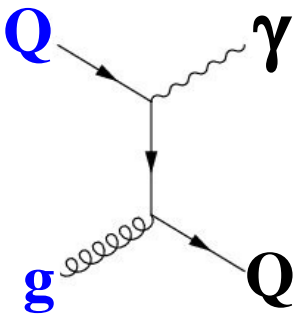
Measurement of γ + charm + X and γ + bottom + X Production Cross Sections at $\sqrt{s}$ = 1.96 TeV

Dan Duggan
Florida State University
on behalf of the DØ Collaboration

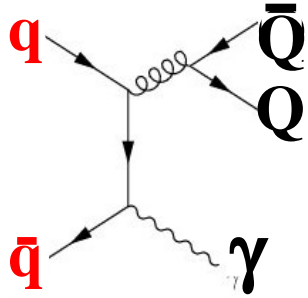
Outline

- Motivation
- Event Selection
  - Photon candidates
  - Heavy flavor jets
  - Uncertainties
- Results
  - Final cross sections of γ + b jet and γ + c jet
  - Comparisons of measurements to theoretical results

γ + Heavy Flavor QCD

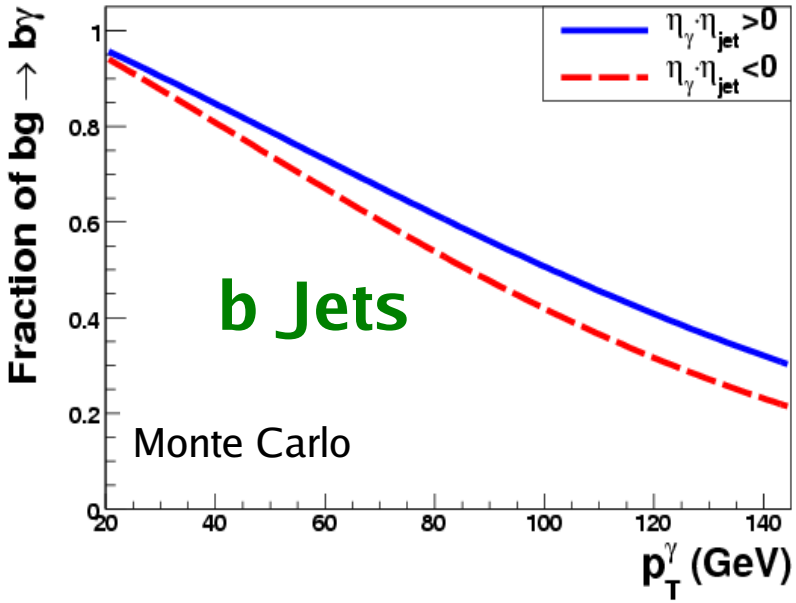


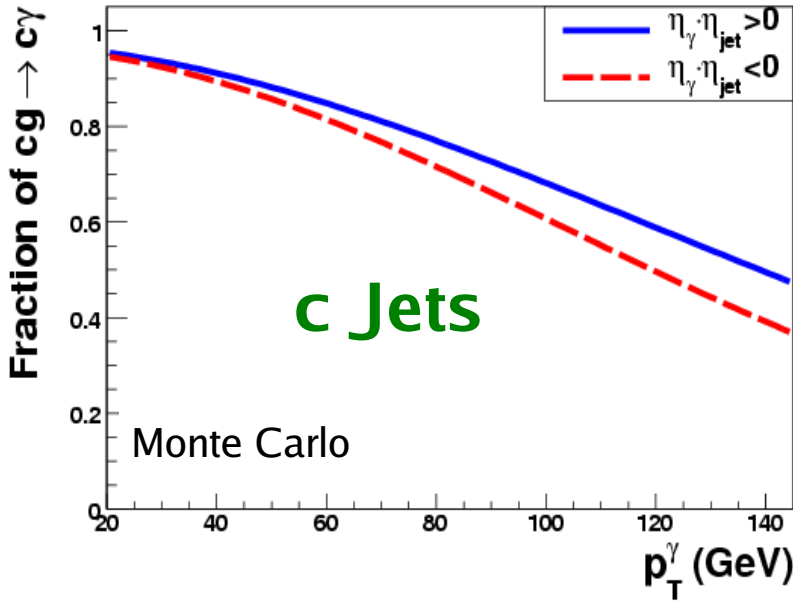
- The Compton-like scattering diagram
  - Probes heavy flavor quark content of incident proton
  - Provides possible important constraints to PDFs
  - Tests the evolution of pQCD as a function of p^{γ}_{T}



- The quark-antiquark annihilation diagram
  - Probes gluon splitting to heavy flavor quark pairs
  - Dominates for p^{γ}_{T} larger than ~100 GeV

Fraction of Events from Compton-like Scattering



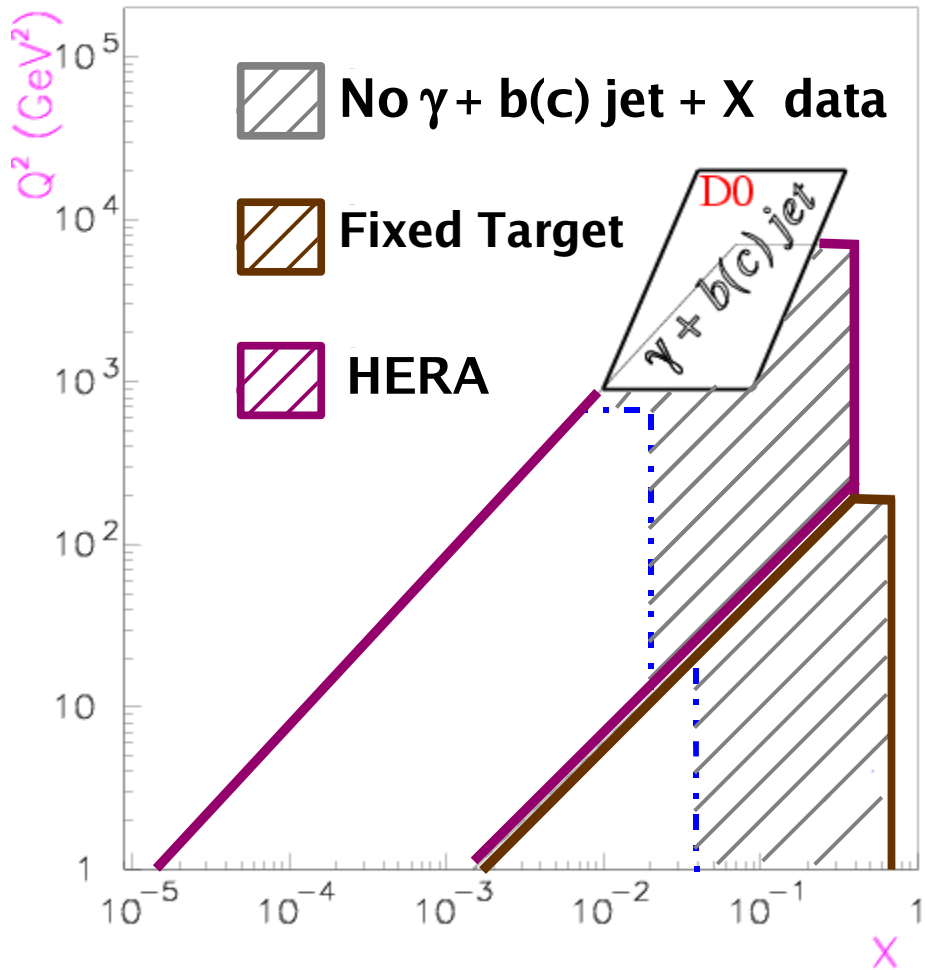


Uncharted Territories

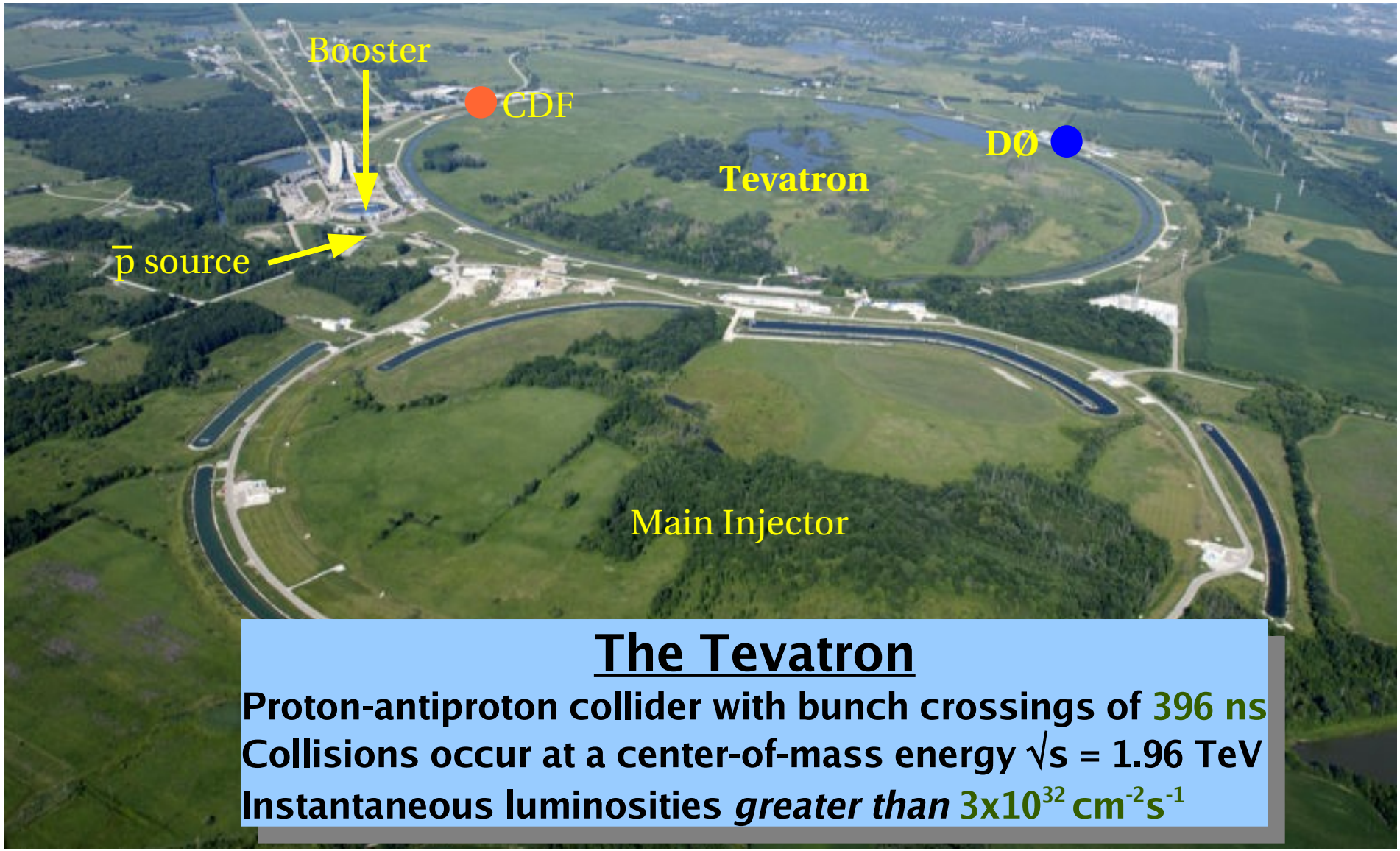
- Sensitive to previously unexplored regions of x-Q^2 phase space

