Two Photon Physics from LEP and BELLE to the ILC and PLC

Selected Topics

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Outline

1. Introduction, basics and a bit of history
2. QCD : F_2^γ, jet production and total cross section
3. ILC/CLIC hadronic background
4. HLBL and Belle
5. ILC/PLC
6. Two fermion/meson pair production in two photon collisions
7. Low Energy Photon Collider
8. Conclusions

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 $\gamma^*\gamma^*$) and *ep* with HERA (γp,$\gamma^* p$).
- 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.

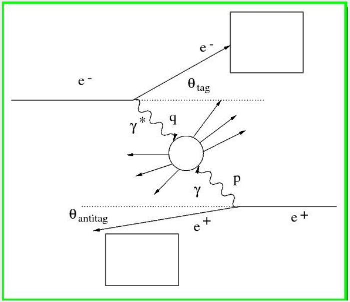
35 years ago the basic tools were available:

- 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 (Tsuneo Uematsu and Ken Sasaki) "schools"
- VMD and GVMD
- 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

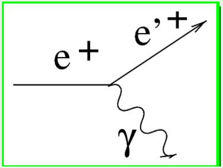
- The art of QED factorisation developped from 1934 to nowadays through HERA and LEP200.

$P^2 \simeq 0$

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

$e^+\gamma$ vertex

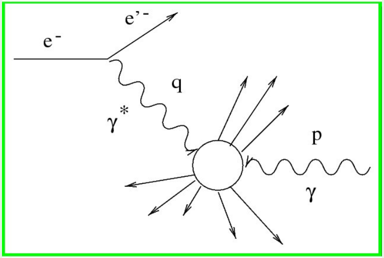
$z = \frac{p.e^-}{e^+.e^-}$



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

$e^-\gamma$ 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 $y \ll 1$

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

- 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

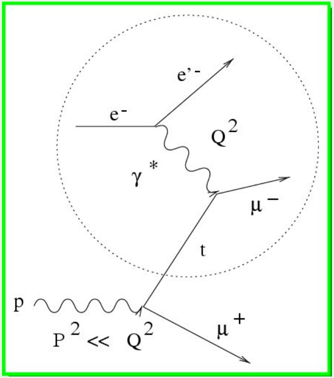
When $X = \mu^+\mu^-$

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

Basic process and many scales

- 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)

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



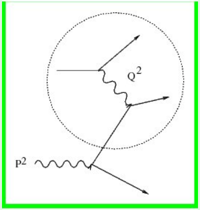
QCD

35 years ago, QCD really started

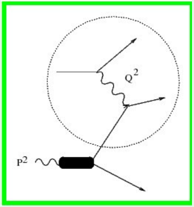
- $\gamma\gamma \to$ jets inspired from QED : QPM or "QCD improved parton model"
- Hope to get from $F_2^\gamma(x, Q^2)$ obtained through Unfolding and according to Witten a measurement of Λ_{QCD}

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



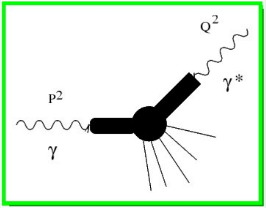
m_q : constituent or current mass



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 $Q^2 \to 0$ limit.

With GVDM



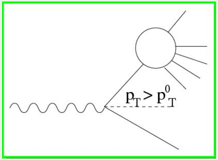
$\sigma^{\gamma\gamma^*}(W^2, Q^2, P^2 \simeq 0) \simeq$
$F_{GVDM}(Q^2)(A + \frac{B}{W})(1-x)$
leading to
$F_2^\gamma/\alpha = a(Q^2)(1-x) + b(Q^2)\sqrt{x}(1-x)$
for a finite $\sigma^{\gamma\gamma^*}$ at $Q^2 = 0$

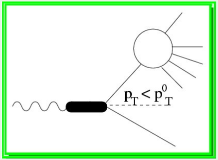
QCD : FKP

- 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

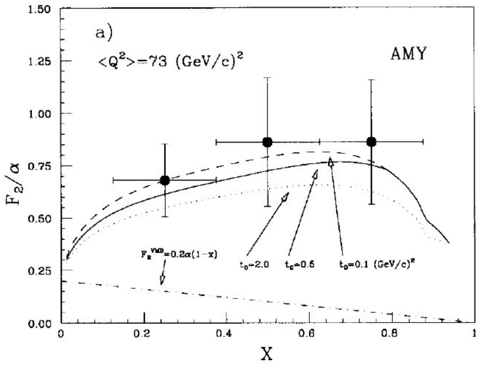
For $Q^2 \gg P^2$

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

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

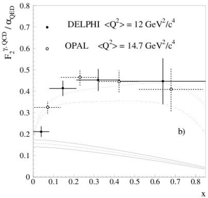
with $Y_0 = \ln \frac{t_0}{\Lambda^2}$, $t_0 = \frac{m_q^2 + p_{T0}^2}{(1-x)} + P^2 x$, $C = \frac{8}{33 - 2N_f}$ and $f(x) = 2 \ln \frac{1}{(1-x)} - x - \frac{1}{2} x^2$

