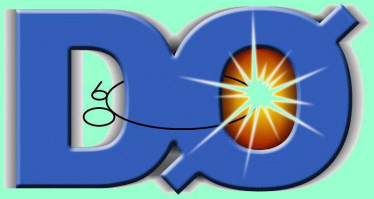


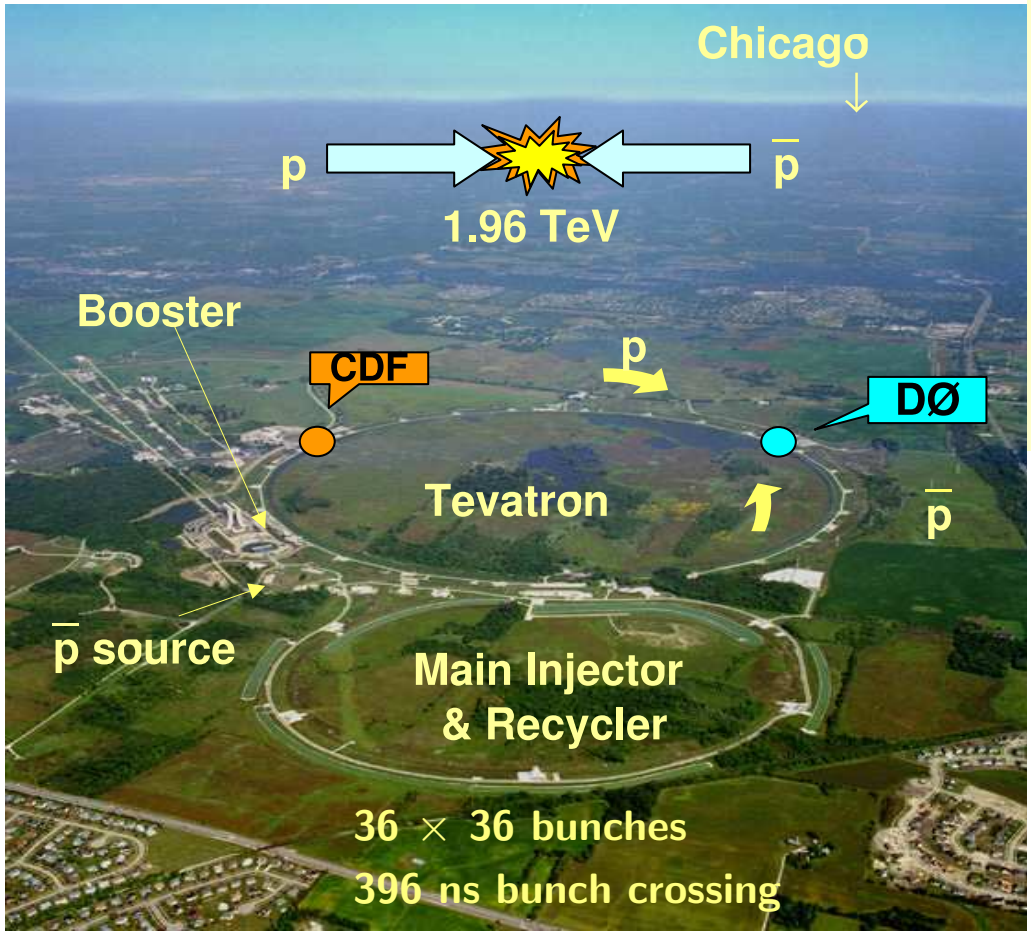
Photon + Jets at Tevatron

Lars Sonnenschein

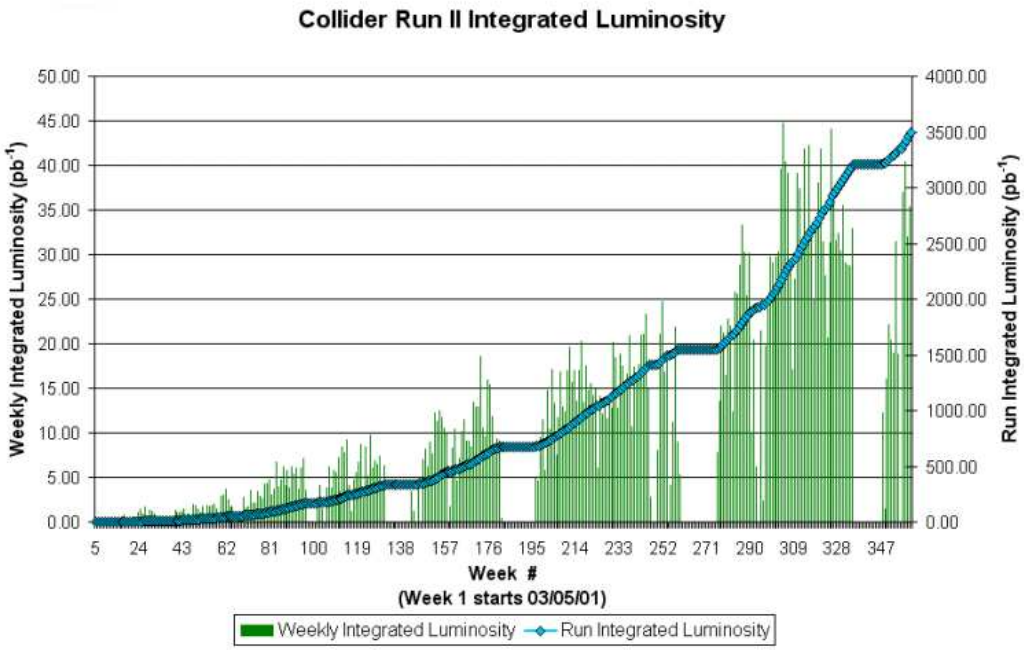
on behalf of the DØ and CDF collaborations

XLIII Rencontres de Moriond
QCD and High Energy Interactions
La Thuile, Italy, 8-15 March, 2008

Fermilab Tevatron Run II

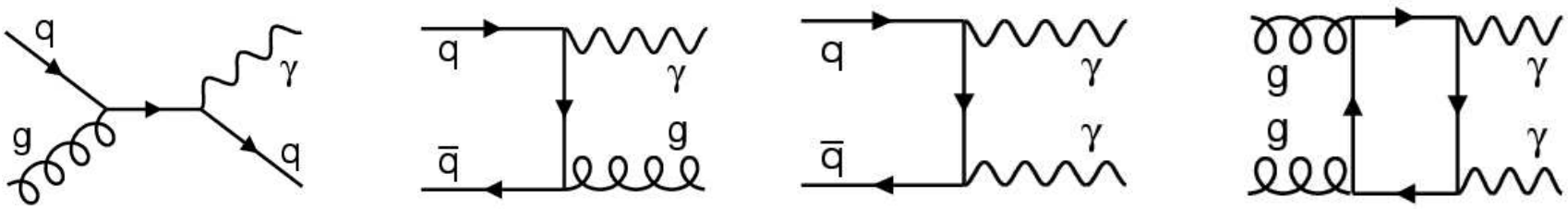


- Run II started in March 2001
- Peak Luminosity: $2.85 \cdot 10^{32}$ cm^{-2}s^{-1}
- Delivered: > 3.75 fb^{-1} (Run I: 0.16 fb^{-1})
- 6-8 fb^{-1} expected by end of 2009



Thanks to all colleagues at the Tevatron for their contributions to this talk

Motivation



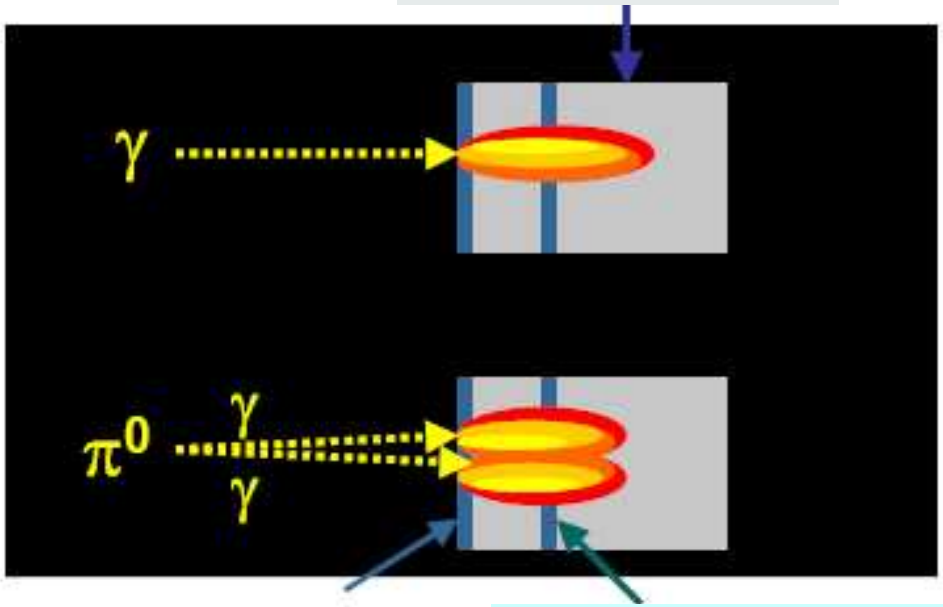
Direct photons come unaltered from the hard subprocess
$\Rightarrow$ direct probe of the hard scattering dynamics

