

Photon + Jets at DØ

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on behalf of the DØ collaboration

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- DØ at Tevatron and photon physics

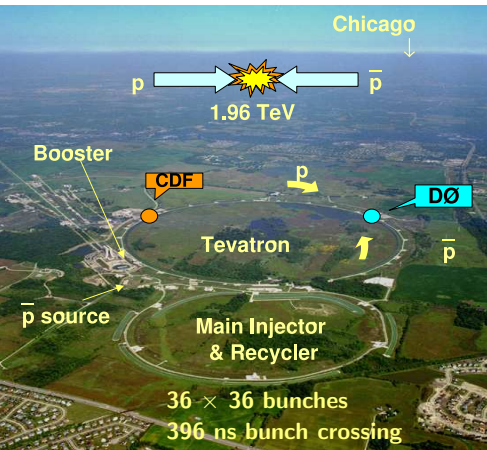
- Inclusive photon cross section

- Inclusive photon + jet cross section

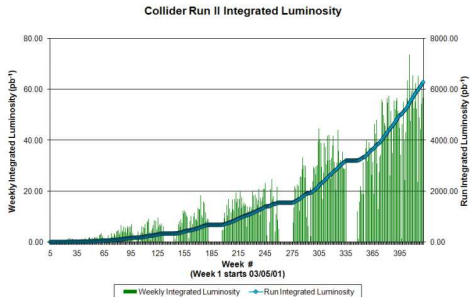
- Inclusive photon + heavy flavour jet cross section

- Double parton interactions in $\gamma + 3$ jet events

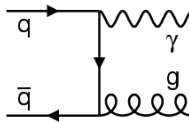
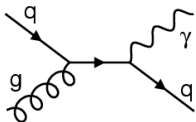
- Summary



- Run II started in March 2001
- Peak luminosity: $3.5 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- Delivered: $> 6.4 \text{ fb}^{-1}$ (Run I: 0.16 fb^{-1})
- 8-9 fb^{-1} expected by end of 2010

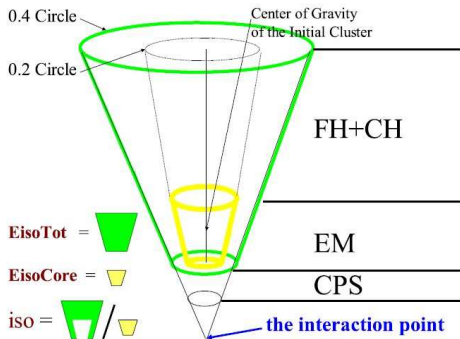
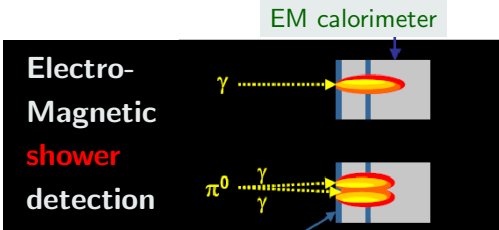


Motivation



Direct photons come unaltered from the hard subprocess
 \Rightarrow direct probe of the hard scattering dynamics

- ▶ Energy calibration of photons is better than for jets
- ▶ Large statistics
- ▶ Direct photons are important background to many physics processes
- ▶ Multi-jet production dominates:
Understanding QCD production mechanism is indispensable
in search for new physics



- EM shower in calorimeter
→ γ candidate
- Shower profile
- Isolation criteria (geometrical):
 - Define $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$
 - $Isol = \frac{E_{tot}(R=0.4) - E_{EM}(R=0.2)}{E_{EM}(R=0.2)} < 0.07$
- Very low energy in hadronic calorimeter
- No associated track
- $\Delta R(\gamma, Jet) > 0.7$ (cone jets, $R = 0.7$)

Background estimation

- Origins: Neutral mesons: π^0, η
+ Instrumental: EM jets
- Shower shape (low E_T)
- Multi photon preshower hits

