Measurement of the Direct Photon with Associated Jet Production Differential Cross Section in ppbar Collisions

at $\sqrt{s} = 1.96$ TeV

$$\frac{d^3\sigma}{dp_T^{\gamma}\, d\eta^{\gamma}\, d\eta^{jet}}$$

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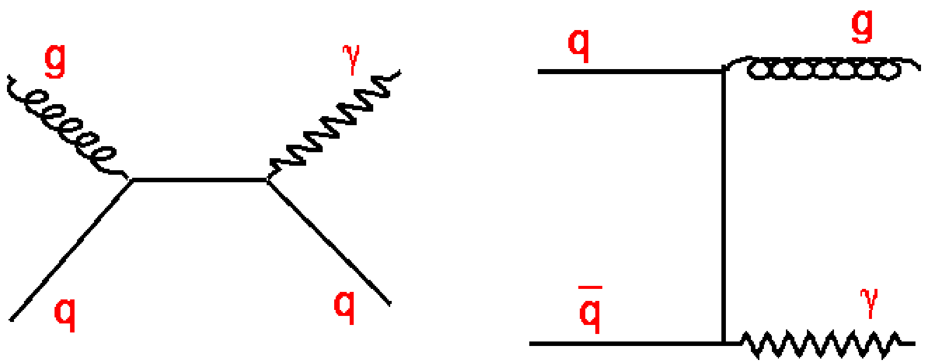
The paper draft would not be possible without help of Duncan Brown

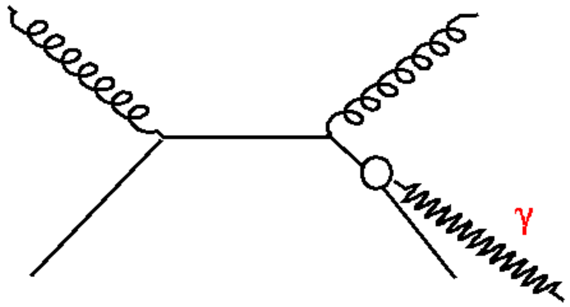
Many thanks !!!

Introduction

• Just two main subprocesses participate , contribution from the fragmentation diagrams can be substantially suppresed.



direct



fragmentation

Main mechanism: just two kinds of processes!

(can be suppressed up to ≤ 8-10% at pT=30 GeV and even less at higher pT).

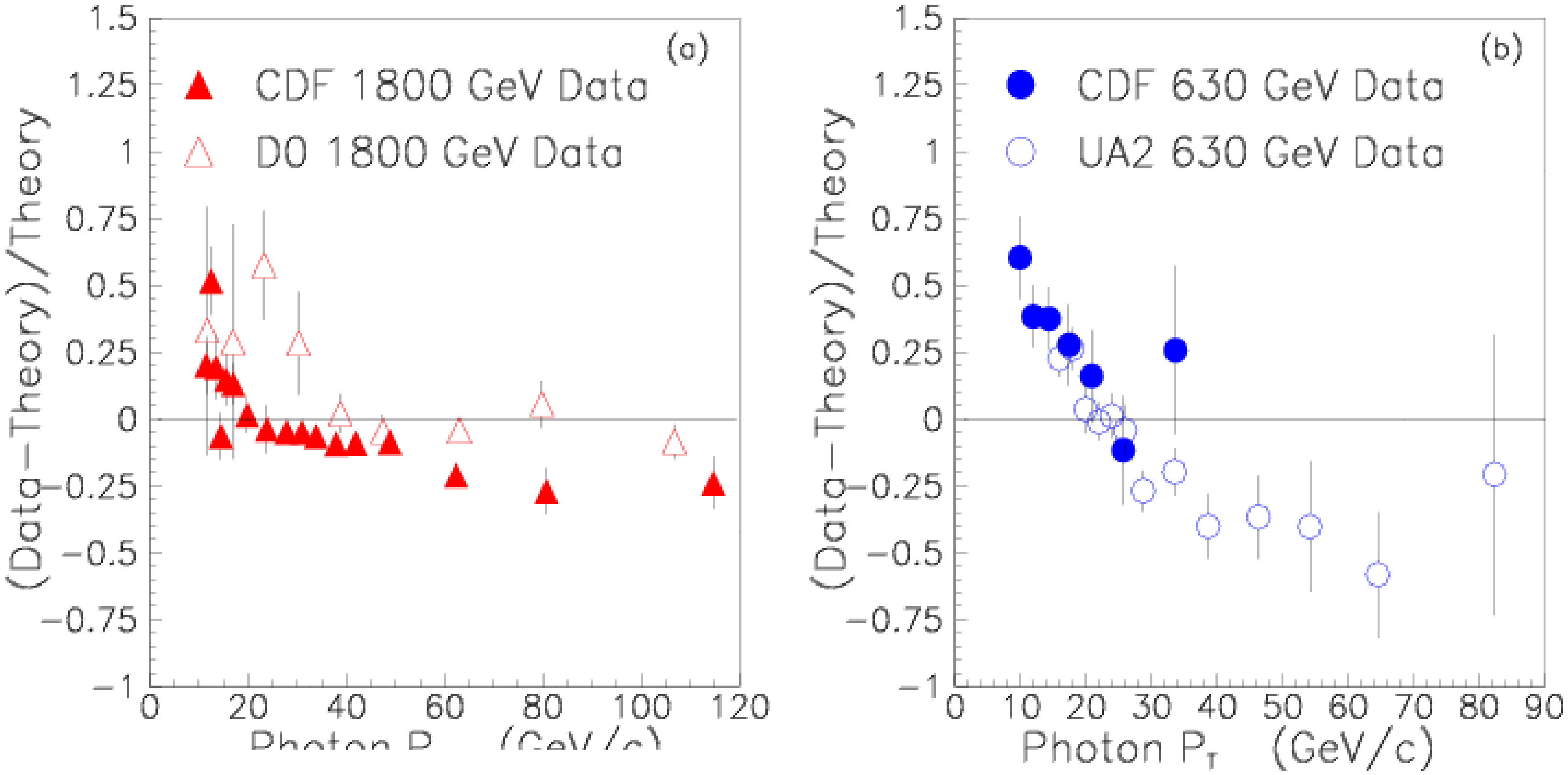
==> gluon PDF involved already in LO (in contrast to DIS or DY processes)

It can be tested by direct measurement of cross section in different X and Q2 bins

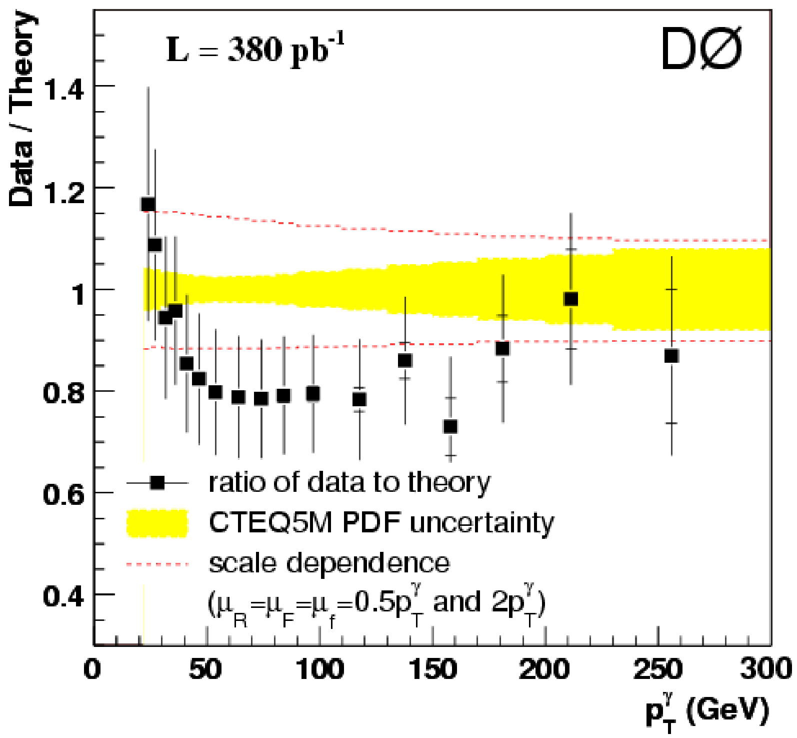
Other reasons:

- photons come unaltered from the hard interaction and have better energy resolution than jets. Their pT can serve as natural scale in the measurement.
- A large statistics as compared with e.g. Z/W+jet production.
- Direct photons are one of substantial backgrounds to many SM/BSM physical processes.
- *And finally:* It is a natural extention of inclusive photon measurement.

Some last inclusive photon collider data vs. theory



Code: W.Vogelsang &Co. (1994), PDF: CTEQ5M



Code: JetPhoX (2002) and W.Vogelsang (2002)
PDF: CTEQ5M

Common tendency in the three experiments [UA2 for pp at 630 GeV (1992), latest CDF at 1800 GeV (2002) and Run II D0 (2006)] is seen: theory overestimates photon XS (for central rapidities) at medium and large pT.

What physics we can do with photon+jet events

In the kinematic region where one can neglect ISR effects (and fragm. contribution) one can express the triple differential photon+jet XS vs. a simple sum of products of PDFs and partonic XS:

$$\frac{d\sigma}{d\eta_1 d\eta_2 dP_t^2} = \sum_{a,b} x_a f_a(x_a, Q^2) x_b f_b(x_b, Q^2) \frac{d\sigma}{d\hat{t}}(ab \to cd),$$

where

$$x_{a,b} = P_t/\sqrt{s} \cdot (exp(\pm\eta_1) + exp(\pm\eta_2)).$$

Here $\eta_1(\eta_2) = \eta$_jet(photon), Pt = photon Pt.

==> No integration over all parton *x* as for fully inclusive cross sections.

==> Knowledge of q, qbar distributions allows gluon distribution to be determined in each (x,Q2) bin (D0 Note 3948(2002), hep-ex/0304010, Eur.Phys.J.C37,185(2004)).

This method was used in ISR-AFS, UA2 and UA6 experiments where gluon PDF has been extracted *directly* from photon+jet data.

Selection criteria

Data Sample

- "1 EM loose" skim and runs **166503-215670** (the whole Run IIa)
- reco: PASS3_p17.09.03, PASS3_p17.09.06, PASS3_p17.09.06b
- Good or Reasonable for CALO and SMT, CFT subdetectors.
- just events with good luminosity blocks
- OR'ed trigger combinations for v8-14 (***eff-cies start at 96-99% at pT=30 GeV***)
- Total accumulated luminosity in good blocks without duplicates is 1.01 fb^{-1}

We select events with

- at least one PV within **|Z|<50 cm** and **>= 3 associated tracks**
- at least one photon candidate (see below) and at least one hadron jet
- limited missing ET: **missET < 12.5 + 0.36*photonPT**

Photon candidates :

- **in eta-phi fiducial regions**
- in the two CC regions **[-1,0] or [0,1] and pT > 30 GeV**
- **Iso < 0.07**
- **Emfrac > 0.96**
- **Spatial track match probability < 0.001**
- **SigRphi < 14 cm^2**

- Photon vertex pointing cut:

  if (#cps > 0) |FitZVtx -Zvtx| < 10 cm (90% of events)

  if (#cps == 0) |FitZVtx -Zvtx| < 32 cm (10% of events)

All the criteria are certified photon ID criteria for p17 analysis (D0 Note 4976)

- **NN output > 0.7** (Based on the same input parameters as for the inclusive photon analysis.

D0 Note 5245 with ANN description was issued in the end of September. More info and examples:
http://www-d0.fnal.gov/~bandurin/ANN_Note/ann.pdf

Jet selections:

- Lead. jet is required to be inside **[-0.8,0] or [0,0.8] or [-2.5,-1.5] or [1.5, 2.5]**
- Just good jets are selected with **JCCA** algorithm
- leading jet **pT > 15 GeV**

Photonic jet and hadron jet should be separated (~100% eff. for signals)

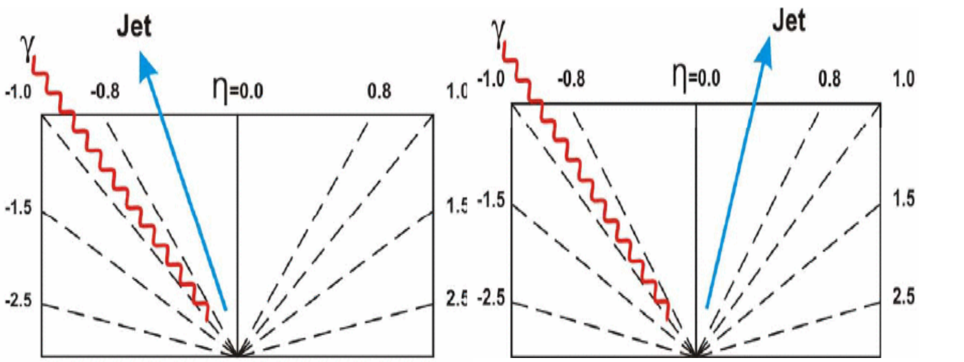
- **dR(γ, jet) > 0.7**

What me measure

- Cross section is directly proportional to PDFs in a given (x,Q^2) interval with $Q^2 = (p_T^\gamma)^2$
- $30 < p_T^\gamma < 400$ (200) GeV, four photon and jet rapidity regions:

- Quantization of parton $x_{1,2}$ space: example for $p_T^\gamma \approx 35$ GeV with LO: $x_{1,2} = p_T^\gamma/\mathrm{sqrt}(s)\,[\exp(\pm y^{jet}) + \exp(\pm y^\gamma)]$

Region	x_1	↔	x_2
1	0.02 -- 0.04		0.05 – 0.10
2	0.03 -- 0.07		0.03 -- 0.07
3	0.01 – 0.03		0.14 -- 0.37
4	0.10 -- 0.26		0.02 -- 0.06

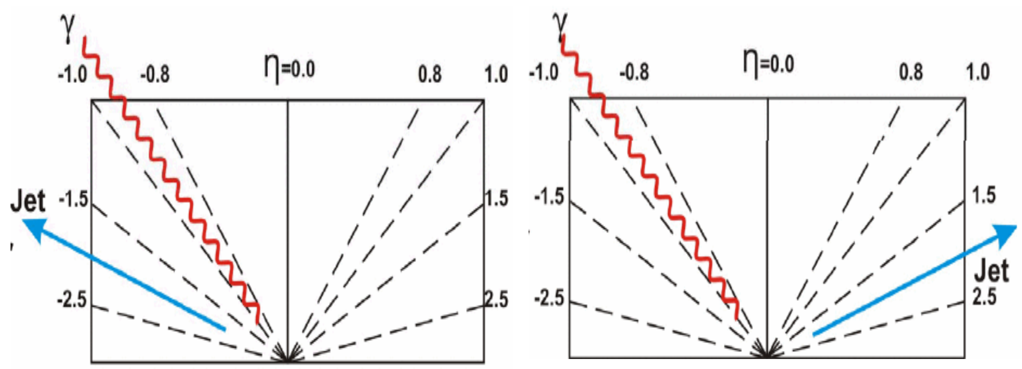


1:$|y^{jet}|<0.8$, $y^{jet}\bullet y^\gamma>0$ 2:$|y^{jet}|<0.8$, $y^{jet}\bullet y^\gamma<0$

- Total covered x-Q^2 range :

$$0.007 \leq x \leq 0.7$$

$$900 \leq Q^2 \leq (0.4 - 1.6)\mathrm{x}10^5 \ \mathrm{GeV}^2$$



3:$1.5<|y^{jet}|<2.5, y^{jet}\bullet y^\gamma>0$ 4:$1.5<|y^{jet}|<2.5, y^{jet}\bullet y^\gamma<0$

- Significantly extends analogous measurements done by ISR-AFS, UA2, UA6 and CDF Collaborations .

