PA04-009

Jet Production in Photon-Photon Interactions

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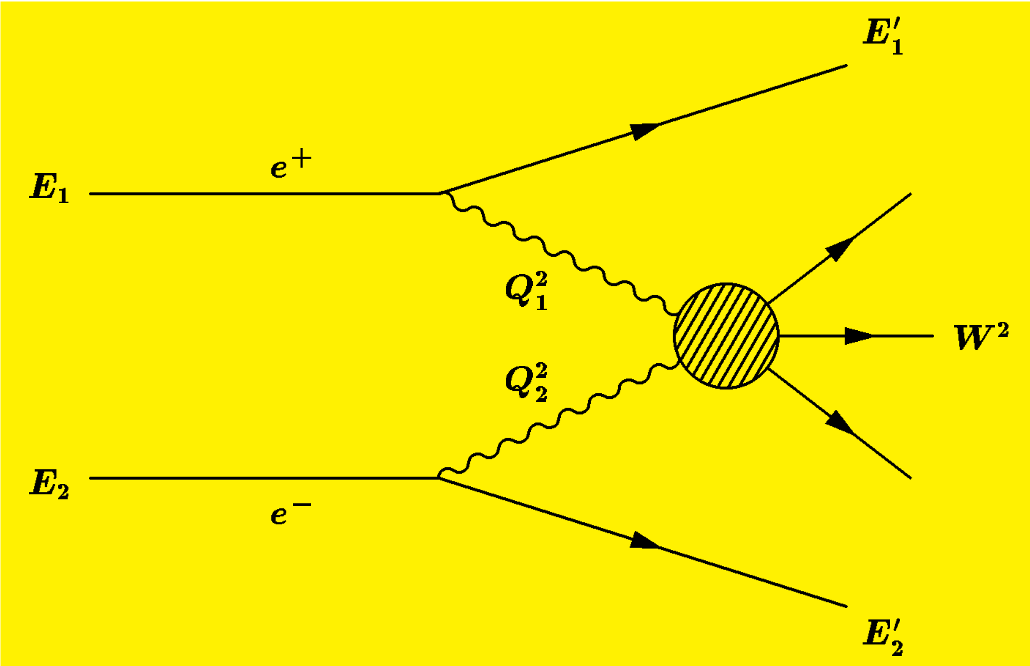
for the OPAL collaboration

Measurement of jet production in $\gamma\gamma$ interactions at highest available energy ($\sqrt{s}_{\mathrm{ee}} = 130 - 136$ GeV)

Motivation:

- Study of new $\gamma\gamma$ Monte Carlo generators
- Comparison with NLO perturbative QCD calculations
- Study structure of the photon and its interactions



$$Q_i^2 \approx 2E_iE_i'(1 - \cos\Theta_i)$$

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

1. $e\gamma$ scattering ("single tagged")

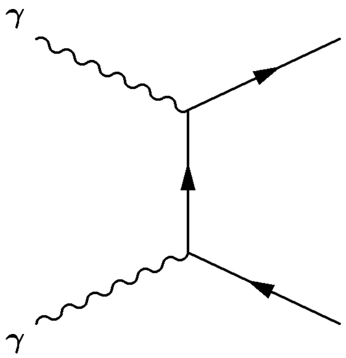
   $Q_1^2 >> 0$ and $Q_2^2 \approx 0$ (or v. v.)

2. $\gamma\gamma$ scattering ("anti-tagged")

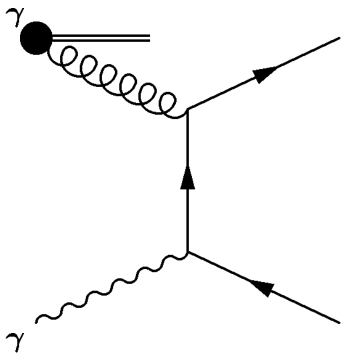
   $Q_1^2 \approx 0$ and $Q_2^2 \approx 0$

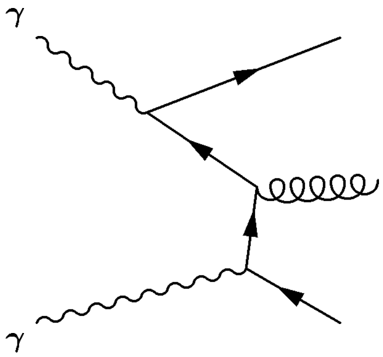
Leading order $\gamma\gamma$ interactions

Direct:

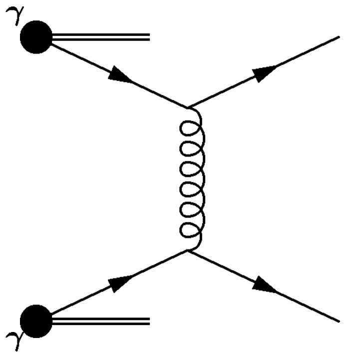


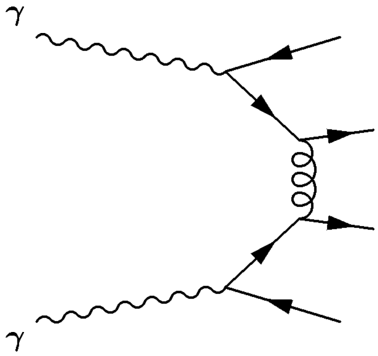
Single-Resolved:

