Structure of the Photon

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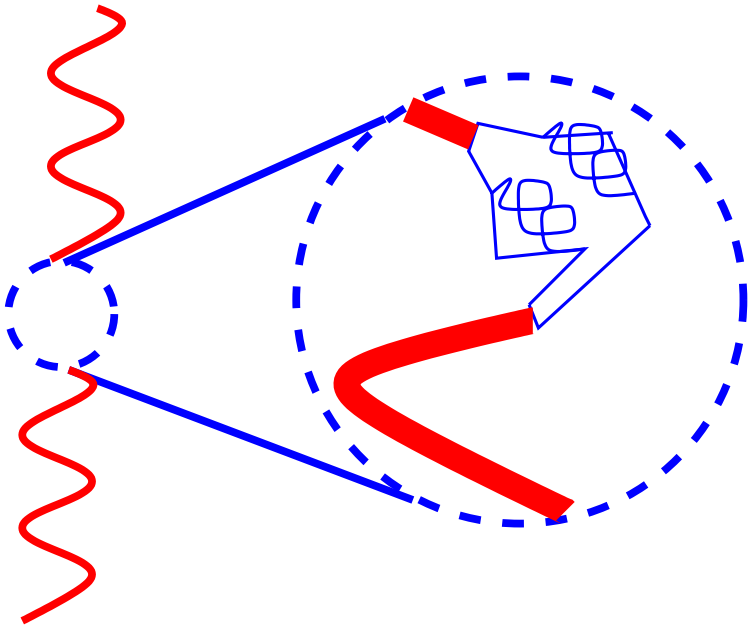
Lepton-Photon 12/8/99

Outline:

- **Introduction**
- **QCD and the Real Photon**
- **Charm and the Real Photon**
- **Virtual Photon Structure?**

Acknowledgements to all the hard work involved on the LEP and HERA experiments, the clearly written papers for EPS and particularly all the lively discussions at Photon99. Extra thanks to Richard Nisius for useful discussions and some lovely summary plots.

Introduction: The Structure of a Fundamental Gauge Boson?



Probing quantum fluctuations of the field theory.

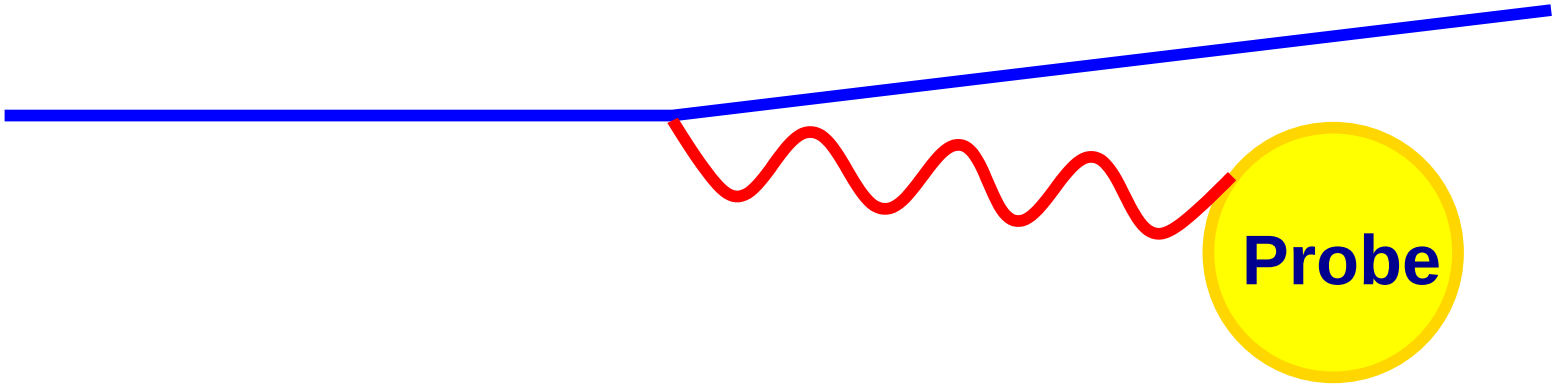
Coupling via leptons and quarks into Electroweak and QCD.

How well is this behaviour understood? How similar is it to what happens inside hadrons?

What happens when the photon becomes virtual itself?

INTRODUCTION: HOW IS IT MEASURED?

With great difficulty...



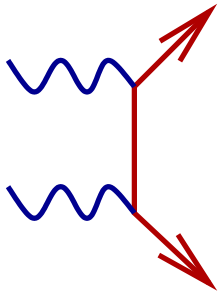
Use “almost real” photons accompanying e^+ or e^- beams.

Probed by a highly virtual photon (LEP,TRISTAN,PETRA,PEP), by high transverse energy jets and particles (HERA,LEP) or by heavy quarks (HERA,LEP).

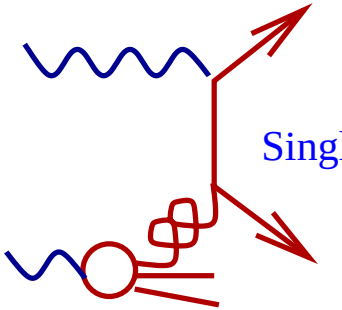
Challenging measurements: Photon energy? Distance scale of probe?

Introduction: How is it described?

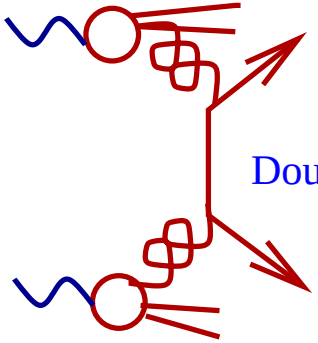
Photon-Photon



Direct

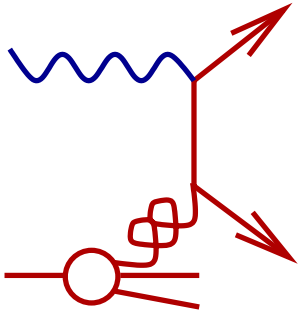


Single Resolved

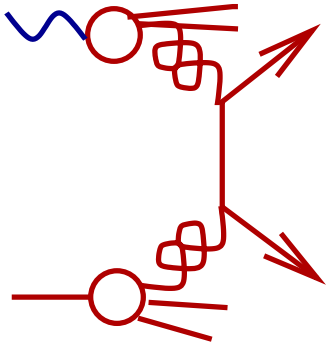


Double Resolved

Photon-Proton



Direct



Resolved

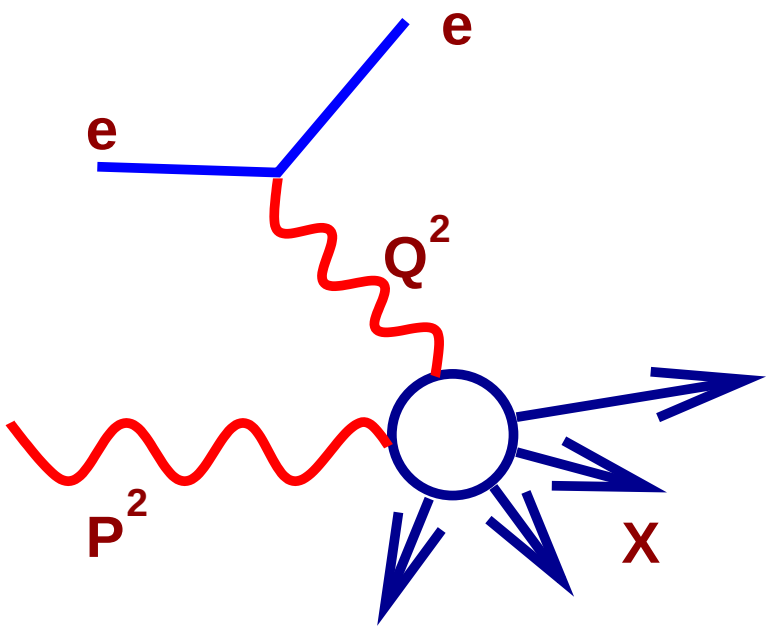
Leading order processes for jet, particle and heavy quark production.

Photon virtualities P^2 (Q^2 at HERA!). Virtual parton probes "less virtual" photon at scale related to E_T^2.

Resolved and direct separation becomes a matter of choice at higher orders (and in real life...)

INTRODUCTION: HOW IS IT DESCRIBED?

Leading order Deep Inelastic Electron-Photon Scattering



Photon virtualities $\mathrm{Q}^2 \gg \mathrm{P}^2$. "Highly virtual" photon probes "less virtual" photon at scale Q^2.

More Terminology & Definitions

"Resolved Photon": Fluctuations of the photon occured at longer distance scale than the the probing scale. Includes ideas such as "VDM", "Anomalous", "Pointlike"...

"Direct Photon": No Fluctuations occurred. Photon enters directly in the hard scatter.

"Prompt Photon": Photon emerges directly from the hard scatter.

Structure functions - defined in terms of highly virtual lepton vertex, neglecting weak interactions ($\mathrm{Q}^2 \ll M_W^2$).

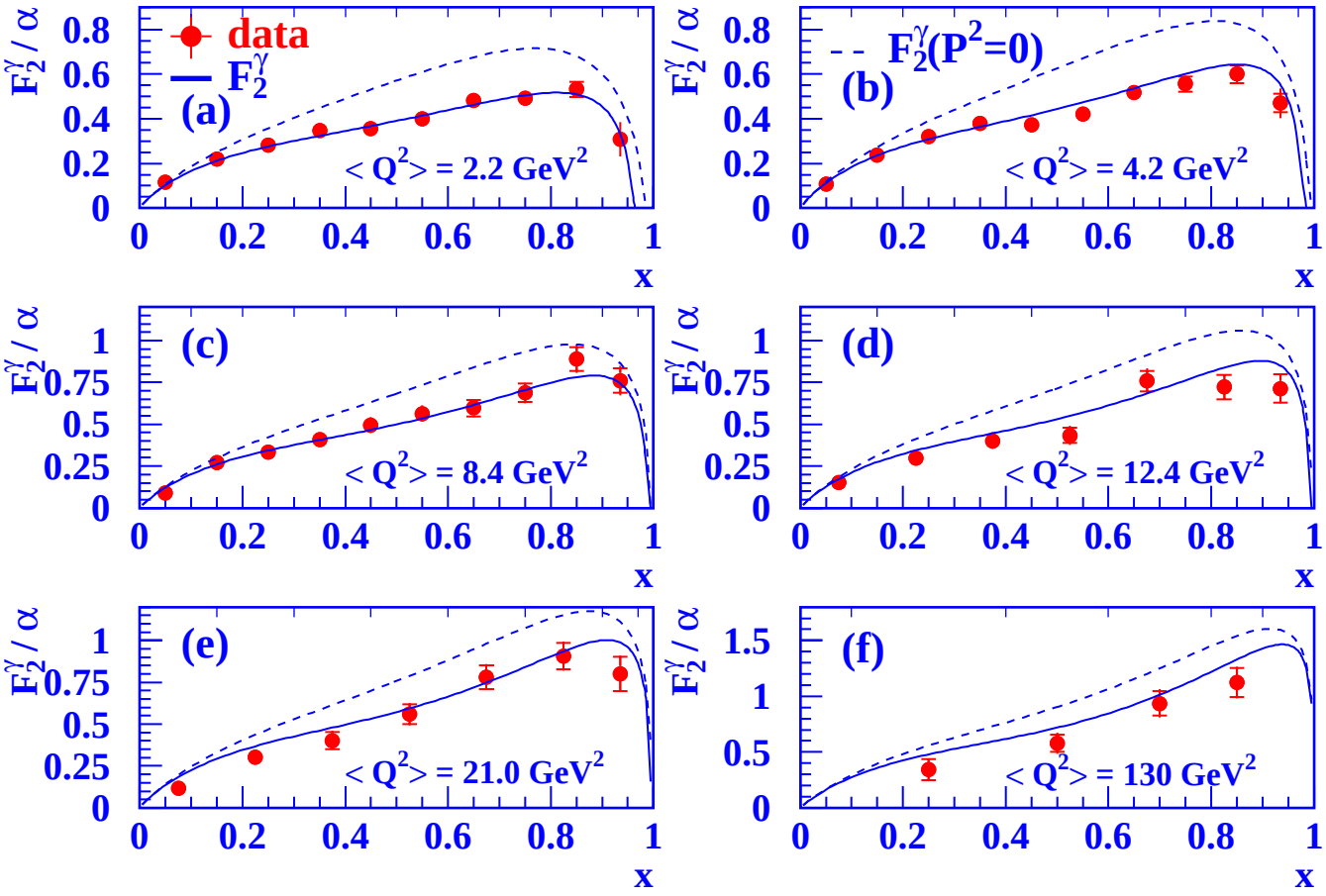
$$\frac{d^2\sigma_{e\gamma\to eX}}{dx d\mathrm{Q}^2} = \frac{2\pi\alpha^2}{xQ^4}\left[(1+(1-y)^2)F_2^\gamma(x,\mathrm{Q}^2,\mathrm{P}^2) - y^2 F_L^\gamma(x,\mathrm{Q}^2,\mathrm{P}^2)\right]$$

