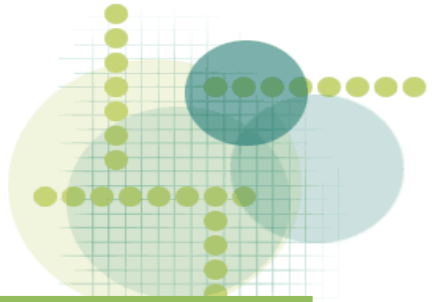


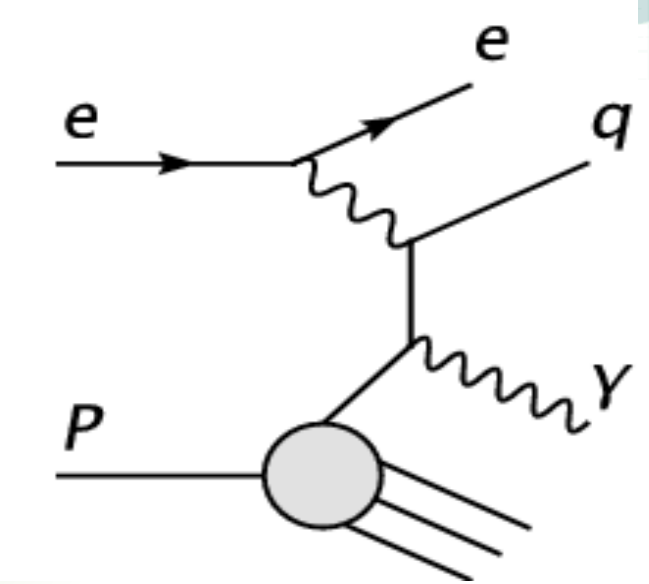
Prompt photons with associated jet at LHC

R.Blair (ANL), S.Chekanov (ANL),
G.Heinrich (Edinburgh Univ.)

DESY-LHC Workshop
DESY, Germany October 2007

Prompt-photon production at HERA

- **Sensitive to quark and gluon densities**
- **Several QCD calculations can be confronted with the data**
  - NLO QCD, k_T-factorization, Monte Carlo models (LO+PS)
- **Avoid systematics associated with jet identification and measurement**
  - photons are simple, well measured EM objects
  - emerge directly from the hard scattering without fragmentation
    - no need for "hadronisation" corrections at low transverse momenta



Still experimentally challenging measurement:

- large background expected from fragmentation (decays of π^0, η,)
- must be subtracted on statistical basis for data
- conventional isolation requirement: $E_T^{\gamma(true)} > 0.9\ E_T$

γ+jet final state at HERA

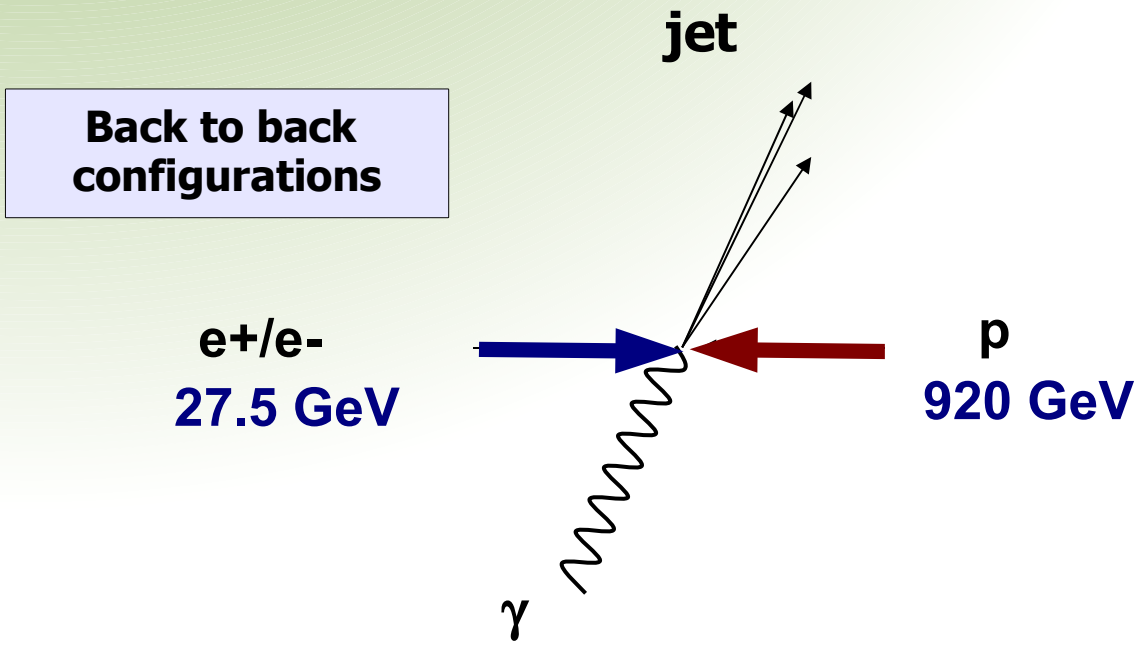
Look at γ+jet topologies: $e + p \rightarrow e + \gamma\,(prompt) + jet + X$

- **Expected to be more sensitive to the underlaying partonic process than the inclusive prompt photons**
- **Hadronisation corrections are smaller than for dijets at similar E_T**

  - more reliable predictions

- **Experimentally, very clean signatures**

  - jet should balance EM object in P_T



QCD predictions

NLO QCD
Collinear factorisation

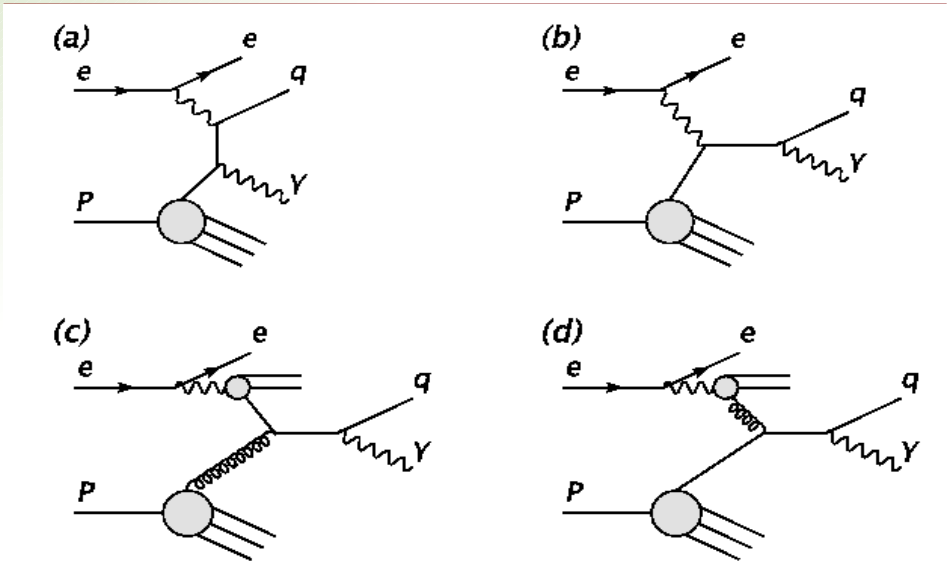
- dominant contribution from diagrams where partons are strongly ordered in virtualities.
- DGLAP evolution for PDF

- K.Krawczyk & A.Zembrzuski (KZ)
  - (not all) NLO corrections
  - resolved & direct contributions
  - GRV PDF
- Fontanaz, Guillet, Heinrich (FGH)
  - full NLO corrections for resolved component
  - MST01 proton PDF
  - AFG02 photon PDF
- $\mu_R = \mu_F = E_T^{\gamma}$ for all above

k_T factorization QCD predictions
Virtualities/k_T are no longer ordered:

- Off-shell matrix elements
- Unintegrated PDF
- Kimber-Martin-Ryskin prescription for PDF

- A.Lipatov & N.Zotov (LZ)
  - Direct & resolved processes taken into account



+ some more high-order terms ..

