Two-Photon Physics
with the OPAL detector

Richard Nisius, CERN

PPE Seminar, February 10, 1997

1. Photon-Photon scattering
   - Inclusive hadronic final states
2. Electron-Photon DIS
   - Lepton pairs and $F_{2,\mathrm{QED}}^{\gamma}$
   - The structure function $F_2^{\gamma}(x, Q^2)$

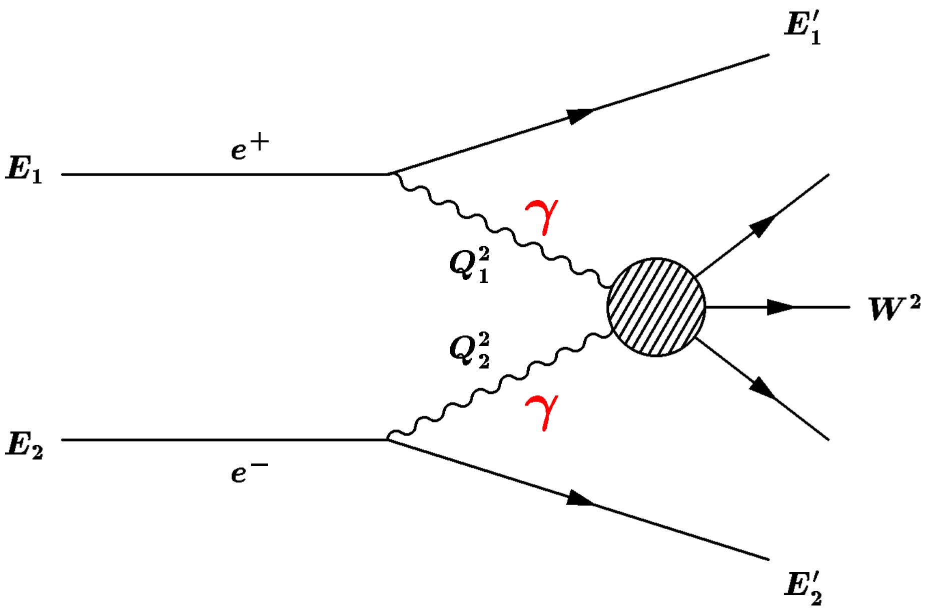
For the OPAL Collaboration

Analysis topics in Two-Photon events at LEP

	$\gamma\gamma$ scattering untagged events			$e\gamma$ scattering singly tagged events	
	exclusive hadronic f.s.	lepton pairs	$\gamma\,\gamma \longrightarrow$ hadrons	lepton pairs	$\gamma^\star\,\gamma \longrightarrow$ hadrons
A	$\mathrm{D}^*(2010)^\pm$		hadron flow		
D			hadron flow	μ $F^\gamma_{2,\mathrm{QED}}$	F^γ_2 hadron flow
L	$\mathrm{f}'_2(1525)\ \eta'(958)$ $\mathrm{a}_2(1320)\ \eta_c(2980)$ $\chi_{c2}(3555)$	$\mathrm{e}\,\mu\,\tau$	$\sigma(W_{\gamma\,\gamma})$	$\mathrm{e}\,\mu$ $F^\gamma_{2,\mathrm{QED}}$ az. correl.	
O			$\frac{\mathrm{d}\sigma}{\mathrm{d}\eta^{\mathrm{jet}}}\ \frac{\mathrm{d}\sigma}{\mathrm{dE}^{\mathrm{jet}}_{\mathrm{T}}}$	$\mathrm{e}\,\mu\,\tau$ $F^\gamma_{2,\mathrm{QED}}$ F^γ_{B} / F^γ_2	F^γ_2 hadron flow

preliminary published presented

Photon–photon scattering



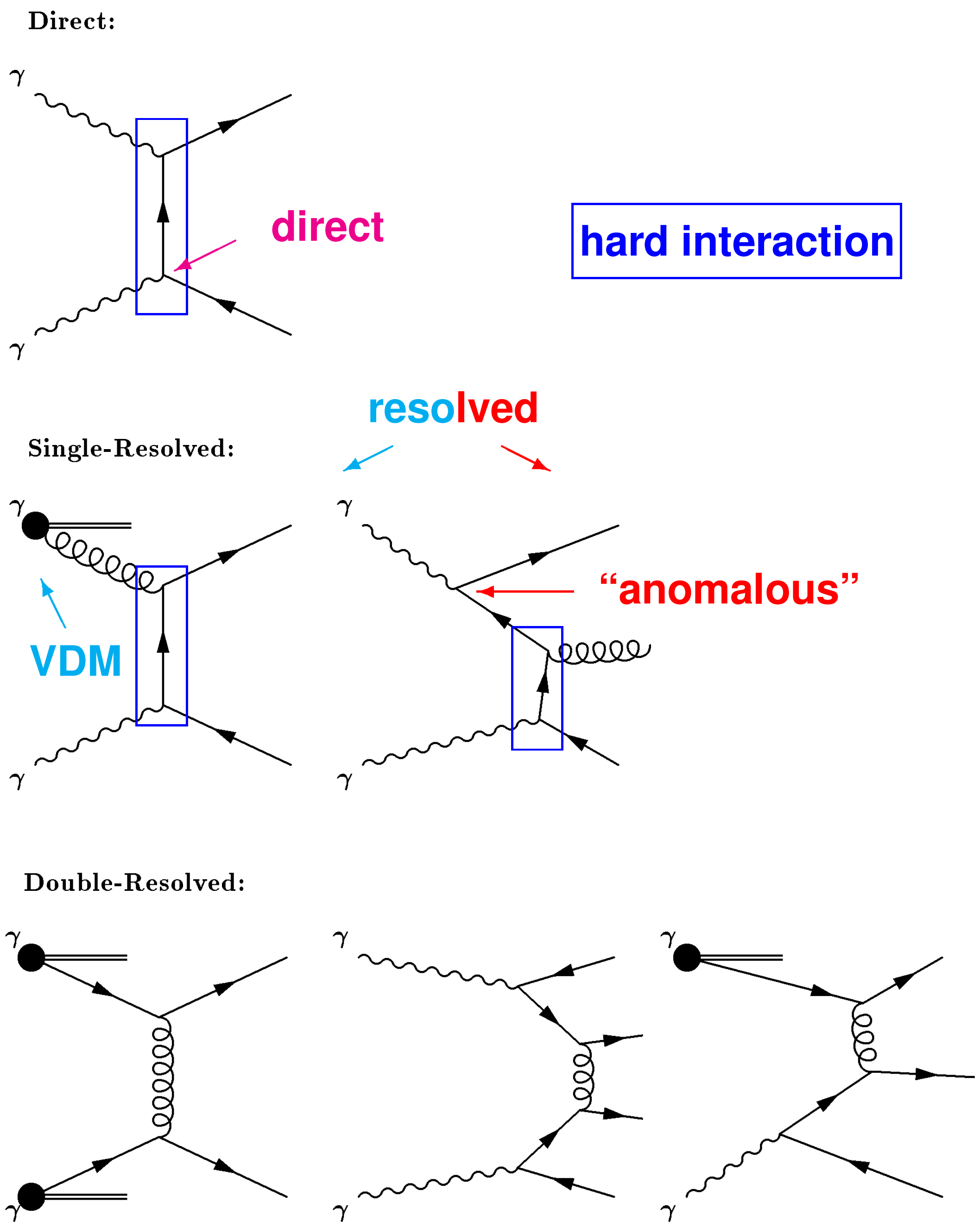
Exchange of two quasi-real photons (γ)

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

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

At $\sqrt{s_{ee}} = 130\,\mathrm{GeV}$, for $W^2 > 4\,\mathrm{GeV}^2$ and $Q_i^2 < 1\,\mathrm{GeV}^2$:
$\sigma(\mathrm{e}^+\mathrm{e}^- \to \mathrm{e}^+\mathrm{e}^- + hadrons) \approx 14\,nb \approx 40 \cdot \sigma(\mathrm{e}^+\mathrm{e}^- \to (\gamma, \mathrm{Z}^0) \to hadrons)$

Leading order diagrams



Monte Carlo models

PYTHIA 5.721 and PHOJET 1.05

Monte Carlo ingredients:

1. Leading order (LO) QCD matrix elements
2. Hard and soft processes
3. Total cross sections from Regge models
4. Initial state parton radiation
5. Fragmentation based on by JETSET 7.408
6. Multiple interactions

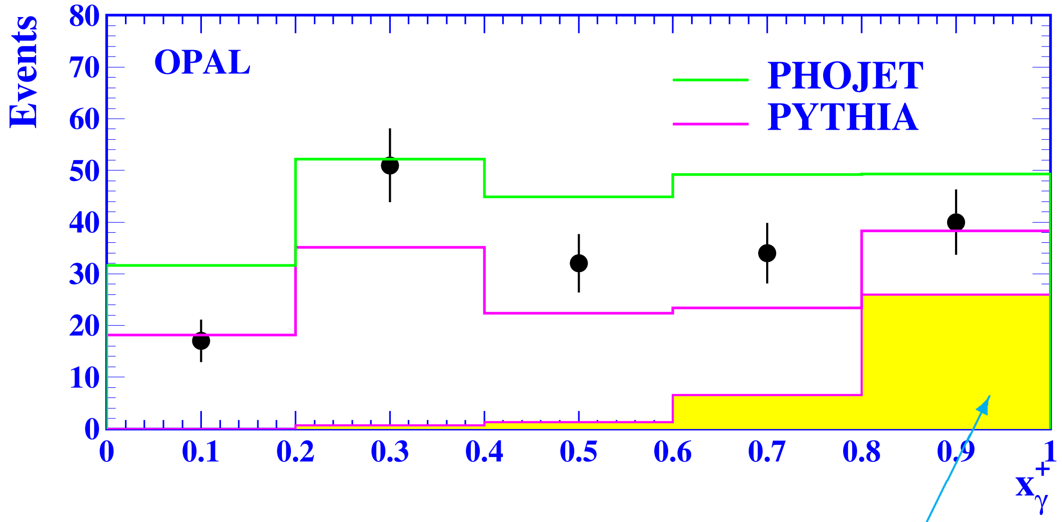
NLO calculations

- NLO calculations for inclusive jet cross sections by T. Kleinwort and G. Kramer, DESY-96-035 (1996), hep-ph/9509321 and Phys. Lett. B370 (1996) 141, hep-ph/9602418.

The x_γ distribution for 2–jet events at $\sqrt{s_{ee}}$ = 133 GeV

x_γ is the fraction of the photon momentum participating in the hard interaction

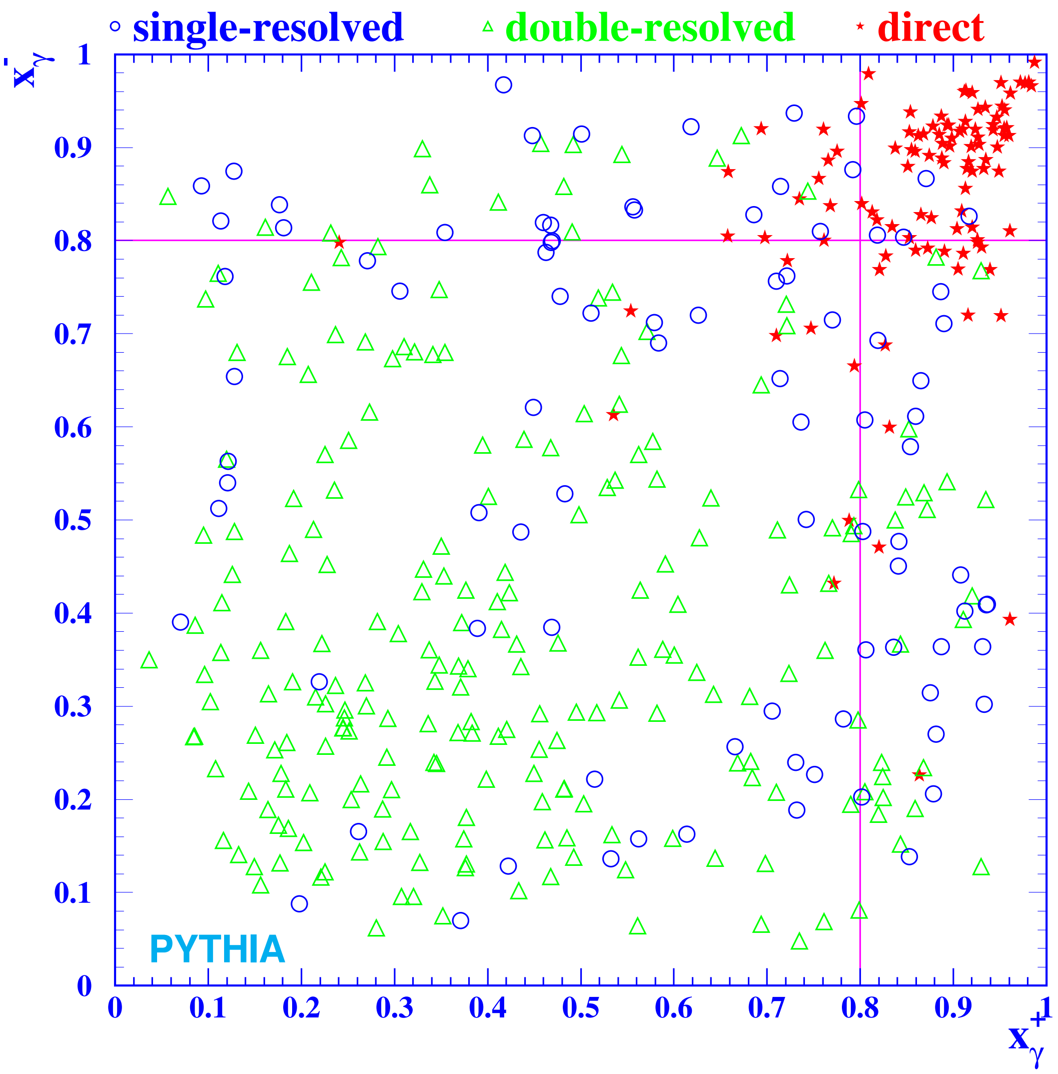
$$x_\gamma^\pm = \frac{\sum_{\mathrm{jets}}(E \pm p_z)}{\sum_{\mathrm{hadrons}}(E \pm p_z)}$$



