Photon + jet measurements at D0

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on behalf of D0 Collaboration

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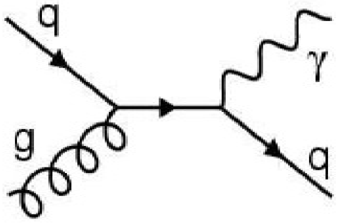
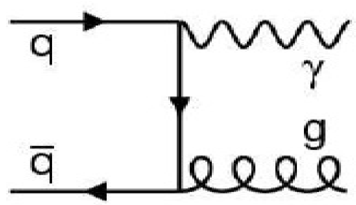
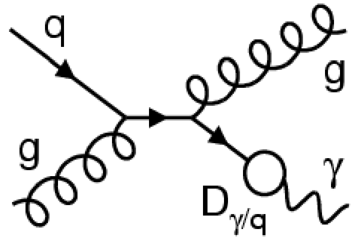
Outline

- D0 at Tevatron and photon+jet physics
- Photon plus Heavy Flavor Production Cross Section
- Double Parton Scattering
- Summary

Motivations for photon physics







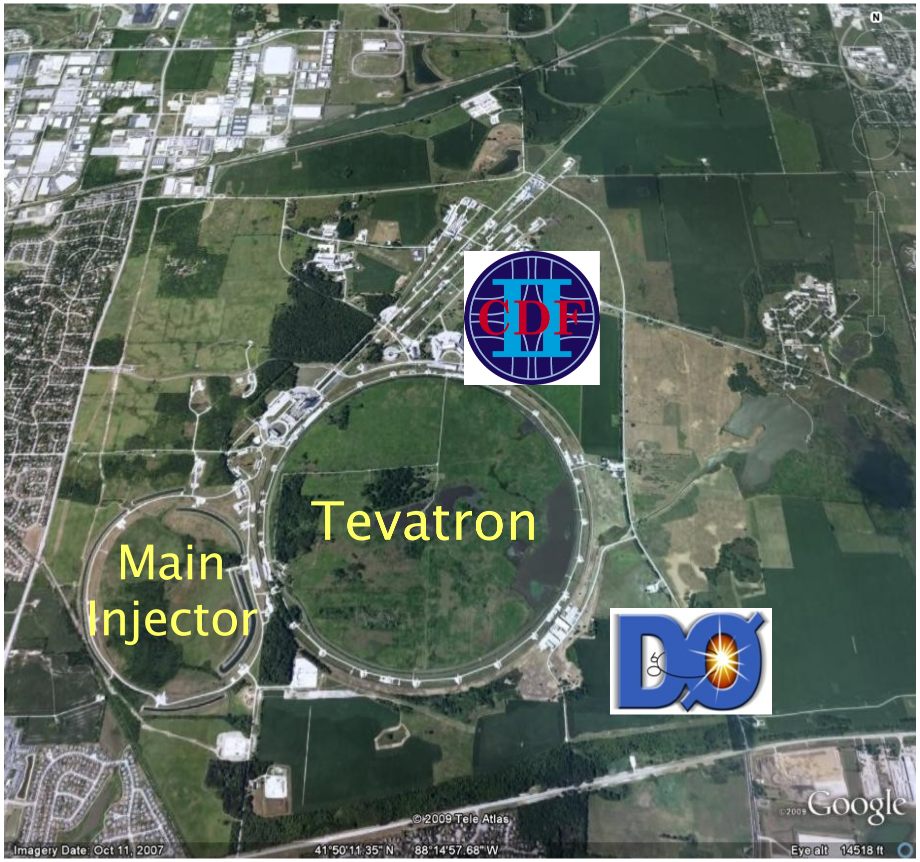
- Photons have a good energy resolution and almost free from fragmentation & systematics related with jet ID and measurements.
- Much better statistics than for W/Z(+jet) production.
- Price to pay: higher background.

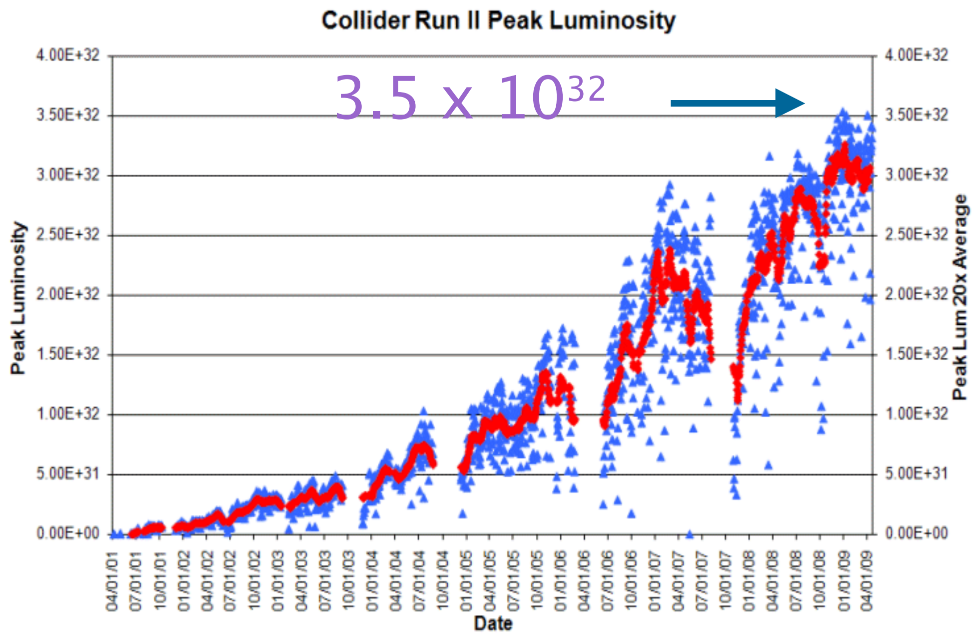
Precision test of pQCD

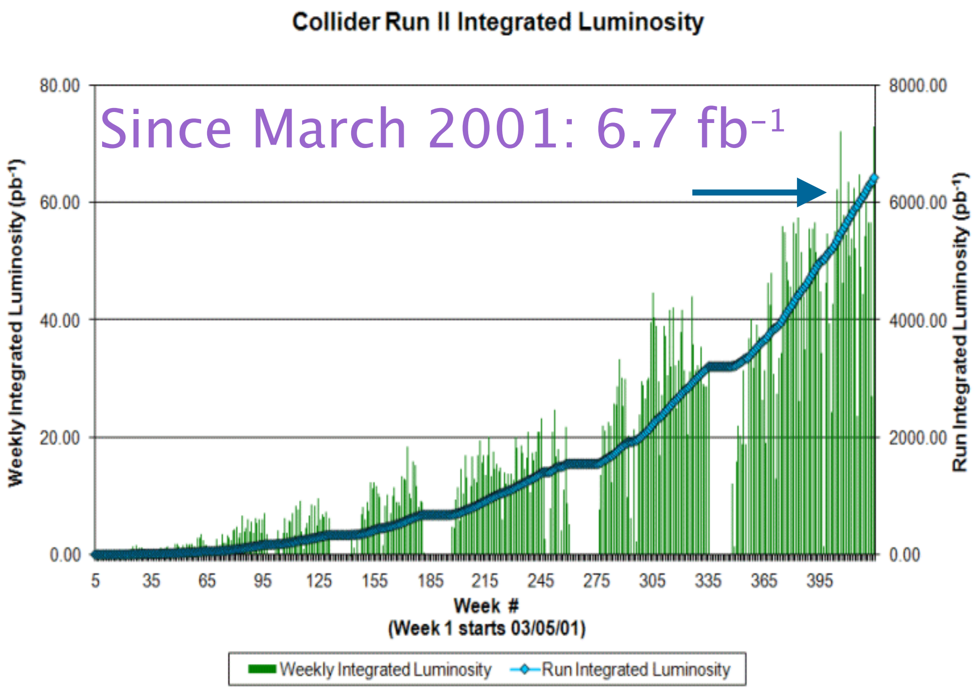
- Direct information on gluon density in the proton :
  - ☞ gluon involved at LO in contrast to DIS & DY processes
- Test of soft gluon resummation, models of gluon radiation
- Probes of gluon and b, c –quark PDFs and b/c fragmentations
- Tests of spatial distribution of partons in the proton and understanding of multi-jet production mechanism.

Fermilab Tevatron Run II

- $\sqrt{s}$ = 1.96 TeV
- Peak Luminosity: 3.5×10^{32} $cm^{-2}s^{-1}$
- About 6.7 fb^{-1} delivered
- Experiments typically collect data with 80–90% efficiency



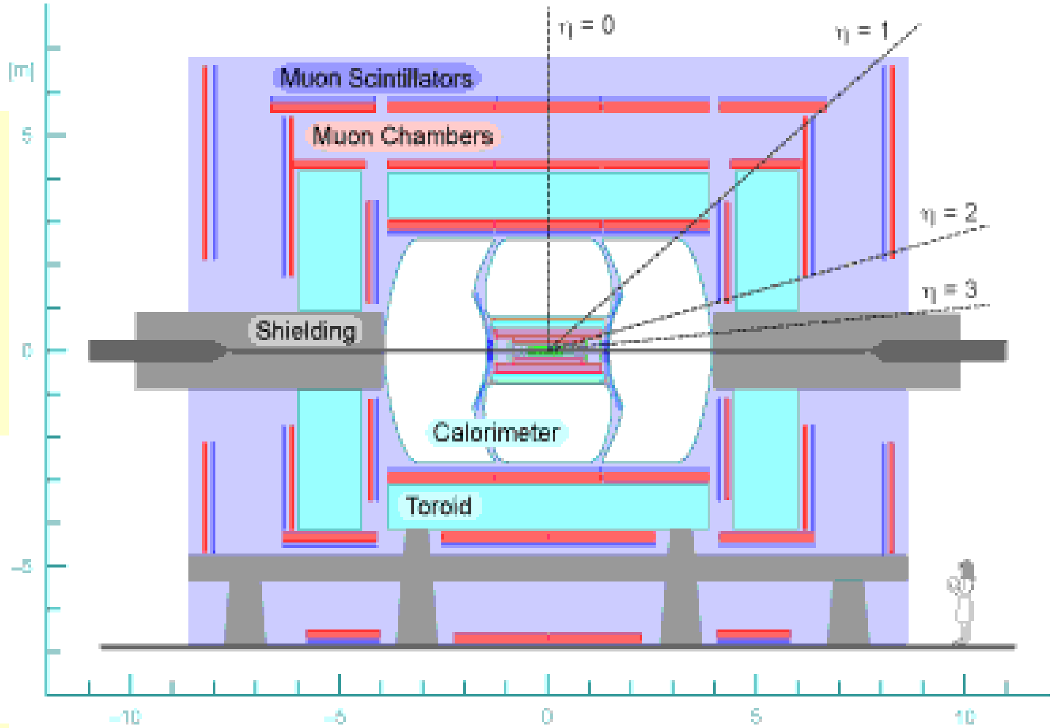




D0 detector

Three main systems

- Tracker (silicon and scintillating fiber)
- Calorimeter (LAr/U, some scintillator)
- Muon chambers and scintillators