$X = \mu^+\mu^- \Rightarrow$ QED structure. (*Number of μ 'in' the photon*)

$X =$ hadrons $\Rightarrow$ QCD structure. (*Number of q 'in' the photon*)

QED Structure Function

OPAL



Note high x peak, and increase with Q^2.

x resolution 0.03. ($\mu^+\mu^-$ mass well measured)

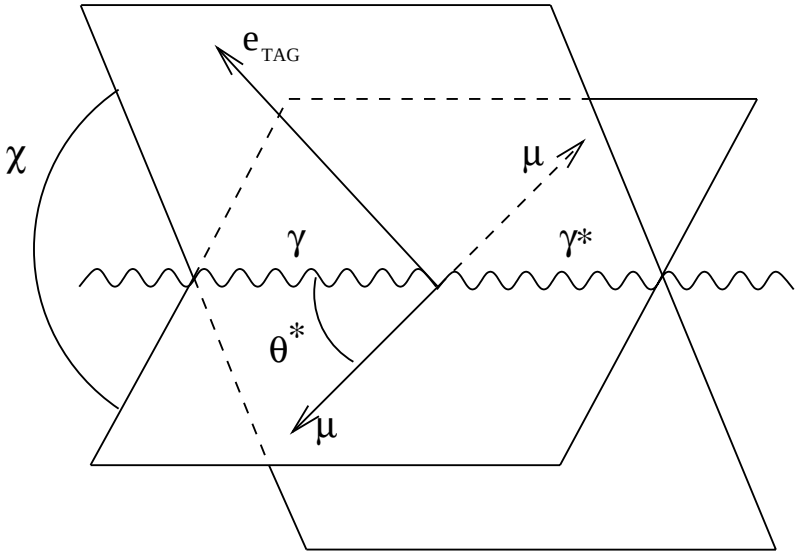
Virtuality of target photon has a significant effect for all Q^2, even though

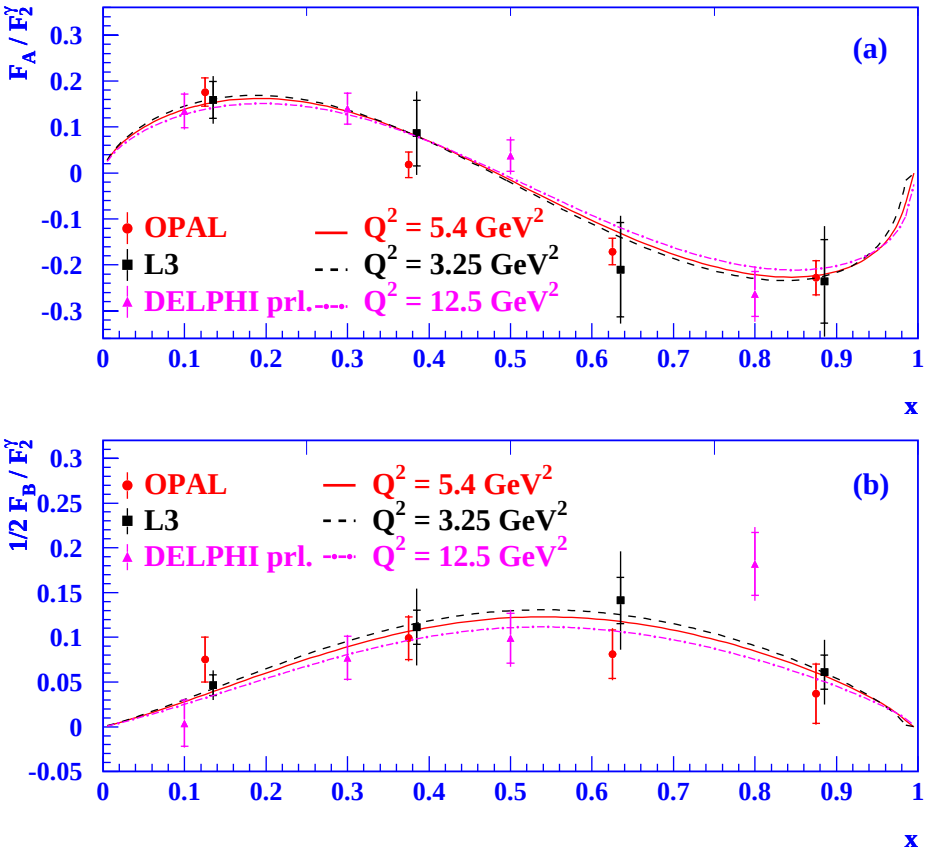
$$\langle P^2 \rangle = 0.05\,\mathrm{GeV}^2$$

Good agreement with fundamental prediction of QED

(Also measured by ALEPH,DELPHI,L3)

QED Structure Function





Also measure the dependence on angle χ between μ^- and highest angle scattered lepton.

(Theory curves in small y limit).

F_A^γ multiplies a $\cos\chi$ term,

F_B^γ multiplies a $\cos 2\chi$ term.

Again, agreement with QED.

QCD AND THE 'REAL' PHOTON

- **Theoretically more complex**

Non-perturbative QCD in initial state, and in the final state for jet and particle production.

- **Experimentally more difficult**

Non-perturbative QCD in final state. Does not just affect jet or particle production, since in DIS the photon energy must be measured from the hadronic final state.

Dealing with model dependence is a *major* issue for the experiments. Dilemma!

Too many assumptions $\Rightarrow$ Misleadingly small or discouragingly large error bars, mainly reflecting theoretical uncertainties.

Minimal assumptions $\Rightarrow$ Measurements very hard to interpret and compare with each other or with fundamental QCD.

QCD AND THE 'REAL' PHOTON

- **Potential rewards are very high**

Sensitive to many important effects: Photon (and proton) structure, QCD radiation, α_s, low-x QCD, hadronization and "underlying" events.

Not much use being sensitive to all these at the same time...

Dilemma has led theorists and experimentalists deep into the realm of Monte Carlo simulations. Need consistent picture over widest possible data set.

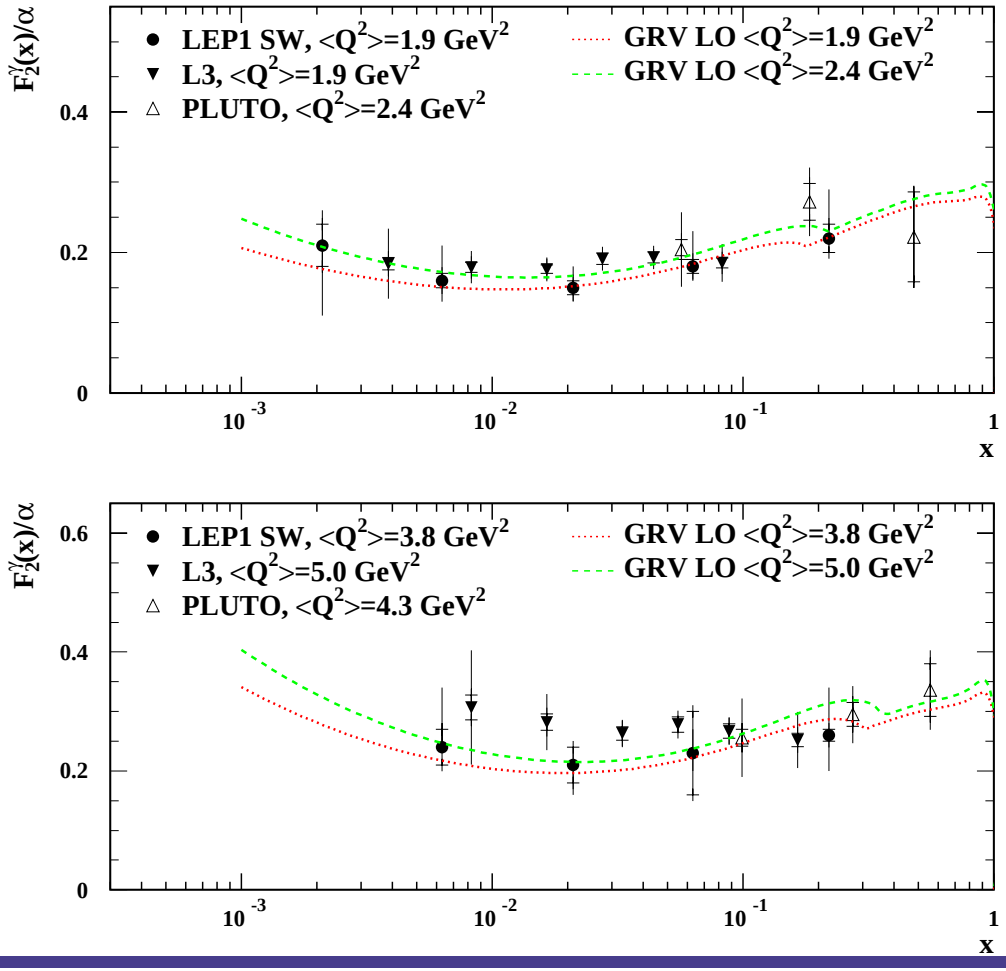
LEP-wide $\gamma\gamma$ working group, HERA Monte Carlo workshop: Conversation via **general purpose simulations** (PYTHIA, HERWIG, PHOJET). See proceedings of Photon99, Freiburg.

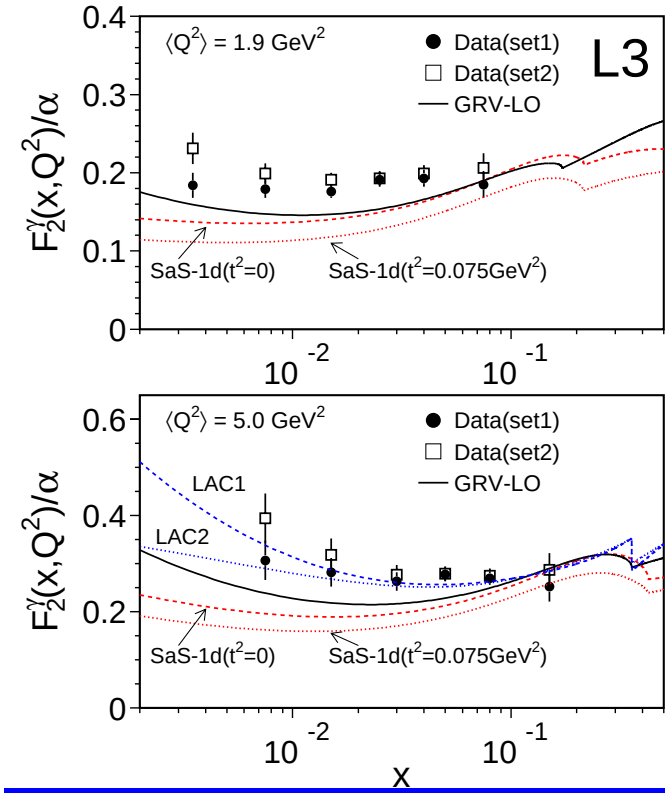
Exciting times for those involved, but hard to draw clear physics statements at this stage for a wider audience. What progress has been made? What can we say so far?