Direct events : $x_\gamma \equiv 1$ no remnant jet

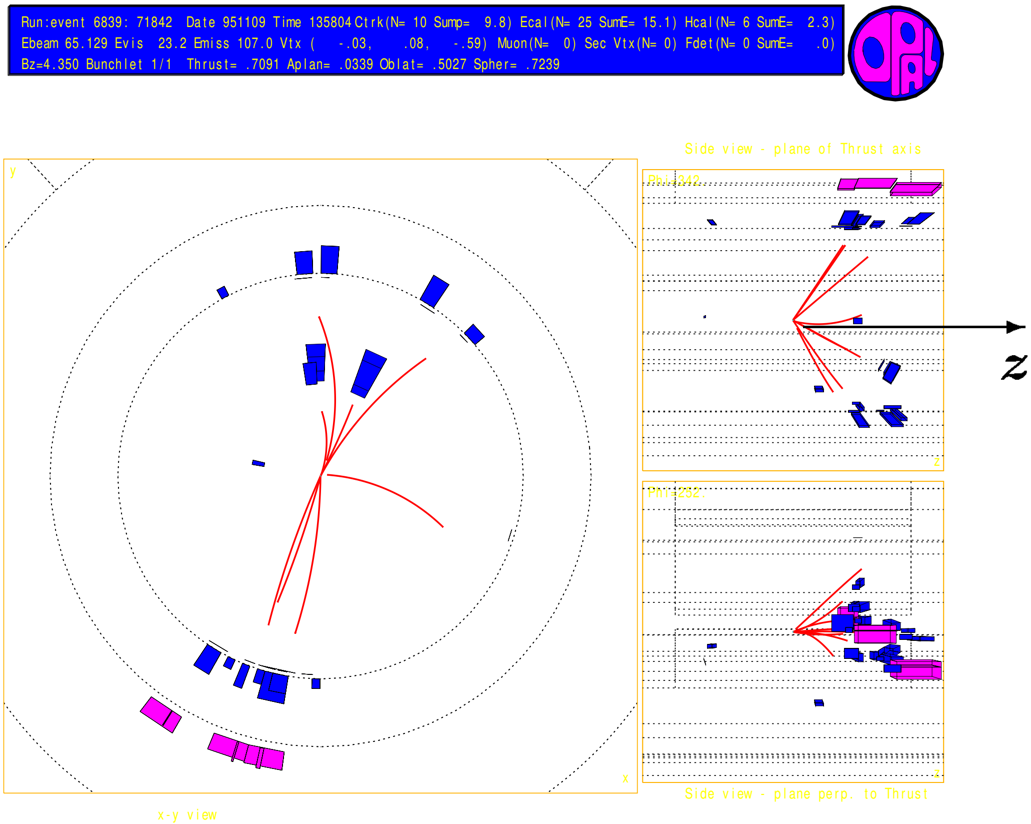
Resolved events : $x_\gamma < 1$ remnant jets possible

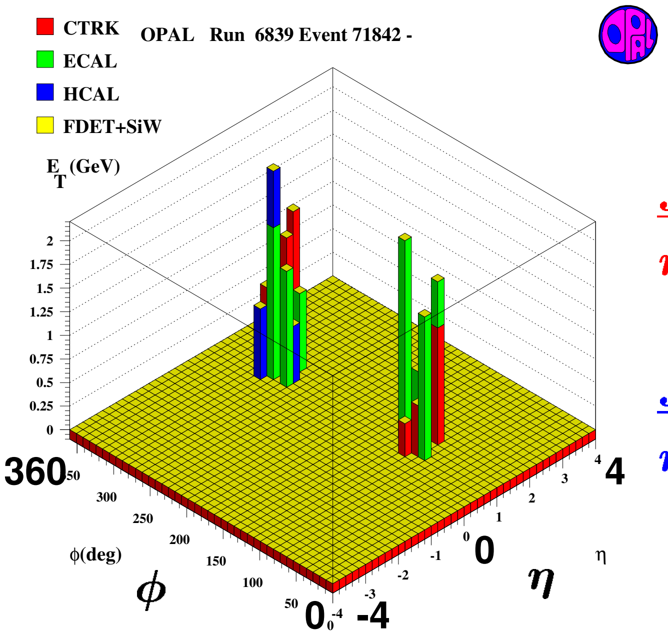
The separation of event classes at $\sqrt{s_{ee}}$ = 133 GeV



$$x_\gamma^\pm = \frac{\sum_{\mathrm{jets}}(E \pm p_z)}{\sum_{\mathrm{hadrons}}(E \pm p_z)}$$

A direct two-jet event





***Jet* 1 :**

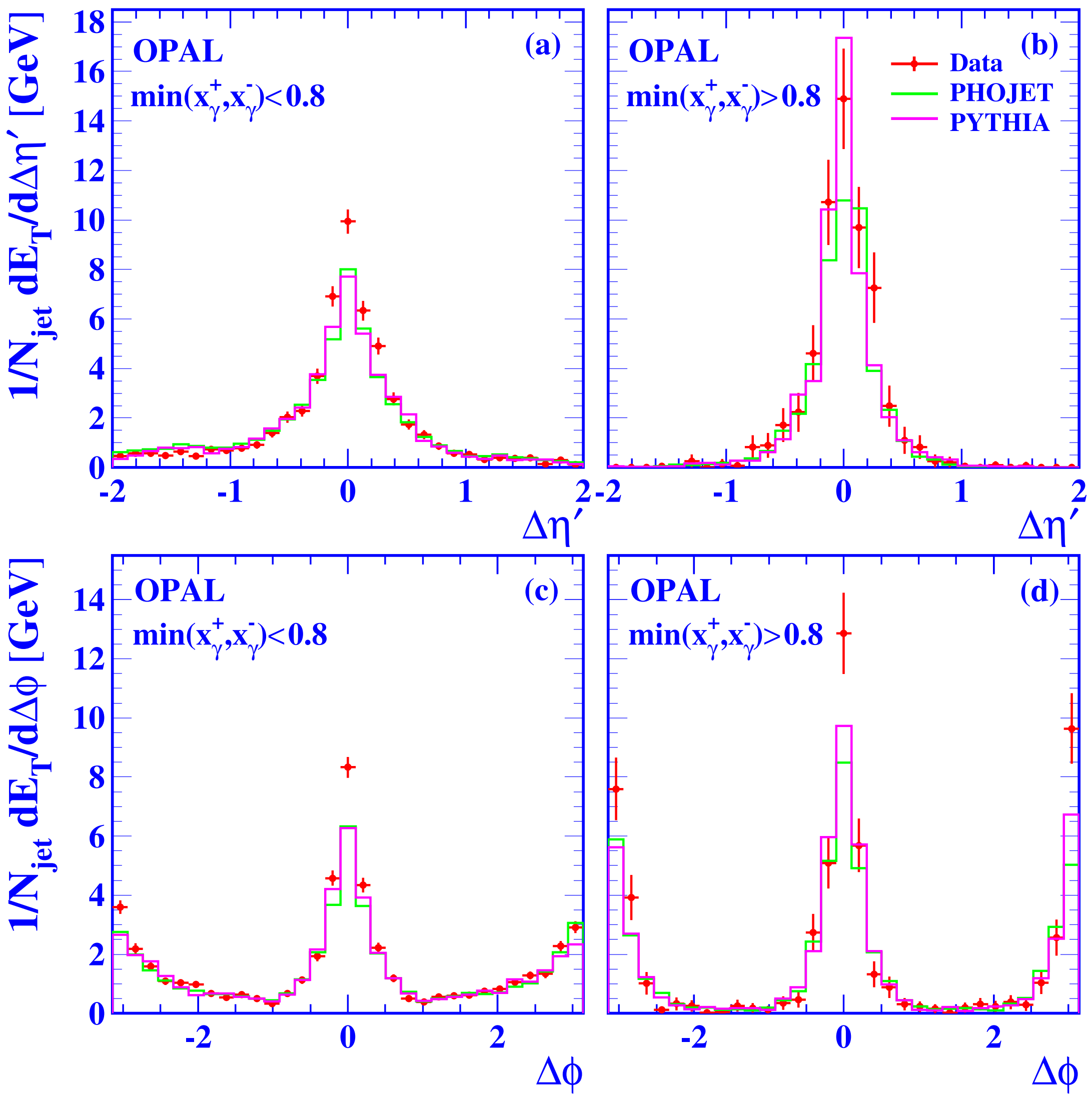
$\eta = 0.9,\ E_T^{\rm jet} = 6.6\ \mathrm{GeV}$

***Jet* 2 :**

$\eta = 0.7,\ E_T^{\rm jet} = 6.9\ \mathrm{GeV}$

The energy flow for 2–jet events

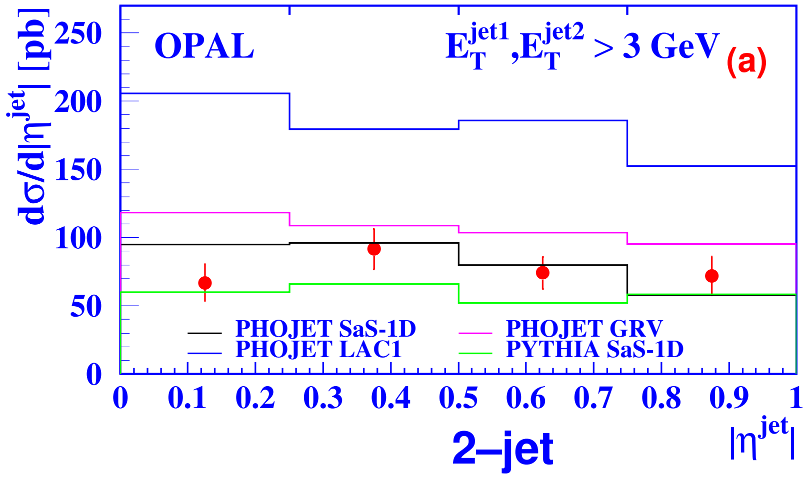
$$\Delta\eta' = \pm(\eta - \eta_{\rm jet})$$



"resolved" ⟷ "direct"

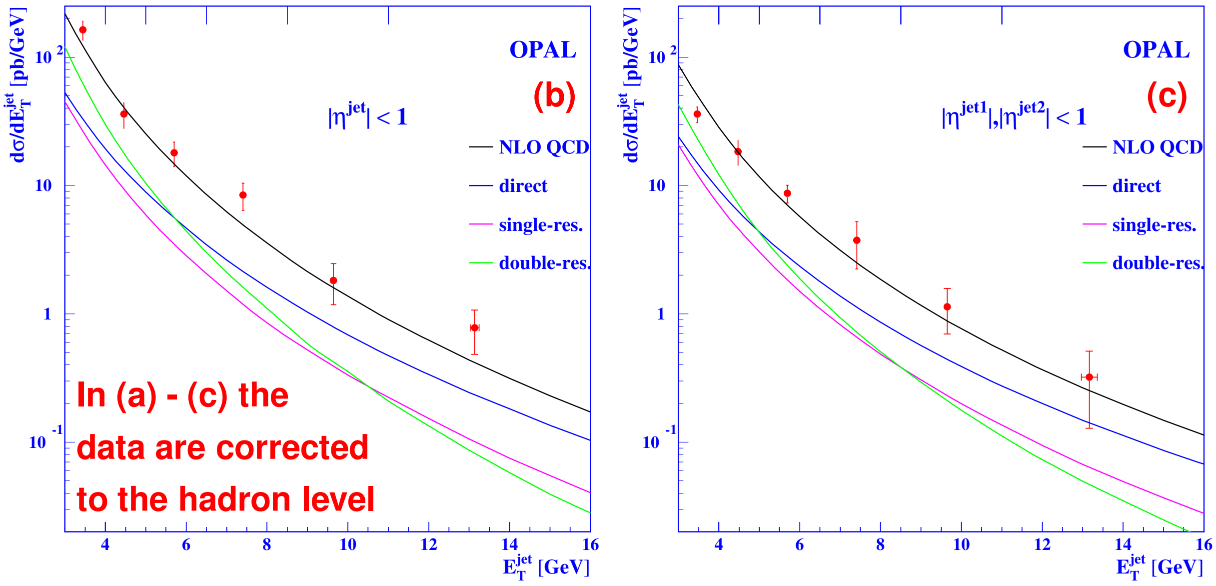
The inclusive jet cross-sections at $\sqrt{s_{ee}} = 133\,\mathrm{GeV}$

$\frac{d\sigma}{d\eta^{jet}}$ compared to *Monte Carlo models*



2–jet

$\frac{d\sigma}{dE_T^{jet}}$ compared to *NLO Calculations*



1–jet ⟷ **2–jet**

Systematic error determination

1. ECAL energy scale varied by $\pm 5\%$
2. Degradation of track resolution in MC
3. Unfolding using PYTHIA and PHOJET

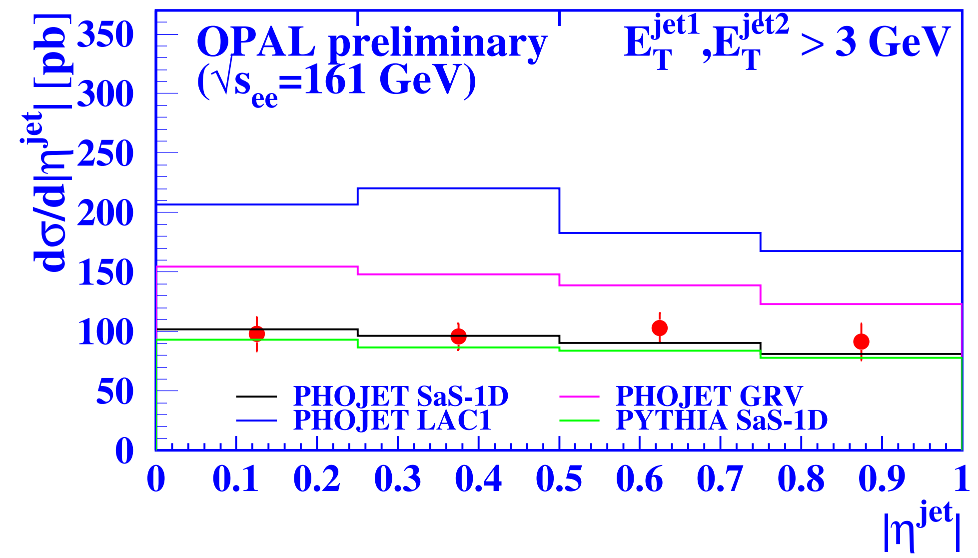
The inclusive one-jet cross section

$\langle E_T^{\mathrm{jet}} \rangle$ (GeV)	$d\sigma/dE_T^{\mathrm{jet}}$ (pb/GeV)
3.45 ± 0.02	$163.4 \pm 5.8 \pm 26.7$
4.46 ± 0.01	$36.0 \pm 2.3 \pm 7.7$
5.70 ± 0.03	$18.0 \pm 1.5 \pm 3.6$
7.41 ± 0.04	$8.4 \pm 1.0 \pm 1.8$
9.64 ± 0.08	$1.8 \pm 0.3 \pm 0.5$
13.14 ± 0.11	$0.78 \pm 0.17 \pm 0.24$

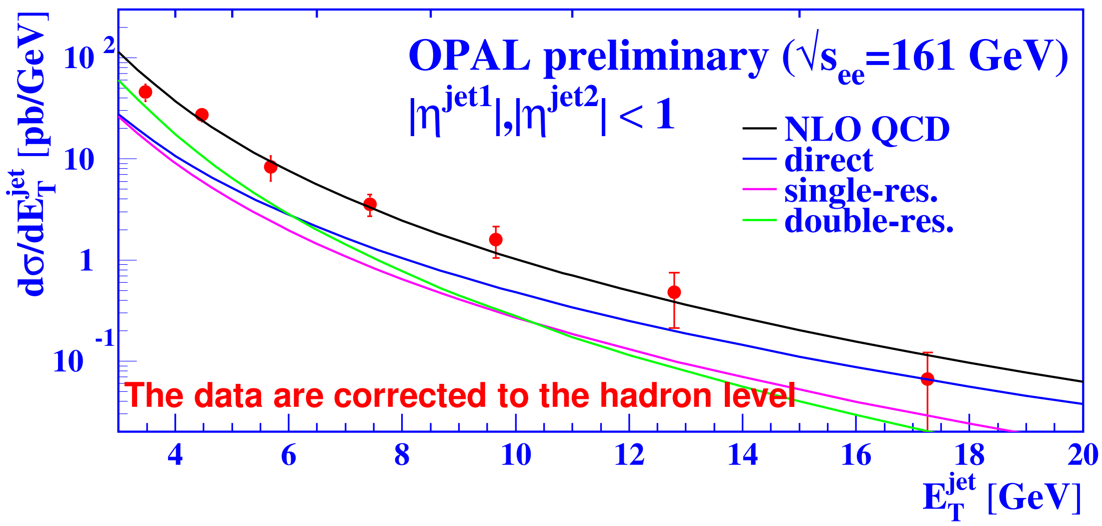
$\Rightarrow$ Need to improve on the systematic error