$$Q^2 \approx (p^{\gamma}_{T})^2, \; x = \frac{\text{parton } \bar{p}}{\text{proton } \bar{p}}$$

- For our measurement, we can probe the phase space:
  - $9 \times 10^2 < Q^2 < 2 \times 10^4$ GeV^2
  - $0.01 < x < 0.3$
- Compared to HF production at HERA:
  - Maximum Q^2 is ~650 GeV^2
  - Maximum x value is ~0.02
    (Different initial states)



The Tevatron at Fermilab



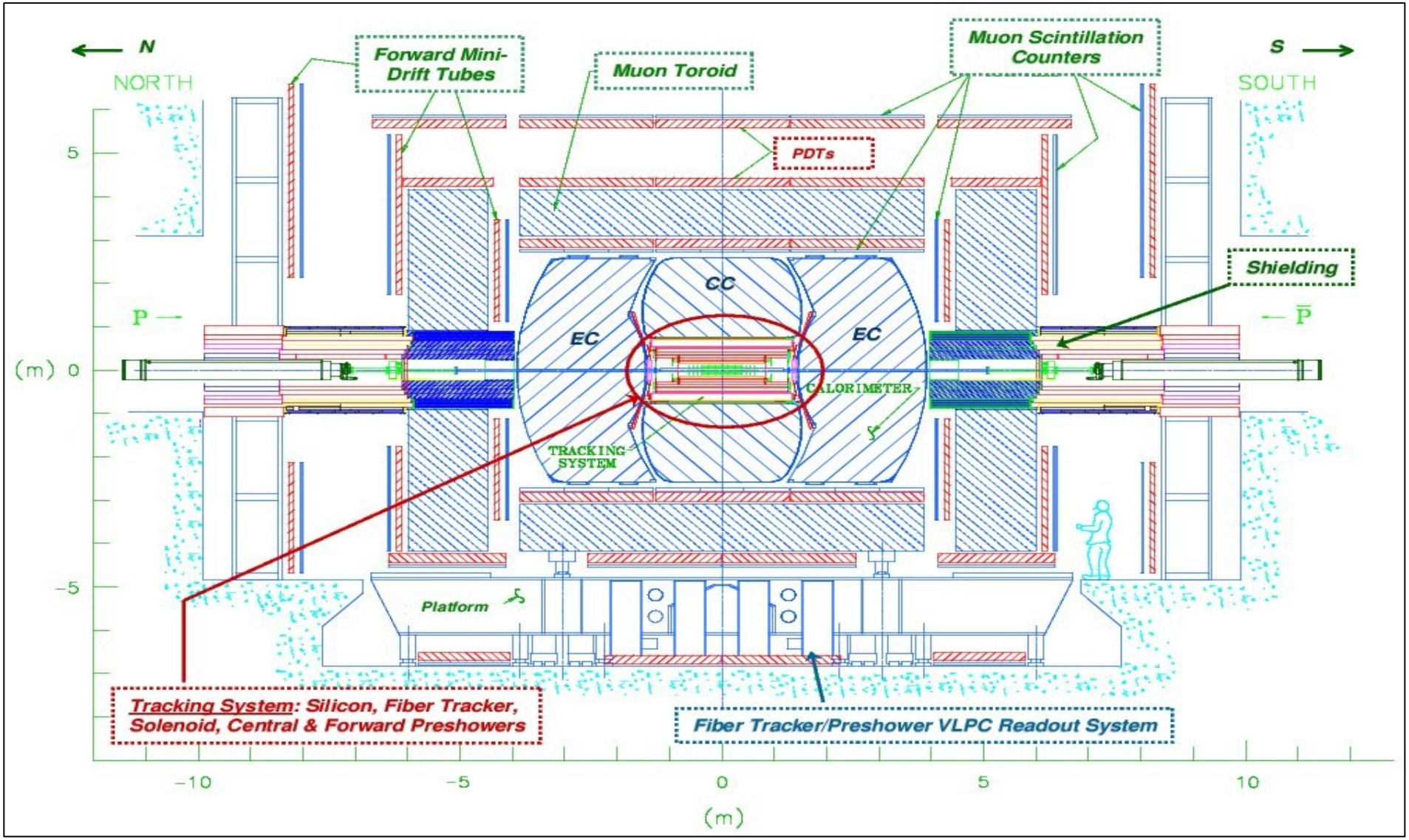
The Tevatron

Proton-antiproton collider with bunch crossings of 396 ns

Collisions occur at a center-of-mass energy $\sqrt{s}$ = 1.96 TeV

Instantaneous luminosities *greater than* 3×10^{32} $cm^{-2}s^{-1}$

The DØ Detector



Signature Selection

Photon candidate

$p_T > 30$ GeV

$|y^{\gamma}| < 1.0$

Leading p_T jet

$p_T > 15$ GeV

$|y^{jet}| < 0.8$

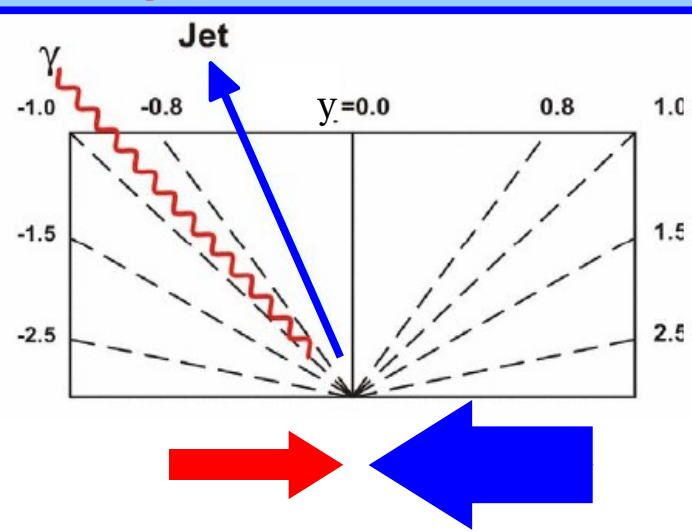
Differential ⇒ Binning in p^{γ}_T, y^{γ}, and y^{jet}:

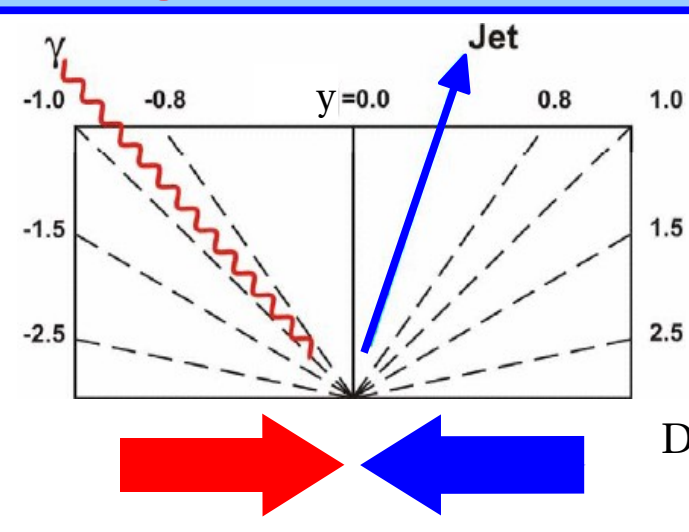
p^{γ}_T bins: 30 - 40, 40 - 50, 50 - 70, 70 - 90, 90 - 150 GeV

(No binning in jet p_T)

Two rapidity regions:

Region 1: $y^{\gamma} y^{jet} > 0$ **Region 2: $y^{\gamma} y^{jet} < 0$**

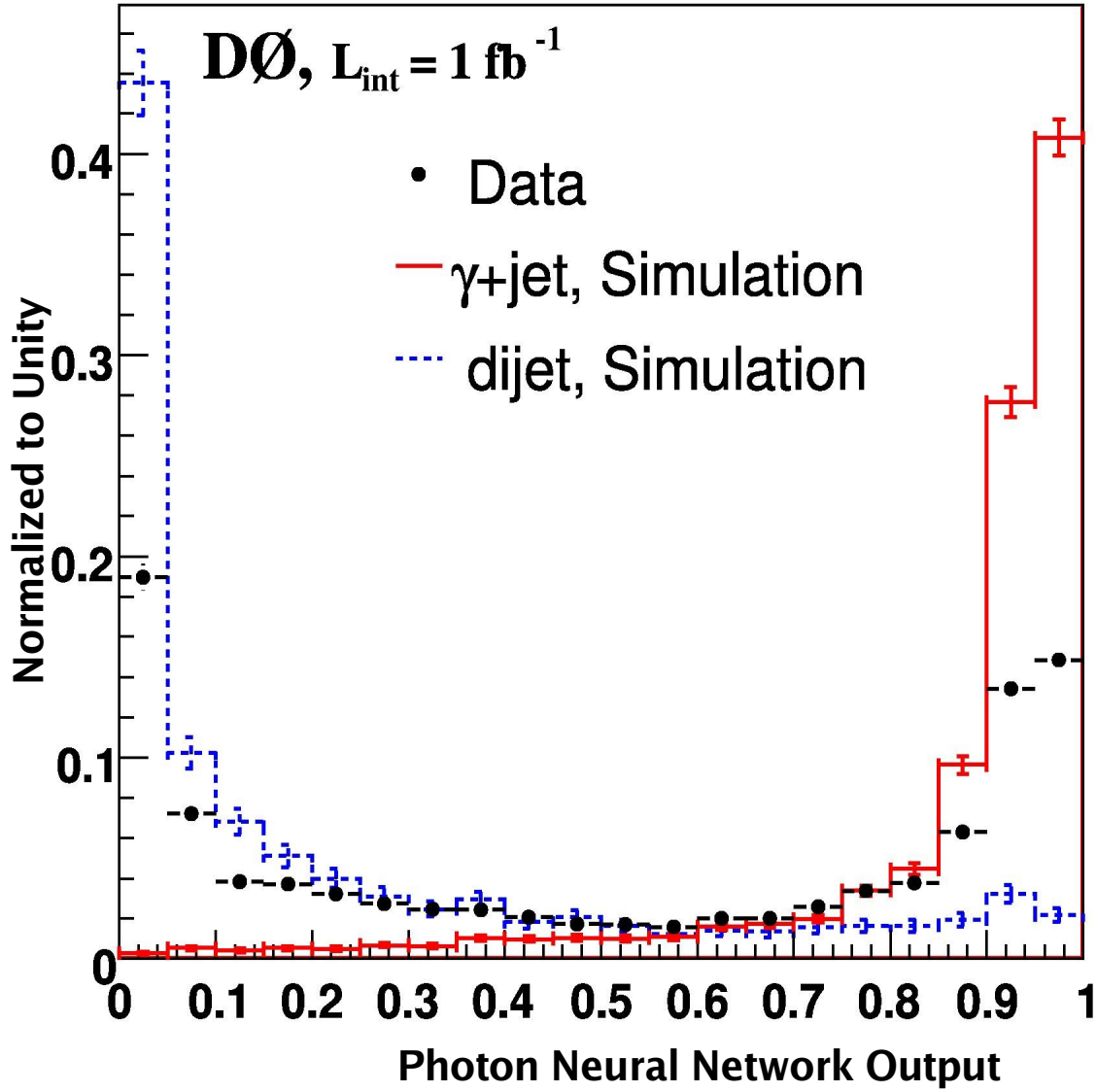




Final Photon Selection

Photon Neural Network

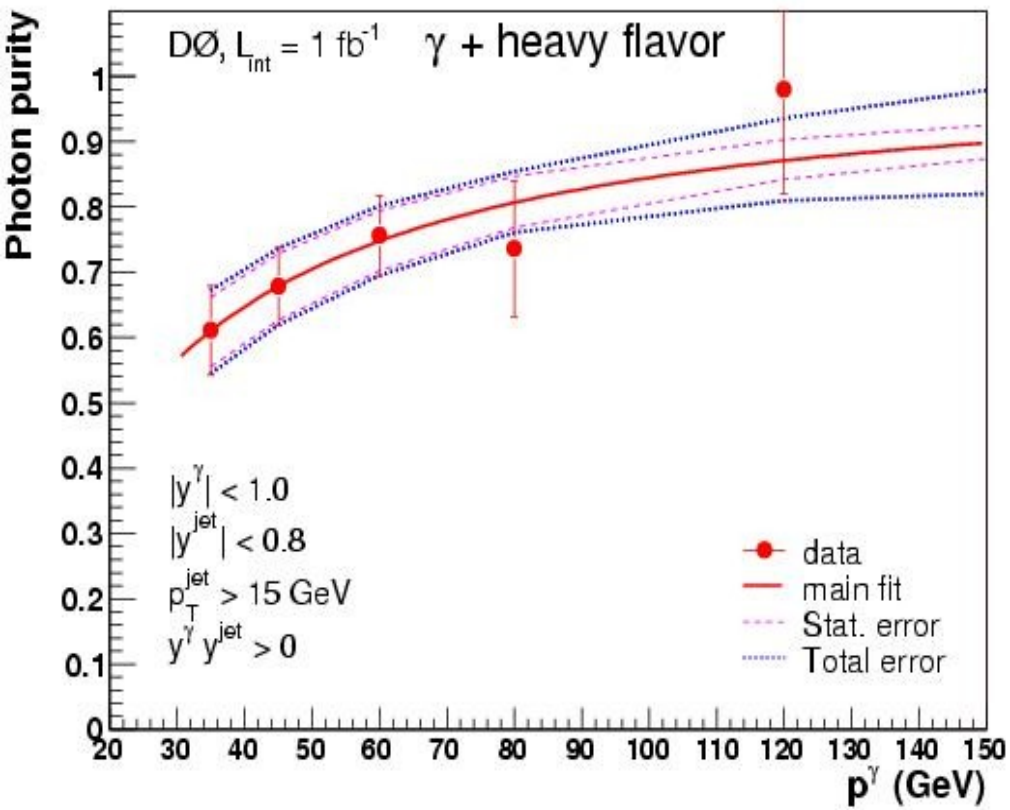
- Multiple input variables combine for one output
  - Output constrained to {0 – 1}
- Neural Net is trained with signal and background Monte Carlo
  - Direct photon output ⇒ 1
  - Background output ⇒ 0
- After photon pre-selection
  - The output shows that background events still contaminate the data sample
- Using output shape distribution
  - Estimate the *fraction* of direct photons in the data (Purity)



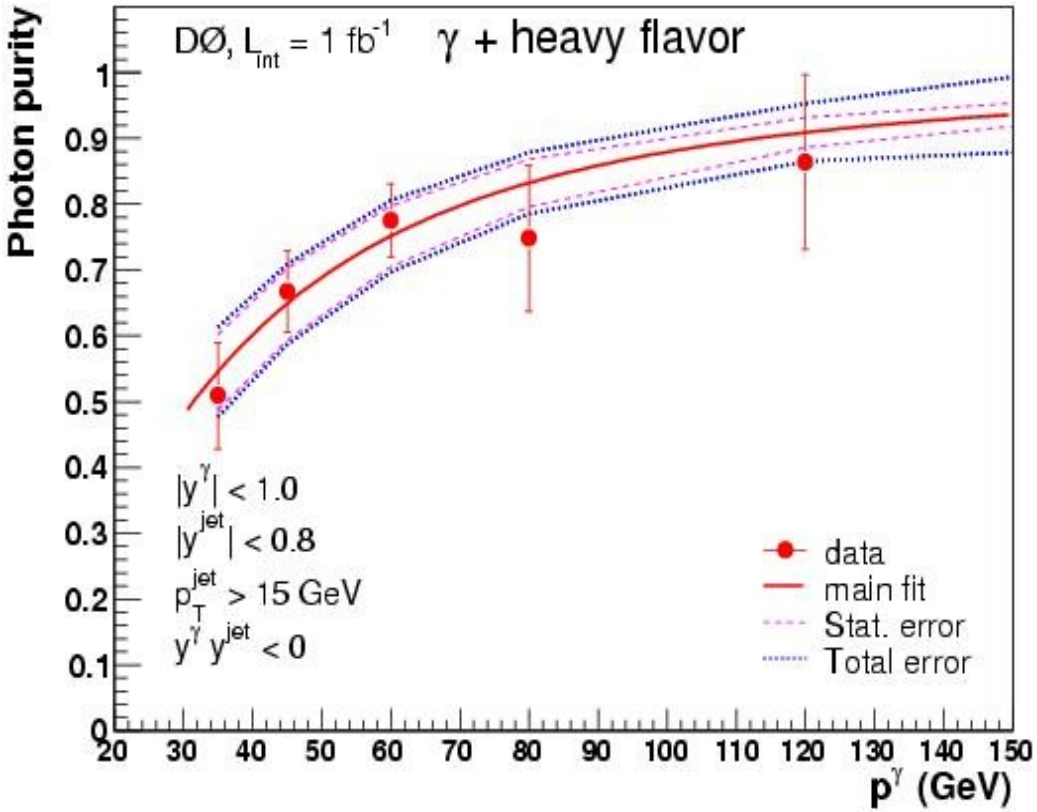
Photon Purity Results

- **Finally, we determine the photon purity of the data sample**
  - **Fit signal and background Monte Carlo shape to the data**
    - **Calculates the best description of the data shape**
  - **The fits are performed in each photon p_T bin for each Region separately**

