PROMPT PHOTON PRODUCTION

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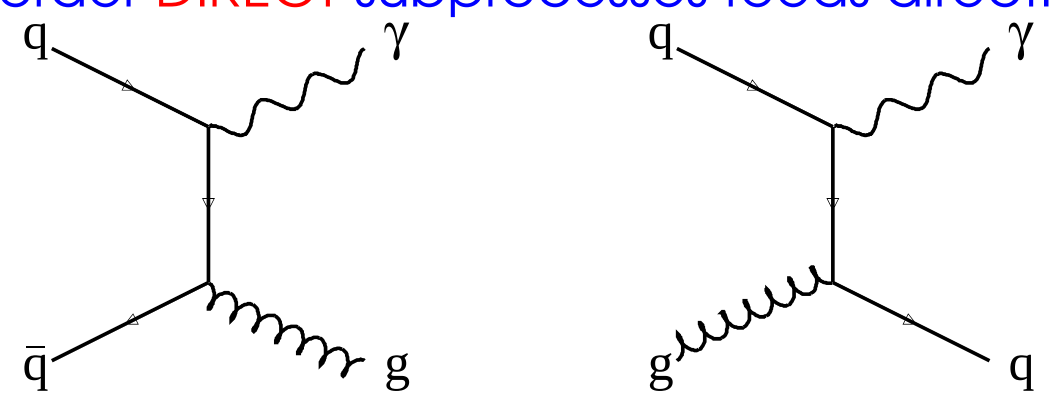
    - $pp \rightarrow \gamma\gamma X$ at $\sqrt{S} = 14$ TeV
3. Summary

1. Single Photon Production

$$pp \rightarrow \gamma X$$
$$p\bar{p} \rightarrow \gamma X$$

Direct Production of Prompt Photons

- The study of "prompt" photons (γ's) with large transverse momentum p_T has a history almost as old as QCD
- "Prompt": γ cannot be said to originate from the decay of a hadron (e.g., a π^0 or η) itself produced with large p_T
- Appeal: Prompt γ is a hard, point-like, colorless probe of the short-distance dynamics of quark and gluons
- One motivation, in both spin-averaged and spin-dependent scattering, is access to the gluon density of hadrons since one of the two leading order DIRECT subprocesses feeds directly from the gluon density



Annihilation

Compton Scattering

Single-photon fragmentation

- Reality. The promise and naive simplicity of prompt γ's are compromised by two issues: fragmentation contributions and isolation
- Fragmentation. A hard γ that brems off a final-state quark will emerge as part of a jet, if the opening angle between the quark and photon is too small. This long-distance "showering" process must be parameterized by a non-perturbative single-photon fragmentation function $D_\gamma(z, \mu_f)$ ()
- Variable z denotes the fraction of the fragmenting quark's momentum that the γ retains. Fragmentation scale μ_f serves as the boundary in momentum (μ) space between the long-distance dynamics included in $D_\gamma(z, \mu_f)$ when $\mu < \mu_f$, and the short-distance next-to-leading order dynamics in the region $\mu > \mu_f$ (i.e., large angle separation between the final quark and photon).

  new variable μ_f enters the mix, along with the usual μ_R and μ_F

Photon Isolation

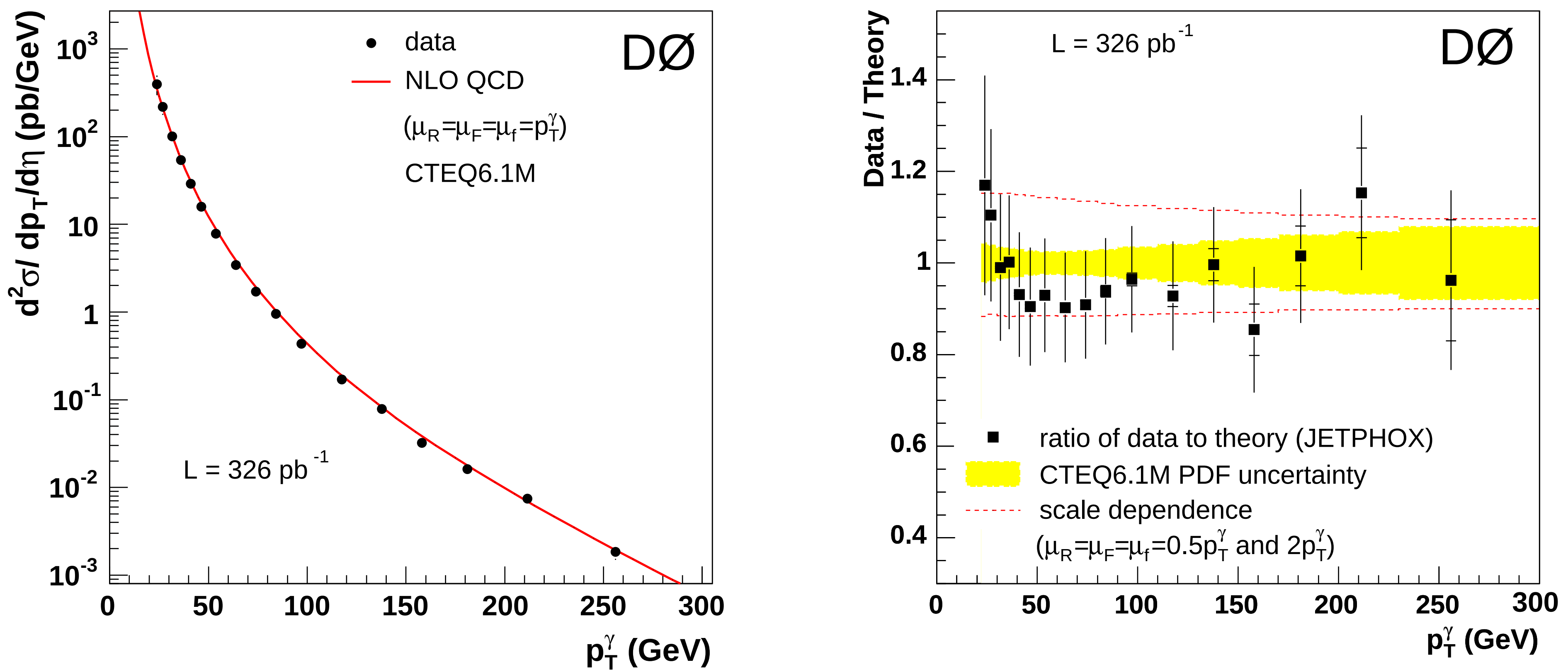
- Isolation. A theory calculation is most reliable for inclusive observables: infra-red and collinear singularities can be shown to cancel between real-emission and loop diagrams. However, Tevatron and LHC collider experiments measure isolated γ's, in which part of the (real-emission) final state phase space is cut-out.
- Why isolation? Otherwise, the prompt signal would be overwhelmed by secondary γ's from hadron decays, and it is hard to discern a prompt γ if it is buried in a jet (unless z is very large)
- Isolation. Define a cone, with radius R, in rapidity y and azimuthal angle ϕ space around the γ. $R^2 = [(y - y_\gamma)^2 + (\phi - \phi_\gamma)^2]$.
  γ is "isolated" if, inside R, hadronic energy $E_T^{\rm had} < E_T^{\rm iso}$.
  $\rightarrow$ Isolation will reduce the fragmentation contribution, AND two new variables are introduced: R and $E_T^{\rm iso}$
- Theoretical representations of isolation are at best approximate. Calculations tend to require Monte Carlo modeling of fragmentation in order to implement experiment-like isolation cuts

