Measurements with Prompt Isolated Photons at CDF using the full Data Set

Costas Vellidis

for the CDF Collaboration

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Prompt photon production in hadron colliders

- **Prompt photons** = emitted from quarks in hard scattering processes, as opposed to coming from neutral hadron decays (reducible background in cross section measurements)

- The cleanest probe of QCD – elementary particles, can be measured with *high precision* in modern calorimeters

- Probe for searching *new phenomena* – $\gamma\gamma$ is signature of possible heavy resonance decays

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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 η–φ plane, and requiring:
  - Fiducial to the central calorimeter: |η|<1.1
  - \( E_T \geq 17,15 \) GeV (\( γγ \) events), 30 GeV (\( γ+b/c \) events)
  - Isolated in the calorimeter: \( I_{cal} = E_{tot}(R=0.4) - E_{EM}(R=0.4) \leq 2 \) GeV
  - Low HAD fraction: \( E_{HAD}/E_{EM} \leq 0.055 + 0.00045 \times E_T/\)GeV
  - At most one track in cluster with \( p_T^{trak} \leq 1 \) GeV/c + 0.005\( E_Tγ/c \)
  - Shower profile consistent with predefined patterns: \( \chi^2_{CES} \leq 20 \)
  - Only one high energy CES cluster: \( E_T \) of 2\(^{nd} \) CES cluster \( \leq 2.4 \) GeV + 0.01\( E_T \)

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γ+b/c production

- **Probe heavy flavor content in hadrons**

- **LO contribution**: Compton scattering – dominant at low photon $p_T$

- **NLO contribution**: Annihilation + brems – dominant at high photon $p_T$

\[ \text{Compton scattering} \sim \alpha \alpha_s \]

\[ \text{annihilation} \sim \alpha \alpha_s^2 \]

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Theoretical predictions

- **NLO** [Stavreva and Owens, 0901.3791v1]
- **Pythia** [T. Sjöstrand et al., Comp. Phys. Comm. **135**, 238 (2001)]
- **Sherpa** [T. Gleisberg et al., JHEP **02**, 007 (2009)]
- **$k_T$ factorization** [A. Lipatov et al., JHEP 1205 (2012) 104]

- **Kinematic cuts:**
  - Generated photon: $|y|<1$, $30<p_T<300$ GeV/c, $E_T$ (iso)$<2$ GeV in the cone of 0.4 around the photon
  - b or c quark: $|y|<1.5$, $p_T>20$ GeV/c
  - $\Delta R$ between photon and the leading b or c quark $>0.4$
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<table>
<thead>
<tr>
<th></th>
<th>Total $\gamma+b$ cross section (pb)</th>
<th>Total $\gamma+c$ cross section (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>$19.7 \pm 0.7_{\text{stat}} \ (+ 5.0 – 4.2)_{\text{syst}}$</td>
<td>$132.2 \pm 4.6_{\text{stat}} \ (+ 13.2 – 19.2)_{\text{syst}}$</td>
</tr>
<tr>
<td><strong>PYTHIA</strong></td>
<td>19.5</td>
<td>106.0</td>
</tr>
<tr>
<td>SHERPA</td>
<td>29.4</td>
<td>173.9</td>
</tr>
<tr>
<td>NLO</td>
<td>$27.3 + 2.3 – 1.5$</td>
<td>$152.6 + 12.2 – 9.6$</td>
</tr>
<tr>
<td>$k_T$ factorization</td>
<td>25.2</td>
<td>106.4</td>
</tr>
</tbody>
</table>

- $b$ or $c$ quark: $|\eta|<1.5$, $p_T>20$ GeV/c
- $\Delta R$ between photon and the leading $b$ or $c$ quark $>0.4$
Best agreement with the data achieved by the \( k_T \)-factorization calculation
Comparisons – $\gamma + c$

- Comparisons look similar: $k_T$-factorization calculation is in best agreement with the data
Prompt $\gamma\gamma$ production in hadron colliders

Hard QCD (“direct” $\gamma\gamma$ production):

- $q\bar{q} \rightarrow \gamma\gamma$
- $gq \rightarrow \gamma\gamma q$
- $gg \rightarrow \gamma\gamma$

  Born: Dominant at the Tevatron

  Brems: Suppressed by the isolation requirement

  “Box”: Dominant at the LHC

Possible heavy resonance decays:

- $H \rightarrow \gamma\gamma$
- $G^* \rightarrow \gamma\gamma$
- $W \rightarrow \gamma\gamma + X$

  Low-mass Higgs boson (most sensitive channel at LHC for $m_H < 125$ GeV/c$^2$)