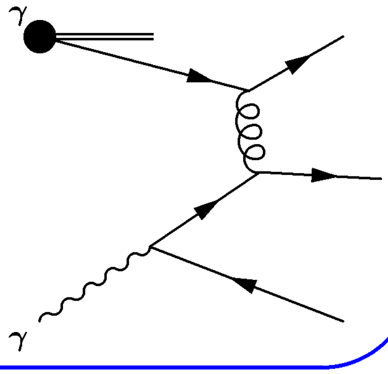


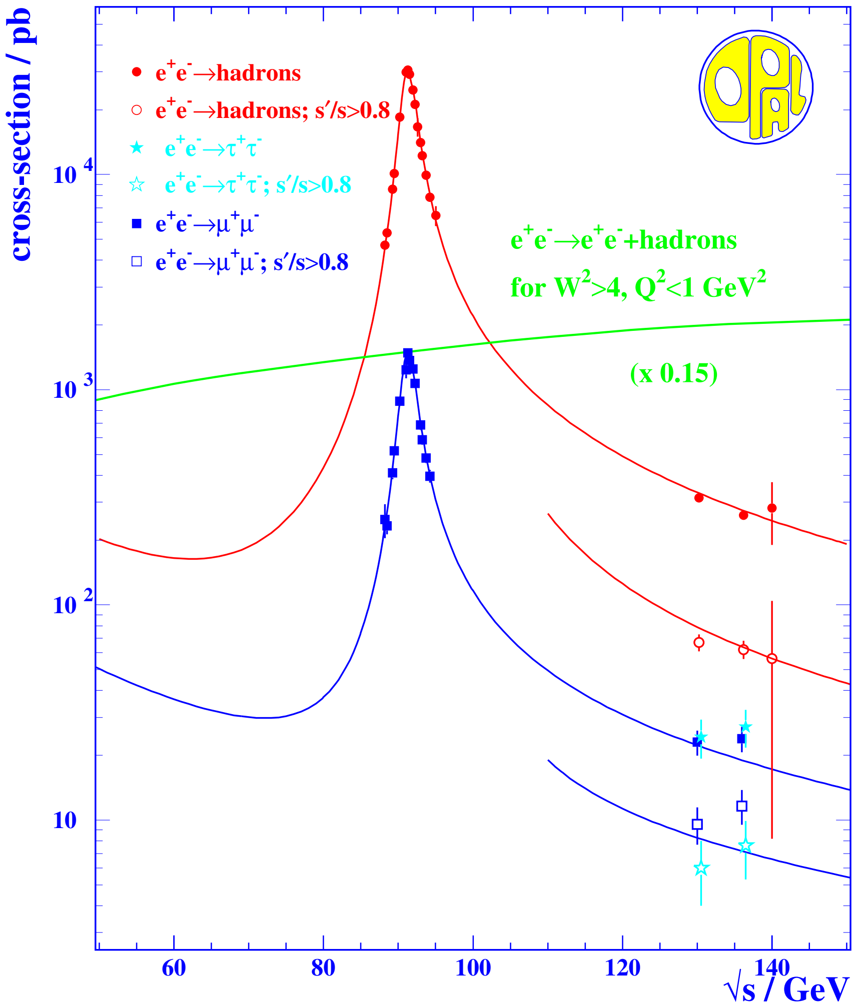


Double-Resolved:









LEP 1.5 ($L = 5$ pb^{-1})	$\sigma_{e^+e^-}$	N_{sel}
$e^+e^- \rightarrow (\gamma, Z) \rightarrow q\bar{q}$ ($s'/s > 0.01$)	0.3 nb	1488
$e^+e^- \rightarrow e^+e^- +$ had ($W^2 > 4\,, Q^2 < 1$ GeV^2)	$\sim$ 14 nb	$\sim$ 10000

Monte Carlo Generators

PYTHIA 5.721 and PHOJET 1.05

- **Leading order (LO) QCD matrix elements**
- **Hard and soft processes**
- **Total cross sections from Regge models**
- **Initial state parton radiation**
- **Fragmentation done by JETSET 7.408**
- **Multiple interactions**

NEVER TESTED WITH $\gamma\gamma$ DATA !!

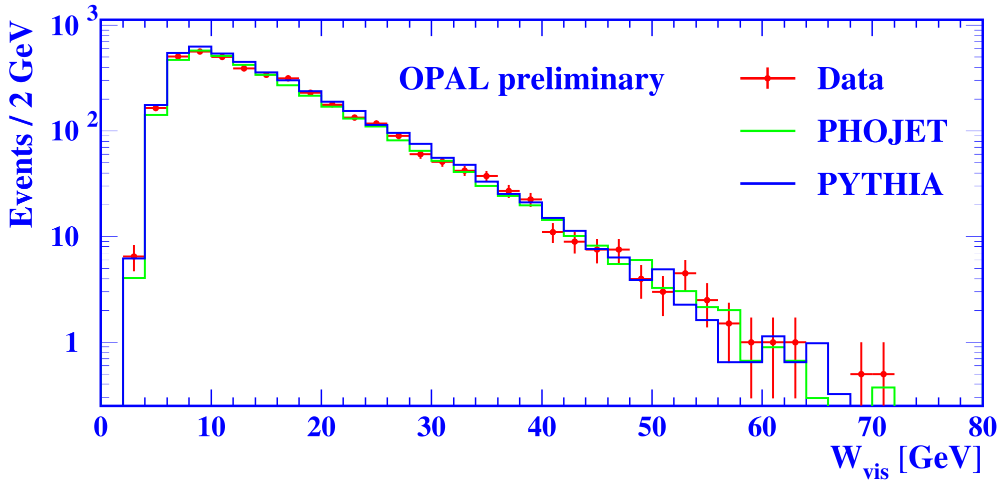
Event Selection at LEP 1.5

- $W_{\mathrm{ECAL}} > 3$ GeV
- Energy sum in all calorimeters less than 50 GeV
- Missing transverse energy less than 5 GeV
- $n_{\mathrm{ch}} > 4$
- Maximum momentum of any charged track less than 15 GeV
- Sum of all charges less than 4
- No electron tags in forward calorimeters

$$\Longrightarrow$$

7663 events in 4.9 pb^{-1}

$W_{\rm vis}$ distribution



- $W_{\rm vis}$ measured using
  - ECAL, HCAL
  - tracking chambers
  - forward calorimeters
- Photon energy spectrum in Monte Carlo generated with the Equivalent Photon Approximation (EPA)
- $\langle W_{\rm vis}\rangle = 15$ GeV and $\langle W_{\rm true}\rangle = 24$ GeV