The inclusive 2-jet cross-sections at $\sqrt{s_{ee}} = 161\,\mathrm{GeV}$

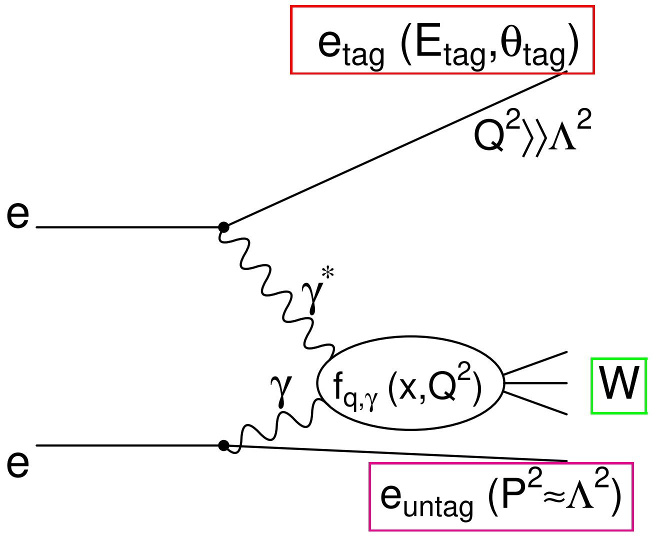
$\frac{d\sigma}{d\eta^{\rm jet}}$ compared to <u>*Monte Carlo models*</u>



$\frac{d\sigma}{dE_T^{\rm jet}}$ compared to <u>*NLO Calculations*</u>



Electron-Photon Scattering

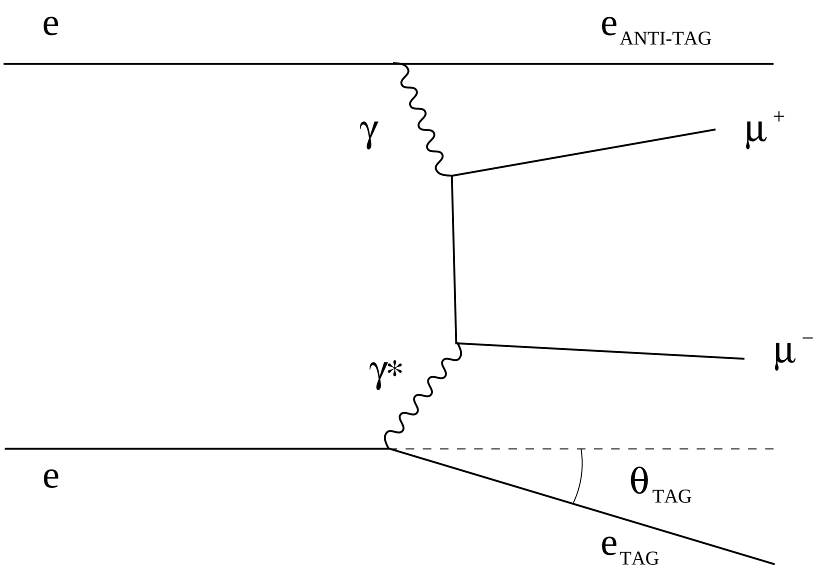


$$\frac{d^2\sigma_{e\gamma\to eX}}{dx dQ^2} = \frac{2\pi\alpha^2}{x\,Q^4}\cdot$$

$$\left[(1+(1-y)^2)\,F_2^\gamma(x,Q^2) - \underbrace{y^2 F_L^\gamma(x,Q^2)}_{\to 0}\right]$$

$$\begin{aligned} Q^2 &= 2\,E_b\,E_{tag}\,(1-\cos\theta_{tag}) \gg P^2 \\ x &= \frac{Q^2}{Q^2+W^2+P^2} \\ y &= 1-\frac{E_{tag}}{E_b}\cos^2\!\left(\frac{\theta_{tag}}{2}\right) \ll 1 \end{aligned}$$

The production of lepton pairs



$$\frac{d^2\sigma_{e\gamma\to e\mu^+\mu^-}}{dx\,dQ^2} =$$

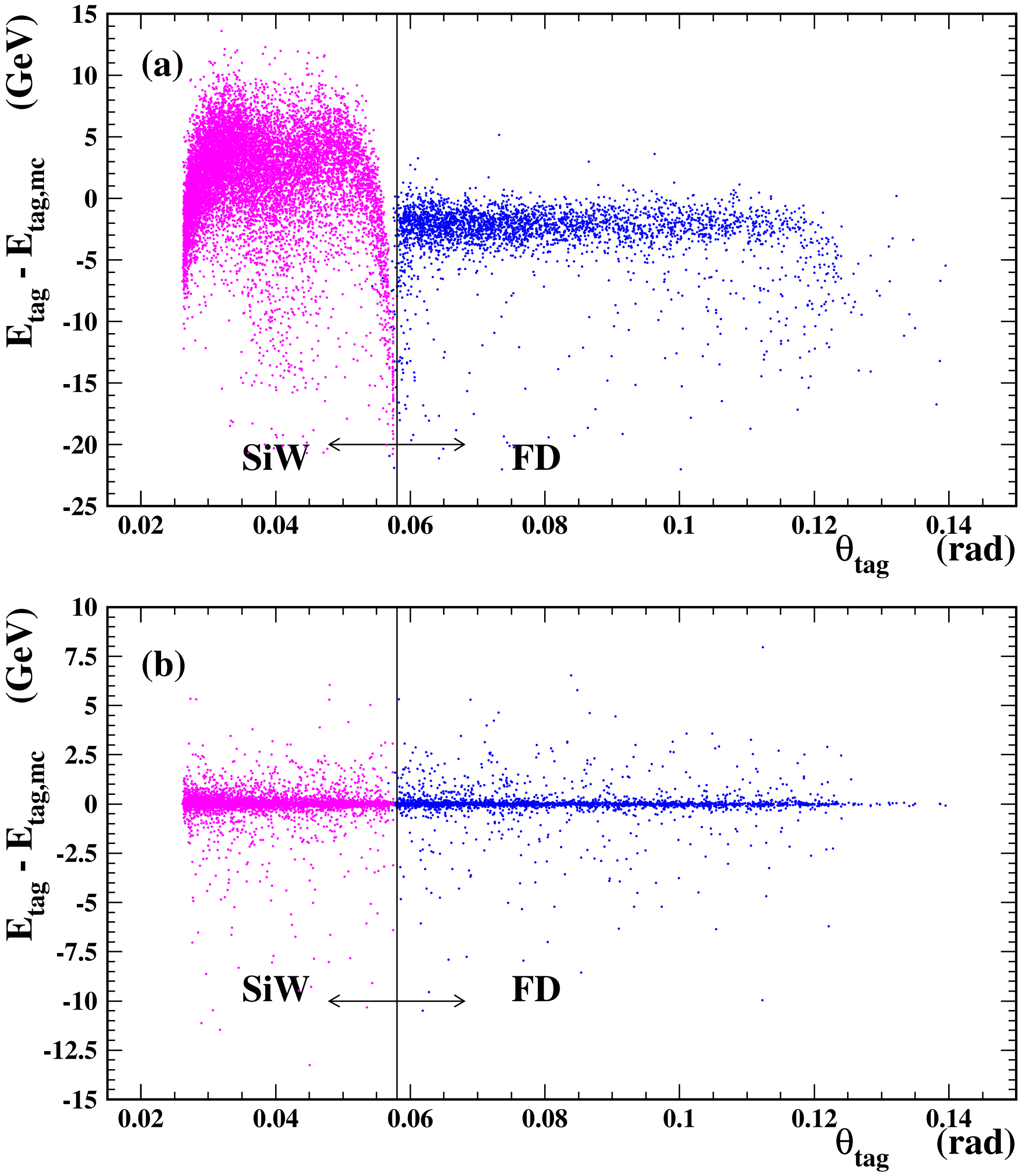
$$\frac{2\pi\alpha^2}{x\,Q^4}\left[\left(1+(1-y)^2\right)F^{\gamma}_{2,\mathrm{QED}} - y^2 F^{\gamma}_{\mathrm{L},\mathrm{QED}}\right]$$

$$F^{\gamma}_{2,\mathrm{QED}}(x,Q^2,P^2=0)/\alpha \approx$$

$$\frac{x}{\pi}\left[1-2x(1-x)\ln\frac{Q^2(1-x)}{x m_\mu^2} - 1 + 8x(1-x)\right]$$

$$F^{\gamma}_{\mathrm{L},\mathrm{QED}}(x,Q^2,P^2=0)/\alpha \approx \frac{4}{\pi}x^2(1-x)$$

