M. Krawczyk
M. Wing
S. Söldner-R.

TERA

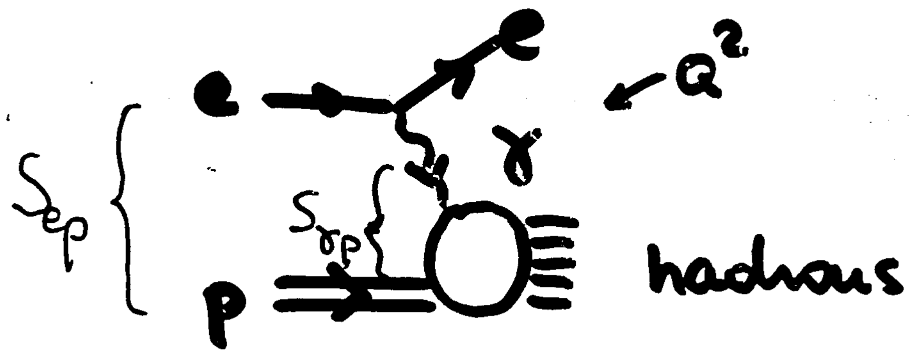
Energy : e - 250 GeV

p - 920 GeV

$s_{ep} = 9.2\,10^5\,\text{GeV} \sim 1\,\text{TeV}^2$

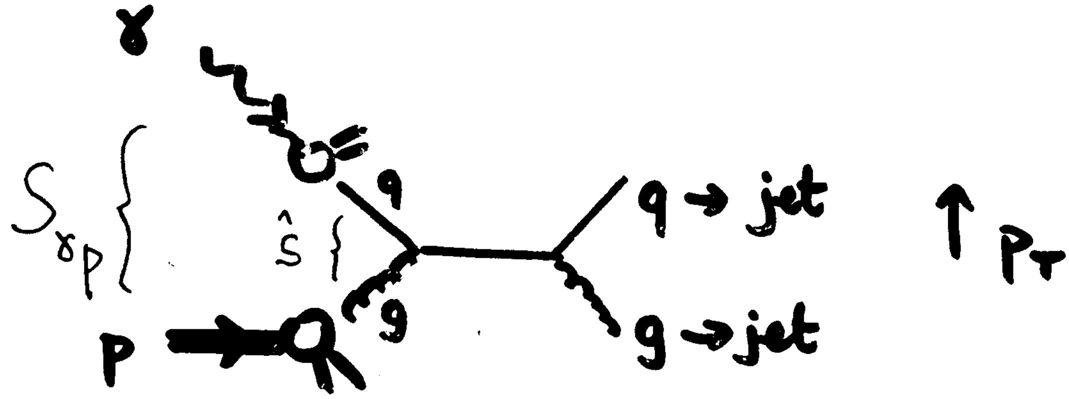
$\sqrt{s_{ep}} = 959\,\text{GeV} \sim 1\,\text{TeV}$

Photon-hadron interaction at high energy ~ 1 TeV



- HARD PROCESSES for $Q^2 \lesssim 1\,\mathrm{GeV}^2$ with $E_\gamma = y E_e$ $y \in 0.2 - 0.8$

⇝ resolved photon processes



$$\boxed{\hat{s} = x_p x_\gamma \underbrace{y S_{ep}}_{S_{\gamma p}}} \qquad \hat{s} \geq 4 p_T^2$$

γp at $\sqrt{s_{\gamma p}} \leq 1$ TeV

e^+e^-		ep	
LEP	(TESLA?)	HERA	TERA

$1 < Q^2 < 10^3 \quad \rightarrow \quad 25 < E_T^2 < 10^3 \quad 10^2 < E_T^2 < 10^4$

(all in GeV^2)

$\underbrace{5 \cdot 10^{-3}}_{Q^2 \approx 2\,\mathrm{GeV}^2} < x < 1 \quad \rightarrow \quad 10^{-1} < x_\gamma < 1 \quad 5 \cdot 10^{-4} < x_\gamma < 1$

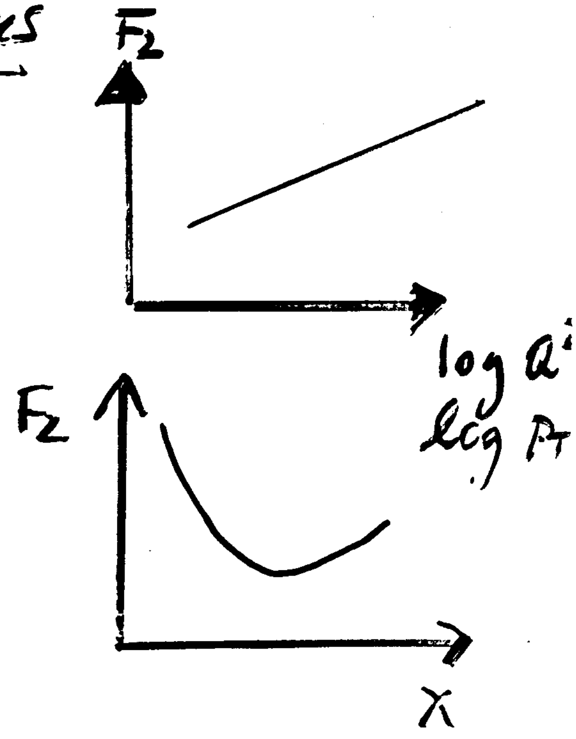
mainly quarking

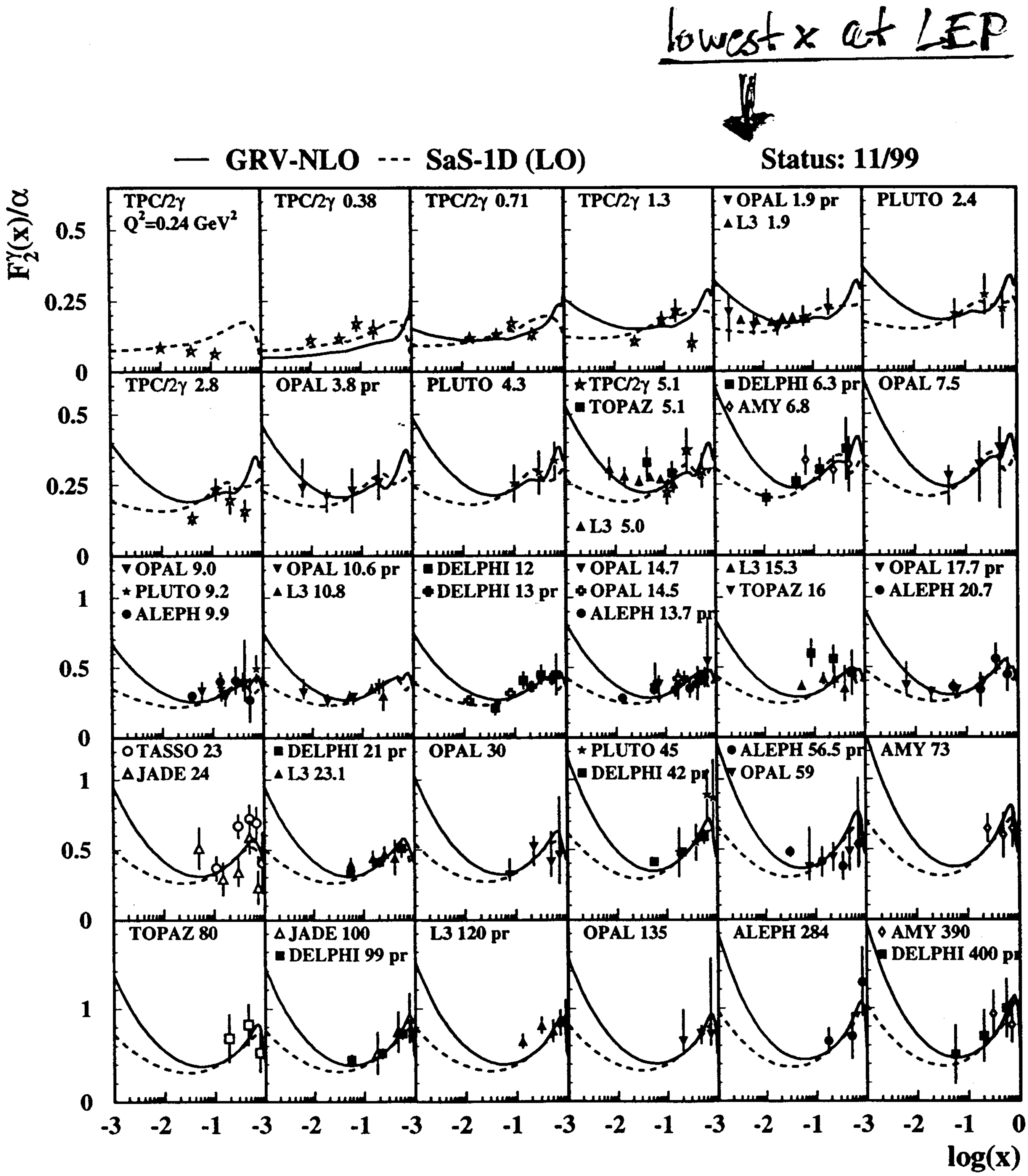
mainly gluoning

Two interesting regions

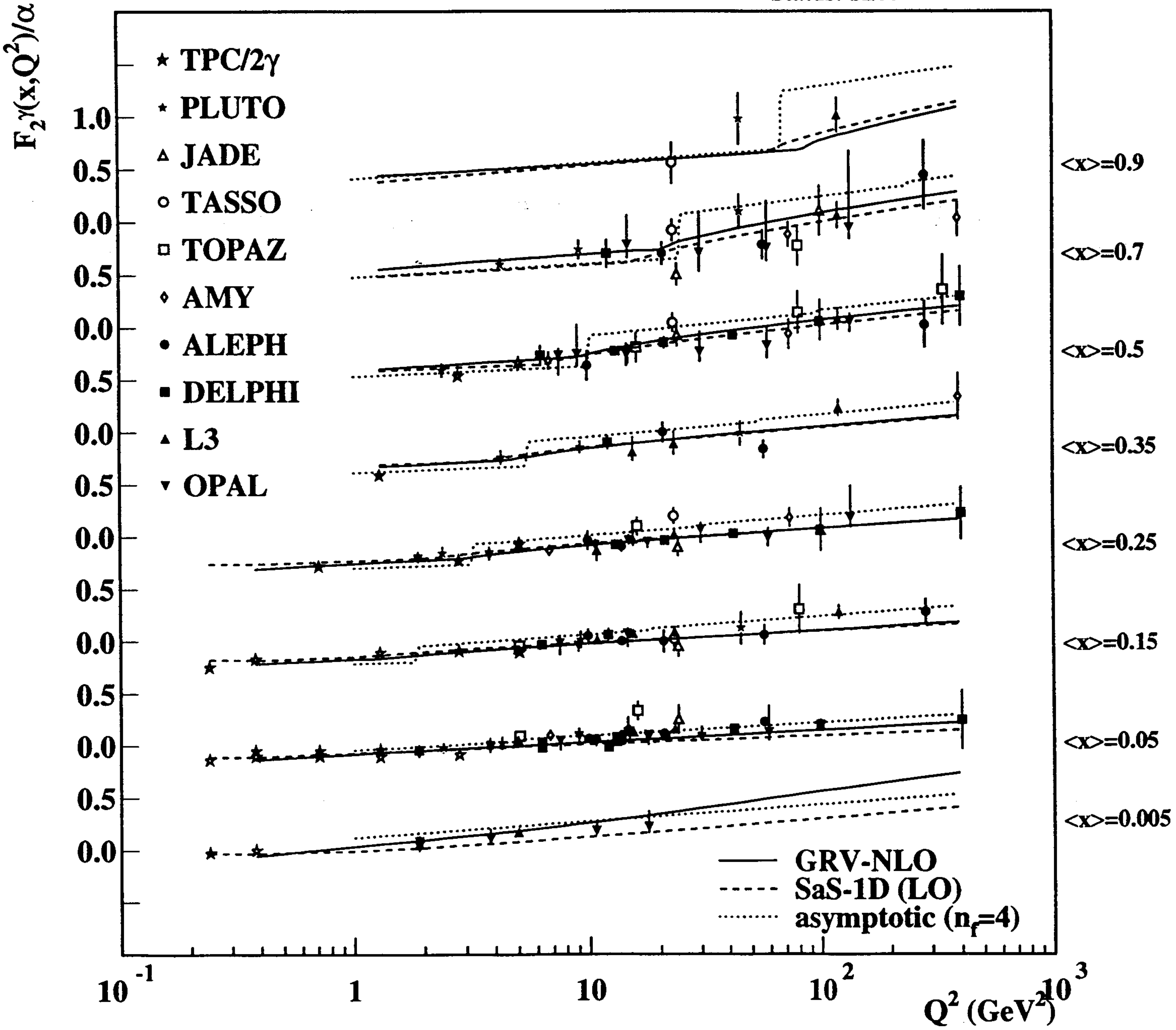
1) very high Q^2, medium x

2) very low x




lowest x at LEP
— GRV-NLO --- SaS-1D (LO)
Status: 11/99
$F_2^\gamma(x)/\alpha$
TPC/2γ Q^2=0.24 GeV^2
TPC/2γ 0.38
TPC/2γ 0.71
TPC/2γ 1.3
OPAL 1.9 pr
L3 1.9
PLUTO 2.4
TPC/2γ 2.8
OPAL 3.8 pr
PLUTO 4.3
TPC/2γ 5.1
TOPAZ 5.1
L3 5.0
DELPHI 6.3 pr
AMY 6.8
OPAL 7.5
OPAL 9.0
PLUTO 9.2
ALEPH 9.9
OPAL 10.6 pr
L3 10.8
DELPHI 12
DELPHI 13 pr
OPAL 14.7
OPAL 14.5
ALEPH 13.7 pr
L3 15.3
TOPAZ 16
OPAL 17.7 pr
ALEPH 20.7
TASSO 23
JADE 24
DELPHI 21 pr
L3 23.1
OPAL 30
PLUTO 45
DELPHI 42 pr
ALEPH 56.5 pr
OPAL 59
AMY 73
TOPAZ 80
JADE 100
DELPHI 99 pr
L3 120 pr
OPAL 135
ALEPH 284
AMY 390
DELPHI 400 pr
log(x)

Status: 11/99



$F_2^\gamma(x,Q^2)/\alpha$
TPC/2γ
PLUTO
JADE
TASSO
TOPAZ
AMY
ALEPH
DELPHI
L3
OPAL
1.0
0.5
0.0
<x>=0.9
<x>=0.7
<x>=0.5
<x>=0.35
<x>=0.25
<x>=0.15
<x>=0.05
<x>=0.005
GRV-NLO
SaS-1D (LO)
asymptotic (n_f=4)
10^{-1}
1
10
10^2
10^3
Q^2 (GeV^2)

