Photon Pair Production at the LHC Higgs Signal and QCD Backgrounds

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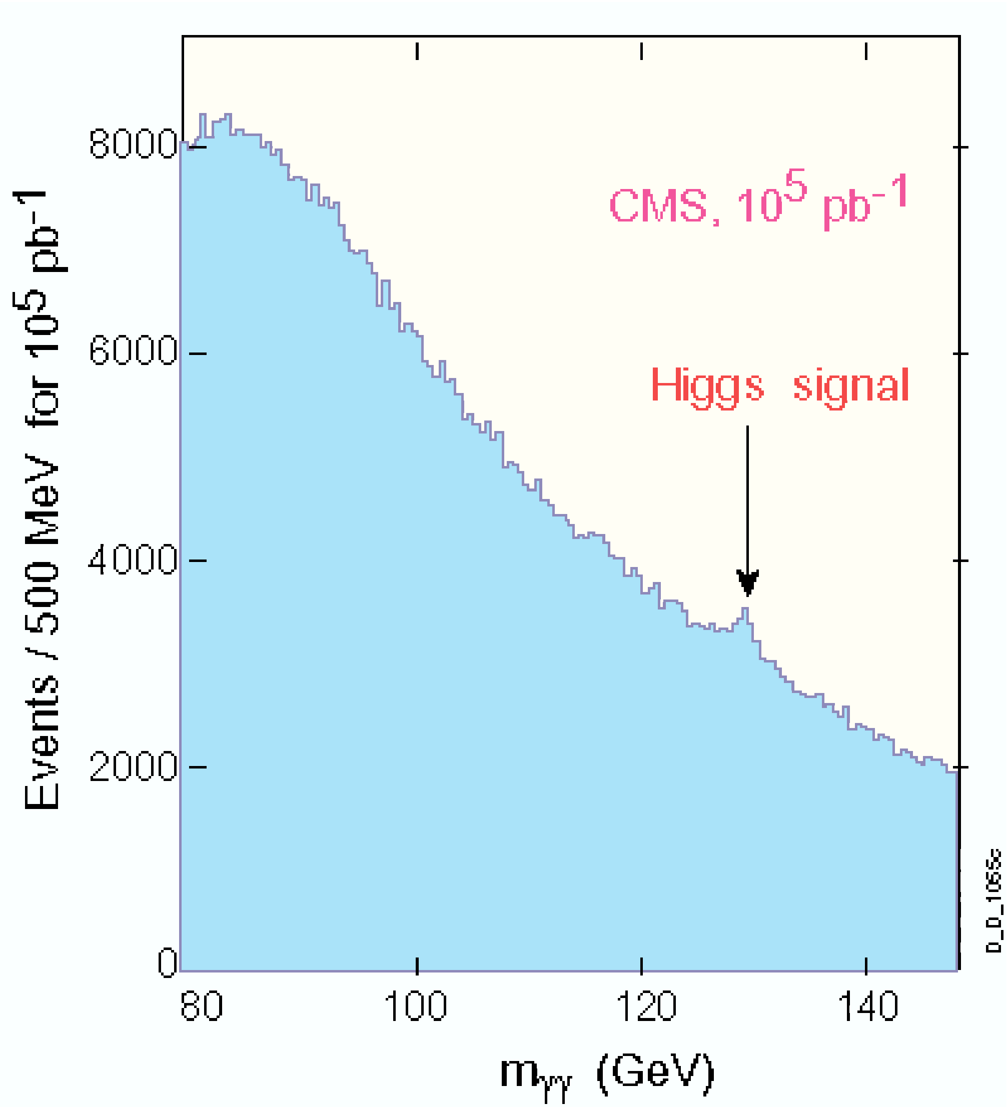
5. Summary and Discussion

Higgs Boson Search at the LHC

- Discover/understand the mechanism for electroweak symmetry breaking: a clear goal of hadron collider experiments during the next decade
- ATLAS and CMS Objectives:
  - Do a thorough search for Higgs bosons
  - Measure their properties and determine their couplings
- Help guide the search with theoretical predictions for the signal and backgrounds
- Focus in this talk on the $\gamma\gamma$ final state:
  - Signal $h \rightarrow \gamma\gamma$ and background from all QCD subprocesses