Inclusive isolated photon production



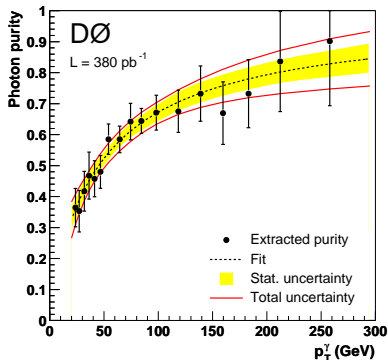
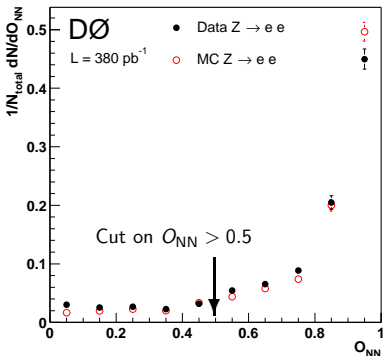
DØ Collab., Phys. Lett. **B 639**, 151 (2006)

$\mathcal{L} = 380 \text{ pb}^{-1}$

$p\bar{p} \rightarrow \gamma + X$: Event selection

- $p_T^\gamma > 23 \text{ GeV}$ (up to 300 GeV), $|\eta^\gamma| < 0.9$
- $\text{Isol} < 0.10$, $\text{frac}(EM) > 0.95$, $O_{NN} > 0.5$
- $\cancel{E}_T < 0.7 p_T^\gamma$ (cosmics, $W \rightarrow e\nu$)

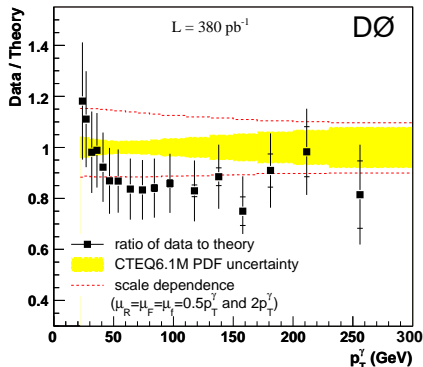
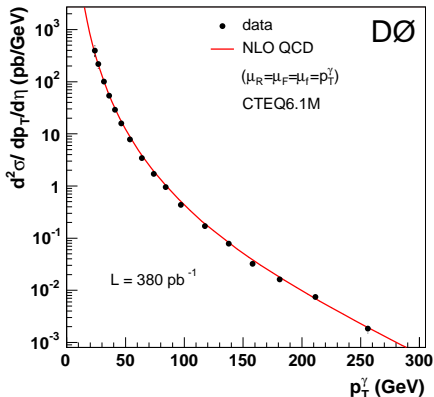
Main background: jets with large EM fraction



- Neural Net is trained to discriminate photons from EM jets
- EM shower shape + track p_T input to NN
- Tested on $Z \rightarrow ee$
- γ purity obtained from fit of NN output for MC signal and EM jets to data

Double differential photon cross section

- Plotted: p_T^γ -weighted bin centres
- Large p_T^γ range from 23 to 300 GeV
- BFG photon fragmentation functions
- Compared to JetPhoX (NLO QCD)

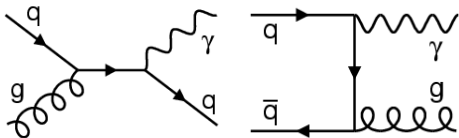


Data over theory comparison

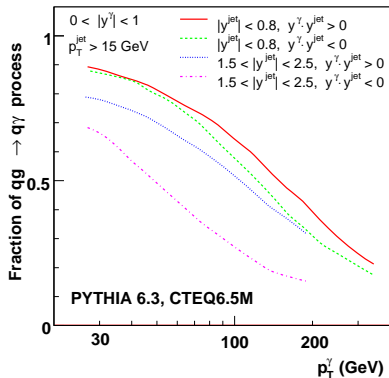
- Results consistent with theory
- Systematics (triggers) dominate at lower p_T^γ
- Variation/Shape similar to former observations (UA2, CDF)

⇒ Suggests more detailed check

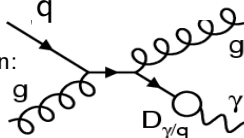
Prompt photon + jet production



- Inclusive photon + jet cross section
- Fraction of $qg \rightarrow q + \gamma$ production



Also fragmentation:



- Dominant production at low p_T^γ ($\lesssim 120$ GeV) through Compton scattering: $qg \rightarrow q + \gamma$