Cone jet algorithm

Cone radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

pseudo-rapidity $\eta = -\ln\tan\frac{\theta}{2}$

azimuthal angle ϕ

$$R = 1 \quad E_T^{\mathrm{jet}} > 3\ \mathrm{GeV} \quad \left|\eta^{\mathrm{jet}}\right| < 1$$

- Detector:
  - calorimeter clusters
  - charged tracks
- Monte Carlo Generator:
  - primary hadronic multiplicity

Jet multiplicity and background

	0-jet	1-jet	2-jet
data	6813	709	132
$\gamma\gamma \to \tau\tau$	2.7 ± 0.7	1.9 ± 0.6	0.6 ± 0.4
e$\gamma \to$ e + had (single tagged)	60.5 ± 5.5	1.0 ± 0.7	< 0.5
$e^+e^- \to$ had(γ)	4.3 ± 0.3	3.8 ± 0.3	1.1 ± 0.2
$e^+e^- \to \tau\tau(\gamma)$	0.06 ± 0.01	0.09 ± 0.02	0.06 ± 0.01

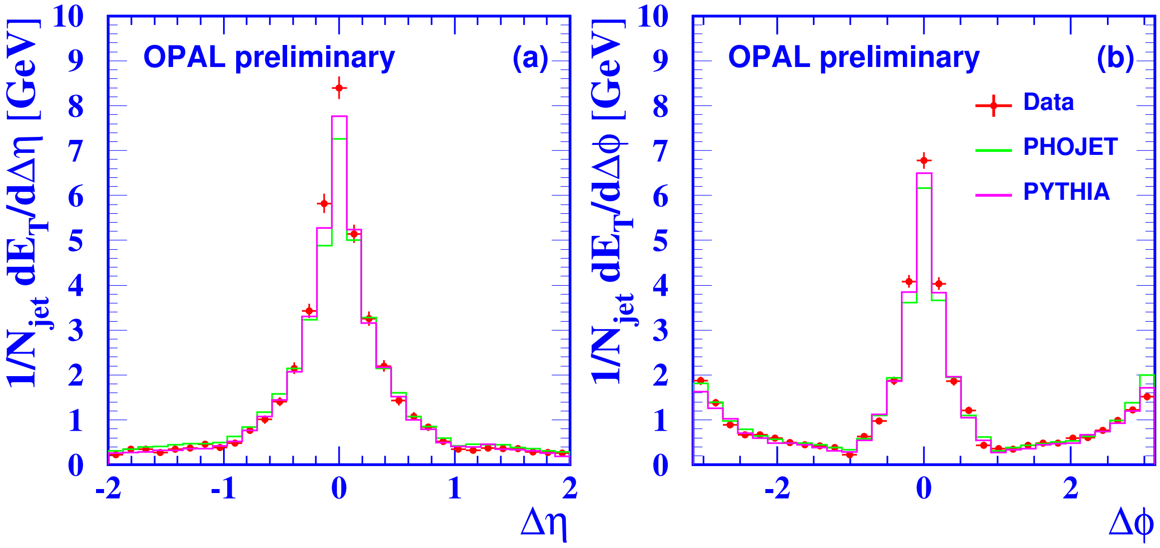
	3-jet	4-jet
data	8	1
$\gamma\gamma \to \tau\tau$	< 0.3	< 0.3
e$\gamma \to$ e + had	< 0.5	< 0.5
$e^+e^- \to$ had(γ)	0.1 ± 0.1	< 0.1
$e^+e^- \to \tau\tau(\gamma)$	< 0.01	< 0.01

- **Negligible background from beam-gas and beam-wall interactions**
- **Total background less than 1 %**

Energy flow around jet axes

$$\frac{1}{N_{\rm jet}}\frac{dE_T}{d(\Delta\eta)} \quad \text{and} \quad \frac{1}{N_{\rm jet}}\frac{dE_T}{d(\Delta\phi)}$$

$$\Delta\eta = \eta - \eta_{\rm jet} \quad \text{and} \quad \Delta\phi = \phi - \phi_{\rm jet}$$