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

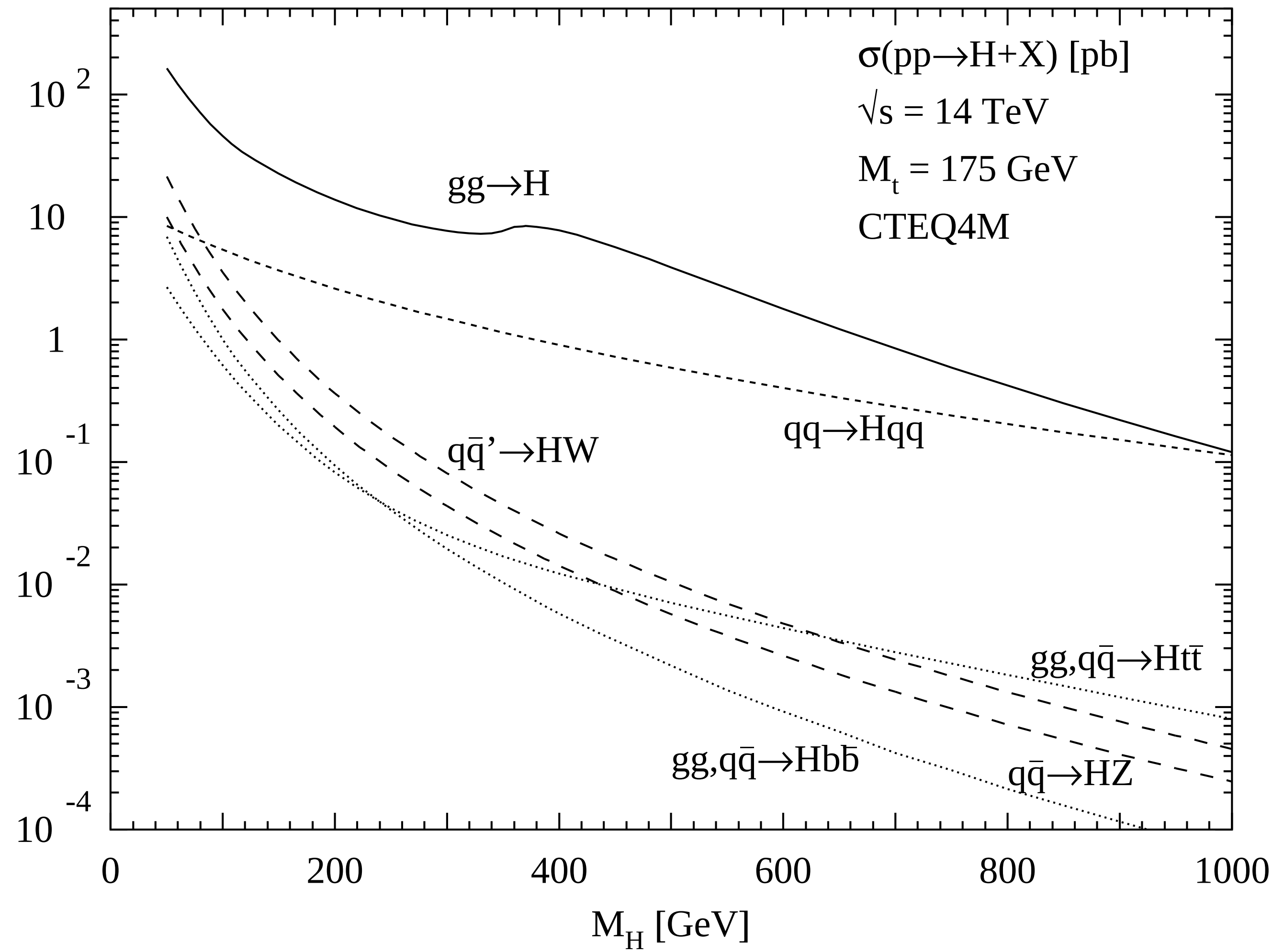
Transverse momentum Q_T distribution

- Event modeling, kinematical 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

