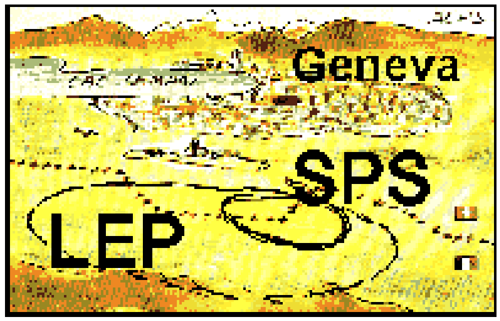
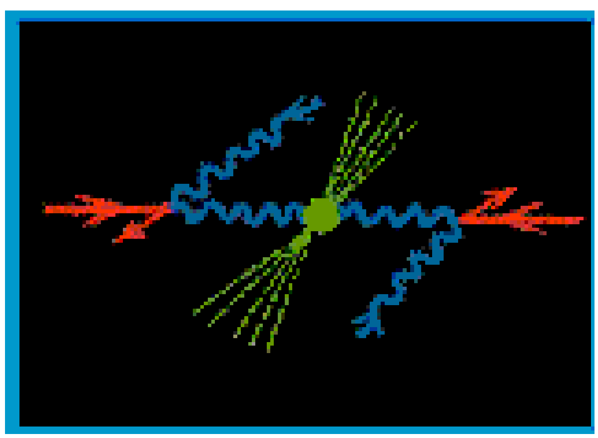
Photon – Photon Physics

From



to



Richard Nisius (CERN)

Gießen, 12 October 1

The programme

- Introduction
- Photon–photon scattering

1. Total cross-section

- Deep–inelastic electron–photon scattering

1. The QED structure
2. The hadronic structure

- Interactions of two virtual photons

1. BFKL signatures

- New signatures

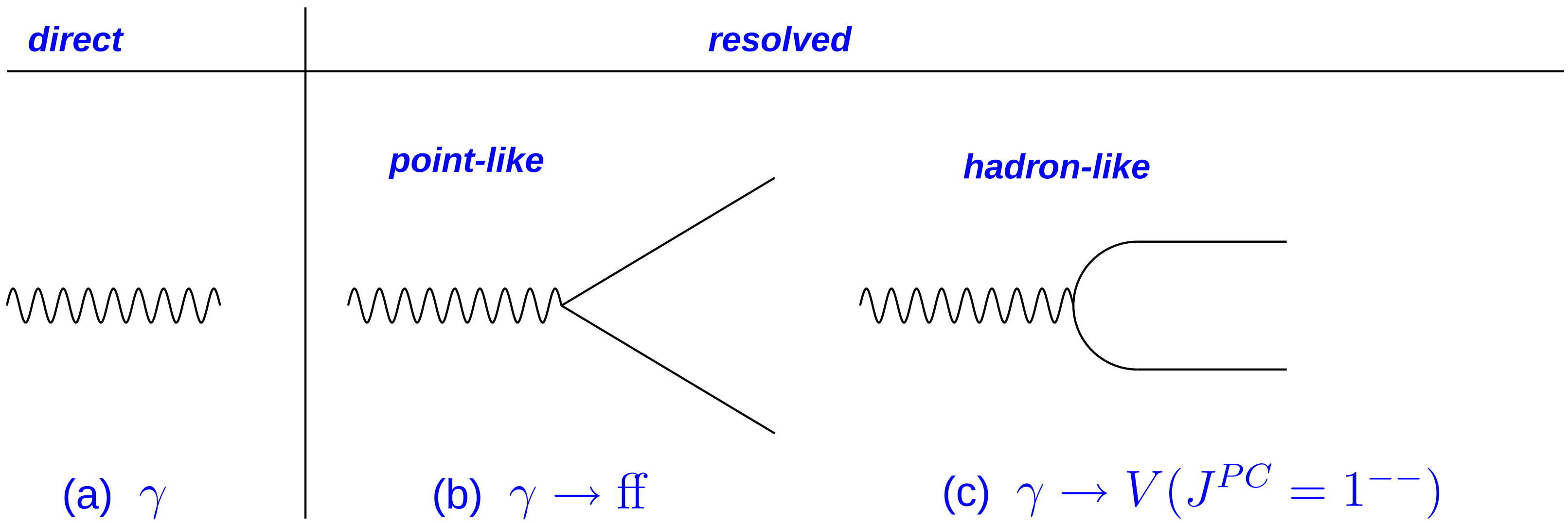
1. Higgs production

- Conclusions

The 'history' of the photon

Date	Event
8.11.1895	Röntgen discovers the X-rays (first Nobel Prize for physics 1901).
1900	Planck interprets light as 'energy quanta' $E = h\,\nu$, with $h = 6.626 \cdot 10^{-34} Js$.
1905	Einstein explains the photoelectric effect by 'photons'.
1922	Discovery of Compton scattering $\mathrm{e}\gamma \longrightarrow \mathrm{e}'\gamma'$.
1927	Heisenberg formulates the uncertainty principle e. g. $\Delta E \Delta t \geq \hbar$.
1930	Fist attempt to measure photon-photon scattering by Hughes et. al.
1936	First calculation of photon-photon scattering by Euler und Kockel.
1981	First measurement of the hadronic structure function of the photon by PLUTO.
2011	The Higgs Boson will be produced through photon-photon fusion at TESLA?

Why do we talk about photon structure?



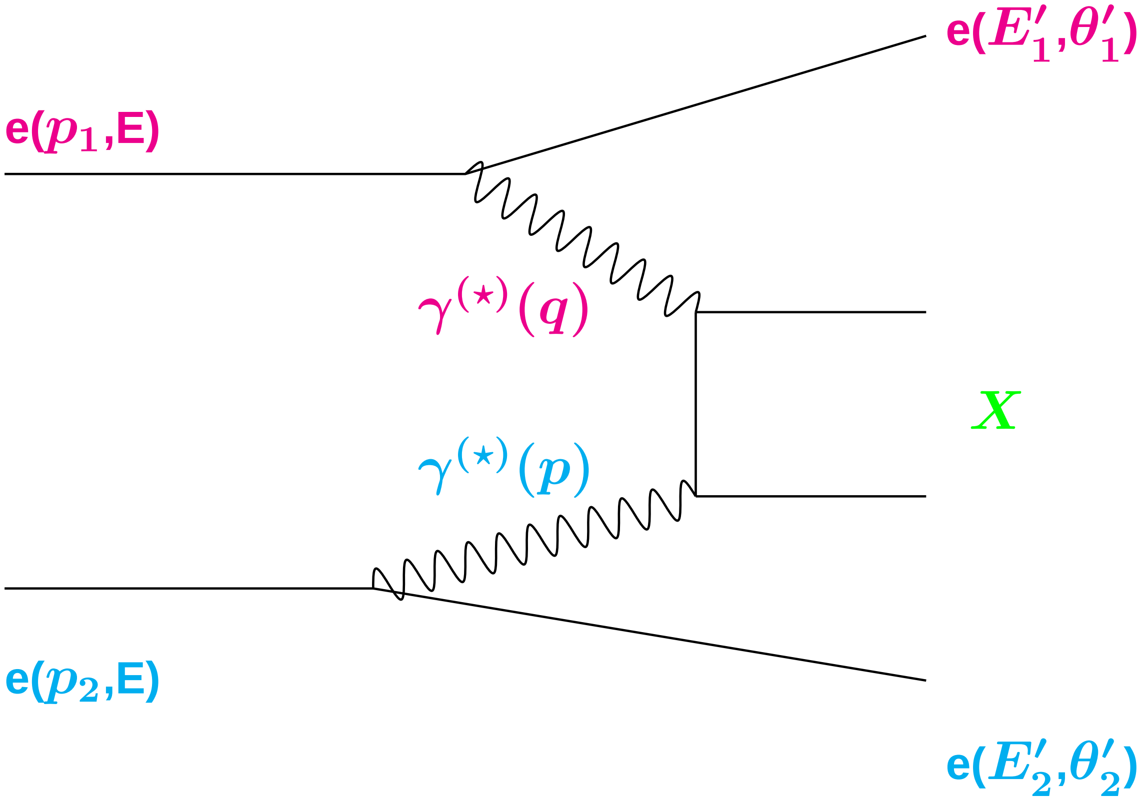
(a) γ (b) $\gamma \to \mathrm{f\bar{f}}$ (c) $\gamma \to V(J^{PC} = 1^{--})$

1) In (a) the whole photon interacts $\Rightarrow$ **NO structure.**

2) The fluctuations (b,c) exist due to the uncertainty principle $\Rightarrow$ **photon 'structure'.**

3) The typical lifetime of the fluctuations **increases** with the **photon energy** and **decreases** with the **photon virtuality.**

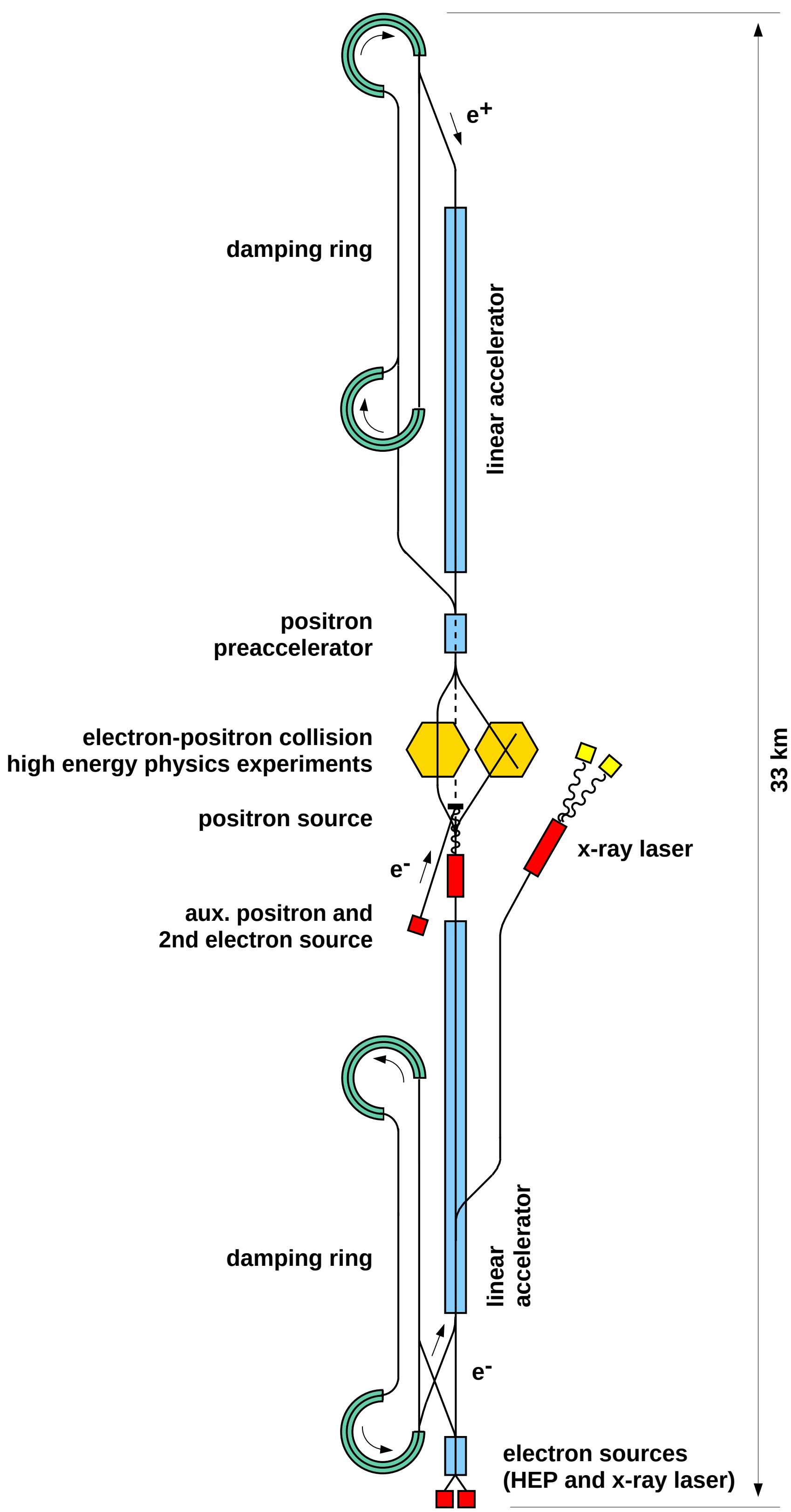
The reaction e e ⟶ e e X



$$
\begin{aligned}
\mathrm{d}^6\sigma &= \frac{\mathrm{d}^3p_1'\,\mathrm{d}^3p_2'}{E_1'E_2'}\,\frac{\alpha^2}{16\pi^4Q^2P^2}\left[\frac{(q\cdot p)^2-Q^2P^2}{(p_1\cdot p_2)^2-m_e^2m_e^2}\right]^{1/2}\\
&\Big(4\rho_1^{++}\rho_2^{++}\sigma_{TT}+2\rho_1^{++}\rho_2^{00}\sigma_{TL}\\
&+2\rho_1^{00}\rho_2^{++}\sigma_{LT}+\rho_1^{00}\rho_2^{00}\sigma_{LL}+\\
&2|\rho_1^{+-}\rho_2^{+-}|\tau_{TT}\cos 2\bar{\phi}-8|\rho_1^{+0}\rho_2^{+0}|\tau_{TL}\cos\bar{\phi}\Big)\\
Q^2 &= -q^2 = 2\,E\,E_1'\,(1-\cos\theta_1')\\
P^2 &= -p^2 = 2\,E\,E_2'\,(1-\cos\theta_2')\\
x &= \frac{Q^2}{Q^2+W^2+P^2}
\end{aligned}
$$