Witten (77, LO), Bardeen & Buras (80, NLO):

$$\frac{F_2^\gamma}{\alpha} = \frac{a(x)}{\alpha_s(Q^2)} + b(x)$$

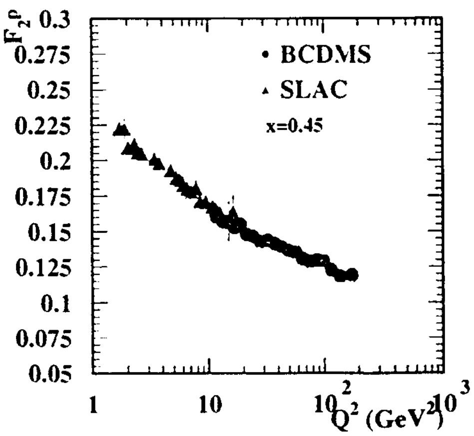
$a(x), b(x)$ **calculable, but divergent for** $x \to 0$

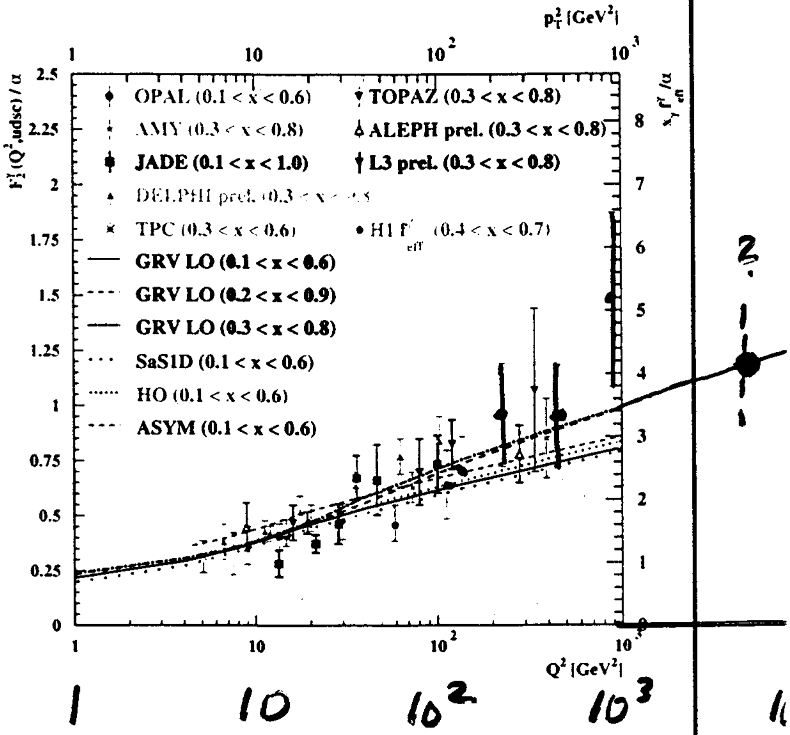
non-perturbative Input (VDM) needed

$\Rightarrow$ **largest systematic uncertaintly**

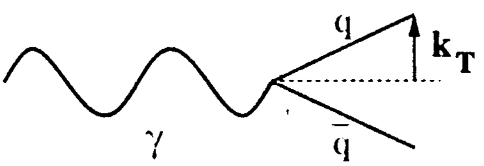
hadronic contribution is about 15 % at $x = 0.5, Q^2 = 59$ **GeV**^{2}

Scaling Violation





Important prediction of perturbative QCD

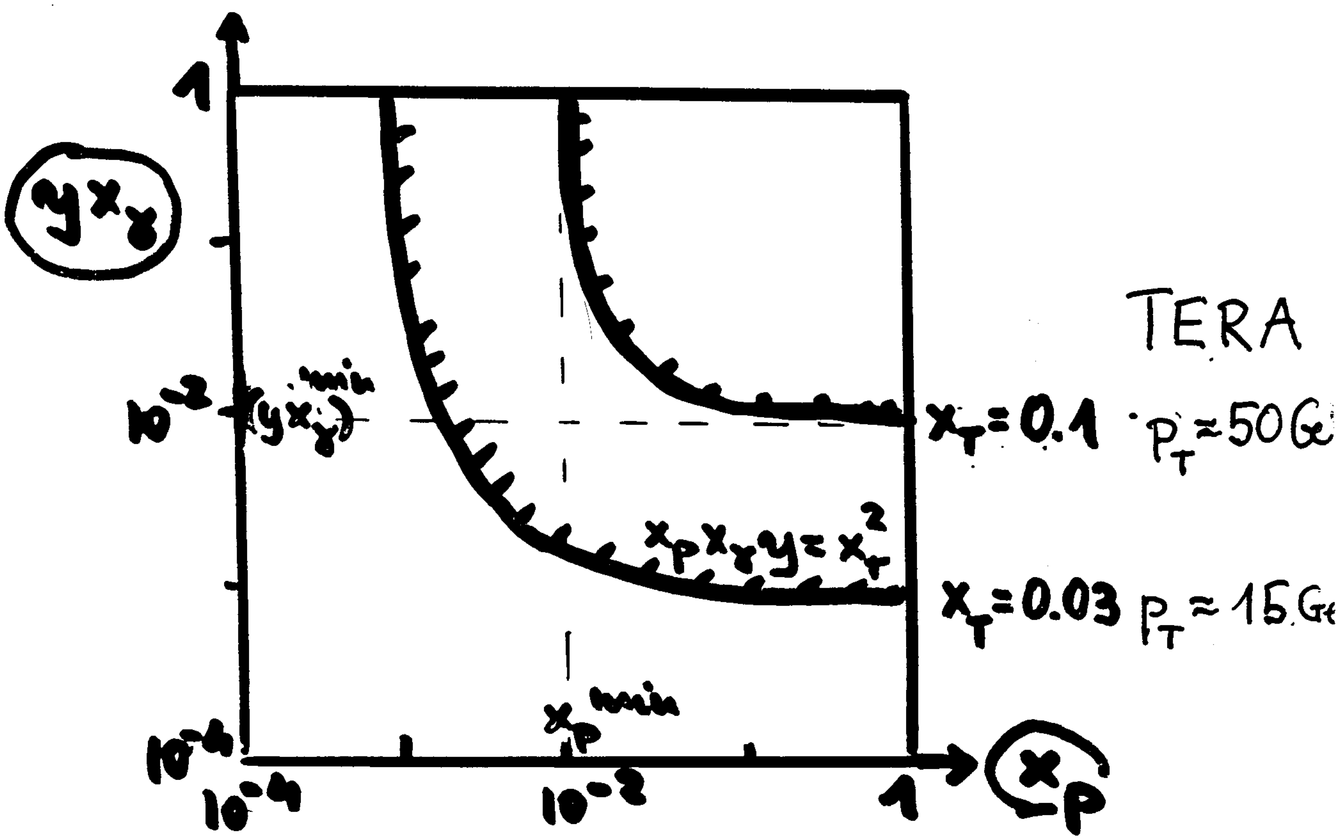


Kinematics

$\hat{s} = x_p x_\gamma y S_{ep}$ $\hat{s} \geq 4p_T^2$

$x_T = \frac{2p_T}{\sqrt{S_{ep}}}$ $\rightarrow$ $x_p x_\gamma y = \frac{\hat{s}}{S_{ep}} \geq x_T^2$

min x ? $\rightsquigarrow$ $x_p^{min} = x_\gamma^{min} = x_T^2$

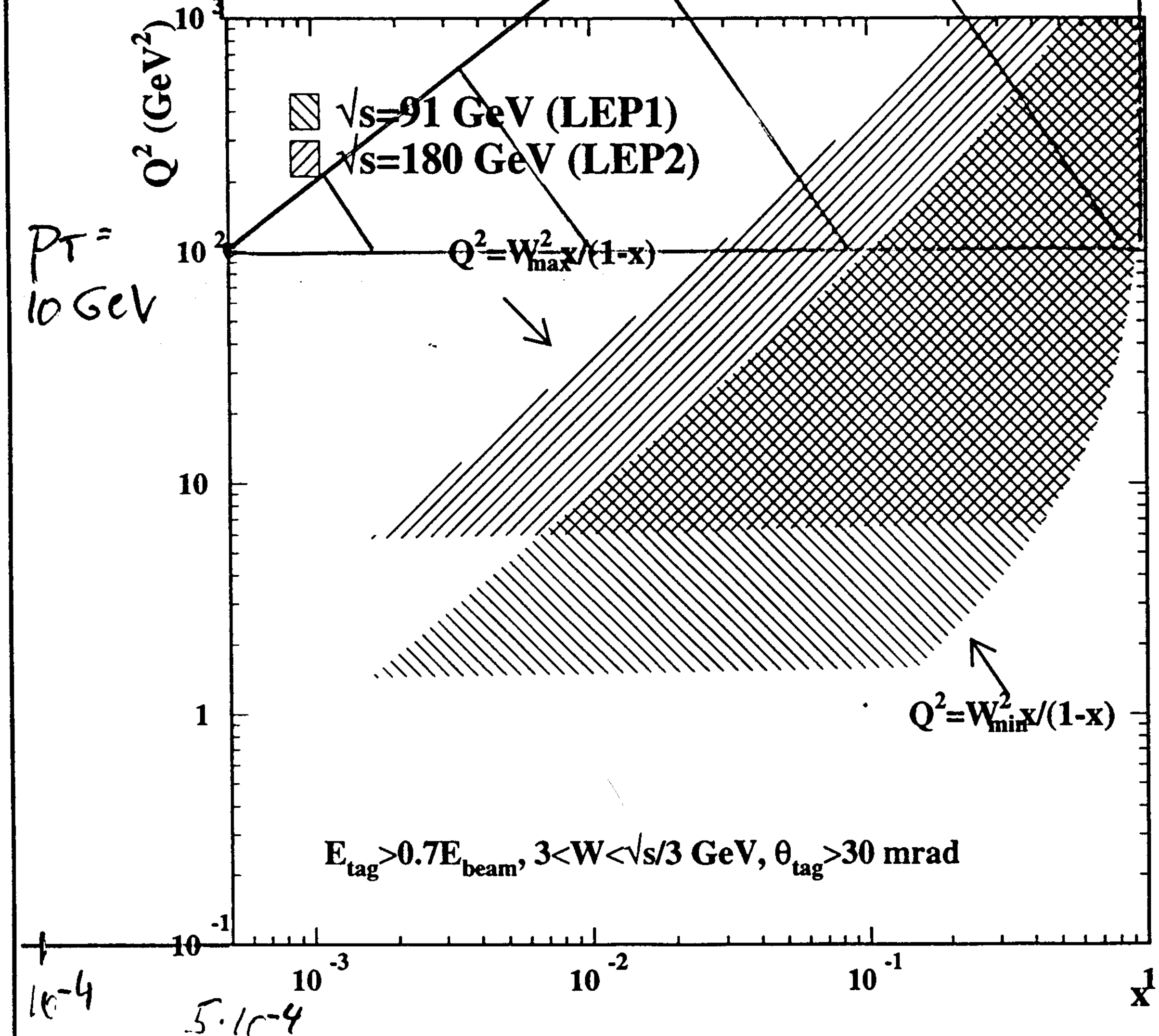


TERA for $p_T = 10$ GeV :

