Phenomenology at low Q^2

Lecture III

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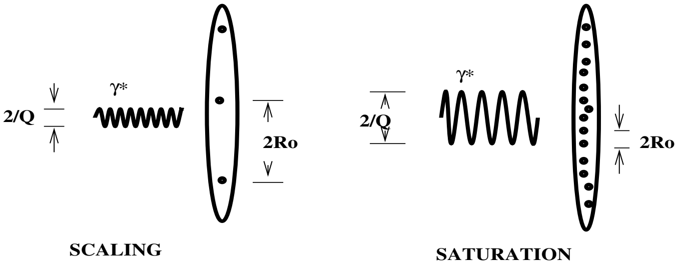
Outline

1. Parton shadowing at low x
2. Saturation and geometric scaling at low x
3. R and F_L in the low Q^2, low x region
   - Introduction
   - F_L at HERA
   - BKS
   - R1999
4. F_2^{γ} in the low Q^2, low x region
5. Summary

DIS in the proton rest frame: a clear separation in time between between γ^* forming a $q\bar{q}$ dipole and dipole's interaction with proton.

Postulate dipole's cross section and fit its parameters.

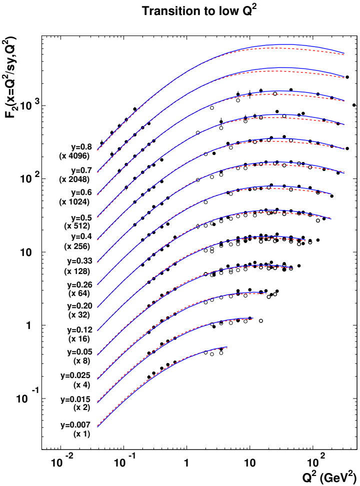


Observe that 2 scales matter: dipole's size ($\sim 1/Q$) and separation between partons (R_0).

Gives good description of the electroproduction data and of the diffraction!

Parton shadowing at low x ...cont'd

Golec-Biernat, Wüsthoff, Phys. Rev. D59 (1999) 014017



$\Downarrow x$

Data: H1 and ZEUS;
curves (plotted for $x < 0.01$): the saturation model of Bartels, Golec-Biernat, Kowalski, Phys. Rev. D66 (2002) 014001.

Saturation and geometric scaling at low x

see e.g. Golec-Biernat, hep-ph/0109010

$\tau = Q^2 R_0^2(x)$

G.s. is a manifestation
of an internal saturation scale,

$Q_s(x) \sim 1/R_0(x)$

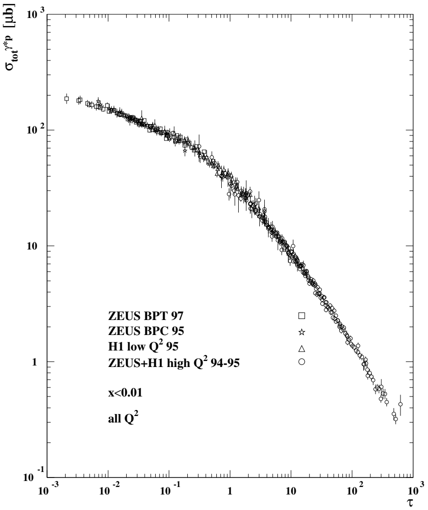
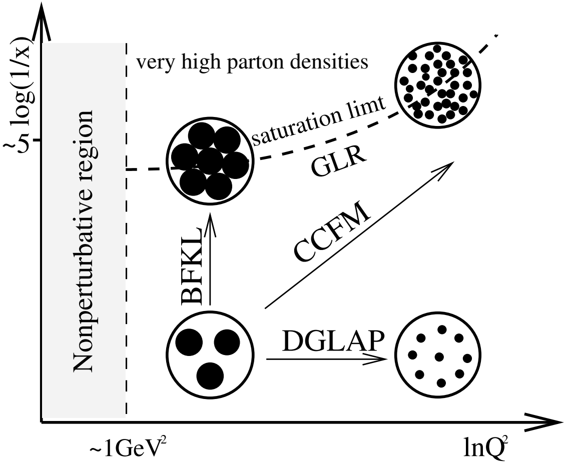


Figure 5. *Experimental data on $\sigma_{\gamma^* p}$ from the region $x < 0.01$ plotted versus scaling variable $\tau = Q^2 R_0^2(x)$. Q^2 values are between* 0.045 *and* 450 GeV^2.