- Probe PDF's at low x (down to $x \simeq 0.007$)
 - where quarks are constrained by HERA data
 - \Rightarrow sensitive to gluon density
- Test of NLO pQCD
 - soft gluon resummation
 - models of gluon radiation

Inclusive photon + jet production



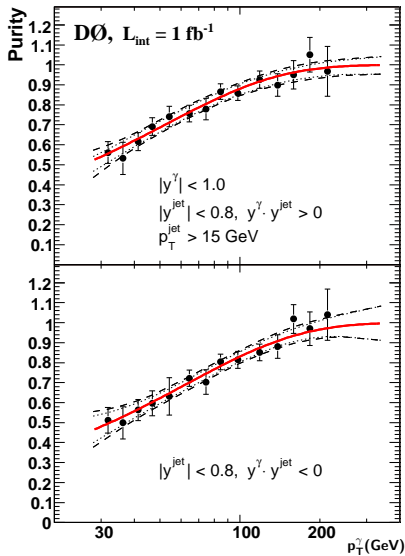
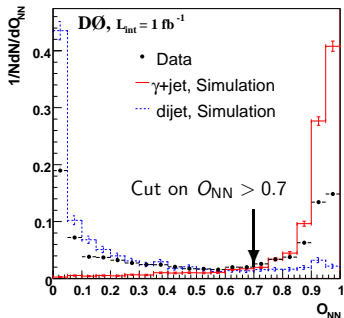
DØ Collab., Phys. Lett. **B 666**, 435 (2008)

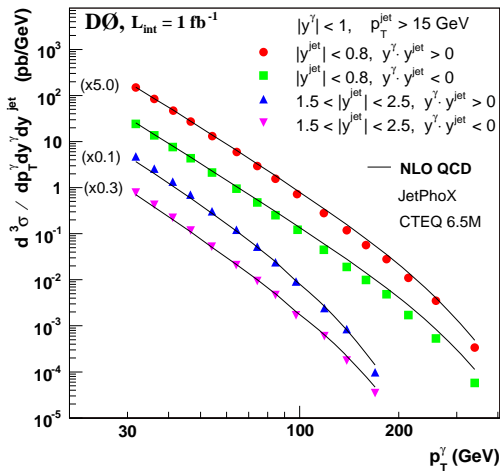
$\mathcal{L} = 1.0 \text{ fb}^{-1}$

$p\bar{p} \rightarrow \gamma + \text{jet} + X$: Event selection

- $p_T^\gamma > 30 \text{ GeV}$ (up to 400 GeV), $|y^\gamma| < 1.0$
- $\text{Isol} < 0.07$, $\text{frac}(EM) > 0.96$, $O_{NN} > 0.7$
- $\cancel{E}_T < 12.5 \text{ GeV} + 0.36 p_T^\gamma$ (cosmics, $W \rightarrow e\nu$)
- $p_T^{\text{jet}} > 15 \text{ GeV}$
- $|y^{\text{jet}}| < 0.8$ (central), $1.5 < |y^{\text{jet}}| < 2.5$ (forward)

4 regions: $y^\gamma \cdot y^{\text{jet}} \leq 0$, central and forward jets





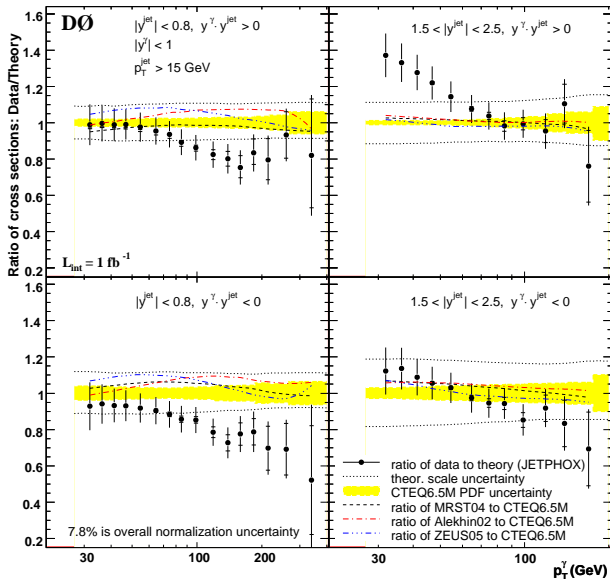
Triple differential cross section

- Plotted: p_T^γ -weighted bin centres
- Analytical unfolding for detector resolution
- Cross section results shown with stat. + sys. uncertainties

