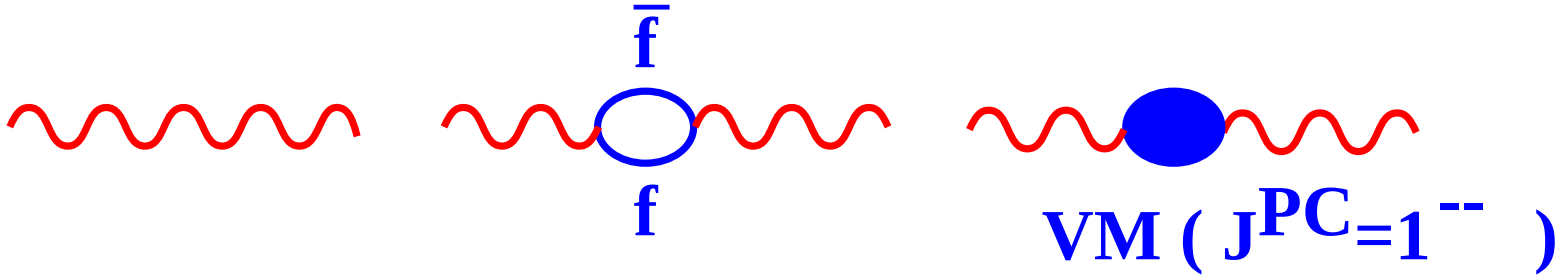
PHOTON STRUCTURE

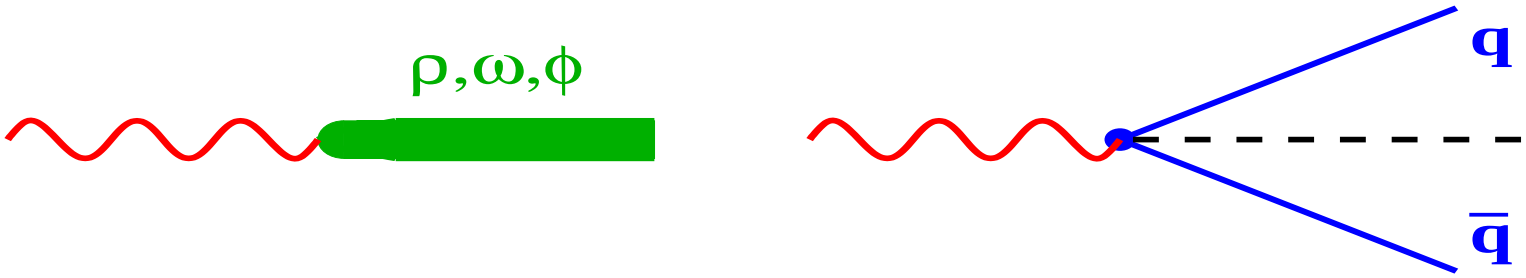
- Introduction
- The structure of the real photon
- Charm in/from the photon
- The structure of the virtual photon
- Scattering of virtual photons
- Scattering of real photons
- Outlook/Conclusion

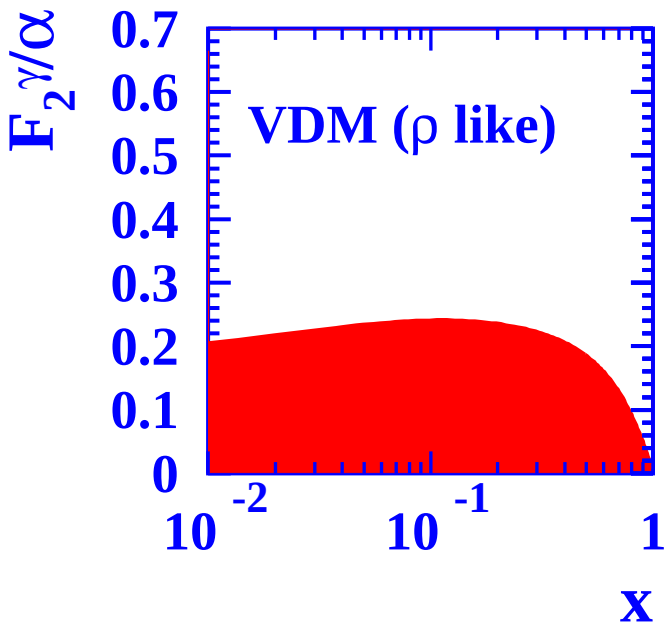
Thanks to V.Andreev, J. Butterworth, M.Kienzle, R.Nisius, J.Vossebeld, T.Wengler and to all parallel session speakers on photon structure

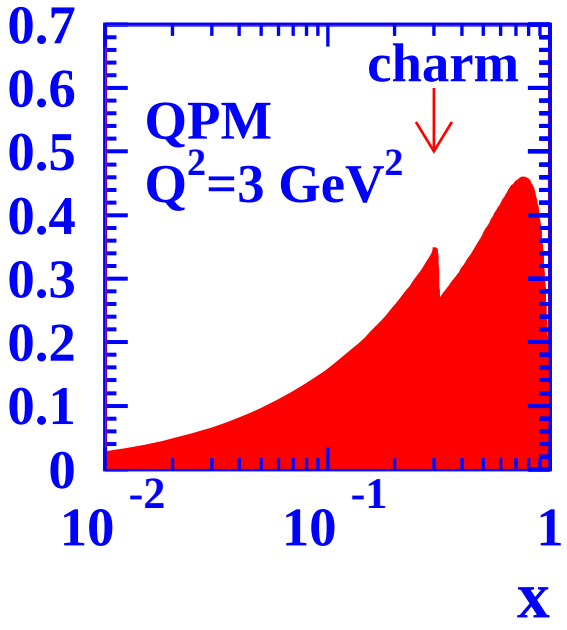
Introduction



- Photon couples to any kind of charged particle
- Sensitive to quantum structure (QED, QCD)
- Understand high energy scattering of photons
- How proton-like is the photon ?
- How are the quarks and gluons distributed ?
- What happens if the photon becomes virtual ?
- Are the HERA and LEP results consistent ?



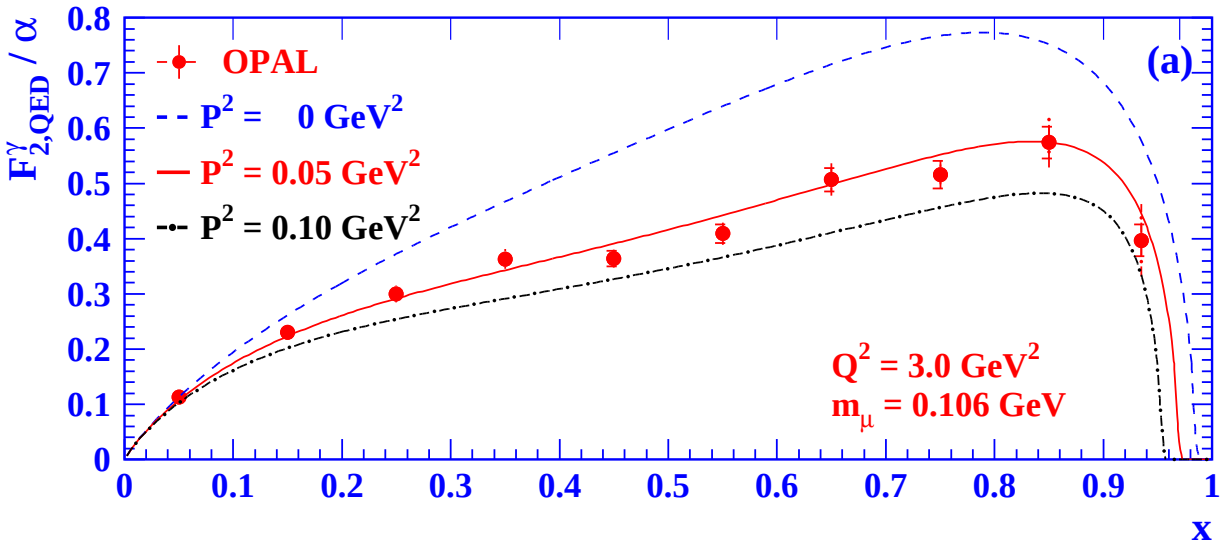




$$F_2^{\gamma,\mathrm{QPM}}(x,Q^2) = \frac{N_c\alpha}{\pi}\sum_q e_q^4 x\left[(x^2+(1-x)^2)\left(\ln\frac{Q^2}{m_q^2}-\ln\frac{x}{1-x}\right)-1+8x(1-x)\right]$$

A 'simple' model: QED

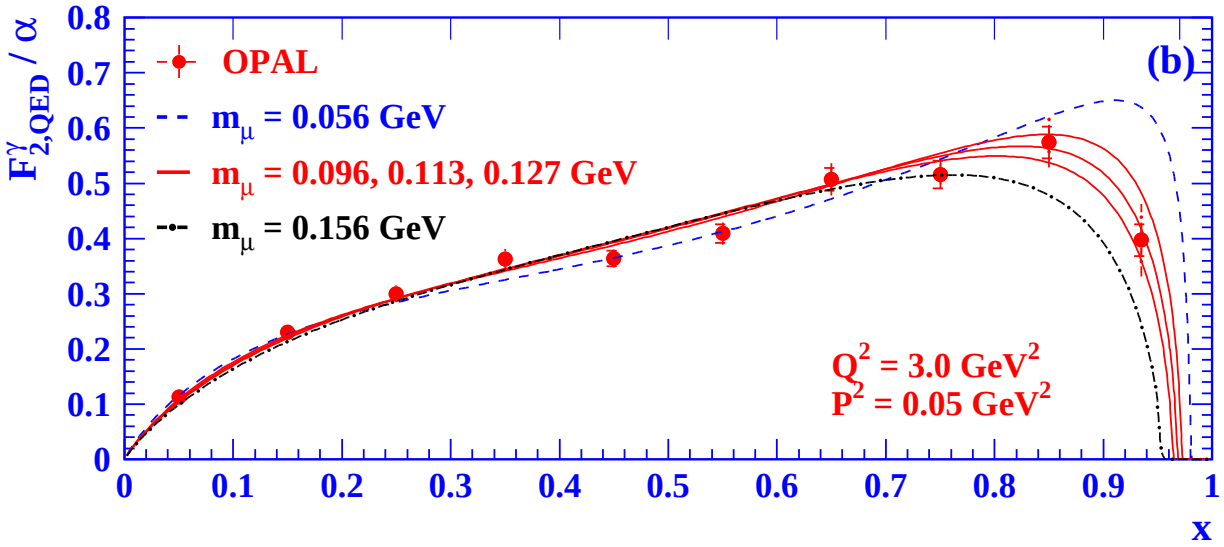
$e^+e^- \to e^+e^- \mu^+\mu^-$



structure function depends on virtuality of probed photon

=>

virtual photon structure



structure function depends on the muon mass

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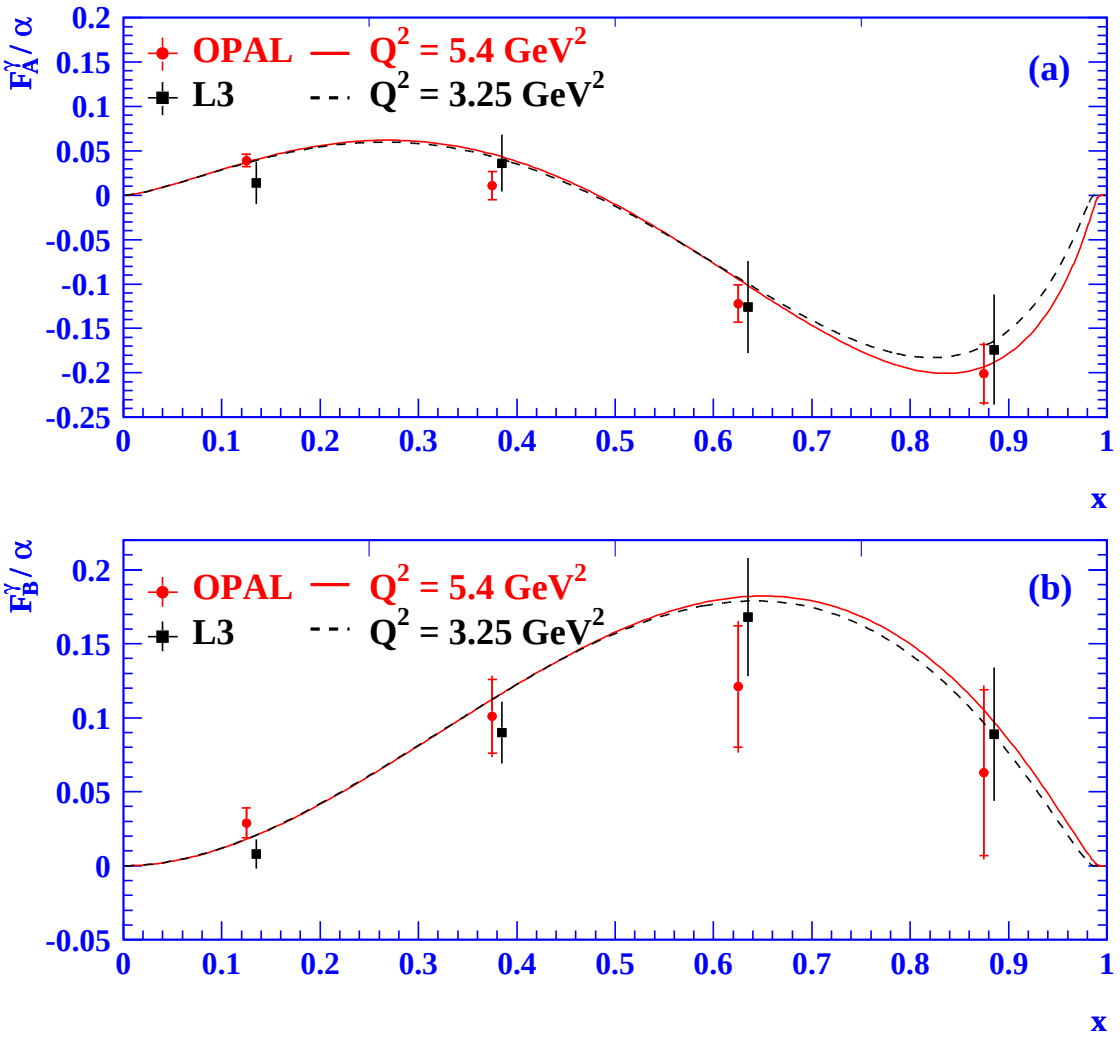
hadronic SF: Λ_{QCD}