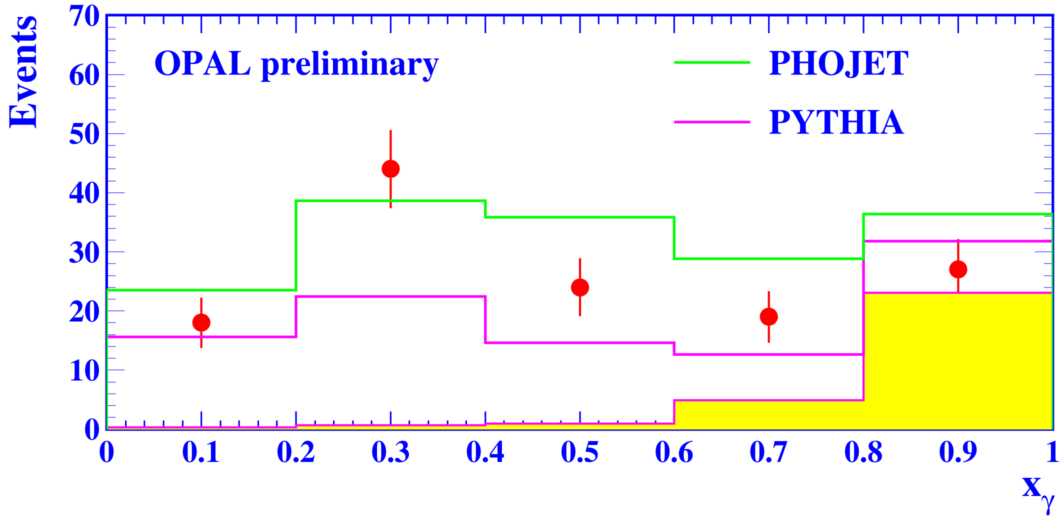


Integrated over $|\Delta\phi| < \pi/2$ for $\Delta\eta$

Integrated over $|\Delta\eta| < 1$ for $\Delta\phi$

Only central detectors used

Two-jet events



$$x_\gamma = \max\left\{\frac{\sum_{\rm jets}(E+p_z)}{\sum_{\rm hadrons}(E+p_z)}, \frac{\sum_{\rm jets}(E-p_z)}{\sum_{\rm hadrons}(E-p_z)}\right\}$$

'Fraction of photon momentum participating in the hard interaction'

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

Resolved events: $x_\gamma < 1$

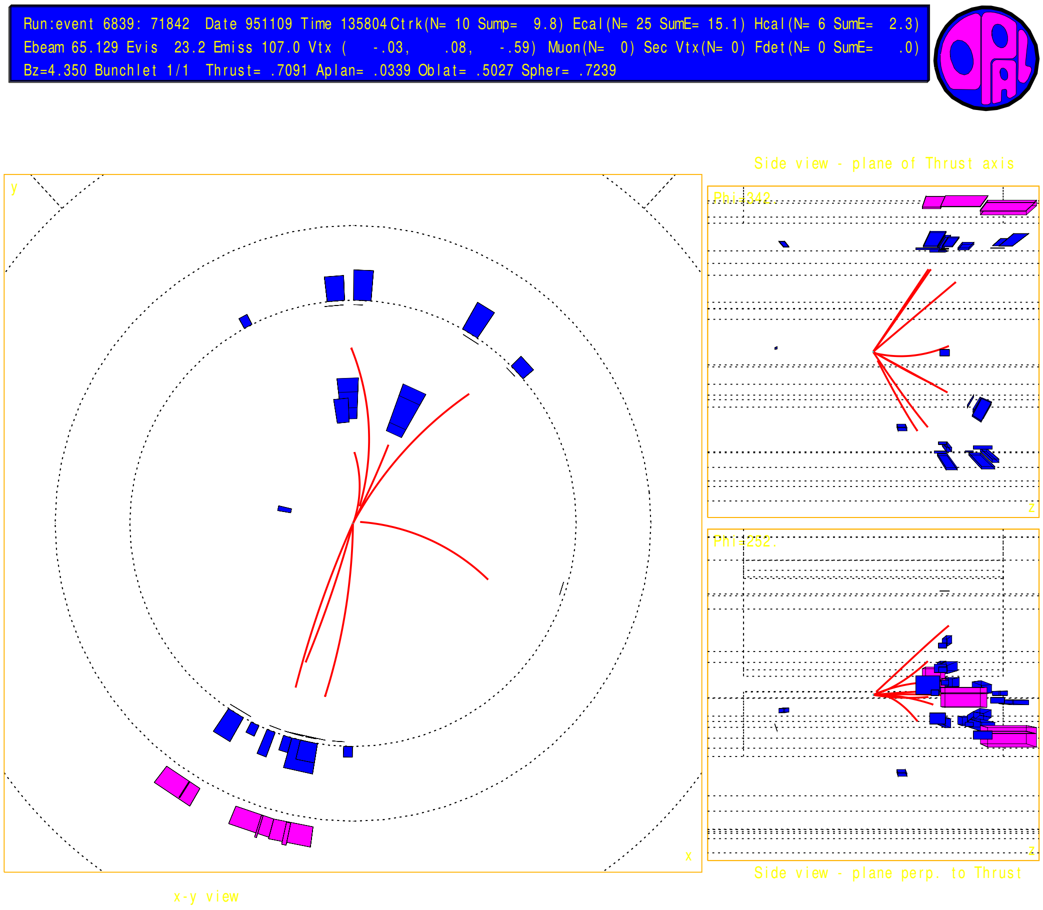
Smearing due to detector, hadronization and higher order QCD (gluon radiation)