- Theory: NLO QCD from JETPHOX with CTEQ 6.5M PDF's and $\mu_r = \mu_F = \mu_f = p_T^\gamma \cdot f(y^*)$,

$$f(y^*) = \sqrt{\frac{1}{2}(1 + \exp(-2y^*))}, \quad y^* = \frac{1}{2}(y^\gamma - y^{\text{jet}}), \text{ suggested scale choice by JetPhoX authors}$$

Data over theory comparison

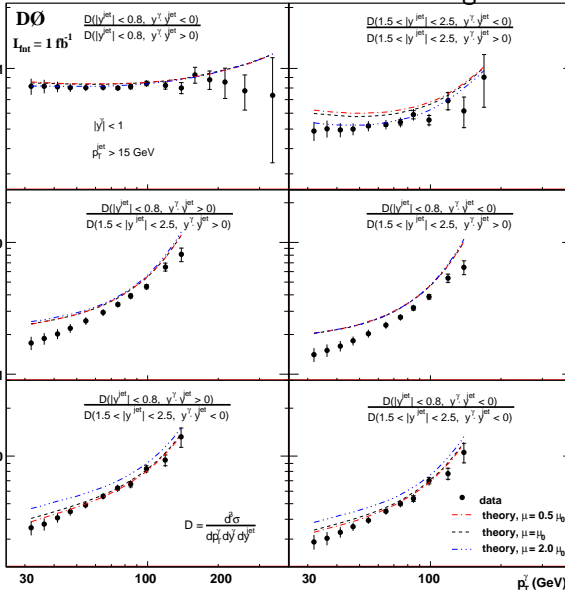


- Theory does not describe shape of data in whole measured range
- Deviation for central jets at $p_T^\gamma > 100 \text{ GeV}$
- Deviation for forward jets ($y^\gamma \cdot y^{\text{jet}} > 0$) at $p_T^\gamma < 50 \text{ GeV}$
- Structure similar to previous observations of UA2, CDF and DØ

Inclusive photon + jet production



Cross section ratios of different regions



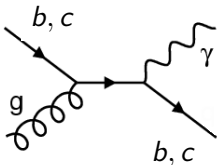
- Cross section ratio vs p_T^{γ} : **reduced systematics**
- Shapes of measured cross section ratios in data **qualitatively reproduced** by theory in general
- But **quantitative disagreement** for some kinematic regions, in particular central jets over same rapidity side forward jets

Inclusive photon + heavy flavour jet production

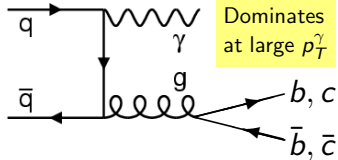


DØ Collab., accepted PRL, FERMILAB-PUB-08-582-E

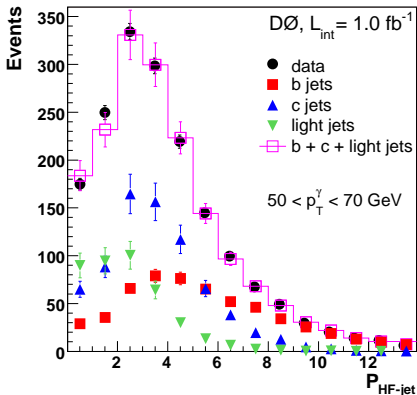
$\mathcal{L} = 1.0 \text{ fb}^{-1}$



- Outgoing = incoming quark flavour
- QCD Compton dominates for b (c) up to $p_T^\gamma \sim 120$ (90) GeV
- \Rightarrow Constraints on HF PDF's