Monte Carlo models (LO+parton showers) also available: PYTHIA and HERWIG

Typical event selection in ep

Selected events:

- 77 pb^{-1}
- Q^2 <1 GeV^2
- 0.2< y < 0.8

Reconstruction:

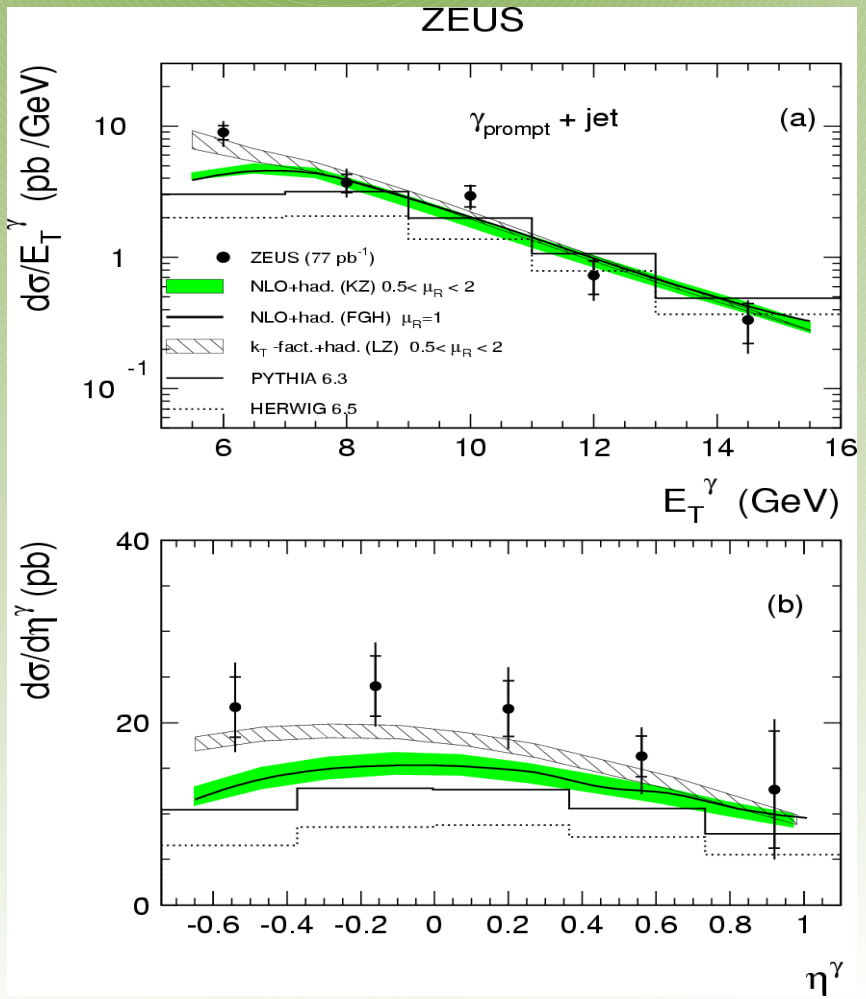
- Use Energy-Flow Objects (EFO)
- Reconstruct > 1 jets using longitudinally-invariant k_T algorithm
- γ candidates:
  - large electromagnetic fraction E^{EMC}/E^{tot} >0.9
  - E_T >5 GeV -0.74 < η < 1.1
- Associated jet:
- E_T >6 GeV -1.6 < η < 2.4
- E^{EMC}/E^{tot} <0.9

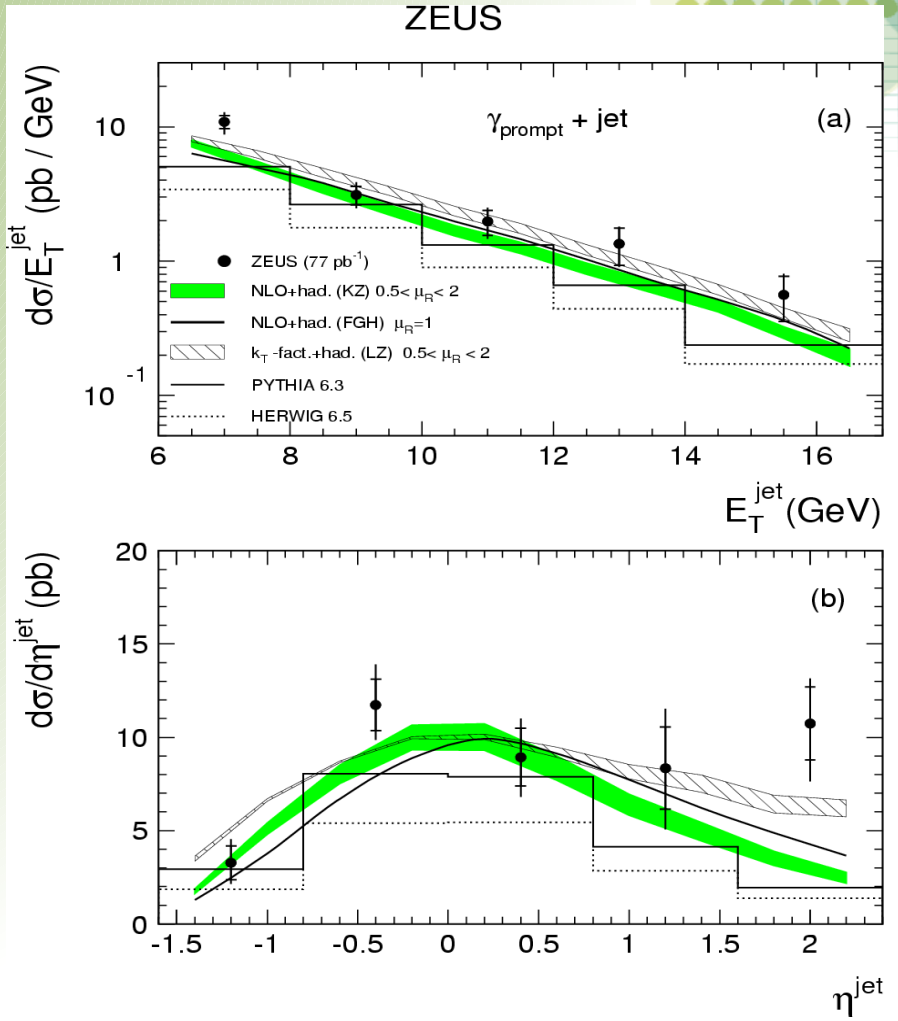
Detector correction:

- correct data using a MC
- assume isolation $E_t^{\gamma(true)}>0.9E_T$ requirement
- apply parton-to-hadron correction to QCD parton predictions based on PYTHIA (due to measurement of associated jet at rather low E_T)

γ+jet cross sections in ep

ZEUS Collaboration European Physical Journal C49 (2007) 511-522

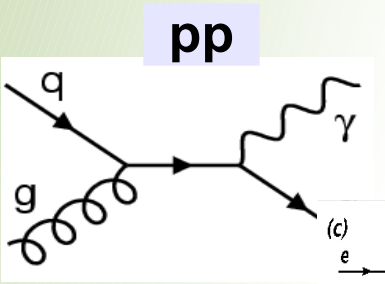


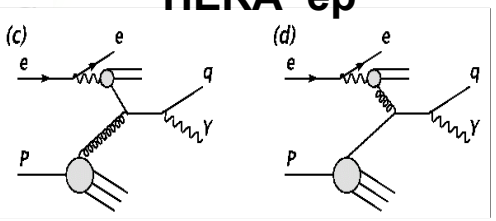


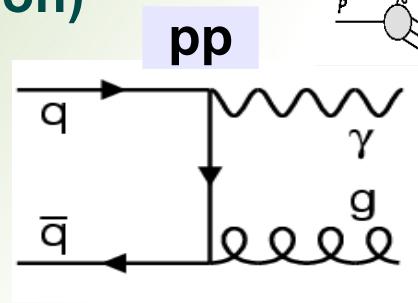
- **Both PYTHIA & HERWIG fail (both in normalization & shape)**
- **NLO QCD calculations are closer to the data, but also fail at low E_T**
- **k_T - factorization approach works the best (but somewhat larger scale uncertainty)**

Prompt photons in pp collisions

- LO contributions:
  - $qg \rightarrow q\gamma$ ("compton-like" process)
    - dominant process (~90%)
    - direct sensitivity to gluon
    - similar to ep (resolved photoproduction)
  - $q\bar{q} \rightarrow g\gamma$ ("annihilation" process)
    - small contribution (~10%)
  - $q\bar{q} \rightarrow \gamma\gamma$ – very small (<0.1%)







Sensitive probe of:

- gluon density
- NLO QCD calculations
- low x physics. Collinear or kt factorization?