More examples of parton x intervals we are covering

Region 1: γ & jet ∈ CC,

same y signs

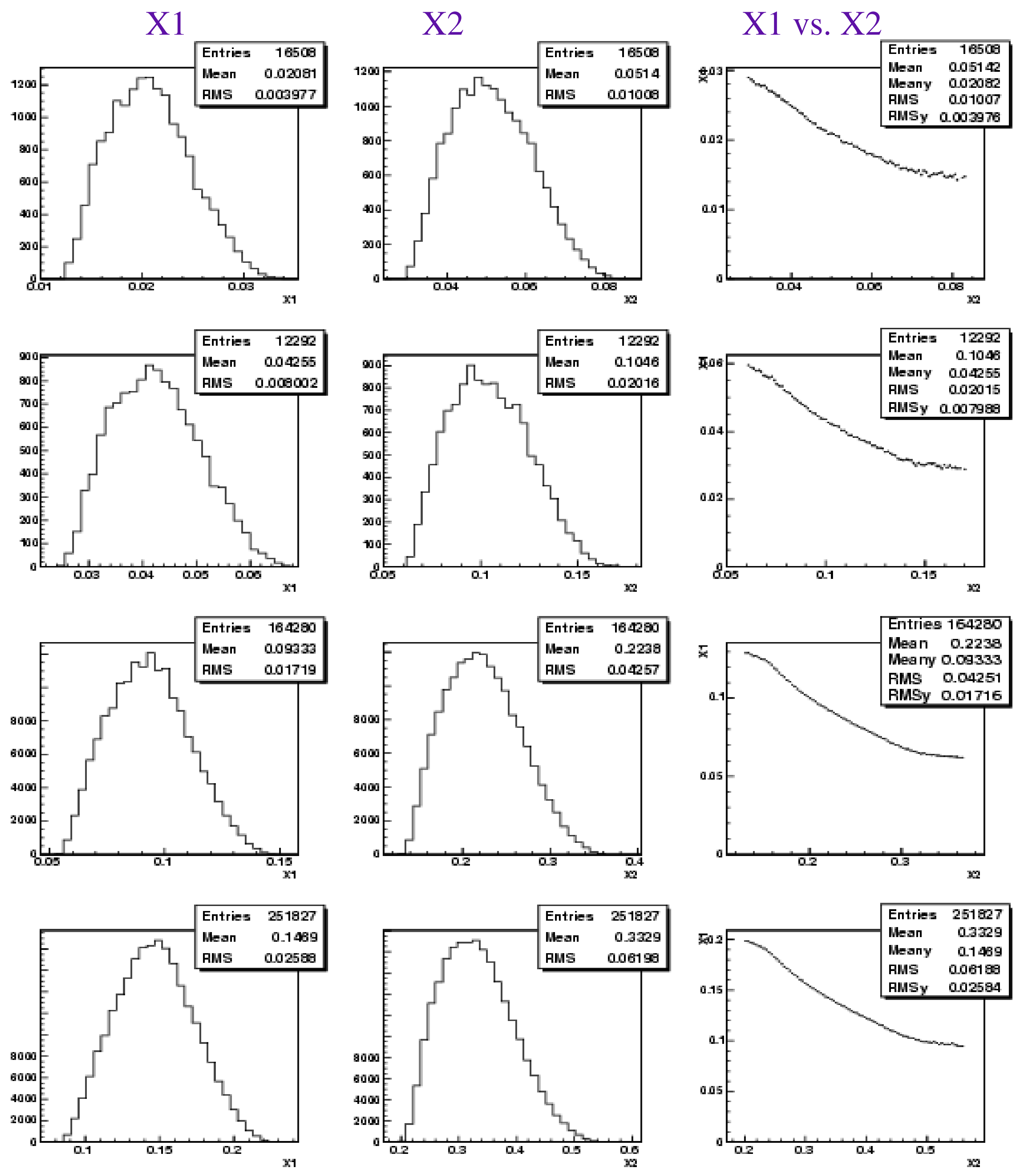
pT	X1	X2
30	0.012 -- 0.030	0.030 -- 0.074
60	0.025 -- 0.060	0.060 -- 0.148
120	0.049 -- 0.120	0.120 -- 0.297
240	0.098 -- 0.240	0.240 -- 0.593

Region 3: γ ∈ CC, jet ∈ EC,

same y signs

pT	X1	X2
30	0.007 -- 0.018	0.082 -- 0.224
60	0.013 -- 0.037	0.164 -- 0.447
120	0.027 -- 0.073	0.329 -- 0.894
240	0.054 -- 0.147	0.658 -- 1.000

⇒



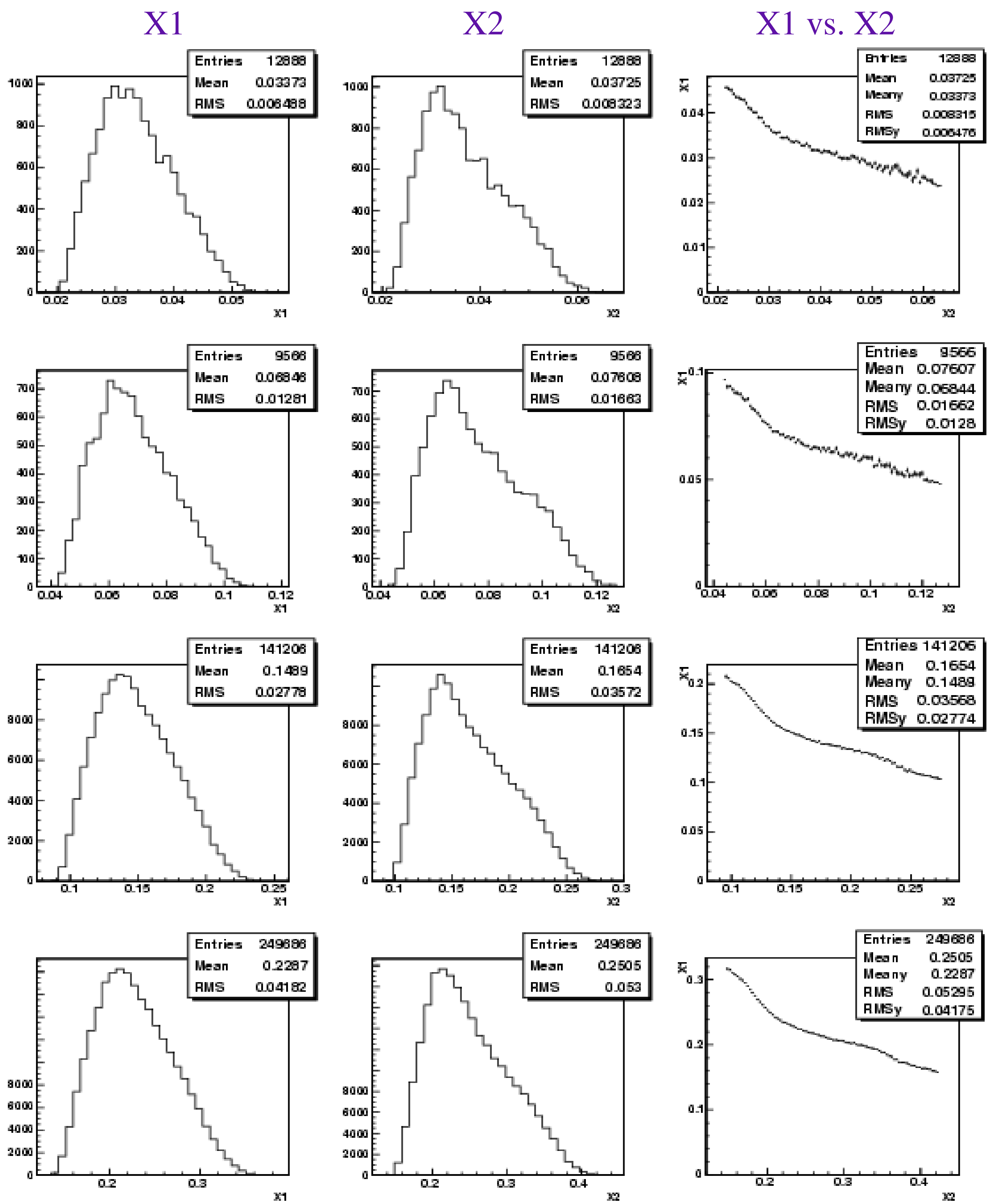
Region 2: γ & jet $\in$ CC, diff. y signs

X1 ~= X2

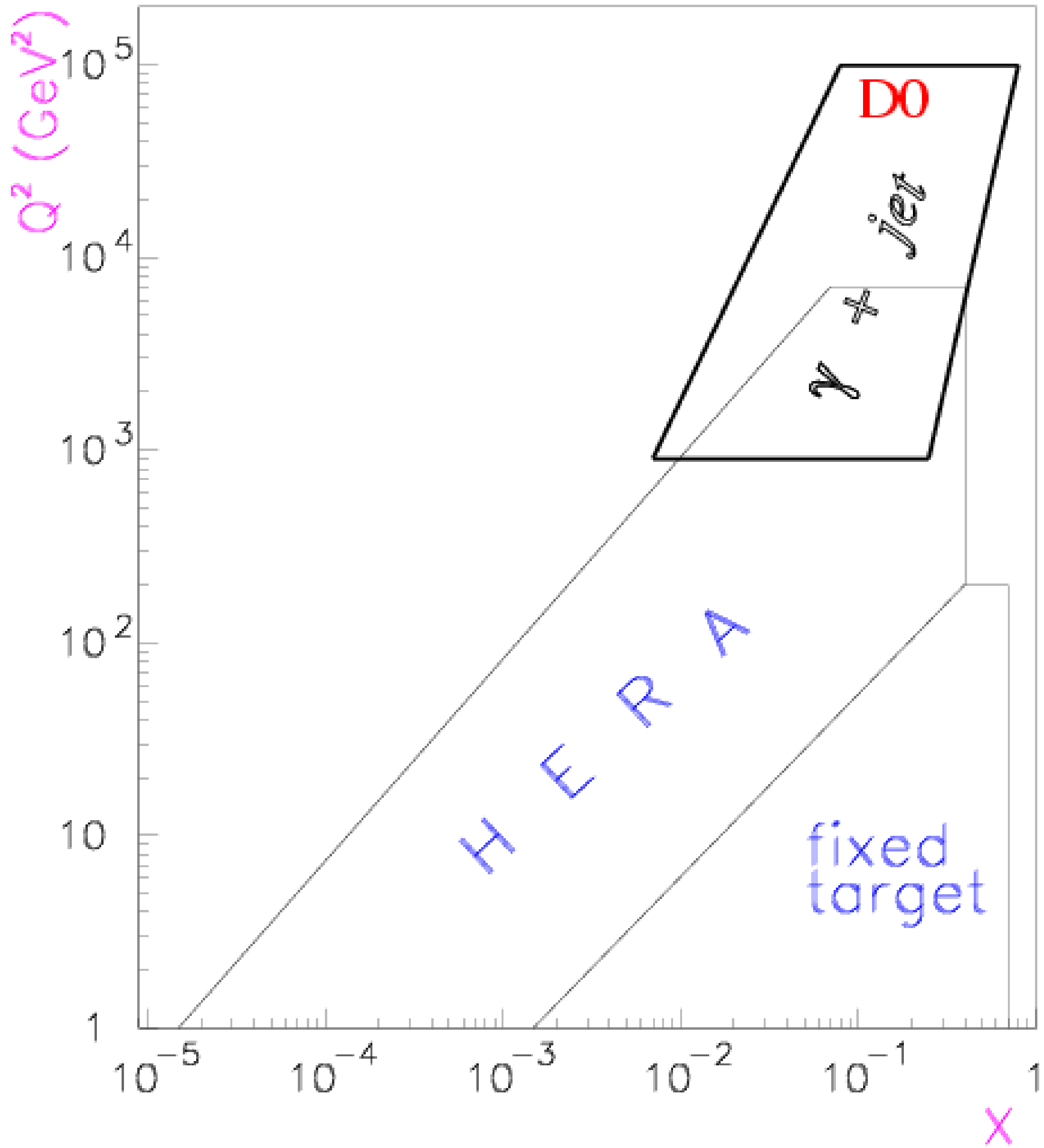
I.e. in the theoretical cross section we will have product of two PDFs with same Q^2 and about same parton ***x*.**

Also note:

In Regions 1 and 2 for pT>200 GeV parton *x1 and x2 are always > 0.1 i.e. where gluon PDF has huge uncertainties.*

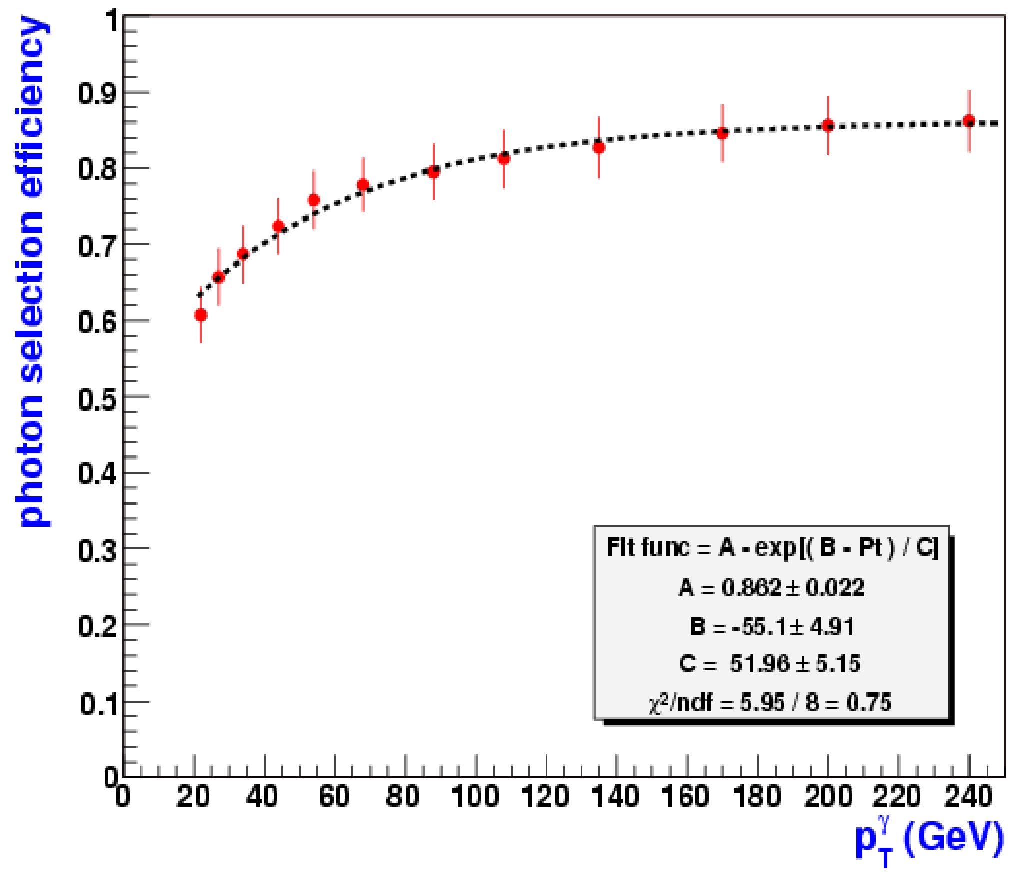


x-Q^2 region covered by γ+jet data



==> Test of DGLAP evolution equation over 2 orders of magnitude in Q^2 using one measurement.