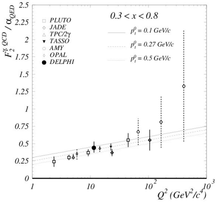
- When $\Lambda \to 0$ i.e. $\alpha_s(t)$ recover $\simeq$ QPM
- "Natural" P^2 dependence
- Importance of "constant" terms
- Natural introduction of two scales Q^2,p_T^2
- Tribute to Tadao Nozaki (AMY) visiting Paris
- In 94-95 G. Schuler and T. Sjostrand introduce a p_T^0 cut in SaS1D$_{LO}$ and SaS2D$_{LO}$ 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



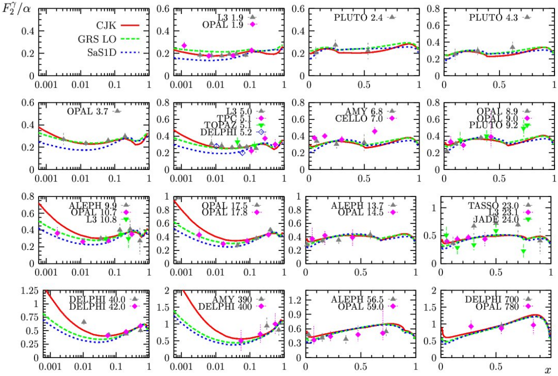
From FKP to SaS : comments

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



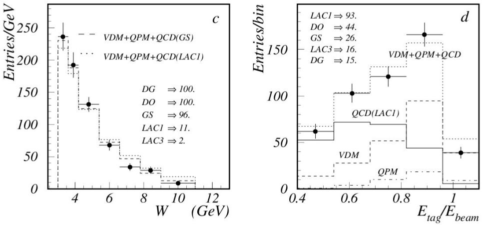


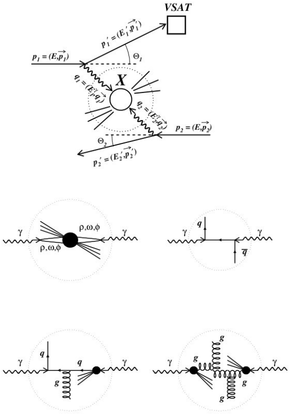
All existing parametrisations come from a fit to all Q^2 existing unfolded data



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.

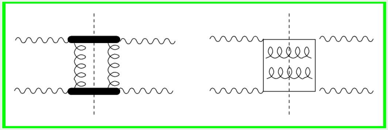
$\sigma^{\gamma\gamma}_{TOT}$

- 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 :

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

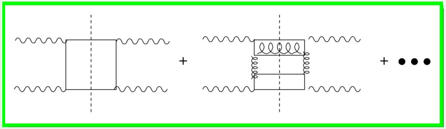
"Pomeron Reggeon"

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



"Pomeron Soft"

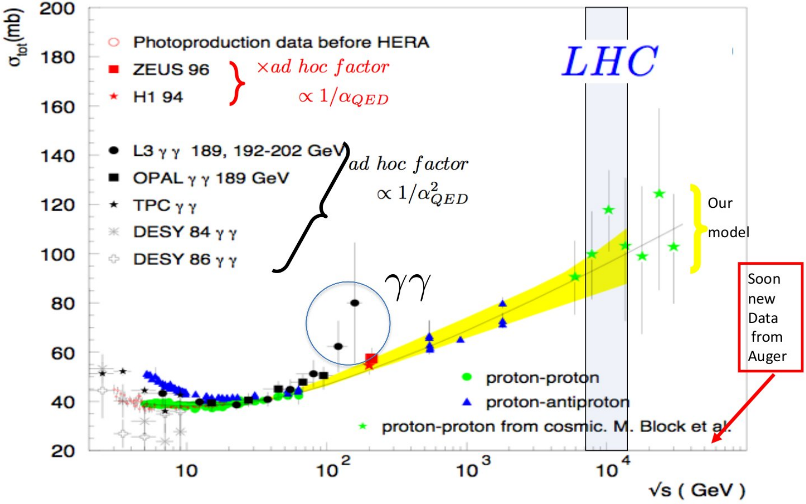
$$+\frac{C}{W^2}\ln\frac{W^2}{2t_0} + D(W^2)^{\epsilon} + F(W^2)^{\epsilon}\ln\frac{W^2}{2t_0}$$



- 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.