$x_\gamma^{min} = 2.2 \cdot 10^{-3}$ $y = 0.2$ $(E_\gamma = y E_p)$

$= 5.4 \cdot 10^{-4}$ $y = 0.8$

F_2^γ at LEP I and LEP II



$$Q^2 \approx 2E_{\rm beam}E_{\rm tag}(1-\cos\Theta_{\rm tag})$$

Identical Q^2 ranges can be covered with different detectors at LEP1 and LEP2

List of topics

1) Jets — M. Wing, J. Butterworth, M. Klasen

2) Heavy quarks (charm / bottom) — J. Butterworth, P. Jankowski

3) Prompt photons — M. Krawczyk + student

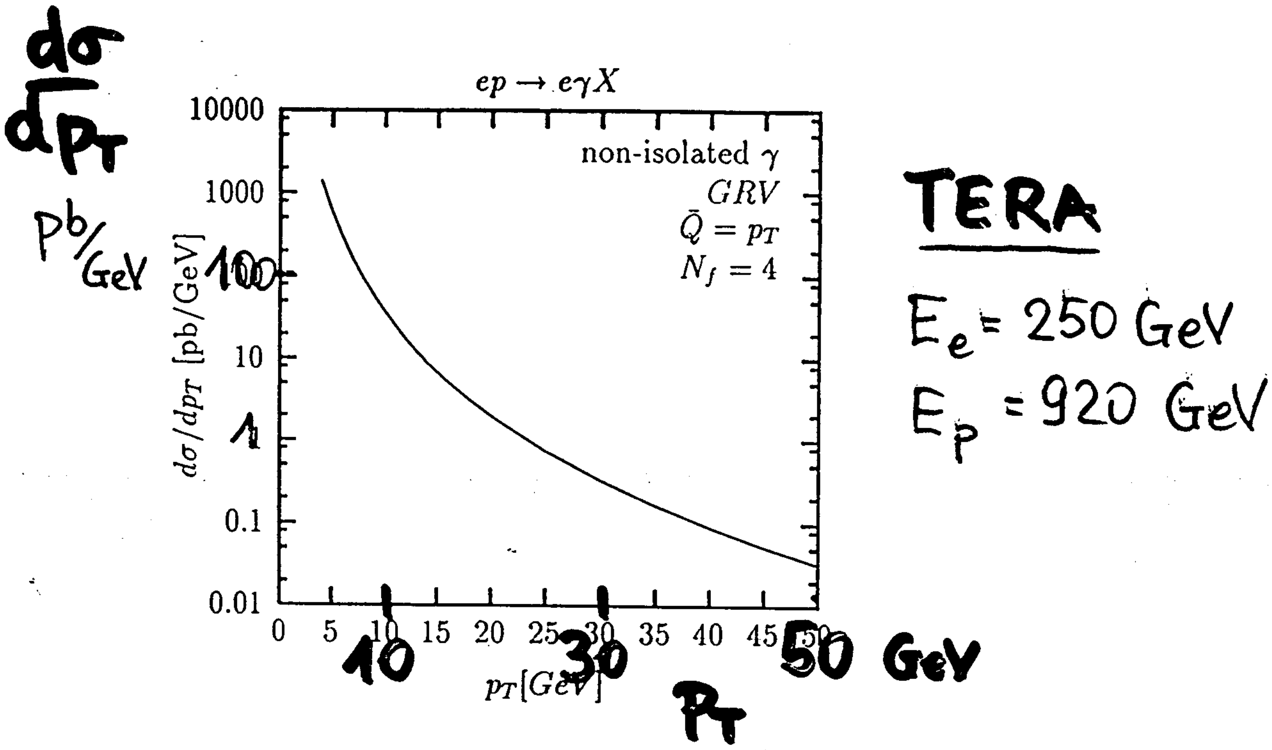
4) Virtual photon structure

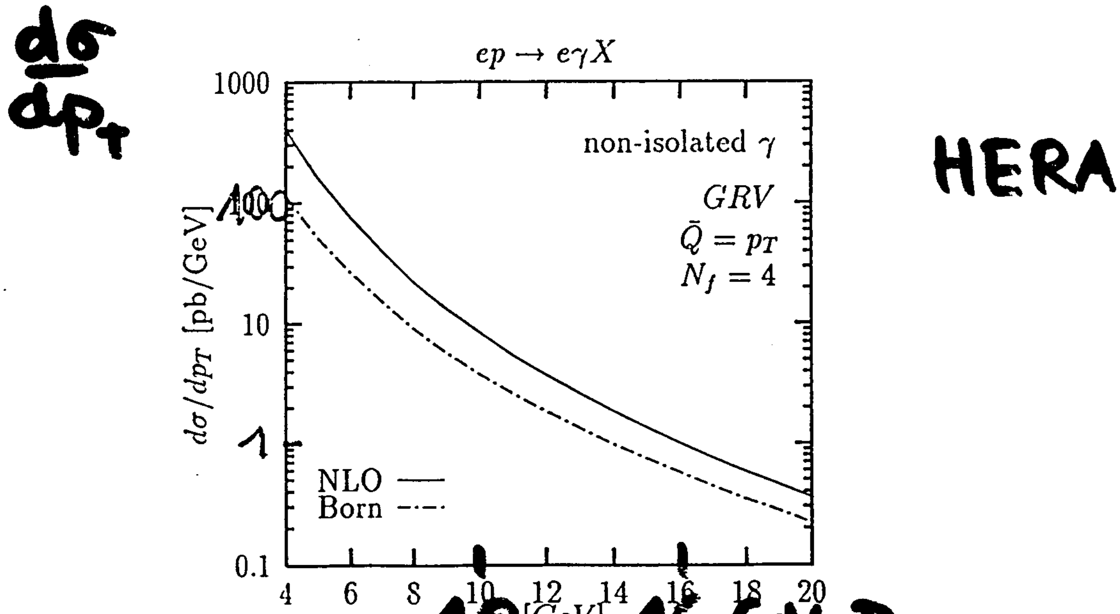
5) Polarisation

(6) $\sigma_{tot}^{\gamma p} \rightarrow$ low x ?)

from LEP: Bernd Surrow, Albert de Roeck, Stefan Söldner-Rembold

PROMPT PHOTON PRODUCTION





The final photon p_T-dependence of the cross section $d\sigma/dp_T$ for non-isolated γ photoproduction calculated in NLO$_+$ accuracy (solid lowest order Born contribution is shown separately (dash-dotted line). The results are obtained using GRV NLL parametrizations gmentation function and for parton densities in the proton and photon. The scale $\bar{Q}$ is assumed equal to the final photon transverse n. The number of active flavours is $N_f = 4$.

A.Zembruski, MK

Kinematics

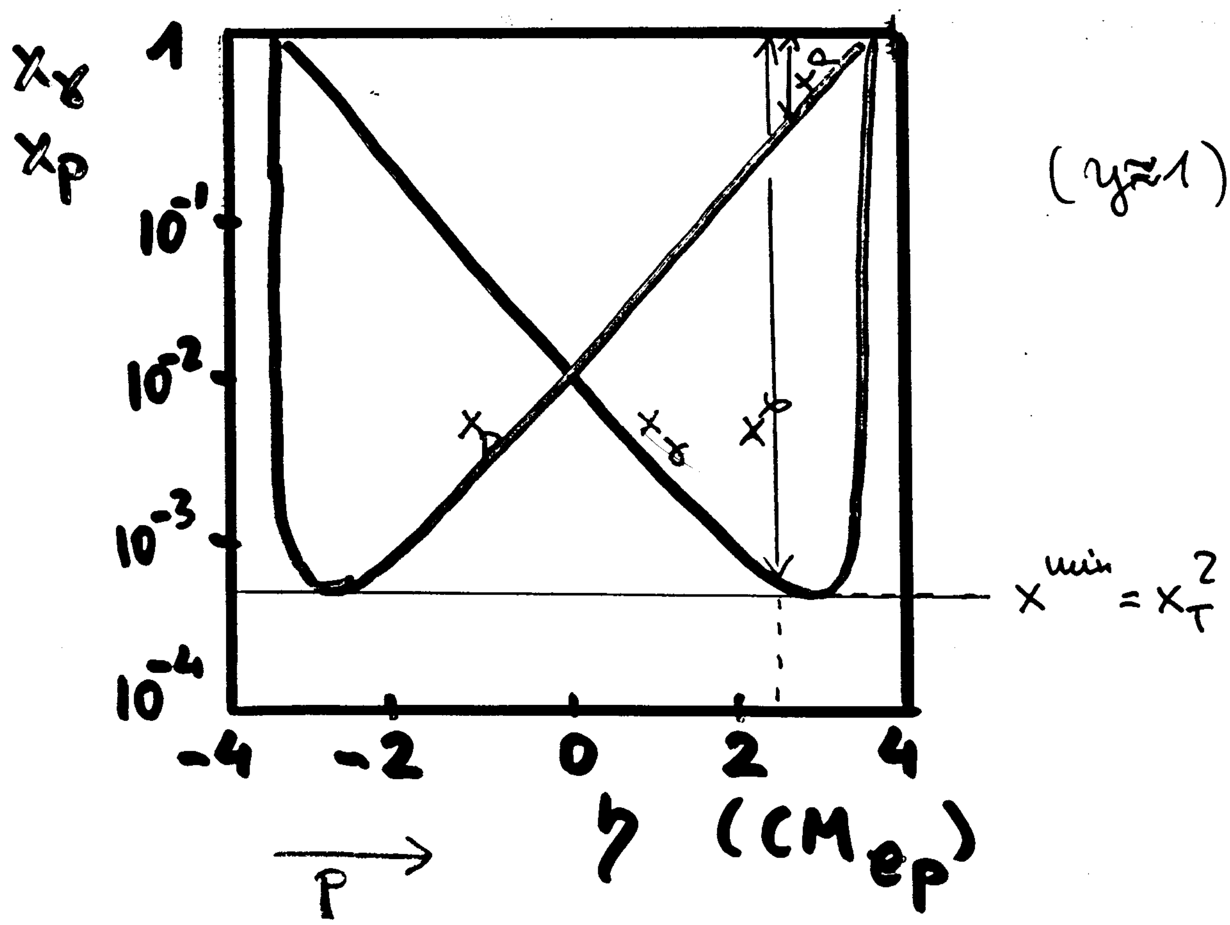
At fixed $p_T \rightarrow \underline{x_T}$

⇝ range x_γ (η - pseudorapidity (= Y for mass = 0)

⇝ range $x_p (\eta)$

$$x_\gamma^{min}(\eta) = \frac{x_T e^{\eta}}{2 - x_T e^{-\eta}} \quad CM$$

$x_p^{min} \rightarrow (\eta \rightarrow -\eta)$



the lowest x_γ^{min} at $\eta_0 = -\ln x_T$

TERA $\quad \eta^{max}|_{CM} = \ln \tan \frac{\arcsin x_T}{2} = \underline{4.6}$ (p_T=10 GeV

$E_e = 250$ GeV
$E_p = 920$ GeV

$$\eta^{max}|_{LAB} = \eta^{max}|_{CM} + 0.65$$

Questions

- **timeframe of project?**

photon structure can also be studied at TESLA (perhaps even in $e\gamma$ or $\gamma\gamma$ mode)

- **detector requirements?**

no detailed study necessary, but we (I) must understand

$\eta \leftrightarrow x_\gamma$ mapping

jet energy/position resolution

Dijet Photoproduction and Photon Structure at TERA

Matthew Wing (McGill Univ.)

and

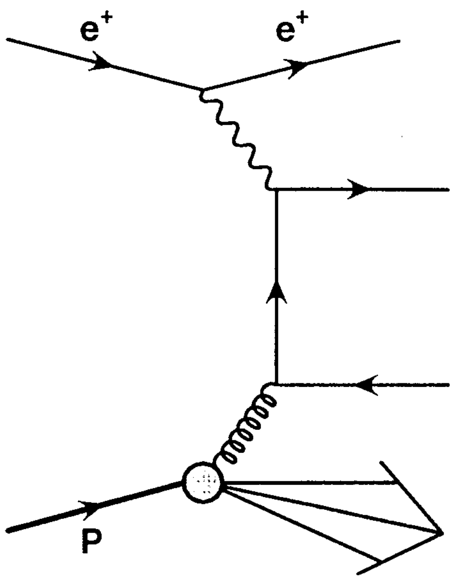
Jon Butterworth (UCL)

TERA Workshop

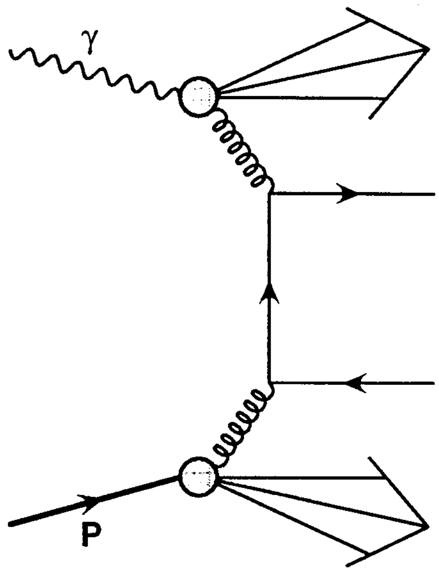
9 February 2000

Introduction to Photoproduction

Leading Order (LO) picture:



Direct



Resolved

Resolved cross-section

$$d\sigma_{\gamma p\rightarrow cd} = \sum_{ab} \int_{x_p} \int_{x_\gamma} f_{p\rightarrow b}(x_p, \mu^2)\, f_{\gamma\rightarrow a}(x_\gamma, \mu^2)\, \mathcal{M}_{ab\rightarrow cd}$$

$\mu^2 \Rightarrow$ scale $\rightarrow (E_T^{\text{jet}})^2$

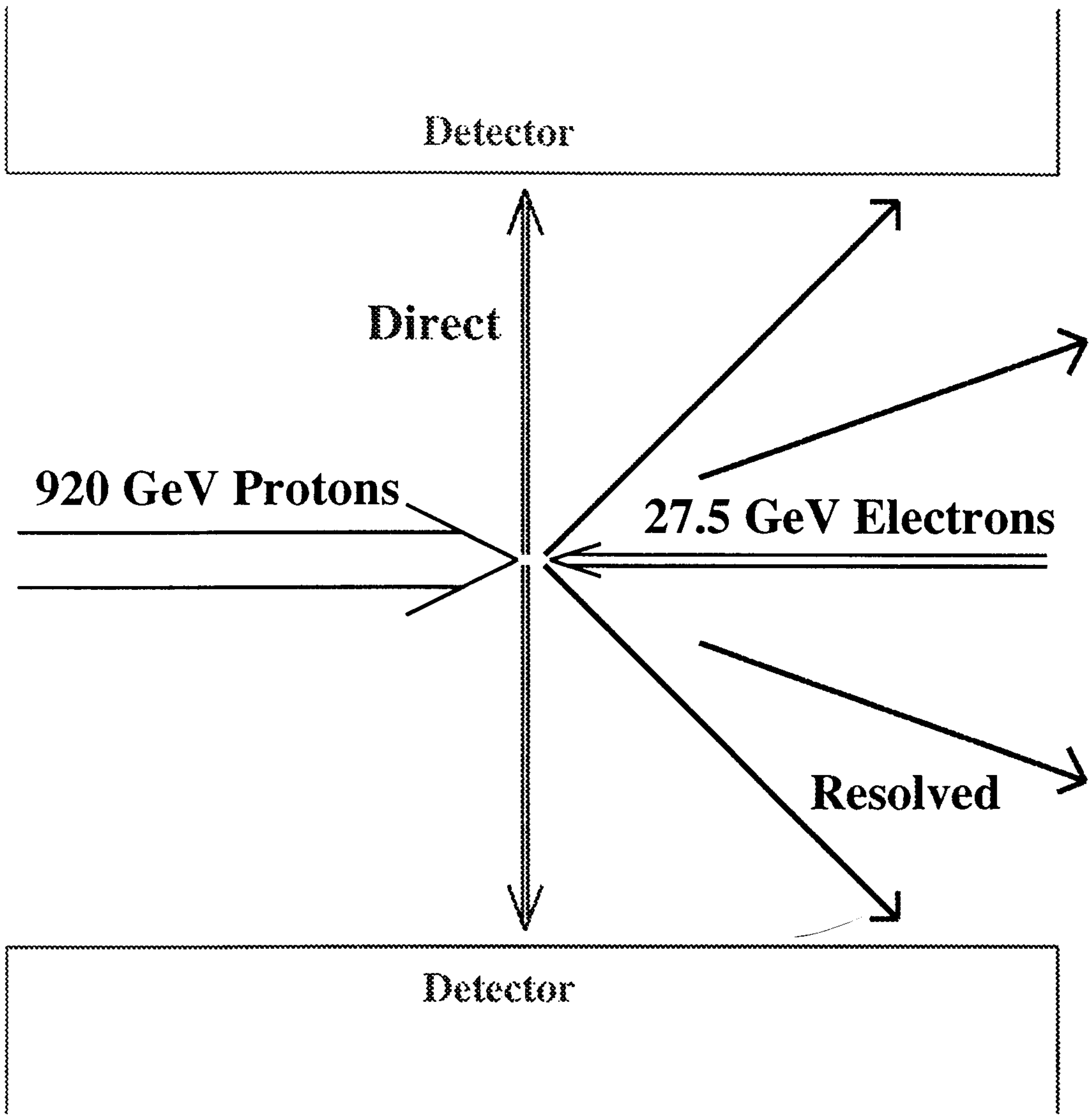
$\mathcal{M}_{ab\rightarrow cd} \Rightarrow$ perturbatively calculable

$f_{p\rightarrow b} \Rightarrow$ experimentally constrained

$f_{\gamma\rightarrow a} \Rightarrow$ photon structure?

Current Situation at HERA, $\sqrt{s} = 318$ GeV

Where are the resolved photon processes?



