Photon - 2003

Theoretical Summary - (overview)

- Introduction
- Current theoretical developments for photon str. fn.

What has photon helped us to learn? (current data)

- Some of the recent challenges thrown to theorists by the photon studies?

- Where does photon physics go in near future?

- What do we need photons to tell us?

- What are more futuristic prospects for photon studies and opportunities offered by studying new physics using photons?
Exclusive Physics $\xleftarrow{\text{LEP}}$ (HERA) $\xrightarrow{\text{Forward Physics, $\sigma_{\text{total}}$}}$ (T.J., M.B., Y.S.)

New Calculations $\xleftarrow{\text{(R.E.) (S.G.) (C.S.D.) (N.F.)}}$ Looking for (T.K.)

NC commutative part.

How photons help us to look/ check exotic

$(\gamma, J) \to (\gamma, 2) \omega$

Charge asymm. (r.e. A. de Roeck) (V.K.), (V.T.)

In $\gamma p$ Calculation futuristic tech.

Programmes $\xrightarrow{\text{Luminosity}}$
1) Photon str. f²
   M. K.

2) Photon str. f³
   E.W.

3) Diffraction at HERA A.M.

4) Forward physics at HERA J.T. (future HERA)

5) Charm at HERA (inclusive) & V.K. G.K.

6) Jets in NLO in ττ (L.B.)

7) Exclusive production in θθ, γγ M.D.

     T. Aibling

8) Total x-sections M.B., G.P., Y.S., A. Frolov

     Pomeran

9) Sum rules, quarkonia S.B., N.F., S.D.

10) Hermitian duality D. Hnoch

11) θ-theta, noncommutative F.T. (F.J.), I.T.K.

12) Future ττ I.G., V.S., A. de Roeck

     V.T., V.K.
Introduction

Photons: Almost a 100 years old!

Heralded led to new, important directions for physics beginning from the Black body radiation. Photons have 'shown' the way, shined on the path!!

Quantum theory of radiation + interaction between a photons \( \rightarrow \) Era of Quantum Gauge Theories.

Atomic spectra \( \rightarrow \) Atomic Structure

Virtual photons \( \rightarrow \) proton structure

DIS: first glimpse of the fundamental constituents

"Self analysing" \( \rightarrow \) photon structure

- Proton structure
- Photon structure
- Probing new physics with photons
- Using photons as a theoretical laboratory to understand QCD dynamics
Photon XX conferences:

have a character and history of its own. From the years of discussing
photoproduction & η Physics - which meant mainly

spectroscopy → photon str. f°

hadronic interactions of a high energy J°

High Energy Photoproduction - HERA
Proton structure, Photon structure

LEP

2γ Physics:

Photon physics: One big laboratory for QCD + QED
A new 5 Flavour LO Analysis of Parton Distributions

and

the Parton Parametrization of the Real Photon

http://www.fuw.edu.pl/ pjank/para.html
http://www-zeuthen.desy.de/alorca/id4.html

F. Cornet, Granada U.
P. Jankowski and M. Krawczyk Warsaw U.
A. Lorca, DESY-Zeuthen

PHOTON 2003, April 2003, Frascati, Italy
ACOT$\chi$ approach for a photon– heavy quarks $h$

In DGLAP evolution eqs. heavy quarks as partons and/or Bether-Heitler production of heavy quarks (FFNS=B-H)

There is a double counting here, one should subtract some terms: logarithmic contribution in diagrams with "="
Threshold for heavy quark $h$

