Measurements of the Cross Section for the Process $\gamma\gamma \rightarrow \mathrm{p\bar{p}}$ *at* $\sqrt{s_{\rm ee}} = 183\ -\ 189\,\mathrm{GeV}$ *with the* ***OPAL*** *Detector at LEP*

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- Kinematics
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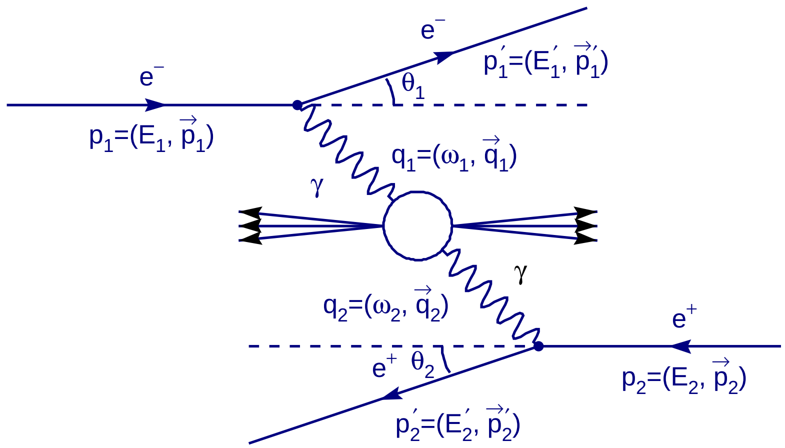
Introduction

- OPAL paper "Measurement of the Cross-Section for the Process $\gamma\gamma \rightarrow \mathrm{p\bar{p}}$ at $\sqrt{s_{\mathrm{ee}}} = 183 - 189\,\mathrm{GeV}$ at LEP" accepted for publication in Eur. Phys. J. C
  - see: G. Abbiendi et al., hep-ex/0209052
- Work motivated by the quark-diquark model to test non pQCD calculations
  - see: C. F. Berger, W. Schweiger, hep-ph/0212066 (2002); M. Anselmino et al., Int. J. Mod. Phys. A4 (1989)
- Three quark model yields cross-sections about one order of magnitude smaller than the experimental results for $\mathrm{W} > 2.5\,\mathrm{GeV}$
  - see: G. P. Lepage et S. J, Brodsky Phys. Rev. D22 (1980); G. R. Farrar et al., Nucl. Phys. B259 (1985), V. L. Chernyak et al., Nucl. Phys. B246 (1984)

Kinematics

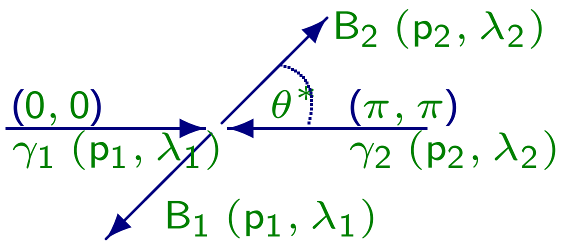
$e^+e^- \to e^+e^-\gamma\gamma \to e^+e^- X$

$X = p\bar{p}, \Lambda\bar{\Lambda}, \ldots$ (Baryons)



$$Q_i^2 \approx 2E_iE_i^{'}(1 - \cos\theta_i)$$
$$Q_i^2 = (q_i^2 - w_i^2)$$

$\gamma\gamma$ center-of-mass system (CMS)



$W_{\gamma\gamma}$, invariant mass in the $\gamma\gamma$ CMS

θ^*, polar angle in the $\gamma\gamma$ CMS

- "Untagged $\gamma\gamma$ events": both scattered electrons go undetected
- The final state X has small $p_\perp$ and low mass
- The $\gamma\gamma$ CMS is boosted along the beam axis, the produced particles are close to the beam direction and they are almost back-to-back in x-y

⇨ Detection and trigger efficiencies limited

Hard scattering picture (HSP)

In pQCD (or HSP) an exclusive process: $\mathsf{A} + \mathsf{B} \to \mathsf{C} + \mathsf{D}$

is described by the exclusive hadronic amplitude

see: Brodsky et al., Phys. Rev. D24 (1981); Brodsky et al., ECFA 87/108 (1987)

$$\mathcal{M} = \int_0^1 T_H(x_j, p_\perp) \prod_{H_i} \left(\phi_{H_i}(x_j, \tilde{p}_\perp) \delta(1 - \sum_{k=1}^{n_i} x_k) \prod_{j=1}^{n_i} d\,x_j \right)$$

⇨ $\mathcal{M}$ separates: "short-range" from "long-range" phenomena

- ▷ ϕ_{H_i}: Parton distribution amplitude (DA) for each hadron in the process
- ▷ T_H: Hard scattering amplitude

$\mathcal{M}$ has "two" phenomenological consequences

- The dimensional counting rules: $\mathcal{M} \approx \frac{1}{(\mathrm{p}_\perp^2)^{(\mathrm{n}-4)/2}} f(\theta_{\mathrm{c.m.}})$

  with $\frac{\mathrm{d}\sigma(\gamma\gamma\to\mathrm{p}\bar{\mathrm{p}})}{\mathrm{d}t} \sim s^{-6}$
- The hadron helicity conservation rules: $\lambda_A + \lambda_B = \lambda_C + \lambda_D$