Photon and jet selection efficency

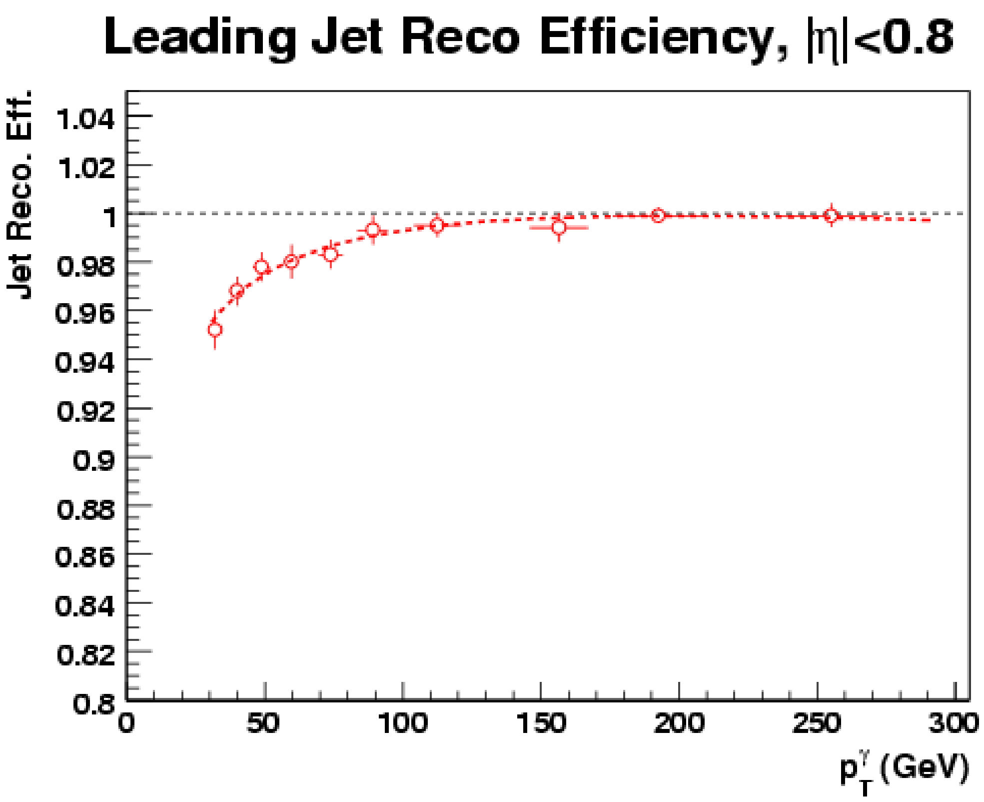


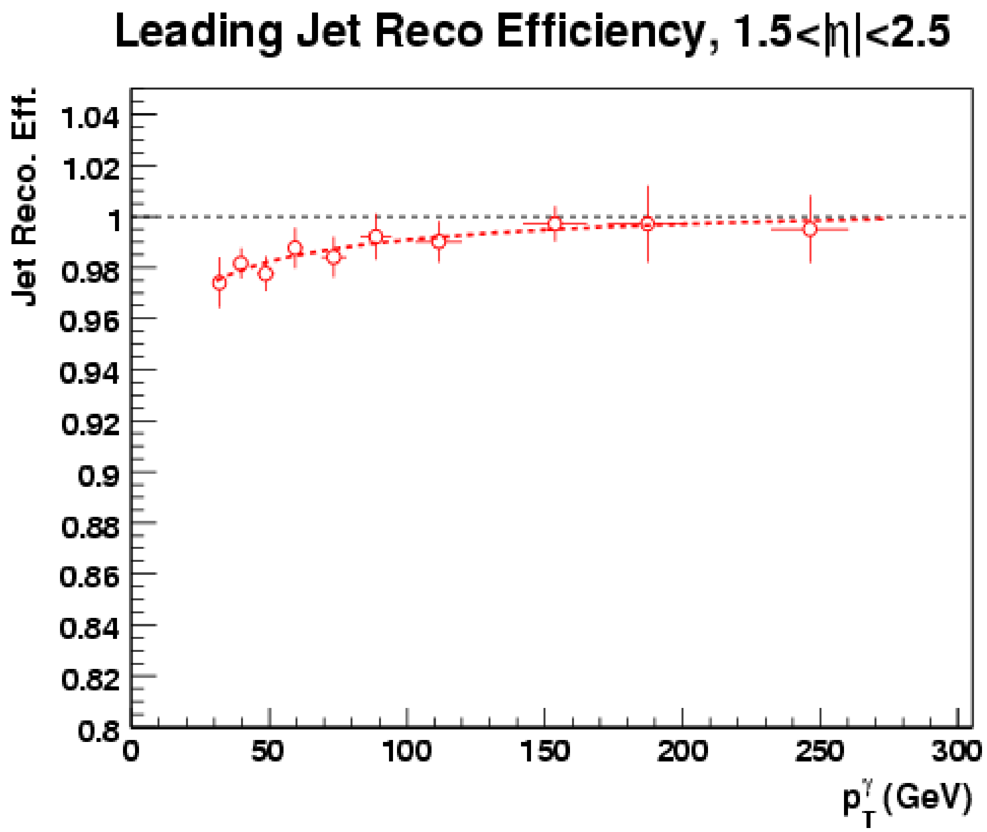
Main sources of photon inefficiency: isolation, track matching, ANN, vertex pointing cuts

Systematic uncertainties are 4.7-5.2% :

Mainly due to uncertainty in anti-track match eff. (4%), ANN cut of (2.2%),

MC/data correction [0.95-1.0] from Z→ee events (2%).





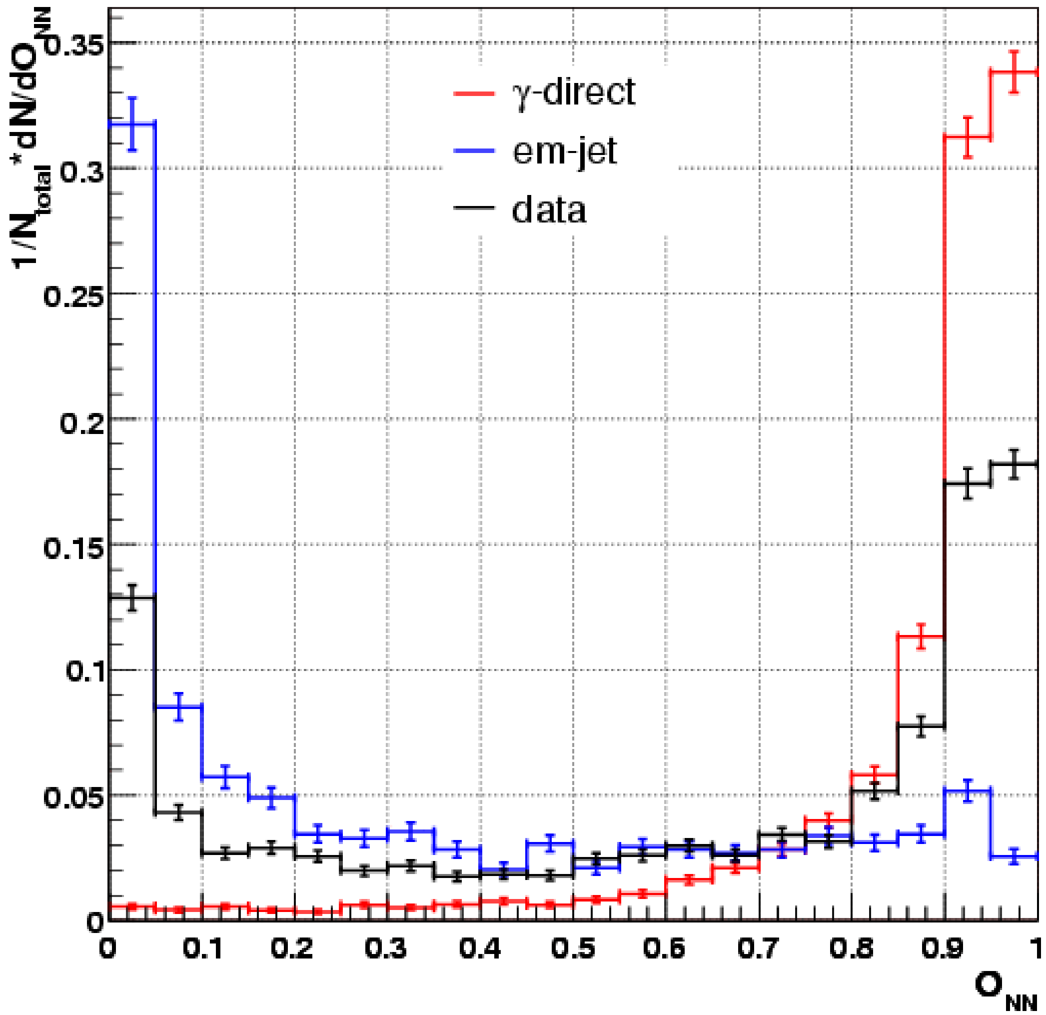
Jet reco efficency: 95-100% with 5.7 – 2% inefficiency (JES, pT resolution).

"Jet migration" effect (particle → reco) is taking into account using MC (Pythia).

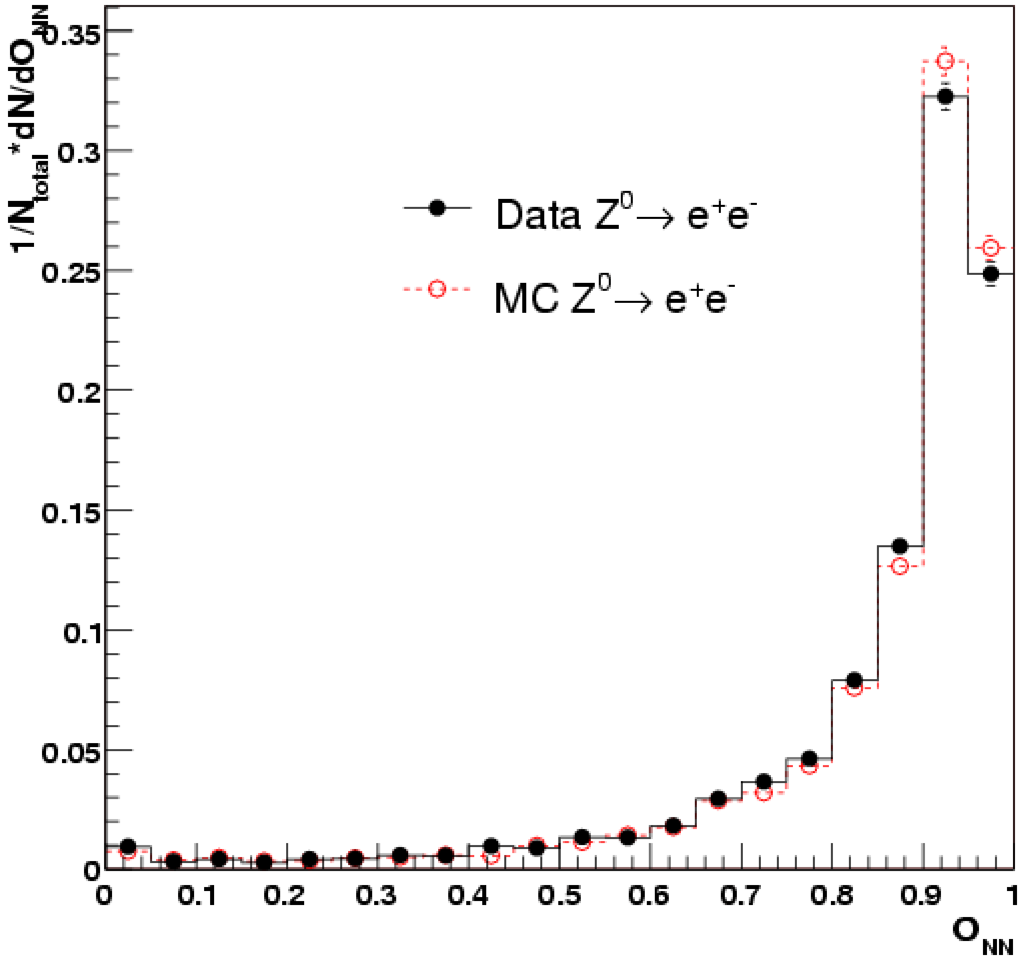
Photon ANN

- *Input: # EM1 cells (pT_cell > 0.4 GeV), EM1 fraction, HC_PT04 (pT_track>0.4 GeV)*
- *Trained on the signal and QCD background MC events*
- *Tested on Zee MC/data*

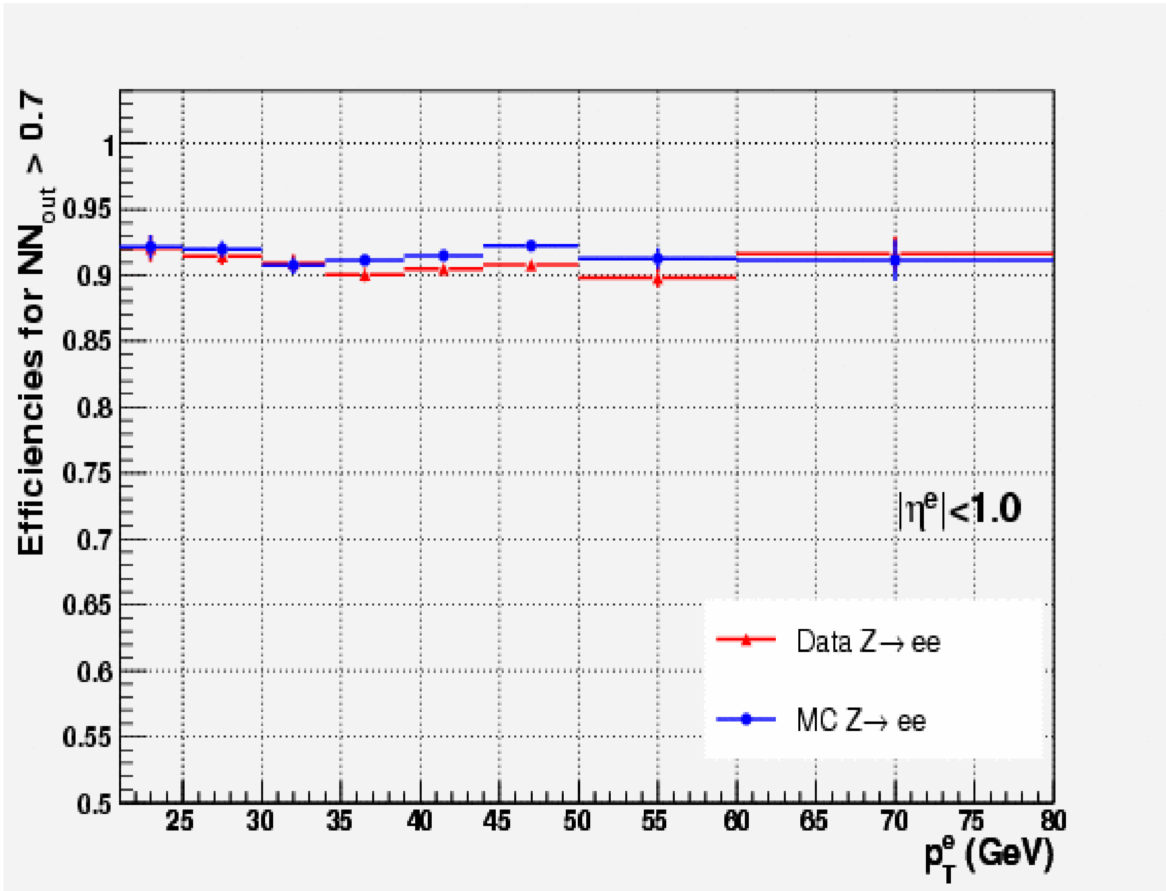
... is a part of current photon ID, being extended to 4 and 5 input variables.



