The Structure of the Photon

XVIII INTERNATIONAL SYMPOSIUM ON

LEPTON PHOTON INTERACTIONS

July 28 - August 1, 1997

Congress Centrum Hamburg

Stefan Söldner-Rembold

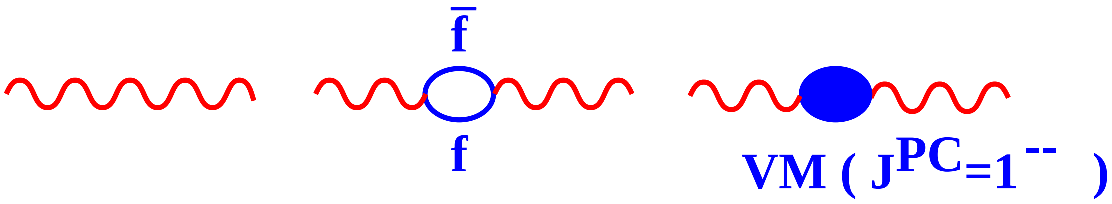
Universität Freiburg

I want to thank the HERA and LEP collaborations and CLEO (especially J.Butterworth, J.Dainton, M.Erdmann, A.Finch, M.Kienzle, A.Levy, R.Nisius, I.Tyapkin)

Structure of the Photon ?

no photon-photon vertex in QED

higher order processes possible



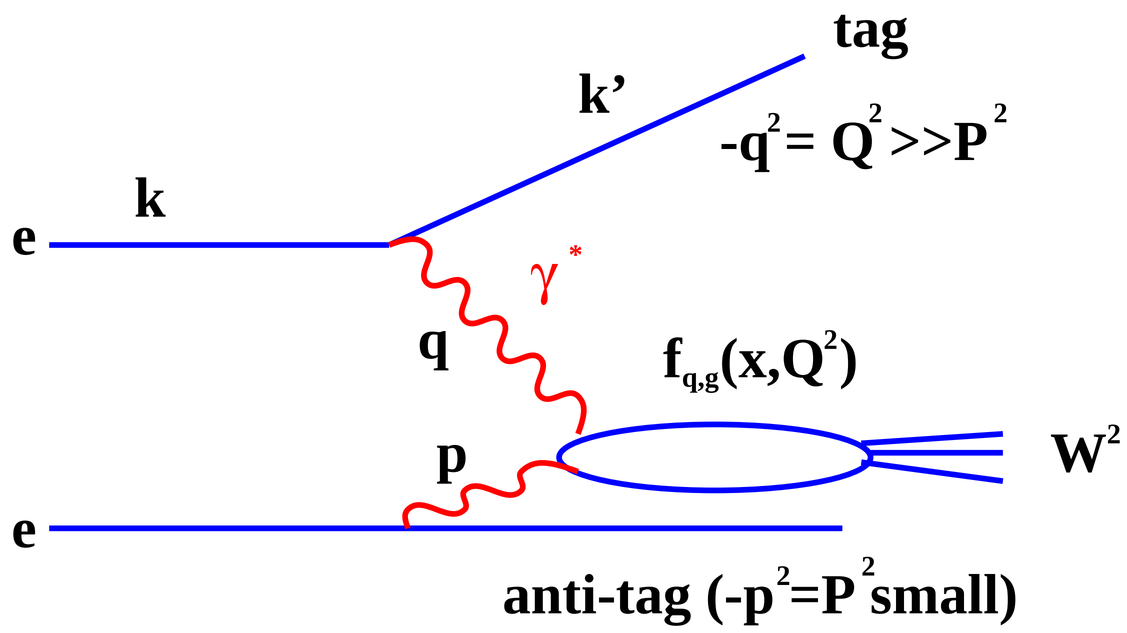
Quantum Fluctuations $\Leftrightarrow$ Photon Structure

- Tests of QED and QCD predictions
- How hadron-like is the photon ?
- What is the parton content of the photon ?

structure of the photon is currently probed in

1. F_2^γ from eγ scattering
2. Total cross-section $\gamma\gamma \rightarrow$ hadrons
3. Jet production in $\gamma\gamma$ and γp scattering
4. Resonance production in $\gamma\gamma$ scattering

1.) Electron-Photon Scattering



$W^2 = (q+p)^2$ **Inv. mass of final state**

$Q^2 = -q^2 = -(k-k')^2$ **-(mass of exchanged photon)^2**

$x = \frac{Q^2}{2p\cdot q} = \frac{Q^2}{Q^2+W^2+P^2}$ **Bjorken x**

$y = \frac{p\cdot q}{p\cdot k}$ **Inelasticity**

Deep-inelastic scattering (photon flux from WWA):

$$\frac{d\sigma_{e\gamma}}{dx dQ^2} =$$
$$\frac{2\pi\alpha^2}{xQ^4}\left[(1+(1-y)^2)F_2^\gamma - y^2 F_L^\gamma\right]$$

Leading order parton distributions $q(x, Q^2)$:

$$F_2^\gamma(x, Q^2) = 2x \sum_{u,d,s,(c)} e_q^2 q(x, Q^2)$$

$$y \approx 1 - \frac{E_{\rm tag}}{E_{\rm beam}} \cos^2 \frac{\theta_{\rm tag}}{2}$$

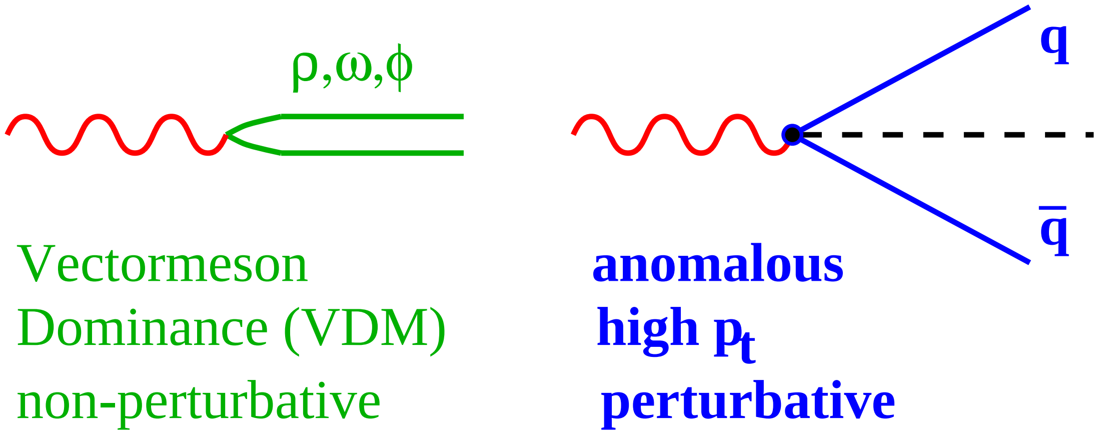
Experiments:

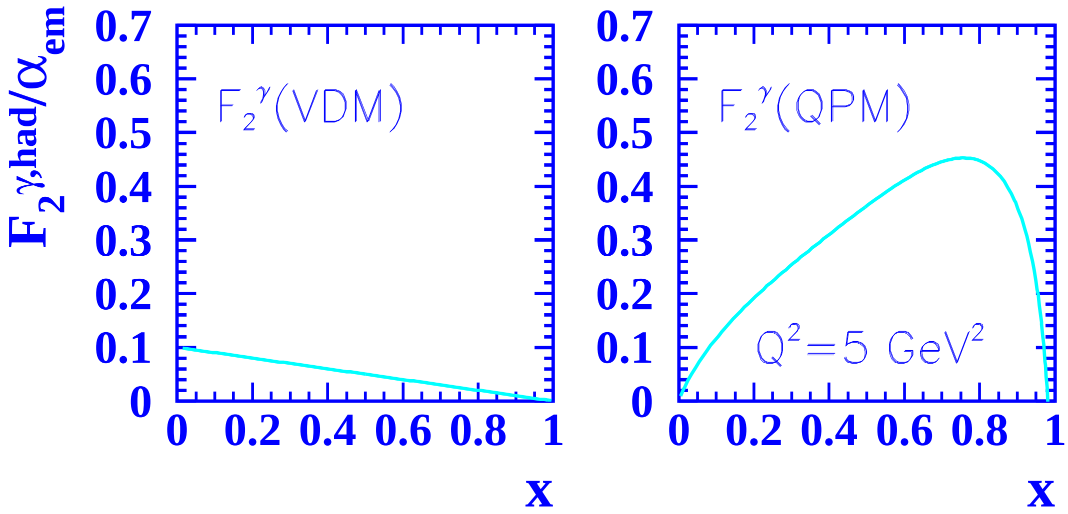
$E_{\rm tag}$ large and $\theta_{\rm tag}$ small

$$\Rightarrow$$

Only F_2^γ directly measurable, since $y^2 F_L^\gamma$ small

Contributions to F_2^γ (hadronic):



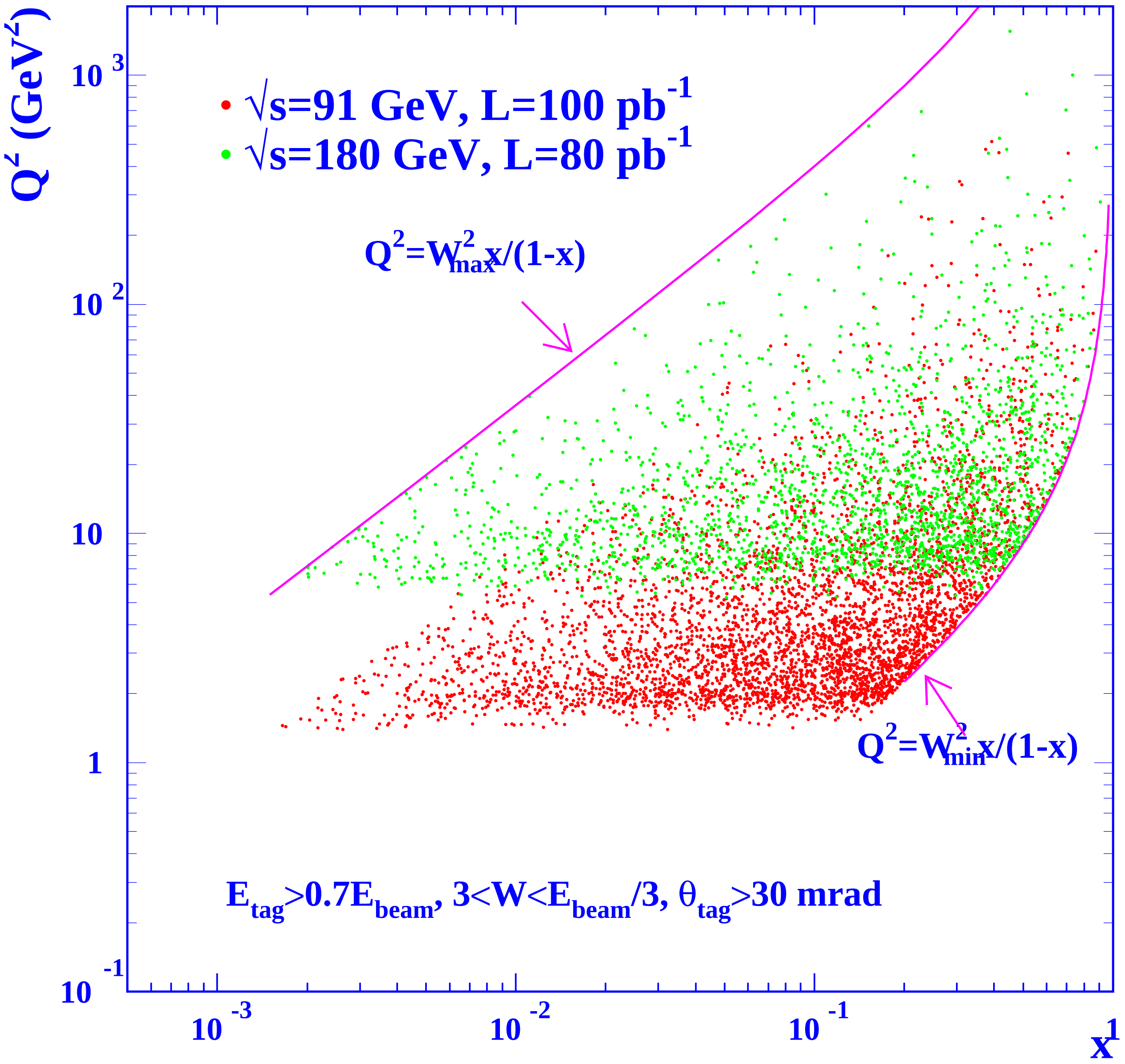


Parametrisations (GRV, SaS..):

the shape of the quark densities of the photon at low scales Q_0^2 are assumed to be identical to the hadronic (VDM) shape

evolution using inhomogenous DGLAP equations

F_2^γ at LEP1 and LEP2



1. Q^2 reconstruction (electron)

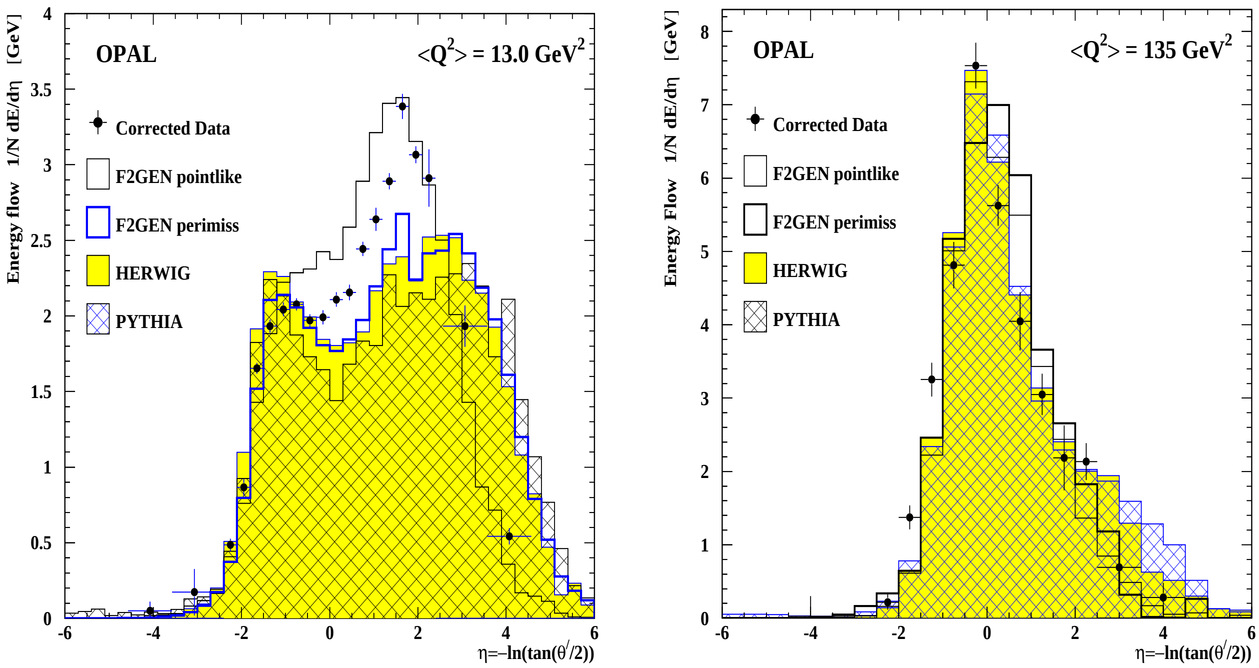
$$Q^2 \approx 2E_{\rm beam}E_{\rm tag}(1-\cos\Theta_{\rm tag})$$

2. x reconstruction (mixed)

$$x_{\rm vis} = \frac{Q^2}{Q^2+W^2_{\rm vis}}$$

Study F_2^γ evolution in wide range of x and Q^2

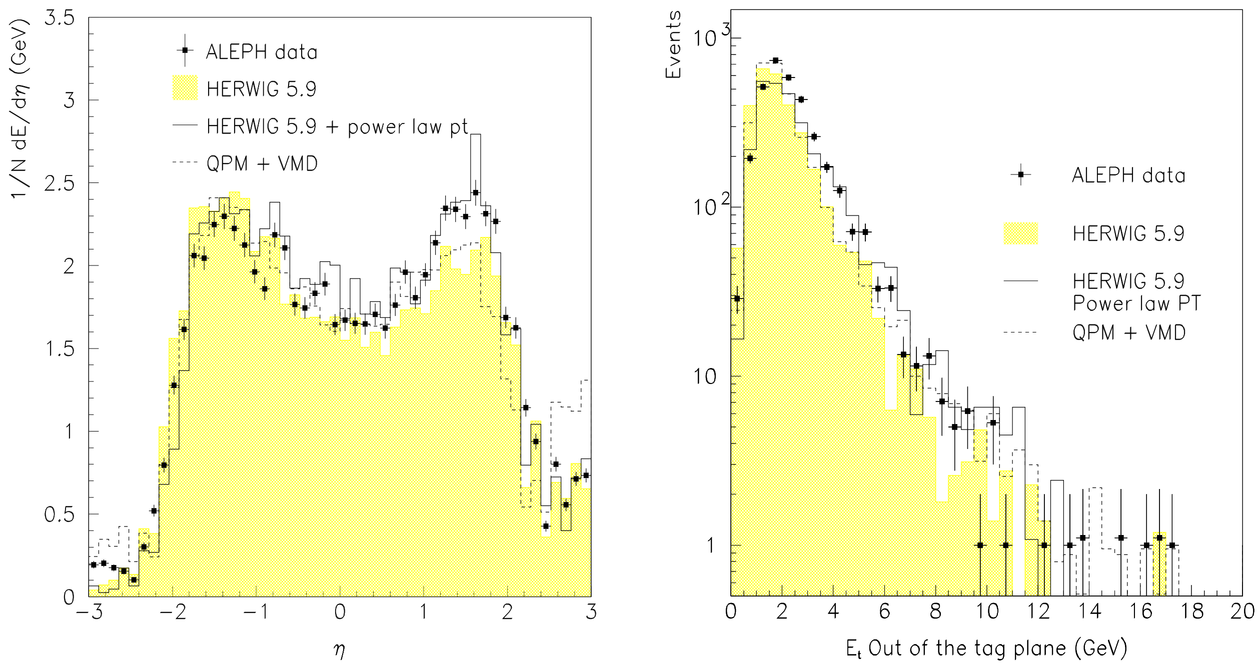
- **OPAL (LEP1) L=156 pb^{-1} (Z. f. Phys. C74 (1997) 33)**



bad agreement at low Q^2 (=low x)

