Two-Photon physics : the LEP Legacy

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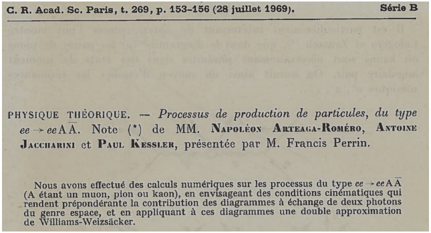
14 december 2018

Introduction: the origins

- Two-Photon physics started 50 years ago with the advent of the first low energy e^+e^- colliders.
- Paul Kessler (1926-2014) initiated the study of Two-Photon physics in France.
- He already published in Il Nuovo Cimento (1960) "A simplified computing method for the relativistic processes in QED" mastering helicity amplitudes computation and factorization techniques.
- The motivation of a Note to the Scientific Academy in 1969 was that the future e^+e^- colliders were in preparation and it was the time to quantify the idea of Calogero and Zemach to study "$ee \to eeA\bar{A}$ events, with A being a muon, a pion or a kaon".



C. R. Acad. Sc. Paris, t. 269, p. 153-156 (28 juillet 1969). Série B

PHYSIQUE THÉORIQUE. — *Processus de production de particules, du type* $ee \to eeA\bar{A}$. Note (*) de MM. **Napoléon Arteaga-Roméro**, **Antoine Jaccharini** et **Paul Kessler**, présentée par M. Francis Perrin.

Nous avons effectué des calculs numériques sur les processus du type $ee \to eeA\bar{A}$ (A étant un muon, pion ou kaon), en envisageant des conditions cinématiques qui rendent prépondérante la contribution des diagrammes à échange de deux photons du genre espace, et en appliquant à ces diagrammes une double approximation de Williams-Weizsäcker.

Introduction: the origins

PHYSICAL REVIEW D VOLUME 3, NUMBER 7 1 APRIL 1971

Photon-Photon Collisions, a New Area of Experimental Investigation in High-Energy Physics*

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and

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(Received 7 December 1970)

The purpose of this paper is to show that the conditions of photon-photon collisions at high energy can be almost perfectly reproduced by using the "quasi-real" photon spectra originating from electron-positron colliding beams. We show that (a) the problem of background elimination can be properly solved by detecting both the outgoing electron and positron at very small angles with respect to their incident directions; (b) in spite of this very stringent restriction on phase space, and of possible additional restrictions due to experimental conditions, reasonably high counting rates will be achieved with the new electron-positron storage rings (of beam energy 2–3 GeV and of luminosity $\sim 10^{32}$ cm^{-2} sec^{-1}) now planned or under construction; and (c) these counting rates increase with rising beam energy. We discuss a number of applications: particle-pair creation (e^-e^+, $\mu^-\mu^+$, $\pi^-\pi^+$, K^-K^+, $p\bar{p}$, ...) or single-particle creation (π^0, η, η'). Angular distributions of particles produced are also shown.

- Two papers were published in Phys. Rev. in april and november 1971 : "Photon-Photon Collisions, a New Area of Experimental Investigation" and "Comment on the Experimental Investigation of Photon-Photon Collisions in Electron-Positron Storage Rings".
- P. Kessler and J. Parisi attended the 1970 e^+e^- storage rings conference in Frascati.
- In 1972 Marcel Froissart unified the Francis Perrin and the Leprince-Ringuet laboratories : LPA (Atomic Physics) + LPN(Nuclear Physics) = LPC (Corpuscular Physics Laboratory)
- Paul Kessler prepared in 1972 the first 1973 conference.
  The "International Colloquium on photon-photon collisions in electron-positron storage rings"

Introduction and a few comments

A bit of history

- The physics of two photon interactions has really started at PETRA in the 80's.
- The evolution of the ideas concerning the hadronic structure of a real or virtual photon has followed the advent of e^+e^- colliders :
  PETRA/PEP, TRISTAN, LEP/SLC ($\gamma\gamma$, $\gamma\gamma^*$ and $\gamma^*\gamma^*$), *ep* with HERA (γp,$\gamma^* p$) and the LHC ($\gamma\gamma$ from *pp* collisions).
- The photon structure is still not yet exactly known : quark and gluon content of the photon , $\gamma\gamma$ total cross section, heavy quark production, mixed QED-QCD processes.

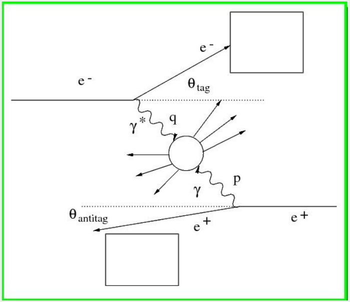
40 years ago the basic tools were available:

- Witten for $F_2^\gamma \simeq \ln Q^2$ asymptotically in QCD (but true also in QED ...)
- Altarelli-Parisi equations and the russian, french, american and japanese "schools"
- VDM and GVDM
- The LUND Monte Carlo (ancestor of PYTHIA)
- OPE vs DGLAP : F_2^γ vs MC approaches

Basic process and experimental setup

- A photon fluctuates in many virtual pairs but only another photon can make them real.
- $W^2 = (p+q)^2$ with $P^2 = -p^2$, $Q^2 = -q^2$ and $x = \frac{Q^2}{2pq}$
- At e^+e^- colliders photons are "tagged" or "antitagged" by a forward calorimeter.
- Need a correct treatment of radiative corrections.
- $< P^2 > \neq 0$ and $< Q^2 > \neq 0$ source of difficulties to extract $\sigma^{\gamma\gamma}$ from $\sigma^{e^+e^-}$

$\gamma\gamma^* \rightarrow X$



QED factorisation considered as one of the fine arts

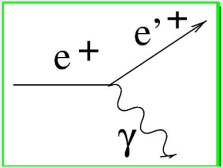
- The art of QED factorisation developped from 1934 (Weiszacker-Williams) to nowadays through HERA and LEP200.