Cross sections for Higgs Boson Production

M. Spira

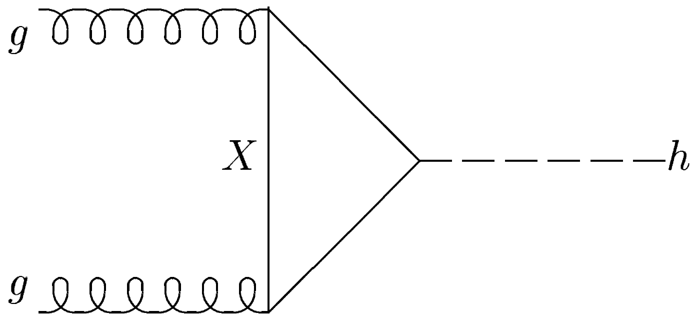
- The fully inclusive gluon-gluon fusion subprocess $gg \to hX$ is the dominant production mechanism for Higgs bosons



glue glue fusion for Higgs production

- lowest order triangle graph

  $X = t, b, \tilde{q}$

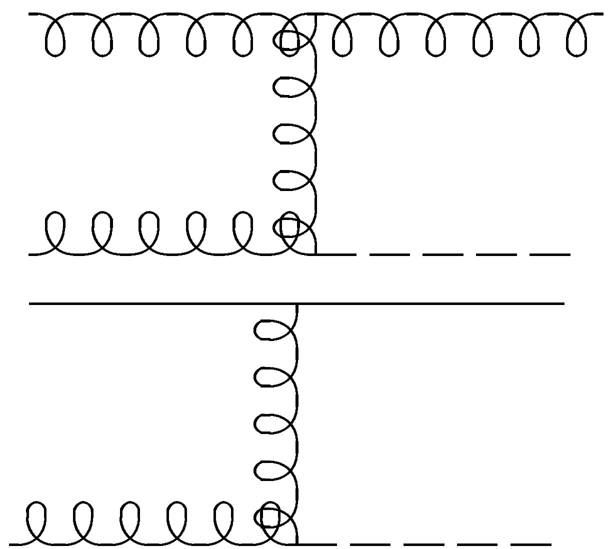


- In the SM, the top quark t contribution dominates
- Take the limit $m_t \to \infty$. The triangle collapses to a point. The predicted cross section agrees within 5% with the triangle cross section for $m_h < 2m_t$
- NLO and NNLO contributions to the inclusive rate are large

  Spira, Djouadi, Graudenz, and Zerwas; Dawson and Kauffman; Harlander and Kilgore; Anastasiou and Melnikov

Cross section at finite transverse momentum Q_T

- At zero-th order, the triangle diagram produces a $\delta^2(\vec{Q}_T)$-function transverse momentum distribution
- Finite Higgs boson transverse momentum is provided at order α_s by gg, qg, and $q\bar{q}$ subprocesses