QCD Structure Function

Now measured for samples with $0.24\ \mathrm{GeV}^2 < \langle Q^2 \rangle < 400\ \mathrm{GeV}^2$

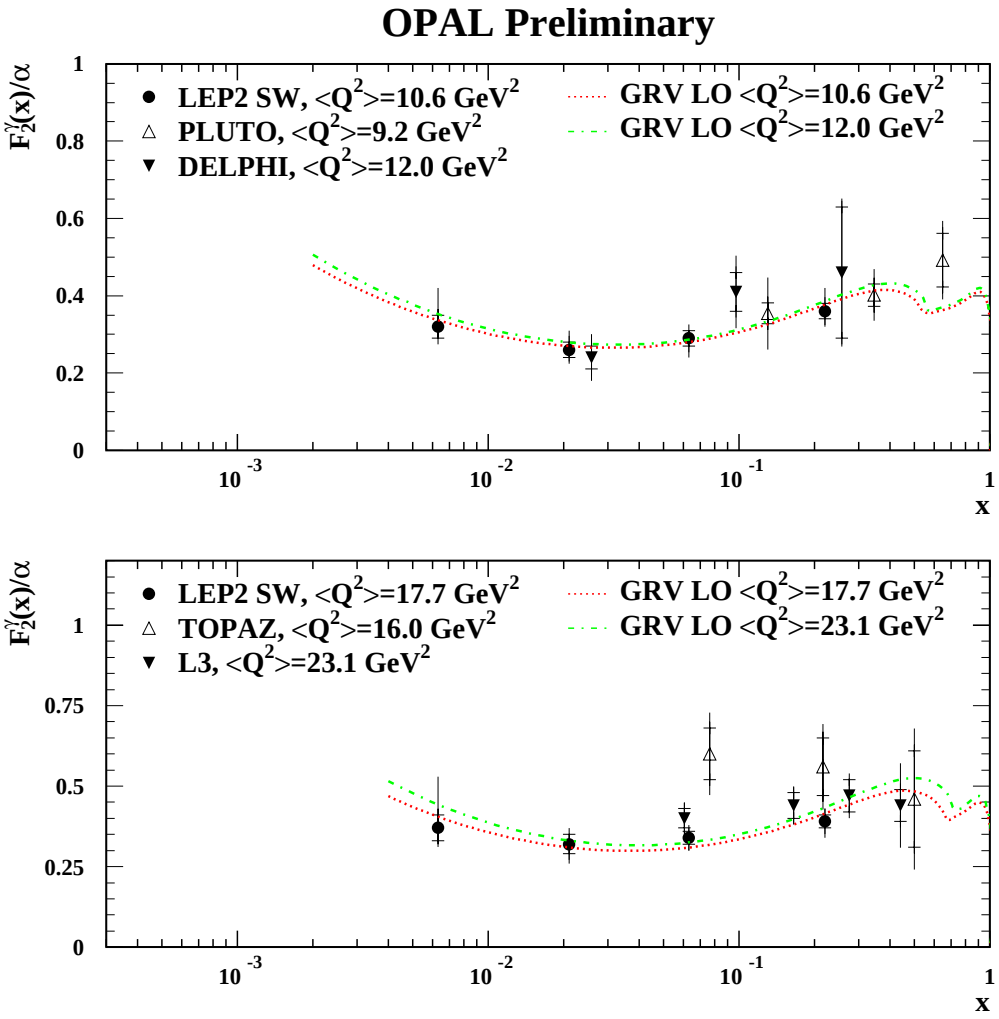
OPAL Preliminary, and L3 Low Q^2

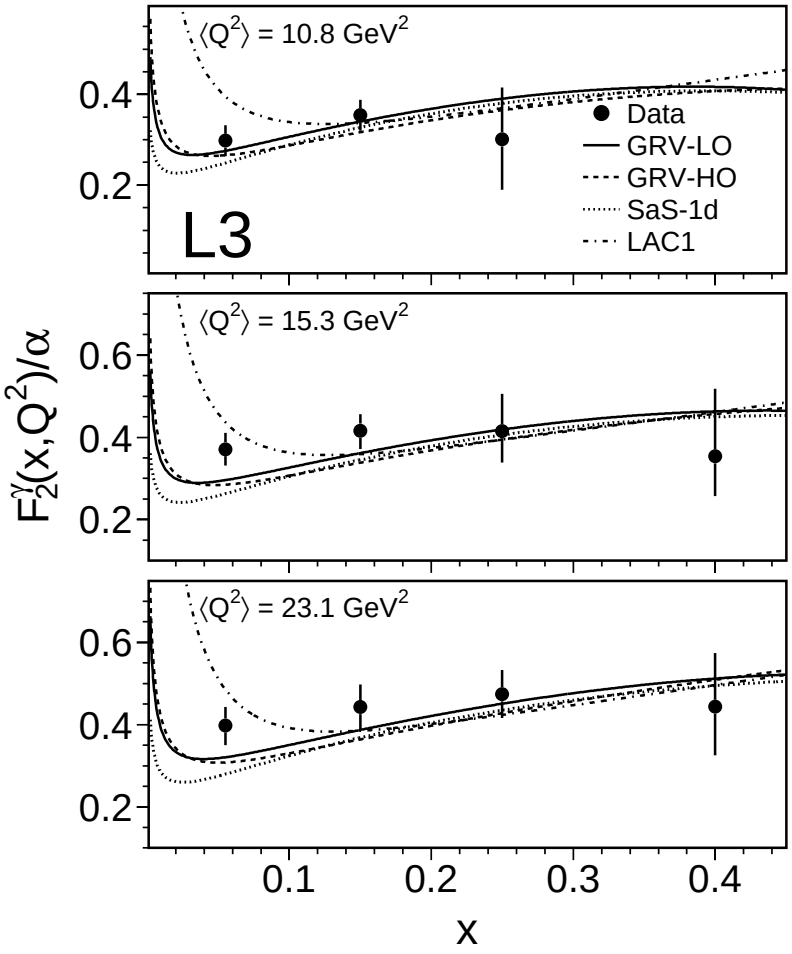




* Two "data" sets ⇒ Large model dependence.
* P^2 dependence (later).

QCD Structure Function - Higher Q^2



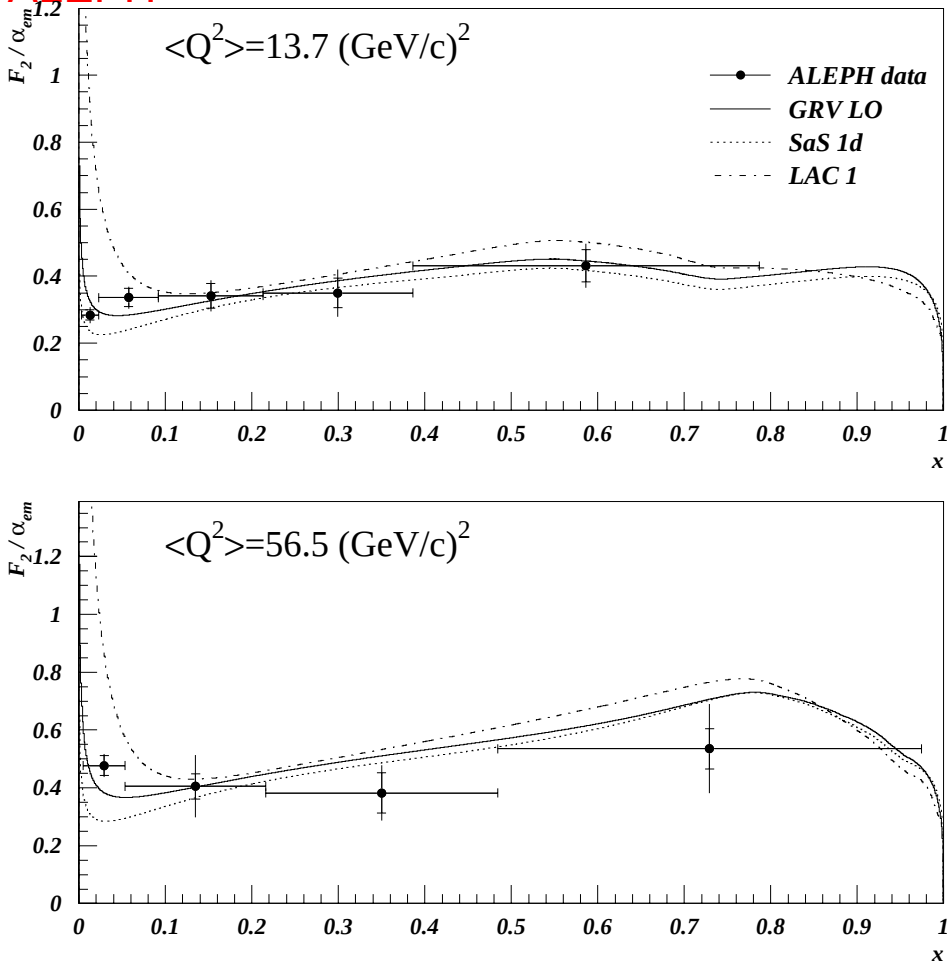


NB: No model dependence systematic shown for L3 data on right.

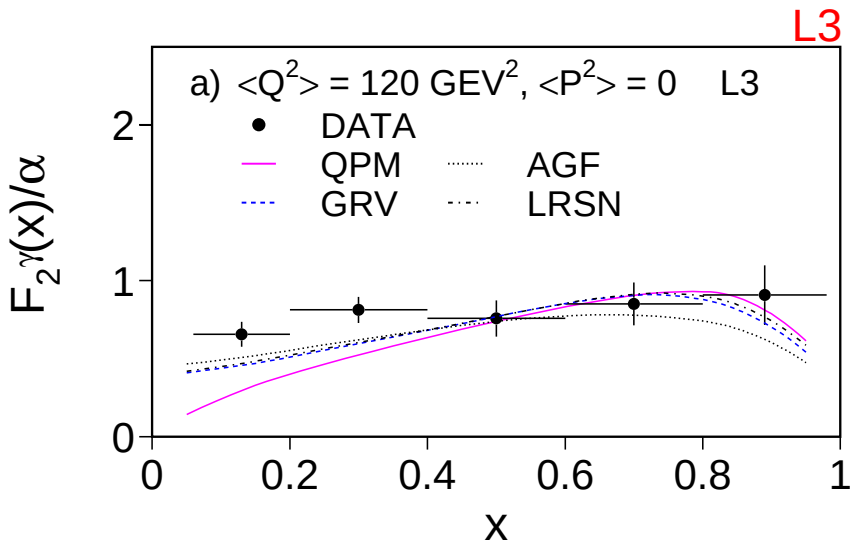
QCD Structure Function - Still Higher Q^2