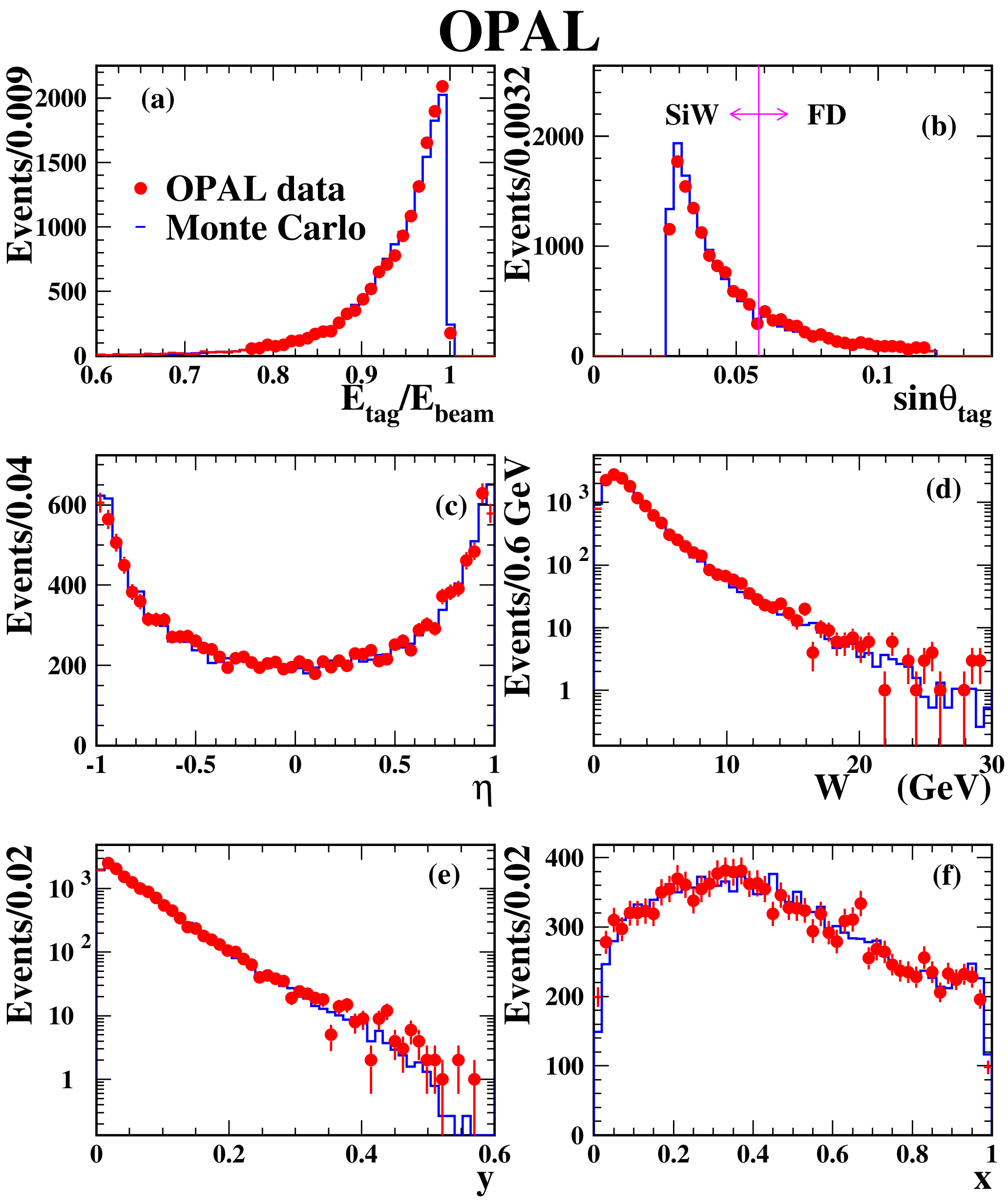
$E_{\rm tag}$ obtained from the μ- pair



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

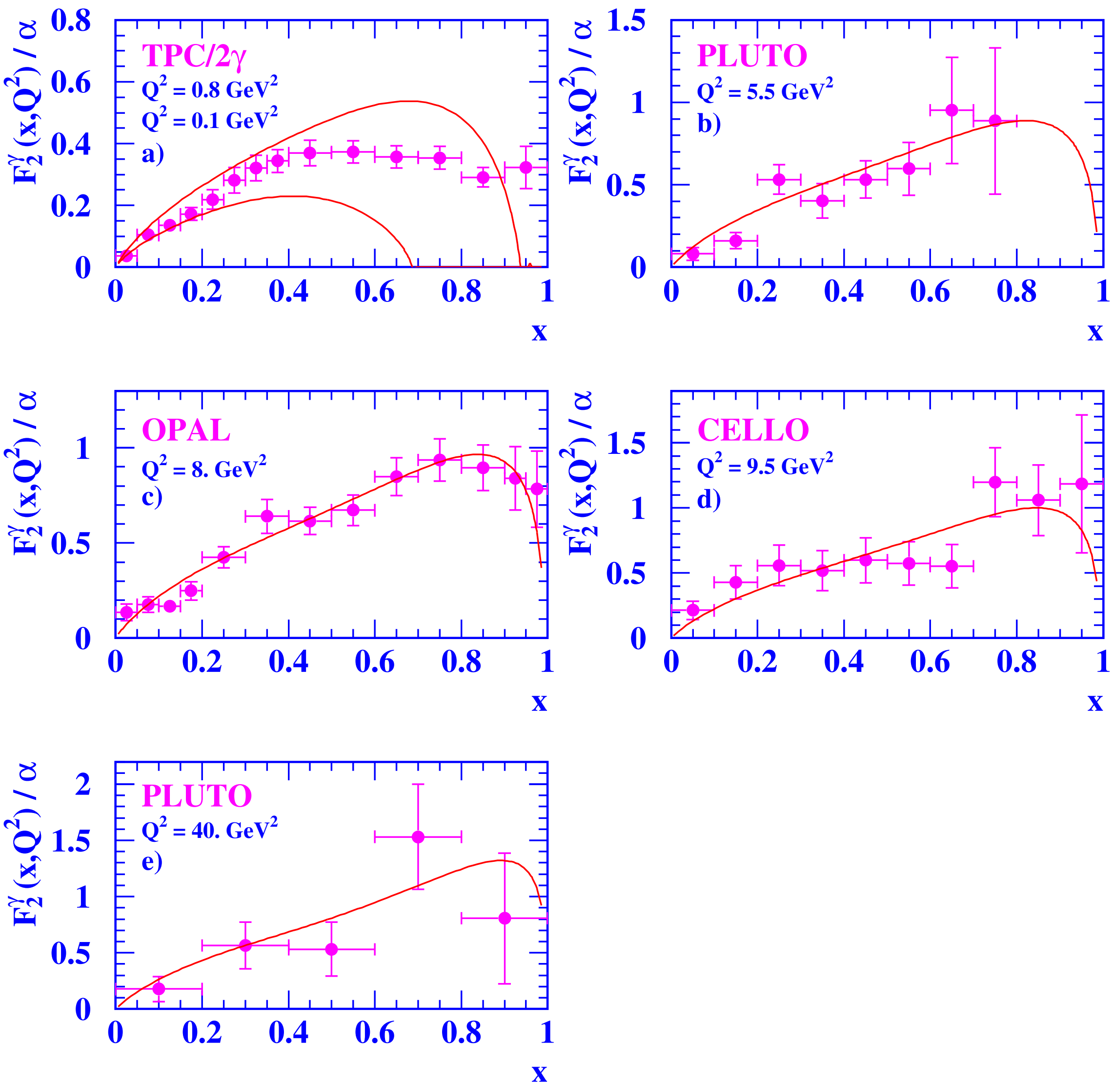
assume $\theta_{\rm anti} = 0, \pi$

Some check distributions

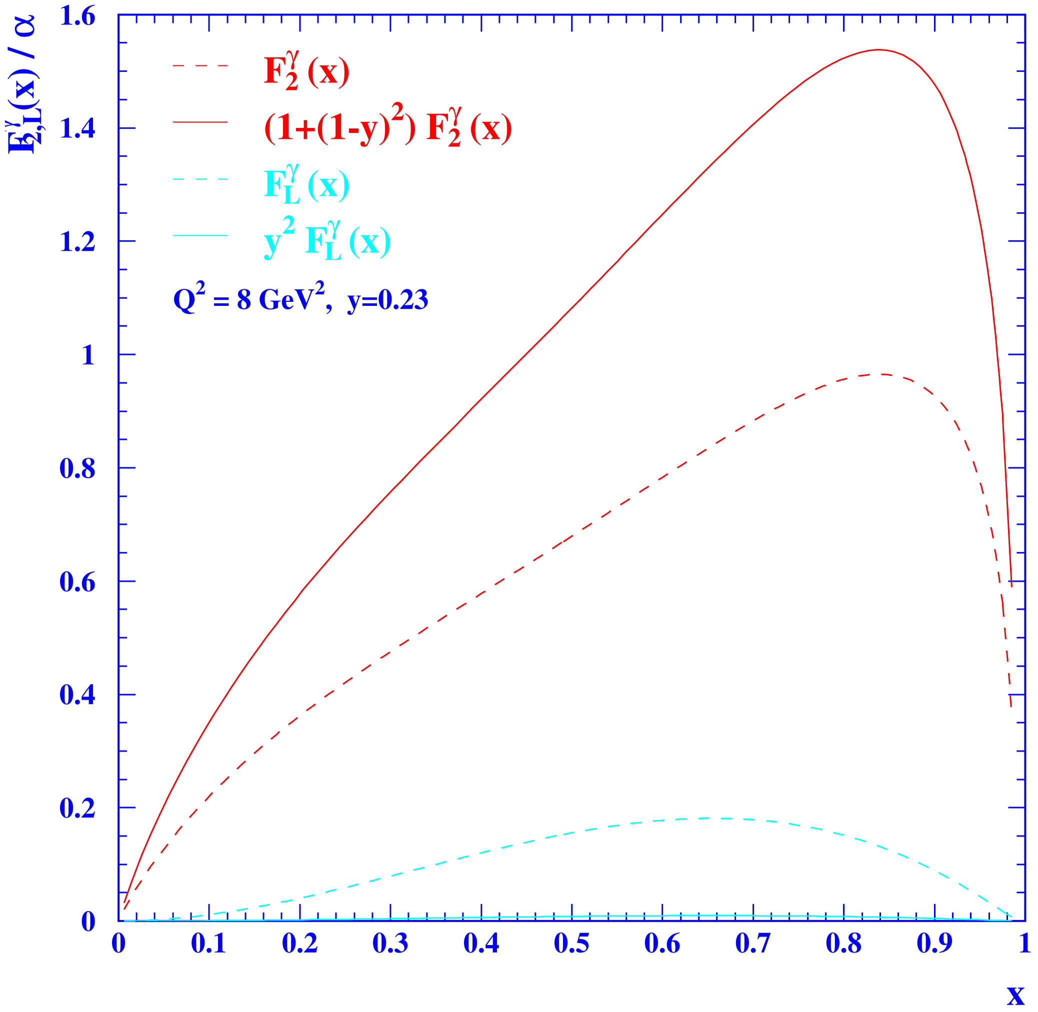


The data is well described by the QED Monte Carlo

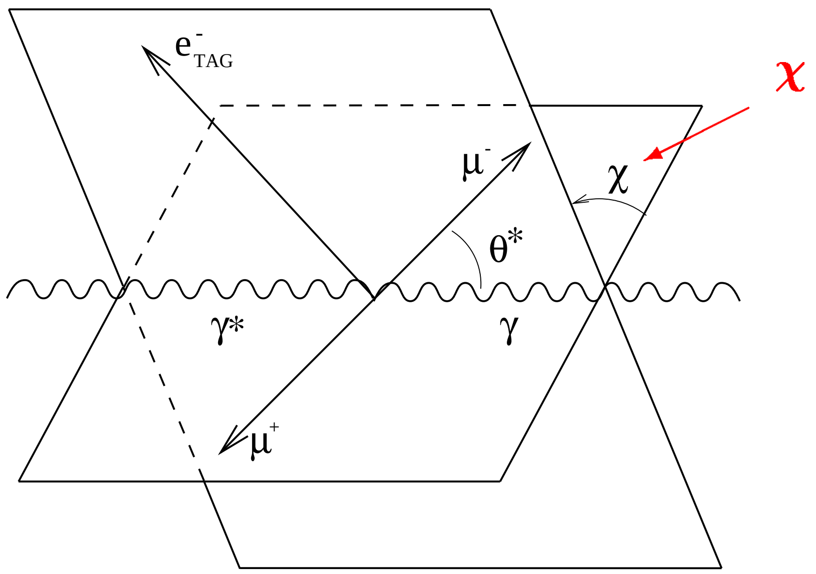
The world data on $F_{2,\mathrm{QED}}^{\gamma}$ compared to QED



The contribution of $F^{\gamma}_{\mathrm{L,QED}}$



Azimuthal Correlations

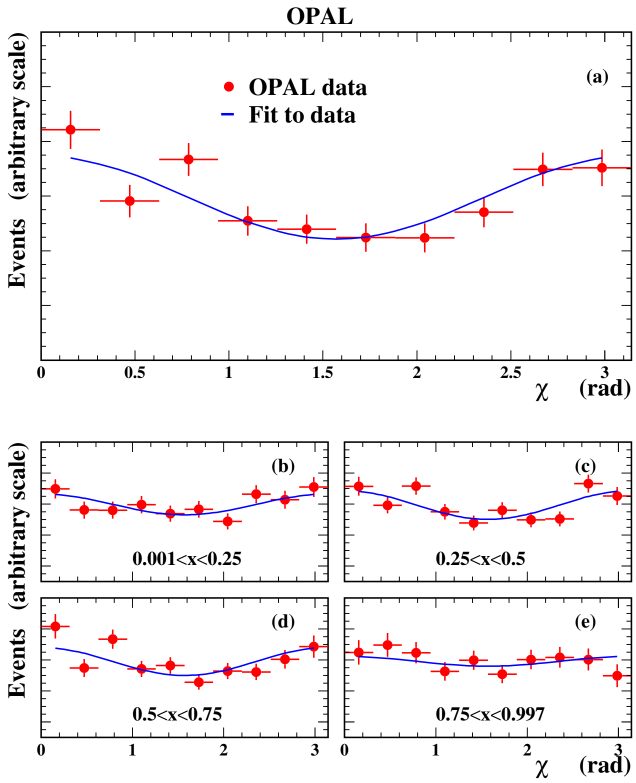


$$\frac{d\sigma(\mathrm{e}\gamma\to\mathrm{e}\mu^+\mu^-)}{dx\,dy\,d\chi/2\pi} \simeq \frac{2\pi\alpha^2}{Q^2}\left(\frac{1+(1-y)^2}{xy}\right)\cdot F_2^\gamma\cdot \left(1+\frac{1}{2}\epsilon(F_\mathrm{B}^\gamma/F_2^\gamma)\cdot\cos 2\chi\right)$$

$\frac{1}{2}\epsilon = \frac{(1-y)}{1+(1-y)^2} \approx 1, \quad F_\mathrm{B}^\gamma = F_\mathrm{L}^\gamma = \frac{4\alpha}{\pi}x^2(1-x)$ **(in LO)**

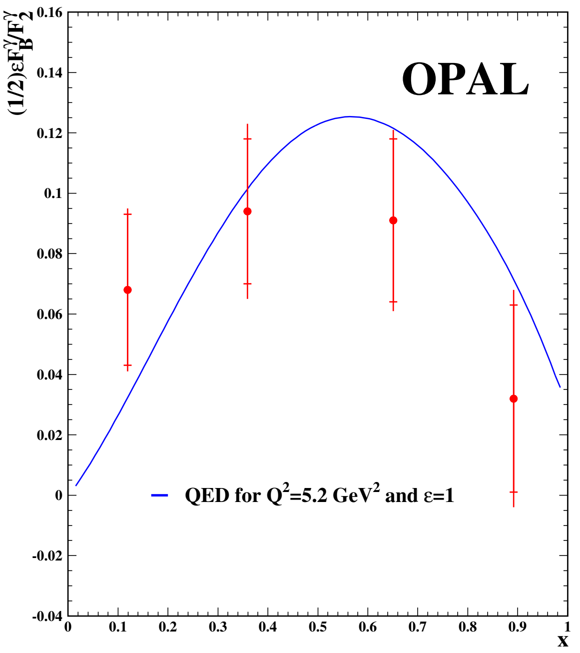
The measurement of F_B^γ / F_2^γ

arbitrary scales



χ

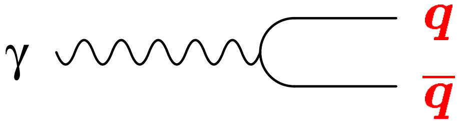
$\frac{1}{2}\epsilon(F_B^\gamma/F_2^\gamma)$

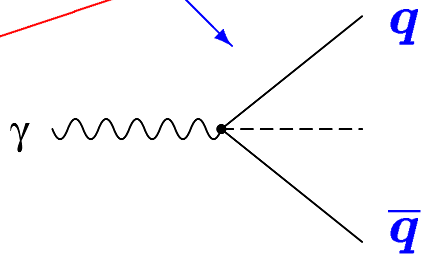


x

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

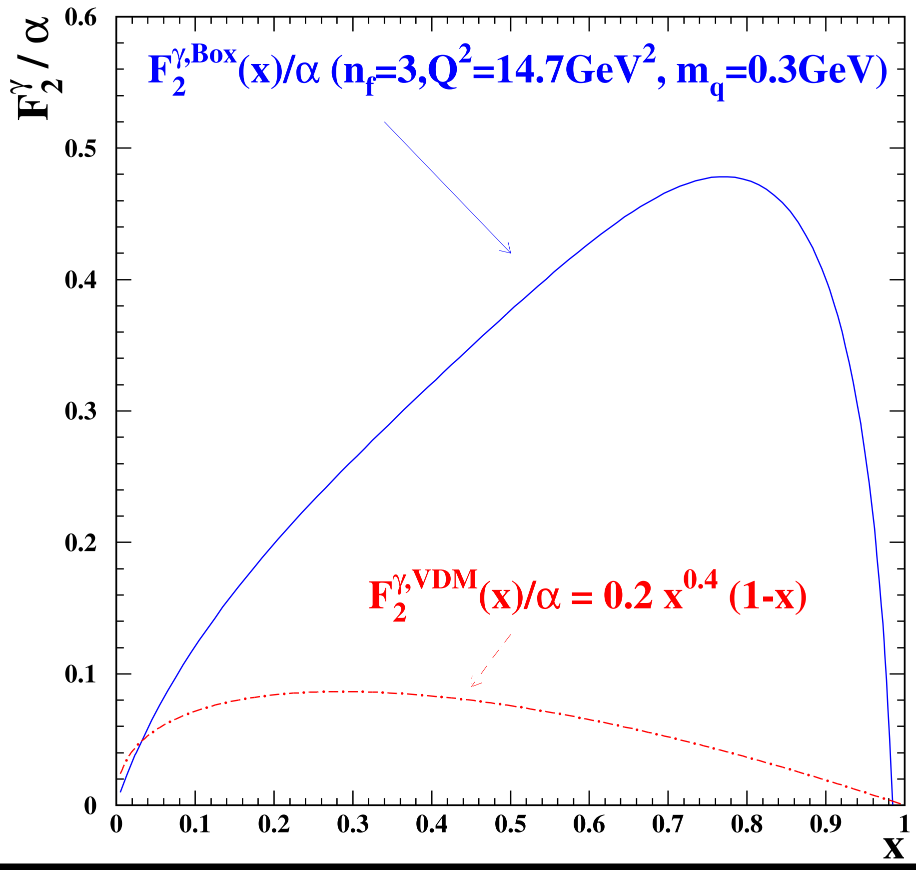
$$F_2^\gamma(x, Q^2) = x \sum_{c,f} e_q^2 \, f_{\mathrm{q},\gamma}(x, Q^2)$$





hadronic, VDM, p_{T} = "small"
ρ, ω, ϕ, *non–perturbative*

pointlike, p_{T} = "large"
perturbative



Event selection

$$\mathcal{L}_{int} = 156.4\,\mathrm{pb}^{-1}$$

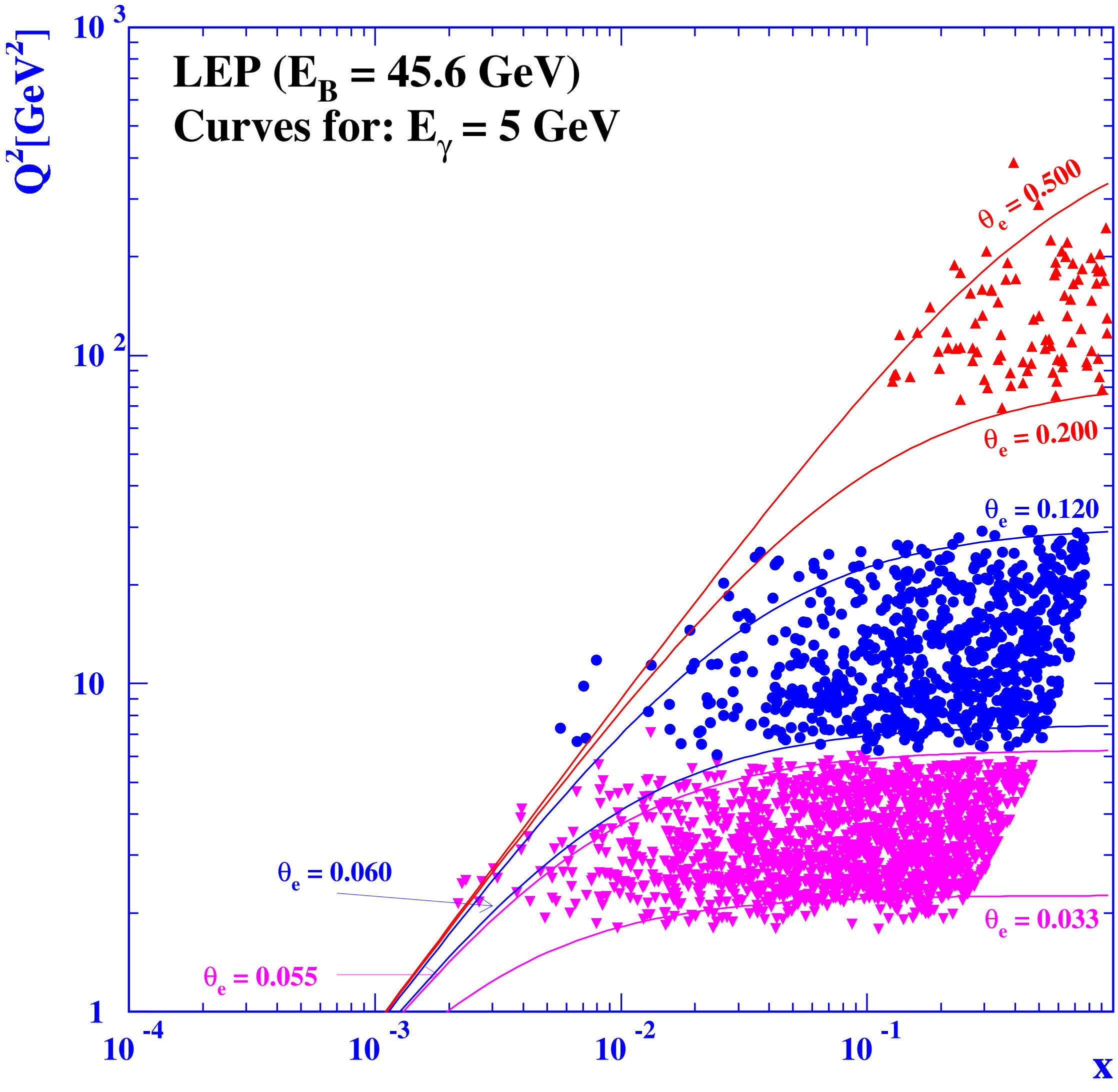
1. Electron Tag: $E_{\mathrm{tag}} \geq 0.775\ E_{\mathrm{b}}$ and $0.06 \leq \theta_{\mathrm{tag}} \leq 0.12$ rad
2. Antitag: $E_{\mathrm{a}} \leq 0.25\ E_{\mathrm{b}}$
3. $N_{\mathrm{ch}} \geq 3$, and $(2.5 \leq W_{\mathrm{vis}} \leq 40)\ \mathrm{GeV}$

