The Hadronic Structure of $\gamma^*\gamma^*$ Interactions at LEP

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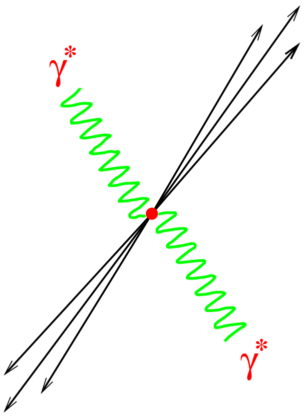
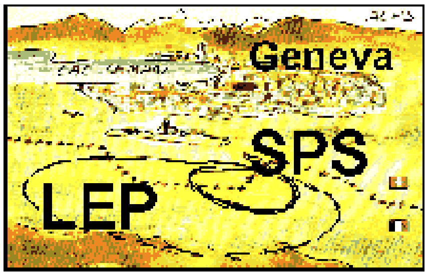
For the

LEP Collaborations



EPS HEP '99



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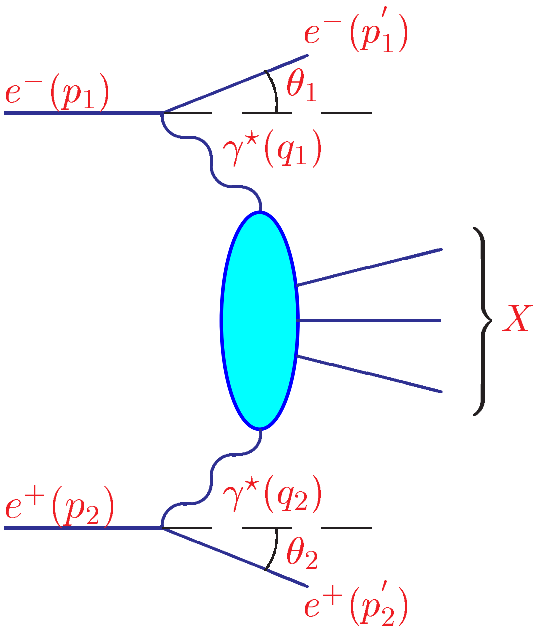
1. Introduction

- **Kinematics and cross-sections**



$$Q_i^2 = -q_i^2 = -(p_i - p_i^{'})^2 \quad (Q^2, P^2)$$

$$x_1 = \frac{Q_1^2}{2q_1q_2} \qquad x_2 = \frac{Q_2^2}{2q_2q_1}$$

$$y_1 = \frac{q_1q_2}{p_1q_2} \qquad y_2 = \frac{q_2q_1}{p_2q_1}$$

$$s = (p_1 + p_2)^2 \qquad W^2 = (q_1 + q_2)^2$$

$$Y = \ln\left(\frac{W^2}{\sqrt{Q_1^2Q_2^2}}\right)$$

Cross-section for the process $e(p_1)e(p_2) \to e(p_1^{'})e(p_2^{'})X$ which proceeds via the exchange of two virtual photons, $\gamma^*(q_1)$ and $\gamma^*(q_1)$:

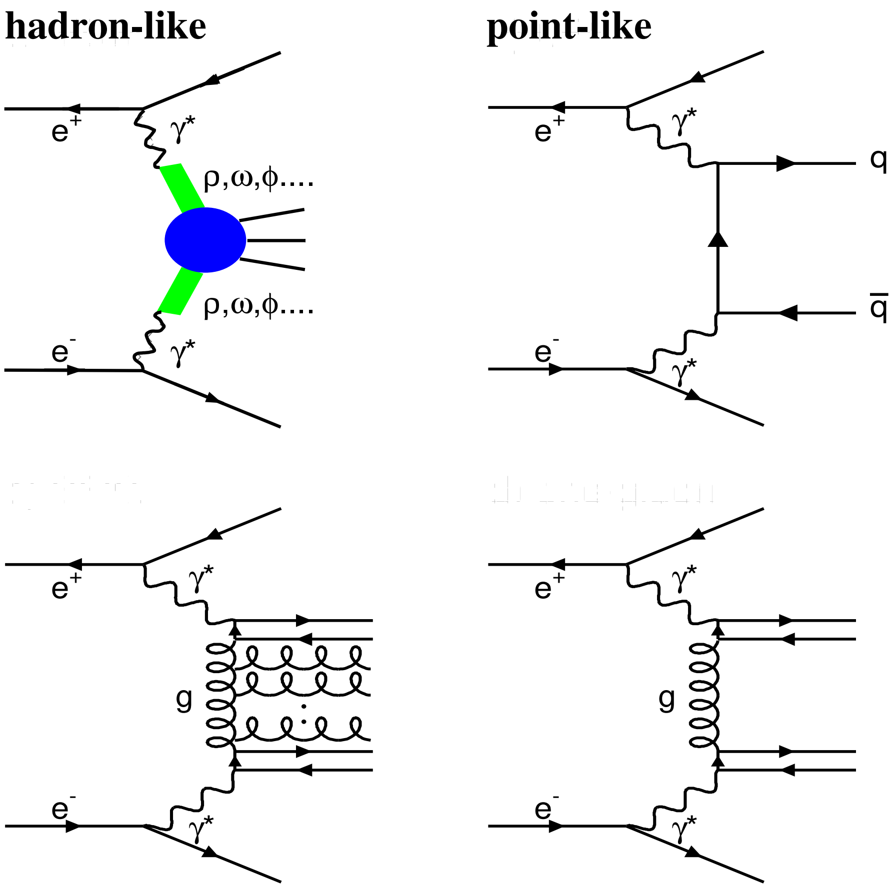
$$\mathrm{d}^6\sigma = \frac{\mathrm{d}^3\mathrm{p}_1^{\prime}\mathrm{d}^3\mathrm{p}_2^{\prime}}{E_1^{\prime}E_2^{\prime}}\frac{\alpha^2}{16\pi^4q_1^2q_2^2}\left[\frac{(q_1\cdot q_2)^2 - q_1^2q_2^2}{(p_1\cdot p_2)^2 - m_\mathrm{e}^2m_\mathrm{e}^2}\right]^{1/2} 4\rho_1^{++}\rho_2^{++}\cdot$$
$$\Big(\sigma_{\mathrm{TT}}+\epsilon_1\sigma_{\mathrm{LT}}+\epsilon_2\sigma_{\mathrm{TL}}+\epsilon_1\epsilon_2\sigma_{\mathrm{LL}}+$$
$$\frac{1}{2}\epsilon_1\epsilon_2\tau_{\mathrm{TT}}\cos 2\bar{\phi}-2\sqrt{\epsilon_1(1+\epsilon_1)}\sqrt{\epsilon_2(1+\epsilon_2)}\tau_{\mathrm{TL}}\cos\bar{\phi}\Big)$$

Effective Structure function of virtual photons: $Q^2 \gg P^2 \gg \Lambda^2$

$$F_{\mathrm{eff}}^{\gamma} \propto \sigma_{\mathrm{TT}}+\sigma_{\mathrm{LT}}+\sigma_{\mathrm{TL}}+\sigma_{\mathrm{LL}}+\frac{1}{2}\tau_{\mathrm{TT}}\cos 2\bar{\phi} - 4\tau_{\mathrm{TL}}\cos\bar{\phi}$$

• $\gamma^*\gamma^*$ physics

Underlying processes for $\gamma^*\gamma^* \to$ hadrons:



$\Rightarrow$ Alternative QCD approach: BFKL calc. of $\sigma_{\gamma^*\gamma^*}$ $(Q_1^2 \simeq Q_2^2, W^2 \gg Q_1^2, Q_2^2)$

$$\sigma_{\gamma^*\gamma^*} = \sigma_0(Q_1^2, Q_2^2, Y)\left(\frac{s}{s_0}\right)^{\alpha_P - 1} = \sigma_0(Q_1^2, Q_2^2, Y)e^{Y\cdot(\alpha_P - 1)}$$

In LO, $\alpha_P - 1 = (4\ln 2)N_c\alpha_s/\pi \simeq 0.53$ with $N_c = 3$ and $\alpha_s = 0.2$!