$P^2 \simeq 0$

$$d\sigma(e^+e^- \to e^+e^- X) = \underbrace{dW_{e^+}(\gamma)}_{\textit{Photon density}} \, . \, \underbrace{d\sigma(e^-\gamma \to e^- X)}_{\textit{Hard subprocess}}$$

$e^+\gamma$ vertex

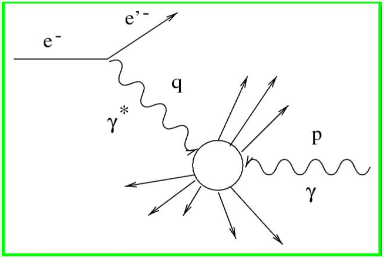
$z = \frac{p.e^-}{e^+.e^-}$



$\propto \frac{\alpha}{2\pi} \frac{1+(1-z)^2}{z} dz \frac{P^2}{P^2} \frac{d\varphi}{2\pi}$

$e^-\gamma$ interaction

$y = \frac{q.p}{e^-.p} = \frac{Q^2}{x\, s_{e\gamma}}$



$\propto \frac{\alpha}{2\pi} \frac{1+(1-y)^2}{y} dy \frac{dQ^2}{Q^2} [\sigma_{TT} + \epsilon(y)\sigma_{TL}]$

$$\epsilon(y) = \frac{\textit{longitudinal flux}}{\textit{transverse flux}} = \frac{2(1-y)}{1+(1-y)^2}$$

QED factorisation considered as one of the fine arts

Experimentally $y \ll 1$

$$d\sigma(e\gamma \to eX) = \underbrace{2\pi\alpha^2[1+(1-y)^2]\frac{dQ^2}{Q^2}\frac{dx}{x}}_{\text{"}Kinematics\text{"}} \cdot \underbrace{[2xF_T + F_L]}_{\substack{F_2^\gamma(x,Q^2) \\ \text{"}Physics\text{"}}}$$

- Scales $Q^2 \gg P^2 \simeq 0$
- If$P^2 \neq 0$ consider $F_2^{\gamma\ eff}(x, Q^2, P^2)$
- If$Q^2 \simeq 0$ $\sigma^{\gamma\gamma} = \sigma_{TT}$ and
  $d\sigma(e^+e^- \to X) = \underbrace{dW_{e^+}(\gamma)dW_{e^-}(\gamma)}_{dL_{\gamma\gamma}}\ \sigma^{\gamma\gamma}$

F_2^γ vs $\sigma^{\gamma\gamma^*}$

$$\frac{F_2^\gamma}{\alpha} \simeq \frac{Q^2\sigma^{\gamma\gamma^*}}{4\pi^2\alpha^2}$$

Think always in terms of total cross-section even when discussing structure functions

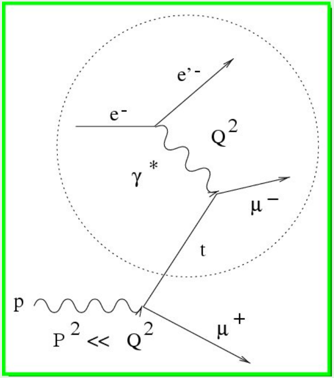
When $X = \mu^+\mu^-$

$$d\sigma(e\gamma \to e\mu^+\mu^-) = dx\ dQ^2\ \underbrace{\frac{4\pi\alpha^2}{Q^4}}_{e\mu\to e\mu} \cdot \underbrace{[\mu^\gamma(x,Q^2) + \bar{\mu}^\gamma(x,Q^2)]}_{\mu\ content\ of\ a\ photon}$$

The many scales basic process

- Basic process to test the tagging devices.
- Test of "Unfolding"
- Exact Computation of all Helicity Amplitudes
- Already for QED processes many scales appear. In DIS $e\gamma$ scattering we have $< P^2 >, < Q^2 >, m_\mu^2$ or $p_T^2 + m_\mu^2$ scales.
- $F_2^{\gamma QED} \propto \ln \frac{t_{max}}{t_{min}}$ with $t_{max} \simeq Q^2/x$ and $t_{min} \simeq \frac{m_\mu^2}{1-x} + P^2 x$ plus $x(1-x)$ terms coming from $2xm_\mu^2 \int_{t_{min}}^{t_{max}} \frac{dt}{t^2}$ giving $\frac{2x(1-x)m_\mu^2}{m_\mu^2 + P^2 x(1-x)}$
- Experimentally isolate "multiperipheral" diagrams with kinematical cuts.
- Study azimuthal correlations (interference terms)