- 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

Photon Identification

ElectroMagnetic Shower Detection



- EM shower in Calorimeter
  $\rightarrow \gamma$ candidate
- Shower profile
- Isolation criteria (geometrical):
  - Define $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$
  - DØ: $\frac{E_{\text{tot}}(R{=}0.4) - E_{\text{EM}}(R{=}0.2)}{E_{\text{EM}}(R{=}0.2)} < 0.07$
  - CDF: $E_T^{\text{cand.}} - E_T(R = 0.4) < 1$ GeV
- ○ Very low energy in hadronic calorimeter
- No associated track
- $\Delta R(\gamma, \text{Jet}) > 0.7$ (cone jets, $R = 0.7$)

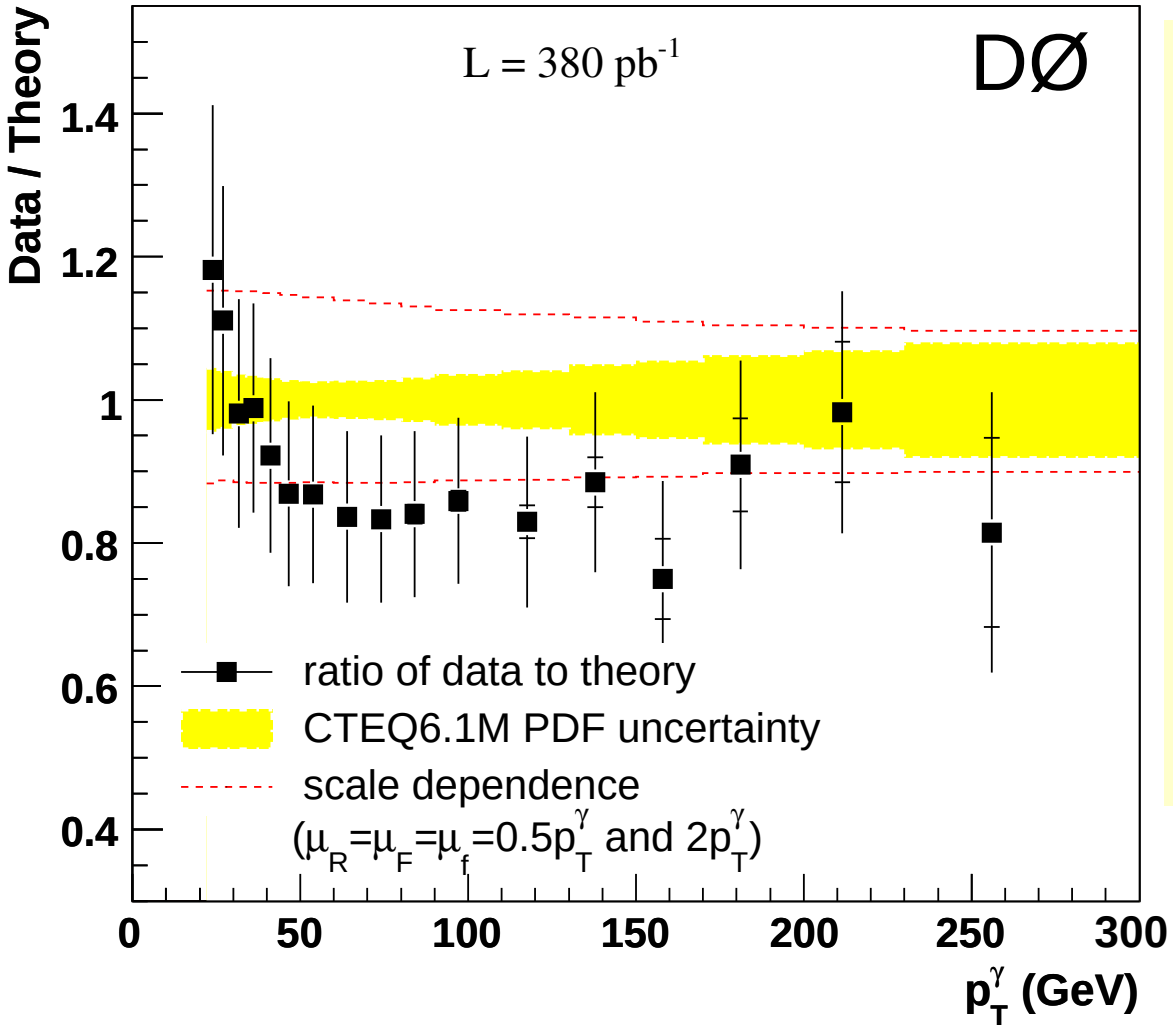
Background estimation

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

Isolated photon + X cross section

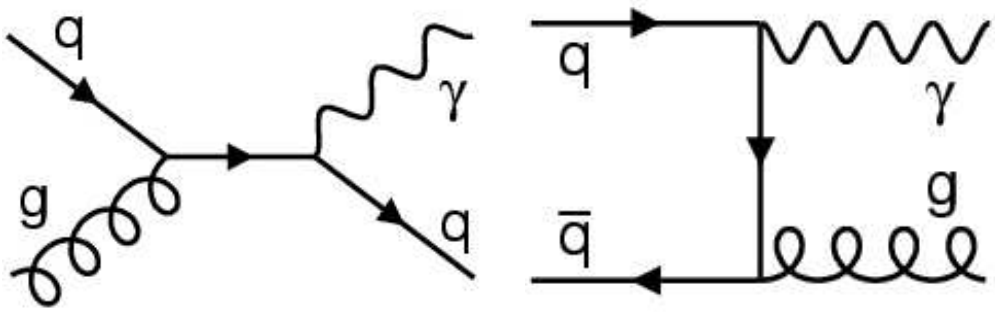
Previous measurement

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

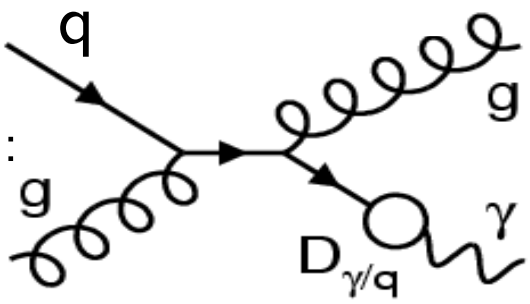


- Previously published DØ analysis
- Results consistent with theory
- But variation/shape similar to former observations (UA2, CDF)
- Suggests more detailed check with higher statistics

Prompt photon + jet production

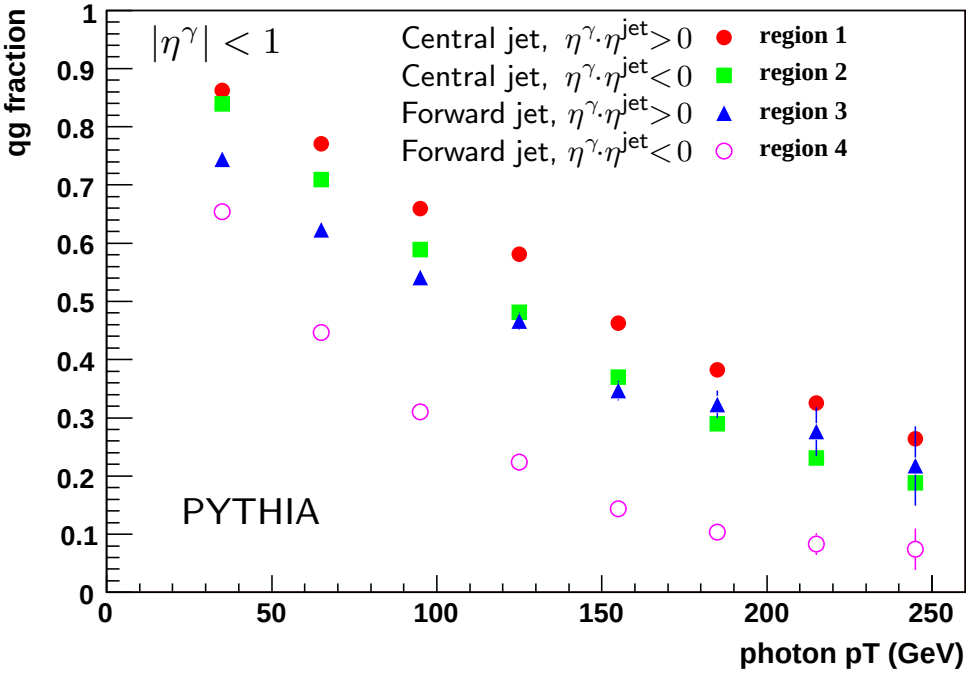


Also fragmentation:



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

- 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

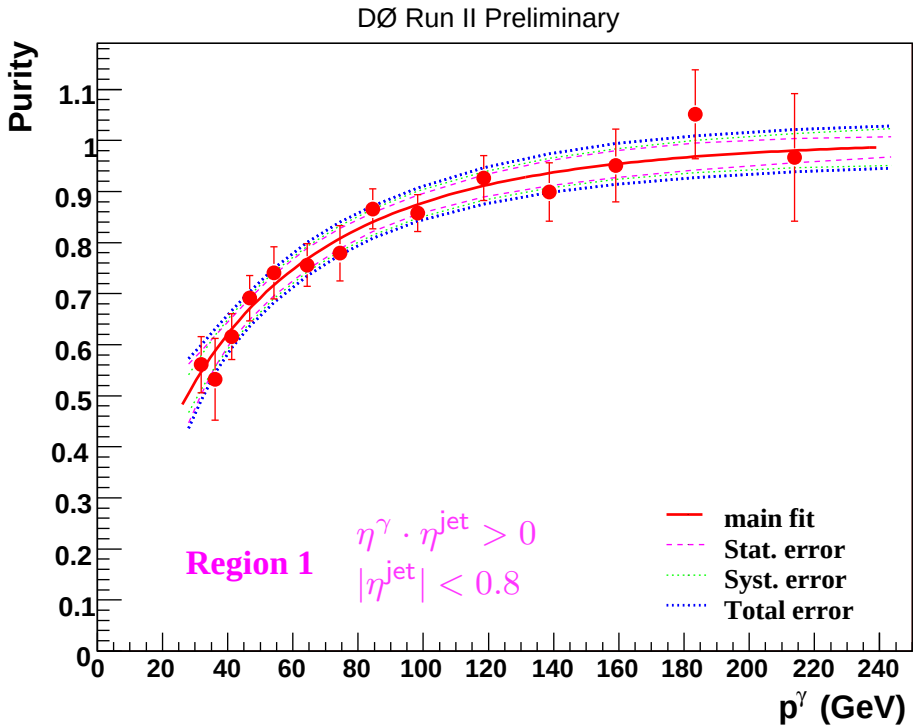
$p\bar{p} \to \gamma$+jet+X: Event selection