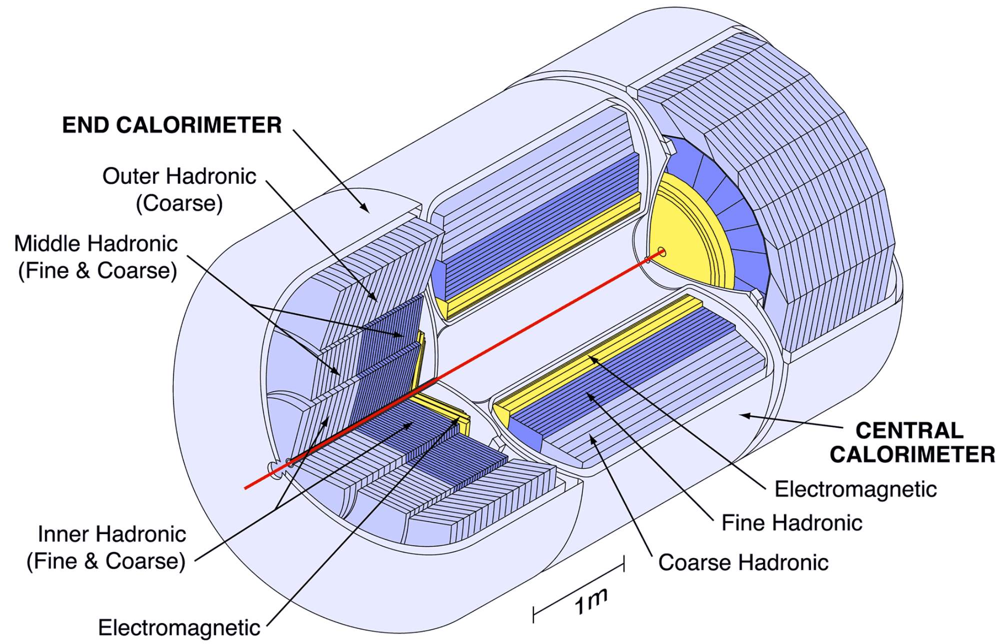
D0 calorimeter

✓ The most important detector for photon and jet measurements

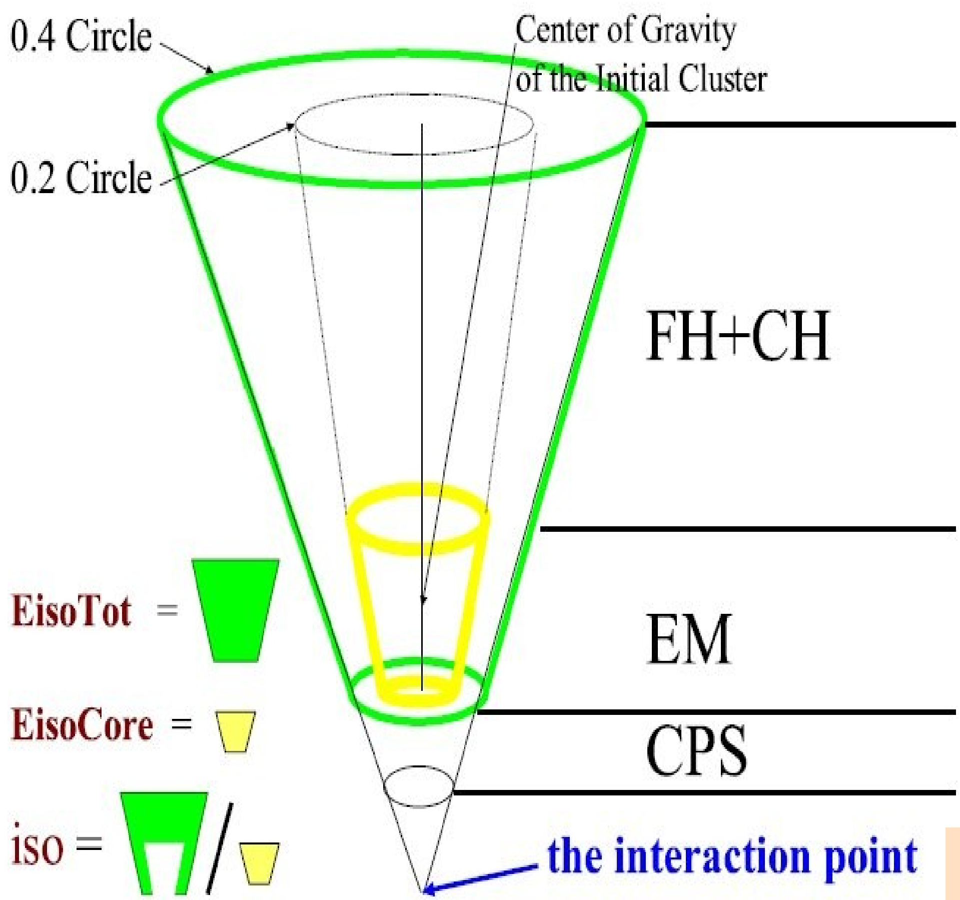
✓ Three main subregions: Central ($|\eta|<1.1$), Intercryostat ($1.1<|\eta|<1.5$) and End calorimeters ($1.5 < |\eta| < 4.2$)

✓ Liquid Argon/Uranium calorimeter:

- Stable response, good resolution
- Partially compensating (e/h ~1)



Photon Identification



- EM shower in calorimeter
  $\rightarrow \gamma$ candidate
- No associated track
- Isolation criteria

  Define $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

  $$Isol = \frac{E_{tot}(R{=}0.4) - E_{EM}(R{=}0.2)}{E_{EM}(R{=}0.2)} < 0.07$$

- EM fraction > 96%
- dR(γ, jet) > 0.7

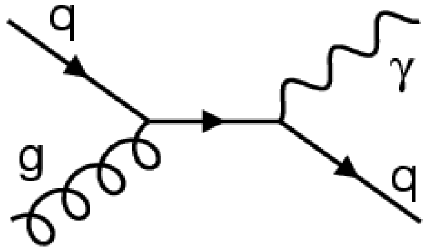
Background estimation

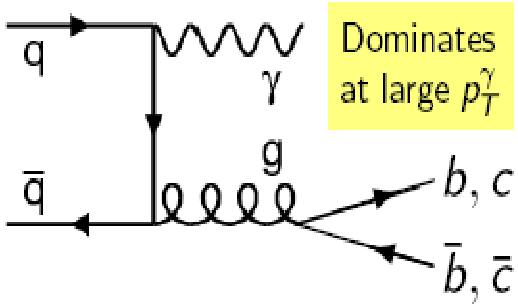
Origin: EM jets composed of $\pi^0, \eta, K^0_s, \omega$ mesons surrounded by (soft) hadrons

Tool: Photon ANN based on calorimeter and track information

Photon+ heavy flavor jet production in D0

D0 Collab., Phys.Rev.Lett. 102, 192002 (2009)

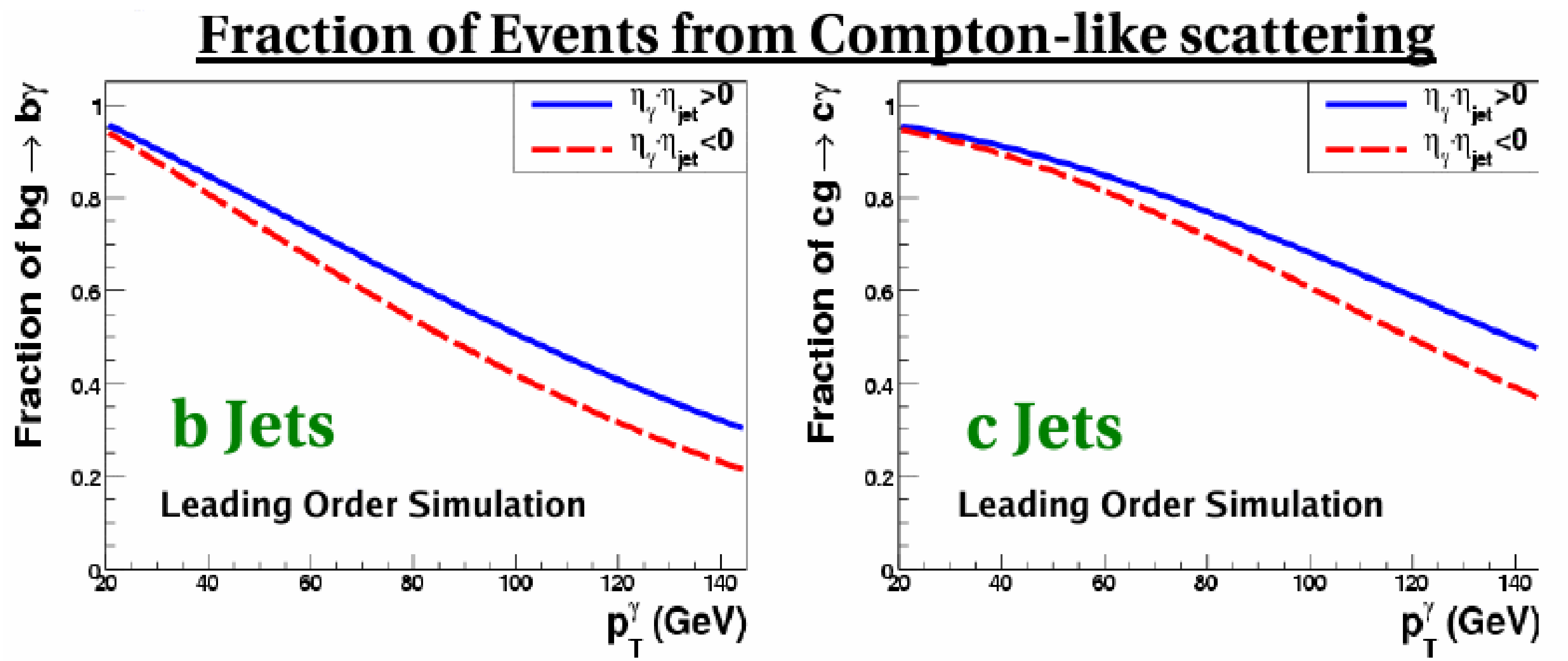




- QCD Compton-like scattering dominates for b(c) production up to 90(120) GeV
- Outgoing = incoming quark