Comparison with data

- Calculations at next-to-leading order accuracy exist of both direct and fragmentation contributions. One approach is encoded in the Monte Carlo program JETPHOX

  Aurenche, Fontannaz, Guillet, Pilon, and Werlen hep-ph/0602133

- Comparison here with Tevatron Run-2 data from DØ hep-ex/0511054



Other recent theoretical contributions

- Phase space boundary $x_T = 2p_T/\sqrt{s} \to 1$
  - relevant at fixed-target energies
  - next-to-leading logarithmic resummation of log contributions

    Laenen, Oderda, Sterman; Catani, Mangano, Nason, Oleari, Vogelsang; Sterman, Vogelsang; deFlorian, Vogelsang
- Joint resummation of logarithmically enhanced threshold and p_T effects associated with soft gluon emission

  Sterman, Vogelsang (2005)

2. Photon Pair Production

$$pp \to \gamma\gamma X$$
$$p\bar{p} \to \gamma\gamma X$$

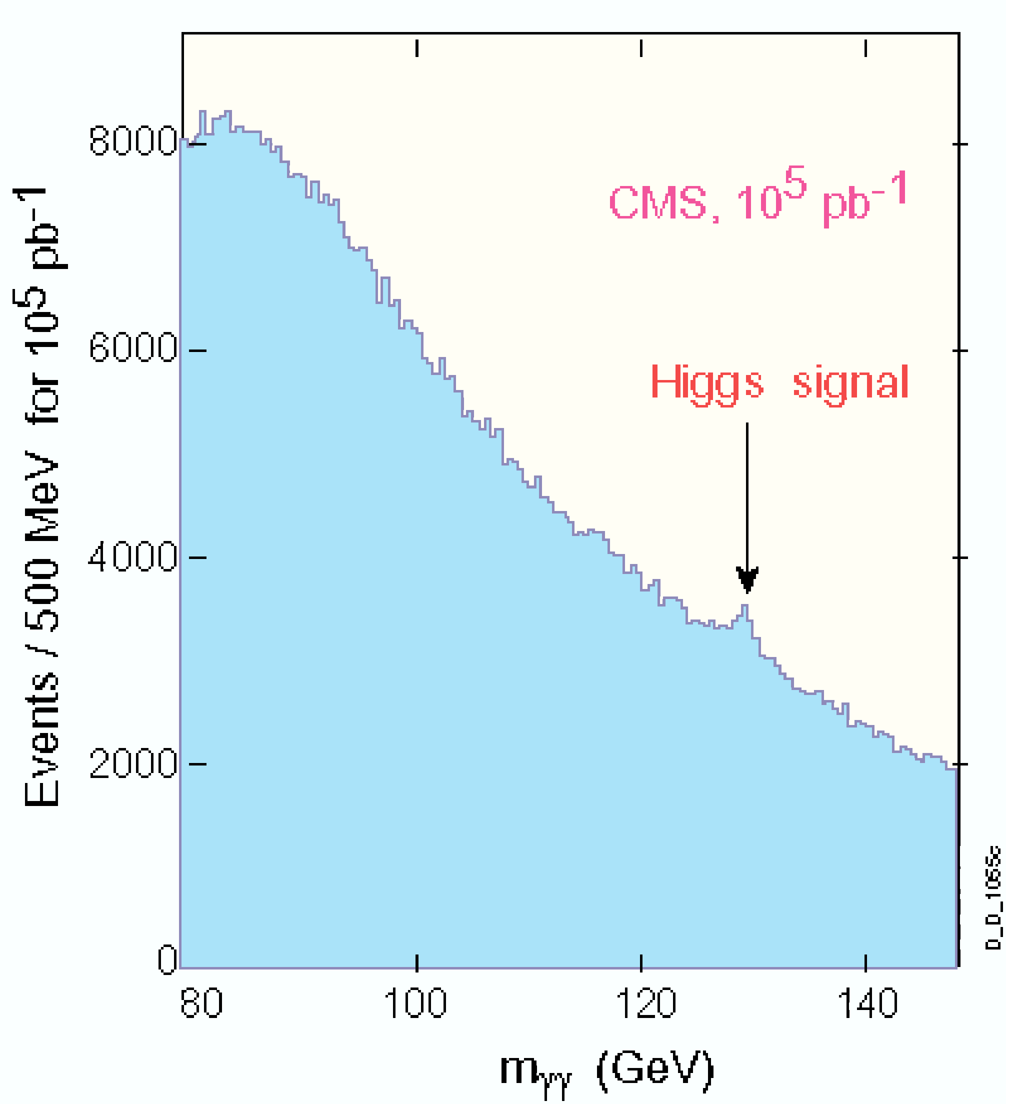
Focus on the transverse momentum Q_T of the pair