ALEPH

PRELIMINARY



L3



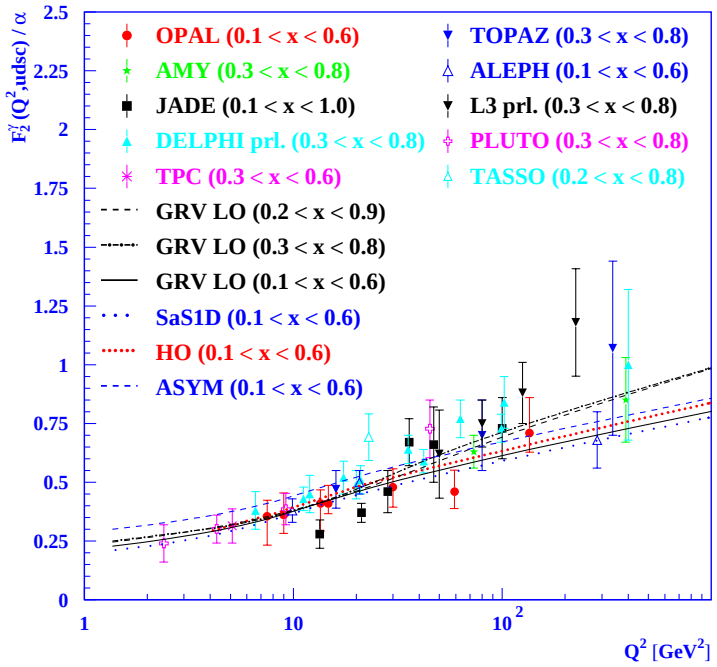
Compare to QED F_2 -

Hard (high x) as before,

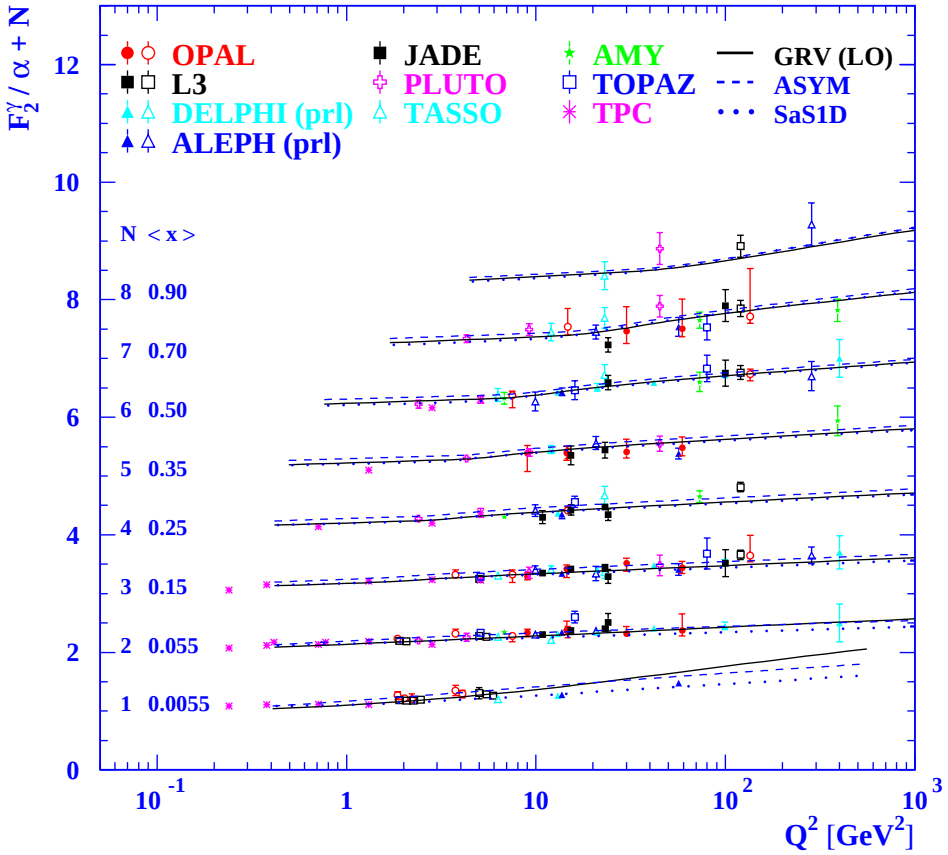
but more happening at low-x

due to soft QCD radiation.

QCD Structure Function - Q^2 Dependence



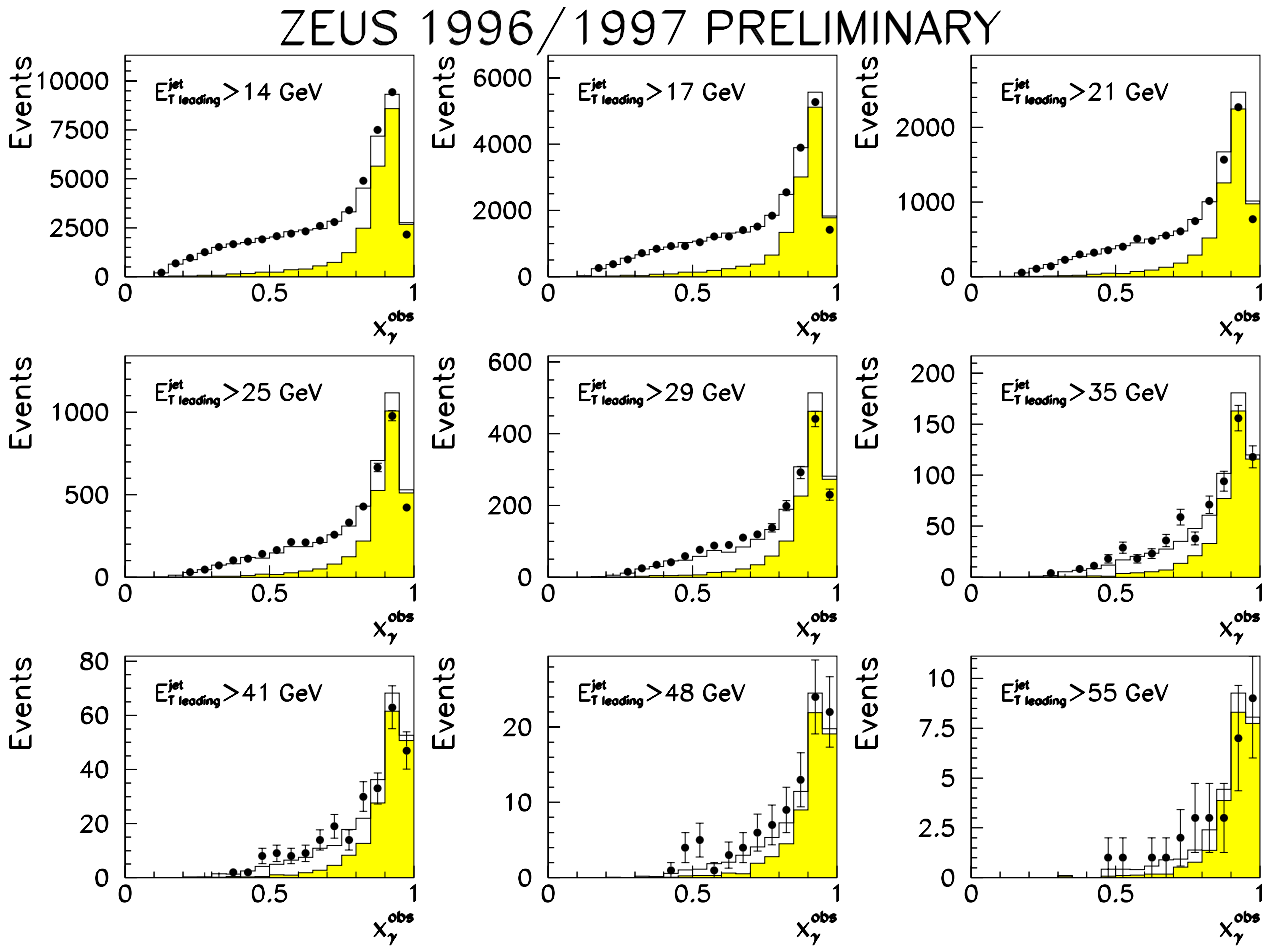
Clear positive scaling violation, driven by photon splitting.



Hints that dF_2^γ / dQ^2 increases as x increases. Unlike proton.

QCD AND THE REAL PHOTON AT HERA

The HERA equivalent of F_2^γ is a jet cross section... EWWW!



Jets define the 'hard process' which is to be interpreted as probing the photon.

Define jets (algorithm, cuts) and calculate the observable

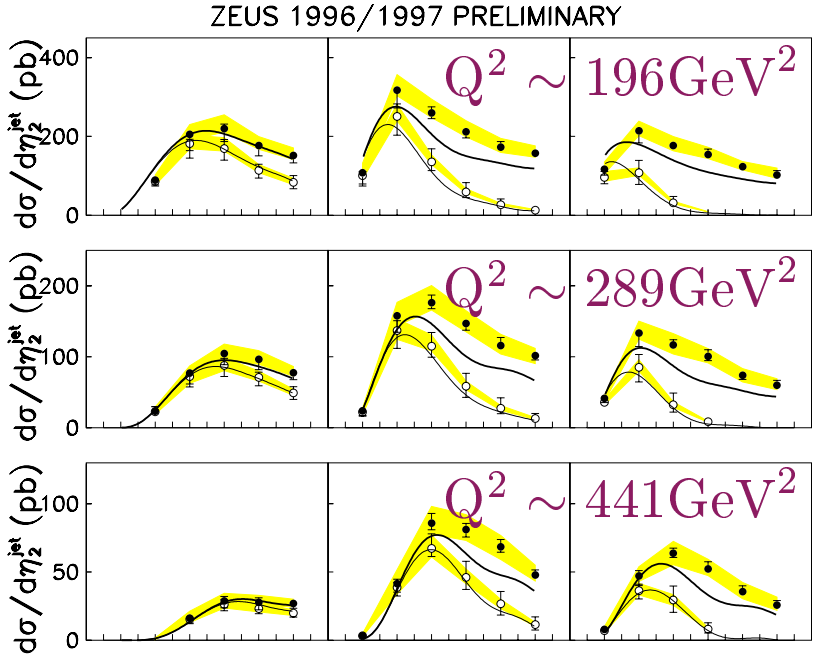
$$x_\gamma^{\mathrm{OBS}} = \frac{\sum E_T^{\mathrm{Jet}} e^{-\eta^{jet}}}{2yE_e} = \frac{\sum_{jets} E - p_z}{(E-p_z)_\gamma}$$

$$\mathrm{Q}^2 \sim (E_T^{\mathrm{Jet}})^2$$

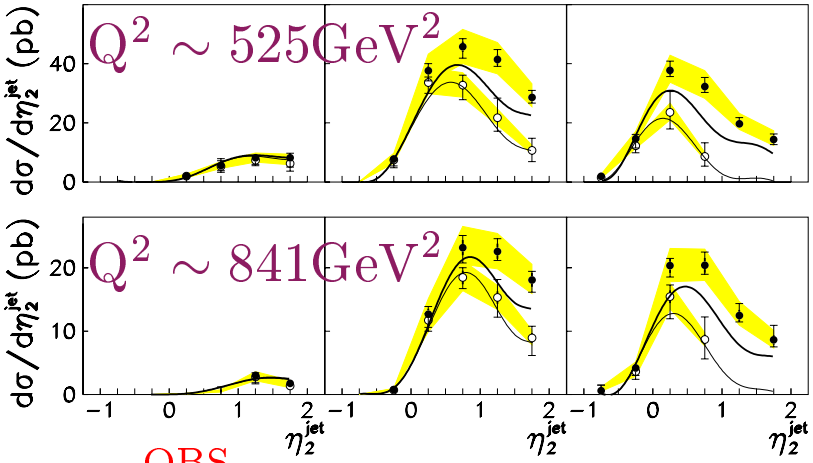
$$\mathrm{P}^2 \sim 0$$

QCD AND THE REAL PHOTON AT HERA

Compare to NLO pQCD calculations, taking a photon parton distribution function as input.



