A Historical Retrospect of Two-Photon Physics in the 1980ies at DORIS, SPEAR, PETRA and PEP

A Prosperous Era of $\gamma\gamma$ Physics

Hermann Kolanoski
Humboldt-Universität zu Berlin and DESY
Novosibirsk 30 Years Ago


prof. H. Kolanoski
Ph. Inst. Univ. Novosibirsk

C3. 200.

ad to Annice

you to visit the USSR for two 

in Novosibirsk

in March 1985 stop. We shall cover all expenses. For your stay in USSR including transportation inside

our Cymra stop. Best regards

Director Nuclear Physics Institute Novosibirsk

A N Grinimsky
How to become сибиря́к – Siberian?

Prof. H. Kolanoski

for the first results
on snow in Siberia
10 km!

From first ski teacher
Prof. A.P. Onuchin

24 March 1985

Novosibirsk
An Experimentalists View of Two-Photon Physics

H. Kolanoski, Univ. Dortmund

4 years ago, the y\(y\)-Workshop in Shoresh summarized the PETRA and PEP era.

Purpose of this talk is to build a bridge from the y\(y\)-Workshops of the 70-80ies by recalling for the newcomers the status of two-photon experiments as of the Shoresh Workshop.
Reviews

Proceedings of the International Workshops on Photon-Photon Collisions

- Sheffield, 1995
- San Diego, 1992
- Jerusalem, 1988
- Paris, 1986
- Lake Tahoe, 1984
- Aachen, 1983
- Paris, 1981
- Amiens, 1980
- Lake Tahoe, 1979
- Paris, 1973

Pioneering Times of Two-Photon Physics

light-light scattering calculated in the 1930ies by Heisenberg’s student Euler

first photon-photon reactions measured: beginning of 70ties

problem for VHE gamma astronomy:

..... and on earth:

possible because of advent of e⁺e⁻ storage rings

photon “beams”
My first encounter with two photon reactions:

**Quark Trigger** in Crystal Ball experiment

... and the second encounter: the Bonn group at the TASSO experiment at the storage ring PETRA in Hamburg
The PETRA/PEP Era of Two-Photon Physics

<table>
<thead>
<tr>
<th>Machine</th>
<th>Running</th>
<th>Location</th>
<th>$E_{\text{beam}}$ [GeV]</th>
<th>$E_{\text{cm}}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPEAR</td>
<td>1972-1990</td>
<td>Stanford (USA)</td>
<td>4 + 4</td>
<td>8</td>
</tr>
<tr>
<td>DORIS</td>
<td>1973-1993</td>
<td>DESY (Hamburg)</td>
<td>5.6 + 5.6</td>
<td>11.2</td>
</tr>
<tr>
<td>CESR</td>
<td>1979-2002</td>
<td>Cornell (USA)</td>
<td>6 + 6</td>
<td>12</td>
</tr>
<tr>
<td>VEPP-4M</td>
<td>1994-</td>
<td>Novosibirsk</td>
<td>6 + 6</td>
<td>12</td>
</tr>
<tr>
<td>PETRA</td>
<td>1978-1986</td>
<td>DESY (Hamburg)</td>
<td>20 + 20</td>
<td>40</td>
</tr>
<tr>
<td>PEP</td>
<td>1980-1990</td>
<td>Stanford (USA)</td>
<td>15 + 15</td>
<td>30</td>
</tr>
<tr>
<td>TRISTAN</td>
<td>1987-1995</td>
<td>KEK (Japan)</td>
<td>32 + 32</td>
<td>74</td>
</tr>
</tbody>
</table>

- QED: $\gamma\gamma \rightarrow$ lepton pairs
- C=+ meson resonances
- total cross section $\gamma\gamma \rightarrow$ hadrons
- inclusive particle spectra
- hard scattering, high-$p_T$, jets
- structure of the photon

**Basic and detailed theory in the 1970ies:**

**Kessler, Budnev et al., Walsh and Zerwas, Witten, Brodsky-Lepage, Bardeen&Buras . . .**

**THE TWO-PHOTON PARTICLE PRODUCTION MECHANISM. PHYSICAL PROBLEMS. APPLICATIONS. EQUIVALENT PHOTON APPROXIMATION**

PHYSICS REPORTS 15, no. 4 (1975)