$e\gamma^* \to e\mu^+\mu^-$

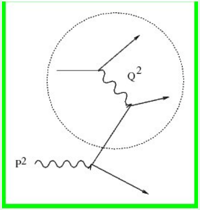


40 years ago, QCD really started

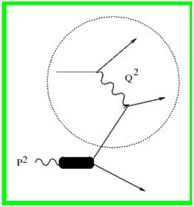
- $\gamma\gamma \rightarrow$ jets inspired from QED : QPM or "QCD improved parton model"
- Hope to get from $F_2^\gamma(x, Q^2)$ obtained through Unfolding and according to Witten a measurement of Λ_{QCD}

Basic description of DIS eγ for $Q^2 \geq 4GeV^2/c^4$
For one flavour $F_2^\gamma(x, Q^2, P^2 \simeq 0) = e_q^2 x(q+\bar{q})$

QPM $\oplus$ VDM



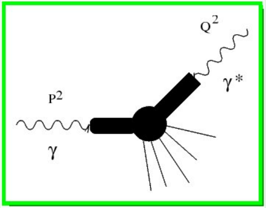
m_q : constituent or current mass



Target VDM

$< q|\gamma >= \sum_V < q|V >< V|\gamma >$ coherent or incoherent sum $\Rightarrow F_2^\gamma/\alpha \simeq 0.2(1-x)$ with undefined $Q^2 \rightarrow 0$ limit.

With GVDM

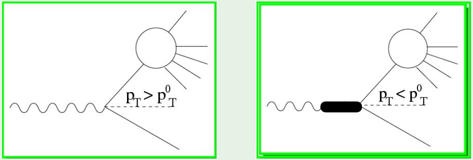


$\sigma^{\gamma\gamma^*}(W^2, Q^2, P^2 \simeq 0) \simeq F_{GVDM}(Q^2)(A + \frac{B}{W})(1-x)$
leading to
$F_2^\gamma/\alpha = a(Q^2)(1-x) + b(Q^2)\sqrt{x}(1-x)$
for a finite $\sigma^{\gamma\gamma^*}$ at $Q^2 = 0$

- Perturbative Non-Perturbative transition
- QCD modifies the x behavior
- $F_2^\gamma(x, Q^2) \Rightarrow q^\gamma(x, Q^2)$
- $\gamma\gamma \to jets \Rightarrow q^\gamma(x, p_T^2), g^\gamma(x, p_T^2)$
- Link between p_T^{jet} and $p_T^{inclusive}$

$\Rightarrow$ introduce a p_T (or t) cut.

Pointlike $\oplus$ Hadronlike couplings



$\Rightarrow$ compact formula (1989)for the "point-like" component obtained from

$$t\frac{d}{dt}q(x,t) = 3\frac{\alpha}{2\pi}e_q^2 a(x) + \frac{\alpha_s(t)}{2\pi}\int_x^1 \frac{dz}{z}P_{qq}(z)q(\frac{x}{z},t)$$

$\Rightarrow$ "valence" approximation
$\Rightarrow$ boundary conditions : physical ingredients

- $q^{PL}(x, t_0) = 0$ flavor per flavor
- $q^{PL}(x, Q^2) = \int_{t_0}^{Q^2/x - t_0} dt \frac{d}{dt} q(x, t)$ to include simply the kinematics
- usually $q(x, Q_0^2) = q^{Data}(x, Q_0^2)$ with $Q_0^2 \simeq O(1)GeV^2$

$\Rightarrow$ No gluon density
$\Rightarrow$ Simplified interpolation at small x
$\Rightarrow$ No QCD corrections to the NP component

From FKP to SaS

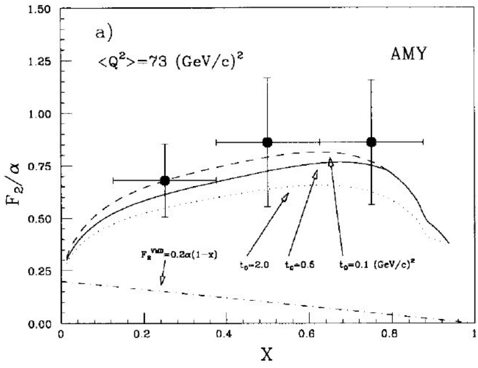
For $Q^2 \gg P^2$

$$F_2^{\gamma FKP}(x, Q^2, P^2) = 2\sum_q e_q^2 x q(x, Q^2, P^2)$$

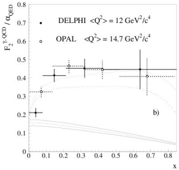
$$q(x, Q^2, P^2) = 3\frac{\alpha}{2\pi} e_q^2 \{ \frac{a(x)}{x^C + Cf(x)} Y[1 - (\frac{Y_0}{Y})^{1+Cf(x)}] + [6x(1-x) - 1 + \frac{x(1-x)(2m_q^2 - P^2)}{m_q^2 + p_{T0}^2 + x(1-x)P^2}]\}$$

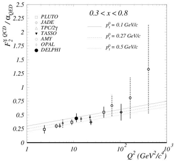
with $Y_0 = \ln\frac{t_0}{\Lambda^2}$, $t_0 = \frac{m_q^2 + p_{T0}^2}{(1-x)} + P^2 x$, $C = \frac{8}{33 - 2N_f}$ and $f(x) = 2\ln\frac{1}{(1-x)} - x - \frac{1}{2}x^2$

