Measurements of the QED Structure of the Photon

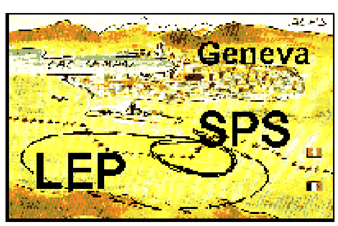
Richard Nisius (CERN) April,22 ’99

- Introduction

1. The Structure Function $F^{\gamma}_{2,\mathrm{QED}}$
2. Azimuthal Correlations

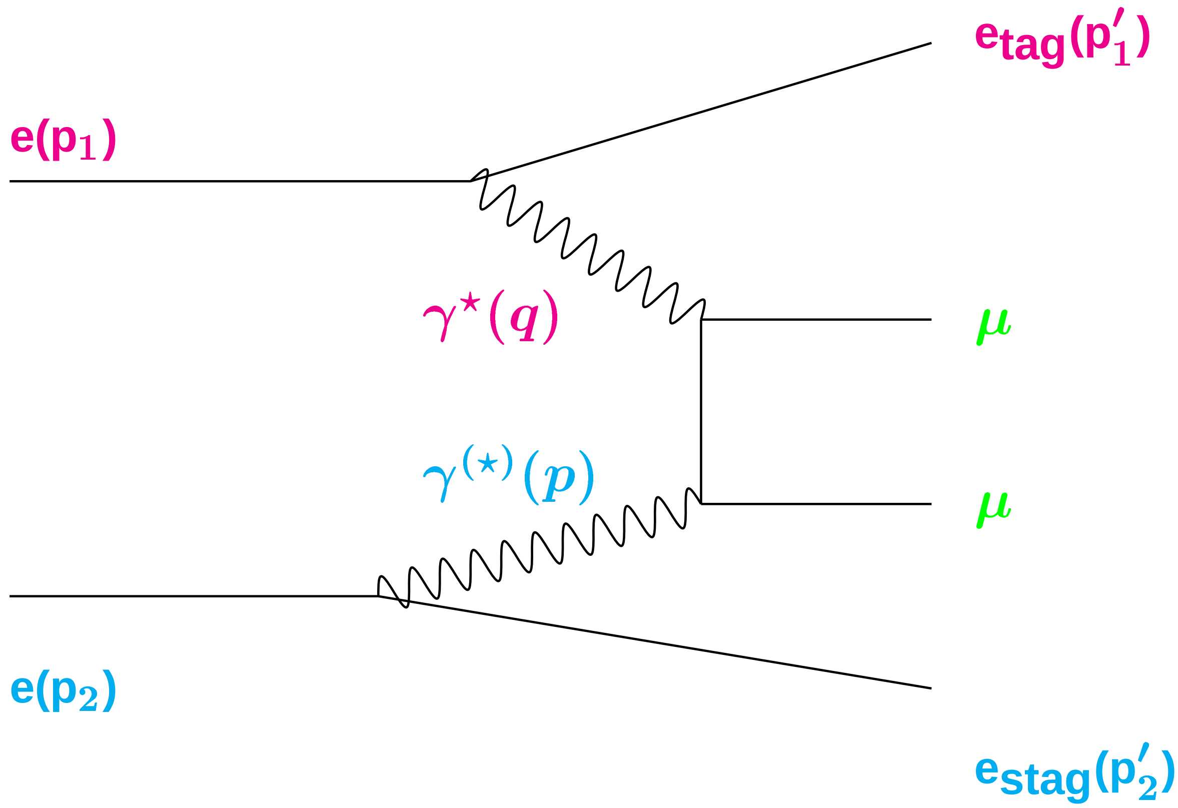
- Conclusions

For the



Collaborations

The production of lepton pairs



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

$$y = 1 - \frac{E_{tag}}{E_b}\cos^2\left(\frac{\theta_{tag}}{2}\right) \ll 1$$

$$Q^2 = 2\,E_b\,E_{tag}\,(1-\cos\theta_{tag})$$

$$P^2 = 2\,E_b\,E_{stag}\,(1-\cos\theta_{stag})$$

$$x = \frac{Q^2}{Q^2+W^2+P^2}$$

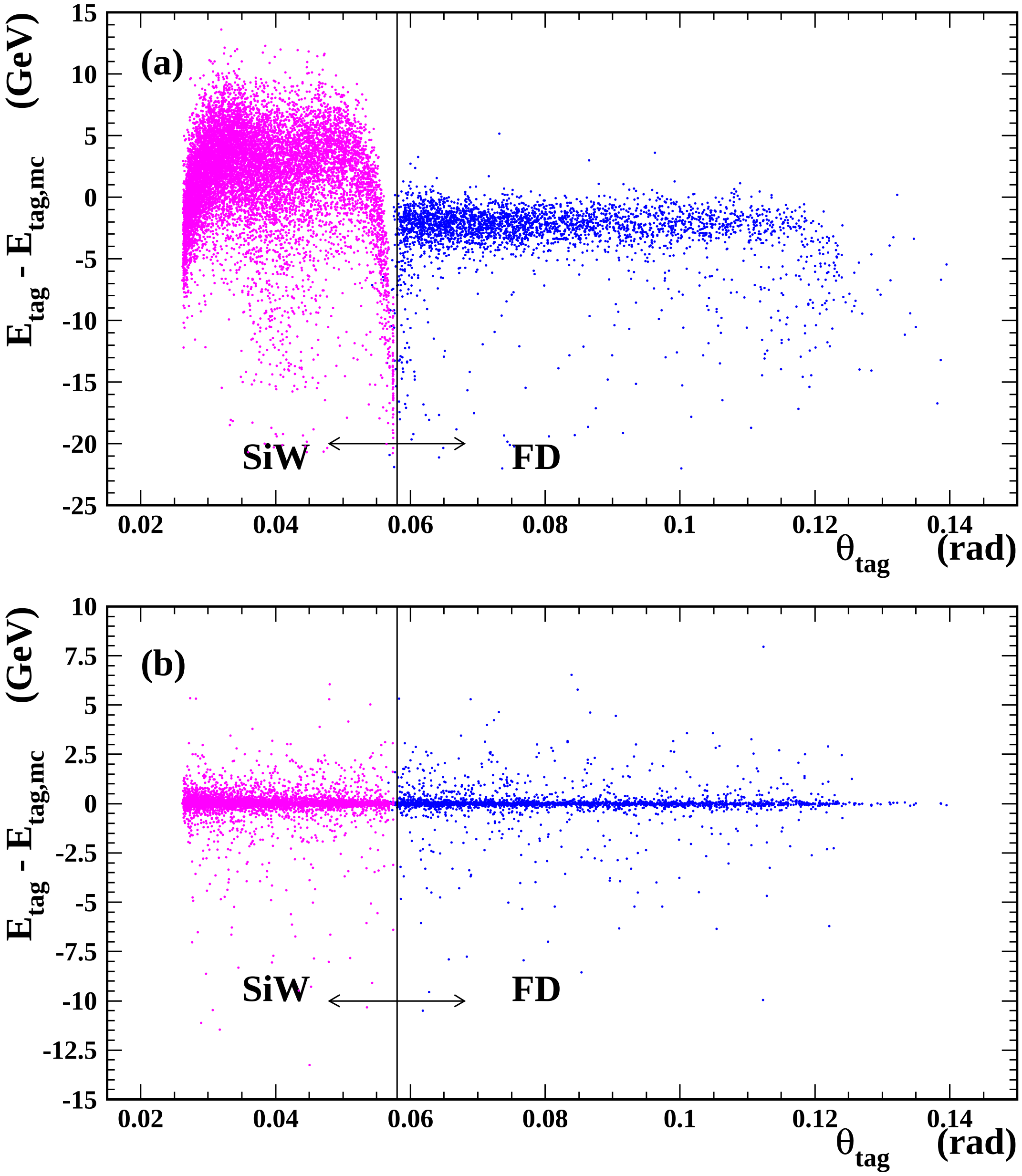
$\Rightarrow$**QED is a well suited to study the photon structure.**
The cross section is mainly sensitive to F_2^γ.