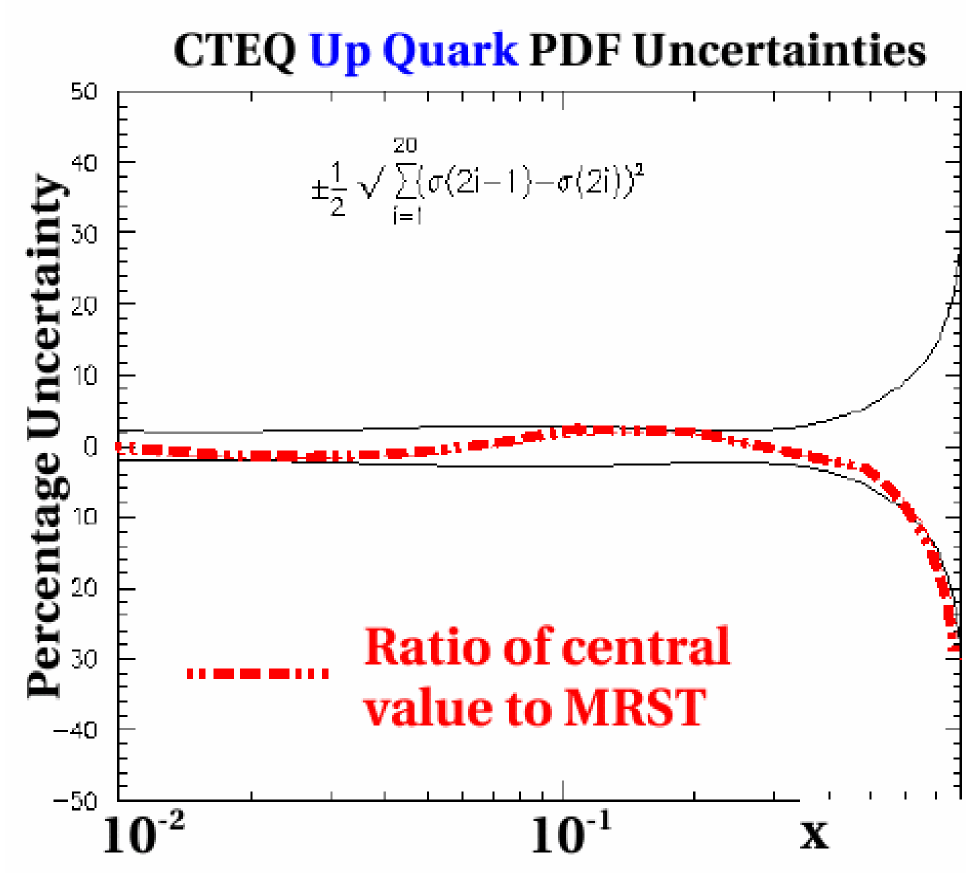
⇒ Constraints on HF PDF

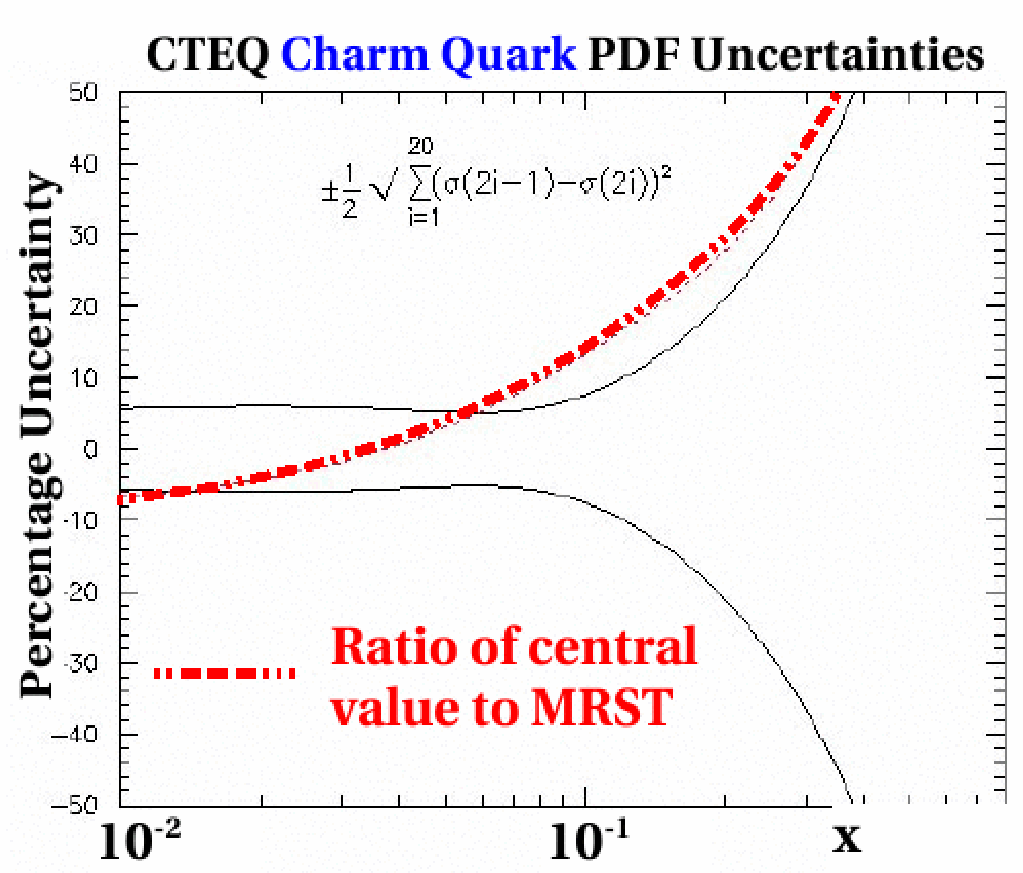
- Triple differential with two photon-HF jet rapidity regions => better splitting of parton x intervals.



Current PDF uncertainties

- Cross section is sensitive to charm, bottom and gluon PDFs content of the proton/antiproton
- These PDFs are under-constrained by experimental data





Uncharted x-Q2 area

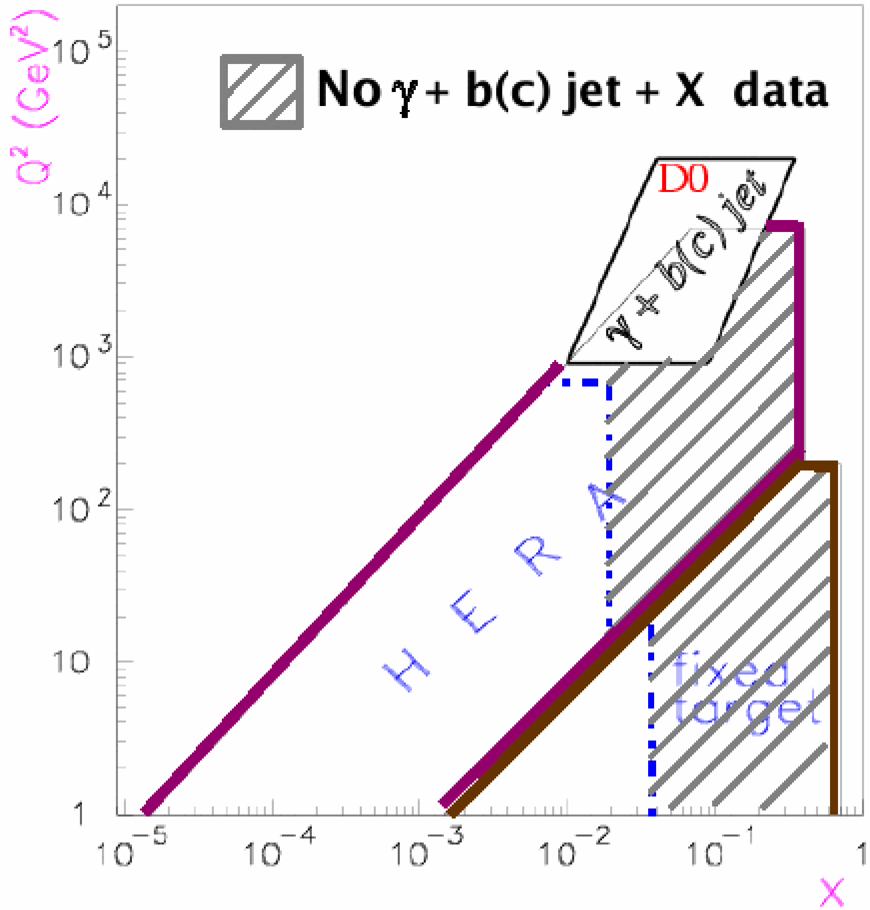
– **Sensitive to previously unexplored regions of x-Q^2 phase space**

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

– **For our measurement, we can probe the phase space:**
  - $9 \times 10^2 < Q^2 < 2 \times 10^4$ 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**

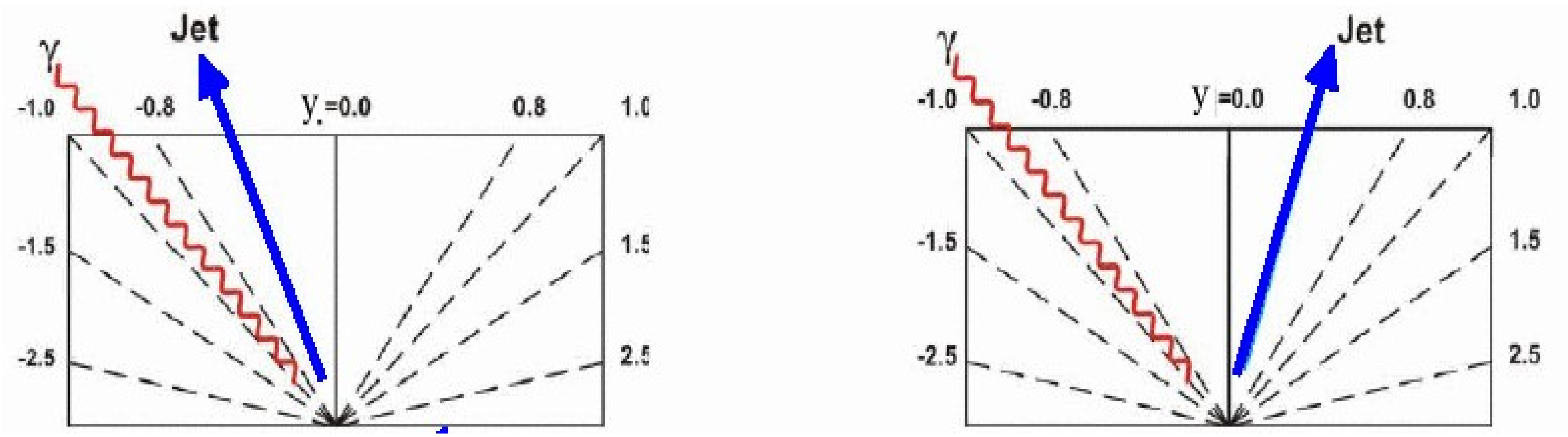
  (Different initial states)



Main Kinematic Selections

- $p_T^\gamma > 30$ GeV (up to 150 GeV), $|y^\gamma| < 1.0$
- Isol< 0.07, frac$(EM) > 0.96$, $\mathcal{O}_{\rm NN}(\gamma) > 0.7$
- $\not{E}_T < 0.7 p_T^\gamma$ (cosmics, $W \to e\nu$)
- $p_T^{\rm jet} > 15$ GeV, $|y^{\rm jet}| < 0.8$, ($R_{\rm jets} = 0.5$)
- Leading jet: $N_{\rm Track} \geq 2$, $\mathcal{O}_{\rm NN}({\rm HF}) > 0.85$

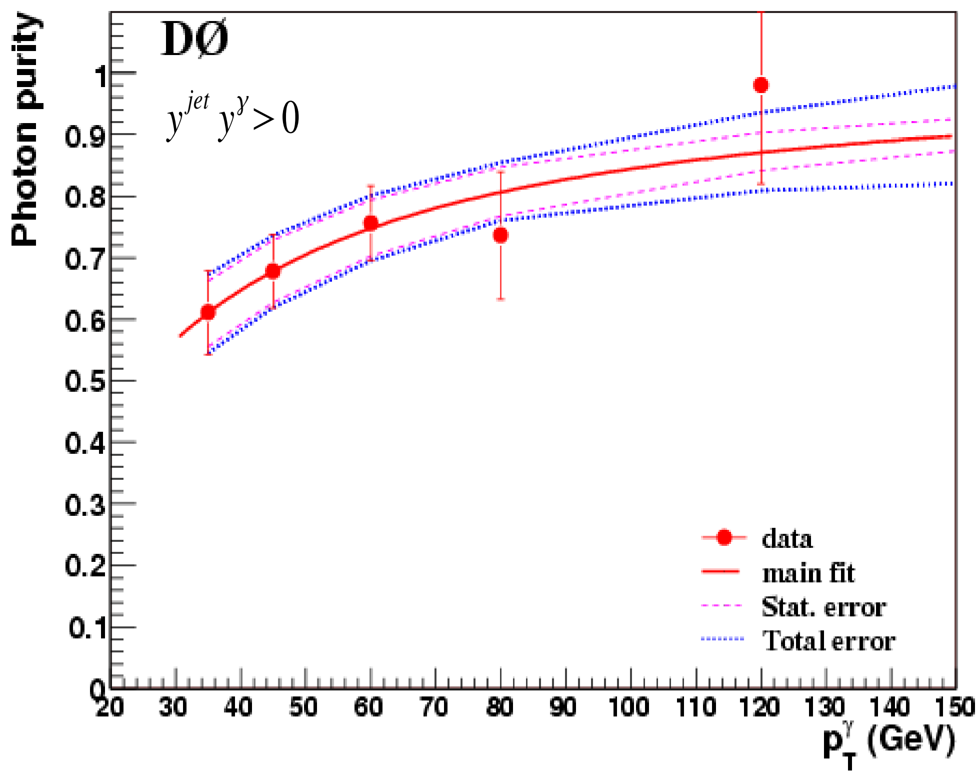
2 regions: $y^\gamma \cdot y^{\rm jet} > 0$, $y^\gamma \cdot y^{\rm jet} < 0$