- When $\Lambda \to 0$ i.e. $\alpha_s(t)$ recover $\simeq$ QPM
- "Natural" P^2 dependence
- Importance of "constant" terms
- Natural introduction of two scales Q^2,p_T^2
- Tribute to Tadao Nozaki (AMY) visiting Paris
- In 94-95 G. Schuler and T. Sjostrand introduce a p_T^0 cut in SaS1D$_{LO}$ and SaS2D$_{LO}$ to describe $\gamma\gamma$ and γp collisions
- Fontannaz too in AFG parametrisations, improved from the first 1985 Aurenche, Douiri, Baier, Fontannnaz and Schiff inclusive distributions in $\gamma\gamma$ scattering

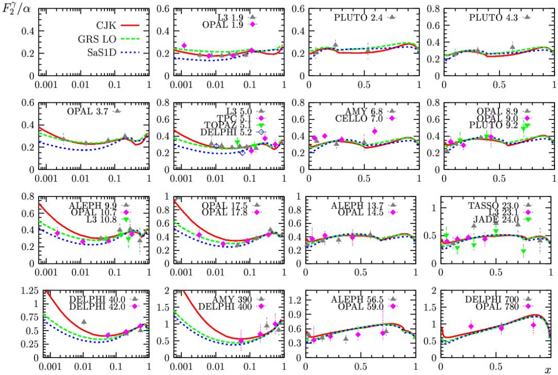


- Same for DELPHI
- BFKL treatment needed at low x : J. Forshaw and P. Harriman





All existing parametrisations come from a fit to all Q^2 existing unfolded data from ALEPH, DELPHI, L3, OPAL after TPC2γ, CELLO, JADE, PLUTO, TASSO, AMY and TOPAZ (Plot from Maria Krawczyk who died in 2017)



Comments

- The right time to get new parametrizations of the partonic content of the photon with physical inputs.
- It took nearly 7 years to PYTHIA to include p_T cuts in SaS parametrizations, with comments on FKP by G. Schuler.
- FKP arose from the question of how to build a Monte Carlo from $F_2^\gamma(x, Q^2)$.
  Just unintegrate, using APE and choosing you kinematical boundaries. Thanks to the tuesday theory seminar at DESY in 1979 and the Reya QCD course.
- Even Fontannaz used a cut without saying it in the AFG parameterization.
- The 1992 Two-Photon Conference saw the end of PETRA, the start of LEP and the preparation of HERA (under the impulse of David Miller, Two Photon Conferences became PhotonXX starting 95, including officially single photon interactions).
- In the 1992 conference A. Finch commented the total $\gamma\gamma$ cross-section :
  difficult to unfold a component you do not see at low angles or only a few tracks.
- Rely anyway on Monte-Carlo for acceptance effects.
- Resonances and exclusive processes suffered from the lack of a good trigger simulation.

Jet production in $\gamma\gamma$ collisions : LEP after PETRA and TRISTAN

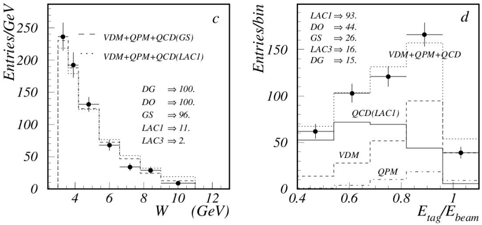
TRISTAN opened the door.

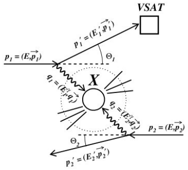
Data vs MC

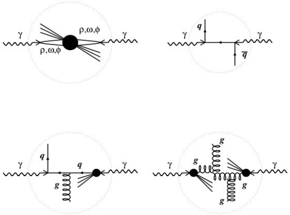
First "real" Monte Carlo tests (TRISTAN, LEP) $\sim$ 1990 $(q^{\gamma}(x, p_T^2)\ ,\ g^{\gamma}(x, p_T^2)) \otimes p_T^{min}$

Dominant contribution of the single and double resolved processes

Looking for $q^{\gamma}(x, p_T^2, P^2)$ and $g^{\gamma}(x, p_T^2, P^2)$







- DELPHI VSAT single tagged jets
  $P^2 \ll (p_T^{min})^2$: W and E_{tag} distributions
- Coherent building of the MC generators wrt the different scales.
- NLO inclusive distributions for dijet production.

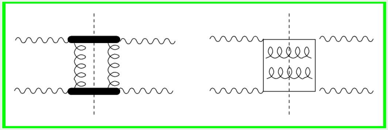
$\sigma^{\gamma\gamma}_{TOT}$

- Donnachie Landshoff $\sigma^{\gamma p}(pb) = 115E_{cmGeV}^{-0.56} + 74E_{cm}^{0.085}$
- Simple approach with an effective parton density $P = g^{\gamma} + \frac{4}{9}\sum_i(q_i^{\gamma} + \bar{q}_i^{\gamma})$ with q^{γ} and $g^{\gamma} \propto \frac{1}{x^{1+\epsilon}}$
- For example , double resolved contribution at LO :

$$\sigma^{2-res} = \int\int dy_1 dy_2 \int dtP(y_1,t,0)\frac{9}{4}4\pi\frac{\alpha_s(t)}{t^2}P(y_2,t,0)$$