x_γ^{OBS} gets smaller $\rightarrow$



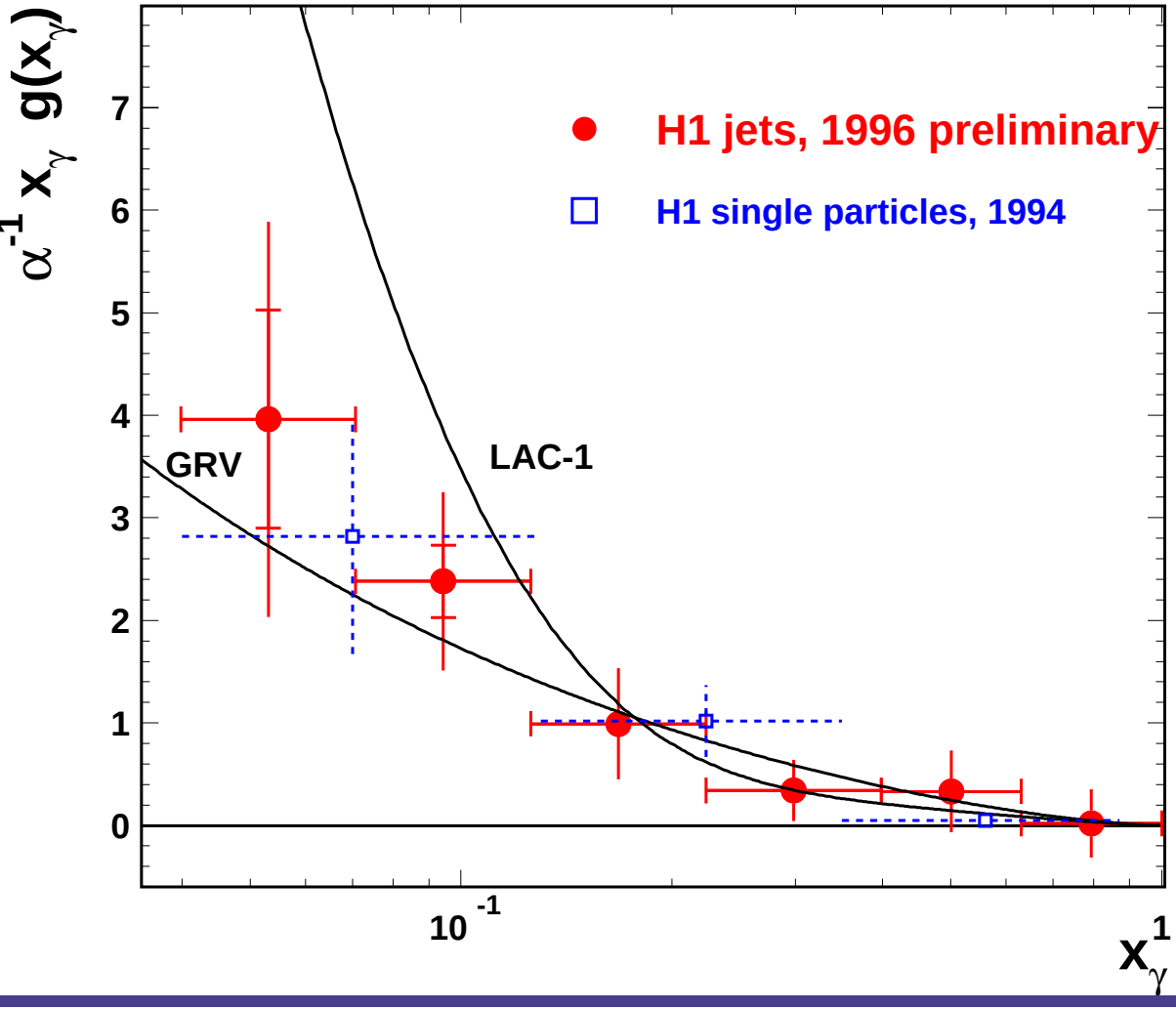
x_γ^{OBS} gets smaller $\rightarrow$

AFG-HO Photon PDF.

Discrepancy appears in resolved photon interactions, at highest E_T^{Jet}, where hadronization effects are smallest. $(E_T^{\mathrm{Jet}})^2 \sim \mathrm{Q}^2 > 196\mathrm{GeV}^2$: Higher than LEP?

QCD AND THE REAL PHOTON AT HERA

Assuming LO QCD & MC models, can extract an effective parton density.



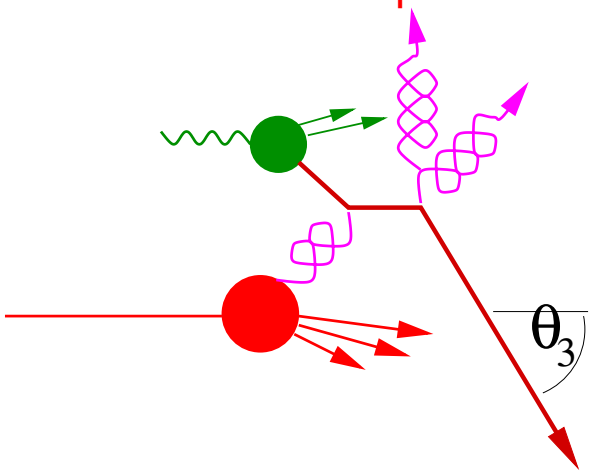
QCD AND THE REAL PHOTON AT HERA

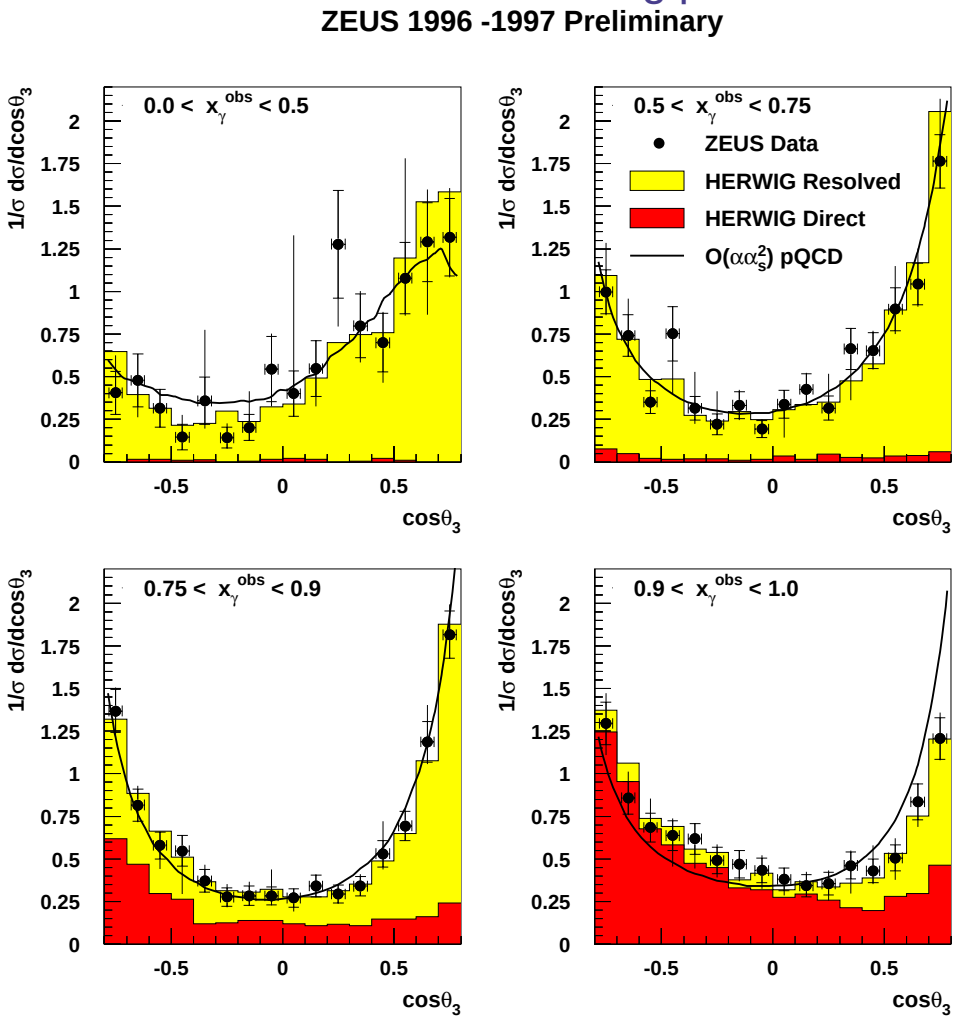
Three jet distributions. QCD dynamics sensitive to colour of incoming parton.

In 3-jet centre-of-mass system:
$\theta_3 =$ angle between highest energy jet and the proton beam direction.

Compare to $\mathcal{O}(\alpha\alpha_s^2)$ QCD and to LO MC simulation. (3^{rd} jet from parton shower)

Change in shape of distribution as x_γ^{OBS} increases is driven by mix of incoming resolved and direct photons.



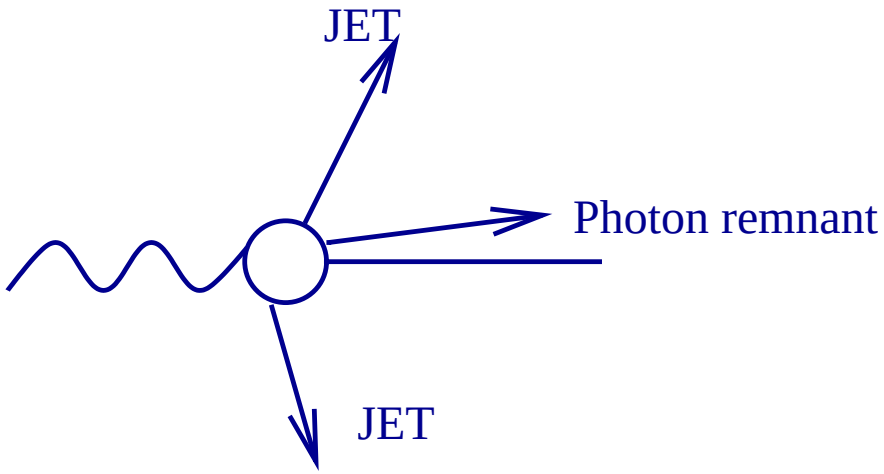


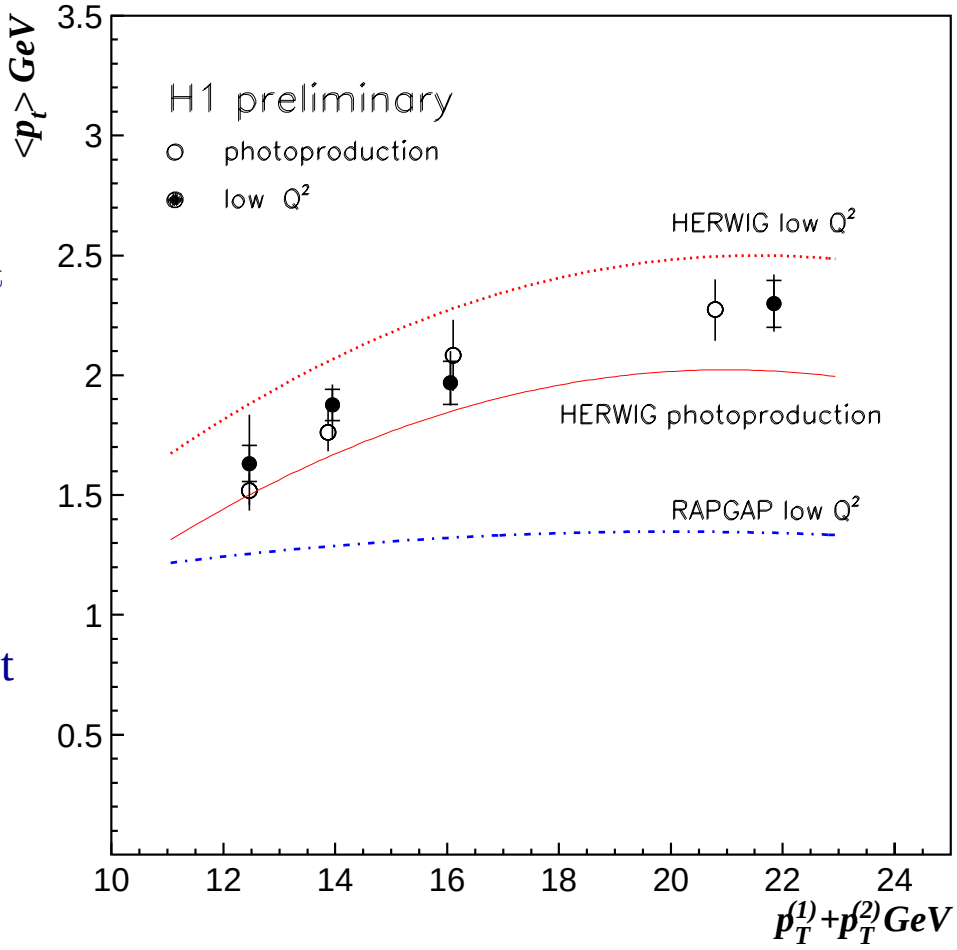
QCD AND THE REAL PHOTON AT HERA

The photon remnant revisited.