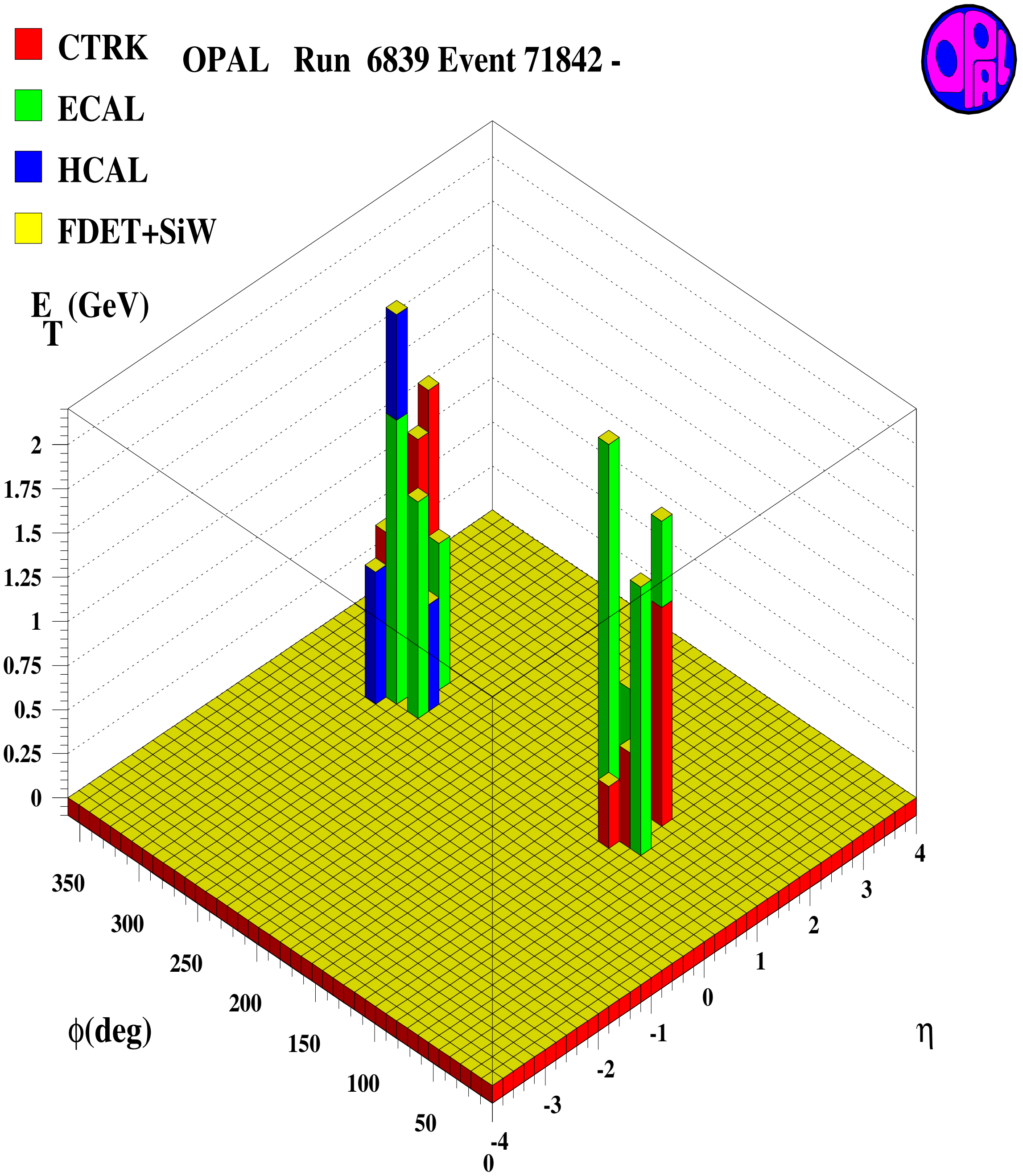
A direct two-jet event

Jet 1: $E_T^{\rm jet} = 6.9\ \mathrm{GeV}, \eta_{\rm jet} = 0.7$

Jet 2: $E_T^{\rm jet} = 6.6\ \mathrm{GeV}, \eta_{\rm jet} = 0.9$

$x_\gamma = 0.94$



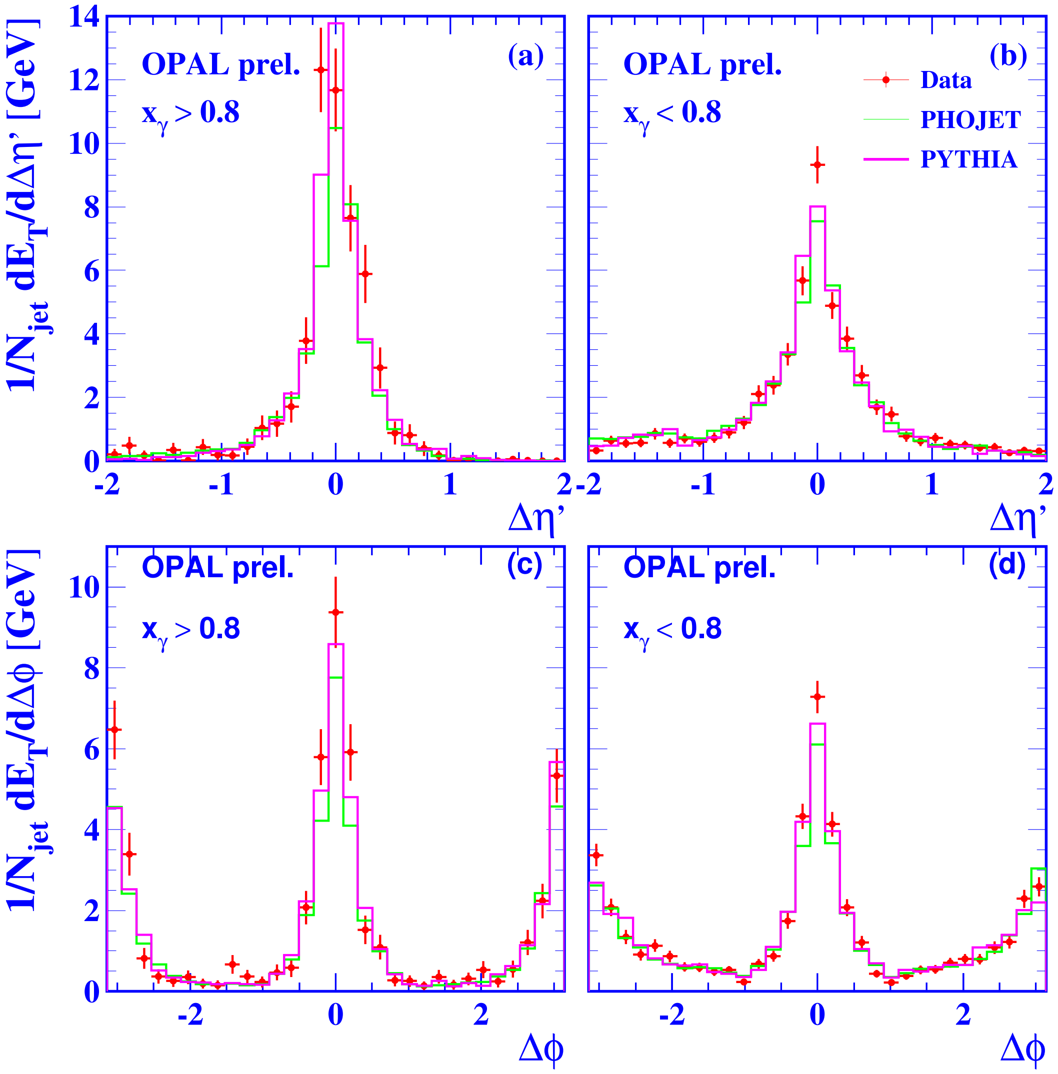


$$\Delta\Phi \approx \pi$$

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

Always more remnant at $\Delta\eta' < 0$

"direct" $x_\gamma > 0.8$ "resolved" $x_\gamma < 0.8$



Inclusive NLO jet cross sections

T. Kleinwort and G. Kramer,

DESY-96-035 (1996) and Phys. Lett. B370 (1996) 141