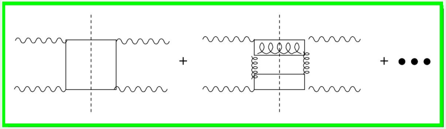
"Pomeron Reggeon"

$$\sigma^{\gamma\gamma} = A + \frac{B}{W}$$



"Pomeron Soft"

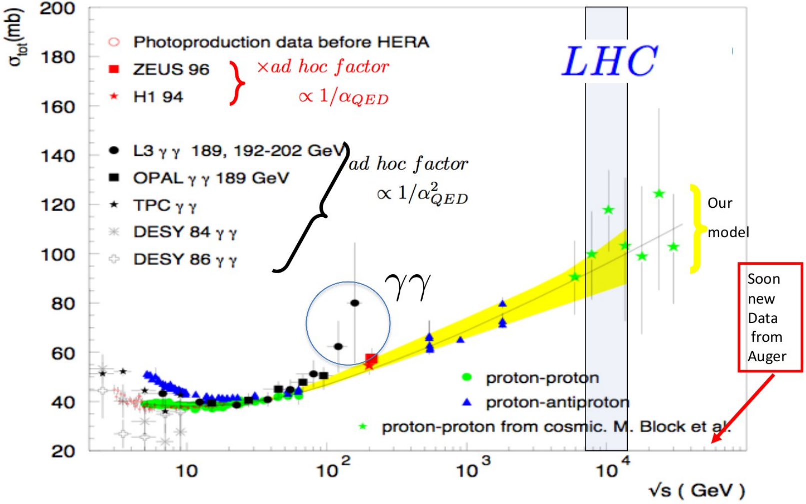
$$+\frac{C}{W^2}\ln\frac{W^2}{2t_0} + D(W^2)^{\epsilon} + F(W^2)^{\epsilon}\ln\frac{W^2}{2t_0}$$



- L3 an OPAL unfolded LEP data with PHOJET an PYTHIA
- $\sigma^{\gamma\gamma}_{TOT}(pb) = As^{\epsilon} + Bs^{-\eta}$ with $\eta \simeq 0.46$ and $\epsilon \simeq 0.15$
- Hard to unfold a component you hardly see or do not see.
- Tails of diffractive events and MC modelling.

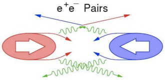
$\sigma_{TOT}^{\gamma\gamma}$

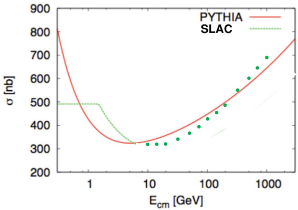
Giulia Pancheri (LC11, Trento 9/13/2011) Improved eikonalized minijet model



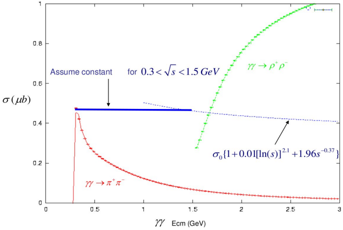
$\sigma^{\gamma\gamma}_{TOT}$ and ILC/CLIC hadronic background

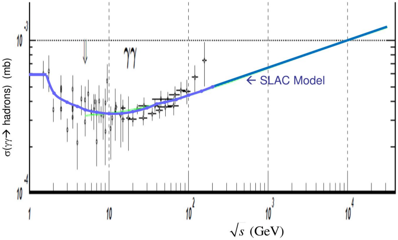
- The low W region is poorly described.
- Important for the hadronic background estimation at ILC/CLIC.
- Less critical at the ILC (Sitges 1999 Wilfrid da Silva : 0.05 evt/BX)





- Godbole : Beamstrahlung and Bremsstrahlung $\Rightarrow$ from 1 to 4 evts/BX
- From Tim Barklow : SLAC model 3 to 4 evts/BX at 3 TeV : 50 GeV and 30 particles

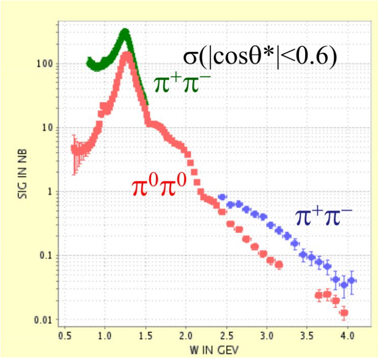


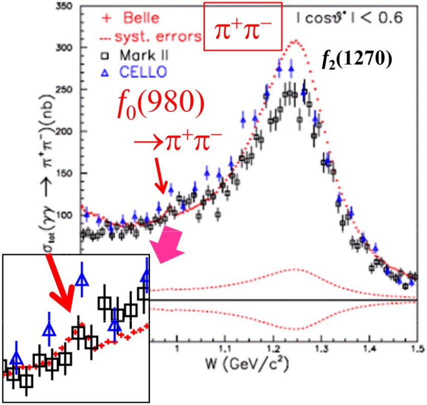


- SLAC model isotropic for $0.2 < W < 2$ GeV, not too much energy , but FWD occupancy

$\sigma^{\gamma\gamma}_{TOT}$, ILC/CLIC hadronic background and BELLE

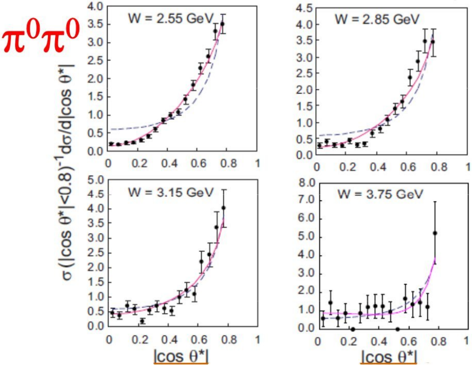
- Impressive BELLE results : important for MC modelling, in the resonance region and for exclusive processes.
- "Return to the early times of HEP", but with more precise detectors and higher statistics.