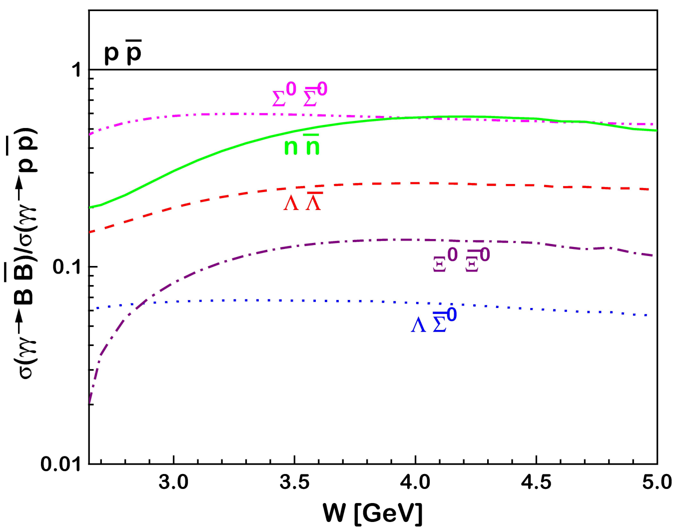
⇨ Hadron helicity conservation rules not in agreement with data

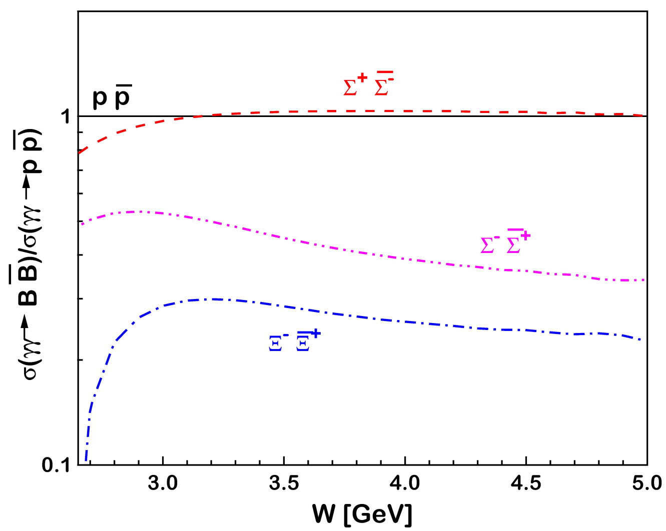
Quark-diquark model

There are applications of the quark-diquark model to the reactions:

$\gamma\gamma \to \mathrm{B}\overline{\mathrm{B}}$ where $\mathrm{B} = \mathrm{p}, \Lambda, \Xi^-$, etc.,

see: C. F. Berger, W. Schweiger, hep-ph/0212066 (2002); M. Anselmino et al., Int. J. Mod. Phys. A4 (1989)





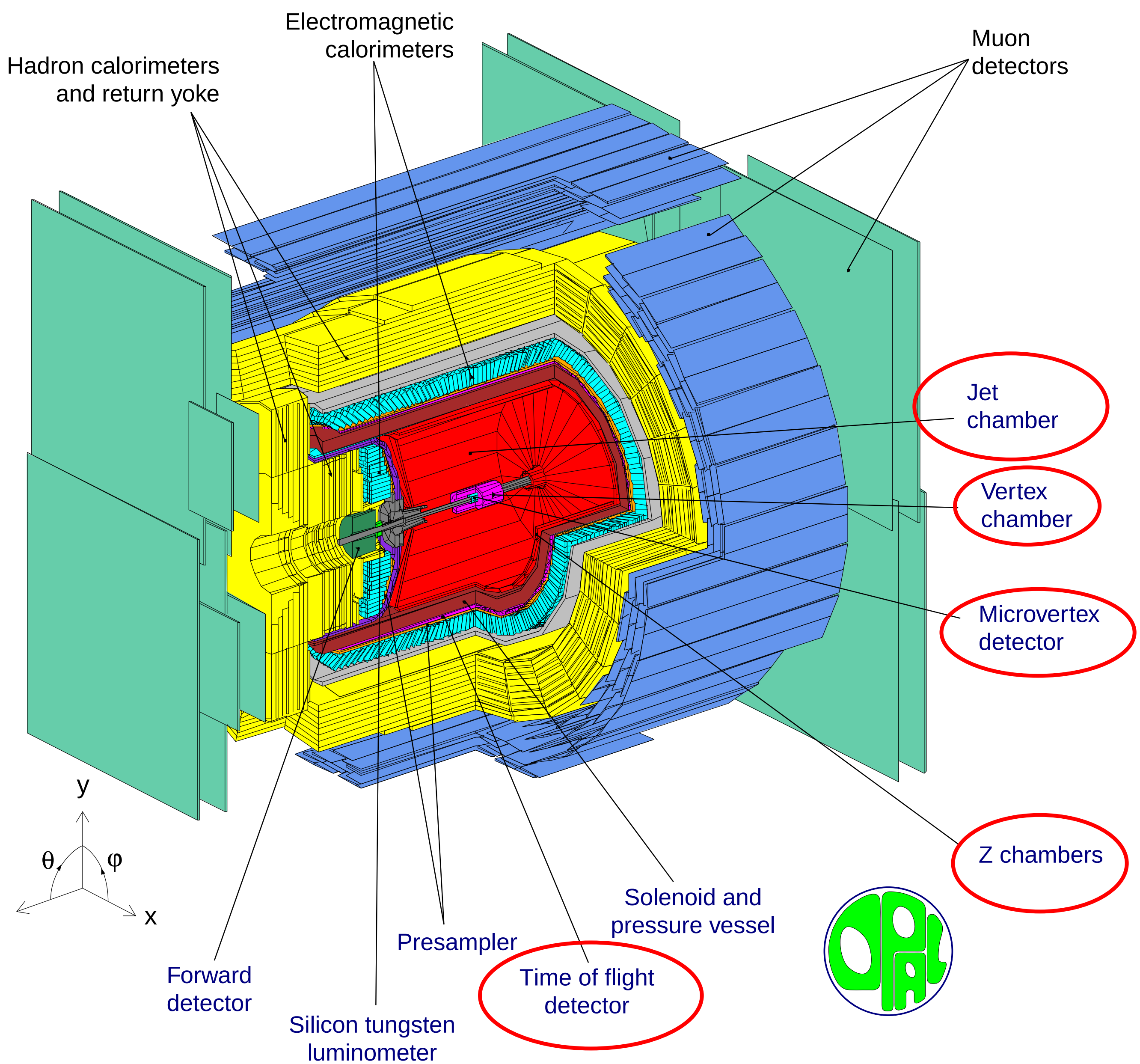
Diquarks modify the dimensional counting rules by decreasing n and can violate the hadron helicity conservation rules

