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
• $\gamma +$ heavy flavor production
• $\gamma \gamma$ 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

Direct photon.

Fragmentation photon.

Photons produced in fragmentation process fail the isolation & energy cuts
The Experimental Apparatus

Both CDF & D0 detectors measure $e, \mu, \gamma, \text{jets}, \tau$ 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

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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

D0: “SVT”, “JLIP” algorithms
NIM A 620 490 (2010)
# Photon Fiducials

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<tr>
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<th>CDF</th>
<th>DØ</th>
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<tr>
<td><strong>ΔR Isolation Cones</strong></td>
<td>$E_{\text{TOT}}(&lt;0.4) - E_{\text{EM}}(&lt;0.4) \leq 2 \text{ GeV}$</td>
<td>$E_{\text{TOT}}(&lt;0.4) - E_{\text{EM}}(&lt;0.2) \leq 2.5 \text{ GeV}$</td>
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<tr>
<td></td>
<td>Tracking isolation analysis dependent</td>
<td>$P_T(&lt;0.4) - P_T(&lt;0.2) \leq 1.5 \text{ GeV}$</td>
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<td><strong>Minimum momentum ⊥ to beam (calorimeter)</strong></td>
<td>$E_T(\gamma) &gt; 30 \text{ GeV}$  $\gamma + \text{HF}$</td>
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<td>$E_T(\gamma) &gt; 17 / 15 \text{ GeV}$  $\gamma\gamma$</td>
<td>$E_T(\gamma) &gt; 18 / 17 \text{ GeV}$  $\gamma\gamma$</td>
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Photons for $\gamma + HF$

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.

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Photons for $\gamma\gamma$

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

\[
\begin{bmatrix}
N_{ff} \\
N_{fp} \\
N_{pf} \\
N_{pp}
\end{bmatrix} =
\begin{bmatrix}
(1-\epsilon_b)(1-\epsilon_b) & (1-\epsilon_b)(1-\epsilon_s) & (1-\epsilon_s)(1-\epsilon_b) & (1-\epsilon_s)(1-\epsilon_s) \\
(1-\epsilon_b)\epsilon_b & (1-\epsilon_b)\epsilon_s & (1-\epsilon_s)\epsilon_b & (1-\epsilon_s)\epsilon_s \\
\epsilon_b(1-\epsilon_b) & \epsilon_b(1-\epsilon_s) & \epsilon_s(1-\epsilon_b) & \epsilon_s(1-\epsilon_s) \\
\epsilon_b\epsilon_b & \epsilon_b\epsilon_s & \epsilon_s\epsilon_b & \epsilon_s\epsilon_s
\end{bmatrix}
\begin{bmatrix}
N_{bb} \\
N_{bs} \\
N_{sb} \\
N_{ss}
\end{bmatrix}
\]

- D0 does a 2D fit to neural network outputs (cross-checks w/ matrix)
\( \gamma + \text{HF production in } p\bar{p} \)

“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-\(|\eta|\) \( \gamma \) detection, covers parton \( x \) between 0.007 and 0.4
\[ \gamma + \text{HF} \; \frac{d\sigma}{dE_T^\gamma} \; \text{Results} \]

Experimental systematics $\sim 16\text{-}35\%$

and dominated by $b/c$ jet fraction uncertainties

Parton $\rightarrow$ hadron correction for NLO and $k_T$ from SHERPA

$c$ results much more uncertain than $b$ 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
\section*{\textbf{\textgamma + HF \ d\sigma/dE_T^\gamma \ Results}}

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

Parton $\rightarrow$ 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 $E_T(\gamma)$

$\gamma + \text{HF} \quad d\sigma/dE_T^\gamma$ 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

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\( \gamma \gamma \) production in \( pp \)

Leading contributions at Tevatron are \( q\bar{q} \)

\( gg \) when glue PDFs are large; \( gg \) larger at LHC

\( gq \) also large at LHC

Even after isolation cuts, fragmentation contributions are still considerable

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

and azimuthal opening angle \( \Delta\phi(\gamma\gamma) < \pi/2 \)
NNLO is Catani et al. PRL 108, 072011 (2012)

$2\gamma$NNLO 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

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

arXiv:1301.4536
Submitted to PLB
$m(\gamma\gamma)$ Results

Integrated cross section (pb)

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<th>Value</th>
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<tbody>
<tr>
<td>Data</td>
<td>$12.3 \pm 0.2_{\text{STAT}} \pm 3.5_{\text{SYST}}$</td>
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<tr>
<td>SHERPA</td>
<td>$12.4 \pm 4.4$</td>
</tr>
<tr>
<td>MCFM</td>
<td>$11.5 \pm 0.3$</td>
</tr>
<tr>
<td>NNLO</td>
<td>$11.8 \pm 1.7$</td>
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Many distributions available in the papers-

arXiv:1212.4204
Conclusions

$\gamma + \text{HF}$ and $\gamma\gamma$ production measured with full Tevatron dataset
NLO predictions below data for $\gamma + \text{HF}$ at $E_{T}(\gamma) > 70$ GeV
PYTHIA also low for $\gamma + \text{HF}$, 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 $\gamma+\text{jet}$ 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

DØ, $L = 8.7 \text{ fb}^{-1}$

(a) $|y|<1.0$

(b) $1.5<|y|<2.5$

CDF Run II Preliminary

CDF data, $L=9.1 \text{ fb}^{-1}$

- observed light jets
- observed c jets
- observed b jets
Re. models for $\gamma + \text{HF}$

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

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

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

- SHERPA has matrix elements for $\gamma +$ up to 3 jets of which one is HF. CT10 [CDF] and CTEQ6.6M [D0]
Re. models for $\gamma\gamma$

- **PYTHIA**: $2\rightarrow 2$ ME + PS, string fragmentation; can (& should) include $\gamma + \text{jet}$ and then filter cases where a 2nd $\gamma$ appears. CDF uses v6.2.16, D0 uses v6.420 with Tune A
- **SHERPA**: $2\rightarrow 2,3,4$ ME + PS, cluster fragmentation; novel method for matching hard to soft physics. D0 uses CTEQ6.6M & $Q_{\text{cut}} = 10$ 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 $2m_b < m(\gamma\gamma) < 2m_t$
$H\rightarrow gg$

Figure 43: $p_{T1}+p_{T2}$ in inclusive region: data and background modeling comparisons in terms of $E_T^\gamma$, $\Delta\phi^{\gamma\gamma}$ 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.
Collins–Soper Frame

We approximate $|\cos \theta|$ with $|\tanh \frac{\Delta \eta}{2}|$
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:

$$|h_{3}^{\gamma,Z}| < 0.022 \quad |h_{4}^{\gamma,Z}| < 0.0009$$
True photon fraction

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

CDF Run II Preliminary

CDF data, $L=9.1$ fb$^{-1}$

$40<\frac{E_T}{E}\leq 50$ GeV

- signal
- background

Events/0.05