$\Rightarrow$ 5455 events with $(6 \lessapprox Q^2 \lessapprox 30)\ \mathrm{GeV}^2$

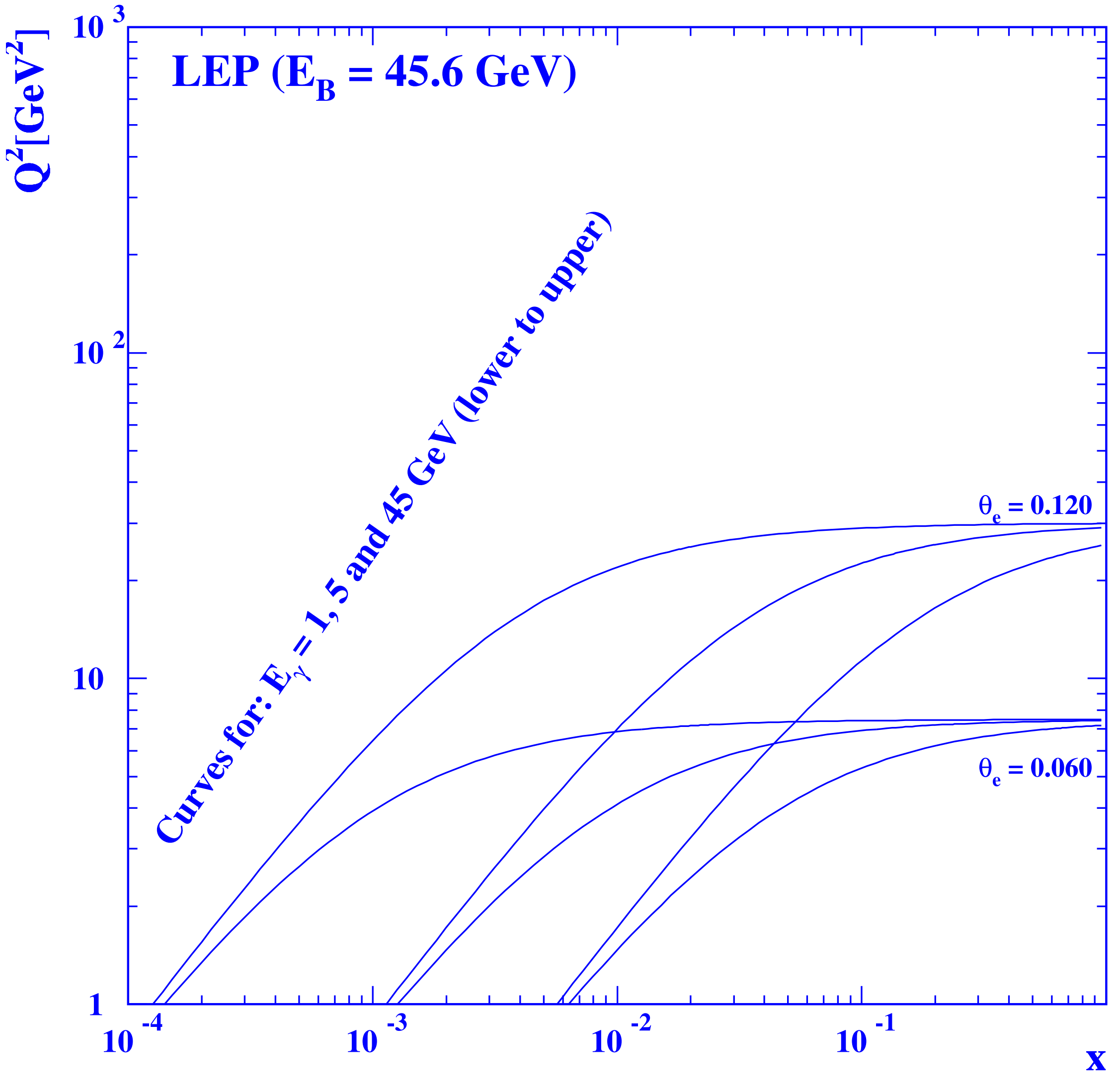
1. Electron Tag: $0.75\ E_{\mathrm{b}} \leq E_{\mathrm{tag}} \leq 1.15\ E_{\mathrm{b}}$ and $0.2 \leq \theta_{\mathrm{tag}} \leq 0.5$ rad, plus isolation criteria
2. Antitag: $E_{\mathrm{a}} \leq 0.15\ E_{\mathrm{b}}$
3. $N_{\mathrm{ch}} \geq 3$, and $(2.5 \leq W_{\mathrm{vis}} \leq 25)\ \mathrm{GeV}$
4. $p_{\mathrm{t,bal}} < 5\ \mathrm{GeV}$, $p_{\mathrm{t,out}} < 4\ \mathrm{GeV}$, $-0.5\ E_{\mathrm{b}} \leq p_{\mathrm{z,miss}} \leq 0.5\ E_{\mathrm{b}}$

$\Rightarrow$ 225 events with $(60 \lessapprox Q^2 \lessapprox 400)\ \mathrm{GeV}^2$

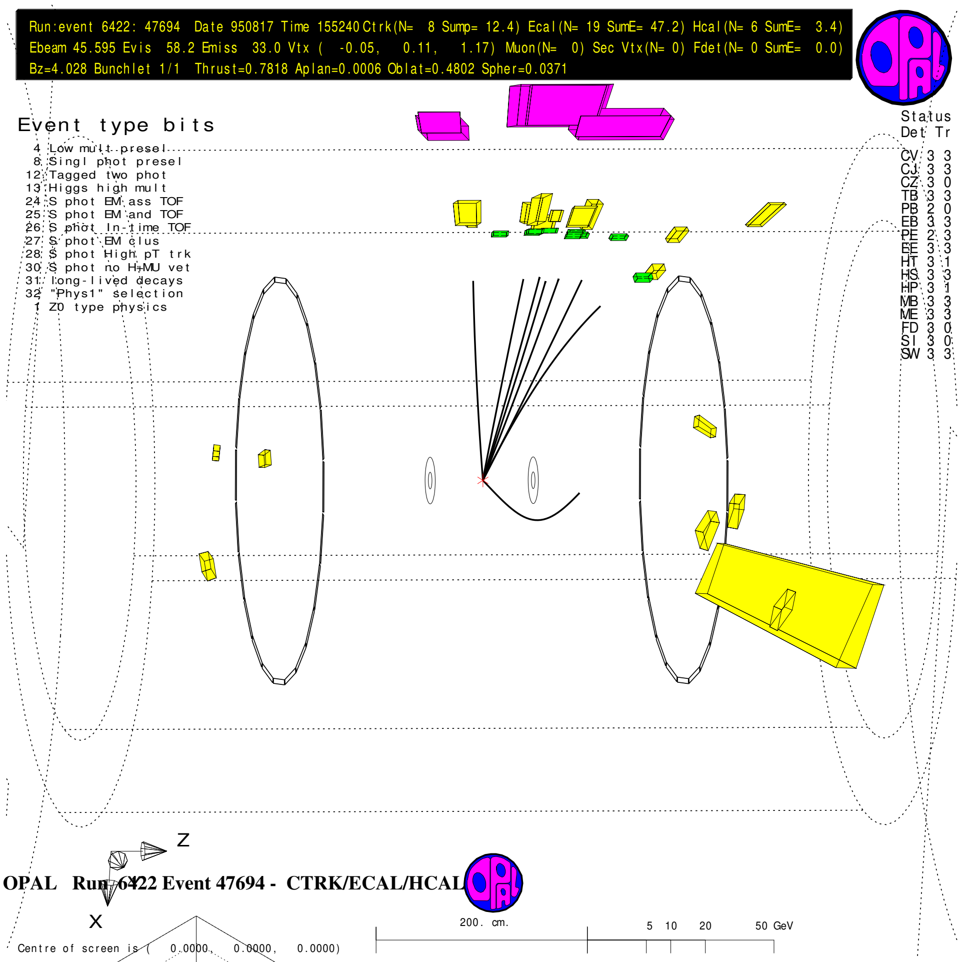
The phase space at $\sqrt{s_{ee}} = M_{Z^0}$

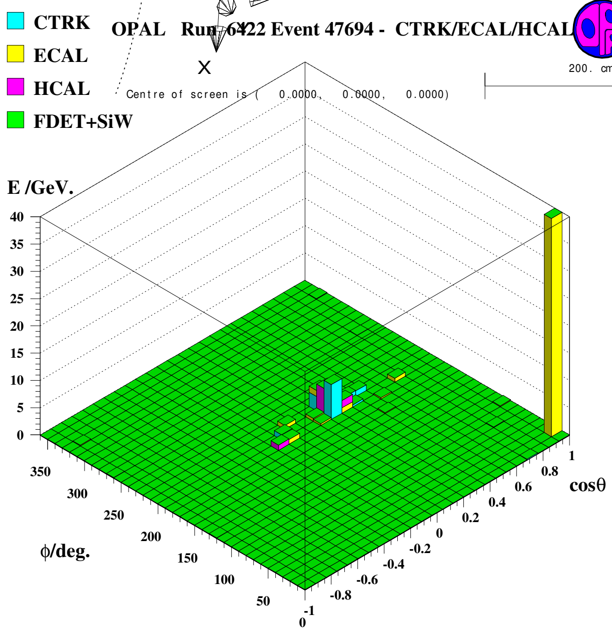


The effect of different E_γ



A tagged two-photon event





Kinematics :

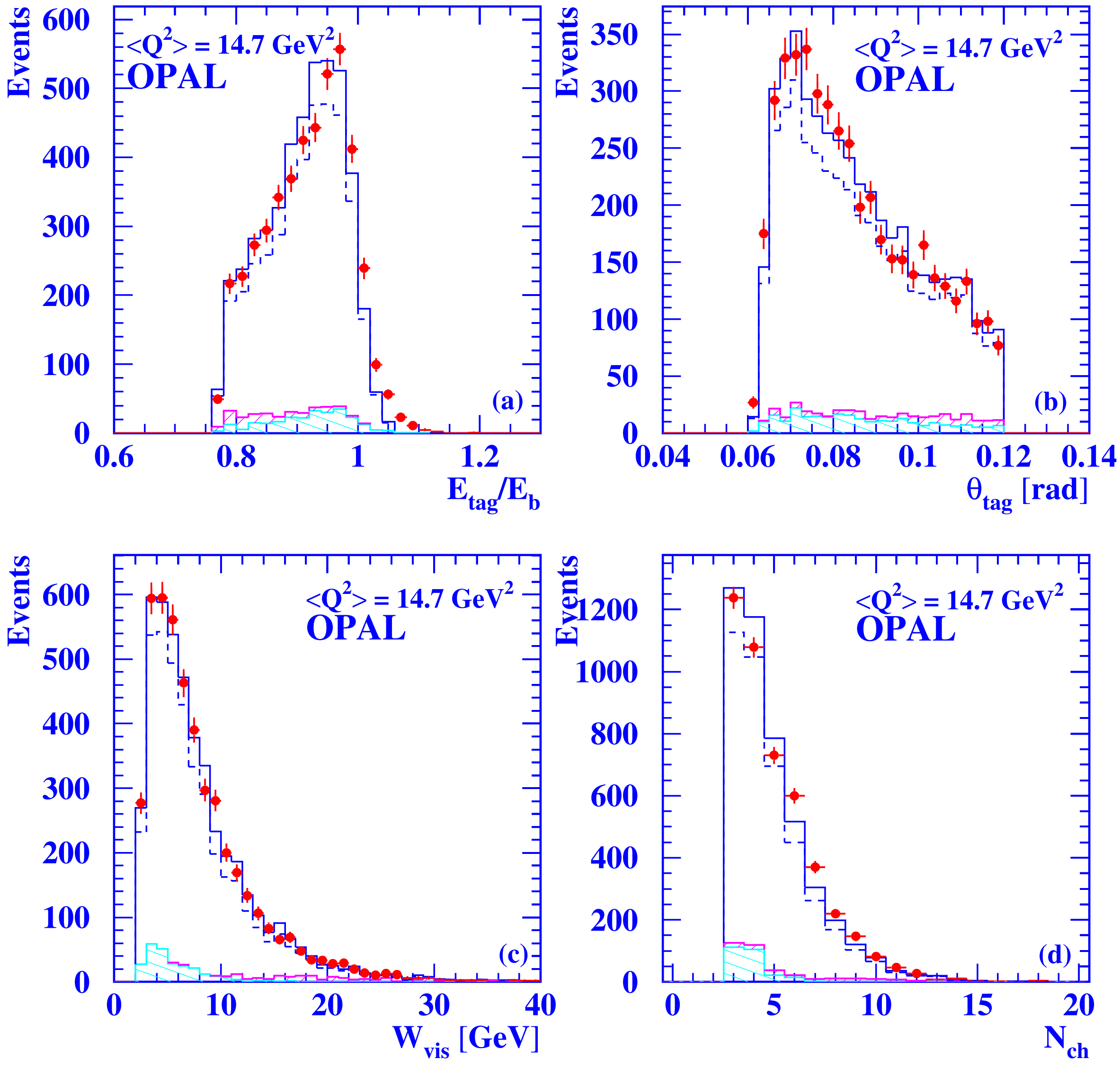
$$E_{\mathrm{tag}} = 39.2\ \mathrm{GeV}$$