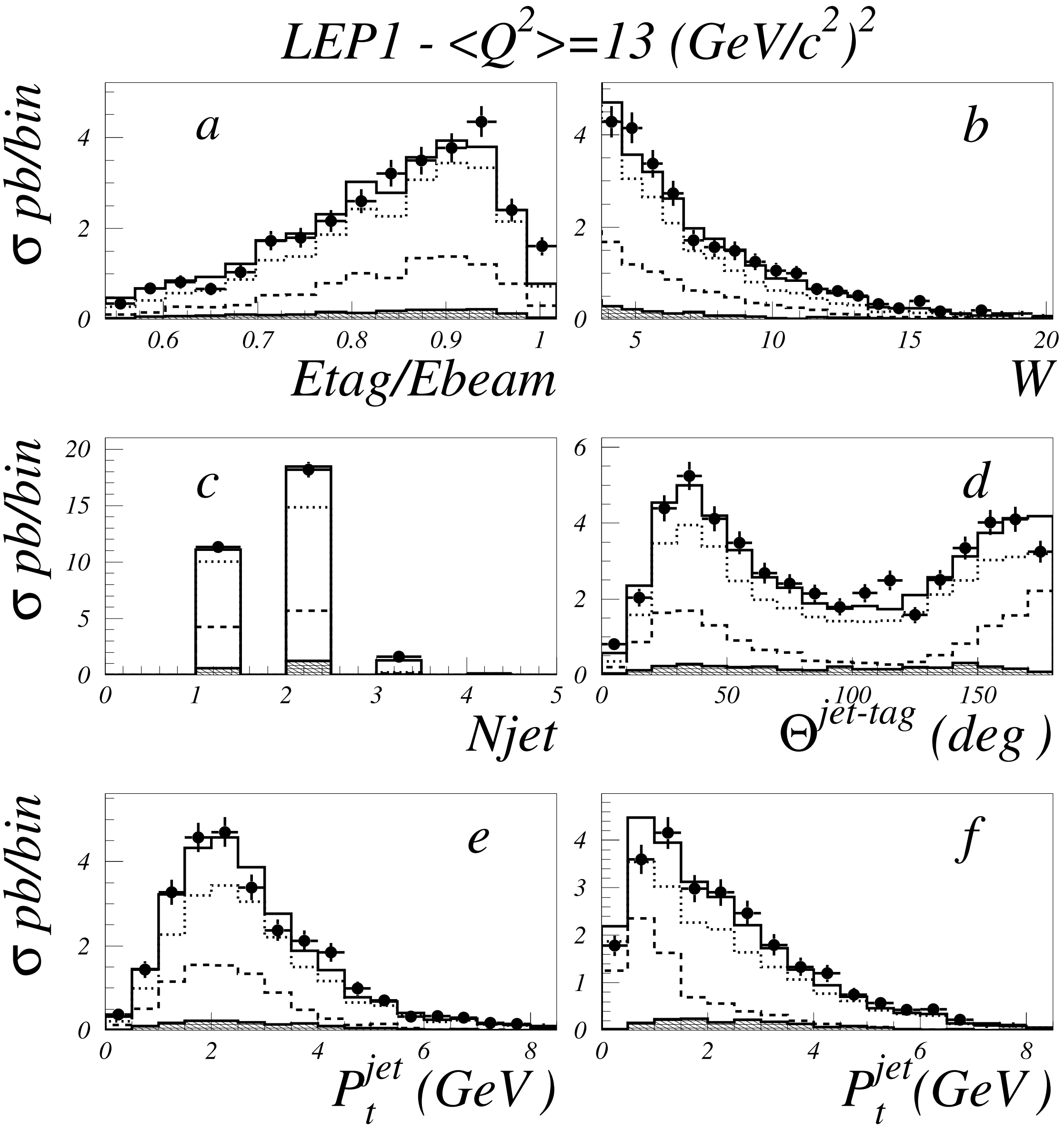
- **ALEPH (LEP1) L=102 pb^{-1}, $Q^2 = 14.2$ GeV^2**

LP-253



(careful) tuning improves agreement

• DELPHI (LEP1+LEP2)



DELPHI Monte Carlo: TWOGAM

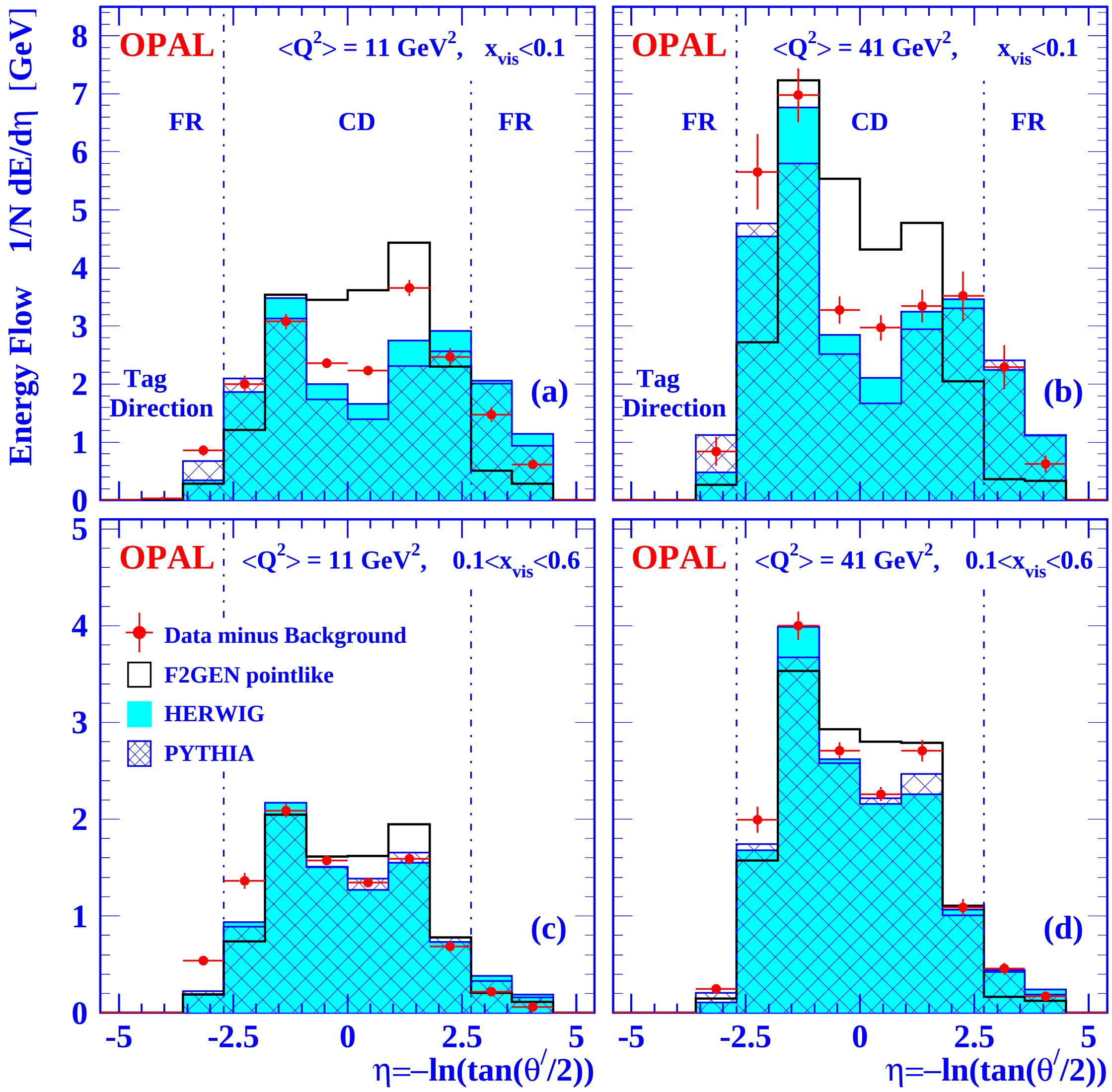
solid line:

QPM + GVDM + RPC (“resolved photon component”)

dotted line: GVDM+QPM

dashed line: GVDM

● OPAL (LEP2) L=18.1 pb^{-1} (subm. to Phys. Lett. B)



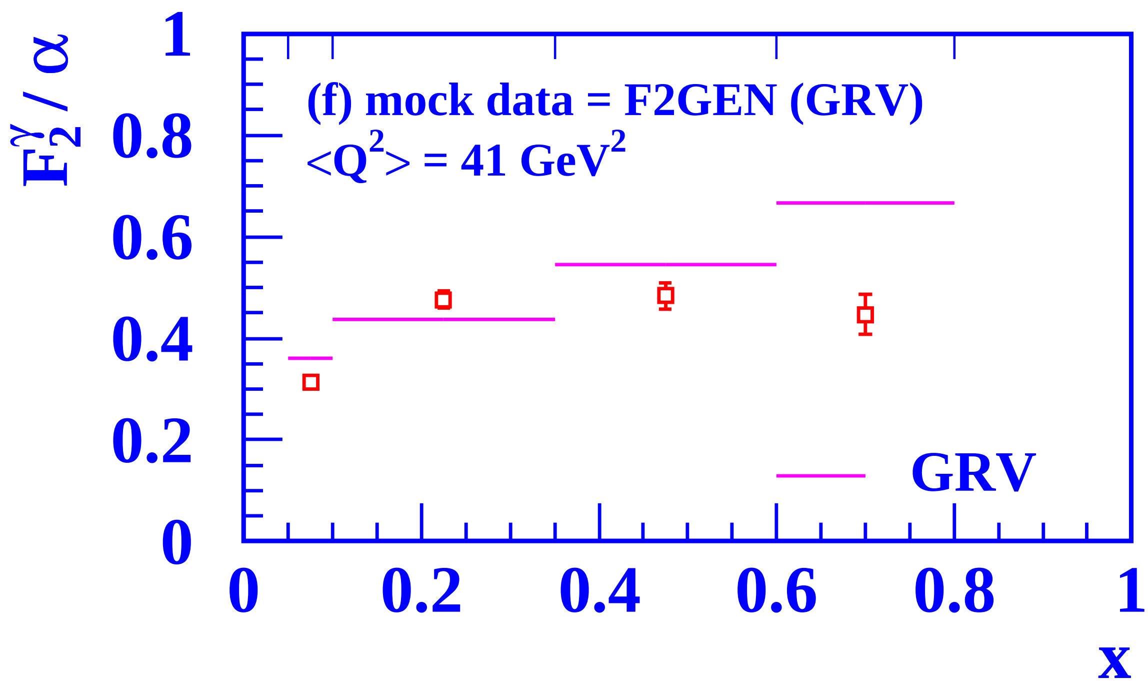
discrepancies large for low x and low Q^2

Regularized unfolding

$$g^{\mathrm{det}}(x_{\mathrm{vis}}) = \int A(x_{\mathrm{vis}}, x) f^{\mathrm{part}}(x) dx + B(x_{\mathrm{vis}})$$

Usually the unfolding program by Blobel is used

Use same structure function (here GRV) and unfold F2GEN with HERWIG (different fragmentation):



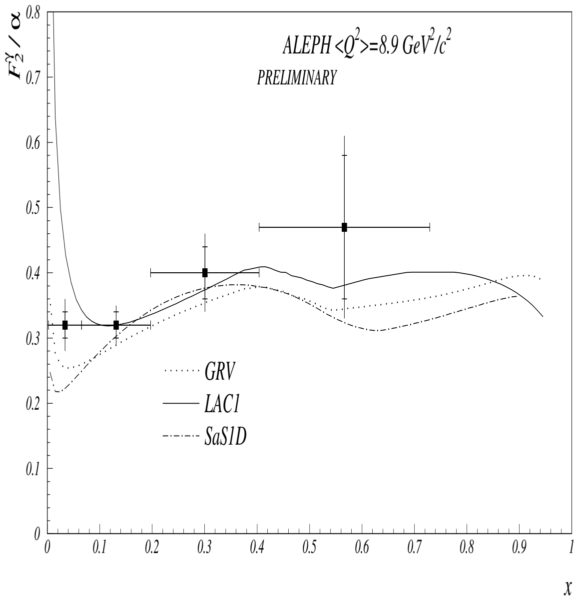
Unfolding is only independent of the input F_2^γ,

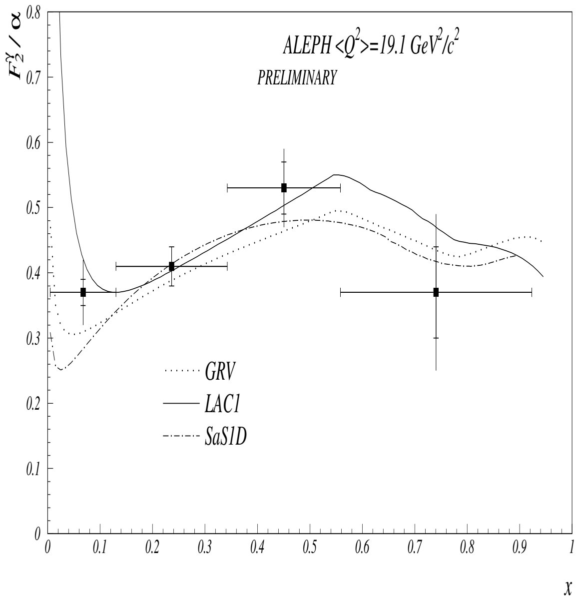
if the $\gamma^*\gamma$ fragmentation and F_2^γ 'factorize'!

$\Rightarrow$ largest systematic error

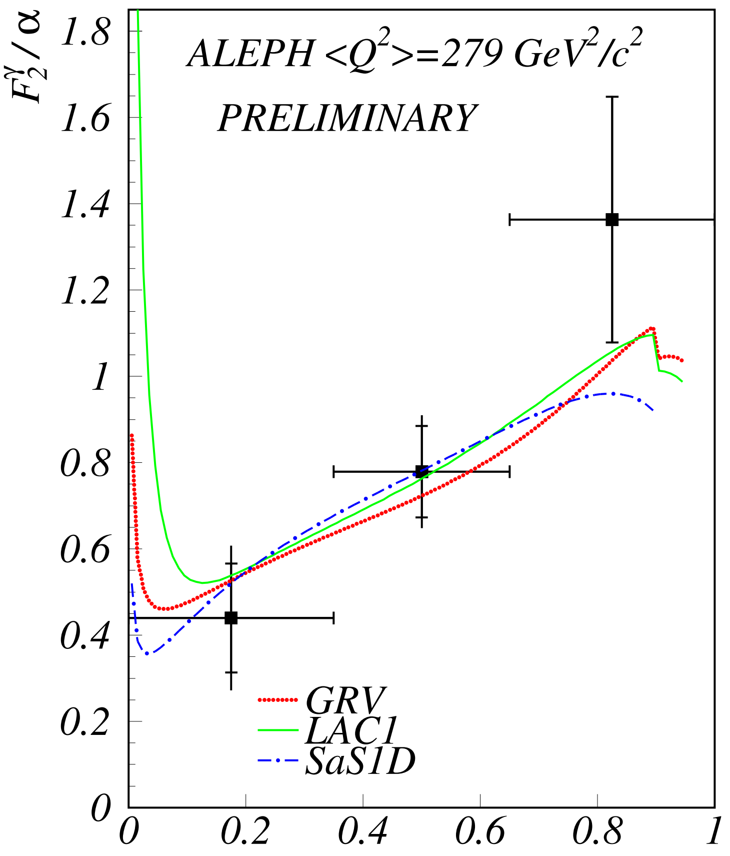
New measurements presented at LP97

- **ALEPH (LEP1 data, medium Q^2)**

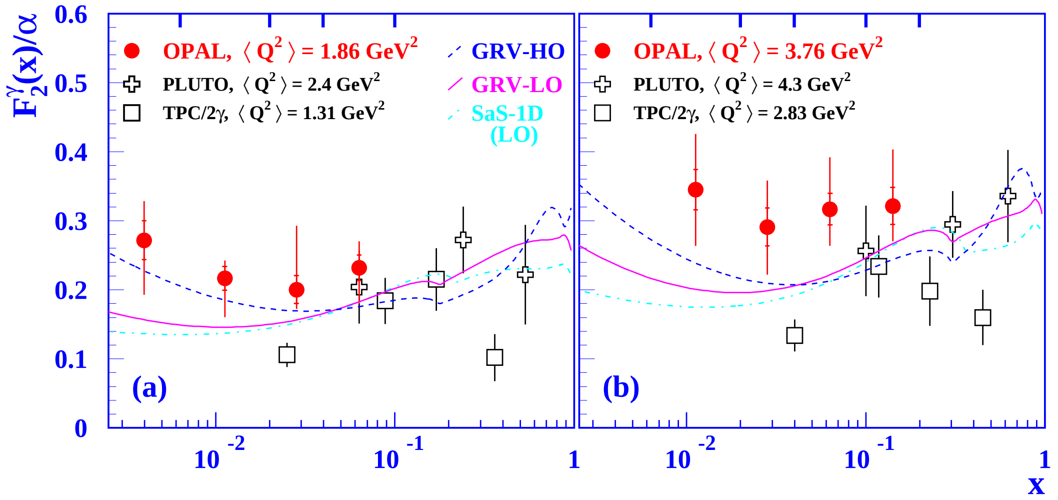




- **ALEPH (LEP1 data, high Q^2)**

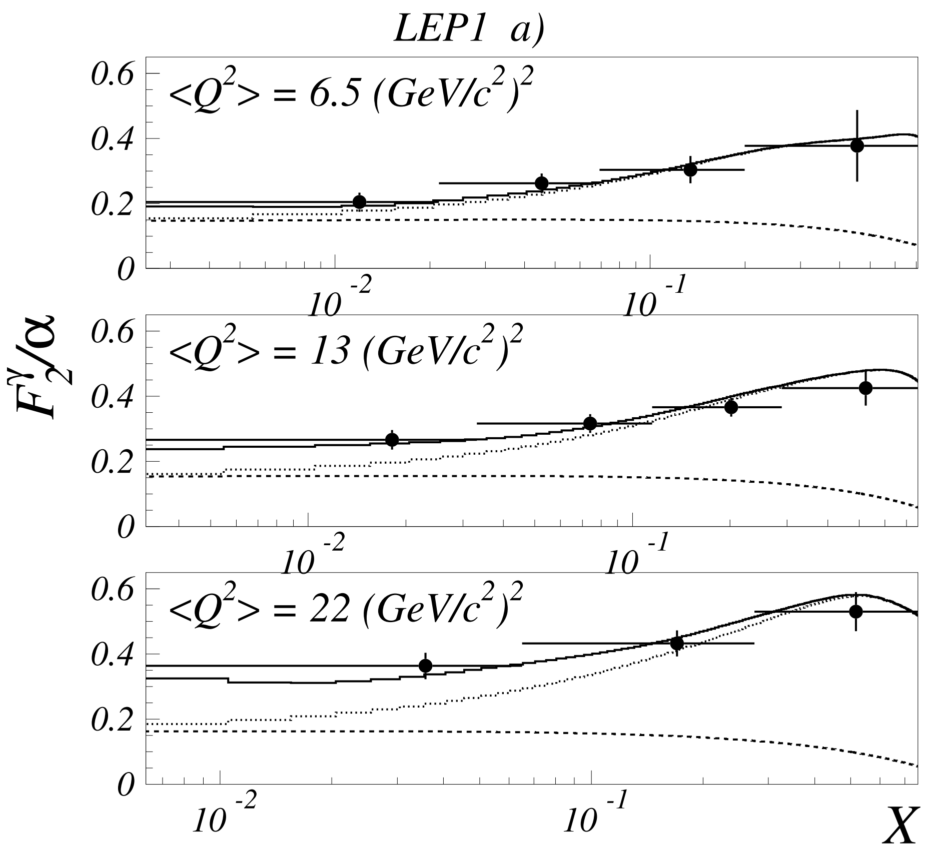


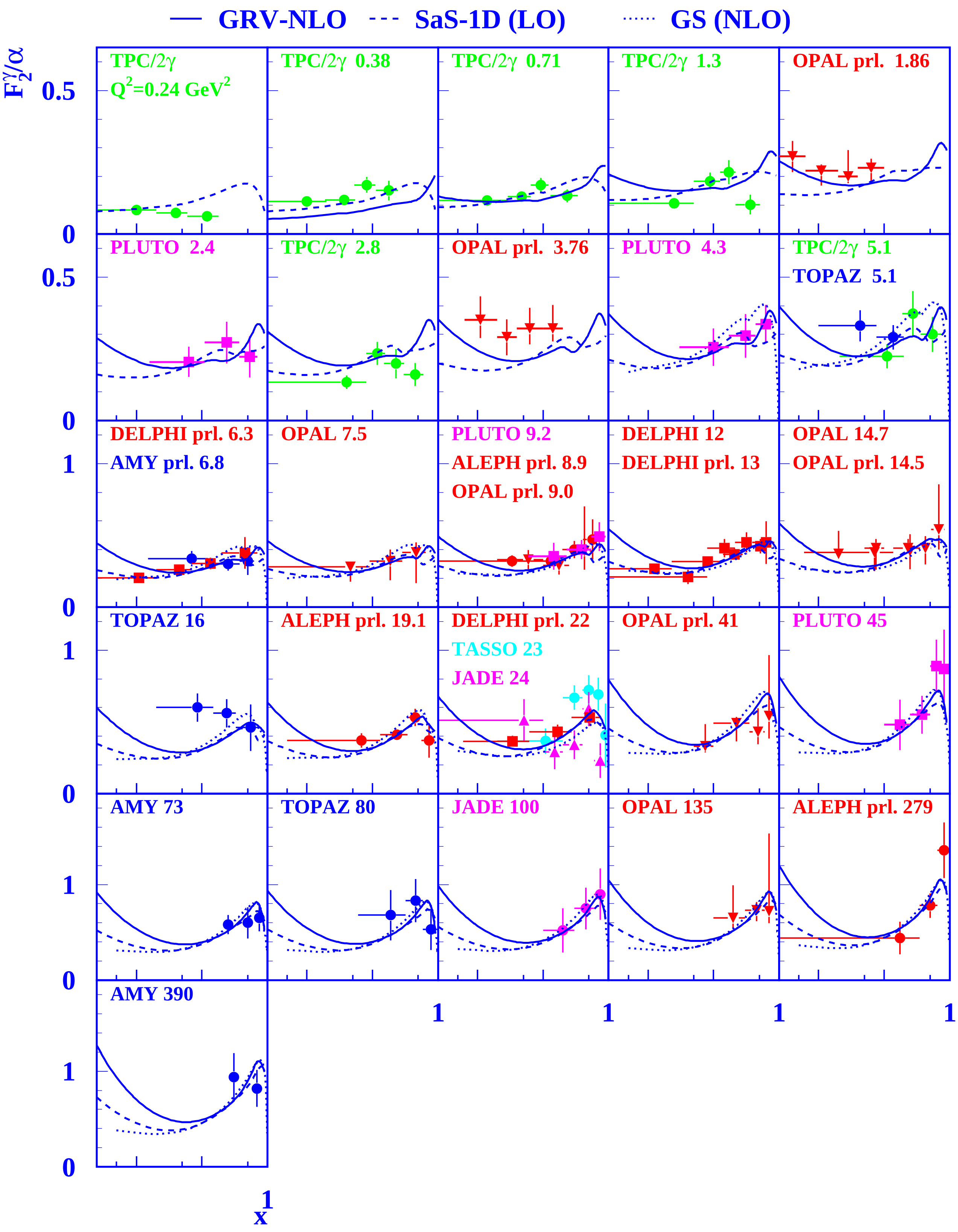
- OPAL (LEP1 data, low x and Q^2)



significantly higher than TPC/2γ

- DELPHI (LEP1,2 data, medium x and Q^2)