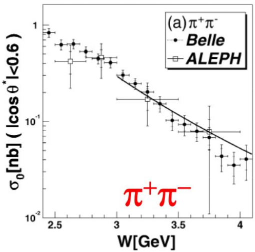


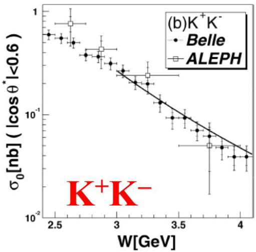


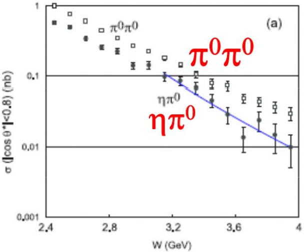
From Sadaharu Uehara GPD2010, Trento.

- *W* dependance and angular distributions of pions.
- Big improvement over LEP.



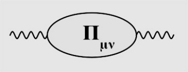


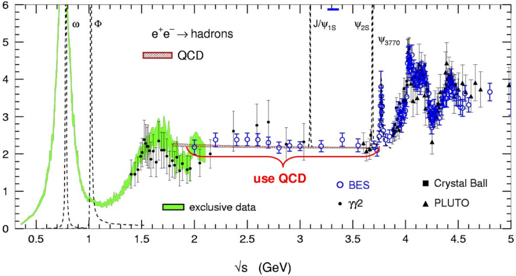




g-2 and HLBL

In a similar way to the vacuum polarisation contribution to g-2 ...



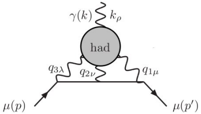


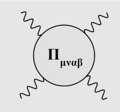
- Taken from M. Davier, ICFA Seminar Oct 3-6 2011

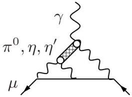
...the Hadronic Light By Light (HLBL) contribution enters the game.

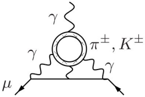
But dispersion relation not possible (4 point function)

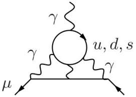
Model dependent with pole dominance





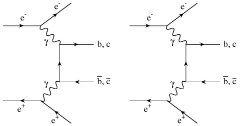




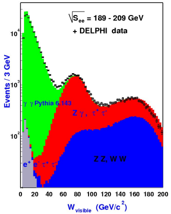


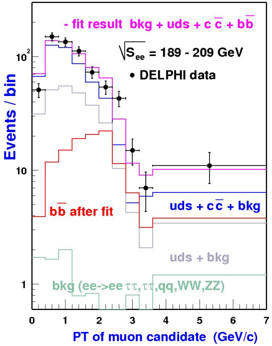
As for Form factors for the pion in R(s), Belle-II will test $\gamma^*\gamma$ and $\gamma^*\gamma^*$ for π and $\pi\pi$ production

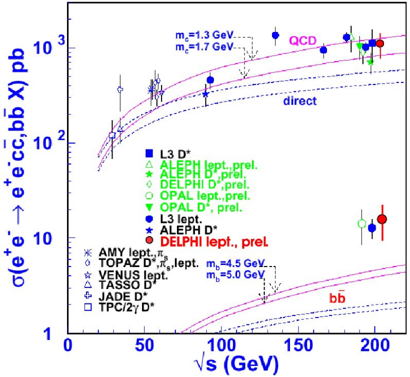
- $c\bar{c}$ and $b\bar{b}$ production at LEP



- μ semileptonic decays.







ALEPH not quoted : different selection criteria.

ILC Two-Photon Physics

- Beamstrahlung limit the acceptance and the tagging.
- But not so many studies of the standard processes studies at LEP/Belle.
- Update and continue the full LEP program.

Measure double tagged cross sections as proposed by Ken Sasaki

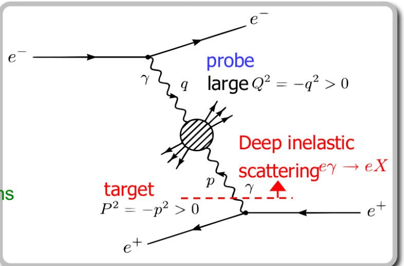
- Future linear collider experiment (e.g. ILC)

Two-photon process $e^+e^- \to (e^+e^-\gamma\gamma) \to e^+e^- X$

Viewed as a deep-inelastic electron-photon scattering

We can study the structures of photon

$\Rightarrow$ $F_2^\gamma(x, Q^2, P^2)$
$F_L^\gamma(x, Q^2, P^2)$



- Highly virtual photon target

$(\Lambda^2 \ll P^2 \ll Q^2)$

pQCD gives definite predictions for

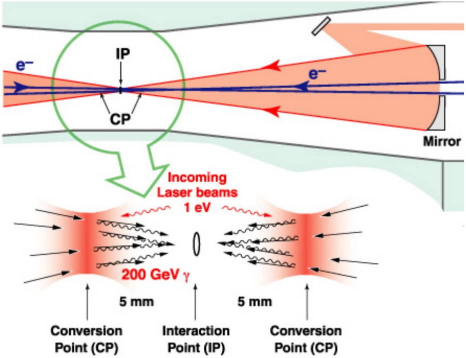
- $F_2^\gamma(x, Q^2, P^2)$ $F_L^\gamma(x, Q^2, P^2)$
- pdf in the virtual photon