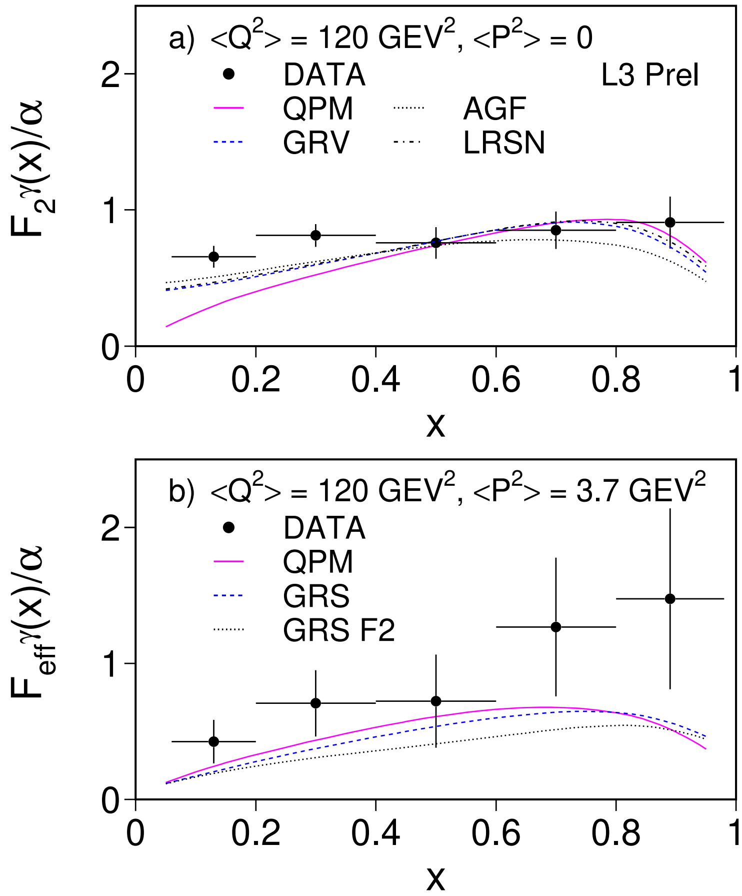
NLO corrections are expected to be large ($\to$ reduce α_P)!

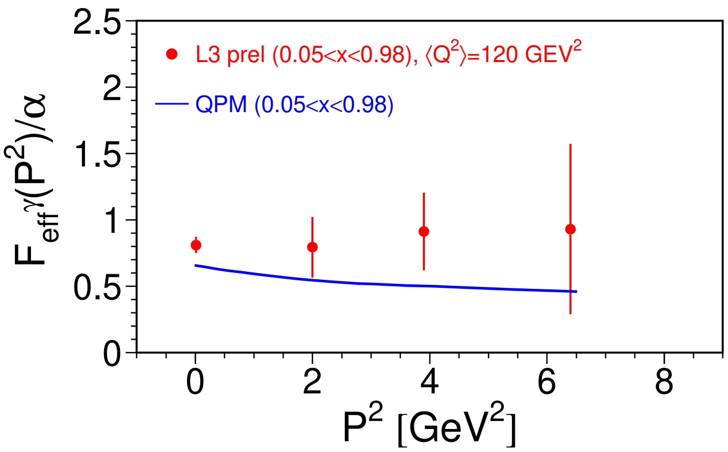
Phenomenological determination of higher order (HO) effects!