V.M. BUDNEV, I.F. GINZBURG, G.V. MELEDIN and V.G. SERBO

USSR Academy of Science, Siberian Division, Institute for Mathematics, Novosibirsk, USSR
Only TT terms remain \( \neq 0 \) at \( Q_i^2 = 0 \) (i=1,2)

with the strengthening of computers the `equivalent photon approximation’ (EPA) became less important for the actual analyses

\[ \frac{d^2L_{\gamma\gamma}}{d\omega_1d\omega_2} \frac{dN_{\gamma}(\omega_1)}{d\omega_1} \frac{dN_{\gamma}(\omega_2)}{d\omega_2} \]
Experimental Characteristics

**γγ** versus **1γ**:
**γγ** more demanding (trigger, efficiency, ...)

In general boosted with flat rapidity distribution

**Complete γγ event**
**Incomplete γγ event**

Tagging system

Events per 0.002 GeV²

γγ versus 1γ:
γγ more demanding (trigger, efficiency, ...)

\( \frac{E_{vis}}{E} \)

\( p_T \)

\( p_L \)

\( e^+ \)

\( e^- \)
Experimental Characteristics: (No-)Tagging

**Tagging conditions:**
- **no-tag:** mostly 2 real photons
- **single tag:** 1 real/1 virtual photon
- **double tag:** 2 virtual photons
- **0° tagging:** real photons

**double tag** allows in principle
determination of kinematics of γγ system
e.g. for \( \sigma_{\text{tot}} \) measurements
(usually not sufficient resolution)

- Selecting γγ events
- fixing \( Q^2 \)
A Bit of History of Events

Experim. highlights in γγ physics

- 1971 Novosibirsk + Frascati: 1st observation of γγ - QED: ee → ee e⁺e⁻
- 1979 Mark II (SPERR): γγ → γ'
- 1980 PLUTO (PETRA): γγ → f_2(1270)
- 1980 TASSO (PETRA): γγ → s⁺s⁻ (9999?)
- 1981 PLUTO (PETRA): <_total (γγ → hadrons)
- 1981 TASSO + JADE: γγ → jets
- 1981 PLUTO: F₂^γ
  : (phase of detailed work)
- 1986 TPC/γγ (PEP): γ*γ → A_1 (1420)

From QED to QCD
Gamma-Gamma Couplings to Resonances

\[ \sigma(ee \rightarrow ee \, R) \approx 16\alpha^2 \left( \log \frac{E}{m_e} \right)^2 \left( \frac{M_R}{2E} \right) \left( \frac{2J+1}{M_R} \right) \frac{\Gamma_{\gamma\gamma}}{M_R^2} \]

in the resonance range
not much dependence
on machine energy

at higher energies
more boosted energy

Goal: clarify meson systematics

- quark (or other) content
- singlet-octet mixing
- glueballs?
- 4-quark states?
- . . . .

quark states

\[ \sim e_q^2 \]

\[ = \frac{1}{10} \cdot \Gamma_{\gamma\gamma} (q\bar{q}) \]

\[ \sim g^\gamma \cdot g^{\gamma'} (VGP) \]

glueballs

4-quark states
Resonances in $\gamma\gamma \rightarrow \gamma\gamma$

- quark content
- singlet-octet mixing
- $\Gamma(\gamma\gamma \rightarrow \eta')$ excludes Han-Nambu model of integer quark charges

\[
\begin{align*}
\Gamma_{\pi^0 \rightarrow \gamma\gamma} &= 7.7 \pm 0.5 \pm 0.5 \text{ eV} \\
\Gamma_{\eta \rightarrow \gamma\gamma} &= 0.514 \pm 0.017 \pm 0.035 \text{ keV} \\
\Gamma_{\eta' \rightarrow \gamma\gamma} &= 4.7 \pm 0.5 \pm 0.5 \text{ keV}
\end{align*}
\]
Resonances Decaying into $\pi$, $K$, $p$ Pairs

\begin{align*}
g_{\gamma\gamma \rightarrow \pi^+\pi^-} & \text{ (ICOS} \theta \text{') < 0.6} \\
\text{f}_2(1270) & \\
\text{f}_0(980) & \\
\text{γγ} \rightarrow \pi^+\pi^- & \\
\text{γγ} \rightarrow p\bar{p} & \\
\text{γγ} \rightarrow K^+K^- & \\
\text{f}_2(1520) & \\
\text{a}_2(1320) & \\
\text{TASSO} & \\
\text{γγ} \rightarrow \pi^+\pi^- & \\
\text{γγ} \rightarrow p\bar{p} & \\
\text{γγ} \rightarrow K^+K^- & \\
\text{BELLE} & \\
\text{f}_0(980) & \\
\text{demonstrates the enormous statistics at BELLE (& BaBar)} & \\
\end{align*}
Gamma-Gamma Couplings to Axial Vectors