The LEP Accelerator

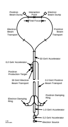
Layout of a future Linear Collider



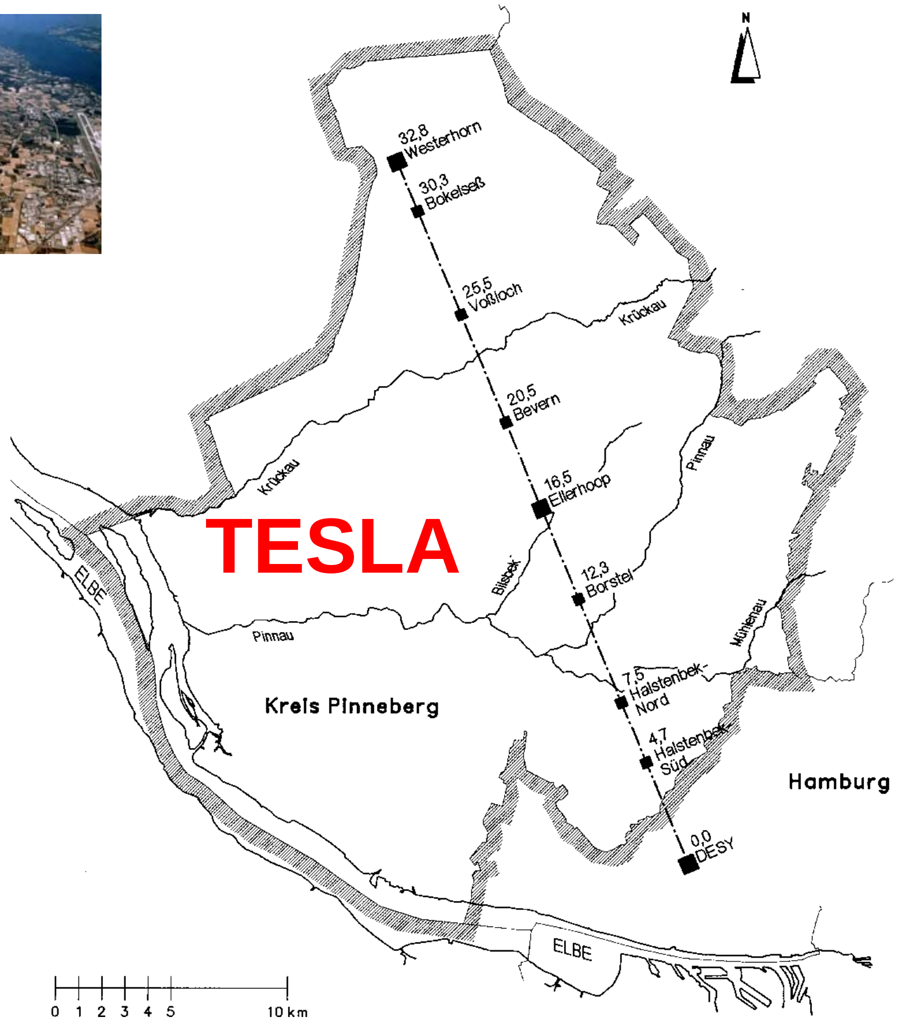
TESLA

From LEP/ SLC to TESLA

LEP

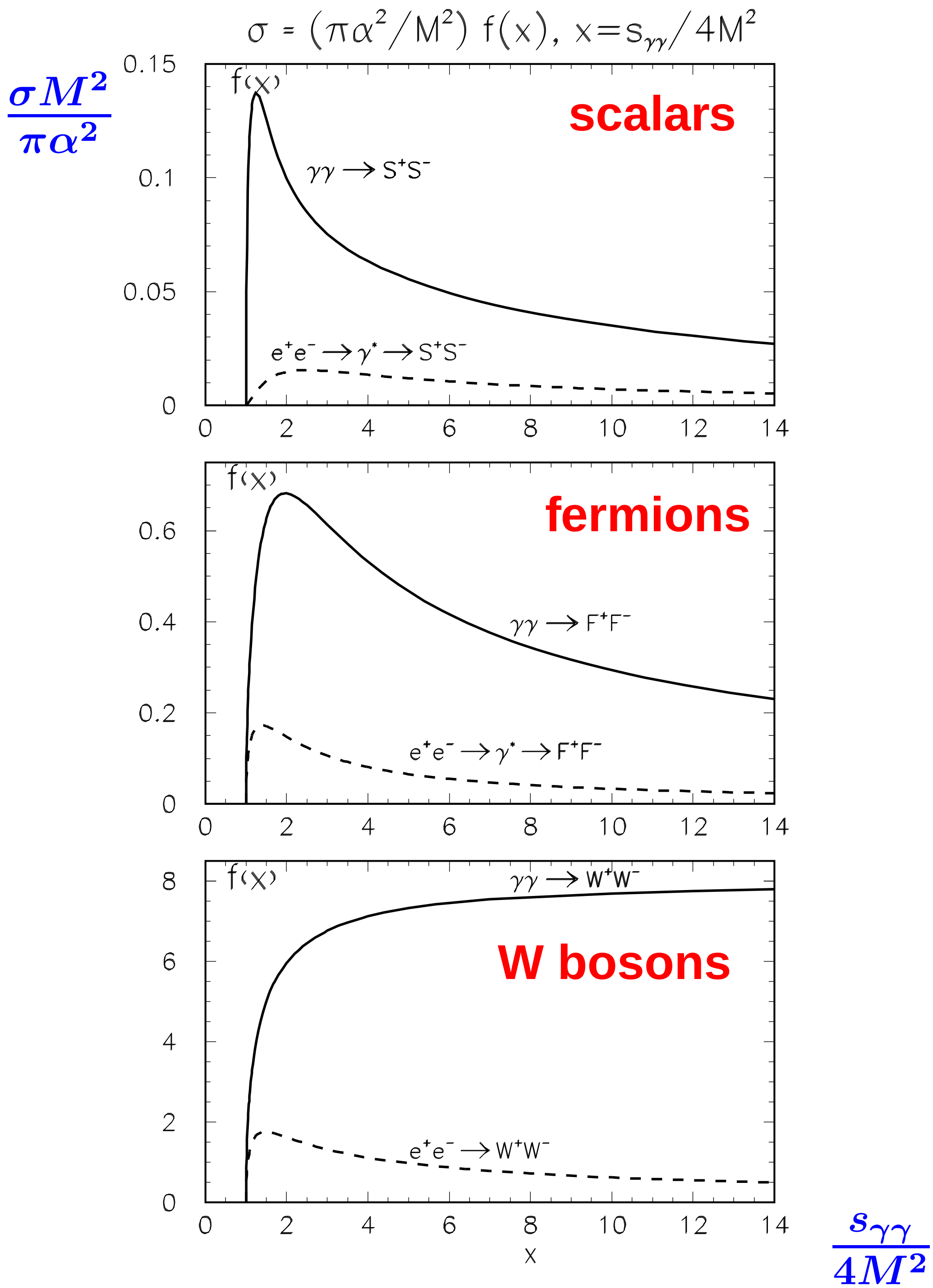


← SLC



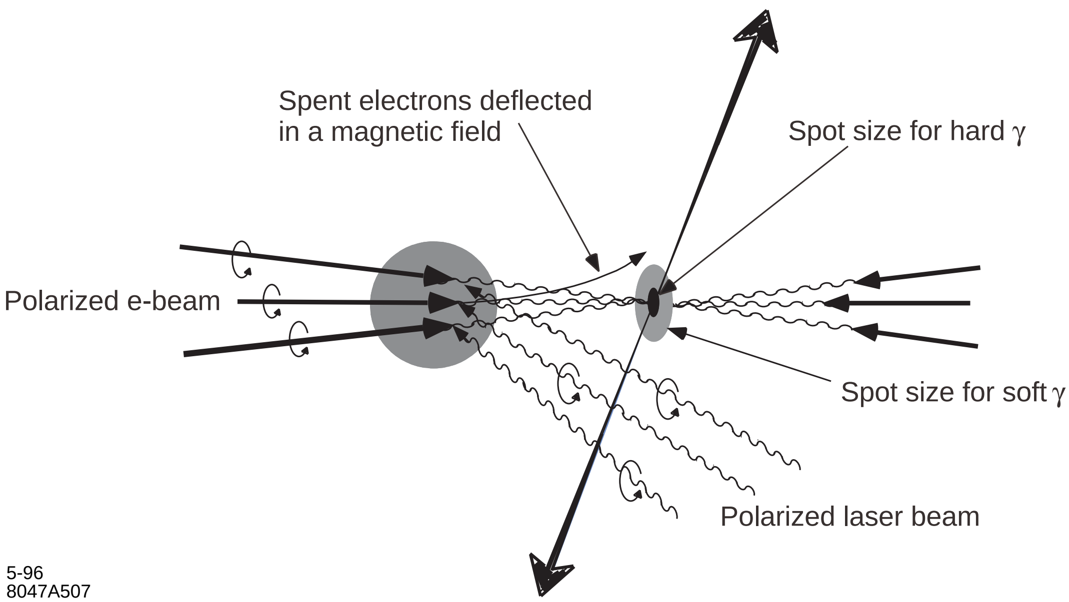
		LEP	SLC	TESLA
radius	[km]	8.5	∞	∞
length	[km]	26.7	4	33
gradient	[MV/m]	6	10	23.4
σ_x/σ_y	[μm/μm]	110 / 5	1.4 / 0.5	0.553/0.005
energy	[GeV]	100	50	250
lumi.	[10^{31}/cm^{2}s]	7.4	0.1	3400
$\mathcal{L}_{\rm int}$	[1/pb y]	250	15	10-100k

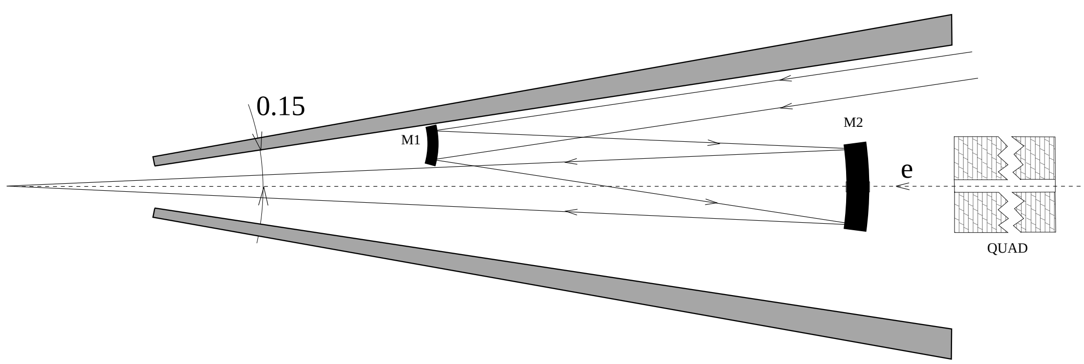
Charged particle pair production

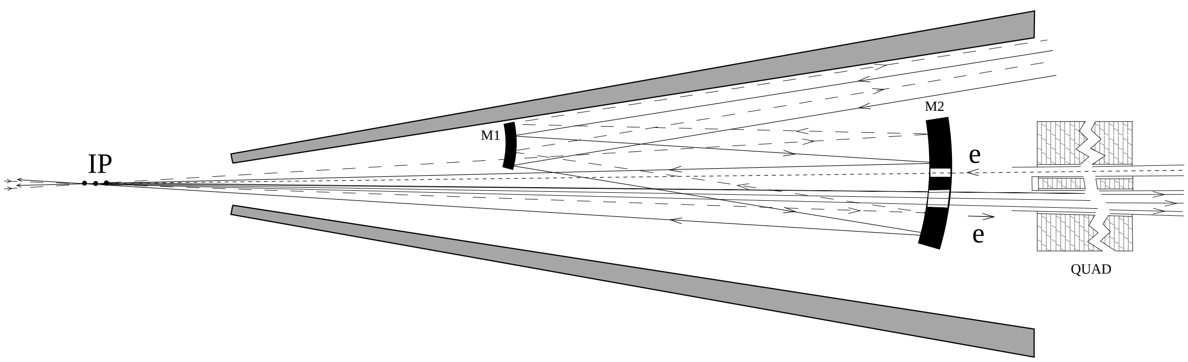


The photon collider has larger cross sections than the e^+e^- collider for several final states.

The creation of the photon beam

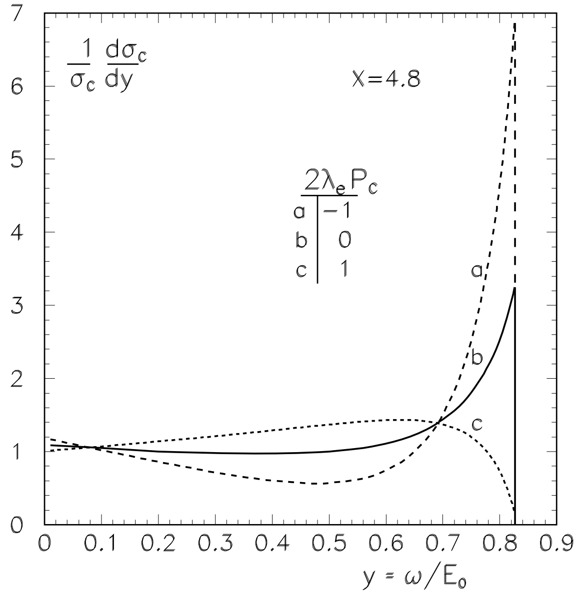




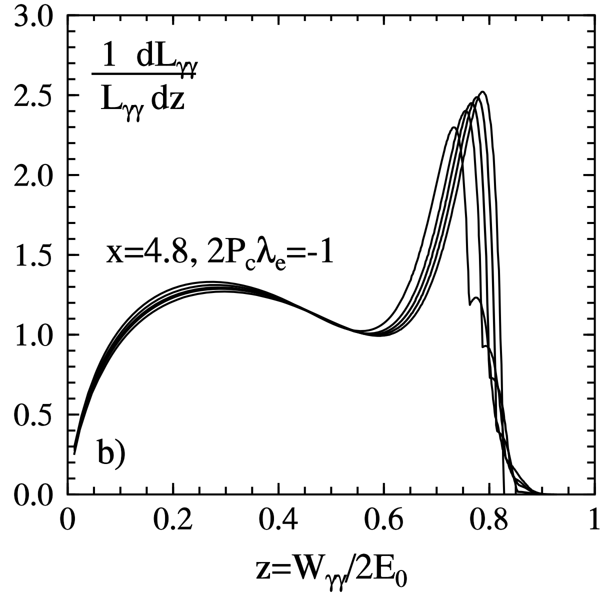


Some features of a Photon Collider

helicities

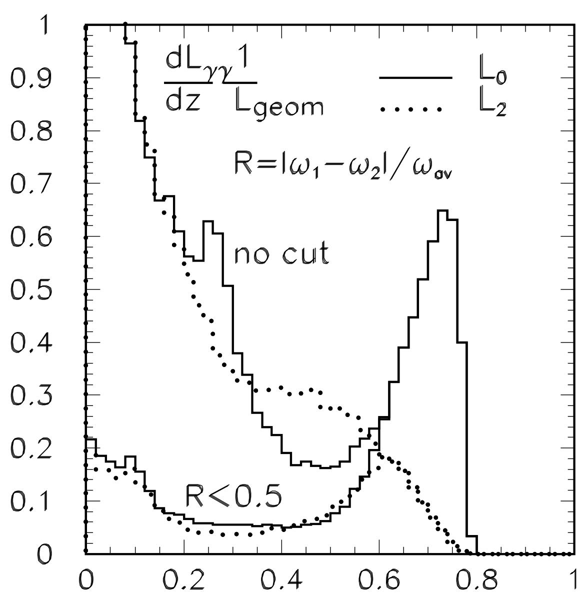


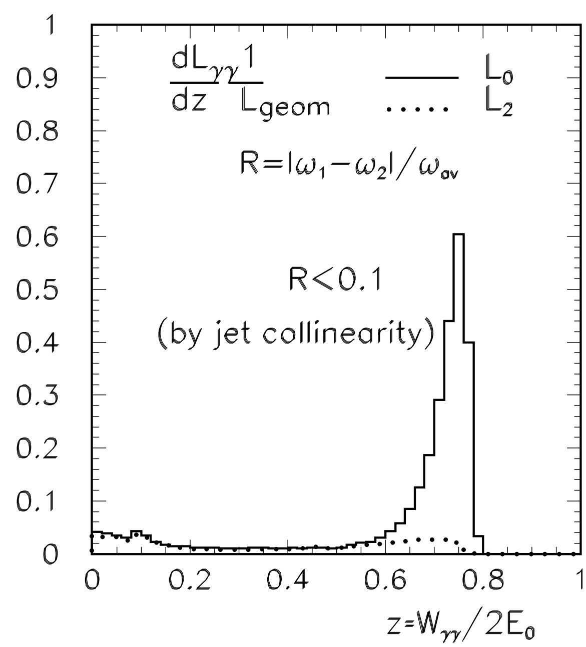
non-linear effects



Photon energy spectra

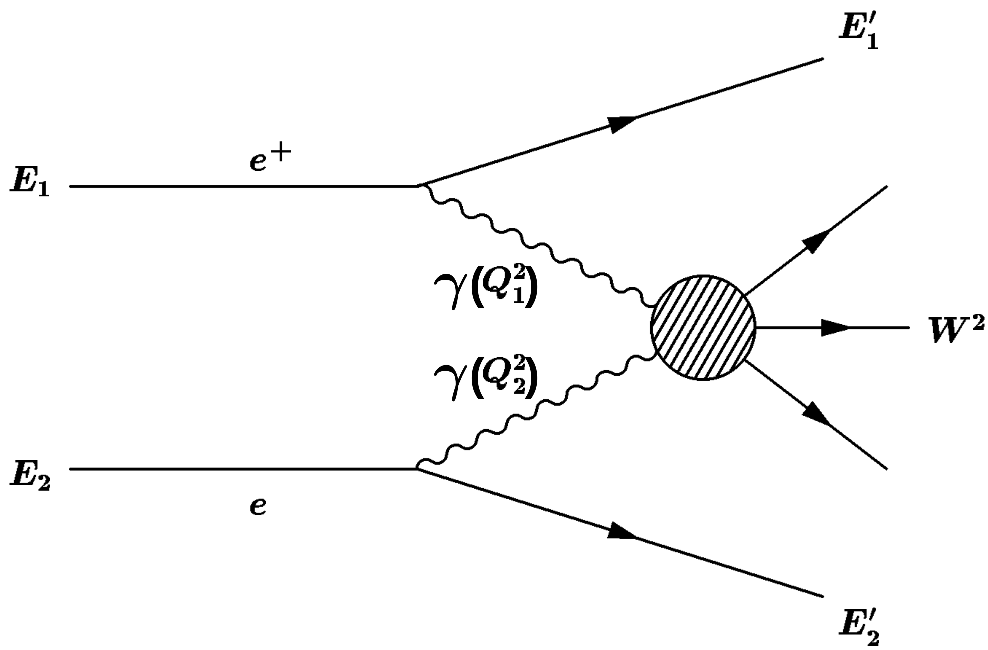
TESLA(500)





Luminosity spectra

Photon — photon scattering



Interaction of two quasi-real photons

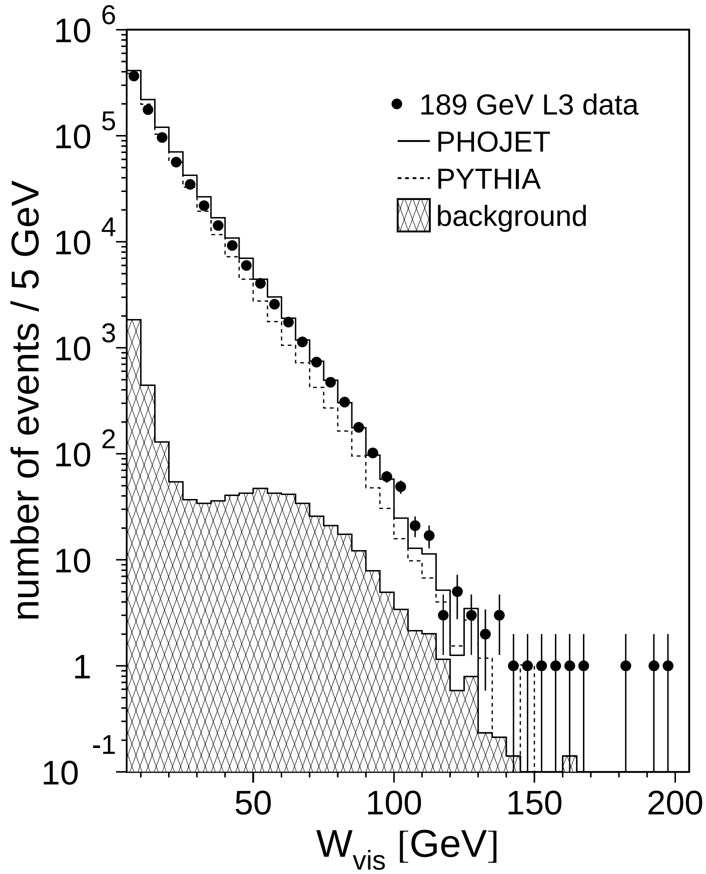
$$\gamma\gamma \longrightarrow X$$

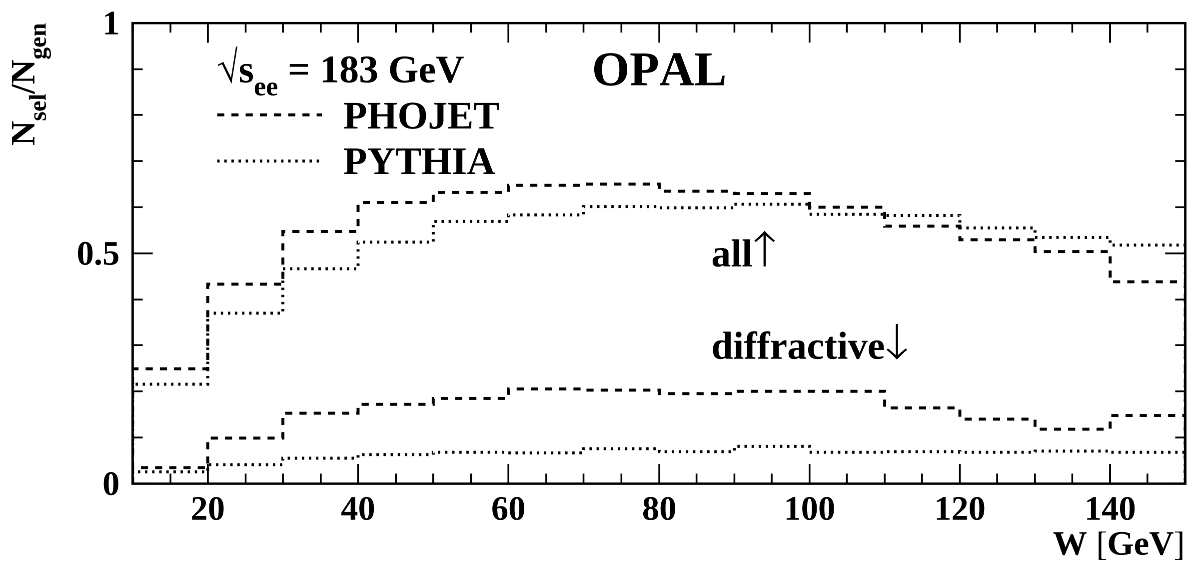
e.g. $X(s_{\gamma\gamma}) = \ell^+\ell^-$, $\mathrm{q\bar{q}}$, $\mathrm{Q\bar{Q}}$, $\mathrm{Z^0Z^0}$, $\mathrm{W^+W^-}$, H

$$Q_i^2 = 2E_iE_i'(1-\cos\theta_i) \approx 0$$

$$W^2 = s_{\gamma\gamma} = \left(\sum_h E_h\right)^2 - \left(\sum_h \vec{p}_h\right)^2$$