$$\theta_{\mathrm{tag}} = 21.3^\circ$$

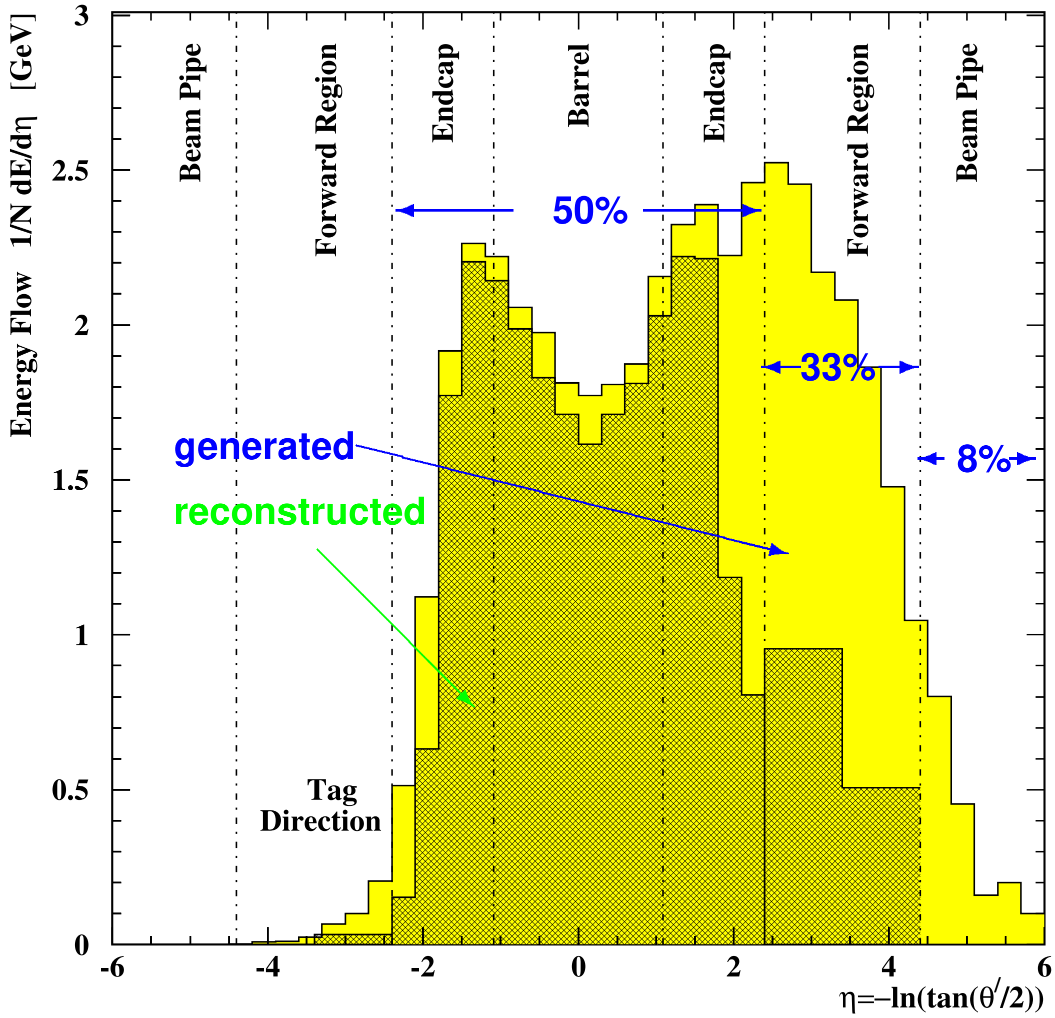
$$Q^2 = 245\ \mathrm{GeV}^2$$

$$W^2_{\mathrm{vis}} = 17\ \mathrm{GeV}^2$$

Event distributions compared to HERWIG

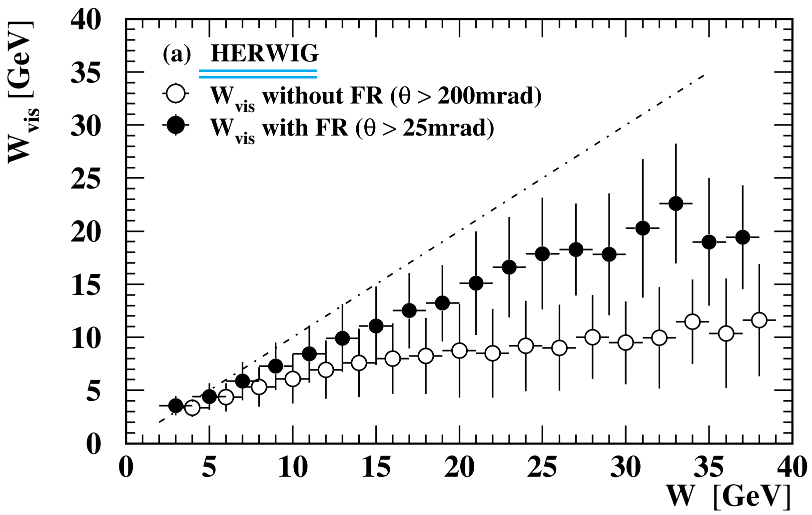


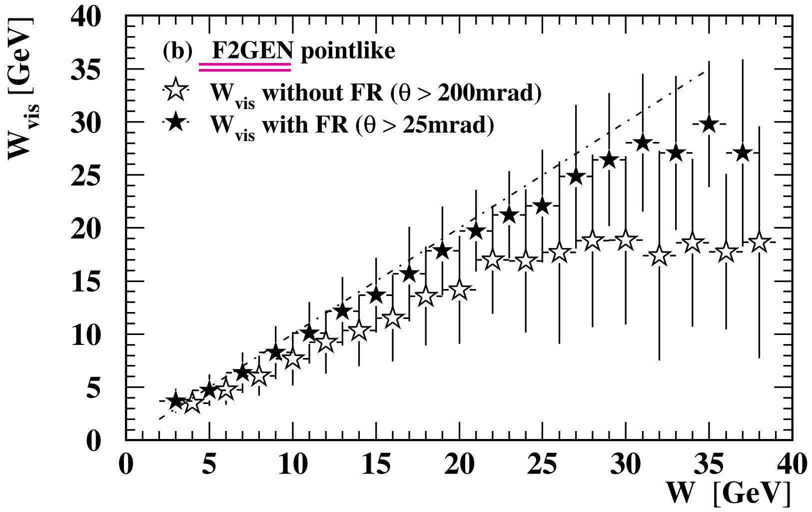
The flow of hadronic energy as predicted by HERWIG



Only about 10% of the energy is deposited outside of the detector acceptance

The $W - W_{\rm vis}$ correlation

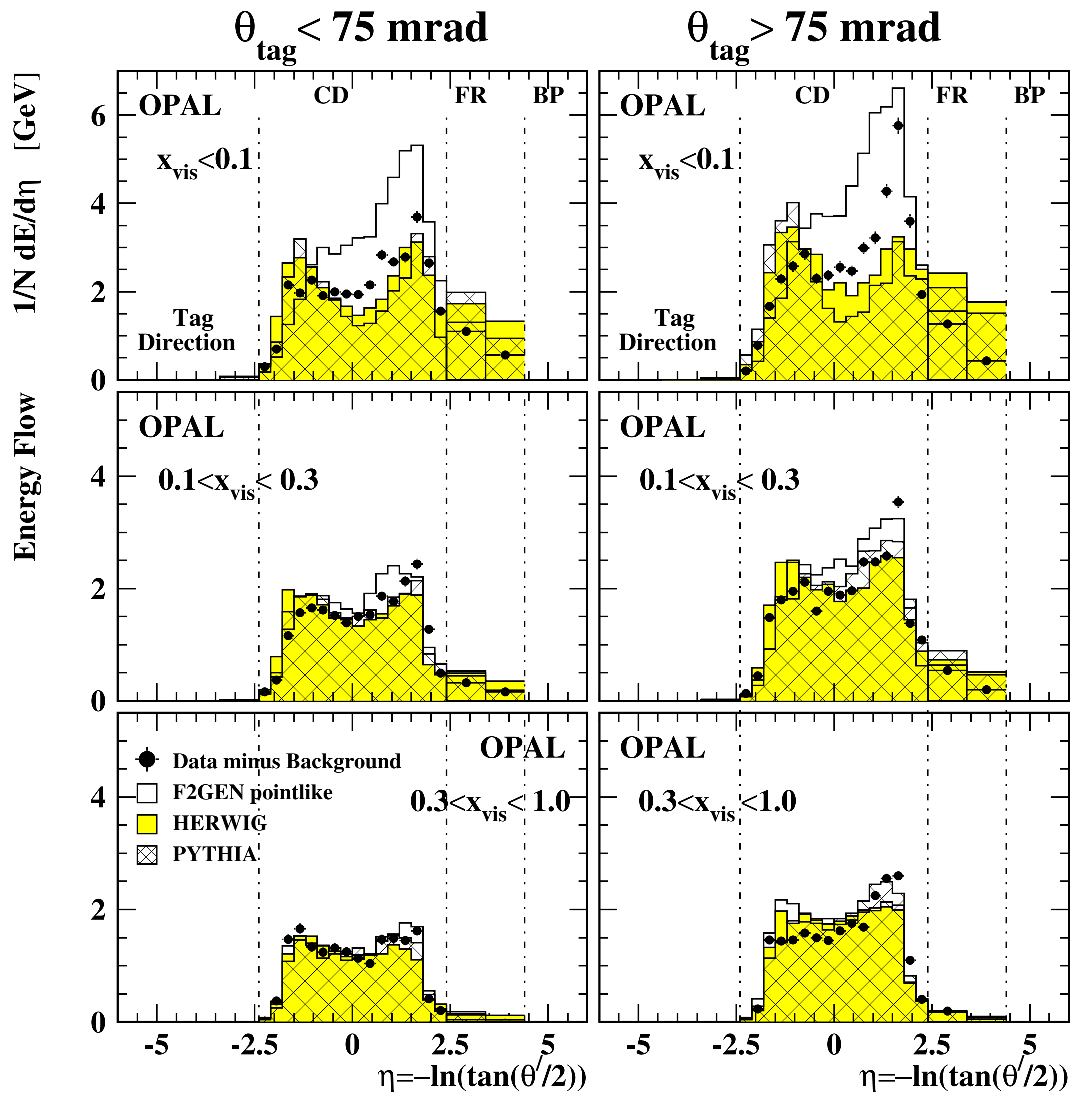




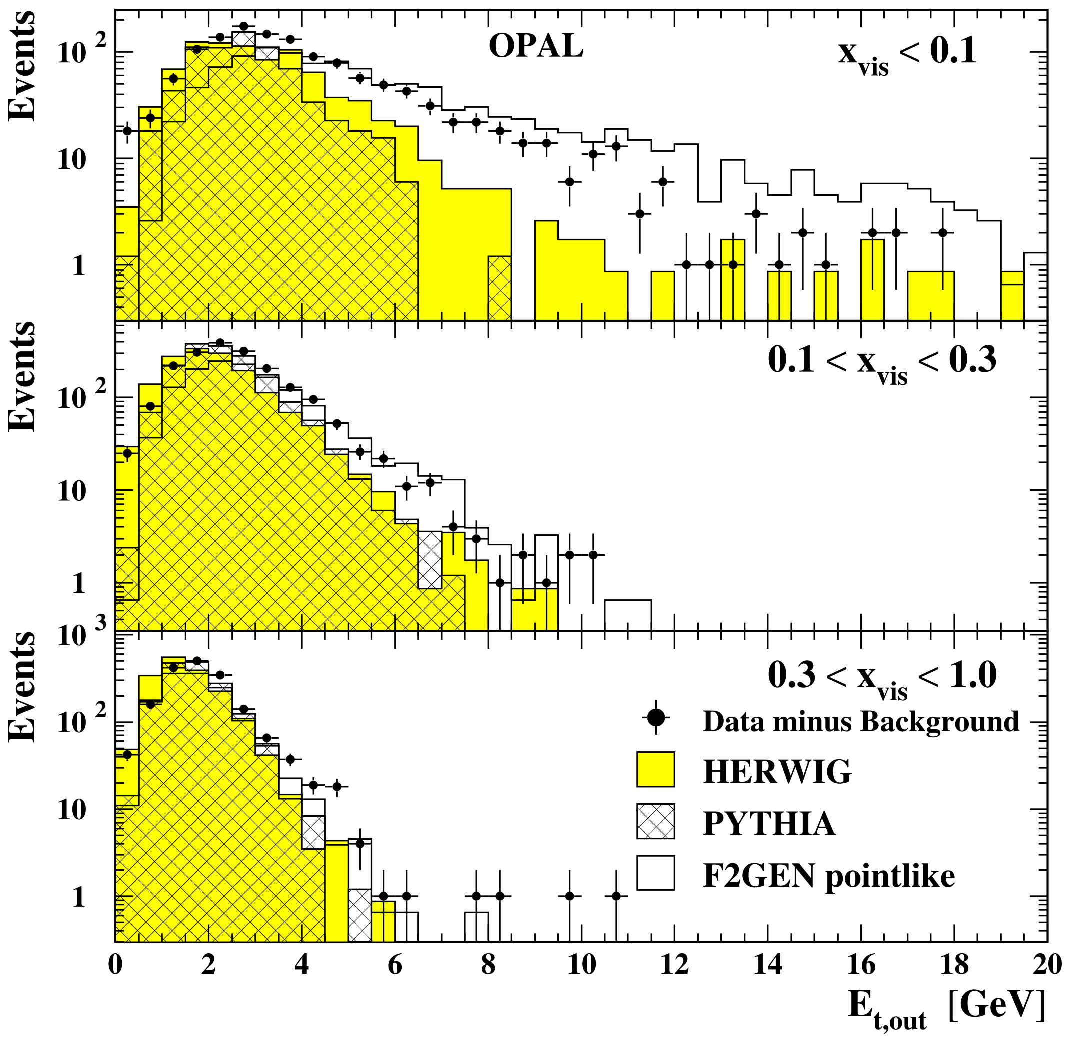
The correlation based on F2GEN is much stronger