- ▷ For the power law, we have now: $\frac{d\sigma(\gamma\gamma\to p\bar{p})}{dt} \sim s^{-4}$

➡ Recent contribution in studing annihilation of $\gamma\gamma \to \mathrm{B}\overline{\mathrm{B}}$ processes comes from: “Handbag Mechanism”

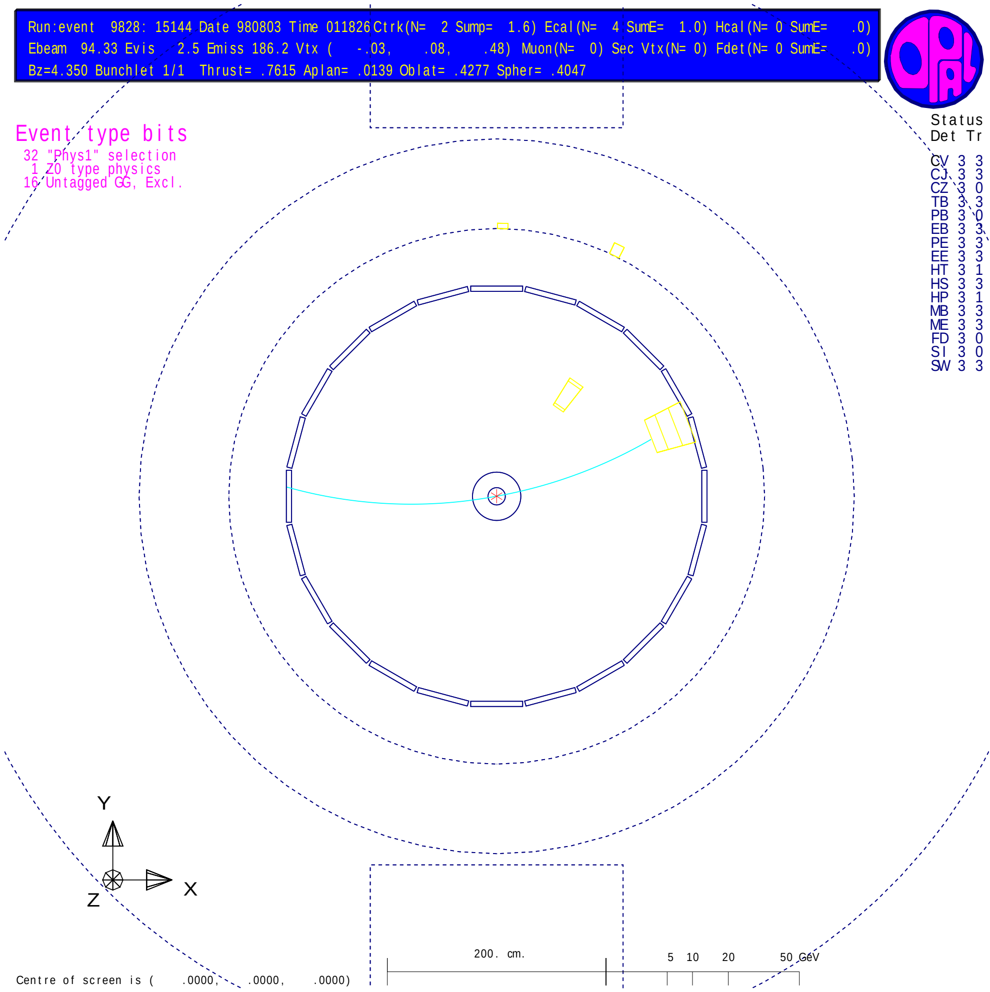
see: M. Diehl, P. Kroll, C. Vogt, hep-ph/0206288 (2002);