Prompt photons in pp collisions

Measurements involving prompt photons:

1) Inclusive prompt photons (no jet requirement):

- simple final state, large cross section
- important background for many discover channels

2) γ+jet, γ+2 jets etc. measurements:

- higher sensitivity to underlaying QCD processes
- simpler event identification (see next slide)

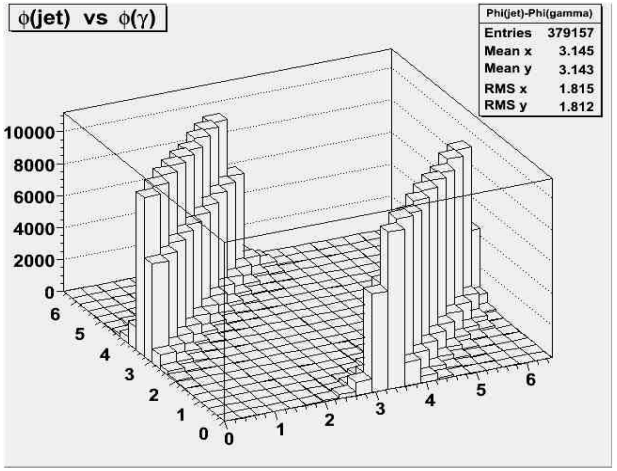
3) Di-photon cross sections:

- smallest cross section
- discovery channel for:
  - Higgs searches
  - Extra Dimensions
  - etc.. etc..

γ+jet cross sections at LHC

pp → γ + jet+ X

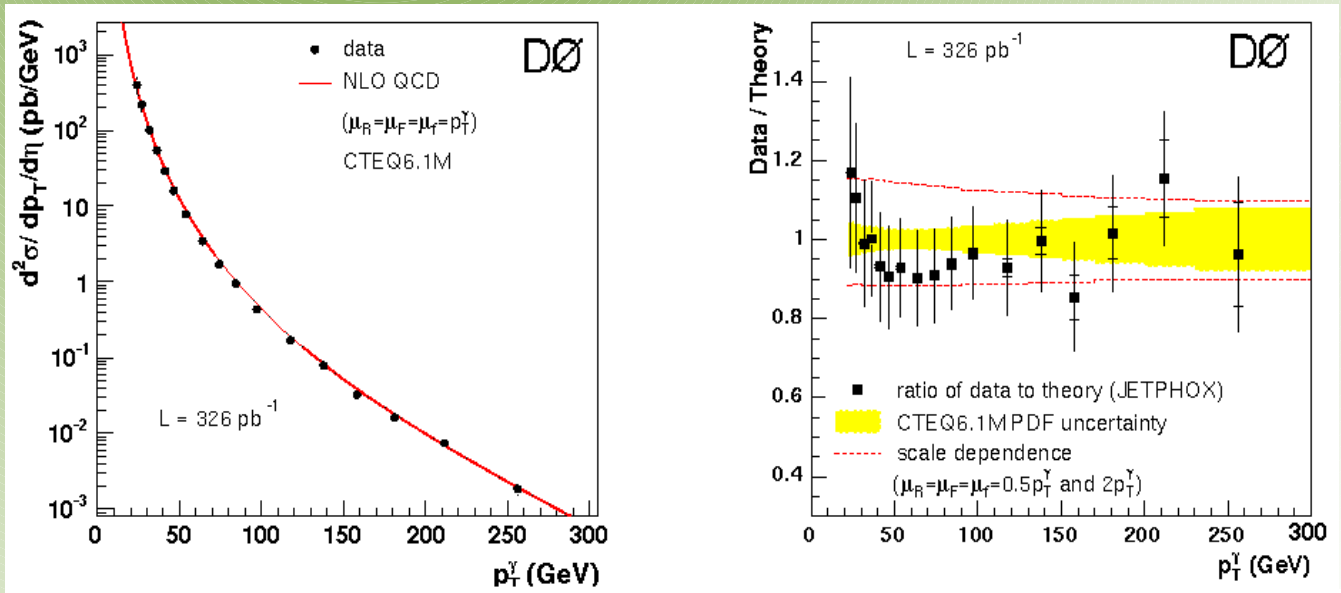
- More sensitive to the underlying QCD production mechanism than inclusive case
- γ+jet is easier to reconstruct than inclusive γ-case
  - an electromagnetic object must balance a jet in P_T - objects are separated in φ
  - Can be used to improve photon purity and reduce $\pi^0 \rightarrow \gamma\gamma$ assuming using a cut on azimuthal angle between the 2 objects
    - Good channel to tune photon selection criteria for searches of Higgs, exotics..
  - Can be used to set absolute jet energy scale
    - Photon energies are well measured by electromagnetic part of a calorimeter:
    - See details: V.Konoplianikov, O. Kodolova, A.Ulyanov. "Jet Calibration using gamma+jet Events in the CMS" Eur.Phys.J.Cd46:37-43,2006.



PYTHIA 6.4 pp (14 TeV)
P_T>100 GeV

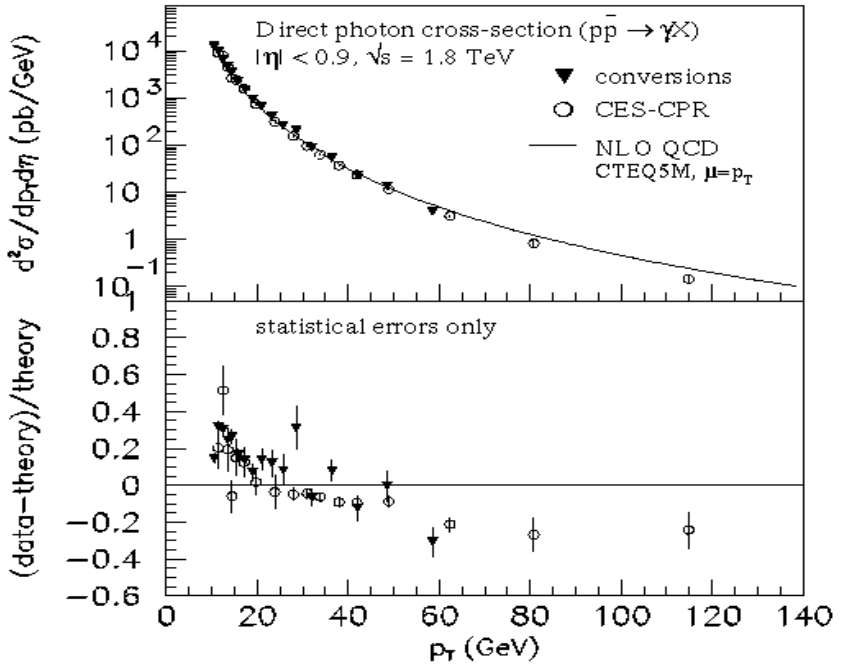
γ cross sections at TEVATRON

pp → γ + X



scale uncertainty ≈ PDF uncertainty at P_T ~ 300 GeV

- **Large PT:**
  - **significant scale and PDF uncertainty!**
- **Low PT:**
  - **Deviation from NLO?**