Based on Balazs, Berger, Nadolsky, Yuan, hep-ph/0603037, Physics Letters, in press, plus long paper to appear shortly

Transverse momentum Q_T distribution – motivation

- Search for the Higgs boson in the $h \to \gamma\gamma$ mode is aided by a good understanding of the Higgs boson production dynamics AND of the dynamics of Standard Model QCD processes that produce $\gamma\gamma$ pairs
- Event modeling, kinematic acceptance, and efficiencies all depend on Q_T
- Expected shape of $d\sigma/dQ_T$ can affect experimental triggering and analysis strategies
- The behavior of $d\sigma/dQ_T$ affects the precision of the determination of the event vertex from which the Higgs boson ($\gamma\gamma$ peak) emerges. Greater Q_T activity associated with Higgs boson production allows a more precise determination of the vertex especially in the case of multiple events per beam crossing
- Selections on Q_T can be used to enhance the signal/background ratio

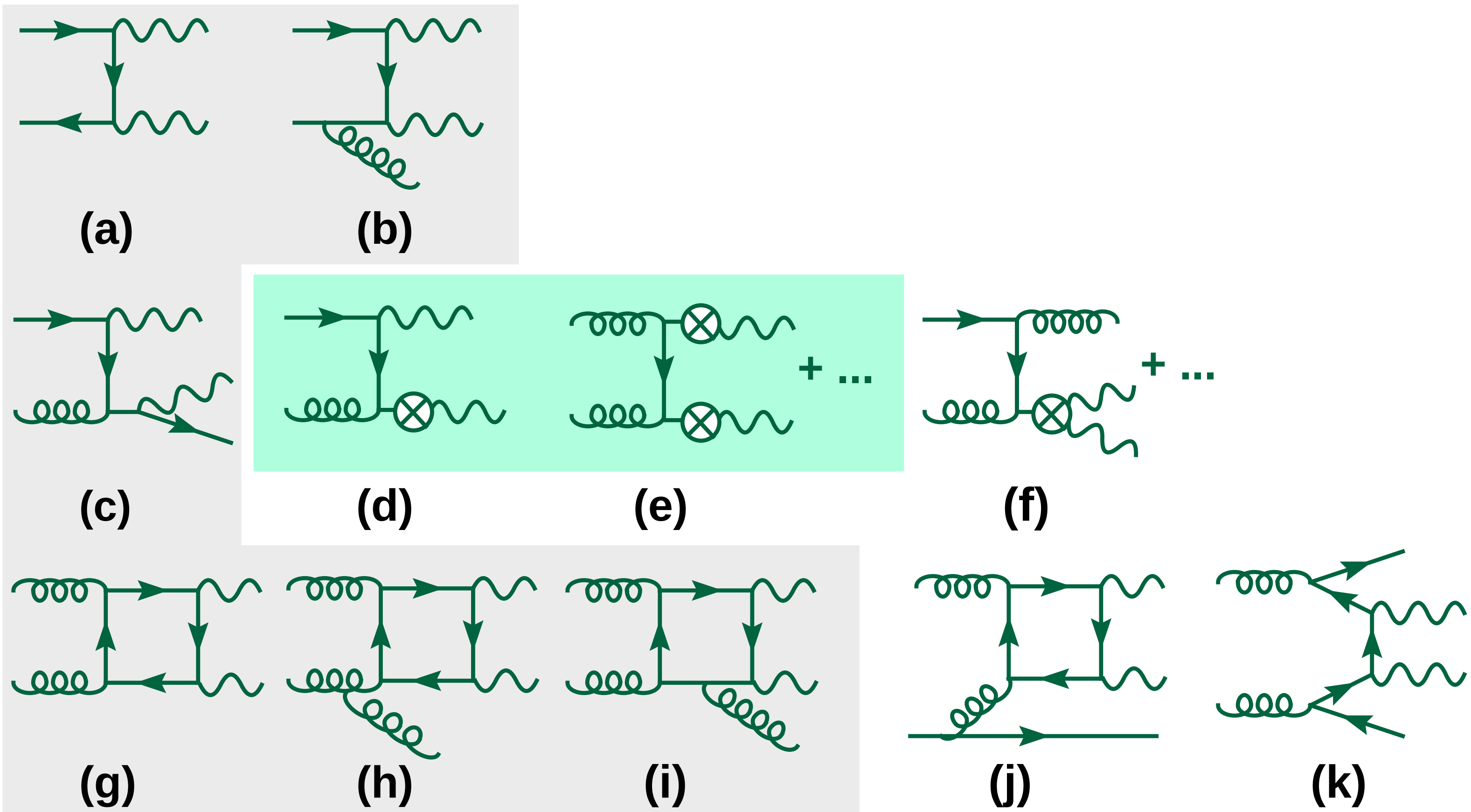
What do we expect to see in the $\gamma\gamma$ mass spectrum?



- Try to improve the signal to background by selecting events with 'large' Q_T

QCD Production of Photon Pairs

- QCD subprocesses are initiated by $q\bar{q}$, qg and gg scattering



- Run 2 data from CDF at FNAL permit test of calculations
- Interesting QCD in its own right

Differential cross section; fixed-order in α_s

- At fixed-order in α_s, the transverse momentum distribution behaves as $\frac{\alpha_s}{Q_T^2}\left[a + b\log(m_{\gamma\gamma}^2/Q_T^2)\right] \to \infty$ as $Q_T^2 \to 0$
  - $1/Q_T^2$ divergence is related to the light parton propagators
  - The logarithmic term $\log(m_{\gamma\gamma}^2/Q_T^2)$ remains after the usual cancellation of infra-red divergences and the absorption of collinear divergences into the renormalized parton densities
- In addition

  $\frac{\sigma^{\rm NLO}}{\sigma^{\rm LO}} = \mathcal{O}(\alpha_s \log^2(m_{\gamma\gamma}^2/Q_T^2))$ is not small $(\alpha_s(\mu)/\pi)\,\ln^2(m_h^2/Q_T^2) \sim 0.7$ if $\mu = m_h = 125$ GeV and $Q_T = 14$ GeV
- The large logarithmic terms spoil conventional factorization in QCD perturbation theory
- The physical cross section peaks below $Q_T \sim m_{\gamma\gamma}/3$. A reliable QCD calculation for small and intermediate Q_T requires that we resum the large logarithmic terms to all orders in α_s