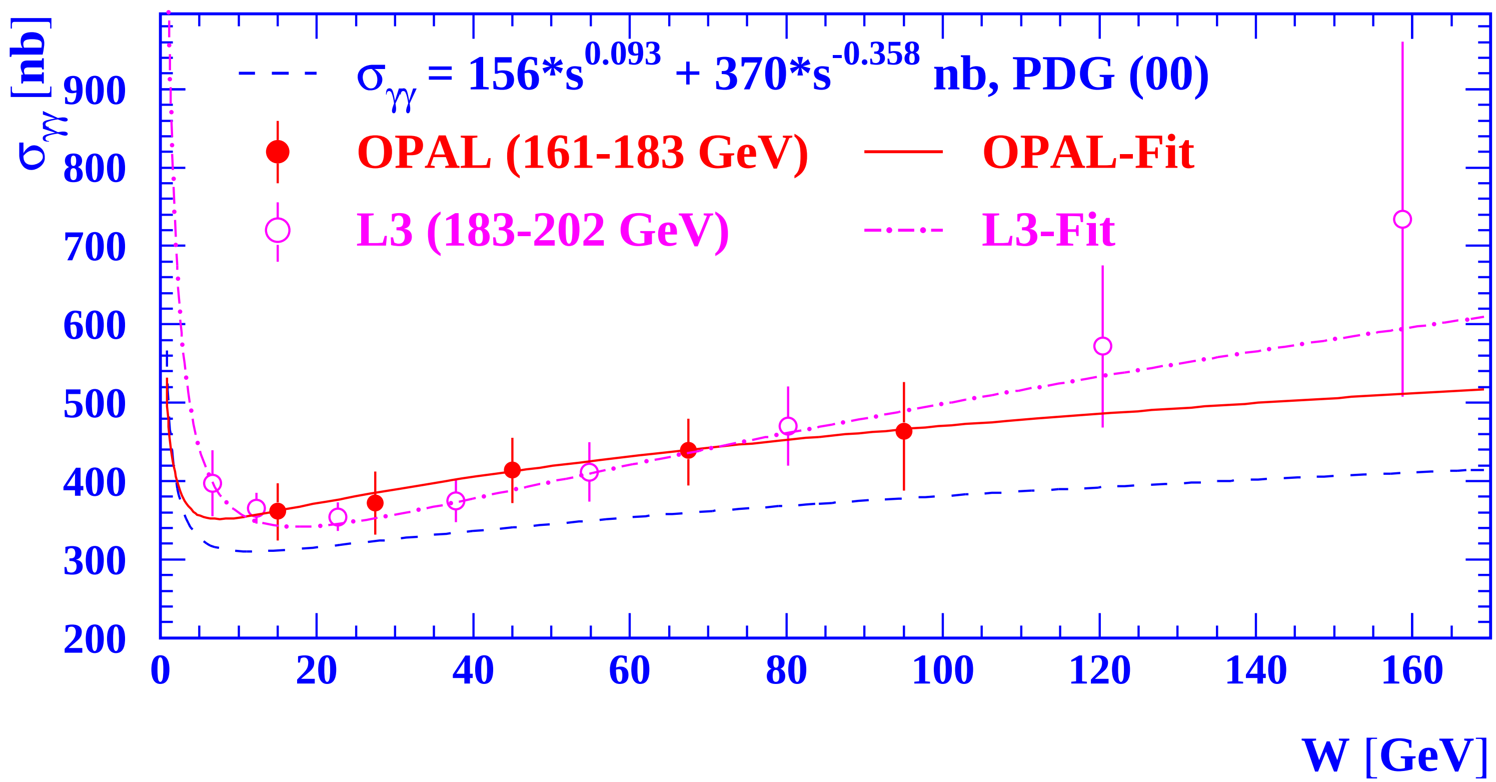
W distributions for anti-tagged events





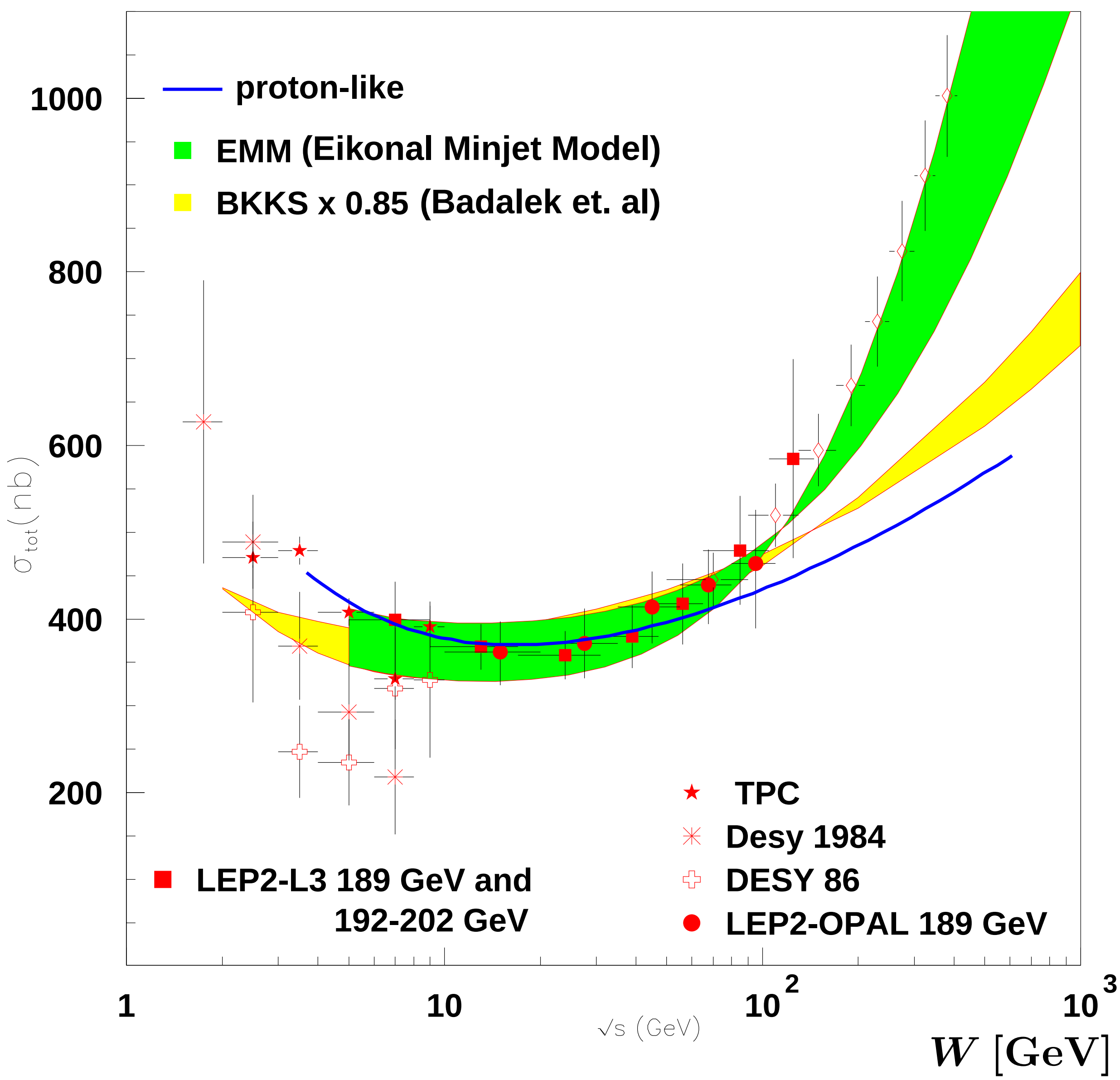
The acceptance for diffractive events is very different for the PHOJET and PYTHIA models.

The total hadronic cross-section $\sigma_{\gamma\gamma}$



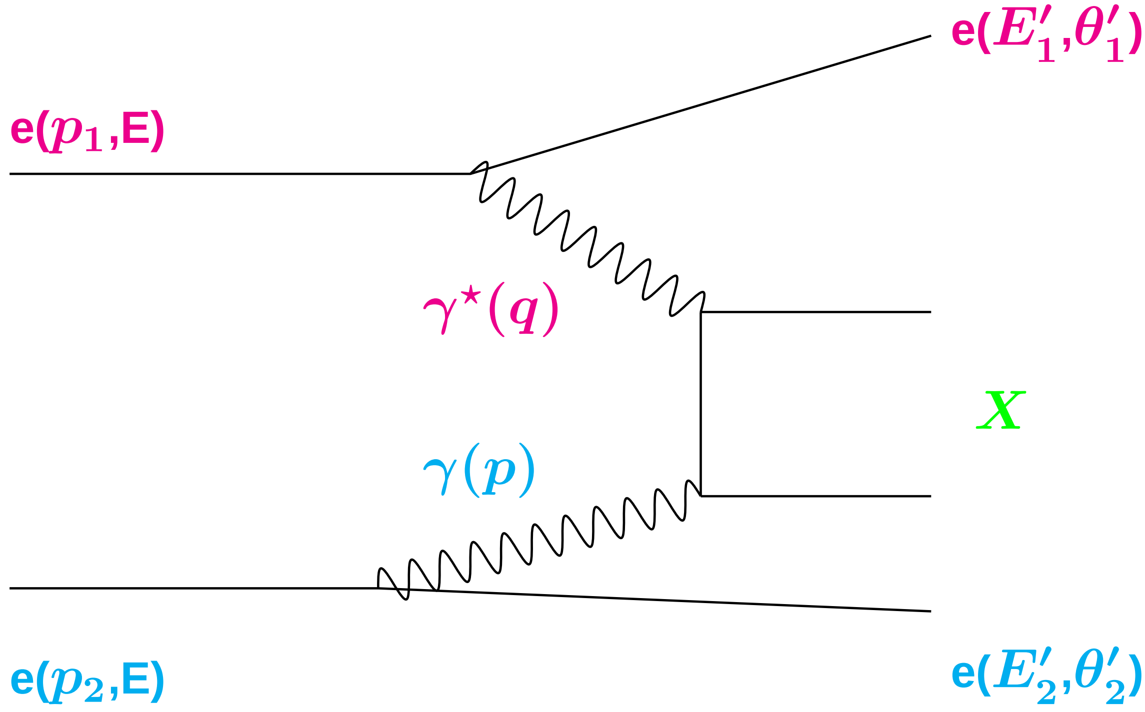
A clear rise of the total cross-section is observed in the data.

Predictions for the cross-section $\sigma_{\gamma\gamma}$



To achieve a 5-10% precision on W a Photon Collider is needed to avoid the reconstruction of W from the hadronic final state.

Electron-photon scattering



$$\frac{\mathrm{d}^4\sigma}{\mathrm{d}x\mathrm{d}Q^2\mathrm{d}z\mathrm{d}P^2} \propto \frac{\mathrm{d}^2N_\gamma^{\mathrm{T}}}{\mathrm{d}z\mathrm{d}P^2}\cdot\frac{2\pi\alpha^2}{x\,Q^4}\cdot f_y\cdot F_2^\gamma(x,Q^2)$$

with:

$$f_y = 1+(1-y)^2$$

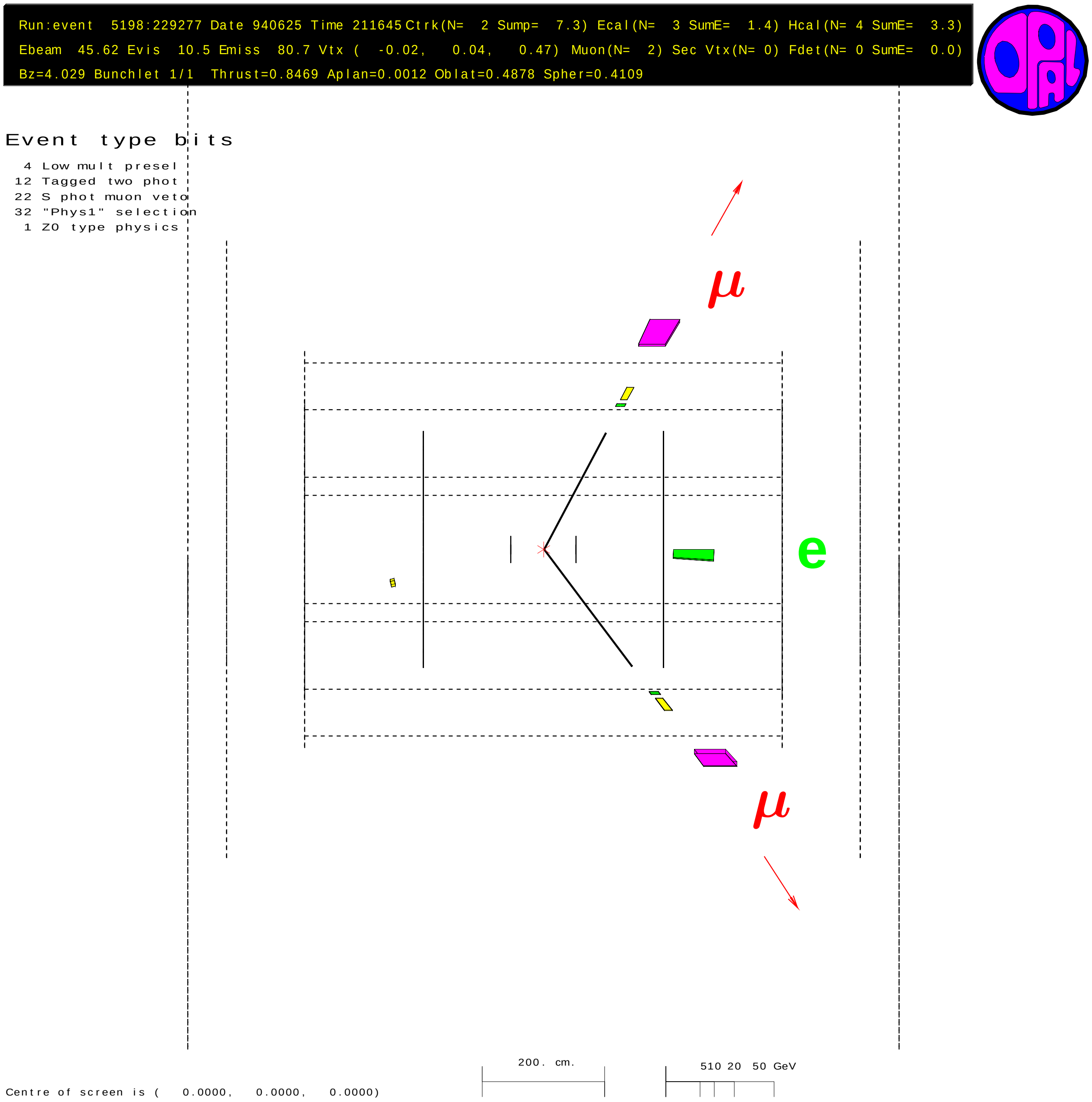
$$Q^2 = -q^2 = 2\,E\,E'_1\,(1-\cos\theta'_1)$$