  Extra dimensions

  SUSY

Better control on these processes [$\sigma \sim O(10 \text{ pb})$ at the Tevatron]

More sensitive searches for such processes [$\sigma \times \text{BR} \sim O(1 \text{ fb})$ at the Tevatron]
Theoretical predictions

- **PYTHIA** LO parton-shower calculation

- **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

- **DIPHOX**: Fixed-order NLO calculation including non-perturbative fragmentation at NLO

- **RESBOS**: Low-$P_T$ analytically resummed calculation matched to high-$P_T$ NLO

- **NNLO** calculation with $q_T$ subtraction

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<table>
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<tr>
<th>Calculation</th>
<th>Total cross section (pb)</th>
</tr>
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<tbody>
<tr>
<td>Data</td>
<td>$12.3 \pm 0.2_{\text{stat}} \pm 3.5_{\text{syst}}$</td>
</tr>
<tr>
<td>RESBOS</td>
<td>$11.3 \pm 2.4$</td>
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<tr>
<td>DIPHOX</td>
<td>$10.6 \pm 0.6$</td>
</tr>
<tr>
<td>MCFM</td>
<td>$11.6 \pm 0.3$</td>
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<tr>
<td>SHERPA</td>
<td>$10.9$</td>
</tr>
<tr>
<td><strong>PYTHIA</strong> $\gamma\gamma + \gamma j$</td>
<td>$9.2$</td>
</tr>
<tr>
<td><strong>PYTHIA</strong> $\gamma\gamma$</td>
<td>$5.0$</td>
</tr>
<tr>
<td><strong>NNLO</strong></td>
<td>$11.8 + 1.7 - 0.6$</td>
</tr>
</tbody>
</table>

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Differential cross sections

- Good agreement between data and theory for $M_{\gamma\gamma}>30$ GeV/c²
- Resummation important for $P_T(\gamma\gamma)>20$ GeV/c
- Fragmentation causes excess of data over theory for $P_T(\gamma\gamma)=20-50$ GeV/c (the “Guillet shoulder”)
- Resummation important for $\Delta\phi_{\gamma\gamma}>2.2$ rad
- Data spectrum harder than predicted

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Data-to-theory cross section ratios

Note: Vertical axis scales are not the same.

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

• SHERPA and NNLO describe the “shoulder” of the data at $P_T(\gamma\gamma) = 20 - 50$ GeV/c

• Only NNLO describes the full $\Delta\phi_{\gamma\gamma}$ data spectrum

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Data-to-theory cross section ratios

NB: Vertical axis scales are not the same

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Summary and conclusions

- High precision measurements of $\gamma+b/c$ and $\gamma\gamma$ cross sections are measured with the full CDF dataset.

- The $\gamma+b/c$ data are compared with PYTHIA, SHERPA, NLO and $k_T$-factorization calculations; the $k_T$-factorization provides the best description of the data.

- The $\gamma\gamma$ data are compared with parton shower, fixed-order NLO and analytically resummed calculations.

- The SHERPA calculation, in the overall, provides a very good description of the $\gamma\gamma$ data, but still is somewhat low in regions sensitive to fragmentation (very low mass, very low $\Delta\phi$, large $|\cos\theta|$).

- The RESBOS calculation provides the best description of the $\gamma\gamma$ data at low $P_T$, where resummation is important, but fails in regions sensitive to fragmentation.

- After top quark and Higgs boson production, a NNLO $\gamma\gamma$ production calculation is now available; in the overall, it provides the best description of the data.

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Backup slides
Operated through 09/30/2011
Delivered $\sim 12 \text{ fb}^{-1}$
Up to $\sim 10 \text{ fb}^{-1}$ recorded by each experiment

Fermilab Tevatron

Many thanks to the Accelerator Division!

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CDF detector overview

- **Tracking:**
  - Drift chamber, $|\eta|<1$
  - Silicon microstrip tracker, $|\eta|<2$
  - Allows also for precise vertex reconstruction

- **Calorimeter:**
  - Split in EM (scintillator – lead) and HAD (scintillator – iron) sampling devices, $|\eta|<1.1$ (central), $1.1<|\eta|<3.6$ (plug)

- **Muon system:**
  - Drift chambers outside calorimeter, $|\eta|<1.5$

- **Central electromagnetic calorimeter ($|\eta|<1.1$):**
  - Tower segmentation: $\Delta\eta \times \Delta\phi \approx 0.1 \times 15^\circ$
  - Resolution: $\sigma(E)/E = 13.5\%/\sqrt{E\text{ (GeV)}} \pm 1.5\%$
  - Proportional chambers (CES) at 6 rad. lengths depth (shower max) give location and 2D profile of the EM showers (position resolution $\sim2$ mm for 50 GeV $\gamma$)