The formalism used for single tags

$$
\begin{aligned}
\mathrm{d}^6\sigma &= \mathrm{d}^6\sigma(\mathrm{ee} \to \mathrm{ee}\, X) \\
&= \frac{\mathrm{d}^3 p_1' \mathrm{d}^3 p_2'}{E_1' E_2'} \frac{\alpha^2}{16\pi^4 q^2 p^2} \left[\frac{(q \cdot p)^2 - q^2 p^2}{(p_1 \cdot p_2)^2 - m_\mathrm{e}^2 m_\mathrm{e}^2} \right]^{1/2} \cdot \\
&\quad \Big(4\rho_1^{++}\rho_2^{++}\sigma_\mathrm{TT} + 2|\rho_1^{+-}\rho_2^{+-}|\tau_\mathrm{TT}\cos 2\bar{\phi} + 2\rho_1^{++}\rho_2^{00}\sigma_\mathrm{TL} + \\
&\quad 2\rho_1^{00}\rho_2^{++}\sigma_\mathrm{LT} + \rho_1^{00}\rho_2^{00}\sigma_\mathrm{LL} - 8|\rho_1^{+0}\rho_2^{+0}|\tau_\mathrm{TL}\cos\bar{\phi} \Big)
\end{aligned}
$$

$$
\begin{aligned}
2xF_1^\gamma &= \frac{-q^2}{4\pi^2\alpha} \frac{\sqrt{(q \cdot p)^2 - q^2 p^2}}{q \cdot p} \left(\sigma_\mathrm{TT}(x, q^2, p^2) - \frac{1}{2}\sigma_\mathrm{TL}(x, q^2, p^2) \right) \\
F_2^\gamma &= \frac{-q^2}{4\pi^2\alpha} \frac{q \cdot p}{\sqrt{(q \cdot p)^2 - q^2 p^2}} \Big(\sigma_\mathrm{TT}(x, q^2, p^2) + \sigma_\mathrm{LT}(x, q^2, p^2) \\
&\quad - \frac{1}{2}\sigma_\mathrm{LL}(x, q^2, p^2) - \frac{1}{2}\sigma_\mathrm{TL}(x, q^2, p^2) \Big) \\
F_\mathrm{L}^\gamma &= F_2^\gamma - 2xF_1^\gamma
\end{aligned}
$$

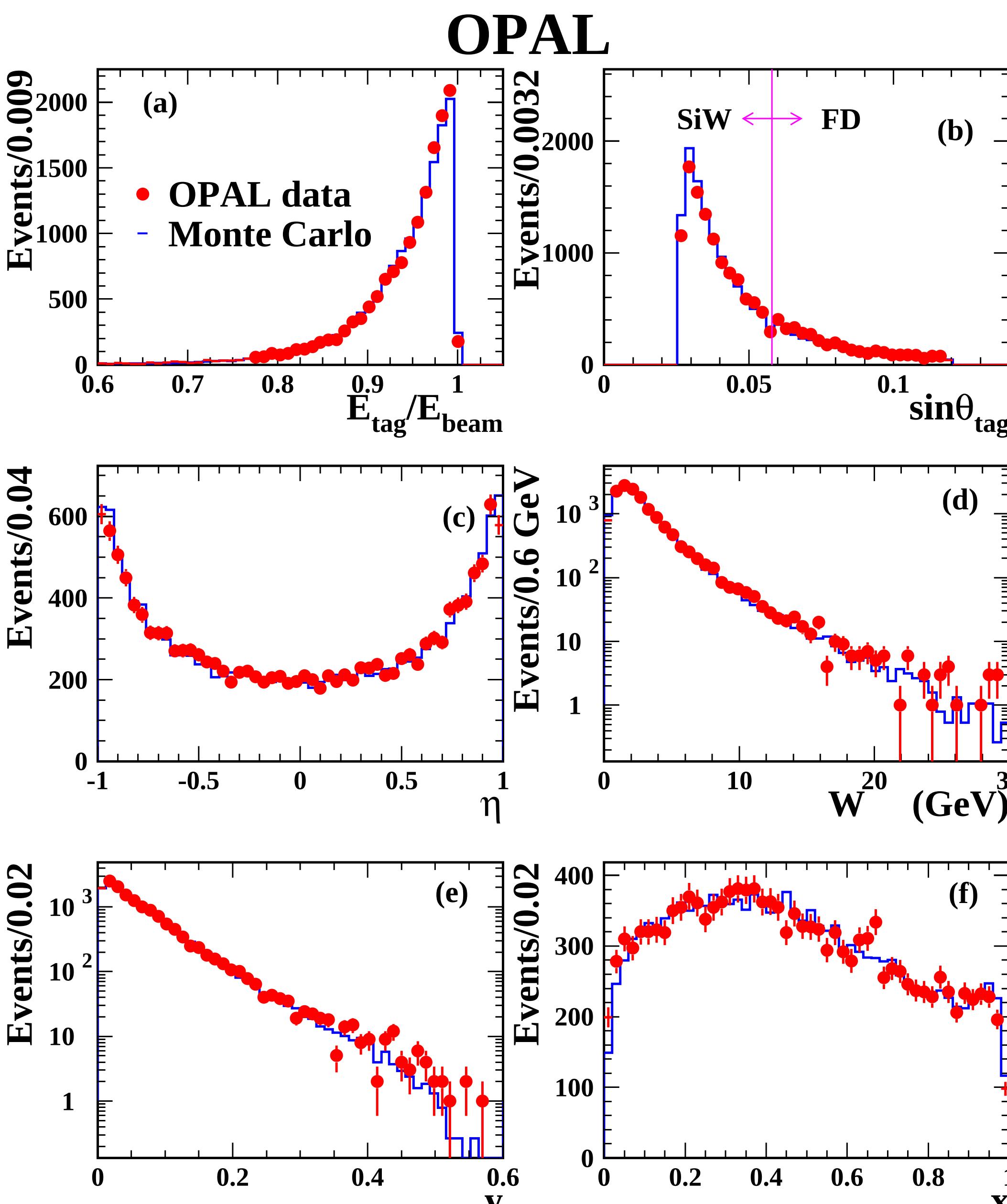
$E_{\rm tag}$ obtained from the μ- pair



$$E_{\rm tag} = \frac{P_{\mu\mu} \cos\theta_{\mu\mu} + (2E_{\rm b} - E_{\mu\mu}) \cos\theta_{\rm stag}}{\cos\theta_{\rm stag} - \cos\theta_{\rm tag}}$$