Restructure the perturbative expansion

- In terms of $\alpha_s \ln^2(Q/Q_T)$, instead of α_s, with $(L = \ln(Q/Q_T))$
- $d\sigma/dQ_T^2 =$

$$Q_T^{-2}\left\{\alpha_s({}_1v_1'L + {}_1v_0') + \alpha_s^2({}_2v_3'L^3 + {}_2v_2'L^2) + \alpha_s^3({}_3v_5'L^5 + {}_3v_4'L^4) + \ldots\right\}$$
$$+ \alpha_s^2({}_2v_1'L + {}_2v_0'L^0) + \alpha_s^3({}_3v_3'L^3 + {}_3v_2'L^2) +$$
$$+ \alpha_s^3(\ldots$$

- In a fixed order calculation (column by column), convergence at small Q_T is compromised by higher order uncalculated logarithmic terms
- In a resummed calculation (line by line), convergence is preserved in each "order" (each line), and higher order corrections are included systematically
- Expand the predictive power of QCD perturbation theory by (re)summing the large logarithmic contributions in an improved calculational scheme

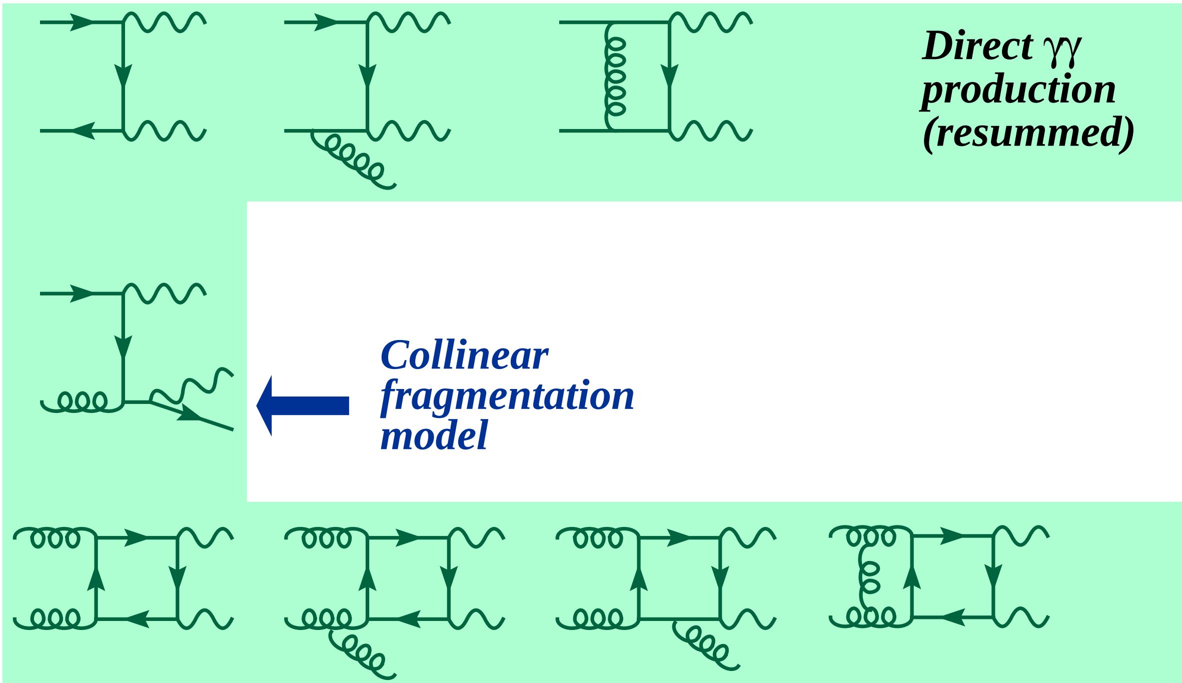
All Orders Soft Gluon Resummation

- Resummation in impact parameter b-space
  - $\vec{b}$-space = Fourier conjugate of $\vec{Q}_T$-space
  - Fourier transform $\frac{d\sigma}{dy dQ_T^2}$ to b-space
  - Sum multiple gluon emission to all orders in α_s
  - Transverse momentum conservation preserved
  - Fourier transform back to Q_T-space
  - Resummation produces a Q_T distribution that is finite as $Q_T \to 0$
- Previous study: Balazs, Berger, Mrenna, Yuan PRD 57, 6934 (1998)
- New in 2006:
  - gg contribution at order α_s^3
  - resummation at NNLL accuracy in direct $q\bar{q}$, qg, AND gg channels
  - improved treatment of the fragmentation component via implementation of a quasi-experimental and smooth-cone isolation procedure

