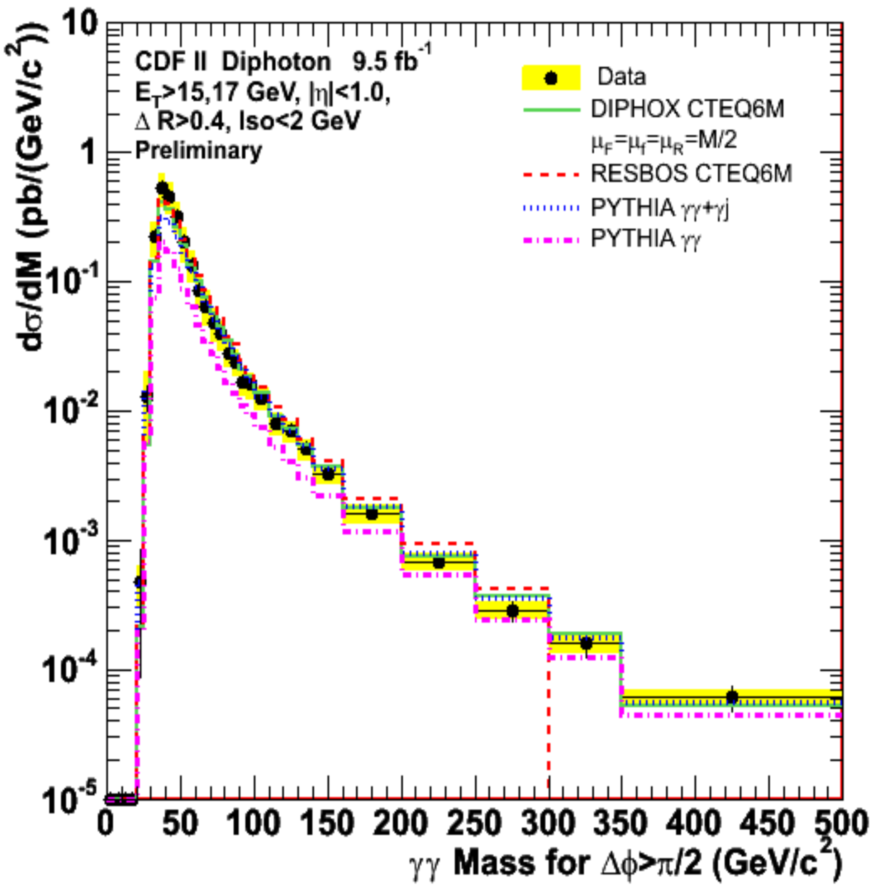
- **PYTHIA 6: 2→2 matrix element with $g \rightarrow bb$ in parton shower; CTEQ5L [CDF] and CTEQ6.1L [D0]**