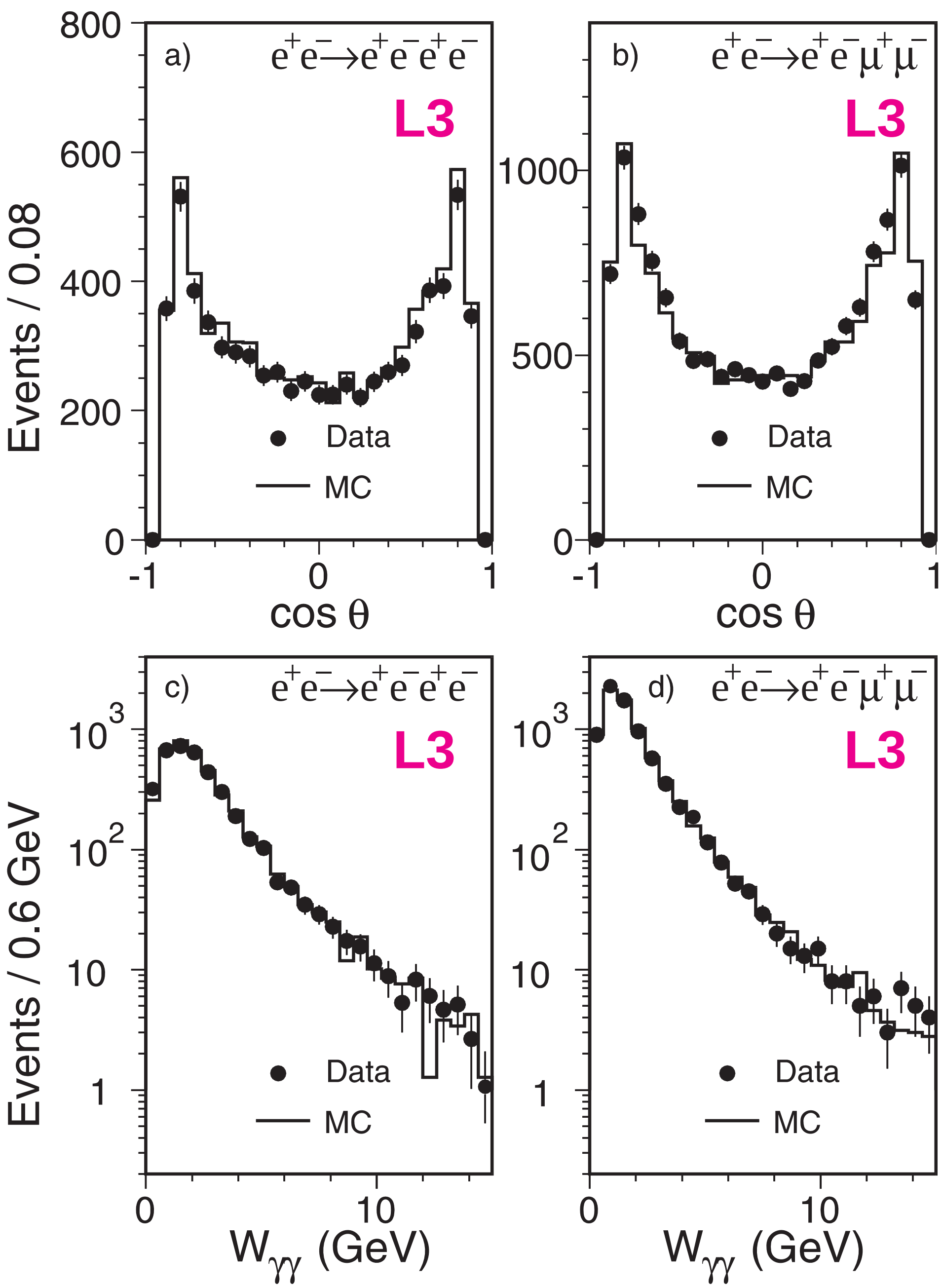
For single tags assume $\theta_{\rm stag} = 0, \pi$.

The data description for $1.5 < Q^2 < 7.0\,\mathrm{GeV}^2$



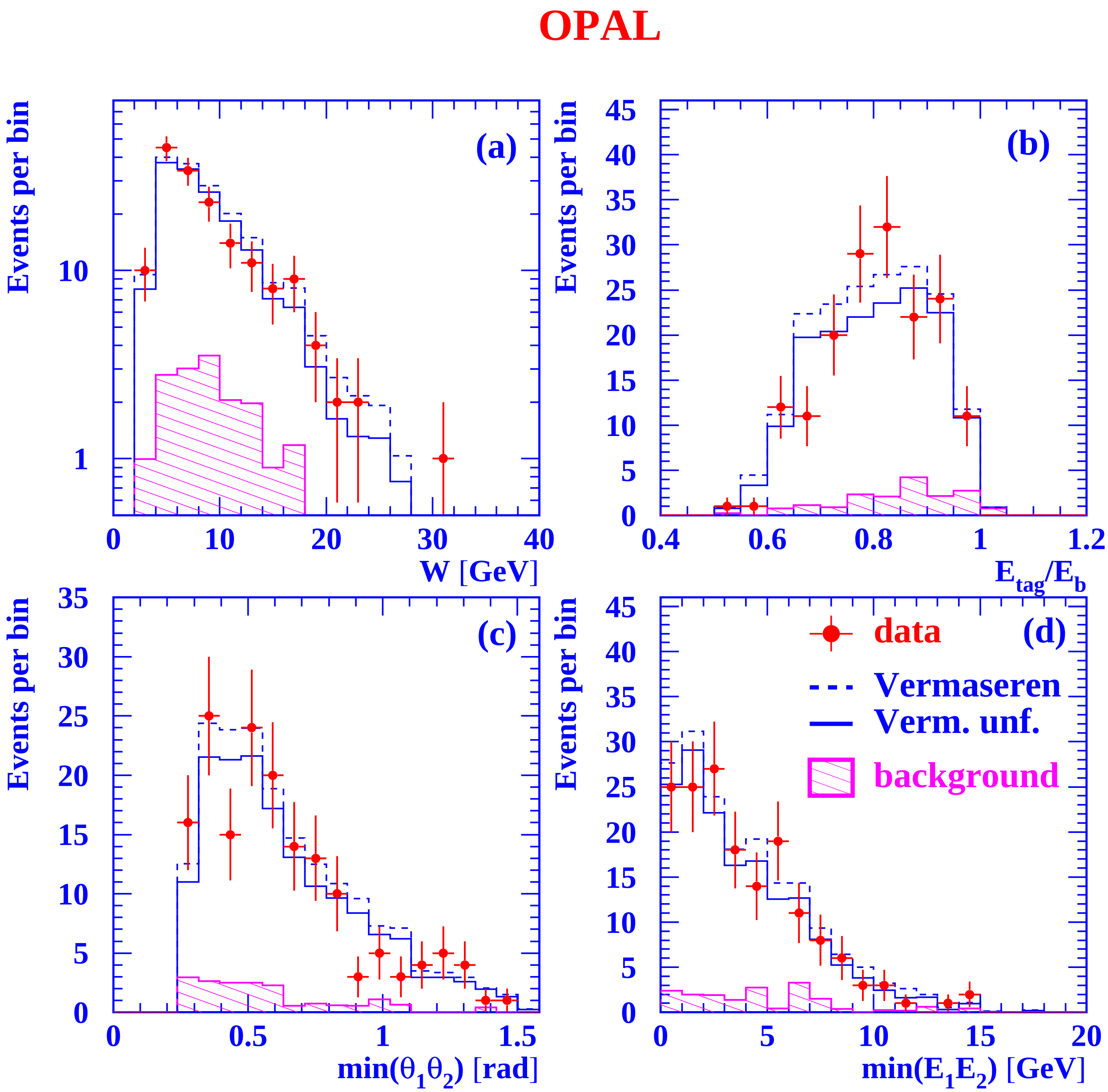
The data are well described by the Vermaseren MC.