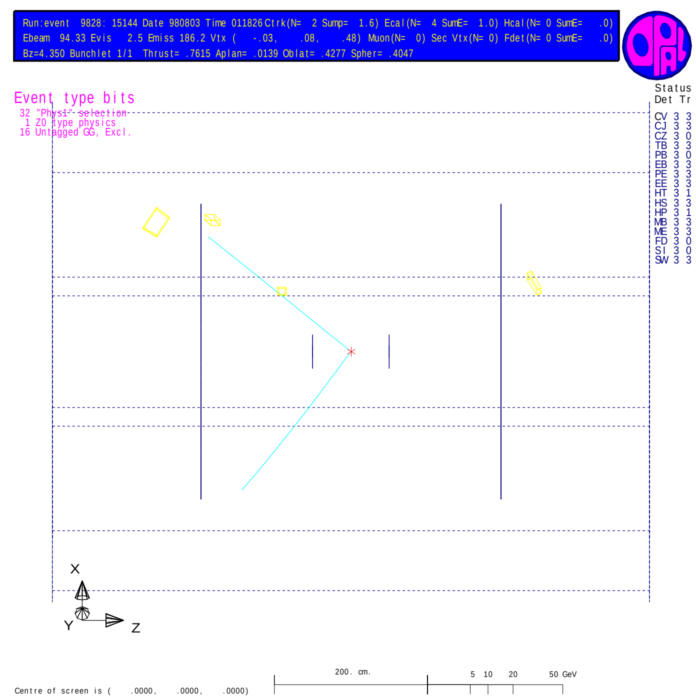
The OPAL detector at LEP



The $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^- p\bar{p}$ *events*

A typical $\gamma\gamma \to p\bar{p}$ event selected with the ***OPAL*** detector at LEP2

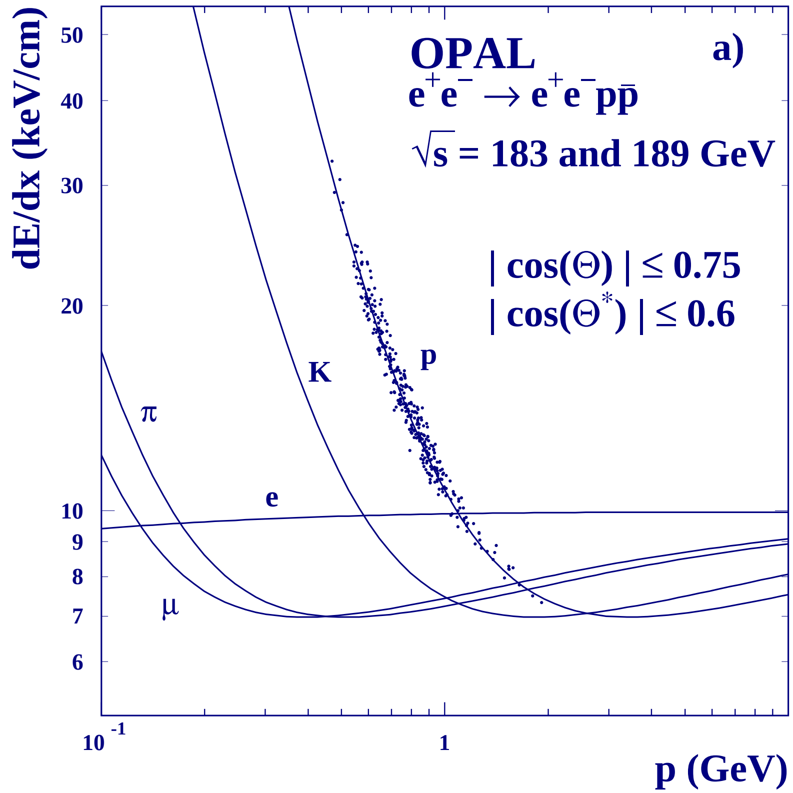




Event selection

- Applied cuts

▷ Number of hits in CJ > 20
▷ 2 tracks with $Q_{\mathrm{Tot}} = 0$
▷ $|\mathrm{d}_0| < 1.0$
▷ $|\cos\theta| < 0.75$
▷ $\mathrm{p}_\perp > 0.4\mathrm{GeV}$
▷ $|\cos\theta^*| < 0.6$
▷ Trigger Conditions
▷ $|\sum \vec{\mathrm{p}}_\perp|^2 < 0.04\mathrm{GeV}^2$
▷ $\mathrm{d}E/\mathrm{d}x$ to eliminate background
▷ $\mathrm{W} > 2.15\,\mathrm{GeV}$



- $163\ \gamma\gamma \rightarrow \mathrm{p}\bar{\mathrm{p}}$ events remained after the selection
- No events with acoplanarity more than 0.262 rad
- $\mathrm{W} = 2.15 - 3.95\,\mathrm{GeV}$

⇒ $\sim 500\ \mathrm{p}\bar{\mathrm{p}}$ events at LEP2 (data from 1997 to 2000)