Zee events: ANN output



Zee events: pT dependence of cut "NNout > 0.7"



(from D0 note 5245 on photon ANN)

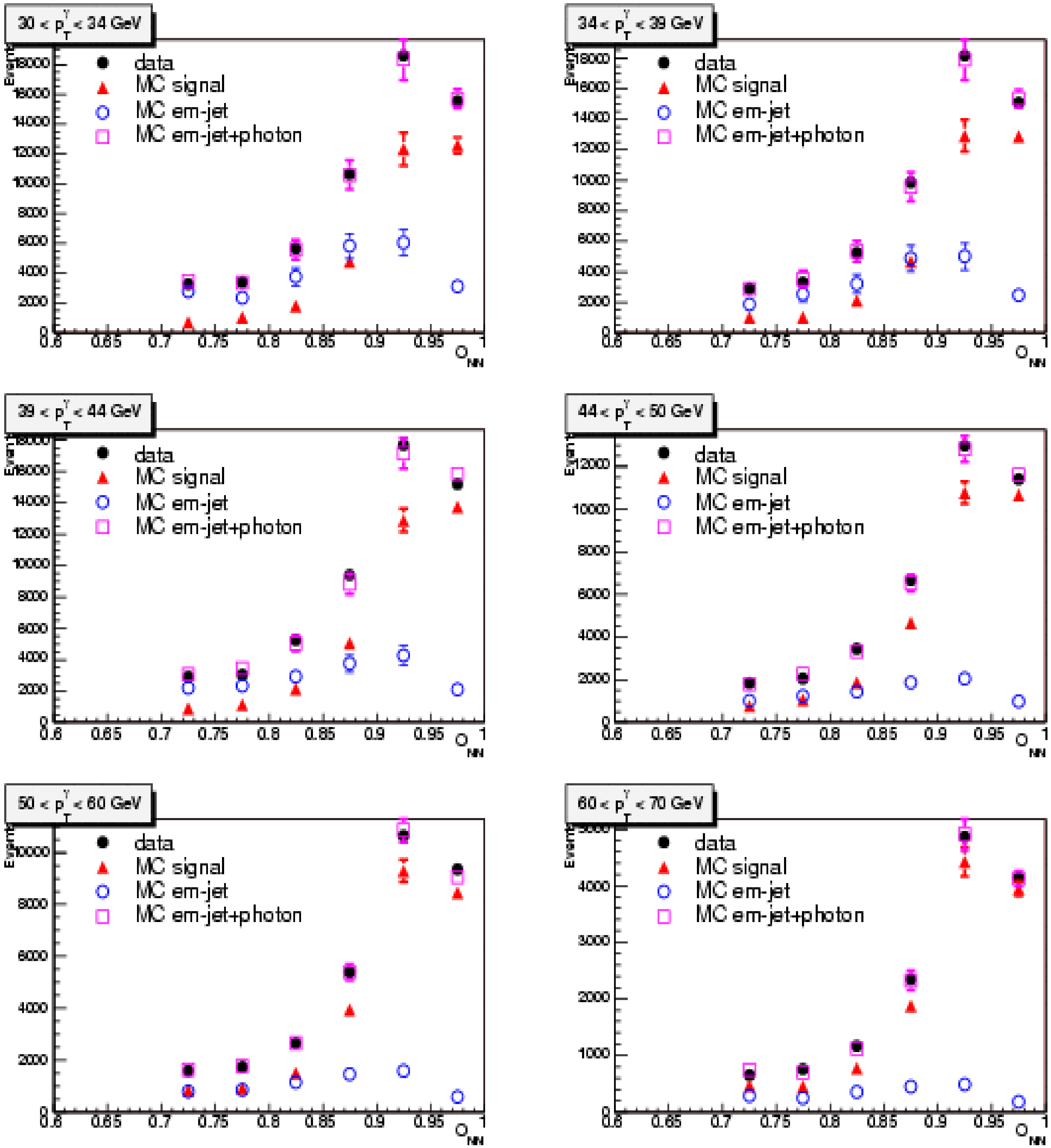
Photon+jet: fit ANN output in MC S & B events to data

Purity is defined from fitting of events with NNO>0.7

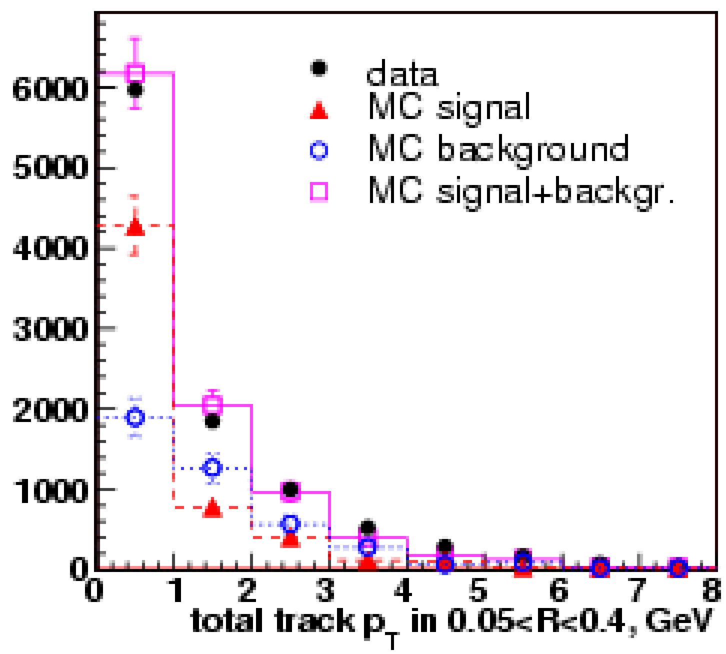
Fit is done with very good quality: always $\chi^2/ndf < 1$

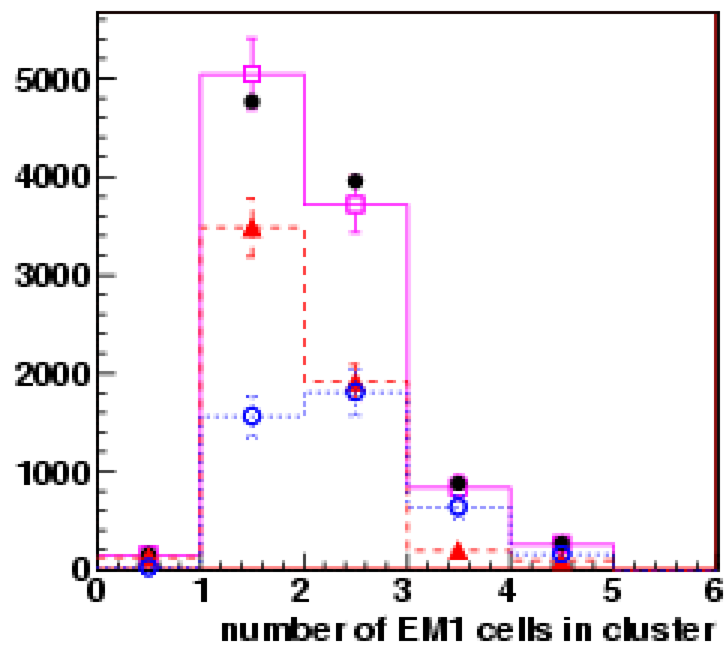
(See all other pT bins in the Analysis Note)

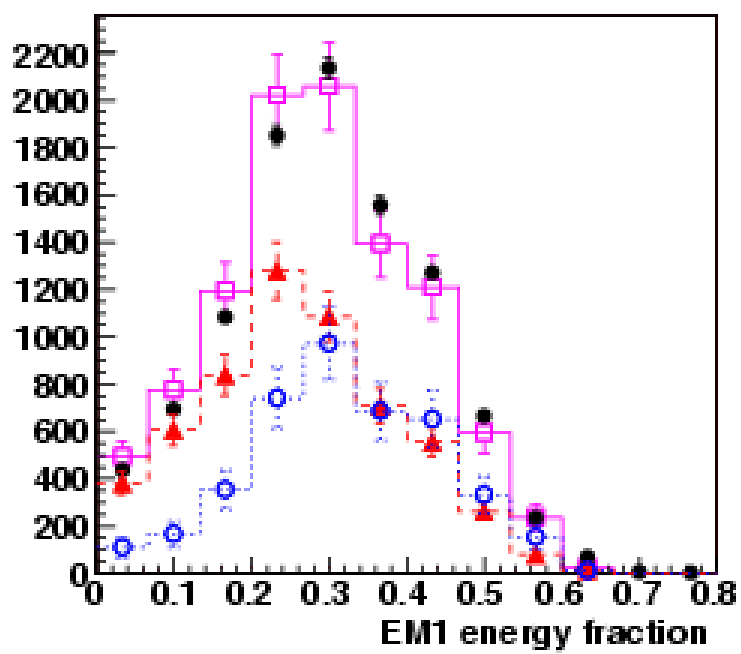
A comparison with the eff-cy method is also done (AN)