$$\frac{d\sigma^{D}}{dE_T d\eta} = \left(\frac{d\sigma^{\gamma\gamma\to jet}}{dE_T d\eta}\right)_{LO} + \frac{\alpha_s(\mu)}{2\pi} K^{D}(R,M)$$

$$\frac{d\sigma^{SR}}{dE_T d\eta} =$$

$$\sum_{i=q,G} \int dx_1 F_{i/\gamma}(x_1)$$

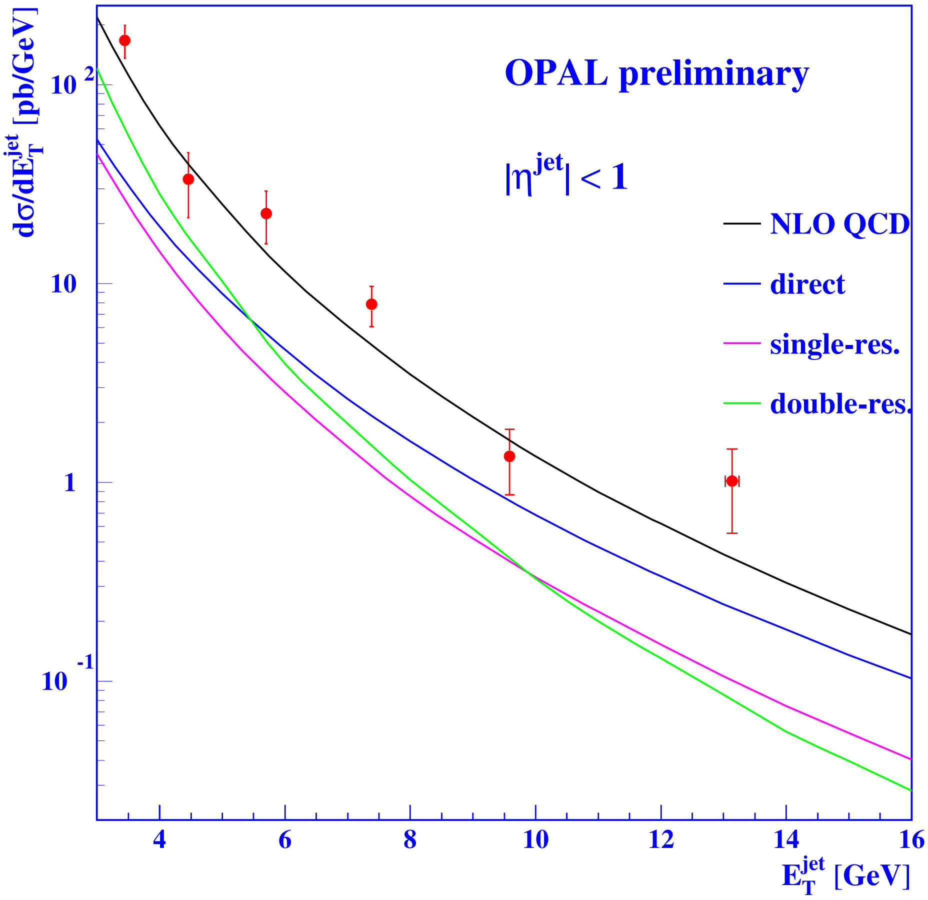
$$\left(\left(\frac{d\sigma^{i\gamma\to jet}}{dE_T d\eta}\right)_{LO} + \frac{\alpha_s(\mu)}{2\pi} K^{SR}_{i\gamma}(R,M)\right) + (1 \leftrightarrow 2)$$

$$\frac{d\sigma^{DR}}{dE_T d\eta} =$$

$$\sum_{i,j=q,G} \int\int dx_1 dx_2 F_{i/\gamma}(x_1) F_{j/\gamma}(x_2)$$

$$\left(\left(\frac{d\sigma^{ij\to jet}}{dE_T d\eta}\right)_{LO} + \frac{\alpha_s(\mu)}{2\pi} K^{DR}_{ij}(R,M)\right)$$