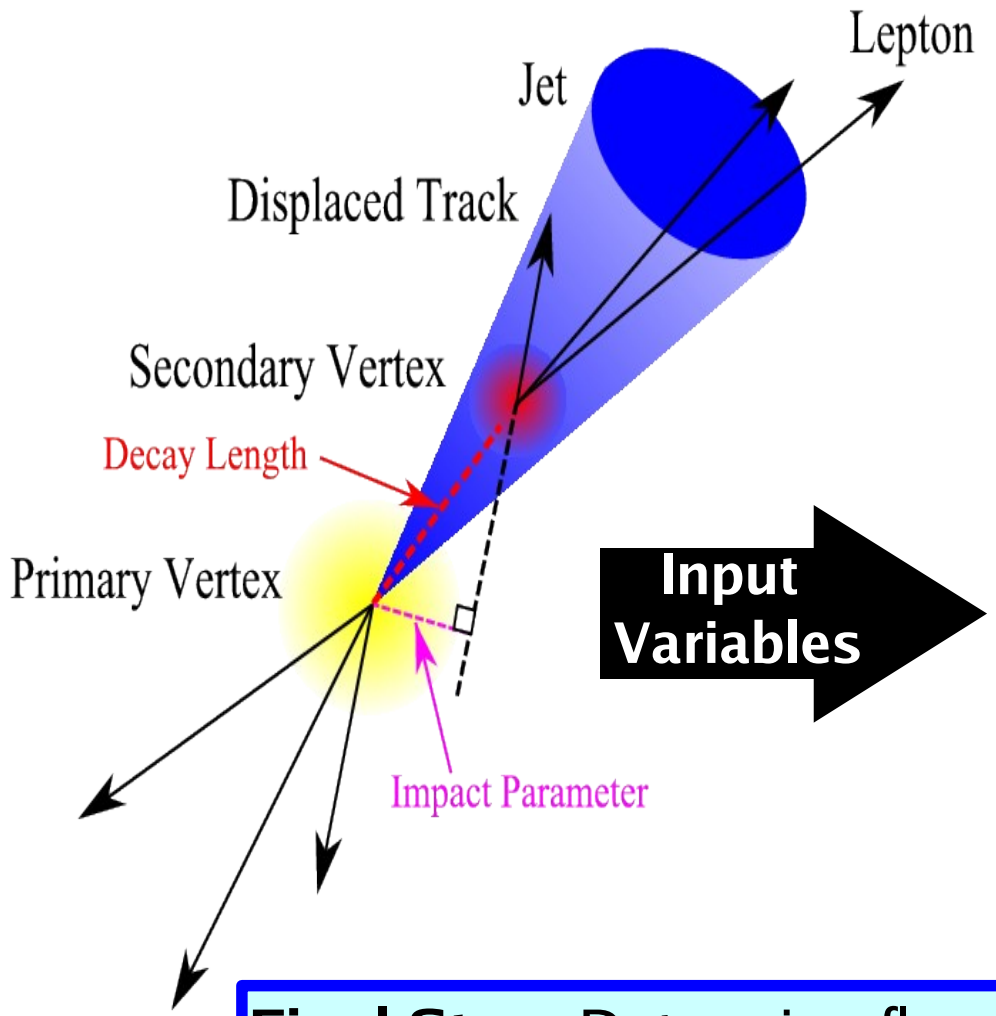
Region 1: $y^\gamma y^{jet} > 0$



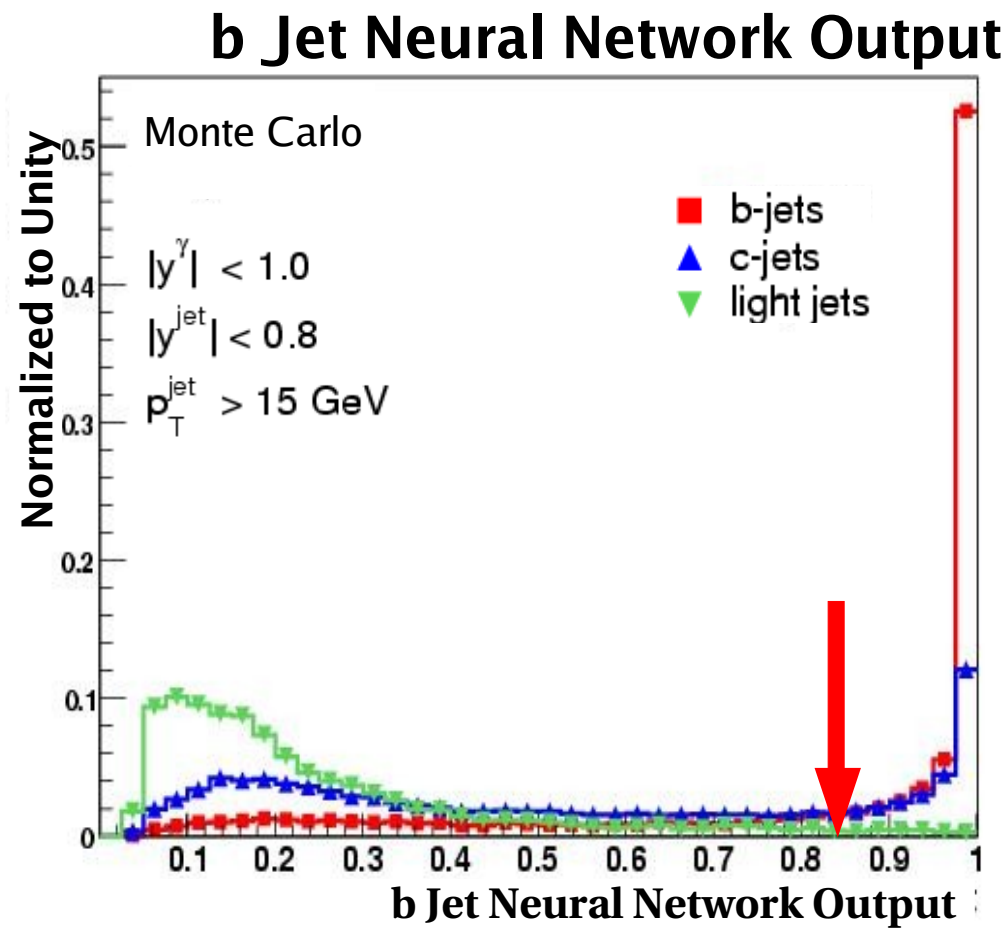
Region 2: $y^\gamma y^{jet} < 0$



Identifying Heavy Flavor Jets



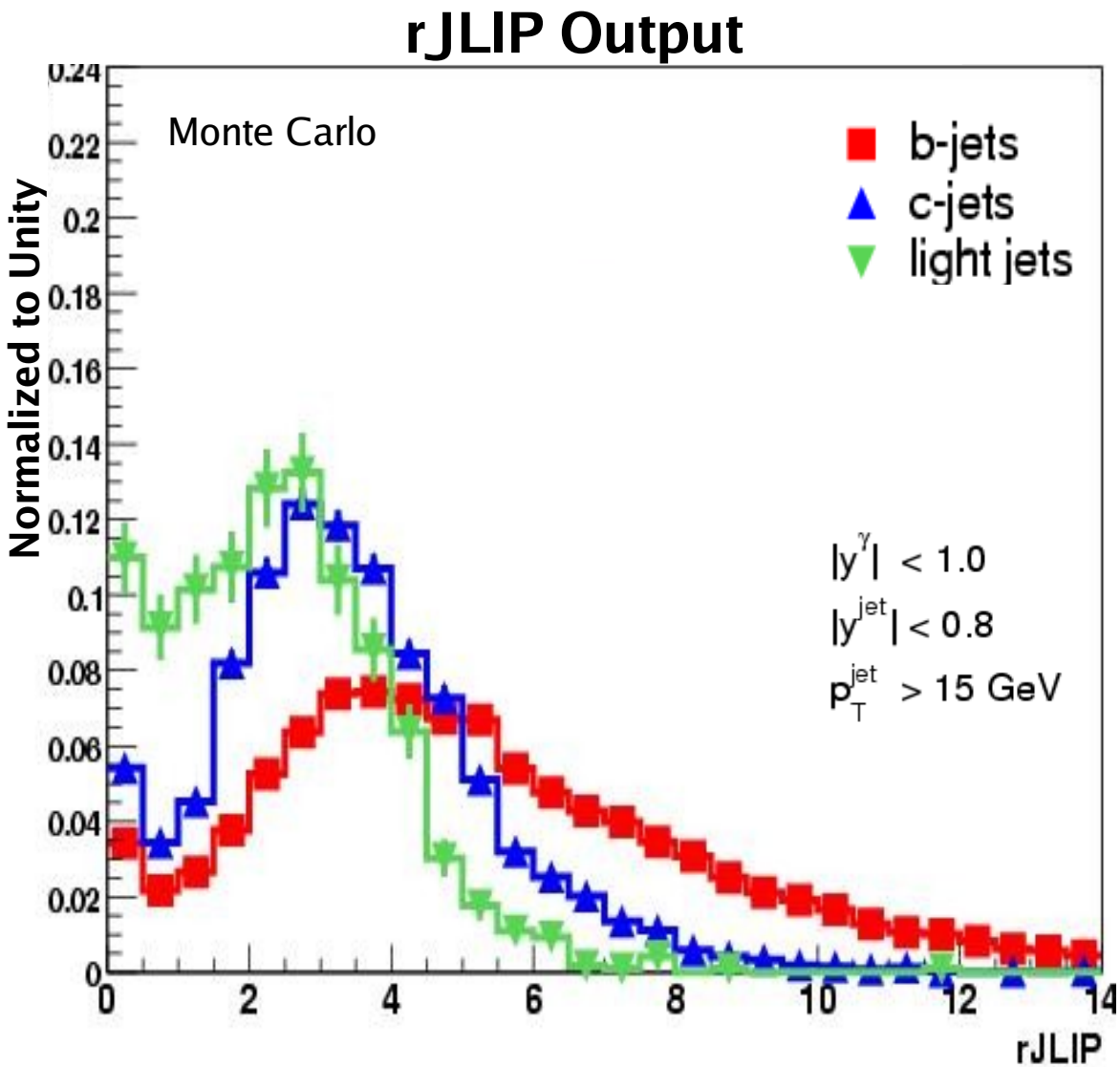
Input Variables



Final Step: Determine flavor fractions in **final data sample**

- **Using additional discriminant ⇒ rJLIP**

Jet Flavor Templates



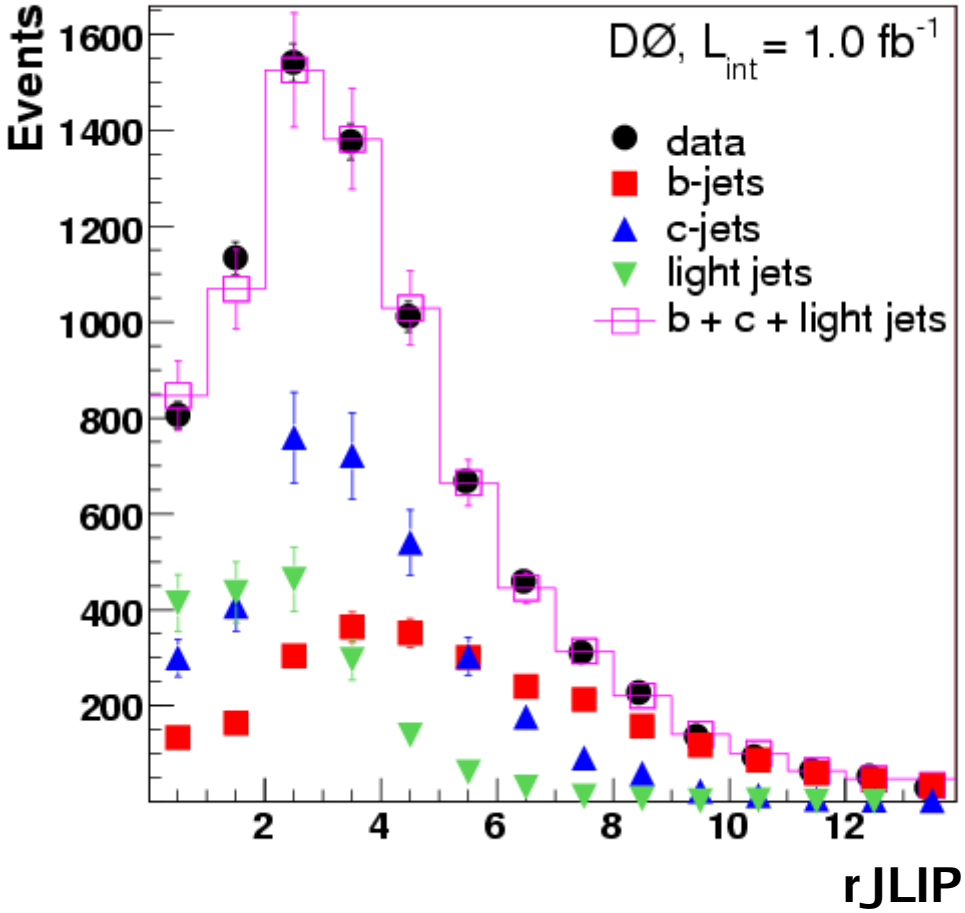
Reduced **J**et **Li**fetime **P**robability

- Probability ($\mathbf{P_{Track}}$) of a track to originate from the primary vertex (Uses *impact parameter* significance)
- $\mathbf{rJLIP = -\ln \prod_{i}^{N_{Tracks}} P^{i}_{Track}}$
- **"Reduced:"** Lowest value of $\mathbf{P_{track}}$ is removed

Heavy Flavor Fractions

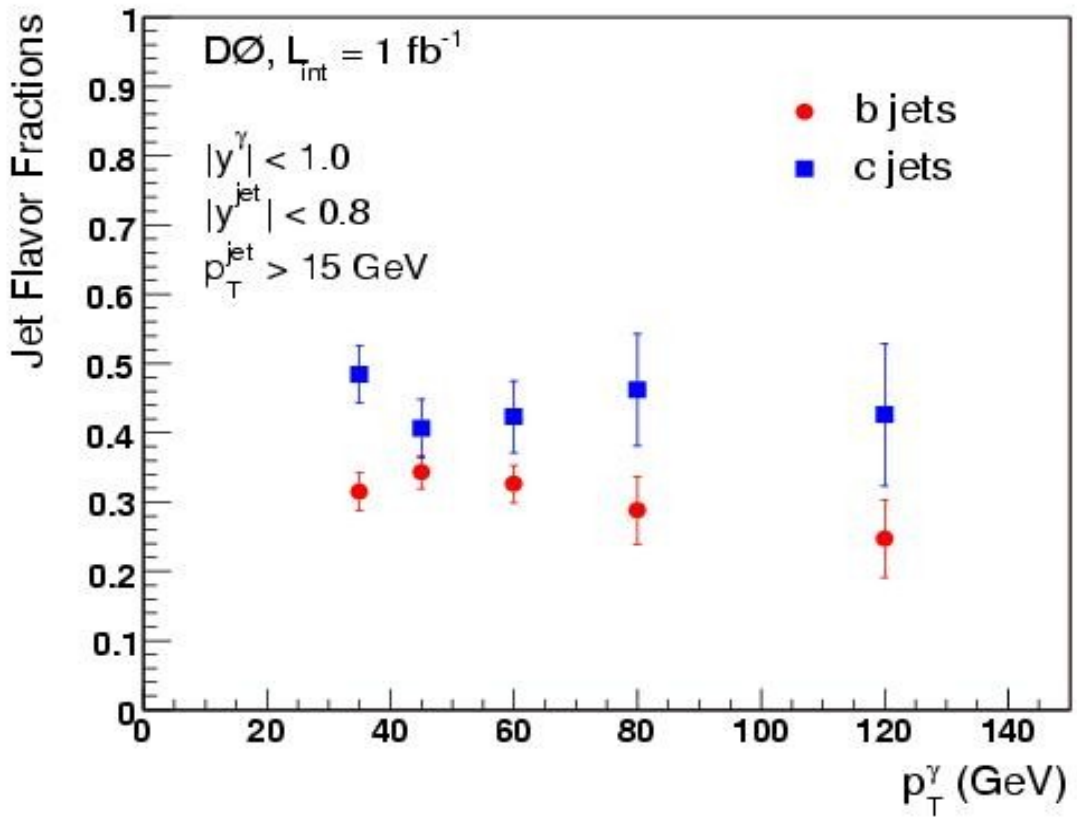
Template Fitting Procedure

- **Analagous technique to photon purity estimate**