Cross section measurements

- The $e^+e^- \to e^+e^- p\bar{p}$ differential cross section is given by:

$$\frac{d\sigma(e^+e^- \to e^+e^- p\bar{p})}{dW\, d|\cos\theta^*|} = \frac{N_{ev}\,(W, |\cos\theta^*|)}{\mathcal{L}_{e^+e^-}\,\varepsilon_{TRIG}\,\varepsilon_{DET}\,(W, |\cos\theta^*|)\,\Delta W\,\Delta|\cos\theta^*|}$$

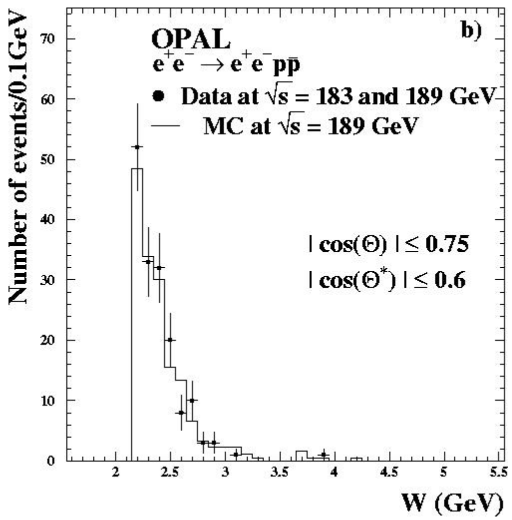
  - ▷ $\mathcal{L}_{e^+e^-}$ = Measured integr. luminosity = $249.10 \pm 0.22 \pm 0.43\,\mathrm{pb}^{-1}$

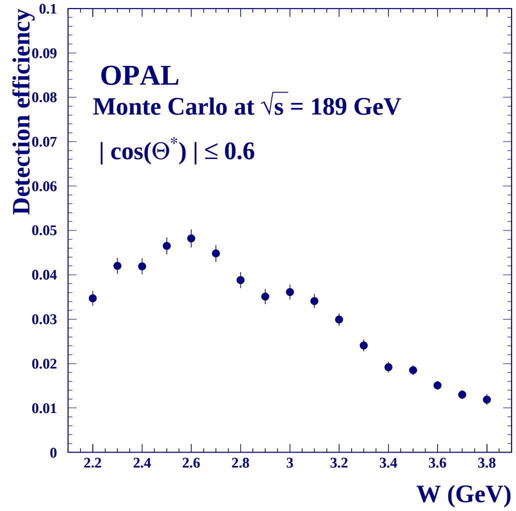
- The total cross section $\sigma(\gamma\gamma \to p\bar{p})$ is given by:

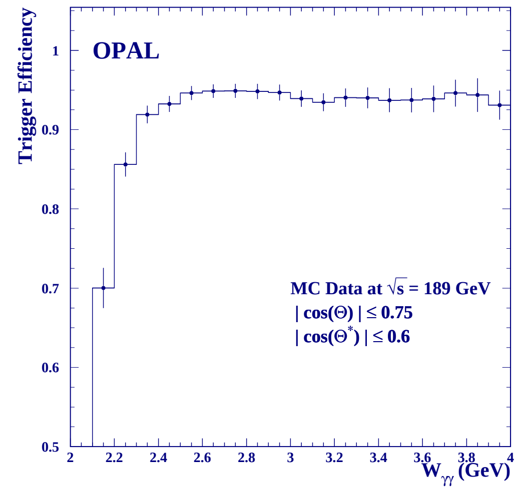
$$\sigma(\gamma\gamma \to p\bar{p}) = \frac{d\sigma(e^+e^- \to e^+e^- p\bar{p})}{dW} \Bigg/ \frac{d\mathcal{L}_{\gamma\gamma}}{dW}$$

  - ▷ $d\mathcal{L}_{\gamma\gamma}/dW$ = GALUGA $\gamma\gamma$ luminosity function
    - see: G. Schuler, hep-ph/9610406 (1996); G. Schuler, hep-ph/9710506 (1997)

