Recent Results of $\gamma + c + X$ and $\gamma + b + X$ Production Cross Sections at DØ

Dan Duggan
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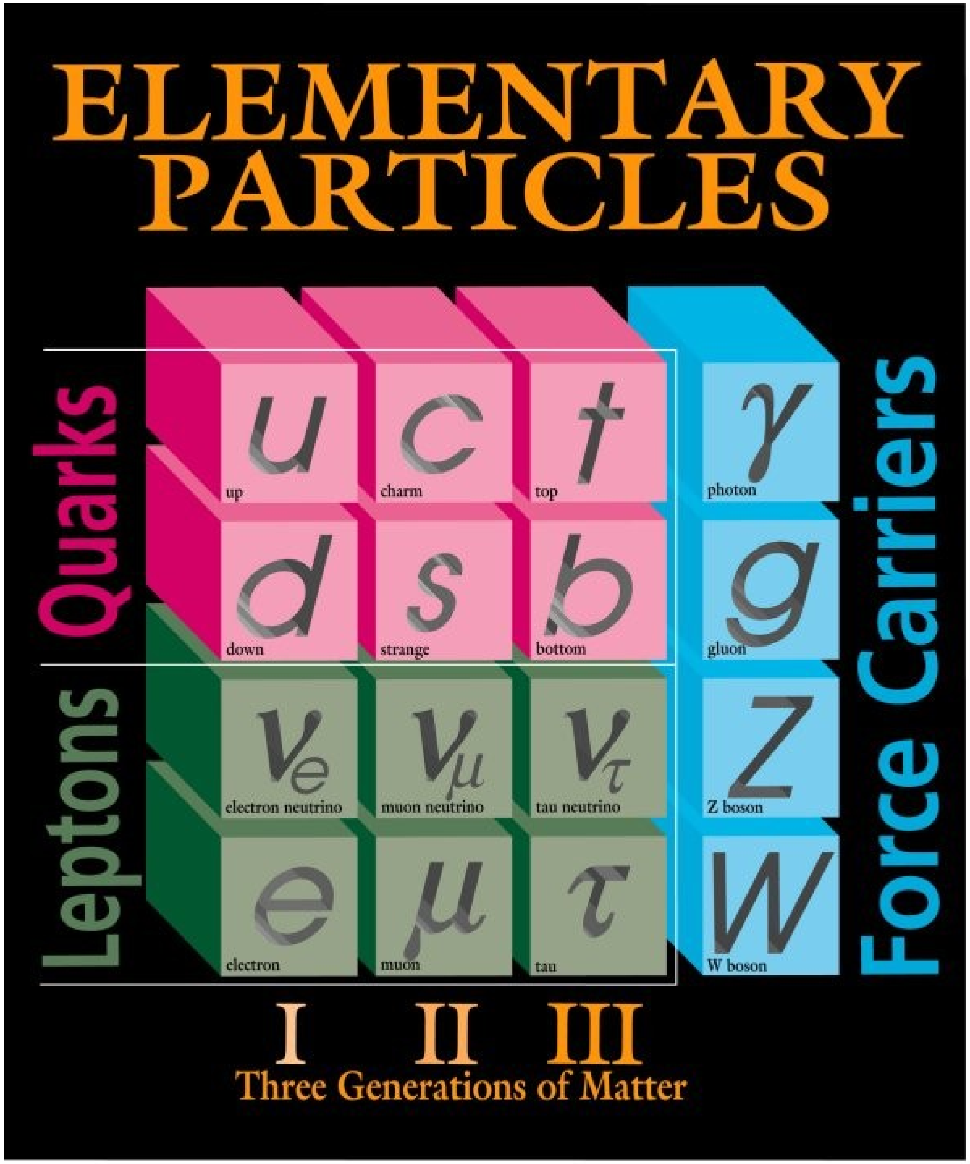
The Standard Model (SM)

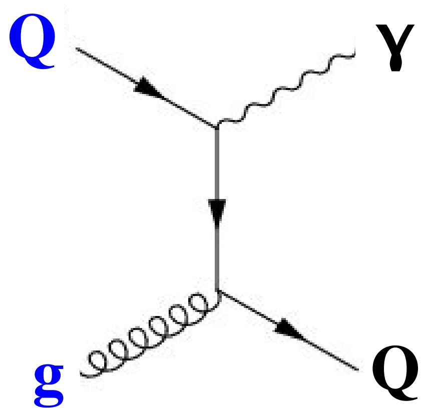


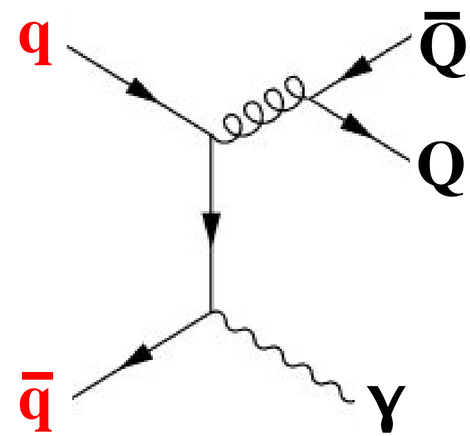
Fermilab 95-759

- The Standard Model (SM) describes the strong force
  - **Quantum Chromodynamics (QCD)**
- Three generations of particles (quarks and leptons)
- Bosons are the force carriers
  - **Photons ⇔ Electromagnetism**
  - **Gluons ⇔ Strong force**
- Charm and bottom are the heaviest flavors in the proton
  - **Sea quark contribution**

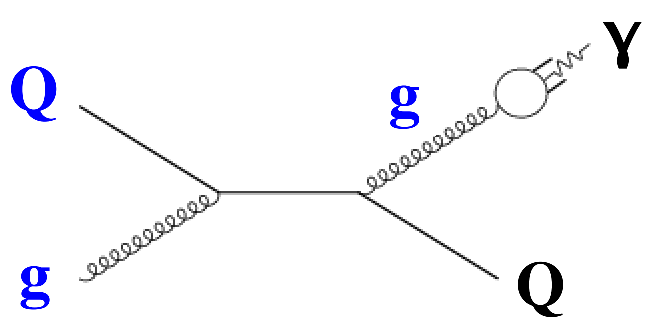
QCD Production

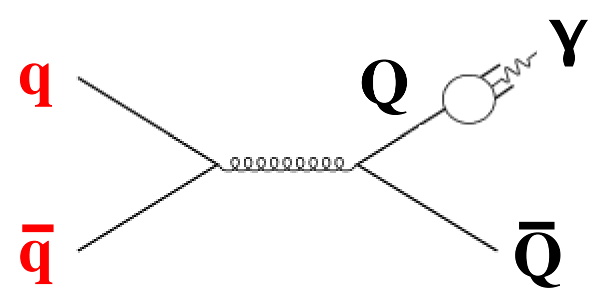
- What contributes to these cross sections?
- The final state is dominated by mainly <u>two diagrams</u>





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

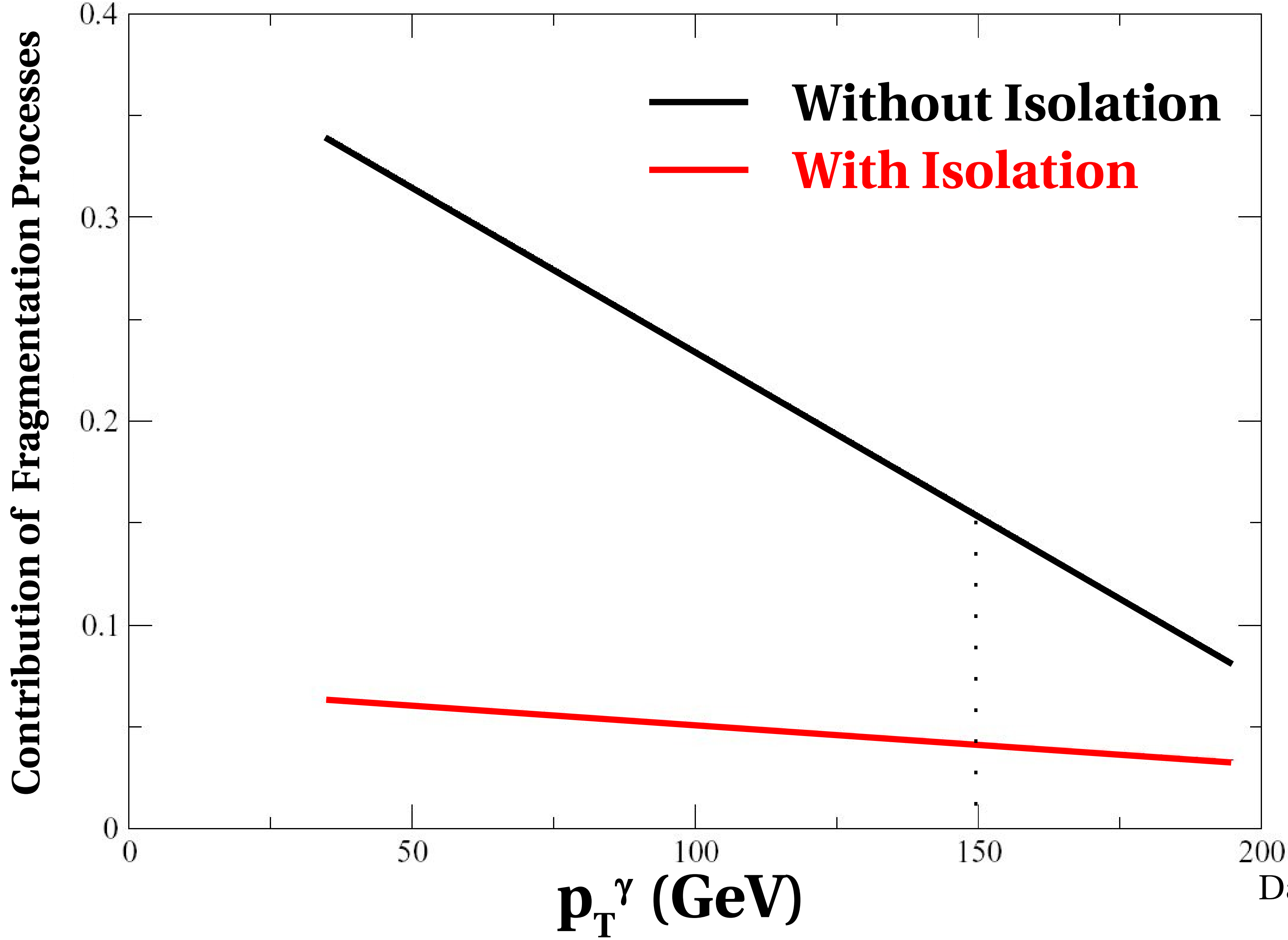




Factoring in Isolation

$p + \bar{p} \rightarrow \gamma + b + X$

$\sqrt{S} = 1.96$ TeV



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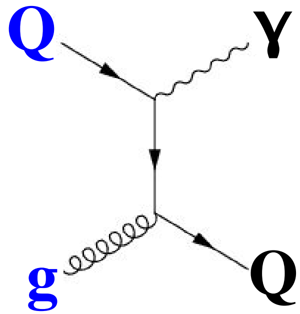
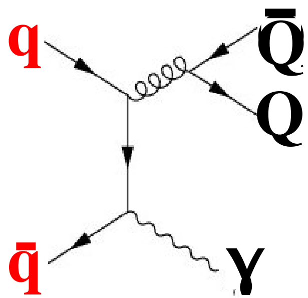
The Physics of QCD

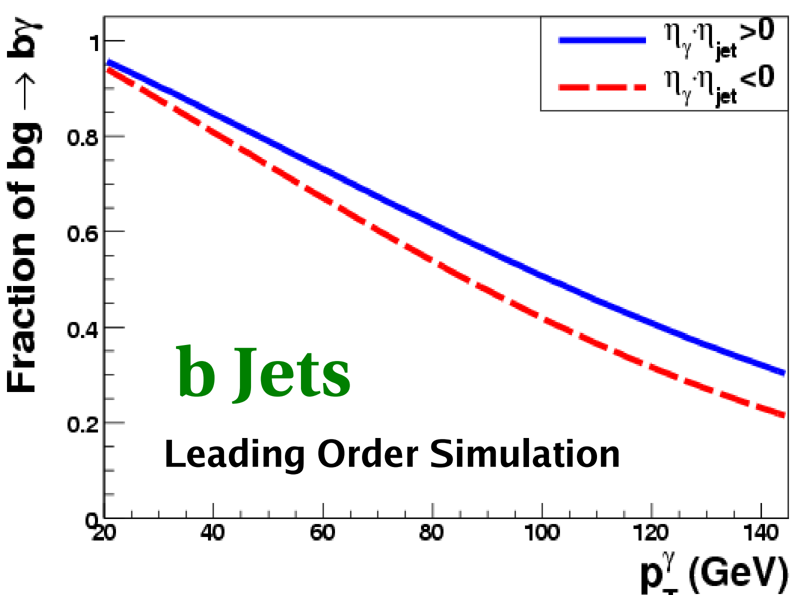


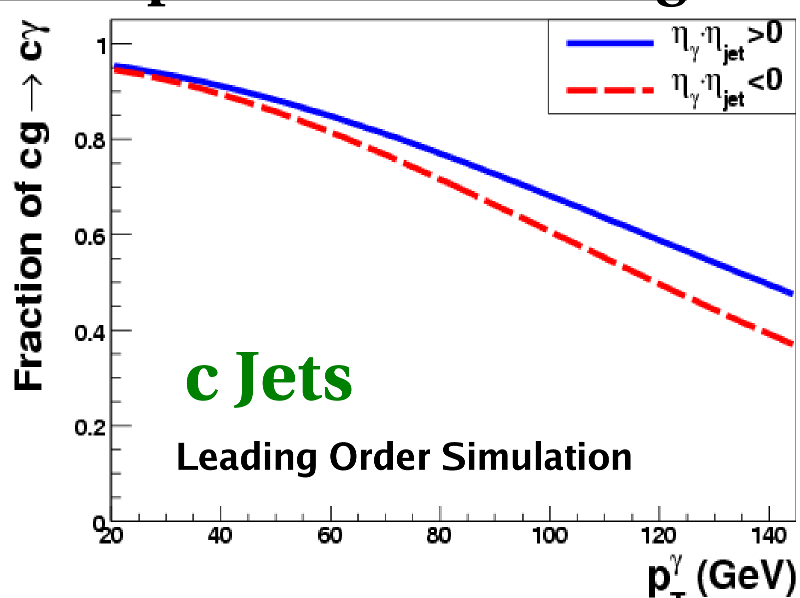
– The Compton-like scattering diagram
  - Heavy flavor quark comes from the incident parton
  - Provides possible important constraints to PDFs
  - Tests the evolution of pQCD as a function of p^{γ}_{T}



– The quark-antiquark annihilation diagram
  - Heavy flavor quark comes from gluon splitting
  - Dominates for p^{γ}_{T} larger than ~100 GeV

Fraction of Events from Compton-like scattering

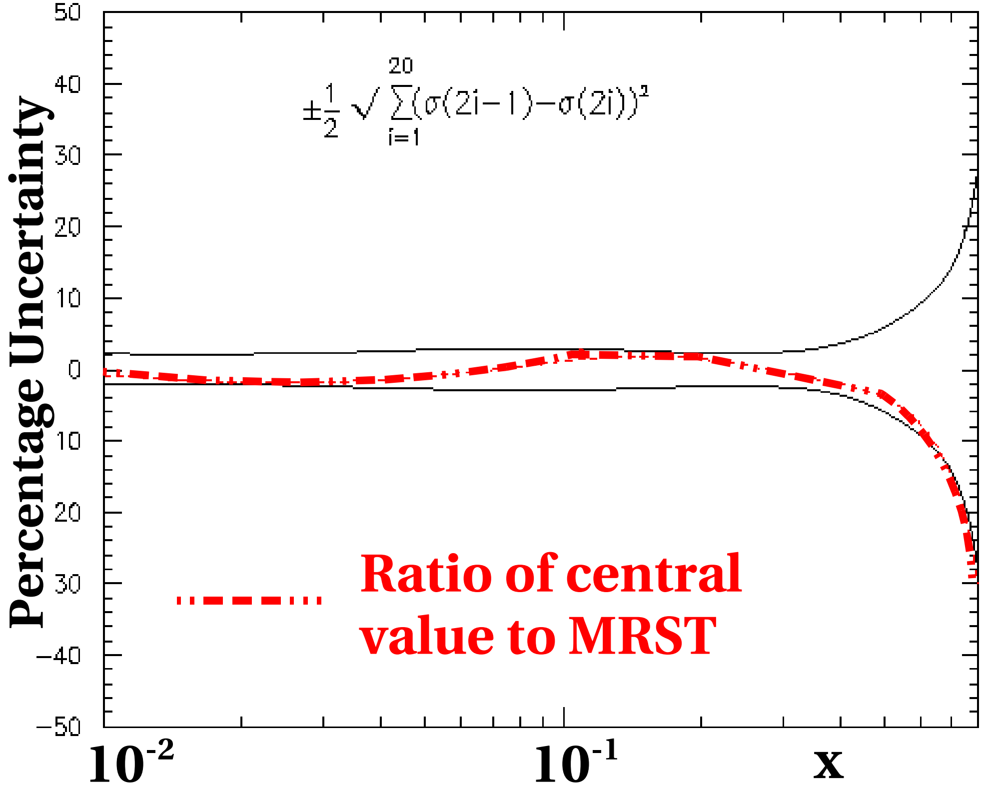




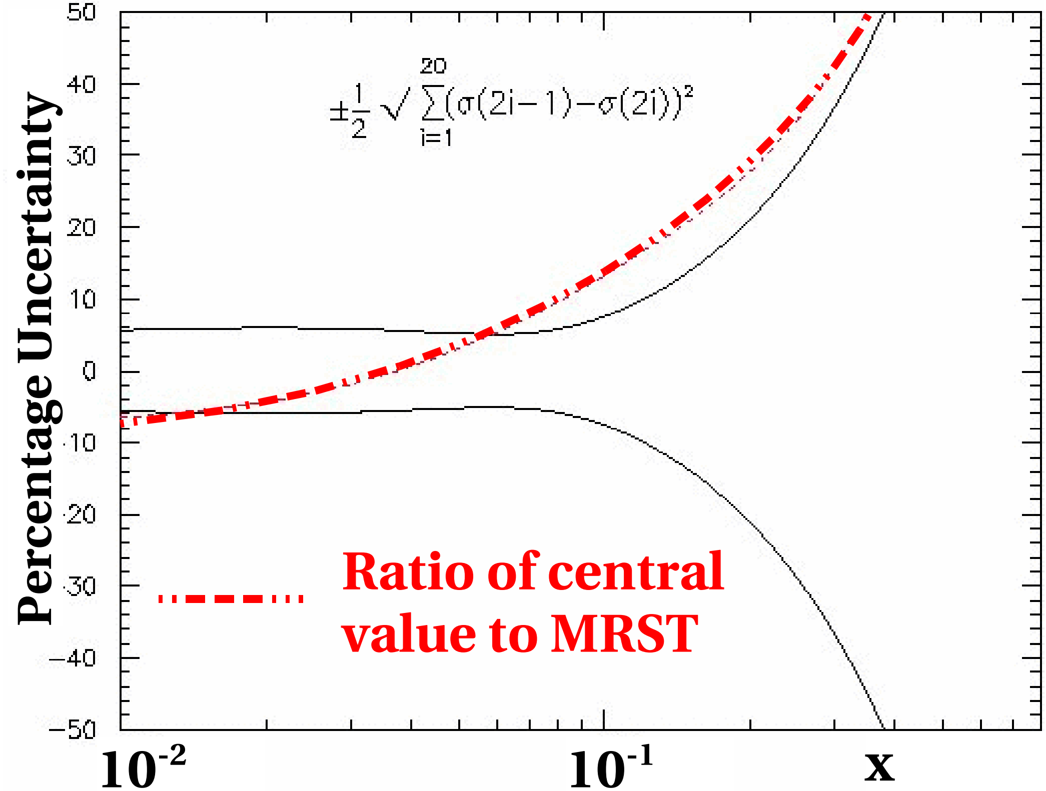
Current PDF Uncertainties

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

CTEQ Up Quark PDF Uncertainties



CTEQ Charm Quark PDF Uncertainties

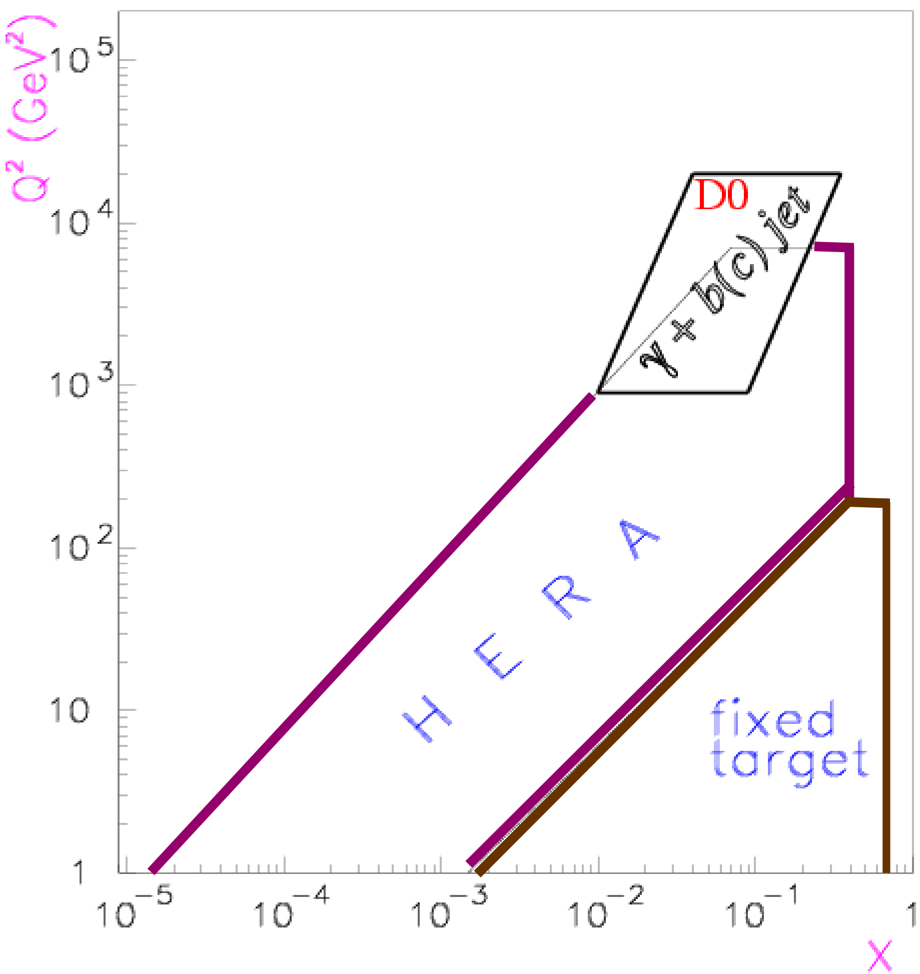


Uncharted Territories

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

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

- For our measurement, we can probe the phase space:
  - $9 \times 10^2 < Q^2 < 2 \times 10^4 \text{ GeV}^2$
  - $0.01 < x < 0.3$