Landau-Yang Theorem:

Particle \((J=1) \rightarrow \gamma\gamma\) forbidden for real photons

if \(qq\) it must be an axial vector state \(J^{PC} = 1^{++}\)

\(f_1(1420)\) could be the mainly \(ss\) partner of the \(f_1(1285)\)
(seen also in tagged \(\gamma\gamma\) by MARK II)
### γγ Couplings for $J^{PC} = 0^{-+}, 0^{++}, 2^{++}$

#### $0^{-+}$
Two photon decay width of $0^{-+}$ states as measured in $2\gamma$ experiments

<table>
<thead>
<tr>
<th>Res.</th>
<th>$\Gamma_{\gamma\gamma}$ [keV]</th>
<th>Ref.</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0$</td>
<td>$(7.9 \pm 1.4 \pm 1.6) \times 10^{-3}$</td>
<td>Crystal Ball [3.7]</td>
<td>prel.</td>
</tr>
<tr>
<td>$\eta$</td>
<td>$0.56 \pm 0.12 \pm 0.1$</td>
<td>Crystal Ball [3.8]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$0.64 \pm 0.14 \pm 0.13$</td>
<td>TPC/2γ [3.9]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$0.58 \pm 0.02 \pm 0.06$</td>
<td>Crystal Ball [3.10]</td>
<td>prel.</td>
</tr>
<tr>
<td></td>
<td>$0.53 \pm 0.04 \pm 0.00$</td>
<td>JADE [3.11]</td>
<td></td>
</tr>
<tr>
<td>Average: $0.56 \pm 0.04$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### $0^{++}$

The $0^{++}$ states are typically the $f_0(980)$ and $a_0(980)$, as indicated in the PDG 86 p.4.

#### $2^{++}$
Two photon decay width of $2^{++}$ states as measured in $2\gamma$ reactions

<table>
<thead>
<tr>
<th>Res.</th>
<th>$\Gamma_{\gamma\gamma}$ [keV]</th>
<th>Ref.</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f(1270)$</td>
<td>$2.3 \pm 0.5 \pm 0.3$</td>
<td>PLUTO [3.24]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$3.2 \pm 0.2 \pm 0.6$</td>
<td>TASSO [3.25]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$3.6 \pm 0.3 \pm 0.5$</td>
<td>Mark II [3.26]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$2.7 \pm 0.2 \pm 0.6$</td>
<td>Crystal Ball [3.27]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$2.5 \pm 0.1 \pm 0.5$</td>
<td>CELLO [3.28]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$2.52 \pm 0.13 \pm 0.38$</td>
<td>Mark II [3.29]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$2.7 \pm 0.05 \pm 0.02$</td>
<td>DELCO [3.30]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$2.85 \pm 0.25 \pm 0.5$</td>
<td>PLUTO [3.31]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$3.2 \pm 0.1 \pm 0.4$</td>
<td>TPC/2γ [3.32]</td>
<td></td>
</tr>
<tr>
<td>Average: $2.78 \pm 0.14$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### $2^{++}$

The $2^{++}$ states $f_0(1370)$ and $a_0(1370)$ are typically observed in $2\gamma$ reactions.

#### $4^{++}$

The $4^{++}$ states are typically the $f_2(1270)$ and $a_2(1270)$, as indicated in the PDG 86 p.4.

### Results

**From Berger & Wagner**

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**Photon’15 Novosibirsk 15-19-Jun-15**

H.Kolanoski - Two-Photon Physics in the 1980ies 17
It looks as if there is a resonant $\rho^0\rho^0$ state below threshold. Why not in $\rho^+\rho^-$?

4-quark model: $I=0$ & $I=2$ interference;

VDM same pattern but no enhancement

4-quark model predicts spin-parity and resonances in other $\gamma\gamma \to VV'$ ($V, V' = \rho, \omega, \phi$)

Some predictions work - others not (e.g. for $\gamma\gamma \to \rho\phi$)
Vector Meson Pairs: 4-Quark States?