Invariant mass, efficiencies, and systematics



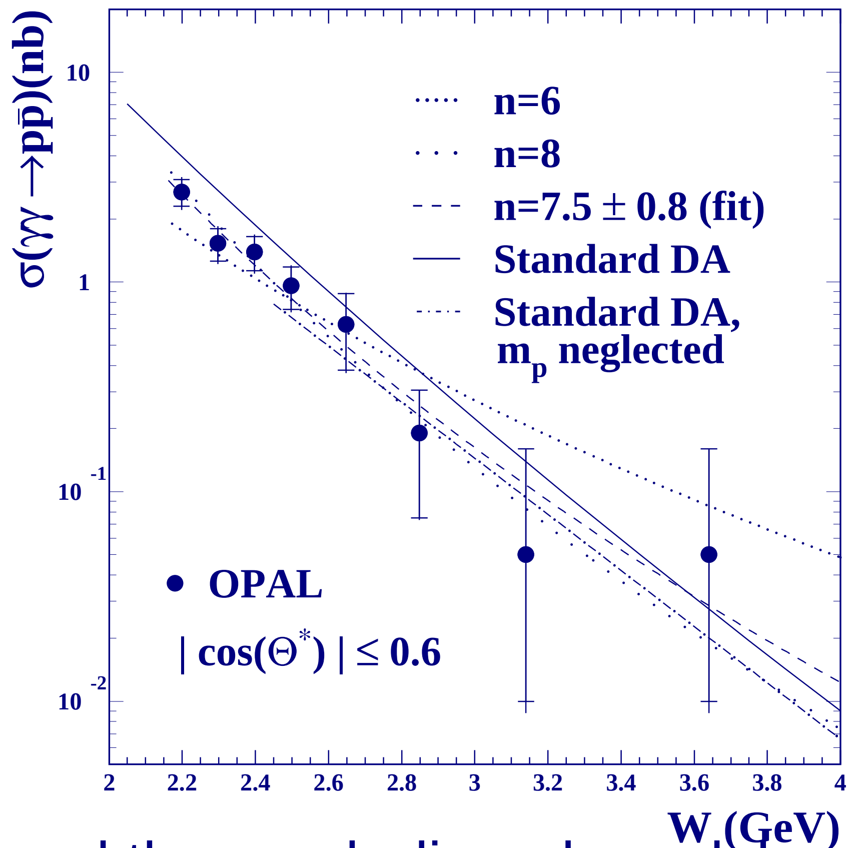




Source of Systematic uncertainties	Systematic uncertainty (%)
Luminosity Function	5.0
Trigger Efficiency	5.0
Monte Carlo statistics ($W < 2.55$ GeV)	4.5
($W > 2.55$ GeV)	6.0
$\mathrm{d}E/\mathrm{d}x$ cuts ($W < 2.55$ GeV)	0.1
($W > 2.55$ GeV)	5.0
Residual Background	6.0
Total ($W < 2.55$ GeV)	10.3
Total ($W > 2.55$ GeV)	12.1

OPAL cross section measurements

W range (GeV)	$\langle W \rangle$ (GeV)	Events	$\sigma(\gamma\gamma \rightarrow p\bar{p})$ (nb)
2.15-2.25	2.20	52	$2.69 \pm 0.39 \pm 0.28$
2.25-2.35	2.30	33	$1.53 \pm 0.27 \pm 0.16$
2.35-2.45	2.40	32	$1.39 \pm 0.26 \pm 0.14$
2.45-2.55	2.50	20	$0.96 \pm 0.22 \pm 0.10$
2.55-2.75	2.65	18	$0.62 \pm 0.22 \pm 0.08$
2.75-2.95	2.85	6	$0.19 \pm 0.11 \pm 0.02$
2.95-3.45	3.14	1	$0.05\,^{+0.11}_{-0.04} \pm 0.01$
3.45-3.95	3.64	1	$0.05\,^{+0.11}_{-0.04} \pm 0.01$