Bethe-Heitler process leads to:

$$\frac{1}{x} F^\gamma_{2,h}(x, Q^2)|_{\text{direct}} = 3 \frac{e^4_h}{\pi} \alpha \omega(x, Q^2)$$

with

$$\omega(x, Q^2) = \left[ \beta \left( -1 + 8x(1 - x) - x(1 - x) \frac{4m^2_h}{Q^2} \right) 
+ \left( x^2 + (1 - x)^2 + x(1 - 3x) \frac{4m^2_h}{Q^2} - x^2 \frac{8m^4_h}{Q^4} \right) \ln \left( \frac{1 + \beta}{1 - \beta} \right) \right],$$

$$\beta = \sqrt{1 - \frac{4m^2_h x}{(1 - x)Q^2}} = \sqrt{1 - \frac{4m^2_h}{W^2}}.$$

for large $Q^2$: $\ln \left( \frac{1 + \beta}{1 - \beta} \right) \rightarrow \ln \frac{Q^2}{m^2_h}$

Threshold: $1 - \frac{4m^2_h}{W^2} > 0$ - In the evolution $Q^2$ is a natural variable - setting a threshold condition difficult
Another heavy quark contribution to $F_2^\gamma$:

$$\gamma^* G^\gamma \to h \bar{h},$$

with a gluonic parton of the initial real photon

$$F_{2,h}^\gamma(x, Q^2)|_{\text{resolved}} = \frac{\alpha_s(Q^2)}{2\pi} e_h^2 \int_{\chi}^{1} \frac{x}{z} \omega \left( \frac{x}{z}, Q^2 \right) G^\gamma(z, Q^2) dz$$

$$\chi \equiv x (1 + 4m_h^2/Q^2)$$

Kinematics OK: $\chi$ - lower limit of integration over $z$ - the (relative) momentum of gluon in a photon

$\chi \to 1$ contribution $\to 0!$

Note, that $\chi$ approaches $x$ for a large $Q^2$
We follow $\text{ACOT}_\chi$ approach, and introduce the $\chi$ variable instead of $x$ to deal with the heavy quark threshold.

Finally, we have

$$F_2^\gamma(x, Q^2) = \sum_{i=1}^{2\times3} x e_i^2 q_i^\gamma(x, Q^2) + \sum_{h=c,b}^{2\times2} x e_h^2 q_h^\gamma(\chi, Q^2) + \sum_{h=c,b}^{2\times2} \left[ F_2^\gamma_{2,h}(x, Q^2) \right]_{\text{direct}} + F_2^\gamma_{2,h}(x, Q^2) \right]_{\text{resolved}}$$

$$-\chi \sum_{h=c,b}^{2\times2} \ln \frac{Q^2}{m_h^2} \left[ e_{h/2}^4 \frac{\alpha_s}{2\pi} k(\chi) + e_{h/2}^2 \frac{\alpha_s}{2\pi} \int \frac{dy}{y} P(q)(\chi) G^\gamma(y, Q^2) \right].$$

Note, that the direct contribution does not disappear at $\chi \to 1$ stage II.
The fits: stage I

\(N_f = 3\) (FFNS), \(N_f = 5\) (CJKL)

\(\alpha_s(Q^2)\)

the direct contribution does not disappears for \(\chi \to 1\) (large \(x\))

no error analysis

<table>
<thead>
<tr>
<th>model</th>
<th>(\chi^2) (208 pts)</th>
<th>(\chi^2/DOF)</th>
<th>(\kappa)</th>
<th>(\alpha)</th>
<th>(\beta)</th>
<th>(N_v)</th>
<th>(N_{gl})</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFNS(_{cijkl})</td>
<td>471</td>
<td>2.30</td>
<td>1.726</td>
<td>0.465</td>
<td>0.127</td>
<td>0.504</td>
<td>1.384</td>
</tr>
<tr>
<td>CJKL</td>
<td>431</td>
<td>2.10</td>
<td>1.125</td>
<td>0.843</td>
<td>2.359</td>
<td>2.435</td>
<td>2.982</td>
</tr>
</tbody>
</table>
CJLK use for initial conditions an incoherent superposition of vector meson state a la GRV. We coherent instead.

$$(rac{u}{d})_{GRV} \text{ quite diff. from } (\frac{u}{d})_{GRS}$$

$$(GRV)_k \gg (GRS)_k \approx \frac{\eta (C I L K)}{c} = 4$$

Zerwas et al. (Freiburg, Photon 91)