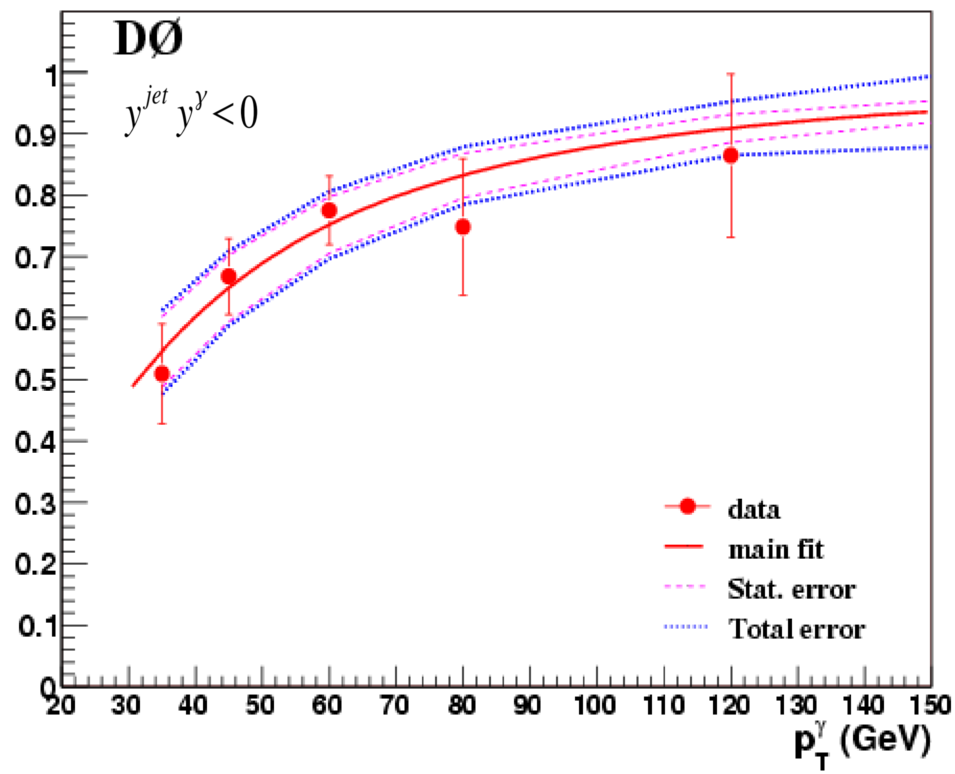
Photon Purity

- It is obtained from the fit of MC signal and background photon ANN outputs to that for the data
- The fits are performed in each photon pT bin for each Region separately.

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



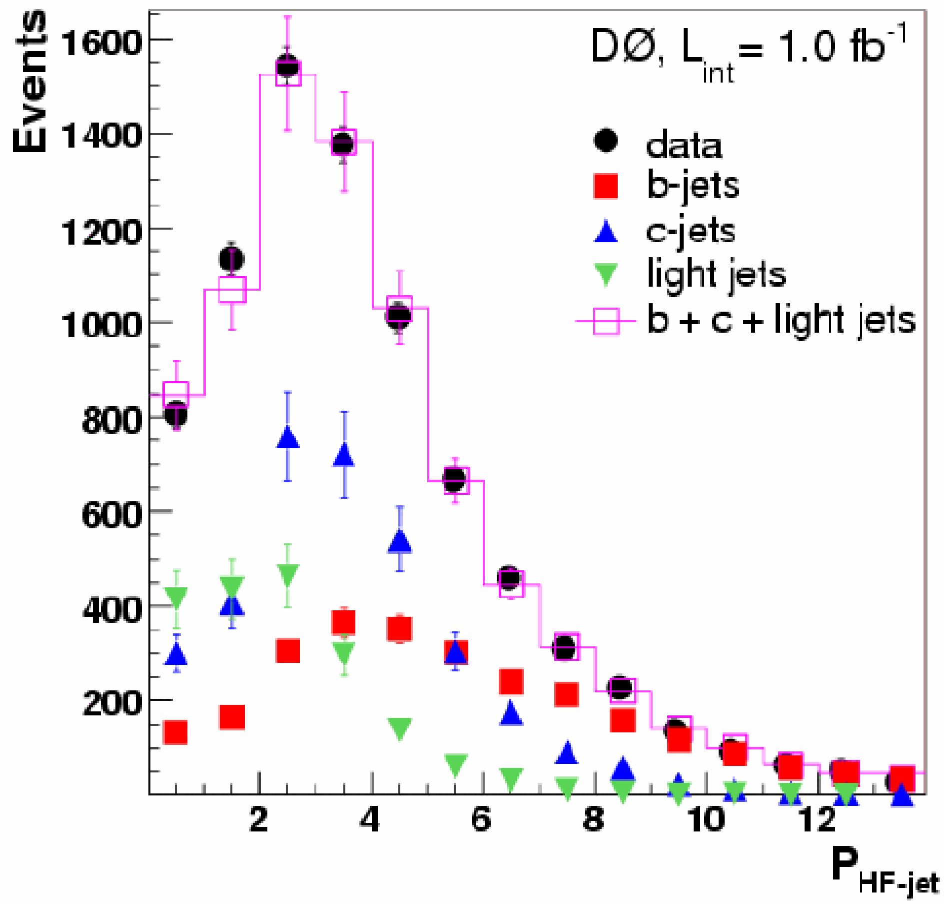
Region 2: $y^{\gamma}y^{jet} < 0$



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**

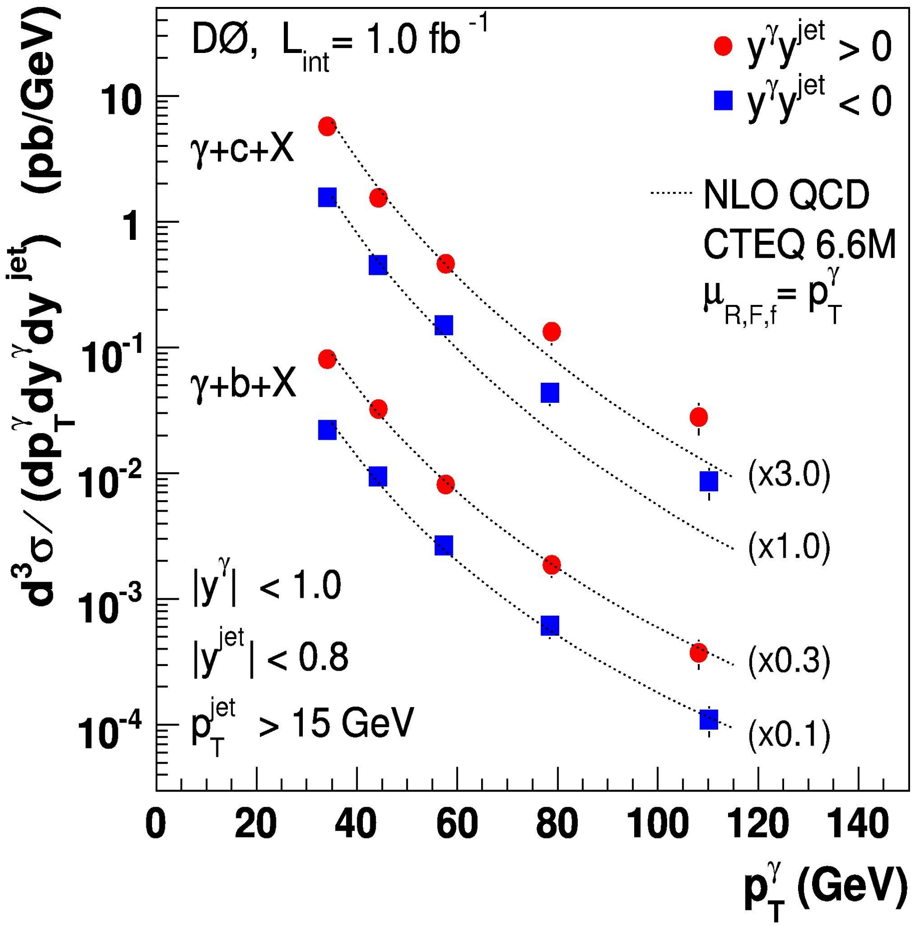


Fitting $P_{\text{HF-jet}} = -\ln \prod_i \text{Prob}^i_{\text{track}}$ templates of b, c (MC) and light jets (data) to shape of data