QED cont'd



$P^2 = 0$ transverse real γ

$F_2^\gamma = 2xF_T^\gamma + F_L^\gamma \propto \sigma_{TT} + \sigma_{LT}$

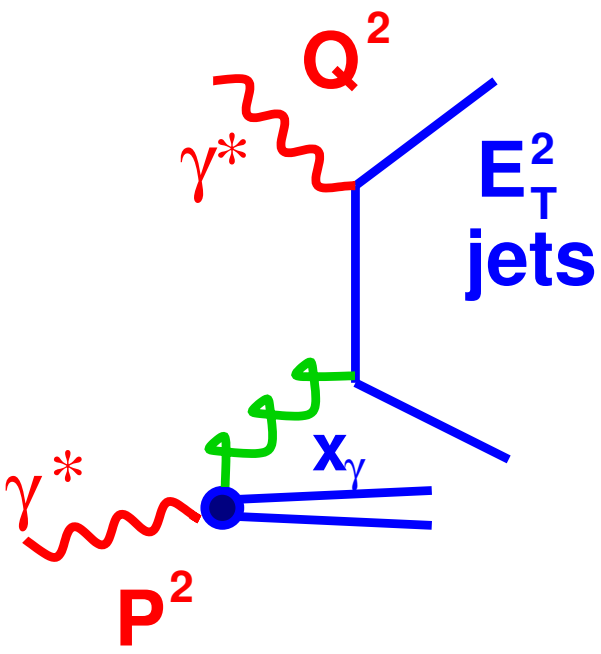
F_A and F_B:

sensitive to interference terms

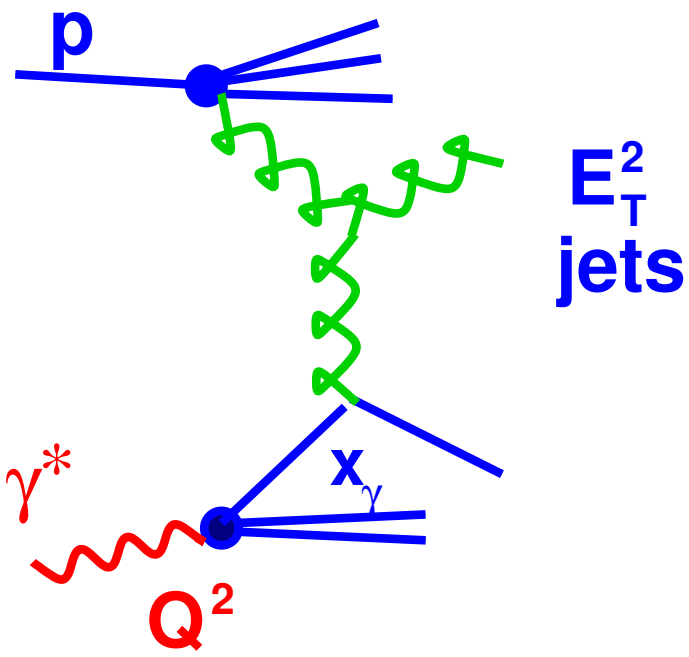
measured from azimuthal correlations

very difficult for hadronic (di-jet) events

LEP



HERA



$$x_{(\gamma)} = \frac{Q^2}{Q^2 + W^2 + P^2}$$

$$x_\gamma = \frac{E_T^{jet1} \cdot e^{-\eta_1^{jet}} + E_T^{jet2} \cdot e^{-\eta_2^{jet}}}{2yE_e}$$

Probing scales:

Q^2, E_T^2 $\qquad\qquad$ E_T^2

Scale of probed photon:

P^2 $\qquad\qquad$ Q^2

The Photon Structure Function

Determined from single tag events

$$\frac{d^2\sigma_{e\gamma \to eX}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^2}[(1+(1-y)^2)\ F_2^{\gamma}(x,Q^2) - y^2\ F_L^{\gamma}(x,Q^2)\ ]$$

Small contribution

$$y = 1 - \frac{E_{tag}}{E_b}\cos^2\theta_e$$

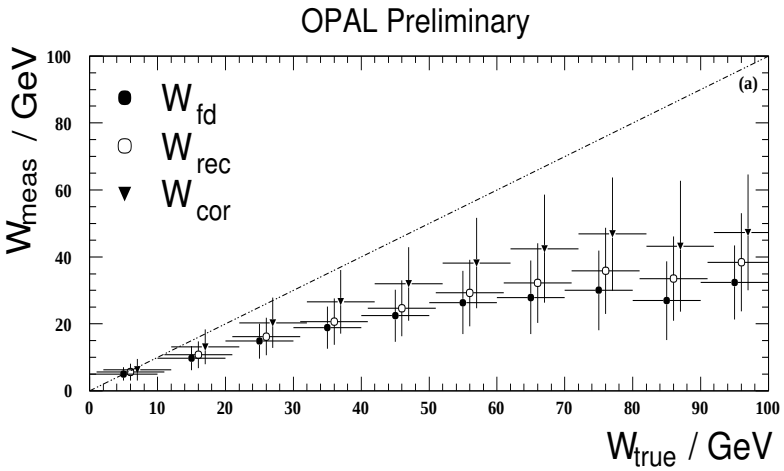
Small for $E_{tag} \geq 0.7\ E_b$ and small θ_e considered