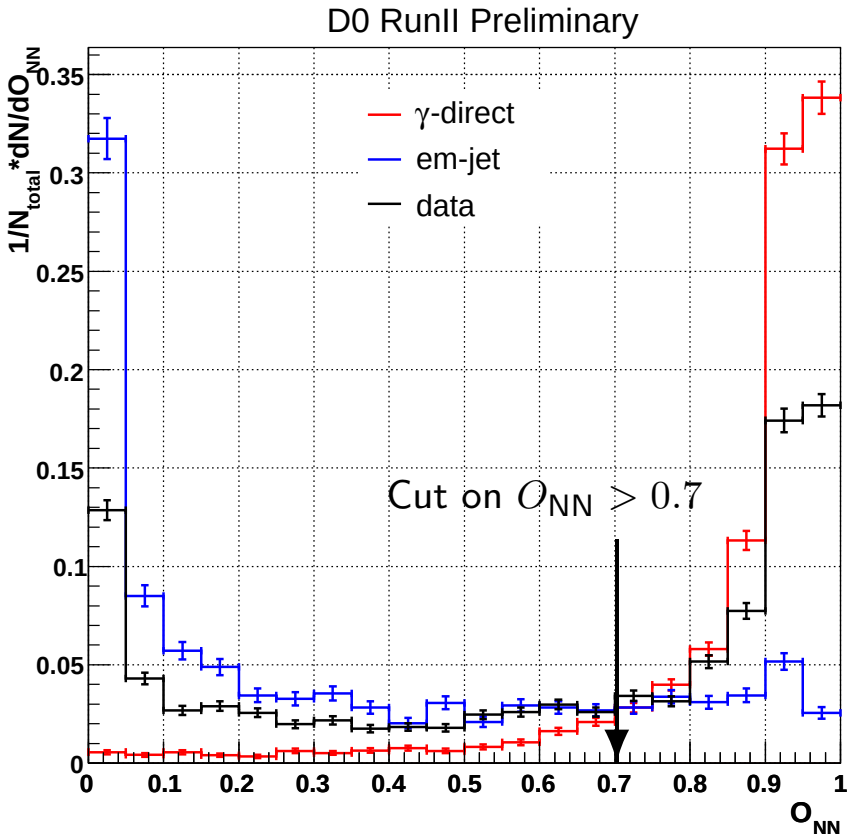
- $|\eta^\gamma| < 1.0$ (isolated)
- $p_T^\gamma > 30$ GeV (up to 300 GeV)
- $|\eta^{\text{jet}}| < 0.8$ (central), $1.5 < |\eta^{\text{jet}}| < 2.5$ (forward)
- $p_T^{\text{jet}} > 15$ GeV

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

- $\not\!\!E_T < 12.5$ GeV $+ 0.36 p_T^\gamma$ (cosmics, $W \to e\nu$)

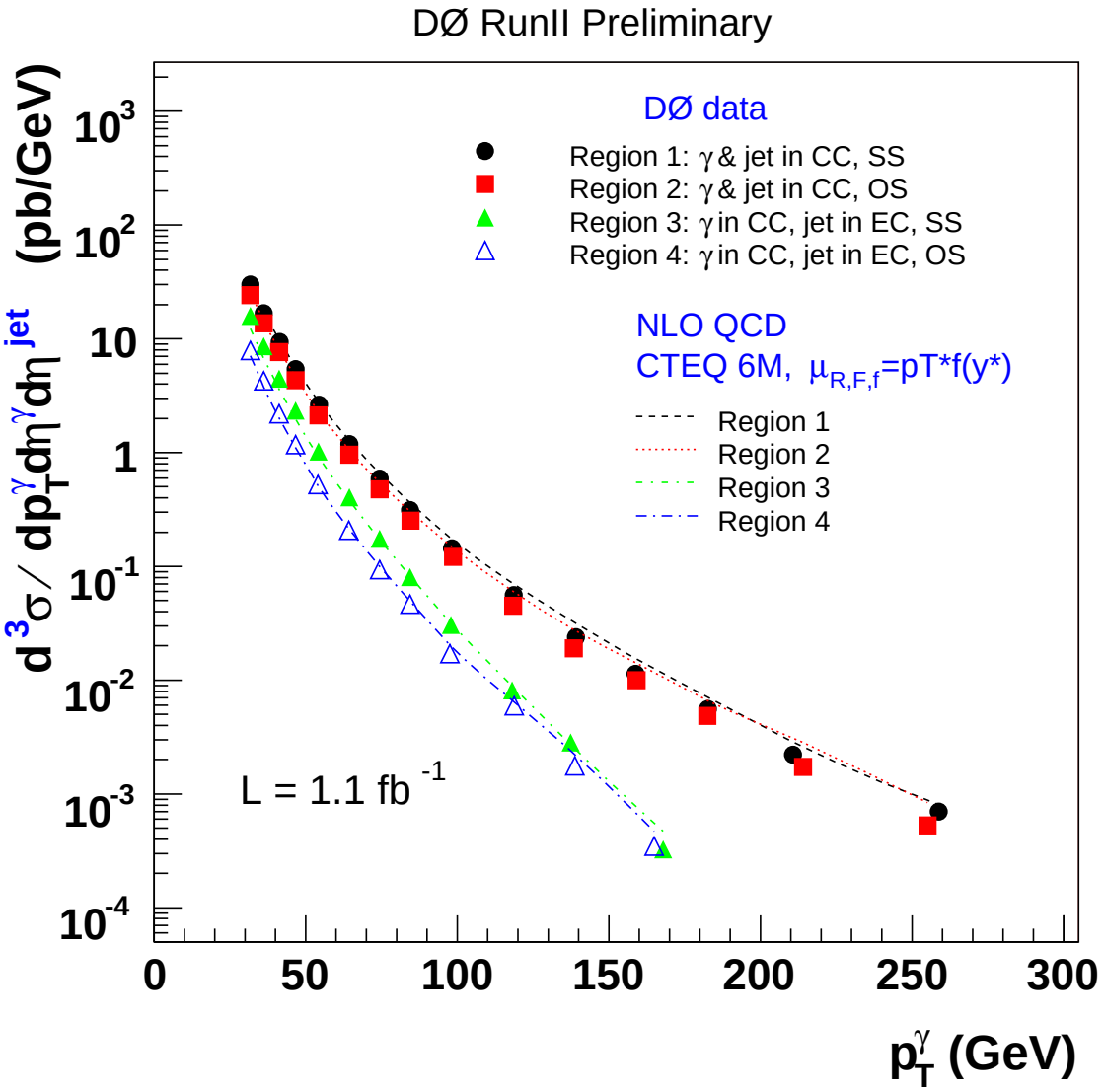
Main background: jets with large EM fraction