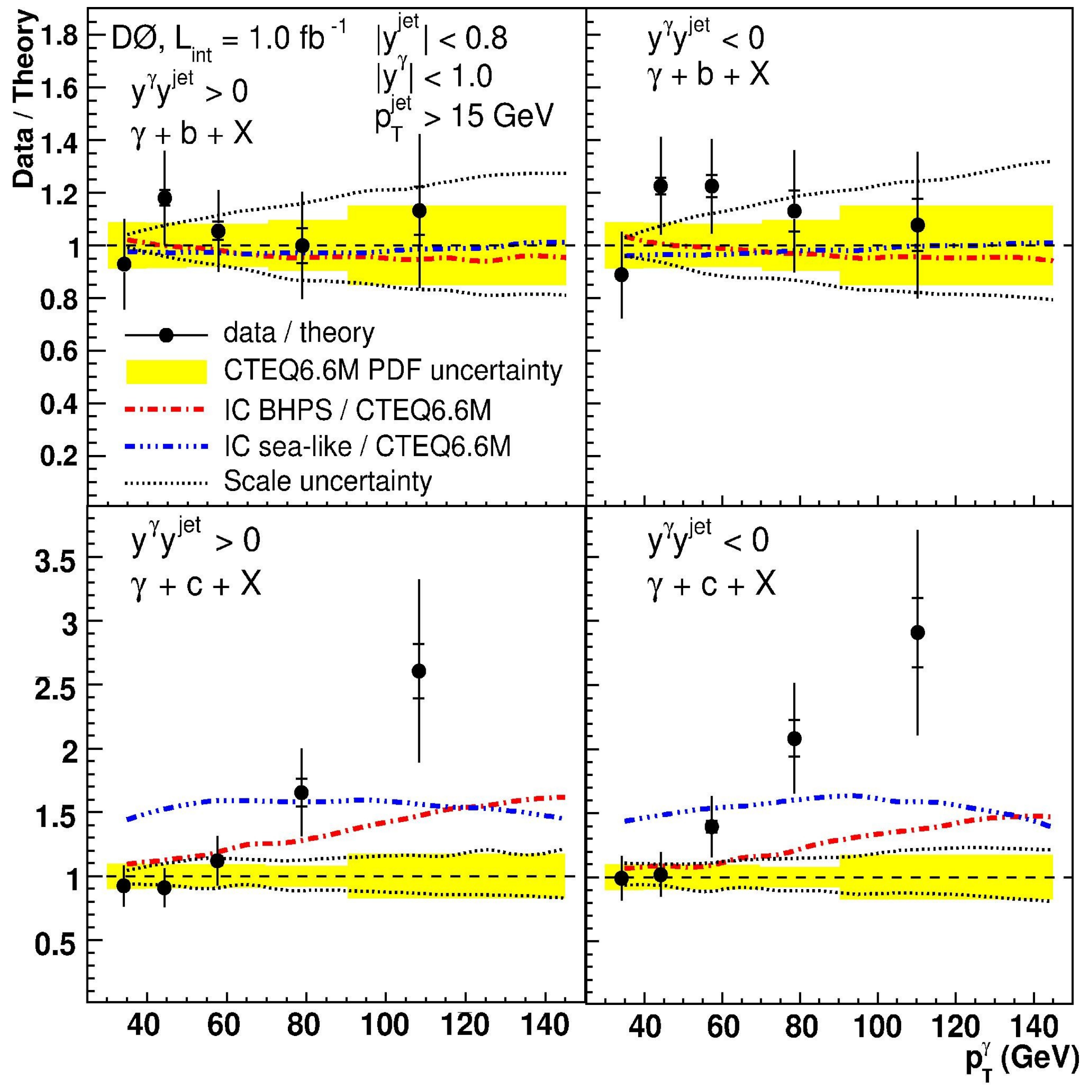
Cross sections

Triple differential cross section

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



Data/theory comparison

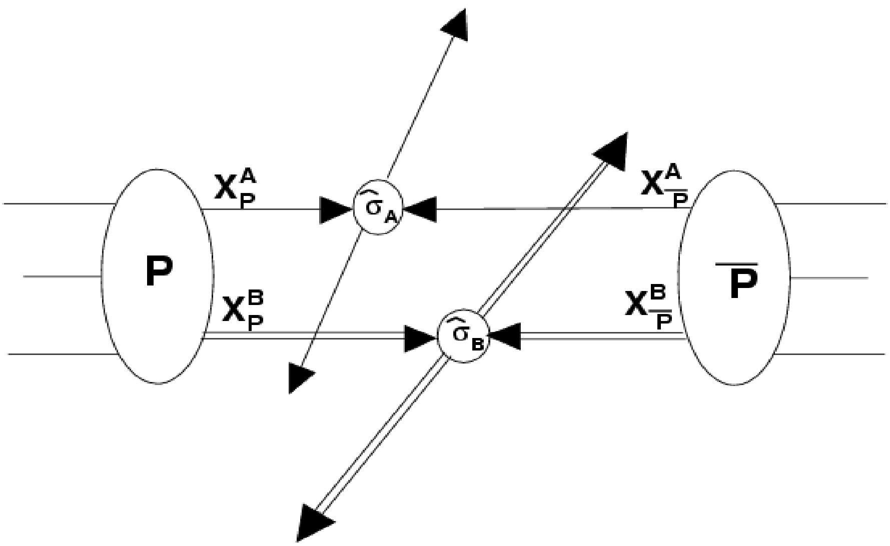


- γ+b cross section agrees in the whole range
- γ+c cross section disagrees at p_T^γ > 70 GeV

Huge amount of internal cross-checks of the results!

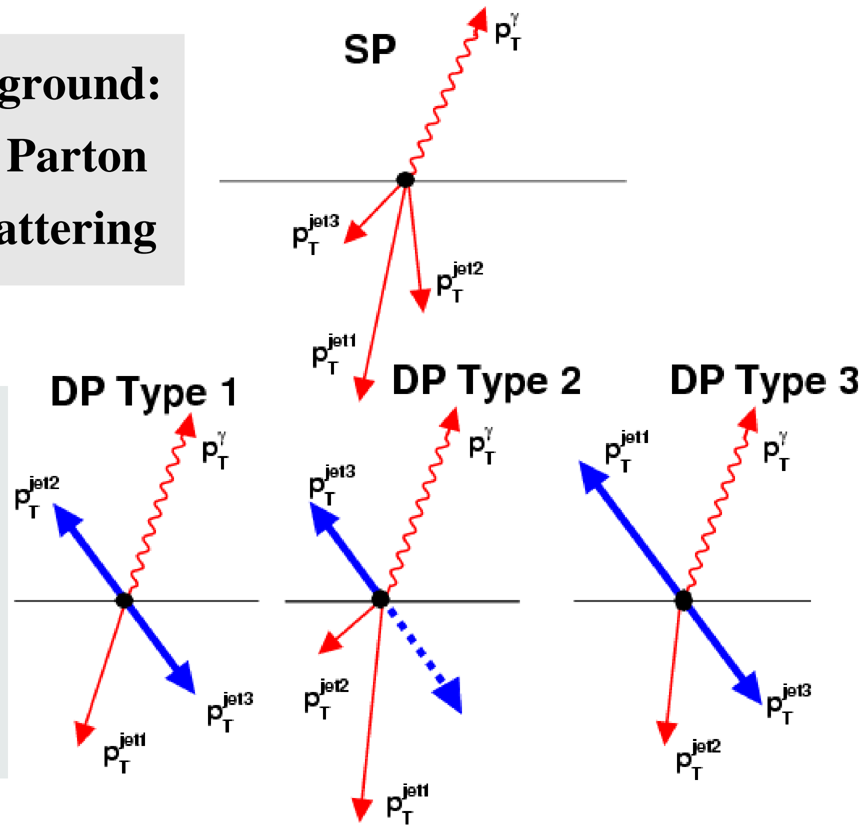
Double Parton Scattering in γ+3 jets events

- Complementary information about proton structure: Spatial distribution of partons
  ⇒ Possible parton-parton correlations. Impact on PDFs?
- Needed for understanding many signal events and correct estimating backgrounds to many rare processes.
- Especially important at high luminosities due to additional pp(bar) interactions.



Selections: 60 < photon pT < 80 GeV, lead. jet pT > 25, other 2 jets with pT > 15 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)

History of measurements

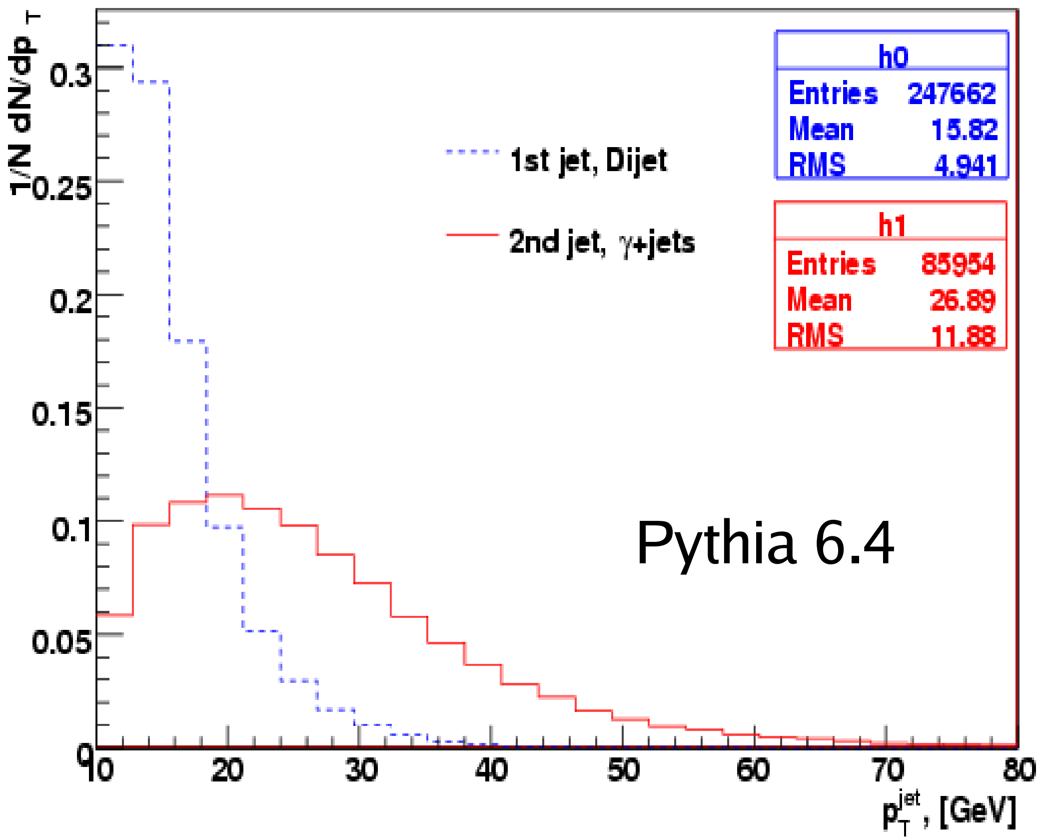
- Theoretical discussion on DPS continues for many years (~beginning of 80's)
- Very small amount of experimental results

	$\sqrt{s}$ (GeV)	final state	p_T^{min} (GeV/c)	η range	Result
AFS, 1986	63	$4jets$	$p_T^{\rm jet} > 4$	$\|\eta^{jet}\| < 1$	$\sigma_{eff} \sim 5$ mb
UA2, 1991	630	$4jets$	$p_T^{\rm jet} > 15$	$\|\eta^{jet}\| < 2$	$\sigma_{eff} > 8.3$ mb (95% C.L.)
CDF, 1993	1800	$4jets$	$p_T^{\rm jet} > 25$	$\|\eta^{jet}\| < 3.5$	$\sigma_{eff} = 12.1^{+10.7}_{-5.4}$ mb
CDF, 1997	1800	$\gamma + 3jets$	$p_T^{\rm jet} > 6$	$\|\eta^{jet}\| < 3.5$	
			$p_T^{\gamma} > 16$	$\|\eta^{\gamma}\| < 0.9$	$\sigma_{eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb

- Experimental problem is extracting DP signal from more probable double bremsstrahlung background.

Motivation of jet pT binning

Jet PT: jet from dijets vs. bremsstrahlung jet from γ+jets



▸ Fraction of dijet (DP) events is expected to drop with increasing jet PT

▸ Measurement is done in the three bins of 2nd jet pT: 15-20, 20-25, 25-30 GeV

Distinguishing variables

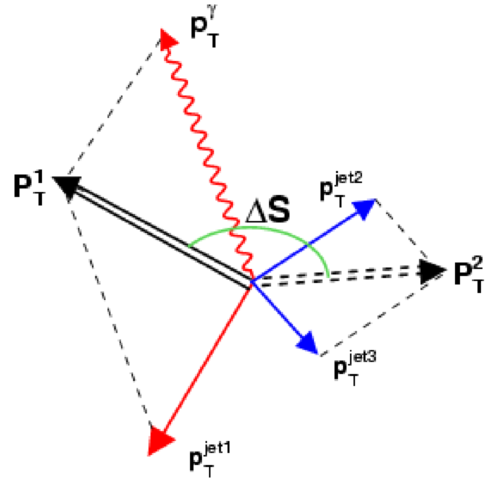
$$S_\phi = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{\Delta\phi(\gamma,i)}{\delta\phi(\gamma,i)}\right)^2 + \left(\frac{\Delta\phi(j,k)}{\delta\phi(j,k)}\right)^2}$$

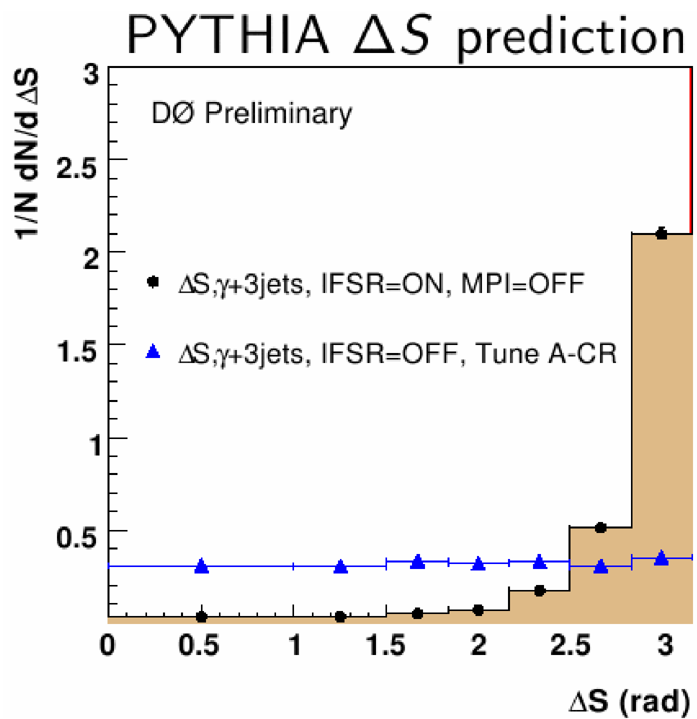
$$S_{p_T} = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{|\vec{P_T}(\gamma,i)|}{\delta P_T(\gamma,i)}\right)^2 + \left(\frac{|\vec{P_T}(j,k)|}{\delta P_T(j,k)}\right)^2}$$

- 92-95% of signal events are minimized by pairing photon and leading jet
- ΔS for SP events is peaked at π, and flat for *ideal* (Type 1) DP events
- One of the dijet jets can be replaced by a radiation jet (Type 2) with a larger pT what makes ΔS distribution less flat with a bump closer to π.