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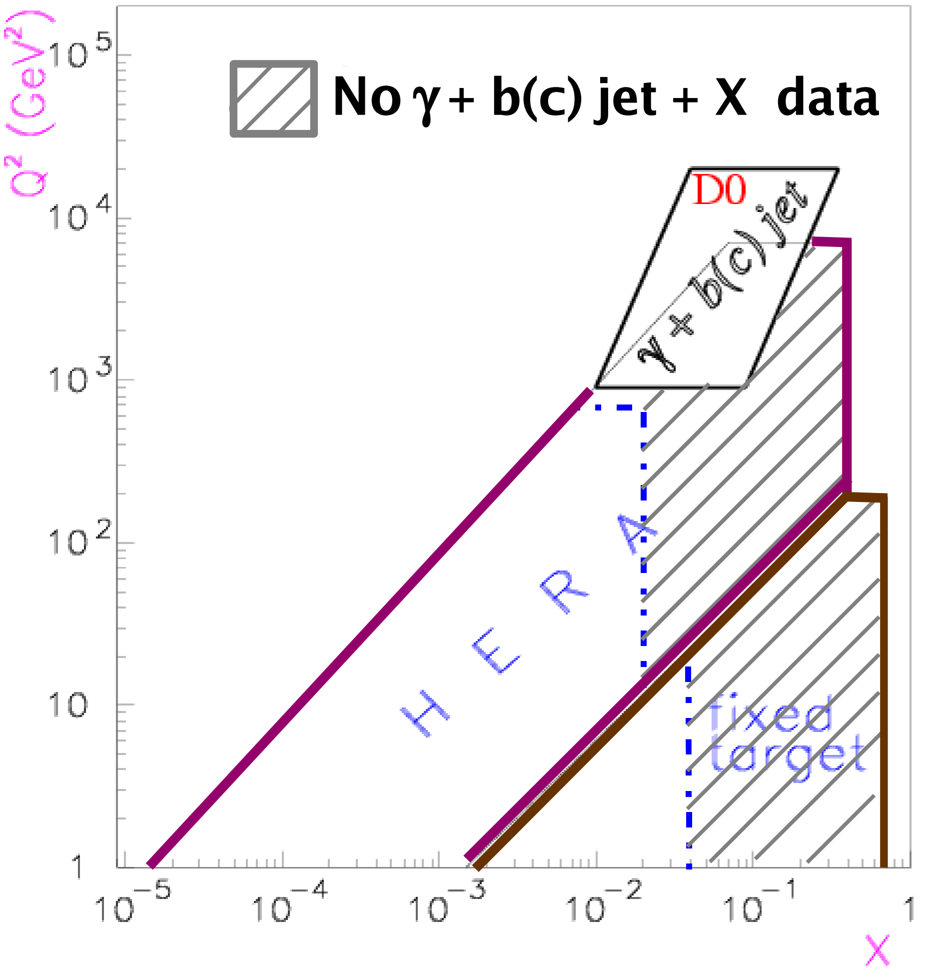
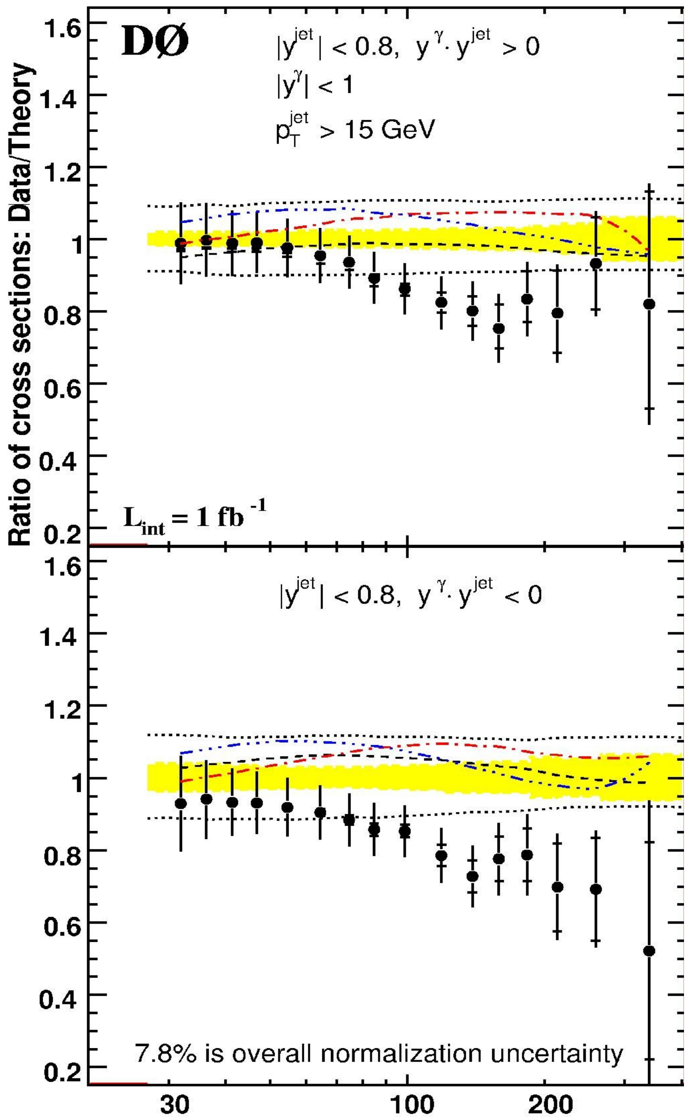
- **For our measurement, we can probe the phase space:**
  - $9 \times 10^2 < Q^2 < 2 \times 10^4 \text{ GeV}^2$
  - $0.01 < x < 0.3$
- **Compared to HF production at HERA:**
  - **Maximum Q^2 is ~650 GeV^2**
  - **Maximum x value is ~0.02**

  (Different initial states)



Building on the Past



Photon + jet measurement

Regions derived from respective rapidities of the jet and photon

Data/theory disagreement

Disagreement varies as a function of **both** photon p_T and the rapidity of the photon-jet system

No change of scale in theory results in agreement across all four regions

Analogous study can be made using **b jet + photon**

Cross Section Calculation

The differential photon + heavy flavor (b, c) jet cross section equation:

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}p_T^\gamma \mathrm{d}y^\gamma \mathrm{d}y^{\mathrm{jet}}} = \frac{N_{\mathrm{Events}}\ \mathcal{P}_{b(c)}\ \mathcal{P}_\gamma}{\Delta y^{\mathrm{jet}}\ \Delta y^\gamma\ \Delta p_T^\gamma\ \epsilon_t\ \epsilon_s^\gamma\ \epsilon_s^{\mathrm{jet}}\ \epsilon_{pv}\ \epsilon_b^{\mathrm{jet}}\ \epsilon_{E_T^{\mathrm{miss}}}\ \mathcal{L}\ \mathcal{A}}$$

What information do we need to experimentally measure the cross section?

- **Differential** ⇒ bins of rapidity and photon momentum (p_T)
- **Luminosity** ⇒ Number of total events from data sample
- **Acceptance** ⇒ Correction factor due to detector geometry
- **# of Events** ⇒ Number of remaining events after all selections imposed
- **Efficiencies** ⇒ Fraction of signal events passing selection criteria
- **Purities** ⇒ Fraction of signal events in final data sample

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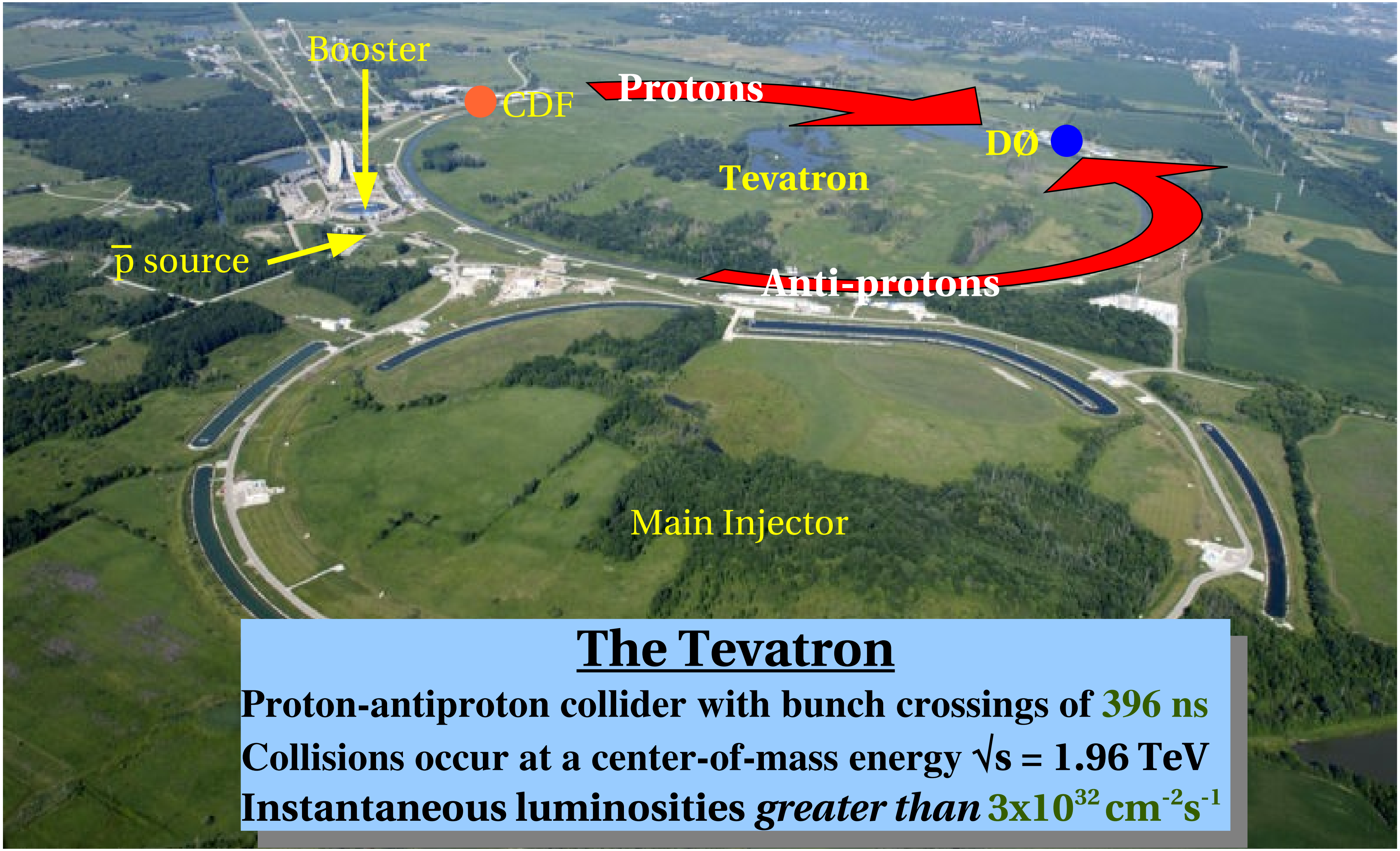
Many studies have been done on all aspects of this measurement, but today I will focus on object selection and purity estimation techniques

The Tevatron at Fermilab



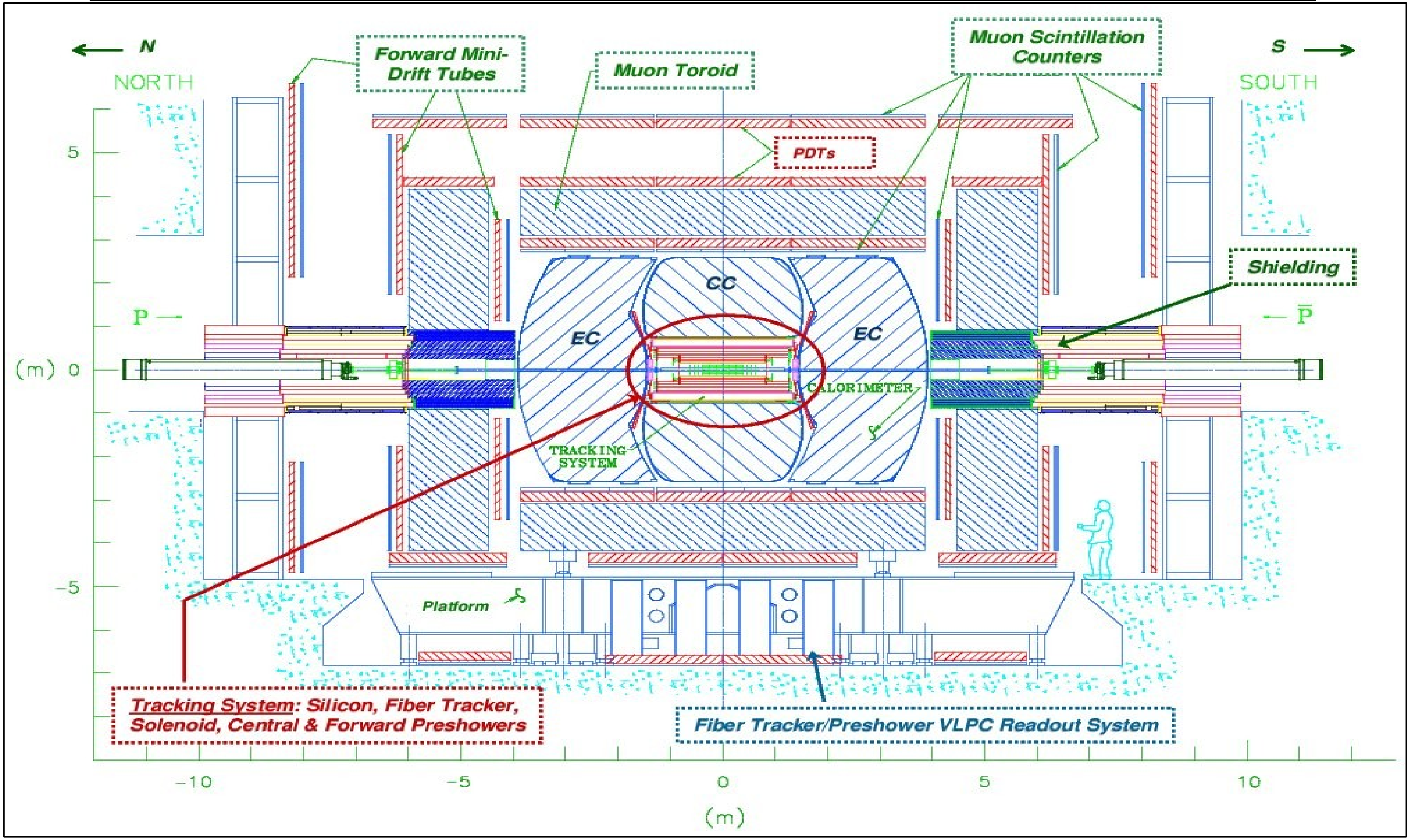
The Tevatron

Proton-antiproton collider with bunch crossings of 396 ns

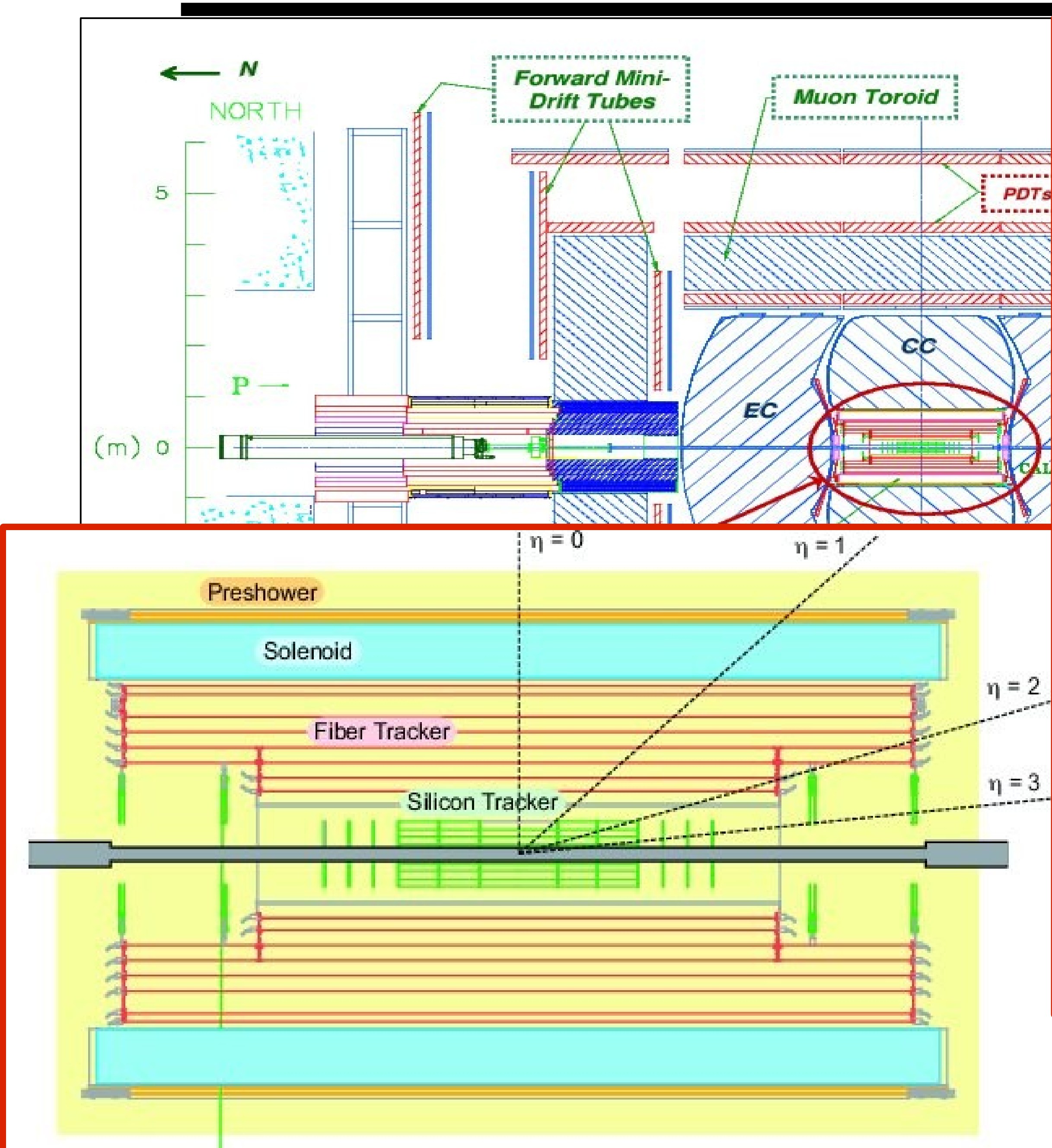
Collisions occur at a center-of-mass energy $\sqrt{s}$ = 1.96 TeV

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

The DØ Detector



The DØ Tracking Systems



Silicon Microstrip Tracker

- ~800,000 readout channels
- 3-D track reconstruction near beam-pipe
- High η coverage (η ~ 3)

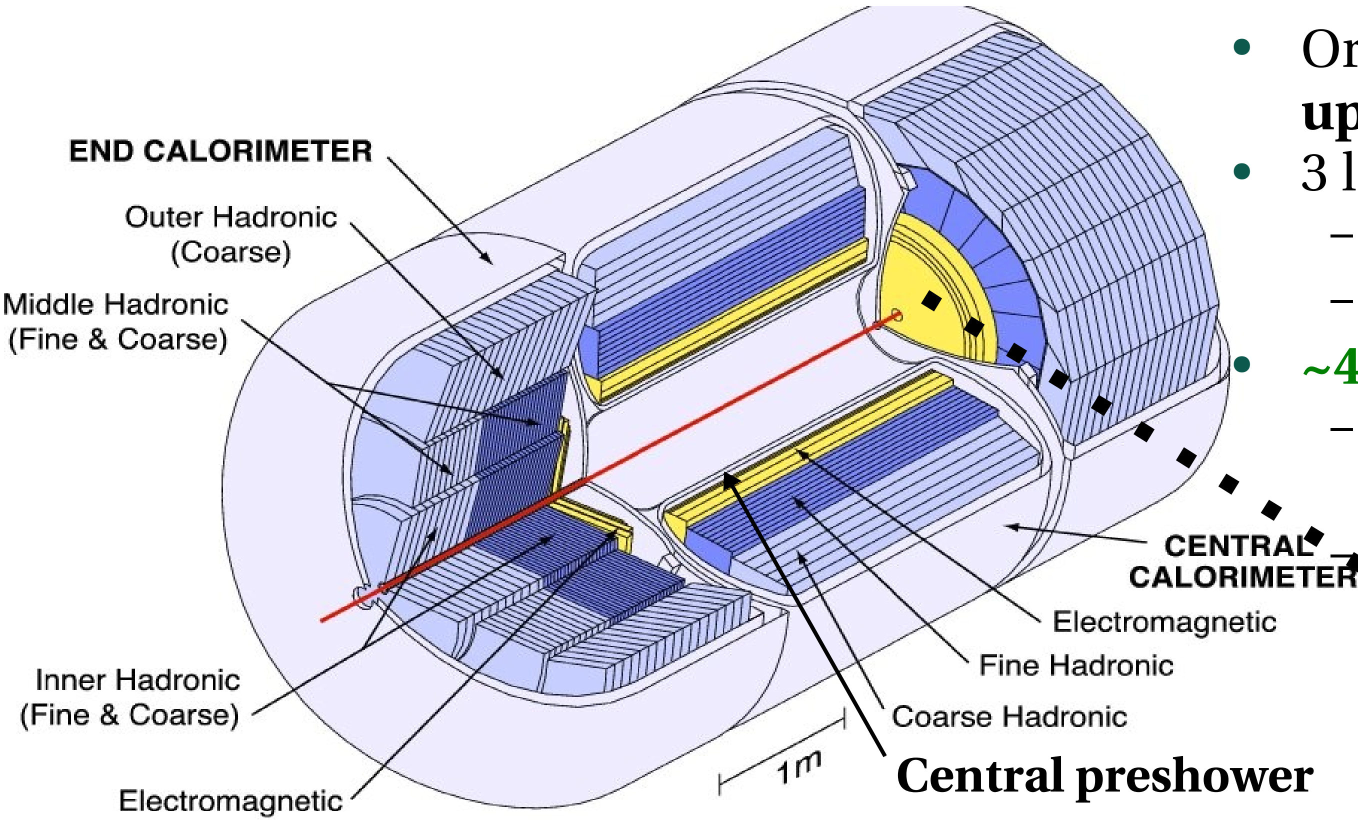
Central Fiber Tracker

- 8 fiber superlayers each with 2 layers: 1 axial, 1 stereo
- Inside of 2 Tesla Solenoid