High energy eX collisions

$$e + \rightarrow eX$$

$$eX \rightarrow uX$$

Can test $u/d$

$$(\frac{u}{d})_{GRV} > (\frac{u}{d})_{C I L K} > (\frac{u}{d})_{GRS}$$
High Q² Proton Structure, H1 & ZEUS

\[ F_2^m = \frac{Q^2}{2} \left[ \frac{1}{F_2} - \frac{1}{F_2^m} \right] \]

\[ F_2^\log_10(x) \]

\[ Q^2 \text{(GeV}^2) \]

\[ x \]

\[ x = 0.01, 0.02, 0.03, \ldots \]

HERA, ZEUS, NLO QCD fit

Int error

H1 94 A E005

ZEUS 96 A E007

BCOMS

NMC
\[ \tilde{\sigma}_{CC} = x \cdot \left[ \bar{u} + \bar{c} + (1 - y)^2 (\bar{d} + \bar{s}) \right] \]

\[ \tilde{\sigma}_{CC}^{-} = x \cdot \left[ u + c + (1 - y)^2 (d + s) \right] \]

- PDF agrees with Data points
- 2 Orders of Magnitude in \( Q^2 \)
- and 2 Orders of Magnitude in \( x \)
- At high \( x \), D contribution dominates
Summary

- $\tilde{\sigma}_{NC}$ and $\tilde{\sigma}_{CC}$ well Measured
- $\tilde{F}_2$ errors to 2%
- $\tilde{F}_3$ errors statistically dominated (reduced with Hera II running)
- $\tilde{F}_L$ Measured with Hera II low energy running
- Hera PDFs Consistent with global fits
- Do not rely on global fits
- Error on u 1%(x=0.01) - 2%(x=0.4) [H1]
- Error on d 3%(x=0.01) - 10%(x=0.4) [H1]
- Error on quark sea $\sim$5 % (x≤0.1) [Zeus]
- Error on gluon $\sim$10 % (x≤0.1) [Zeus]
Diffraction in ep collisions

Anna Mastroberardino
Calabria University

International Conference on the Structure and Interactions of the Photon
Frascati (Italy), 7 – 11 April 2003

on behalf of

H1 ZEUS

- Introduction
- Diffractive structure functions
- $t$ - distribution
- $\Phi$ – distribution
- Summary

Anna Mastroberardino 7th April 2003
Diffractive structure function and the “universal” IP

Fit all data with one value of flux factor

\[ x_P F_2^{D(3)}(x_P, \beta, Q^2) \sim \frac{1}{x_P F_2^{D(4)}(\beta, Q^2)} \]

Regge factorization supported

\[ \alpha_{IP}(0) = 1.173 \pm 0.018 \text{(stat.)} \pm 0.017 \text{(syst.)} \pm 0.063 \text{(mod.)} \]

Anna Mastroberardino

7th April 2003
NLO QCD fit: the gluon density

Assume:
Regge factorization (c.f. data)
Singlet $\Sigma$ and gluon $g$
parameterized at $Q_0^2 = 3$ GeV$^2$
NLO DGLAP evolution

get PDFs:
Extending to large
fractional momenta $z$
Gluon dominated

Momentum fraction of diffractive exchange carried by gluons:

\[ 75 \pm 15 \% \]
Diffractive final states: a test of QCD factorization

Use diffractive PDFs to predict cross sections for diffractive production of charm and dijet

At HERA: Shapes of distributions well reproduced by dPDFs description

Normalization ~ ok within uncertainties

Consistent with QCD factorization

At the Tevatron: Serious breakdown of factorization between ep and pp data due to additional spectator interactions

Anna Mastroberardino  7th April 2003
Measurements of inclusive diffraction at HERA

- used to test QCD factorization
  - dijet and charm cross sections at HERA are found to be approx. consistent
  - a discrepancy ~ one order of magnitude observed in the predictions of
dijet cross sections from the Tevatron