For a pair with minimum S:

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





D0 data and DP model

ΔS distributions for DP enriched and DP depleted datasets

$$D_1 = f_1 M_1 + (1 - f_1) B_1$$

$$D_2 = f_2 M_2 + (1 - f_2) B_2$$

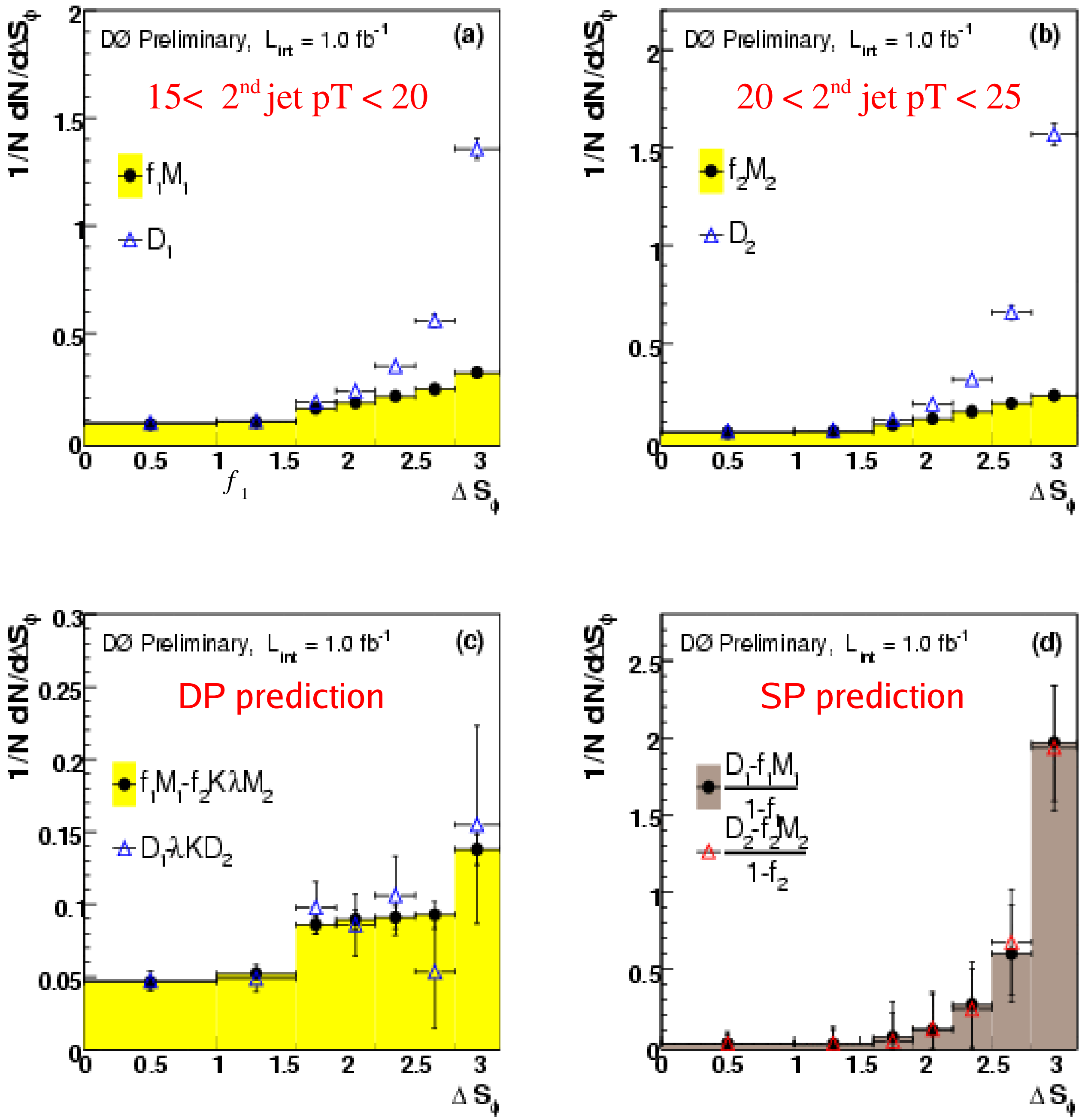
D_i - data

M_i - DP model

B_i - background

f_i - DP fraction

$(1 - f_i)$ - SP fraction



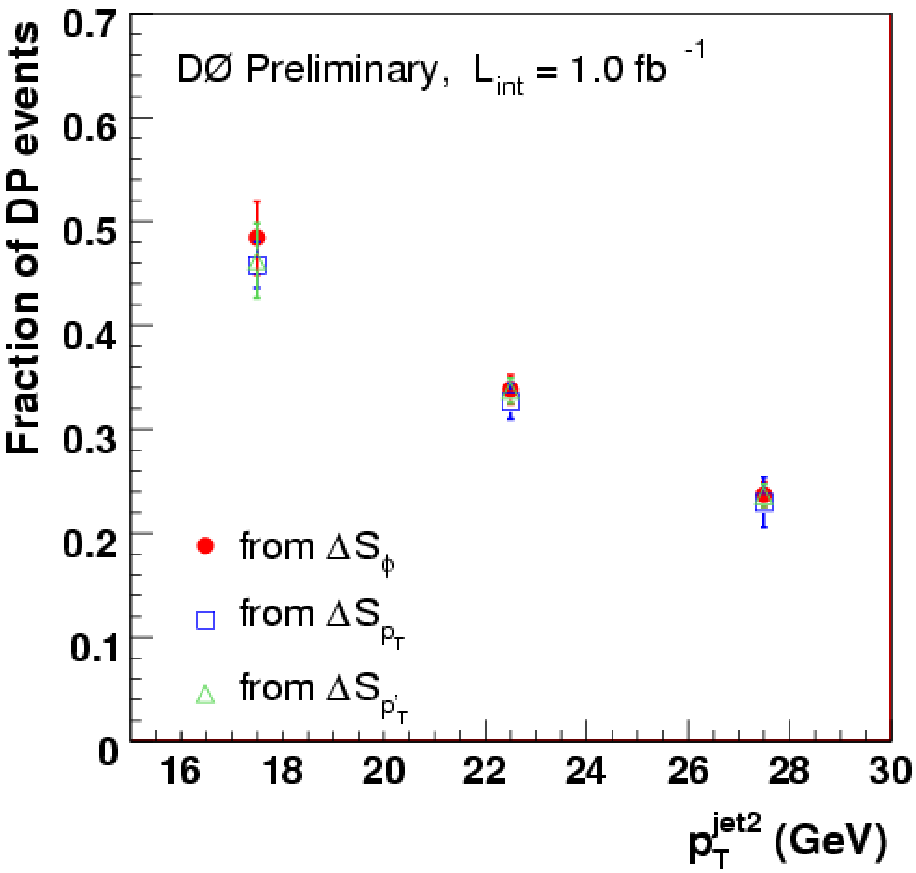
$$D_1 - \lambda K D_2 = f_1 M_1 - \lambda K f_2 M_2$$

$$\lambda = \frac{B_1}{B_2} \qquad K = \frac{(1 - f_1)}{(1 - f_2)}$$

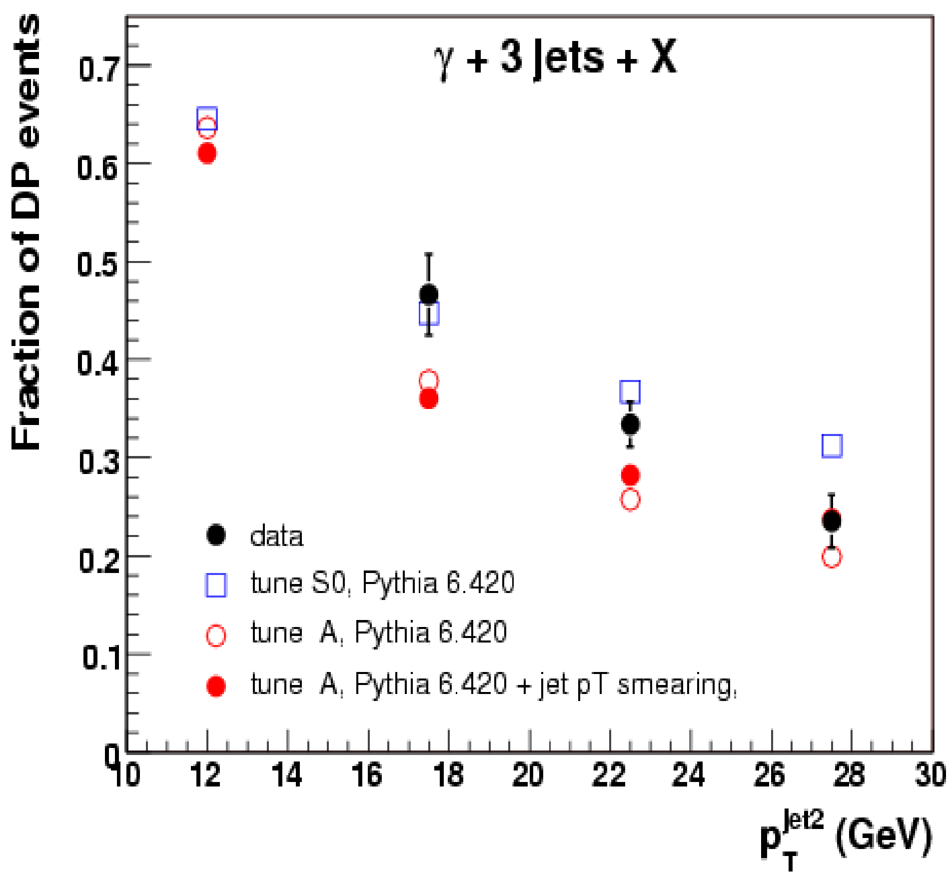
f_i is found from the fit

Fractions of DP events

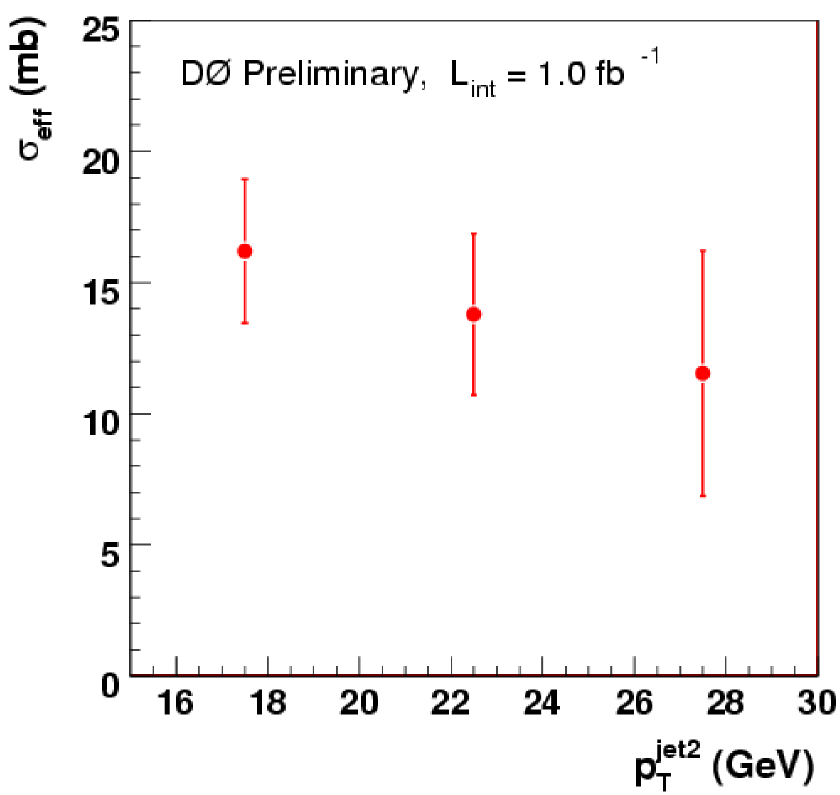
Data



Comparison with Pythia MPI tunes



Effective cross section



- Effective cross section is varied for the same bins as 16.2 ± 2.8 mb to 11.5 ± 4.7 mb and agree for all jet pT bins within uncertainties. Systematic uncertainties have negligible bin-to-bin correlations. Averaging over pT bins gives

$$\sigma_{eff}^{aver} = 15.1 \pm 1.9 \text{ mb}$$

- Good agreement with two previous Run I measurements by CDF ("4 jets", $\sigma_{eff} = 12.1^{+1.7}_{-2.3}$ mb and "γ+3jets", $\sigma_{eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb) and UA2 ($\sigma_{eff} > 8.3$ mb at 95% CL).