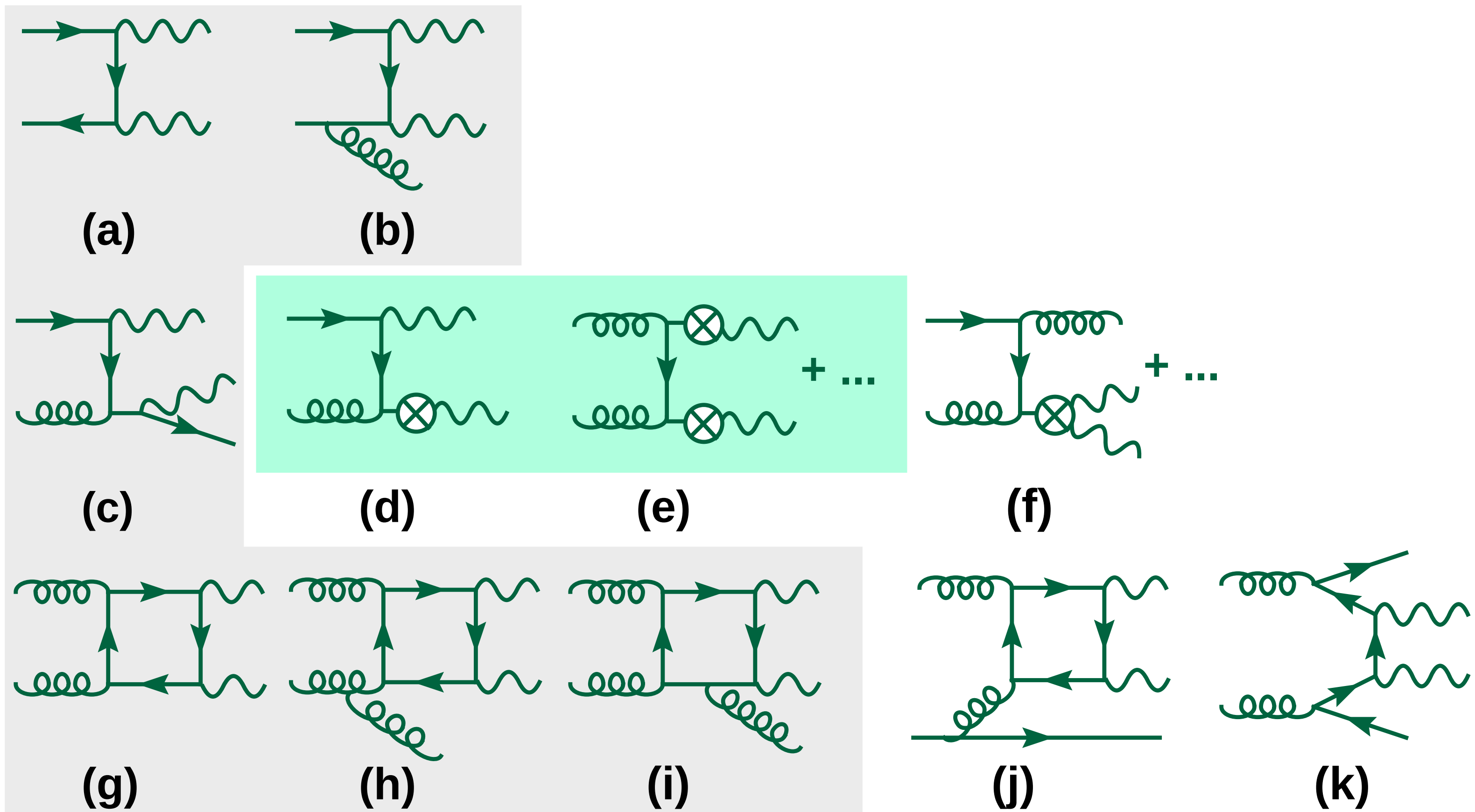


- Also $gg \to g^* \to gh$ and $q\bar{q} \to g^* \to gh$
- Differential cross section at fixed-order, NNLO, exists

Anastasiou, Melnikov, Petriello

QCD Production of Photon Pairs

- QCD 'background' subprocesses initiated by $q\bar{q}$, qg and gg subprocesses



- 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

  $\frac{\sigma^{\mathrm{NLO}}}{\sigma^{\mathrm{LO}}} = \mathcal{O}(\alpha_s \log^2(m_{\gamma\gamma}^2/Q_T^2))$ 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

Structure of the perturbative expansion

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

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

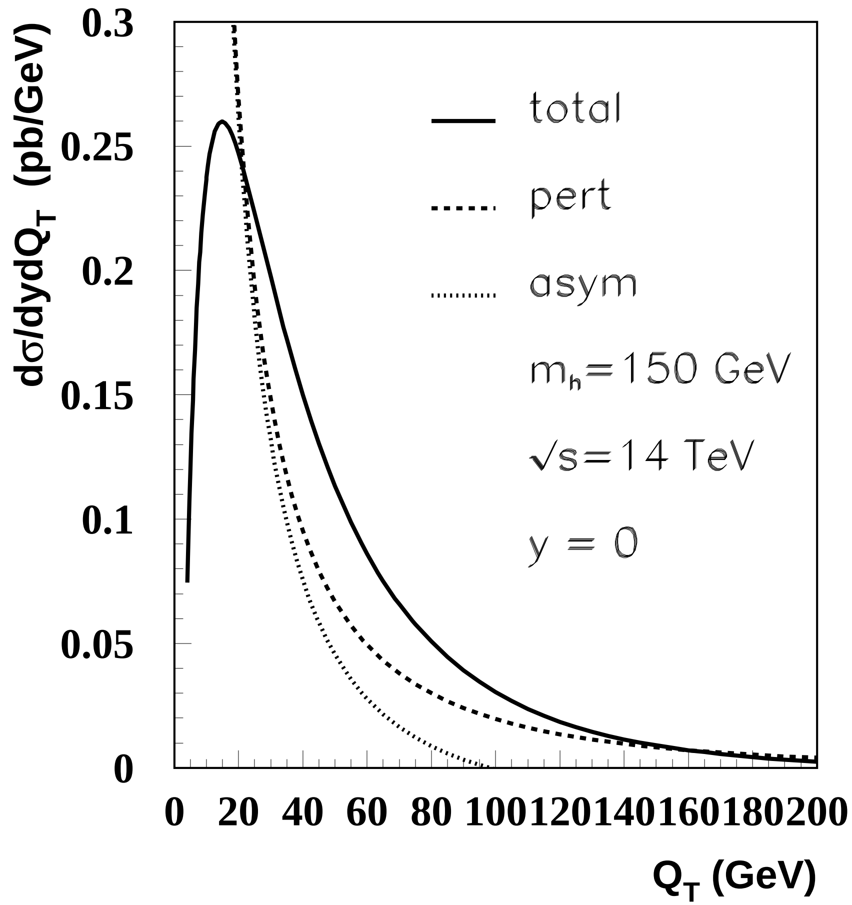
- In a fixed order calculation (column by column), convergence at small Q_T is compromised by higher order uncalculated logarithmic terms
- In a resummed calculation (line by line), convergence is preserved in each "order" (each line), and higher order corrections are included systematically
- Expand 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 $Q_T \to 0$