Dominates at large p_T^γ



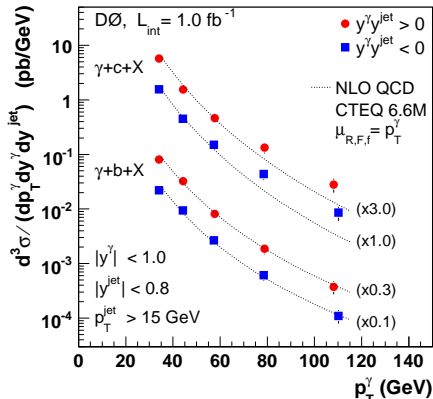
$p\bar{p} \rightarrow \gamma + b, c \text{ jet}$: Event selection

- $p_T^\gamma > 30$ GeV (up to 150 GeV), $|y^\gamma| < 1.0$
- $\text{Isol} < 0.07$, $\text{frac}(EM) > 0.96$, $\mathcal{O}_{\text{NN}}(\gamma) > 0.7$
- $\cancel{E}_T < 0.7 p_T^\gamma$ (cosmics, $W \rightarrow e\nu$)
- $p_T^{\text{jet}} > 15$ GeV, $|y^{\text{jet}}| < 0.8$, ($R_{\text{jets}} = 0.5$)
- Leading jet: $N_{\text{Track}} \geq 2$, $\mathcal{O}_{\text{NN}}(\text{HF}) > 0.85$
- 2 regions: $y^\gamma \cdot y^{\text{jet}} > 0$, $y^\gamma \cdot y^{\text{jet}} < 0$

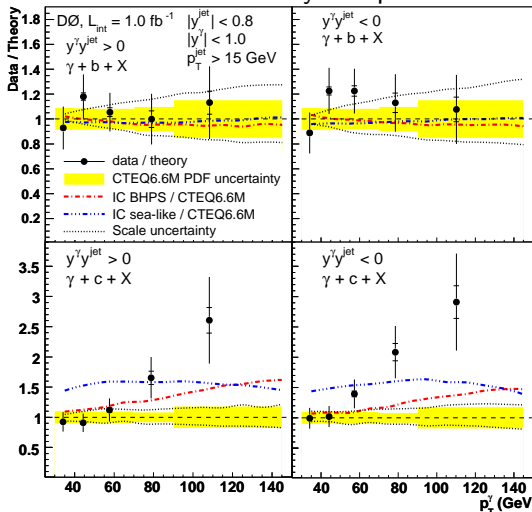
- Fitting $P_{\text{HF-jet}} = -\ln \prod_i \text{Prob}_{\text{track}}^i$ templates of b, c (MC) and light jets (data) to shape of data

Triple differential cross section

- Plotted: p_T^γ -weighted bin centres
- P_{HF-jet} fit in each bin
- For $\gamma + b + X$ and $\gamma + c + X$
- In two regions $y^\gamma \cdot y^{jet} > 0$ and $y^\gamma \cdot y^{jet} < 0$



Data over theory comparison



No agreement for $\gamma + c$ jet at $p_T^\gamma > 70 \text{ GeV}$

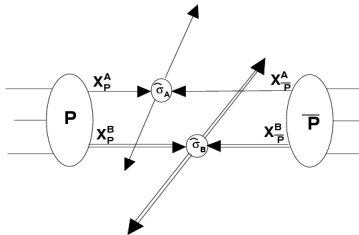
Double parton scattering in $\gamma + 3$ jet events



New: DØ Collab., prelim., DØ note 5910-CONF

$\mathcal{L} = 1.0 \text{ fb}^{-1}$

- Complementary information about proton structure: Spatial distribution of partons
 \Rightarrow Possible parton-parton correlations. Impact on PDF's?
- Background in signal events (important for rare processes)
- Especially important at high luminosities (additional $p\bar{p}$ interactions)

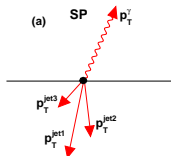


Event selection:

- $60 < p_T^\gamma < 80 \text{ GeV}$
- Isolated
- $p_T^{\text{1st jet}} > 25 \text{ GeV}$
- $p_T^{\text{2nd, 3rd jet}} > 15 \text{ GeV}$

Main background:

Single parton scattering



$$\sigma_{DP} = m \cdot \sigma_A \cdot \frac{\sigma_B}{2\sigma_{eff}}$$

σ_A, σ_B : cross sections of processes A, B

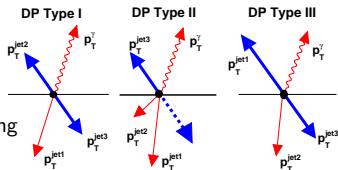
σ_{eff} : characterising size of effective interaction region