Summary

- Tevatron and D0 are performing well

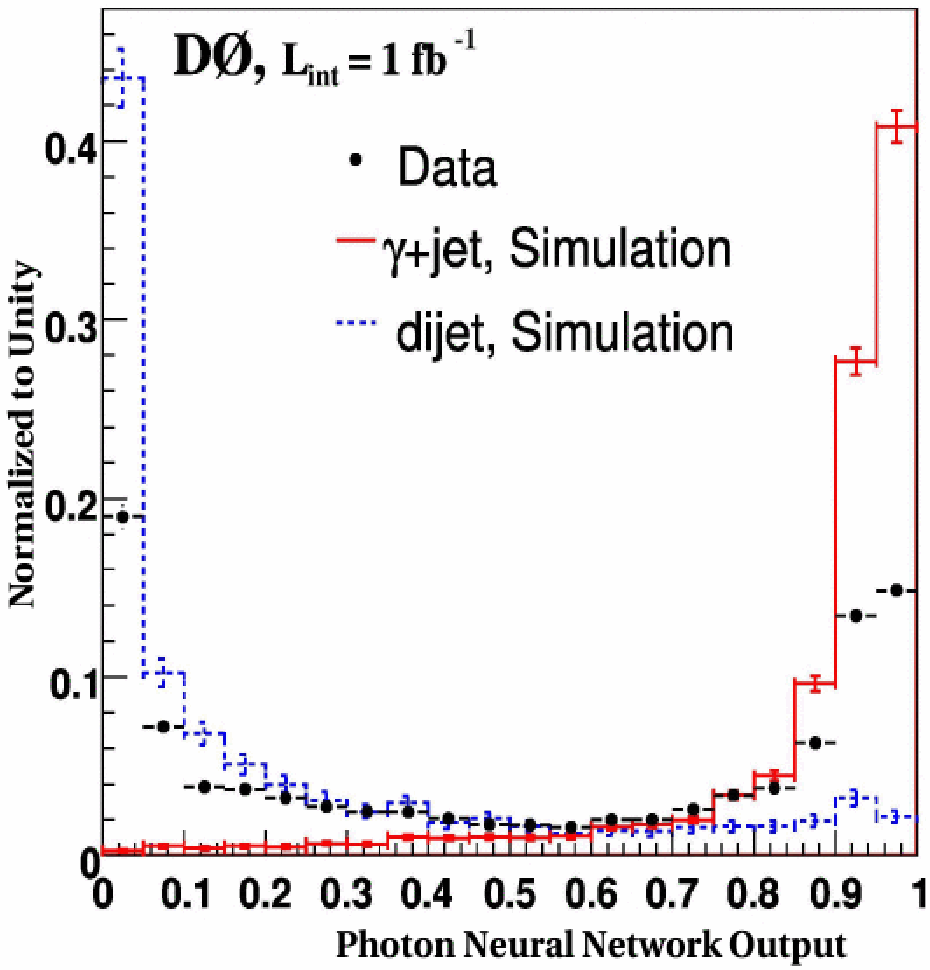
- Photon+HF jet production cross section $d^3\sigma / dp_T^\gamma d\eta^\gamma d\eta^{jet}$ Published
  - γ+b cross section is in agreement with theory
  - γ+c cross section does not agree with theory at p_T^γ > 70 GeV

- Double parton interactions in γ+3 jet events Preliminary
  - Measured DP fractions in three bins of $p_T^{2nd\ jet}$
  - Measured effective cross section in the same bins
  - Good agreement with previous measurements.

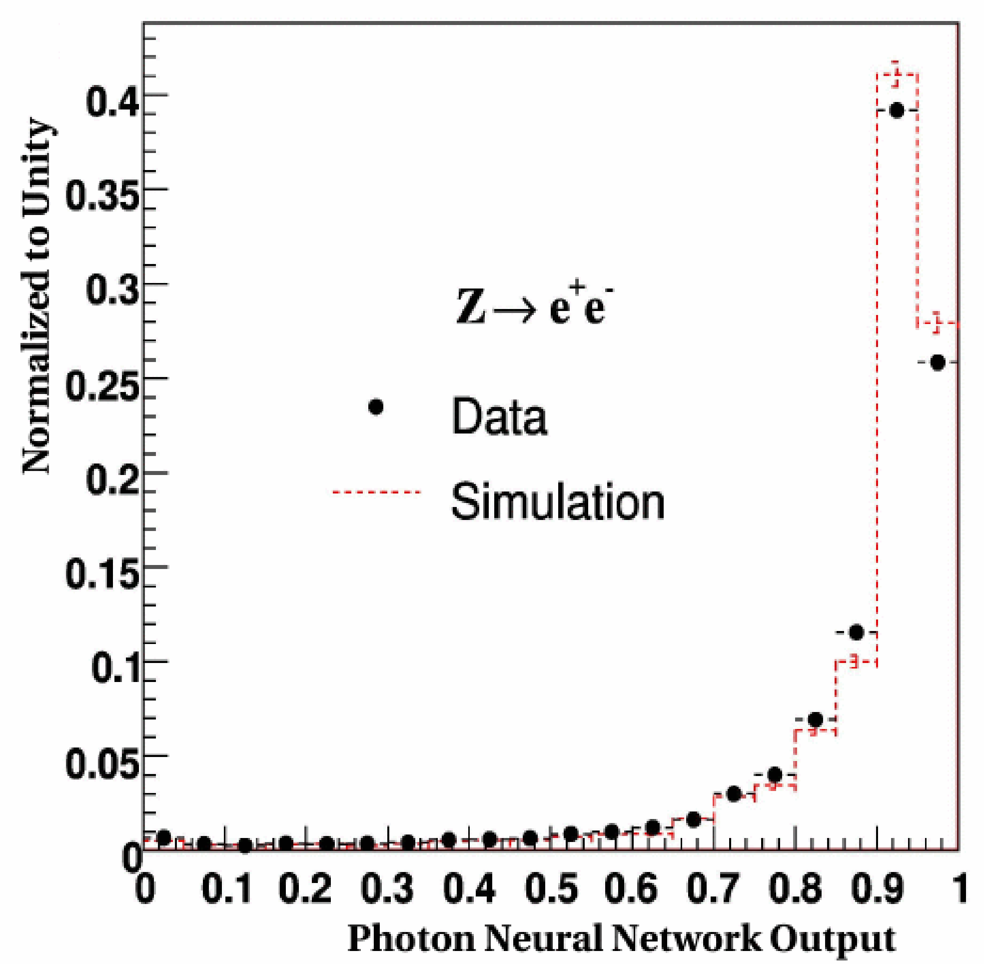
Photon ANN for photon+jets analyses

Photon Neural Network

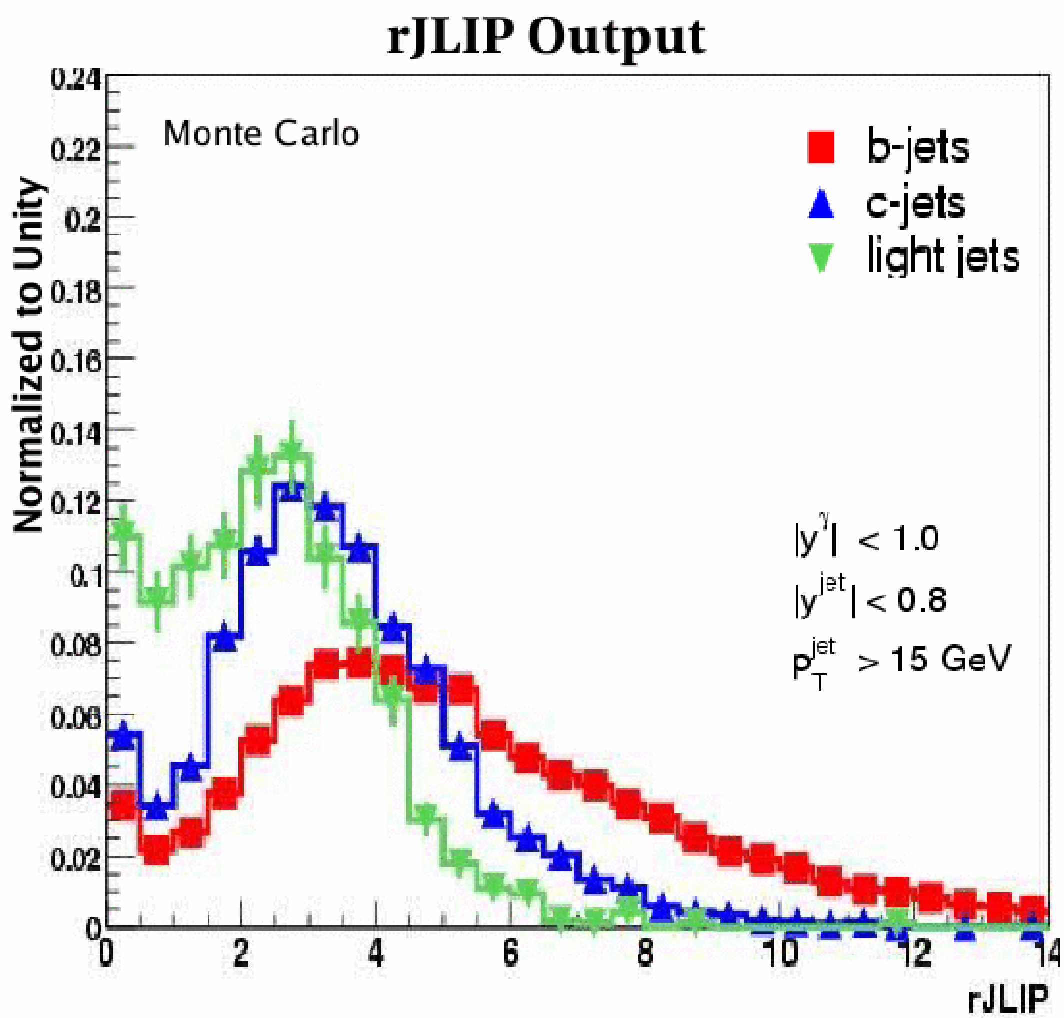
- Multiple input variables combine for one output
  - Output constrained to {0 – 1}
- Neural Net is trained with signal and background Monte Carlo
  - Direct photon output ⇒ 1
  - Background output ⇒ 0
- After photon pre-selection
  - The output shows that background events still contaminate the data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