Saturation and geometric scaling at low x

see e.g. Golec-Biernat, hep-ph/0109010 ...cont'd



Outline

- Experimental determination of $F_L(x,Q^2)$ (or $R = F_L/F_T = F_L/(F_2 - F_L)$ difficult; needed measurements of the y (or energy) dependence of the cross section at fixed x and Q^2 since (neglecting m^2 and M^2 terms):

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{Q^4 x} Y_+ \left(\frac{1+\epsilon R}{1+R}\right) F_2(x,Q^2), \qquad Y_\pm = 1 \pm (1-y)^2 \tag{1}$$

- At low x dominant contribution to F_L comes from gluons $\Longrightarrow$ learning about gluons!
- In QPM, i.e. at $Q^2 \rightarrow 0$, $F_L \sim (< m_q^2 > + < \kappa_T^2 >)/Q^2$ where m_q and κ_T are quark's mass and transverse momentum (limited in QPM). This is $\approx$ valid in the LLQ^2 QCD.
- In the NLO QCD, $< \kappa_T^2 >$ grows as Q^2 with $Q^2 \nearrow \Longrightarrow F_L$ acquires a LT contribution, $\sim \alpha_s(Q^2)$.
- For $Q^2 \rightarrow 0$, $F_L \sim Q^4$ (for fixed ν). Observe that $\sigma_L \sim F_L/Q^2$ vanishes at photoproduction.
- Measurements of R extend down to $Q^2 \approx$0.3 GeV^2 and $x \approx$0.01. They come from different targets since $R^A - R^d$ is consistent with 0 (e.g. NMC, Nucl. Phys. B481 (1996) 23). Thus in the data analysis one usually assumes that $R(x,Q^2) = R(x,Q^2 =$0.5 GeV^2) with 100% uncertainty for $Q^2 < 0.5$ GeV$^2 \Longrightarrow$ systematic errors. Models ?
- At large Q^2 and large x ($x \gtrsim$ 0.1) data on R well described by the QCD. At moderate Q^2, HT contribution $\sim 1/Q^2$ needed. Little known about R (or F_L) at low Q^2.

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F_L Extraction - H1

$$\sigma_r = \left(\frac{2\pi\alpha^2 Y_+}{xQ^4}\right)^{-1} \frac{d^2\sigma}{dxdQ^2} = \left[F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)\right]$$

Three techniques:

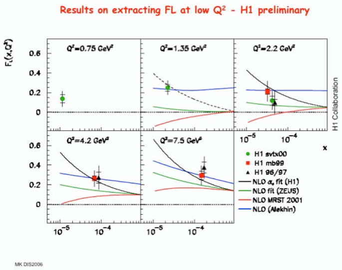
1. Subtraction method: $F_L = \frac{Y_+}{y^2}\left[F_2 - \sigma_r\right]$
   - Extract F_2 in low y region, extrapolate to higher y (Q^2) using NLO DGLAP
2. Derivative Method: $\left.\frac{\partial \sigma_r}{\partial \ln y}\right|_{Q^2}$
   - F_L dominates the derivative at large y. Subtract contribution from F_2
3. Shape Method: Fit σ_r assuming $F_2 = ax^{-\lambda}$ and $F_L = c$ at high y