Direct diphotons

The dominant production mode; evaluated here up to full NLO/NNLL accuracy

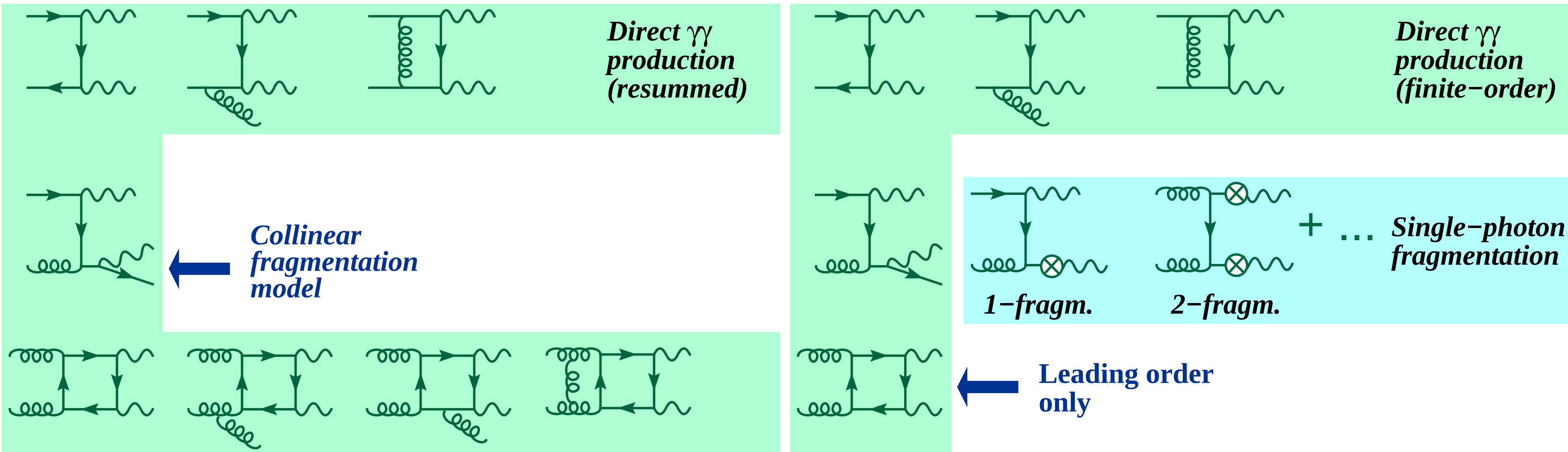
Balazs, Berger, Nadolsky, Yuan, 2006



- qg and gg channels are enhanced at $x \sim Q^2/s \ll 1$ by large gluon PDF
- $q\bar{q}$ and qg channels at NLO: Aurenche et al.; Bailey, Owens, Ohnemus
- gg channel at NLO: Balazs, Nadolsky, Schmidt, Yuan; de Florian, Kunzst; Bern, De Freitas, Dixon; Bern, Dixon, Schmidt

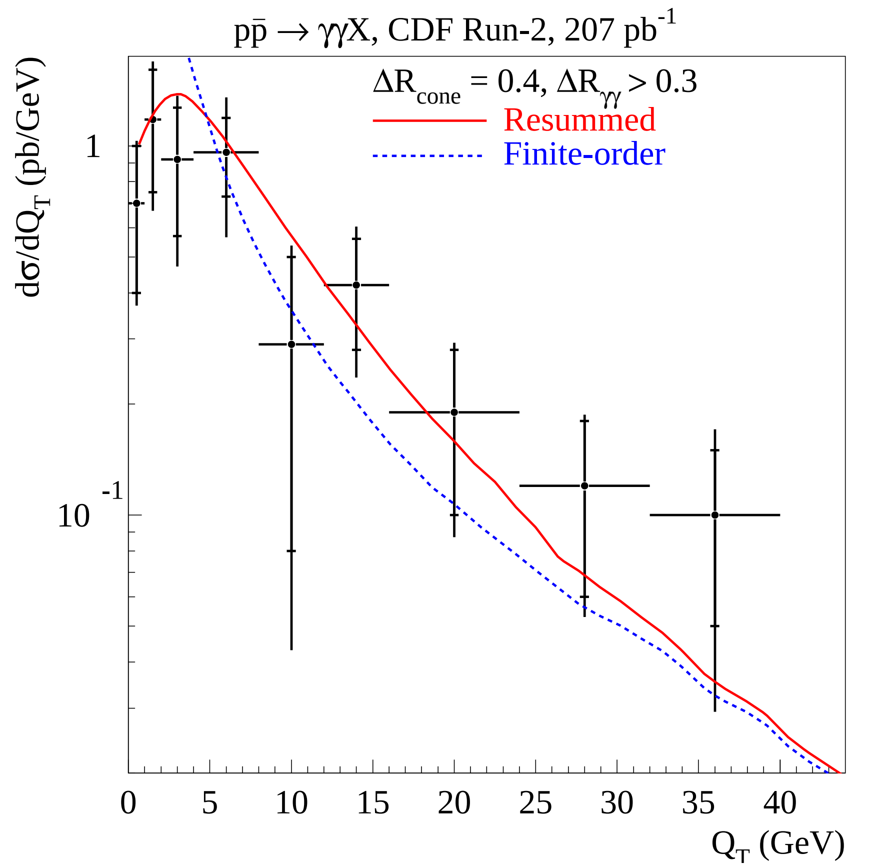
Comparison of our calculation and DIPHOX (Binoth et al.)

Balazs, Berger, Nadolsky, Yuan, 2006 — Binoth, Guillet, Pilon, Werlen, 2001



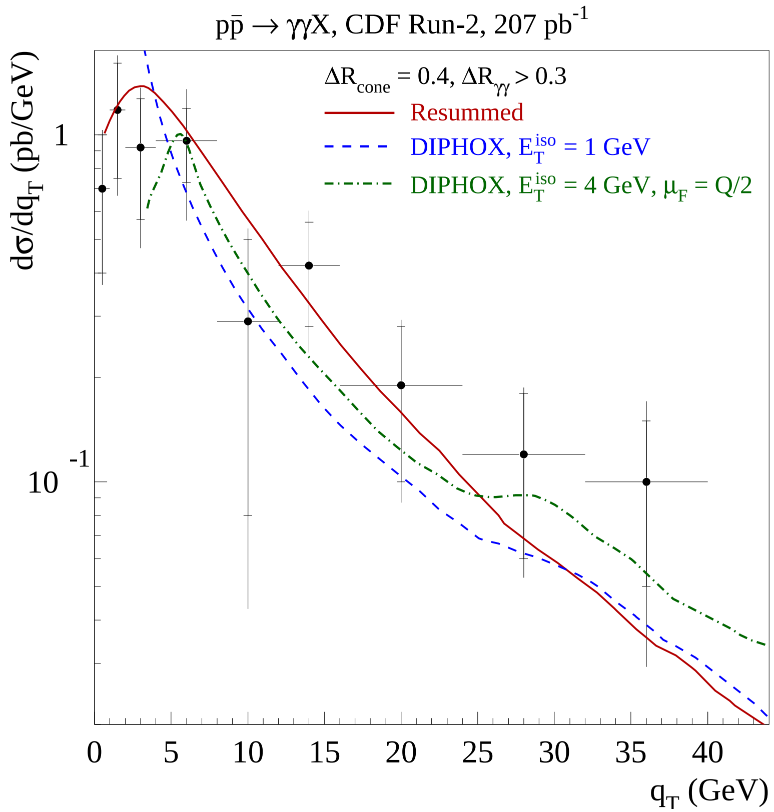
Resummation and CDF Run-2 data

CDF PRL 95, 022003 (2005)



- The finite-order (NLO) expectation diverges at small Q_T
- Our NNLL resummed calculation matches the NLO curve at large Q_T, but it differs in shape and normalization from the finite-order perturbative result elsewhere; it agrees well with the data
- Discrepancy at the larger values of Q_T?