Need distribution of events in Q^2 and x

Scattered electron & hadronic final state

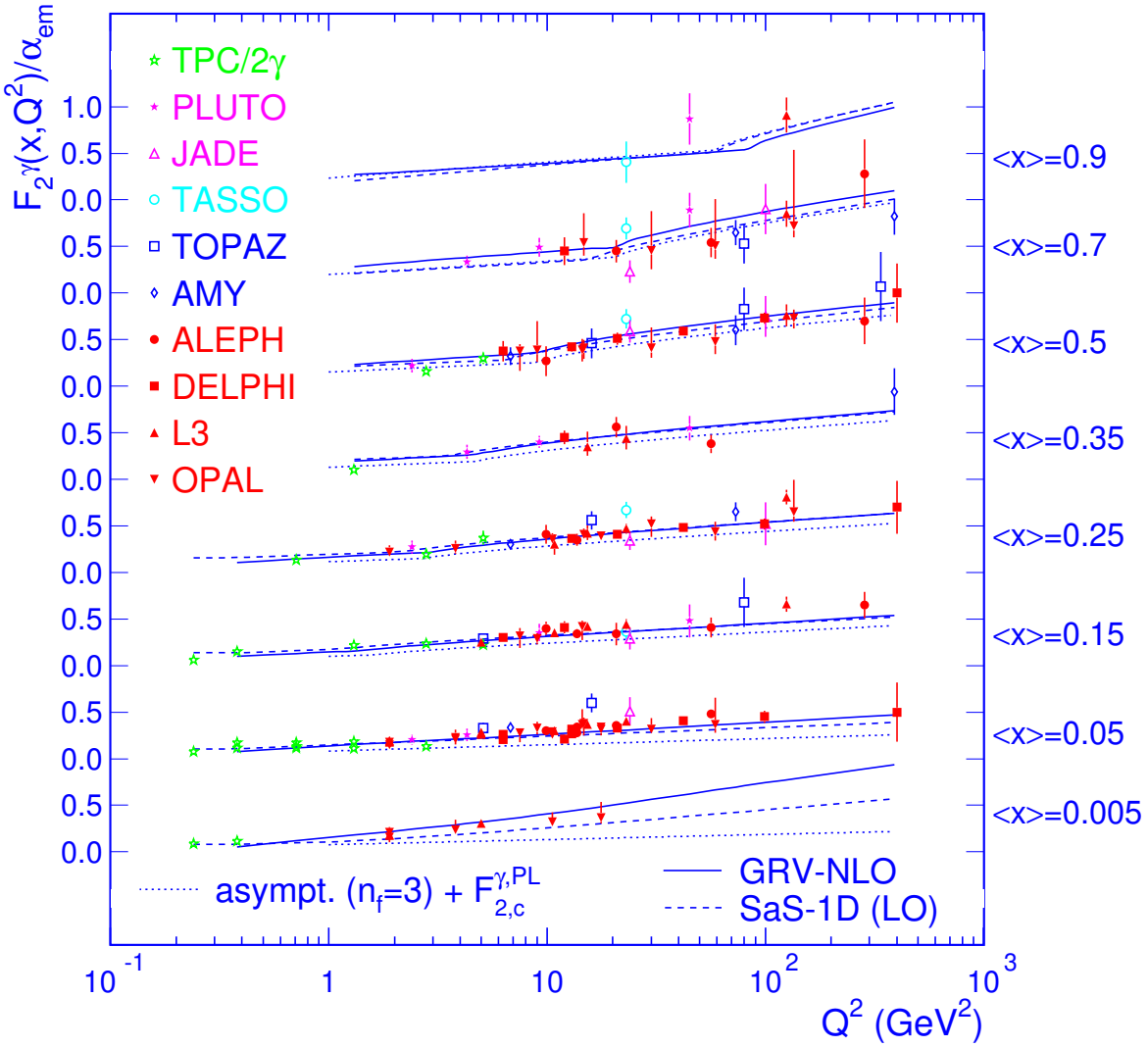
Obtained from the scattered electron

good resolution



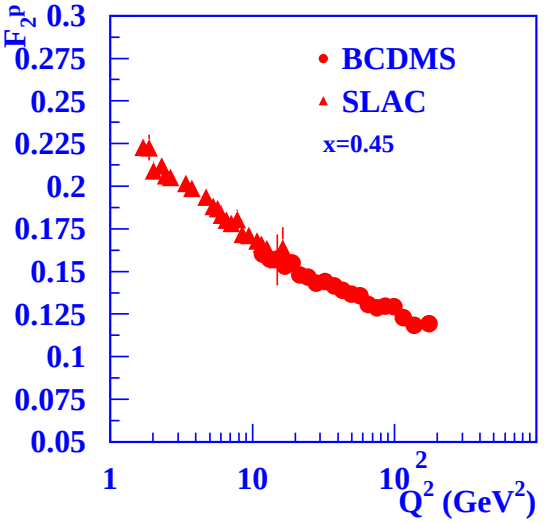
=> unfolding

Scaling violations



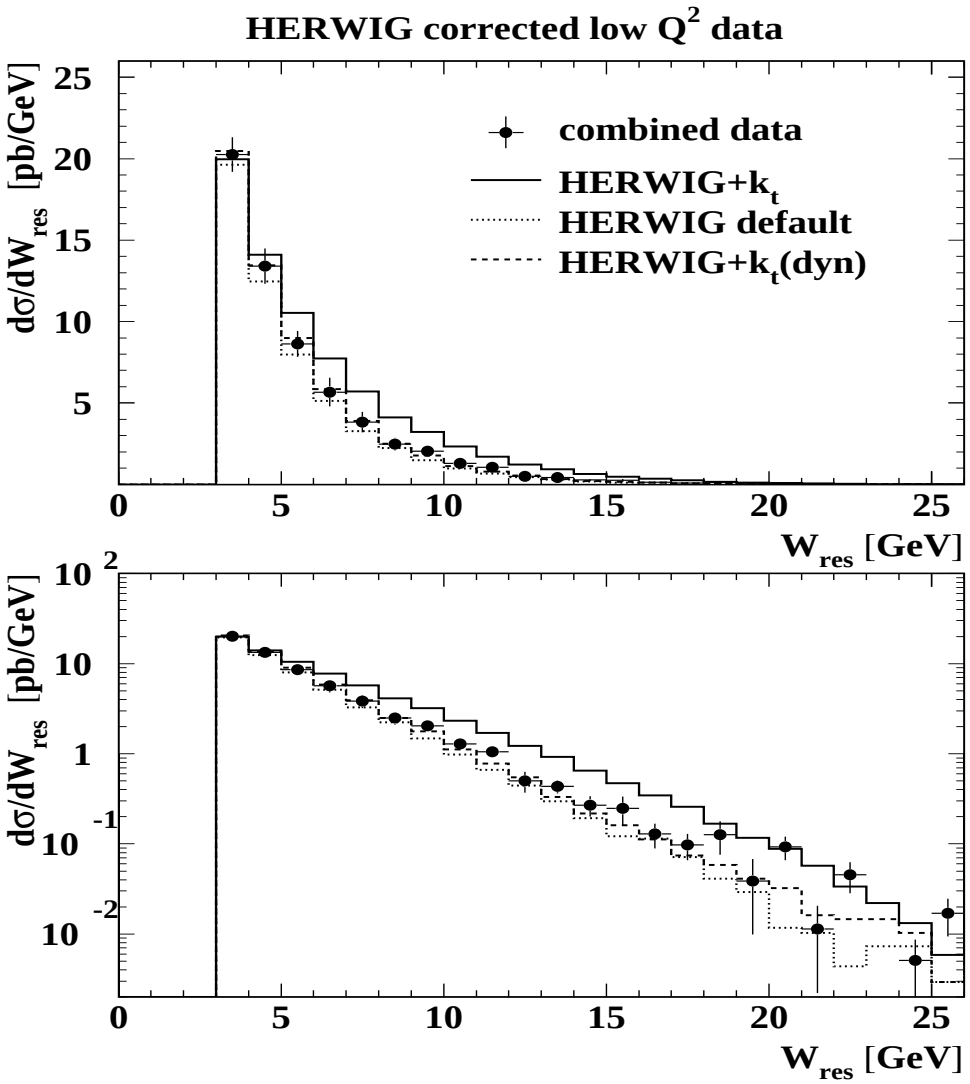
Linear rise with ln Q^2

Prediction of QCD !



Positive scaling violations at all values of x

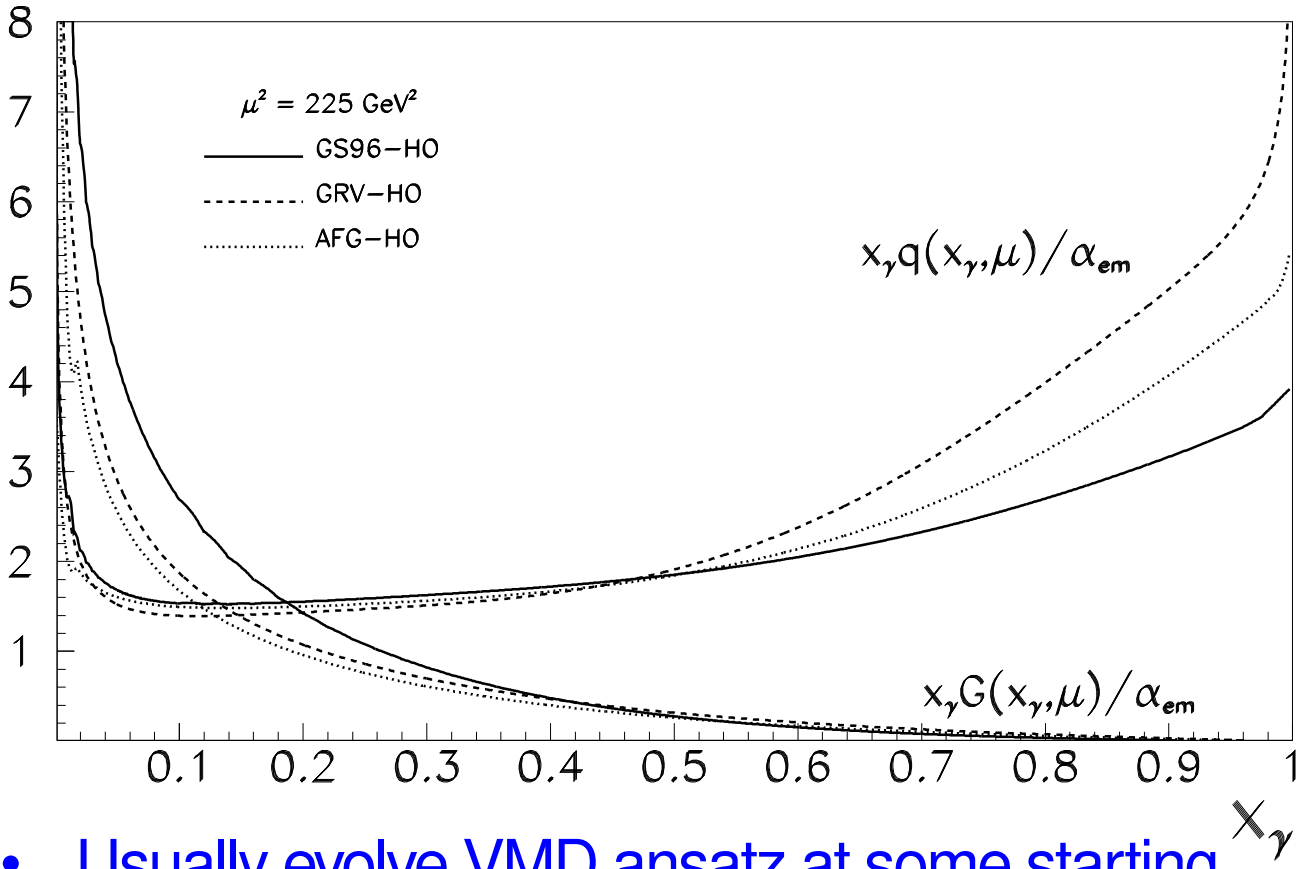
Combination of LEP data to improve generators:



- ALEPH, L3 and OPAL have combined data
- differences between experiments used to estimate systematic errors
- systematic errors smaller than differences between models
- HERWIG and PHOJET studied
- publication soon

Parametrisations

- LO: DG,LAC,SaS,WHIT
- HO: AFG,GRS, GRV, GS



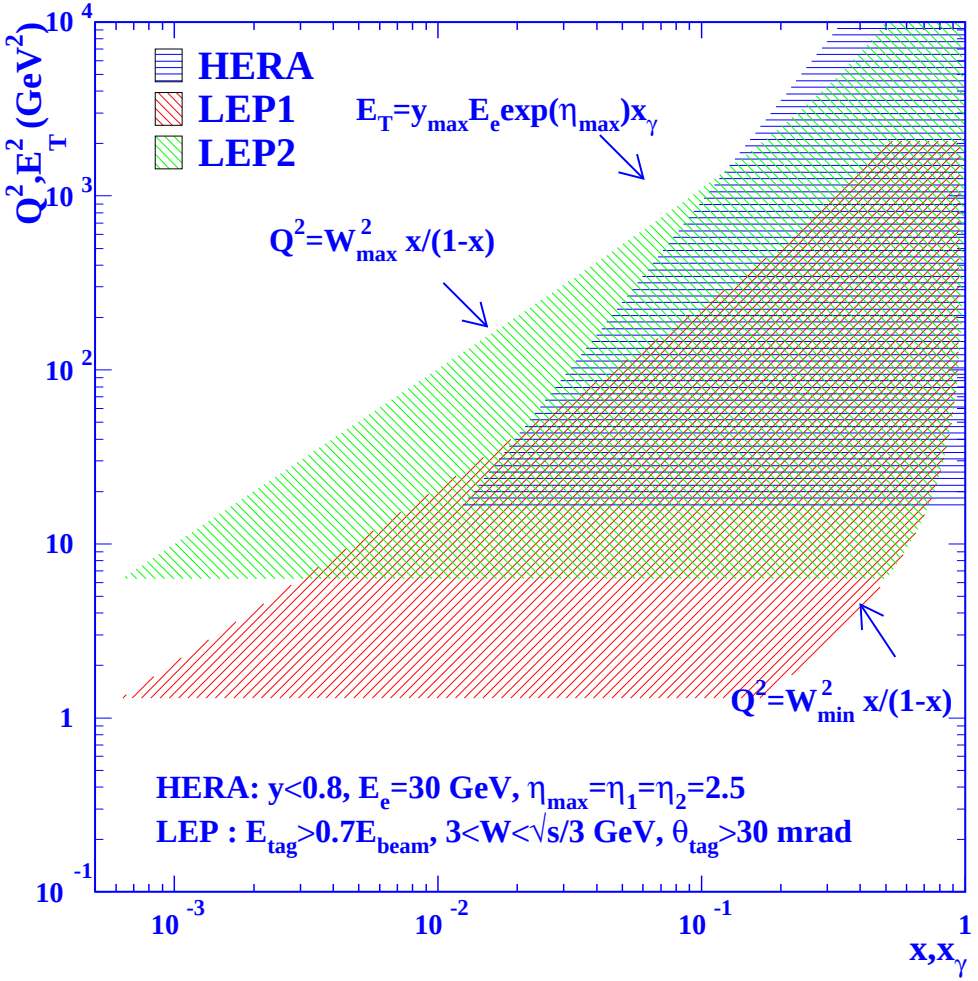
- Usually evolve VMD ansatz at some starting scale Q_0^2 with inhomogenous DGLAP equations (i.e. including $\gamma \to q\bar{q}$ splitting)
- gluon at low x and quark at high x not very well constrained yet