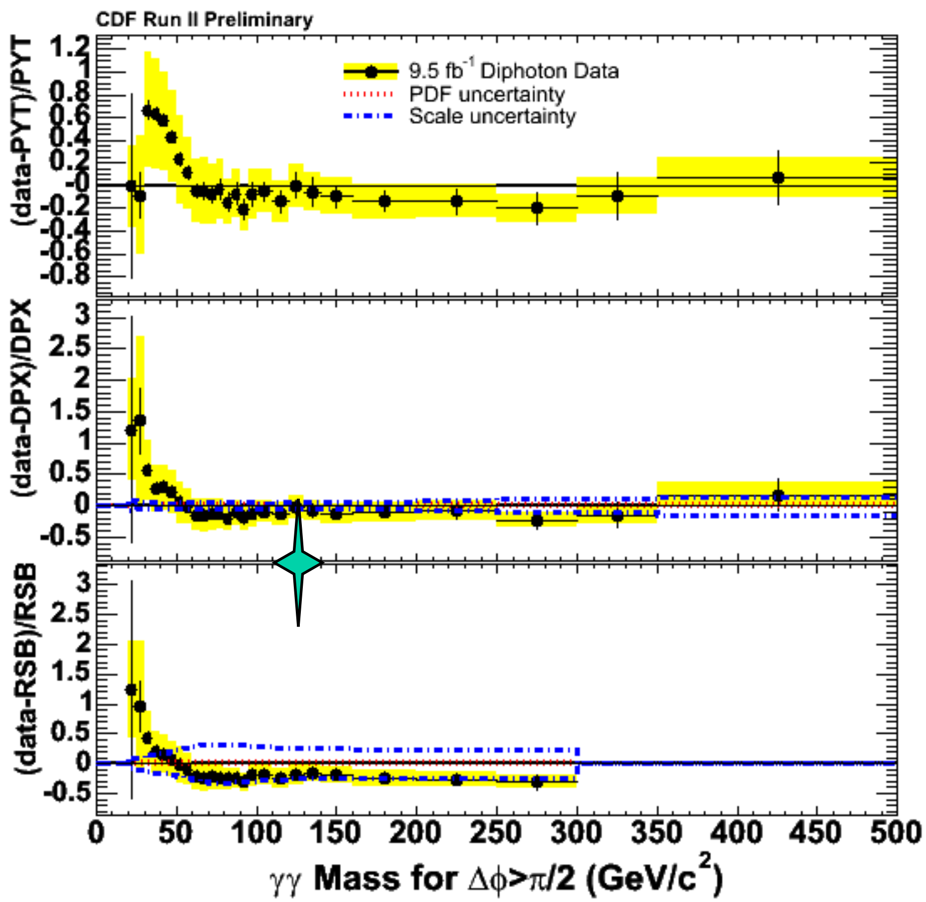
- **SHERPA has matrix elements for γ + up to 3 jets of which one is HF. CT10 [CDF] and CTEQ6.6M [D0]**

Re. models for γ γ

- **PYTHIA: 2→2 ME + PS, string fragmentation; can (& should) include γ + jet and then filter cases where a 2nd γ appears. CDF uses v6.2.16, D0 uses v6.420 with Tune A**
- **SHERPA: 2→2,3,4 ME + PS, cluster fragmentation; novel method for matching hard to soft physics. D0 uses CTEQ6.6M & Q_{CUT} = 10 GeV**
- **MCFM: Fixed-order NLO calculation with nonperturbative fragmentation at NLO; CDF used with CTEQ6.1M**
- **DIPHOX: Fixed-order NLO calculation including single & double fragmentation at NLO into photons; CDF used CTEQ6M, scale $\mu = m(\gamma\gamma)/2$; D0 used CTEQ6.6M, scale $\mu = m(\gamma\gamma)$**
- **RESBOS: NLO with analytic initial-state soft gluon resummation; $\mu = m(\gamma\gamma)/2$; CTEQ6.1M (CDF), CTEQ6.6M (D0)**
- **2gNNLO: Catani & Grazzini, 2007. D0 used with MSTW2008**
- **NNLO: Catani *etal*, 2012. calculation with q_T subtraction**