(S.J. Brodsky et al., J. Bartels et al., M. Boonekamp, A. deRoeck, C. Royon and S. Wallon)

2.1 Virtual photon structure function $F_{\rm eff}^{\gamma}$

- **Results on $F_{\rm eff}^{\gamma}$ (Dependence on x and P^2)**

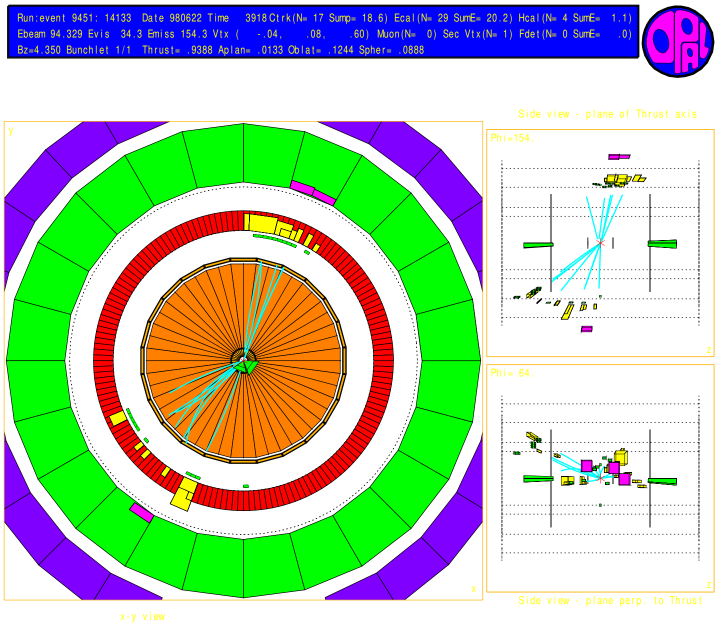




$\Rightarrow$ No significant decrease of $F_{\rm eff}^{\gamma}$ with P^2 found at present experimental uncertainties!

2.2 Cross-section measurements

- **Selection criteria and event samples**



Selection criteria	L3	OPAL
Electron energy	$E_{\rm tag} > 40$ GeV	$E_{\rm tag} > 65$ GeV
Polar angle	$30 < \theta_{\rm tag} < 66$ mrad	$34 < \theta_{\rm tag} < 55$ mrad
Hadr. final state cuts		

***W* reconstruction**	L3	OPAL
Type	Electron kinematics	Hadronic final state
$\Delta E_{\rm tag}/E_{\rm tag}$	$\simeq 1.3\%$	($\simeq 5\%$)
($E_{\rm tag} = 94.5$ GeV)		