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

Inclusive photon + jet production

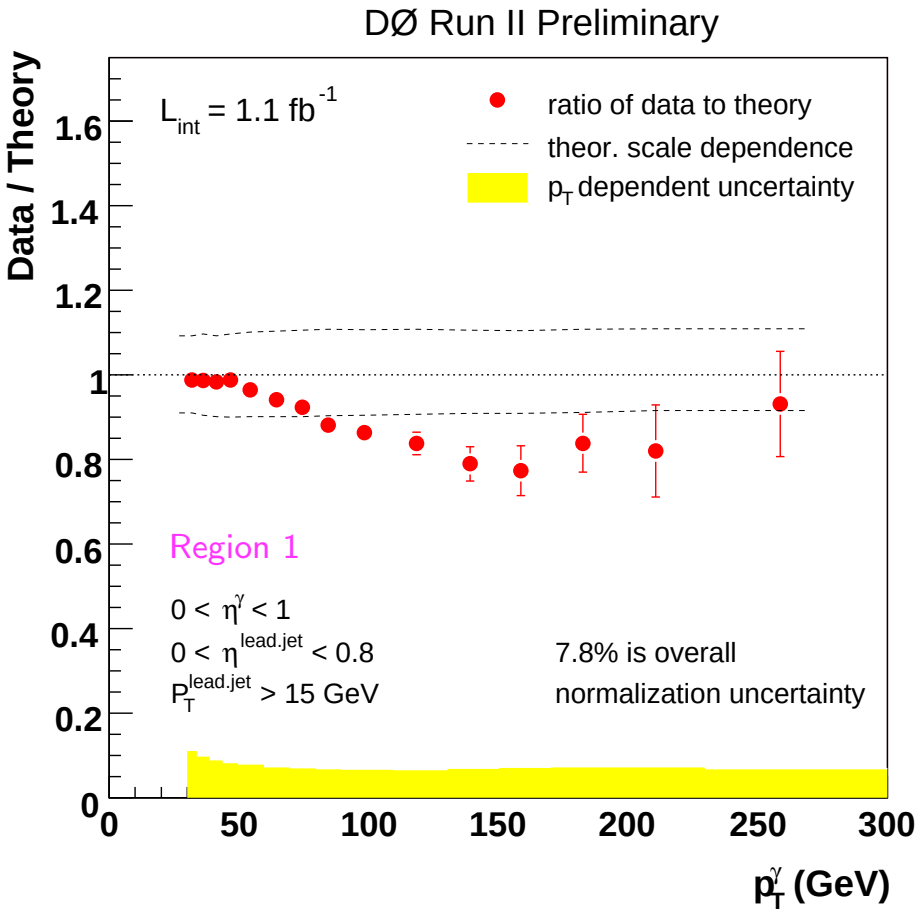


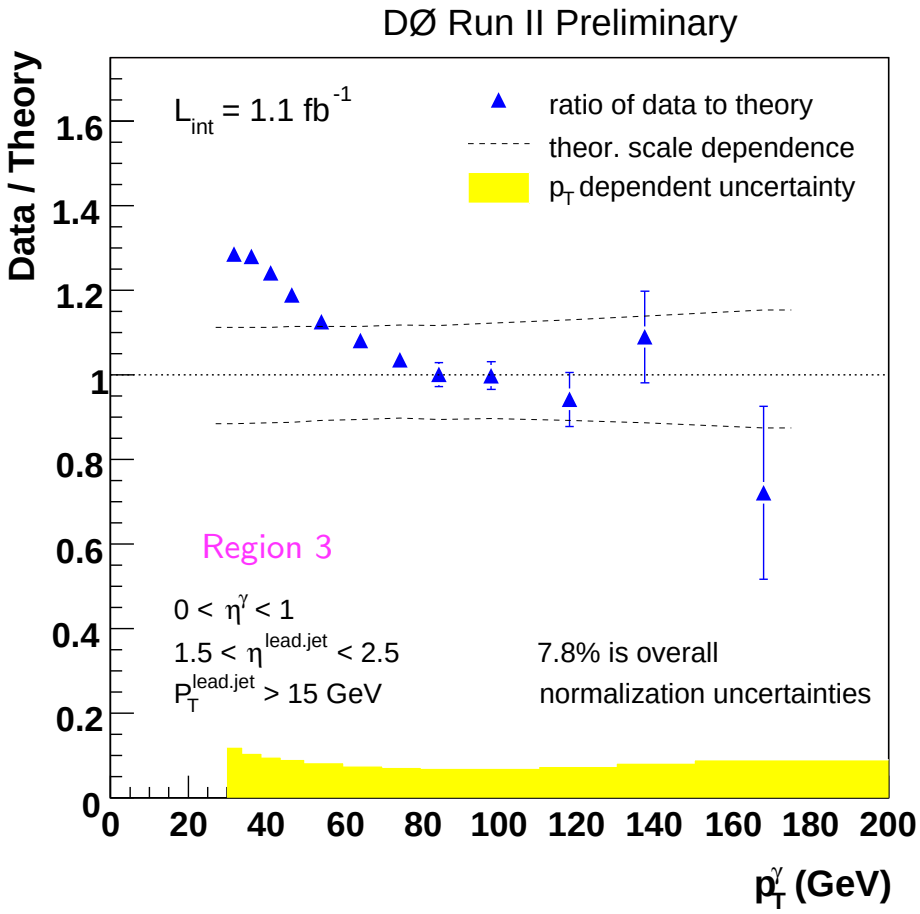
Triple differential cross section

- Plotted: p_T^γ-weighted average of fit in each bin
- $\mathcal{L} = 1.1$ fb^{-1}
- Analytical unfolding for detector resolution
- Cross section results shown with stat. + sys. uncertainties

- Theory: NLO QCD from JETPHOX with CTEQ 6.1M PDF's and $\mu_r = \mu_F = \mu_f = p_T^\gamma \cdot f(y^*)$, $f(y^*) = \sqrt{\frac{1}{2}(1+\exp(-2y^*))}$, $\quad y^* = \frac{1}{2}(\eta^\gamma - \eta^{\text{jet}})$

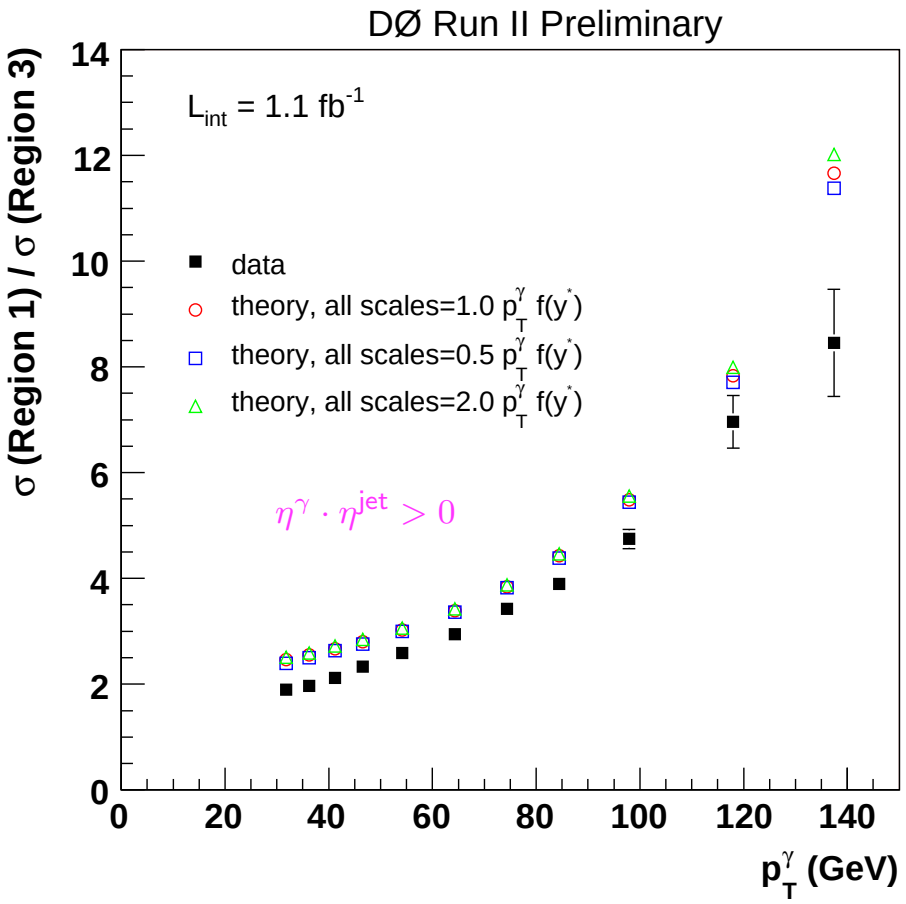
Inclusive photon + jet production

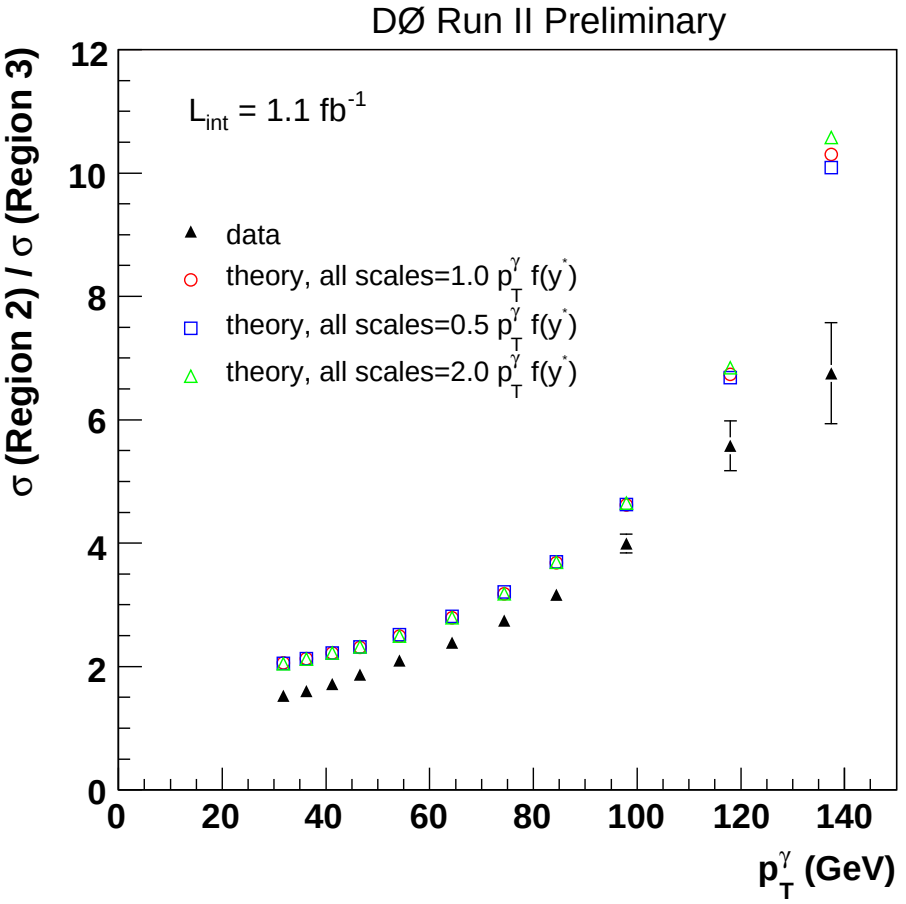




- Deviation from theory for $p_T^{\gamma} > 100$ GeV for central jets ($\eta^{\gamma} \cdot \eta^{\text{jet}} > 0$)
- Deviation from theory for $p_T^{\gamma} < 50$ GeV for forward jets ($\eta^{\gamma} \cdot \eta^{\text{jet}} > 0$)
- Structure similar to previous observations of UA2, CDF and DØ