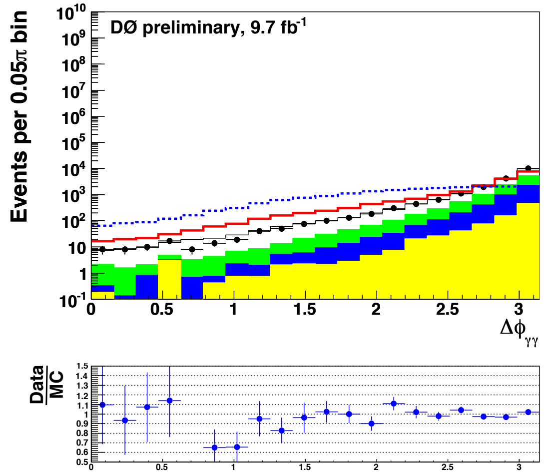
$m(\gamma\gamma)$ Results



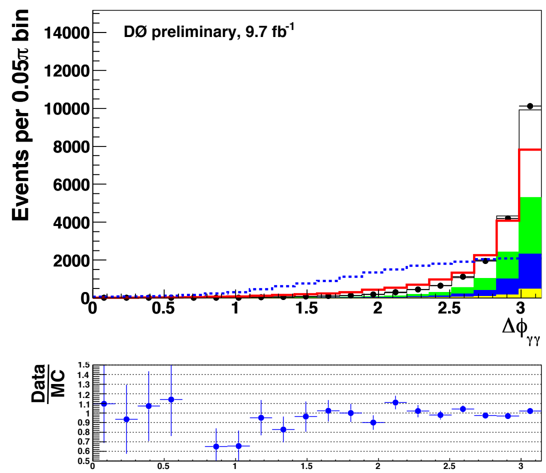


Resbos limited to $2m_b < m(\gamma\gamma) < 2m_t$

H→gg

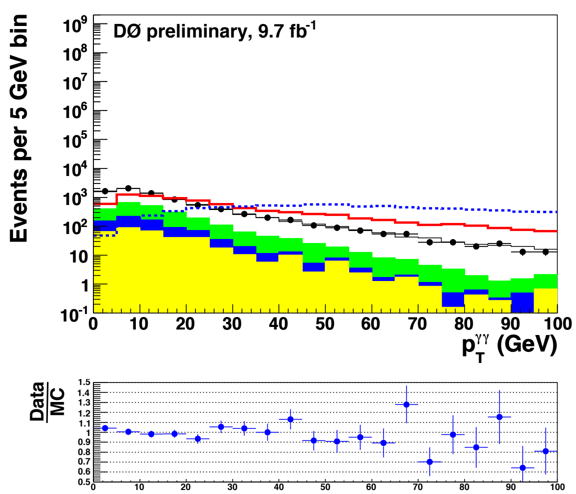


(c) $\Delta\phi^{\gamma\gamma}$ log

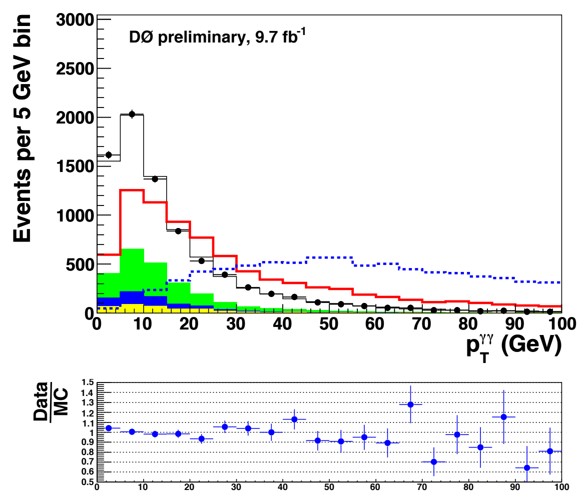


(d) $\Delta\phi^{\gamma\gamma}$ linear

Figure 43: p17+p20 in **inclusive** region: data and background modeling comparisons in terms of E_T^2, $\Delta\phi^{\gamma\gamma}$ for mass range [60, 200] GeV. The signal is assumed of 125 GeV. Signals(SM:red,fermiophobic:blue) are scaled to data to better visualize the shape differences.