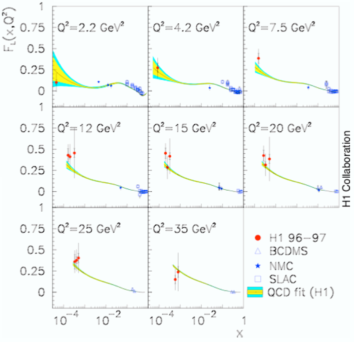
A. Caldwell, DIS2006

R and F_L in the low Q^2, low x region

F_L at HERA...cont'd

F_L Extraction - H1



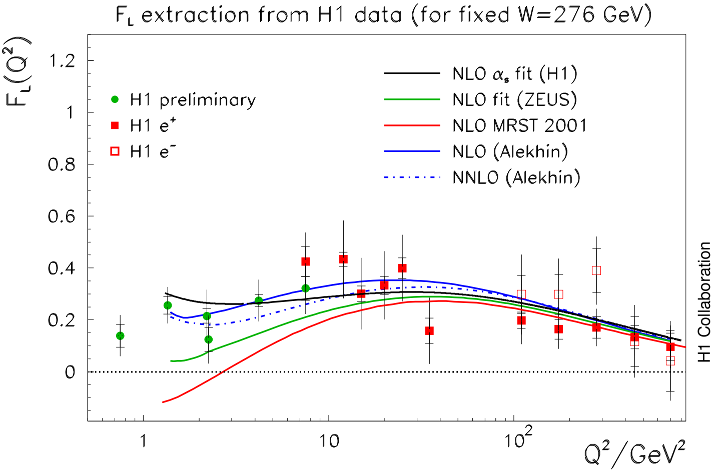


Extraction of F_L with assumptions about behavior of F_2. Could be dangerous since small-x physics not well understood.
Better - direct measurement of F_L by varying the CM energy.

A. Caldwell, DIS2006

R and F_L in the low Q^2, low x region

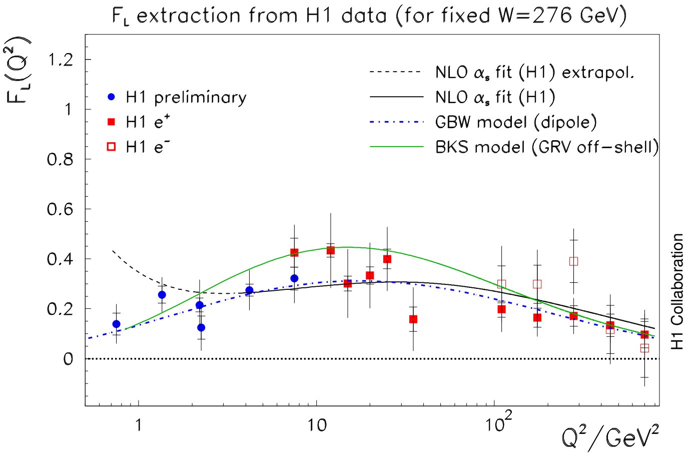
F_L at HERA...cont'd



ICHEP04/Abstract 5–0161

R and F_L in the low Q^2, low x region

F_L at HERA...cont'd



x range of points: $\sim 10^{-5} - 0.01$

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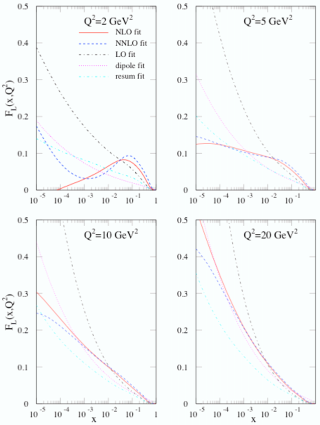
Predictions for F_L



F_L predictions from MRST group at different orders in DGLAP, a fit which resums the leading ln(1/x) and β_0 terms, and a dipole type model. Very large differences at small Q^2 where gluon uncertainty large.