$q_S^\gamma(x, Q^2, P^2),\ G^\gamma(x, Q^2, P^2),\ q_{NS}^\gamma(x, Q^2, P^2)$ $-P^2 = p^2 \leq 0$:mass squared of the target photon

- A good playground to see the scheme-dependence of pdf

PLC

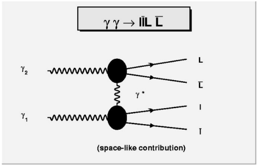
- 30 years ago, I. Ginzburg, G. Kotkin, V. Serbo and V. Telnov proposed the principle of a Photon Linear Collider at an e^+e^- accelerator.
- Taken from Jeff Gronberg (ICHEP 2002)
- The Photon Linear Collider option should stay in the ILC baseline.
- PLC advertised so many years by V. Telnov.



Two fermions pair production in $\gamma\gamma$ collisions : history and motivation

- Total cross section computation
  Two identical lepton pairs production and infinite $\gamma\gamma$ center of mass energy, L.N. Lipatov et al (1969). Two identical pion pair production, H. Chen and al. (1970)
- Total and differential cross section.
  Different pairs produced, logarithmic approximation, $\gamma\gamma$ polarisation V. G. Serbo et al. (1970,1985,1998)
- Factorisation Formula
  cf. Kessler and C. Carimalo thesis (1974)
  Powerful tools for Helicity Amplitudes calculation with Helicity Coupling.

- Motivation Today
  - Reference process for luminosity measurement at PLC
  - Can be a noise hit for low angle detector at ILC
  - Can be a background source to rare processes
  - Interesting mixed QED/QCD events and calculations
  $\Rightarrow$ Only a realistic Monte-Carlo (at low and high angle) can give a correct answer.
- Pseudo Pair Configurations (peripheral diagrams)



QED asymptotic cross-sections

Exact analytical expression for the first time (Photon 2007)

With $u = \frac{m'}{m}$ being the mass ratio,

$$\sigma = \frac{4\alpha^4}{9\pi m m'} \left\{ \frac{19}{16} \left[2 \left(\frac{1}{u} - u \right) \ln u - \left(\frac{1}{u} + u \right) \left(2 + \ln^2 u \right) \right] + \left[\frac{25}{4} + \frac{19}{32} \left(\frac{1}{u} - u \right)^2 \right] P(u) \right\}$$

$$P(u) = \ln^2 u \ln \frac{1+u}{1-u} - 2 \ln u \left[\mathrm{Li}_2(u) - \mathrm{Li}_2(-u) \right] + 2 \left[\mathrm{Li}_3(u) - \mathrm{Li}_3(-u) \right]$$

Very different masses i.e. $m \gg m'$

$$\sigma \simeq \frac{28\alpha^4}{27\pi m^2} \left(\ln^2 u^2 - \frac{103}{21} \ln u^2 + \frac{485}{63} \right)$$

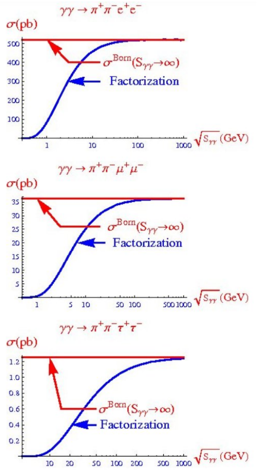
Equal masses

$$\sigma = \frac{\alpha^4}{\pi m^2} \left(\frac{175}{36} \zeta(3) - \frac{19}{18} \right)$$

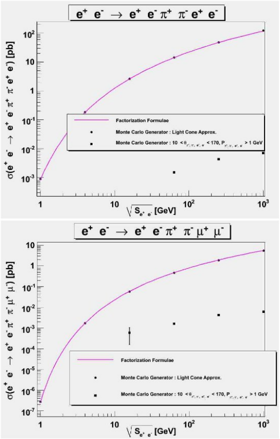
Interesting when masses are not too different since no such an expression was available.

QCD/QED asymptotic cross-sections

- Recent extension $\gamma\gamma \to \pi^+\pi^- l\bar{l}$ and $\gamma\gamma \to \pi^+\pi^- K^+K^-$ (LC11, Trento).



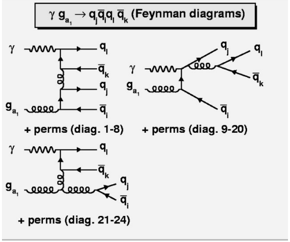
- All computed processes are included in Monte-Carlo Generator (Born Term)

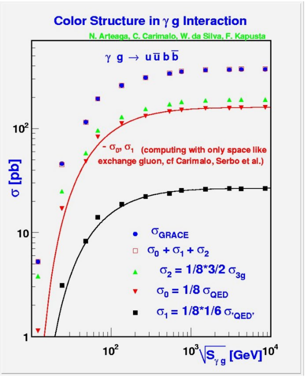


- $\sigma^{vis}_{ILC} \simeq 0.1 - 10\ fb$
- Measurable with Belle-II data?