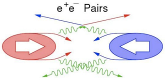
$\sigma^{\gamma\gamma}_{TOT}$

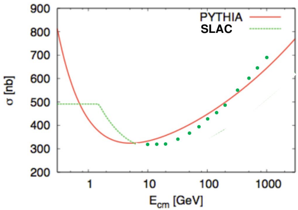
Giulia Pancheri (LC11, Trento 9/13/2011) Improved eikonalized minijet model



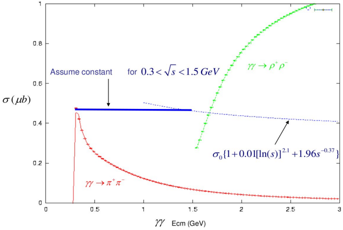
$\sigma^{\gamma\gamma}_{TOT}$ and ILC/CLIC hadronic background

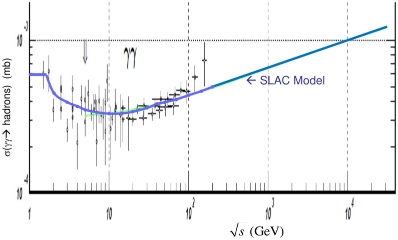
- The low W region is poorly described.
- Important for the hadronic background estimation at ILC/CLIC.
- Less critical at the ILC (Sitges 1999 Wilfrid da Silva : 0.05 evt/BX)





- 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

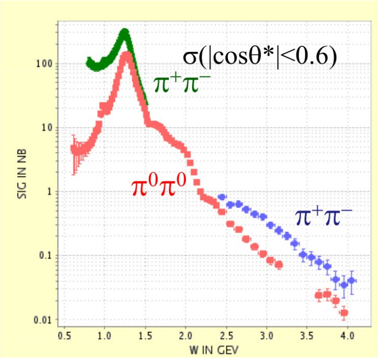


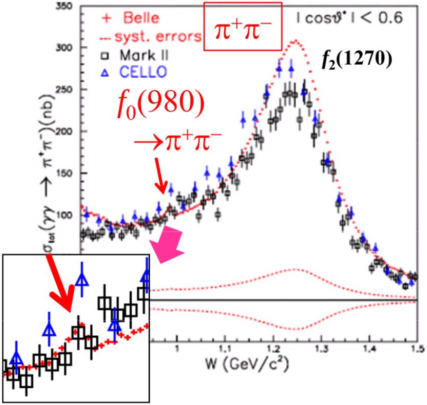


- SLAC model isotropic for $0.2 < W < 2$ GeV, not too much energy , but FWD occupancy

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

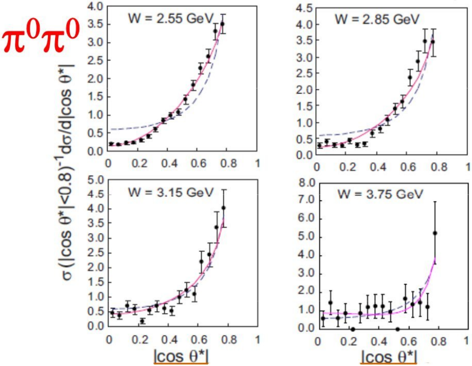


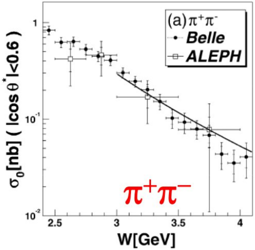


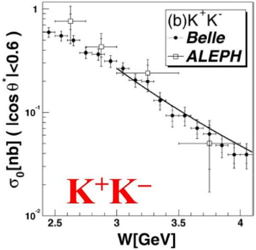
From Sadaharu Uehara GPD2010, Trento.