Measured to have $p_T = 2.1 \pm 0.2$ GeV w.r.t. photon direction.
(ZEUS, PLB 354 (1995) 163).

Now measured by H1 as a function of $E_T^{\rm Jet}$ for photoproduction and for $1.4 < \mathrm{P}^2 < 25\mathrm{GeV}^2$.

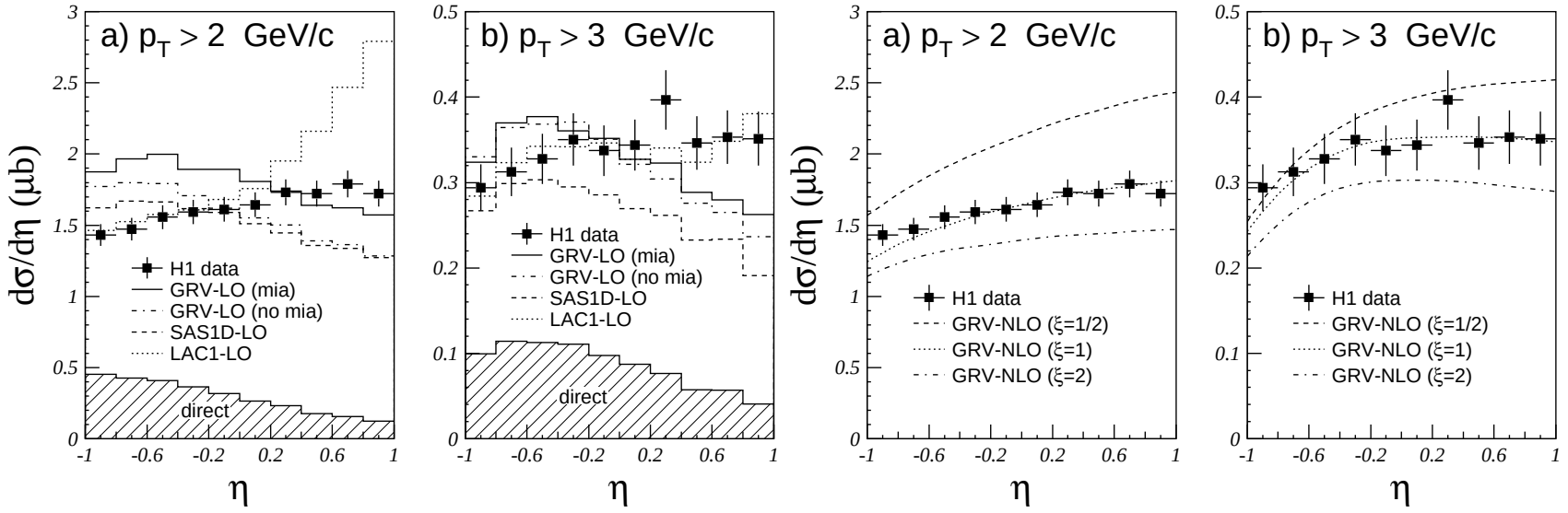




Consistent with ZEUS result. HERWIG does a reasonable job.

QCD AND THE REAL PHOTON AT HERA

Charged particle distributions also sensitive to photon PDFs.



Compare to LO simulation (PYTHIA).

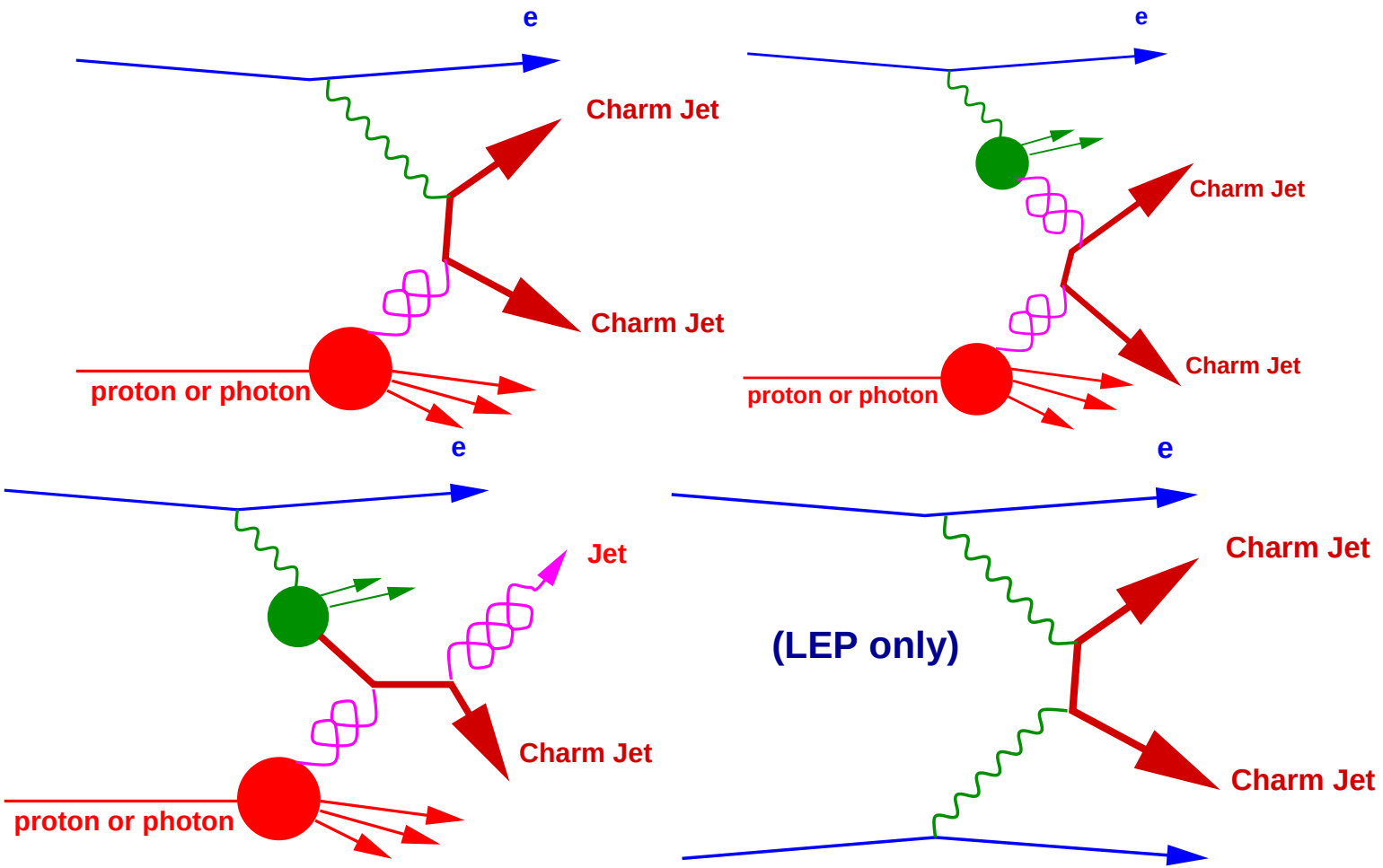
Compare to NLO QCD for various scales.

Also: Prompt photon results, jet shapes, sub-jets...

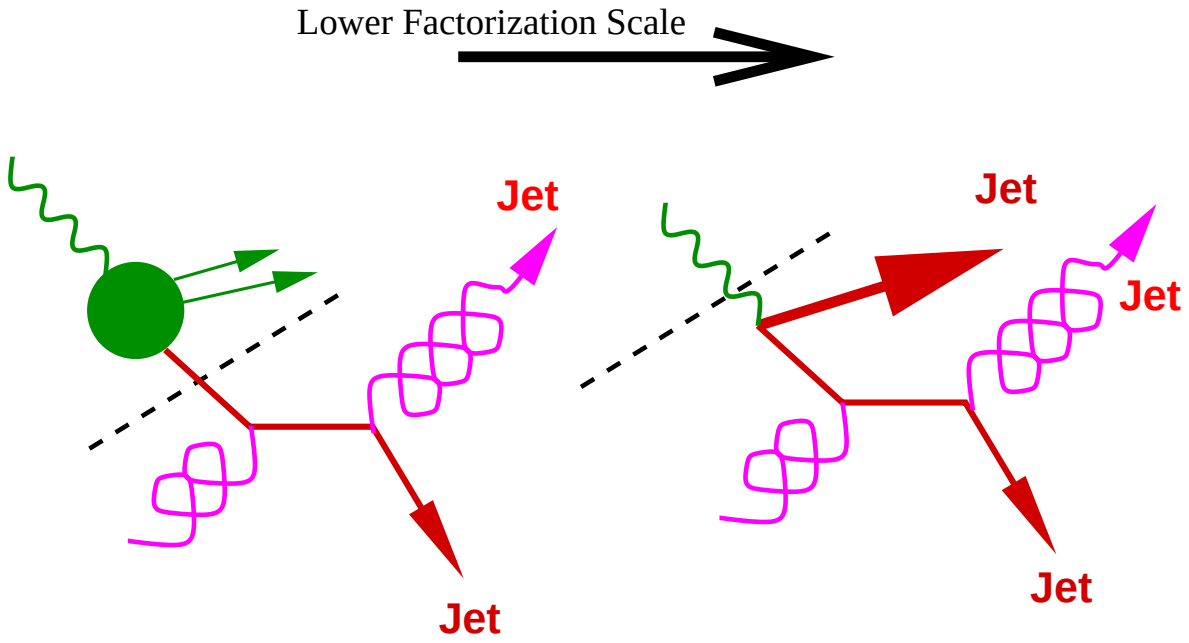
THE TIME IS RIGHT TO DO A SERIOUS QCD FIT TO THE HERA AND LEP DATA!

CHARM AND THE REAL PHOTON

Charm photoproduction at HERA and LEP...



CHARM 'IN' THE REAL PHOTON?