The accessible kinematic range

LEP

$x > 5 \cdot 10^{-4}$

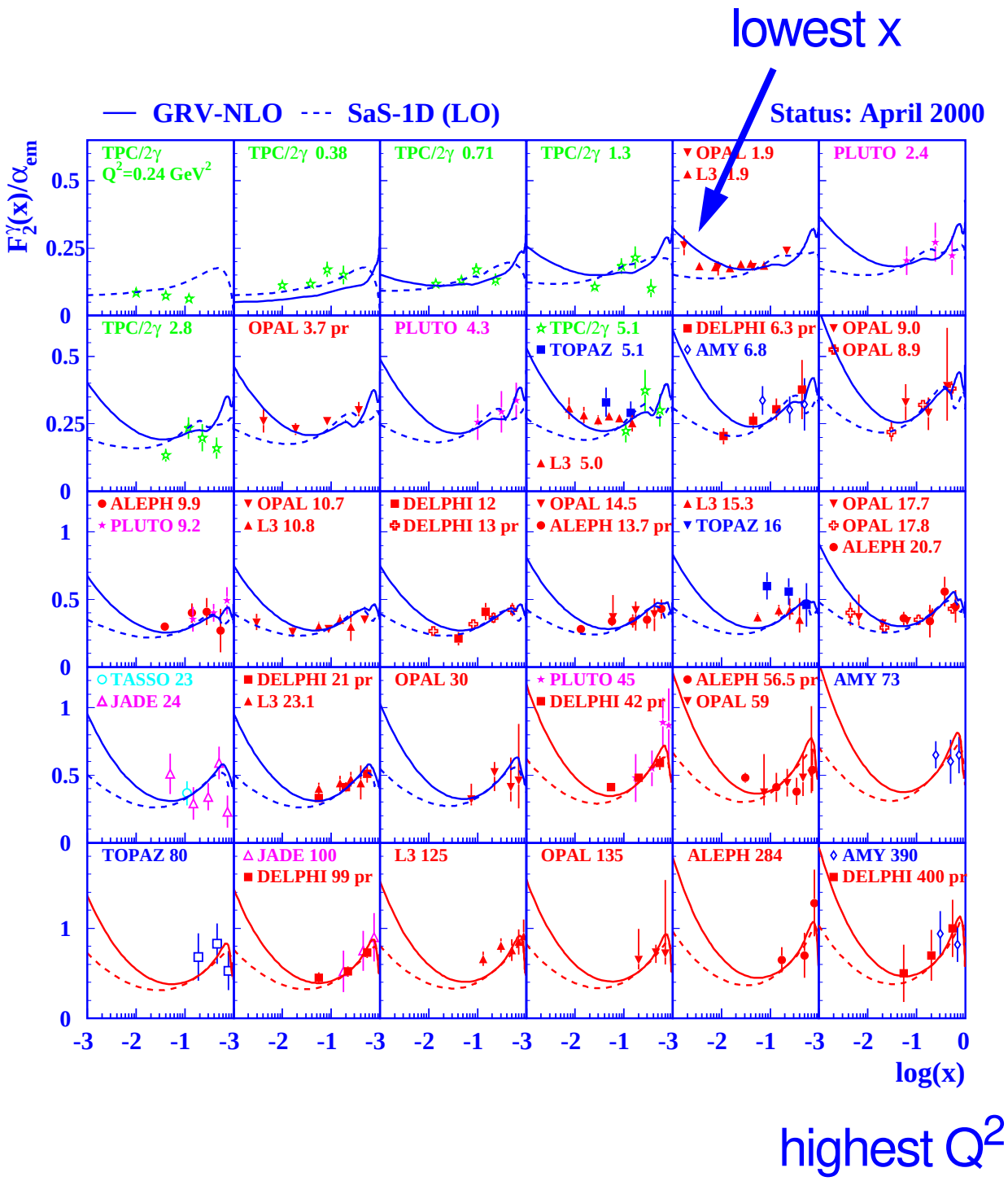
at $Q^2 = 2\text{GeV}^2$



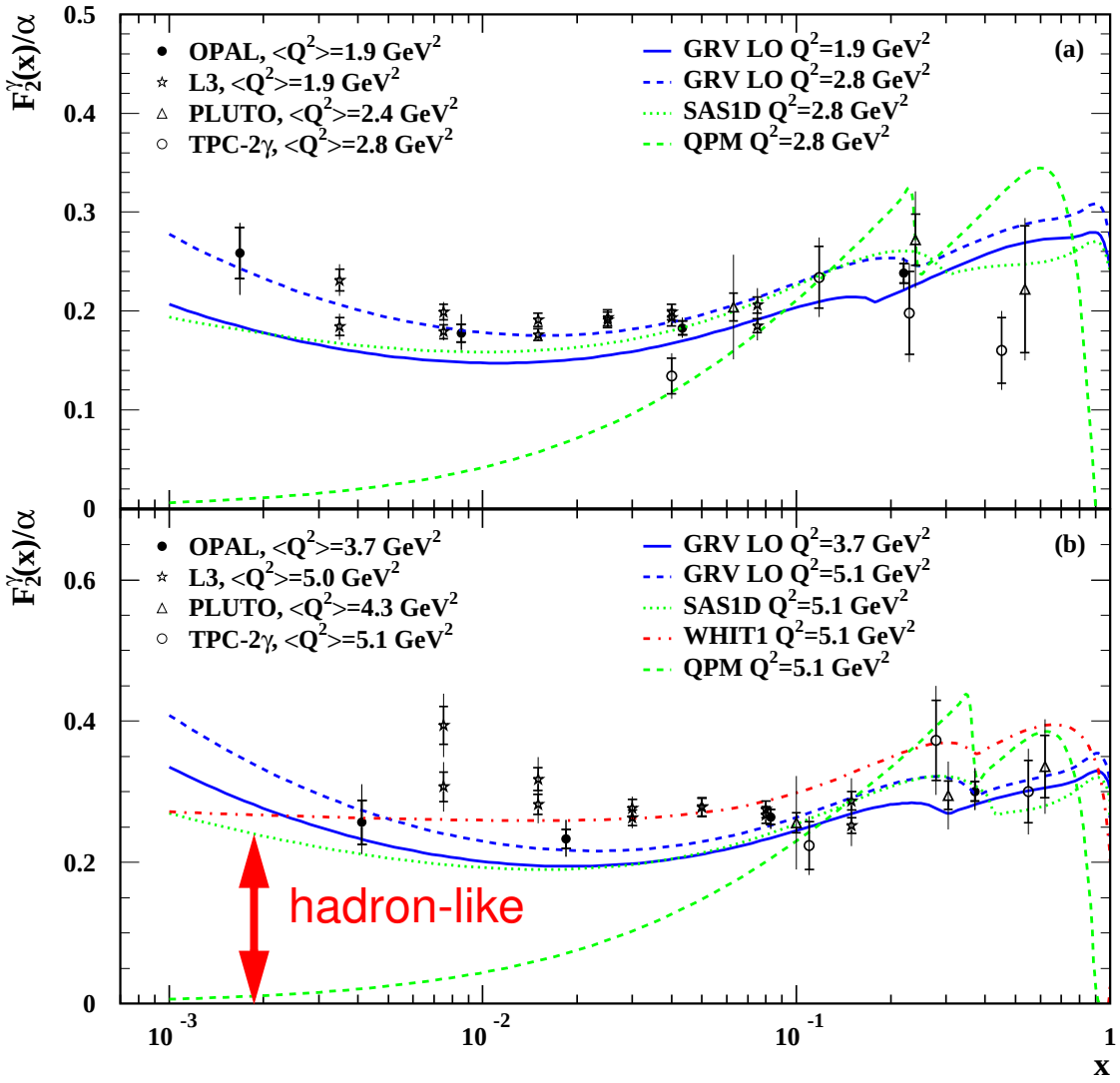
HERA

low x requires reconstruction of jets at low E_T and large η

The photon structure function



A closer look at low x

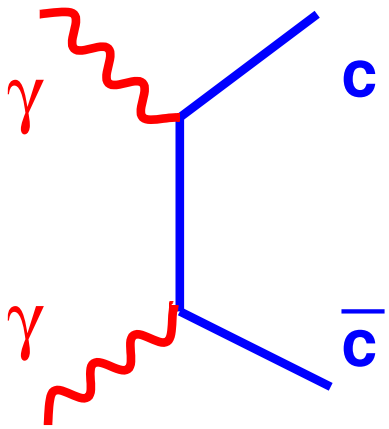


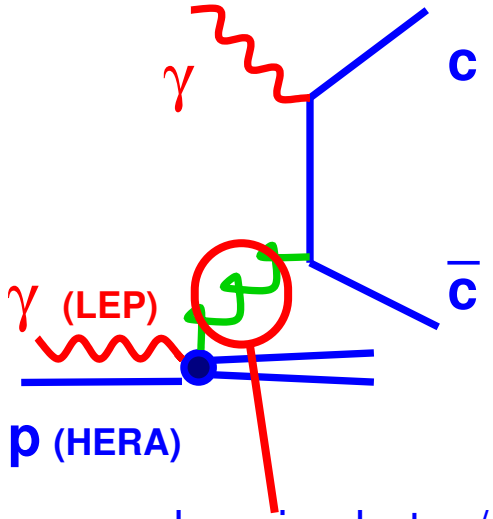
Very large reduction of systematic errors !

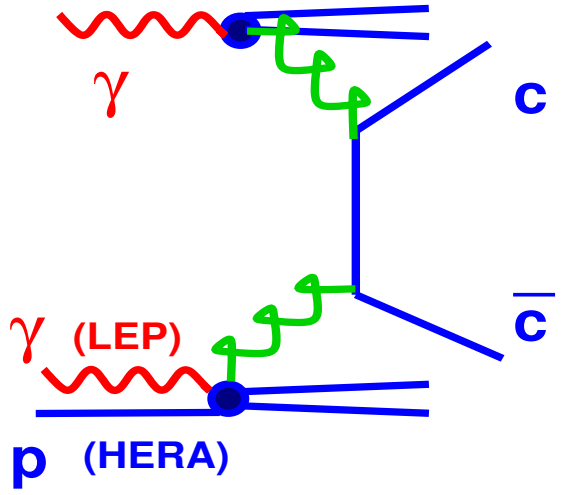
Evidence for low x rise ?!

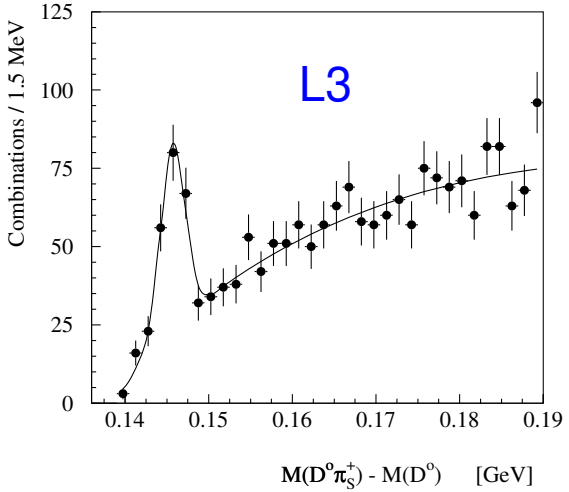
More in parallel session talks by C.Grupen, D.Haas and R.Nisius