Event samples

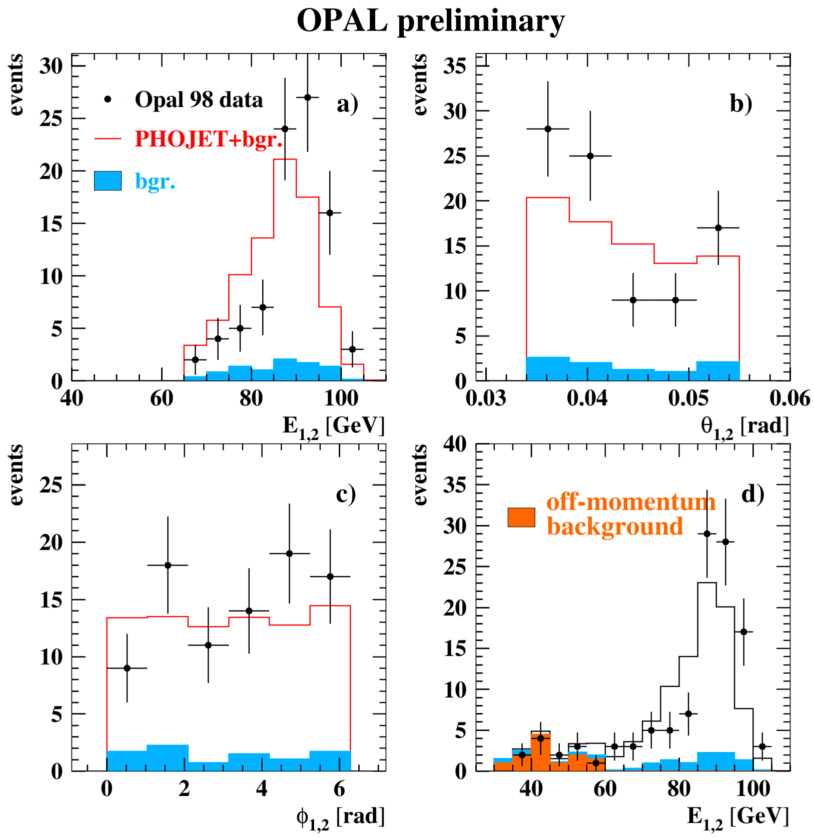
L3

$\sqrt{s}$	91 GeV	183 GeV	189 GeV
L (pb^{-1})	140	52	176
Events	137	34	108

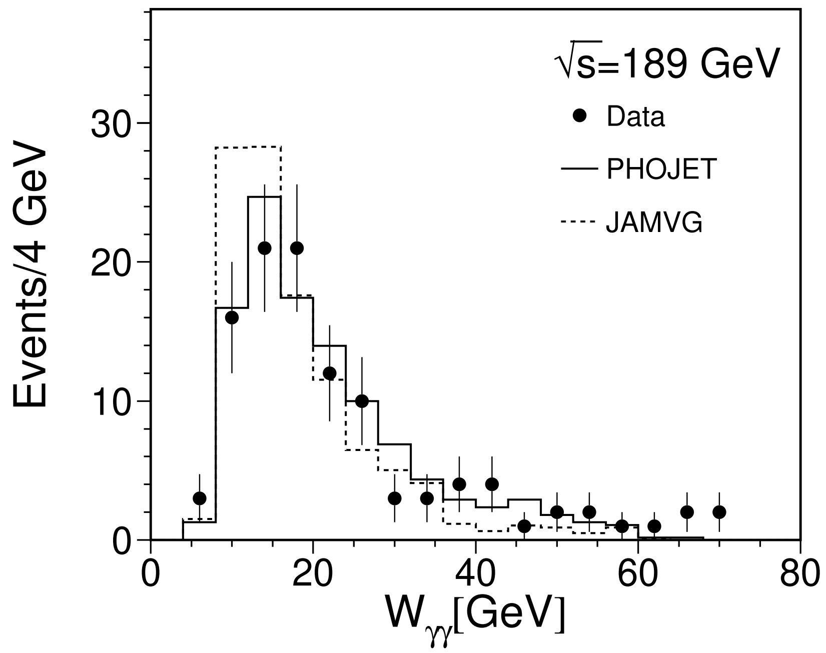
OPAL

$\sqrt{s}$	189 GeV
L (pb^{-1})	169
Events	44

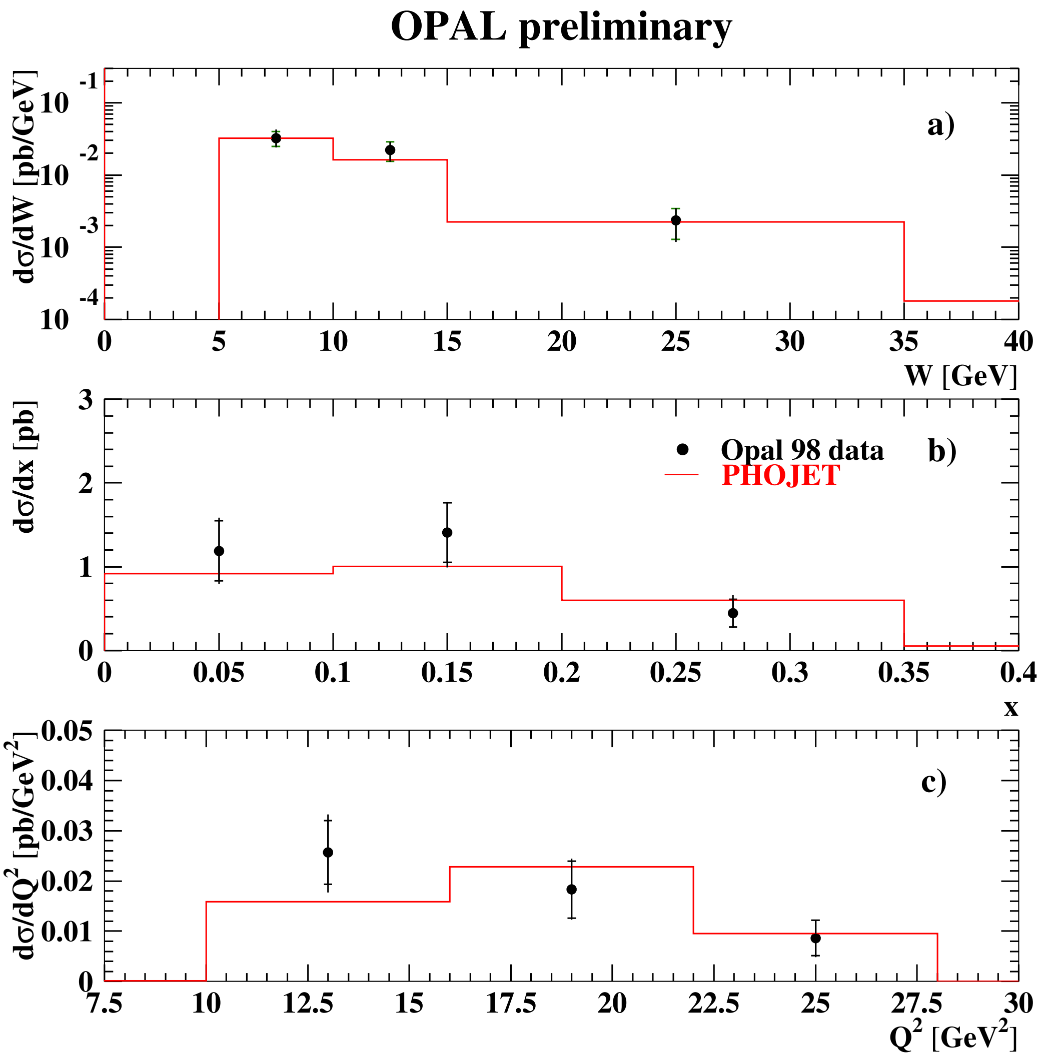
- **Properties of double-tagged $\gamma^*\gamma^*$ events (OPAL)**



- **Properties of double-tagged $\gamma^*\gamma^*$ events (L3)**



• Cross-section measurements in comparison to PHOJET (OPAL)



$\Rightarrow$ Measured region: $E_{\rm tag} > 65\,$GeV, $34 < \theta_{\rm tag} < 55\,$mrad and $W > 5\,$GeV
$\Rightarrow$ Good agreement between **measured** and **predicted** (PHOJET 1.10) differential cross-sections

Integrated measured cross-section:

$0.32 \pm 0.05\ ({\rm stat})\ ^{+0.04}_{-0.05}\ ({\rm sys})$ pb

Total expected cross-section (PHOJET 1.10):