- **Use rJLIP for shape information**
- Monte Carlo is used for c and b jet templates
- **Enriched light jet sample (NT) from data** is used for light jet template
- **Flavor fractions** are determined for light, c **and** b jets with a simultaneous fit
- **Require the sum of the flavor fractions (light + c + b) ≡ 1**
- **Cross check for agreement:**
  - **Compare the sum of the individual jet flavor templates *weighted by the found fractions* to the data**



Flavor Fraction Results

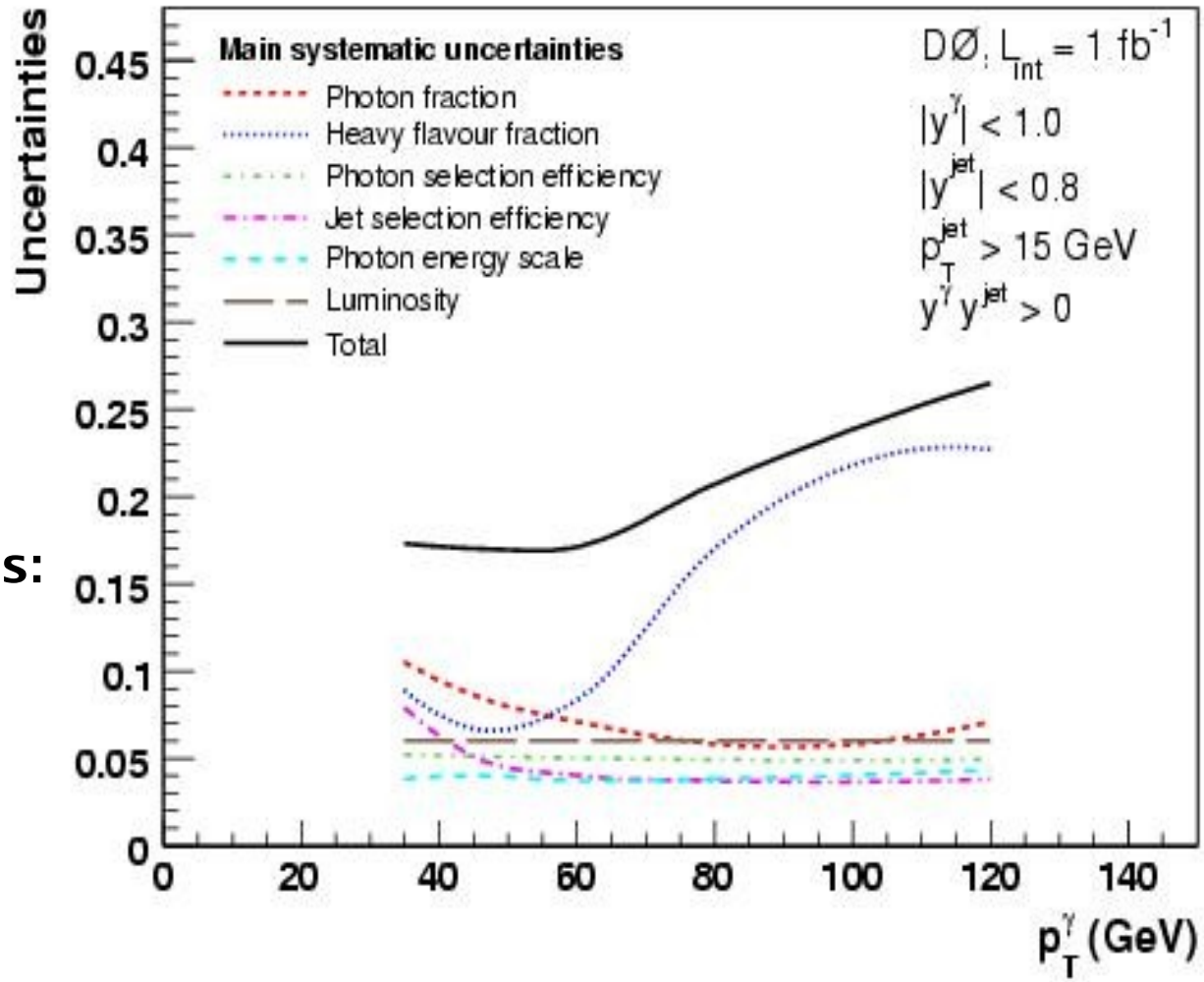
- Heavy flavor fraction results for the entire photon p_T range
  - **Fitting was performed independently in the two rapidity regions**
    - **Very good agreement between regions**
    - **Can combine regions for decreased uncertainties**
  - **Litany of cross-checks performed and fractions found to be *very robust***