A. Caldwell, DIS2006

Predictions for the longitudinal structure function

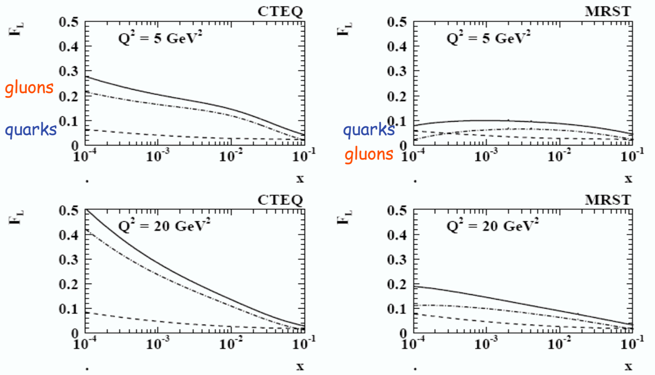


Figure 2. Calculation of the longitudinal structure function $F_L(x,Q^2)$ (solid lines) using the CTEQ6 (left) and the MRST2002 (right) parton distributions and Eq.2 for 4 flavours and α_s to NLO. Note that not only the predicted values for F_L differ but as well drastically the relative contributions from gluons (dashed dotted lines) and sea quarks (dashed lines). For MRST at low x, contrary to common belief, $F_L(x,Q^2)$ is not gluon dominated. Both sets of parton distributions describe the H1 data on F_2 well.

G. Altarelli and G. Martinelli, Phys.Lett. B76 (1978) 89.

$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \cdot \left[\frac{16}{3} F_2 + 8 \sum e_q^2 \left(1 - \frac{x}{z}\right) zg \right]$$

MK DIS2006

M. Klein, DIS2006

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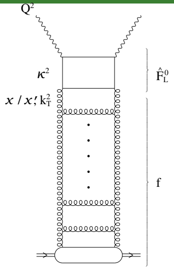
R and F_L in the low Q^2, low x region

BKS (Badelek, Kwiecinski, Stasto, Z. Phys. C74 (1997) 297)



- A model for F_L, valid at low x and low Q^2; based on the photon–gluon fusion, essential at low x and extended to low Q^2. Similar approach in Nikolaev, Zakharov, Z. Phys. C49 (1991) 607, C53 (1992) 331
- The model embodies the constraint $F_L \sim Q^4$ at $Q^2 \to 0$.
-

$$F_L = \int_x^1 \frac{dx'}{x'} \int \frac{dk_T^0}{k_T^0} F_L^0(x', Q^2, k_T^0) f(\frac{x}{x'i}, k_T^2)$$

where F_L^0 comes from $\gamma^* g$ fusion, is a longitudinal structure function of the off-shell gluon of virtuality k_T^2 and is calculated perturbatively; f is an unintegrated gluon distribution related to the "ordinary" $g(y, \mu^2)$ by:

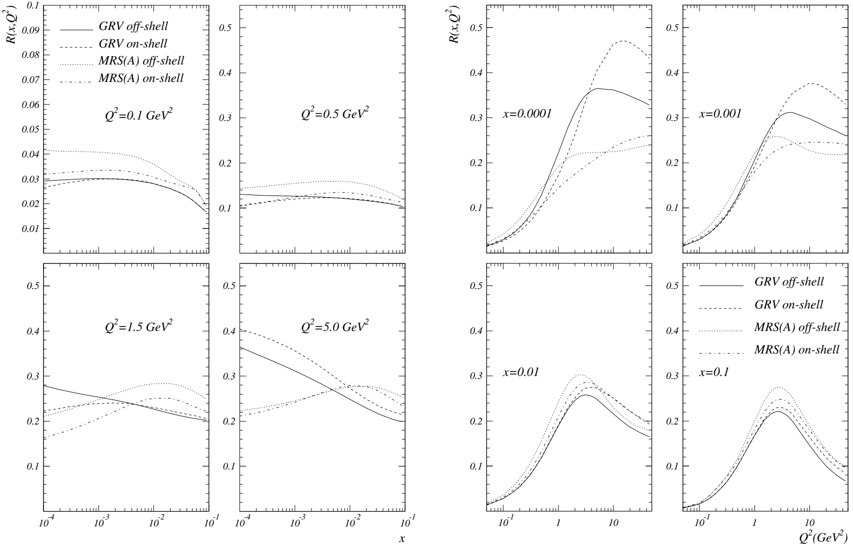
$$yg(y, \mu^2) = \int^{\mu^2} \frac{dk_T^2}{k_T^2} f(y, k_T^2)$$

Its evolution is controlled by (approximate) BFKL.