Resummation and CDF Run-2 data

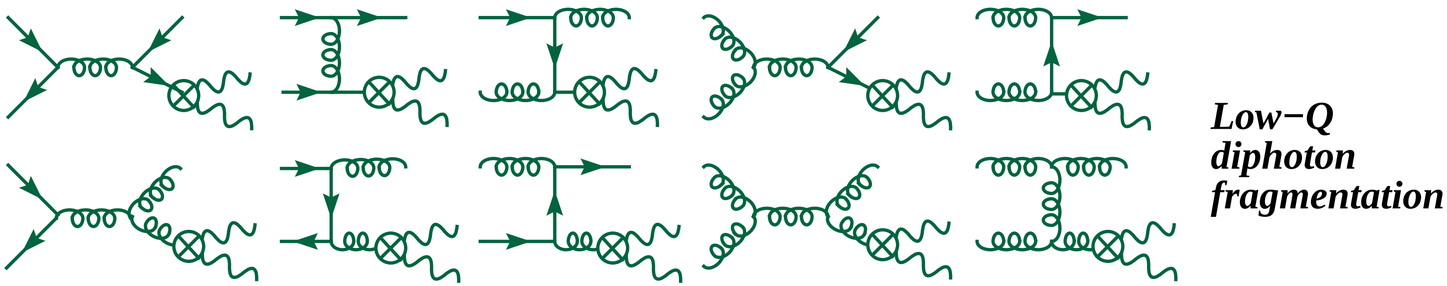


- A "shoulder" is seen in the CDF data at $Q_T > 25$ GeV (and $\Delta\phi < \pi/2$)
- At the larger values of Q_T, the DIPHOX cross section
  - agrees with our calculation for the nominal $E_T^{\rm iso} = 1$ GeV, same μ_F
  - can reproduce the "shoulder" for $E_T^{\rm iso} = 4$ GeV, smaller μ_F
  - for $E_T^{\rm iso} = 4$ GeV, the 1-fragmentation term increases by 400%

Other physics processes also contribute when $Q < Q_T$, $\Delta\phi < \pi/2$

Diphoton fragmentation

- When $Q_T > Q$, as in the "shoulder" region, the calculation must be organized differently: resum logarithms associated with fragmentation of a final state parton into the observed system, here a $\gamma\gamma$ pair.
- Region $Q_T > Q$ investigated for the Drell-Yan process, $pp \to \gamma^* X$
  Berger, Gordon, Klasen, PRD 58, 074012 (1998); Berger, Qiu, Zhang, PRD 65 034006 (2002)
- Diphoton fragmentation $q \to \gamma\gamma X$ is not implemented in any $\gamma\gamma$ calculations. Many diagrams

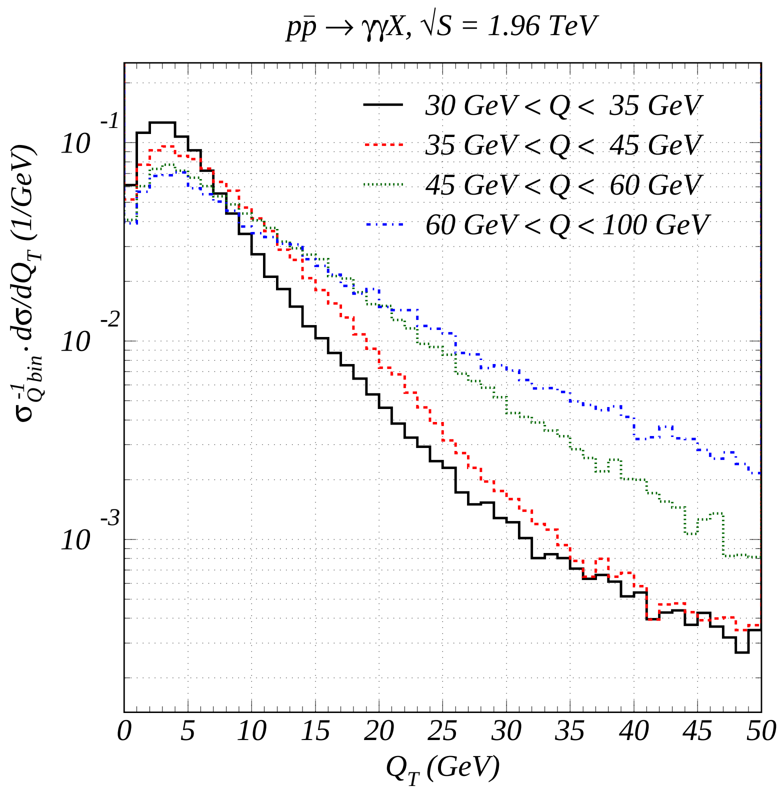


- This contribution populates the region of small invariant mass Q ($Q < Q_T$) and small azimuthal separation $\Delta\phi$, exactly where the "shoulder" appears

Claim: The "shoulder" will disappear from the CDF data if the requirement is imposed that $Q_T < Q$