Photon ANN: test on Z→ee MC and data



Jet Flavor Templates



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 Jet Lifetime Probability

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

Measurement of σ_{eff}

At two hard scattering events: $P_{DI} = 2\left(\frac{\sigma^{\gamma j}}{\sigma_{hard}}\right)\left(\frac{\sigma^{jj}}{\sigma_{hard}}\right)$

The number of DI events: $N_{DI} = 2\frac{\sigma^{\gamma j}}{\sigma_{hard}}\frac{\sigma^{jj}}{\sigma_{hard}}N_C(2)A_{DI}\epsilon_{DI}\epsilon_{2vtx}$

At one hard interaction: $P_{DP} = \left(\frac{\sigma^{\gamma j}}{\sigma_{hard}}\right)\left(\frac{\sigma^{jj}}{\sigma_{eff}}\right)$

Then the number of DP events: $N_{DP} = \frac{\sigma^{\gamma j}}{\sigma_{hard}}\frac{\sigma^{jj}}{\sigma_{eff}}N_C(1)A_{DP}\epsilon_{DP}\epsilon_{1vtx}$

Therefore one can extract:

$$\sigma_{eff} = \frac{N_{DI}}{N_{DP}}\frac{N_C(1)}{2N_C(2)}\frac{A_{DP}}{A_{DI}}\frac{\epsilon_{DP}}{\epsilon_{DI}}\frac{\epsilon_{1vtx}}{\epsilon_{2vtx}}\sigma_{hard}$$

1^{st} and 2^{nd} interactions: Estimates of possible correlations

... in the momentum space:

1st interaction: photon pT $\simeq$ 70 GeV, $\Rightarrow$ parton *xT* $\simeq$ *0.035*
2nd interaction: jet pT $\simeq$ 20 GeV, $\Rightarrow$ parton *xT* $\simeq$ *0.01*

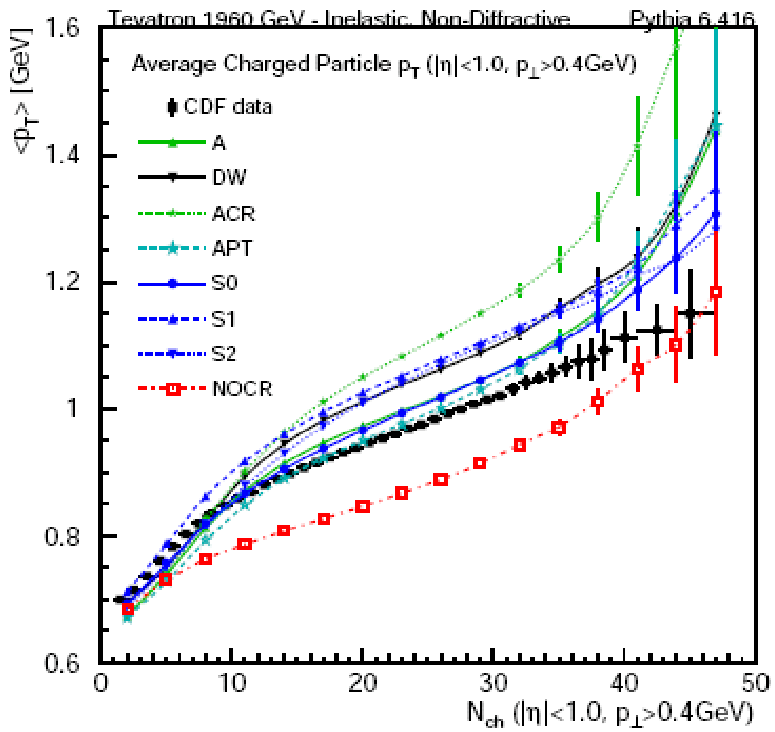
➲ large (almost unlimitted) kinematic space for the 2^{nd} interaction

... at the fragmentation stage :

=> Simulate γ+3 jets and di-jets with switched off ISR/FSR; then additional 2 jets in γ+3 jets should be from 2^{nd} parton interaction

=> compare 2^{nd} (3^{rd}) jets pT/Eta in γ+3 jets with 1^{st} (2^{nd})jet pT/Eta in dijets

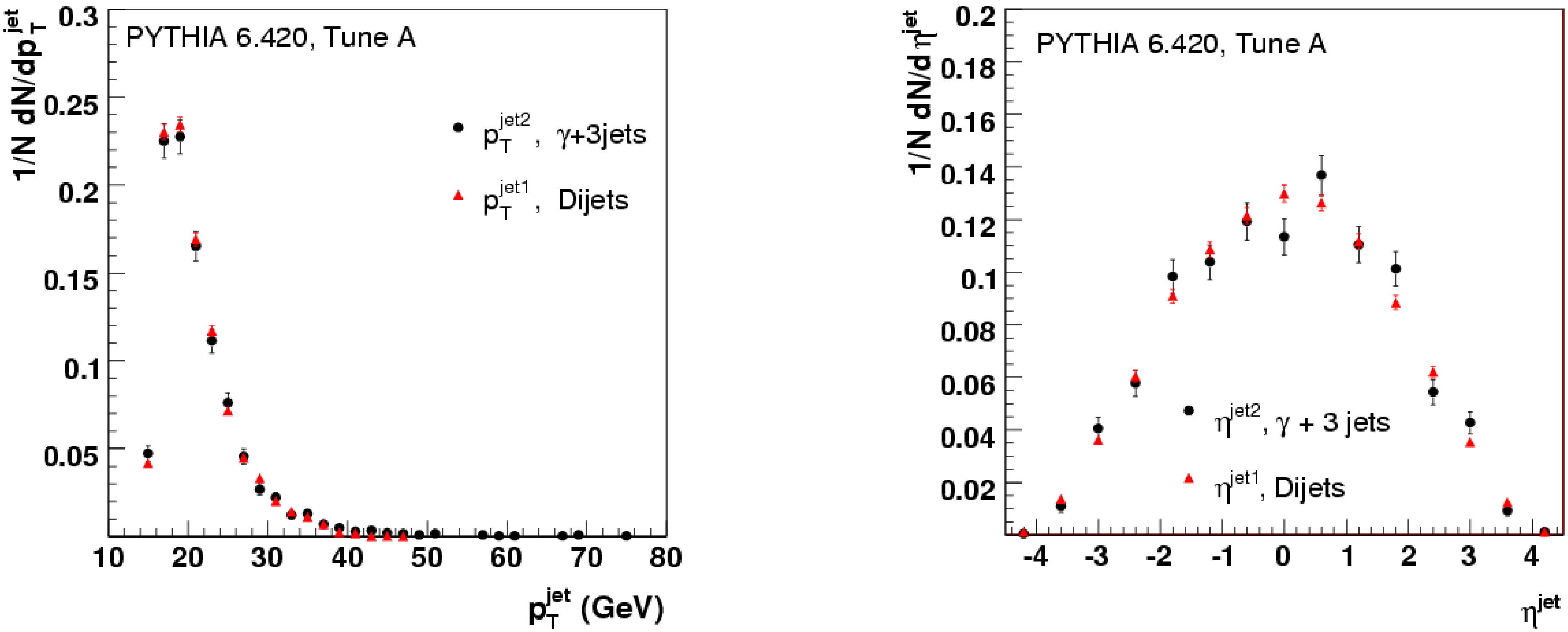
=>Tunes tested: A, A-CR, S0



From D.Wicke & P.Skands hep-ph:0807.3248

γ+3 jets and di-jets, IFSR=OFF: jets pT comparison

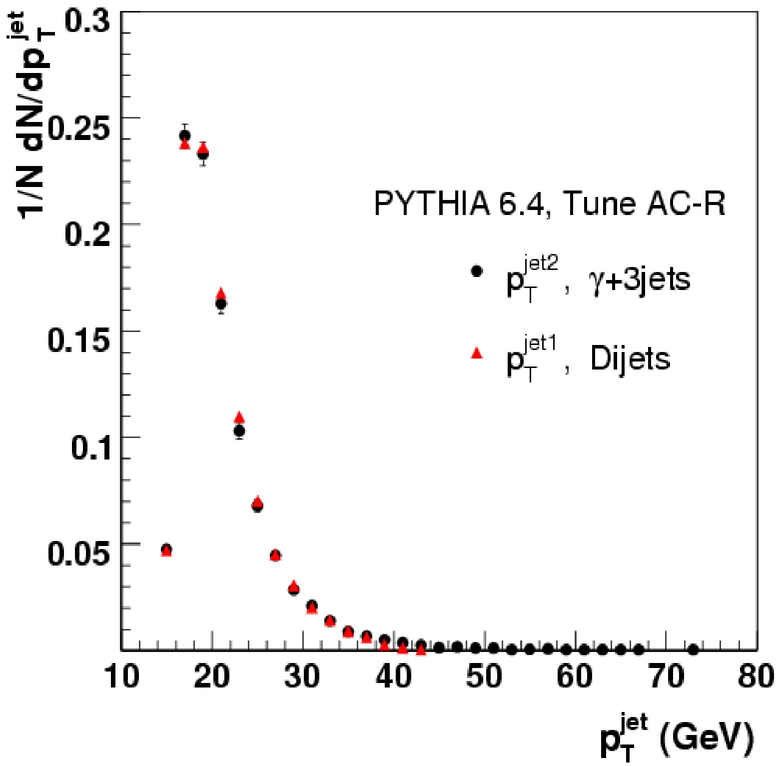
Tune A

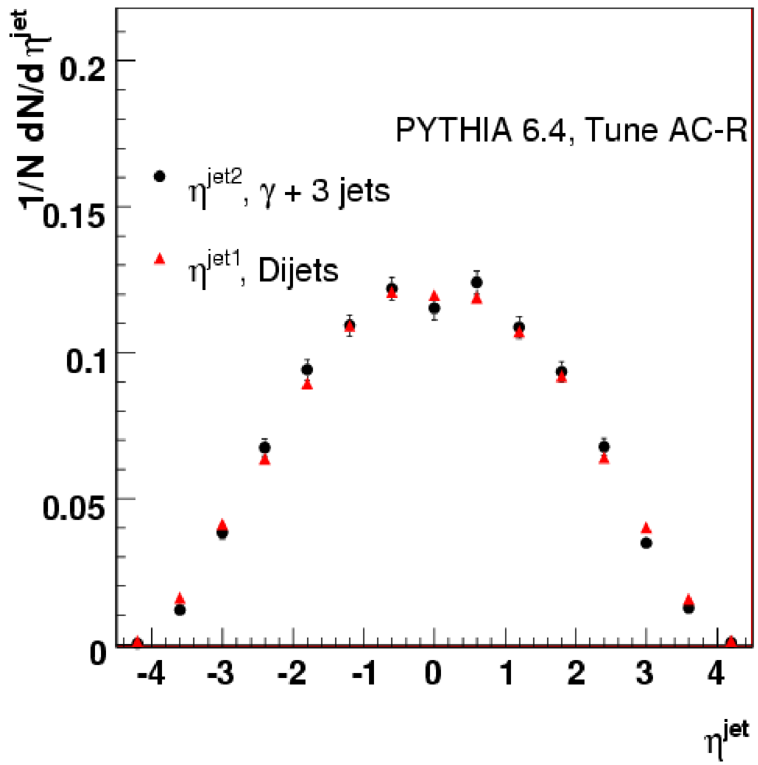


- pT and η distributions are analogous for jets from 2nd interaction in γ+3jets and dijet events.

γ+3 jets and di-jets, IFSR=OFF: jets pT comparison

Tune A-CR





- Analogous results (incl. 3rd jet from γ+3jets and 2nd from di-jets) are for Tunes A-CR, S0.