- To extrapolate F_L to low Q^2 and to $Q^2 = 0$, evolution of $g(y, Q^2)$ and argument of $\alpha_S(Q^2)$ was frozen *via* $Q^2 \to Q^2 + 4m_q^2$.
- HT contribution needed at moderate Q^2, i.e. terms vanishing as $1/Q^2$ for $Q^2 \to \infty$. They were assumed to originate from low values of the quark transverse momenta and interpreted as coming from soft pomeron exchange (intercept = 1). Such HT has a proper behaviour both at $Q^2 \to \infty$ and $Q^2 \to 0$.

R and F_L in the low Q^2, low x region

BKS (Badelek, Kwiecinski, Stasto, Z. Phys. C74 (1997) 297)...cont'd



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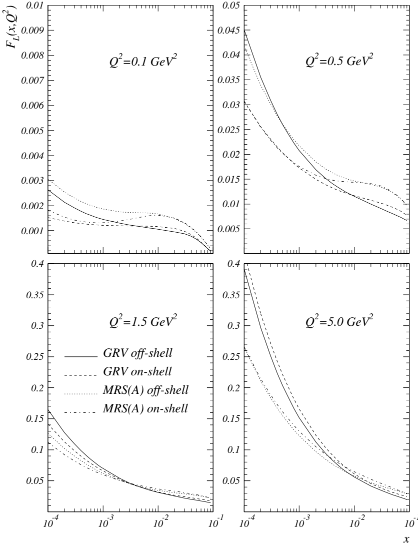

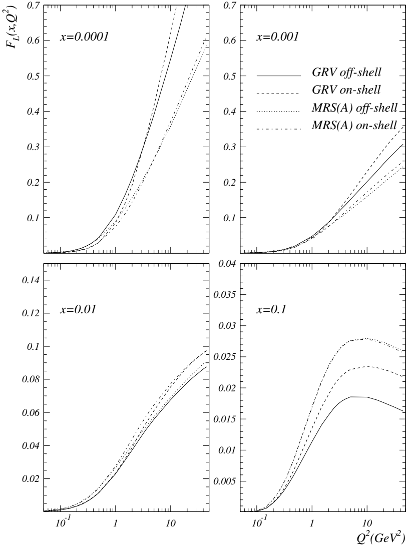

R and F_L in the low Q^2, low x region

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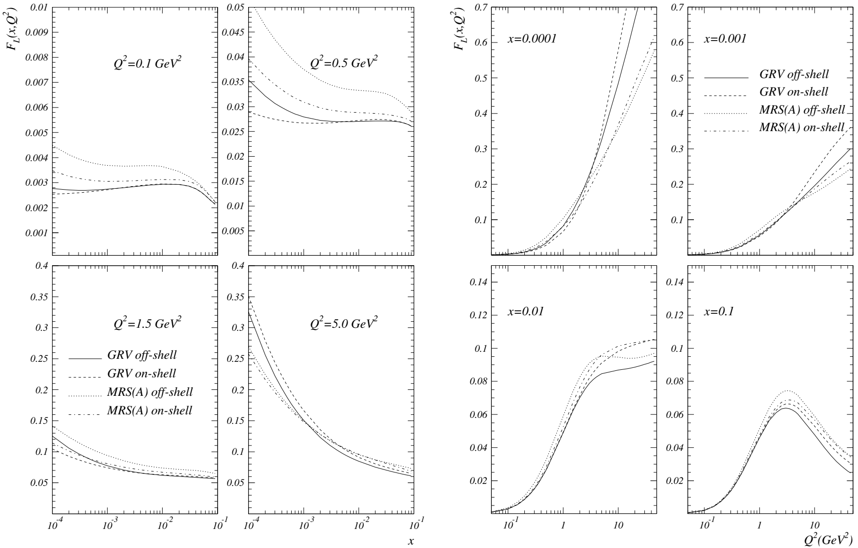
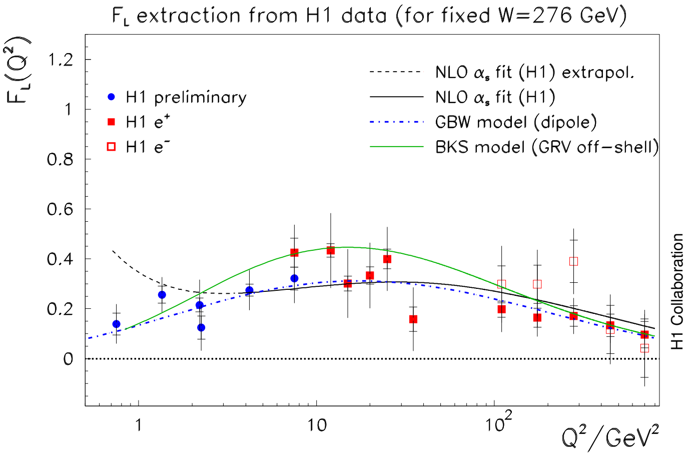