Inclusive one-jet cross section



Regularized unfolding with the method of V. Blobel

Parton calculation compared to hadron level cross section

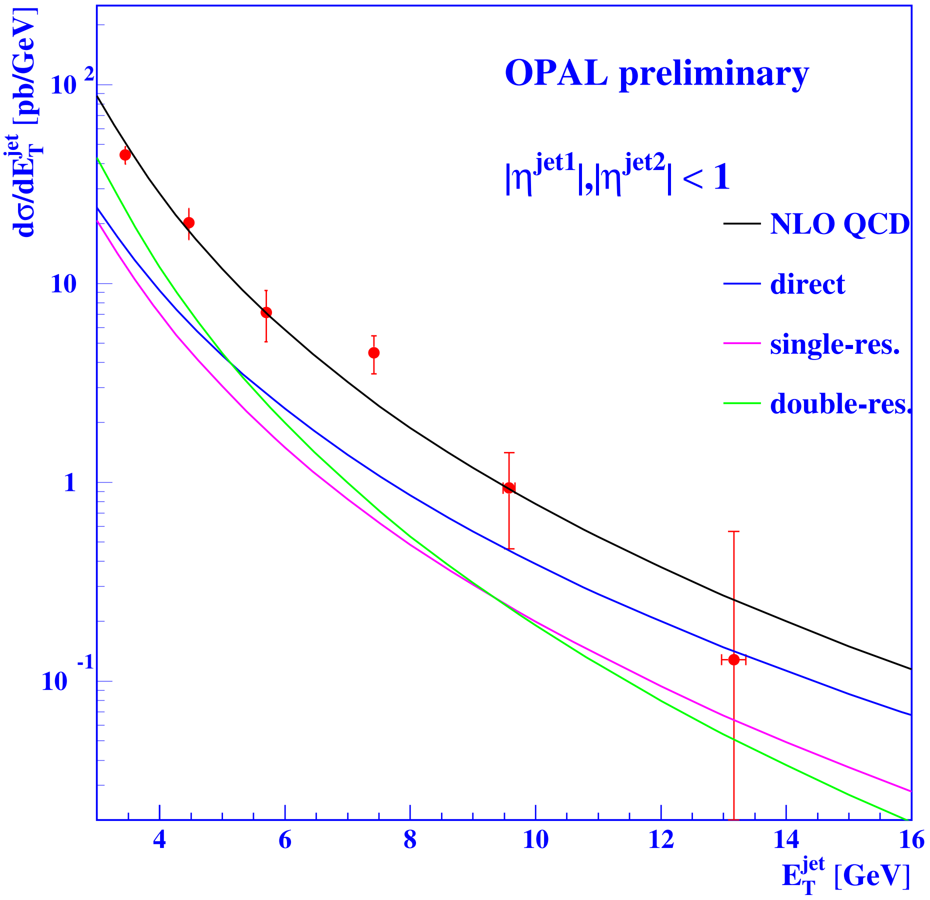
NLO calculation uses NLO-GRV photon structure function and $\Lambda^{(5)}_{\overline{\mathrm{MS}}} = 130$ MeV.

Systematic errors

- ECAL energy scale varied by $\pm 5\%$
- degradation of track resolution in MC
- difference between unfolding using PYTHIA and PHOJET
- unfolding error

$\langle E_T^{\mathrm{jet}} \rangle$ (GeV)	$d\sigma / dE_T^{\mathrm{jet}}$ (pb/GeV)
3.45 ± 0.02	$167.2 \pm 6.8 \pm 31.0$
4.46 ± 0.02	$33.5 \pm 2.4 \pm 11.8$
5.70 ± 0.03	$22.5 \pm 2.0 \pm 6.3$
7.39 ± 0.04	$7.8 \pm 1.1 \pm 1.5$
9.59 ± 0.08	$1.4 \pm 0.3 \pm 0.4$
13.14 ± 0.11	$1.0 \pm 0.3 \pm 0.4$

Inclusive two-jet cross section



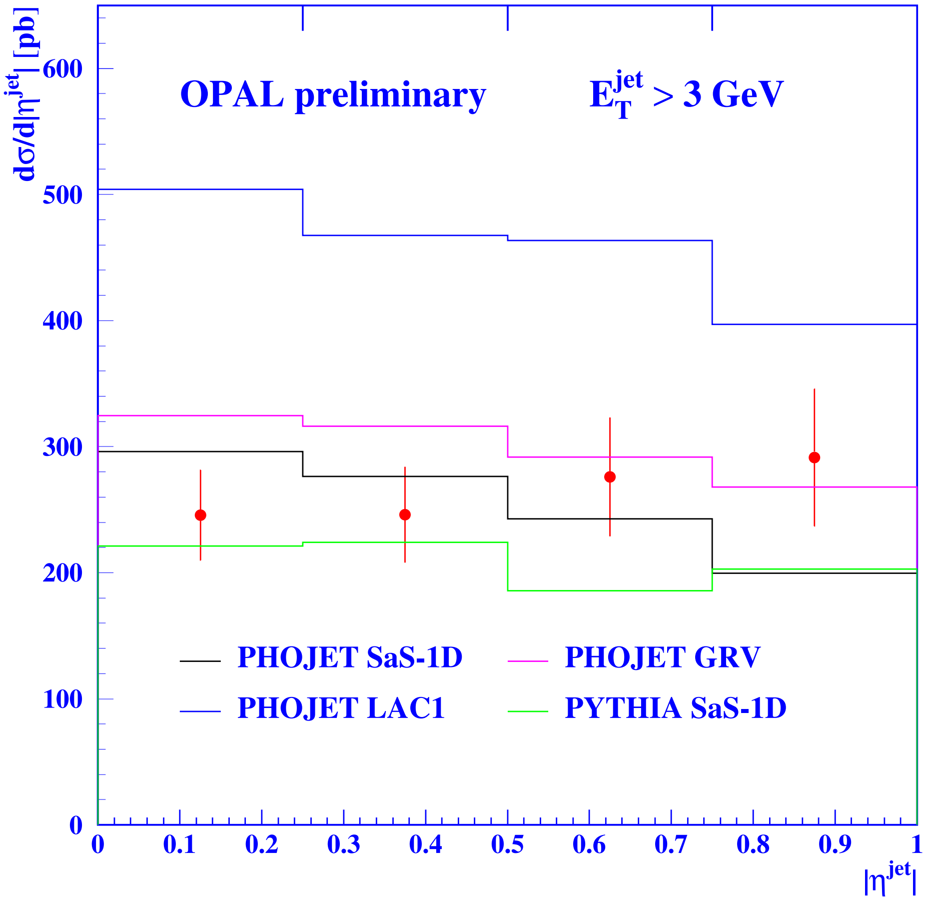
Direct contribution dominates at $E_T^{\mathrm{jet}} > 5$ GeV