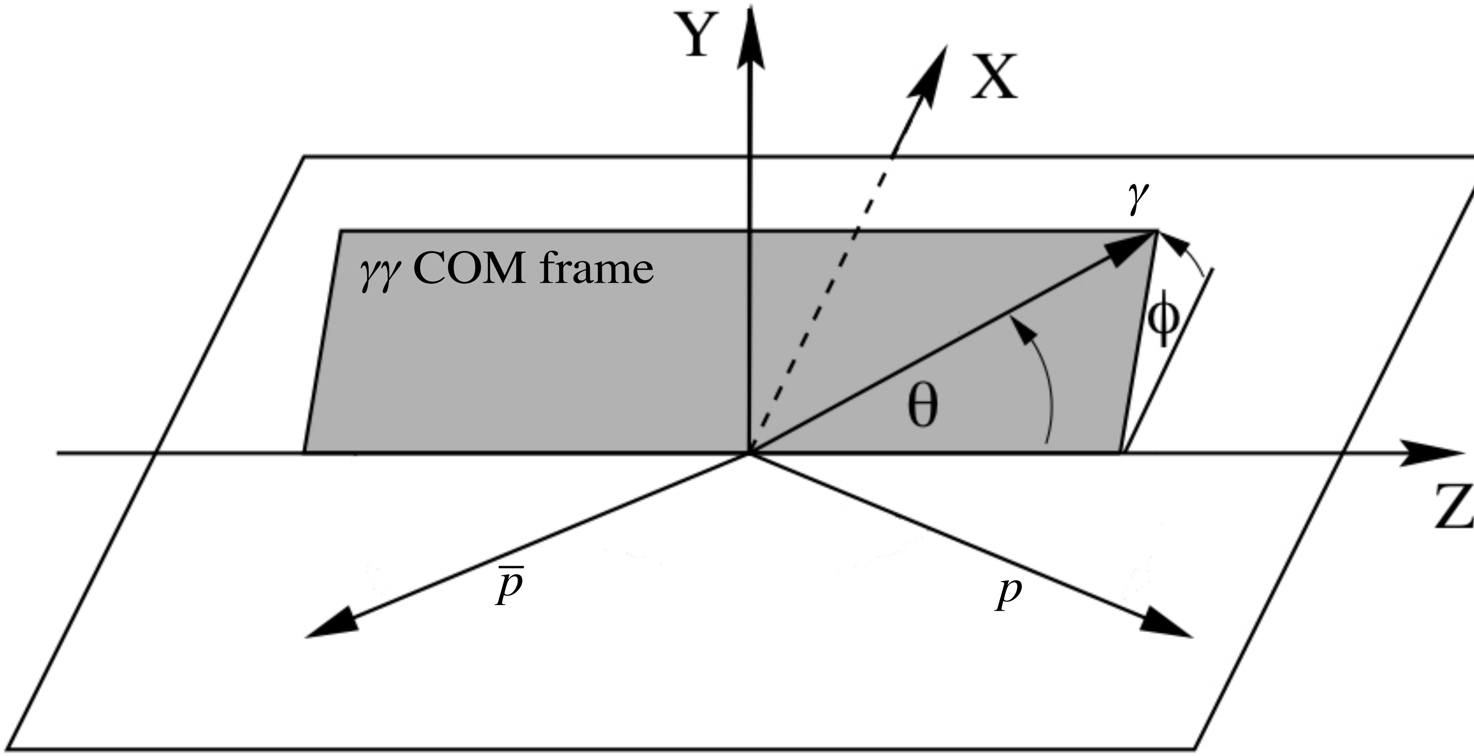


(a) $p_T^{\gamma\gamma}$ log



(b) $p_T^{\gamma\gamma}$ linear

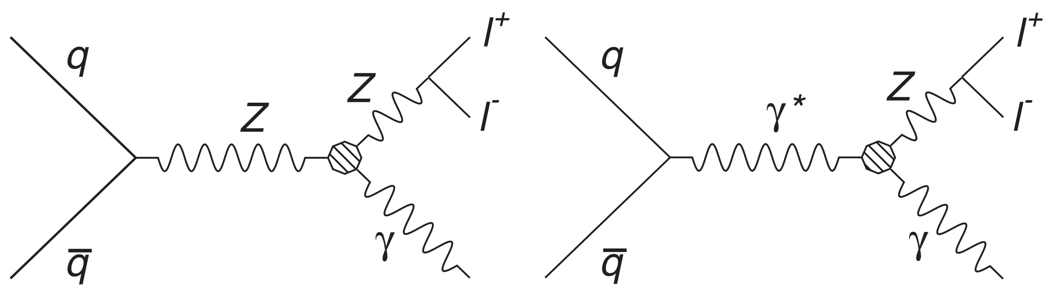
Collins-Soper Frame



We approximate $|\cos\theta|$ *with* $\left|\tanh \frac{\Delta\eta}{2}\right|$

$Z\gamma$ production and anomalous couplings

Abazov *etal* (D0) Phys Rev D 85, 052001 (1 Mar 2012)
Aaltonen *etal* (CDF) Phys Rev Lett 107, 051802 (2011)



In SM, neutral trilinear couplings $ZZ\gamma$ and $Z\gamma\gamma$ do not exist at tree level and are quite small at 1st loop
BSM models can have contributions from new states in loop

but . . . no BSM found and limits on couplings set at:

$$\left|h_3^{\gamma,Z}\right| < 0.022 \qquad \left|h_4^{\gamma,Z}\right| < 0.0009$$

True photon fraction

- **Fit data ANN distribution using signal and background templates to get true photon fraction**