R and F_L in the low Q^2, low x region

BKS ...cont'd



x range of points: $\sim 10^{-5} - 0.01$

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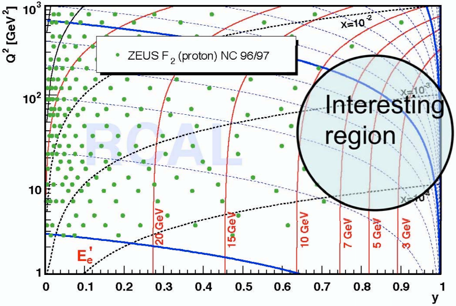
Measuring F_L



Need to go to lowest possible scattered electron energy:

- lower E_P rather than E_e
- trigger efficiency
- electron finder efficiency
- electron finder purity (photoproduction background, wrong candidate)

A. Caldwell, DIS2006

Outline

R and F_L in the low Q^2, low x region

R1999 (SLAC, Phys. Lett. B452 (1999) 194)

Data in the range $0.005 \leq x \leq 0.86$, $0.5 \leq Q^2 \leq 130$ GeV^2 were fitted by 6-parametr fits (3 indep.models).

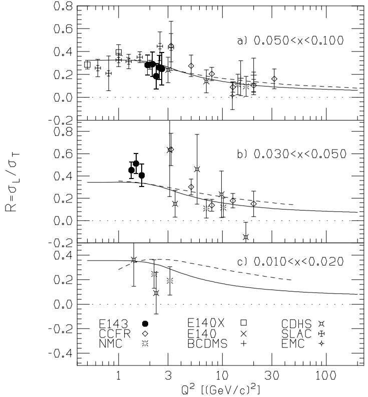


FIG. 3. R as a function of Q^2 for: a) $0.05 \leq x \leq 0.10$; b) $0.03 \leq x \leq 0.05$; c) $0.01 \leq x \leq 0.02$. The solid curve is the average of the new fits, $R1998$, and the dashed curve is the NNLO pQCD calculation described in the text.

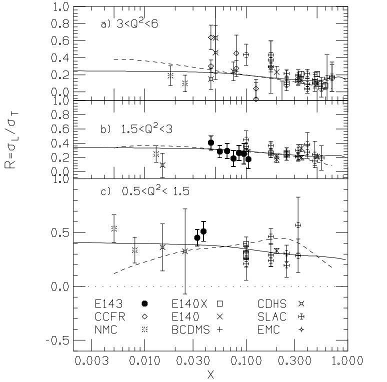


FIG. 4. R as a function of x for: a) $3 \leq Q^2 \leq 6(\mathrm{GeV}/c)^2$; b) $1.5 \leq Q^2 \leq 3\ (\mathrm{GeV}/c)^2$; c) $0.5 \leq Q^2 \leq 1.5\ (\mathrm{GeV}/c)^2$. T curve is the average of the new fits, $R1998$, and the dashed curve is the NNLO pQCD calculation described in the text