The data description for
$1.4 < Q^2 < 7.6\ \mathrm{GeV}^2$



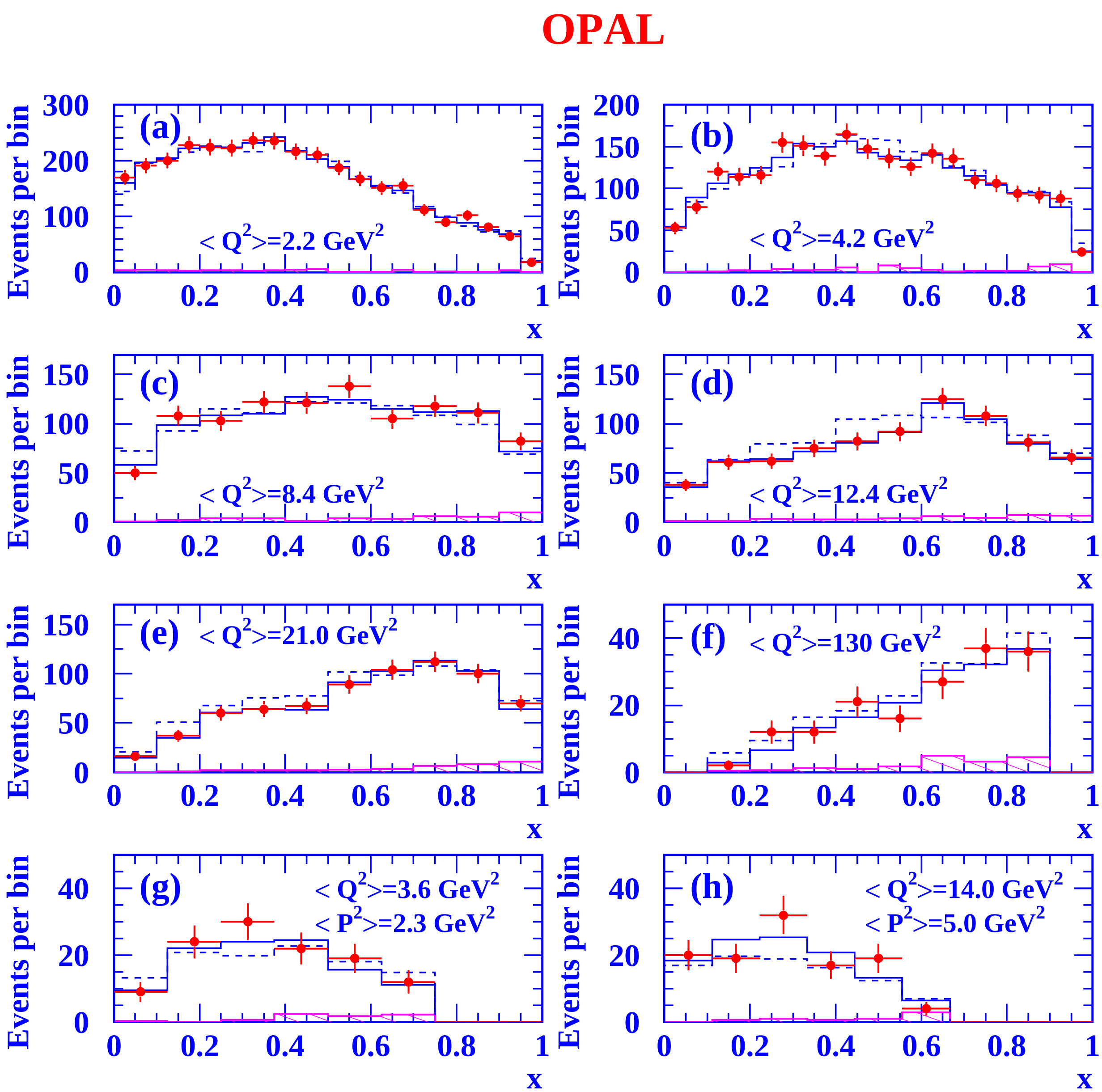
The data are well described by the Vermaseren MC.

The data description for $70 < Q^2 < 400\ \mathrm{GeV}^2$



The background is still small, and within statistics the data are well described by the Vermaseren MC.

The x distributions



The QED predictions agree well with the data over a large range in photon virtualities.

The general analysis strategy

Measurement of $\mathrm{d}\sigma/\mathrm{d}x$ and $F_{2,\mathrm{QED}}^{\gamma}$

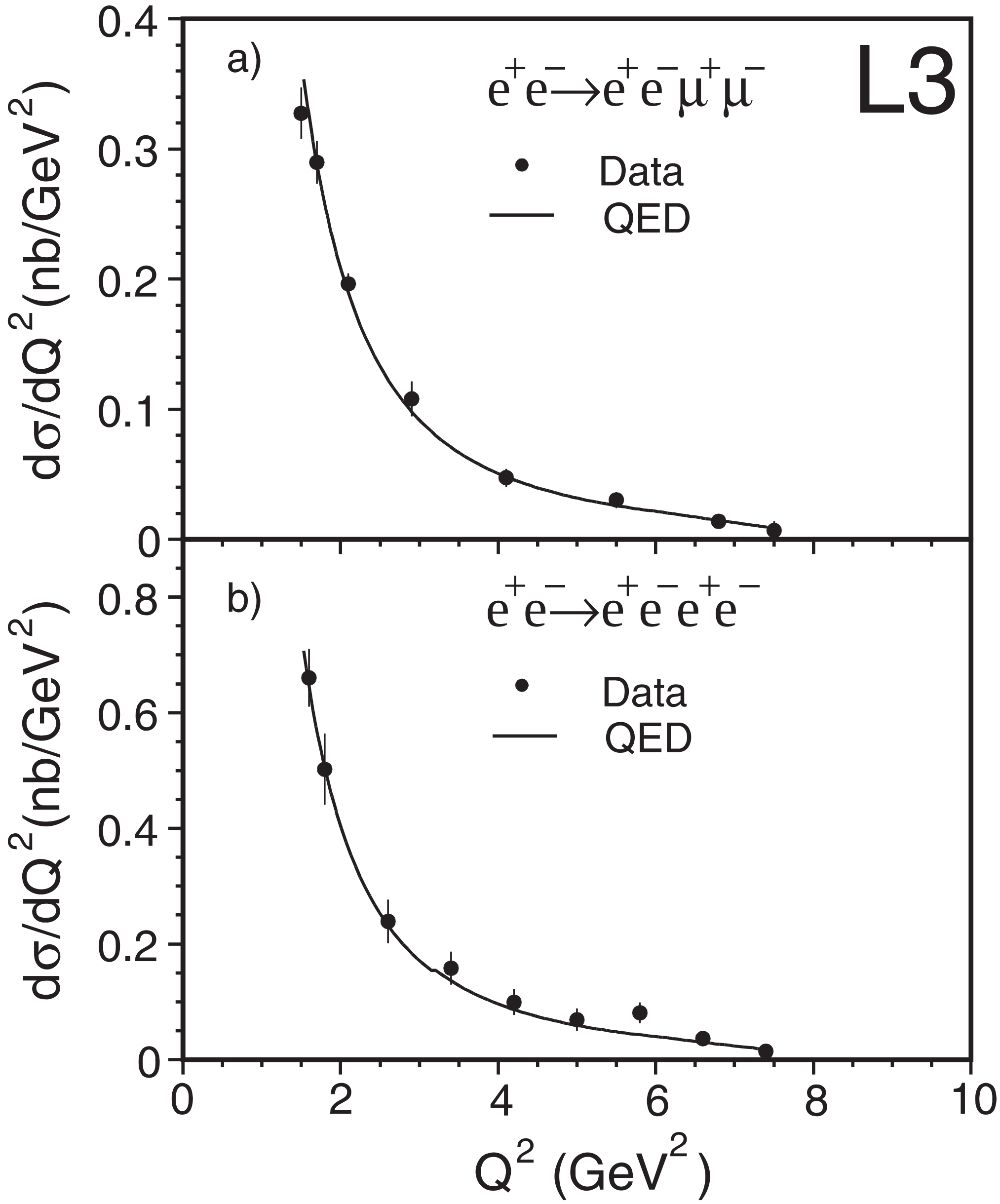
1. Determine $\mathrm{d}\sigma/\mathrm{d}x$ and the average $F_{2,\mathrm{QED}}^{\gamma}$ in bins of x by the unfolding of the measured x distribution for a specific $\langle Q^2\rangle$.
2. Correct for trigger inefficiency, bin size effect and radiative effects and compare to theory.
3. Sys. errors (muon kinematics $p_{\mathrm{t},\mu}$, ϕ_μ, θ_μ, electron kinematics E_{tag}, θ_{tag}, E_{stag}, θ_{stag}, trigger efficiency, radiative corrections.) $\Rightarrow$ At LEP the measurement is mostly limited by the stat. errors and the background contributions are small.