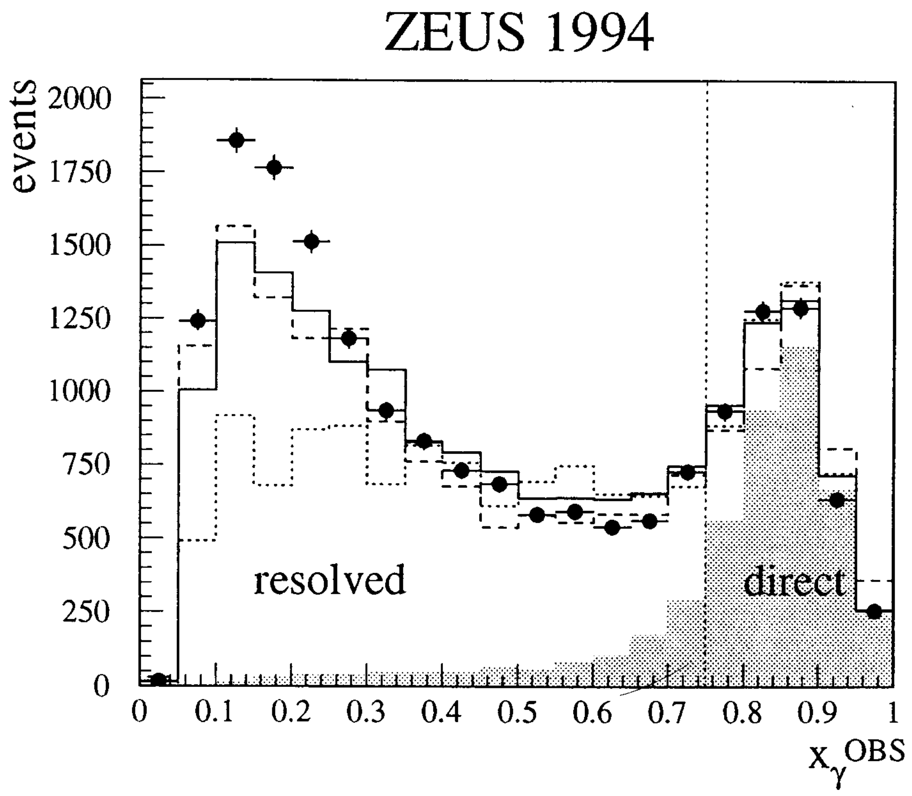
Due to large asymmetry in beam energies:

- Direct photon processes are centralised.
- Resolved photon processes in forward parts of the detector.
- Resolved processes have a large cross-section, but alot is lost in the forward region.

Dijet photoproduction at HERA; lower E_T^{jet}

Here $E_T^{\text{jet}} > 6$ GeV, data compared with MC:

$$x_\gamma^{\text{obs}} = \frac{E_T^{\text{jet1}} e^{-\eta^{\text{jet1}}} + E_T^{\text{jet2}} e^{-\eta^{\text{jet2}}}}{2yE_e}$$



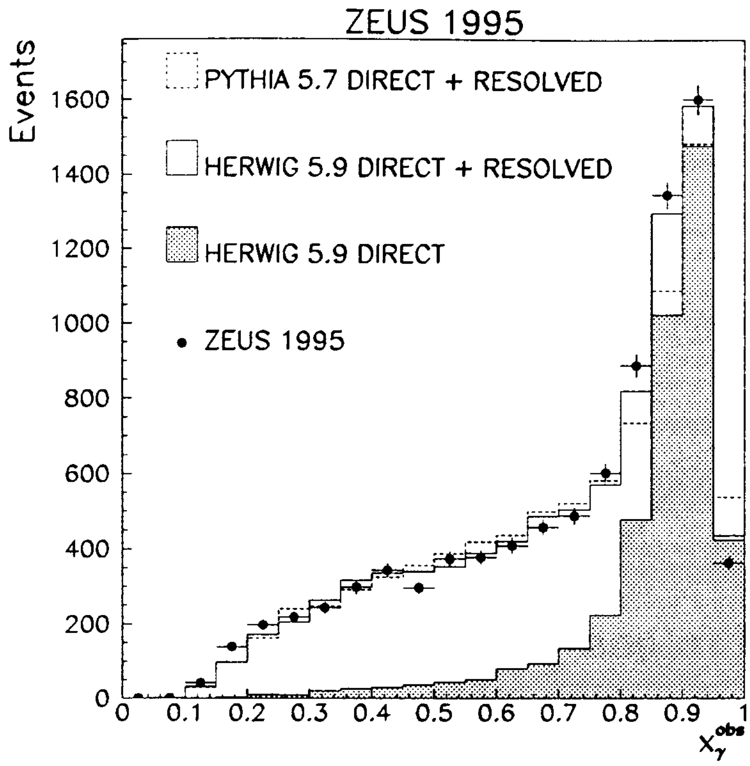
- Large resolved photon cross-section.

BUT:

- Need additional soft physics model to "describe" data.
- Additional soft physics is obstacle to photon structure sensitivity.
- Answer: goto higher E_T^{jet}

Dijet photoproduction at HERA; high E_T^{jet}

Now $E_T^{\text{jet}} > 14$ GeV, data compared with MC:



- The need for additional soft physics now gone.

- Obstacle to photon structure sensitivity, removed.

BUT:

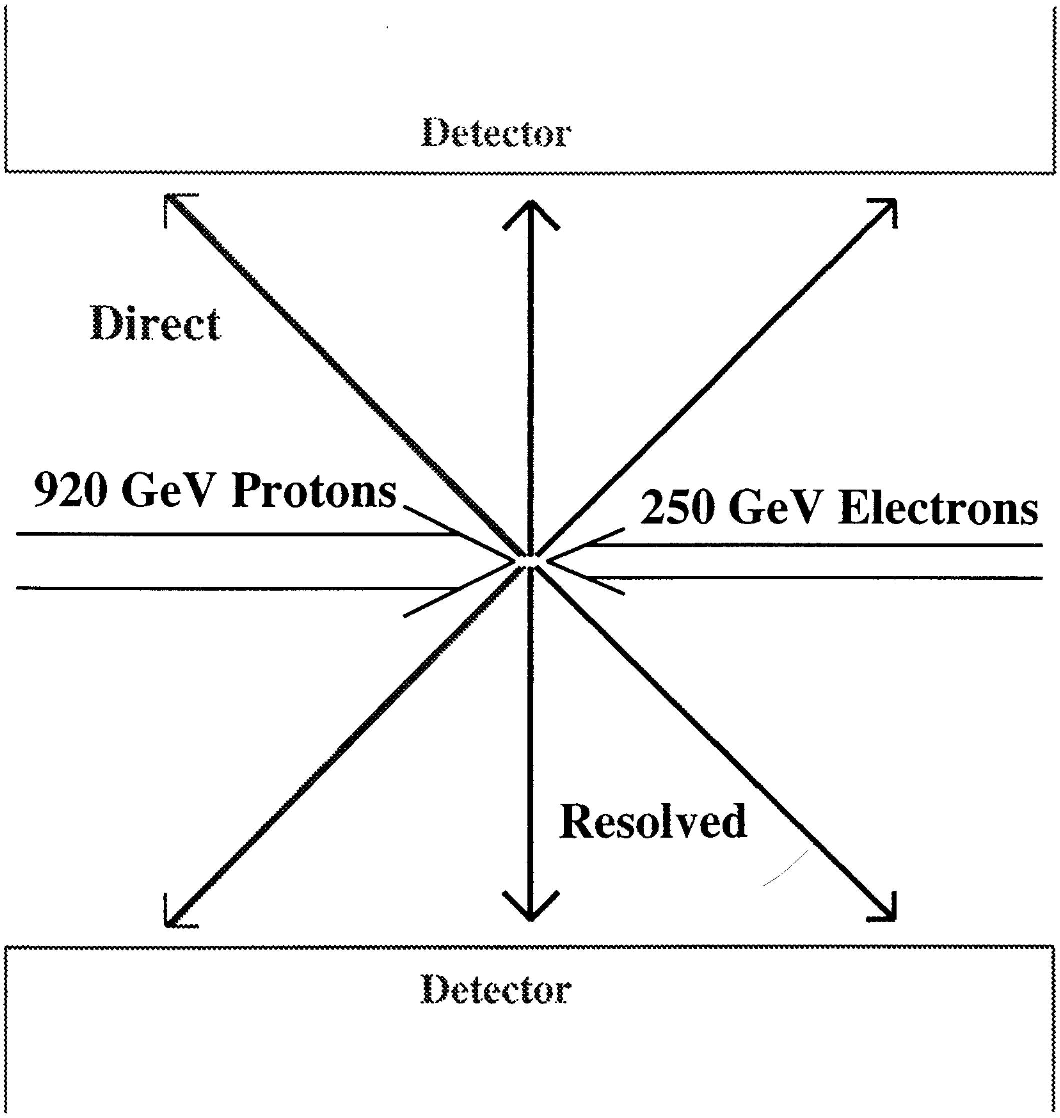
- Much reduced resolved photon cross-section.

AND:

- Loss of sensitivity at low x_γ^{obs}- resolved at higher values.

Potential Situation at TERA, $\sqrt{s} = 959$ GeV

Where are the resolved photon processes?



Due to reduced asymmetry in beam energies:

- Direct photon processes are more in rear part of detector.

- Resolved photon processes in *central* and forward parts of the detector.

Cross-Section Definition

Using 250 GeV electrons on 920 GeV protons.

Take the ZEUS 1995 high dijet analysis *

$$Q^2 < 1 \text{ GeV}^2$$

$$0.2 < y < 0.85$$

$$(429 < W_{\gamma p} < 884 \text{ GeV})$$

Two or more jets using k_T algorithm:

$$E_T^{\text{jet}1,2} > 14, 11 \text{ GeV}$$

$$-1 < \eta^{\text{jet}} < 2$$

With reference to ZEUS 1996/7 analysis † look at raising the E_T^{jet} cut.

*ZEUS Collab., J.Breitweg et al., *Eur. Phys. J.* **C11** (1999) 1, 35.

†ZEUS Collab., "Measurement of Dijet Photoproduction at High Transverse Energies at HERA" EPS-540.

How Predictions Generated

Using NLO program:

- Three photon structure functions: GRV-HO, GS96-HO and AFG-HO. Proton structure function, CTEQ-4M.
- Renormalisation and factorisation scales, $\mu = E_T^{\text{jet}}$
- Variation of scale, 2μ and $\mu/2$.
- Use two NLO programs from Frixione and Ridolfi ‡ and Klasen and Kramer §

  (NB. All plots with F. & R. except for comparison with K. & K.)

Using PYTHIA MC (in default mode):

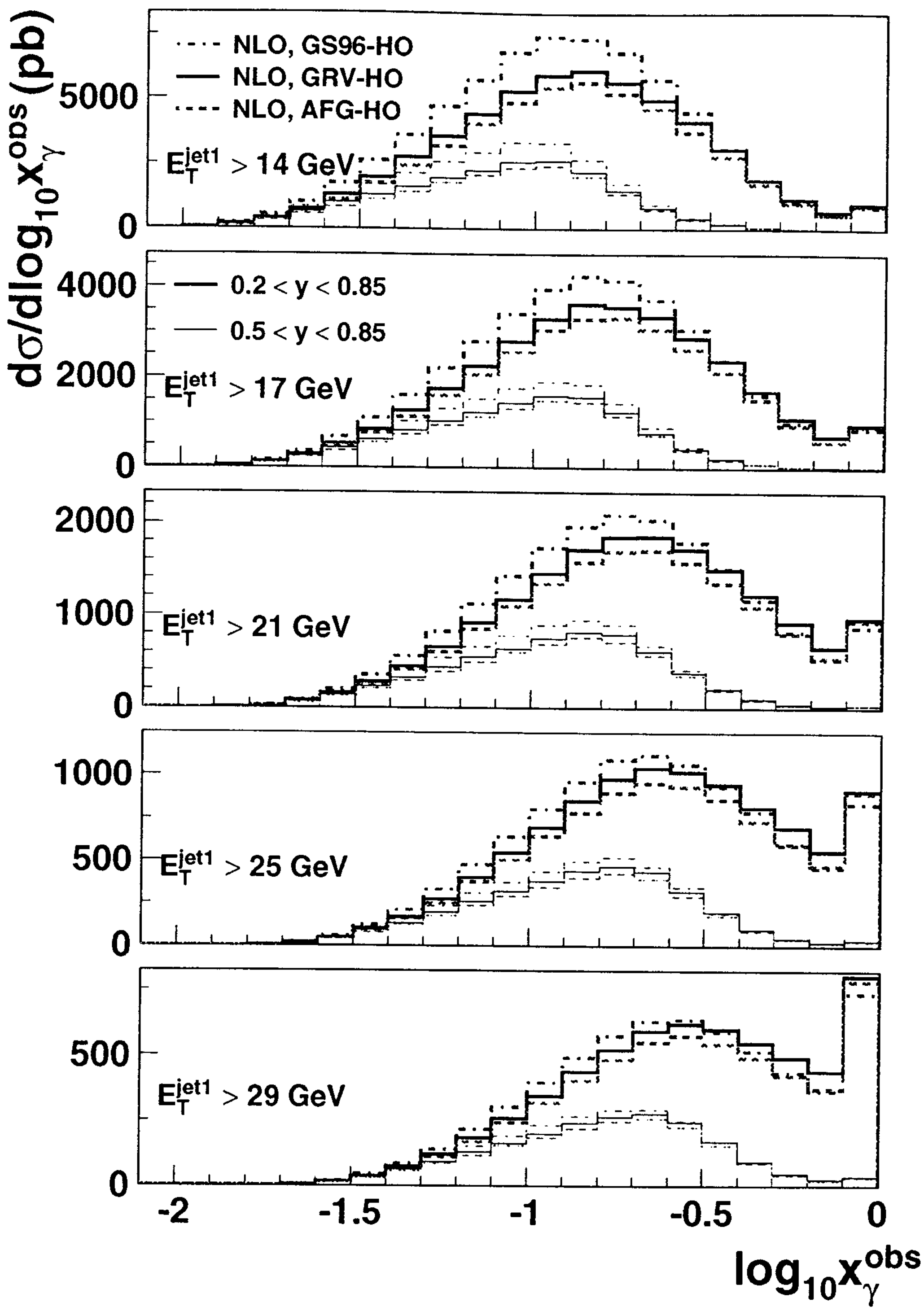
- Two photon structure functions: GRV-LO, SAS-1D. Proton structure function, GRV-LO.
- Also a charm plot (at lower E_T^{jet}).
- NB. only $\mathcal{L} \sim 200$ nb^{-1}.

‡S. Frixione, Z. Kunszt and A. Signer, *Nucl. Phys.* **B467** (1996) 399;
S. Frixione, *Nucl. Phys.* **B507** (1997) 295;
S. Frixione and G. Ridolfi, *Nucl. Phys.* **B507** (1997) 315.