Heavy quark production

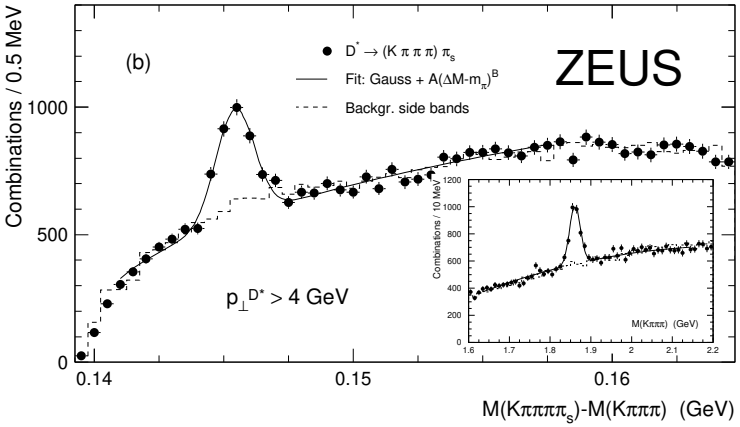




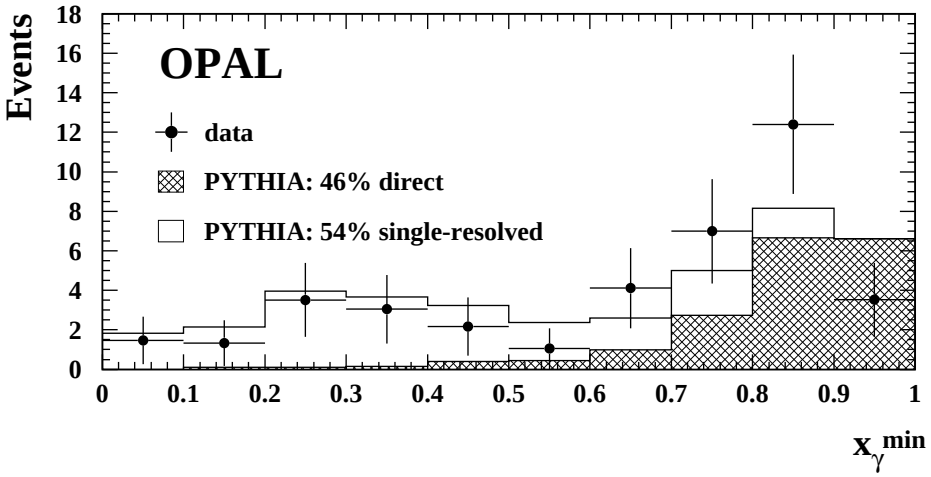


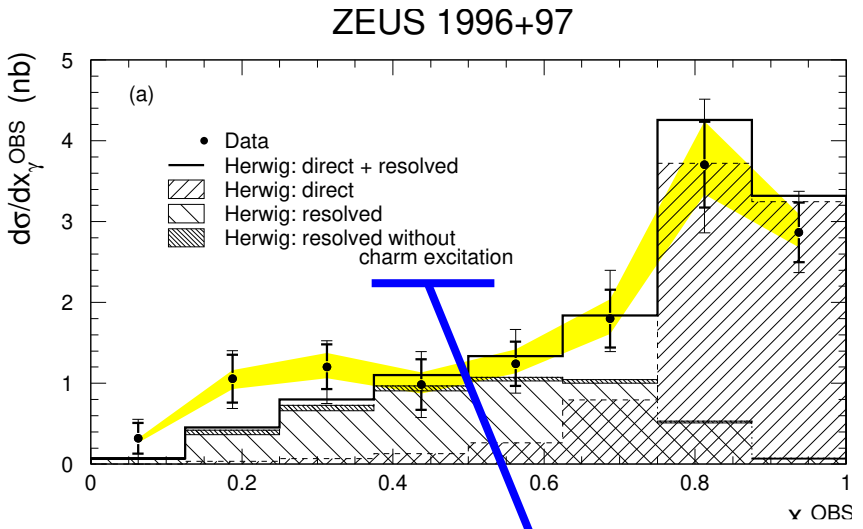


D*

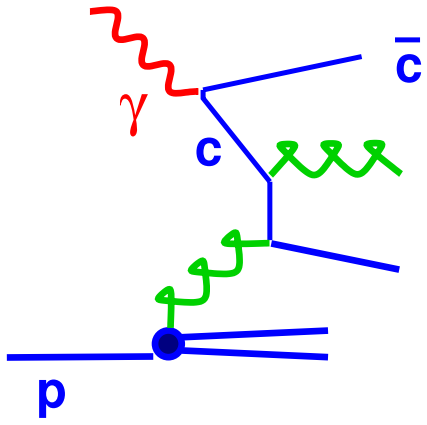


x_γ distributions

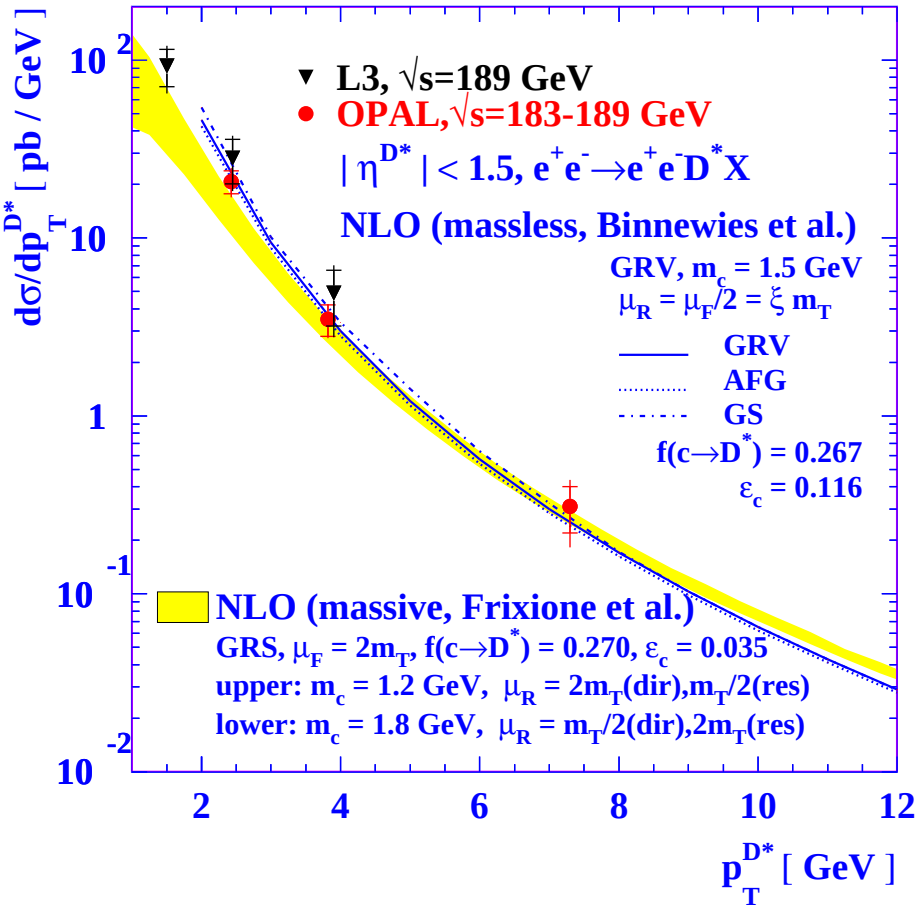




- charm events with jets
- direct and resolved of similar size
- ZEUS: charm excitation important



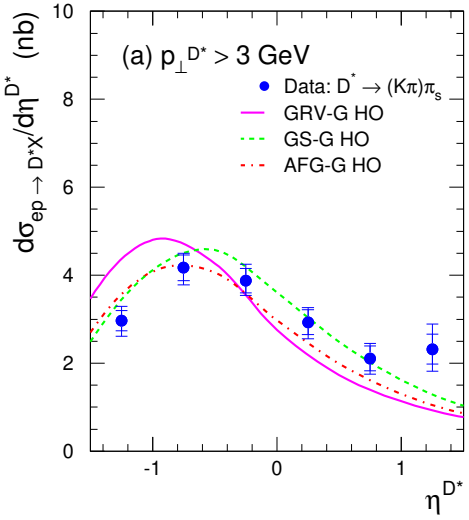
Differential D* cross sections



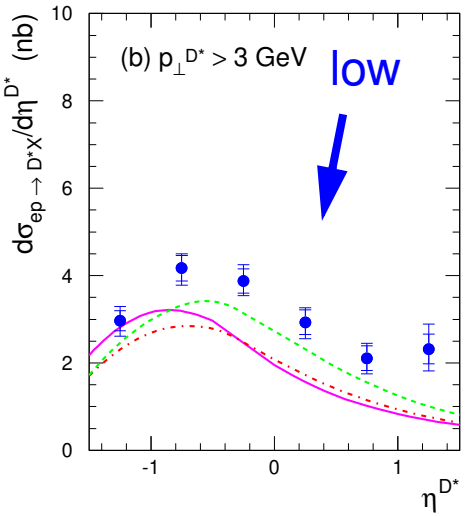
- massive:
- only uds active flavours in photon
- scale: charm mass

- massless
- uds and c active flavours in photon
- scale: p_T
- valid: $p_T >> m_c$

ZEUS

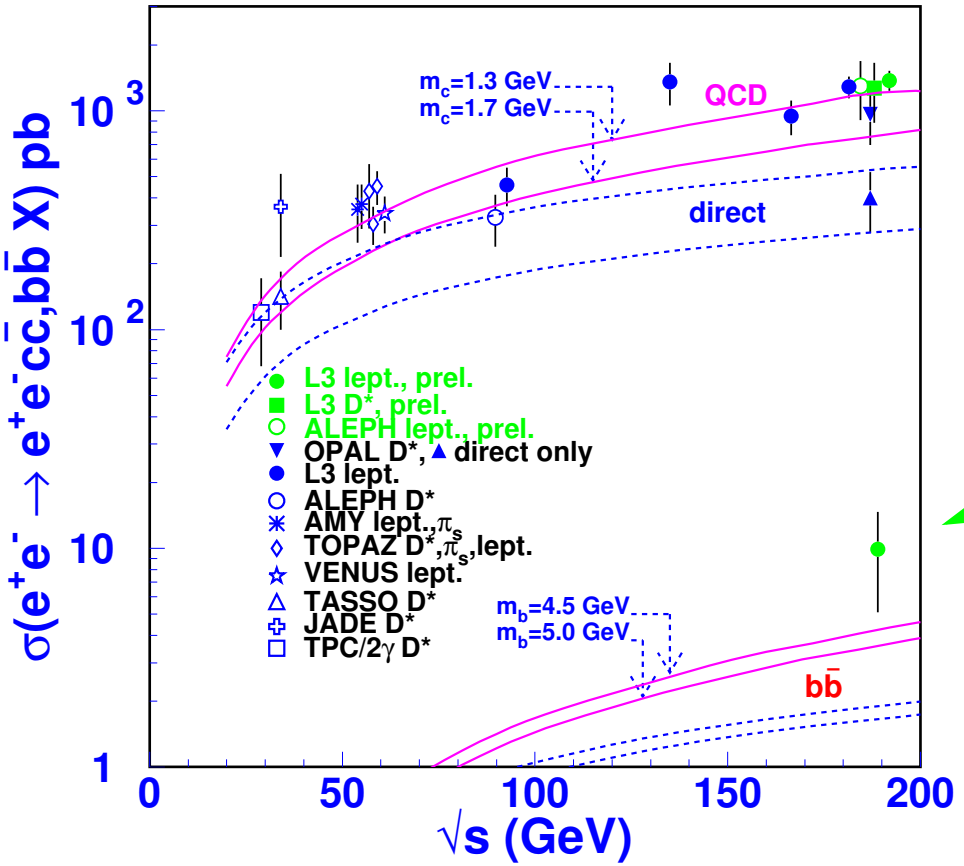


Kniehl et al



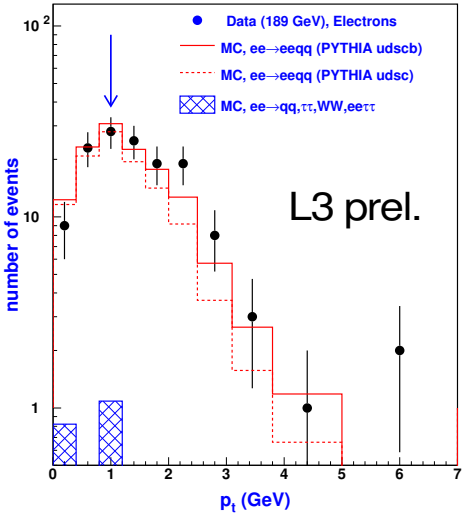
Cacciari et al

New results from ALEPH, L3, OPAL



Extrapolated to full phase space using MC

- good experimental agreement on total $c\bar{c}$ cross-section
- good agreement with upper end of massive NLO calculation (Drees et al.) using GRV-NLO
- see talk by V.Andreev

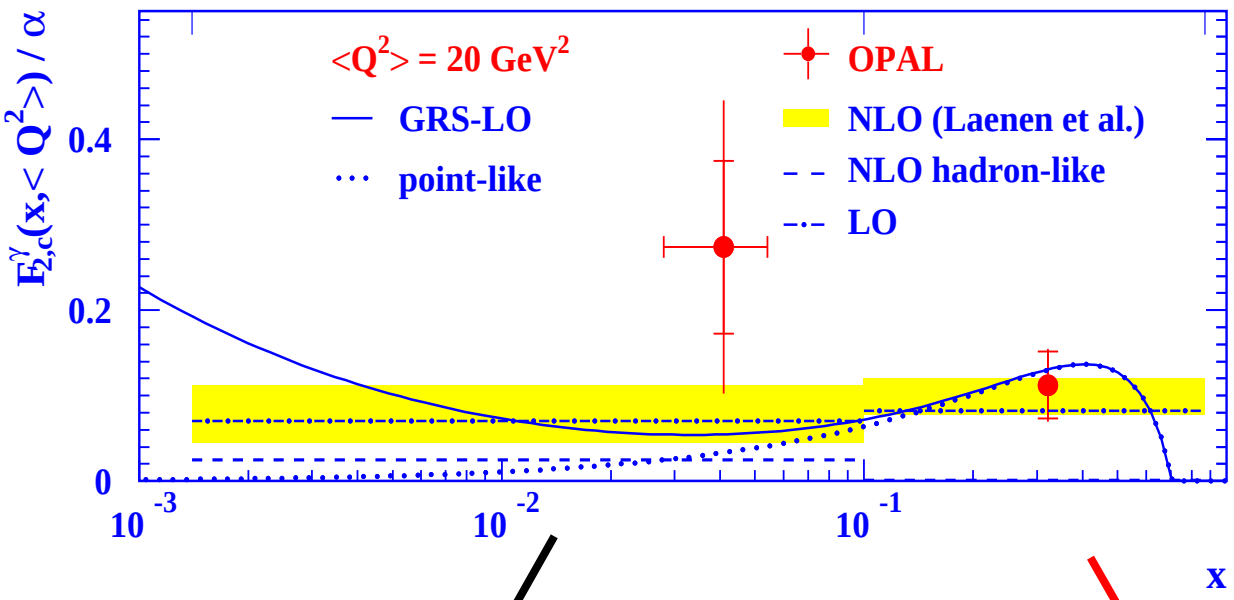


First sign of $b\bar{b}$ in $\gamma\gamma$ (L3):

$$\sigma^{b\bar{b}} = 9.9 \pm 2.9(\text{stat}) \pm 3.8(\text{syst})\ \text{pb}$$

The first measurement of

$$\frac{d^2\sigma_{e\gamma \to ecc}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^2}[(1+(1-y)^2)\ F_{2,c}^{\gamma}(x,Q^2)]$$



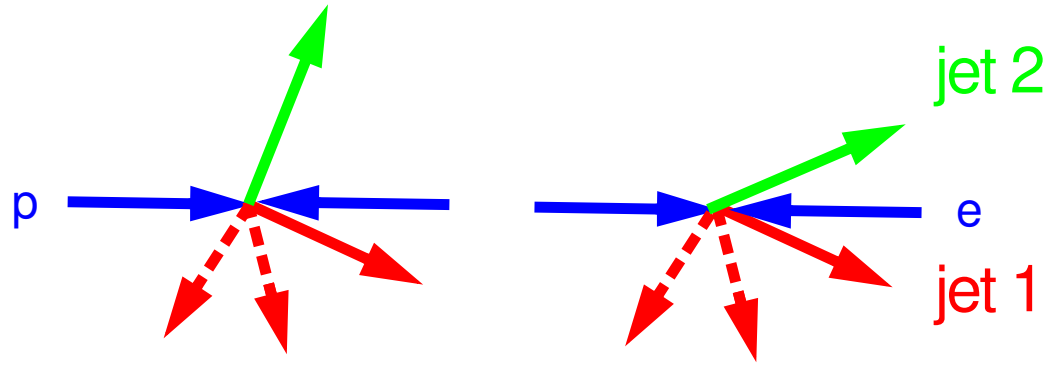
- determined from about 30 single-tagged D*events
- large uncertainty for x<0.1 mostly due to MC model uncertainty (extrapolation to full phase)