$\sigma_B/2\sigma_{eff}$: prob. of 2nd interaction, given 1st one

($m = 2(1)$ when A and B are (not) distinguishable)

Signal:

Double parton scattering



Double parton scattering in $\gamma + 3$ jet events



Discriminating variables

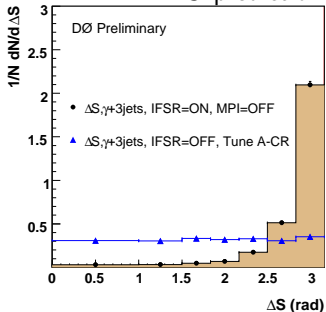
$$S_\phi = \frac{1}{\sqrt{2}} \sqrt{\left(\frac{\Delta\phi(\gamma,i)}{\delta\phi(\gamma,i)}\right)^2 + \left(\frac{\Delta\phi(j,k)}{\delta\phi(j,k)}\right)^2}$$

$$S_{p_T} = \frac{1}{\sqrt{2}} \sqrt{\left(\frac{|P_T^{\gamma,i}|}{\delta P_T(\gamma,i)}\right)^2 + \left(\frac{|P_T^{j,k}|}{\delta P_T(j,k)}\right)^2}$$

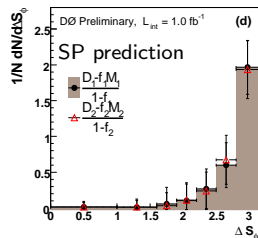
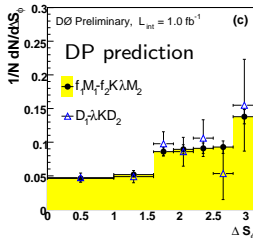
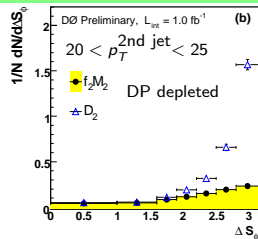
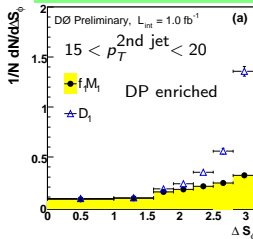
$$\Delta S = \Delta\phi(p_T^{\gamma, \text{jet}}, p_T^{\text{jet}_i, \text{jet}_k})$$

Computed for pair with minimum S

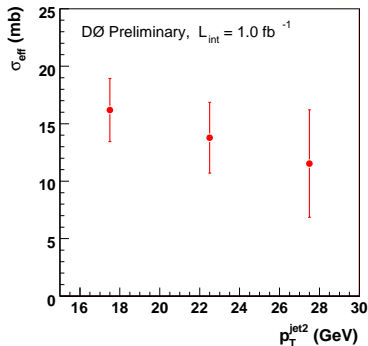
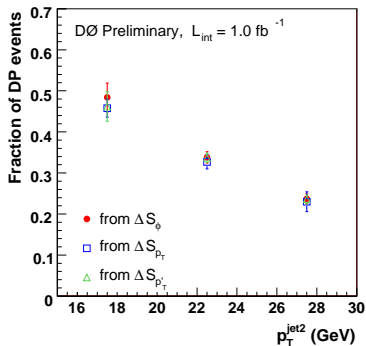
PYTHIA ΔS prediction



- Measurements in three bins of 2nd jet p_T : 15-20, 20-25 and 25-30 GeV
- Using data driven techniques (diff. p_T spectra)



Double parton scattering in $\gamma + 3$ jet events



- Measured DP fractions drop from 0.47 ± 0.04 at $15 < p_T^{2\text{nd jet}} < 20$ to 0.23 ± 0.03 at $25 < p_T^{2\text{nd jet}} < 30$
- Effective cross section varies for same bins from 16.2 ± 2.8 mb to 11.5 ± 4.7 mb and agree for all jet p_T bins within uncertainties
- Negligible bin-to-bin correlations
- Average over three p_T bins: $\langle \sigma_{\text{eff}} \rangle = 15.1 \pm 1.9$ mb
- Good agreement with previous CDF measurements in 4 jet and $\gamma + 3$ jet events