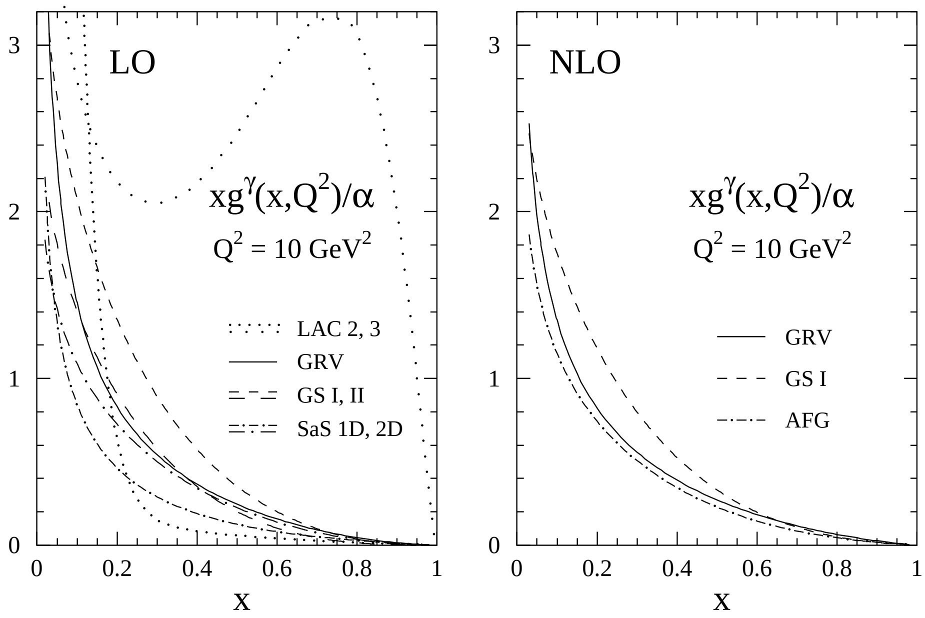




P^2 **dependence ?**

Gluon distribution in the photon:

Sjöstrand, Storrow, Vogt:



$g^\gamma(x, Q^2)$:

Theory:

no constraint due to (simple) momentum sum rule (MSR)

bare photon is $\mathcal{O}(\alpha^0)$ and F_2^γ is $\mathcal{O}(\alpha/\alpha_s)$

Frankfurt-Gurvich MSR:

relates photon structure to the
total cross-section $e^+e^- \to$ hadrons

Experiment:

not well constrained by F_2 data (eγ scattering)

study jets in eγ, $\gamma\gamma$ and γp scattering

New parametrisations at low x:

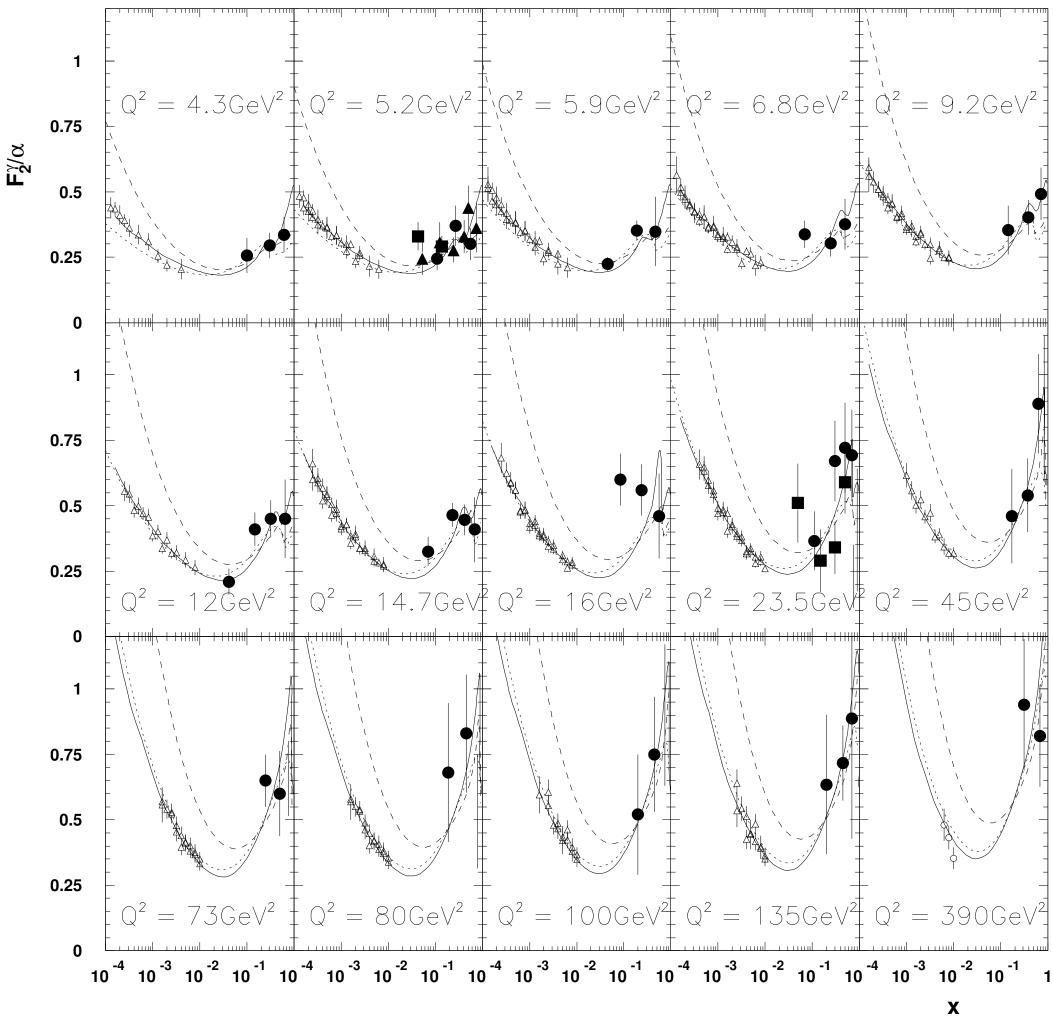
Abramowicz, Gurvich and Levy (LP-234,235)

Gribov factorization (universal Pomeron trajectory):

$$F_2^\gamma(x, Q^2) = F_2^p(x, Q^2)\frac{\sigma_{\gamma p}(W^2)}{\sigma_{pp}(W^2)} \leftarrow \textbf{DL}$$

$\Rightarrow$ use F_2^p measurements as low x 'data'

Leading AP evolution starting with parametrizations (fit) at $Q_0^2 = 4$ GeV^2



dashed: GRV-LO **dotted: SaS-1D** **full line: AGL**

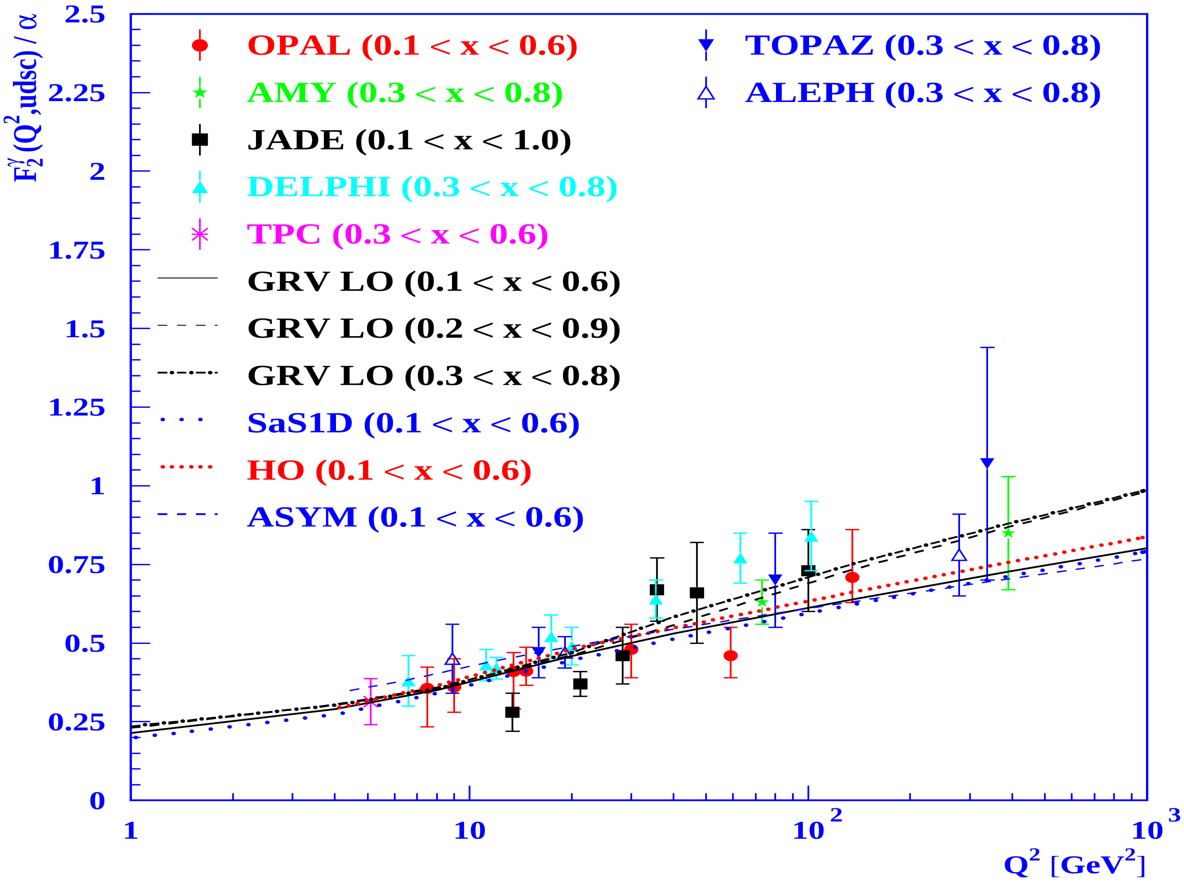
Witten (77, LO), Bardeen & Buras (80, NLO):

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

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

non-perturbative input (VDM) needed

$\Rightarrow$ large theoretical uncertainties

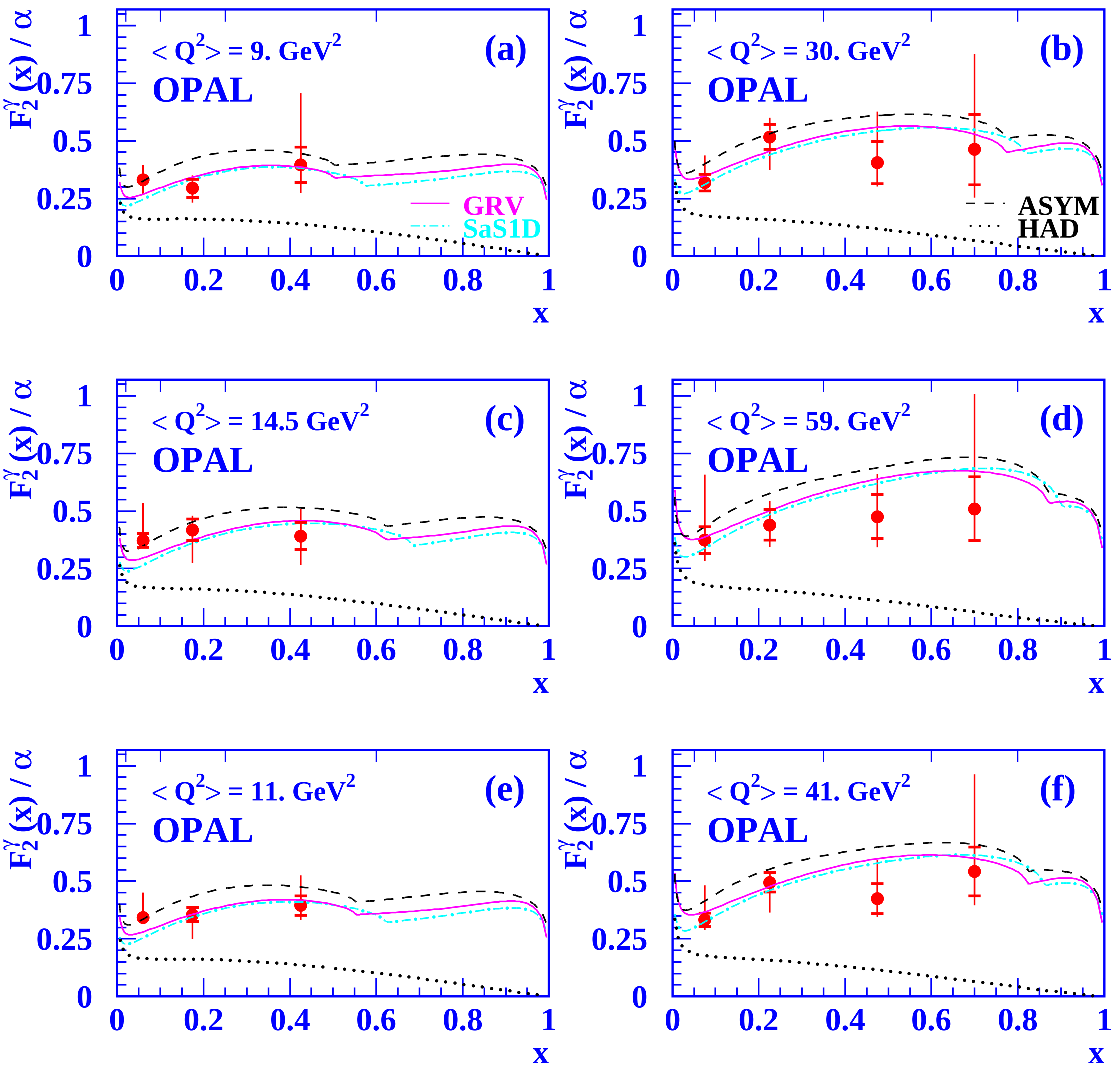


HO: GRV-NLO for u,d,s plus NLO charm (Laenen et al)

ASYM: LO u,d,s plus Bethe-Heitler c plus hadronic part (VDM) from GRV-LO

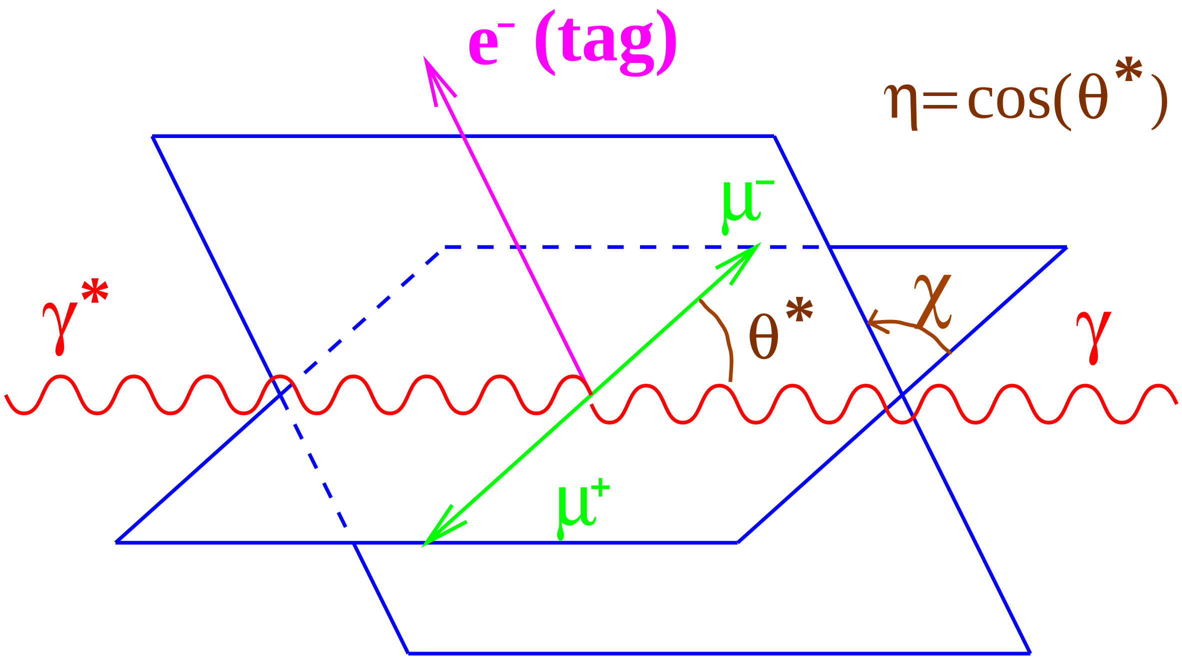
Hadronic contribution (GRV-LO) about 15 % at $x = 0.5, Q^2 = 59$ GeV^2

● OPAL (LEP2 data)



Azimuthal correlations $\Rightarrow$ F_L^γ ?

azimuth χ in $\gamma\gamma^*$ centre-of-mass system:



$$\frac{d\sigma(e\gamma \to e\mu^+\mu^-)}{dx dy d\eta d\chi/2\pi} = \frac{2\pi\alpha^2}{Q^2}\left(\frac{1+(1-y)^2}{xy}\right) \times$$