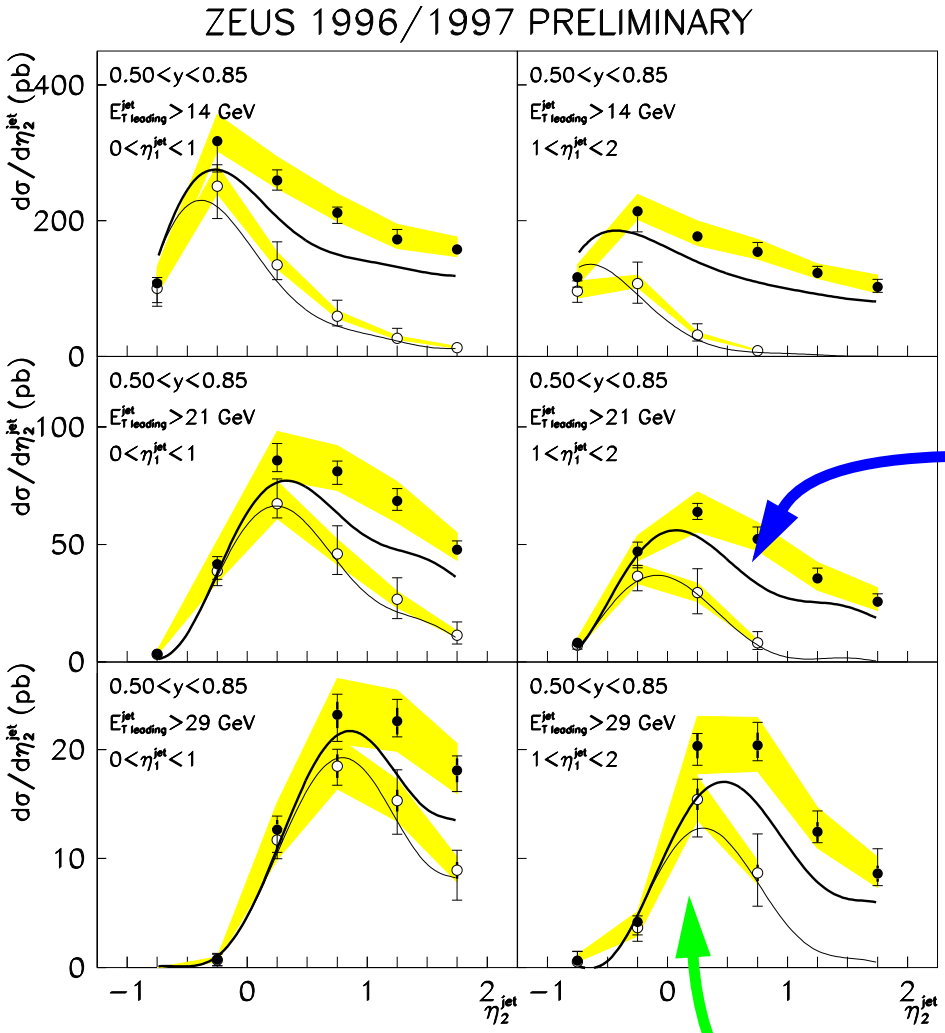
Vermaseren:
no hadron-like component
Herwig:
only massless charm

improvements expected

x < 0.1 data suggest hadron-like component

For x > 0.1 purely perturbative NLO QCD in good agreement with data





E_T

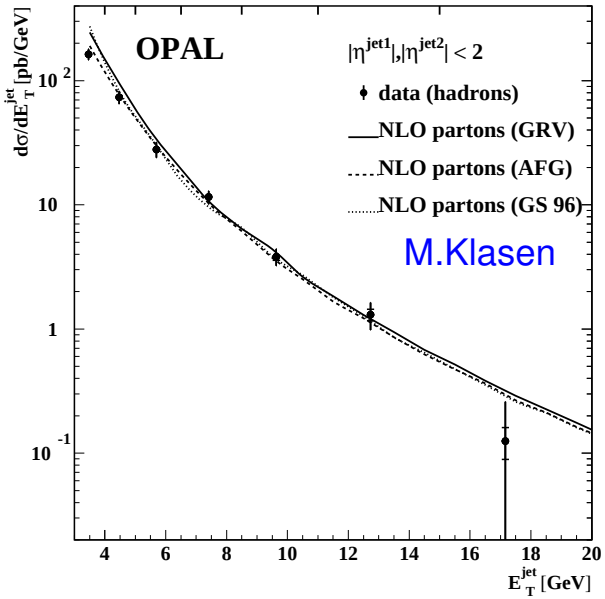
NLO using AFG-HO too low

x_γ

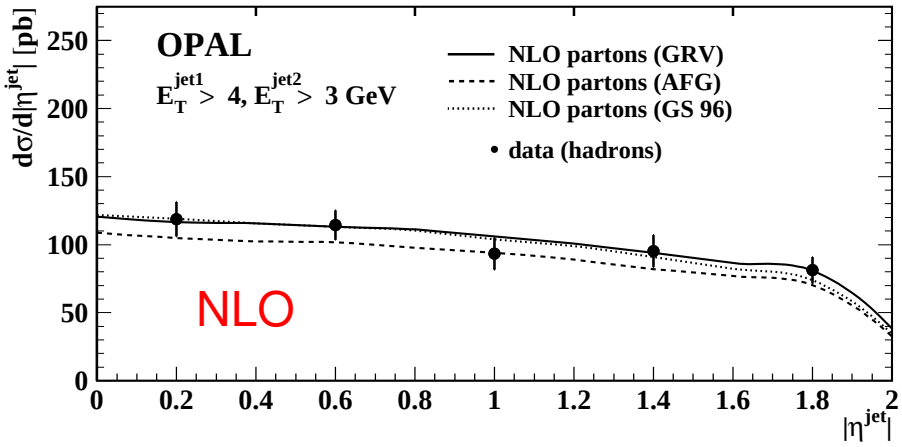
direct (x_γ>0.75)

- Hadronisation effects about 20 %
- Scale uncertainty about 20-30%
- difference still significant
- more in talk by Eileen Heaphy

Jet production in photon-photon scattering

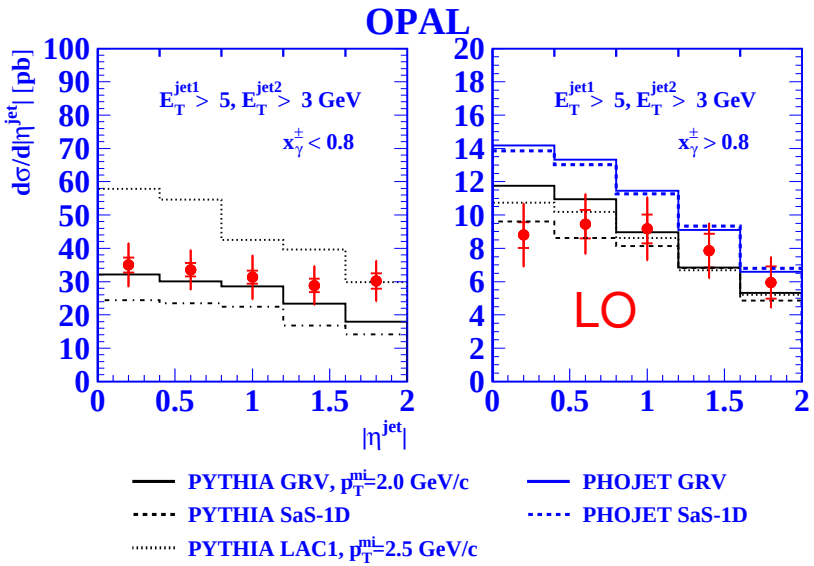


- multiple interactions in MC tuned to data energy flows
- sensitive to gluon in LO parametrisations (GRV,SAS,LAC)
- well described by partonic NLO calculation, but little sensitivity to NLO parametrisations (GRV,AFG,GS96)
- much more data could be analysed by the LEP experiments



-> B.Surrow

resolved direct

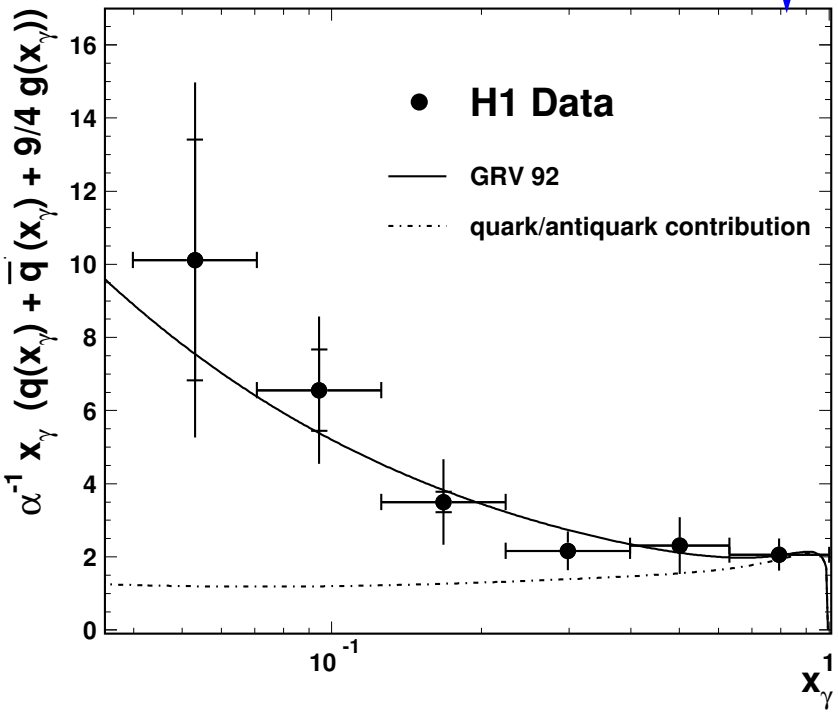


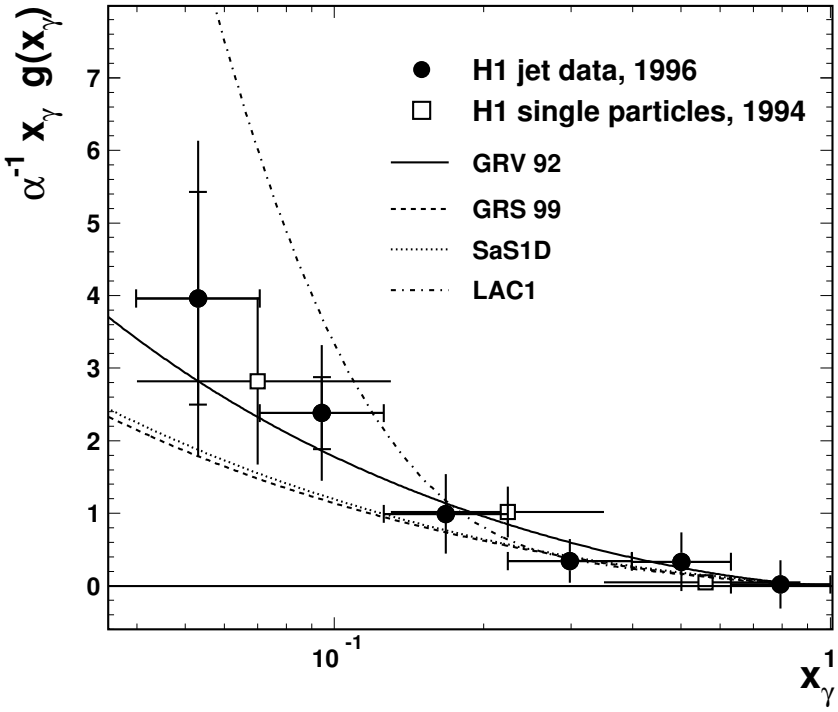
Single effective subprocess:

similiar cos θ* distributions for all resolved processes

$$\frac{d^4\sigma_{ep}}{dy\,dx_\gamma\,dx_p\,d\cos\theta^*} = \frac{1}{32\pi s_{ep}} \frac{f_{\gamma/e}}{y} \frac{f_{\gamma,\mathrm{eff}}(x_\gamma)}{x_\gamma} \frac{f_{p,\mathrm{eff}}(x_p)}{x_p} \frac{d\hat{\sigma}}{d\cos\theta^*}$$

$$f_{\gamma,\mathrm{eff}}(x_\gamma) = \sum_{n_f} (q_\gamma(x_\gamma) + \bar{q}(x_\gamma)) + \frac{9}{4} g(x_\gamma)$$