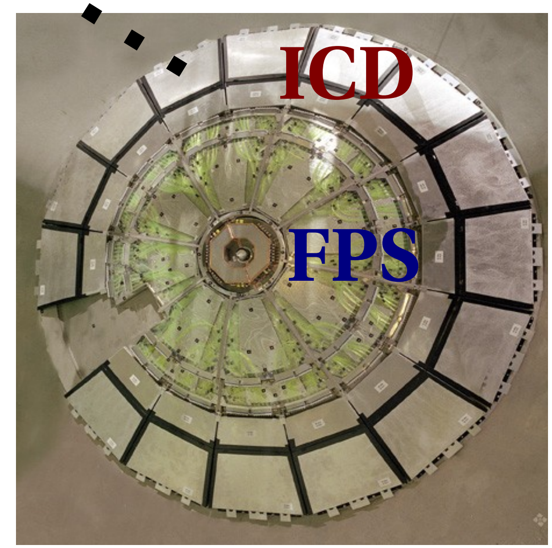
Central Preshower

- ~7700 readout channels
- 3 layers (1 axial, 2 stereo)

The DØ Calorimeter



- Original Run I detector **with upgraded electronics**
- 3 liquid argon cryostats
  - 1 central, 2 endcap
  - Hermetic coverage $|\eta| < 4.2$
- **~48,000 readout channels**
  - Longitudinal segmentation
    - 14 layers in total
  - Up to 12 cells in a (η-ϕ) form pseudo-projective towers



- **Inter-Cryostat Detector (ICD)**
  - Provides scintillator-based coverage **between** central and endcap cryostats
- **Central(CPS) and Forward(FPS) Preshowers**
  - Additional particle position **and** energy measurements **before** calorimeter

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}:

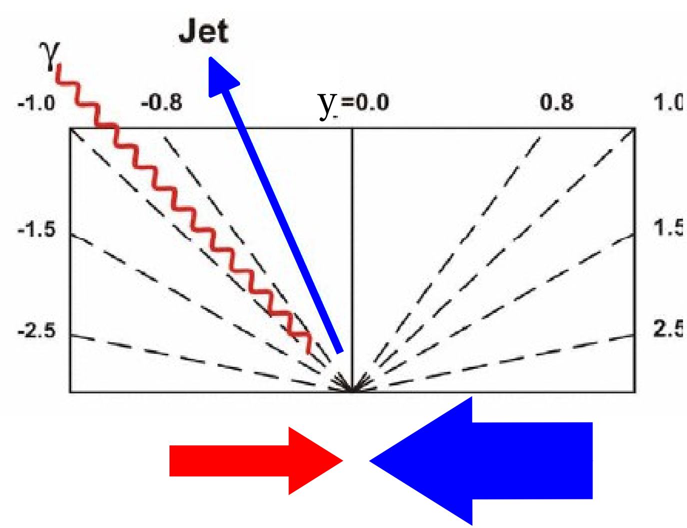
p^γ_T bins: 30 – 40, 40 – 50, 50 – 70, 70 – 90, 90 – 150 GeV

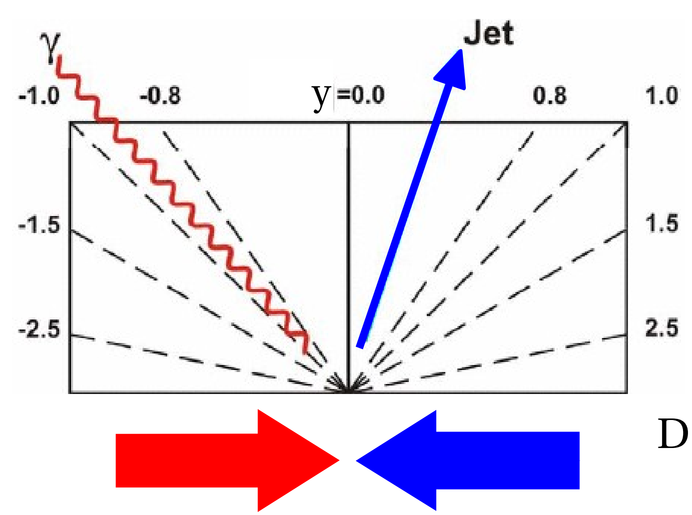
(No binning in jet p_T)

Two rapidity regions:

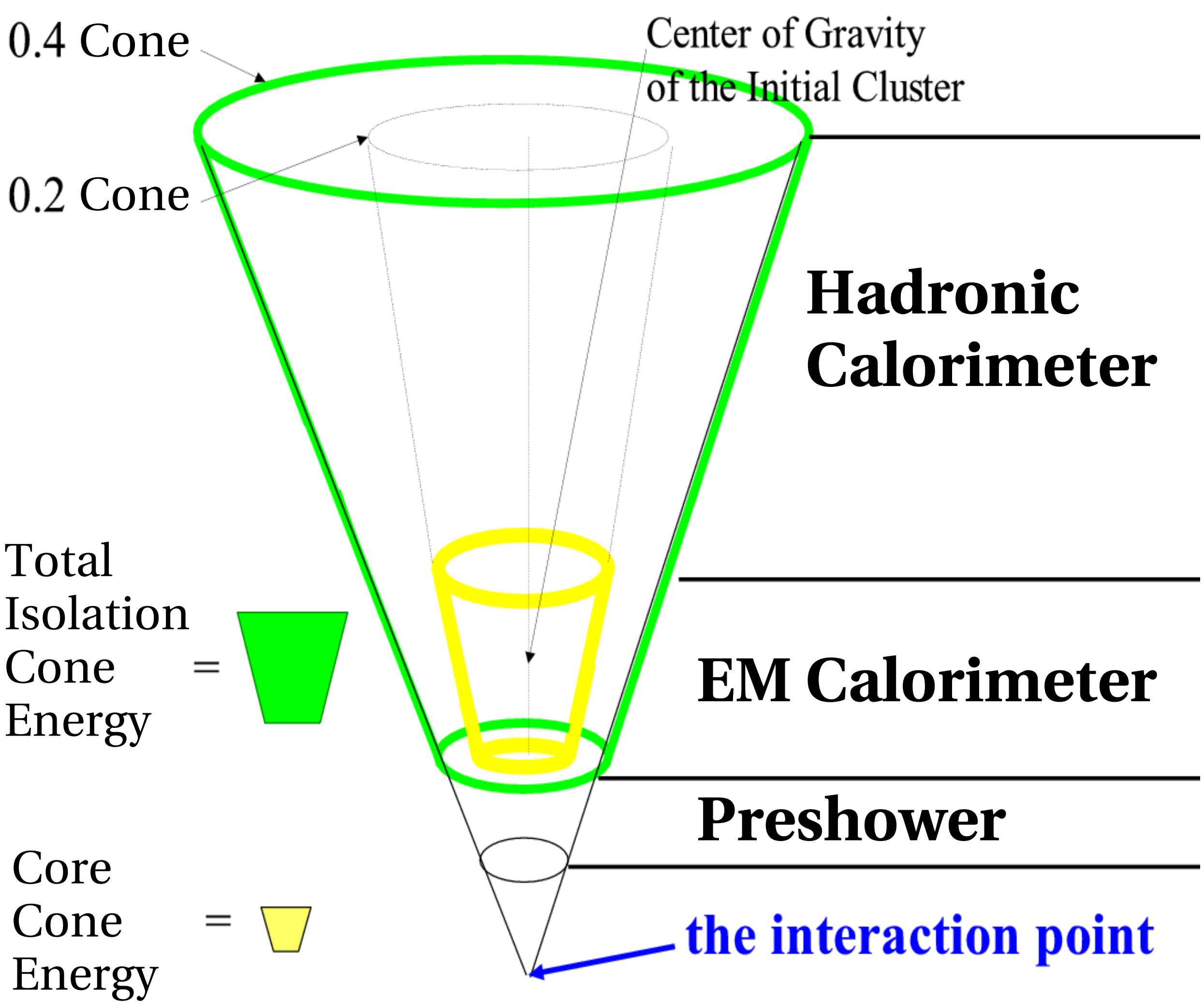
Region 1: $y^\gamma \cdot y^{jet} > 0$

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





Photon Selection



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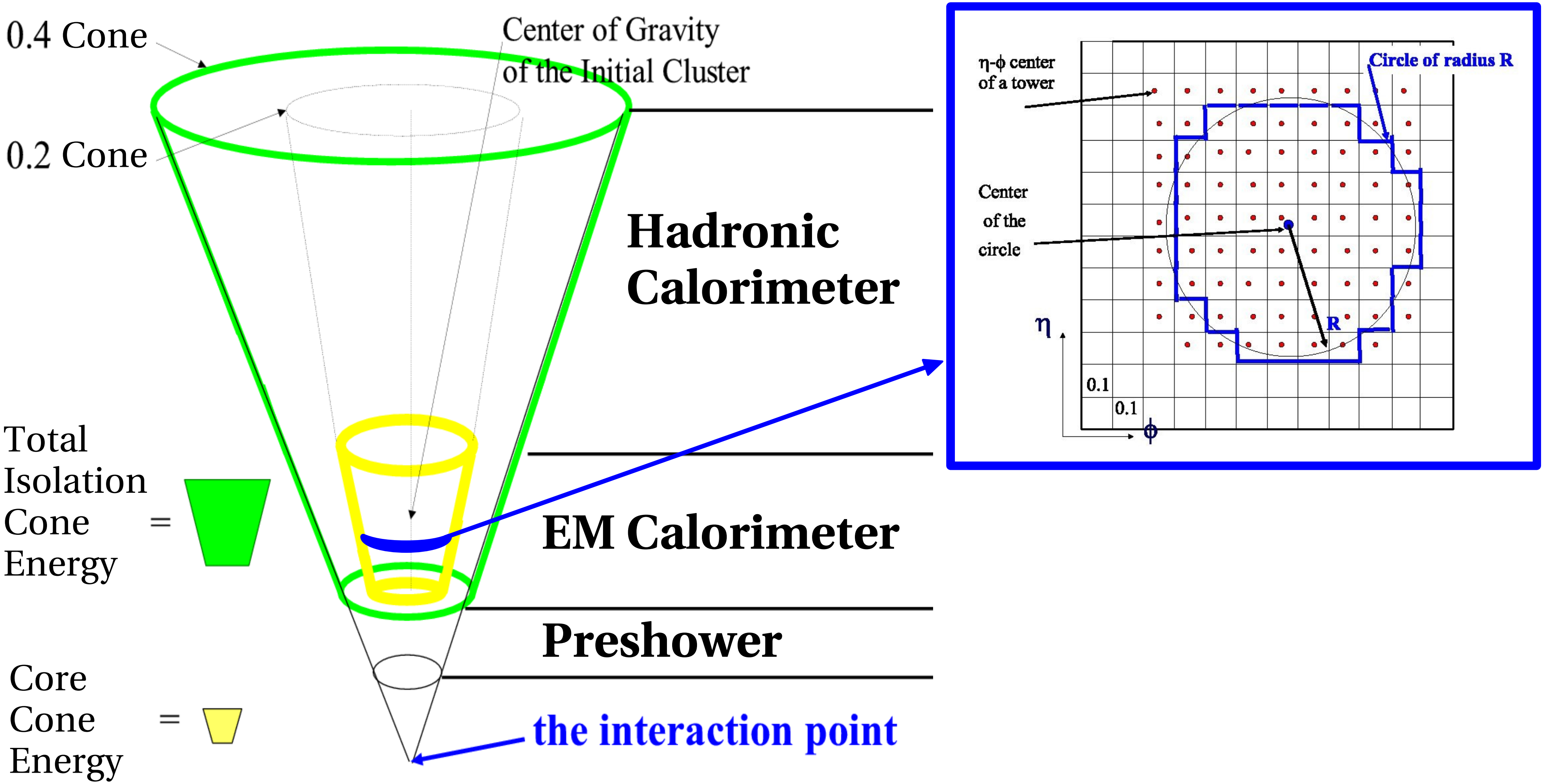

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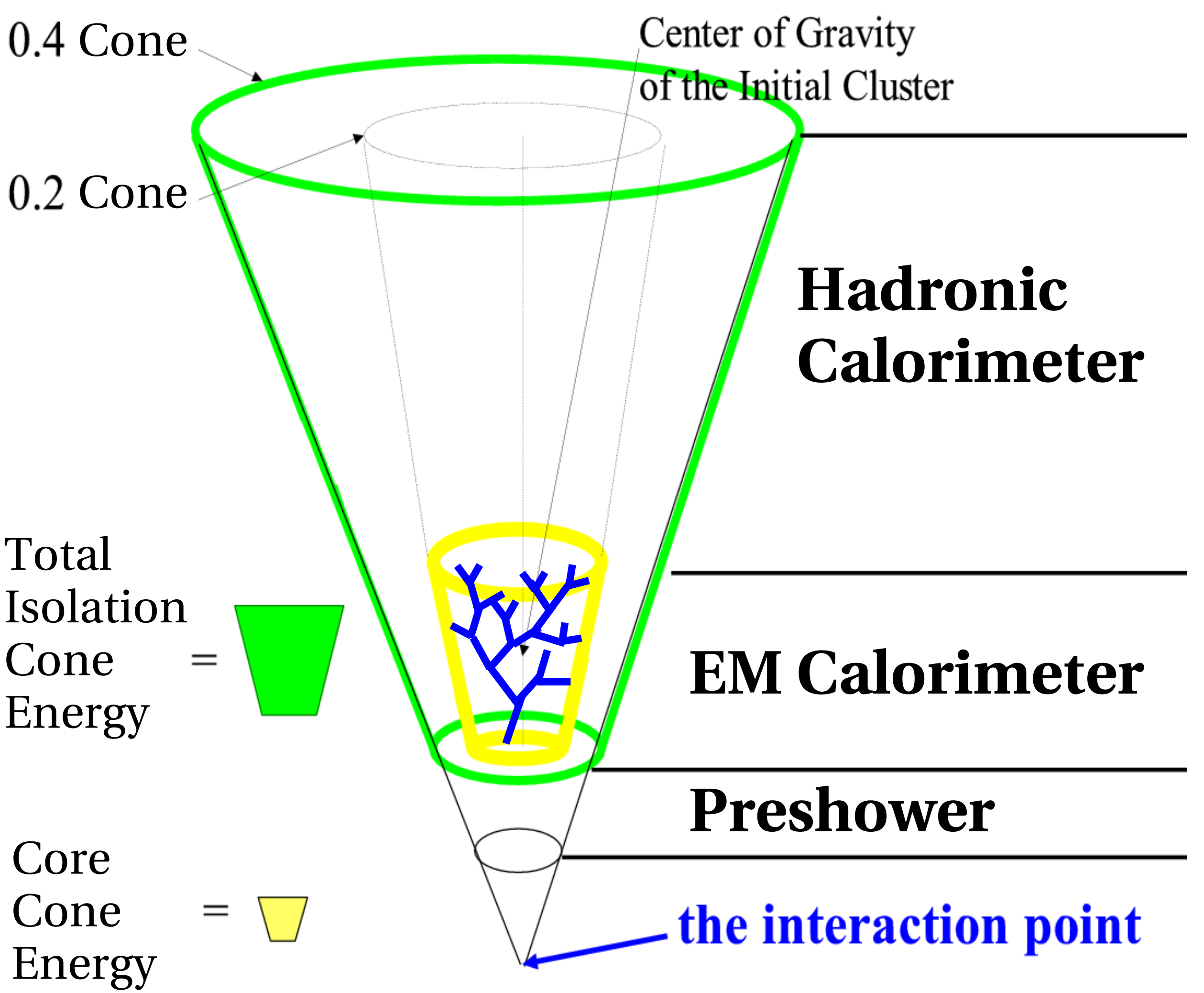

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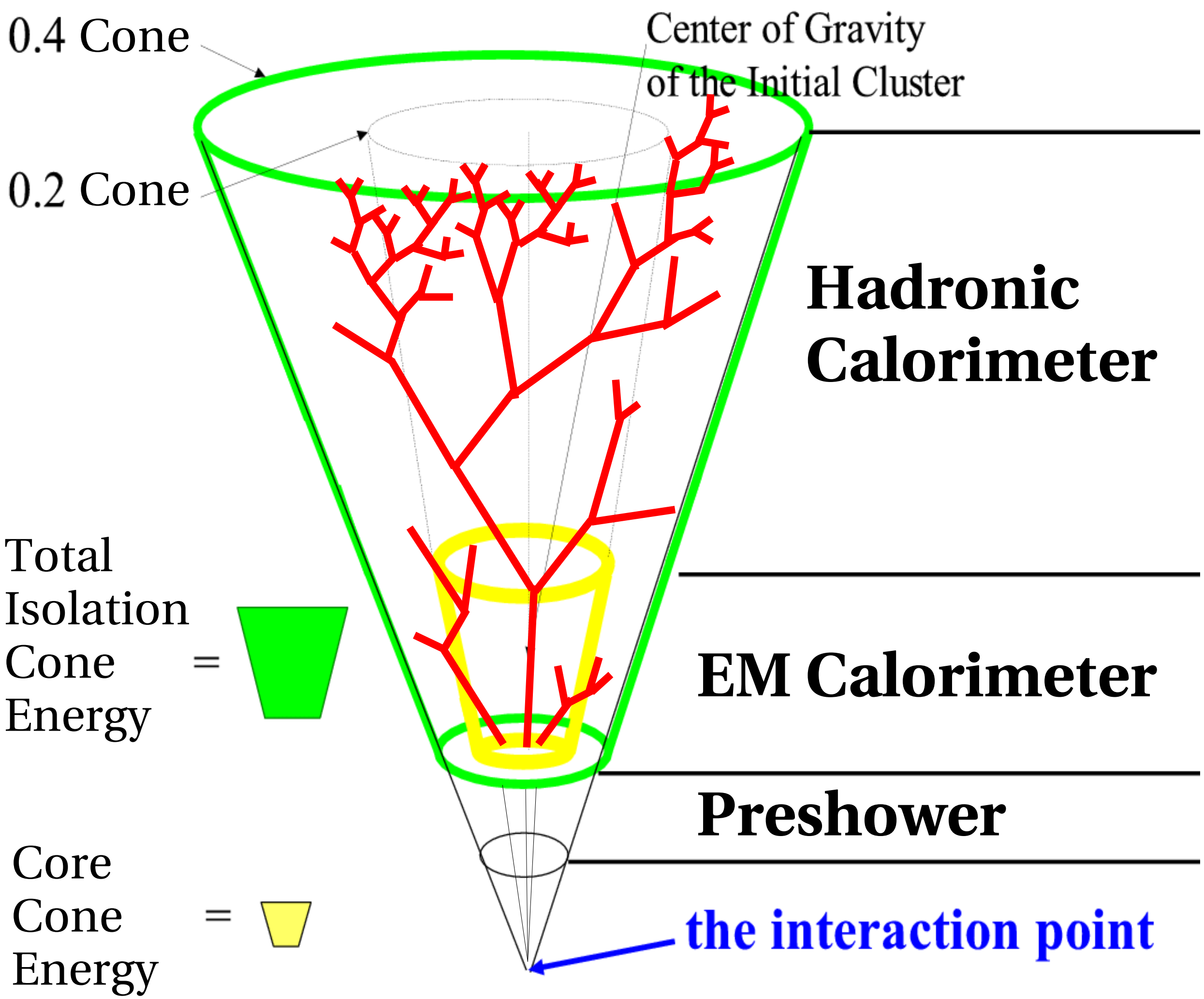

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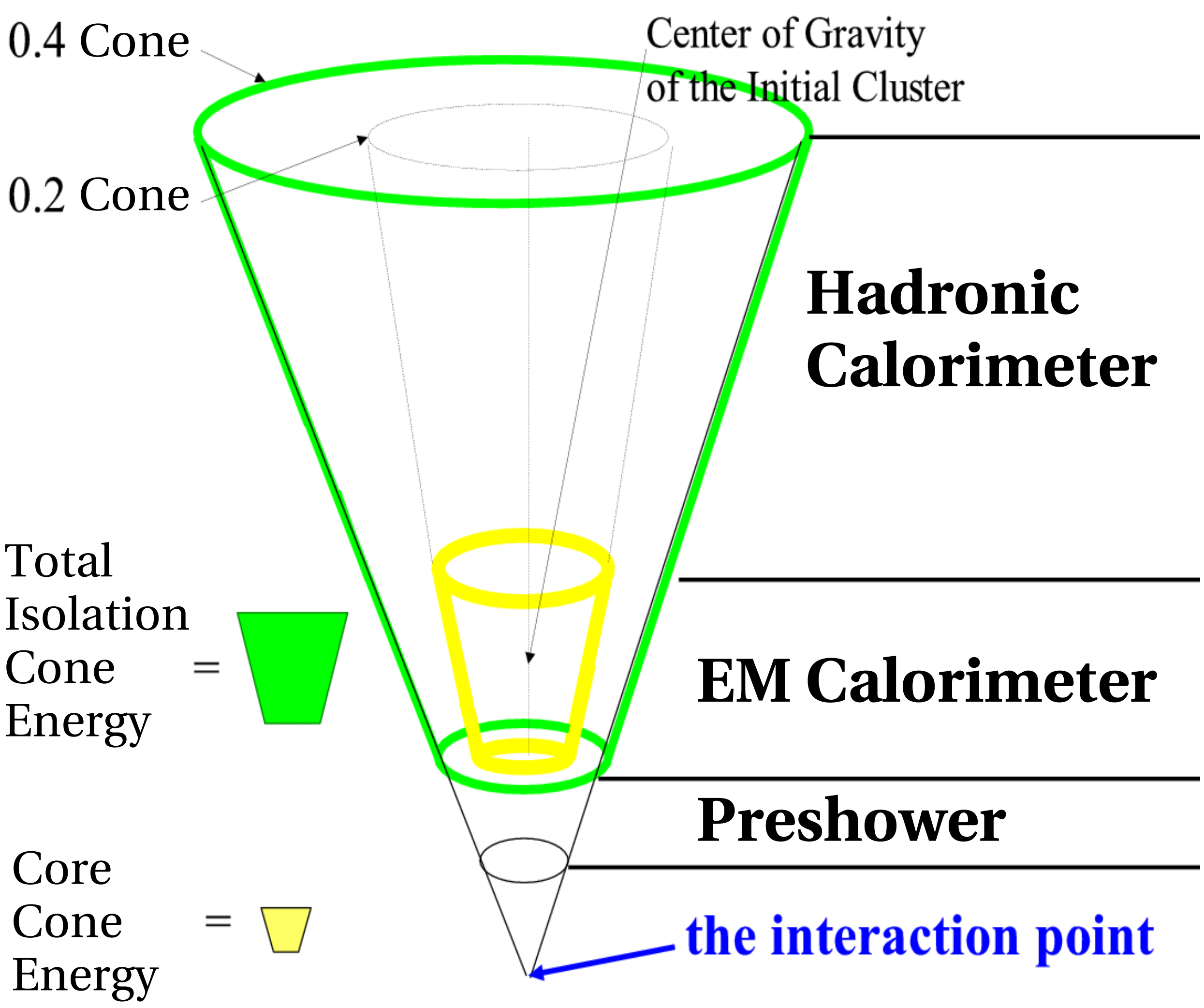
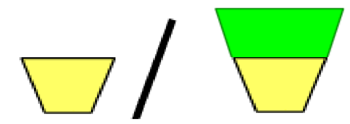
Photon Selection