γ+jet cross sections at LHC

$pp \rightarrow \gamma + jet + X$

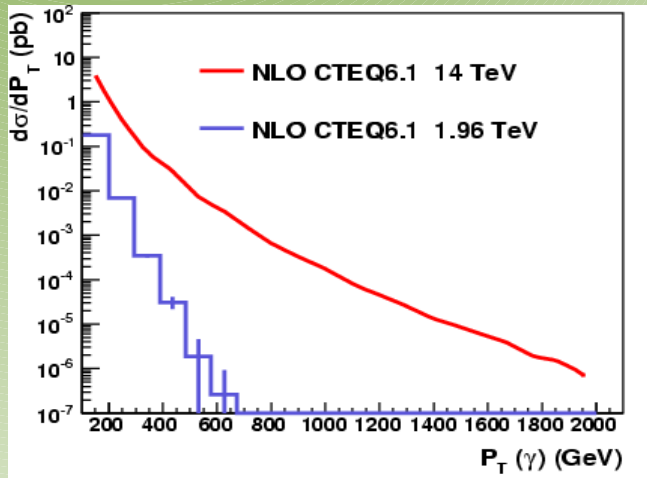
- Long. inv. K_T algorithm to reconstruct more than 1 jet
  - FastJet for MC: M. Cacciari and G.P. Salam, Phys. Lett. B 641 (2006) 57 (2.2 beta)
- Kinematic cuts: 2 highest P_T jets should have:
  - $P_T(jet) > 100$ GeV
  - $P_T(\gamma) > 105$ GeV – after requiring "isolation"
    - $P_T(\text{true } \gamma) > 0.9\, P_T(\gamma)$
    - $P_T(\gamma)$ is measured inside the cone

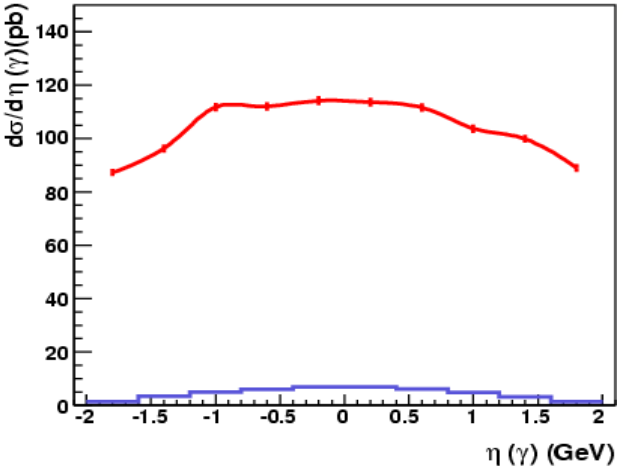
$$R = [\,(\varphi_\gamma - \varphi_{particle})^2 + (\eta_\gamma - \eta_{particle})^2\,]^{1/2} < 1$$

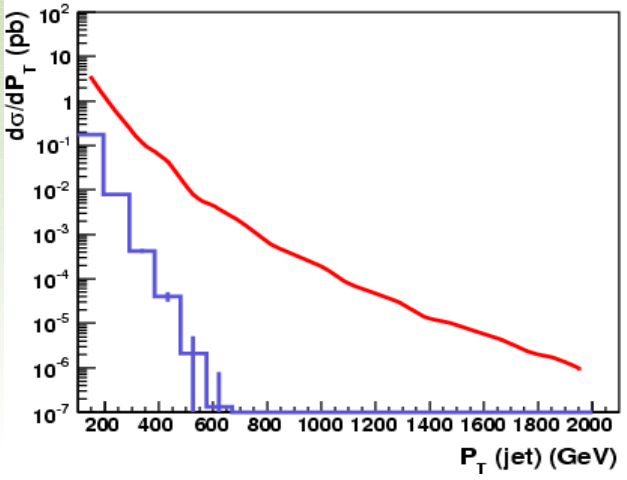
  - $|\eta| < 2$ for both γ and jet

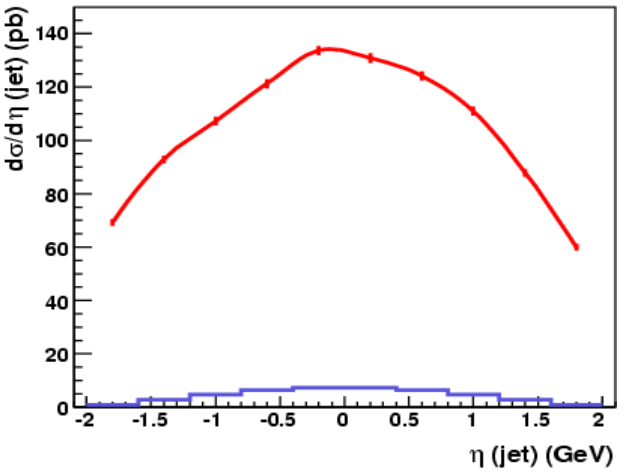
γ+jet cross sections at LHC vs TEVATRON

pp → γ + jet+ X



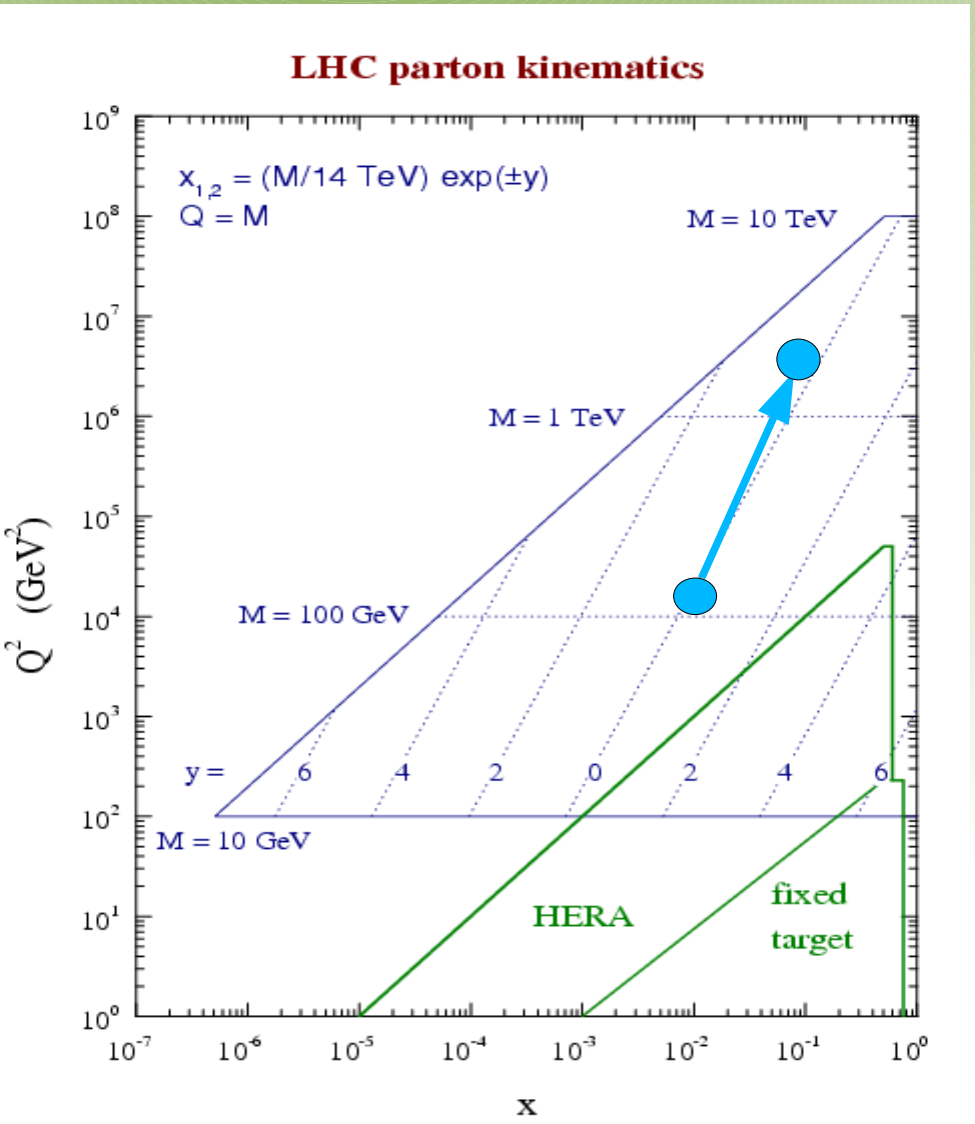






Expected x-section at LHC a factor ~14 larger than at Tevatron

Parton kinematics for γ+jet events from 100 to 2 TeV in P_T (γ, jet)