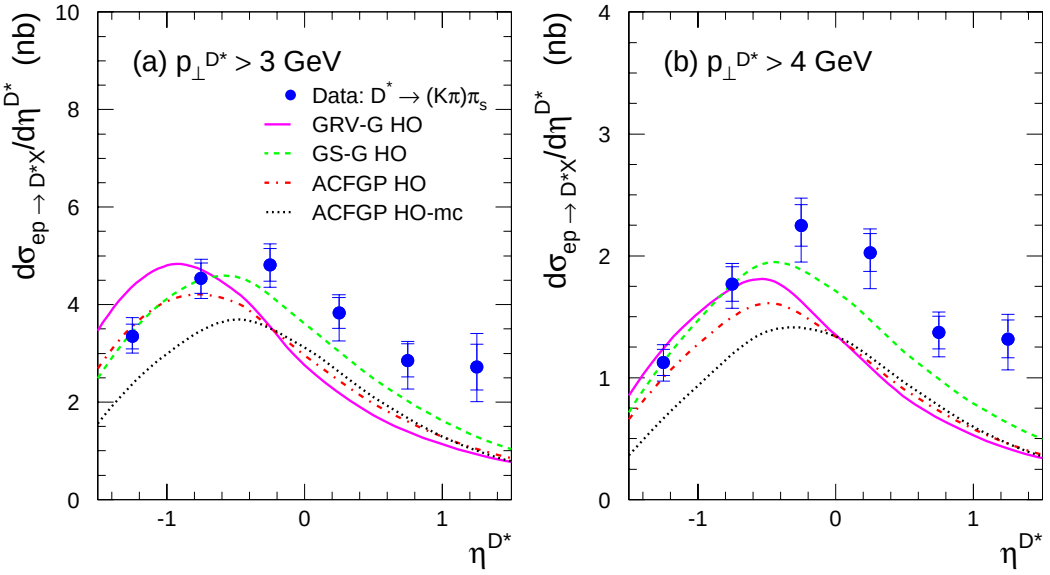
Is it *entirely perturbative*? (charm mass ~ 1.5 GeV)

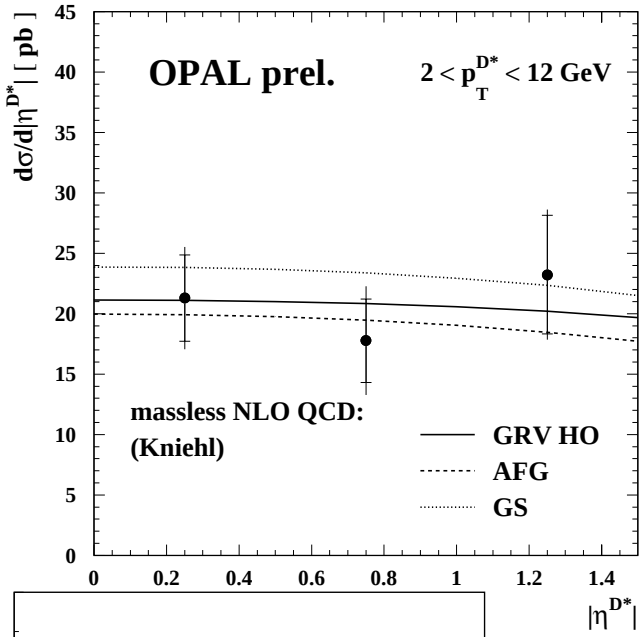
Is it there?

CHARM AND THE REAL PHOTON

Charm is *certainly* produced in γp and $\gamma\gamma$.

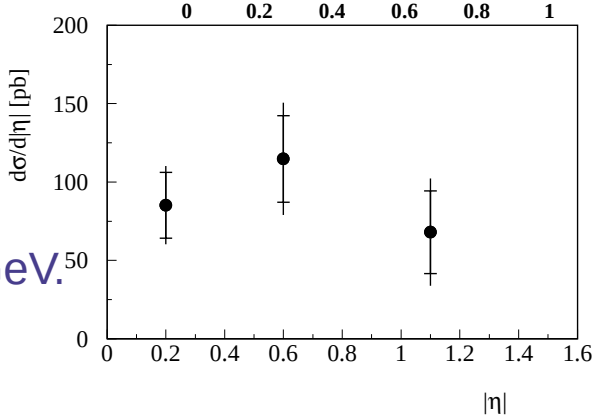
ZEUS 1996+97





D^* tagging.

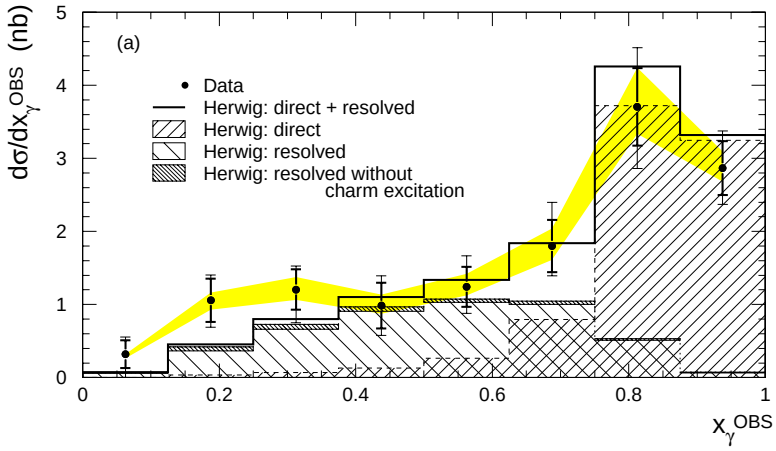
L3: $1 < p_T^{D^*} < 5$ GeV.

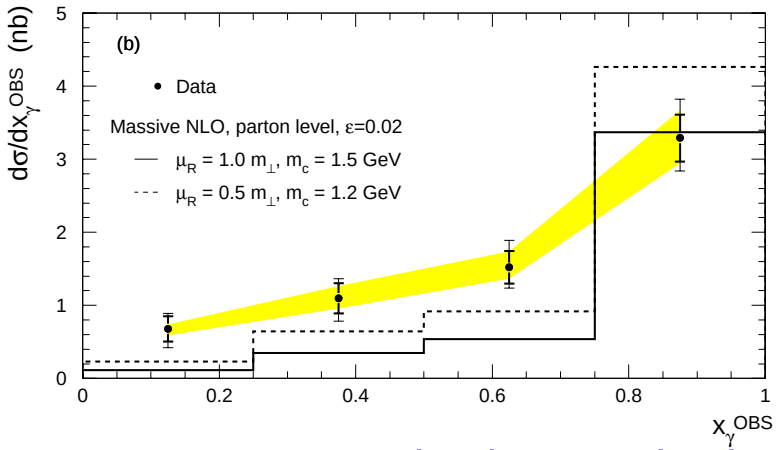


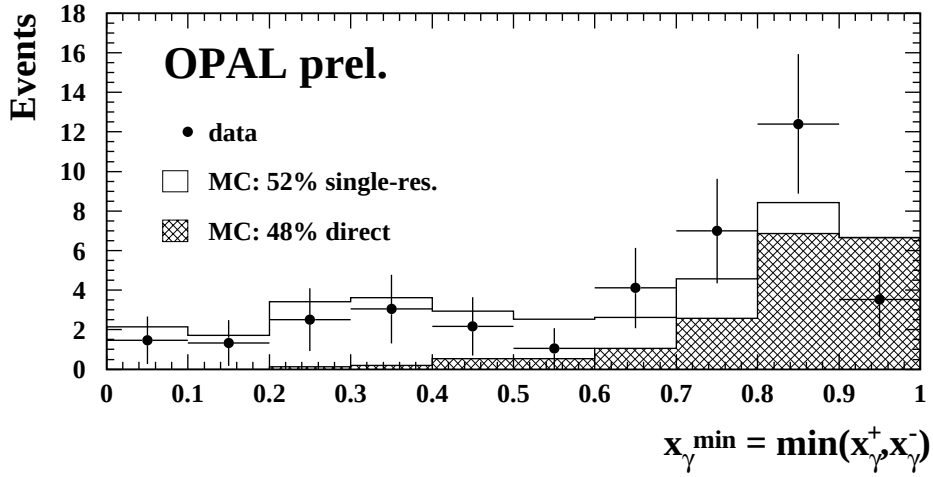
CHARM AND THE REAL PHOTON

How is it produced? ... Look at x_γ^{OBS} again.

ZEUS 1996+97







Jets with D^* tagging.

Direct and resolved both needed.
Resolved is suppressed relative to direct compared to the non charm-tagged case.

Beauty in photoproduction also seen now at both HERA and LEP.

VIRTUAL PHOTON STRUCTURE?

Must be a continuum between $\mathrm{P}^2 = 0$ and $\mathrm{P}^2 \approx \mathrm{Q}^2$.

With respect to direct photon processes, expect the perturbative part of the resolved to fall like $\ln(\mathrm{Q}^2/\mathrm{P}^2)$ whilst the non-perturbative ("Vector Meson") part should fall something like $m_v^2/(m_v^2 + \mathrm{P}^2)$.

Low-x physics: Two virtual photons in collision is as near as we are likely to get to two toponia in collision. Cross section enhanced by multigluon exchange at large rapidities?

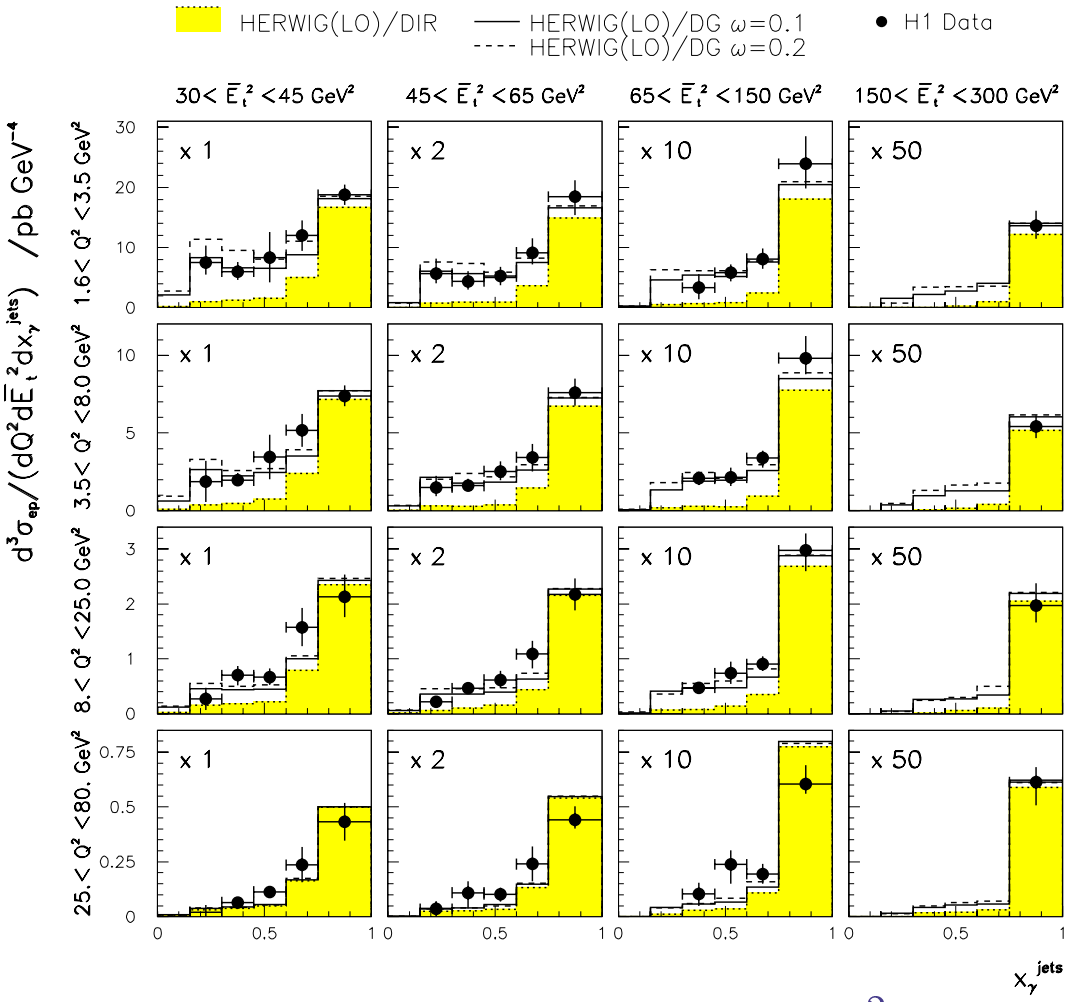
Is it experimentally accessible?