Fraction of hard interactions increases

from $\bar{\mathrm{p}}\mathrm{p}$ to $\gamma\mathrm{p}$ to $\gamma\gamma$

$\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}} \sim 1.1$

inclusive one-jet cross section



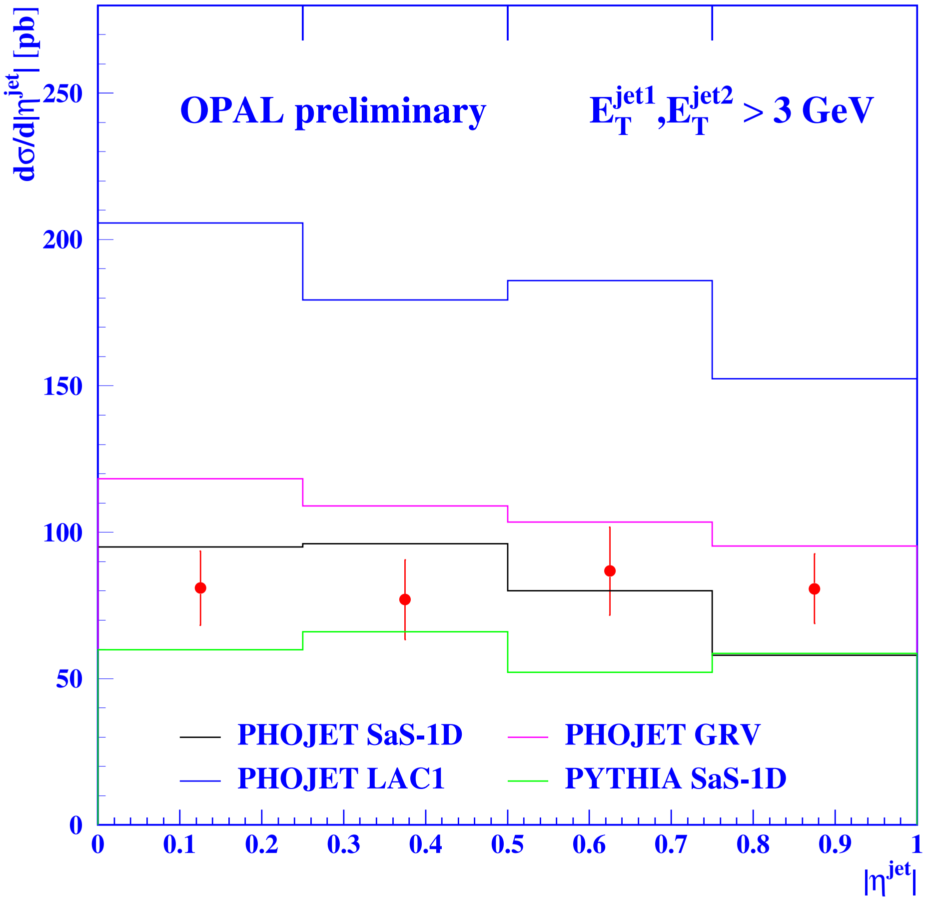
η^{jet} measured in lab frame

Boost from lab to $\gamma\gamma$ frame varies event-by-event

PHOJET and PYTHIA describe data
with GRV and SaS-1D

PHOJET-LAC1 too high by about a factor of two

inclusive two-jet cross section



Within errors the cross section is independent of $\eta^{\rm jet}$ for $|\eta^{\rm jet}| < 1$

Monte Carlo in reasonable agreement using SaS-1D and GRV, but not LAC1

NLO calculations for $\eta^{\rm jet}$ available soon

Conclusion

Jet production in $\gamma\gamma$ interactions at $\sqrt{s}_{\mathrm{ee}} = 130 - 136$ GeV was measured using a cone algorithm with $E_T^{\mathrm{jet}} > 3$ GeV and $|\eta^{\mathrm{jet}}| < 1$.

First such measurement at LEP. E_T^{jet} range extended by about a factor of two compared to TRISTAN.

Direct and resolved events separated by x_γ

Good agreement with NLO calculations.

PYTHIA and PHOJET with SaS-1D or GRV are in reasonable agreement with data.
Jet cross section with LAC1 is too large.

Lots of exciting two-photon physics at LEP2!