Outline

F_2^γ in the low Q^2, low x region

(Badelek, Krawczyk, Kwiecinski, Stasto, Phys.Rev. D62 (2000) 074021)

In a full analogy with the BBJK formulation of the F_2^p:

- $$F_2^\gamma(x,Q^2) = F_2^{\mathrm{VMD}}(x,Q^2) + F_2^{\mathrm{partons}}(x,Q^2) \qquad (2)$$

  where

  $$F_2^{\mathrm{VMD}}(x,Q^2) = \frac{Q^2}{4\pi} \sum_V \frac{M_V^4\, \sigma_{V\gamma}\,(W^2)}{\gamma_V^2 (Q^2 + M_V^2)^2}\,,$$

  $$F_2^{\mathrm{partons}}(x,Q^2) = \frac{Q^2}{Q^2+Q_0^2}\, F_2^{\mathrm{QCD}}(\bar{x}, Q^2+Q_0^2),$$

  $$\bar{x} = \frac{Q^2+Q_0^2}{W^2+Q^2+Q_0^2}.$$

- F_2^{QCD} is taken from the QCD analysis, valid in the large Q^2 region.
- Modifications of the QCD contribution ($\bar{x}$, Q_0^2) introduce power corrections which vanish as $1/Q^2$ (i.e. are negligible at large Q^2).
- Q_0^2 is set to 1.2 GeV^2 as in the F_2^p.
- Sum over V in F_2^{VMD} is for $M_V^2 < Q_0^2$ only, i.e. over ρ, ω, ϕ.
- The model is valid at low x and any value of Q^2
- At $Q^2 \to \infty$, $F_2^\gamma(x,Q^2) \to F_2^{\mathrm{QCD}}(x,Q^2)$

- A total $\gamma^*\gamma$ cross-section in the high energy limit:

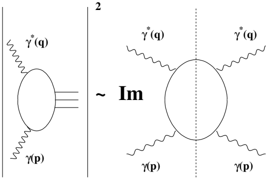
$$\sigma_{\gamma^*\gamma}(W, Q^2) = \frac{4\pi^2\alpha}{Q^2} F_2^\gamma(x, Q^) \tag{3}$$

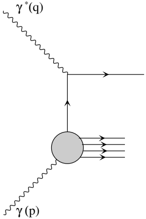
with $x = Q^2/(Q^2 + W^2)$. Its $Q^2 = 0$ (for fixed W) limit of gives the total cross-section $\sigma_{\gamma\gamma}(W^2)$ corresponding to the interaction of two real photons:

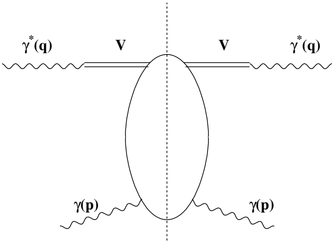
$$\sigma_{\gamma\gamma}(W) = \alpha\pi \sum_{V=\rho,\omega,\phi} \frac{\sigma_{V\gamma}(W^2)}{\gamma_V^2} + \frac{4\pi^2\alpha}{Q_0^2} F_2^{\rm QCD}(Q_0^2/W^2, Q_0^2). \tag{4}$$

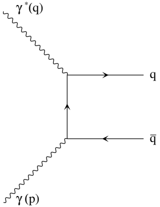
- Data on $\sigma_{\gamma\gamma}(W)$ and on $\sigma_{\gamma^*\gamma}(W, Q^2)$ and on F_2^γ at low Q^2 are fairly well reproduced.
- Natural explanation of the fact that the increase of the total $\gamma\gamma$ cross-section with increasing CM energy W is stronger than that implied by soft Pomeron exchange: the latter describes the VMD part ($W^{2\lambda}$, λ=0.0808) while the partonic component increases faster with energy ($F_2^{\rm QCD}(\bar{x}, Q^2)$ increase with decreasing $\bar{x}$ from the QCD evolution).
- $\sigma_{\gamma\gamma}(W) \sim (W^2)^{\lambda_{eff}}$ with λ_{eff} slowly increasing with energy: $\lambda_{eff} \sim 0.1 - 0.12$ for 30 GeV $< W < 10^3$ GeV.