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

$$P^2 = -p^2 = 2\,E\,E'_2\,(1-\cos\theta'_2) \ll Q^2$$

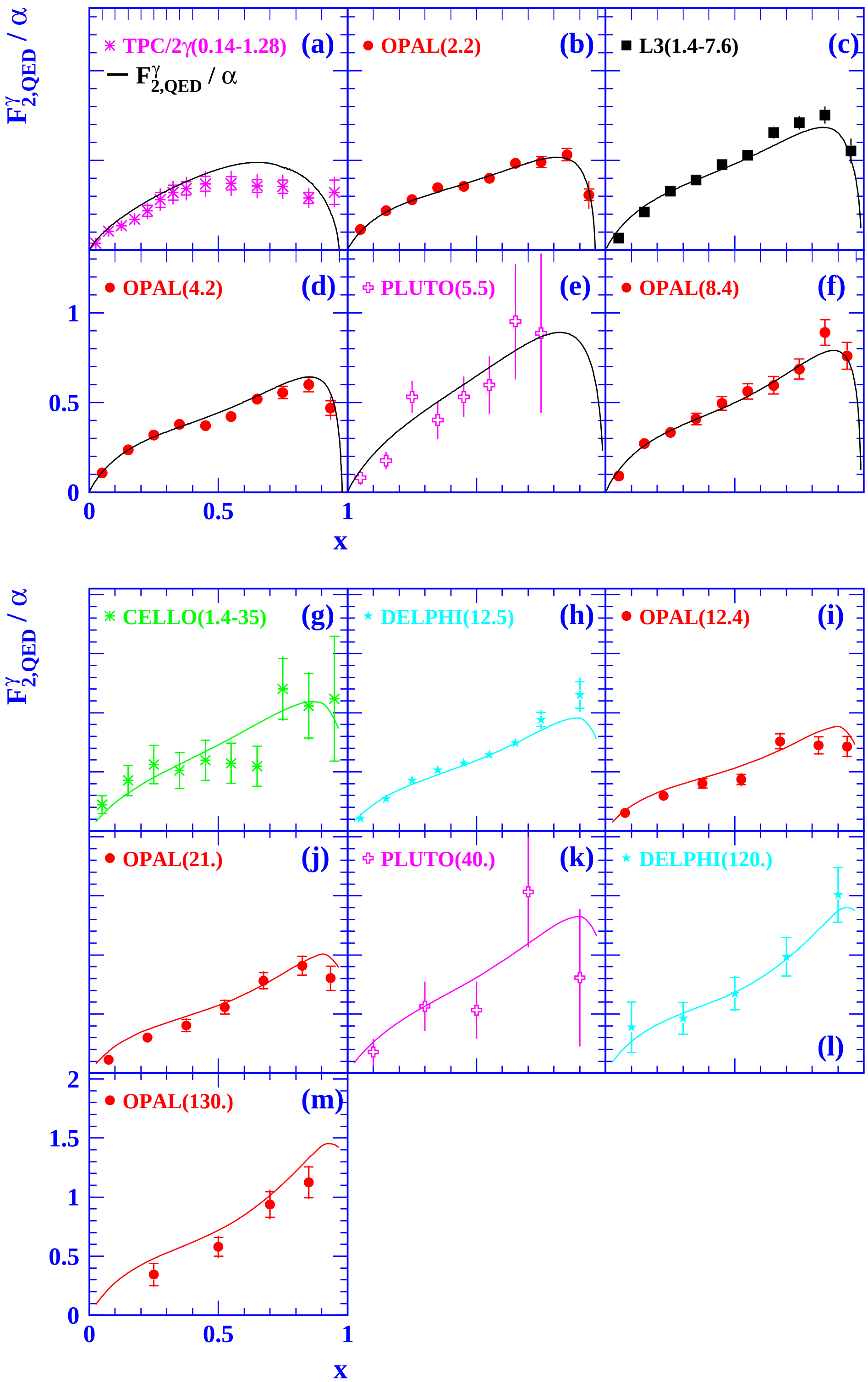
$$\frac{\mathrm{d}^2N_\gamma^{\mathrm{T}}}{\mathrm{d}z\mathrm{d}P^2} = \frac{\alpha}{2\pi}\left[\frac{1+(1-z)^2}{z}\frac{1}{P^2} - \frac{2\,m_{\mathrm{e}}^2\,z}{P^4}\right]$$

The muon pair final state

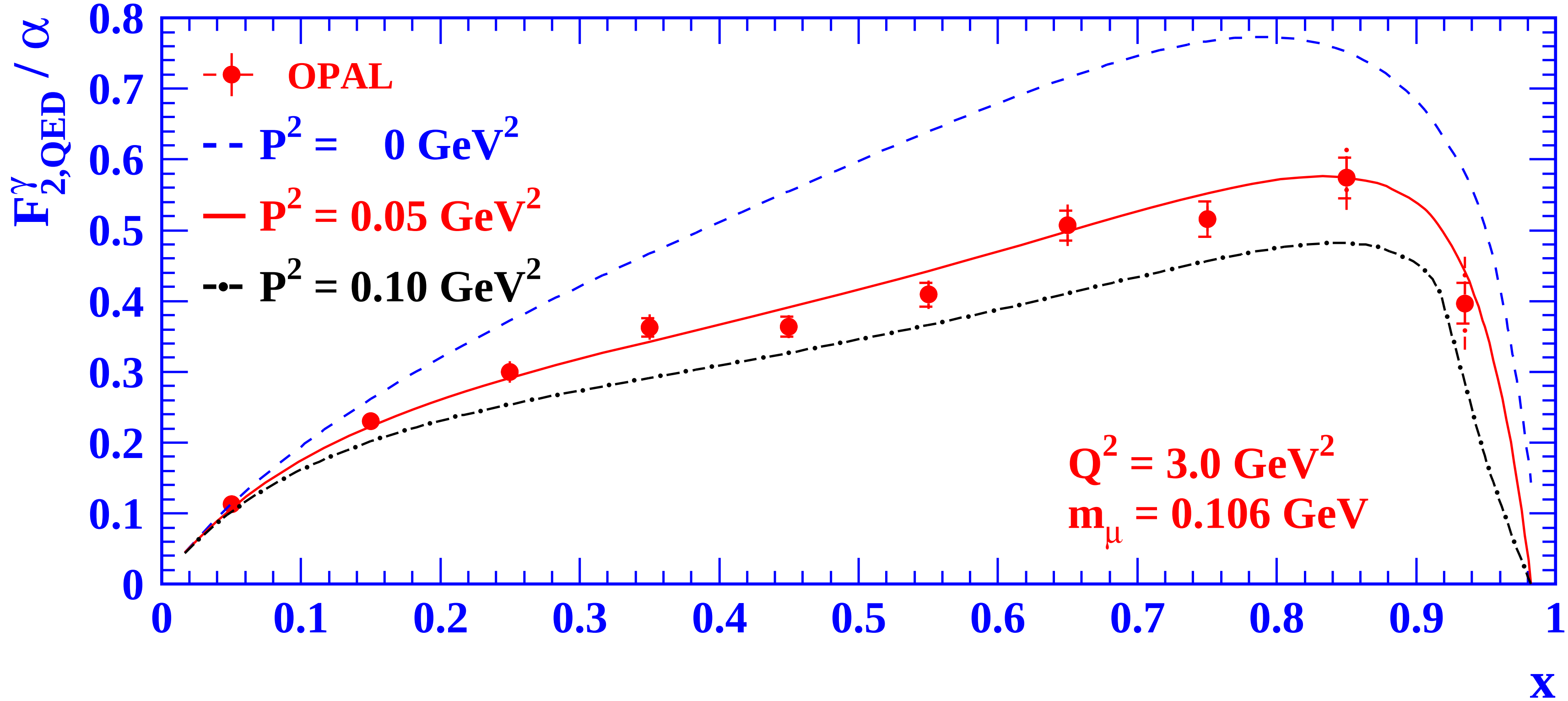


The muon pair final state is a clear topology with good mass resolution.

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

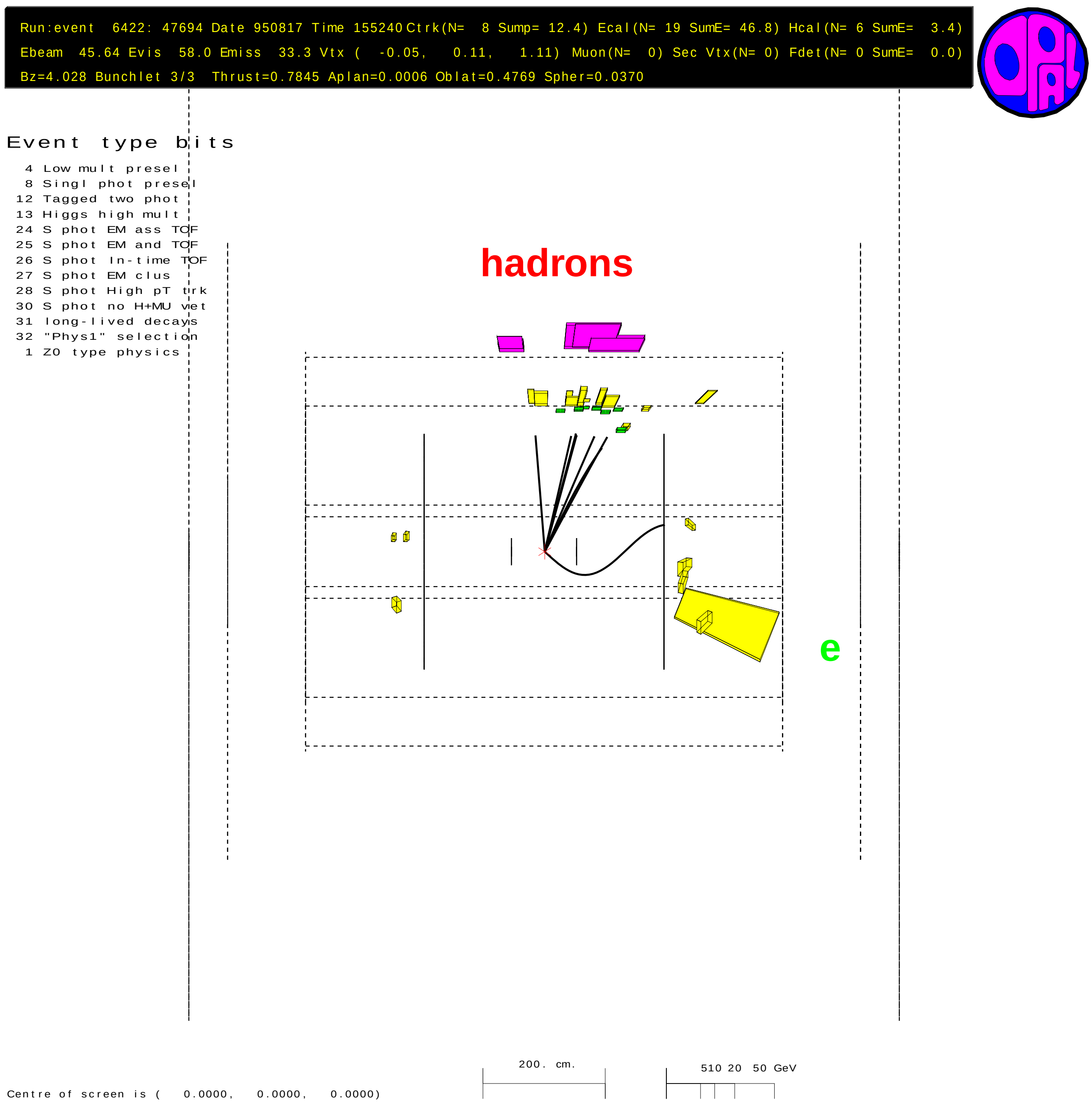


The P^2 dependence of F_2^γ



The suppression of the photon structure with the photon virtuality P^2 is clearly observed in the data.

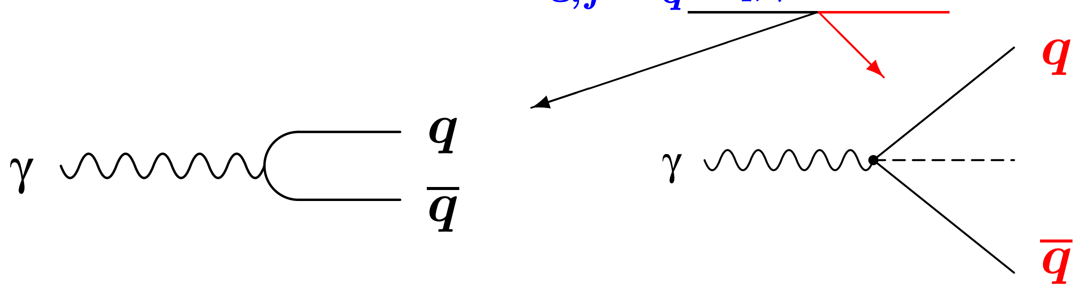
The hadronic final state



The scattered electron is clearly visible.
However, the hadronic final state may partly disappear along the beam axis.

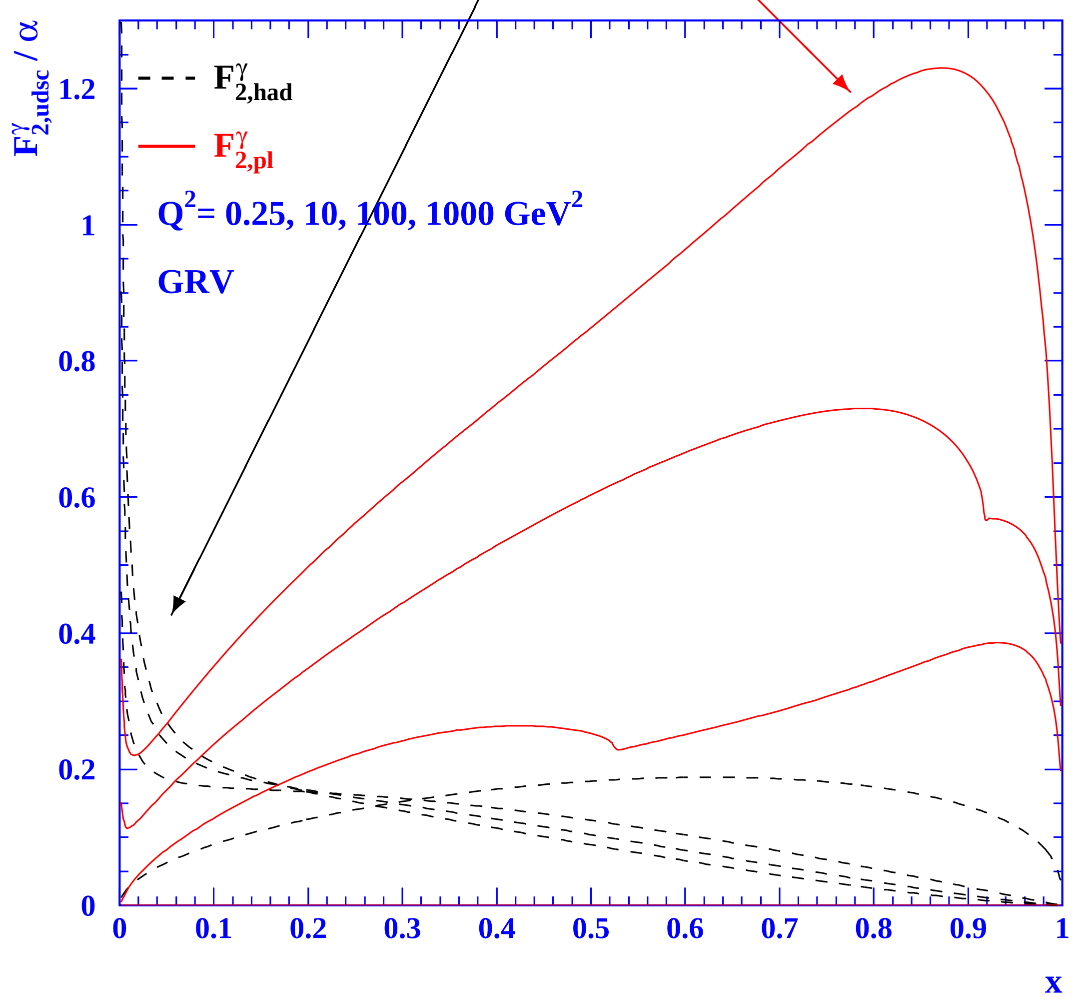
The contributions to $F_2^\gamma(x, Q^2)$