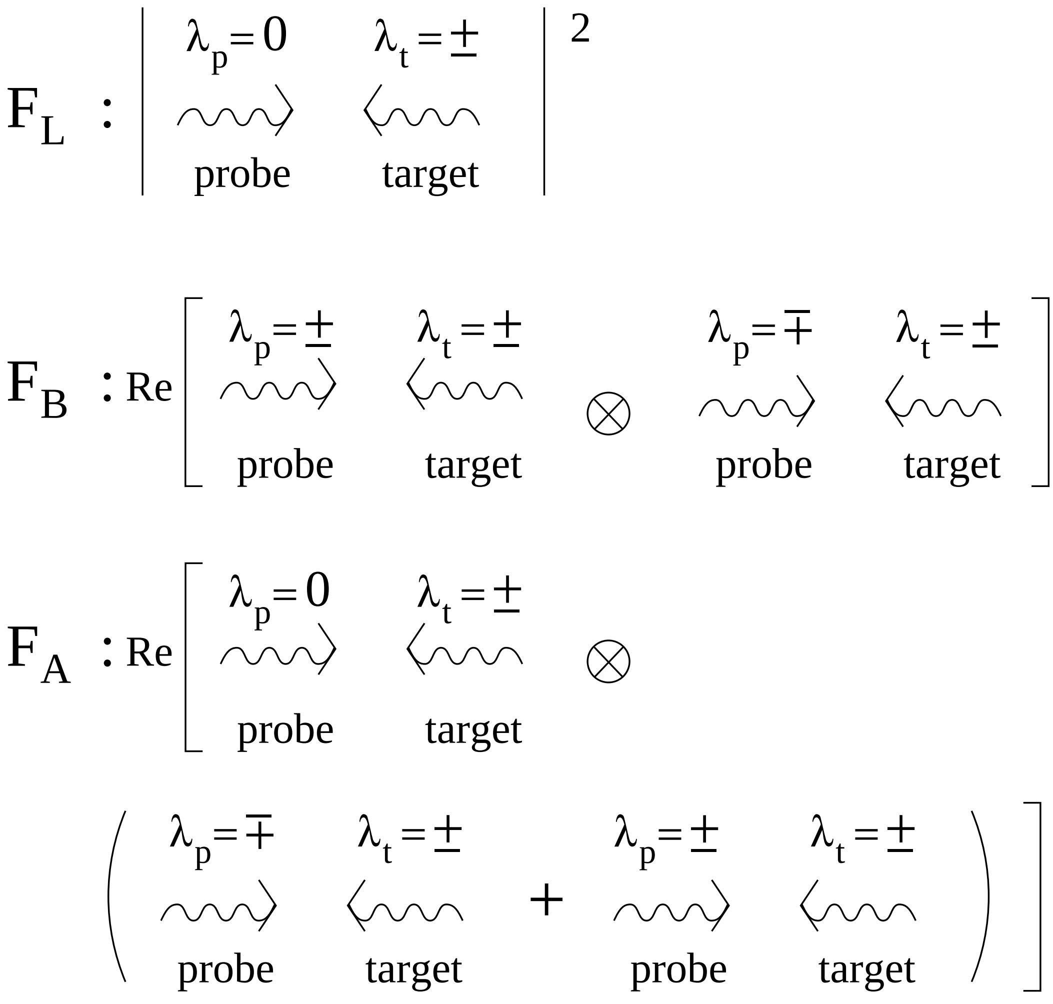
$$\left[2x\tilde{F}_T^\gamma + \epsilon(y)\tilde{F}_L^\gamma - \rho(y)\tilde{F}_A^\gamma \cos\chi + \frac{\epsilon(y)}{2}\tilde{F}_B^\gamma \cos 2\chi\right]$$

$$F_2^\gamma = 2xF_T^\gamma + F_L^\gamma \quad ; \quad F_{T,L}^\gamma = \int_{-1}^{1}\int_0^{2\pi} \frac{d\chi d\eta}{2\pi} \tilde{F}_{T,L}^\gamma$$

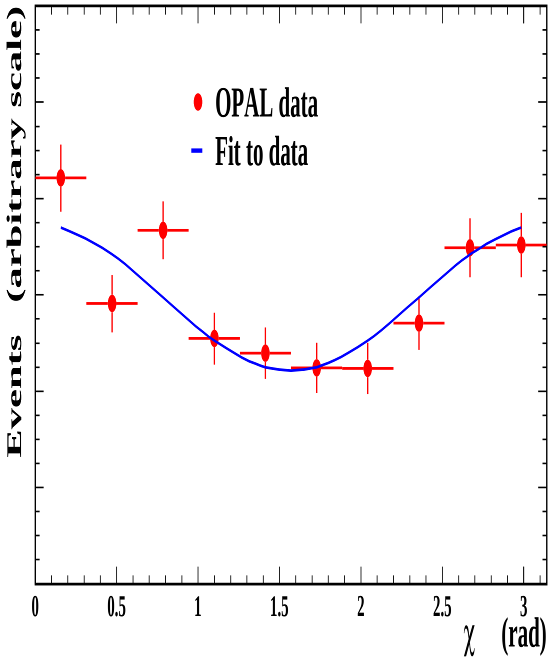
In leading order and for $m_\mu = 0$

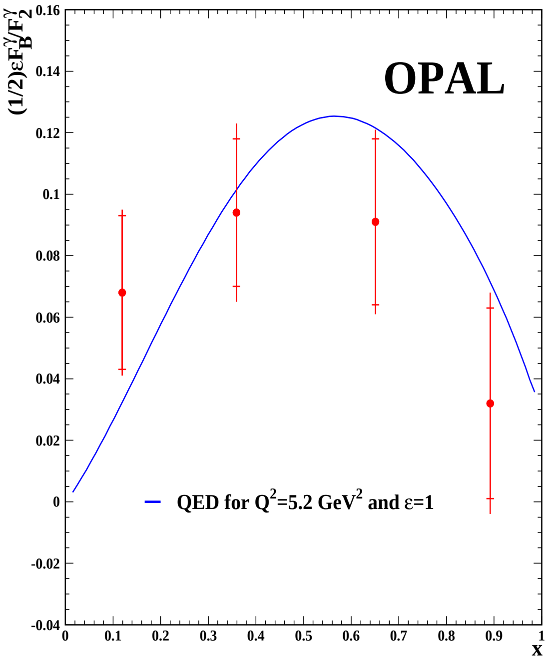
$$F_B^\gamma = F_L^\gamma = \frac{4\alpha}{\pi} x^2 (1 - x)$$

different helicities λ of interacting photons:

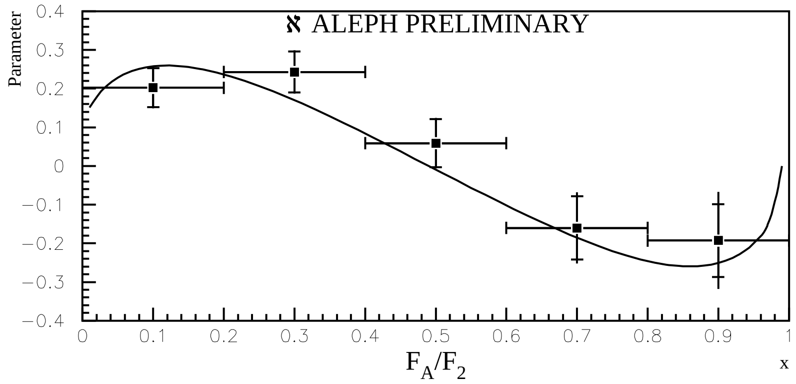


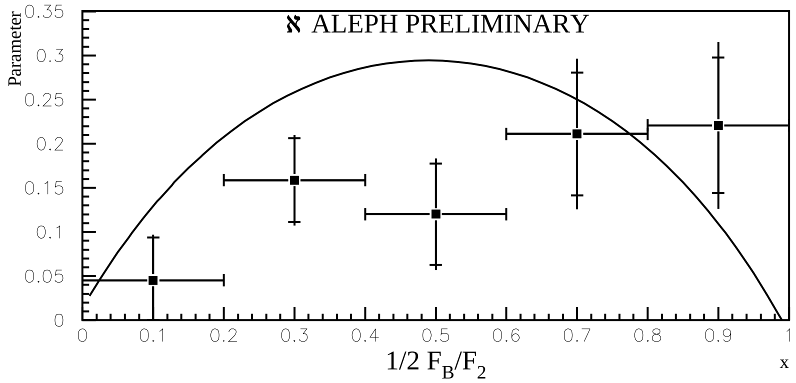
Zeit. f. Physik C74 (1997) 49-55





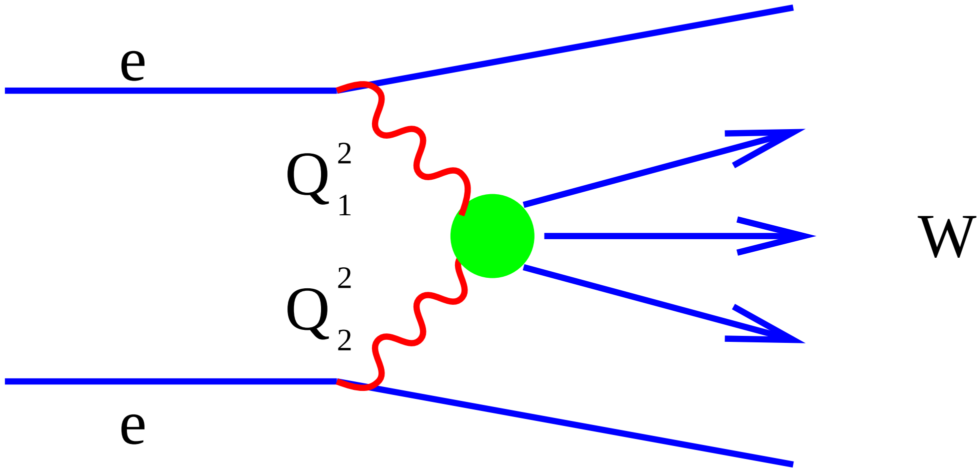
Results for 1994 Data





Hadronic two-jet events ?

photon-photon (mainly LEP2):

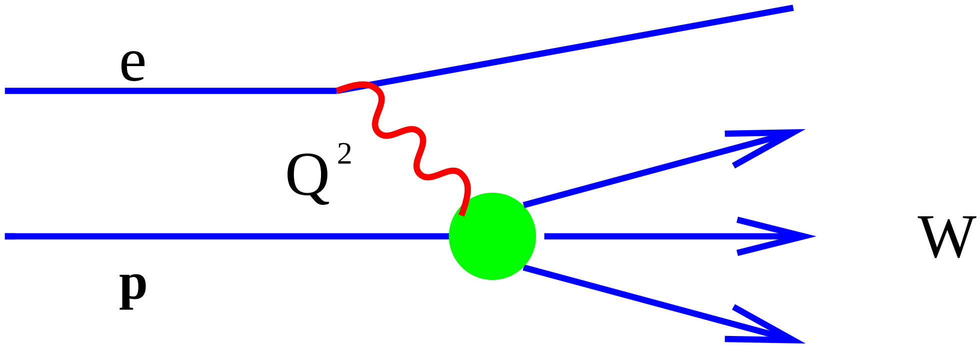


$$W_{\gamma\gamma} = \sqrt{s}_{\gamma\gamma} = \sqrt{\left(\sum E_h\right)^2 - \left(\sum \vec{p}_h\right)^2}$$

$10 < W_{\gamma\gamma} < 120$ GeV

$Q^2, P^2 < 5$ GeV^2

photon-proton (HERA):



$40 < W_{\gamma p} < 300$ GeV

$Q^2 < 4$ GeV^2

2.) Total $\gamma\gamma$ cross-section

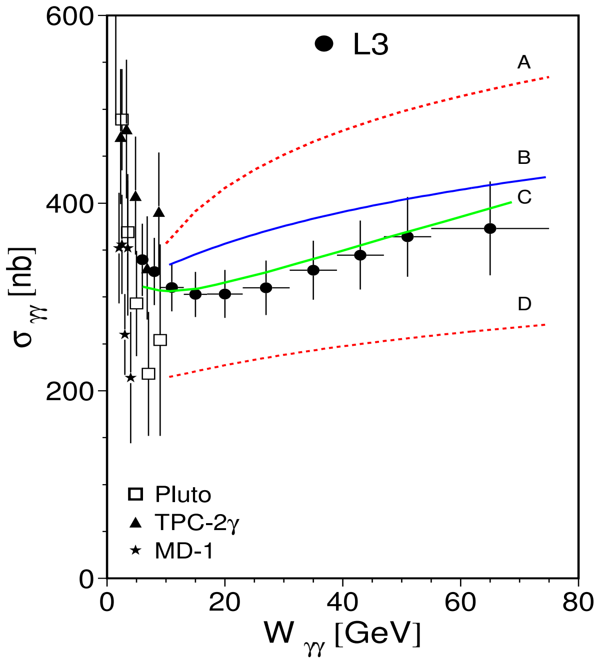
Gribov factorization (hadronic photon):

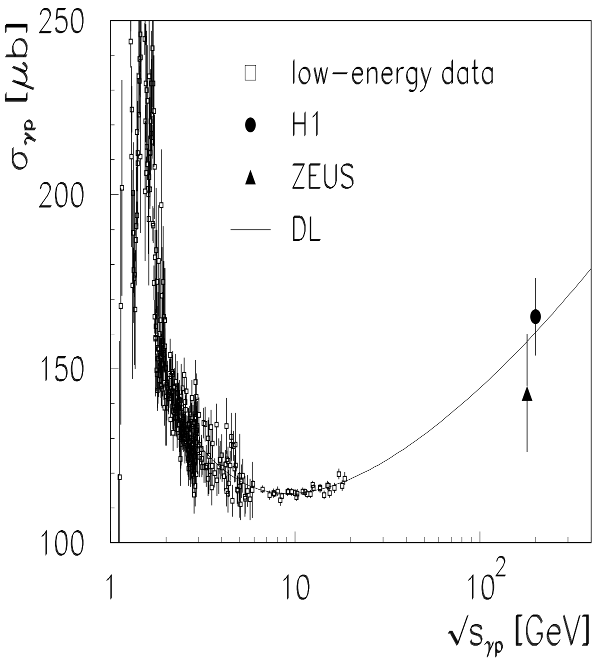
$$\sigma_{\gamma\gamma} = \frac{(\sigma_{\gamma p})^2}{\sigma_{pp}} \approx 250 - 400 \text{ nb}$$

Regge parametrisation:

$$\sigma(s) = X s^{-\eta} + Y s^{\epsilon}$$

(Donnachie-Landshoff)





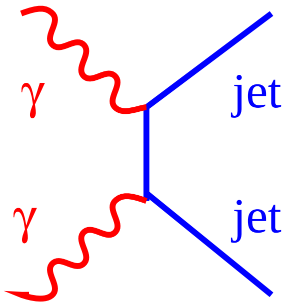
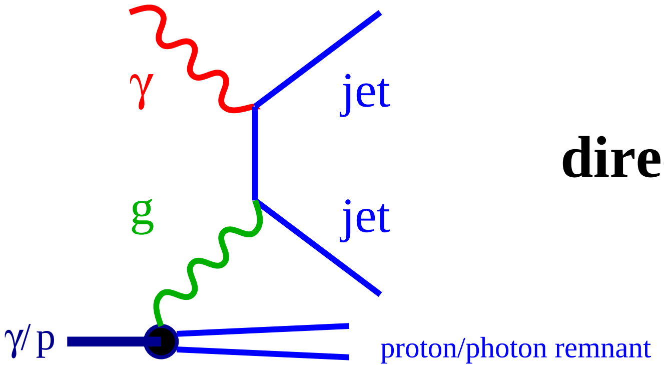
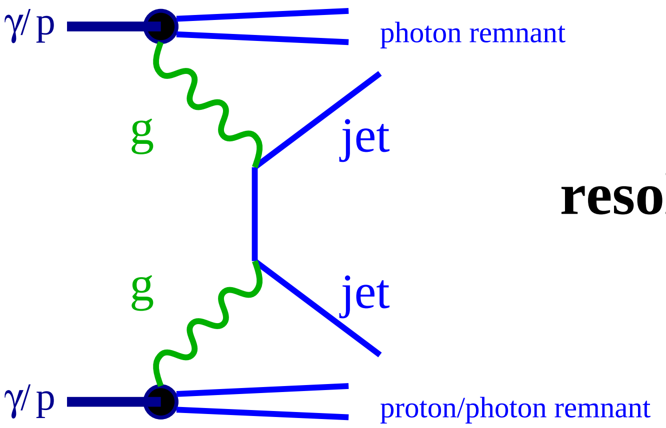
L3 (LP-047) ($W_{\gamma\gamma} = \sqrt{s}$):

$\sigma_{\gamma\gamma}$ consistent with PDG values:

$$\epsilon = 0.0790 \pm 0.0011$$

$$\eta = 0.4678 \pm 0.0059$$

Leading order $\gamma\gamma$ and γp

	HERA	LEP
	—	direct
	direct	single-resolved
	resolved	double-resolved

3.) Jets in $\gamma\gamma$ and γp

Jets are related to parton dynamics

Hard scale present in the event (usually jet E_{T})

$\Rightarrow$ Photon Structure

Jet Algorithms:

- Several kind of cone algorithms with

$$R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

($\eta = -\ln\tan\theta/2$ and azimuth ϕ)

- k_{T} cluster algorithm (KTCLUS) with

$$d_{ij} = \min(E_{Ti}, E_{Tj})^2 R_{ij}^2$$

Comparison to

- Leading Order QCD Monte Carlo models:

  PYTHIA, HERWIG, PHOJET

- Next-to-leading order QCD calculations (cone jets):

  P.Aurenche, L.Bourhis, M.Fontannaz, J.-P.Guillet (γp)

  B.W.Harris, J.F.Owens (γp)

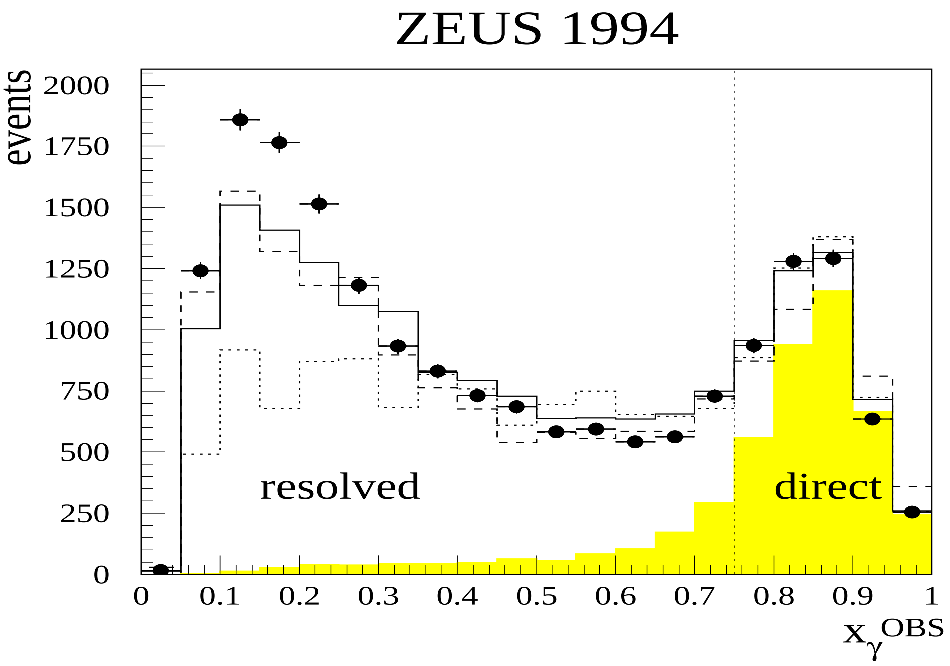
  M.Klasen, G.Kramer (γp)

  P.Aurenche, J.-P.Guillet, M.Fontannaz, Y.Shimizu, J.Fujimoto, K.Kato ($\gamma\gamma$)