Measurement of F_{A}^{γ} and F_{B}^{γ}

1. Fit to: $1 + F_{\mathrm{A}}^{\gamma}/F_2^{\gamma}\cos\chi + \frac{1}{2}F_{\mathrm{B}}^{\gamma}/F_2^{\gamma}\cos 2\chi$
2. Correct for bin size effect and compare to theory.
3. Sys errors (as above + fit error).
4. Determine F_2^{γ} as detailed above and multiply to obtain F_{A}^{γ} and F_{B}^{γ}.

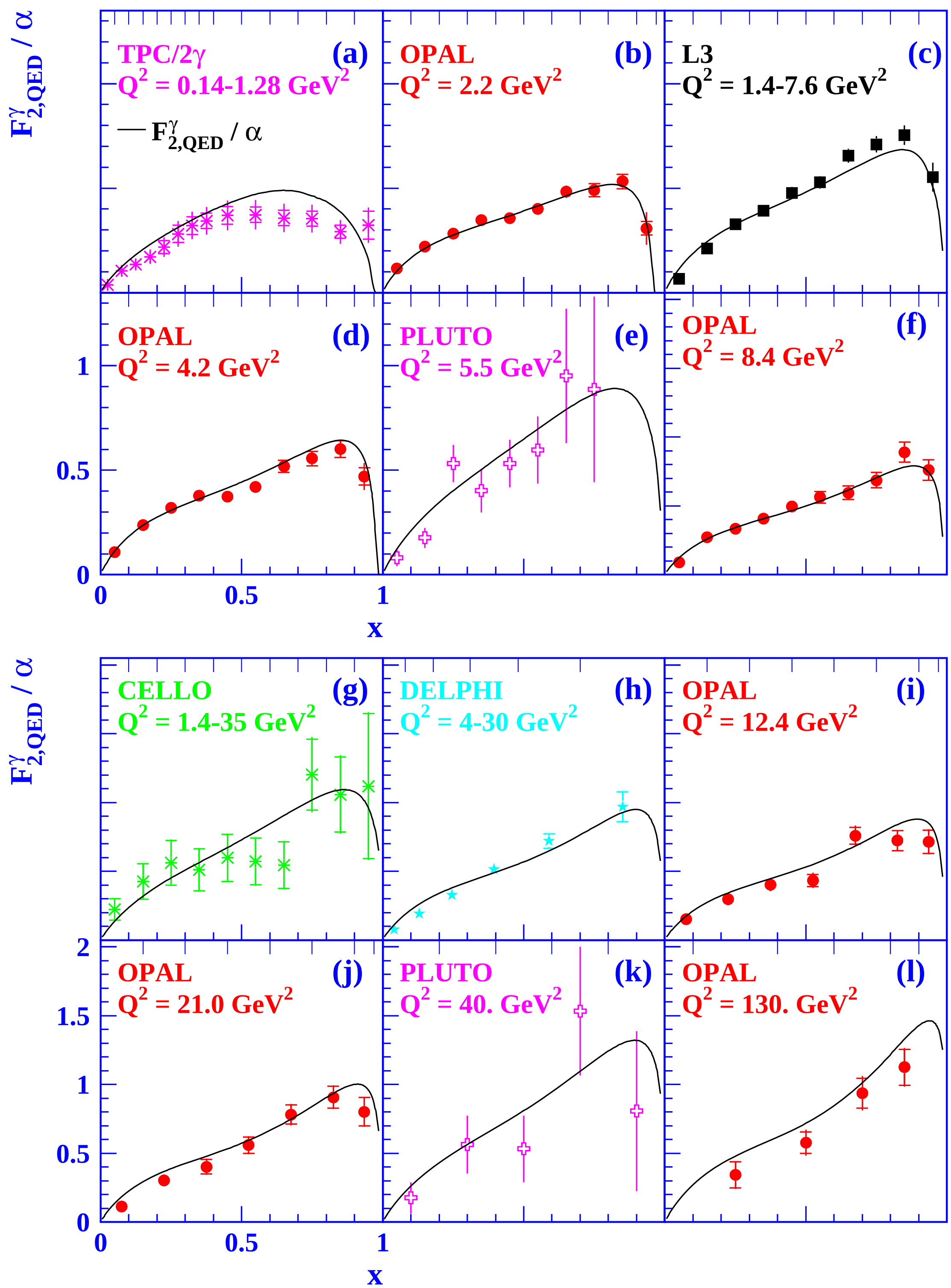
The experiments slightly differ in their procedures.