Overall Systematics

Main systematic uncertainties

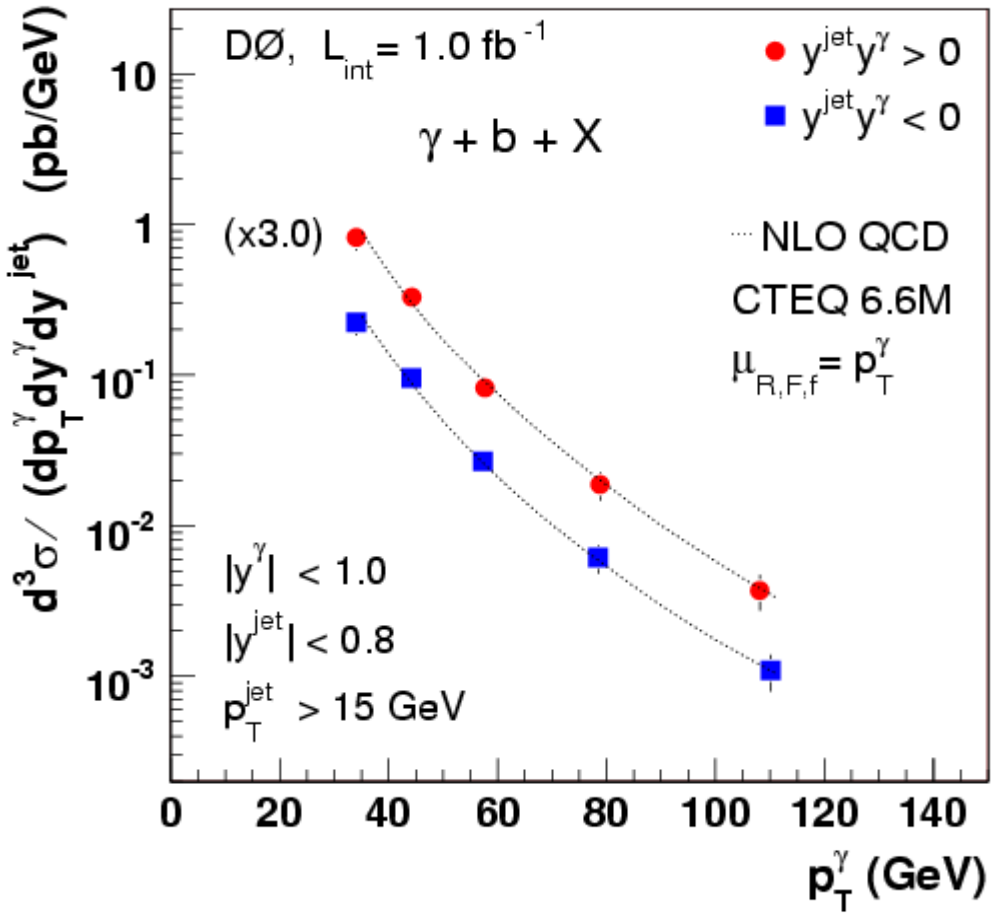
- Photon fraction
- Heavy flavour fraction
- Photon selection efficiency
- Jet selection efficiency
- Photon energy scale
- Luminosity
- Total

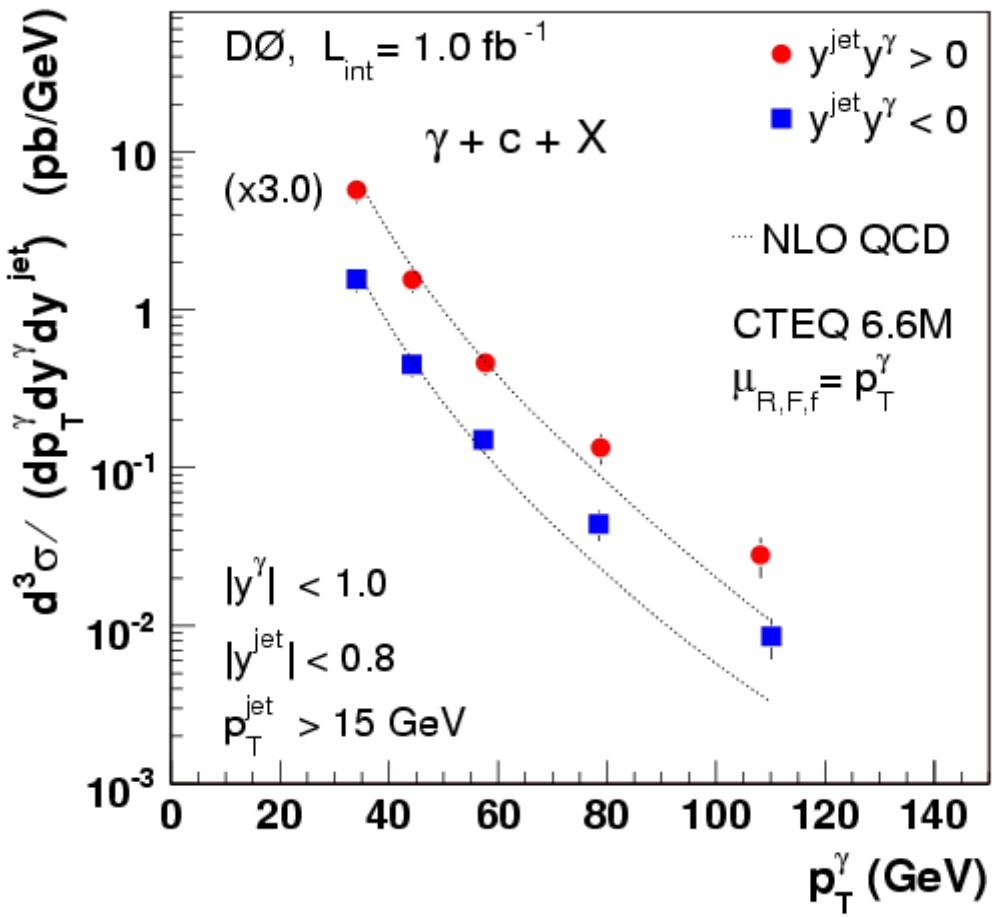


- **The two dominant systematics:**
  - **At low p^{γ}_T, the photon fitting fraction dominates**
  - **At high p^{γ}_T, the jet flavor fraction fitting dominates**

b and c Jet Cross Sections

- **Results for the γ + b jet and γ + c jet cross sections**
- Theory curves calculated with next-to-leading-order predictions
  - **Calculations provided by T. Stavreva and J. Owens (of CTEQ)**
  - CTEQ6.6M PDFs were used in the calculation