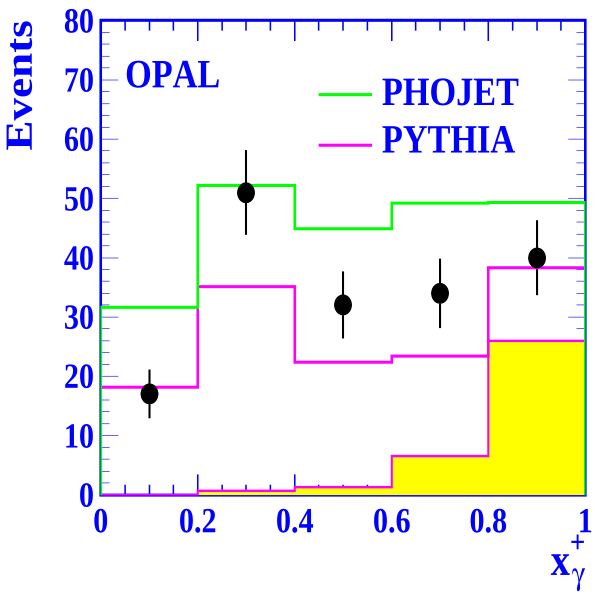
  T.Kleinwort, G.Kramer ($\gamma\gamma$)

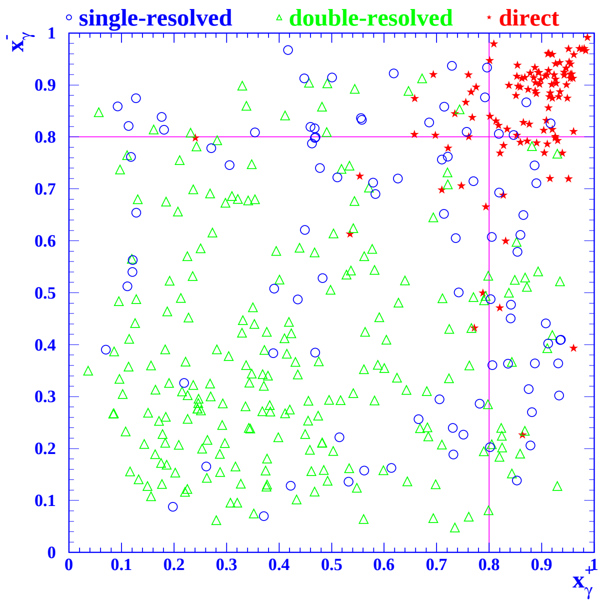
Requires good matching of theoretical and experimental jet definition

$$\textbf{HERA: } x_\gamma^{\mathrm{obs}} = \frac{\sum\limits_{\mathrm{jets}=1,2} \left(E_T^{\mathrm{jet}} e^{-\eta^{\mathrm{jet}}}\right)}{2yE_e}$$

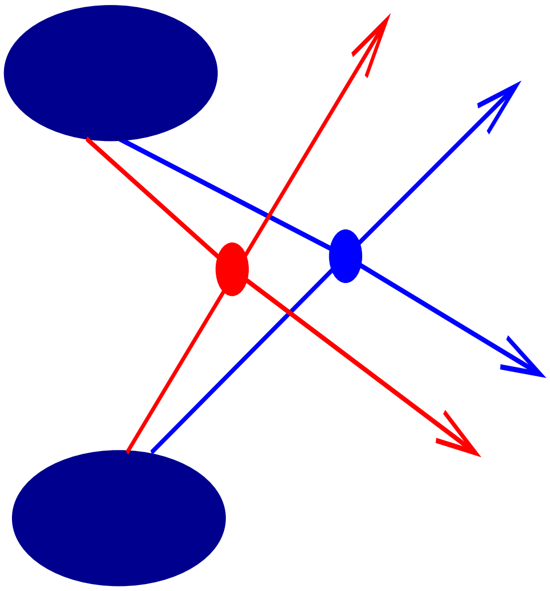


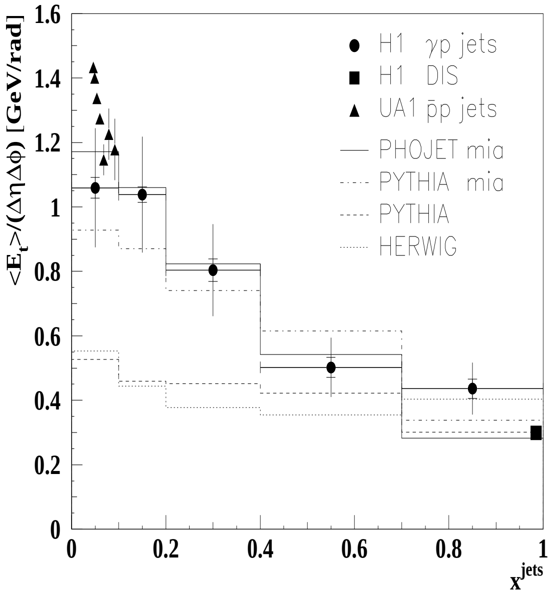
$$\textbf{LEP: } x_\gamma^{\pm} = \frac{\sum\limits_{\mathrm{jets}=1,2} \left(E^{\mathrm{jet}} \pm p_z^{\mathrm{jet}}\right)}{\sum\limits_{\mathrm{hadrons}} \left(E \pm p_z\right)}$$





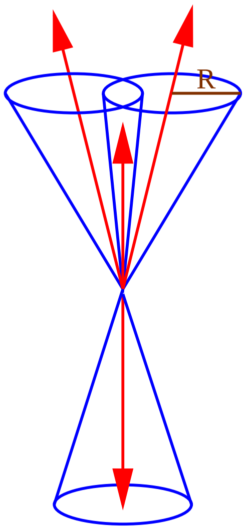
- multiple interactions





MI contained in generators (PHOJET, PYTHIA, HERWIG), but not in NLO theory

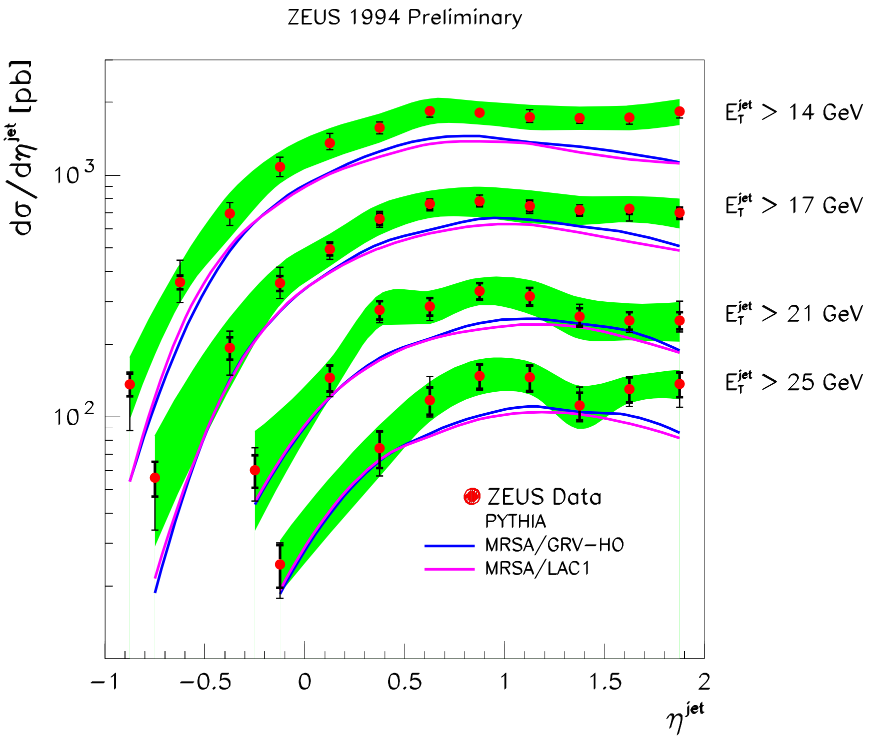
- jet algorithm (iterative cone)



Experiment:
overlapping jets with more than 3 partons can be merged

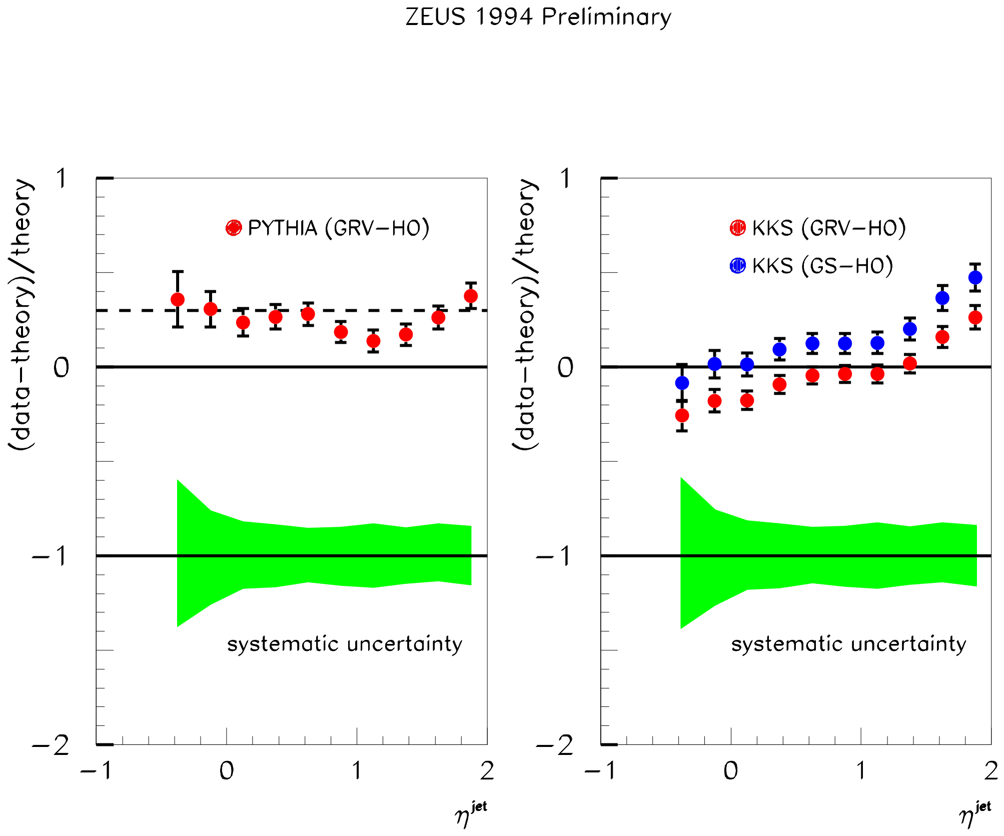
NLO-Theory:
Restrict max. separation:
$R_{ij} < R_{sep} = 1..2\ R$

Inclusive Jet Cross Sections

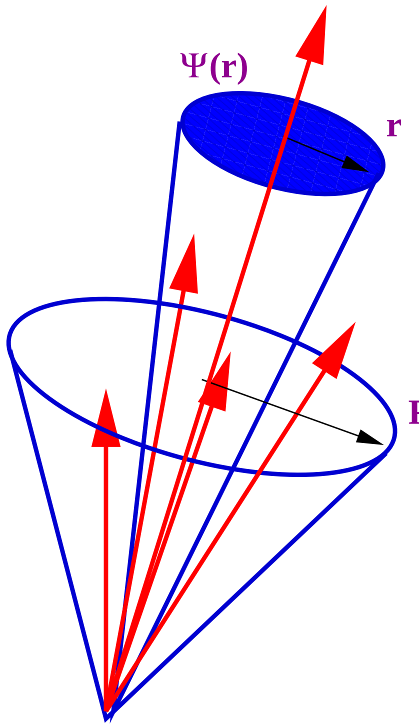


$\eta^{\rm jet} > 0$ proton direction

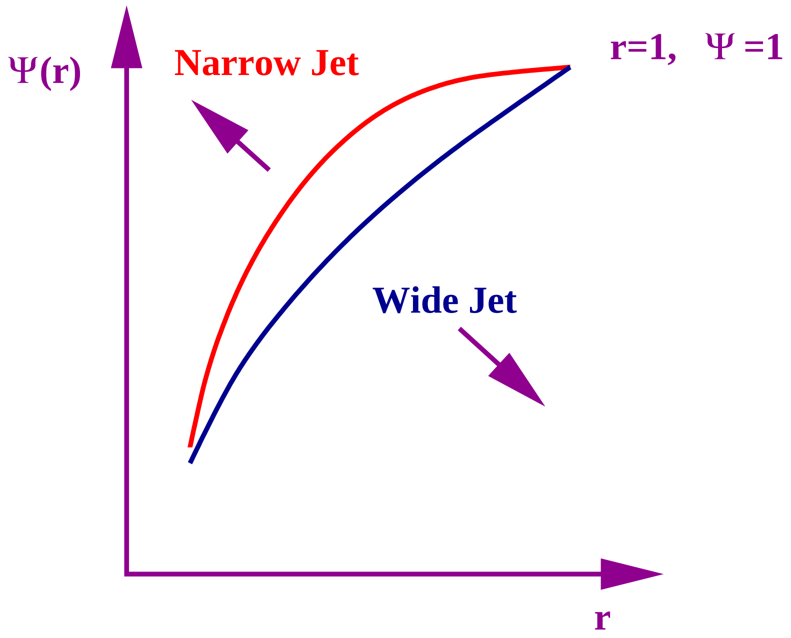
LO PYTHIA (w/o multiple interactions) too low



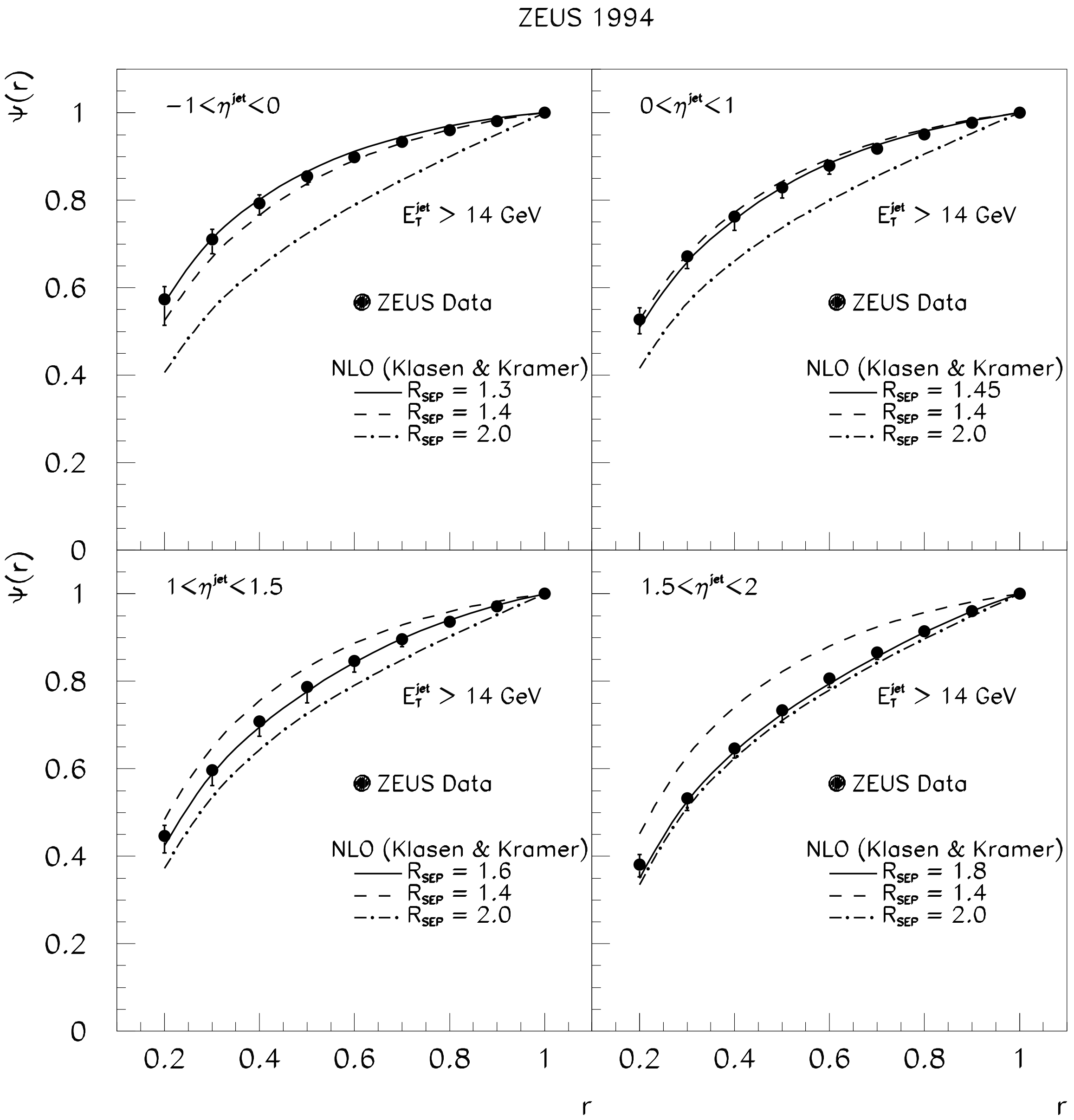
Jet Shapes



$$\psi(r) = \frac{1}{N_{\mathrm{jets}}} \sum_{\mathrm{jets}} \frac{E_{\mathrm{T}}(r)}{E_{\mathrm{T}}(r=R)}$$

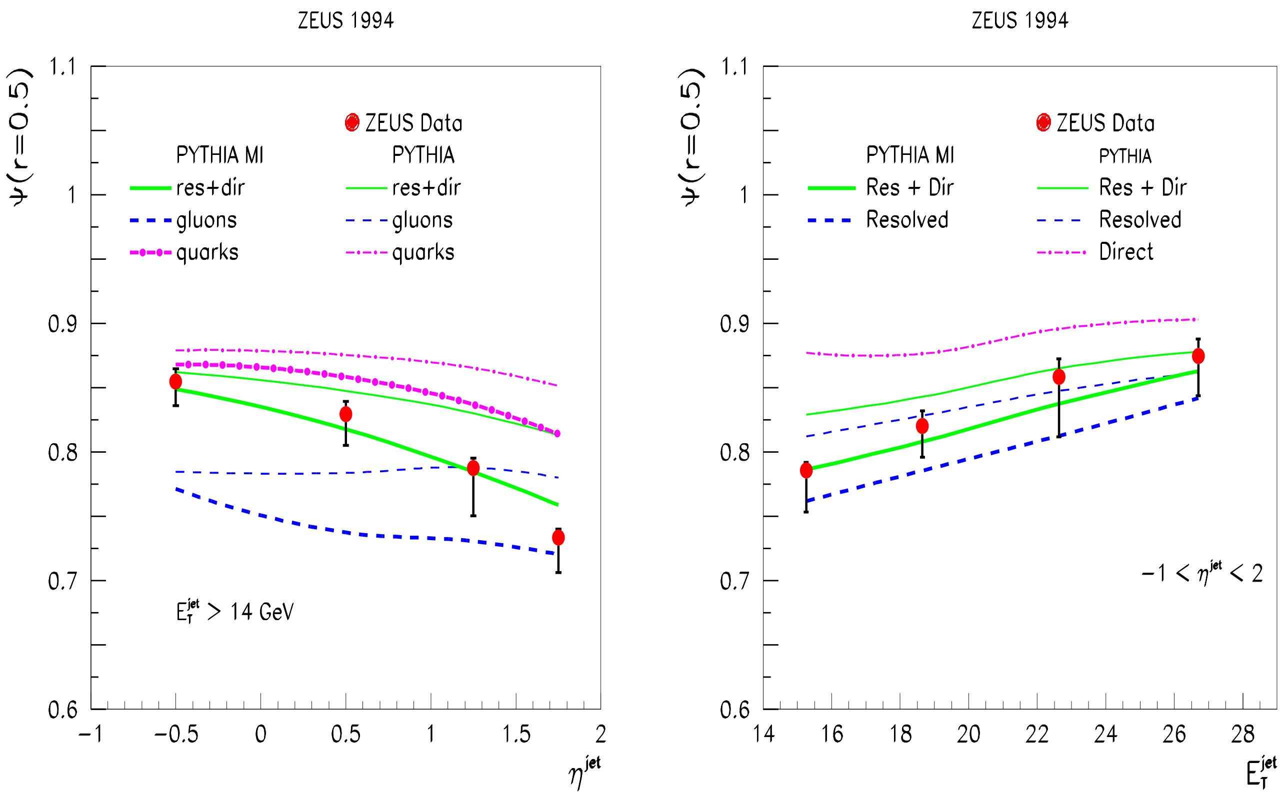


$\psi(r)$ versus r:



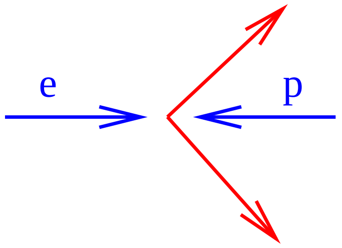
- **Additional parameter R_{sep} fitted using jet shapes**
- **For large $\eta^{\rm jet}$ and small $E_T^{\rm jet}$ multiple interactions important $\Rightarrow$ R_{sep} large**
- **Fitting of $R_{\rm sep}$ and reducing cone size from $R = 1$ to $R = 0.7$ improves agreement between NLO and data**

$\psi(r = 0.5) = 1$: 'pencil jet'

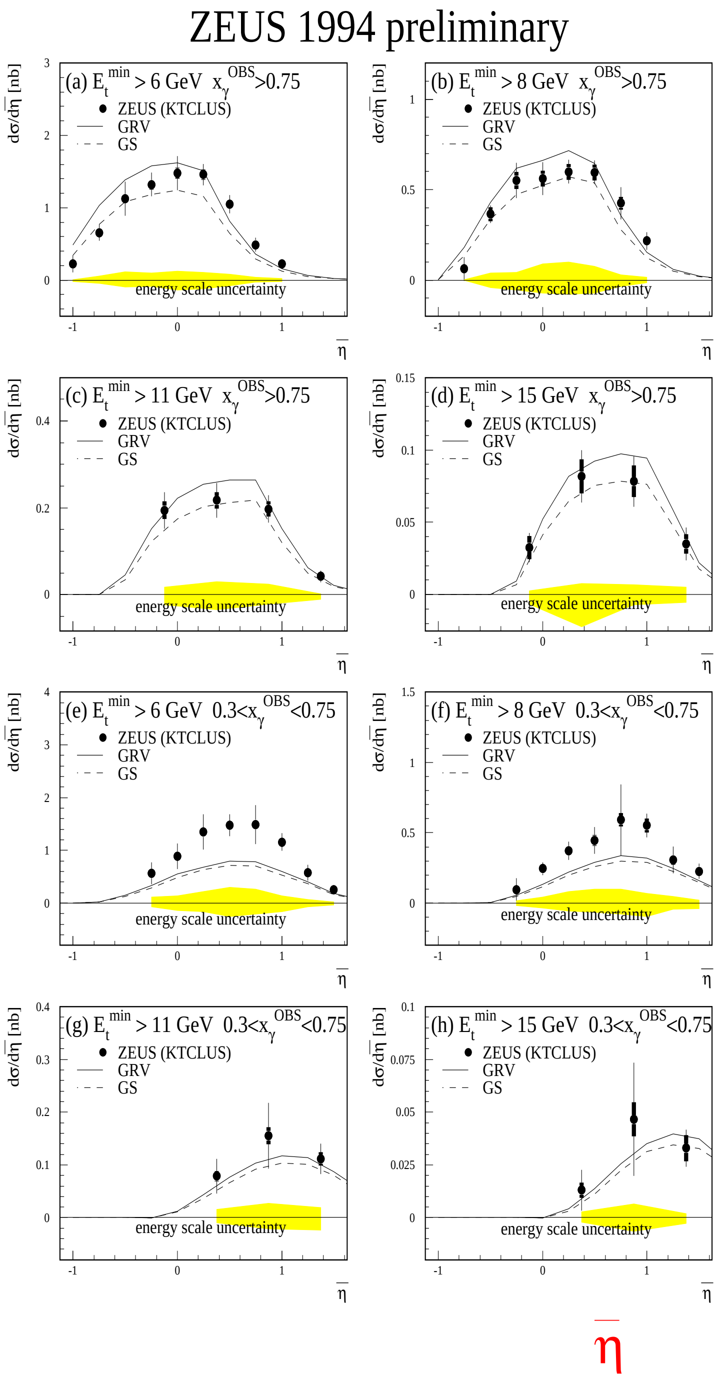


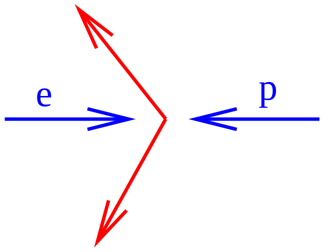
- gluon jets are broader than quark jets (similar to e^+e^-)
- jets at high $\eta^{\rm jet}$ are broader
- jets at low $E_T^{\rm jet}$ are broader
- multiple interactions (MI) broaden jets
  $\Rightarrow$ better agreement
- less MI at high $E_T^{\rm jet}$
- parton shower needed (not shown here)

Deduce information on parton densities from comparing jet cross-section for different parametrisations



low $\overline{\eta}$ = high x_γ





high $\overline{\eta}$ = low x_γ

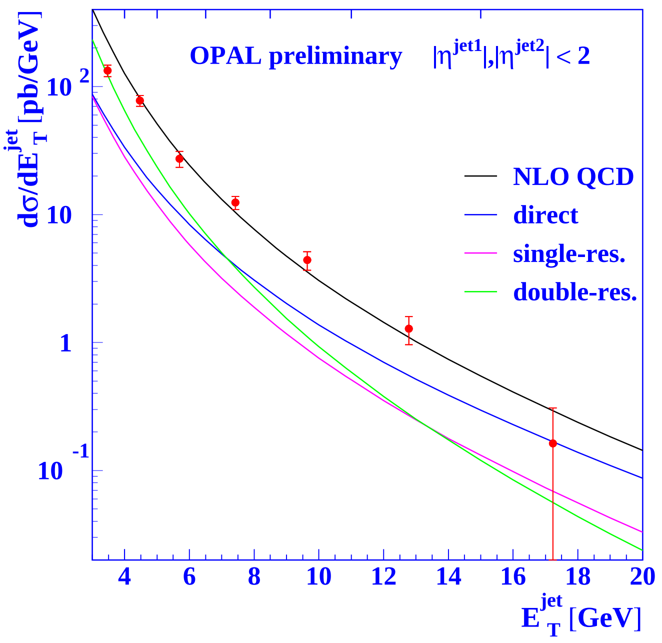
$$\overline{\eta} = \frac{1}{2}(\eta^{\mathrm{jet1}} + \eta^{\mathrm{jet2}})$$

largest difference between data and theory for low x_γ, low $E_T^{\min}$

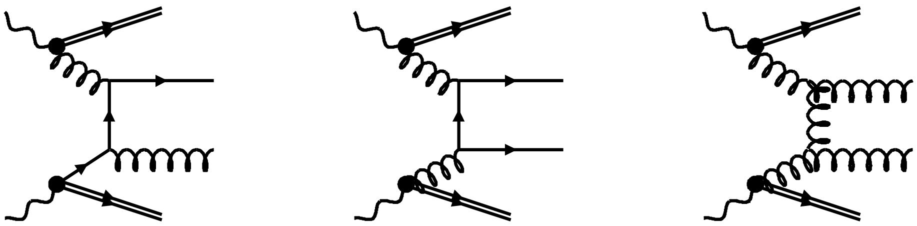
largest difference between GS and GRV for $x_\gamma^{\mathrm{obs}} > 0.75$

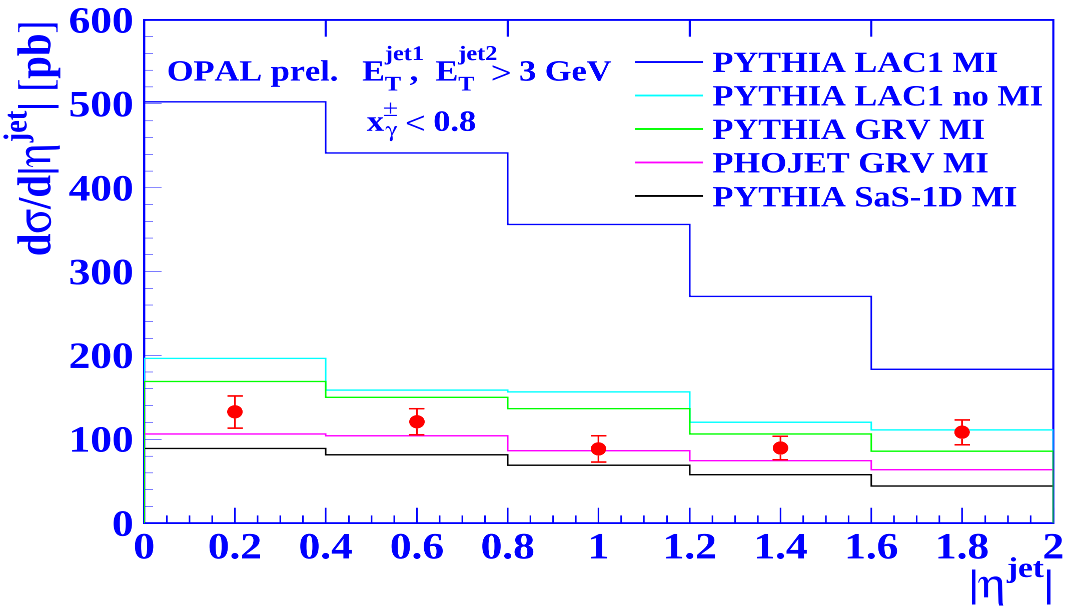
Dijet cross-sections in $\gamma\gamma$ ($\sqrt{s}_{ee} = 161, 172$ GeV):

NLO-QCD by Kleinwort und Kramer (GRV-NLO)

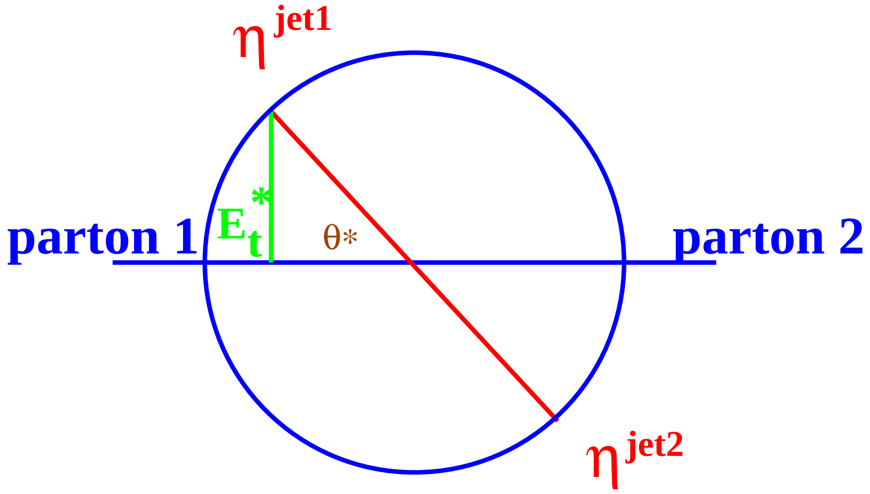


Double-resolved processes $\Rightarrow$ gluons in the photon





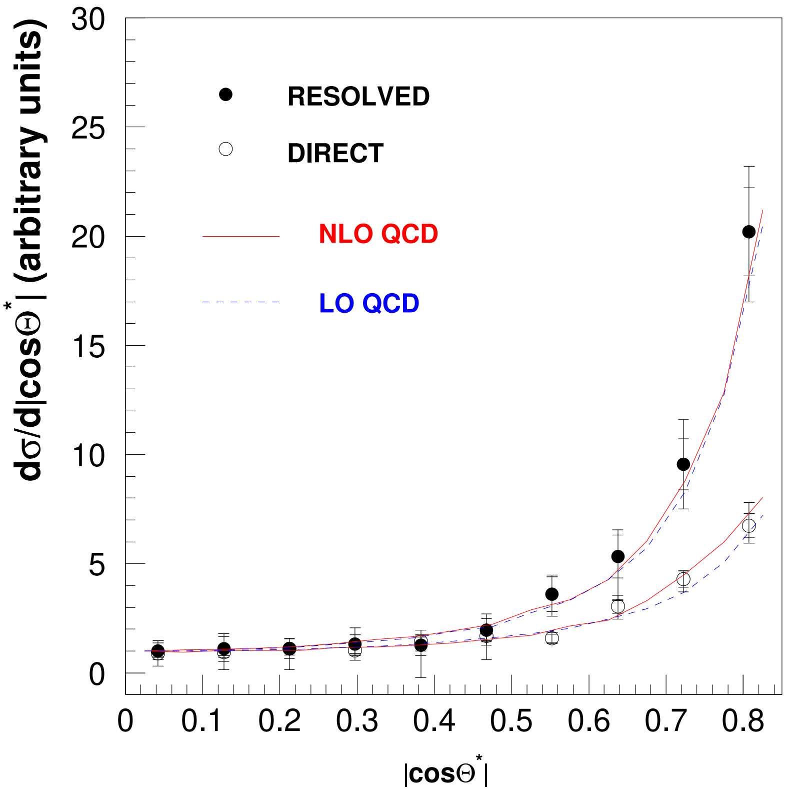
Parton scattering angles (ZEUS)



quark (fermion) exchange dominates direct $\propto |1 - \cos\theta^*|^{-1}$

gluon (boson) exchange dominates resolved $\propto |1 - \cos\theta^*|^{-2}$

ZEUS 1994



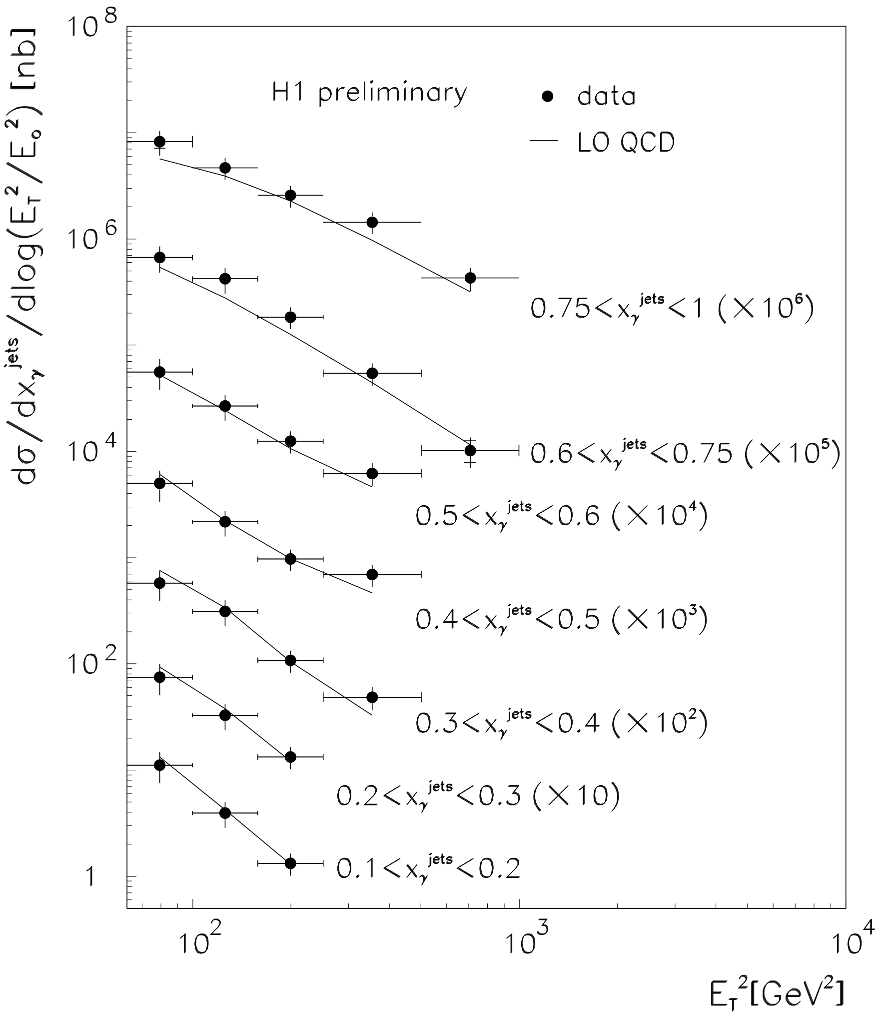
dijet invariant mass > 23 GeV

Effective parton densities (H1)

Idea: B. L. Combridge, C. J. Maxwell, Nucl.Phys.B239 (1984) 429.

Dijet cross-section:

$$\frac{d\sigma}{dy\,dx_\gamma\,dx_p\,d\cos\theta^*} \propto \sum_{ij} \frac{f_{\gamma/e}}{y}\frac{f_{i/\gamma}}{x_\gamma}\frac{f_{j/p}}{x_p}\,|M_{ij}(\cos\theta^*)|^2$$



Cone jets

$R = 0.7$, $E_T^{\rm jet} > 8$ **GeV**, $-0.5 < \eta^{\rm jet} < 2.5$, $\Delta\eta < 1$

dominating processes in the region $0.4 < x_\gamma < 0.7$:

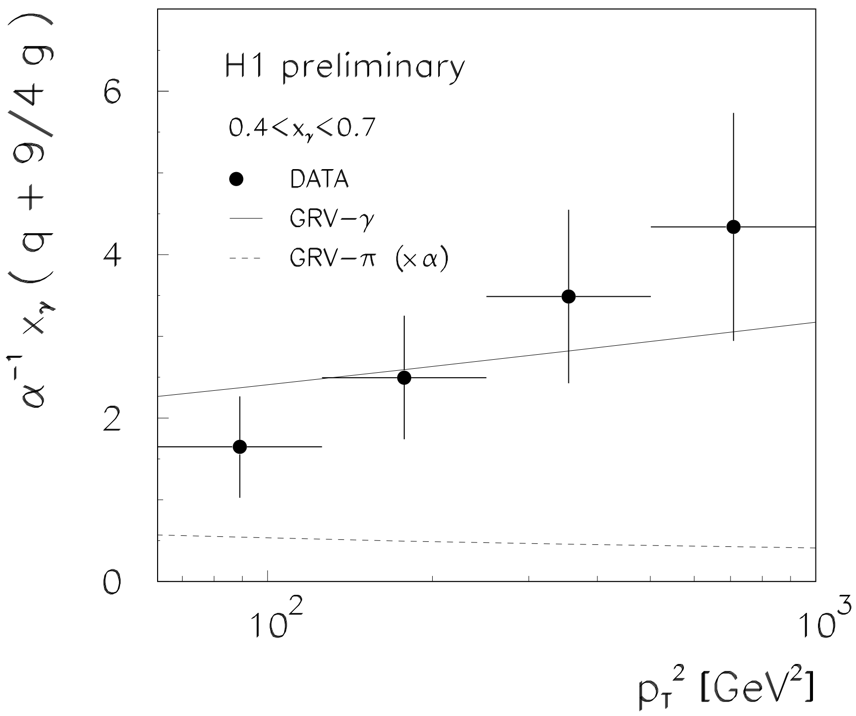
qq⟶qq; qg⟶qg; gg⟶gg

with similar $|M_{ij}(\cos\theta^*)|^2$

$$\tilde{f}_\gamma \equiv \sum_{n_f} \left(q_\gamma + \overline{q}_\gamma\right) + \frac{9}{4} g_\gamma$$

$$\tilde{f}_p \equiv \sum_{n_f} \left(q_p + \overline{q}_p\right) + \frac{9}{4} g_p$$

Replace: $\sum_{ij} f_{i/\gamma} f_{j/p} |M_{ij}|^2 \to \tilde{f}_\gamma \tilde{f}_p |M_{\mathrm{SES}}|^2$