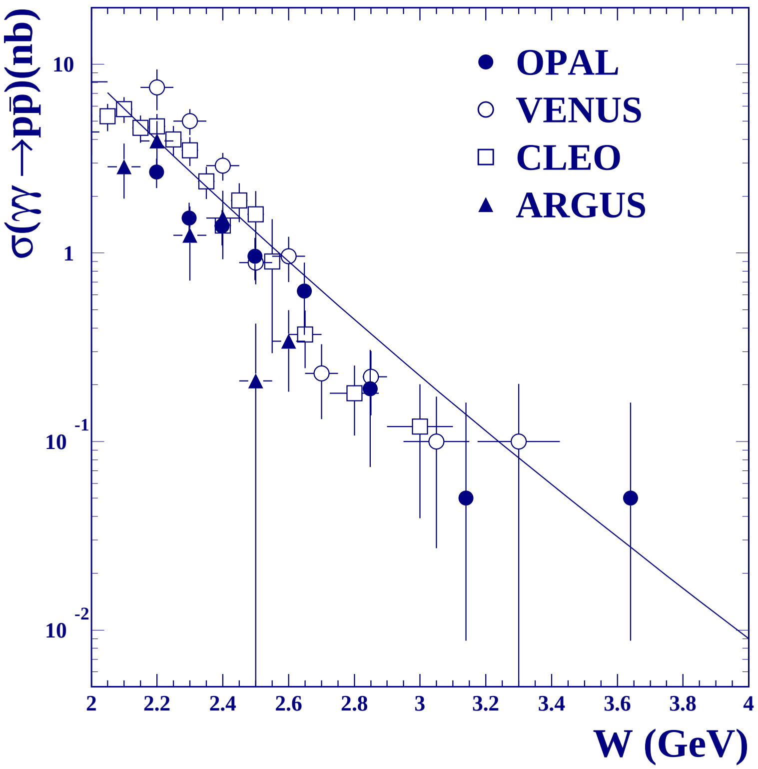


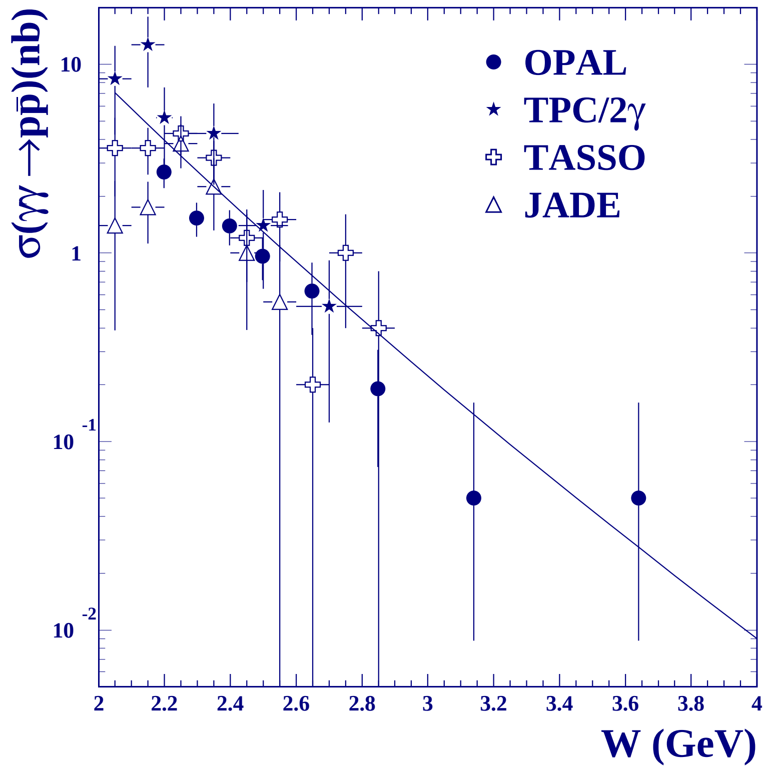
- Good agreement between our results and the quark-diquark model predictions
- Power law compared to the data with $\sigma(\gamma\gamma \rightarrow p\bar{p}) \approx -W^{-2(n-3)}$ for three values of n. For data with $W > 2.5$GeV we obtain $n = 9 \pm 2$

Existing $\gamma\gamma \rightarrow p\bar{p}$ cross section measurements

e^+e^- Experiments	E_{Beam} (GeV)	Integrated Luminosity (pb^{-1})	W (GeV)	Number of $p\bar{p}$ events
TASSO (DESY) 1982	15 - 18.3	19.685	2.0 - 2.6	8
TASSO (DESY) 1983	17	74	2.0 - 3.1	72
JADE (DESY) 1986	17.4 - 21.9	59.3 + 24.2	2.0 - 2.6	41
TPC/2γ (SLAC) 1987	14.5	75	2.0 - 2.8	50
ARGUS (DESY) 1989	4.5 - 5.3	234	2.6 - 3.0	60
CLEO (CESR) 1994	5.29	1310	2.0 - 3.25	484
VENUS (TRISTAN) 1997	57 - 64	331	2.2 - 3.3	311
OPAL (LEP) 2003	91.5 - 94.5	249	2.15 - 3.95	163