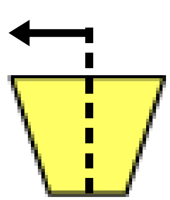
Calorimeter Criteria

Fractional isolation

EM energy fraction



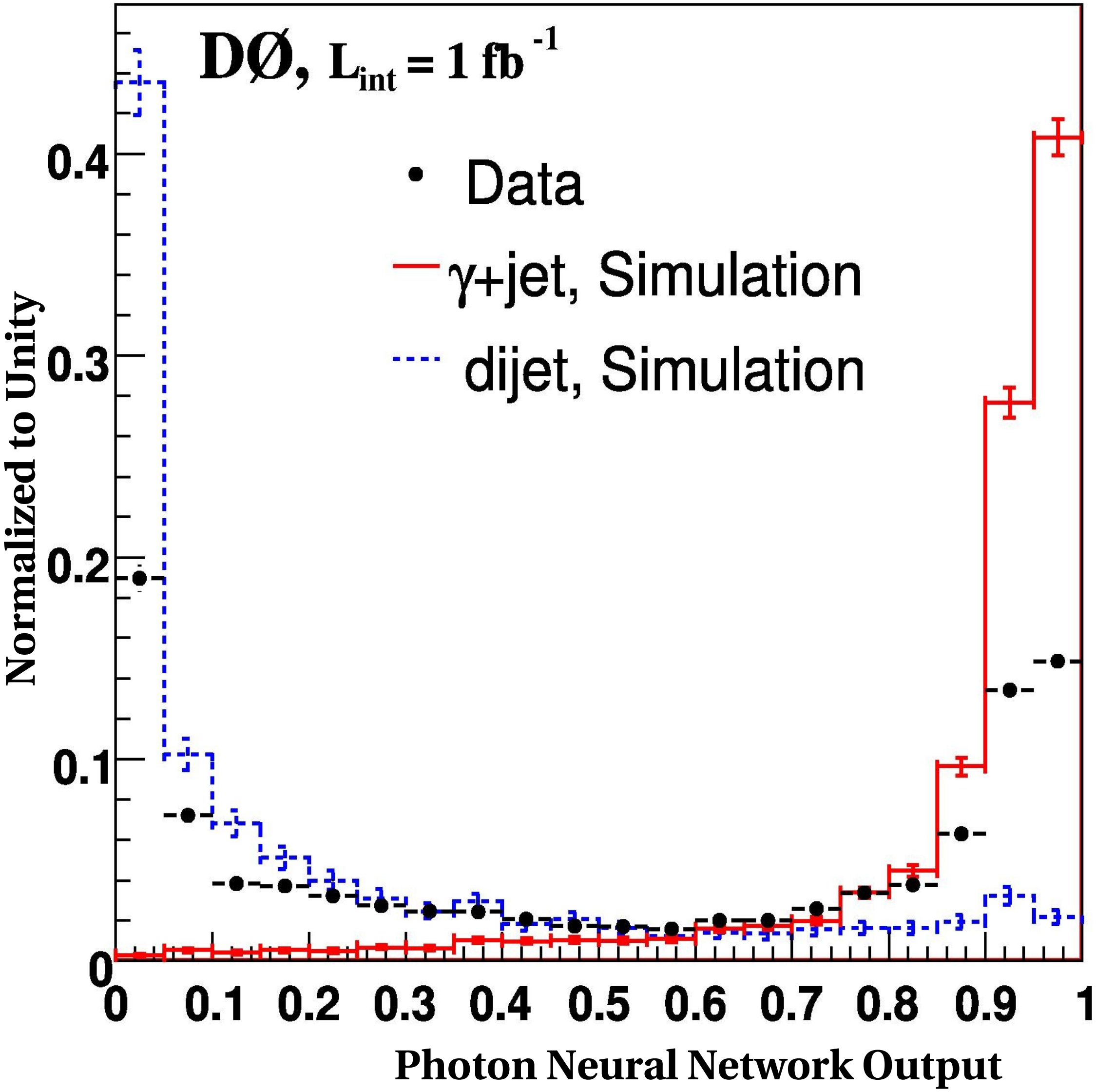
Energy shower ϕ width



Final Photon Selection

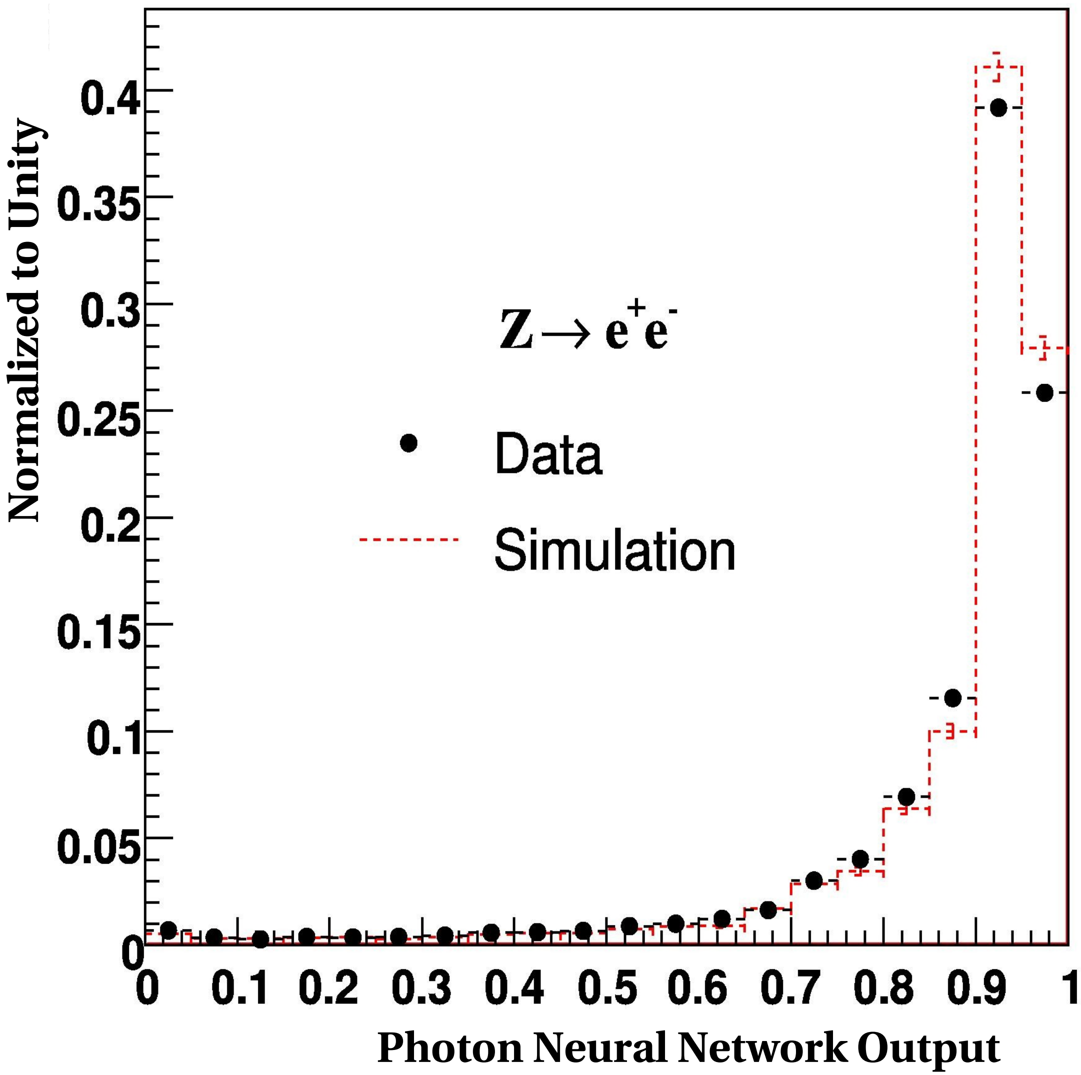
Photon Neural Network

- 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



Photon Signal Modeling

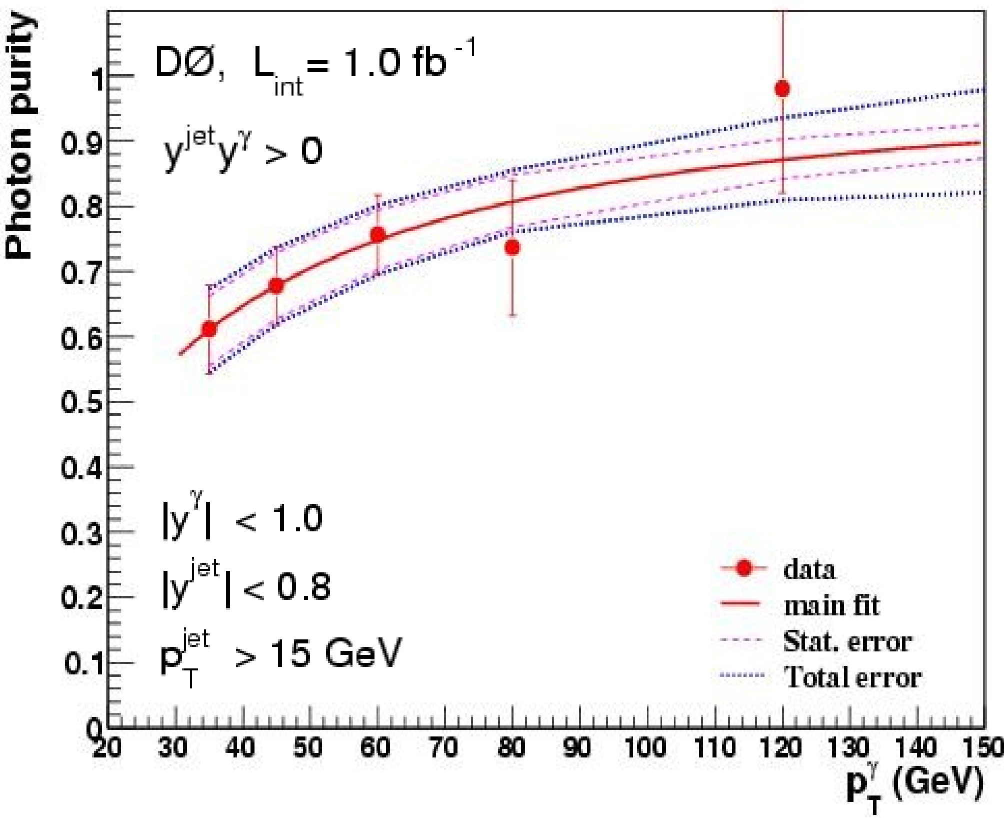
- **Important that Neural Network output describes the data well**
  - **To verify this, look at electron resonance:**
    - **Compare to $Z \rightarrow e^+e^-$ samples of data to Monte Carlo**



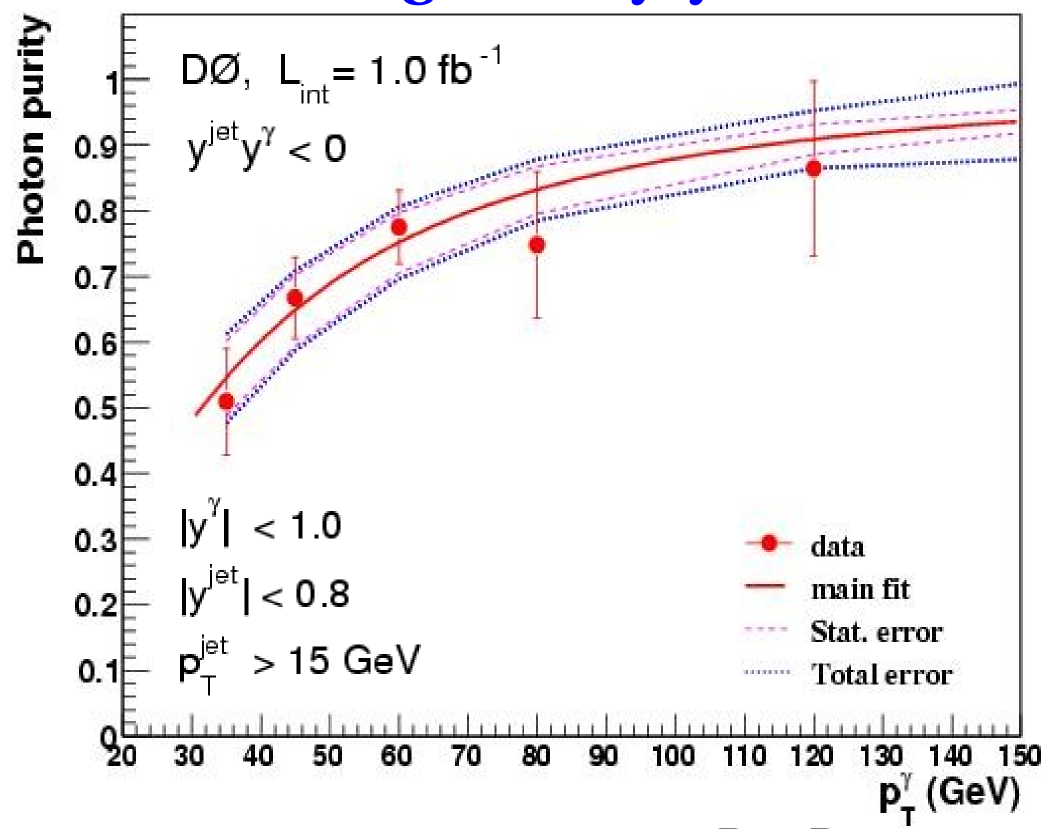
Photon Purity Results

- 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

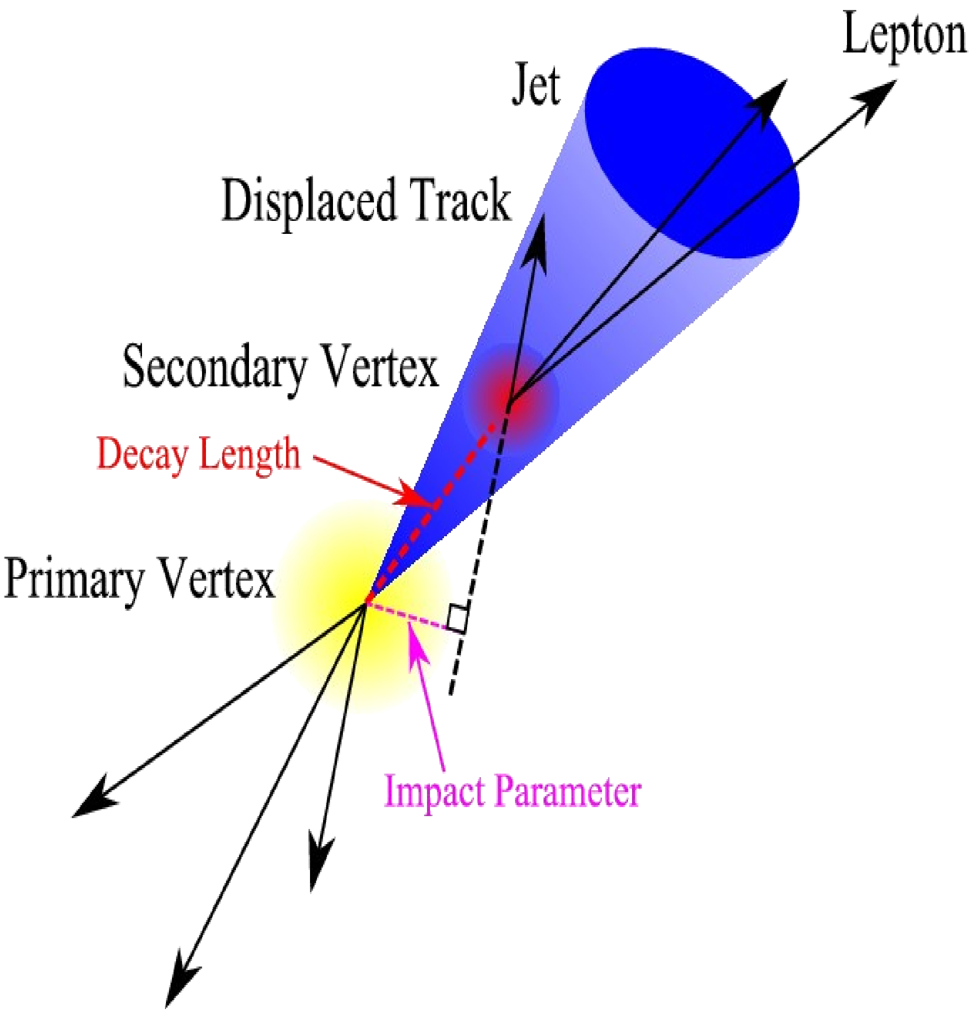
Region 1: $y^{\gamma} y^{jet} > 0$



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

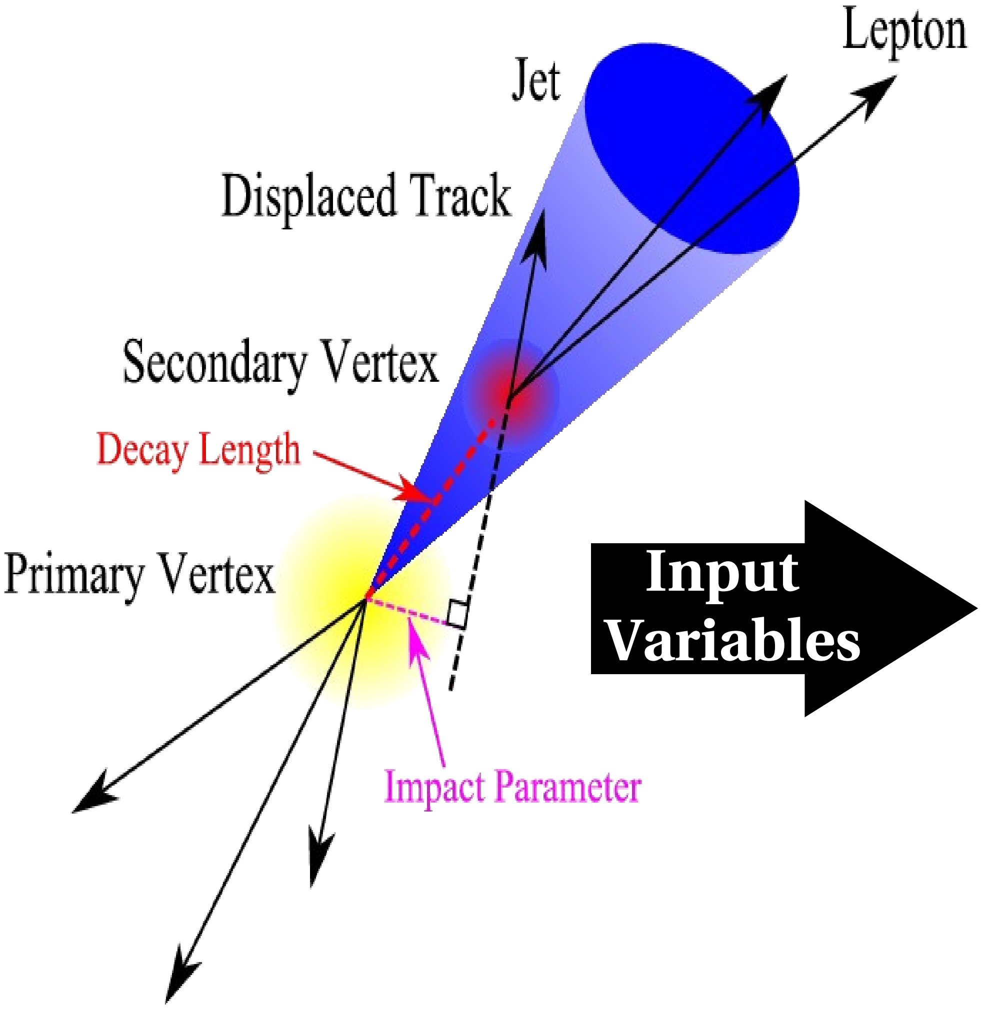


Identifying Heavy Flavor Jets

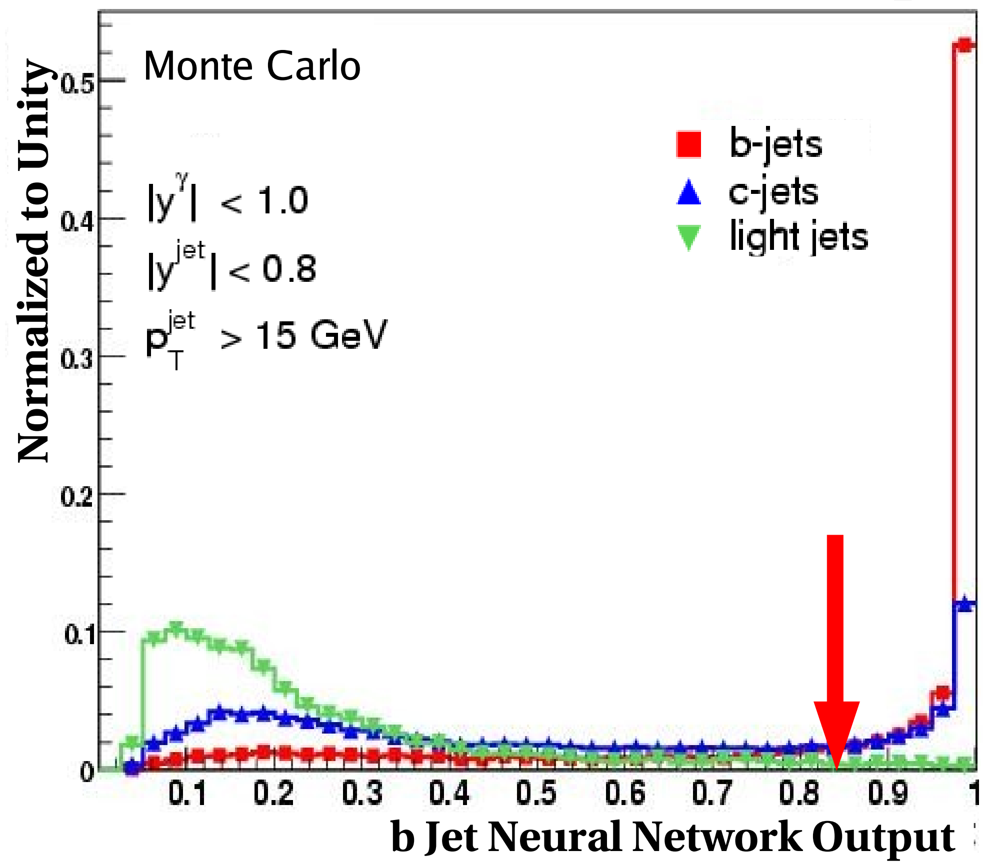


- Light jets have a much higher production rate than heavy flavor jets
  - **~100:1 light jets to b jets**
  - **~10:1 light jets to c jets**
  - **~10:1 c jets to b jets**
- But, heavy flavor jets can be distinguished due to **the long lifetimes of their mesons**
  - Average meson lifetimes
    - ~1.5 x 10^{-12} seconds (B mesons)
    - ~0.8 x 10^{-12} seconds (C mesons)
  - Decay ***measurable distances*** from the primary vertex
- The **secondary vertex:**
  - Contains valuable information to identify heavy flavor jets