$\gamma g \to q\bar{q}Q\bar{Q}$ and $gg \to q\bar{q}Q\bar{Q}$

- $\gamma\gamma$ collisions involve resolved photons.
- At Photon2007 it was shown that computing QCD helicity amplitudes involving gluons and quark-antiquark pairs need to get explicit color bases. The projection operator technique misses useful information coming from the various amplitudes recombination such as the separation of gauge invariant QED-like and pure QCD terms.
- Example : $\gamma g \to q\bar{q}Q\bar{Q}$





$$M = \mathrm{u}_{2\,ik}^{a_1\,jl}(M_1 + M_2 + \dots + M_8) +$$

$$\frac{1}{\sqrt{6}}\mathrm{u}_{3\,ik}^{a_1\,jl}(M_1 - M_2 \dots + M_{20}) + \sqrt{\frac{3}{2}}\,\mathrm{u}_{4\,ik}^{a_1\,jl}(M_1 + \dots + M_{24})$$

$$\sigma = \frac{1}{8}\sigma_{QED-Space} + \frac{1}{8}\frac{1}{6}\sigma_{\text{“}QED''} + \frac{1}{8}\frac{3}{2}\sigma_{3g}$$

$(\frac{1}{8} =$ average gluon color, $|F_1|^2 = 1, |F_2|^2 = \frac{1}{6}, |F_3|^2 = \frac{3}{2})$

Low Energy Photon Collider

- 1991 was the year of the first official meeting in Saariselka concerning a future linear collider and a Photon Linear Collider project was presented in 1992 at San Diego by D. Borden.
- A lot of physics to check and measure again at low energy.
- LEP "the lord of the rings" has been dismantled abruptly in 2000, leaving physicists without additional high energy e^+e^- collider data and the possibility to develop a demonstrator of real $\gamma\gamma$ collisions. And still now we miss a high energy e^+e^- collider.
- Jeff Gronberg propopsed ten years after to build a "Photon Collider Experiment" based on the SLC : the principle accepted by SLAC and abandoned due to lack of money.
- Laser Compton backscattering is used for getting positron beams for the ILC/CLIC : POSIPOL.
- Maybe IHEP could envisage a LEPC.

Comments on the future

- A Low (and Large) Energy Photon Collider (LEPC) has to be built to describe more precisely the partonic content of the photon before the LEP generation disappears

- There is a need for measuring low energy two photon cross sections and form factors.

- Photon beams and a Low Energy Photon Collider
  are necessary to validate a future PLC.

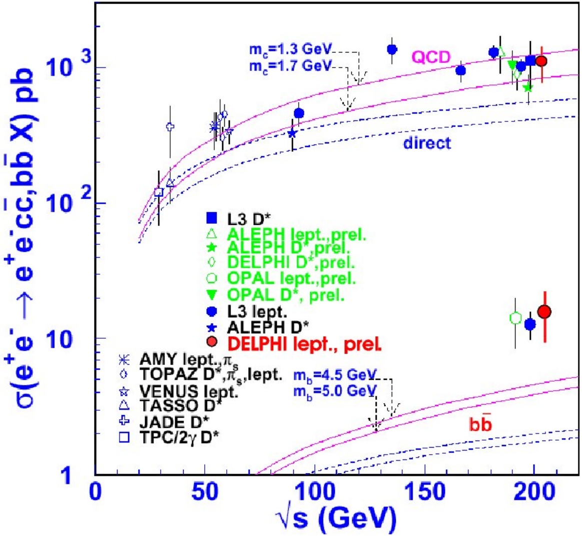
- IHEP might have an important rôle to play in the advent of a CEPC for Two-Photon physics

Comment on the sociological aspect of Two-Photon Physics at LEP

- LEP1 and LEP2 periods correspond to the "Golden Age" of Two-Photon Physics with new data available.
- In DELPHI, request to Ugo Amaldi to create a T13 after showing that multihadrons from two-photon interactions where clearly present in visible energy plots. Agreed with two conveeners Igor Tyapkin and I, but imposing that not too many physicists would join.
  In ALEPH : Alex Finch, in L3 : John Field, Maria Kienzle, in OPAL : David Miller.
  HERA colleagues joined afterwards.
- Two Photon Physics : an eastern Europe activity at least in DELPHI. Strong links with Dubna, Krakow, Lund, Prague, Serpukhov and Warsaw.
- 2008 Dubna Scientific Prize for DELPHI $\gamma\gamma$.
- ALEPH, DELPHI, L3 and OPAL brought many results proportional to the weight of physicists in each experiment and the way two-photon physics was perceived by their colleagues.

A DELPHI unpublished result

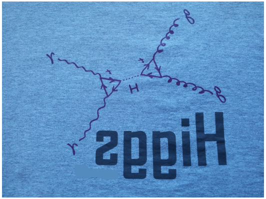
- 2003 in Frascati



Conclusions

We are happy to have Higgs boson production with two photon decay

but would like to measure any decay of produced Higgs boson in two-photon collisions.



Hope to see some of you at Photon2019 in Frascati, june 3-7.