F_2^γ in the low Q^2, low x region (Badelek, Krawczyk, Kwiecinski, Stasto, Phys.Rev. D62 (2000) 074021) ...cont'd









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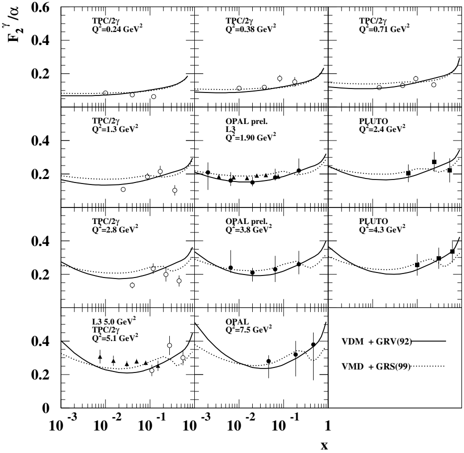

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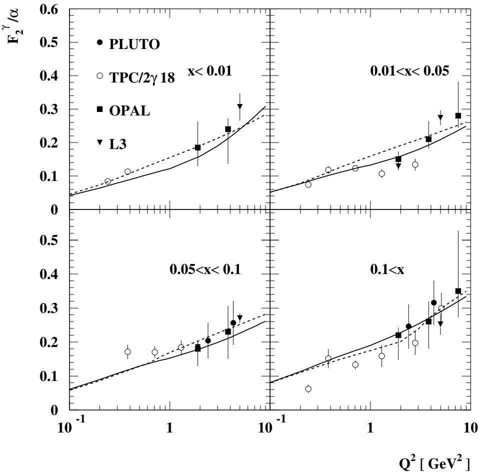

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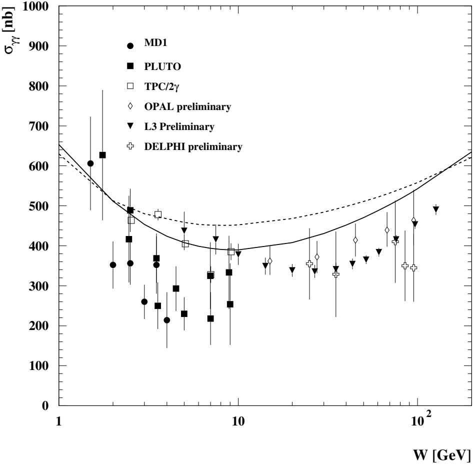

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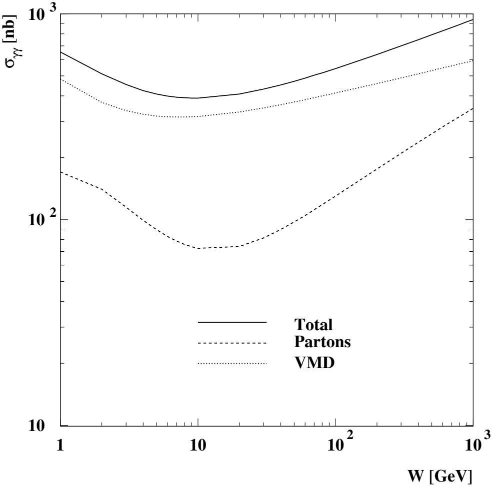

Outline

Summary

- R and F_L poorly measured – especially at low Q^2
- Only one dynamical parametrization of the transition region exists: BKS
- Only one data fit exists: R1999 (SLAC).
- Plans to measure F_L at low x at HERA.