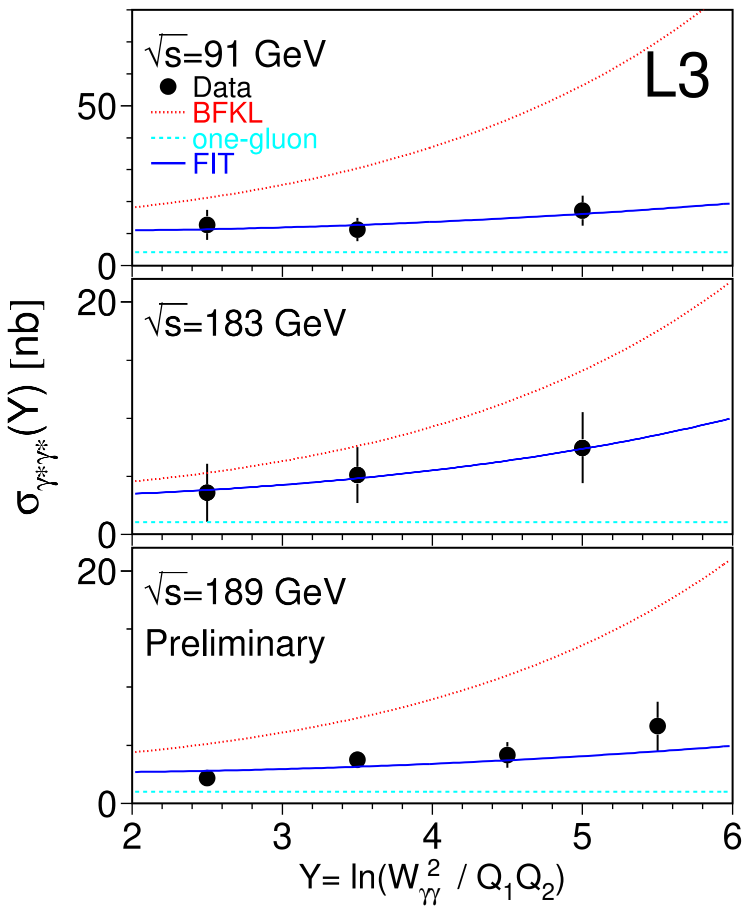
$0.28 \pm 0.03\ ({\rm stat})$ pb

• Cross-section measurements in comparison to BFKL (L3)

$\Rightarrow$ Extract $\sigma_{\gamma^\star\gamma^\star} = \sigma_{\mathrm{TT}} + \epsilon_1\sigma_{\mathrm{LT}} + \epsilon_2\sigma_{\mathrm{TL}} + \epsilon_1\epsilon_2\sigma_{\mathrm{LL}}$ from σ_{ee} neglecting the interference terms, τ_{TT} and τ_{TL}, and using the transverse photon luminosity function, L_{TT}:

$$\sigma_{ee} = L_{\mathrm{TT}} \cdot \sigma_{\gamma^\star\gamma^\star}$$

$\Rightarrow$ $\sigma_{\gamma^\star\gamma^\star}$ as a function of Y (QPM contribution subtracted):



$\Rightarrow$ BFKL (LO) not favored by the data!

$\Rightarrow$ Combined fit of the BFKL-LO expression for $\sigma_{\gamma^\star\gamma^\star}$ to all three data sets yields

$$\alpha_P - 1 = 0.290 \pm 0.025 \quad \chi^2/\mathrm{ndf} = 0.8$$

which is smaller than $\alpha_P^{\mathrm{LO}} - 1 \simeq 0.53$!