$$F_2^\gamma(x,Q^2) = x \sum_{c,f} e_q^2 \, f_{q,\gamma}(x,Q^2)$$

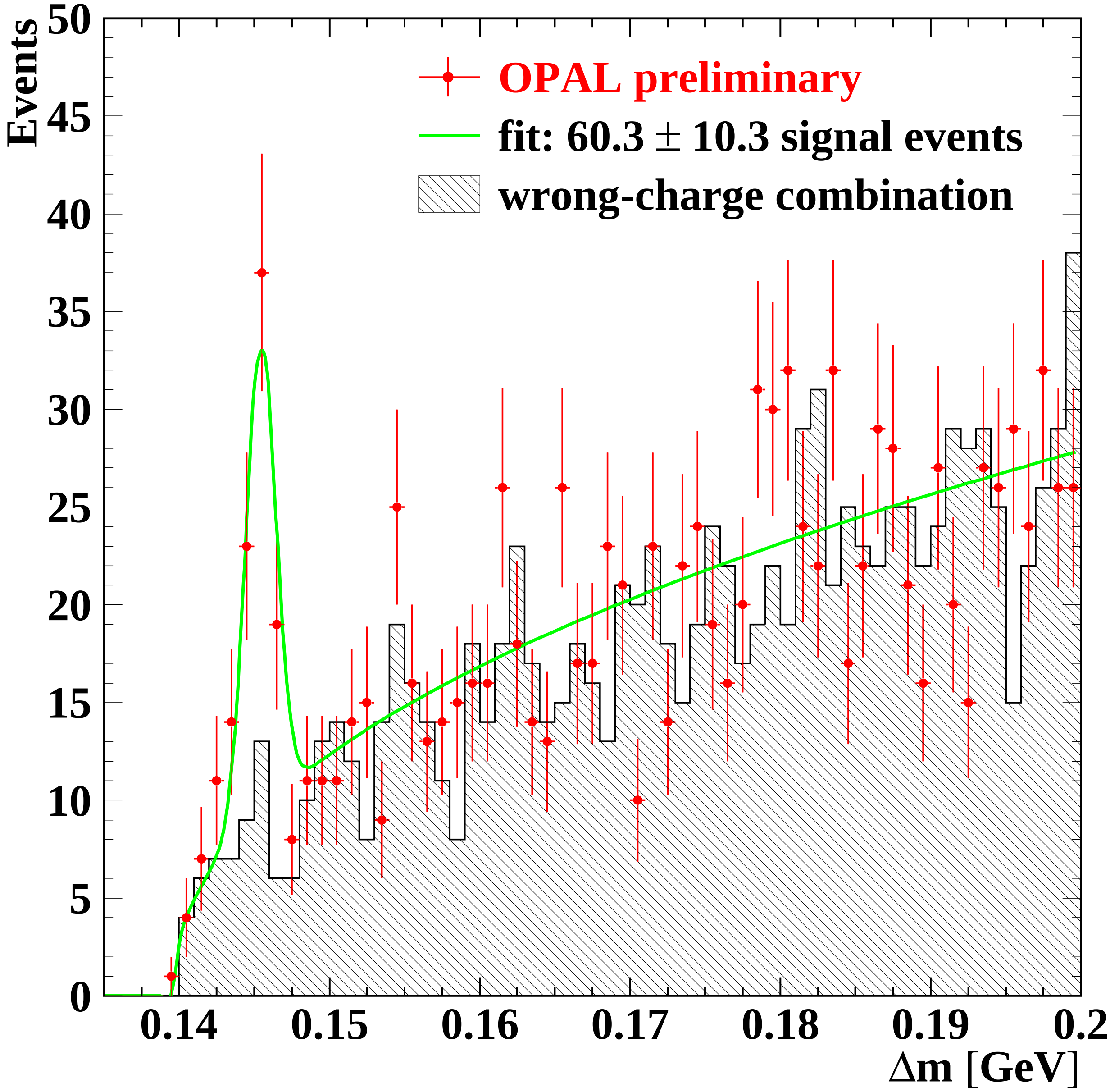


hadron-like, *non–perturbative* **point-like,** *perturbative*

e.g. VMD(ρ, ω, ϕ), low-x **high-x**

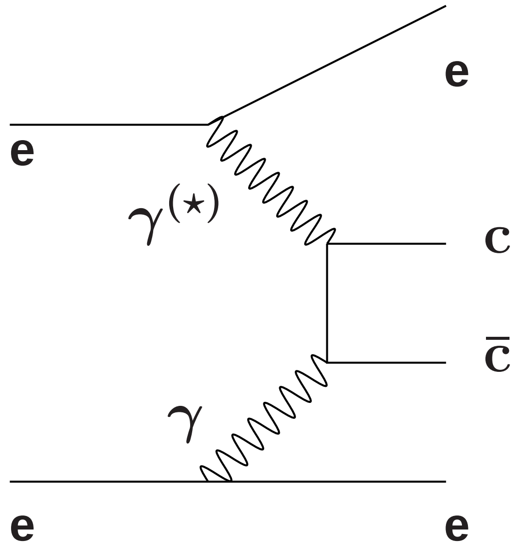


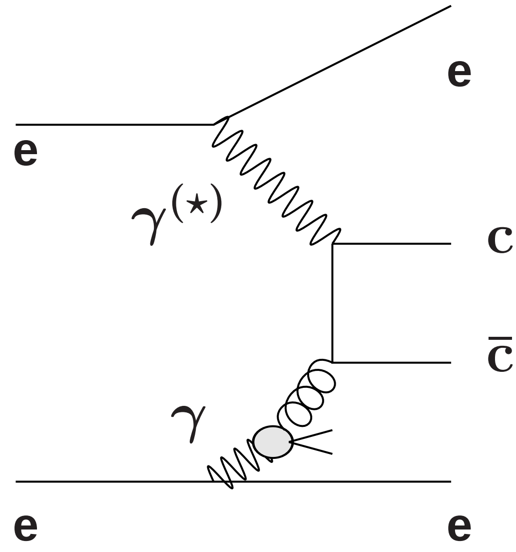
Charm production tagged by D*s



A clear signal in the $\Delta m = M(D^{\star}) - M(D^{0})$ mass spectrum is seen.

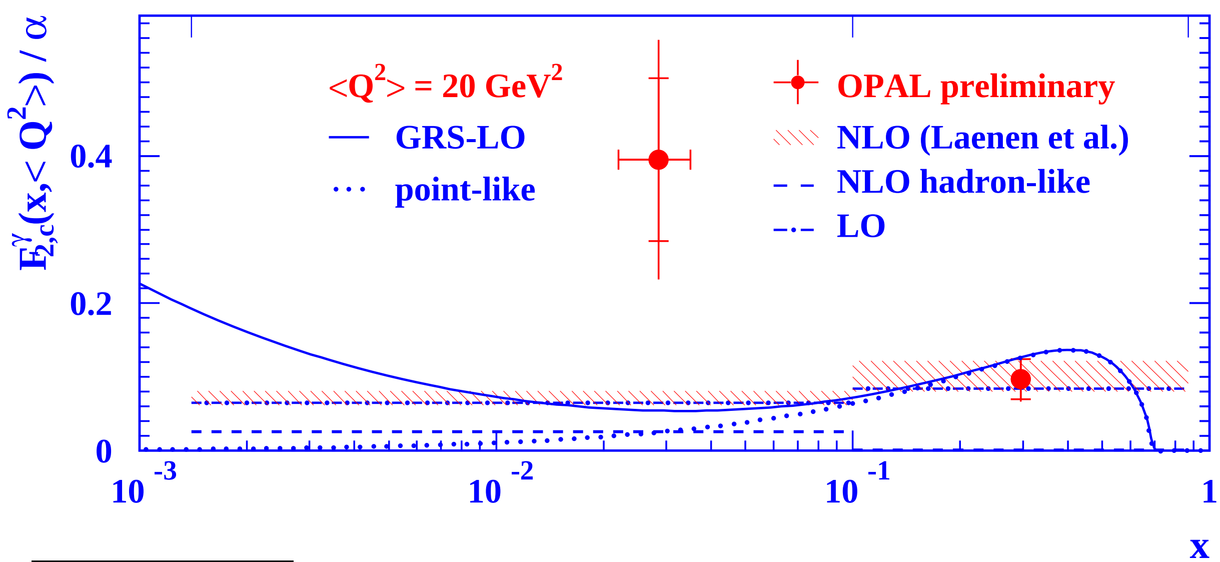
The first measurement of $F_{2,c}^{\gamma}$





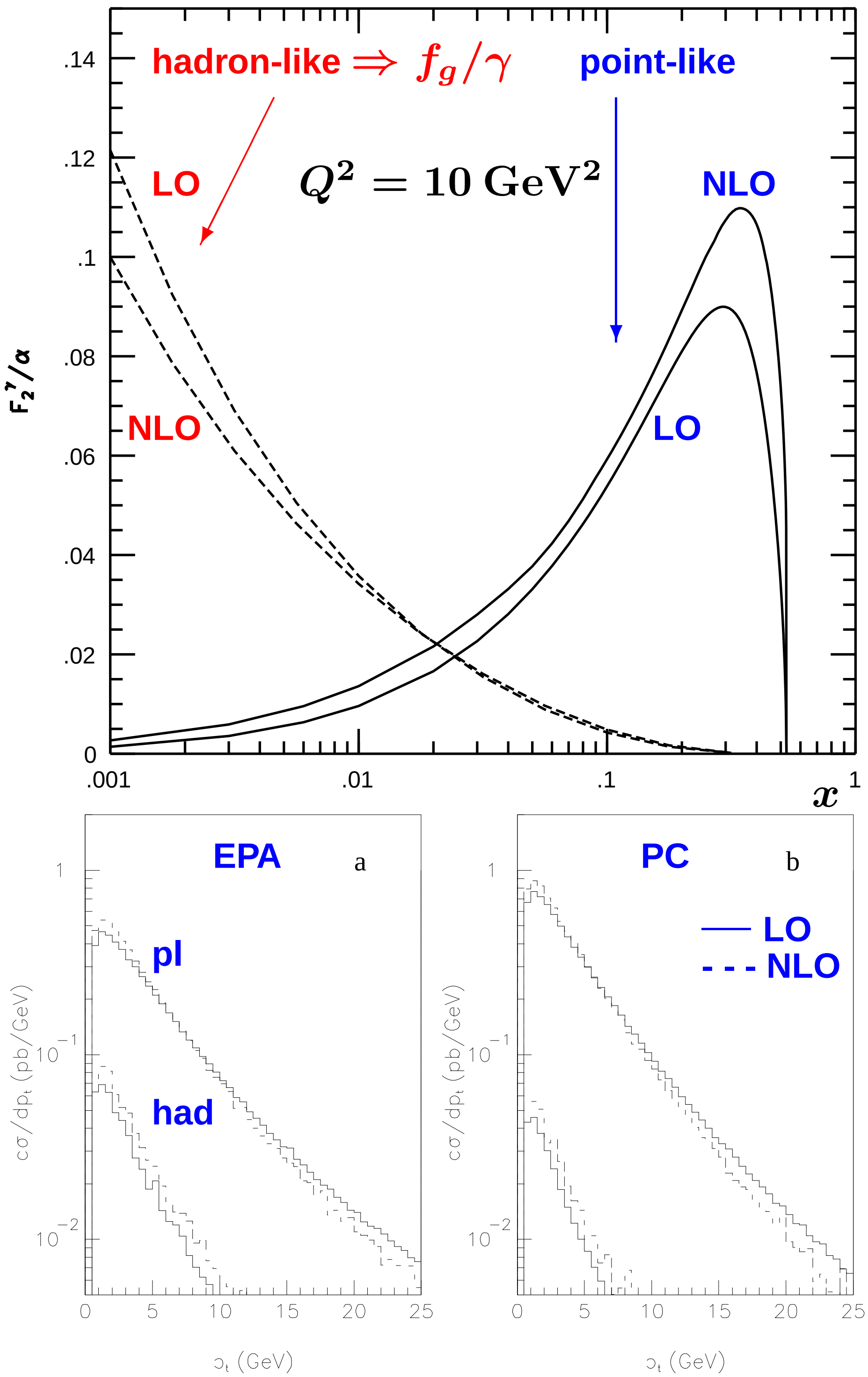
point-like, purely perturbative QCD prediction, dominates at high-x

hadron-like, depends on f_g^{γ}, dominates at low-x



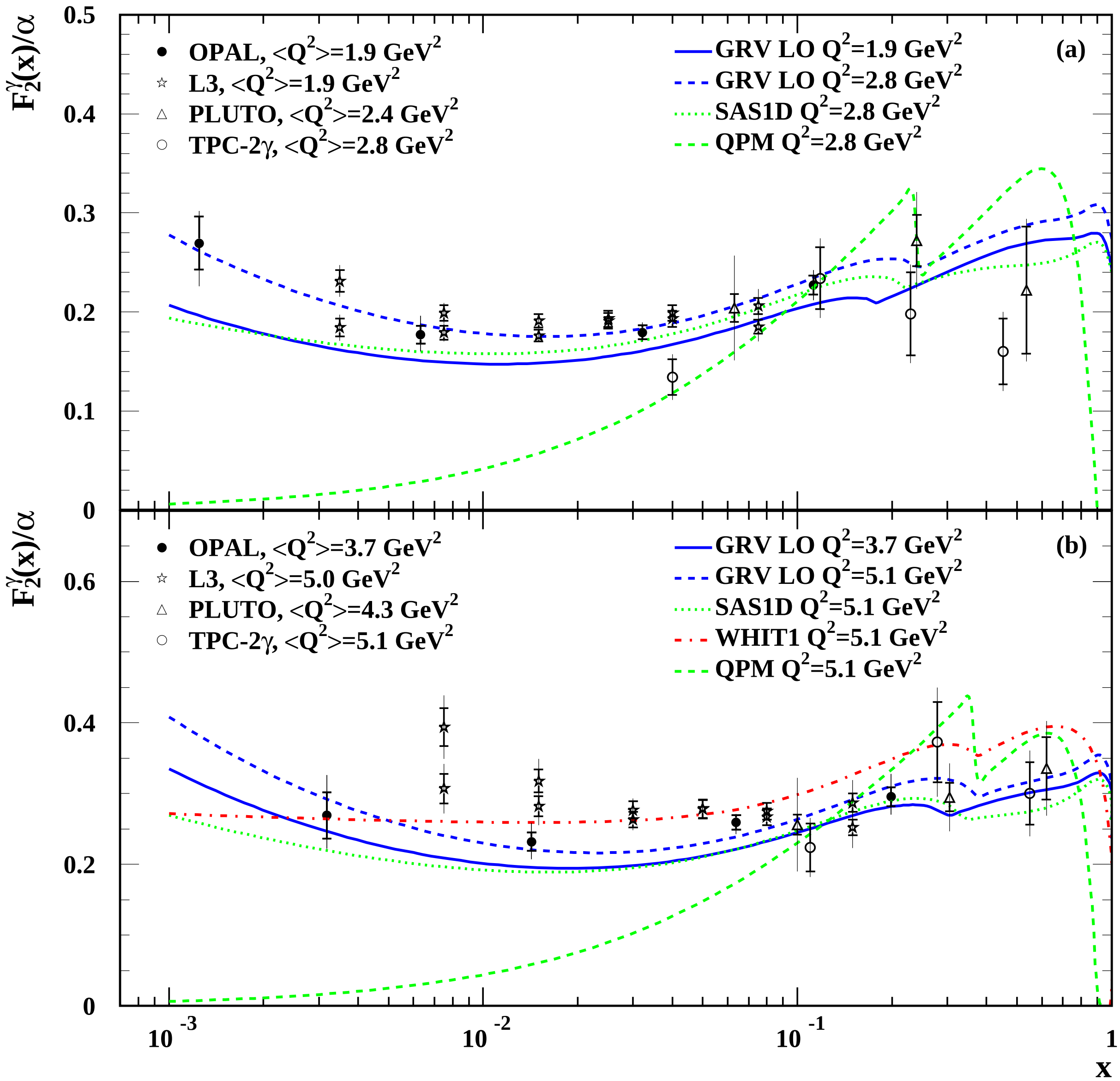
OPAL Collab., Eur. Phys. J. C16 (2000) 579. (updated)

$F_{2,c}^{\gamma}$ at the Linear Collider



$E_{\rm tag}/E_{\rm b} > 0.5, \theta_{\rm tag} > 40$ **mrad**, $m_{\rm c} = 1.5$ GeV, $\mu = Q$

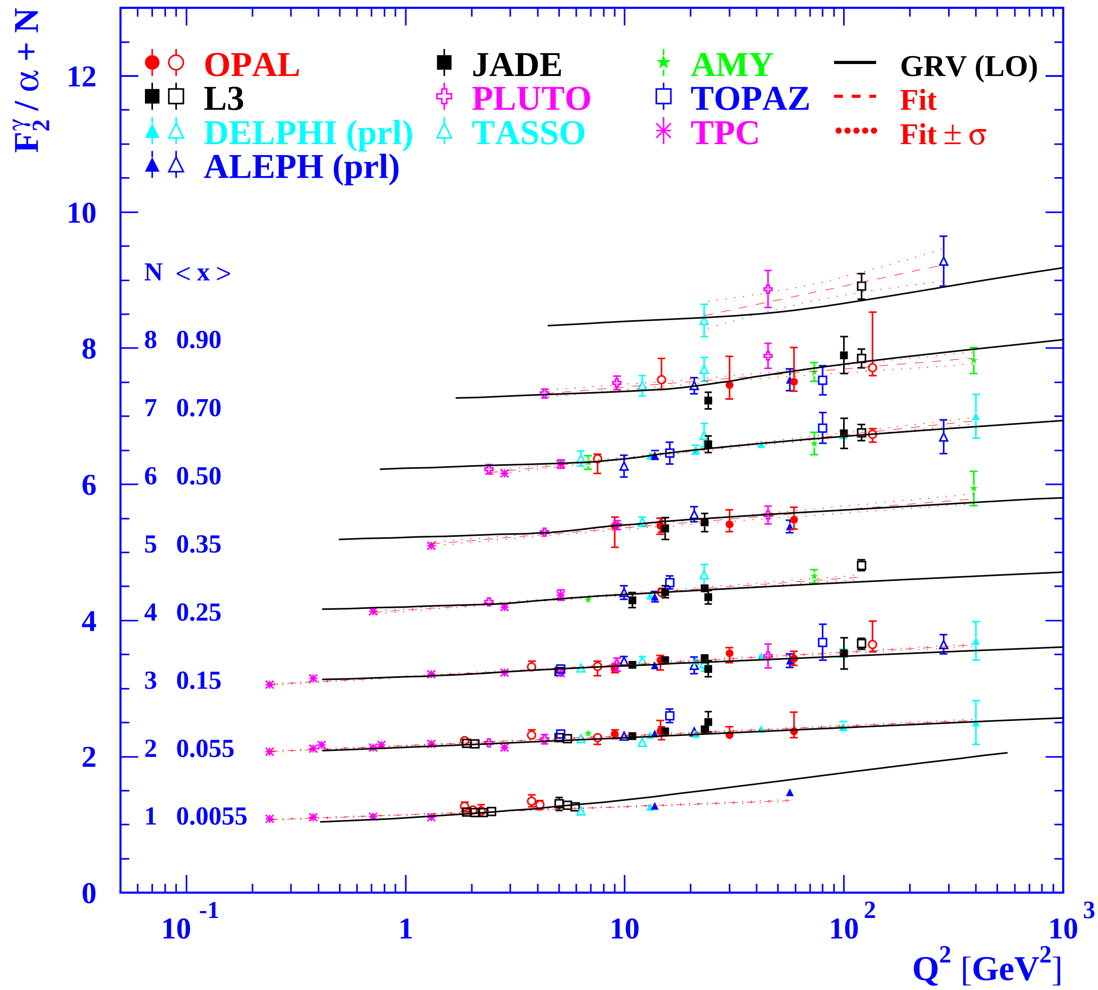
Measurements at low Q^2 and x

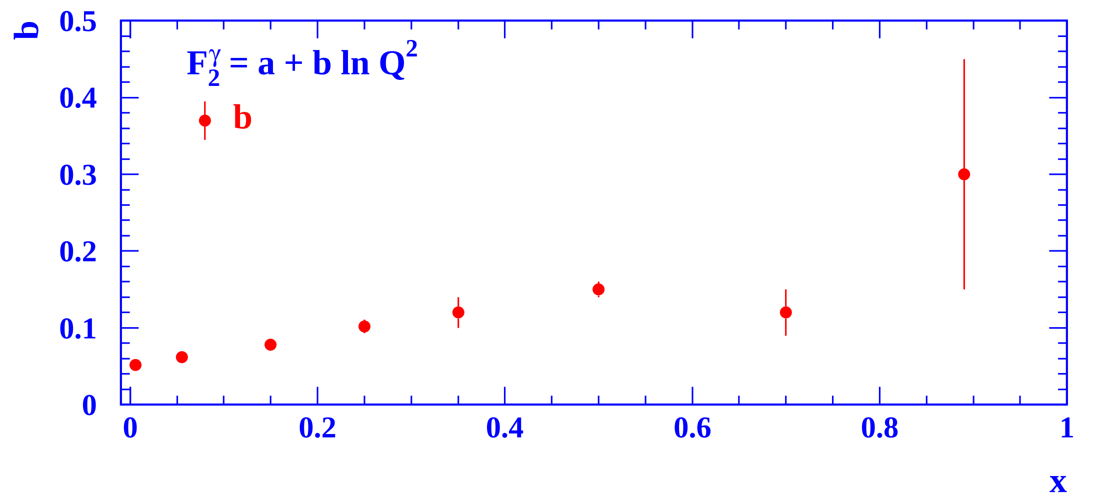


GRV(LO) and SaS1D are slightly too low compared to the data.