Inclusive photon + jet production

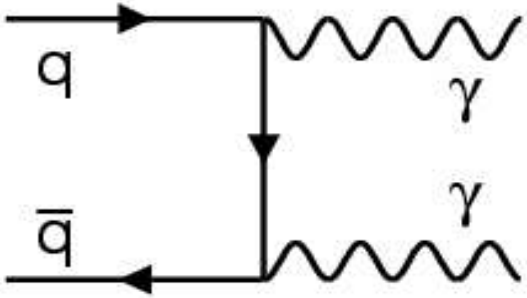




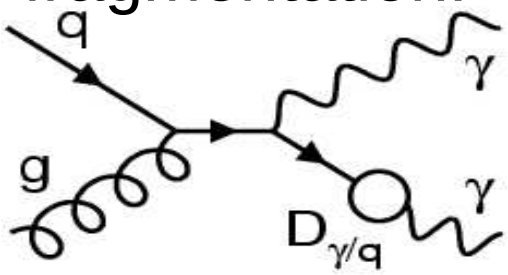
- Cross section ratio vs p_T^γ: reduced systematics
- Shapes of measured cross section ratios in data qualitatively reproduced by theory in general
- But quantitative disagreement for some kinematic regions, in particular for Region 1/Region 3 and Region 2/Region 3

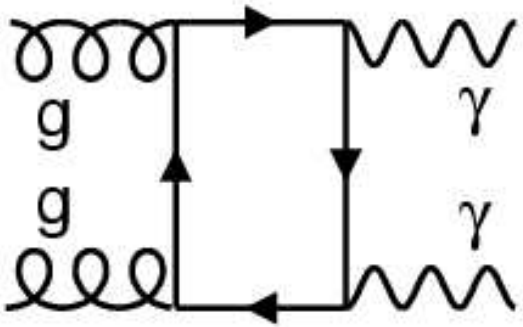
Diphoton production

Di-photon final state: a Higgs discovery channel at LHC
Possible signature of new physics, such as large extra dimensions



fragmentation:





Leading order diagram:
dominant at
high di-photon mass
(Higgs background at LHC)

- Suppressed by photon isolation
- Relevant in different phase space regions

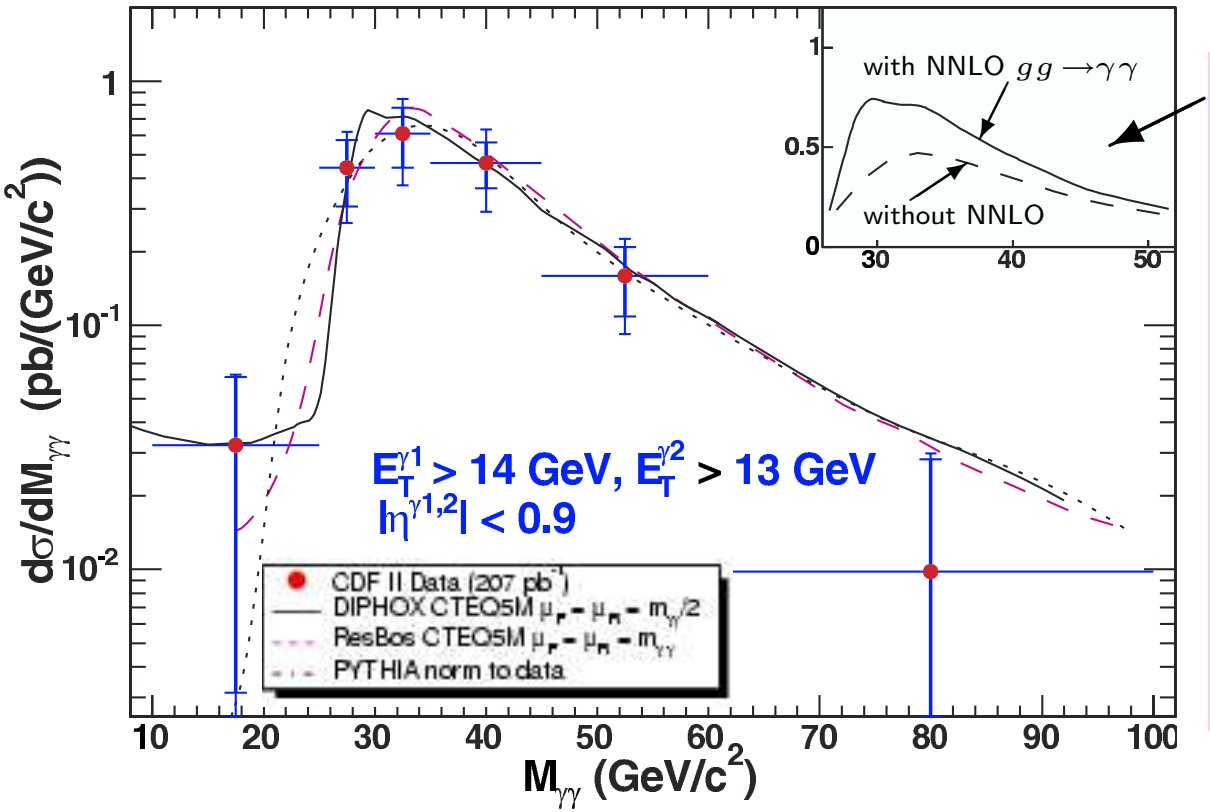
Next-to-next-to leading order contribution:
- Suppressed by factor α_s^2
- But important at low mass (large gluon density)

Di-photon cross section

CDF Collab., Phys. Rev. Lett. **95**, 022003 (2005)

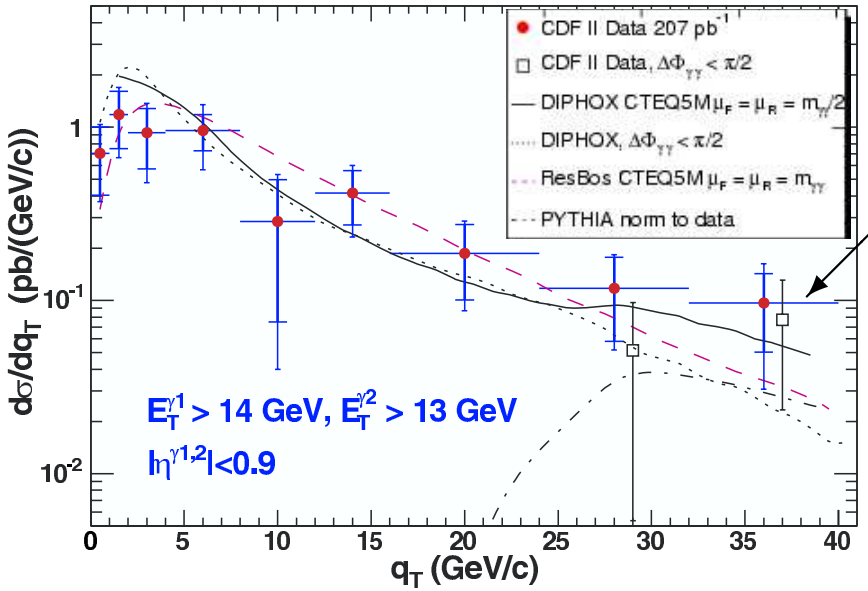
- $\mathcal{L} = 207$ pb^{-1}
- 2 isolated showers in EM calorimeter without associated track
- $|\eta^\gamma| < 0.9$
- $p_T^\gamma > 13$ & 14 GeV (avoiding IR-sensitive regions in pQCD)

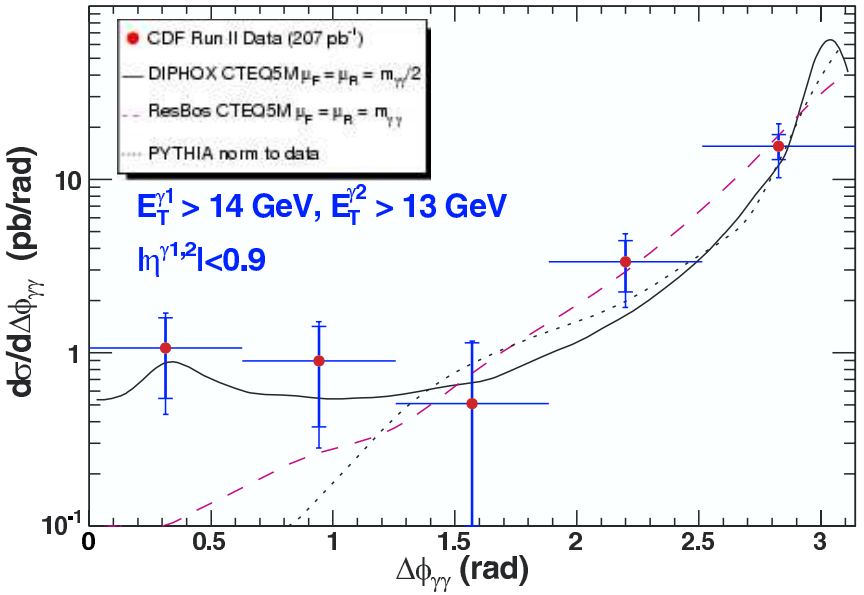
889 di-photon candidate events, tot. eff.: 15.2%, purity $\simeq 50\%$