§M. Klasen and G. Kramer, *Z. Phys.* **C76** (1997) 67;
M. Klasen, T. Kleinwort and G. Kramer, *Eur. Phys. J.* **C1** (1998) 1.

Cross-Sections in x_γ^{obs}

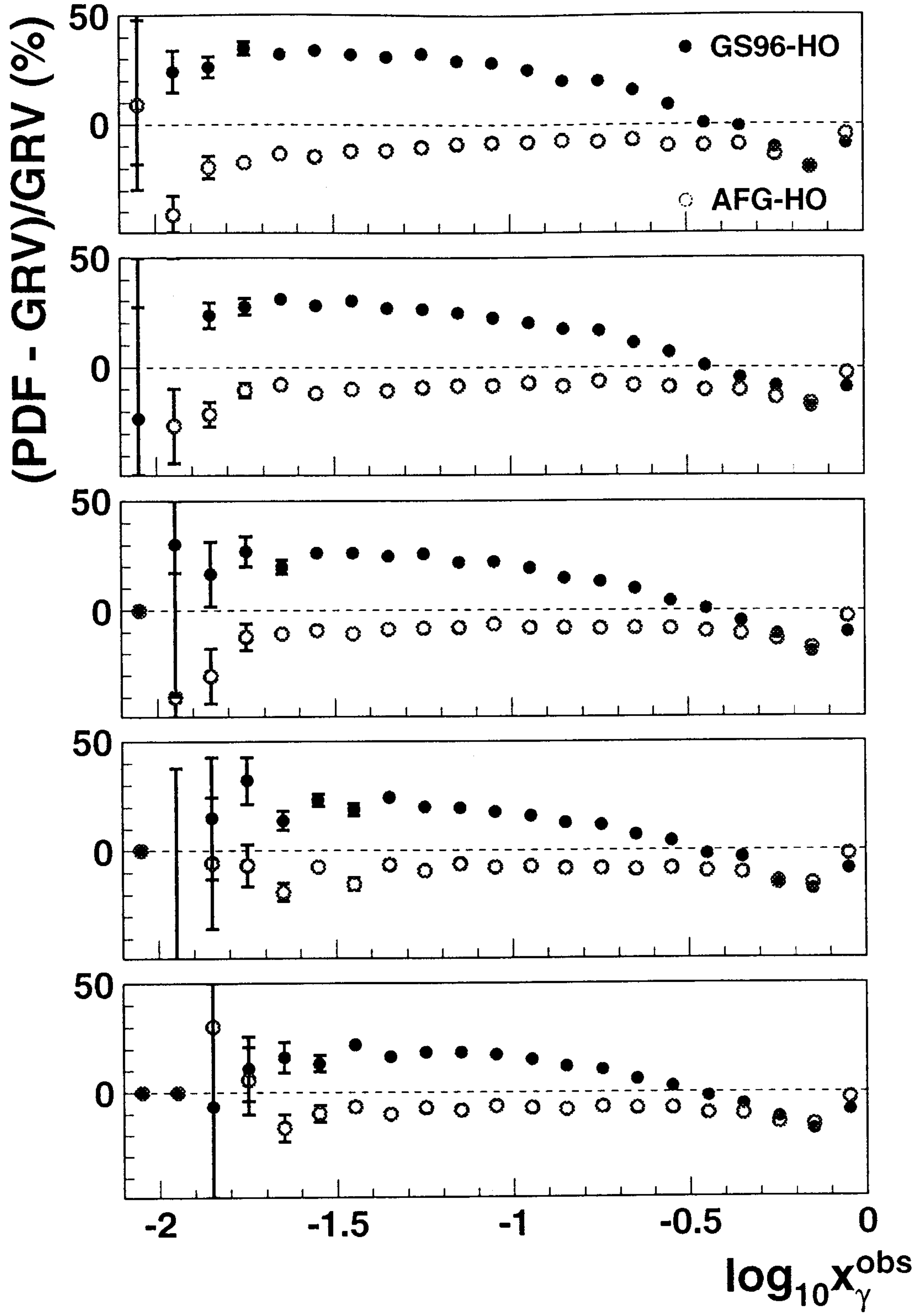
$$x_\gamma^{\text{obs}} = \frac{E_T^{\text{jet1}} e^{-\eta^{\text{jet1}}} + E_T^{\text{jet2}} e^{-\eta^{\text{jet2}}}}{2yE_e}$$



- Large cross-section at low x_γ^{obs}.
- Large variation due to structure function particularly at lower E_T^{jet}.

Differences in PDF

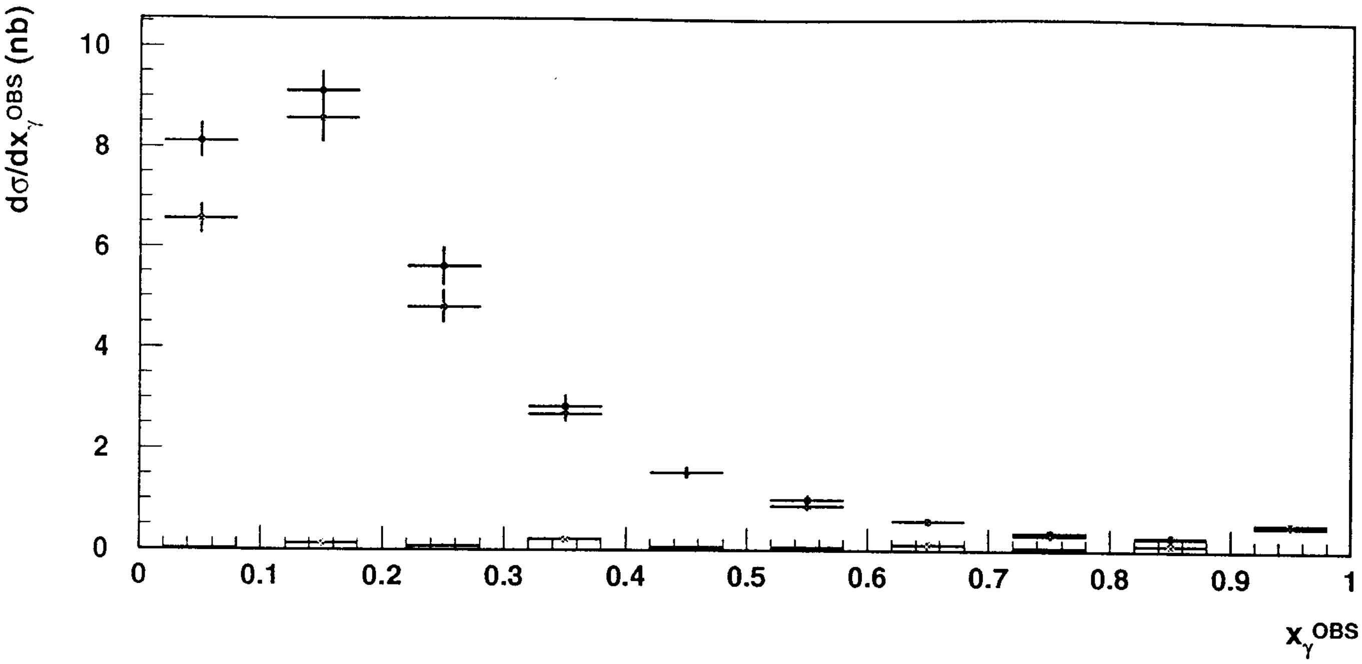
Look at differences with respect to GRV-HO.

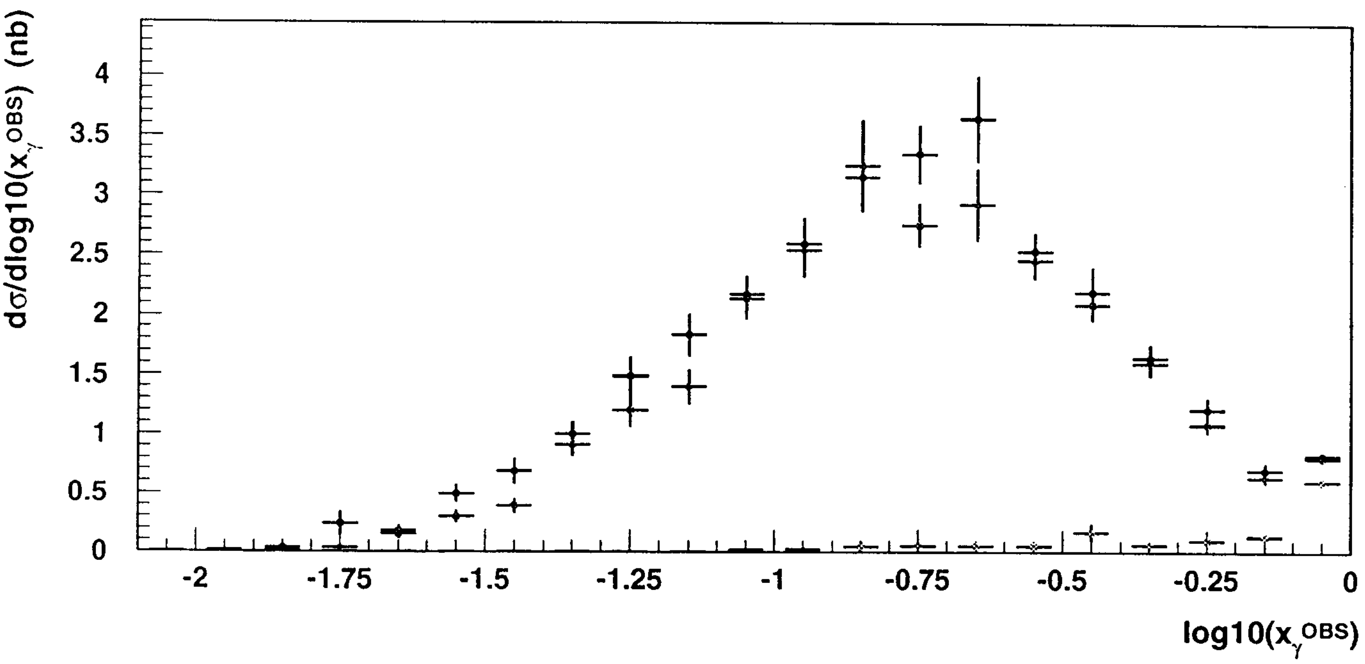


- GS96-HO about 30% higher at low $x_\gamma^{\rm obs}$. Difference decreasing with increasing $x_\gamma^{\rm obs}$.
- AFG-HO generally 10% lower than GRV-HO.

PYTHIA MC Cross-Sections in $x_\gamma^{\rm obs}$

black – GRV-LO, red – SaS-2D

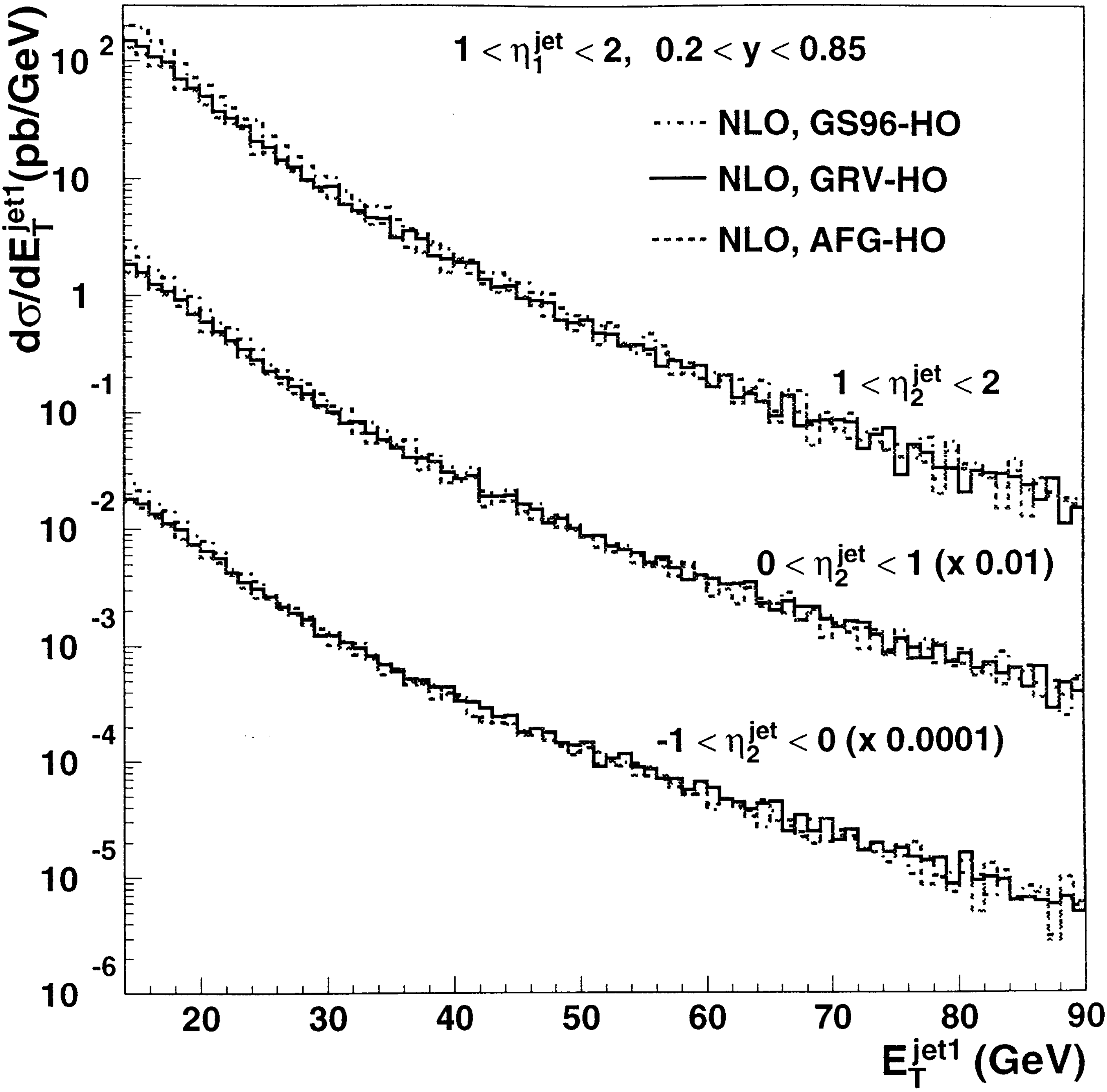




- Sensitivity to PDF also seen

Cross-Sections in $E_T^{\rm jet1}$ (1)

One jet must be forward:

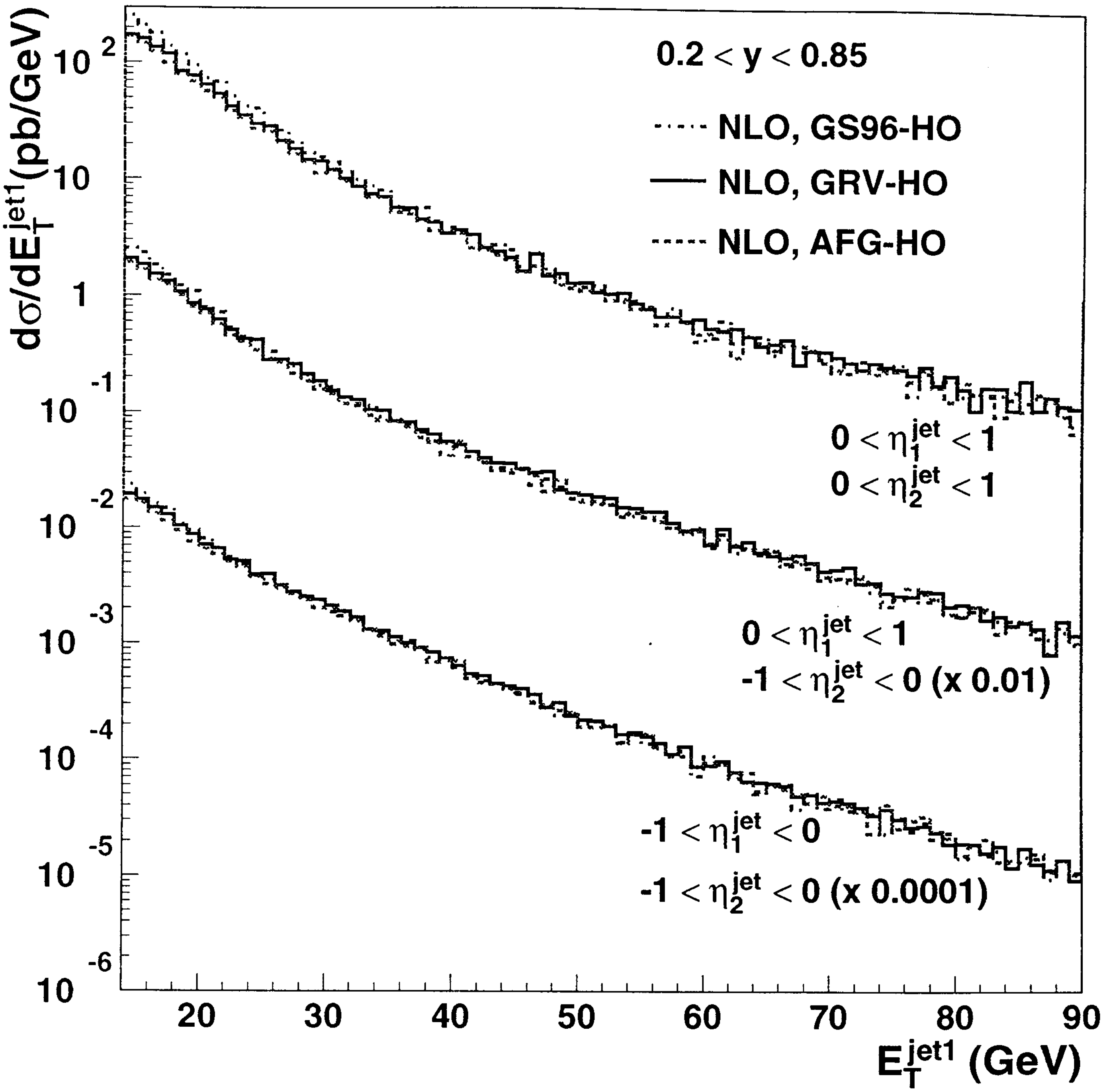


- GS96-HO clearly above at lower $E_T^{\rm jet1}$ and forward $\eta_2^{\rm jet}$.

- All three PDFs converge at high $E_T^{\rm jet1}$.

Cross-Sections in E_T^{jet1} (2)

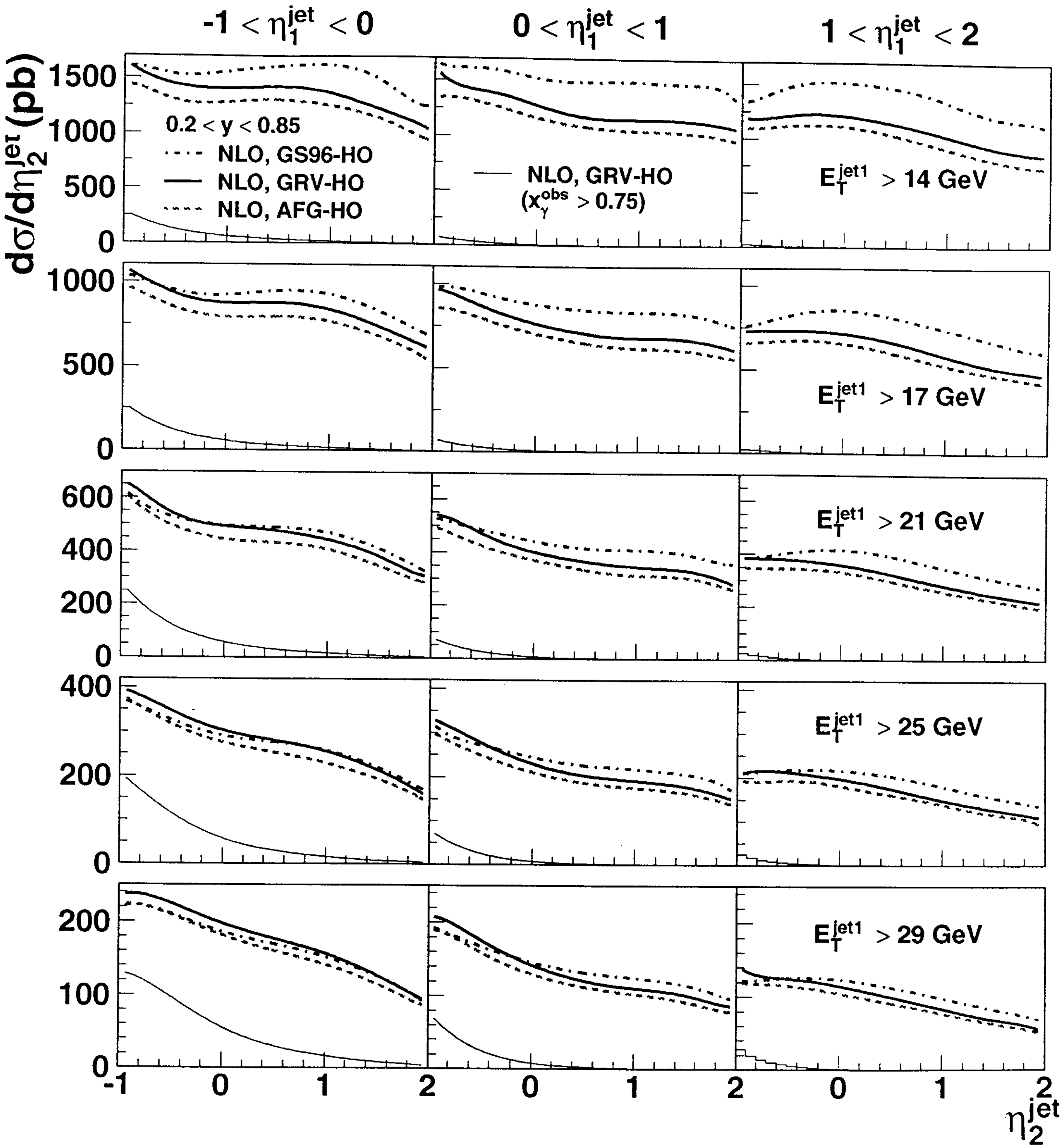
Both jets central or rear:



Starting to lose sensitivity for:

- jets in the rear direction,
- jets of higher E_T^{jet}.

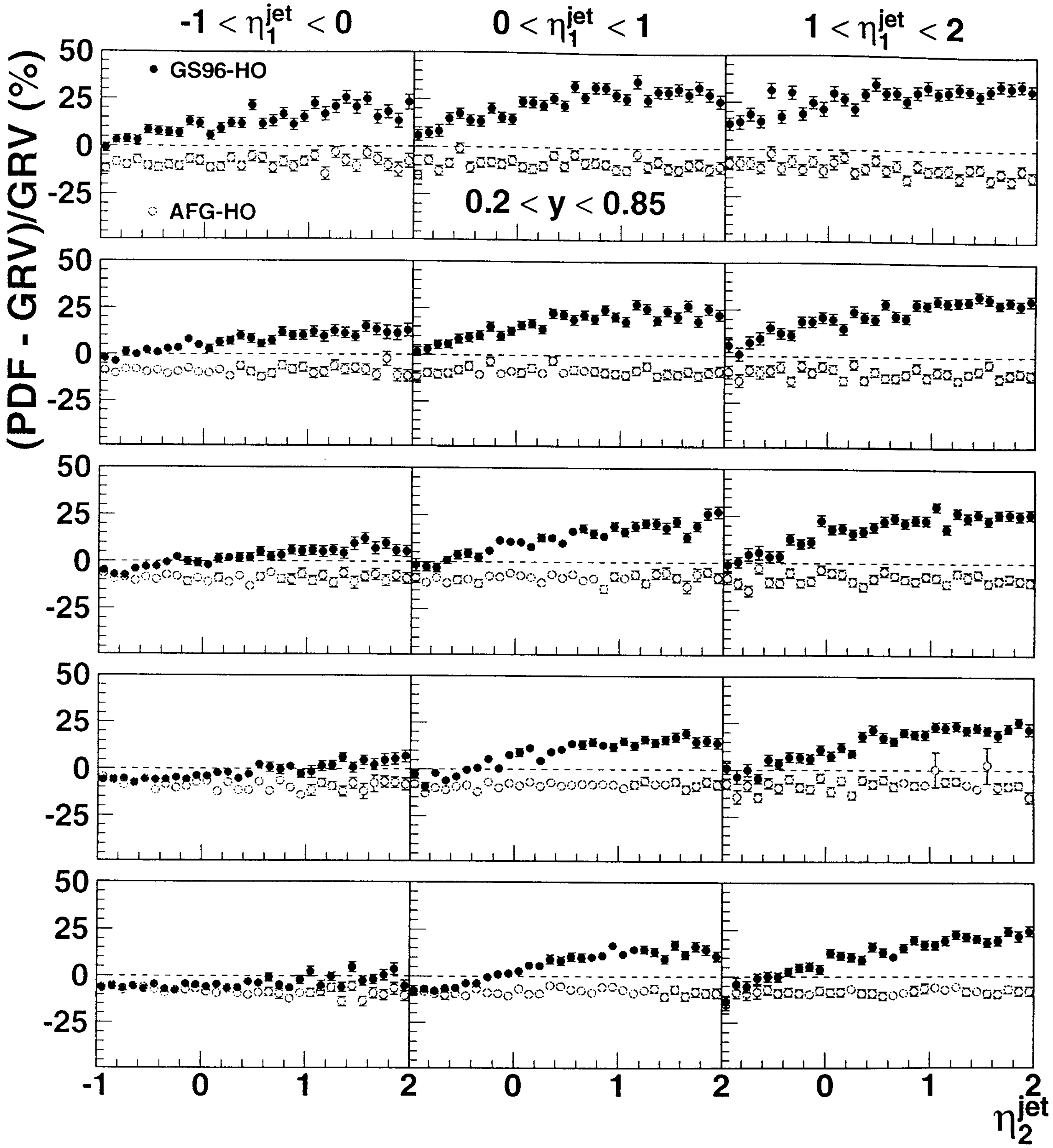
Cross-Sections in η^{jet}



At lower E_T^{jet1}:

- Prediction with GS96-HO is significantly larger.
- Almost all cross-section is from the resolved photon.

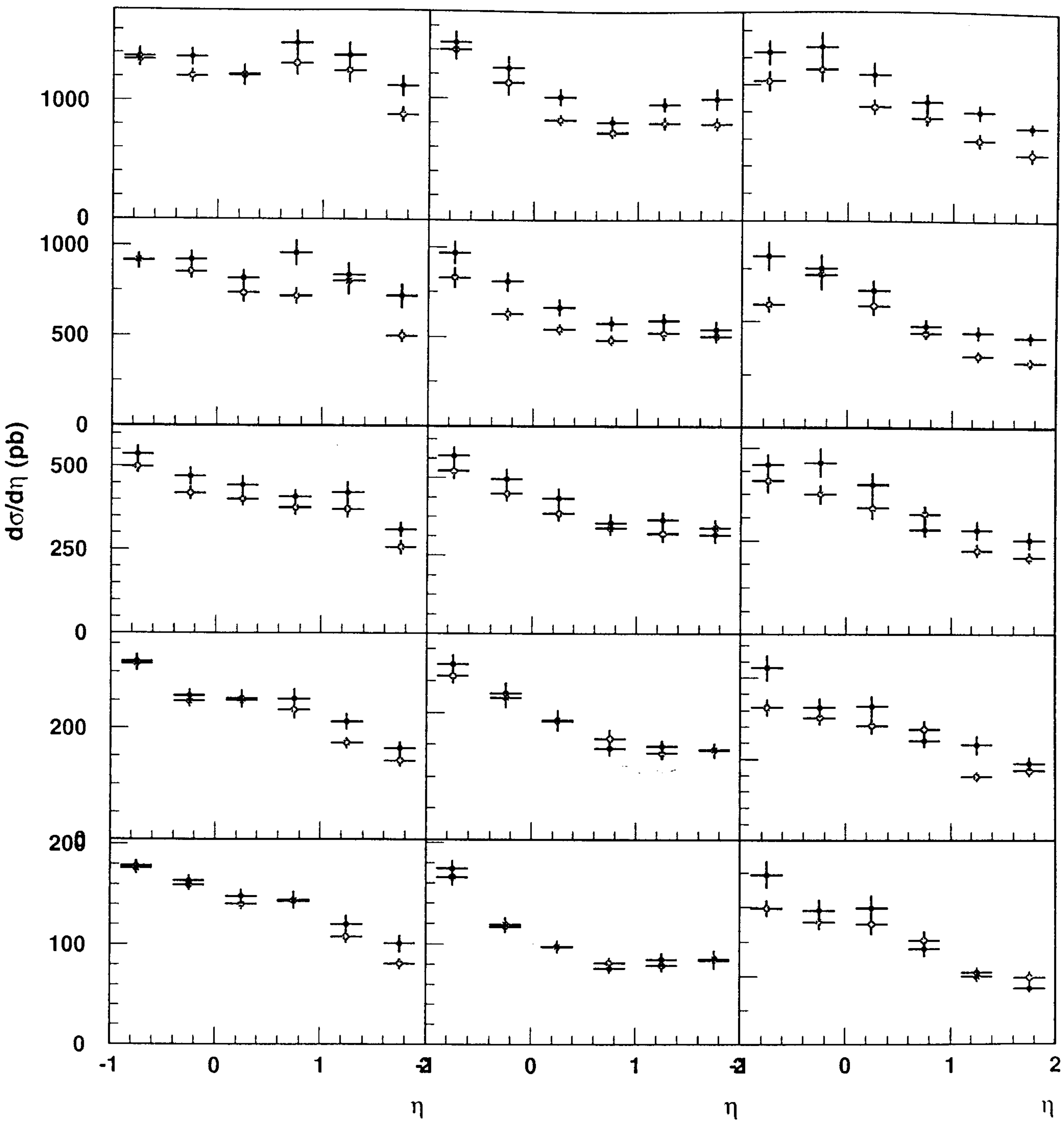
Magnitude of Differences



Cross-sections sensitive to choice of PDF; up to 35%!