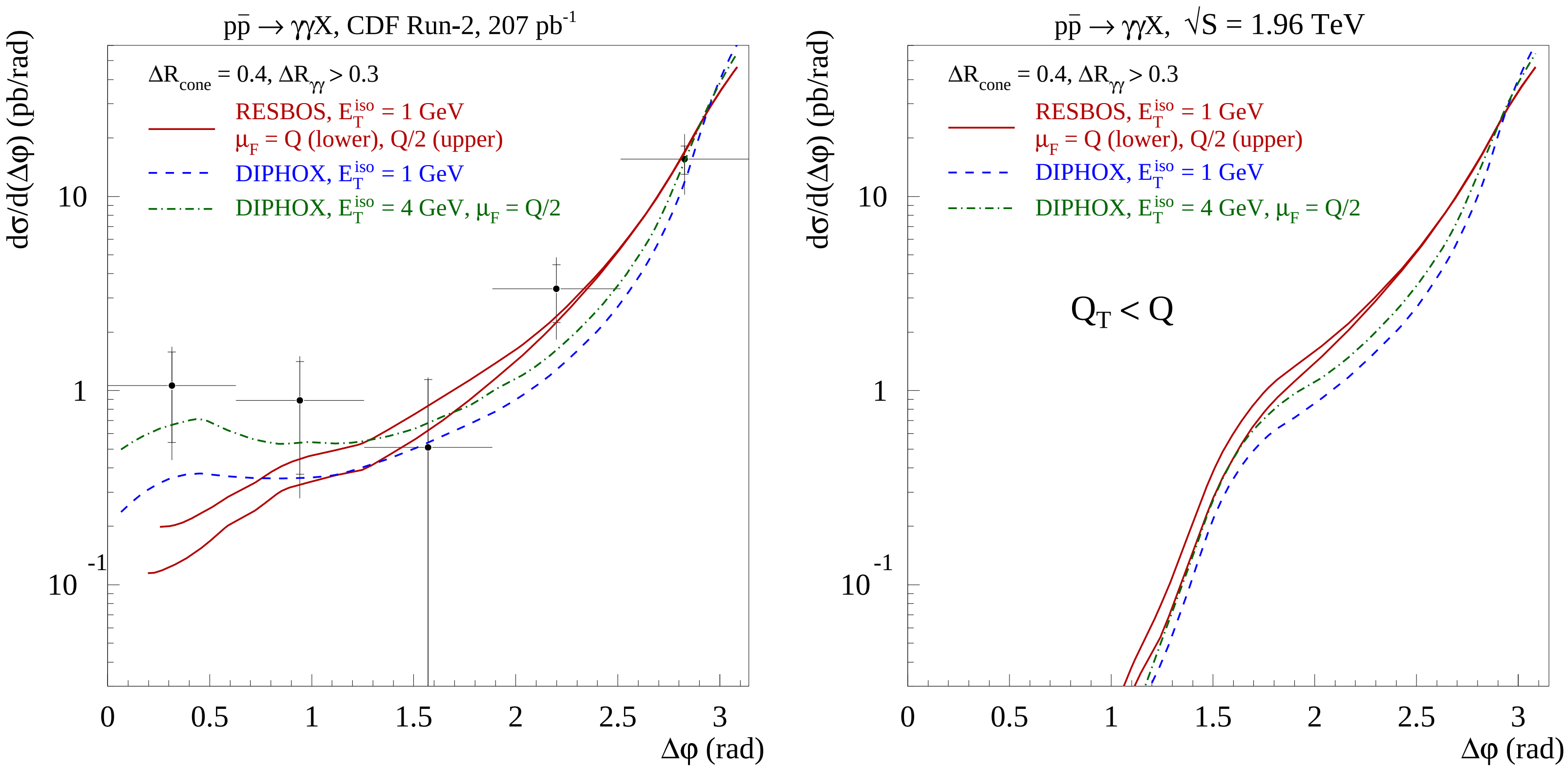
$\gamma\gamma$ mass dependence of the Q_T spectrum

- Tevatron data are presented as $d\sigma/dQ$ integrated over all Q_T or as $d\sigma/dQ_T$ integrated over all Q; a more differential analysis is desirable
- Example: resummation predicts a $\log(Q)$ dependence of the Q_T distribution



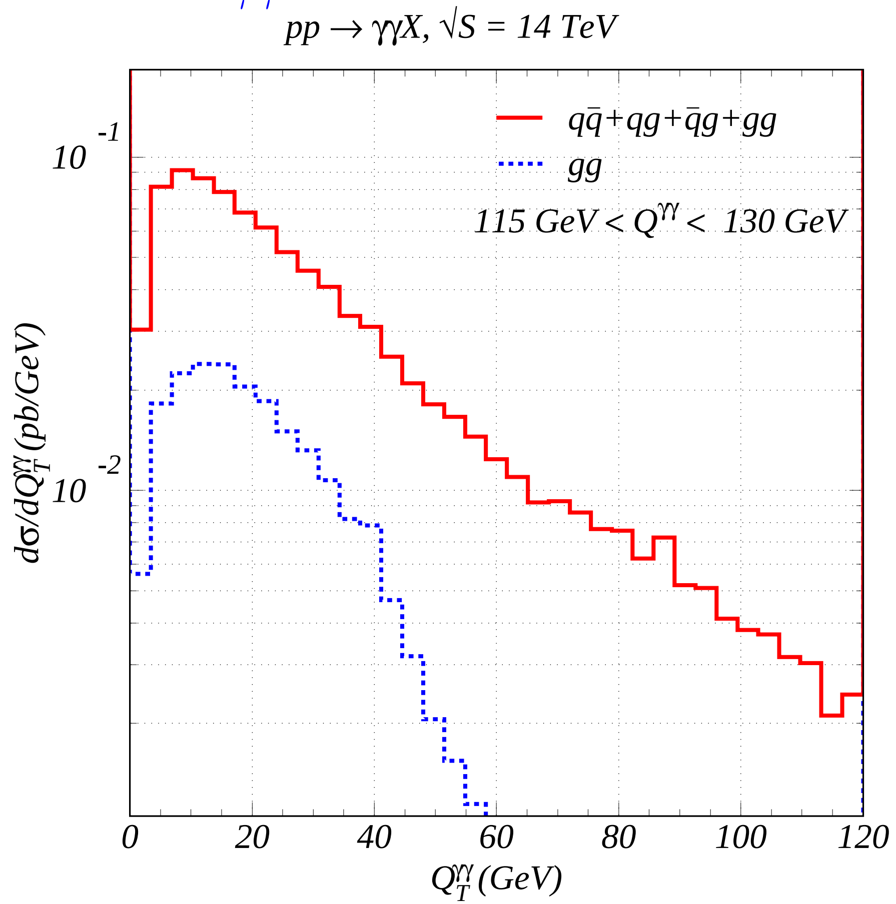
- Valuable to verify this log dependence with Q of the Q_T spectrum with Tevatron data
- Similar predictions for the LHC