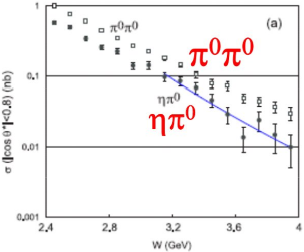
$\sigma^{\gamma\gamma}_{TOT}$, ILC/CLIC hadronic background and BELLE

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



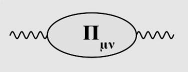


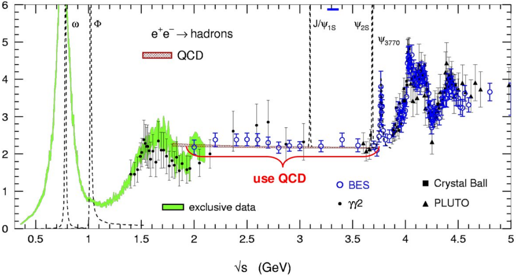




g-2 and BELLE

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



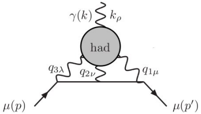


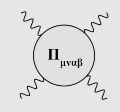
- Taken from M. Davier, ICFA Seminar Oct 3-6 2011

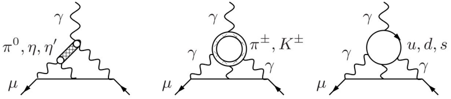
...the Hadronic Light By Light (HLBL) contribution enters the game.

But dispersion relation not possible (4 point function)

Model dependent with pole dominance



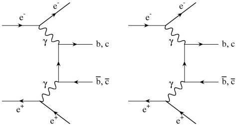


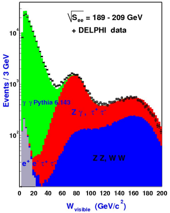


As for Form factors for the pion in R(s), Belle-II will test $\gamma^*\gamma$ and $\gamma^*\gamma^*$ for π and $\pi\pi$ production

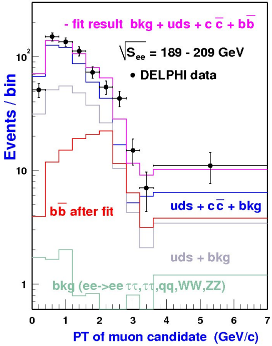
Heavy Quarks : "too much beauty ?"

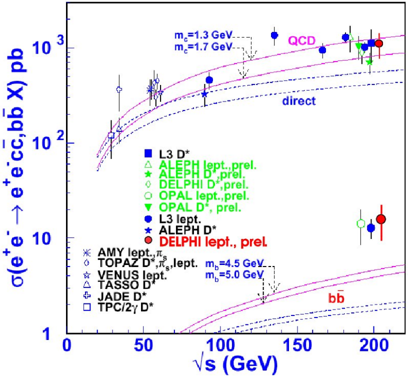
- $c\bar{c}$ and $b\bar{b}$ production at LEP





- 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

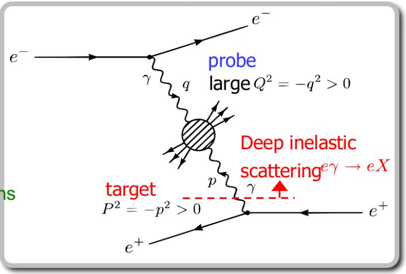
- Future linear collider experiment (e.g. ILC)

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

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



- Highly virtual photon target

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

pQCD gives definite predictions for

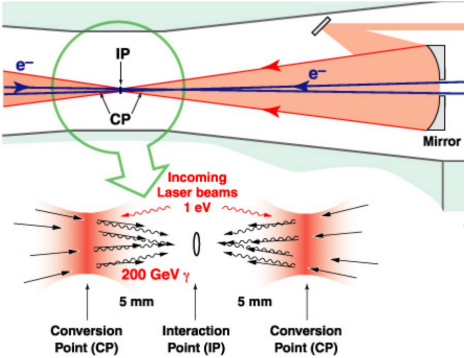
- $F_2^\gamma(x, Q^2, P^2)$ $F_L^\gamma(x, Q^2, P^2)$
- pdf in the virtual photon

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

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

PLC

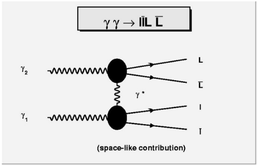
- 30 years ago, I. Ginzburg, G. Kotkin, V. Serbo and V. Telnov proposed the principle of a Photon Linear Collider at an e^+e^- accelerator.
- Taken from Jeff Gronberg (ICHEP 2002)
- The Photon Linear Collider option should stay in the ILC baseline.
- PLC advertised so many years by V. Telnov.