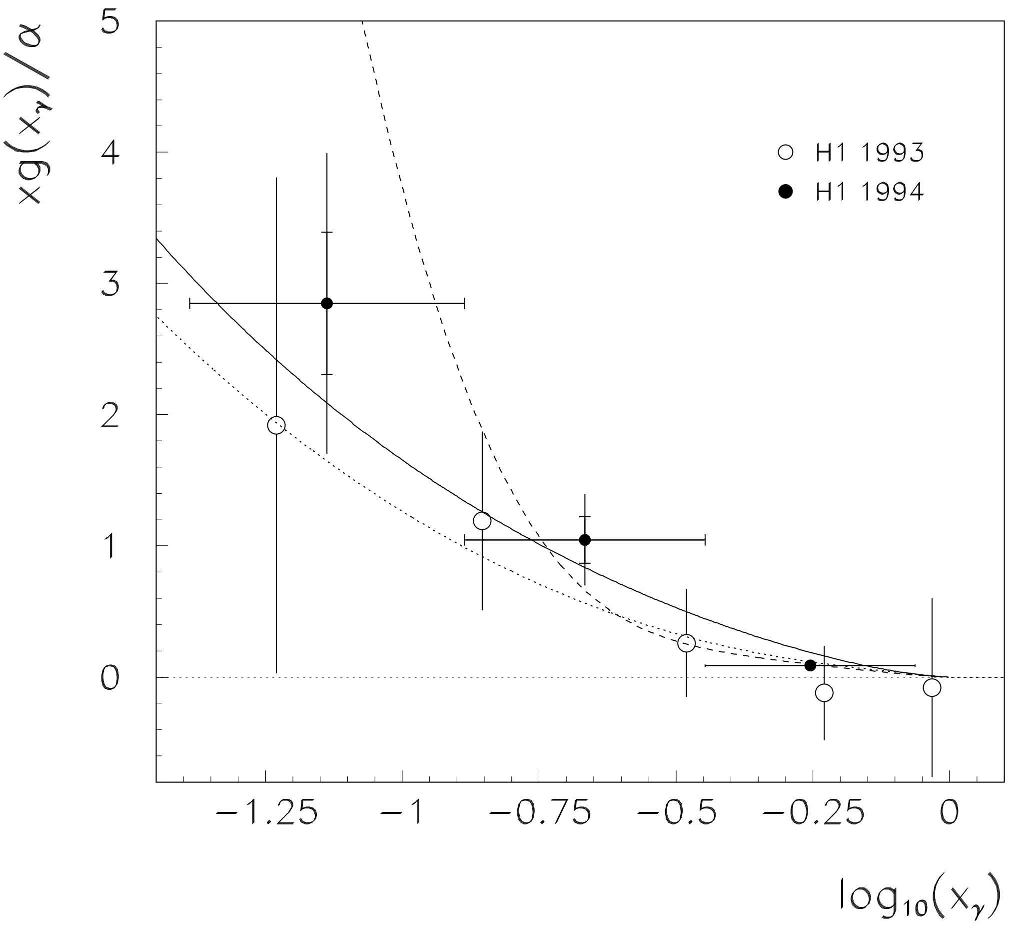
Choice of scales $Q^2 \approx p_T^2$?

$$x_\gamma^{\mathrm{rec}} = \frac{1}{E_\gamma} \sum_n p_\mathrm{T} e^{-\eta} \qquad \langle p_\mathrm{T}^2 \rangle_{\mathrm{part}} = 38 \text{ GeV}^2$$

n: tracks with $p_\mathrm{T} > 2.6$ GeV and $|\eta| < 1$

unfold true x_γ distribution for gluons

from leading order Monte Carlo (H1 prel.):



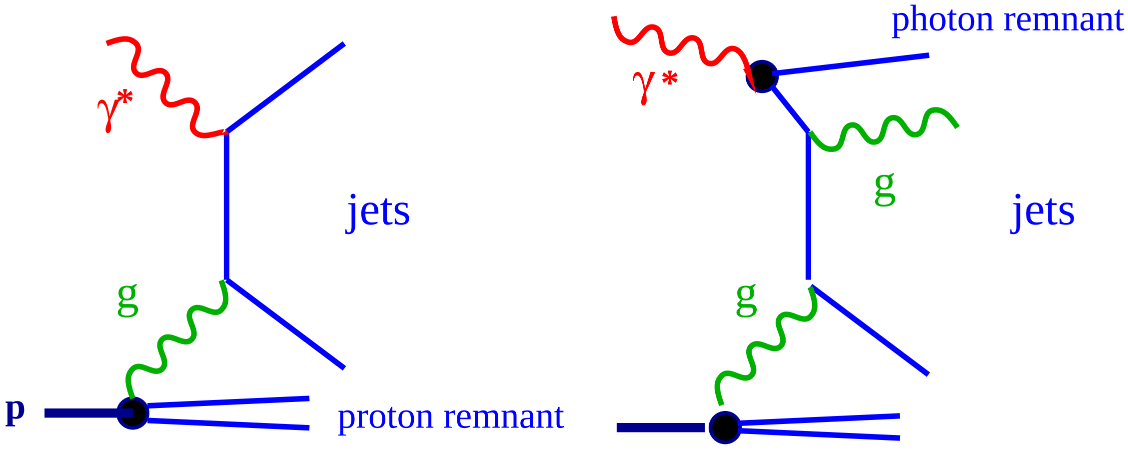
dashed curve: LAC1; full curve: GRV; dotted curve: SaS

H1 1993 (Nucl.Phys.B445 (1995) 195):

LO gluon distribution from dijet events at $\langle p_\mathrm{T}^2 \rangle = 75$ GeV^2

Hadrons depend less on underlying event than jets

The eye of the beholder



$Q^2 >> p_t^2$

proton is probed

(deep-inelastic)

"direct"

$p_t^2 >> Q^2$

photon is probed

"resolved"

In NLO scale dependent separation of 'direct' and 'resolved' (μ_p, μ_γ, μ)

$p_t^2 >> Q^2$: measurement of virtual photon structure

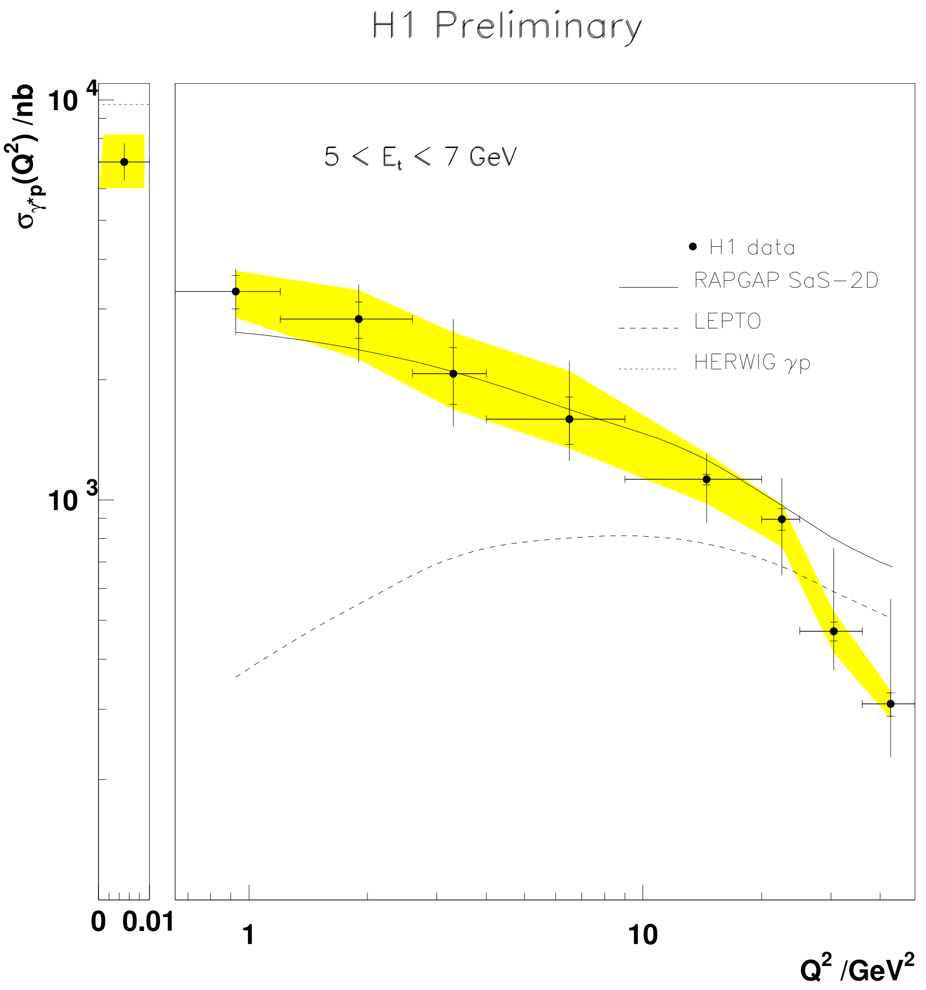
'hot topic', only few measurements on virtual photon structure from e^+e^- (PLUTO 1984), much more expected from LEP

only GRS and SaS parametrisations include virtual photon structure

H1: measure both scales using

γp data ($Q^2 < 0.01$ GeV^2) and DIS data ($0.65 < Q^2 < 49$ GeV^2)

k_{T} clustering algorithm ($-2.5 < \eta^* < -0.5$)



LEPTO: deep-inelastic scattering (no resolved γ)

RAPGAP:

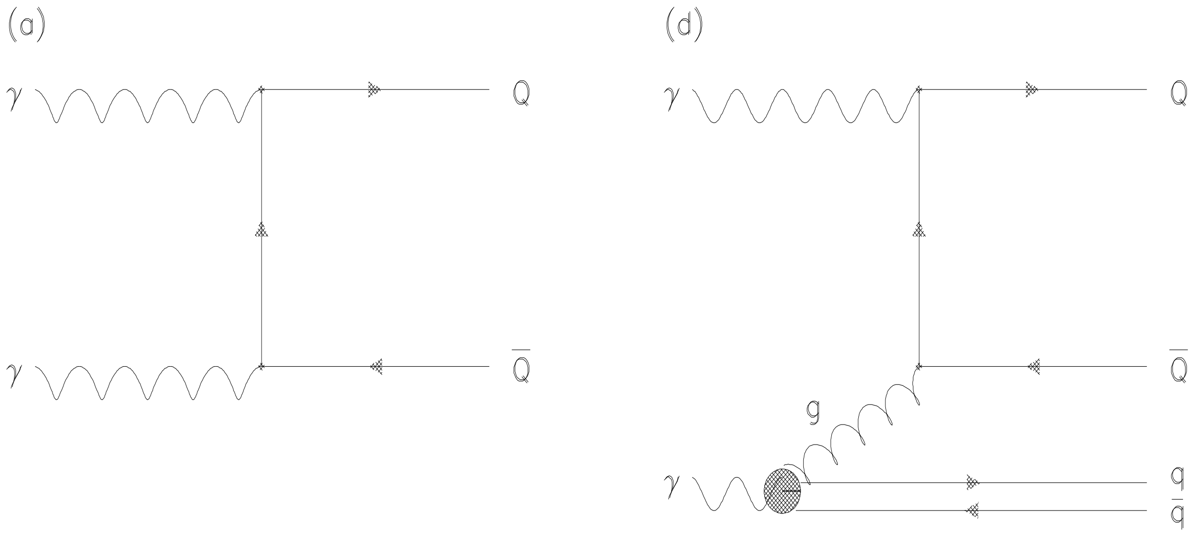
deep-inelastic scattering and resolved processes

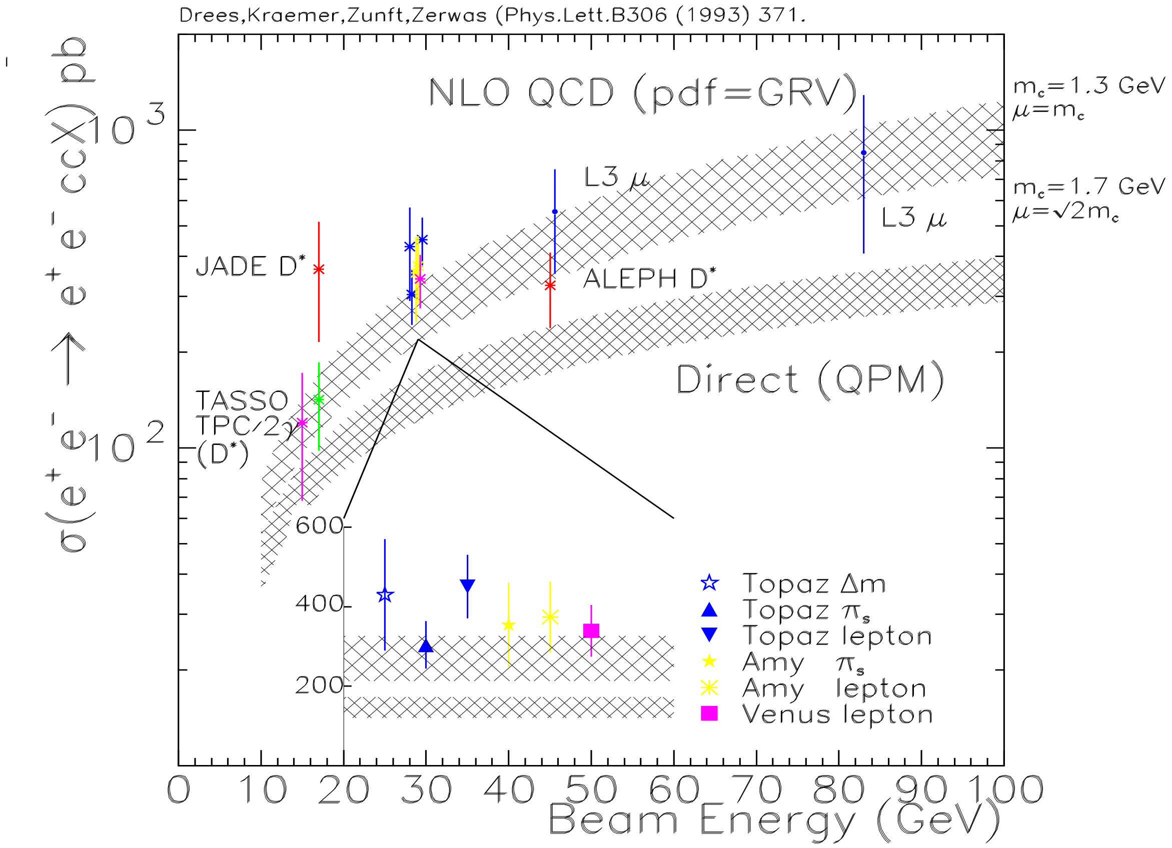
SaS-2D parton distributions include Q^2 suppression
for VDM and anomalous photon

verified by looking for photon remnant

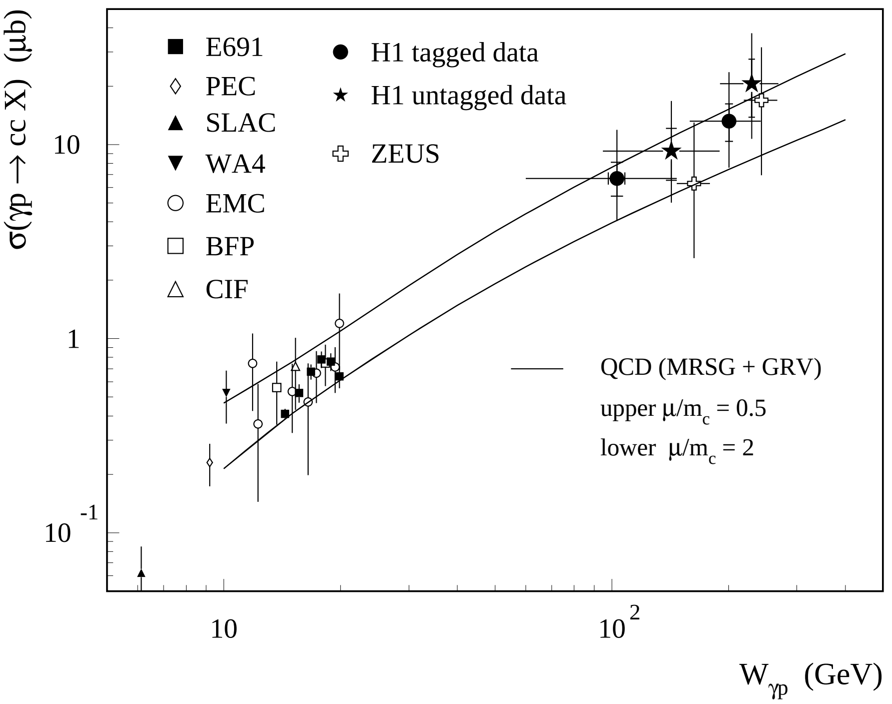
Similar scales for $E_T^2 \approx Q^2 \approx 30$ GeV^2 ?

Charm in (or from) the Photon

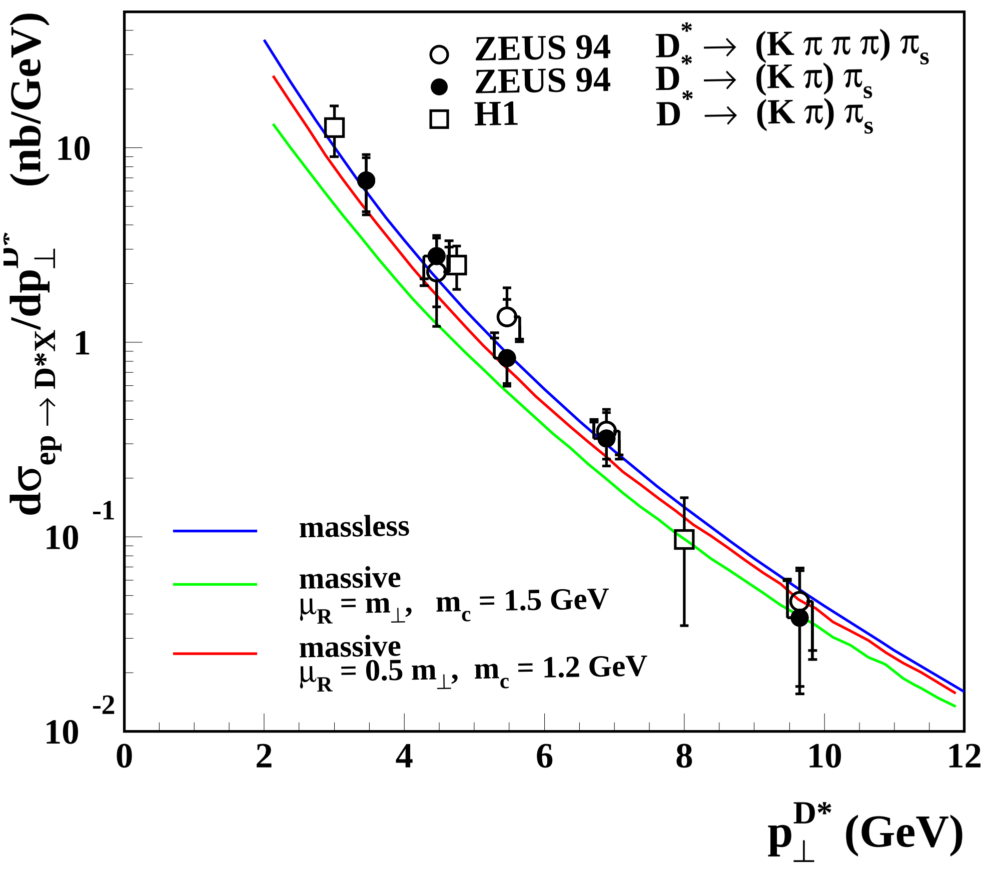




L3: Muons from semi-leptonic charm decays (LP-092)