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• Measure photon+b/c cross section using the full CDF dataset – 9.1 fb⁻¹ inclusive photon data
• Use NN to select photon candidates
  – Fit NN distribution with signal/background templates to get photon fraction
• Use SecVtx tagging to select heavy-flavor jets
  – Fit secondary vertex invariant mass to get light/c/b quark fractions
• Use inclusive photon MC to get unfolding factor
• Cross section:
  – \((N_{\text{data}}-N_{\text{fake photons}}) \times f_{b/c}/\text{unfolding factor/lumi/bin width}\)
Previous results from the Tevatron

**DO: PRL 102, 192002 (2009) - 1 fb⁻¹**

**CDF: PRD 81, 052006 (2010) - 340 pb⁻¹**

Good agreement for $\gamma+b$

Large discrepancy for $\gamma+c$

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The inclusive photon spectrum

![Graph showing the inclusive photon spectrum with various data points and theoretical predictions.](chart.png)
Aspects of the theory: Fragmentation

- The pQCD cross section is divergent when $q$ and $\gamma$ are collinear. Non-perturbative feature of the theory, handled with phenomenological “fragmentation functions” derived e.g. from the VMD model [L. Bourhis et al., Eur. Phys. J. C 2, 529 (1998)].

- Fragmentation contributions can be suppressed by
  - $P_T(\gamma\gamma) < M(\gamma\gamma)$
  - Experimental photon isolation requirements

\[ E_{T_{\text{iso}}} = \sum_{\text{partons or hadrons}} E_T - E_{T\gamma} \]

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Aspects of the theory: Resummation

The cross section for

\[ \frac{\alpha_s^n}{P_T^2(\gamma\gamma)} \ln^m \frac{M^2(\gamma\gamma)}{P_T^2(\gamma\gamma)} \]

contains singular terms at \( P_T(\gamma\gamma) \) and \( M(\gamma\gamma) \neq 0 \) of the form

\[ \alpha_s^n \delta(\tilde{P}_T(\gamma\gamma)) \]

or

\[ \alpha_s^n \ln^m \frac{M^2(\gamma\gamma)}{P_T^2(\gamma\gamma)} \]

\[ n = 1, \ldots, \infty \quad m = 0, \ldots, 2n - 1 \]

Need to add soft gluon emission:

- Two ways of doing this:
  - Approach the \( P_T(\gamma\gamma) \to 0 \) limit with an analytically calculated cross section derived from the sum of the singular terms for all \( n \) and \( m = 1, 2, 3 \) (next-to-next-to-leading log accuracy, NNLL), which is then smoothly matched to the perturbative cross section at high \( P_T(\gamma\gamma) \)
  - Use parton showering to add gluon radiation in a Monte Carlo simulation framework which effectively resums the cross section for all \( n \) and \( m = 1 \) (leading-log accuracy, LL)
Previously measurements at the Tevatron

- CDF publication in Run II with 207 pb$^{-1}$. *PRL 95, 022003 (2005) PRD 76, 013009 (2007)*
- Event selection: $p_{T(1,2)}>14(13)$ GeV, $|\eta_{1,2}|<0.9$, $\Delta R(\gamma,\gamma)>0.3$, $E_{T}^{\text{iso}}<1$ GeV.

- $p\bar{p} \rightarrow \gamma\gamma X$, CDF Run-2, 207 pb$^{-1}$

- $P_{T}(\gamma\gamma)>25$ GeV region in data dominated by events with $P_{T}(\gamma\gamma)>M(\gamma\gamma)$ and $\Delta \phi(\gamma,\gamma)<\pi/2 \Rightarrow$ potentially large fragmentation contributions.

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Previously measurements at the Tevatron

- D0 publication in Run II with 4.2 fb^{-1}
- $p_{T1(2)}>21(20)$ GeV/c, $|\eta_{1,2}|<1$, $\Delta R(\gamma,\gamma)>0.4$, $(E_{\text{tot}}^{R=0.4} - E_{\text{em}}^{R=0.2})/E_{\text{em}}^{R=0.2} < 0.1$, $P_T(\gamma\gamma)<M(\gamma\gamma)$

- Good agreement between data and RESBOS for $M_{\gamma\gamma}>50$ GeV/c^2
- Need for a resummed calculation
- Data spectrum harder than predicted
- Observable nearly insensitive to experimental effects
- Supports conclusion from $P_T(\gamma\gamma)$ measurement

(*) Overall normalization uncertainty (7.3%) not included in data error bars.