Identifying Heavy Flavor Jets

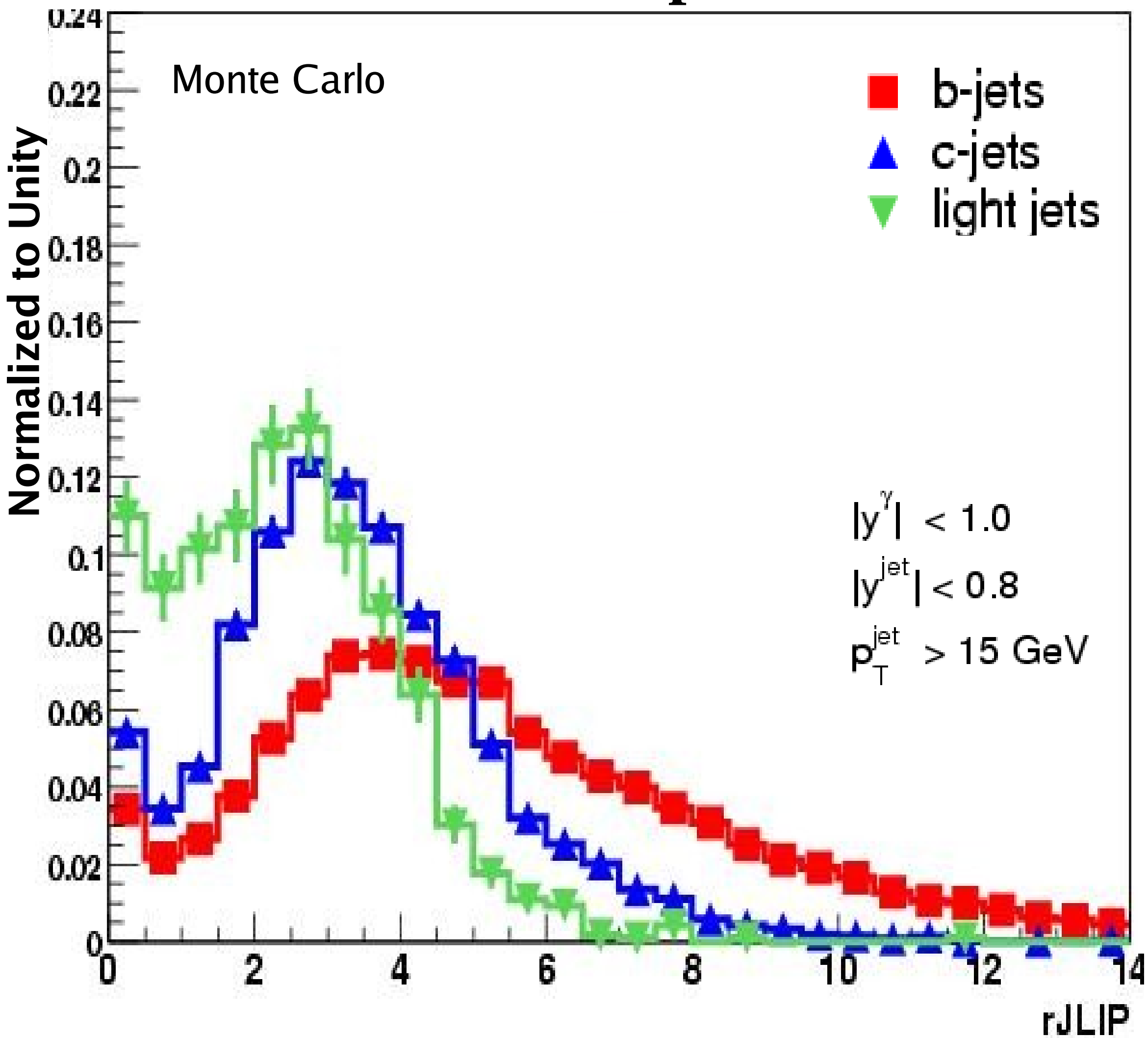


b Jet Neural Network Output



Jet Flavor Templates

rJLIP Output



Now, we need **an additional handle** **for determination of heavy flavor fractions:**

- **Can no longer use the bNN**
- **bNN output shapes above 0.85 are similar for light, c and b jets**

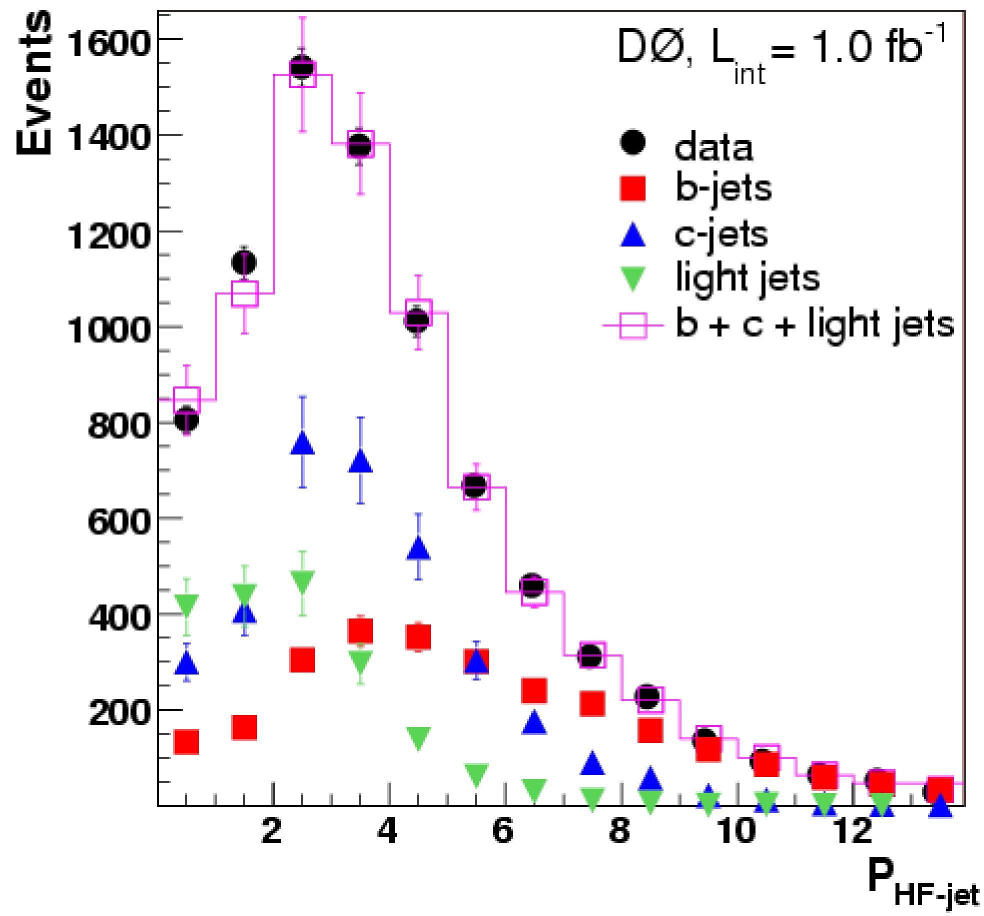
Reduced **J**et **Li**fetime **P**robability

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

Heavy Flavor Fractions

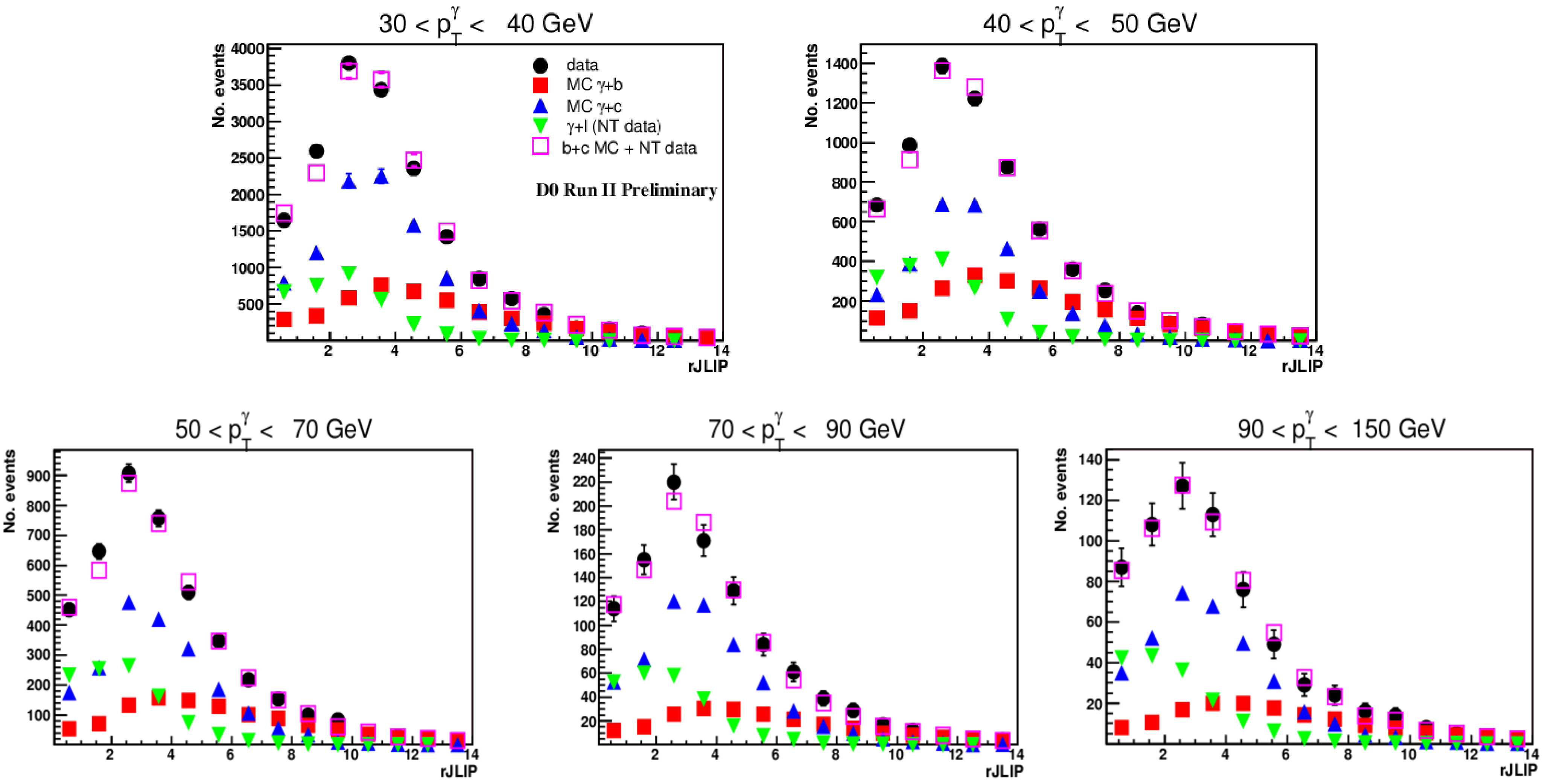
Template Fitting Procedure

- **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**



rJLIP Fitting Comparisons

Flavor fractions were fit independently in each photon p_T bin



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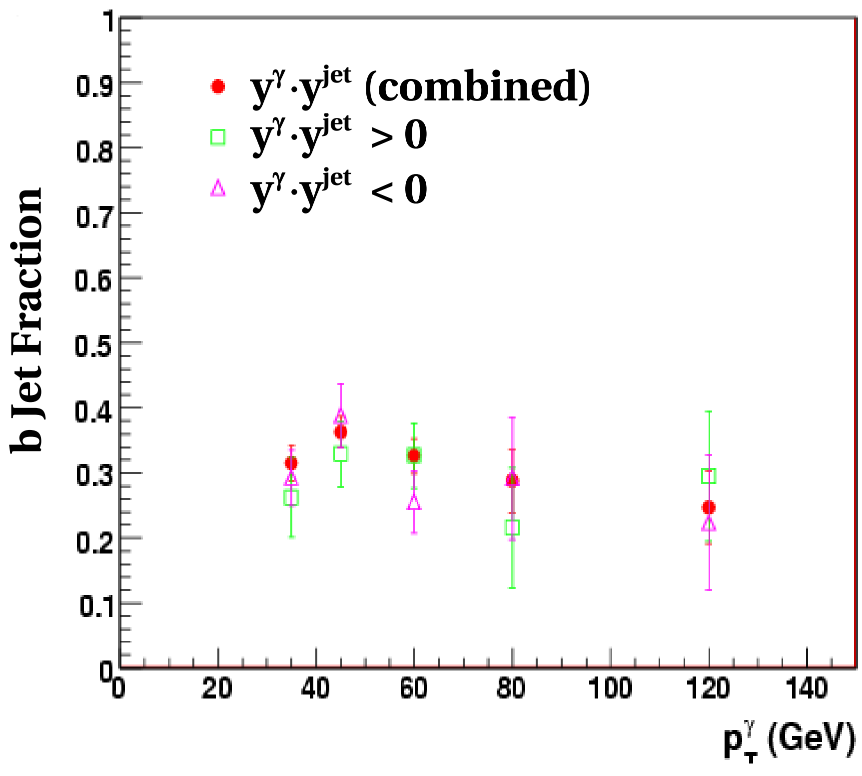
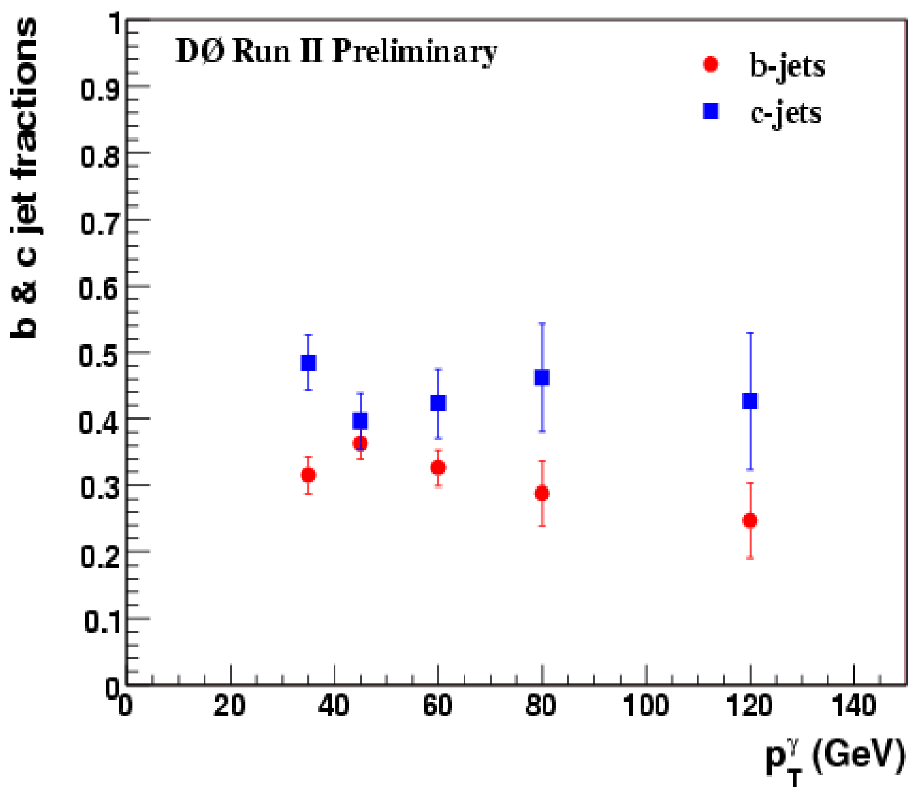
Flavor Fraction Results

- 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**
    - **Flavor fractions do not depend on our rapidity binning**
      - **Can combine regions for decreased uncertainties**



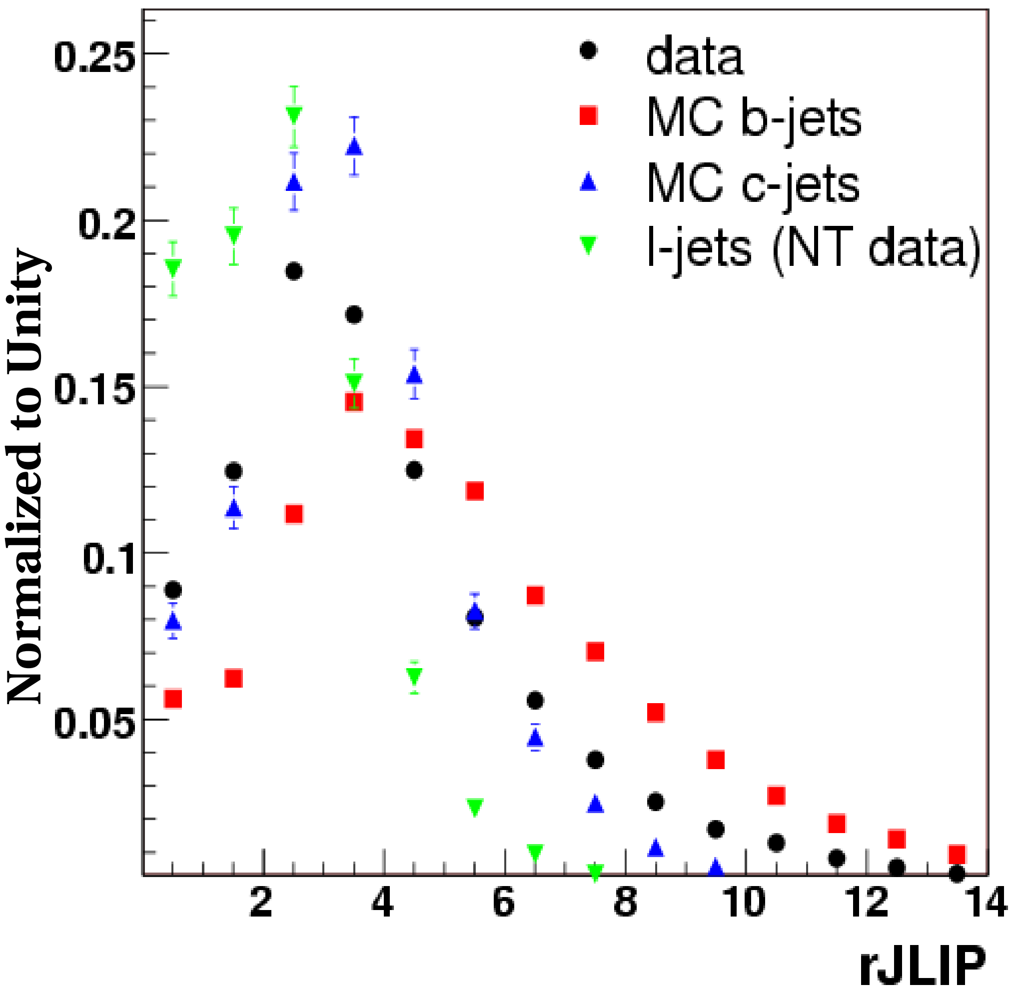


Cross Checking the Fit

Efficiency method as cross check

- **Using a system of equations**
- **Solve them to find flavor fractions**

$$\text{Purity}_b = \frac{N_b}{N_b + N_c + N_l}$$



$$N_{Data} = N_{b\ Jet} + N_{c\ Jet} + N_{light\ Jet}$$

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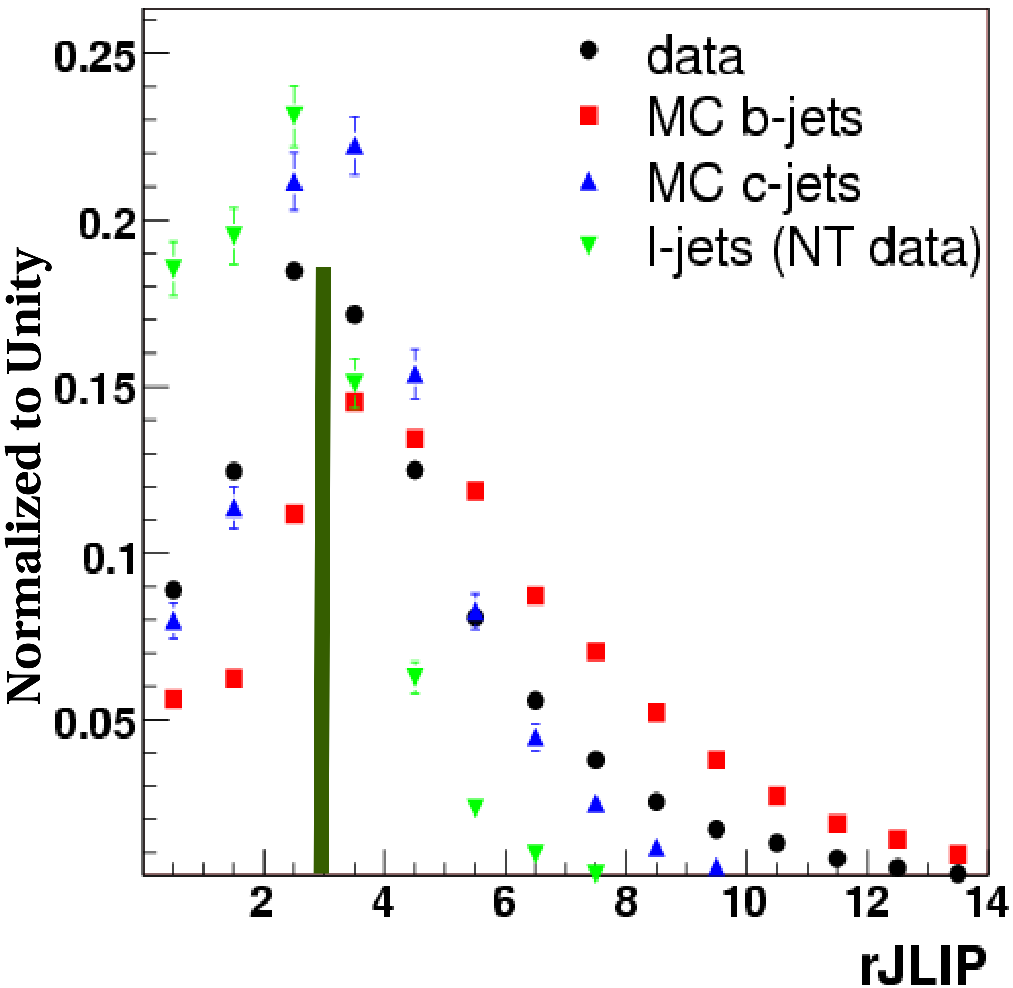

$$N_{Data} = N_{b\,Jet} + N_{c\,Jet} + N_{light\,Jet}$$

$$\varepsilon_D N_D = \varepsilon_b N_b + \varepsilon_c N_c + \varepsilon_l N_l$$