The differential cross-section as a function of Q^2

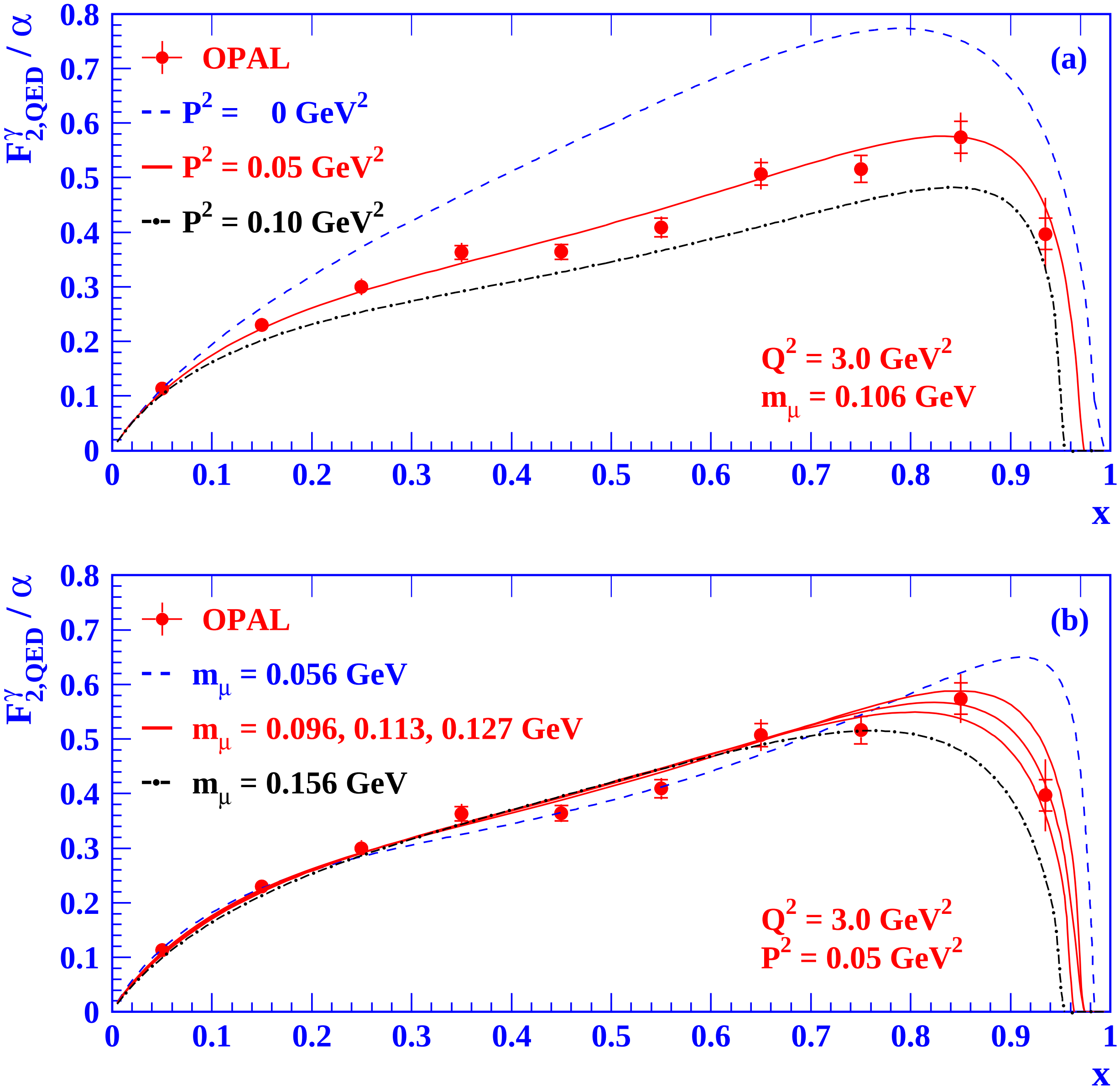


The QED cross-sections agree well for electron as well asfor muon pairs.

The world data on $F_{2,\mathrm{QED}}^{\gamma}$

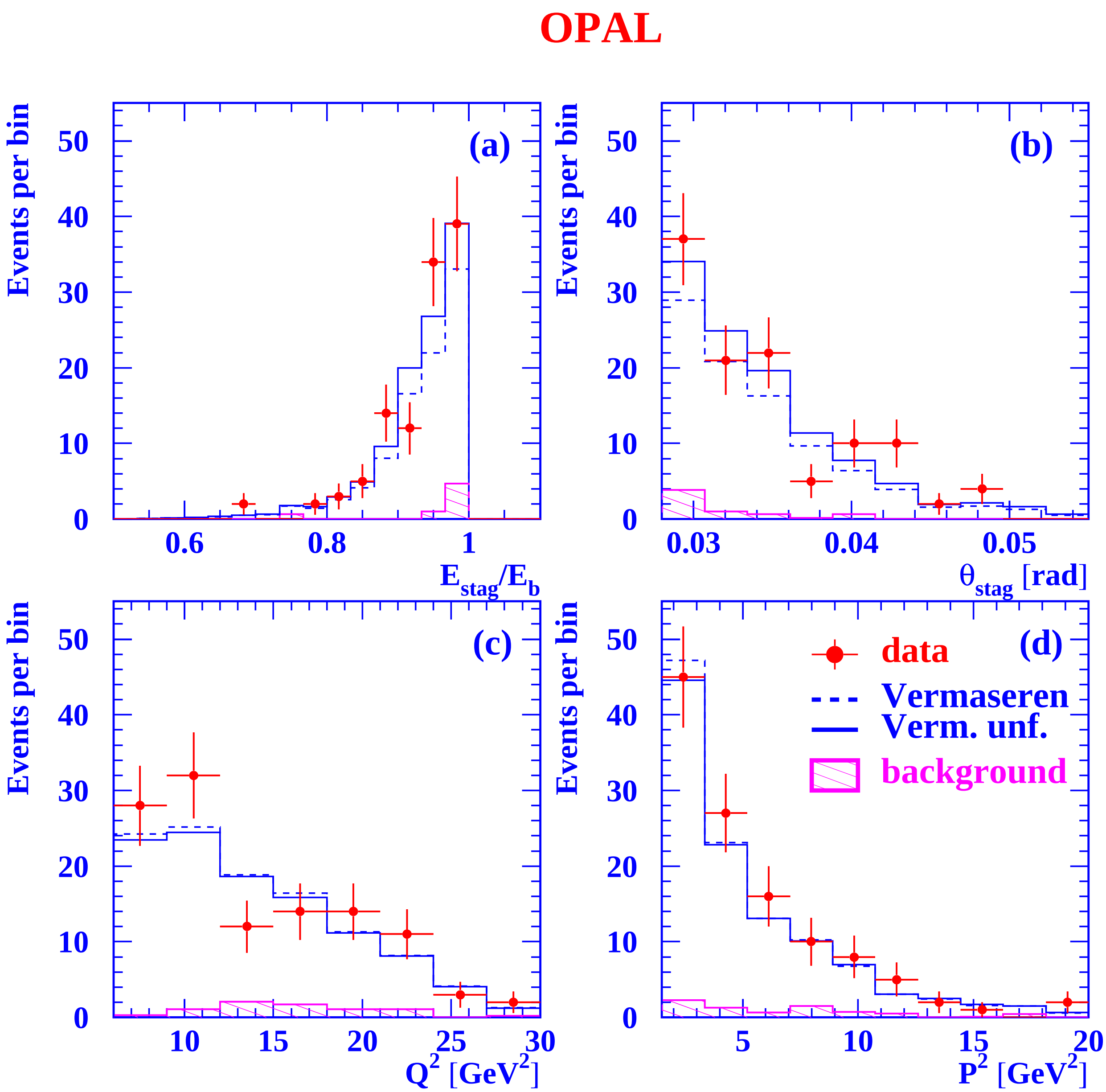


The dependence of F_2^γ on P^2 and m_μ



The P^2 dependence is clearly observed in the data.
The muon mass can be determined to about $\pm 15\%$.