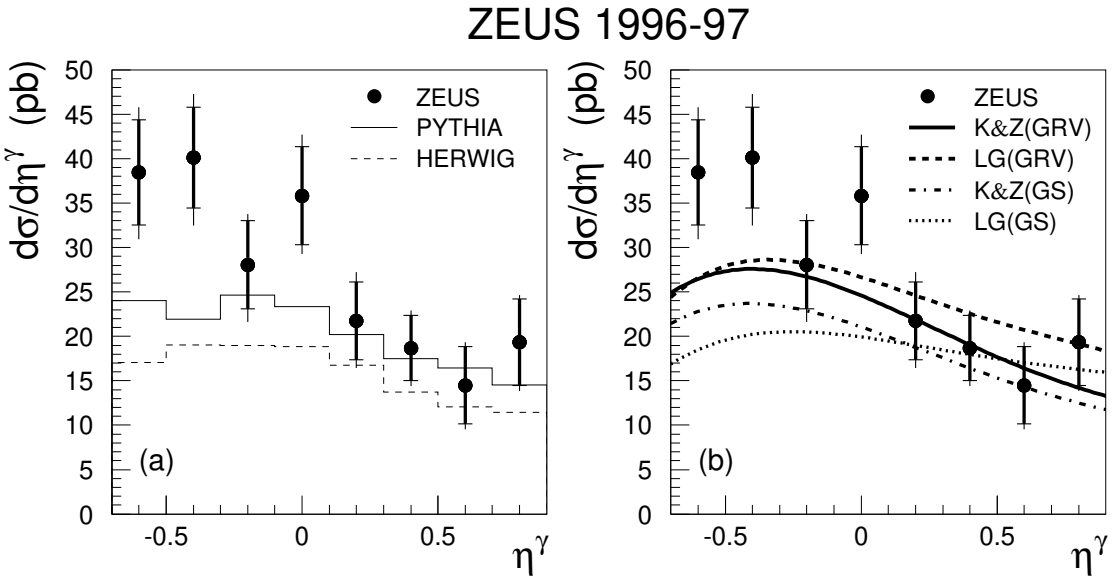


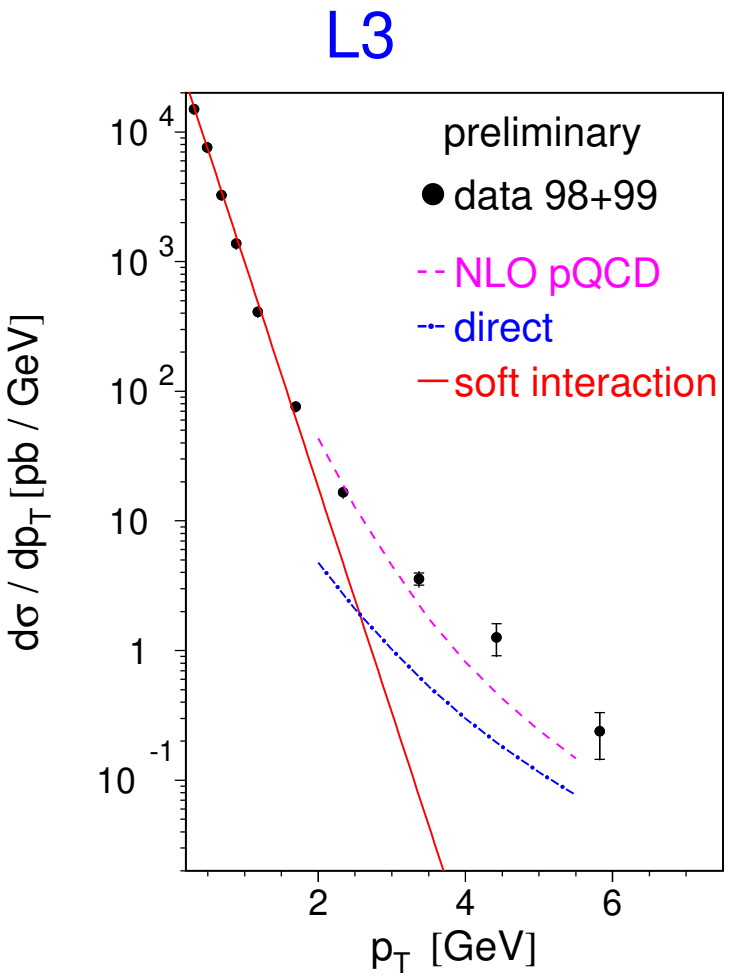


$p_T^2 = 74\,\mathrm{GeV}^2$

$p_T^2 = 38\,\mathrm{GeV}^2$

hadron production, prompt photons:

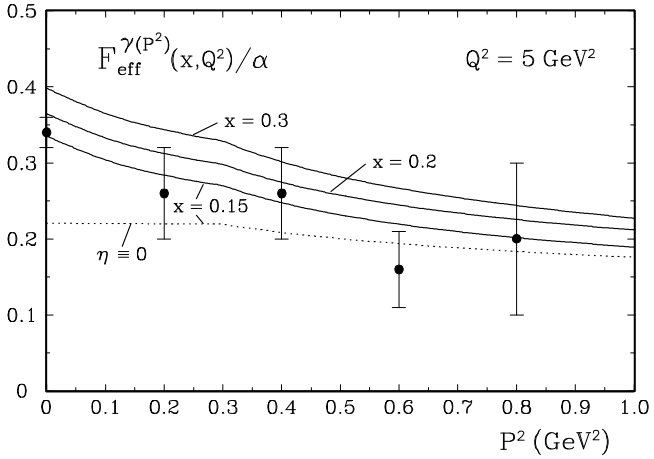


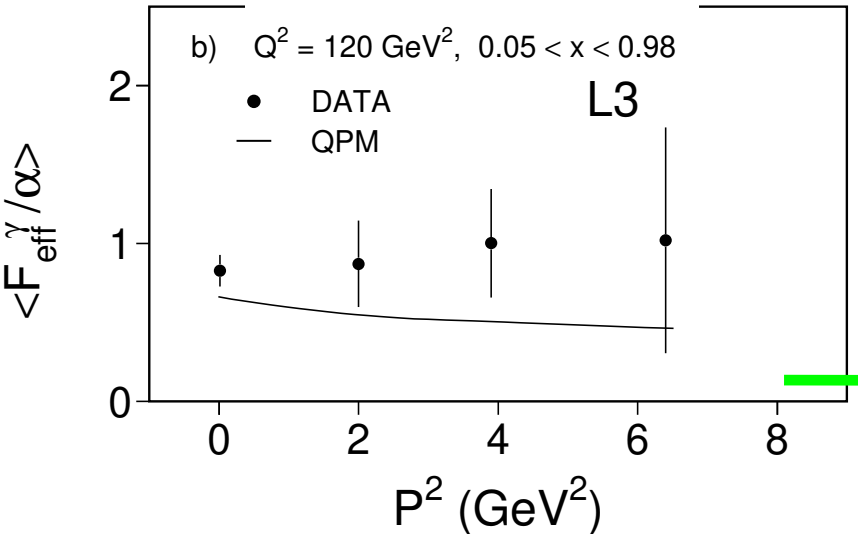


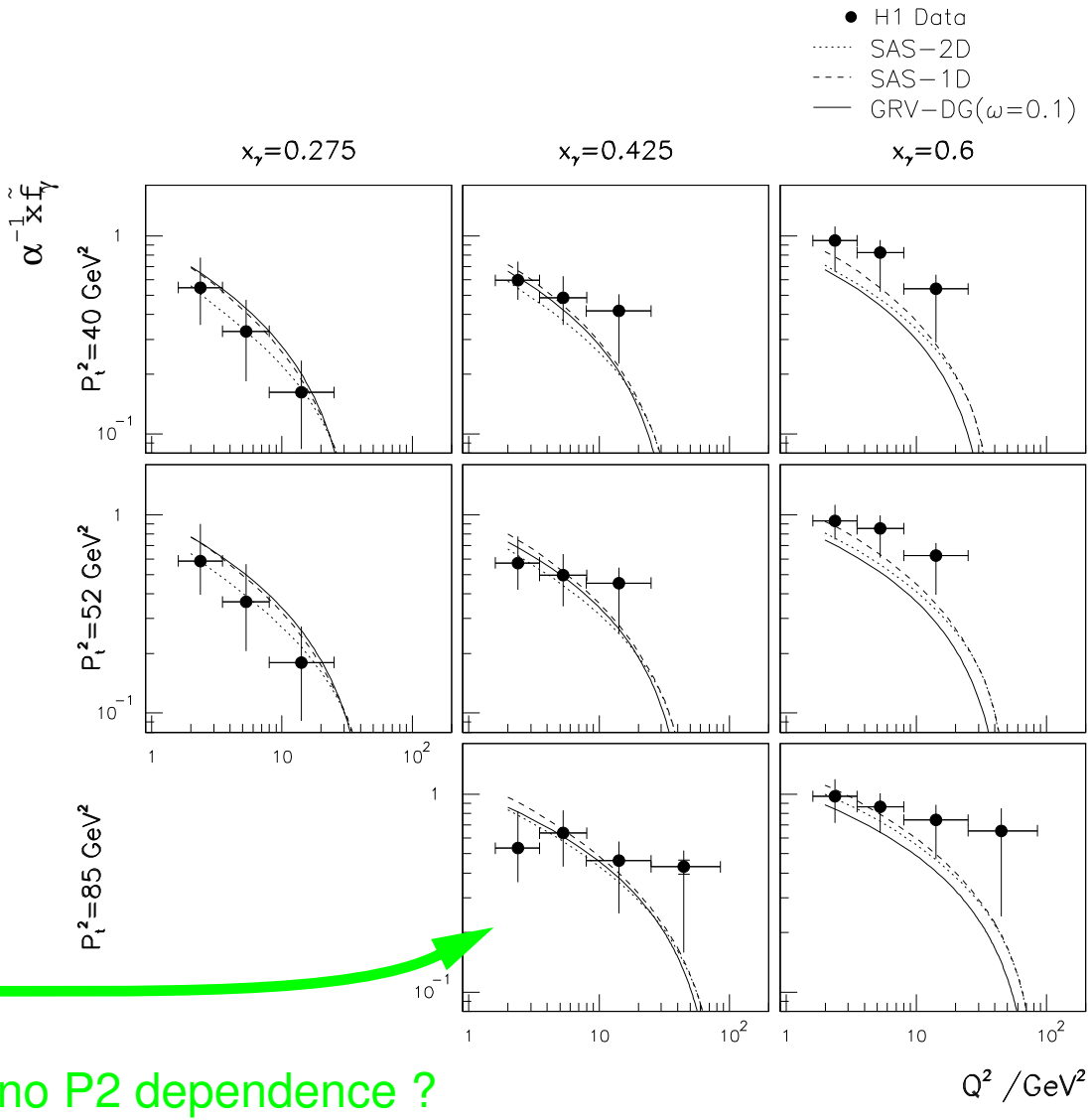
- prompt photon production in γγ and γp has no hadronization uncertainty but only small statistics available (S.W. Lee and W.Vogelsang)
- hadron production in γγ and γp also sensitive to photon structure