Cross Checking the Fit

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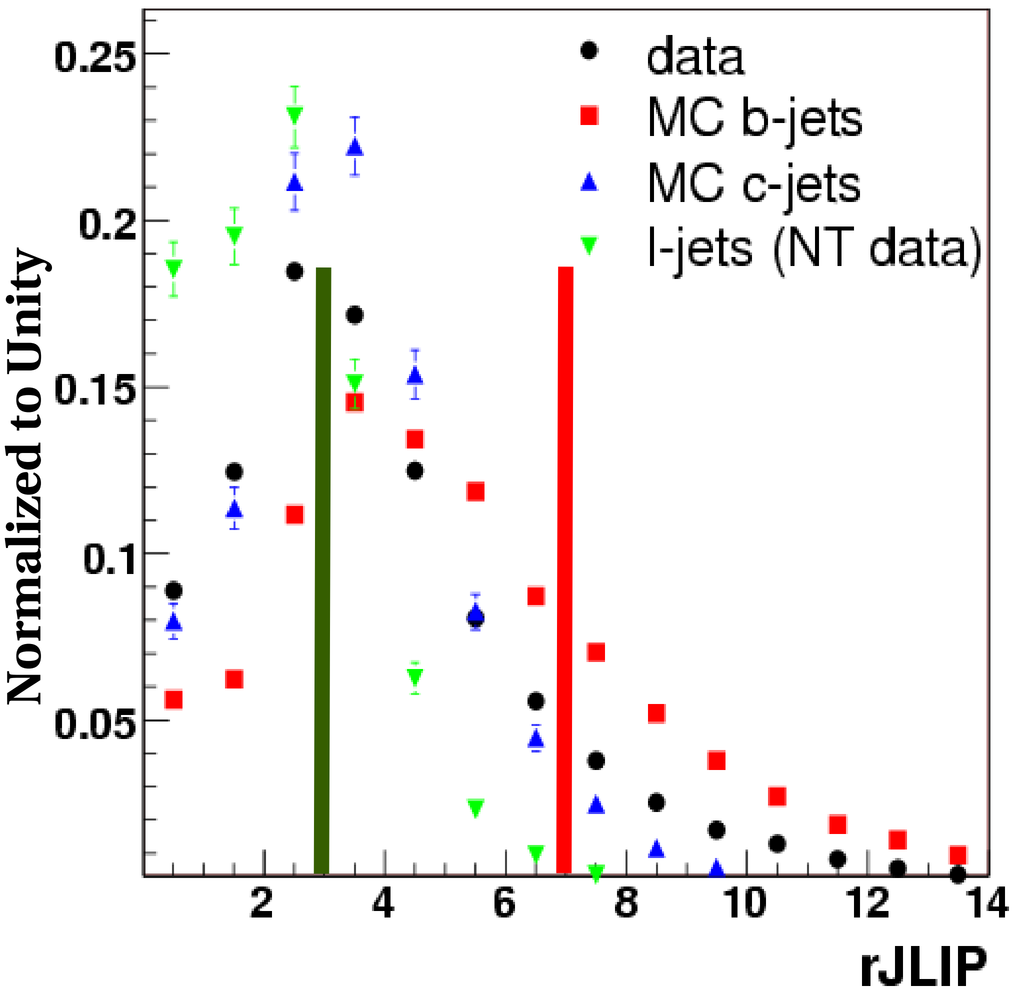
$$\mathbf{P}\text{urity}_{\mathbf{b}} = \frac{N_b}{N_b + N_c + N_l}$$



$$N_{Data} = N_{b\,Jet} + N_{c\,Jet} + N_{light\,Jet}$$

$$\varepsilon_D N_D = \varepsilon_b N_b + \varepsilon_c N_c + \varepsilon_l N_l$$

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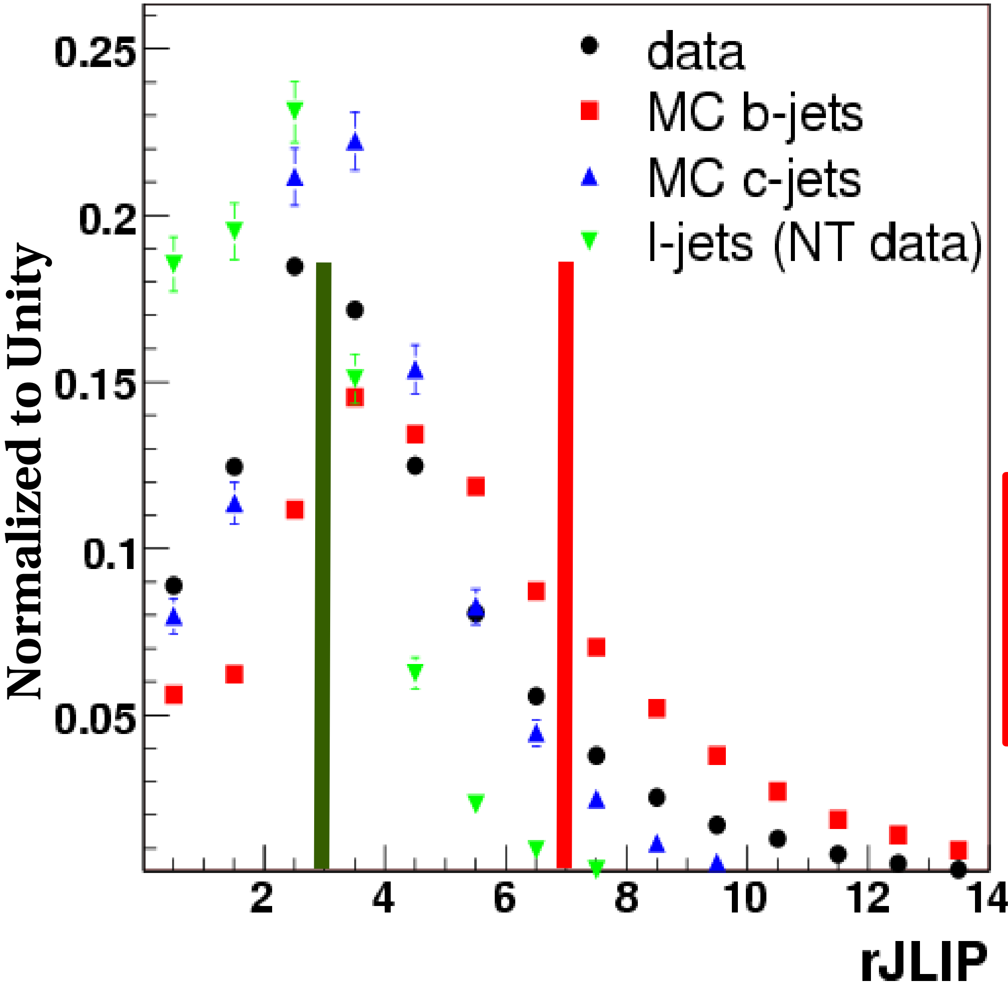


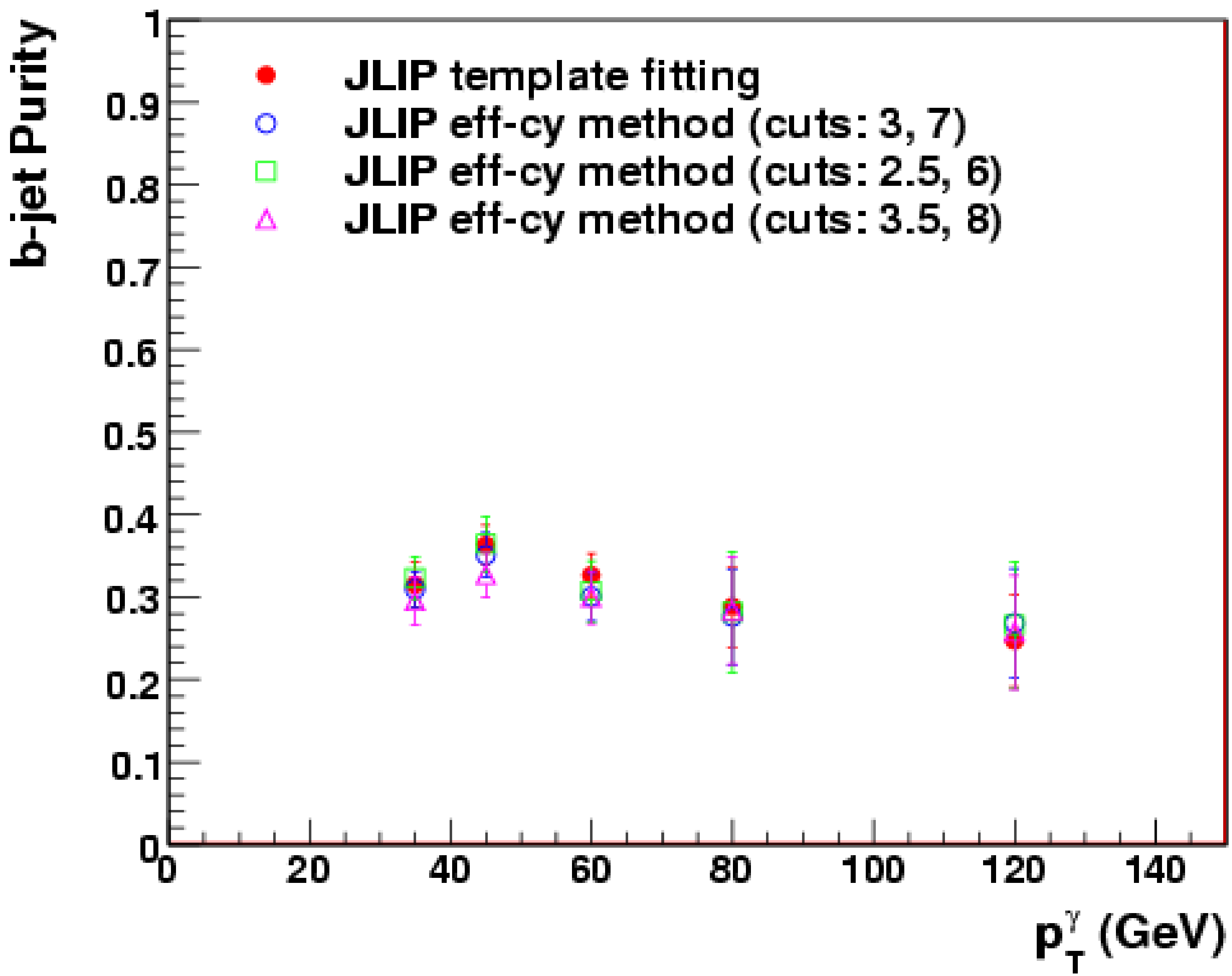
$$N_{Data} = N_{b\,Jet} + N_{c\,Jet} + N_{light\,Jet}$$

$$\varepsilon_D N_D = \varepsilon_b N_b + \varepsilon_c N_c + \varepsilon_l N_l$$

$$\varepsilon'_D N_D = \varepsilon'_b N_b + \varepsilon'_c N_c + \varepsilon'_l N_l$$

$$\mathbf{P_b} = \frac{(\varepsilon_D - \varepsilon_l) - (\varepsilon'_D - \varepsilon'_l)}{(\varepsilon_b - \varepsilon_l) - (\varepsilon'_b - \varepsilon'_l)}\left(\frac{(\varepsilon_c - \varepsilon_l)}{(\varepsilon'_c - \varepsilon'_l)}\right)$$

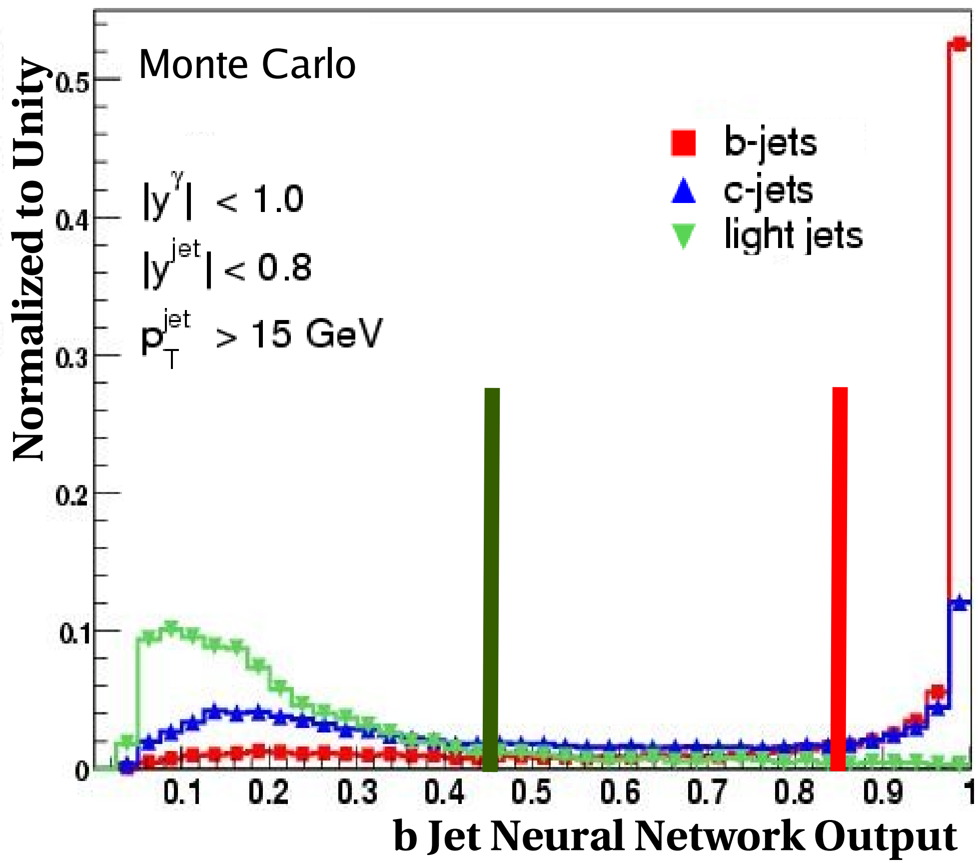
Flavor Fraction Cross Checks

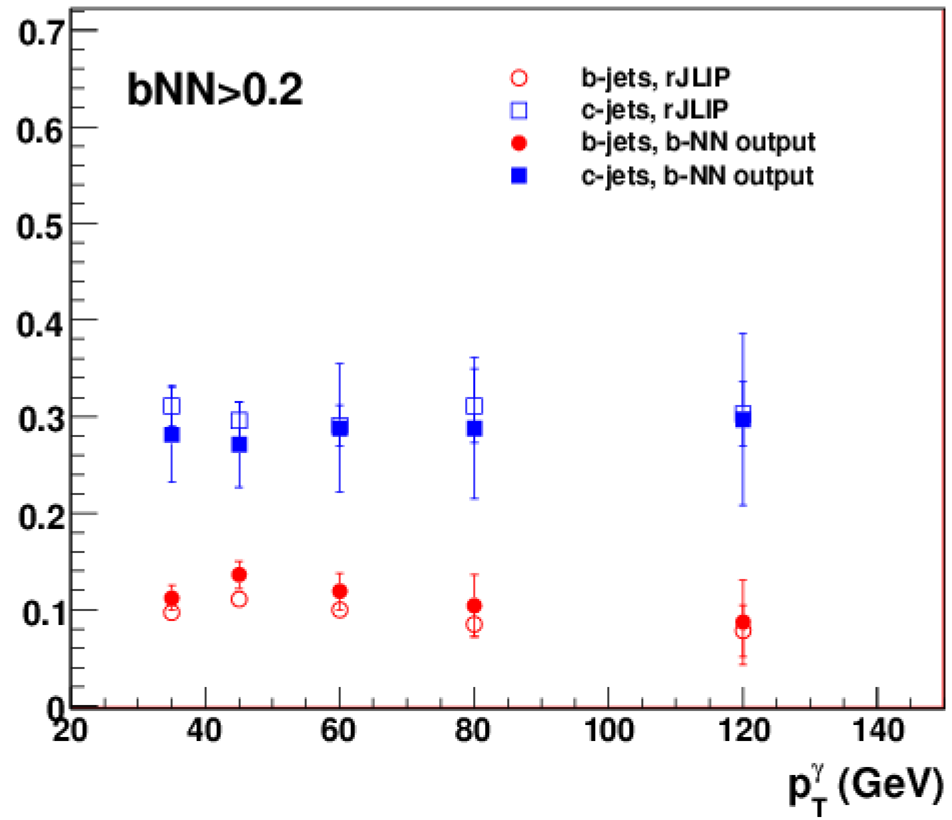


Efficiency Method (Again)

- **We can also use the efficiency method on the bNN directly (same technique!)**
  - **1st require b Jet Neural Network (bNN) > 0.20**
  - **Efficiency method operating points: bNN > {0.45, 0.85}**

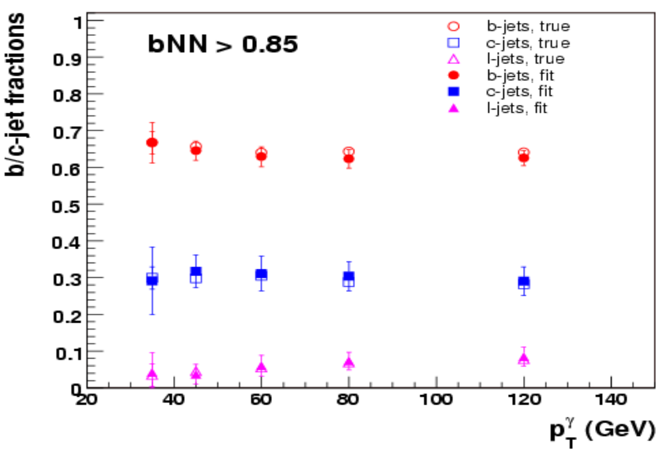
b Jet Neural Network Output

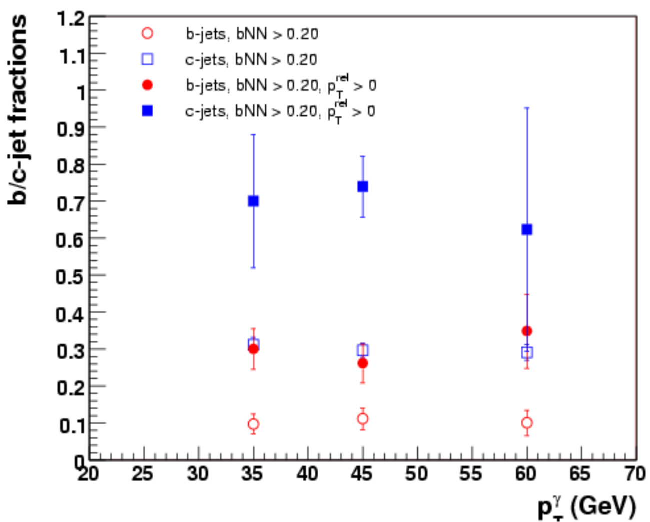


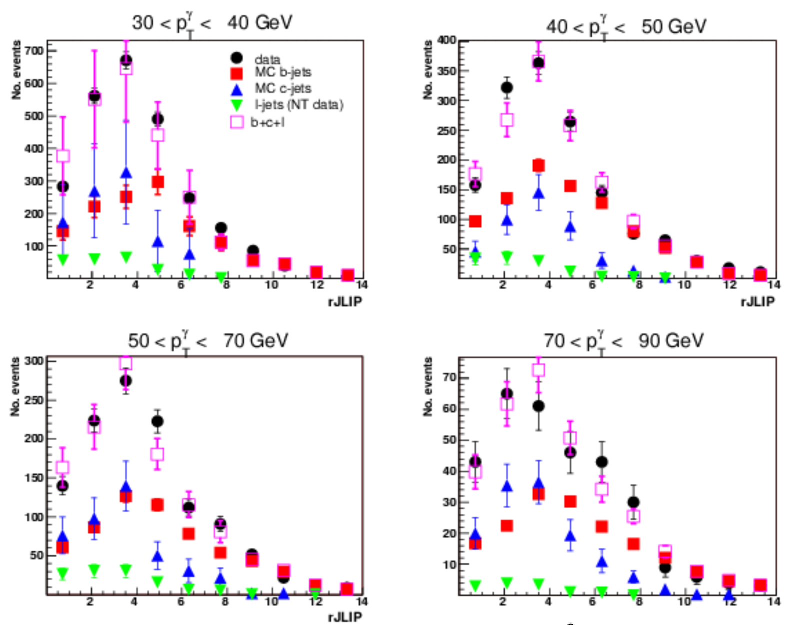


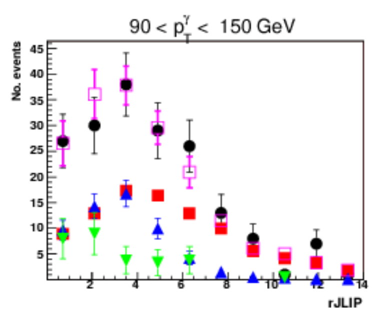
Why So Many Cross-Checks?