Here the PYTHIA prediction uses only matrix element based production of photon pairs

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Background subtraction

\[
\frac{d\sigma}{dX} = \frac{N_{\gamma\gamma}}{\epsilon \cdot A \cdot L \cdot \Delta}
\]

Jets misidentified as photons: dijet and \(\gamma \text{+jet}\)

- Fluctuations in jet fragmentation to leading \(\pi^0\) or \(\eta^0\) meson \((\pi^0, \eta^0 \rightarrow \gamma\gamma)\)
- Normalization and shape estimated from MC using track isolation:
  \[
  I_{\text{trk}} = \sum_{\text{tracks in } R<0.4} p_T^{\text{trk}}
  \]

- Sensitive only to underlying event and jet fragmentation (for fake \(\gamma\)), 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

Substantially different shape of signal and background \(I_{\text{trk}}\) distributions can be used to characterize true and fake \(\gamma\)

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**Acceptance × efficiency**

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

**Number of events with two reconstructed EM clusters passing all cuts**

**Number of events with two generator-level photons passing kinematic and isolation cuts**

- Defined as:

  \[\text{Number of events with two reconstructed EM clusters passing all cuts}\]

  \[\text{Number of events with two generator-level photons passing kinematic and isolation cuts}\]

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

- Procedure iterated to match PYTHIA to the data

- Corrected to parton level for comparison with NLO theory

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

Average efficiency ~40%
Total systematic uncertainty: ~7-15%
Comparable statistical uncertainty

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Experimental kinematic and isolation cuts are also applied to all theoretical calculations compared with the data:

- Central photons required: $|\gamma| < 1.1$
- $E_T \geq 17$ GeV (1\textsuperscript{st} $\gamma$ in the event), 15 GeV (2\textsuperscript{nd} $\gamma$)
- Isolated in the calorimeter: $I_{\text{cal}} = E_{\text{tot}}(R=0.4) - E_{\text{EM}}(R=0.4) \leq 2$ GeV

\[ \Delta R(\gamma, \gamma) \geq 0.4 \]

Applied at the parton level in DIPHOX, RESBOS, MCFM can only approximate the experimental isolation

- NLO theoretical uncertainties:
  - PDFs: 3-6%; use 44 eigenvectors from CTEQ6M
  - Renormalization/factorization/fragmentation scales: $\sim$10-20% depending on the observable; all scales simultaneously varied by $\times2$ up and down

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Kinematic variables

\[ M = \sqrt{\left(p_{\gamma 1}^\mu + p_{\gamma 2}^\mu\right)^2} \]

\[ P_T = \left| \left( \vec{p}_{\gamma 1} + \vec{p}_{\gamma 2} \right) - \left( \vec{p}_{\gamma 1} + \vec{p}_{\gamma 2} \right) \cdot \hat{z} \right| \]

\[ \Delta \phi = \left| \phi_{\gamma 1} - \phi_{\gamma 2} \right| \mod \pi \]

\[ Y_{\gamma\gamma} = \tanh^{-1} \frac{\left( \vec{p}_{\gamma 1} + \vec{p}_{\gamma 2} \right) \cdot \hat{z}}{\left| \vec{p}_{\gamma 1} \right| + \left| \vec{p}_{\gamma 1} \right|} \]

\[ z = \frac{p_{T\gamma 1}^<}{p_{T\gamma}} \]

\[ \cos \theta = \frac{2p_{T\gamma 1}p_{T\gamma 2} \sinh(y_{\gamma 1} - y_{\gamma 2})}{M \sqrt{M^2 + P_T^2}} \]

\[ \begin{align*}
\cos \theta &\rightarrow \tanh \frac{y_{\gamma 1} - y_{\gamma 2}}{2} \approx 0 \quad (P_T \ll M) \\
\cos^2 \theta &\rightarrow \frac{4p_{T\gamma 1}p_{T\gamma 2}}{\left( p_{T\gamma 1} + p_{T\gamma 2} \right)^2} \approx 1 \quad (P_T \gg M)
\end{align*} \]

Low-\(p_T\)/high-\(p_T\) ratio of the photon pair (\(z\leq1\))

Cosine of the leading photon polar angle in the Collins-Soper frame (\(\gamma\gamma\) rest frame with the polar axis bisecting the angle between the colliding hadrons)

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The success of parton-shower Monte Carlo is important for the search of a low-mass Higgs boson and of new physics:

- Provides a reliable background model for these searches in the framework of realistic event representation suitable for simulation of collider experiments

- Can be used in the Higgs→γγ search based on a multivariate analysis that exploits the full γγ event information—all kinematic variables that can help discriminate Higgs boson decays from QCD γγ events (see arXiv:1107.4587)

- Can also be used in searches of new physics in the mass range where data are not enough to model the QCD background by data-driven methods

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