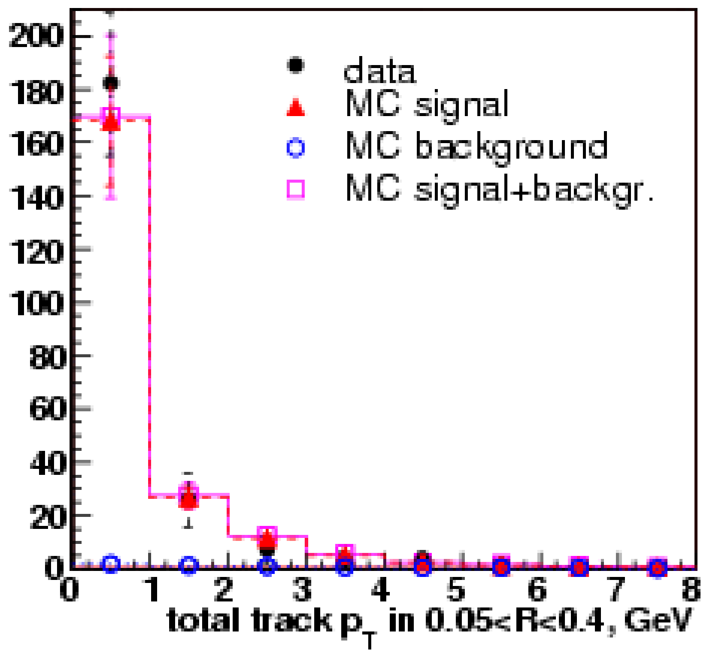
Test of ANN variables

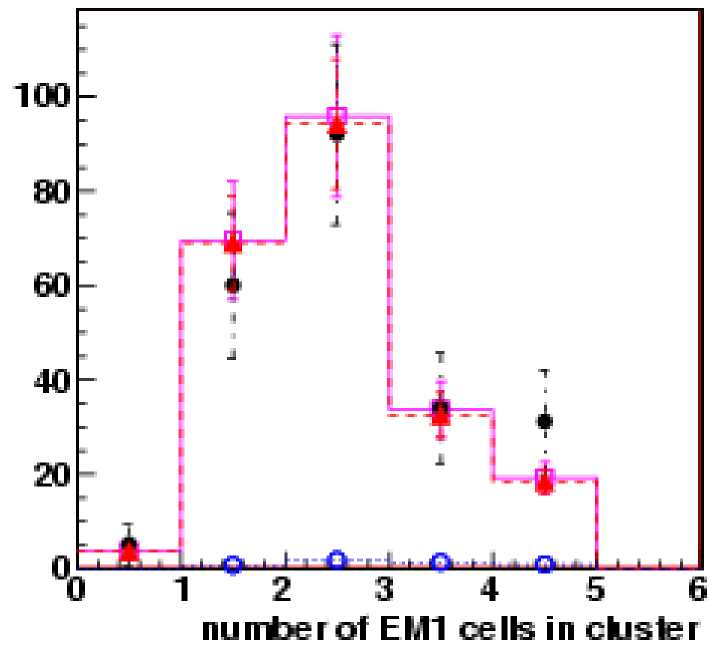


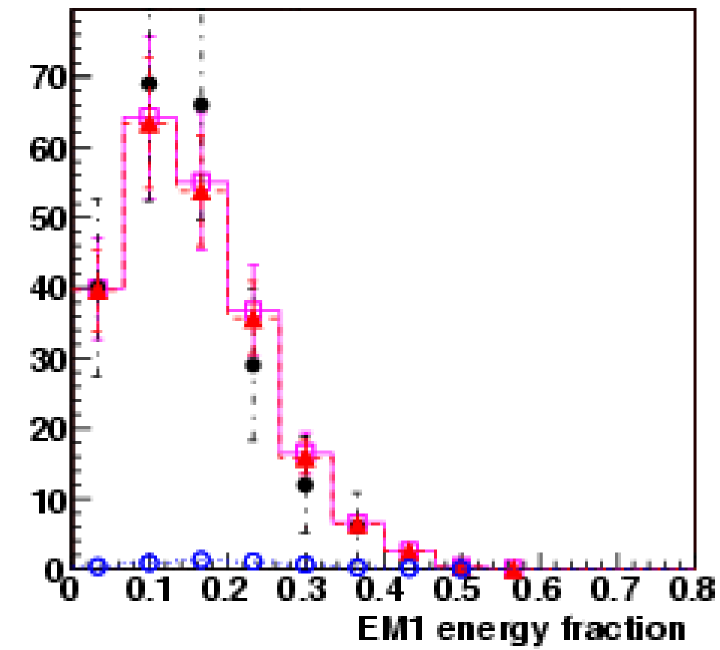




30 < pT < 34 GeV



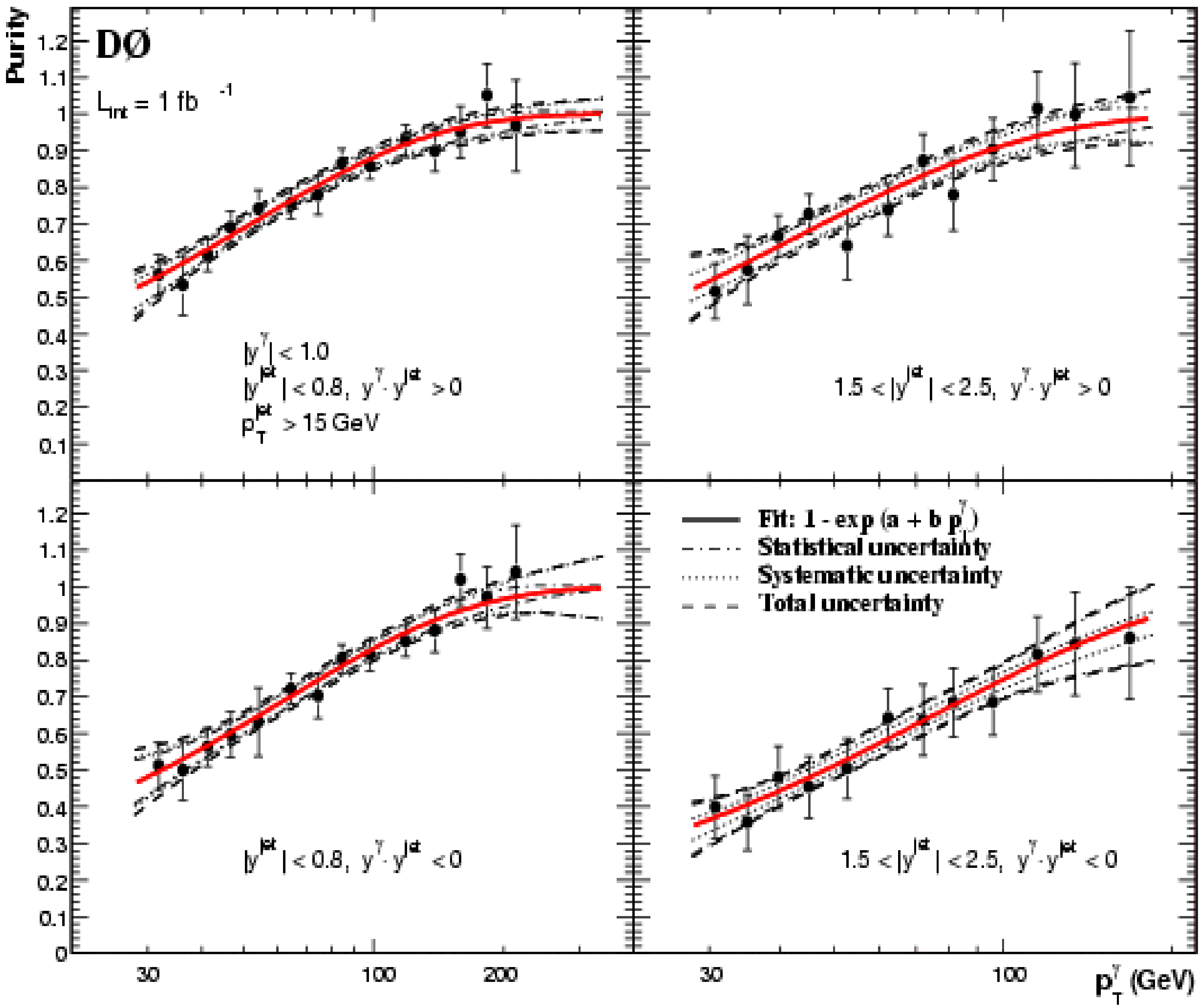




200 < pT < 230 GeV

See all pT bins in the Analysis Note.

Photon+jet purities



Systematics: Pythia fragmentation model (5% at pT=30 GeV, <2% for pT>50 GeV), #bins variation in the fraction fitting and photon pT(3-4%), of the fit vs. photon pT (5-10% all together).

Estimation of W+jet background

- Was estimated separately from generation with pT_min = 40, 80 and 160 GeV of ***q qbar*** $\rightarrow$ ***g W*** (u,t channels) and ***qg*** $\rightarrow$ ***q W*** (s,u channels) in Pythia and reconstruction.

Table 5: Cross section ratios and efficiencies to pass anti-track match and E_T^{miss} cuts for $W(\rightarrow e\nu) + jet$ events.

Cut / $\hat{p}_\perp^{min}$	40 GeV	80 GeV	160 GeV
$\sigma_{wj}/\sigma_{\gamma j}$	0.056	0.136	0.168
anti-track	0.15 ± 0.01	0.13 ± 0.01	0.12 ± 0.01
Miss E_T cut	0.36 ± 0.03	0.35 ± 0.03	0.30 ± 0.04

Table 4: $S(\gamma j)/B(W_{e\nu} j)$ ratios.

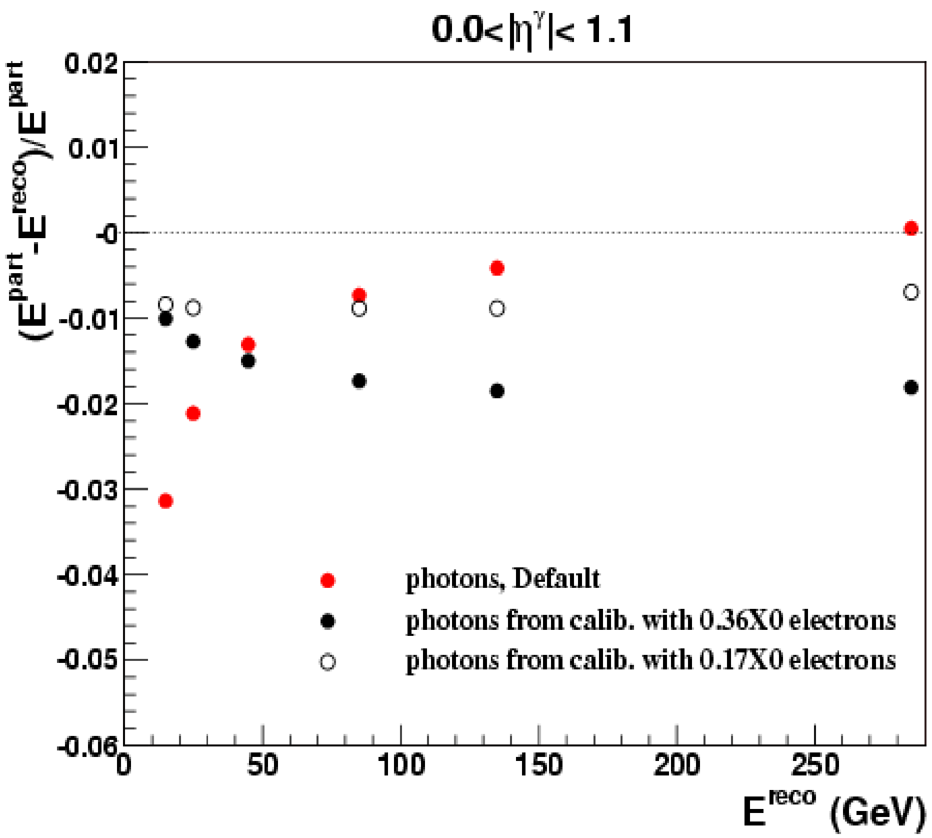
$\hat{p}_\perp^{min}$ (GeV)	40–60	60–80	80–120	120–170	170–230	230–300
$S(\gamma j)/B(W_{e\nu} j)$	1997 ± 426	1476 ± 246	525 ± 85	563 ± 87	442 ± 82	477 ± 87

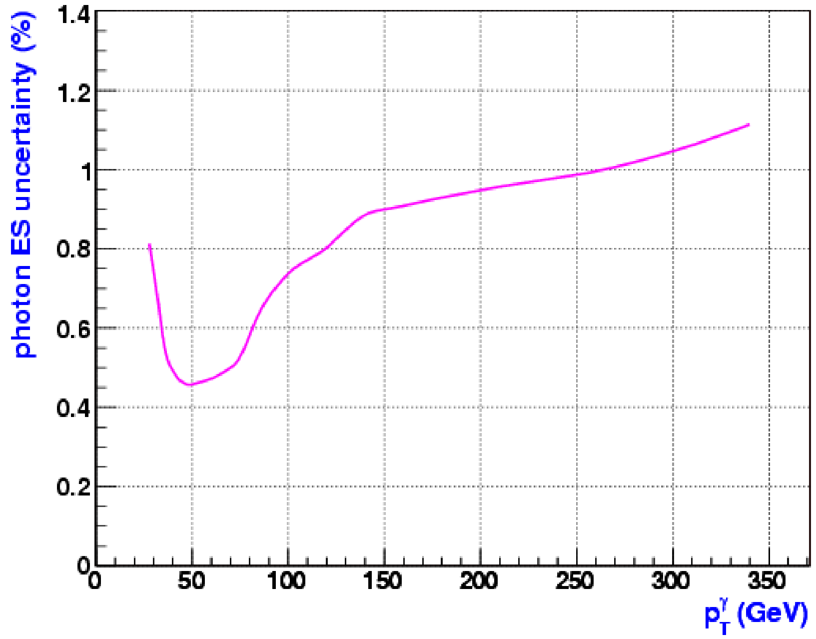
Errors are statistical.

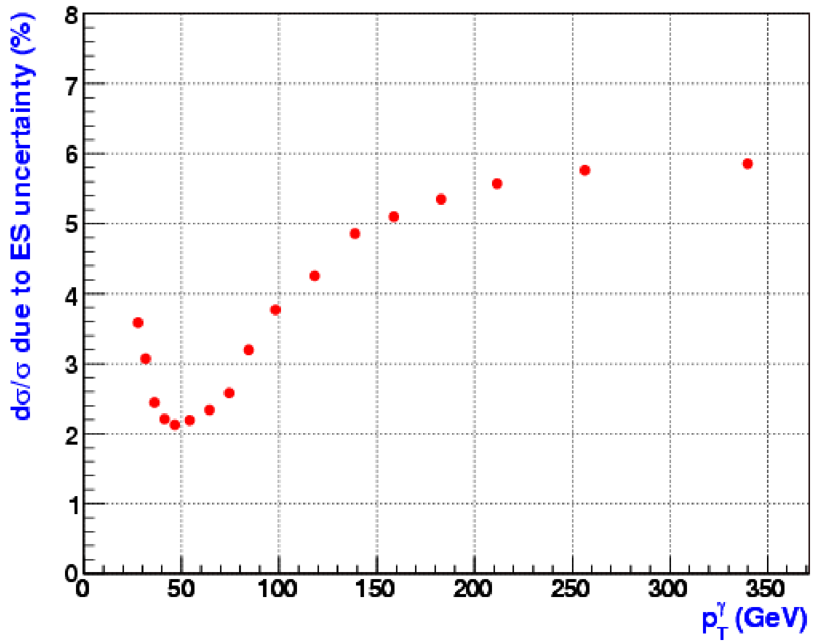
Thus, even with 3σ, after all applied cuts, W+jet contribution here is < 1%.

Photon Energy scale uncertainties

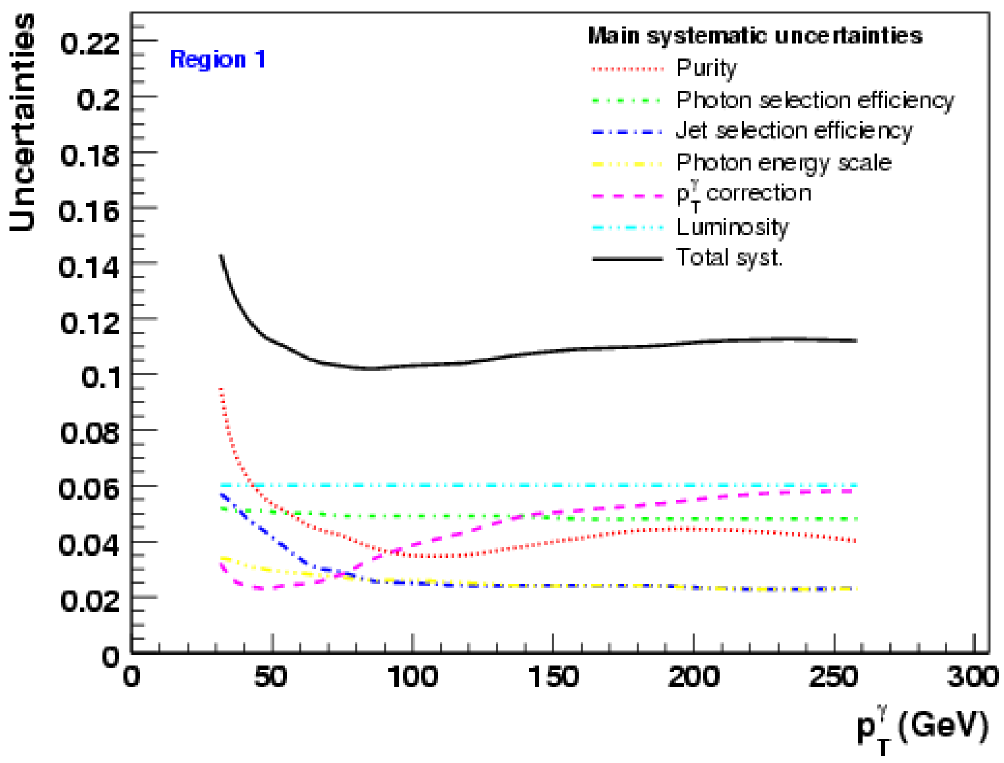
- They are caused by Zee calibration (~0.5%) and the scale shift due to admixture of QCD background (0.5-1%)
- Additional source is uncertainty in MC material