Higgs boson differential cross section at LHC

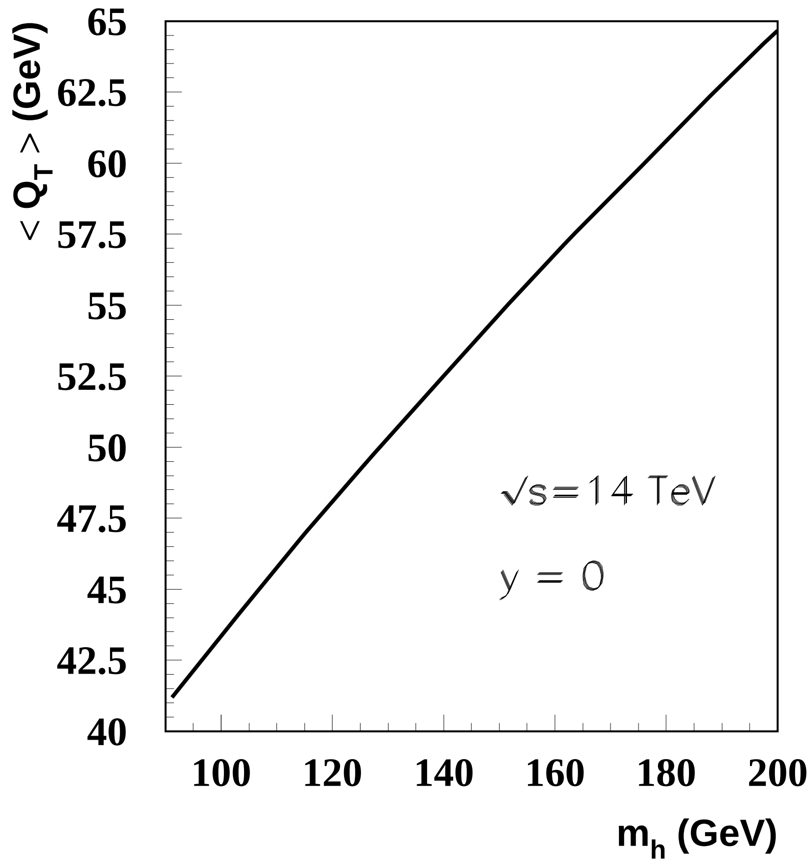
Berger and Qiu Phys Rev D67, 034026 (2003)



- Observe the divergence as $Q_T \to 0$ of the fixed-order result (`pert')
- The total prediction is dominated by the resummed result for $Q_T \leq Q$
- Resummation provides a well behaved $d\sigma/dQ_T$ at all Q_T.