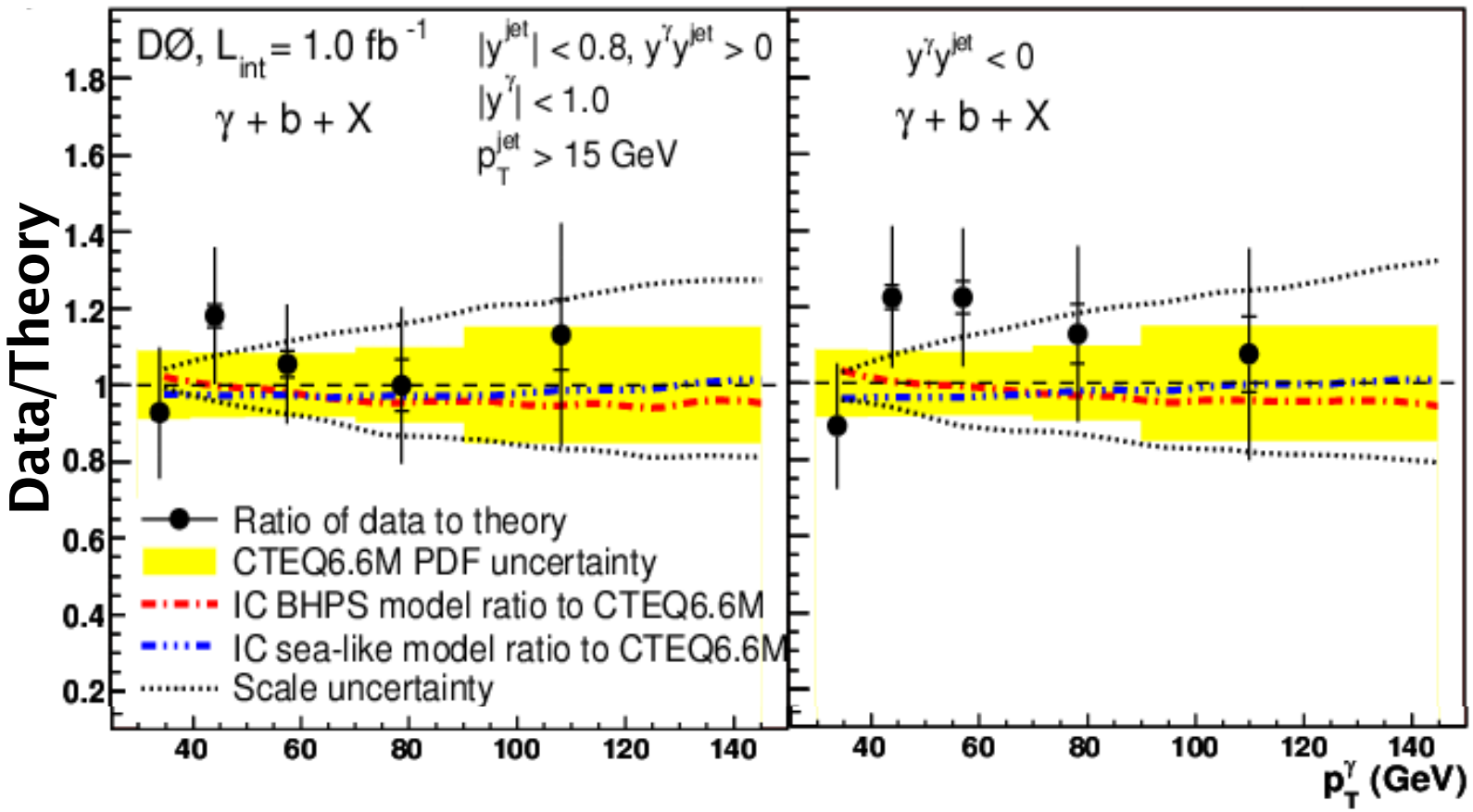




Data to Theory Ratios (γ + b Jet)

- **Overall agreement between data and theory is within the given uncertainties**
  - **Agreement is seen across all photon p_T's in both rapidity regions**

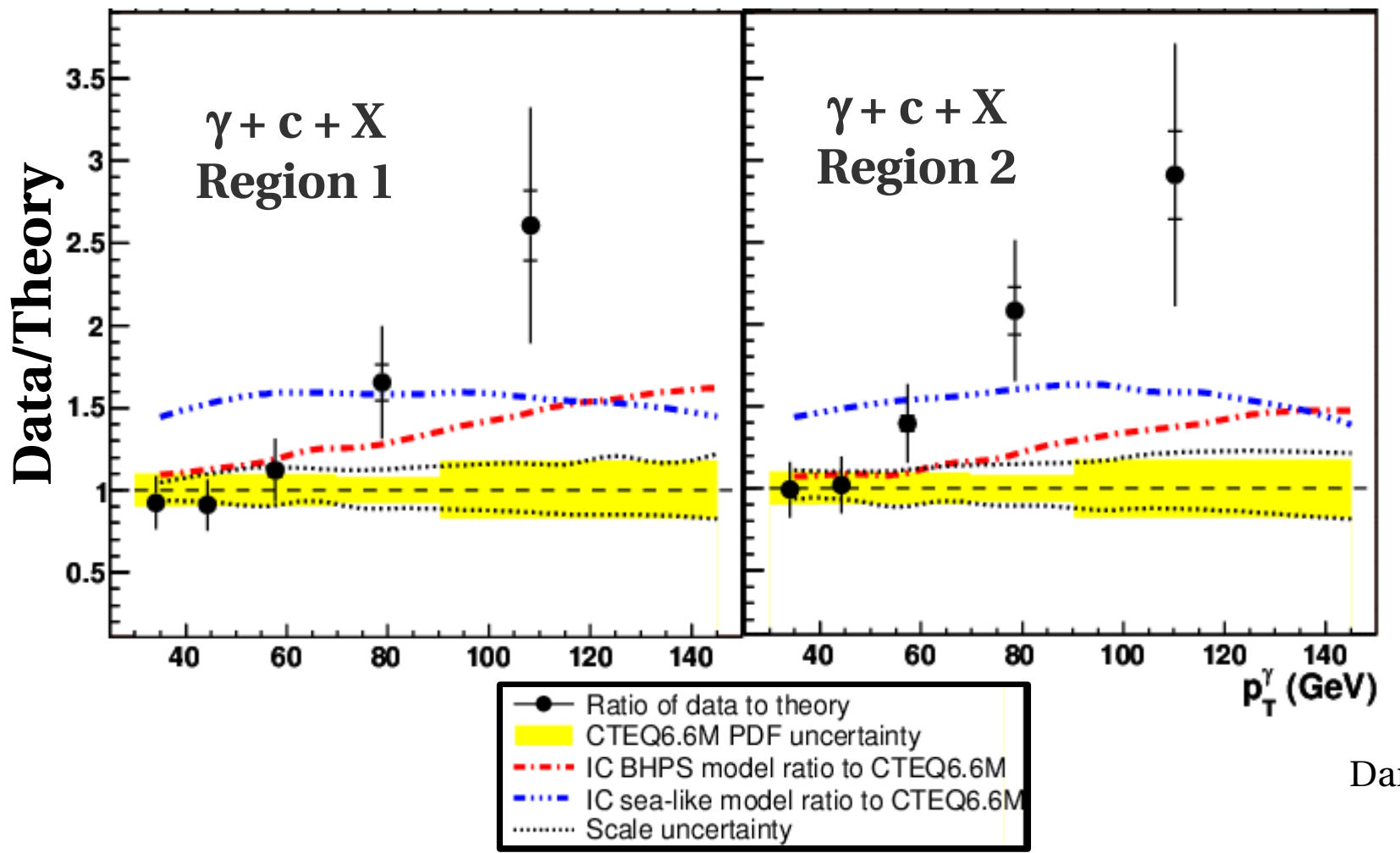
Region 1: $y^{\gamma} y^{jet} > 0$ **Region 2: $y^{\gamma} y^{jet} < 0$**



Data to Theory Ratios (γ + c Jet)

- Discrepancy between data and theory is present for photon p_T > 70 GeV in both Region 1 and Region 2
  - Comparisons to CTEQ PDF sets with intrinsic charm are included

Region 1: $y^{\gamma} y^{jet} > 0$ Region 2: $y^{\gamma} y^{jet} < 0$



Conclusions

- **Results** for the triple differential cross section for **γ + b + X and γ + c + X** in 2 rapidity regions and in five photon p_T bins
  - **The γ + b jet cross section shows agreement in both regions**
  - **The γ + c jet cross section shows agreement until p^{γ}_{T} ~70 GeV**

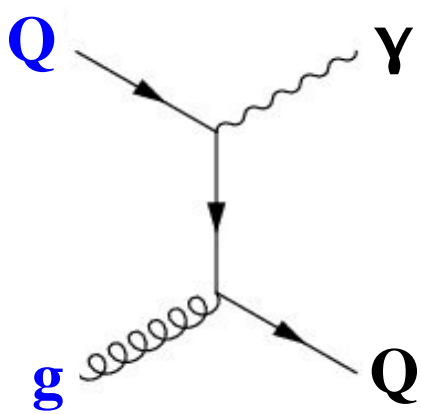
- **First differential measurement of either the γ + b + X or the γ + c + X cross sections ever at a hadron collider**
  - New combination of techniques made measurement possible
  - **Submitted to PRL**

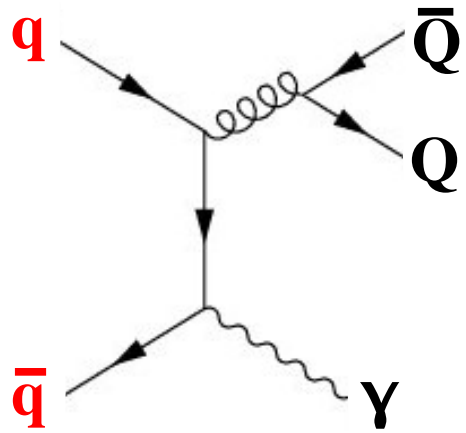
- **More information can be found at:**
  - **http://arxiv.org/abs/0901.0739**
  - **http://www-d0.fnal.gov/Run2Physics/WWW/results/final/QCD/Q09A/**

Backup Slides

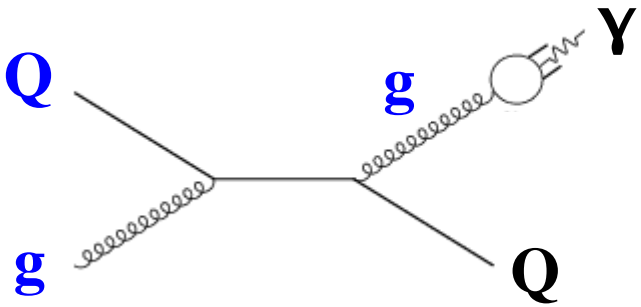
QCD Production

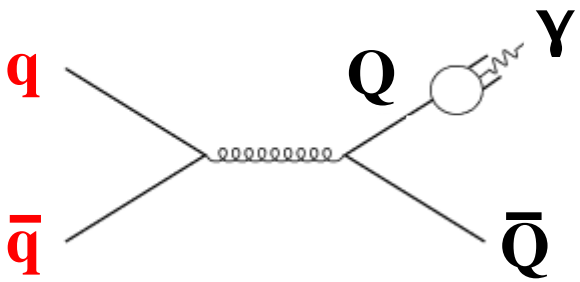
- What contributes to these cross sections?
- The final state is dominated by mainly <u>two diagrams</u>