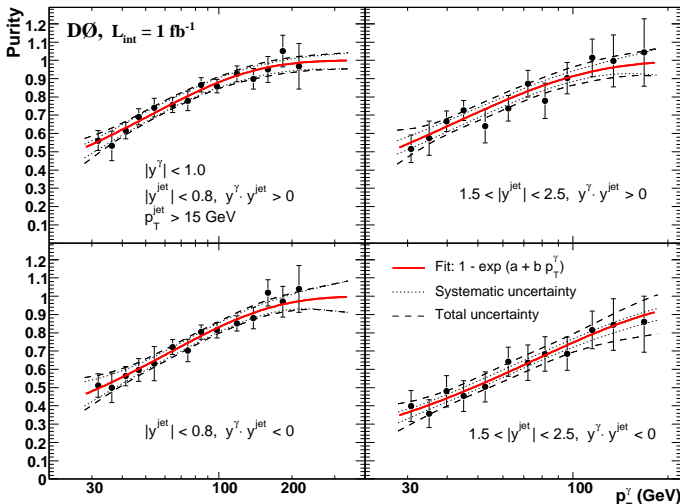
- Tevatron and DØ are performing well (CDF too)
- Inclusive photon production measured
 - Double differential cross section $\frac{d^3\sigma}{dp_T^\gamma d\eta^\gamma}$
 - Data/theory variation/shape starts to emerge
- Photon plus jet production measured
 - Triple differential cross section $\frac{d^3\sigma}{dp_T^\gamma dy^\gamma dy^{\text{jet}}}$ in 4 regions and ratios
 - Deviation from theory, structure similar to previous observations of UA2, CDF, DØ
- γ + HF jet production measured
 - $\gamma + b$ production in agreement with theory
 - $\gamma + c$ production does not agree with theory at $p_T^\gamma > 70$ GeV
- Double parton interactions in $\gamma + 3$ jet events measured
 - In three $p_T^{\text{2nd jet}}$ bins, $\langle \sigma_{\text{eff}} \rangle = 15.1 \pm 1.9$ mb
 - Good agreement with previous CDF measurements

Acknowledgements

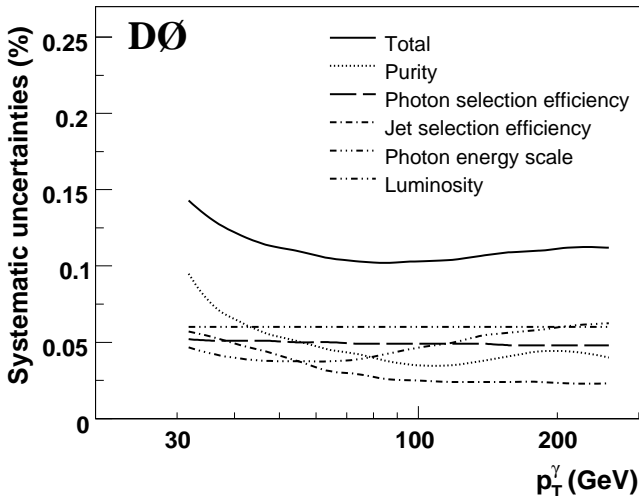
Many thanks to the staff members at Fermilab and collaborating institutions. This work has been supported by the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Columbia); CONA-CyT (Mexico); KRF and KOSEF (Korea); CONICET and UBA-CyT (Argentina); FOM (The Netherlands); STFC (United Kingdom); MSMT and GACR (Czech Republic); CRC Program, CDF, NSERC and WestGrid Project (Canada); BMBF, DFG and the Alexander von Humboldt Foundation (Germany); SFI (Ireland); The Swedish Research Council (Sweden); and CAS and CNSF (China).