3. Summary and outlook

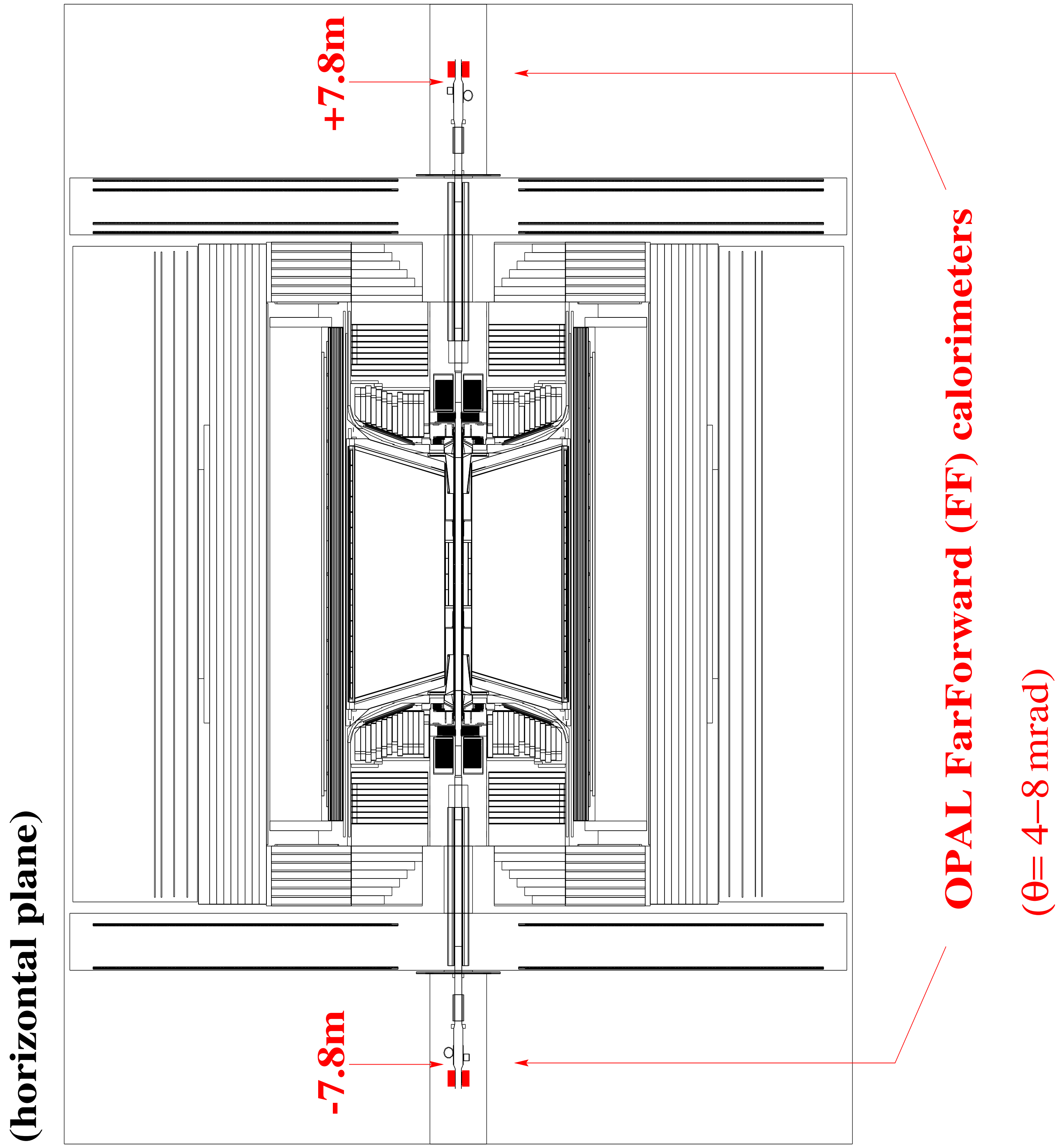
⇒ Results on $\gamma^*\gamma^* \to$ hadrons at LEP

- Virtual photon structure function
  - First measurement of $F_{\mathrm{eff}}^{\gamma}$ at LEP
  - No significant decrease of $F_{\mathrm{eff}}^{\gamma}$ with P^2 found
- Cross-section measurements
  - Total and differential cross-sections for the process $\mathrm{ee} \to \mathrm{ee}\gamma^\star\gamma^\star \to \mathrm{eeX}$ are well described by leading order Monte Carlo models such as PHOJET (no BFKL-like effects)
  - BFKL-LO predictions are disfavored by the data

⇒ Outlook

- Current results on $\gamma^*\gamma^* \to \mathrm{hadrons}$ will profit from the expected luminosity at LEP until 2000 (1998-2000: $\approx 500\,\mathrm{pb}^{-1}$)
- Extend double-tag analyses towards low values of P^2/Q^2 ($< 1.0\,\mathrm{GeV}^2$) using the LEP very forward calorimeters (e.g. ...)

- **Measurement of $\gamma^{*}\gamma^{*}$ interactions at low P^2/Q^2 (GEANT)**



$\Rightarrow$ **P^2/Q^2 range: 0.1 $<$ P^2 $<$ 1.0 GeV^2**