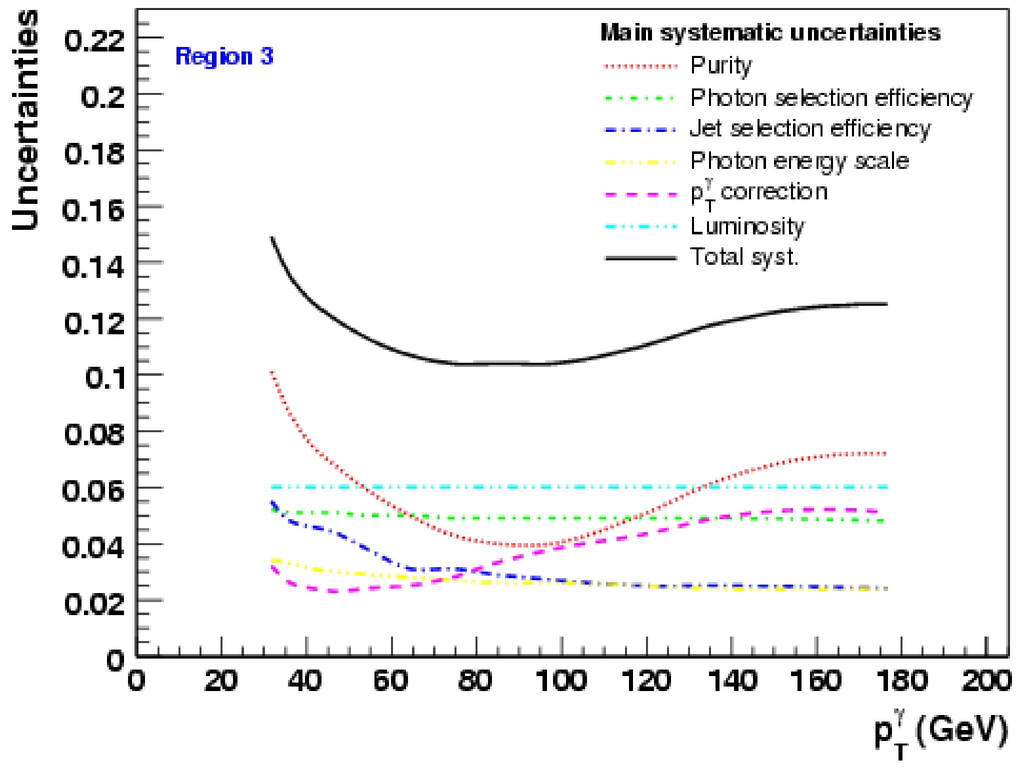






Main Uncertainties

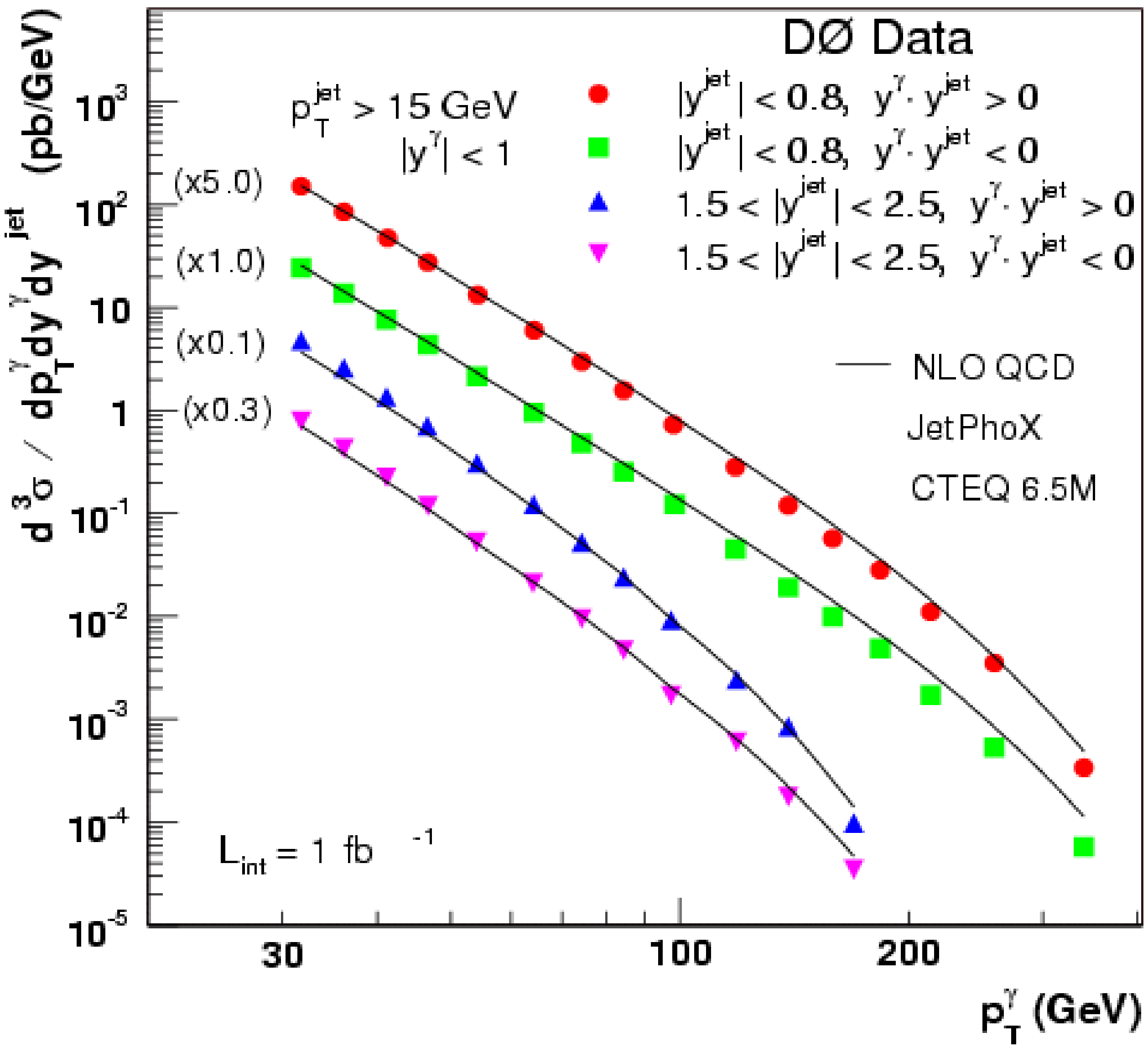




==> dominated by **Purity, photon** and **jet selections** and **luminosity**.

Uncertainties of a comparable size are also caused by **electromagnetic energy resolution** together with **photon pT correction.**

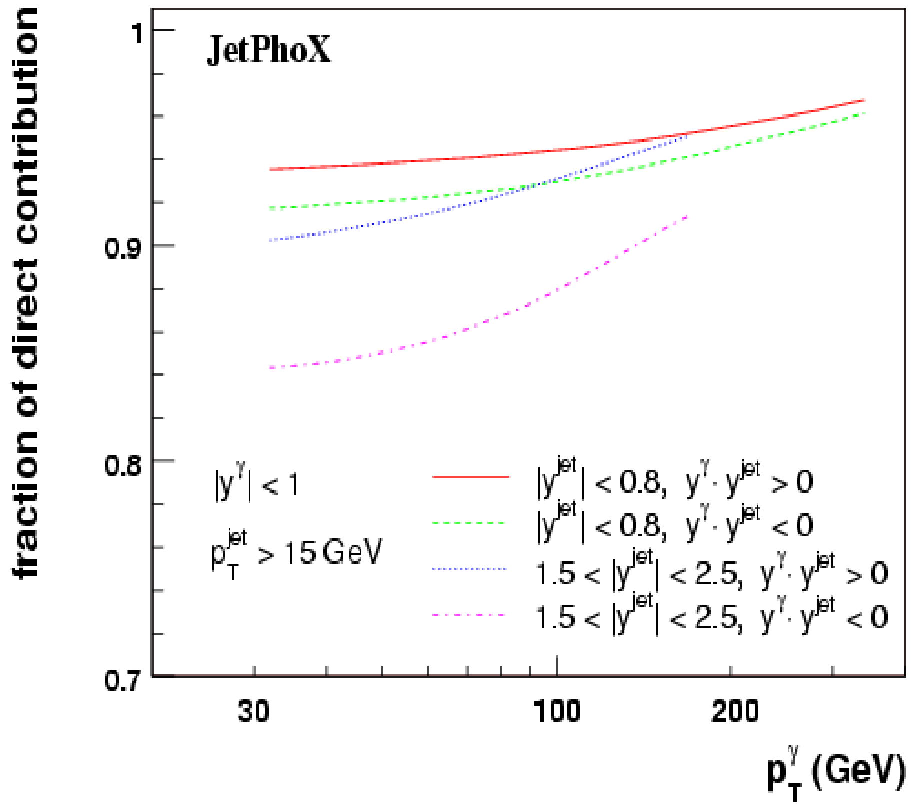
Cross sections

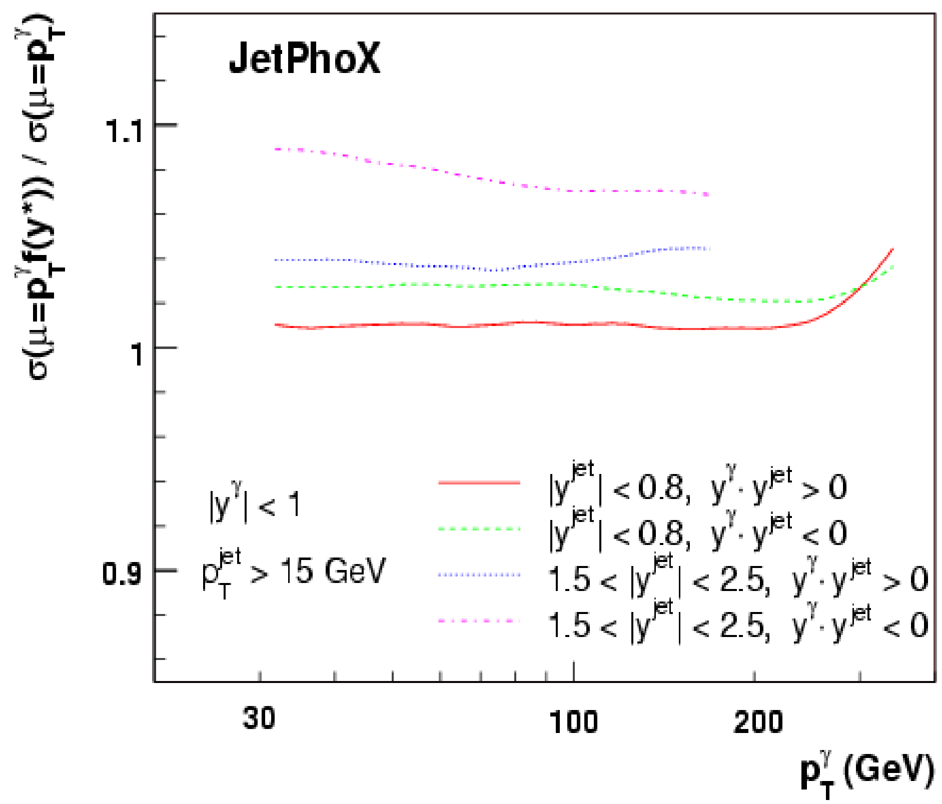


- ~1.45mln events all together.
- Cross section drops by almost 6(5) orders for the central(forward) jet regions.
- Stat. errors are varied as 0.2% at 30-34 GeV up to 35% at 300-400 GeV for the regions with central jets and up to 25% at 150-200 GeV for the forward jets.
- Number of unaccounted events is 1(3) with the central (forward) jets.

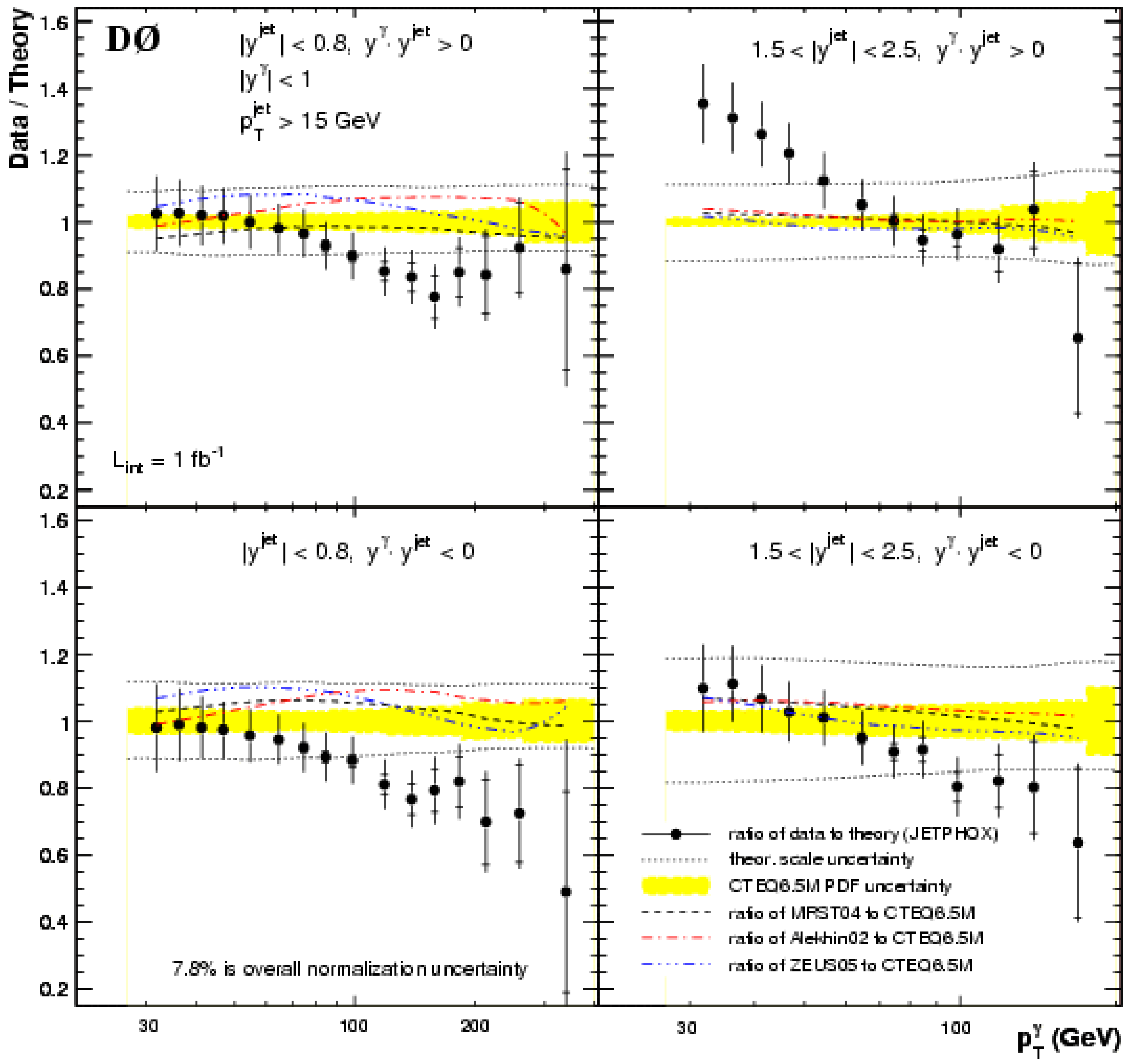
Theory

-- theory is QCD NLO predictions done with JetPhoX (tuned to our selections and jet algorithm)
-- CTEQ6.5M
--- The proposal of theorists (J-P Guillet, M.Fontannaz) to use all scales (fragm., factor., renorm.)
as (pT/2)*sqrt[1+exp(-2 * |y_star|)/2], where y_star = 0.5 *(y_gamma - y_jet)
Their motivation: choice of the scale depends on the energy exchanged by the two initial partons (e.g. should be different for different s- and t- channel dominated processes/events).





Data / Theory



DØ
Data / Theory
$|y^{jet}| < 0.8,\ y^{\gamma} \cdot y^{jet} > 0$
$|y^{\gamma}| < 1$
$p_T^{jet} > 15$ GeV
$L_{int} = 1\ fb^{-1}$
$1.5 < |y^{jet}| < 2.5,\ y^{\gamma} \cdot y^{jet} > 0$
$|y^{jet}| < 0.8,\ y^{\gamma} \cdot y^{jet} < 0$
$1.5 < |y^{jet}| < 2.5,\ y^{\gamma} \cdot y^{jet} < 0$
7.8% is overall normalization uncertainty
ratio of data to theory (JETPHOX)
theor. scale uncertainty
CTEQ6.5M PDF uncertainty
ratio of MRST04 to CTEQ6.5M
ratio of Alekhin02 to CTEQ6.5M
ratio of ZEUS05 to CTEQ6.5M
p_T^{γ} (GeV)

Some observations:

==> The cross sections show a disagreement with the theory for pT > 100 GeV for the two kinematic regions with photon and jet located in the central pseudorapidity region.

==> Shape of the data-to-theory ratios show about the same structure observed earlier in UA2, CDF (latest Run I) and D0(Run II) measurements of inclusive photon cross sections

==> Disagreement is also seen for pT< 50 GeV for Region 3 ($1.5<|y^{jet}|<2.5$, $y^{jet} \cdot y^{\gamma}>0$). Same shape but the Data/Theory ratios are withing theor. scale uncertainties in Region 4 ($1.5<|y^{jet}|<2.5$, $y^{jet} \cdot y^{\gamma}<0$).

==> The scale variation is not able to simultaneously accommodate the measured differential cross sections in all of the measured regions.