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 (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. $m \gg m'$

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

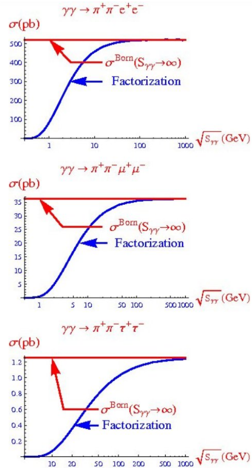
Equal masses

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

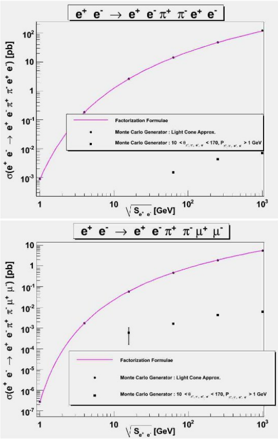
Interesting when masses are not too different since no such an expression was available.

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).



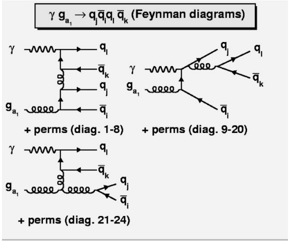
- All computed processes are included in Monte-Carlo Generator (Born Term)

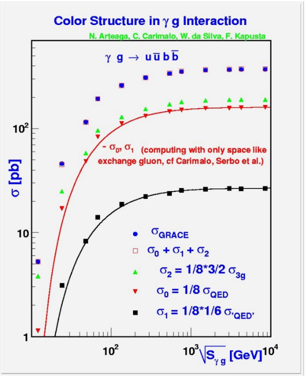


- $\sigma^{vis}_{ILC} \simeq 0.1 - 10\ fb$
- Measurable with Belle-II data?

$\gamma g \to q\bar{q}Q\bar{Q}$ 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 : $\gamma g \to q\bar{q}Q\bar{Q}$





$$M = \mathrm{u}_2^{a_1}{}_{ik}^{jl}(M_1 + M_2 + \ldots + M_8) +$$
$$\frac{1}{\sqrt{6}}\mathrm{u}_3^{a_1}{}_{ik}^{jl}(M_1 - M_2 \ldots + M_{20}) + \sqrt{\frac{3}{2}}\mathrm{u}_4^{a_1}{}_{ik}^{jl}(M_1 + \ldots + M_{24})$$
$$\sigma = \frac{1}{8}\sigma_{QED-Space} + \frac{1}{8}\frac{1}{6}\sigma_{\text{``}QED\text{''}} + \frac{1}{8}\frac{3}{2}\sigma_{3g}$$
($\frac{1}{8}$ = average gluon color, $|F_1|^2 = 1, |F_2|^2 = \frac{1}{6}, |F_3|^2 = \frac{3}{2}$)

Comment on the Number of Color Factors

- A_0^n = number of color singlets.
- $\begin{bmatrix} 1 \\ 1 \end{bmatrix}^{n+1} = \begin{bmatrix} 1 \\ 1 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix}^{n}$ give useful relations between n and $n+1$ coefficients.
- $A_0^n \propto (n-1)!$ for large n.
- $A_0^1 = 0, A_0^2 = 1$, $A_0^3 = 2$, $A_0^4 = 8$, $A_0^5 = 32$, $A_0^6 = 145$, ...
- Diagrams with n gluons and m quark antiquark pairs. The number of color factors is :

  $N_{n,m} = \sum_{p=0}^{p=m} C\,_m^p A_0^{n+m-p}$

- $\gamma g \to q\bar{q}$
  $n = 1\ ,\ m = 1$
  $N_{1,1} = A_0^2 + A_0^1 = 1$
- $\gamma g \to q\bar{q}Q\bar{Q}$
  $n = 1\ ,\ m = 2$
  $N_{1,2} = A_0^3 + 2A_0^2 + A_0^1 = 4$
- $gg \to q\bar{q}$
  $n = 2\ ,\ m = 1$
  $N_{2,1} = A_0^3 + A_0^2 = 3$
- $gg \to q\bar{q}Q\bar{Q}$
  $n = 2\ ,\ m = 2$
  $N_{2,2} = A_0^4 + 2A_0^3 + A_0^2 = 13$
- $gg \to q\bar{q}q'\bar{q}'Q\bar{Q}$
  $n = 2\ ,\ m = 3$
  $N_{2,3} = A_0^5 + 3A_0^4 + 3A_0^3 + A_0^2 = 63$

Low Energy Photon Collider

- Already proposed 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.
- 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.
- High energy photon beams advocated by Hirotaka Sugawara : " Photon-photon collider Higgs factory as a precursor to ILC" (Panofsky Symposium at SLAC, april 10, 2008)
- We have still a "low energy" e^+e^- collider : KEKB.
- Maybe KEK could envisage a LEPC...

Conclusions and Outlook

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

- High energy two photon collisions are a tool to unravel
  and study the new physics which should appear at the LHC.

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

- Belle and KEK have a major rôle to play.