Data description for double tags

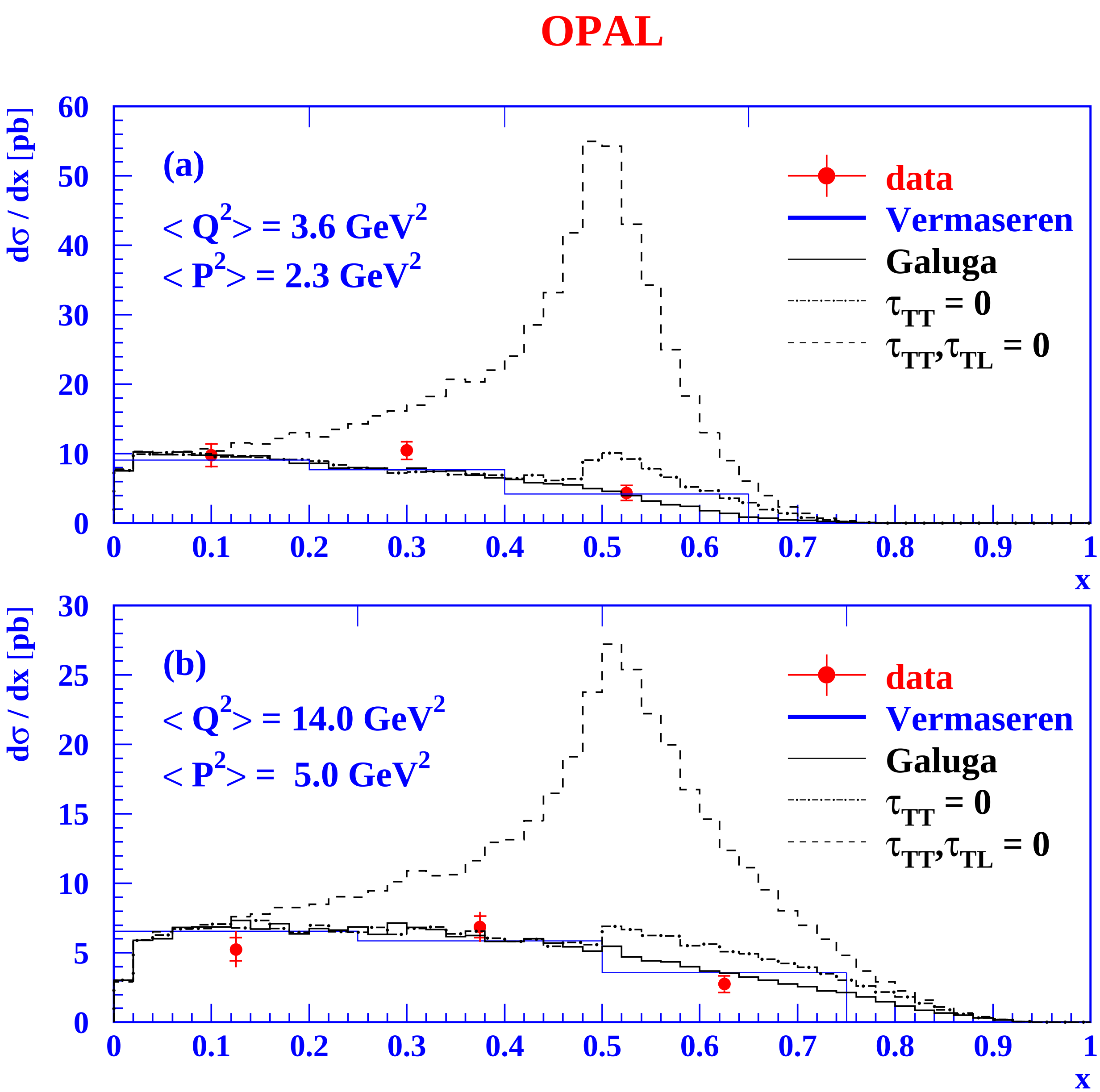


This is the first quantitative measurement of double tagged muon-pair events.

The formalism used for double tags

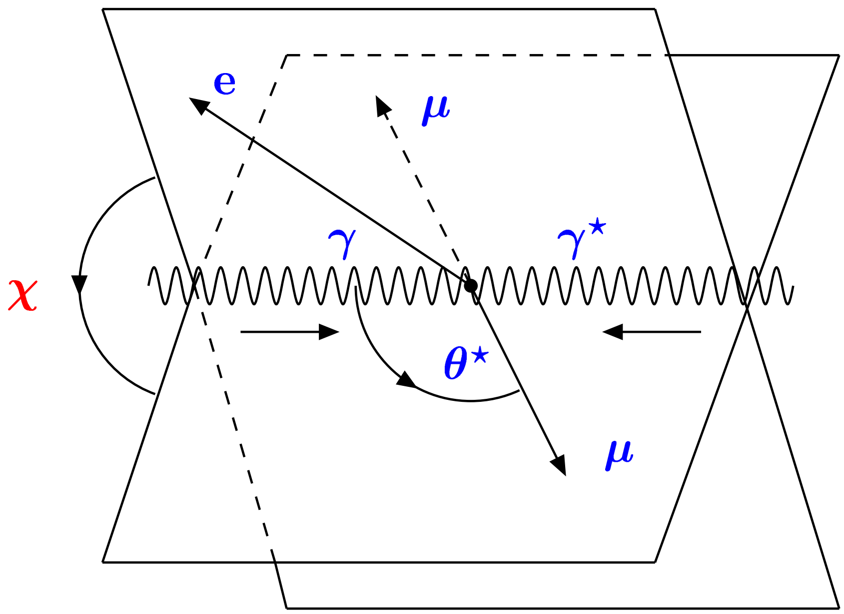
$$\mathrm{d}^6\sigma = \frac{\mathrm{d}^3\mathrm{p}_1'\mathrm{d}^3\mathrm{p}_2'}{E_1' E_2'} \frac{\alpha^2}{16\pi^4 q^2 p^2} \left[\frac{(q\cdot p)^2 - q^2 p^2}{(p_1\cdot p_2)^2 - m_\mathrm{e}^2 m_\mathrm{e}^2}\right]^{1/2} 4\rho_1^{++}\rho_2^{++} \cdot \left(\sigma_\mathrm{TT} + \sigma_\mathrm{TL} + \sigma_\mathrm{LT} + \sigma_\mathrm{LL} + \frac{1}{2}\tau_\mathrm{TT}\cos 2\bar{\phi} - 4\tau_\mathrm{TL}\cos\bar{\phi}\right)$$

The cross section for double tags



QED agrees well with the data and the interference terms are clearly observed for the first time.

Azimuthal Correlations



$$\mathbf{e}\gamma \rightarrow \mathbf{e}\mu\mu$$

$$d\sigma \quad \propto \quad 1 - \rho(y) F_A^\gamma / F_2^\gamma \cos\chi + \frac{1}{2}\epsilon(y) F_B^\gamma / F_2^\gamma \cos 2\chi$$

$$\epsilon(y) = \frac{2(1-y)}{1+(1-y)^2} \approx 1, \;\; \rho(y) = \frac{(2-y)\sqrt{1-y}}{1+(1-y)^2} \approx 1$$

The χ dependence gives access to other structure functions besides F_2^γ.

The functional form of $F_{\rm A}^{\gamma}$ and $F_{\rm B}^{\gamma}$

$$F_{\rm A}^{\gamma}(x,\beta) = \frac{4\alpha}{\pi} x\sqrt{x(1-x)}\,(1-2x)\left\{\beta\left[1+(1-\beta^2)\frac{1-x}{1-2x}\right] + \frac{3x-2}{1-2x}\sqrt{1-\beta^2}\arccos\left(\sqrt{1-\beta^2}\right)\right\}$$