Also: *theory predictions with traditional scales (=pT) are smaller what lead to a worse agreement* with data, especially for the cross sections with forward jets.

Cross section ratios

Main motivations:

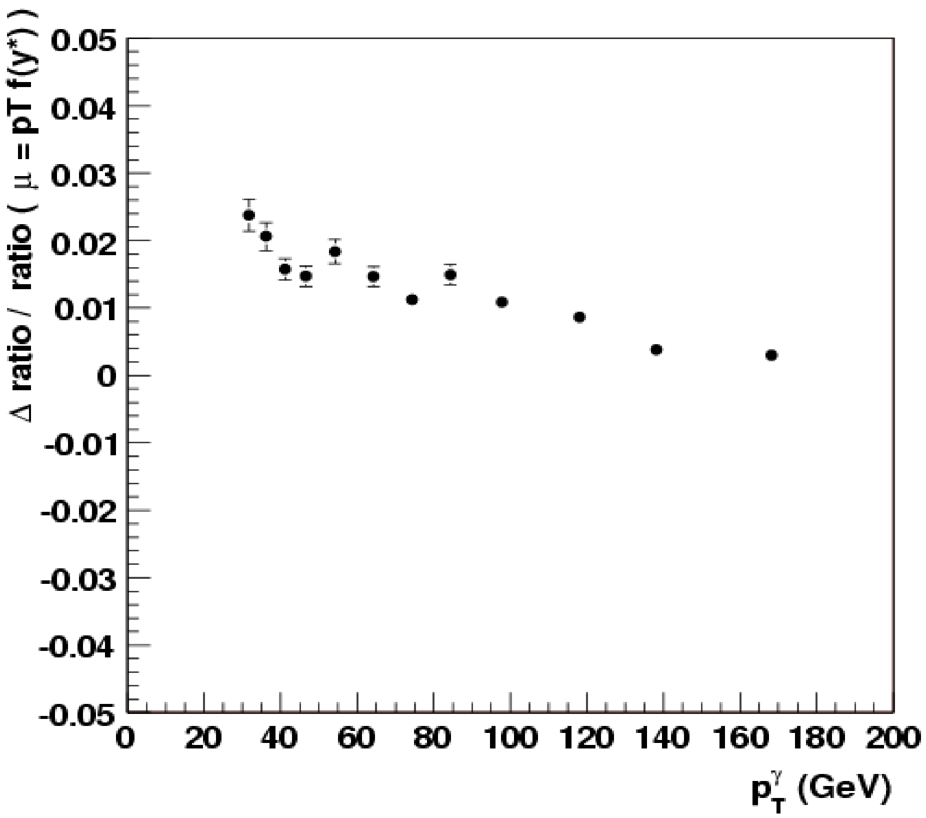
--- Reduction of syst. uncertainties of the measured cross sections (the photons are always in CC);

--- Reduction of theoretical scale uncertainty.

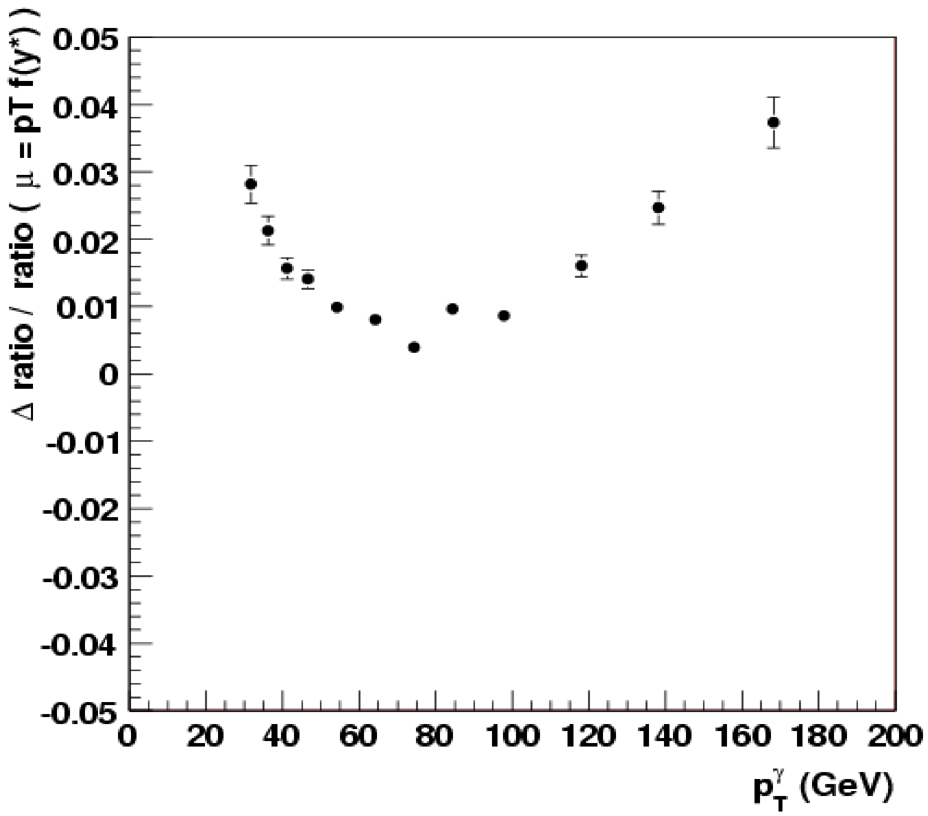
Relative difference of theoretical cross sections ratio calculated with two scales:

$\mu = pT \cdot f(y^*)$ and $\mu' = 0.5pT \cdot f(y^*)$

Regions 1 & 2



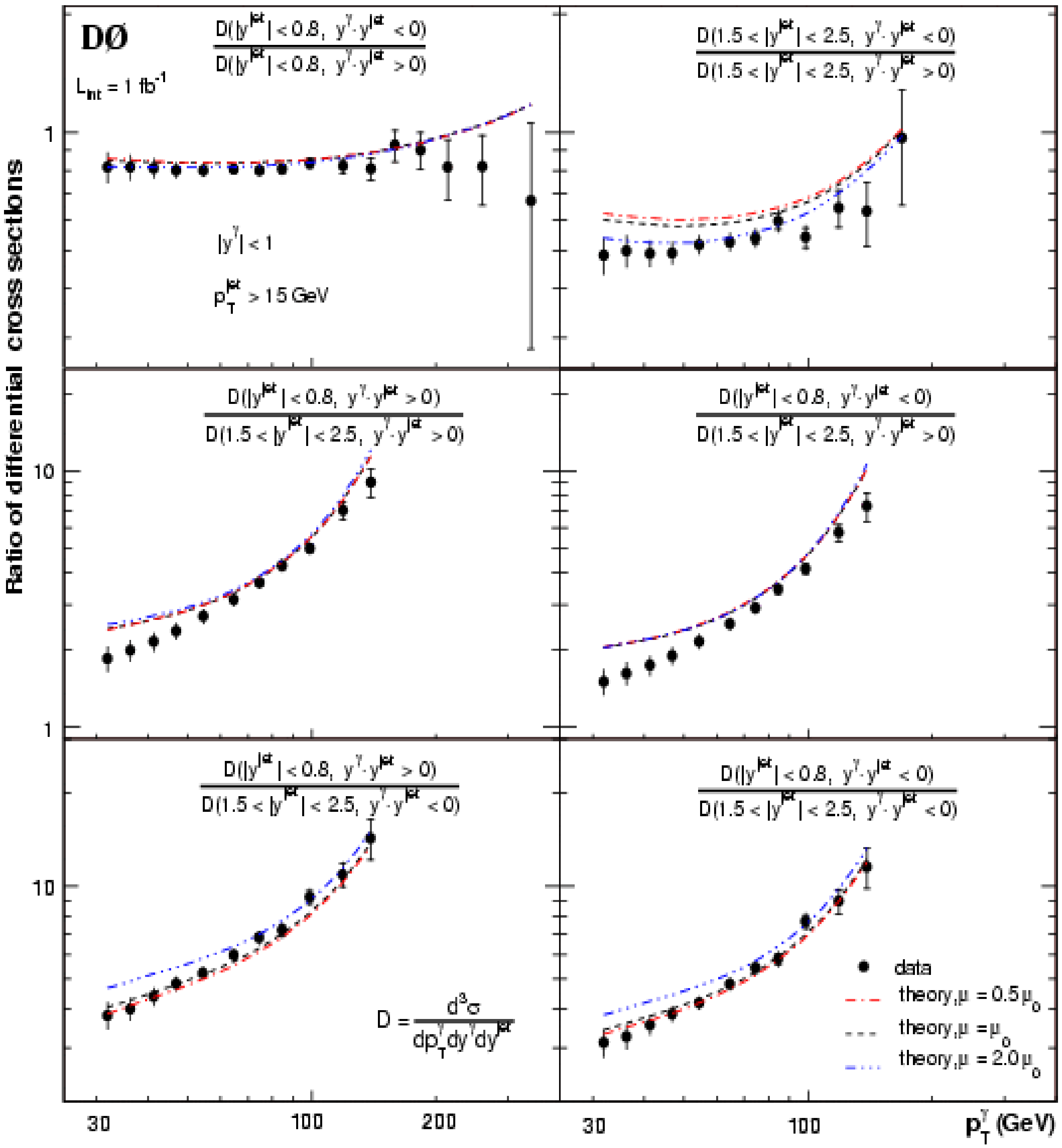
Regions 1 & 3



==> i.e. the theoretical scale caused uncertainty in the ratio is just 0.5-3.5% for those ratios!

(but up to 7.5% for the ratios in Regions 3 & 4, mainly due to scale uncert. in Region 4).

Cross section ratios: data



➢ The systematic uncertainties for ratios of cross sections in Regions 1 & 2 (3 & 4) is a sum in quadrature of statistical uncertainties of the purity fits in the two regions while for those in Regions 1 & 3, 2 & 3 (1&4, 2&4) we have also added uncertainty of the leading jet reconstruction efficiencies, JES and the jet pseudorapidity correction in CC and EC regions.

➢ The overall experimental uncertainty estimated in the way described above is about 4-8% for 44 < pT < 130 GeV and grows to 9-12% for smaller pT (due to systematics) and higher pT (due to statistics).

As an example:

Ratio of differential cross sections in Region 1 to Region 3 with stat. and syst. uncertainties.

p_T^γ bin (GeV)	ratio (r) measured	ratio (r) theory	δr_{stat} (%)	δr_{syst} (%)	δr_{tot}^{exp} (%)	$\delta r^{theor.}$ (%)
30 - 34	1.73	2.44	0.4	11.7	11.7	2.3
34 - 39	1.87	2.54	0.5	10.0	10.0	1.8
39 - 44	2.02	2.67	0.7	8.6	8.7	1.7
44 - 50	2.24	2.81	0.8	7.6	7.7	1.5
50 - 60	2.54	3.03	1.0	6.7	6.8	1.1
60 - 70	2.94	3.36	1.6	5.8	6.0	0.9
70 - 80	3.39	3.80	2.3	5.0	5.5	1.5
80 - 90	3.92	4.35	3.4	4.5	5.6	1.8
90 - 110	4.61	5.33	3.8	4.2	5.7	3.2
110 - 130	6.51	7.54	7.1	3.9	8.1	4.1
130 - 150	8.11	11.18	11.8	3.6	12.3	4.6

Some observations on the ratios:

==> In general, the shapes of the ratios in data are qualitatively reproduced by the theory.

==> A quantitative difference, however, between theory and the measurement is observed for the ratios of the central jet regions to the forward region ($1.5<|y^{jet}|<2.5$, $y^{jet} \bullet y^{\gamma}>0$), even after the theoretical scale variation is taken into account.

==> The ratio between the two forward jet cross sections suggests a scale choice $2\ pT \cdot f(y^*)$. However, the ratios of the central jet regions to the forward region ($1.5<|y^{jet}|<2.5$, $y^{jet} \bullet y^{\gamma} <0$), suggest a theoretical scale closer to $0.5\ pT \cdot f(y^*)$.

Summary

- Photon+jet cross sections at total luminosity ***L=1 inv. fb*** (whole Run IIa) are measured in the four kinematic regions.

- The measured cross sections should allow to extract / limit gluon PDF in the regions of $0.007 < x < \sim 0.7$ ***and*** $900 < Q^2 < (0.4\text{-}1.6) \cdot 10^5\ \mathrm{GeV}^2$ ***(with $Q \equiv$ photon pT).***

- To reduce both, experimental and theoretical, uncertainties the four cross section ratios have also been measured.

- *Next-to-leading order QCD predictions, using different parameterizations of parton distribution functions, are unable to describe the shape of the pT dependence of the cross section across the whole measured range. Similarly, theoretical scale variations are unable to simultaneously describe the normalization of the data in each of the four measured regions.*

- These data can be a good input for following fits for proton PDF tuning.

▷ *Results have been presented at two Moriond conferences (2007/08), DIS'07, HCP'07, Photon'07, Aspen'08*

▷ *Analisis note is D0 Note 5368, Conference note is 5369.*

▷ *Latest version of the paper is available from QCD EB page:*

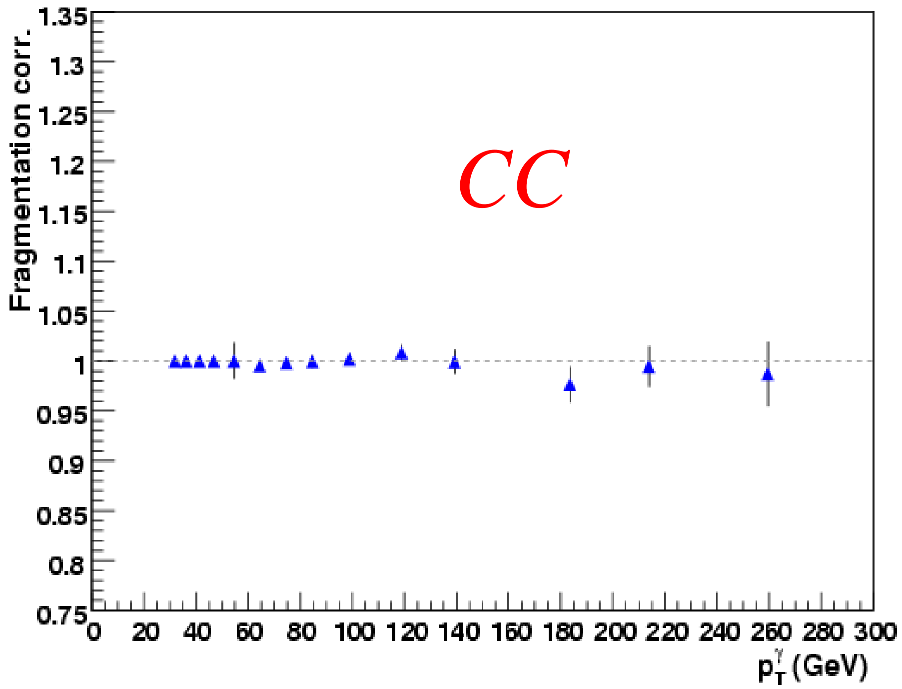
http://www-d0.hef.kun.nl//fullAgenda.php?ida=a07249