PYTHIA MC Cross-Sections in η^{jet}

black – GRV-LO, red – SaS-2D

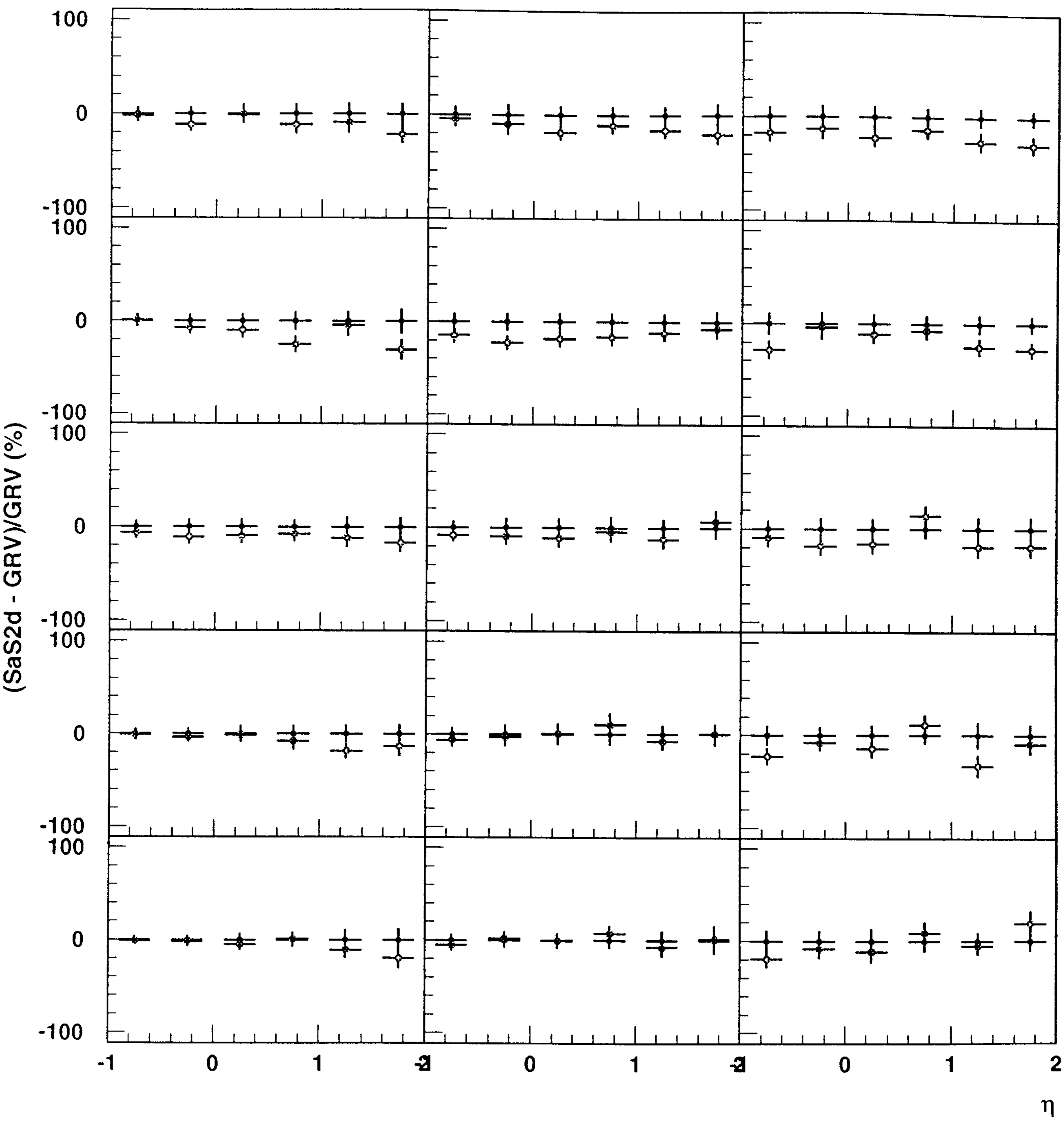


- Also sensitivity to choice of PDF seen.

- Absolute cross-sections similar to NLO predictions - doing something right!

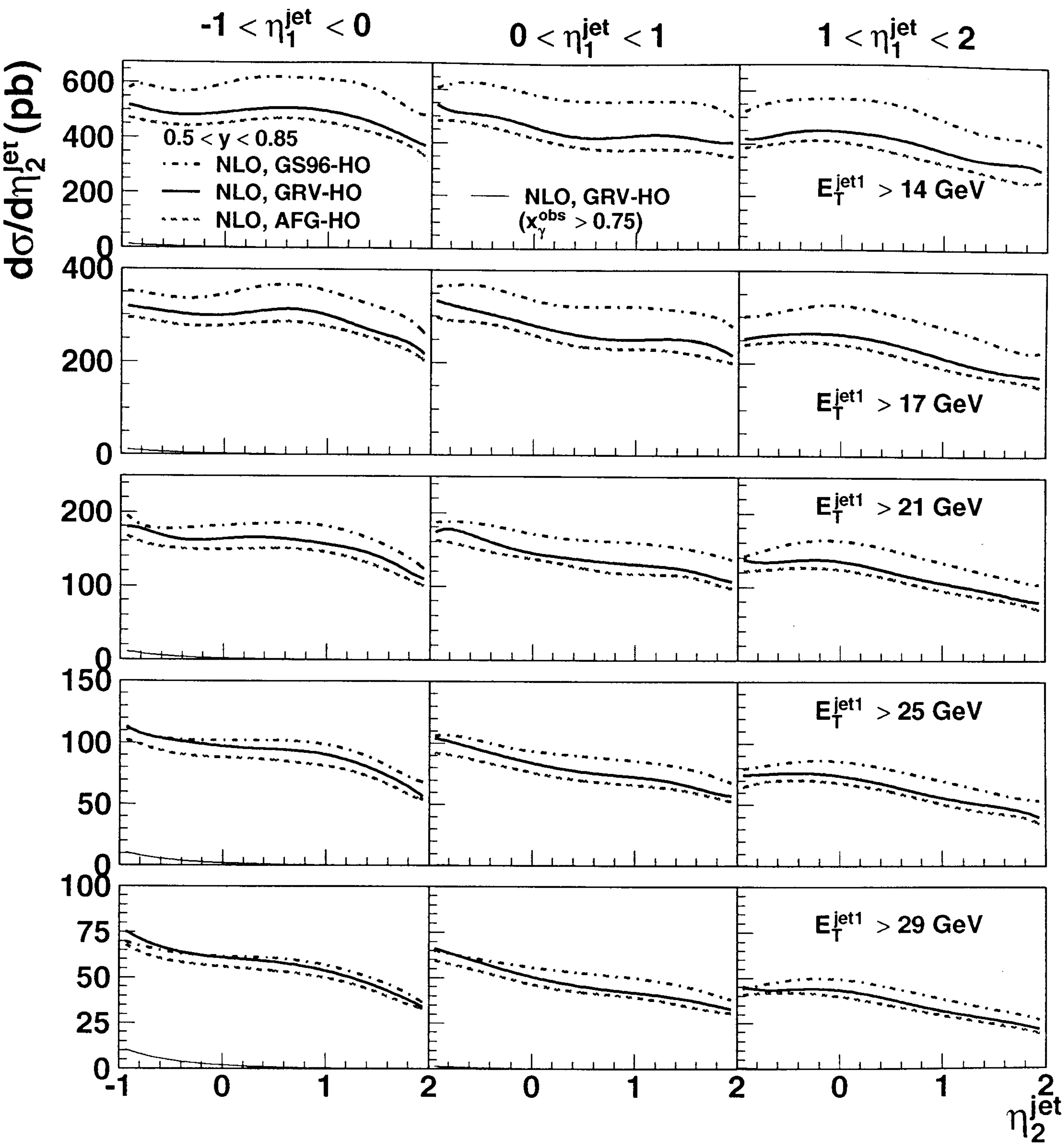
PYTHIA MC Magnitude of Differences

black – GRV-LO, red – SaS-2D



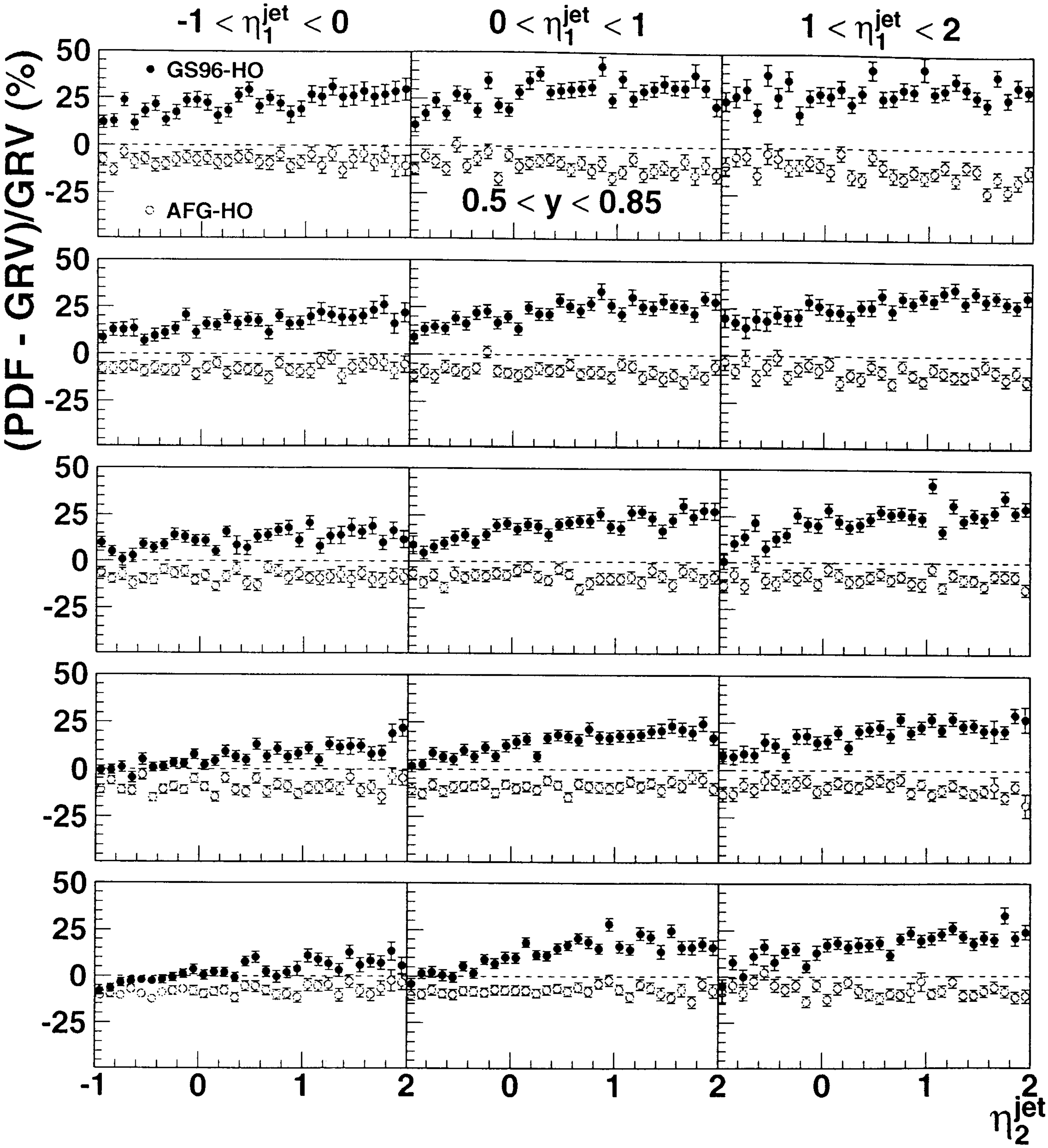
- Differences up to about 20 %, but large errors!

Cross-Sections in $\eta^{\rm jet}$ at Higher y



Similar conclusions to larger y region.

Magnitude of Differences

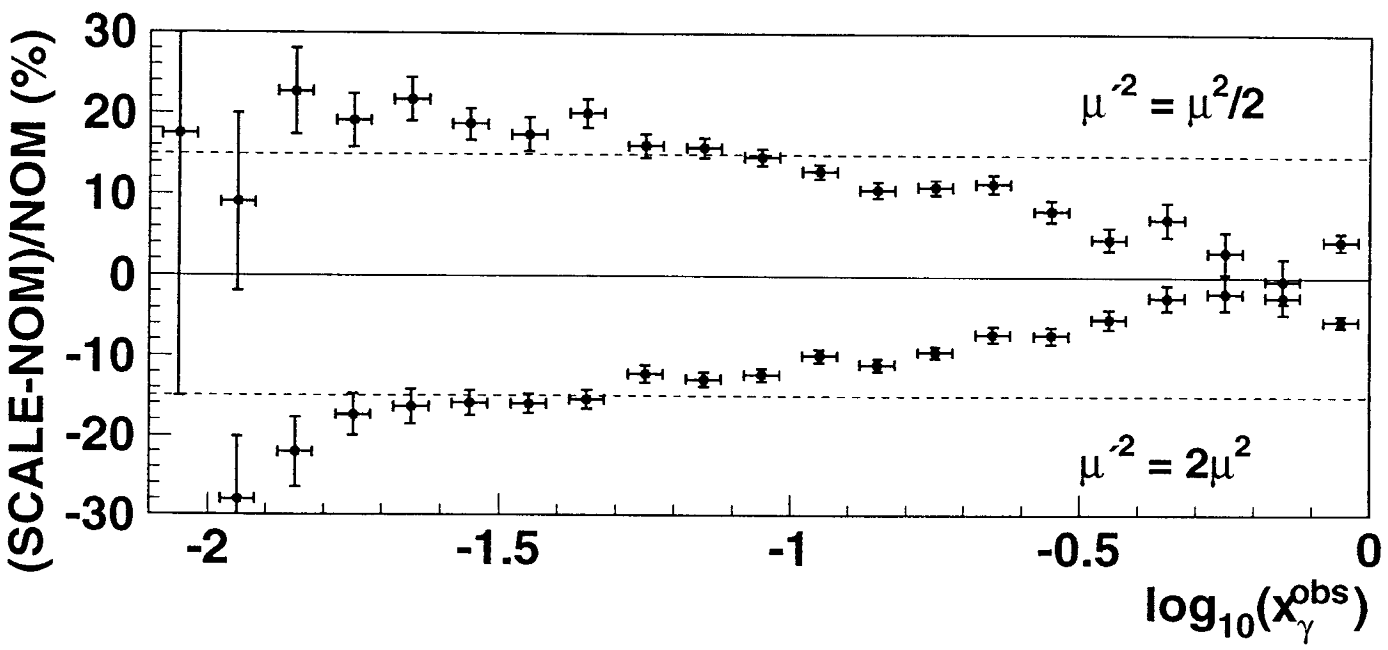


Again, differences up to 35%!