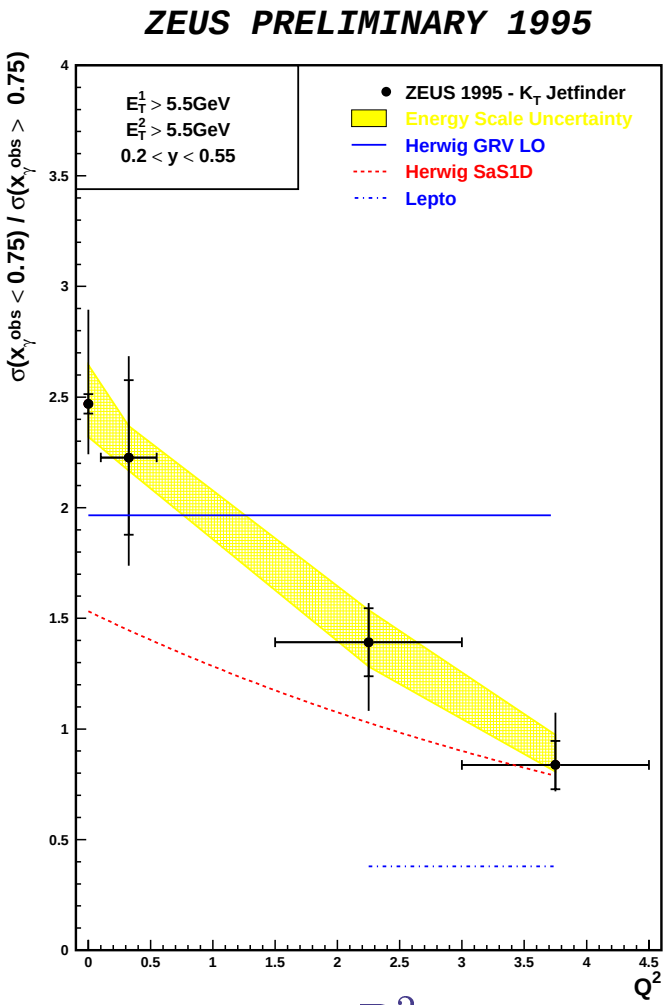
Are these expectations borne out?

How should it be treated theoretically?

How does it 'talk to' (for instance) ep DIS at low Q^2?

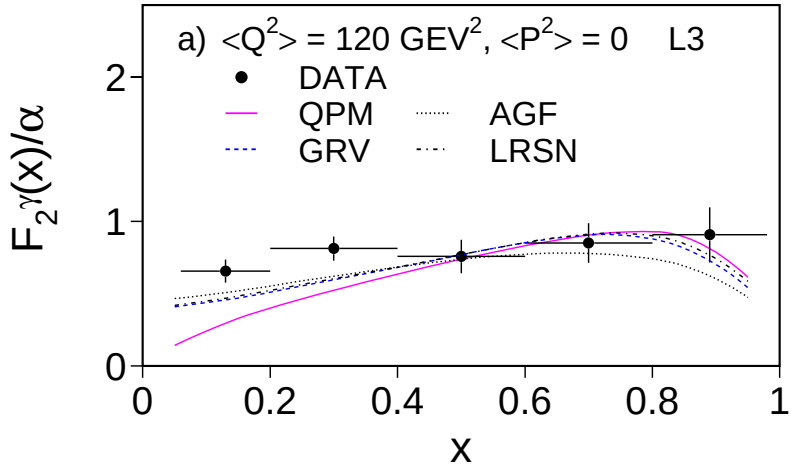
VIRTUAL PHOTONS AT HERA

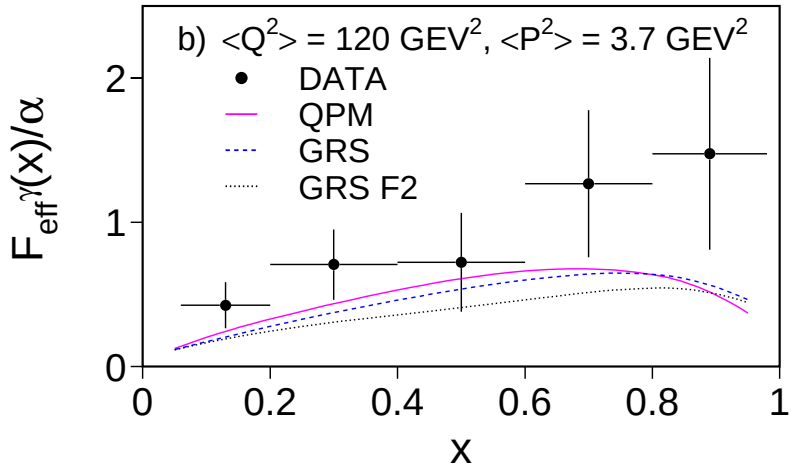


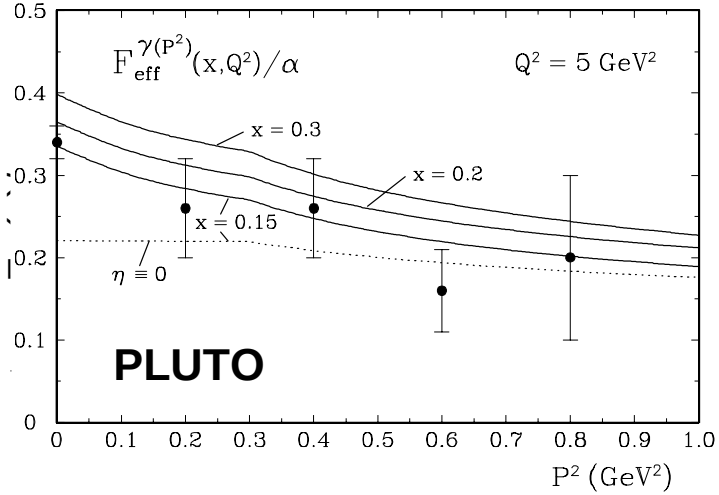


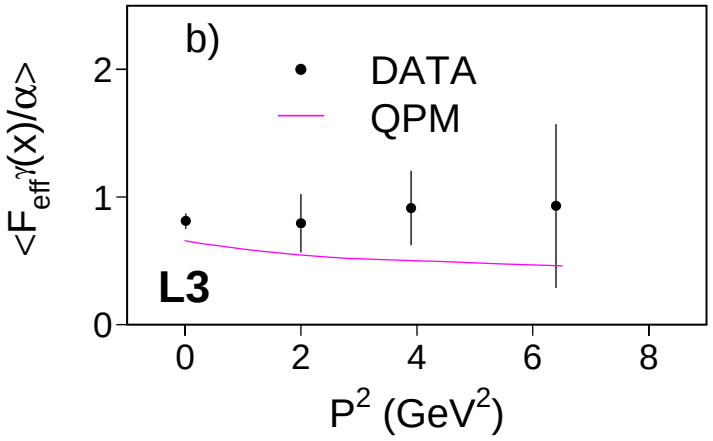
Need for a 'resolved' component at high P^2. It is gradually suppressed as P^2 increases.

VIRTUAL PHOTONS AT LEP





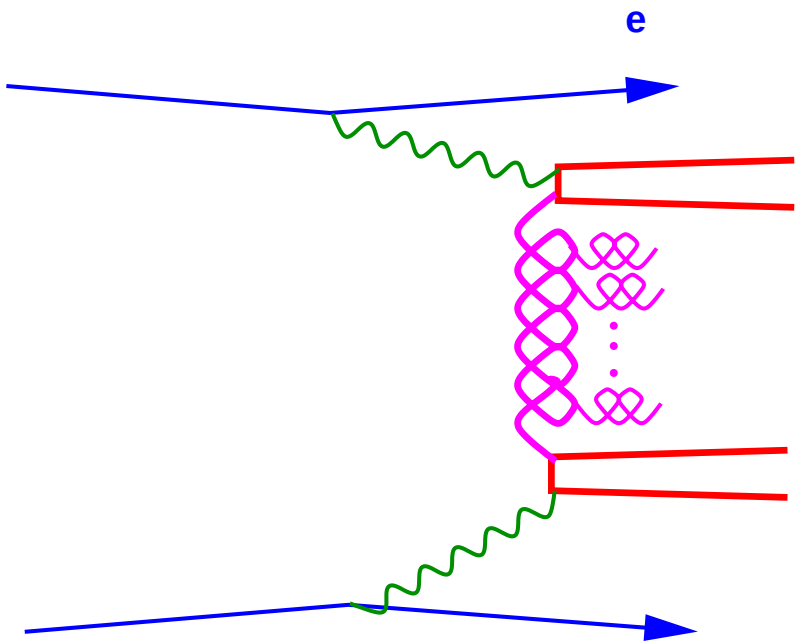


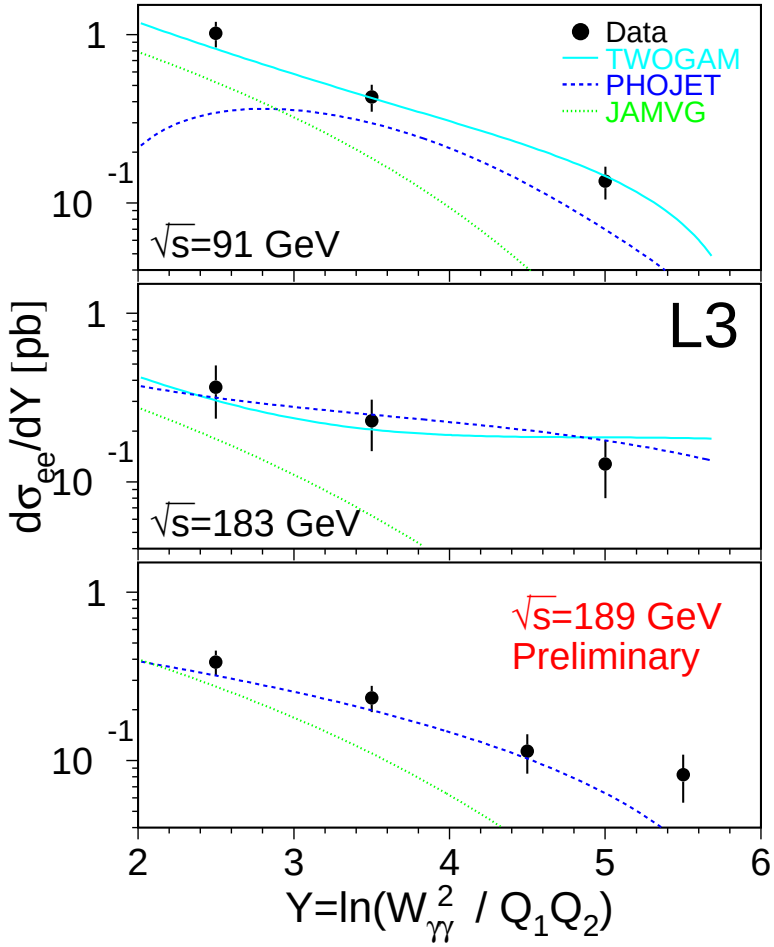


Compare x dependence for real & virtual photons.

Consistent with being flat with P^2
(but also consistent with expected fall).

VIRTUAL PHOTONS AT LEP





Double tag, $Q_1^2 \approx Q_2^2$:
Little evolution in Q^2, large evolution in x. Virtualities mean that non-perturbative effects should be small. $\Rightarrow$ BFKL resummation of $\ln(1/x)$ terms should be applicable.

Also measured by OPAL $\Rightarrow$ Both consistent with PHOJET MC at high Y.

SUMMARY

- **Lots of new data**

New results from LEP and HERA demonstrate the improvements being made in the physics understanding of the hadronic initial and final state.

- **New Theoretical Tools**

Scattered throughout the talk: Better general purpose simulations, virtual photon pdfs, NLO calculations with realistic kinematic cuts. *Crucial* in unravelling the physics content of this rich field.

- **The Final Word from LEP and pre-upgrade HERA...**

... should be: Measurements with much reduced systematic uncertainties over a very wide kinematic range. Unified theoretical analysis (QCD fits, underlying events) exploiting the full power of the data.

- **The Future?**

Charm and Beauty photoproduction will be a boom area at HERA after the upgrade.
The ability to to turn on & off hadronic structure of photons is an potentially an important tool for understanding hadronic and underlying events.