- P_T (γ, jet)>100 GeV:
  - $\langle x_{1,2} \rangle$ ~ 0.05, Q^2~20000 GeV^2
- P_T (γ, jet)>1 TeV:
  - $\langle x_{1,2} \rangle$ ~ 0.2, Q^2~1.4 x 10^6 GeV^2
- P_T (γ, jet)>2 TeV:
  - $\langle x_{1,2} \rangle$ ~ 0.4, Q^2~5 x 10^6 GeV^2

γ+jet cross sections at LHC

$pp \rightarrow \gamma + jet + X$

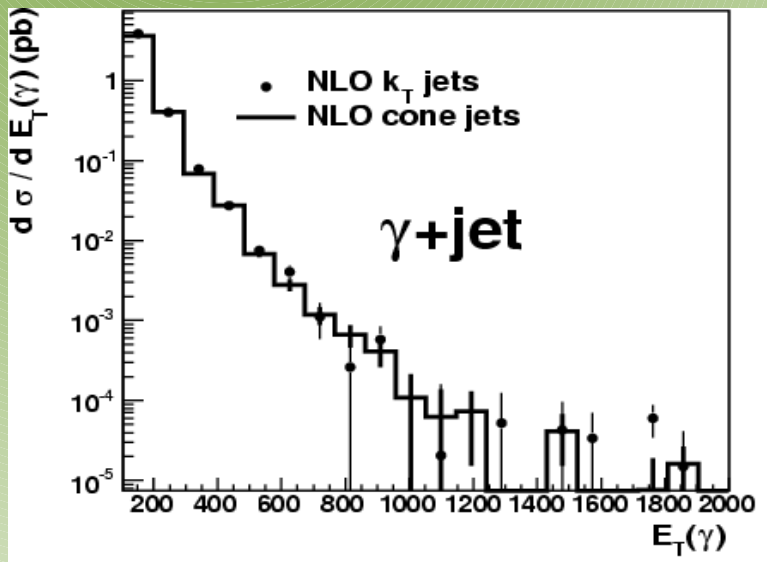
- PYTHIA 6.4 (from RunMC):
  - MSEL=10
  - CTEQ6.1 (LHAPDF)
  - CKIN(3)=50 GeV
  - FastJet K_T
- HERWIG 6.5 (from RunMC)
  - IPRO=1800, PT(min)=50 GeV
  - CTEQ6.1 (LHAPDF)
  - FastJet K_T
- JETPHOX NLO (P. Aurenche, M.Fontannaz, J.Guillet, G.Heinrich,E.Pilon, M.Werlen)
  - CTEQ6.1M
  - Fact. & Renorm. scale: c x $P_T(\gamma)$ (c=1)
    - c=0.5, 2 for scale uncertainty estimates
  - K_T jet algorithm

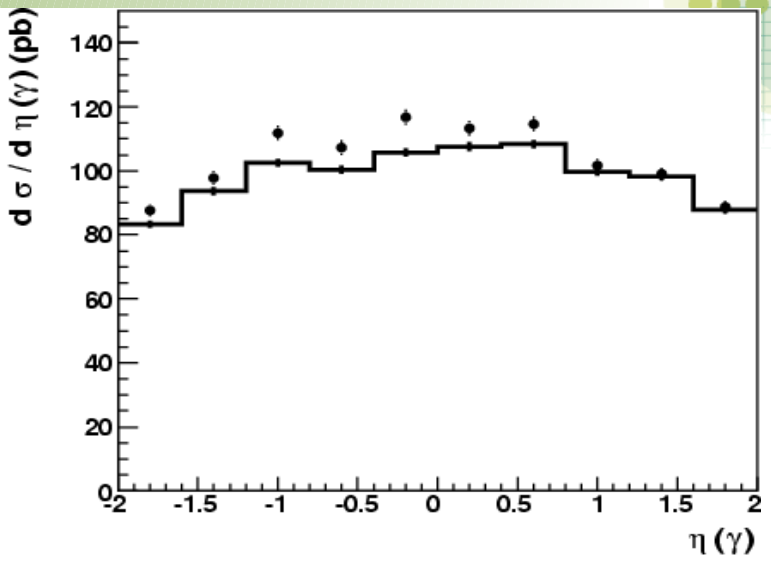
- LO diagrams included:
  - $qg \rightarrow q\gamma$
  - $q\bar{q} \rightarrow g\gamma$
  - $q\bar{q} \rightarrow \gamma\gamma$

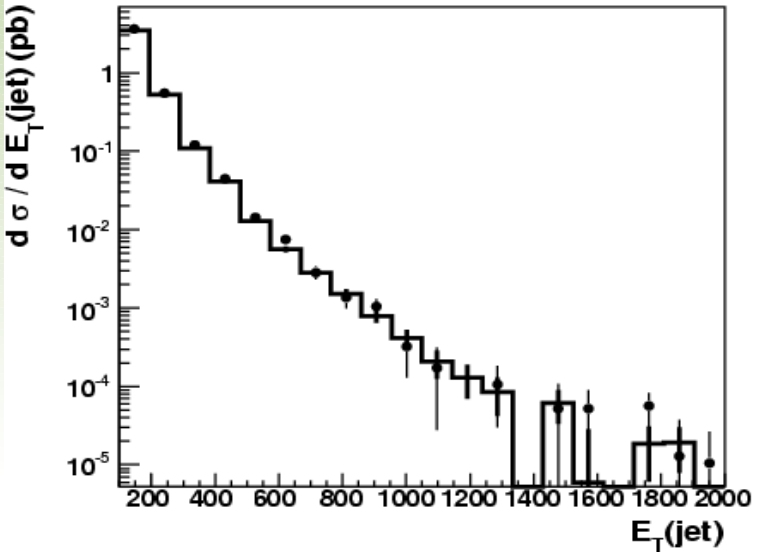
MC vs fixed-order calculations

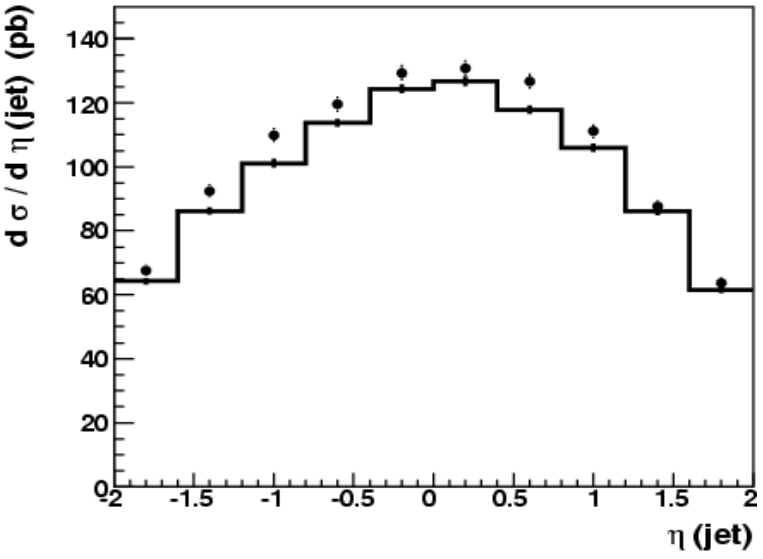
- **General purpose shower Monte Carlo models**
  - **resummation of large logs**
  - **based on soft/collinear branchings**
    - problems with large angle radiation
  - **overall normalisation has to be adjusted**
  - **multi-purpose, hadronic final states, indispensable for realistic comparisons to data**
- **LO fixed order calculation**
  - **useful for description of many hard and well separated partons**
  - **large scale dependence and other LO deficiencies**
- **NLO (NNLO etc.) fixed order calculations**
  - **reduced scale dependence**
  - **can predict rates**
  - **very process specific**