OPAL Collab., Eur. Phys. J. C18 (2000) 15.

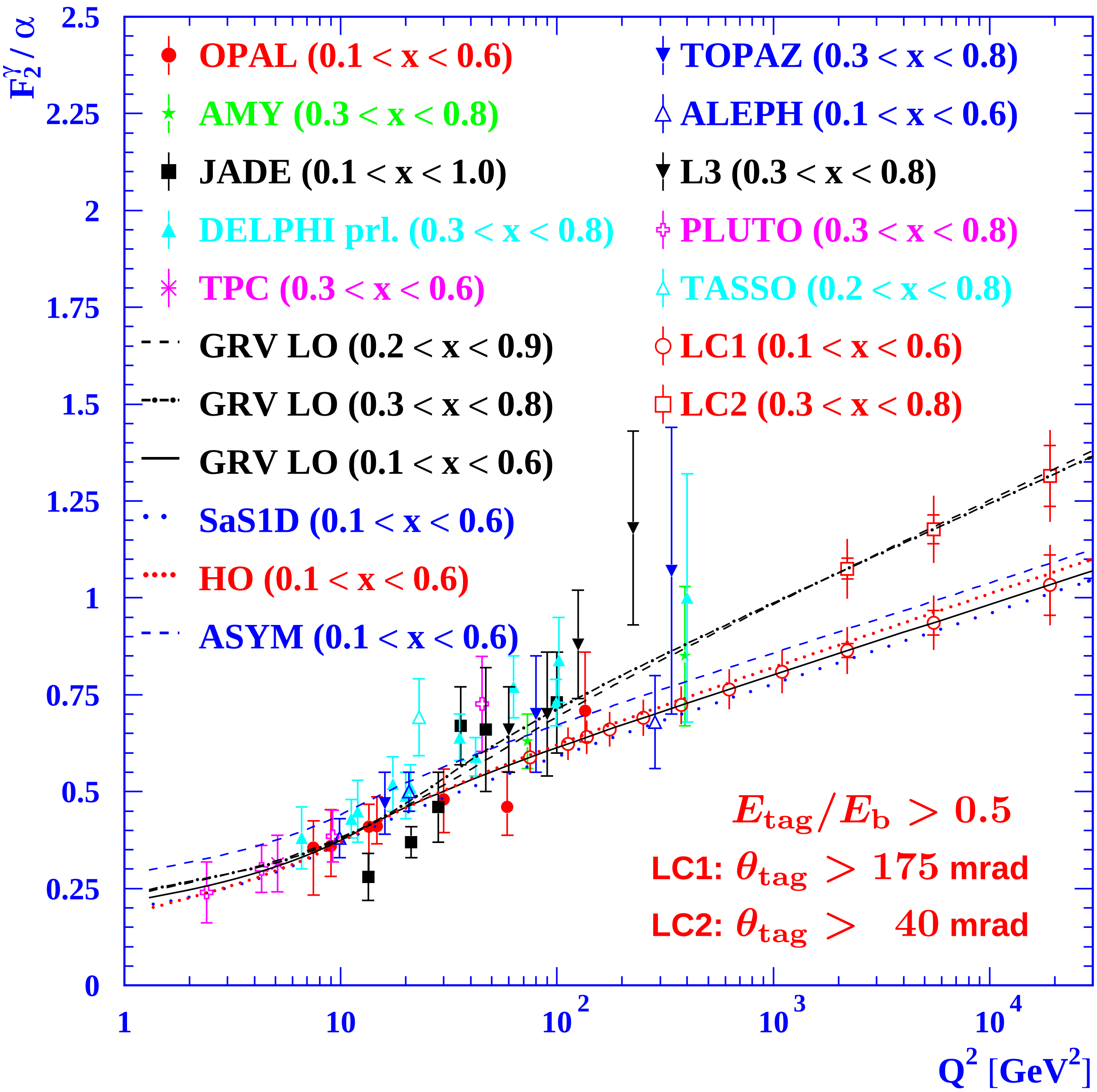
Q^2 evolution compared to linear fits





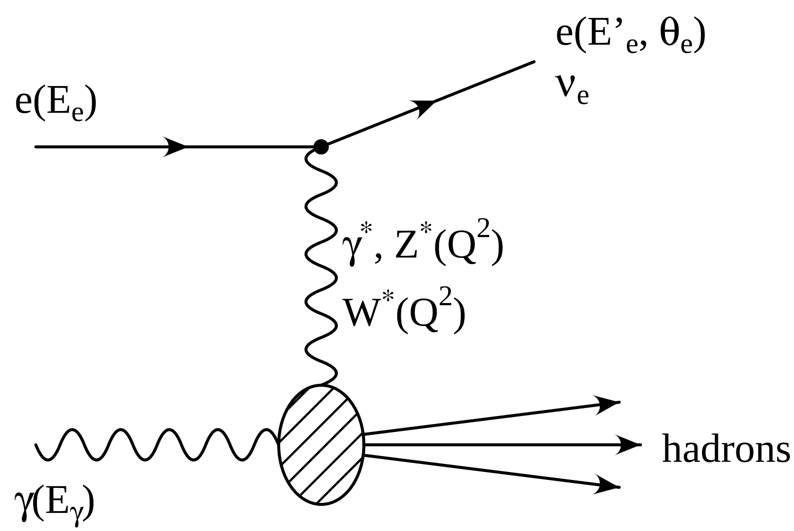
An increasing slope as a function of x is observed.

The future of the F_2^γ measurement



The Linear Collider will play an important role in testing this fundamental prediction of perturbative QCD.

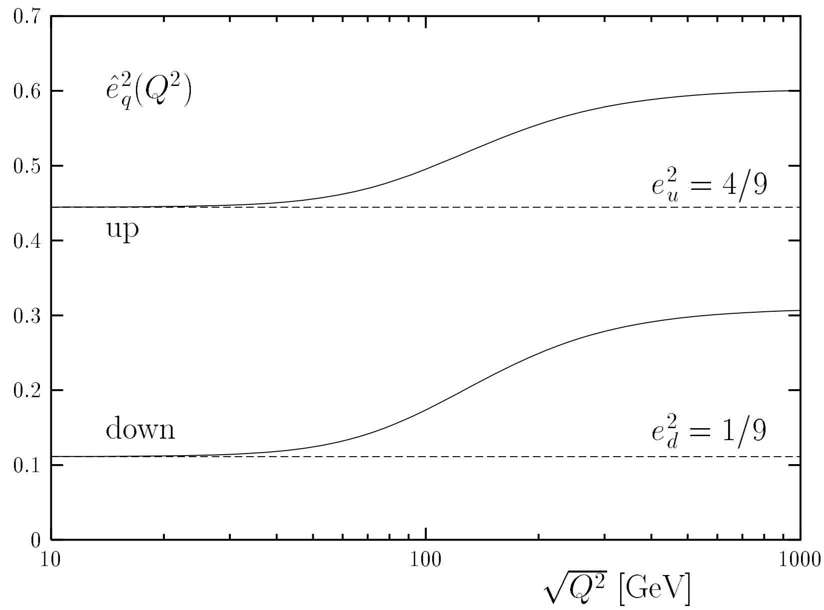
Flavour decomposition of F_2^γ



$$\frac{d\sigma}{dx\,dy}(e\gamma \to eX) \;\propto\; \sum_{q=u..}^{b} \hat{e}_q^2\, x\, q(x, Q^2)$$

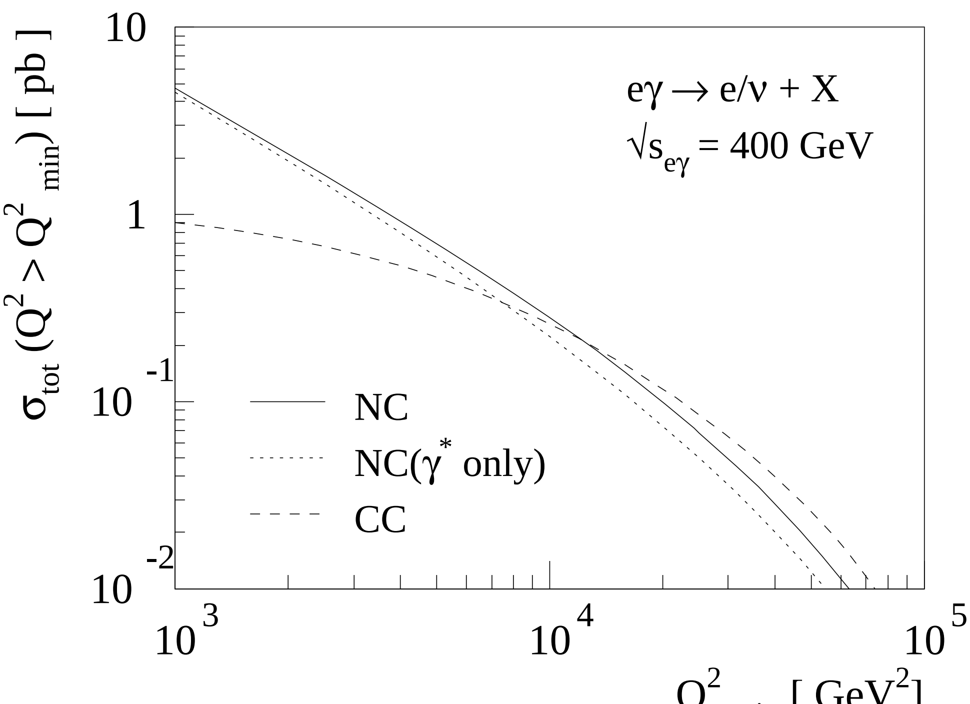
$$\frac{d\sigma}{dx\,dy}(e\gamma \to \nu_e X) \;\propto\; x\,\left[(u+c) + (1-y)^2\,(d+s)\right]$$

Effective charge and cross-section



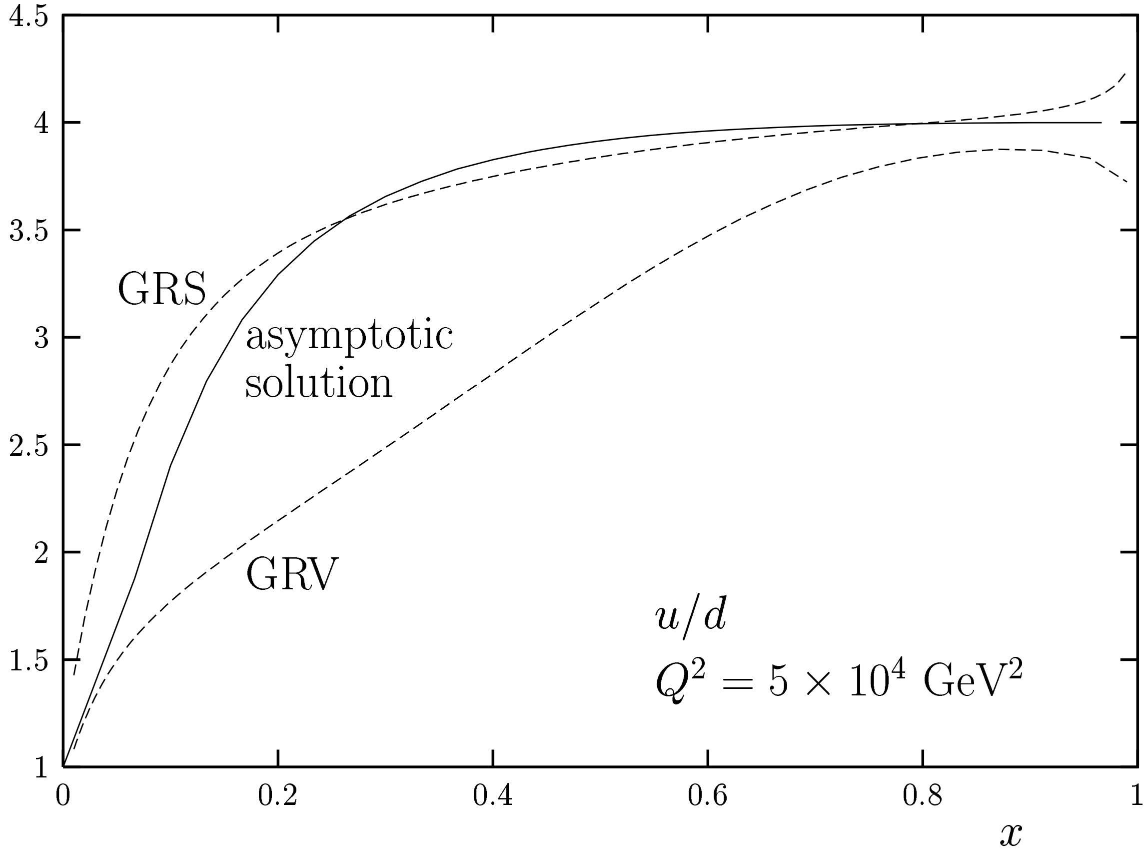
$\mathbf{0.44 \longrightarrow 0.60}$

$\mathbf{0.11 \longrightarrow 0.31}$



This gives 10^4 CC and $4 \cdot 10^4$ NC events per year.

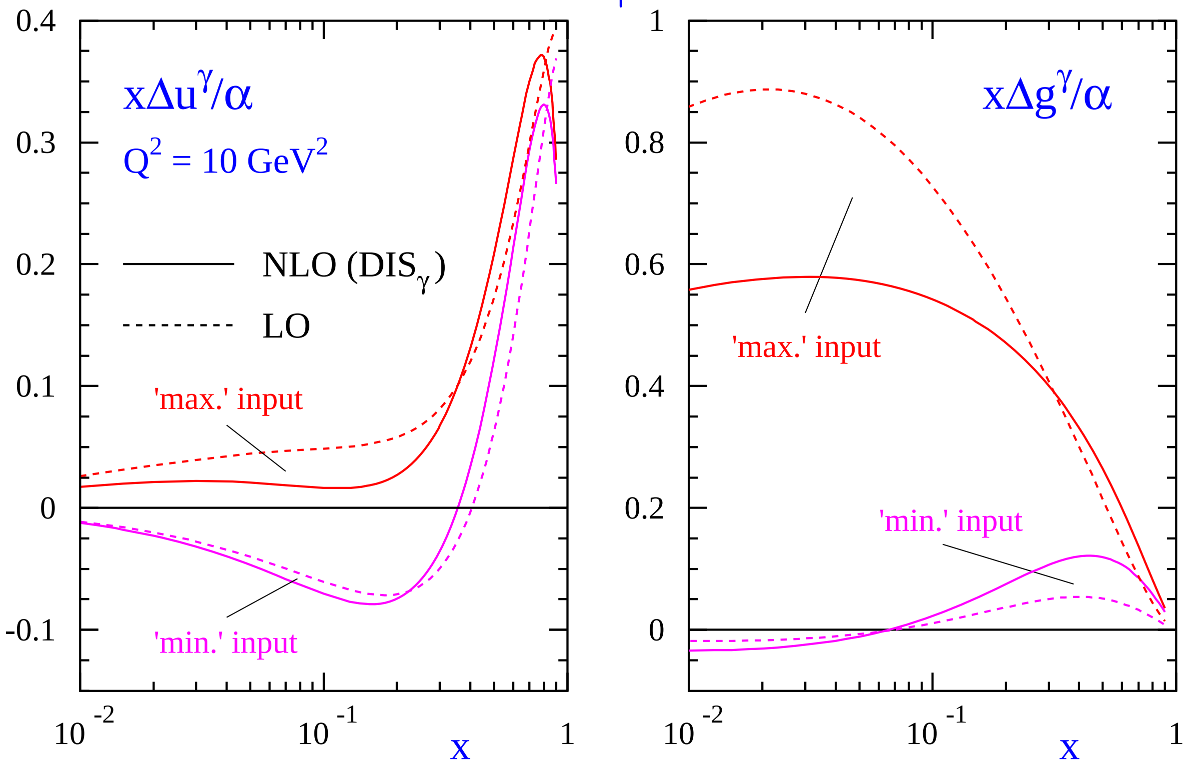
Predictions of the u to d ratio



At present the predictions for the u to d ratio vary within a factor of 2 to 3.