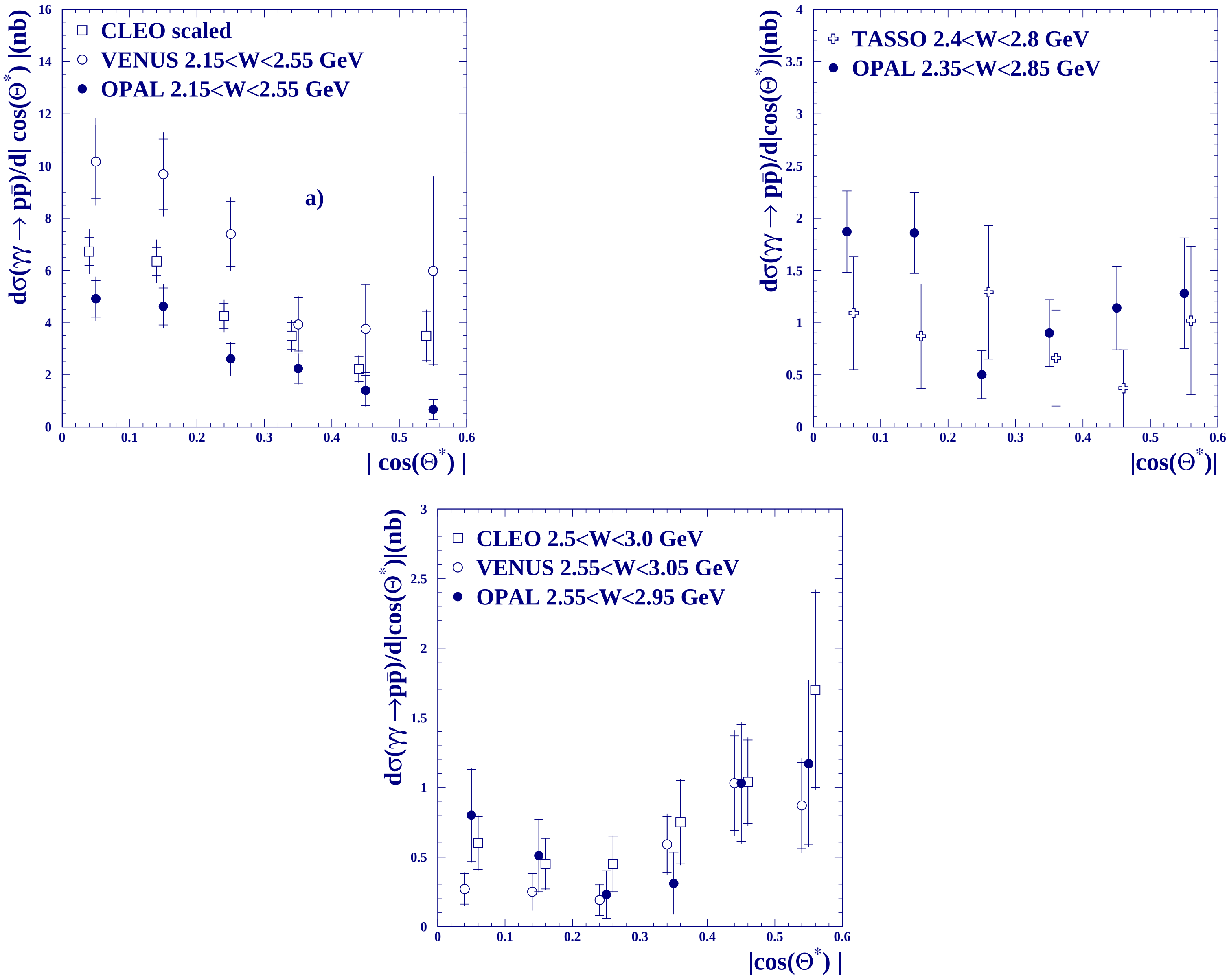
Comparison with other experiments





- Agreement between the ***OPAL*** and the other experiments results for $W > 2.3\,\mathrm{GeV}$

Differential cross-section measurements

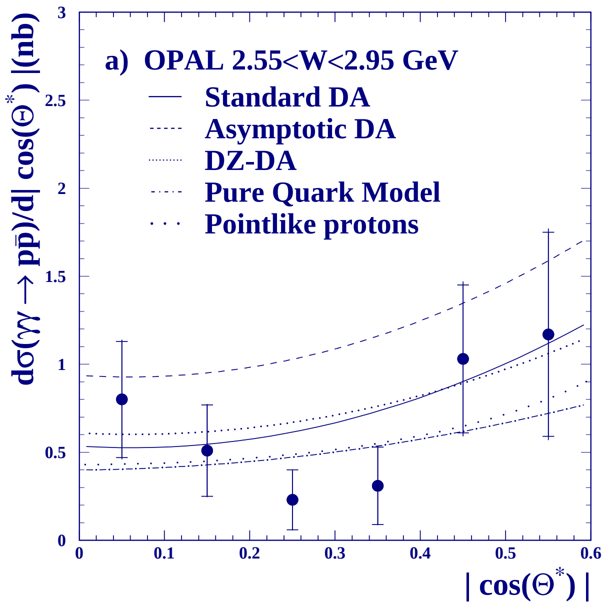


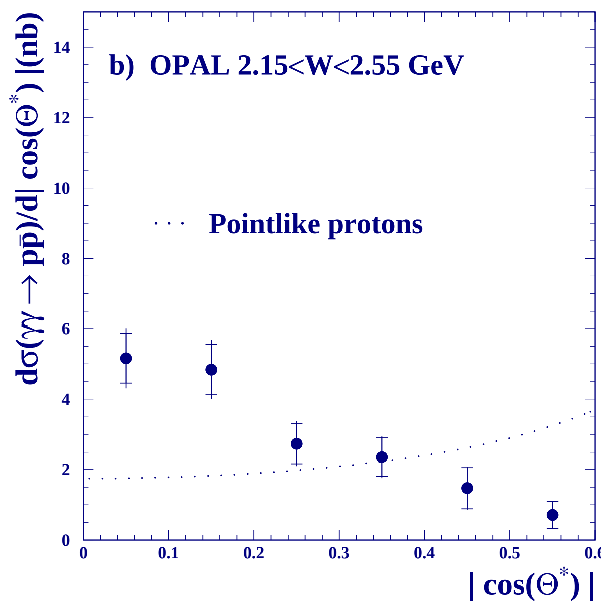
Comparisons with the ***OPAL***, CLEO, VENUS and TASSO measurements

Angular dependence of the cross section

QED angular distribution for massless and pointlike fermions

$$\frac{d\sigma(\gamma\gamma\to p\bar{p})}{d|\cos\theta|} \propto \frac{(1+\cos^2\theta)}{(1-\cos^2\theta)}$$





- At high W, the pointlike p approximation agrees with the data, the diquark and the pure quark model curves.
- At low W, pointlike p approximation not valid anymore.

More experimental investigation needed

Conclusions

OPAL published results for $\gamma\gamma \to p\bar{p}$ cross-section measurements

- Range covered: $2.15\,\mathrm{GeV} < W < 3.95\,\mathrm{GeV}$ and $|\cos\theta^*| < 0.6$
- our $\sigma(\gamma\gamma \to p\bar{p})$ measurements are in agreement with:
  - The other experimental results for $W > 2.3\,\mathrm{GeV}$
  - The quark-diquark model predictions
- The QCD power law fit yields an exponent $n = 7.5 \pm 0.8$ with statistical uncertainty only. More data needed to distinguish the proton seen as a state of three quarks or as a state of quark-diquark system.
- The shape of $d\sigma(\gamma\gamma \to p\bar{p})\,/d|\cos\theta|$ agrees with the other experiments results in comparable W range
- At low W values the $d\sigma(\gamma\gamma \to p\bar{p})\,/d|\cos\theta|$ does not agree with the models. More investigation are neede in this region of W

This is the first $\gamma\gamma \to p\bar{p}$ cross section measurement performed at LEP