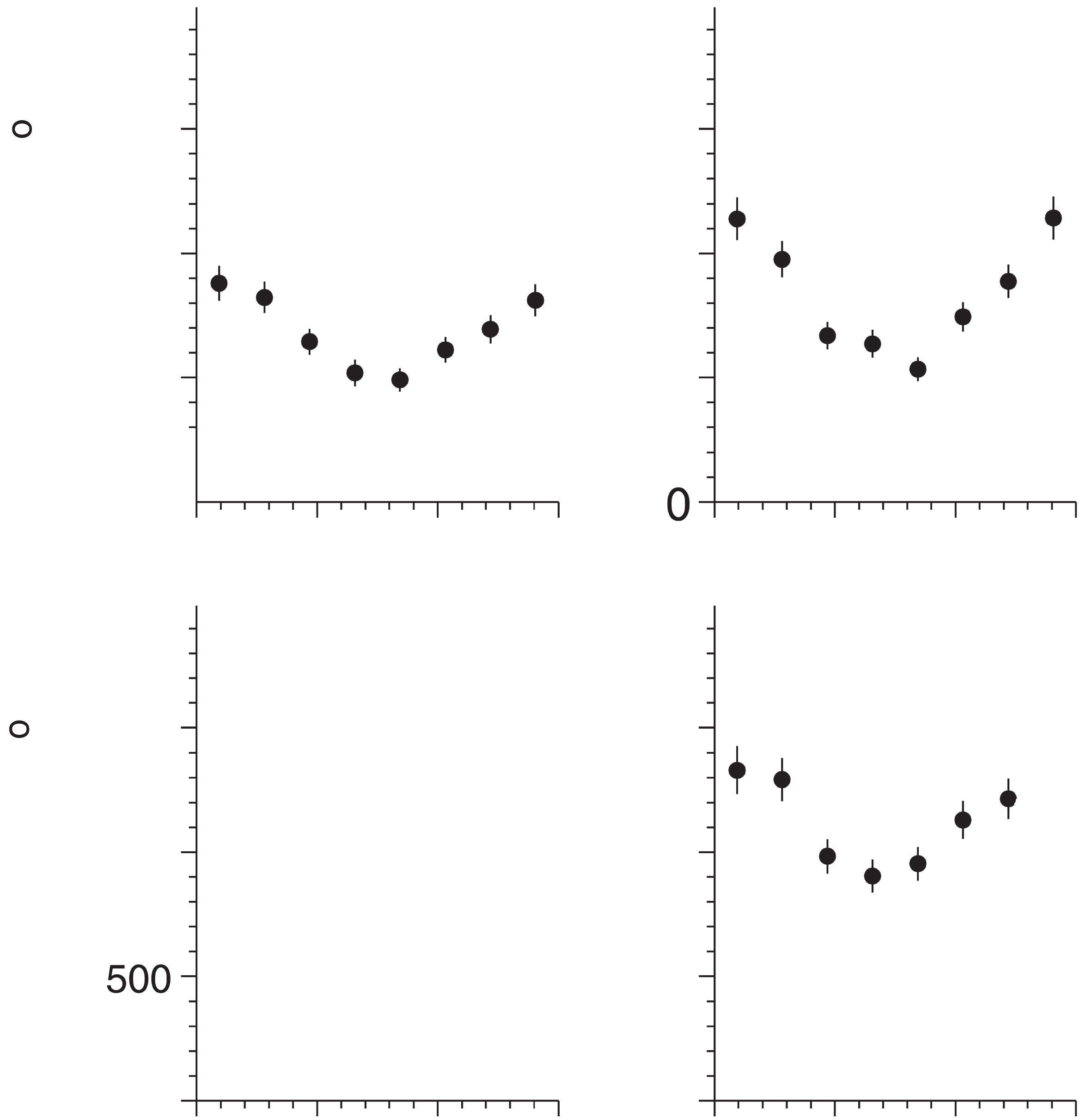
$$F_{\rm B}^{\gamma}(x,\beta) = \frac{4\alpha}{\pi} x^2(1-x)\left\{\beta\left[1-(1-\beta^2)\frac{1-x}{2x}\right] + \frac{1}{2}(1-\beta^2)\left[\frac{1-2x}{x} - \frac{1-x}{2x}(1-\beta^2)\right]\log\left(\frac{1+\beta}{1-\beta}\right)\right\}$$

$$F_{2}^{\gamma}(x,\beta) = \frac{\alpha}{\pi} x\left\{\left[x^2+(1-x)^2\right]\log\left(\frac{1+\beta}{1-\beta}\right) - \beta + 8\beta x(1-x) - \beta(1-\beta^2)(1-x)^2 + (1-\beta^2)(1-x)\left[\frac{1}{2}(1-x)(1+\beta^2) - 2x\right]\log\left(\frac{1+\beta}{1-\beta}\right)\right\}$$

$$\beta = \sqrt{1-\frac{4m_\mu^2}{W^2}},$$

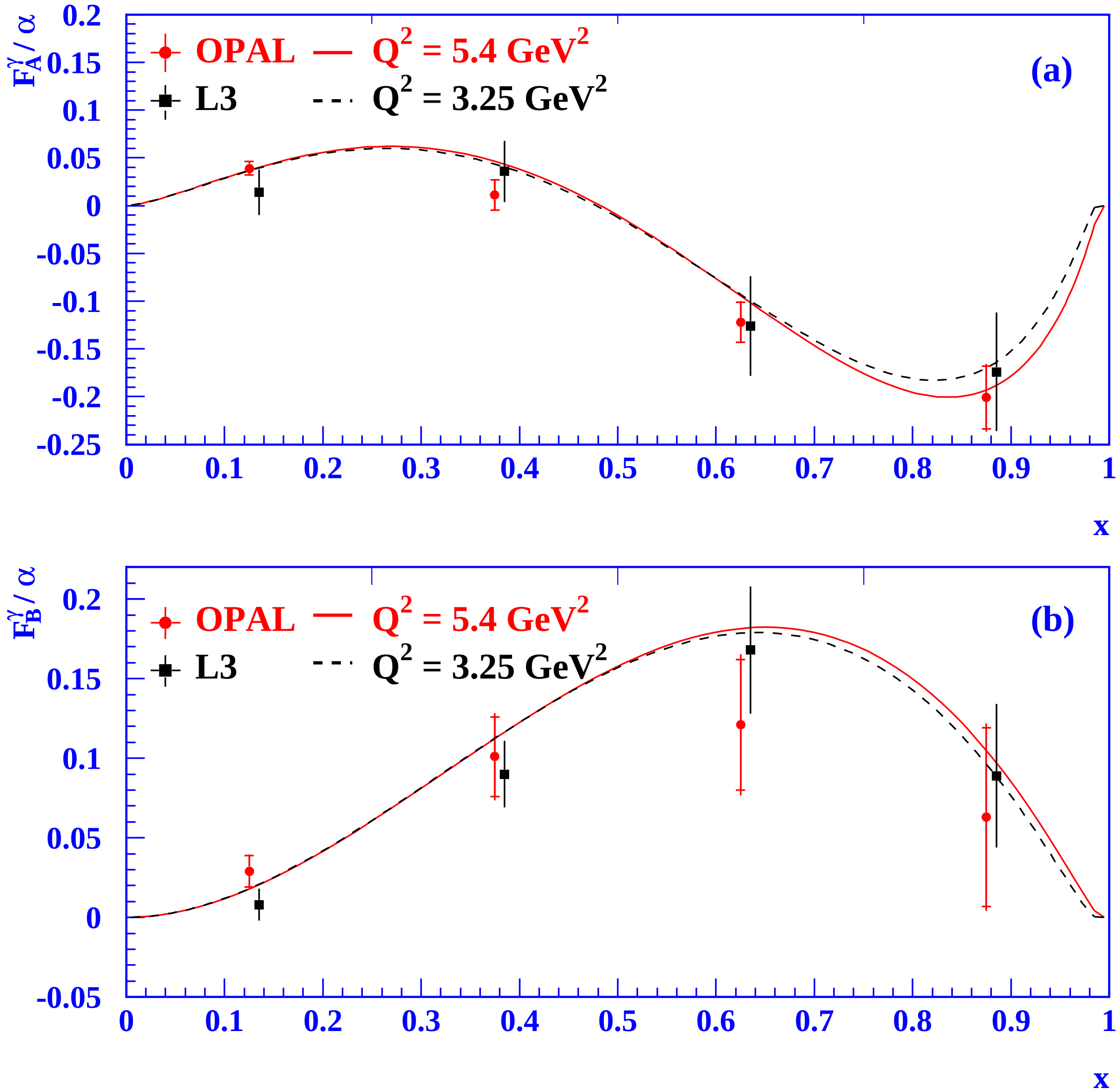
(leading log $\beta \to 1$)

The χ distribution



The structure functions

F_A^γ and F_B^γ



First measurement that goes further than measuring the differential cross-section.

Conclusions

1. The structure function $F_{2,\mathrm{QED}}^{\gamma}$ for singly-tagged events has been measured in a large kinematical range, $1.5 < Q^2 < 400\ \mathrm{GeV}^2$. The effect of the small virtuality of the quasi-real photon P^2 can be experimentally established.

2. The differential cross section $\mathrm{d}\sigma/\mathrm{d}x$ for doubly-tagged events has been measured for $1.5 < P^2, Q^2 < 20, 30\ \mathrm{GeV}^2$. The contributions from the interference terms are clearly seen in the data.

3. The structure functions F_{A}^{γ} and F_{B}^{γ} are measured using the improved theoretical calculations. These structure functions give additional insight into the helicity structure of the photon-photon interaction

The QED predictions are in good agreement with the data.

Slides: http://home.cern.ch/~nisius