Polarized parton distributions

Definition: $\Delta f^{\gamma} \equiv f_{+}^{\gamma+} - f_{-}^{\gamma+}$ for $f = q, \bar{q}, g$



Asymmetries: $\frac{\Delta\sigma}{\sigma} \equiv \frac{\sigma(++)-\sigma(+-)}{\sigma(++)+\sigma(+-)}$

At present we have NO experimental information on Δf^{γ}.

Constraint: $\Delta\sigma \leq \sigma \Rightarrow |\Delta f^{\gamma}(x, Q^2)| \leq f^{\gamma}(x, Q^2)$

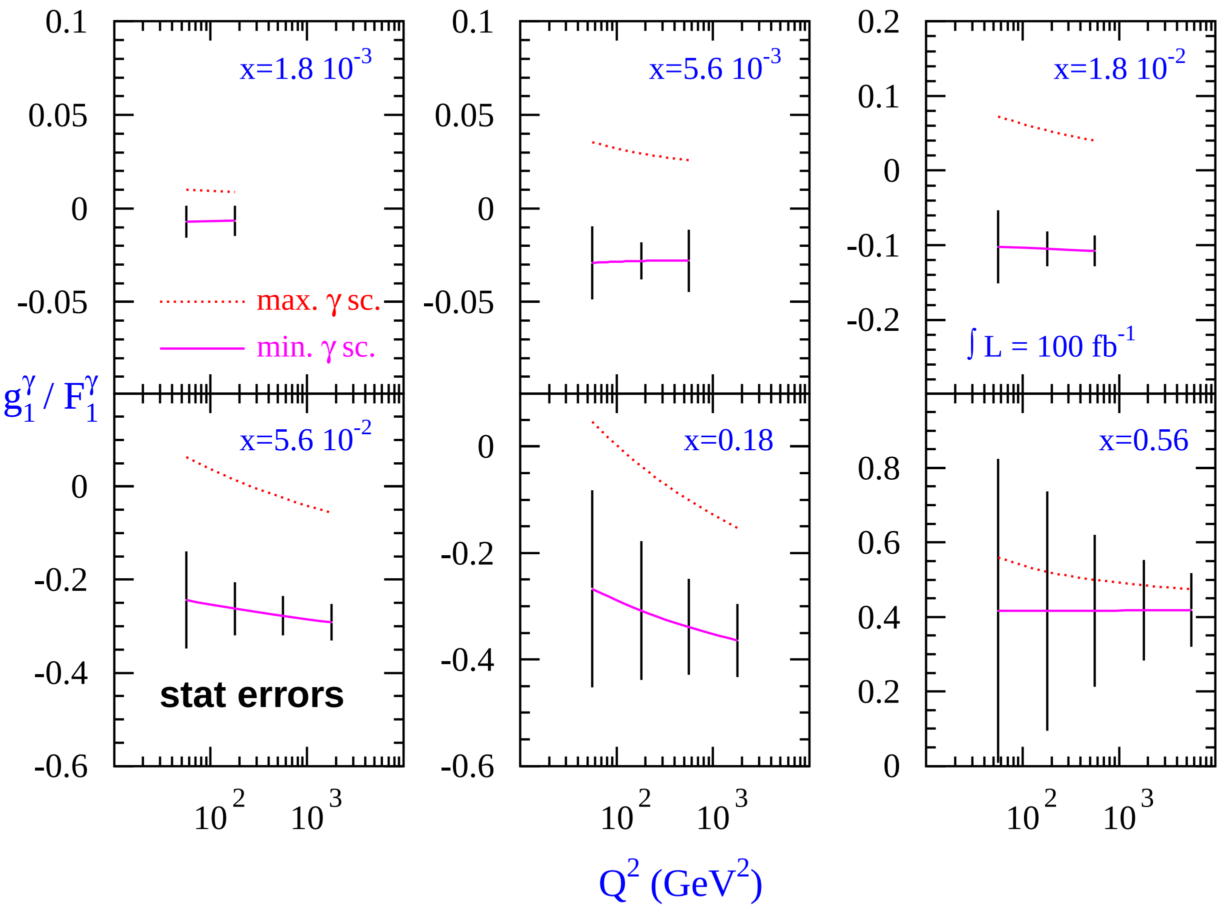
Fullfilled for $\Delta f^{\gamma}_{\mathrm{point-like}}$ but needs to be enforced for $\Delta f^{\gamma}_{\mathrm{hadron-like}}$.

Choices:

$$\Delta f^{\gamma}_{\mathrm{hadron-like}}(x, \mu^2) = \begin{cases} f^{\gamma}(x, \mu^2) & \text{('max input')} \\ 0 & \text{('min input")} \end{cases}$$

Experimental information is highly desirable.

The ratio g_1^γ / F_1^γ from DIS

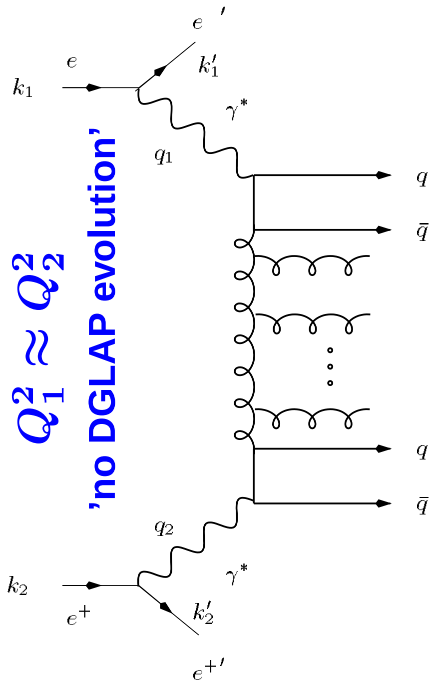


Asymmetry: $\frac{\Delta\sigma}{\sigma} \propto \frac{g_1^\gamma}{F_1^\gamma}$

with: $g_1^\gamma \propto \Delta q^\gamma + \alpha_s \Delta g^\gamma$

The structure function g_1^γ is mainly sensitive to quarks. Use F_1^γ from unpolarized DIS to determine the polarized distribution function Δq^γ.

$\sigma_{\gamma^\star\gamma^\star}$ as a signal of BFKL



$Q_1^2 \approx Q_2^2$
'no DGLAP evolution'

$$y_1 = \frac{q_1 k_2}{k_1 k_2}, \quad Q_1^2 = -q_1^2$$

$$s = (k_1 + k_2)^2, s_0 = \frac{\sqrt{Q_1^2 Q_2^2}}{y_1 y_2}$$

$$\hat{s} = W^2 \approx s\, y_1 y_2$$

1) Take $Q_i^2 \gg \Lambda^2_{\mathrm{QCD}}$ and $Q_1^2 \approx Q_2^2$ to allow for a perturbative prediction without DGLAP evolution.

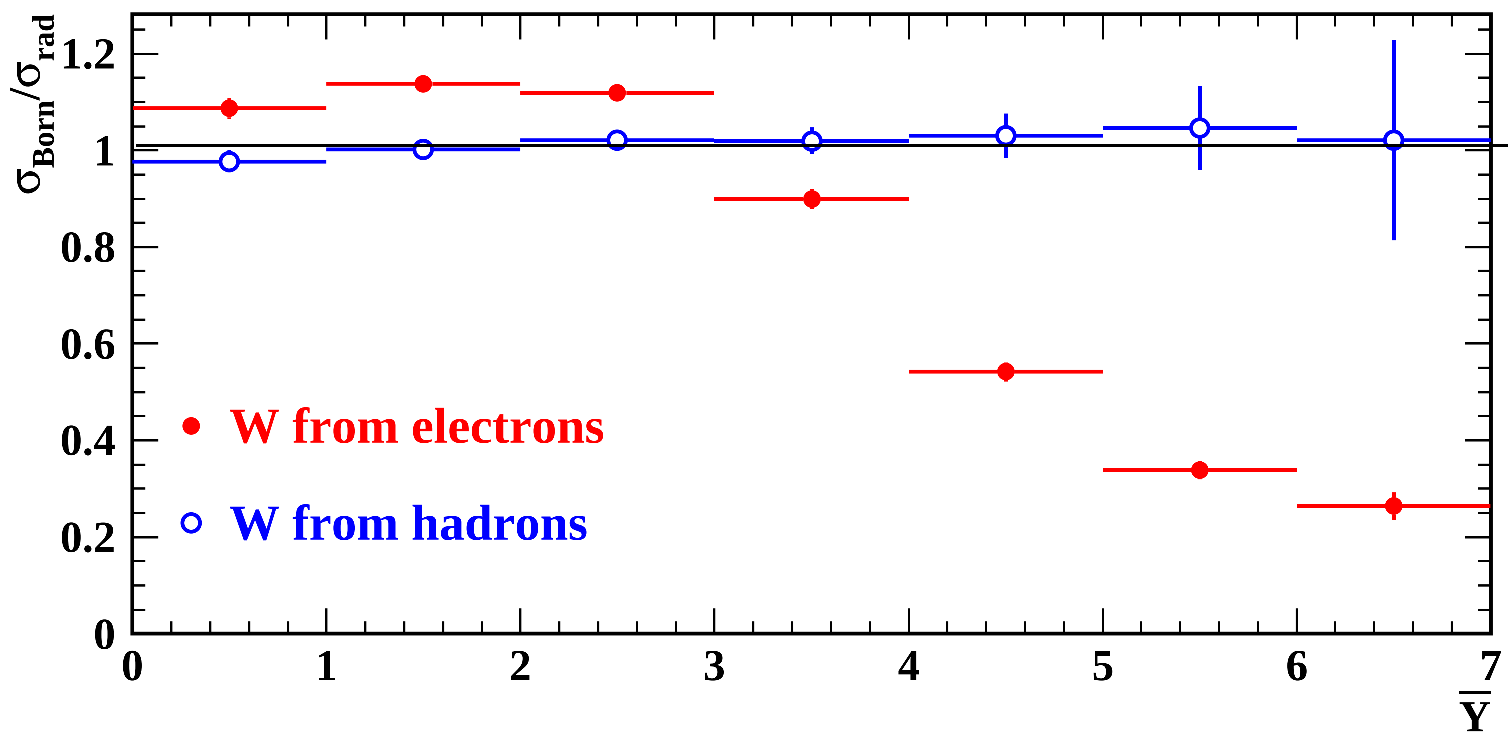
2) Look at a region where the phase space for gluon emission is large $\Rightarrow$ $W^2 \gg Q_1^2, Q_2^2$.

3) Define:

$$Y = \ln\left(\frac{s y_1 y_2}{\sqrt{Q_1^2 Q_2^2}}\right) \simeq \ln\left(\frac{W^2}{\sqrt{Q_1^2 Q_2^2}}\right) = \overline{Y},$$

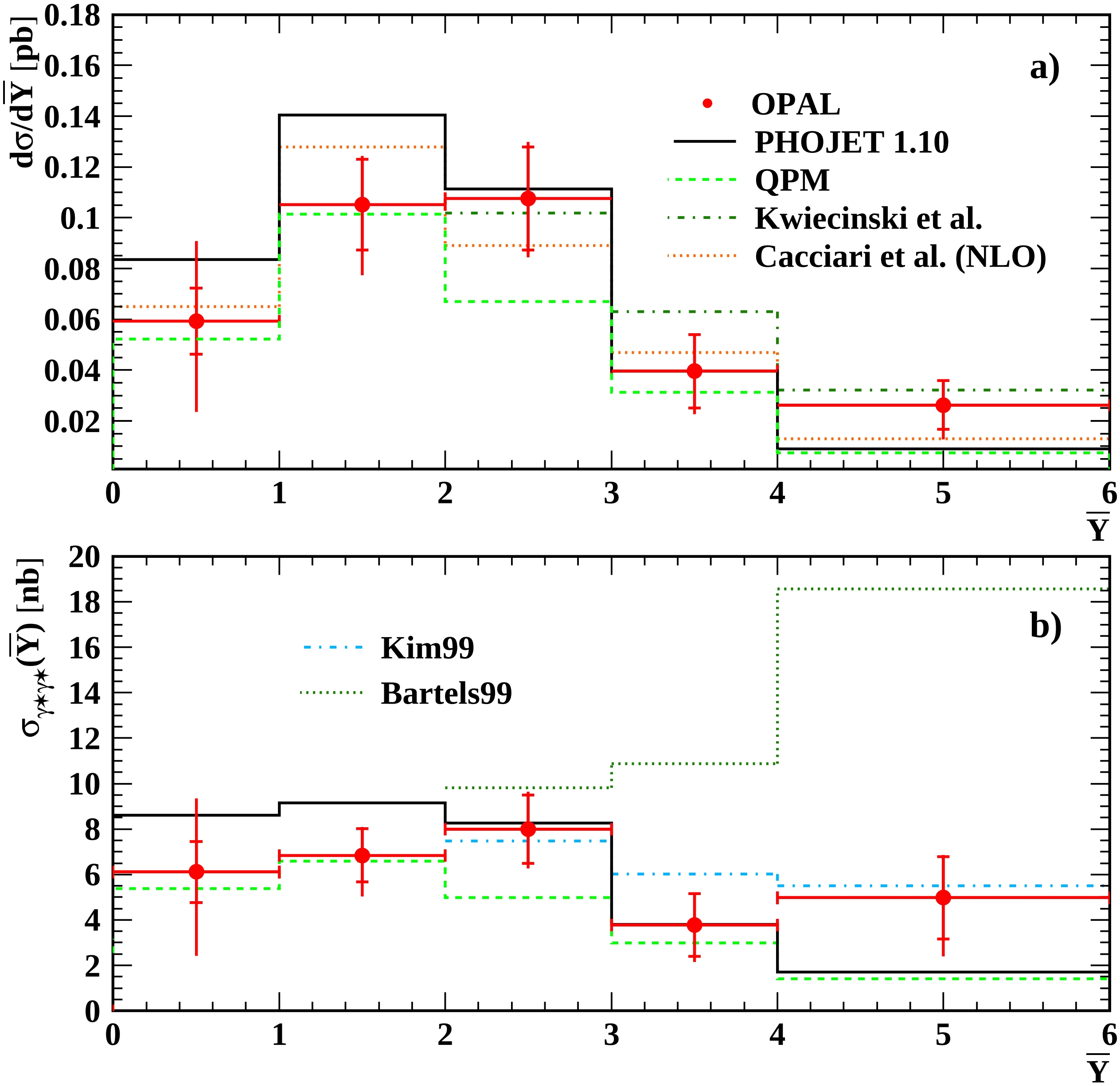
and measure the cross-section as a function of $Y\, or \overline{Y}$.

The importance of QED radiative corrections



Radiative corrections are only important for the electron method, and they are large at large Y which means at low electron energies.

$\sigma_{\gamma^\star\gamma^\star}$ from OPAL

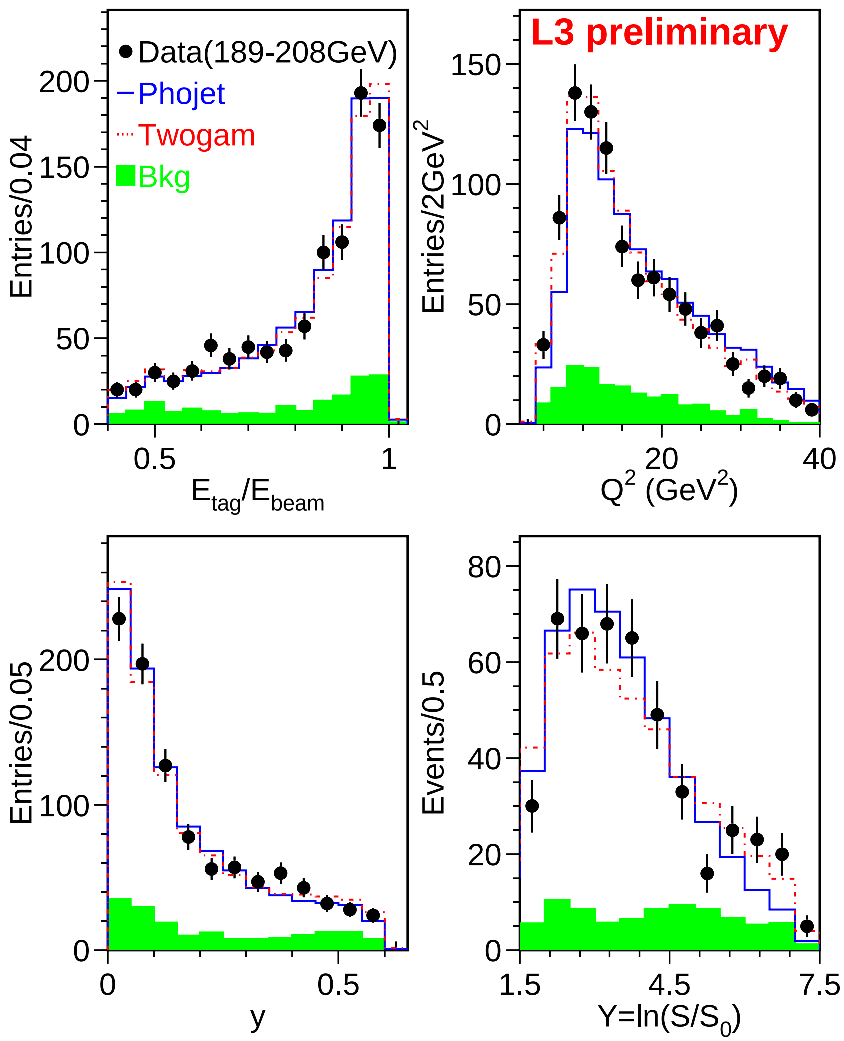


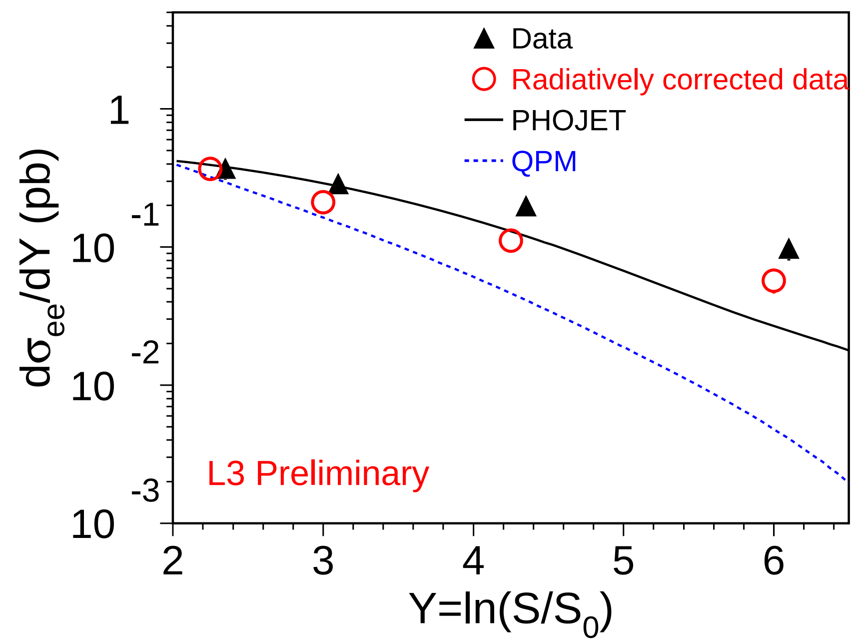
1) Bartels99 $\Rightarrow$ LO BFKL is too high.