- DIPHOX:
  - NLO prompt di-photons
  - NLO fragmentation (1 or 2 γ)
  - NNLO $gg \to \gamma\gamma$ diagram
- ResBos:
  - NLO prompt di-photons
  - LO fragmentation contribution
  - Resummed initial state gluon radiation (important for lower q_T)
- PYTHIA (increased by factor 2)

Di-photon cross section





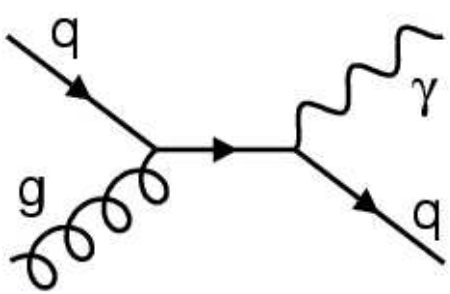
Additional measurement for $\Delta\Phi(\gamma,\gamma) < \pi/2$ (open squares) compared to DIPHOX

- NLO fragmentation contribution
  - only in DIPHOX
    relevant at high q_T, small $\Delta\Phi$, low mass
- Resummed initial state gluon radiation
  - only in ResBos
    relevant at low q_T

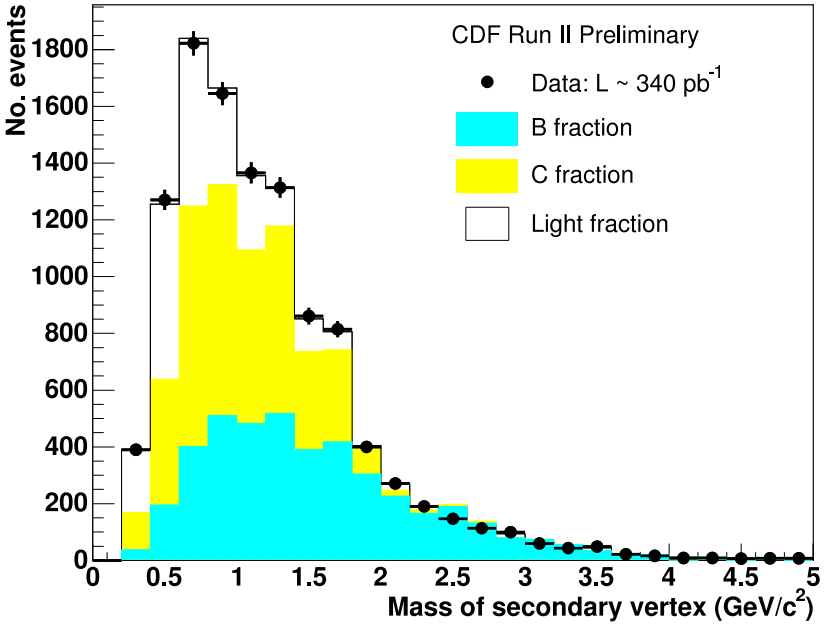
Systematic uncertainties:

- Background subtraction (20 - 30%)
- Selection efficiencies (11%)
- Luminosity (6.5%)

$\gamma + b$ jet production

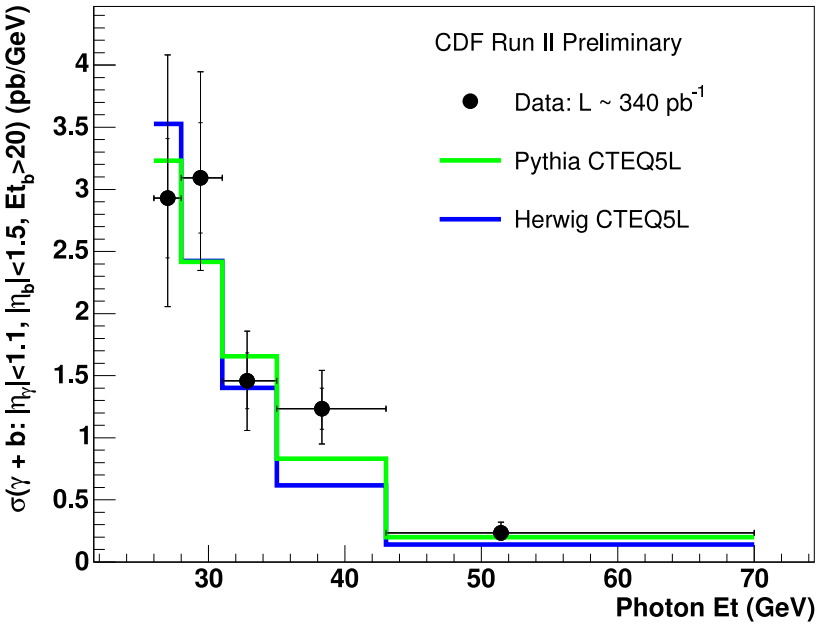


- $\mathcal{L} = 340$ pb^{-1}
- $E_T^\gamma > 26$ GeV, $|\eta^\gamma| < 1.1$
- jet ($E_T > 20$ GeV, $|\eta| < 1.5$) with secondary vertex



- Outgoing = incoming quark flavour
- Dominated by g + HF $\rightarrow \gamma$ + HF
- $\Rightarrow$ Constraints on HF PDF's

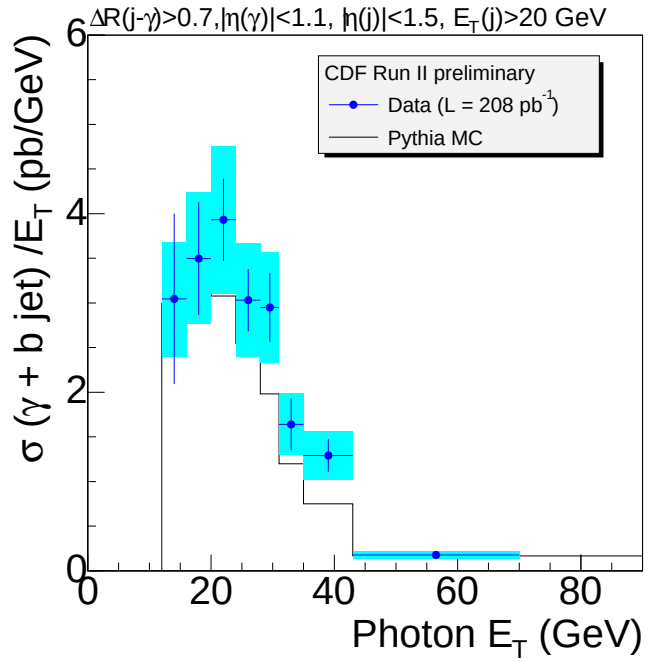
- Determine b, c, light fractions
- Fit secondary vertex mass
- Subtract background
- Determine cross section versus E_T^γ

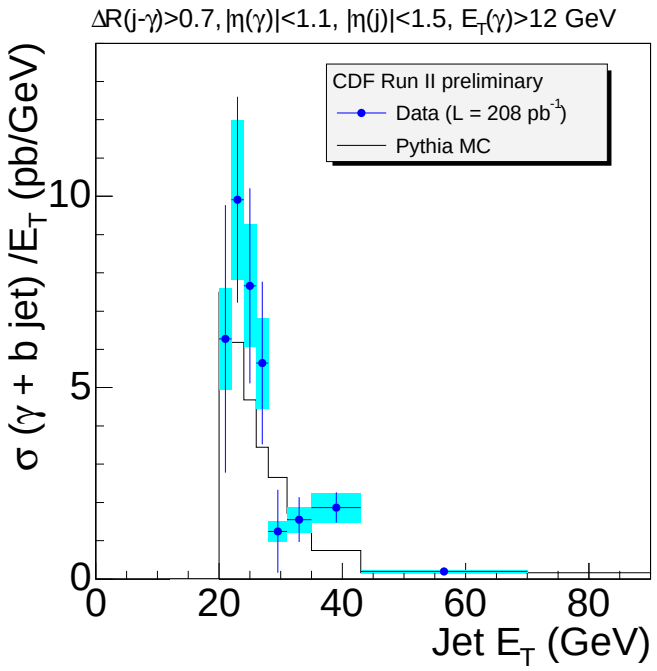


Good description of data by PYTHIA and HERWIG with CTEQ5L

$\gamma + b$ jets with dedicated trigger

- $\mathcal{L} = 208$ pb^{-1}
- γ + displaced track trigger
- On-line IP precision comparable to off-line
- $E_T^\gamma > 12$ GeV, $|\eta^\gamma| < 1.1$
- Lower E_T^γ threshold extends phase space considerably (less than half compared to previous analysis)
- jet ($E_T > 20$ GeV, $|\eta| < 1.5$) with secondary vertex





- Agreement within errors with LO Pythia
- Already limited by systematics (Tracking eff., JES, $g \to b\bar{b}$ into single jet)

Summary

- Tevatron and Experiments are performing well
- Prompt photon production measured at DØ
  - Triple differential cross section $\frac{d^3\sigma}{dp_T^\gamma d\eta^\gamma d\eta^{\text{jet}}}$ in 4 regions and ratios
  - Deviation from theory, structure similar to previous observations of UA2, CDF, DØ
- Di-photon cross section measured at CDF
  - Good agreement with resummed and NLO predictions in different regions of phase space
  - Resummed full NLO calculation necessary
- $\gamma + b$ jet production measured at CDF
  - In agreement with LO predictions
  - $\gamma +$ displaced track triggered sample already systematics limited