<table>
<thead>
<tr>
<th>Model</th>
<th>Ref.</th>
<th>$\rho^0\rho^0$</th>
<th>$\rho^+\rho^-$</th>
<th>$\omega\omega$</th>
<th>$\rho^0\omega$</th>
<th>$\phi\phi$</th>
<th>$\rho\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VDM ($\gamma V$-coupling)</td>
<td>1</td>
<td>0</td>
<td>1/81</td>
<td>1/9</td>
<td>4/81</td>
<td>2/9</td>
<td></td>
</tr>
<tr>
<td>Quark model</td>
<td>[4.12]</td>
<td>1</td>
<td>4/25</td>
<td>-</td>
<td>4/25</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Resonance ($I = 0$)</td>
<td>1</td>
<td>2</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>$qq\bar{q}q$</td>
<td>[4.10]</td>
<td>1</td>
<td>-0</td>
<td>~0.03</td>
<td>~0.6</td>
<td>~0.05</td>
<td>~0.6</td>
</tr>
<tr>
<td>$qq\bar{q}q$</td>
<td>[4.11]</td>
<td>1</td>
<td>-0</td>
<td>~0.06</td>
<td>~0.03</td>
<td>~0.01</td>
<td>~0.1</td>
</tr>
<tr>
<td>$t$ channel factorization</td>
<td>[4.13]</td>
<td>1</td>
<td>small</td>
<td>small</td>
<td>small</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

from Berger&Wagner

- all are measured
- result not conclusive

4-quark model

Achasov et al. 82:
~70 nb

disagreement with
factorization

Alexander et al.: >15 nb
Two-Photon Total Cross Section

Extremely difficult to reconstruct $W_{\gamma\gamma}$ because of $\gamma\gamma$ boost and the soft phase space with

$$d\sigma/dp_T^2 \sim \exp(-6p_T^2)$$

prediction from Regge theory:

$$\sigma(\gamma\gamma\rightarrow\text{hadrons}) = \sigma_0 + \sigma_1/W_{\gamma\gamma} \approx 240\text{ nb} + 270\text{ nb GeV}/W_{\gamma\gamma}$$

in the GeV region measurements remained inconclusive

at high $Q^2$ hard parton interactions become more important
Inclusive Particle Spectra

\[ \gamma \gamma \rightarrow q\bar{q} \quad \text{(VDM)} \]

\[ d\sigma/dp_T^2 \sim \exp(-6p_T) \]

\[ pp \rightarrow \pi^\pm + X \quad \text{at } \sqrt{s} = 23 \text{ GeV} \]
Production of High-$p_T$ Jets

difficult to distinguish from phase space at low energies

small sphericity $\Rightarrow$ slim jets
Brodsky-Lepage: Hadron Pairs

hard-soft factorisation

\[ \text{ME} \sim \Phi T_H \Phi^* \]

quark counting rules

\[ \sim S_{\gamma\gamma}^{-4} \quad \sim S_{\gamma\gamma}^{-6} \]

Predictions:
- energy dependence
- angular distribution
- absolute normalization

for meson pairs above \(~2.5\) GeV QCD ok
Brodsky-Lepage: Baryon Pairs

does not work for baryon pairs at the stat. accessible energies
Most remarkable prediction in the early 1970ies:
point-like photon should dominate $F_2^\gamma$

compare to “QED Structure Function”

deep-inelastic $e\gamma$ scattering
At large $Q^2$ the photon exhibits its point-like nature in principle $\Lambda_{QCD}$ can be determined from the absolute normalisation of $F_2^\gamma$ (not all theoreticians agree on that).
Richard Nisius @ Photon2009:
My “last encounter” of γγ physics: HERA: the “direct” and “resolved” photon

F₂γ yields parton distributions in the photon: Concept should be generalizable

@HERA sensitivity to gluon distribution

H1 thesis H.Rick 1997
Summary, Outlook, what else?

- Basic experiments done at the e+e- colliders of the 80ies
- major improvements in statistics, in particular for meson spectroscopy, from BELLE and BaBar
- LEP opened highest $Q^2$

The LHC as a photon collider


An NLC photon-photon collider?