2) Cacciari et. al $\Rightarrow$ NLO DGLAP QCD is sufficient.

3) Kwiecinski et. al $\Rightarrow$ HO BFKL also fits the data.

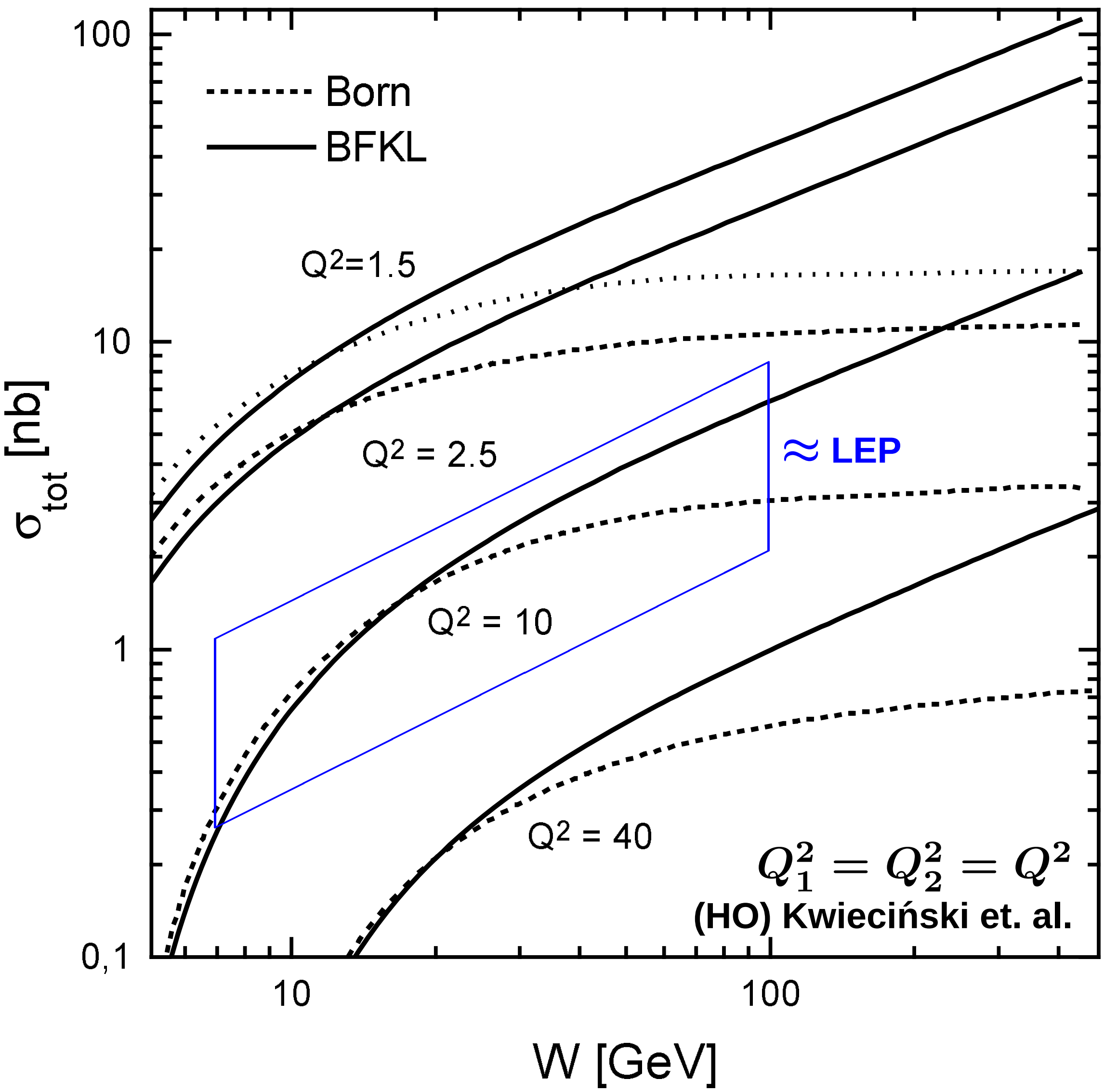
Double tag hadronic cross-section from L3





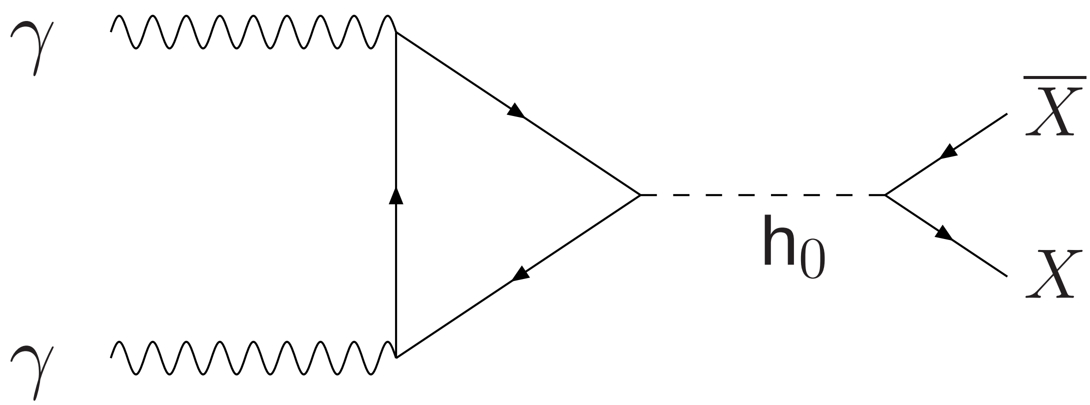
Some excess is seen at large Y

BFKL expectation for large W



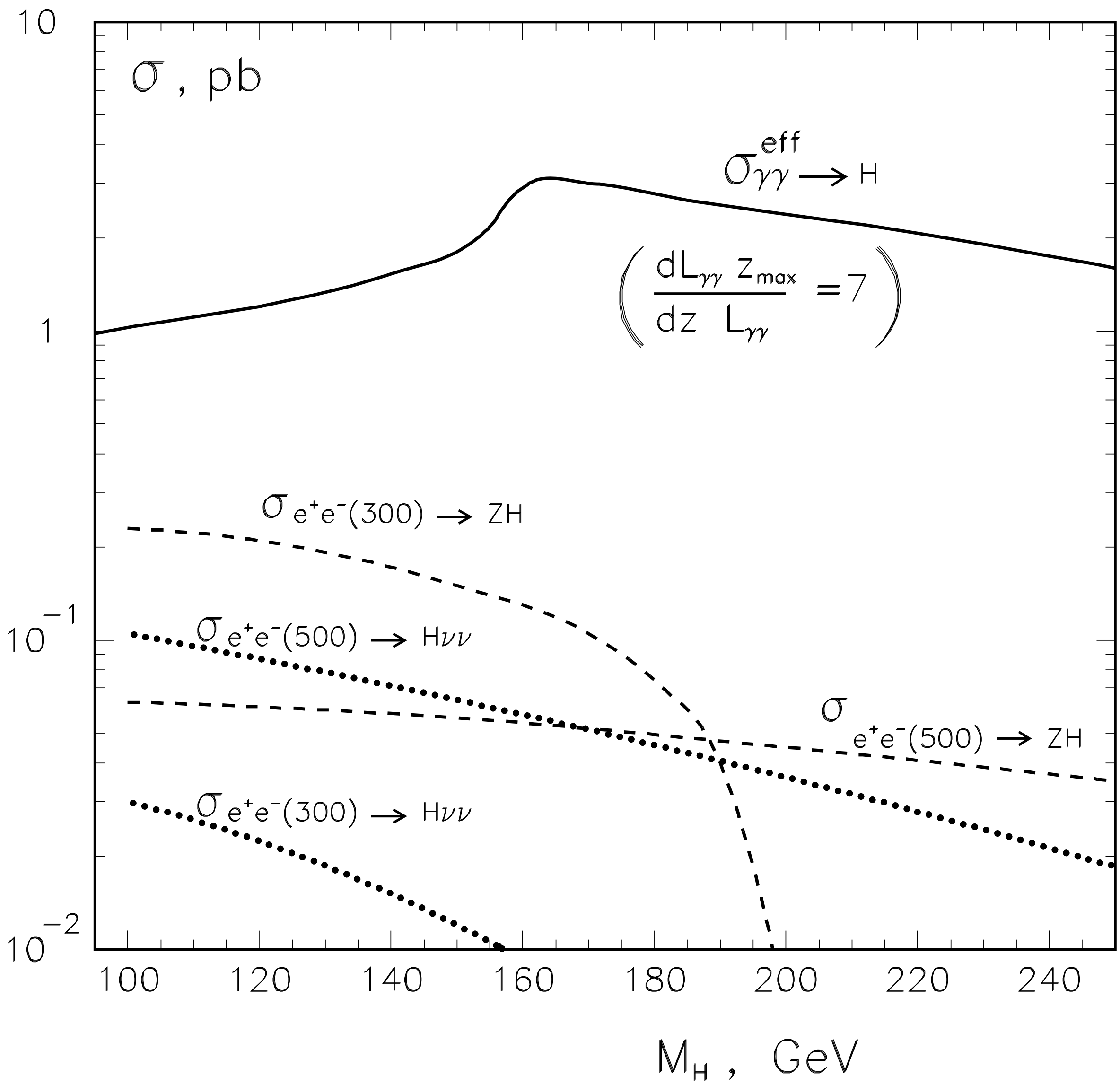
1) LEP probes the region for W up to about 100 GeV and $\langle Q^2 \rangle \approx 15\ \mathrm{GeV}^2$.
2) The Linear Collider will extend the region to larger W^2 for moderate Q^2, giving access to large Y.

Higgs search in $\gamma\gamma \rightarrow h_0 \rightarrow \mathrm{X\overline{X}}$



1. The Higgs is produced as an s-channel resonance. A measurement of $\Gamma(\gamma\gamma \rightarrow h_0)$ is very fundamental as it is sensitive to all charged particles in the loop which couple to the Higgs.
2. The required accuracy for $\Gamma(\gamma\gamma \rightarrow h_0)$ is at the few percent level to be sensitive to new particles in the decoupling limit.
3. Combined measurements of $\Gamma(\gamma\gamma \rightarrow h_0)$ and $\mathrm{BR}(h_0 \rightarrow \gamma\gamma)$ at the e^+e^- and $\gamma\gamma$ collider provide a model independent measurement of the total width of the Higgs.

Higgs production $\gamma\gamma \to h_0$



$$\sigma^{\rm eff}_{\gamma\gamma} = \frac{\mathrm{d}L_{\gamma\gamma}}{\mathrm{d}W_{\gamma\gamma}}\frac{M_{h_0}}{L_{\gamma\gamma}}\frac{4\pi^2\Gamma(\gamma\gamma \to h_0)(1-\lambda_1\lambda_2)}{M^3_{h_0}}$$

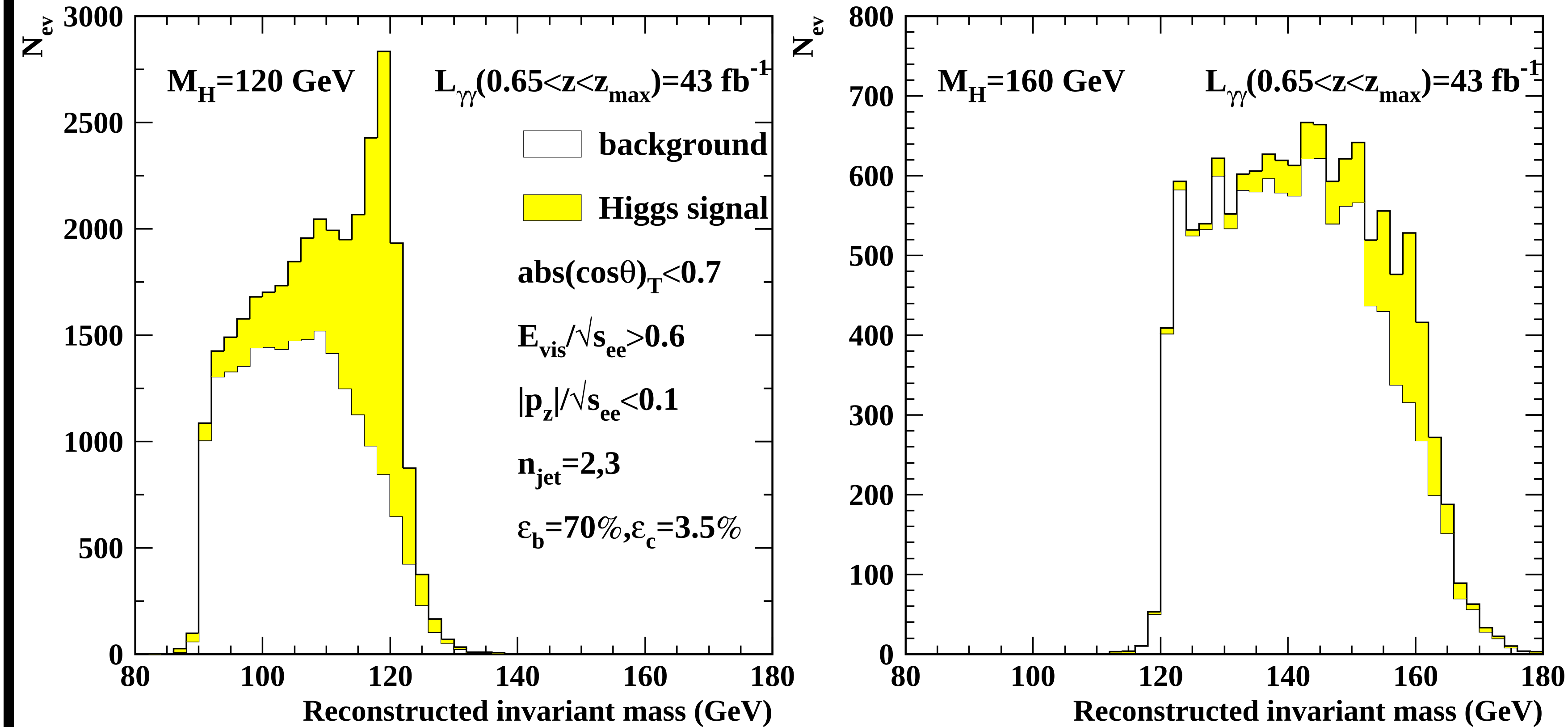
Good prospects for $\gamma\gamma$ production of Higgs bosons, because of the larger cross-section and the reach to higher masses than for e^+e^-.

The test case $\gamma\gamma \to h_0 \to \mathrm{b\bar{b}}$

1. To reduce the continuum production of $\mathrm{b\bar{b}}$ and $\mathrm{c\bar{c}}$ one needs to select $J_z = 0$, because then $\sigma(\gamma\gamma \to \mathrm{q\bar{q}}) \propto m_\mathrm{q}/W_{\gamma\gamma}$.
2. In addition, good b tagging and c suppression is mandatory.
3. Assume 100$\%$ laser and 85$\%$ electron polarization and run the collider at $\sqrt{s_\mathrm{ee}} = M_{h_0}/0.8$ such that the Higgs mass corresponds to the peak of the $\gamma\gamma$ luminosity spectrum.
4. Use additional cuts to further suppress the background.

For $L_{\gamma\gamma} = 43\ \mathrm{fb}^{-1}$ in the peak, which means about $400\ \mathrm{fb}^{-1}$ $\mathrm{e^+e^-}$ luminosity, $\Gamma(\gamma\gamma \to h_0)$ can be determined with a precision of about 2-10$\%$ in the mass range $120 < M_{h_0} < 160\ \mathrm{GeV}$.

Higgs reconstruction for $\gamma\gamma \to h_0 \to b\bar{b}$



Clear signals are observed, especially for low Higgs masses.

Conclusion

1. The Linear Collider is an ideal tool to investigate photon–photon physics at the highest energies.
2. The tagging of electrons down to the lowest possible angles is a challenging task, but it is mandatory to achieve overlap with the results from LEP II in several areas, i.e. structure function measurements.
3. Due to the high centre-of-mass energy, especially in the Photon Collider mode, new channels (Higgs, W, Z^0, LQ, ...) are open to be copiously produced.
4. For some of the reactions the Photon Collider extends the reach of a e^+e^- Collider significantly, and in some cases it is unique.

Much work is ahead of us to bring a Linear Collider to life, but it should be fun and the physics potential is certainly worth the effort.

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