Scale Dependence for $x_\gamma^{\rm obs}$ Cross-Section

Region, $E_T^{\rm jet1} > 14$ GeV, with GRV-HO:

Scale, $\mu = E_T^{\rm jet1}$, then varied by a factor of two.

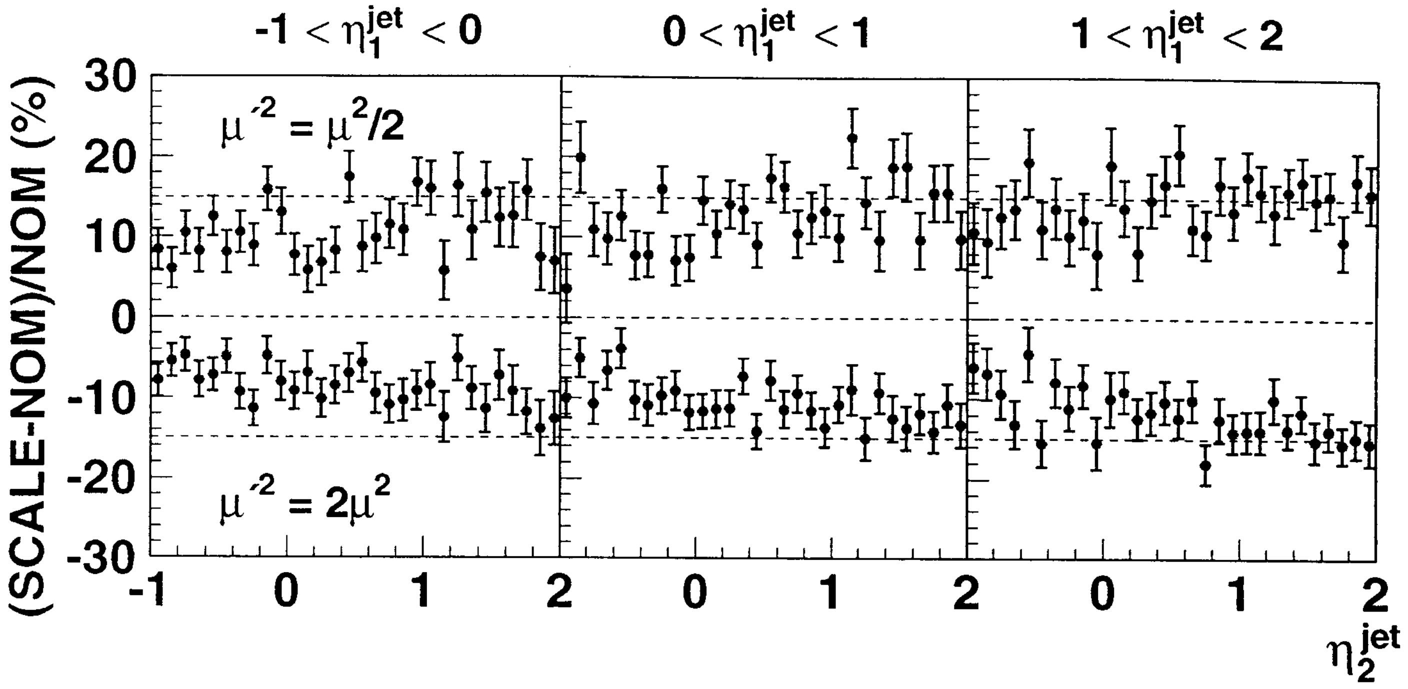


In region of interest, $-1.5 < \log(x_\gamma^{\rm obs}) < -0.5$:

- Scale uncertainty is larger than at higher $x_\gamma^{\rm obs}$.
- Uncertainty is about 15%.

Scale Dependence for η_2^{jet} Cross-Sections

Region, $E_T^{\mathrm{jet1}} > 14$ GeV, with GRV-HO:



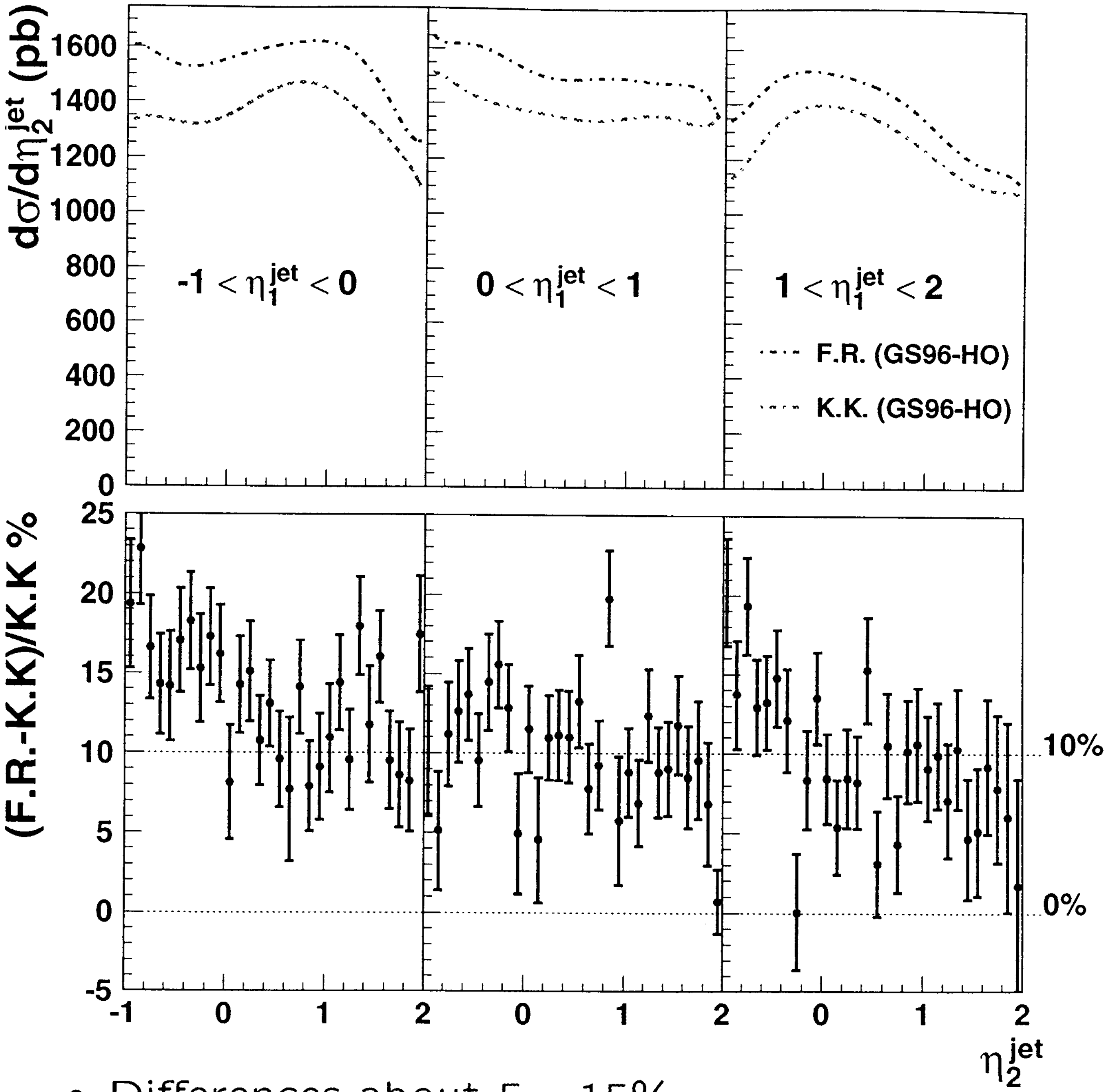
- Uncertainty is $\sim 10 - 15\%$.

- Uncertainty is not small, but less than the difference in the PDFs.

- Dilemma; increase E_T^{jet1}, reduce scale uncertainty, but also reduce PDF sensitivity!

Comparison of two NLO predictions

NLO from F. & R. and K. & K. for $E_T^{jet1} > 14$ GeV



- Differences about 5 – 15%.
- The differences are smallest in the region where the PDF difference is greatest.

Preliminary comparison, requires further work - Both codes were run by me!

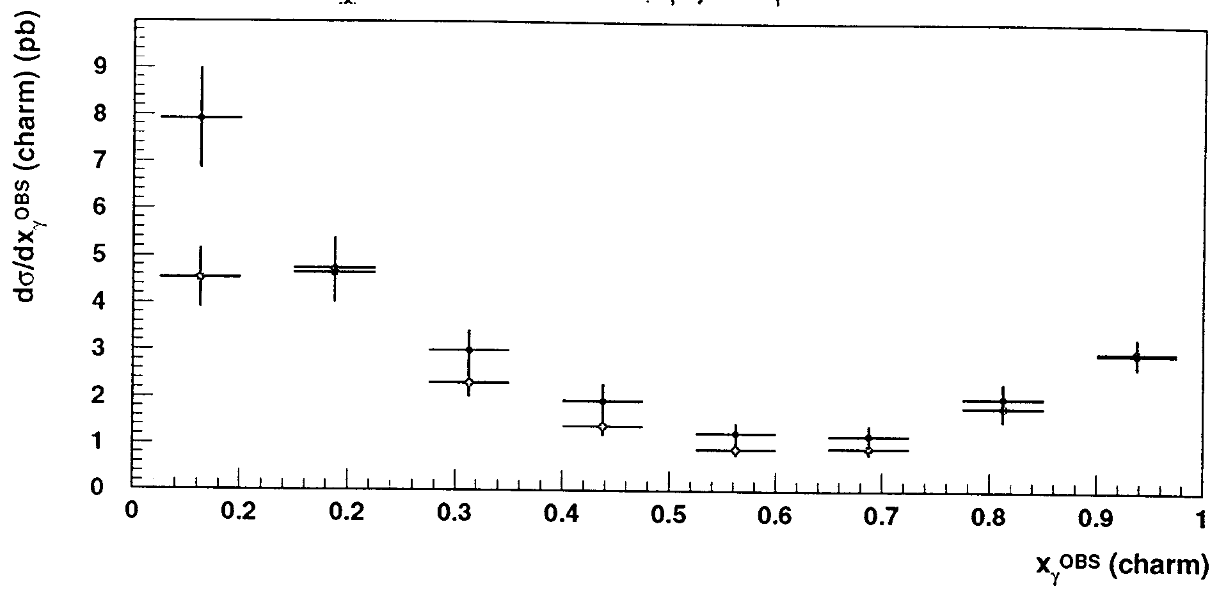
Photon Structure with Charm

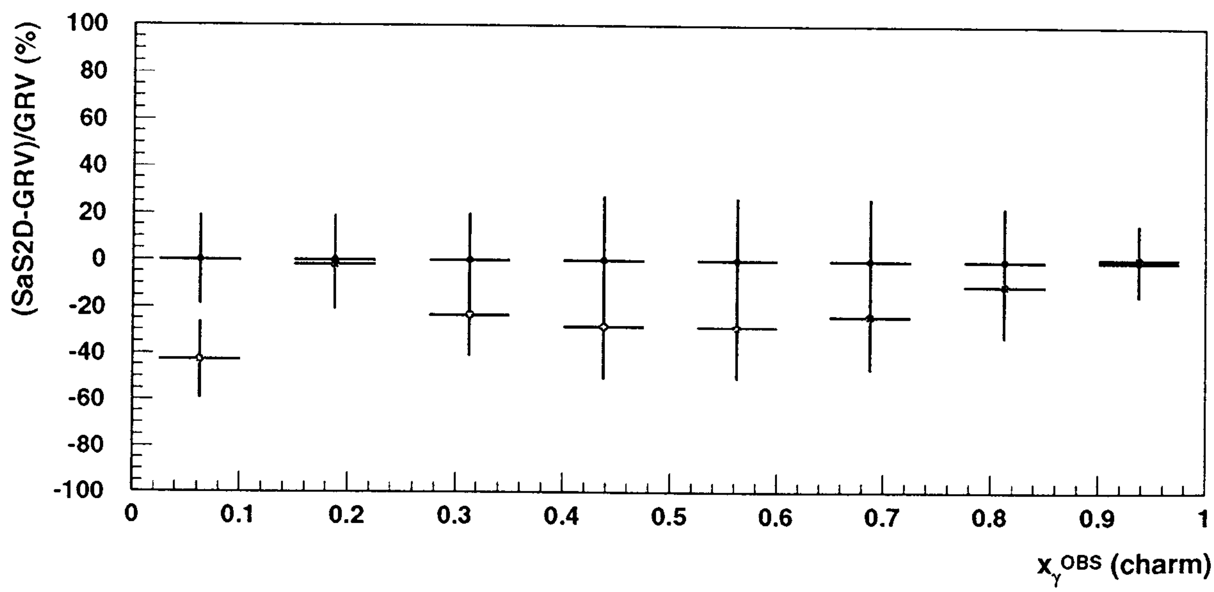
Take another favourite ZEUS analysis:

$$Q^2 < 1 \text{ GeV}^2, 0.19 < y < 0.87$$

$$E_T^{\text{jet}1,2} > 7,6 \text{ GeV}, |\eta^{\text{jet}}| < 2.4$$

$$p_T^{D^*} > 3 \text{ GeV}, |\eta^{D^*}| < 1.5$$





- Large enhancement of resolved photon cross-section.
- Differences of $20 - 40\%$ seen.

Conclusions and Outlook

- Promising first look shown.
  - Studied high E_T^{jet} production and a quick look at charm.
- Both NLO and MC predictions show sensitivity to choice of photon PDF.
- Differences between PDFs up to 35%.
- Plan to work on differenes between NLO calculations (M. Klasen).
- More MC data needed with more structure functions.
- Other ideas... ?