Parton densities of the virtual photon

Pluto

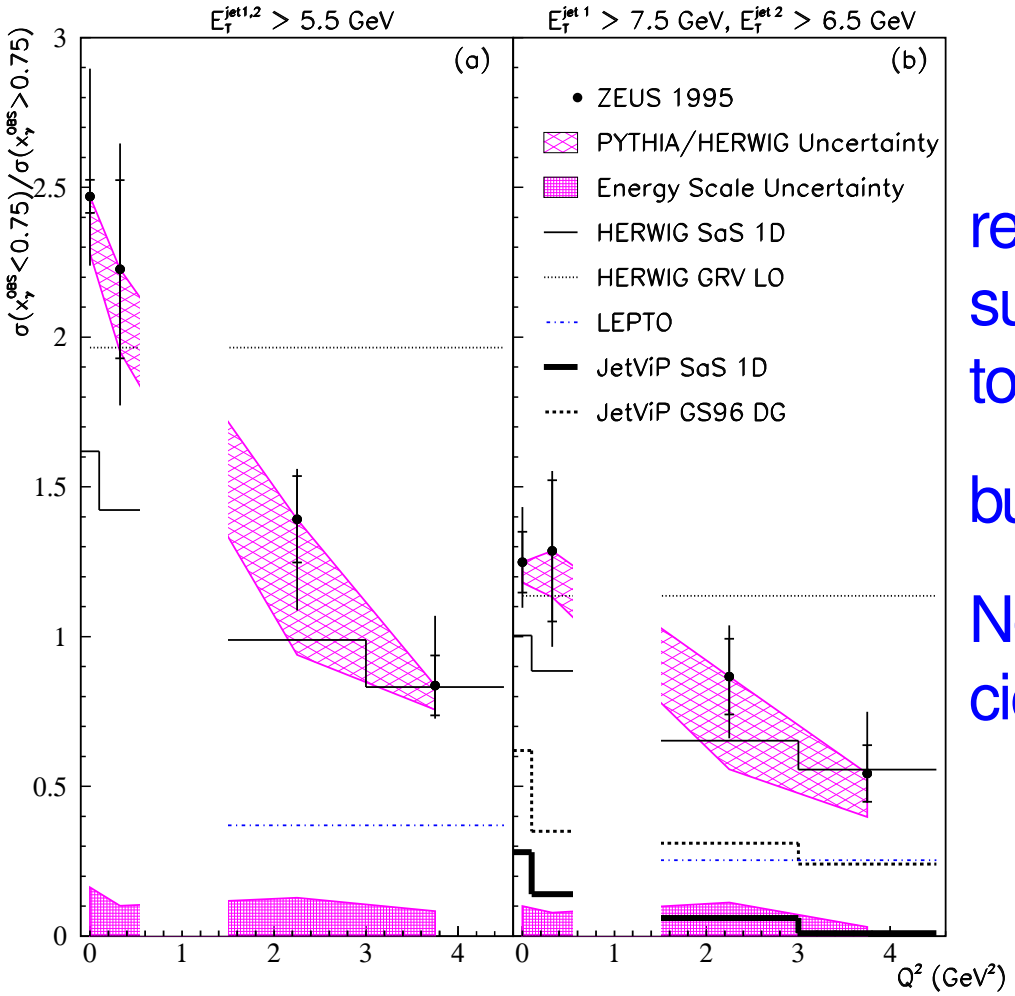






no P2 dependence ?

resolved/direct



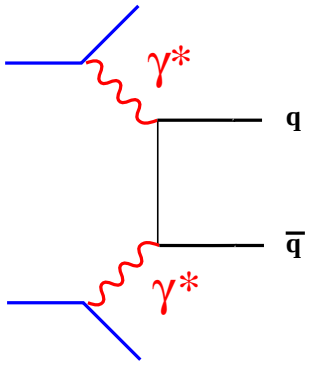
Q^2

resolved photon component is suppressed with increasing photon virtuality

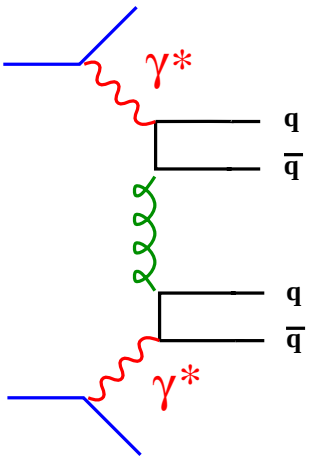
but it doesn't disappear

None of the models give a sufficient description of the data

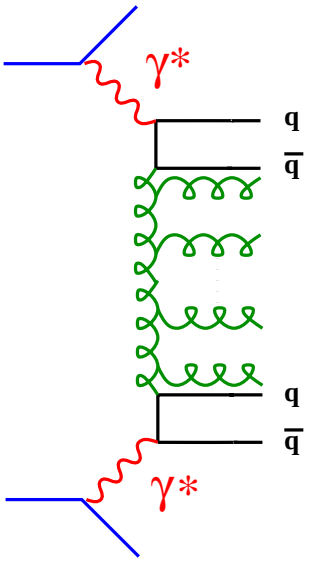
$\gamma^*\gamma^*$ scattering



QPM



gluon exchange



"BFKL"

$Q_1^2 = Q_2^2$

no ĐGLAP evolution

no non-perturbative hadron-like structure function

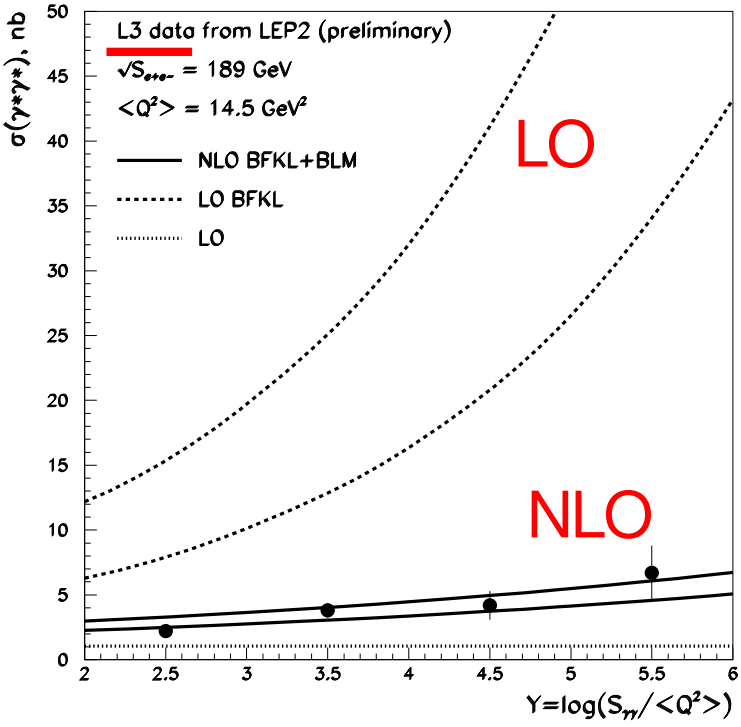
$$\sigma(\gamma^*\gamma^*) \propto e^{(\alpha_P - 1)Y} \text{ with } Y \approx \ln \frac{W^2}{\sqrt{Q_1^2 Q_2^2}} \approx \ln \frac{W^2}{Q_{1,2}^2} >> 1$$

Large uncertainties in LO: charm, scale

Large effects of NLO corrections

QPM subtraction ?

PHOJET describes the data. Why ?

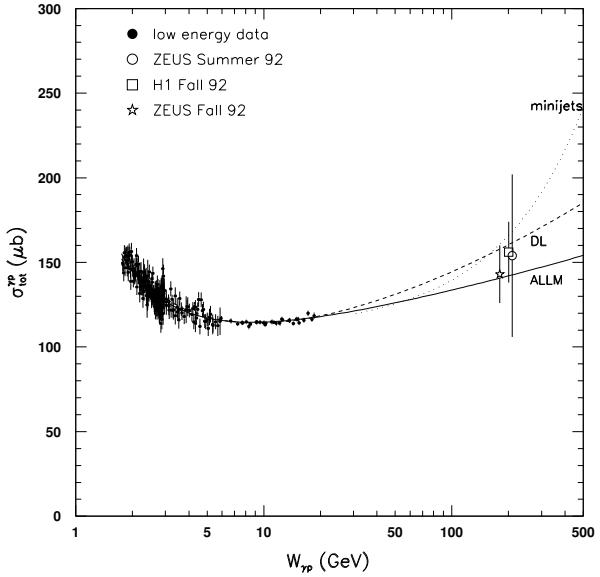


talks by A.Donnachie, C-H. Lin, E.Naftali

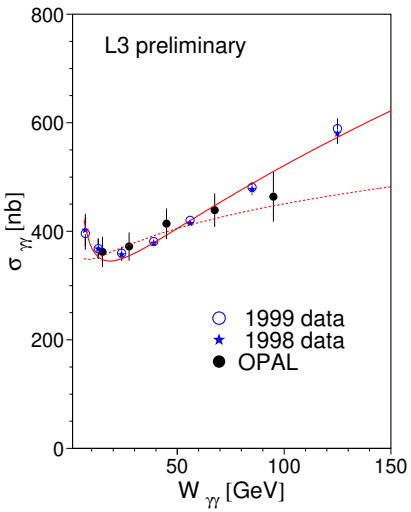
The total hadronic photon-ph/roton cross-section

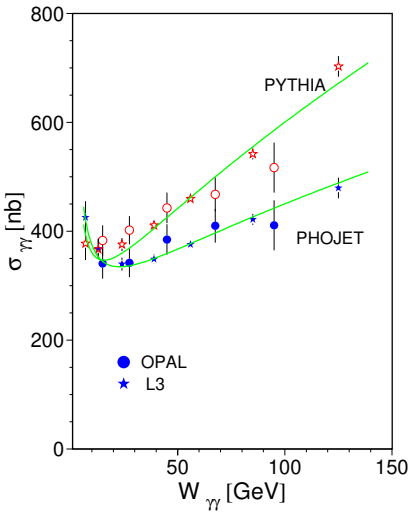
Does $\sigma_{tot}(W)$ rise faster for photon induced processes than for real hadrons ?

$$\sigma_{tot} = As^{\varepsilon} + Bs^{\eta} \quad \sqrt{s} = W$$



- Today's data from HERA is not very precise yet
- but perhaps it will be tomorrow
- talk by C. Ginsburg

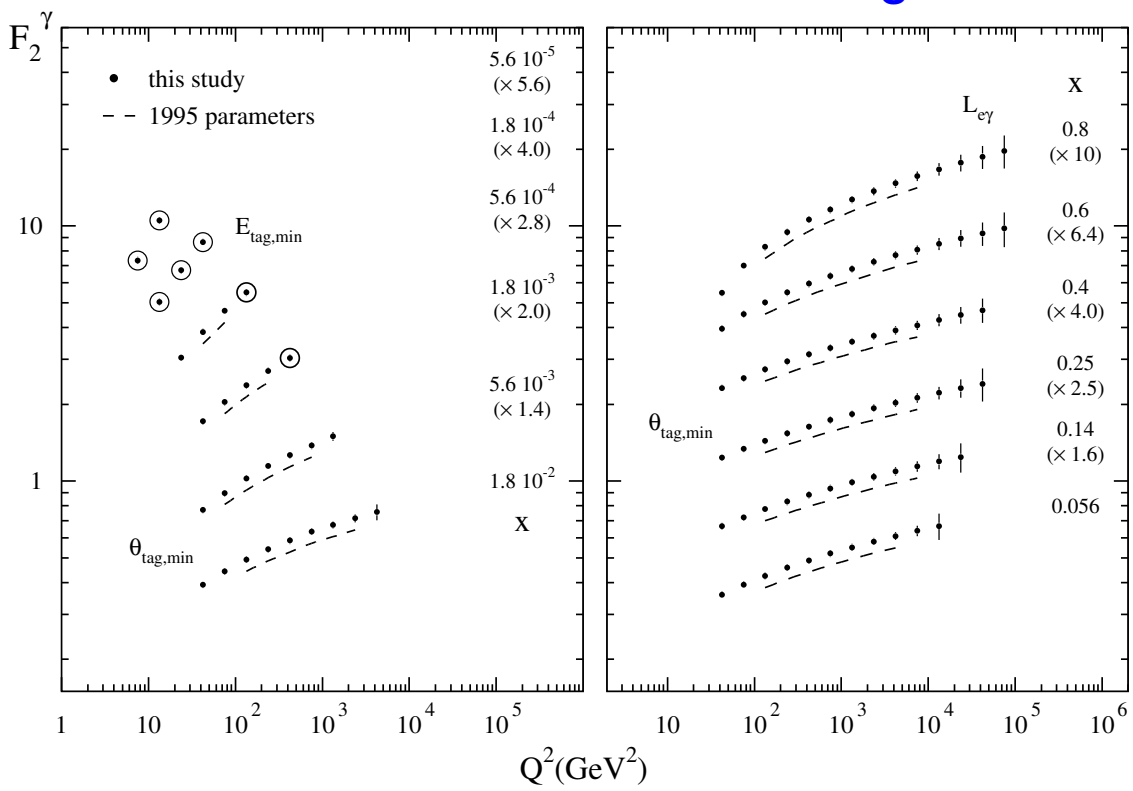




- LEP: model dependence of correction increases with W; needs to be understood (measure diffraction !)
- L3 and OPAL are consistent (talk by P. Achard)
- L3 obtains larger ε from very low (Reggeon) and very high W region
- Pre-LEP low W data is inconsistent

Photon structure in the future

A.Vogt



- At the Linear Collider with WW photons or with back scattered photons (preferred)
- The LC an also be used to study polarized parton densities of the photon (Stratmann)
- At THERA photon structure can be studied with jets (on-going studies)
- Don't forget heavy ions !

Conclusions and questions

- We need an improved quantitative understanding of the consistency between LEP and HERA results on photon structure
- We need new parton densities of the photon which use the new precise data from LEP and HERA
- How well do we understand hadronisation corrections and the influence of non-perturbative effects in jet physics ?
- We urgently need further improvements of the Monte Carlo models (at least at LEP)
- Systematic uncertainties on total cross-section measurements have to be reduced
- What can we learn about photon structure from future machines ?