  It changes the predicted shape and normalization in the region of Q_T where the cross section is large

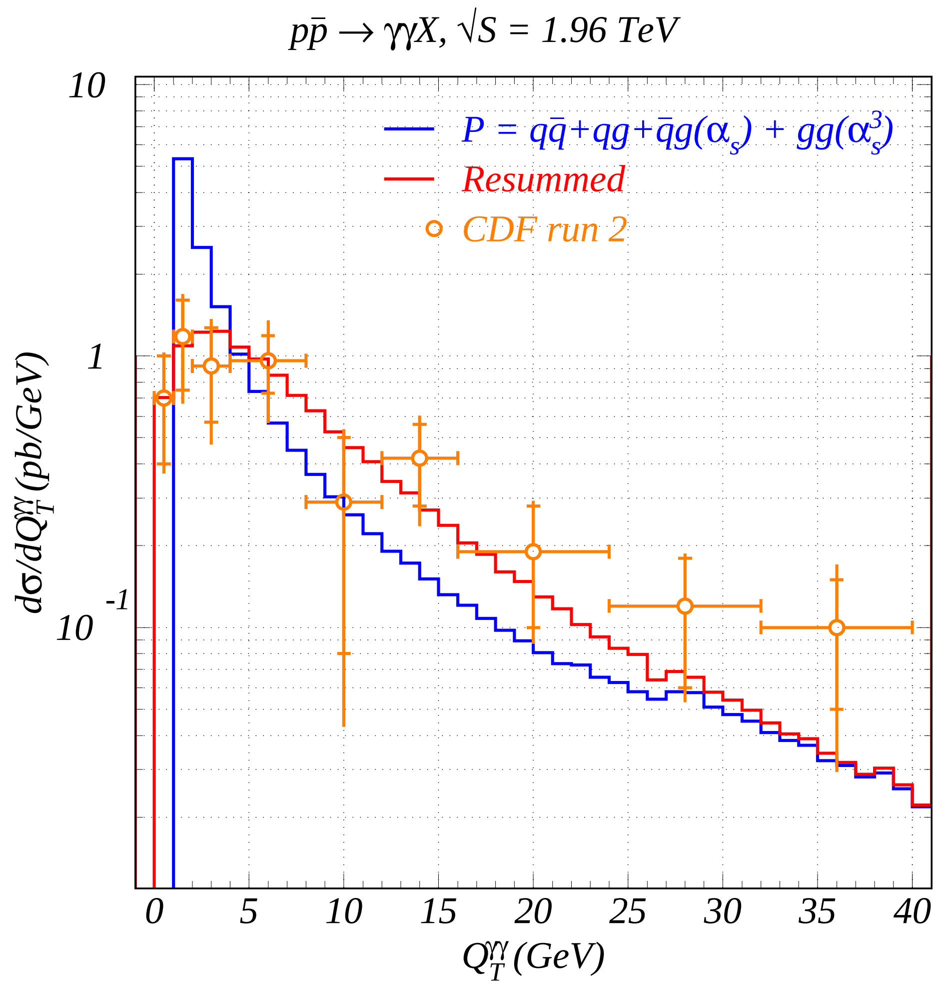
Average $\langle Q_T \rangle$ for Higgs boson production at LHC vs m_h *Berger and Qiu Phys Rev D67, 034026 (2003)*



- $\langle Q_T \rangle$ grows from about 41 GeV at $m_h = M_Z$ to about 65 GeV at $m_h = 200$ GeV
- Nearly a straight line over the range shown, with $\langle Q_T \rangle \simeq 0.21 m_h + 22$ GeV