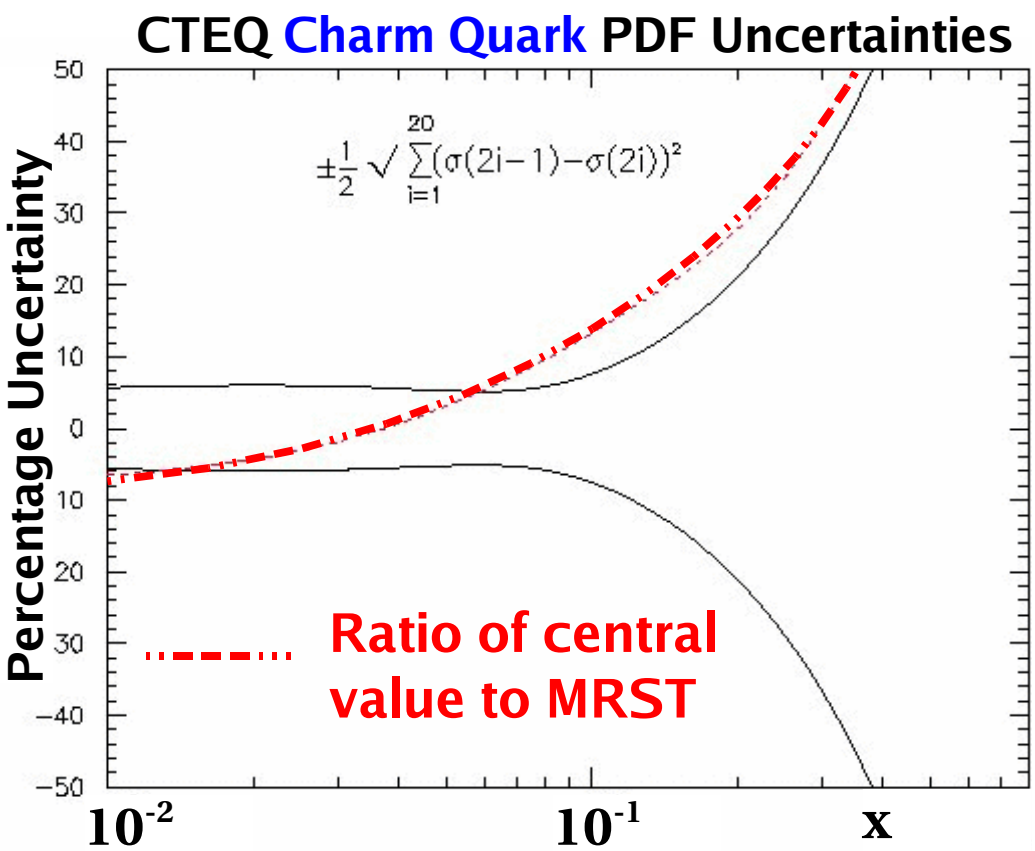
- Additional leading order diagrams from fragmentation are largely suppressed by photon isolation requirements:

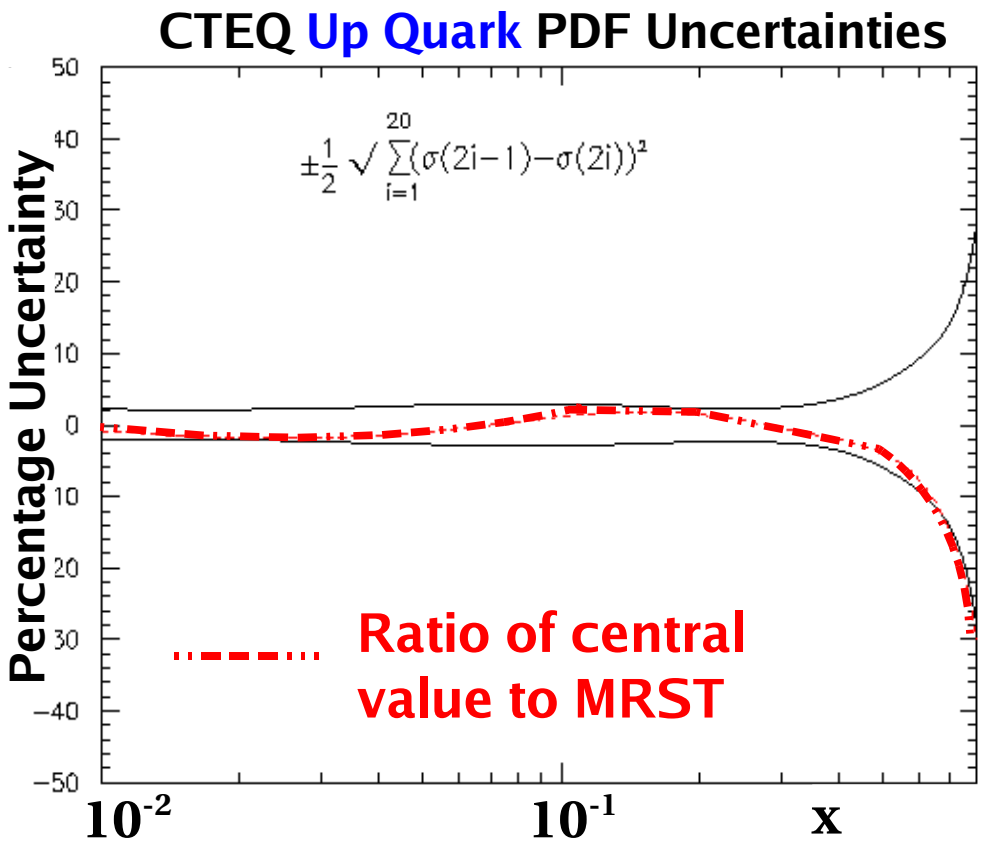




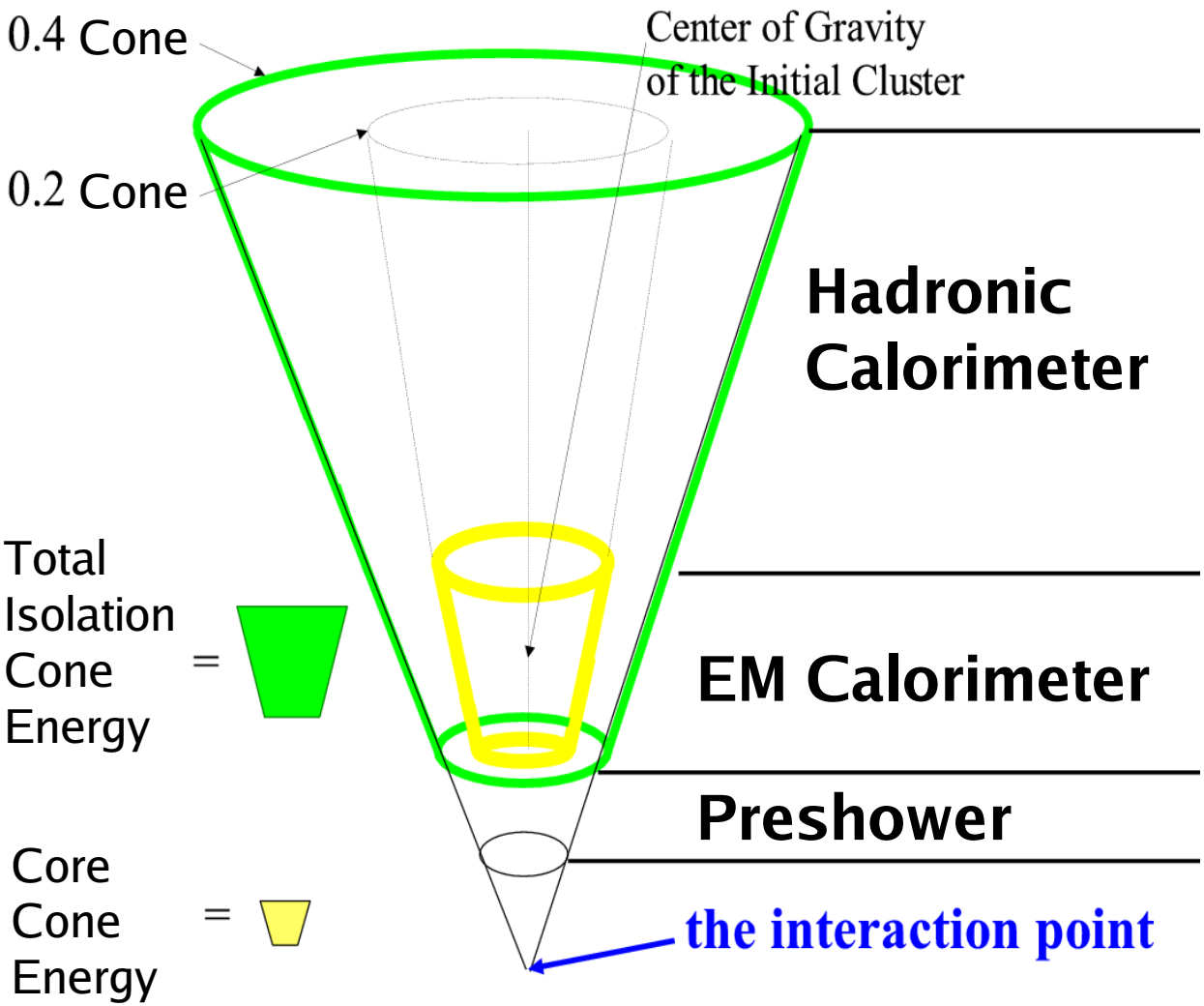
Current PDF Uncertainties

- Sensitive to the charm, bottom, and gluon content of the proton and antiproton
- These PDFs are under-constrained by experimental data





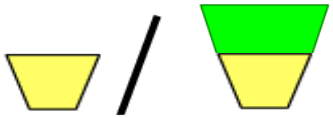
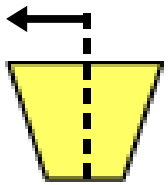
Photon Selection



Calorimeter Criteria

Fractional isolation

EM energy fraction



Energy shower ϕ width