- Backup slides

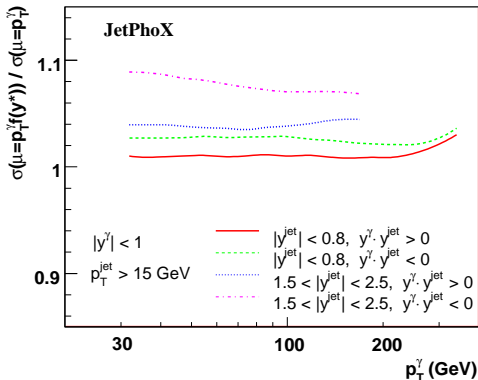
Inclusive photon + jet production



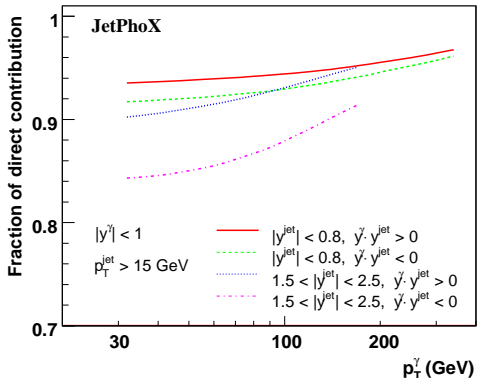
Purity of the selected $p\bar{p} \rightarrow \gamma + \text{jet} + X$ sample as a function of p_T^γ for each measured constellation of photon and jet rapidities



Total and main sources of systematic uncertainty for the cross section measured in the $|y^{\text{jet}}| < 0.8$, $y^\gamma \cdot y^{\text{jet}}$ rapidity region

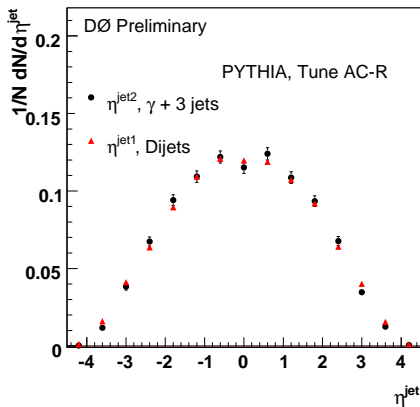
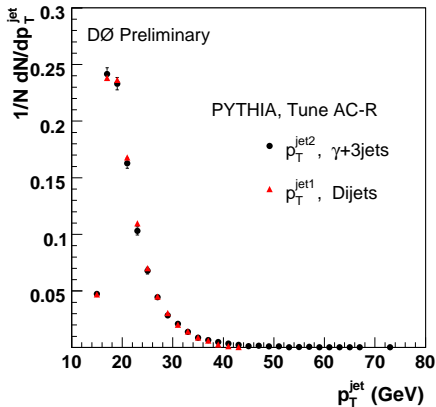


Ratio of predicted cross sections with $\mu_{R,F,f} = p_T^\gamma f(y^*)$ to those with $\mu_{R,F,f} = p_T^\gamma$ in each measured region



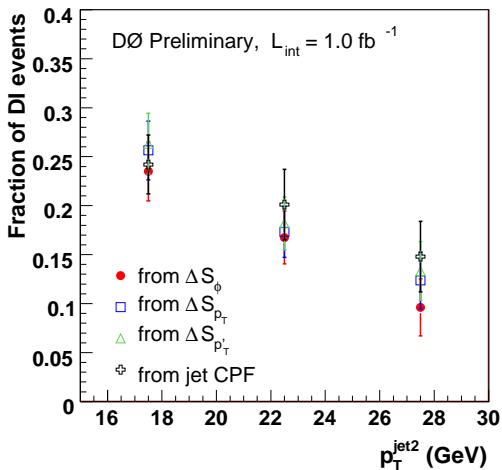
Ratios of predicted $p\bar{p} \rightarrow \gamma + \text{jet} + X$ cross section with just direct (non-fragmentation) contribution to total (direct + fragmentation) contribution in each measured region

Double parton scattering in $\gamma + 3$ jet events



Difference in p_T (left) and η (right) spectra between the second jet in $\gamma + \text{jet}$ events (black circles) and the first jet in the dijet events (red triangles), generated with Tune AC-R MPI model, initial and final state radiation switched off.

Double parton scattering in $\gamma + 3$ jet events



Fractions of DP events found with ΔS_ϕ , ΔS_{p_T} and $\Delta S_{p'_T}$ variables in the three $p_T^{\text{jet}2}$ intervals.