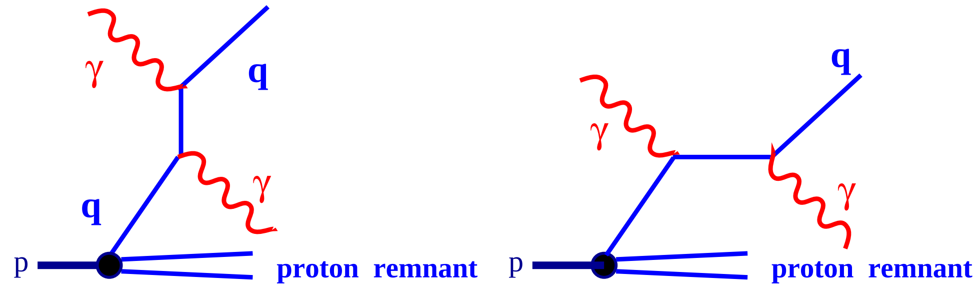


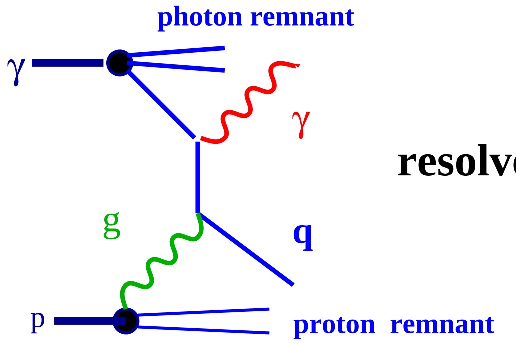
E691
PEC
SLAC
WA4
EMC
BFP
CIF
H1 tagged data
H1 untagged data
ZEUS
QCD (MRSG + GRV)
upper μ/m_c = 0.5
lower μ/m_c = 2
σ(γp → cc̄ X) (μb)
W_γp (GeV)



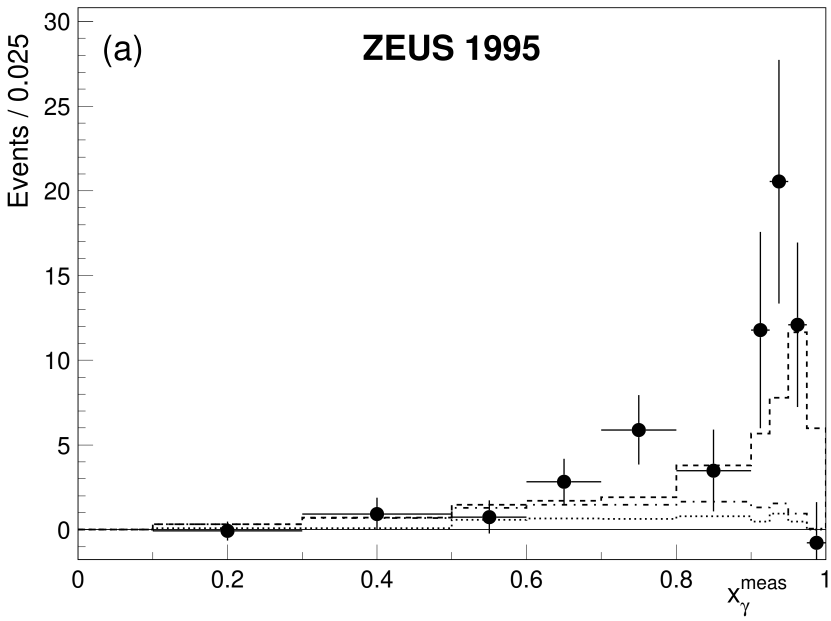
ZEUS 94 D* → (K π π π) π_s
ZEUS 94 D* → (K π) π_s
H1 D* → (K π) π_s
massless
massive
μ_R = m_⊥, m_c = 1.5 GeV
massive
μ_R = 0.5 m_⊥, m_c = 1.2 GeV
dσ_ep → D*X/dp_⊥^D* (nb/GeV)
p_⊥^D* (GeV)

LO direct prompt photon production

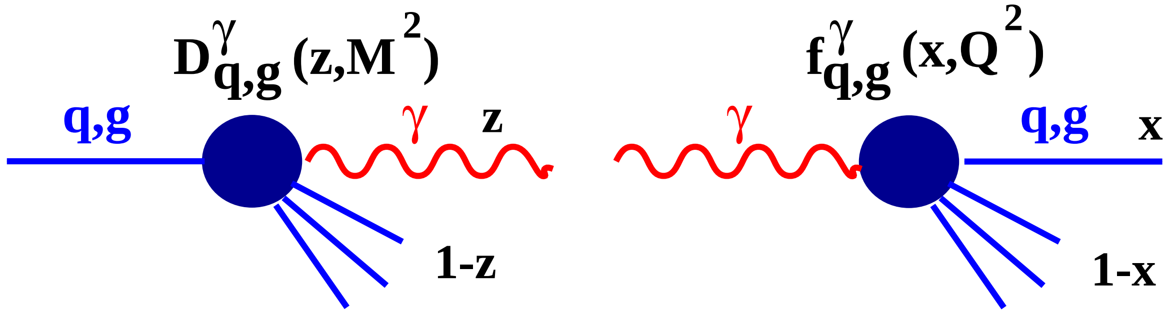




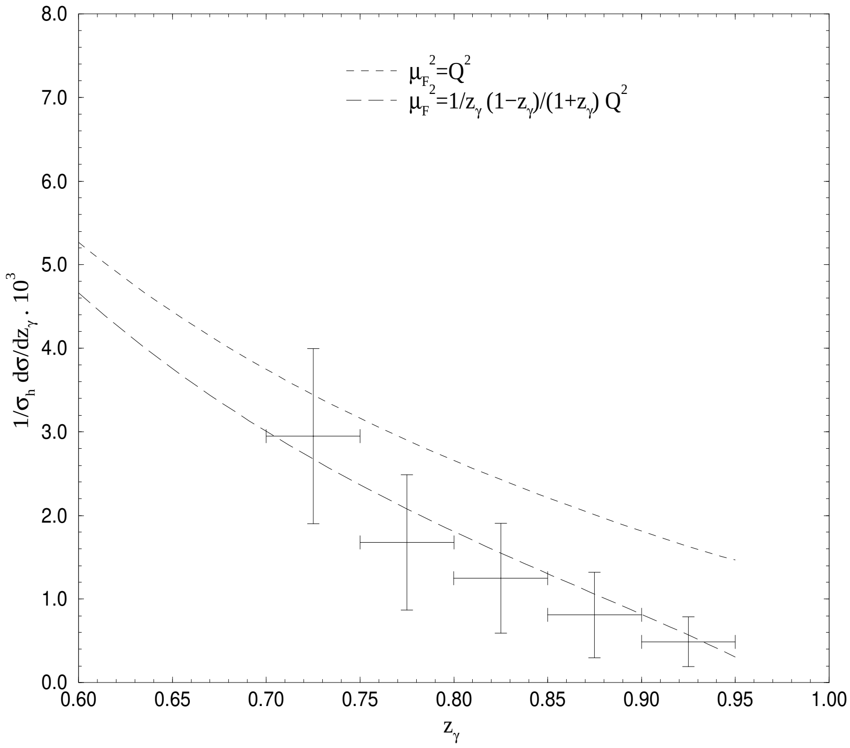
resolved



Photon fragmentation function



Z.Phys.C69 (1996) 365



z_γ

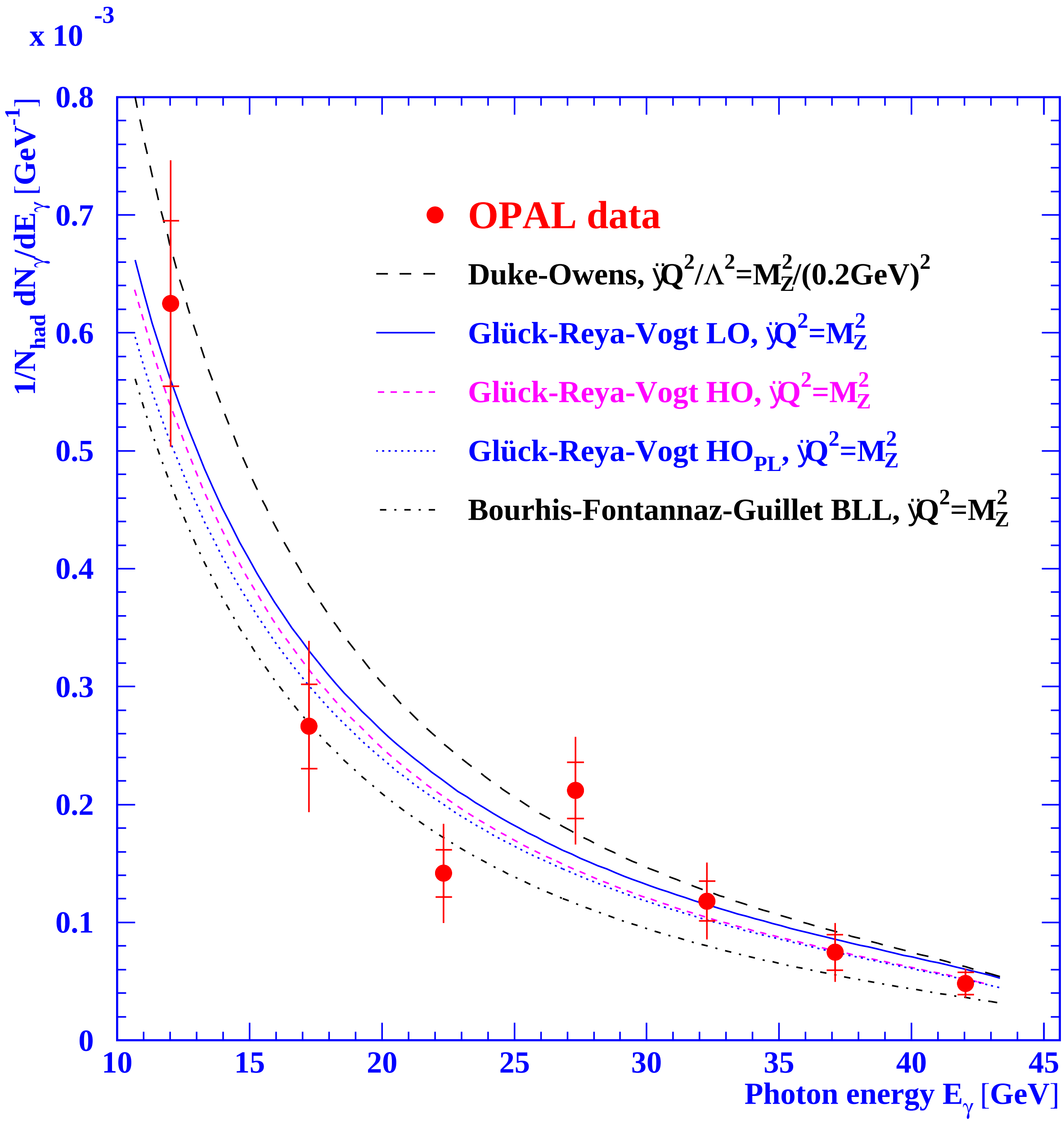
ALEPH: photon production in jets

(Durham $y_{cut}=0.1$)

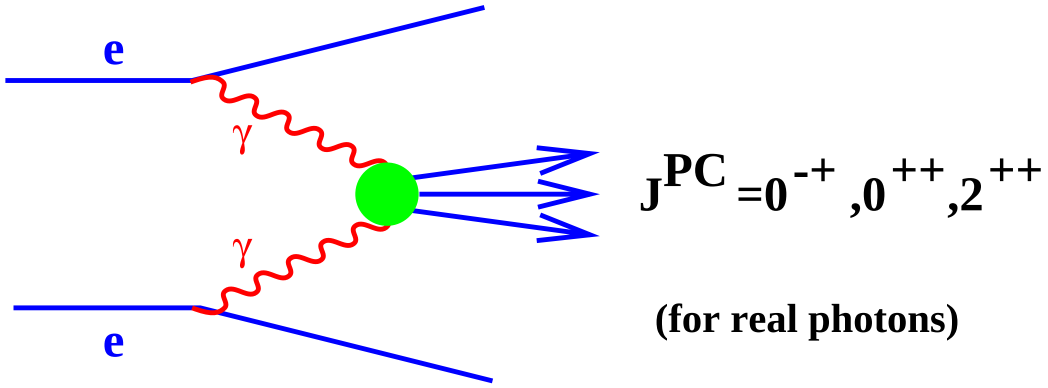
Bourhis, Fontannaz, Guillet (LP-200):

BLL perturbative QCD ($q \to q\gamma$)$_{PL}$ and VDM input (ρ)

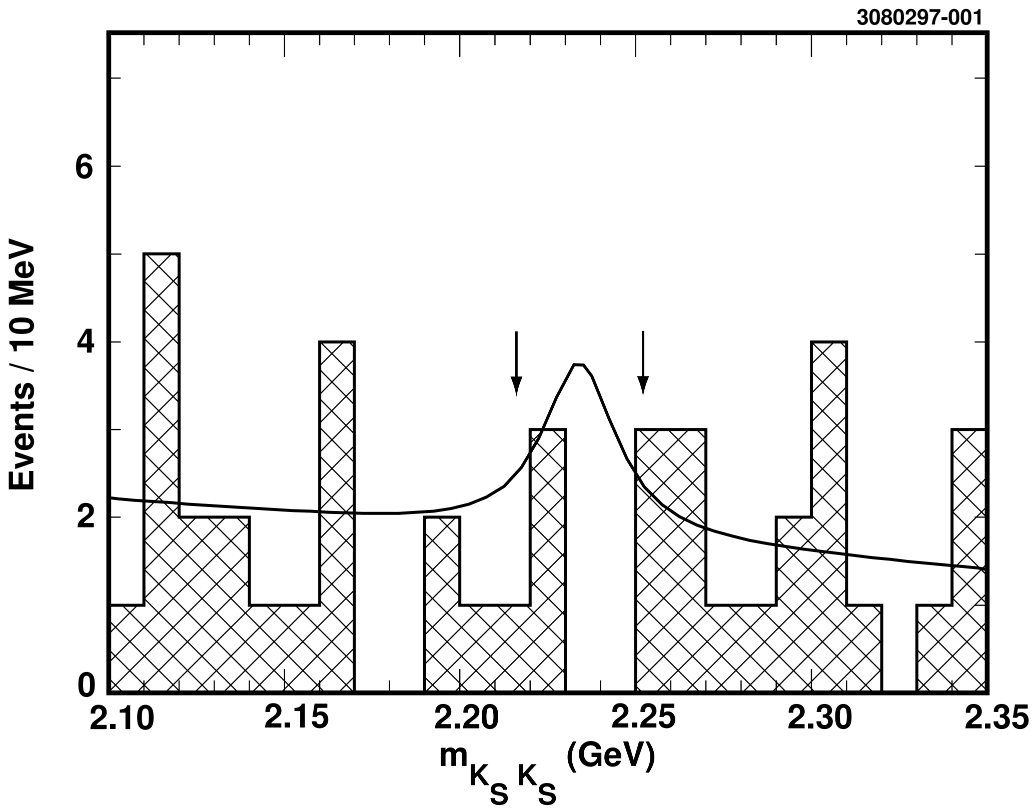
OPAL: inclusive prompt photon production:



4.) Resonance production

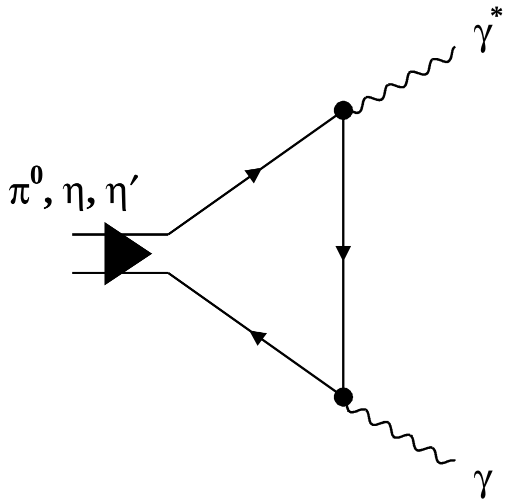


- L3: Many results on resonance formation in $\gamma\gamma$, e. g. η_c, χ_{c2} and $a_2(1320)$ production (LP-052)
- CLEO: Stickiness of 82 (at 95 % CL) for glueball candidate in $f_j(2220) \to K_S K_S$ decays (LP-210)

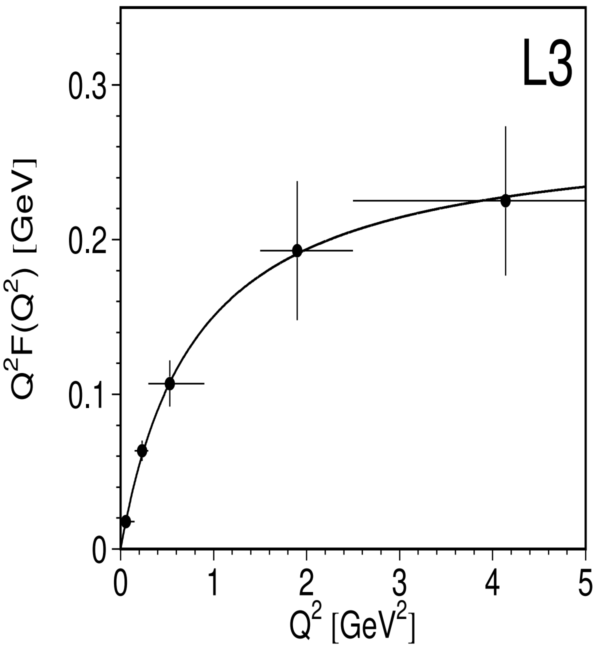


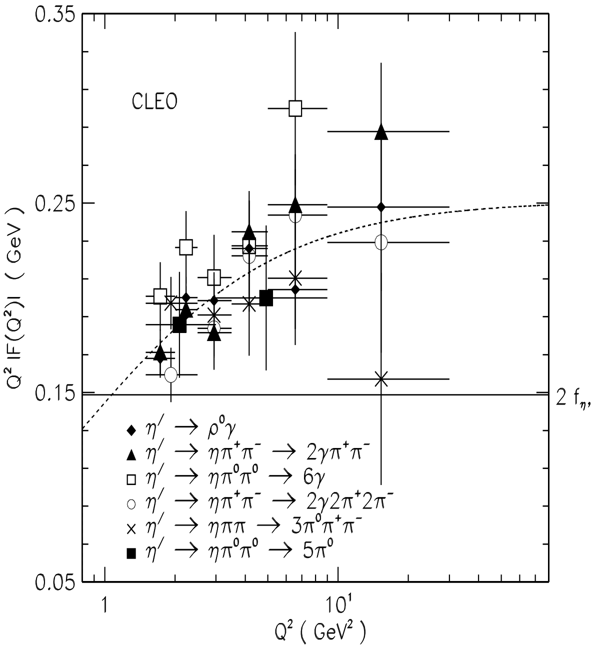
Meson-photon transition form factor

measures quark content and QCD dynamics of bound state



$$F^2(Q^2) \propto \frac{\Gamma_{\gamma\gamma}(\eta')}{m^3_{\eta'}} \left(1 + \frac{Q^2}{\Lambda^2}\right)^{-2}$$





$\Lambda = 900 \pm 46 \pm 22$ **MeV**, $\Lambda = 859 \pm 9 \pm 18 \pm 20$ **MeV**

differs from π^0, η^0 form factors

Conclusion/Outlook

Does the photon have a structure ?

Its interactions can be described using a structure function formalism

The structure function F_2^γ is measured at LEP in a wide range of x and Q^2
$(x > 10^{-3}, 1 < Q^2 < 10^3$ GeV^2).

The gluon distribution of the photon is constrained by jet (hadron) measurements in $\gamma\gamma$ and γp (HERA)

L3 has demonstrated for the first time the high $\sqrt{s}_{\gamma\gamma}$ behaviour of $\sigma^{tot}_{\gamma\gamma\rightarrow}$hadrons

Many more results expected at LP99

$\Rightarrow$

Virtual photon structure at LEP (double tags) and HERA (jets at low Q^2)

$\gamma^*\gamma^*$ cross-section at LEP (possible test of BFKL)