Azimuthal angle dependence



Prediction for the LHC Balazs, Berger, Nadolsky, Yuan

- Q_T spectrum for $115 < m_{\gamma\gamma} < 130$ GeV



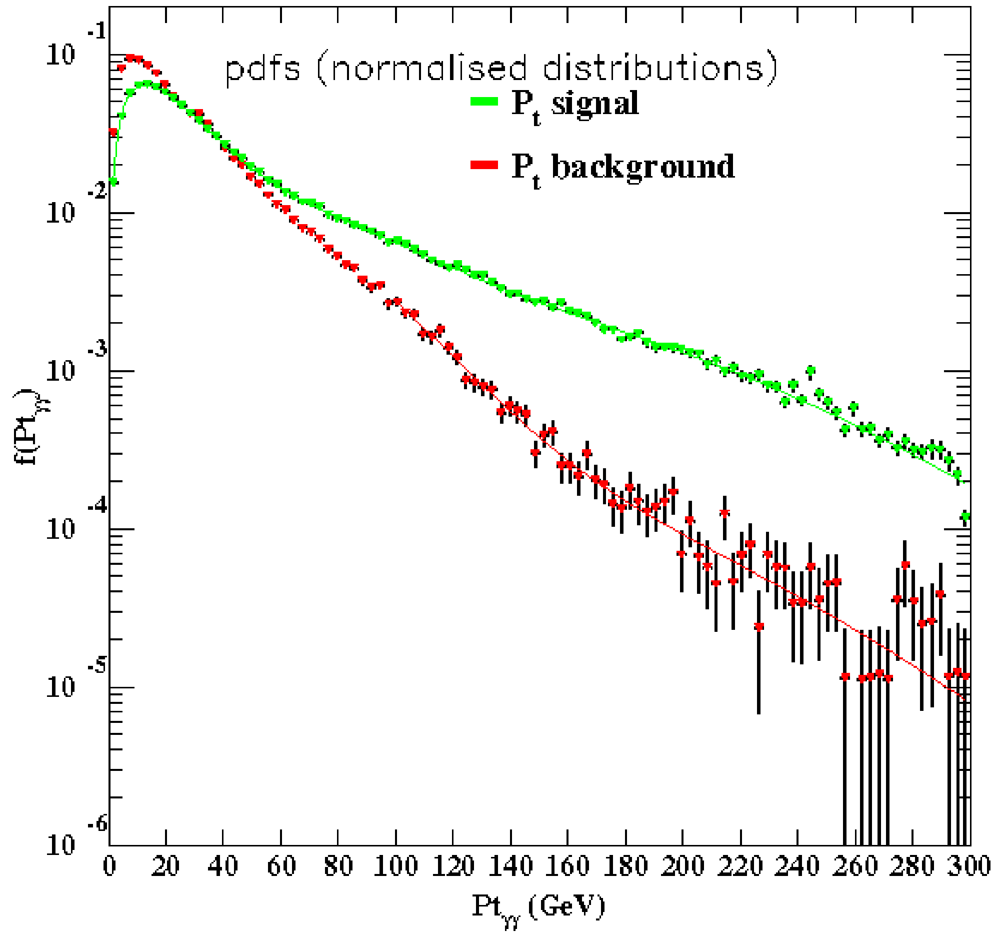
- The qg and $q\bar{q}$ subprocesses dominate. The glue glue portion is small even at the LHC. $q\bar{q}$:qg:$gg = 30 : 50 : 20$ at LHC
  vs. $70 : 20 : 10$ at the Tevatron
  Probably need order α_s^2 corrections for qg at the LHC

$\gamma\gamma$ *Prediction for the LHC*

- The Q_T distribution of the background broadens with increasing $m_{\gamma\gamma}$, (as it does also for the Higgs boson signal for increasing m_h Berger and Qiu, PRD 67, 034026 (2003))
- For the SM Higgs boson mass range, 115 to 130 GeV, the $\gamma\gamma$ background peaks at a smaller value of Q_T than the Higgs boson signal
- The $qg \to \gamma\gamma X$ and $q\bar{q} \to \gamma\gamma X$ subprocesses that dominate QCD background have a softer Q_T spectrum than that for Higgs boson production because there is less gluon radiation in fermionic subprocesses
- Selection of events with large $Q_T^{\gamma\gamma}$ will help to improve S/B, as will selections on other distributions such as $\cos\theta^*$ and $\eta_{\gamma_1} - \eta_{\gamma_2}$

Simulation: Higgs Signal and Background

- Shapes only – normalized distributions



- M. Escalier, Eurogdr Supersymmetry workshop on SM Backgrounds, http://lyoinfo.in2p3.fr/gdrsusy05/

Conclusions and Discussion

- The two large scales, $m_{\gamma\gamma}$ and Q_T, and the fact that the fixed-order QCD contributions are singular as $Q_T \to 0$, necessitate all-orders resummation of large logarithmic contributions to obtain reliable predictions for Q_T distributions of $pp \to \gamma\gamma X$
- Good agreement with CDF data on $p\bar{p} \to \gamma\gamma X$ at $\sqrt{S} = 1.96$ TeV
  - further (more differential) tests suggested in hep-ph/0603037
- Predictions presented for Q_T distributions of Higgs boson and $\gamma\gamma$ production at $\sqrt{S} = 14$ TeV for $m_{\gamma\gamma} = 60$ to 200 GeV
- $g + g \to hX$ dominates inclusive Higgs boson production at the LHC
- Irreducible backgrounds in the $h \to \gamma\gamma$ decay channel arise from fermionic subprocesses ($q\bar{q} \to \gamma\gamma X$; $qg \to \gamma\gamma X$) and gluonic subprocesses ($gg \to \gamma\gamma X$). The qg and $q\bar{q}$ subprocesses dominate. They have a softer Q_T spectrum than $gg \to hX$. $\to$ a selection of events with large $Q_T^{\gamma\gamma}$ should improve S/B