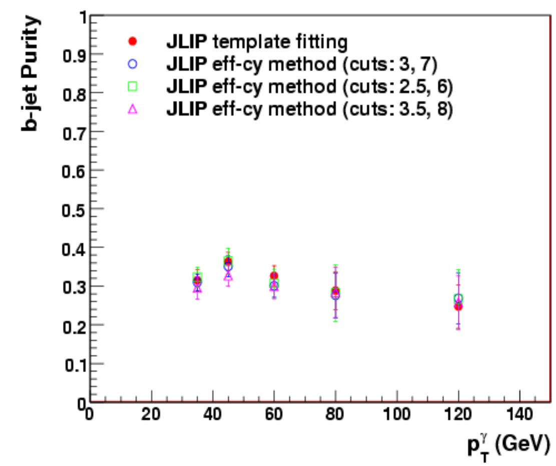
- **First QCD analysis to use flavor fraction fitting at DZero**
  - **It was put under close scrutiny to verify its results**
- Litany of cross checks performed
  - **All showed consistent agreement!**

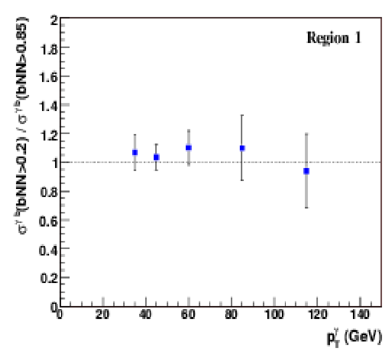


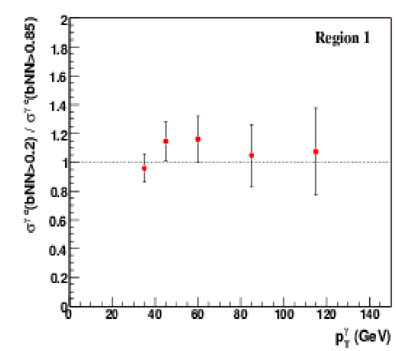




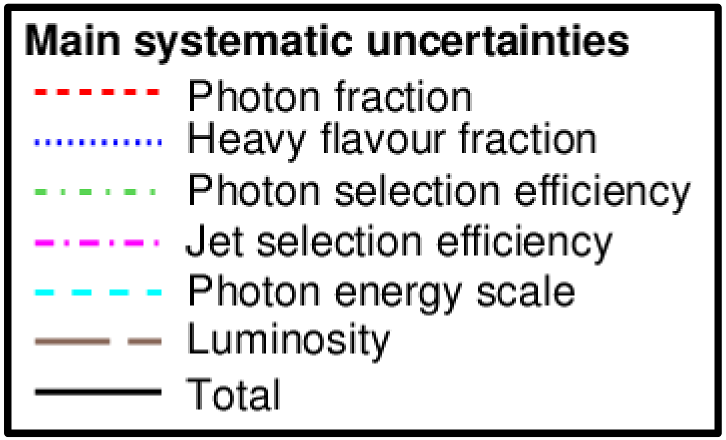




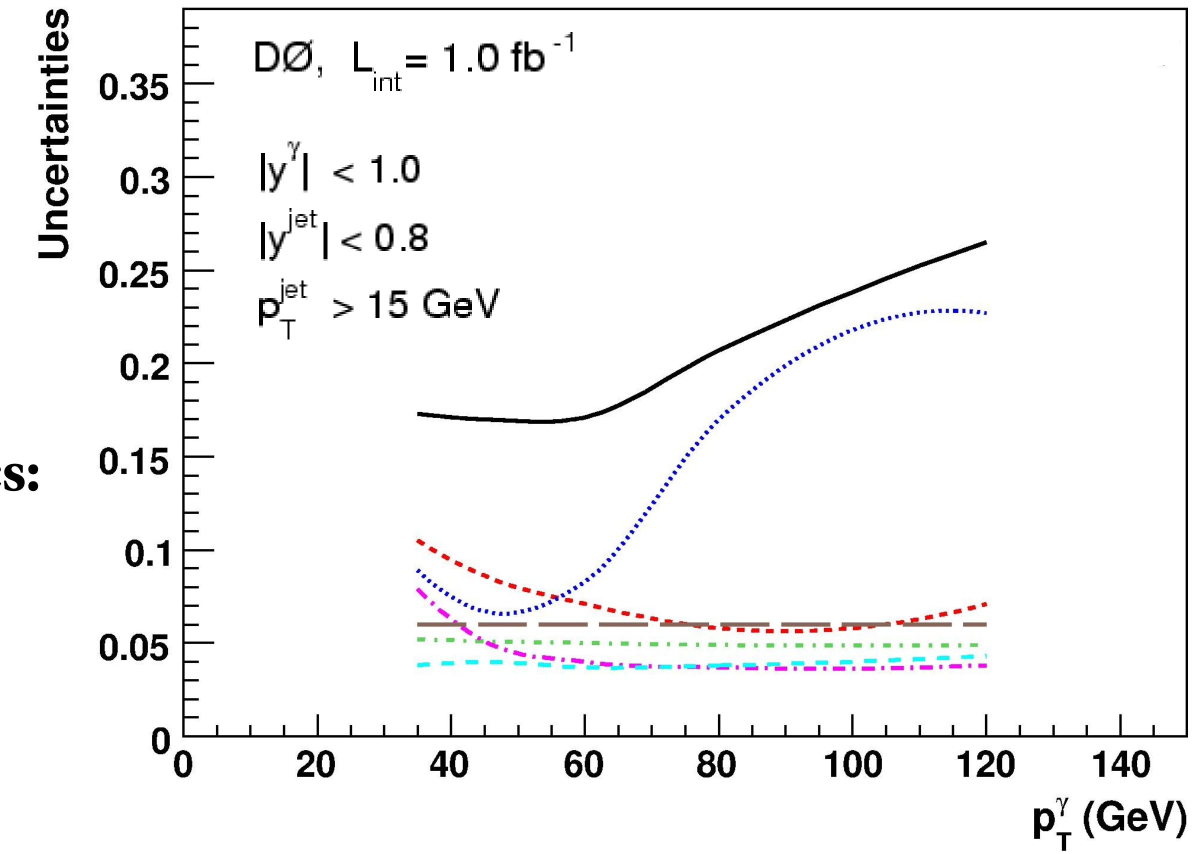




Overall Systematics

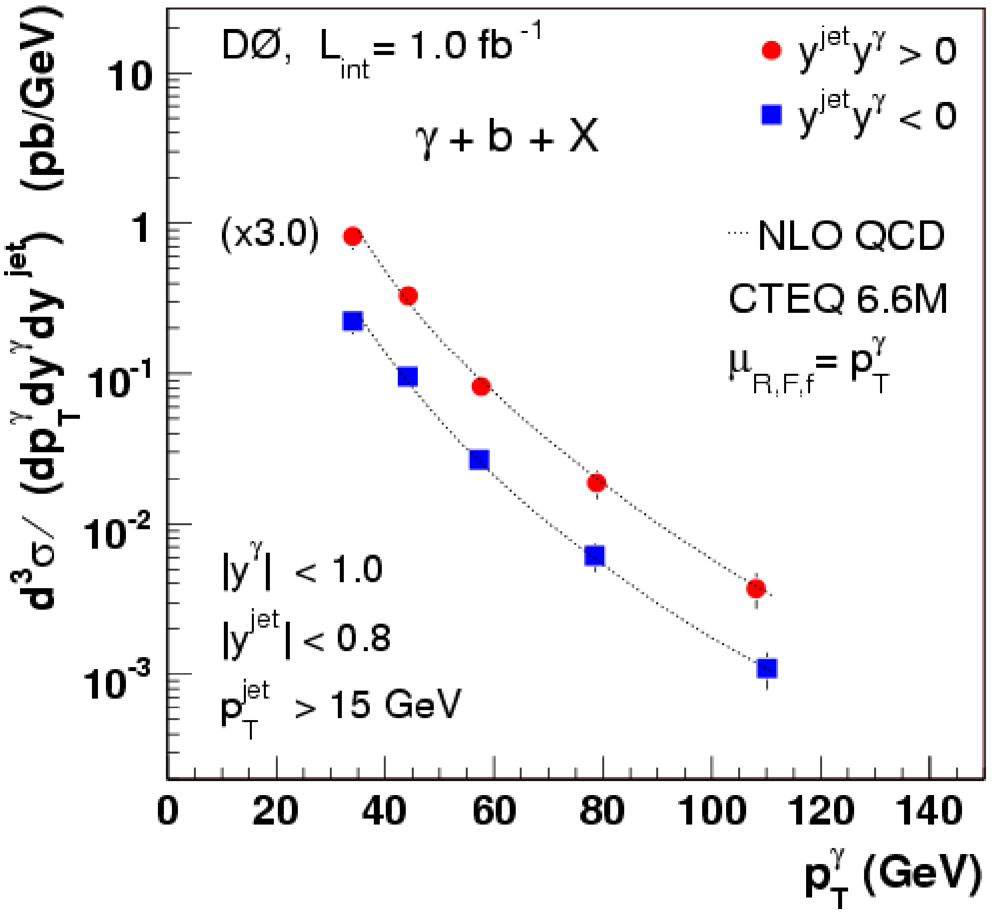


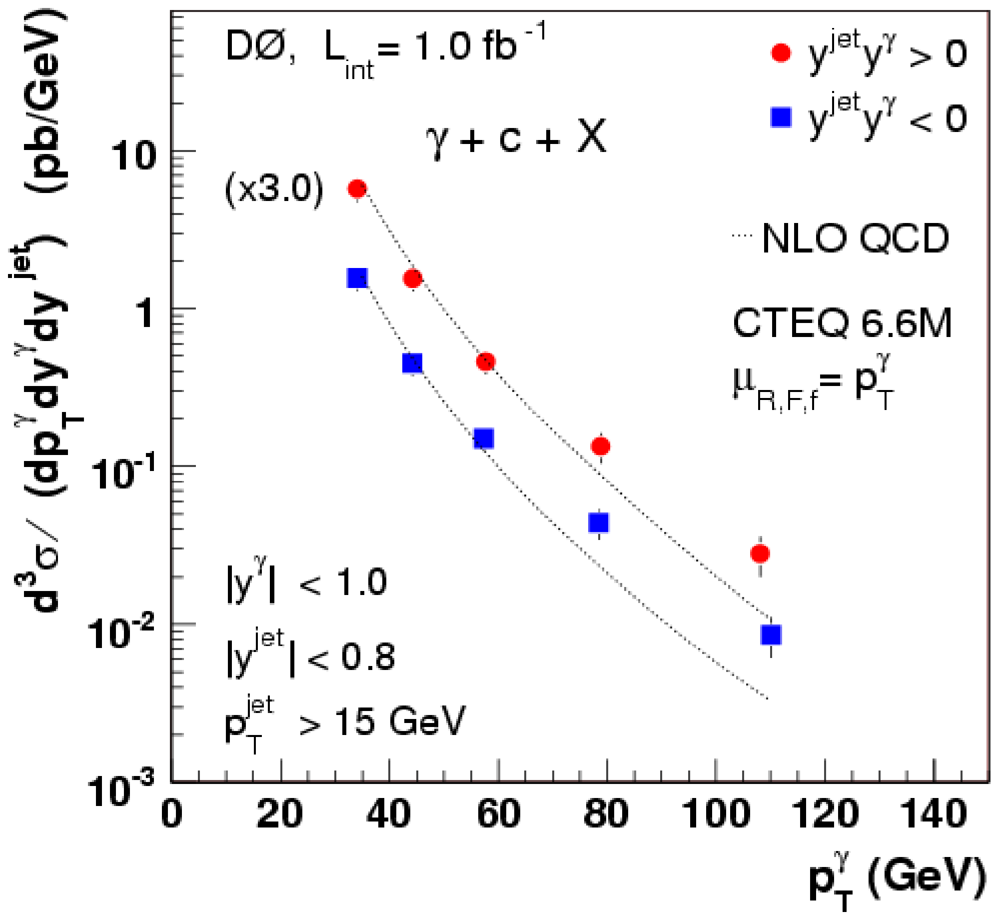
- The two dominant systematics:
  - At low p^{γ}_{T}, the photon fraction dominates
  - At high p^{γ}_{T}, the jet flavor fraction fitting is the largest uncertainty
    - This uncertainty is driven by data statistics especially in the last two p^{γ}_{T} bins



b and c Jet Cross Sections

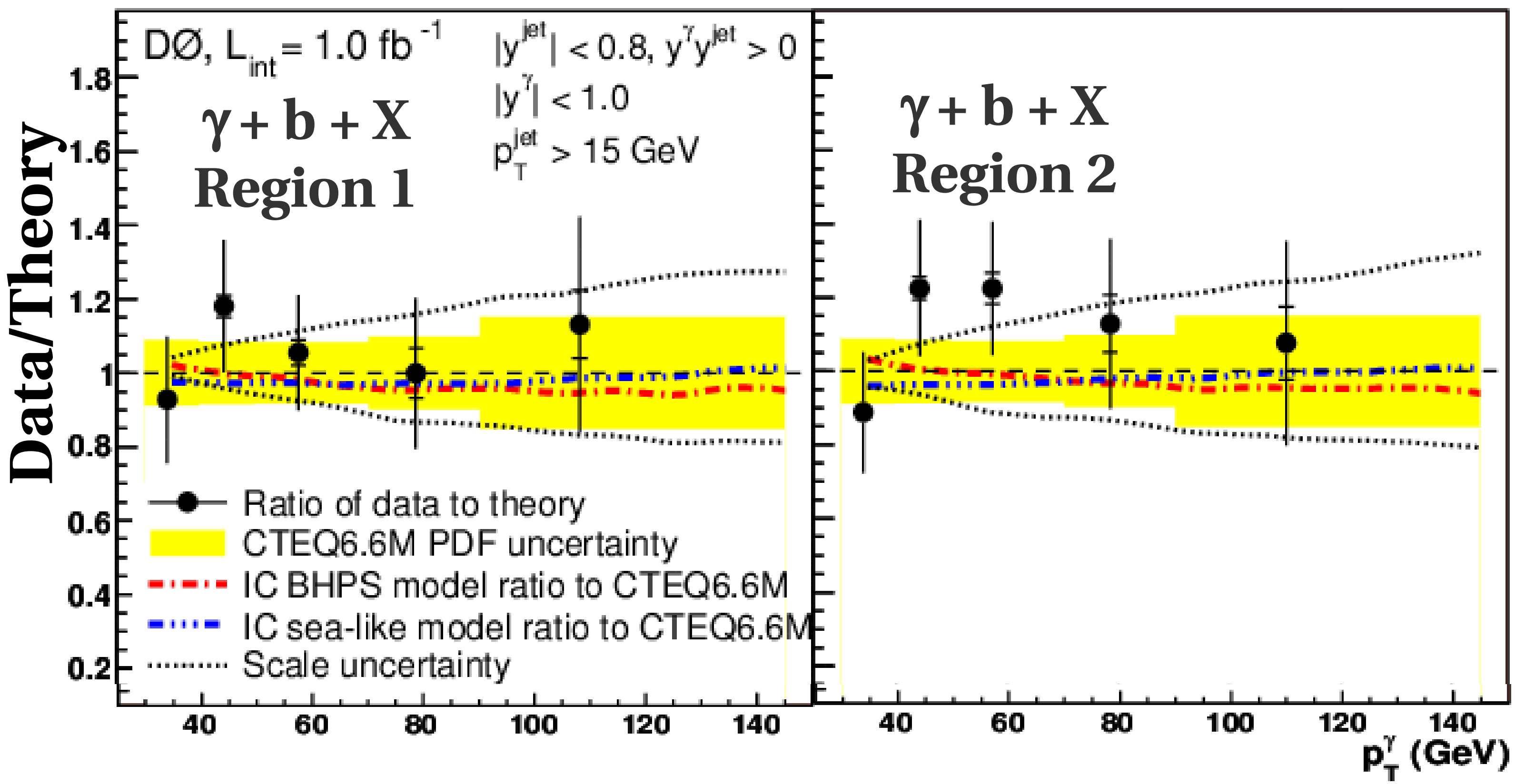
- **Results for the γ + b jet and γ + c jet cross sections**
- Theory curves were calculated using next-to-leading-order predictions
  - **Calculations provided by T. Stavreva and J. Owens (of CTEQ)**
  - CTEQ6.6M PDFs were used in the calculation





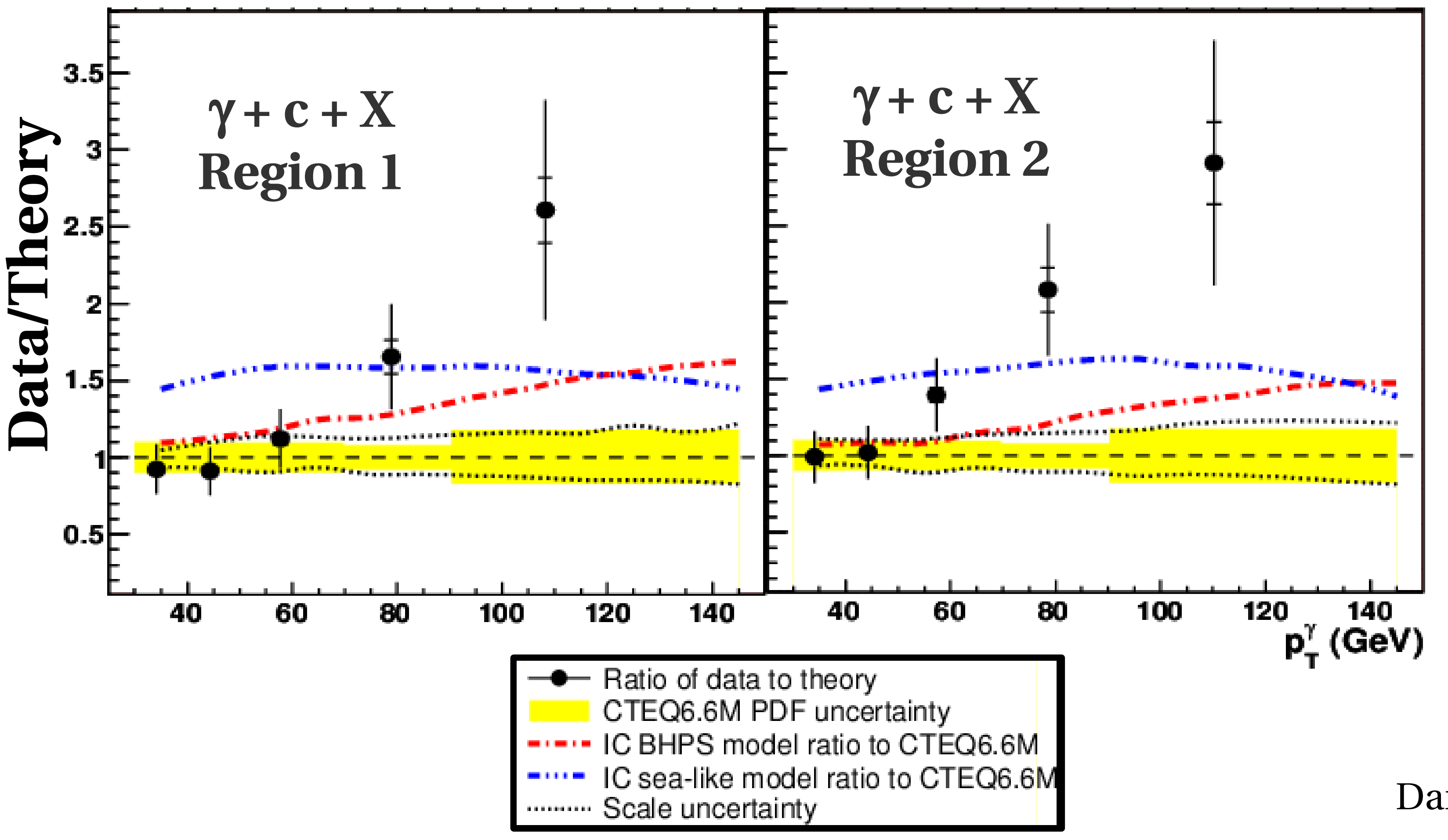
Data to Theory Ratios (γ + b Jet)

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



Data to Theory Ratios (γ + c Jet)

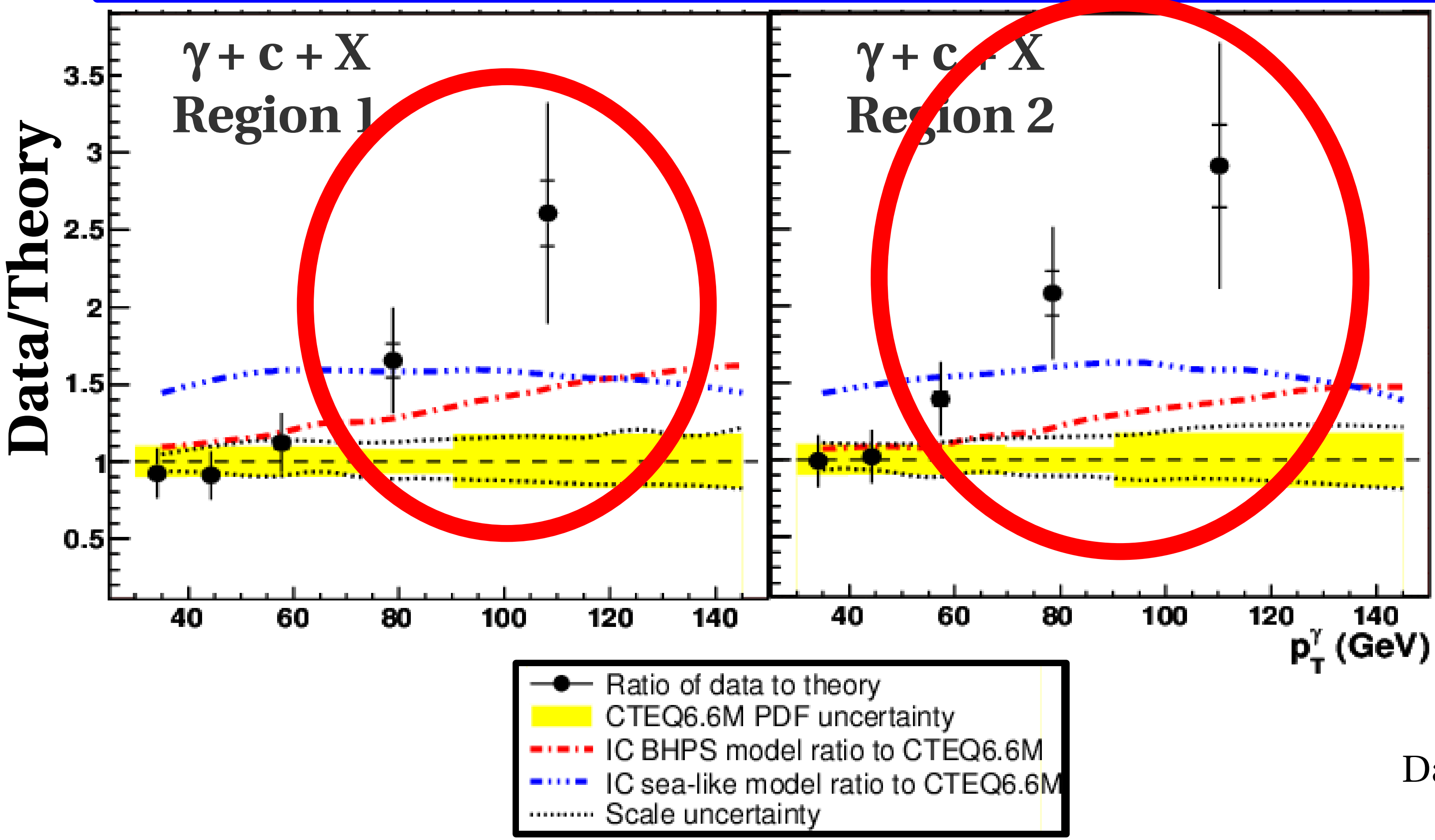
- **Discrepancy between data and theory is present for photon p_T > 70 GeV in both Region 1 and Region 2**
  - **Comparisons to CTEQ PDF sets with intrinsic charm are included**



Data to Theory Ratios (γ + c Jet)

Explaining the Difference

- Sign of intrinsic charm?
- Under-estimate of the $g \rightarrow c\bar{c}$ fraction?
- ??????