The inclusion of the Forward Region significantly improves the correlation

The energy flow for $\sqrt{s_{ee}} = M_{Z^0}$

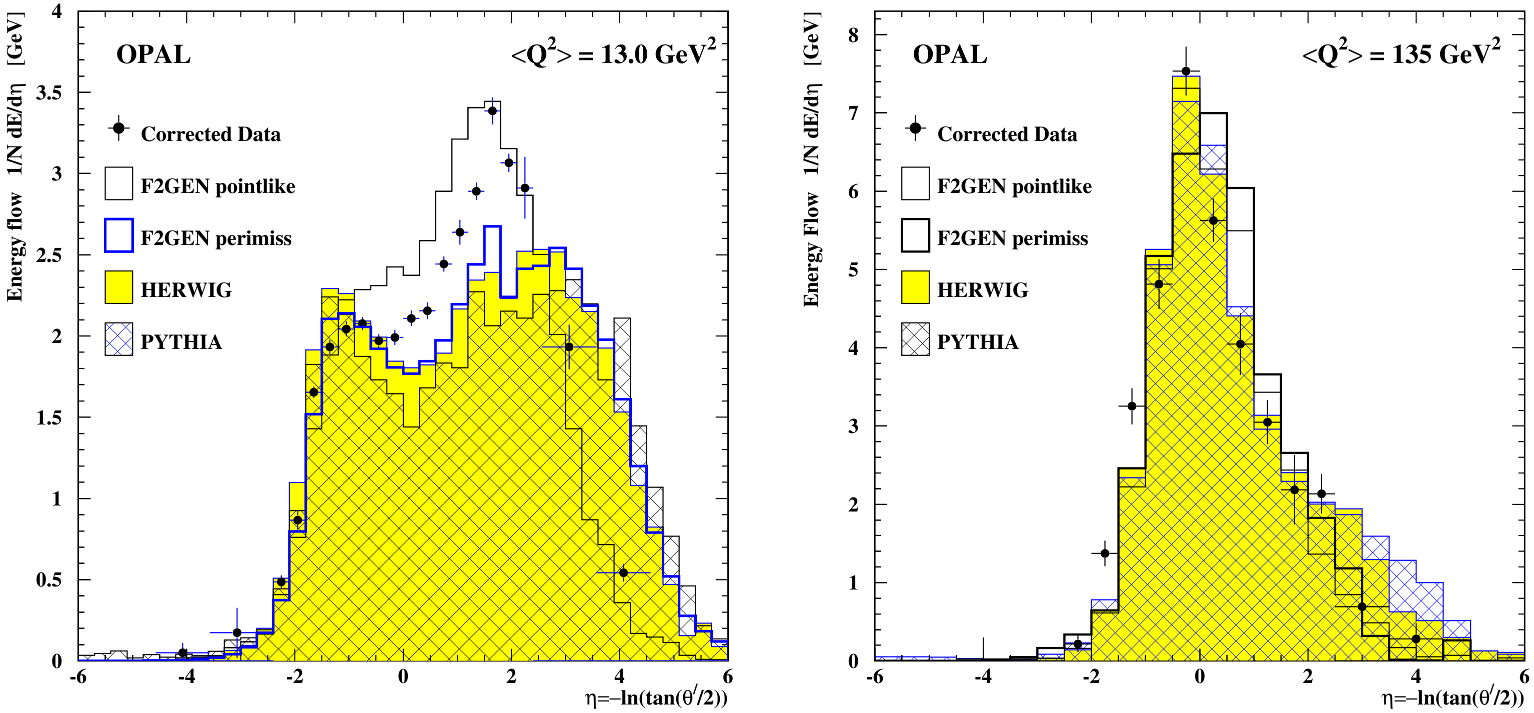


The model dependence as a function of x_{vis}



The agreement gets better for increasing x_{vis}

The corrected flow of hadronic energy



The description of the data by the Monte Carlo models is poor at low x and Q^2 and it improves for higher Q^2. The data, however, is precise enough to further constrain the models!

Some words about unfolding

The Principle:

$$g^{\mathrm{det}}(u) = \int A(u,\omega)\, f^{\mathrm{part}}(\omega)\, d\omega + B(u)$$

1. Our case:
   $g^{\mathrm{det}}(u) = g^{\mathrm{det}}(x_{\mathrm{vis}}),\ \ x_{\mathrm{vis}} = f(E_{\mathrm{tag}}, \theta_{\mathrm{tag}}, W_{\mathrm{vis}})$
   and $f^{\mathrm{part}}(\omega) = f^{\mathrm{part}}(x)$ which is related to F_2^{γ}, $B(u)$ denotes the background events.

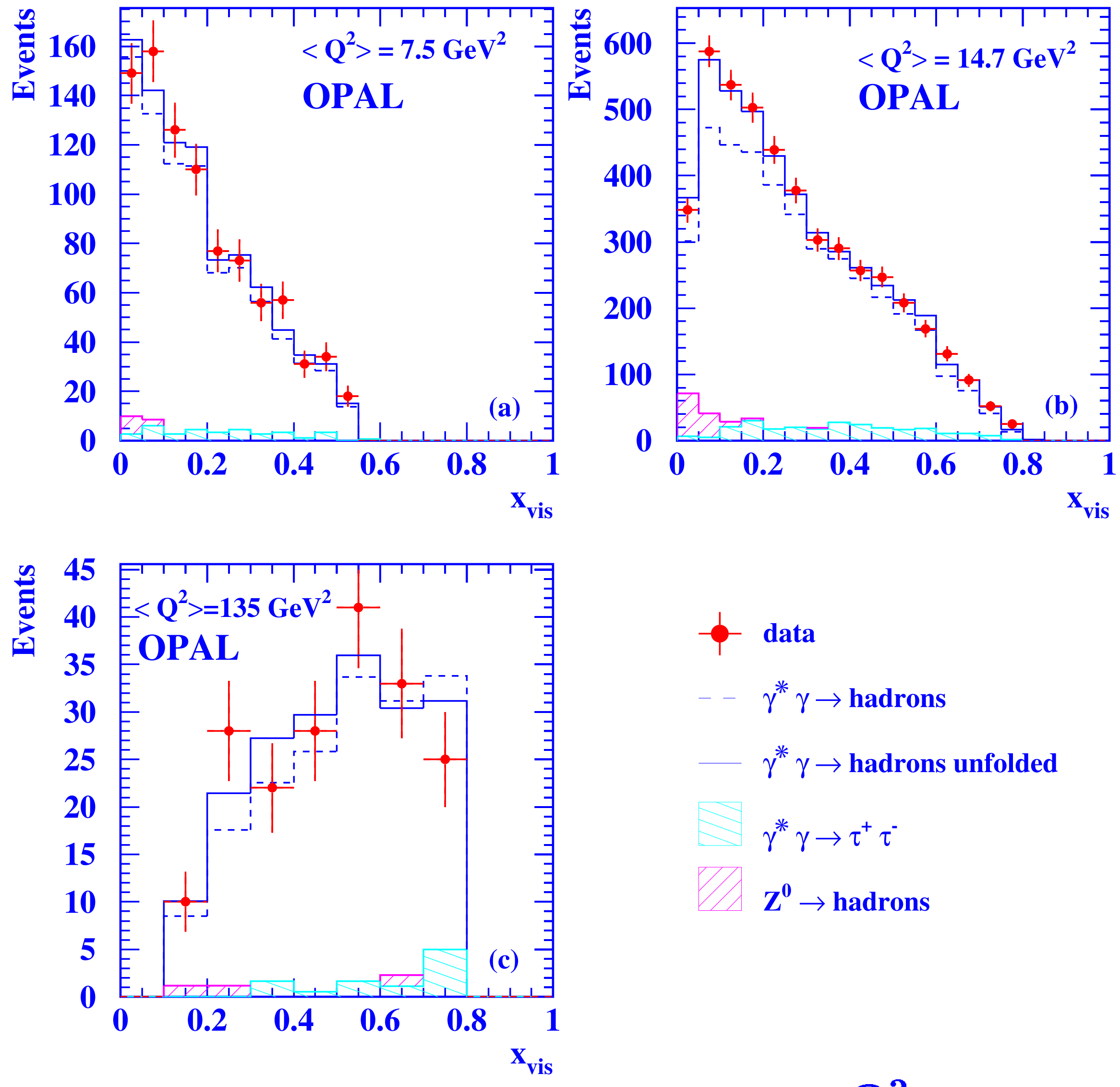
2. $A(u,\omega)$ has to be obtained from the Monte Carlo Models
   $\Rightarrow$ Model Dependence, consider all reasonable models.

3. The g^{det} (x_{vis}) distribution from the Monte Carlo is changed during unfolding, by assigning weights to each Monte Carlo event, in order to match the g^{det} (x_{vis}) distribution of the data.

   - After the unfolding the g^{det} (x_{vis}) distributions of data and Monte Carlo agree on a statistical basis.
   - Other distributions have to be used in order to check whether the unfolding has also improved on them, without using explicitly this variable.

4. The unfolding result should be independent of the F_2^{γ} used in the Monte Carlo. This is not true if F_2^{γ} and the $\gamma^{\star}\gamma$ fragmentation do not factorize.

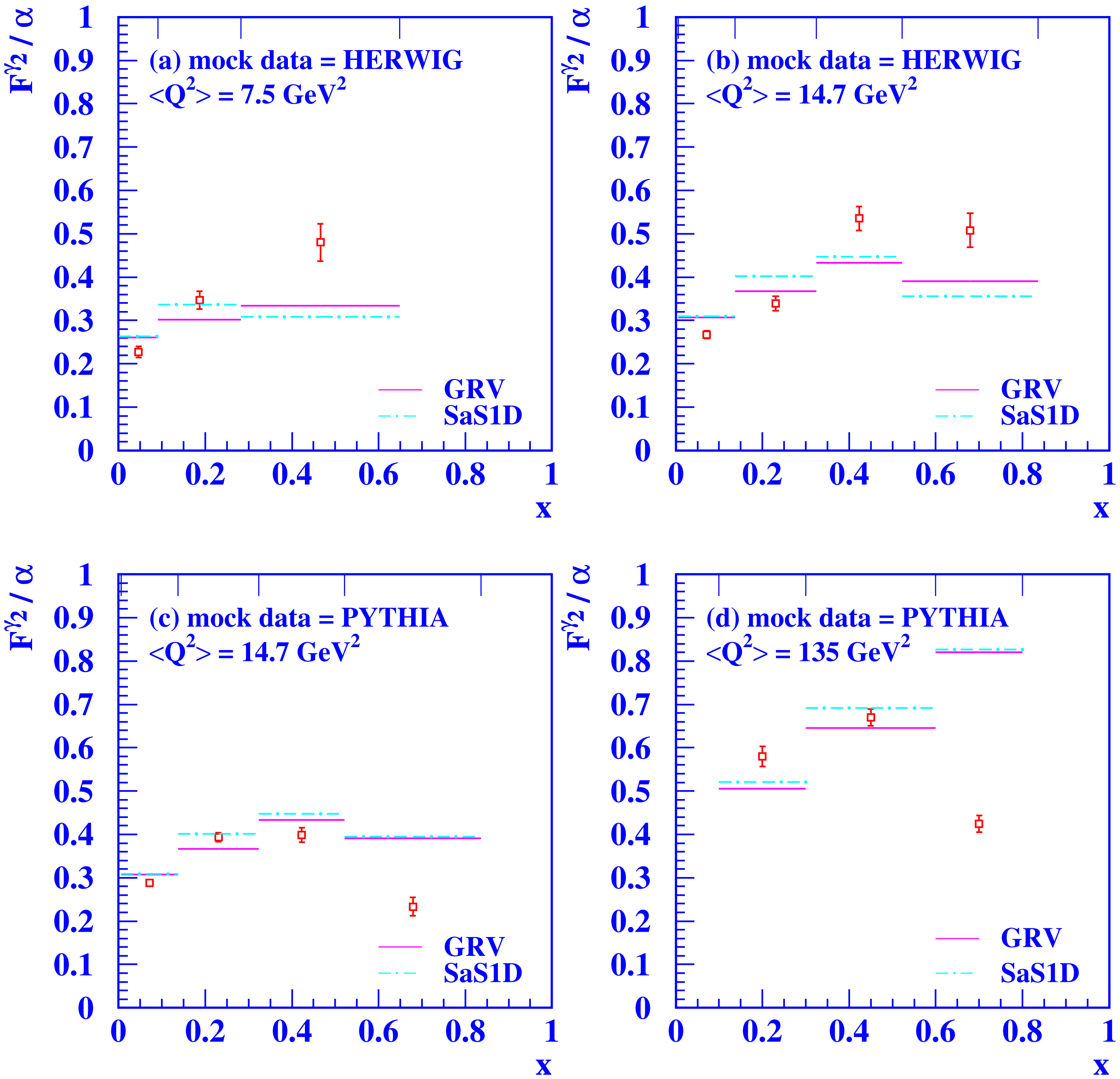
The $x_{\rm vis}$ distributions compared to HERWIG