Comparison of our results with the CDF Run 2 data

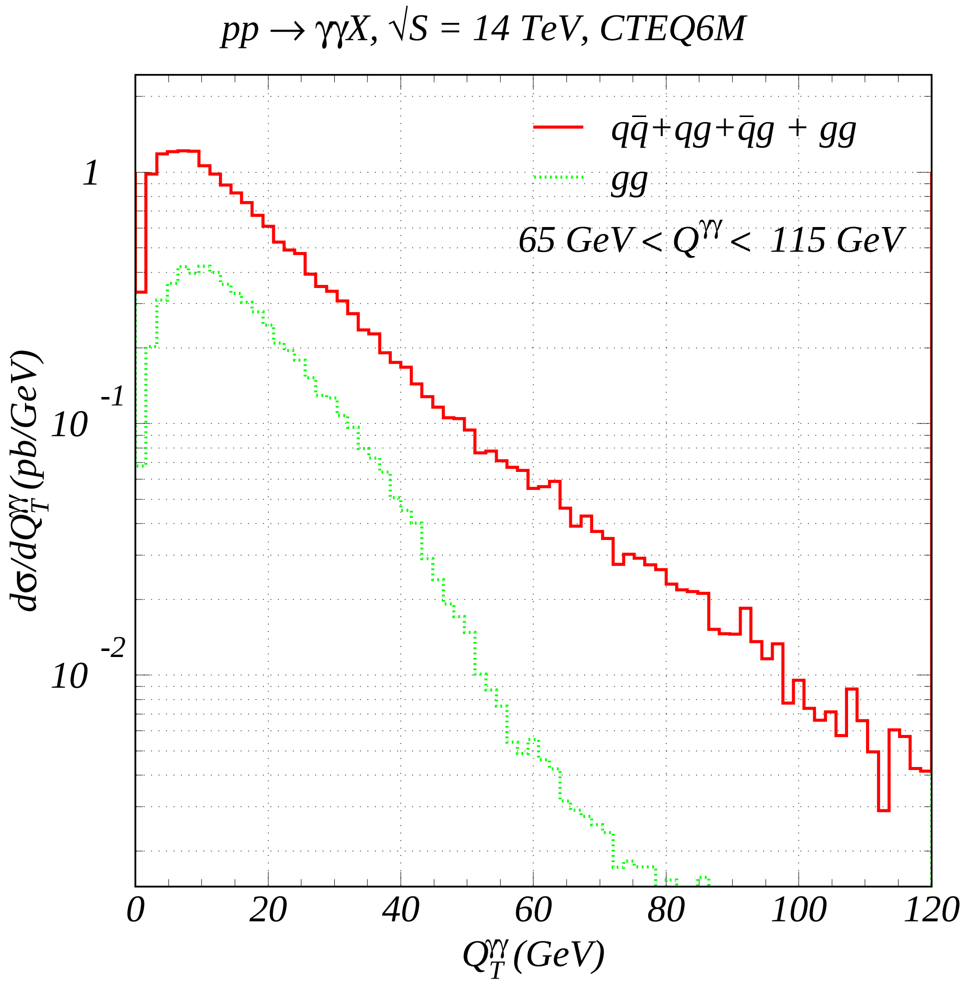
Balazs, Berger, Nadolsky, Yuan, hep-ph/0603037



- Resummed calculation differs in shape and normalization from the finite-order perturbative result (P); it agrees well with data
- Discrepancy at the larger values of Q_T is understood – related to the region of small $m_{\gamma\gamma}$ ($< Q_T$) and small $\Delta\phi$ where other physical effects dominate – not of concern at the LHC

Prediction for the LHC Balazs, Berger, Nadolsky, Yuan

- Example for $\gamma\gamma$ invariant mass in the interval 65 to 115 GeV



- The qg and $q\bar{q}$ subprocesses dominate. The glue glue subprocess is a small portion of the answer even at the LHC

Prediction for the LHC Balazs, Berger, Nadolsky, Yuan

- The Q_T distribution broadens with increasing $m_{\gamma\gamma}$, just as it does for increasing m_h
- For $m_{\gamma\gamma} =$ (55-65, 65-95, 95-130, and 130-250) GeV $\langle Q_T \rangle =$ (14, 17, 25, and 33) GeV.
- For the SM Higgs boson mass range, 115 to 130 GeV, the $\gamma\gamma$ background has $\langle Q_T \rangle \sim 27$ GeV, vs. ~ 40 GeV for the Higgs boson signal

Conclusions and Discussion

- Subprocess $g + g \to hX$ dominates inclusive Higgs boson production at LHC with $m_h < 200$ GeV
- 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 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 predictions for Q_T distributions
- Good agreement with CDF data on $p\bar{p} \to \gamma\gamma X$ at $\sqrt{S} = 1.96$ TeV
- Predictions presented for Q_T distributions of Higgs boson and $\gamma\gamma$ production at $\sqrt{S} = 14$ TeV for $m_{\gamma\gamma} = M_Z$ to 200 GeV

Conclusions, continued

- For $m_{\gamma\gamma} = m_h$, the shape of the Q_T spectrum of the gg contributions to the irreducible background will be the same after soft gluon resummation as that for the Higgs boson
- However, the $qg \to \gamma\gamma X$ and $q\bar{q} \to \gamma\gamma X$ subprocesses dominate the $\gamma\gamma$ QCD background. They have a softer Q_T spectrum than that for the Higgs boson because there is less gluon radiation in fermionic subprocesses
- Suggestion a selection of events with large $Q_T^{\gamma\gamma}$ will help to improve S/B. The challenge at the LHC remains formidable