Conclusions

- **This measurement is the first differential one of either the $\gamma + b + X$ or $\gamma + c + X$ cross sections ever at a hadron collider**
  - New combination of techniques made measurement possible
  - **$\gamma + b$ jet cross section shows agreement in both regions**
  - **$\gamma + c$ jet cross section shows agreement until p^{γ}_{T} ~70 GeV**
  - **Possible explanations for the disagreement**
    - **Intrinsic charm component to the proton**
    - **Incorrect gluon splitting function $g \rightarrow c\bar{c}$**

- **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

Event Selection

- **Entire RunIIa dataset is used: ~1 fb^{-1}**
  - **Require at least one unprescaled EM trigger to be fired**
  - **At least one photon candidate and good hadronic jet**
    - Photon candidate and jet isolated from each other (**$dR > 0.7$**)
- **At least one primary vertex**
  - Primary vertex z position: **$|z_{PV}| < 35$ cm**
  - Primary vertex # of tracks: **$N_{Tracks} \geq 3$**
- **Low missing transverse energy**
  - MET criteria: **$E_T^{MISS} < 0.7 * p^{\gamma}_T$**

Photon Selection

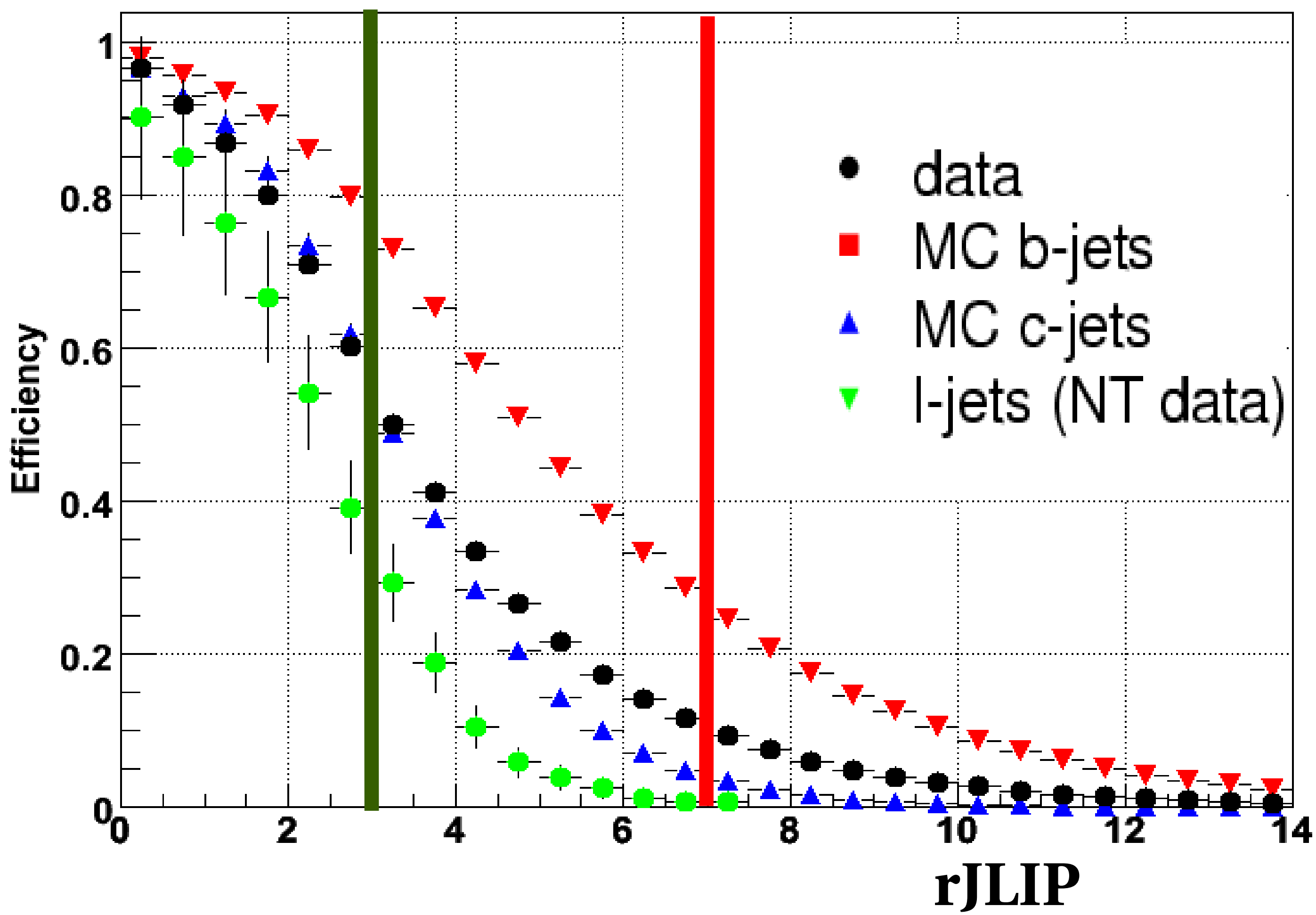
- **Using p17 certified Photon ID criteria (D0Note 4976)**
  - **At least one photon candidate must pass:**
    - **$P_T > 30$ GeV**
    - **$|y_\gamma| < 1.0$**
    - ID = 10, +-11
    - In both eta and phi fiducial regions
    - EM fraction > 0.96
    - Fractional isolation < 0.07
    - Prob of track matched chi squared < 0.001
    - 3^{rd} layer of EM shower width < $14 cm^2$
- **Additional requirements on photon selection**
  - **Photon neural network output > 0.7**
  - **Primary vertex z requirement using "photon pointing"**
    - **$|PV_Z^{EVENT} - PV_Z^{\gamma}| < 10$ cm (matched CPS cluster)**
    - **$|PV_Z^{EVENT} - PV_Z^{\gamma}| < 32$ cm (NO matched CPS cluster)**

Jet Selection

- **Leading p_T jet must satisfy the following:**
  - **Standard jet selection:**
    - $|y_{jet}| < 0.8$
    - $p_T > 15.0$ GeV
    - **Final p17 JES corrections applied**
    - Reconstructed with **JCCB** algorithm
    - Is flagged as **IsGoodJet**
  - **Additional b jet tagging requirements:**
    - Jet must be **taggable**
    - b jet neural network **bNN > 0.85**
    - $0 \leq JLIP_{REDUCED} \leq 1$
      (See slide 16)

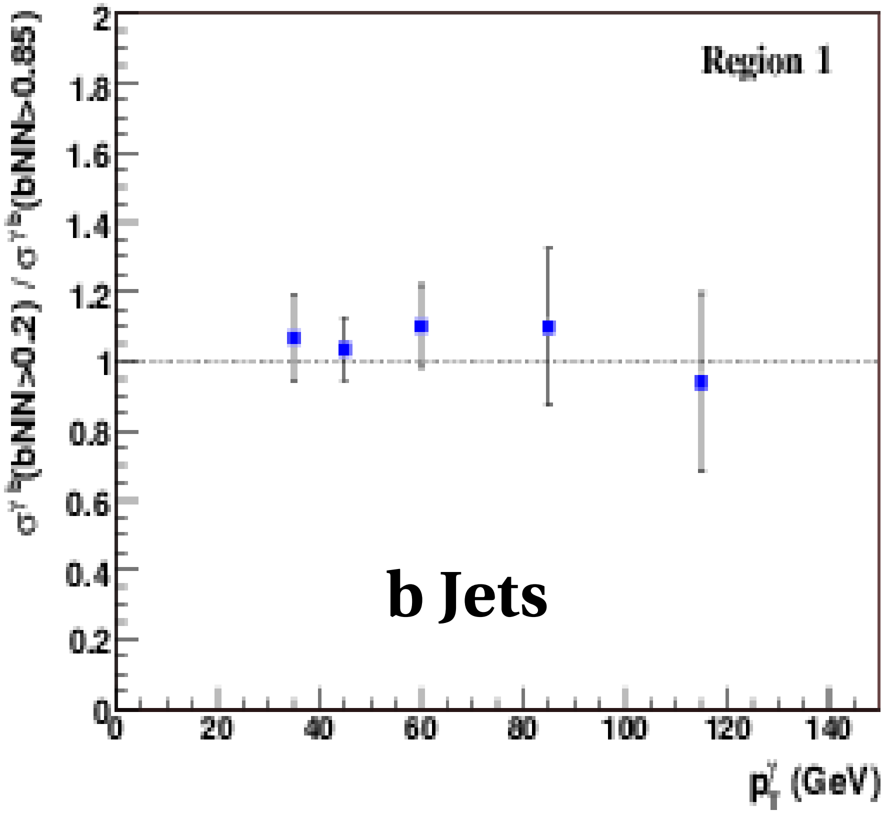
rJLIP Flavor Efficiencies

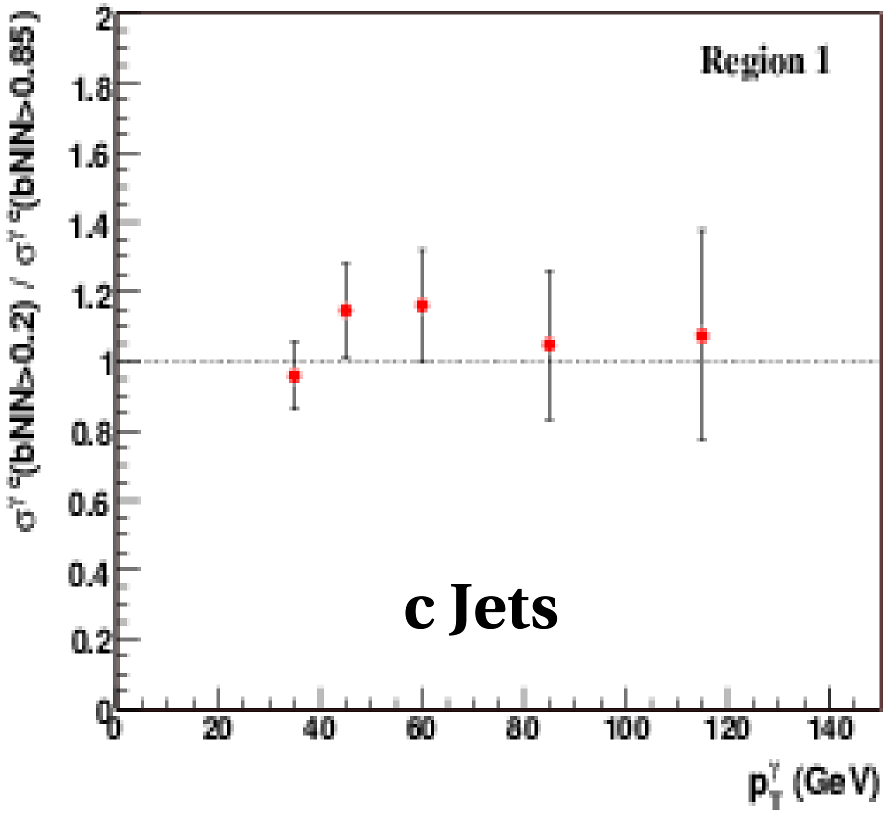
- For the efficiency method to be effective, the relative change in efficiencies between points should be adequately different

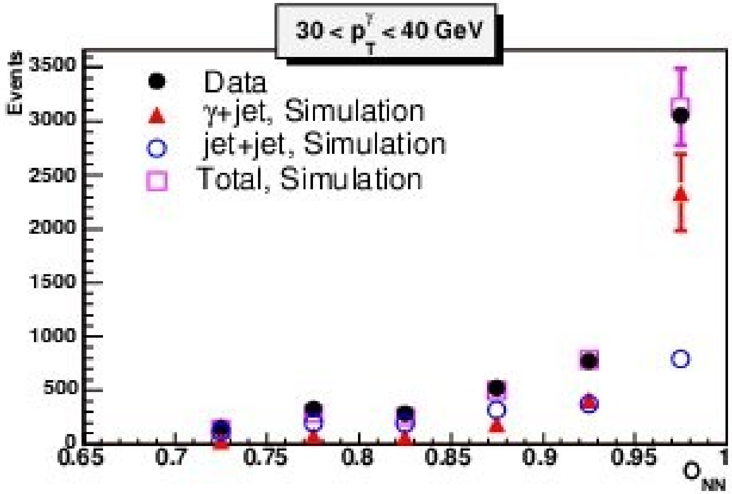


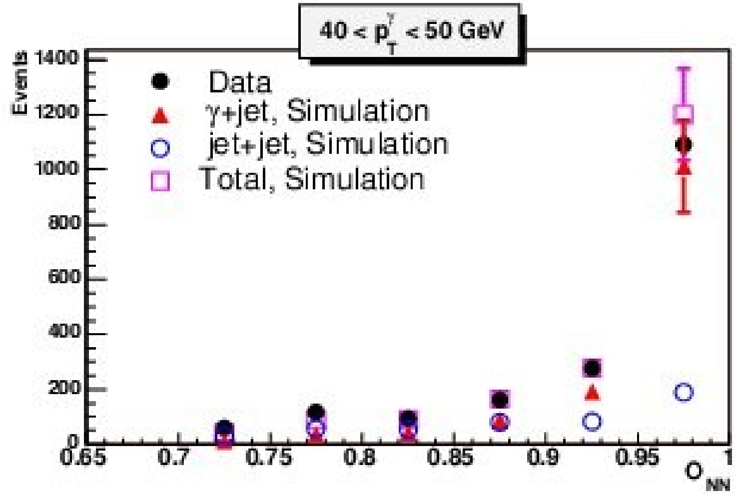
bNN 0.20 and bNN 0.85

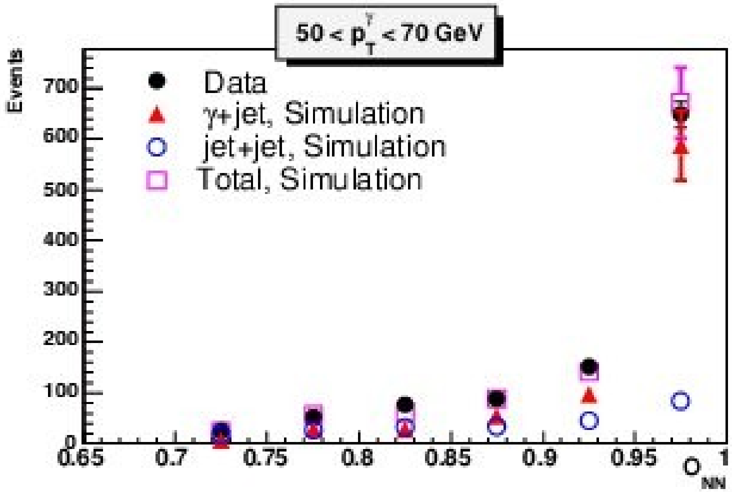
- **We can also recalculate our cross sections from the bNN > 0.20 operating point and compare to the bNN > 0.85 case**
  - **We see very similar agreement for Region 2**

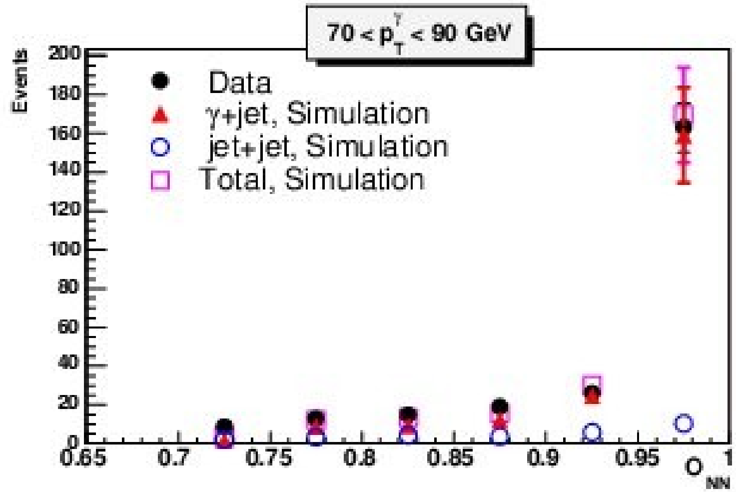


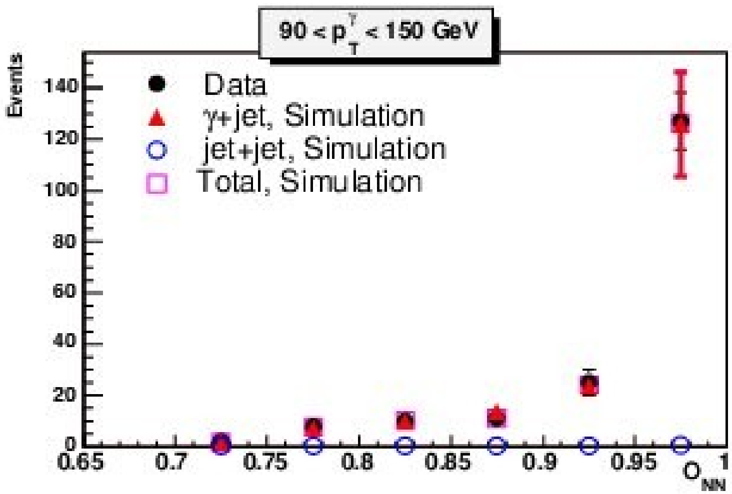



30 < p_T^γ < 40 GeV
Events
Data
γ+jet, Simulation
jet+jet, Simulation
Total, Simulation
O_NN


40 < p_T^γ < 50 GeV
Events
Data
γ+jet, Simulation
jet+jet, Simulation
Total, Simulation
O_NN

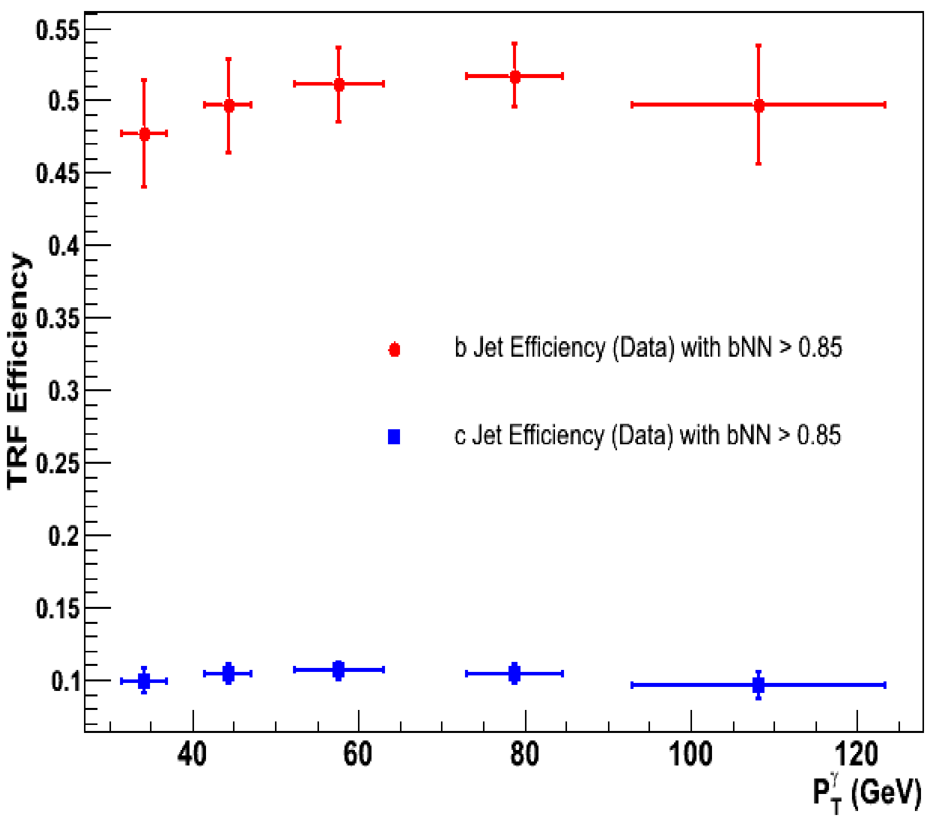

50 < p_T^γ < 70 GeV
Events
Data
γ+jet, Simulation
jet+jet, Simulation
Total, Simulation
O_NN

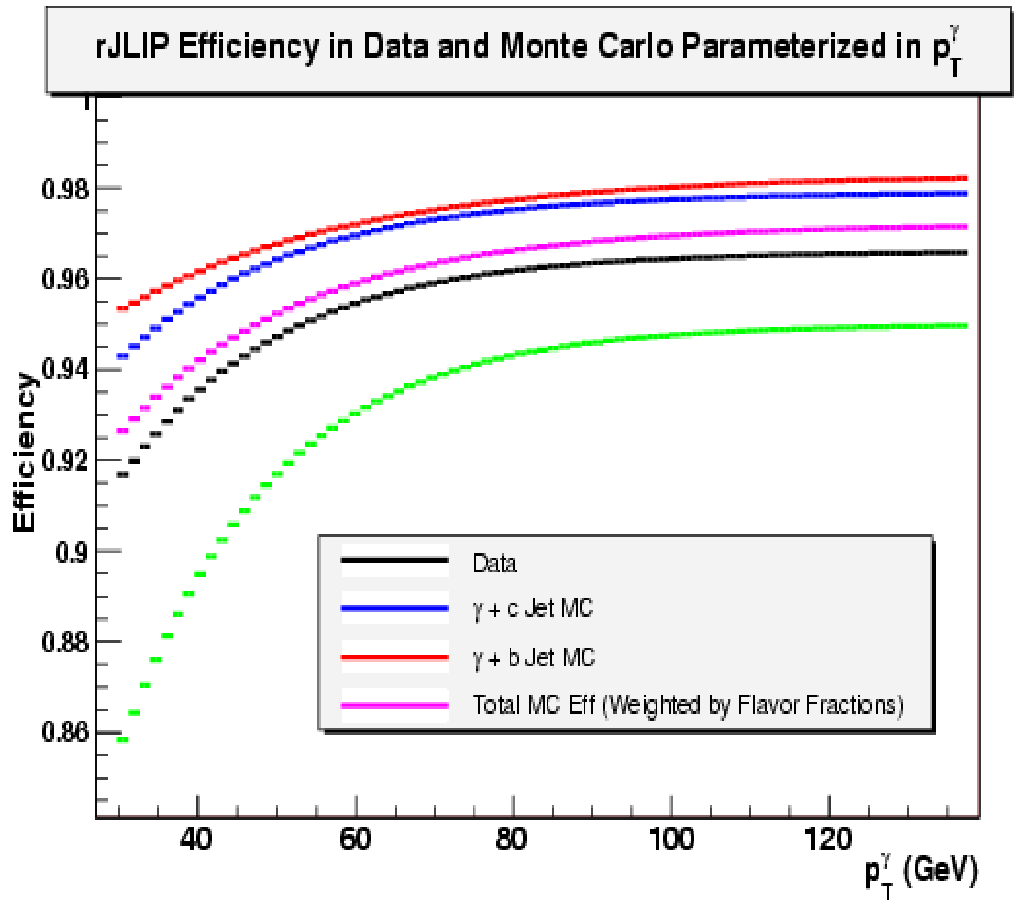

70 < p_T^γ < 90 GeV
Events
Data
γ+jet, Simulation
jet+jet, Simulation
Total, Simulation
O_NN


90 < p_T^γ < 150 GeV
Events
Data
γ+jet, Simulation
jet+jet, Simulation
Total, Simulation
O_NN

bNN and JLIP Efficiencies

- **Efficiencies for b (c) jets to pass bNN > 0.85 from Monte Carlo**
- **Efficiencies for rJLIP to exist in light, c and b jet Monte Carlo and data**
  - **To estimate data/MC agreement, MC efficiencies are weighted by their flavor fractions (coming up)**
  - **Agreement is within ~1.5%**





Photon Eff. and Acceptance