Acknowledgements

Thank you to the Fermilab staff members and collaborating institutions.
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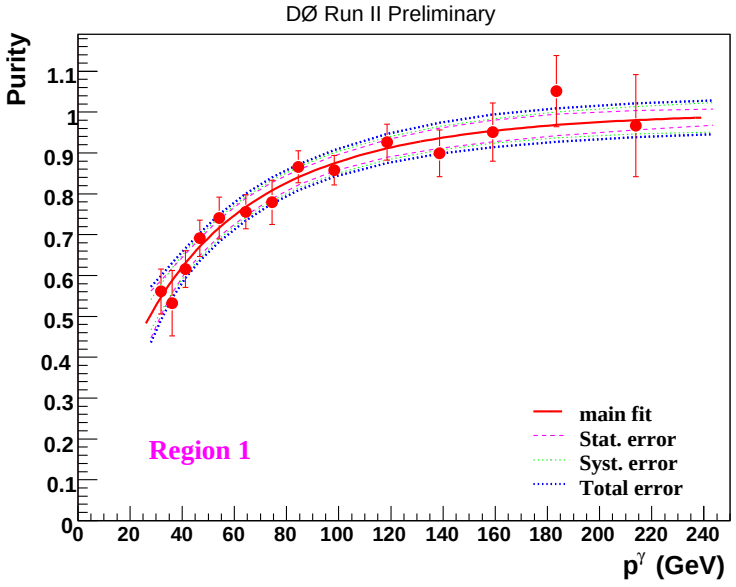
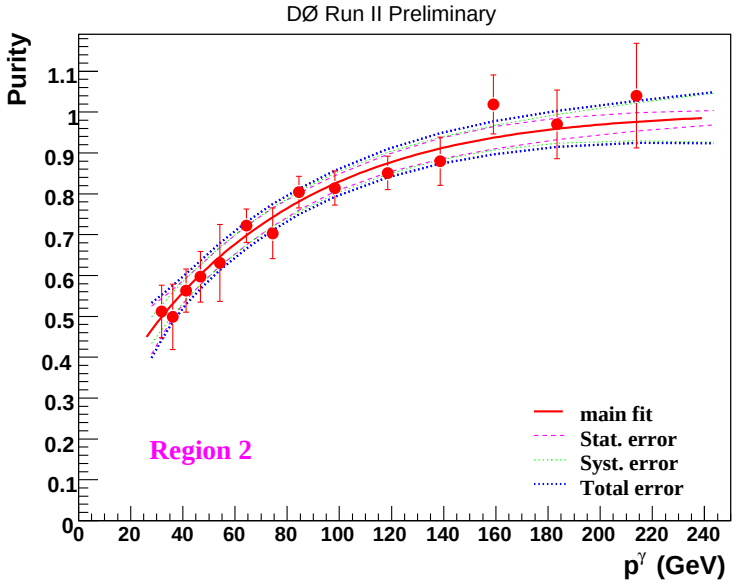
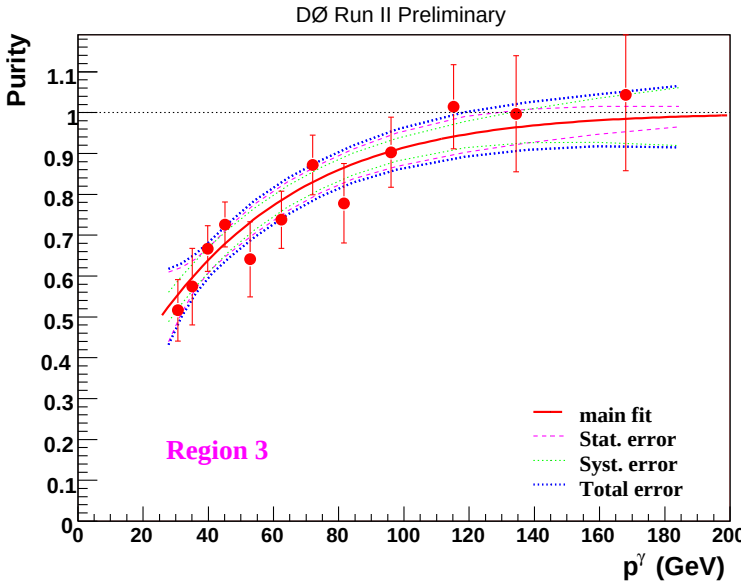
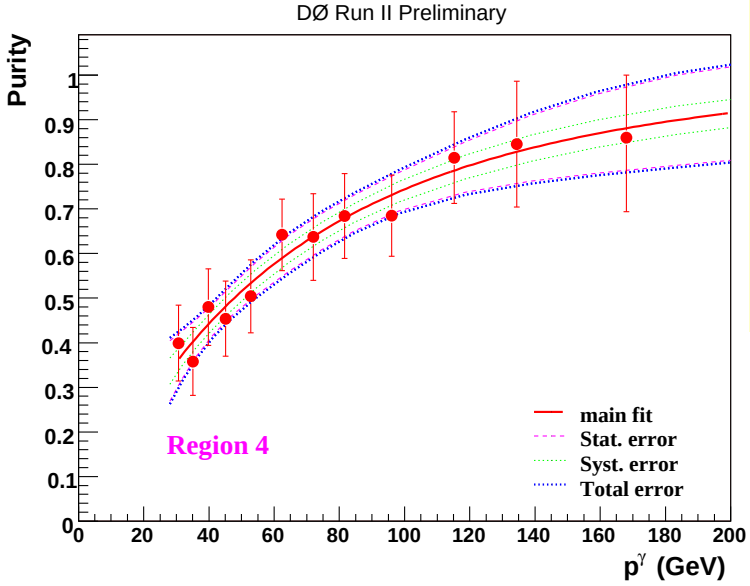
Backup Slides

Inclusive photon + jet production: γ Purity









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

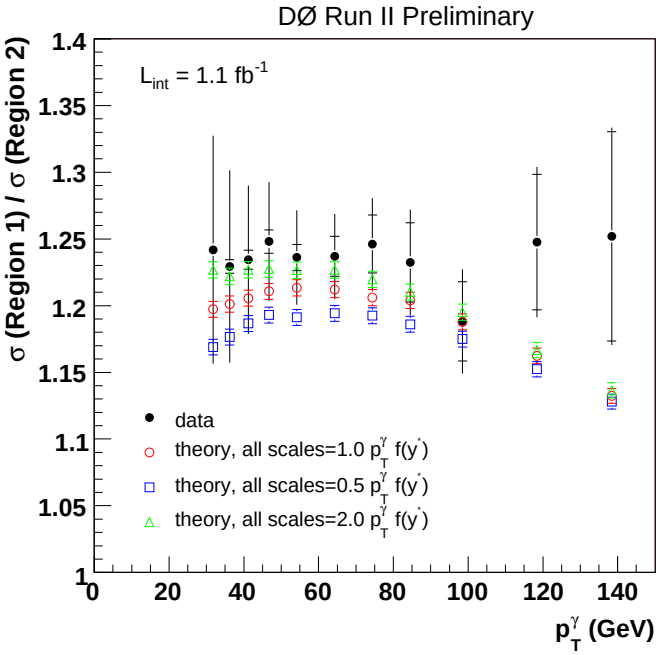
- $|\eta^{\gamma}| < 1.0$
- $p_T^{\gamma} > 30$ GeV
- $|\eta^{\text{jet}}| < 0.8,\ 1.5 < |\eta^{\text{jet}}| < 2.5$
- $p_T^{\text{jet}} > 15$ GeV

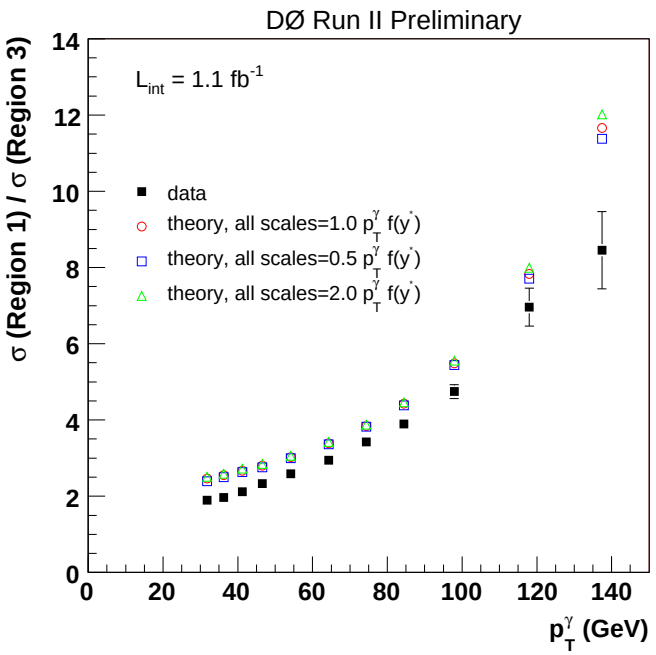
Four Regions:

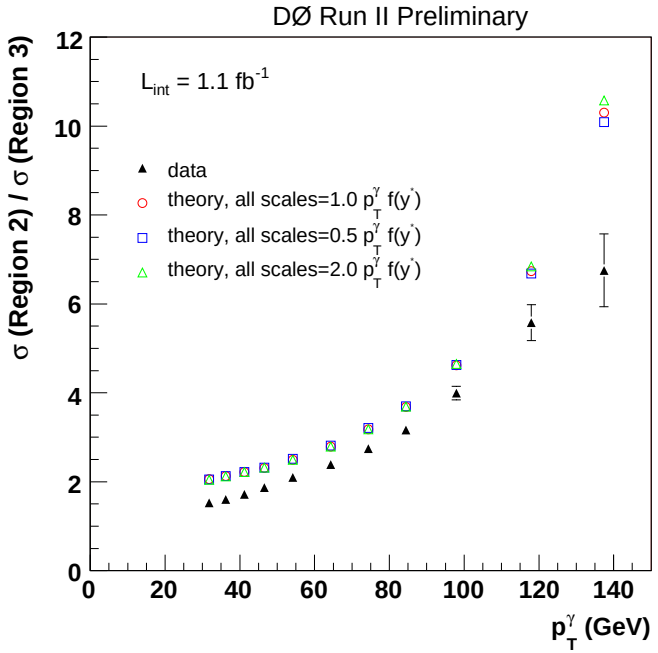
1: $\eta^{\gamma} \cdot \eta^{\text{jet}} > 0$, central jets
2: $\eta^{\gamma} \cdot \eta^{\text{jet}} < 0$, central jets
3: $\eta^{\gamma} \cdot \eta^{\text{jet}} > 0$, forward jets
4: $\eta^{\gamma} \cdot \eta^{\text{jet}} < 0$, forward jets

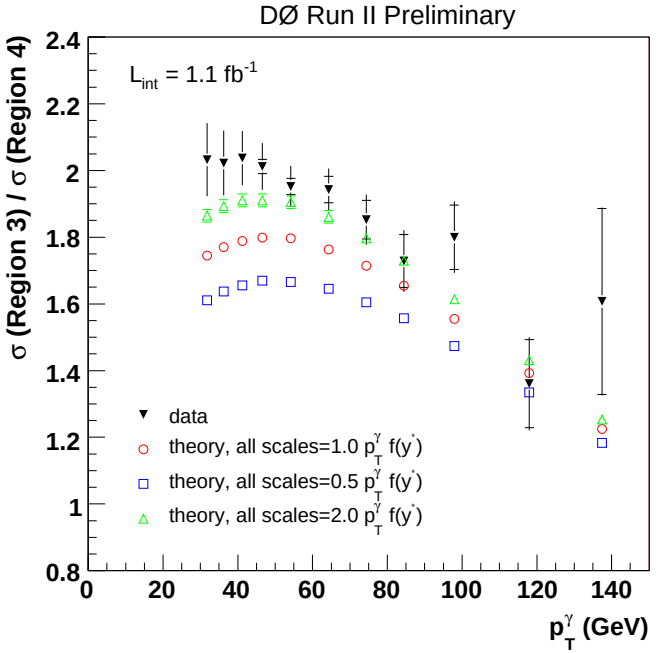
- $\not\!\!E_T < 12.5$ GeV $+ 0.36 p_T^{\gamma}$

Inclusive photon + jet production: Ratios









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Four Regions:

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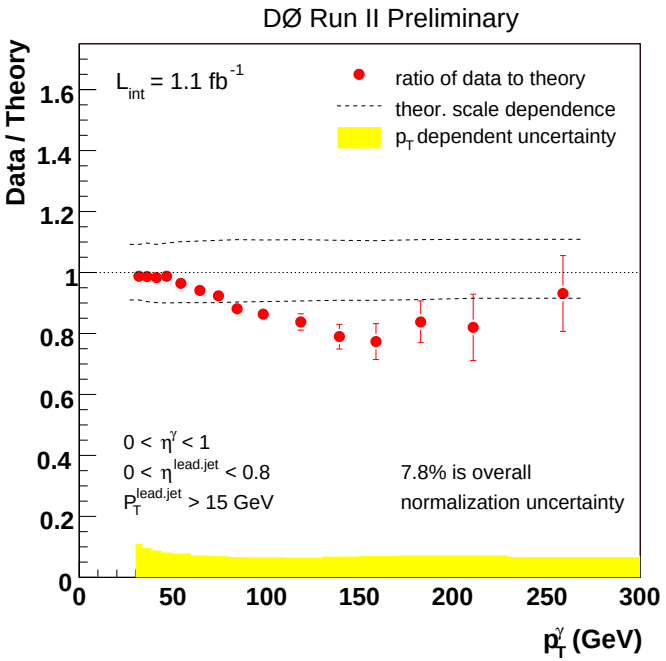
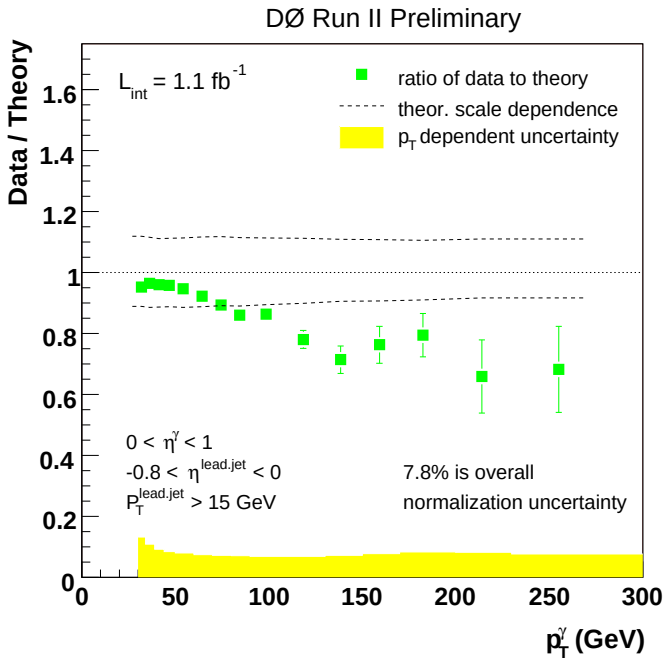
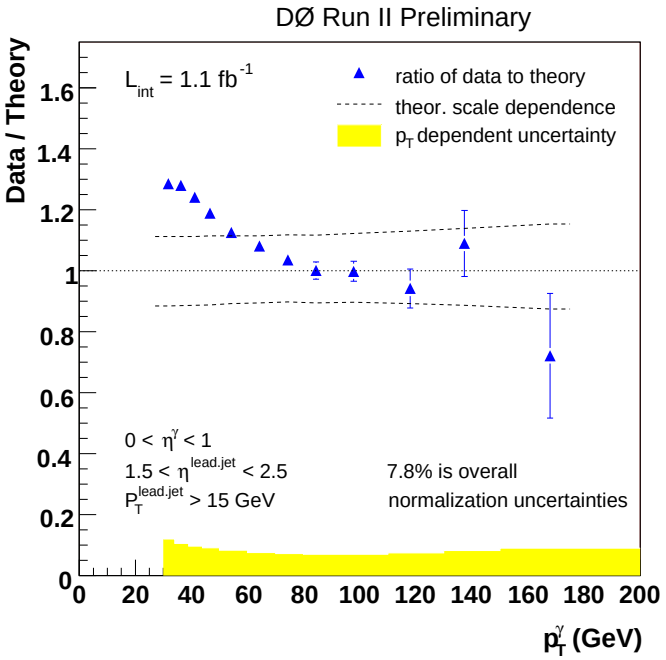
3: $\eta^\gamma \cdot \eta^{\text{jet}} > 0$, forward jets
4: $\eta^\gamma \cdot \eta^{\text{jet}} < 0$, forward jets

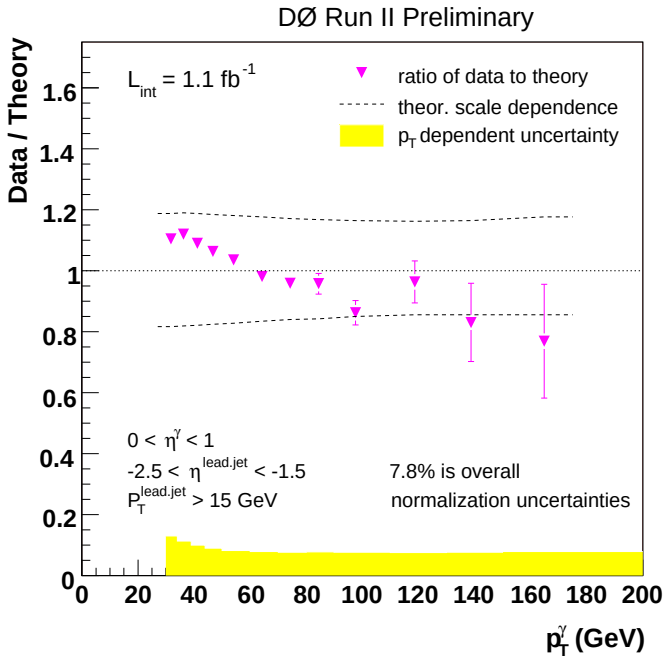
- $\not\!\!E_T < 12.5$ GeV $+ 0.36 p_T^\gamma$

Inclusive photon + jet production: Data vs. Theory









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

- $|\eta^{\gamma}| < 1.0$
- $p_T^{\gamma} > 30$ GeV
- $|\eta^{\text{jet}}| < 0.8,\ 1.5 < |\eta^{\text{jet}}| < 2.5$
- $p_T^{\text{jet}} > 15$ GeV

Four Regions:

1: $\eta^{\gamma} \cdot \eta^{\text{jet}} > 0$, central jets
2: $\eta^{\gamma} \cdot \eta^{\text{jet}} < 0$, central jets
3: $\eta^{\gamma} \cdot \eta^{\text{jet}} > 0$, forward jets
4: $\eta^{\gamma} \cdot \eta^{\text{jet}} < 0$, forward jets

- $\not\!\!E_T < 12.5$ GeV $+ 0.36 p_T^{\gamma}$