The mean $x_{\rm vis}$ increases with Q^2

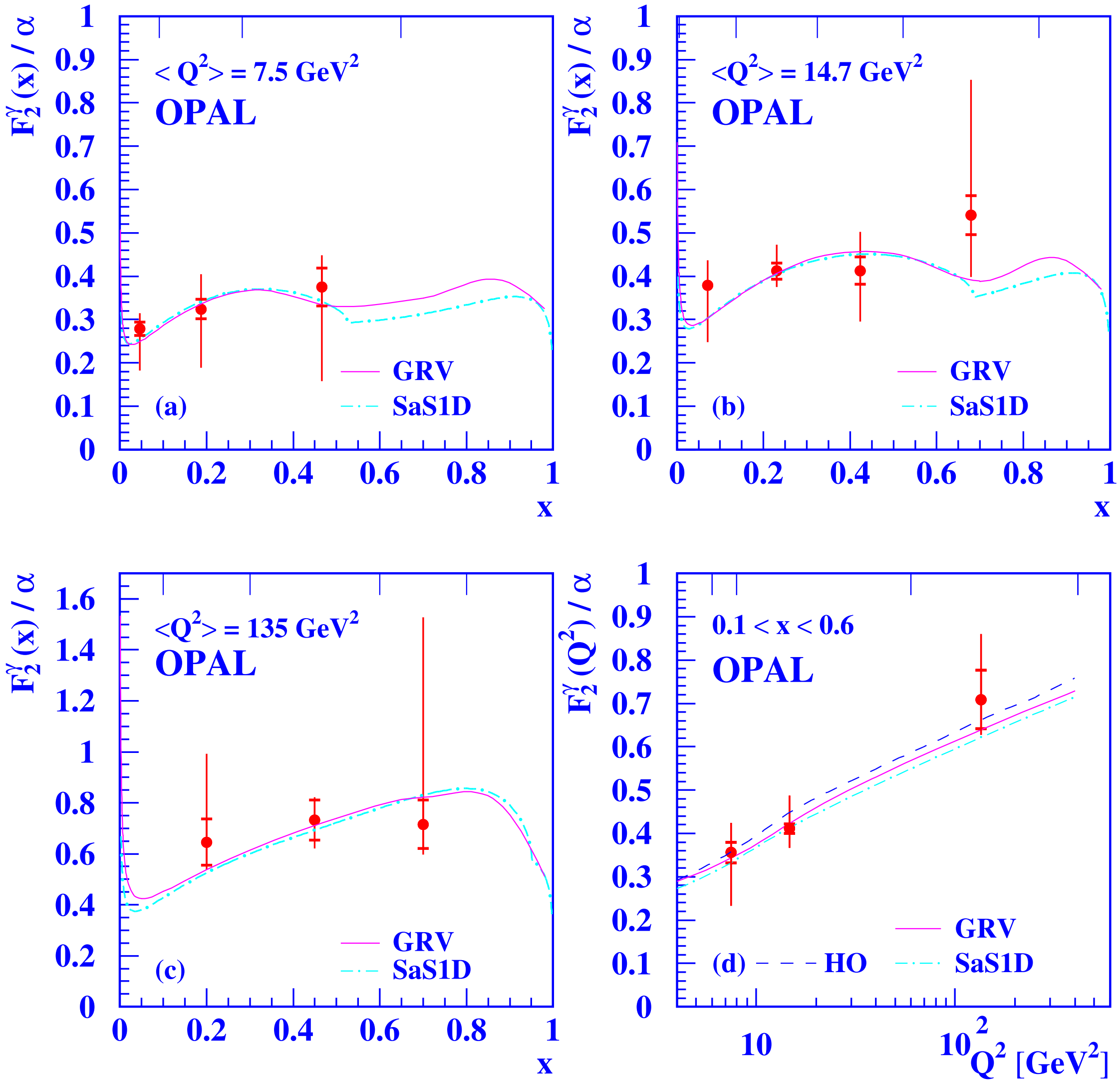
The background contributions are small

Unfolding tests using
HERWIG with GRV as unfolding MC



The error is dominated by systematic effects

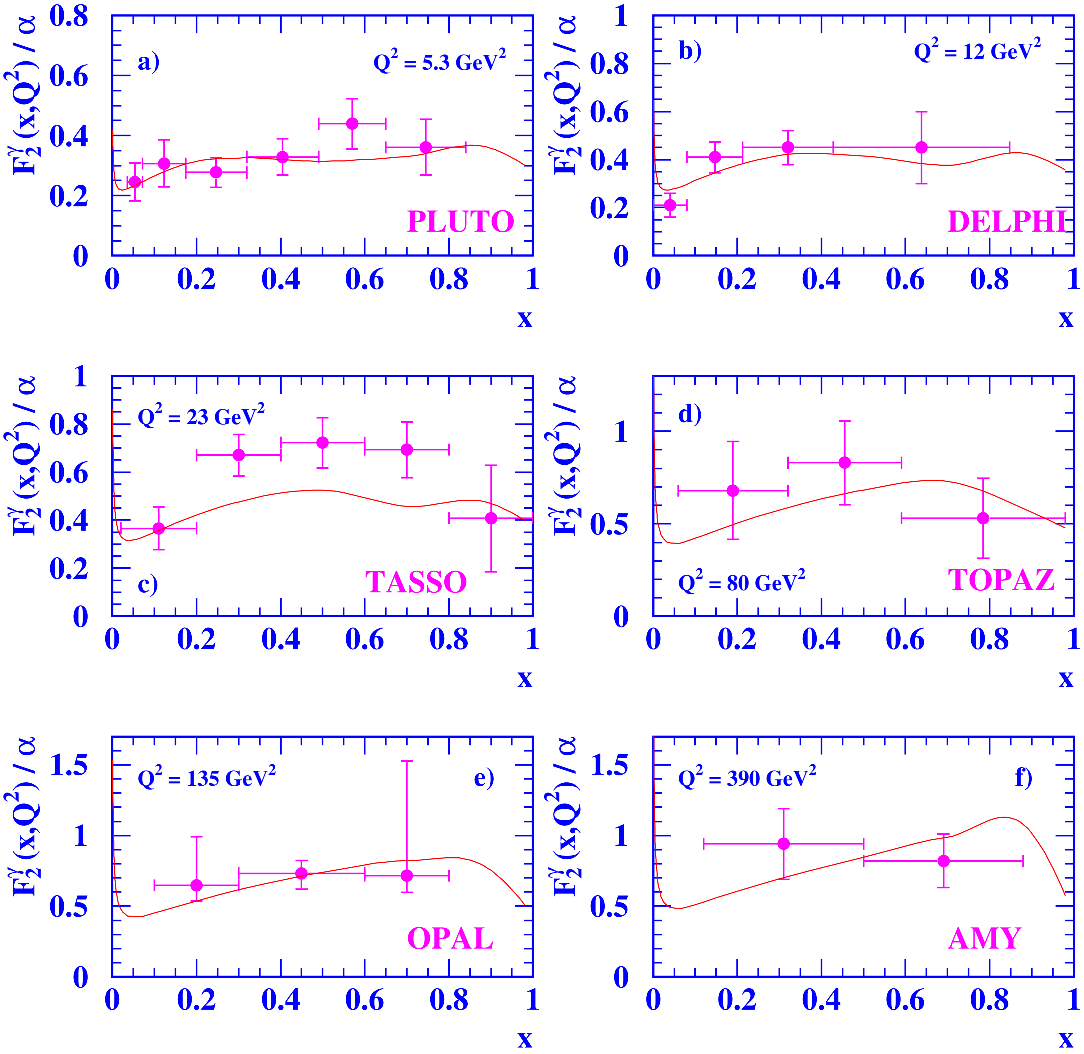
OPAL results on $F_2^\gamma(x, Q^2)$ at $\sqrt{s_{ee}} = M_{Z^0}$



$$F_2^\gamma(Q^2)/\alpha = (0.08\,^{+0.13}_{-0.18}) + (0.13\,^{+0.06}_{-0.04})\ \ln Q^2$$

$$\chi^2/\mathrm{dof} = 0.05 \quad Corr = -0.95$$

A selection of $F_2^\gamma(x,Q^2)$ measurements compared to GRV (LO)



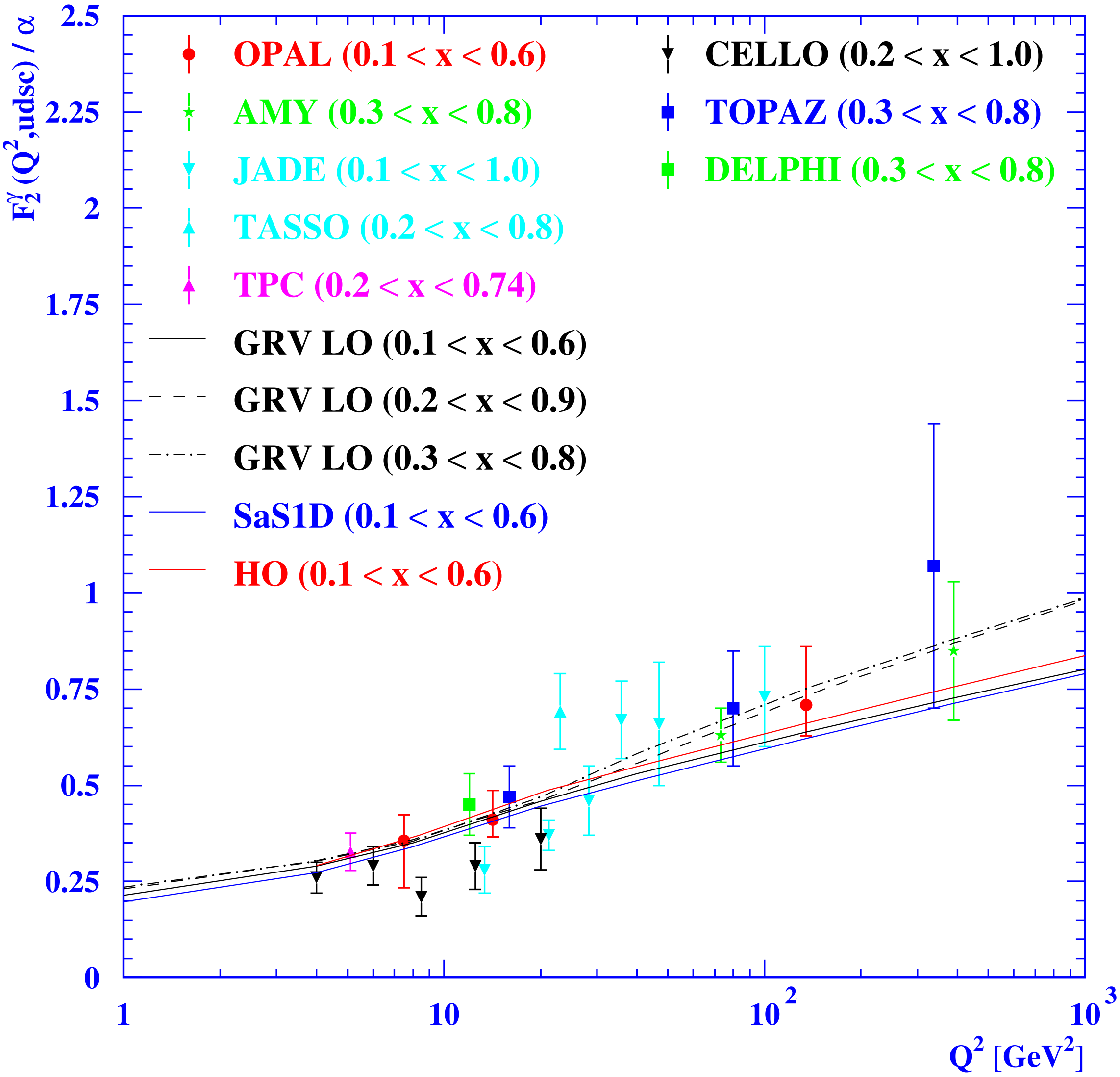
The systematic error on $F_2^\gamma(x, Q^2)$

$\langle Q^2 \rangle$ (GeV^2)	$\langle x \rangle$	x- range	F_2^γ/α	rel (%)
PLUTO 9.2	0.145	$0.060\text{-}0.230$	$0.35 \pm 0.03 \pm 0.09$	25
	0.385	$0.230\text{-}0.540$	$0.40 \pm 0.03 \pm 0.06$	15
	0.720	$0.540\text{-}0.900$	$0.49 \pm 0.07 \pm 0.07$	15
OPAL 14.7	0.072	$0.006\text{-}0.137$	$0.38 \pm 0.01 {}^{+0.06}_{-0.13}$	25
	0.230	$0.137\text{-}0.324$	$0.41 \pm 0.02 {}^{+0.06}_{-0.03}$	11
	0.423	$0.324\text{-}0.522$	$0.41 \pm 0.03 {}^{+0.08}_{-0.11}$	23
	0.679	$0.522\text{-}0.836$	$0.54 \pm 0.05 {}^{+0.31}_{-0.13}$	41
TOPAZ 16	0.085	$0.020\text{-}0.150$	$0.60 \pm 0.08 \pm 0.06$	10
	0.240	$0.150\text{-}0.330$	$0.56 \pm 0.09 \pm 0.04$	7
	0.555	$0.330\text{-}0.780$	$0.46 \pm 0.15 \pm 0.06$	13

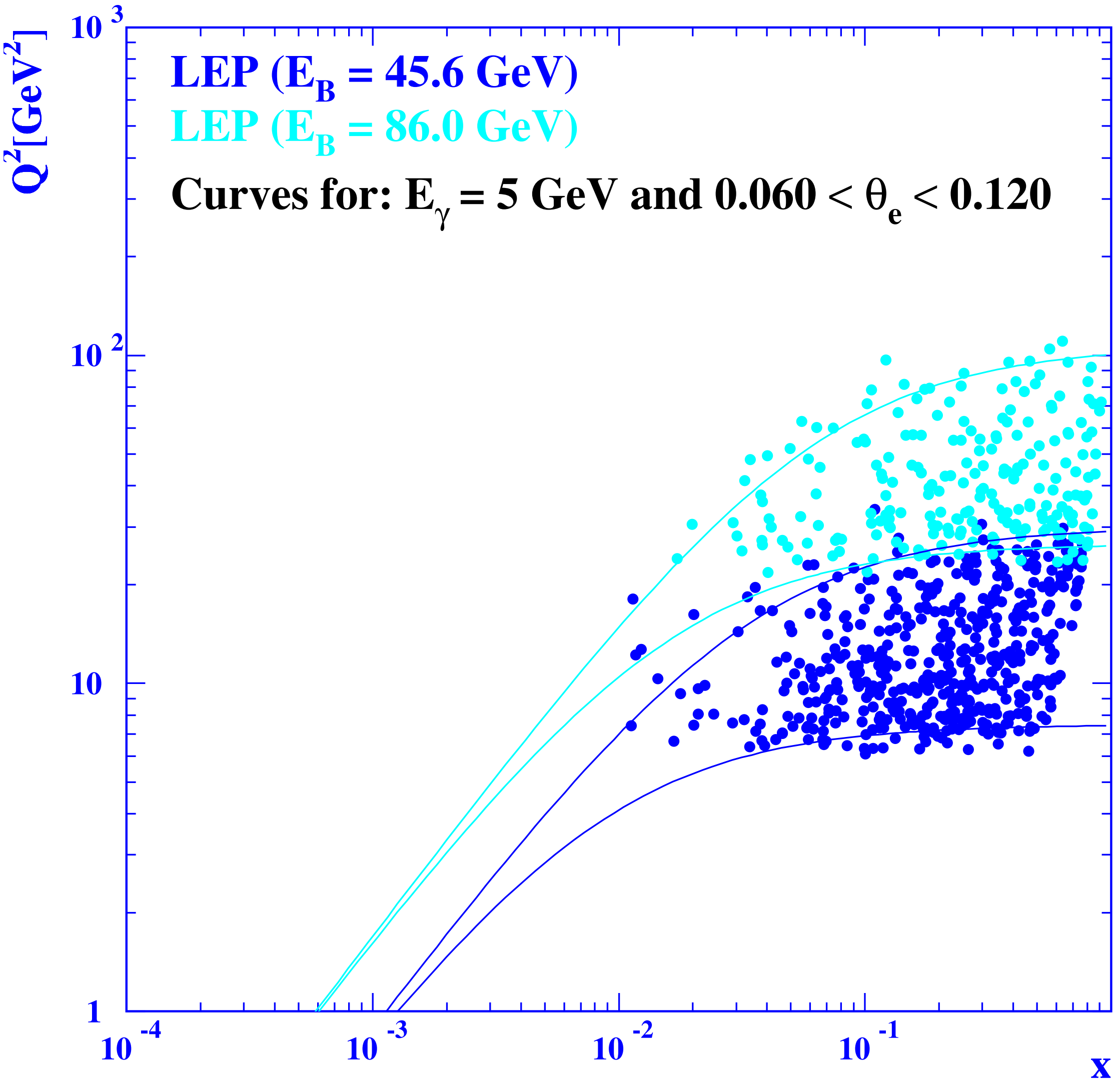
The single contributions for OPAL $\langle Q^2 \rangle$ = 14.7 GeV^2

$\langle x \rangle$	0.072	0.230	0.423	0.679
E_{tag}	${}^{+0.02}_{-0.01}$	${}^{+0.01}_{-0.02}$	${}^{+0.02}_{-0.02}$	${}^{+0.02}_{-0.01}$
θ_{tag}	< 0.01	-0.02	$+0.04$	$<{}^{+0.01}_{-0.10}$
W^2_{vis}	< 0.01	-0.02	$+0.05$	-0.12
p_{t}	< 0.01	< 0.01	< 0.01	< 0.01
PDF	$+0.06$	$+0.02$	-0.11	-0.13
SUE	-0.05	-0.03	< 0.01	$+0.02$
model	${}^{+0.03}_{-0.13}$	$+0.06$	${}^{+0.08}_{-0.03}$	$+0.31$

$\mathrm{d}F_2^\gamma/\mathrm{d}\ln Q^2$ for n_f = 4 = (udsc)



The prospects of F_2^γ at higher E_b



Conclusions

Two-Photon physics is a very active field at LEP with good prospects for LEP2

- **Photon-Photon scattering**
  1. The jet profiles are satisfactory described by the Monte Carlo models.
  2. NLO calculations of jet production agree nicely with the data.
- **Electron-Photon DIS**
  1. There is a good agreement between the QED predictions and the measured $F_{2,\mathrm{QED}}^{\gamma}$ structure function and the ratio $F_{\mathrm{B}}^{\gamma}/F_{2}^{\gamma}$.
  2. The F_2^{γ} structure function was measured for 7.5 $< \langle Q^2 \rangle <$ 135 GeV^2. The systematic errors have a large contribution from the imperfect description of the hadronic final state by the QCD inspired Monte Carlo models.

and . . .

Outlook

What can we expect from LEP on Two-Photon physics in the future

- **Photon-Photon scattering**
  1. More resonances (see list).
  2. Jet production for the direct component alone.
  3. Determination of the gluon content of the photon in jet production.
  4. . . .
- **Electron-Photon DIS**
  1. P^2 dependence of $F_{2,\mathrm{QED}}^{\gamma}$.
  2. Azimuthal correlations in hadronic final states.
  3. F_2^{γ} for 20 $< Q^2 <$ 1000 GeV^2.
  4. Double tag events.
  5. . . .

The LEP2 programme has just started

slides:

http://wwwcn1.cern.ch/~nisius/talks/CERN100297/index.html