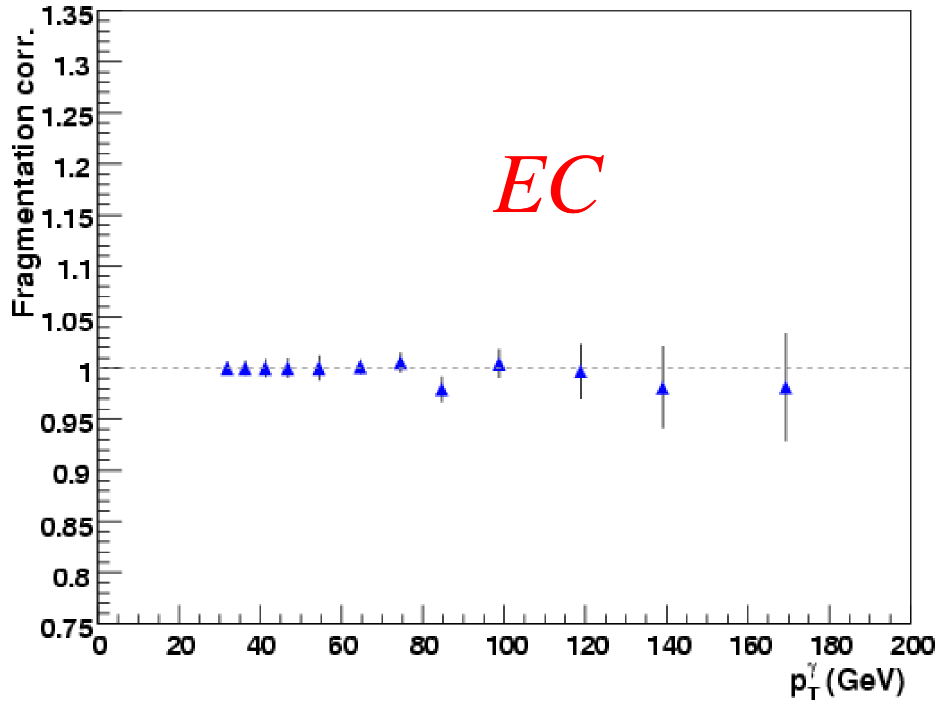
▷ *Many thanks to all members of QC WG, QCD EB for fruitful discussions during a long time, especially to Marskus Wobish, Duncan Brown, Michael Begel, Heidi Schellman.*

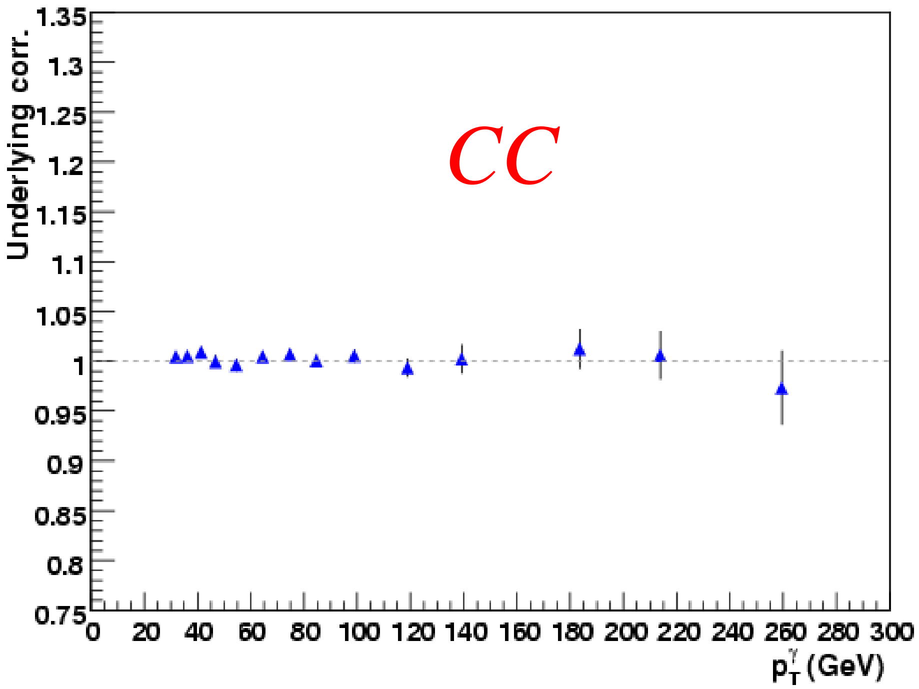
▷ *Special thanks to all members of PhotonID group w/o whom this analysis would not be possible.*

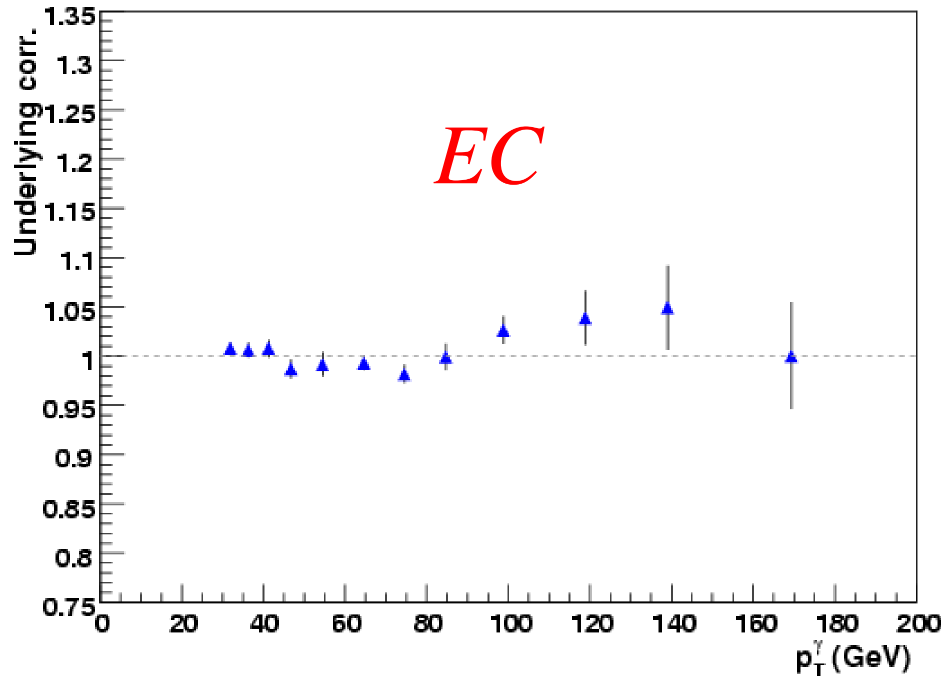
AS A BACKUP: Estimation of fragmentation and underlying effects.

- Done in two stages: (1) using Pythia's default simple cone algo with R=0.7

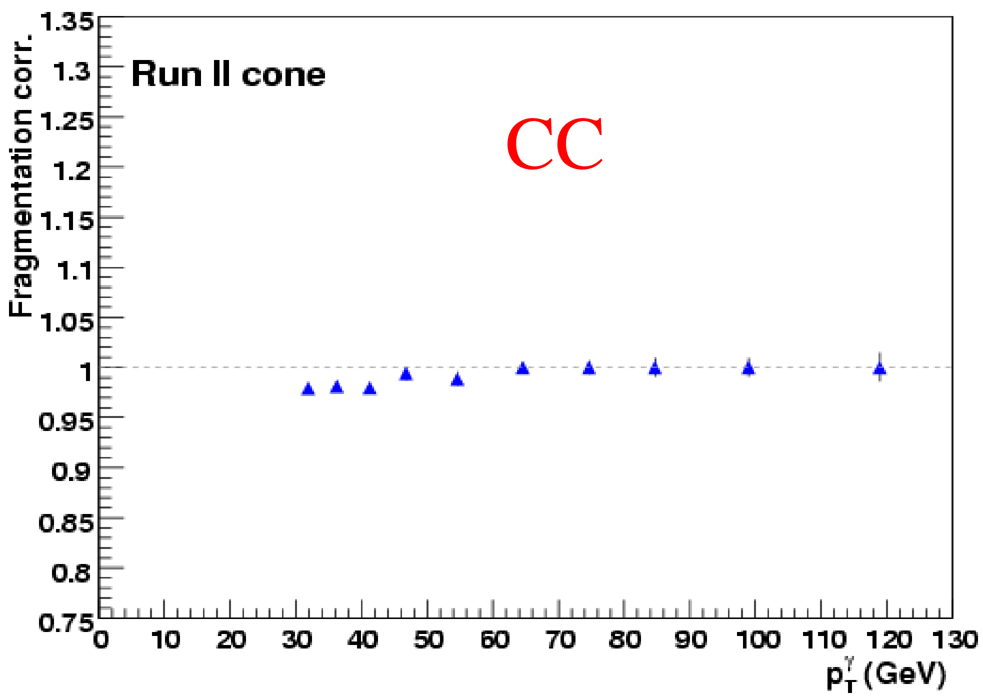


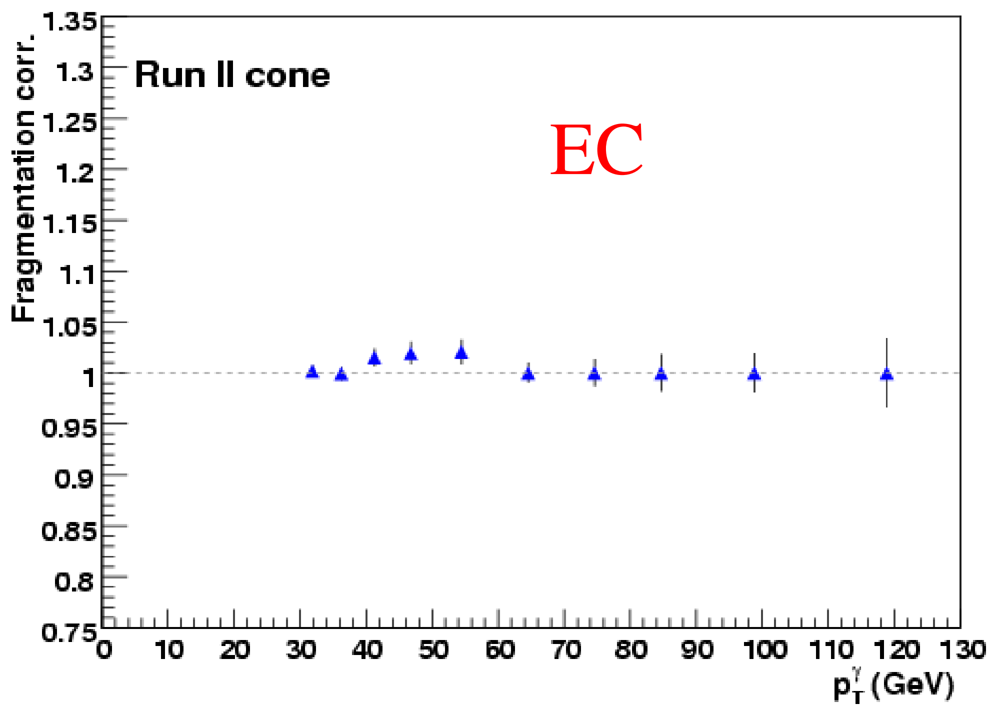


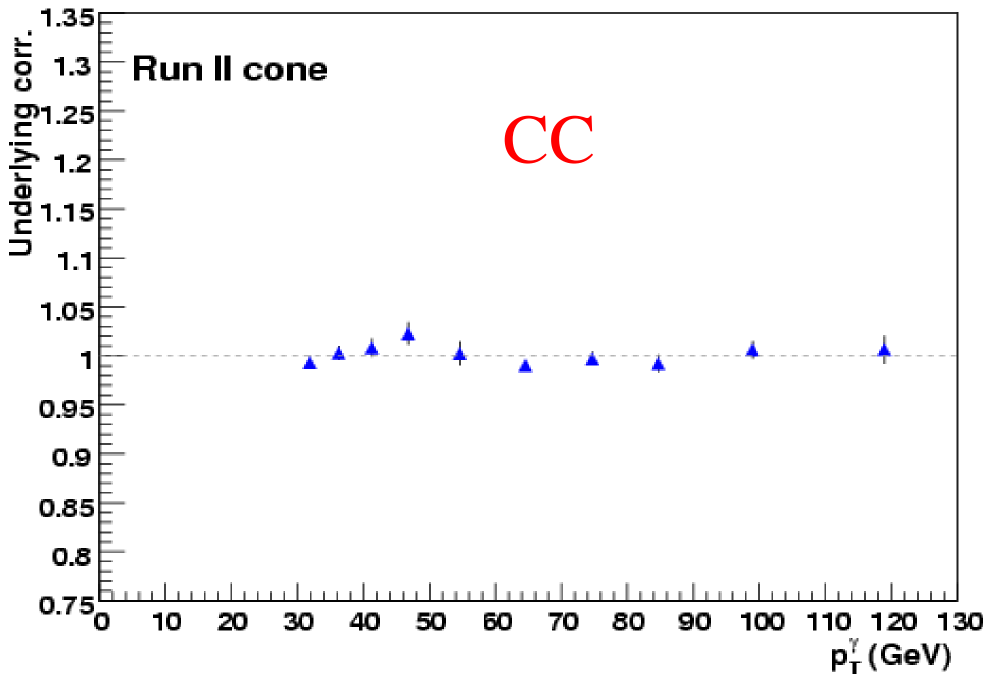


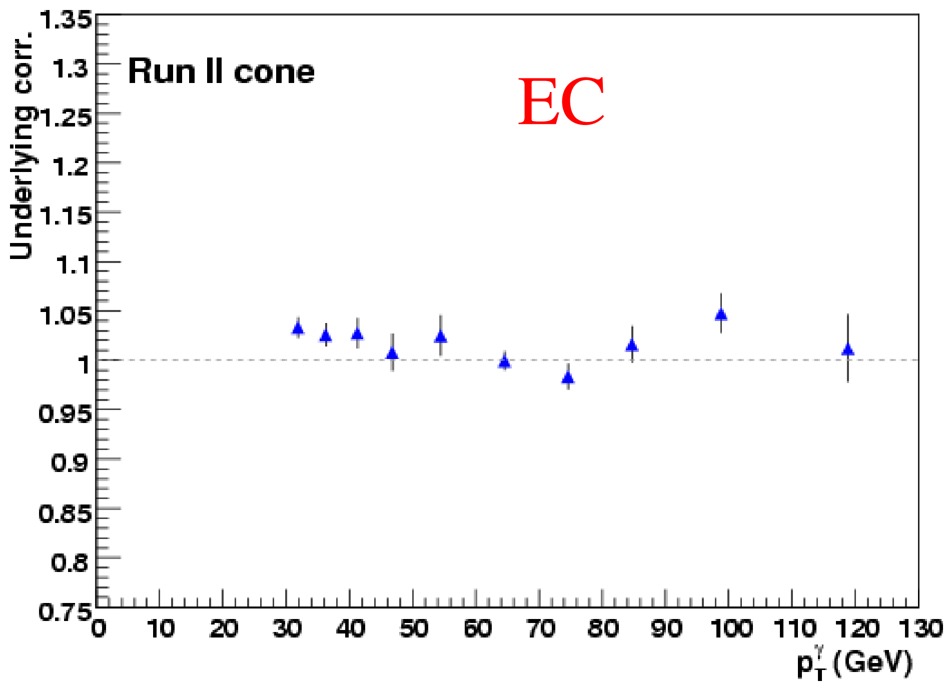


(2) using Run2 cone D0 algo (R=0.7) with interface from Pythia's code.









All points agree with unity within 2-3%.