γ+jet cross sections: Cone vs K_T



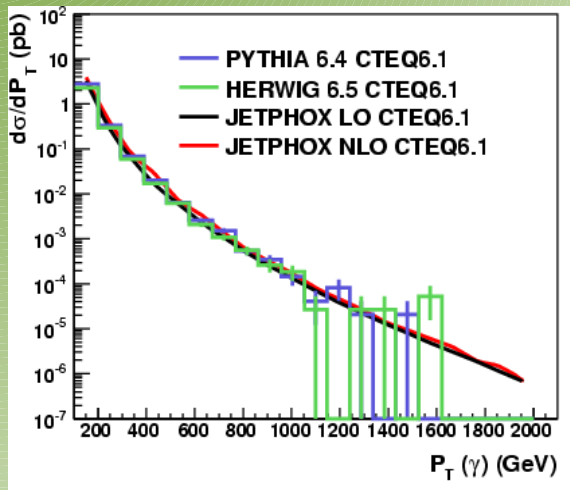


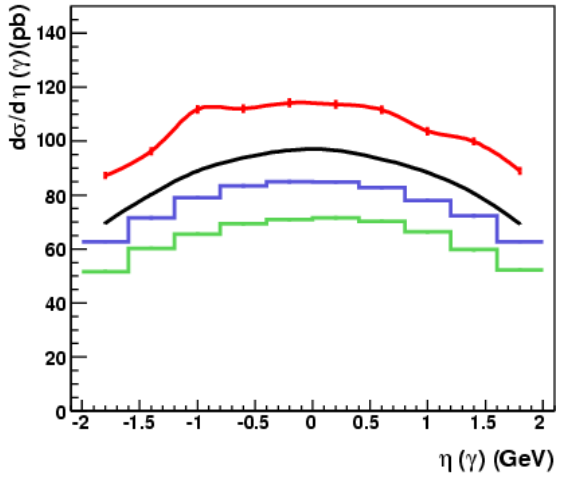


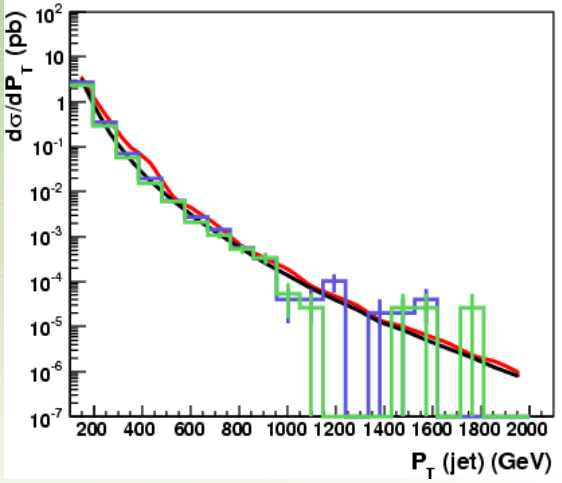


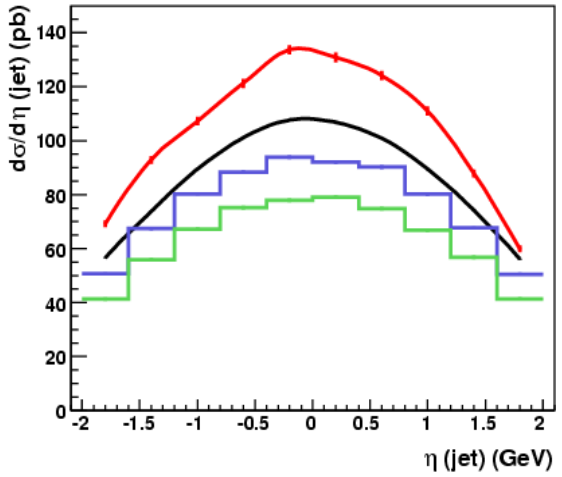
~ few % difference – small effect

γ+jet cross sections: NLO vs MC



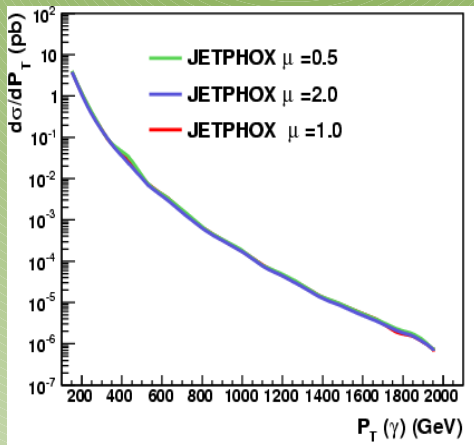


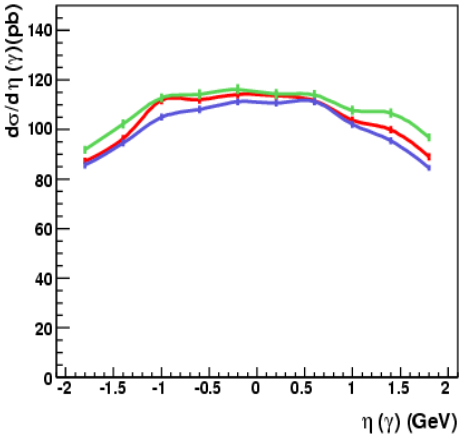


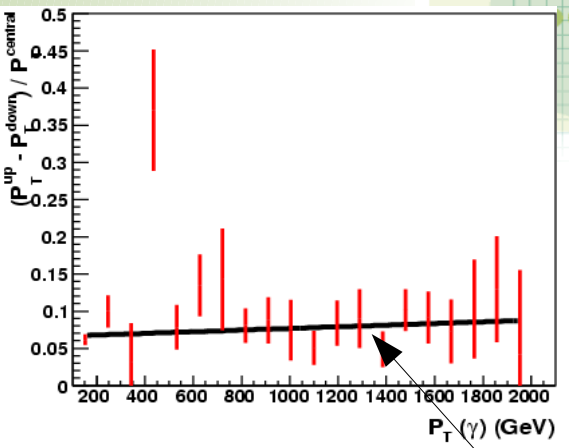


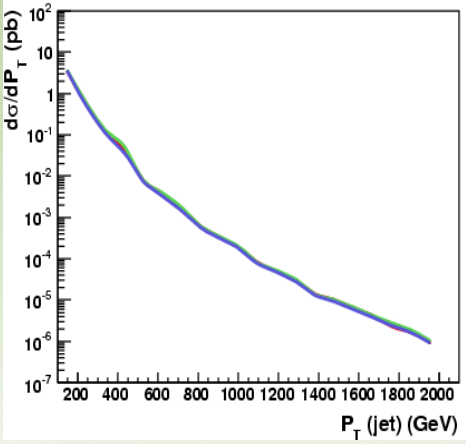
- **Overall k-factor ~ 20%**
- **PYTHIA MC below JETPHOX LO by ~ 7%**
- **HERWIG is below PYTHIA: Differences are mainly at low P_T**
- **Shapes of distributions are similar for all predictions**

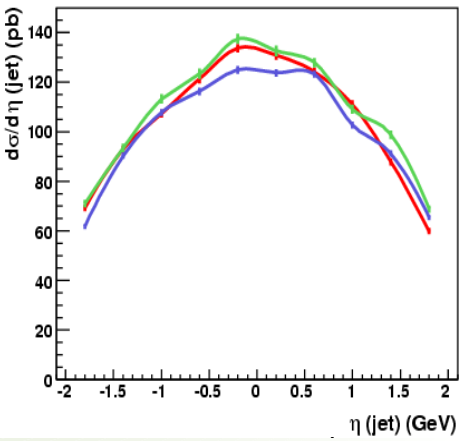
γ+jet theoretical uncertainties

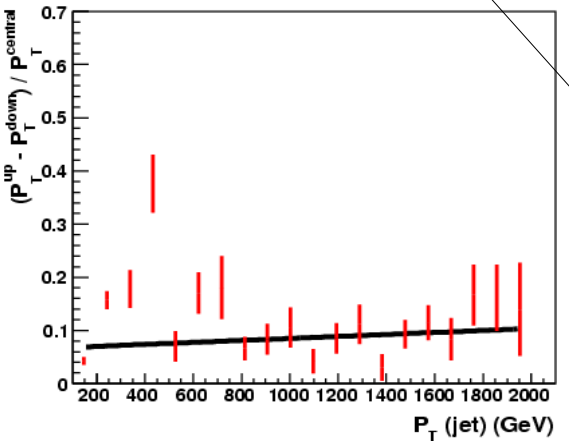






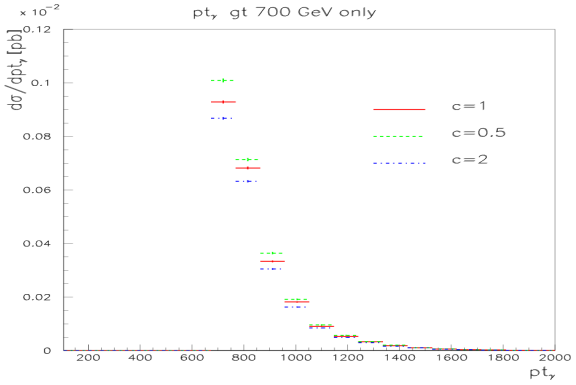




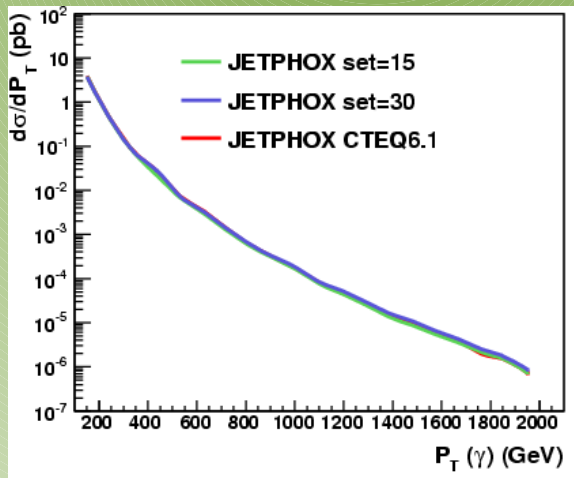


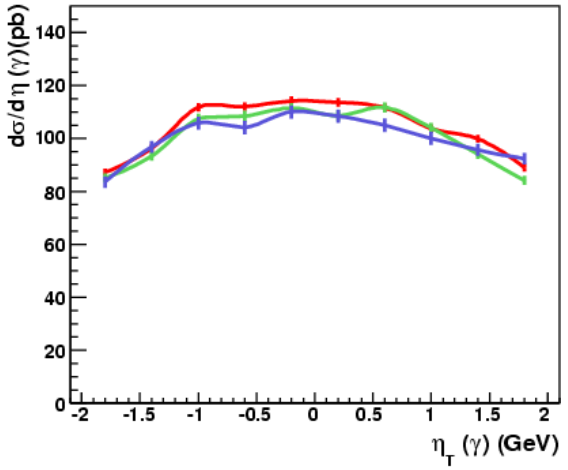
linear fit

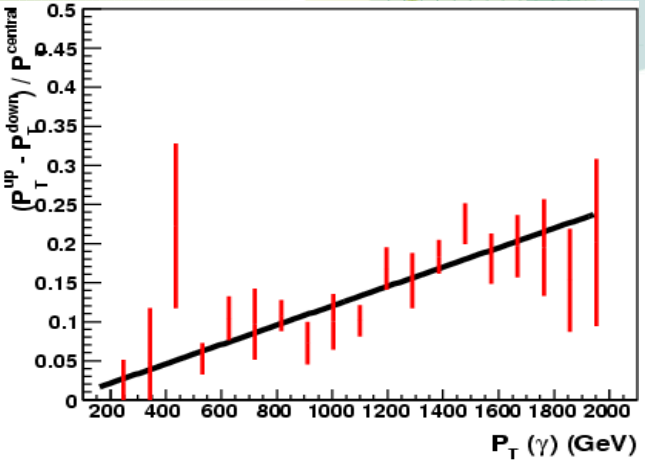
- Overall renom. & factorisation uncertainty is ~10 %
- No strong dependence on P_T between 0.1-2 TeV
  - too low statistics to establish?

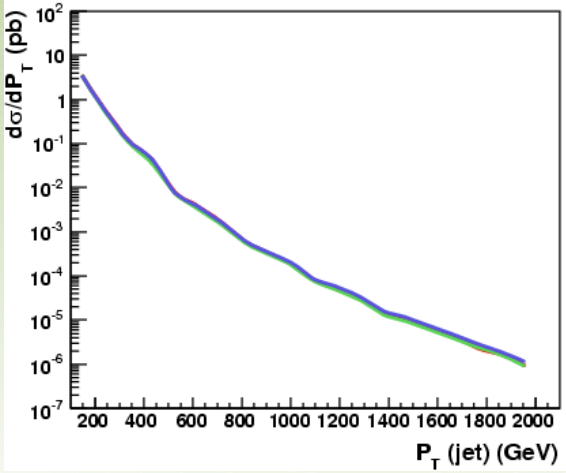


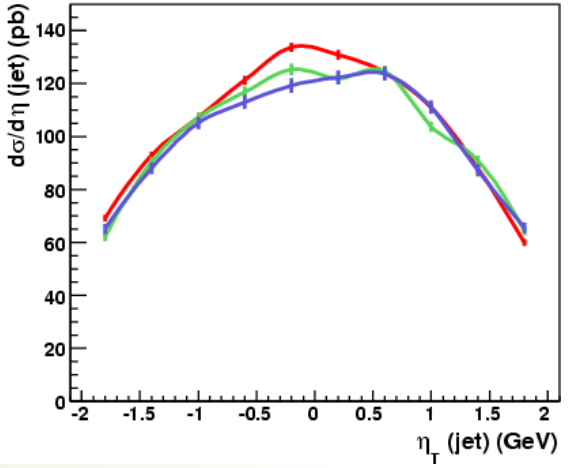
γ+jet PDF uncertainties

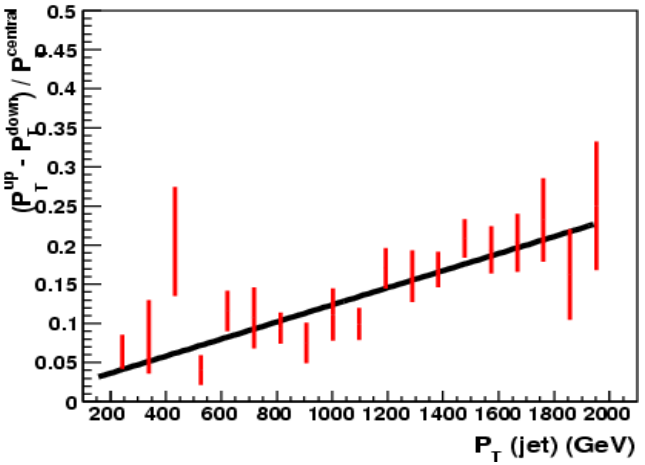






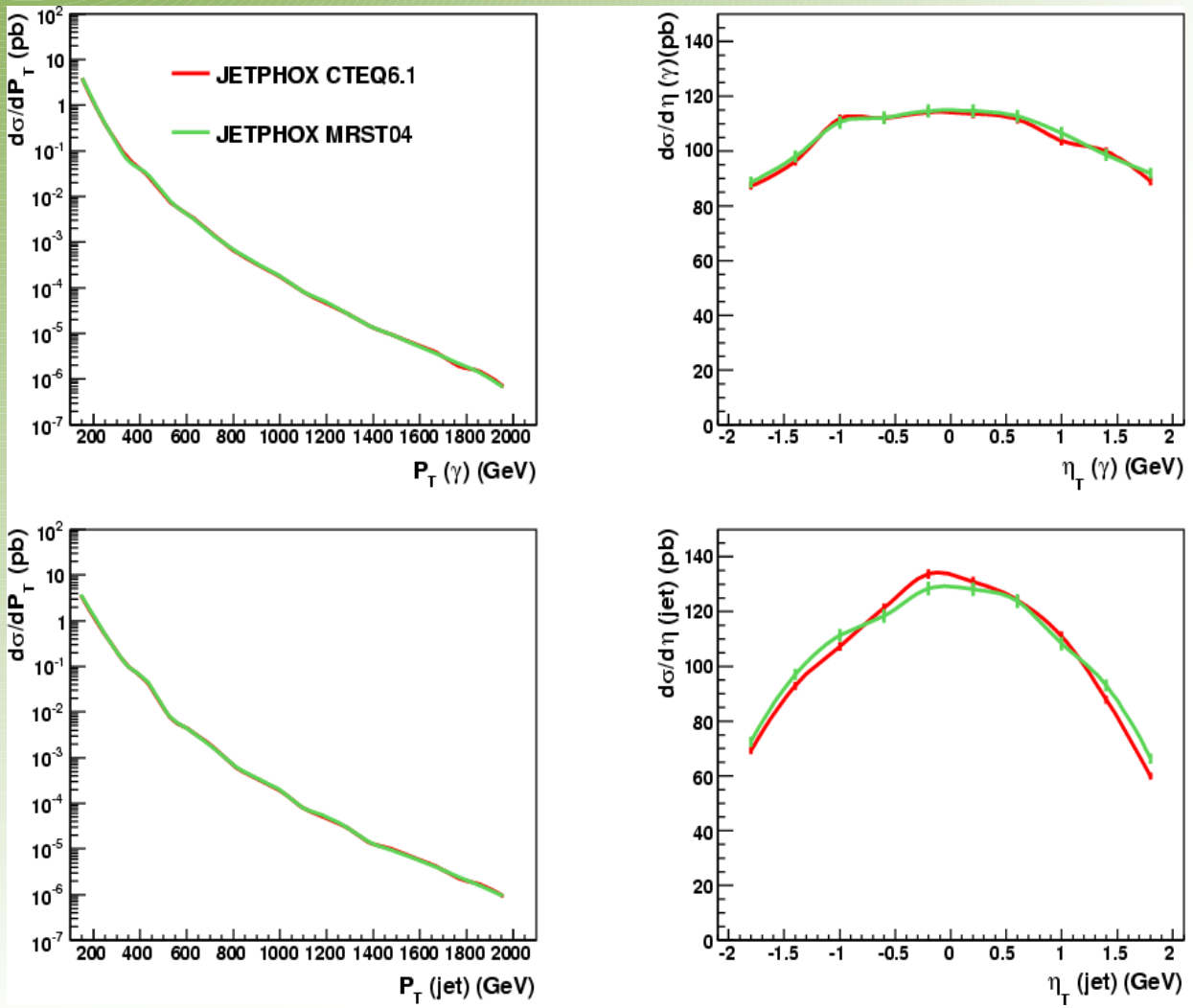






- PDF uncertainty estimated from two CTEQ6.1 sets (+15,-15)
  - corresponds to extremes of the gluon PDF at large x
    D.Stump, J.Huston, J.Pumplin, Wu-Ki Tung, H. L. Lai, S.Kuhlmann, J. F. Owens (JHEP 0310 (2003) 046
- Relative PDF uncertainty increases with P_T and reaches ~20% at 2 TeV

γ+jet: CTEQ6.1 vs MRST04



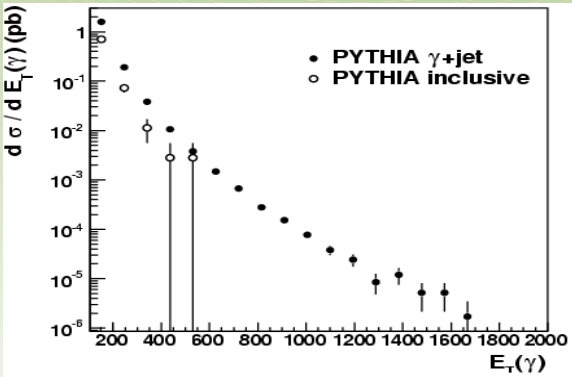
- **Differences between CTEQ6.1 and MRST04 are small**

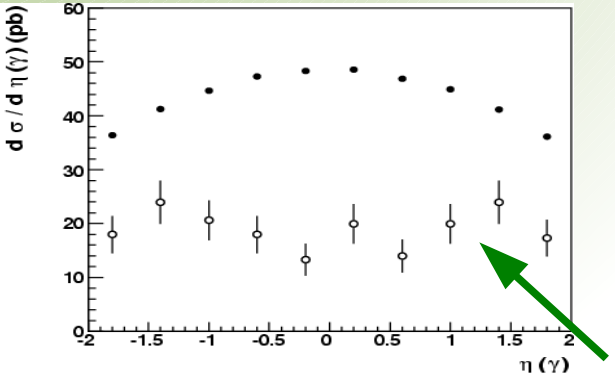
A glimpse of γ+jet of reconstruction

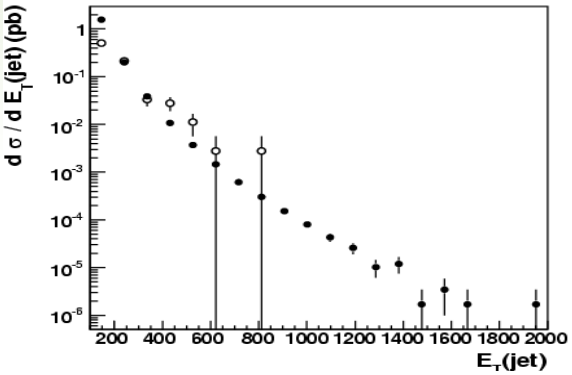
- Use ATLfast simulation:
  - 2 samples: MSEL=10 (prompt photons, 0.5 fb^{-1})
    MSEL=1 (inclusive pp +MI, 0.2 pb^{-1})
  - Build K_T jets from clusters. Same P_T and η cuts as before

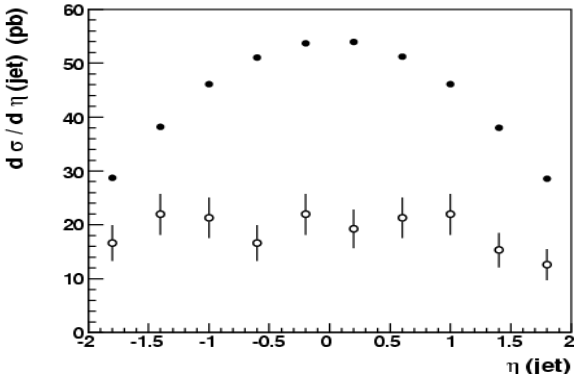
σ(MSEL=1) / σ(MSEL=10) ~ 2000

- Photon candidate requirements:
  - E(EMC)/E(tot)>0.9 + no tracks with pT>1 GeV within the cone R=1









Question:
Can we have reasonable photon purity assuming a huge rate from inclusive QCD process?

Cross section generated by PYTHIA for inclusive pp events (MSEL=1) without prompt photons

- "fake" photons mainly from π^0
- estimated from 3.5M events (0.2 pb^{-1})

Looks rather promising

Summary

- Difference between fixed-order QCD and PYTHIA/HERWIG models
  - mainly at low P_T
  - also HERWIG is below PYTHIA
  - consistent with the observation at HERA
- Cone and K_T jet algorithms give rather similar results for NLO calculations
- Theoretical uncertainties:
  - scale uncertainty ~10%, almost independent of P_T
  - PDF uncertainty is rising to 20% at 1-2 TeV
    - due to the uncertainty on gluon PDF at large x
  - differences between CTEQ6.1 and MRST04 are small
- First attempt to reconstruct γ+jet from a fast simulation looks promising
- Comparisons with BFKL-type calculations will come soon