- support Regge factorization
- can be described within a consistent picture using
  - NLO DGLAP evolution
  - gluon dominated diffractive PDFs

- analyzed for the first time in terms of azimuthal asymmetry indicate
interference between L and T photons small at low $\beta$
Forward Jets and Particles in $ep$ collisions and parton dynamics

On behalf of H1 and ZEUS Collaborations

Jacek Turnau, Institute of Nuclear Physics, Cracow

- Parton dynamics at high energies
- Central region
- Forward Jets
- Forward $\pi^0$
- Conclusions
Inclusive Jets in DIS

$5 < Q^2 < 100$ GeV$^2$, $0.2 < y < 0.6$
incl. $k_T$ algorithm in Breit frame

DGLAP description gradually deteriorates when going from backward to forward direction

Forward region:
- huge NLO correction
- large deviations at small $Q^2$ & $E_T$

Moral: NNLO may be important in forward region
Forward Jets

**DIS**: $5 < Q^2 < 75 \text{ GeV}^2$

Forward jet (incl. k, algo.)

$7.0^\circ < \theta_{jet} < 20.0^\circ$

$x_{jet} > 0.035$

$0.5 < \frac{p_{tjet}^2}{Q^2} < 2.0$

- DGLAP direct: too low
- CCFM: too much
- DGLAP (DIR+RES): OK

**H1 Forward Jet Data (1997)**

$P_{T,\text{JET}} > 3.5 \text{ GeV}$

- H1 data, prel.
- CDM
- RG(DIR)
- RG(DIR+RES)
- CASCADE

$\mu^2 = Q^2 + p_T^2$

Similar pattern of agreement/disagreement for $x_{jet} \ P_{T,\text{jet}}$
Forward jets are experimentally difficult:
- Interference with proton remnant
- Hadronic corrections strongly model dependent at small $x$
**Forward π^0 cross section : x dependence**

- **2.0 < Q^2 < 4.5 GeV^2**
  - H1 data
  - DIR + RES. Q^2 + 4p_T^2
  - CCFM (CASCADE)
  - DIR (LO DGLAP)
  - mod. LO BFKL

- **4.5 < Q^2 < 15.0 GeV^2**
  - DGLAP direct: too low

- **15.0 < Q^2 < 70.0 GeV^2**
  - CCFM too low at small x

**Best description:**
- direct + resolved at scale μ^2 = Q^2 + 4p_T^2

**Mod. LO BFKL tuned to**
- H1 1997 data + recent FF describes the data

**Similar pattern of agreement/disagreement**
- for other distributions
Order of the Day

Require a NLO calculations of Direct + resolved contribution for DIS, forward particle production. (M. Fontannaz, R.A. P.R. Benu in progress)

Recall hints from talk by P. Bussey.

For jet production in DIS, one should use a full NLO calculation of resolved contribution along with NLO direct. (Kramer, Pößner)

Virtual photon structure seems to be throwing surprises.!!

More work for theorists + possibilities of learning more!!
Charm production in CP collisions (PHP)

Charm excitation

Drees, Godbole
Sheffield, Photon '95

Some of the
2→3 FO diagrams

direct
**Dijet scattering angle:** \[ \cos \theta^* = \tanh \frac{\eta_{\text{jet}1} - \eta_{\text{jet}2}}{2} \]

\(\theta^*\): angle between jet-jet axis and beam axis in the dijet rest frame

**ZEUS**

\[ \frac{d\sigma}{d|\cos\theta^*|} (\text{nb}) \]

- **ZEUS 1996 - 2000**
- **HERWIG (x 2.1)**
- **PYTHIA (x 1.2)**
- Jet energy scale uncertainty

\[ x_\gamma^{\text{obs}} < 0.75 \]

\[ x_\gamma^{\text{obs}} > 0.75 \]

"q exchange" \(\propto (1 - |\cos \theta^*|)^{-1}\)

"g exchange" \(\propto (1 - |\cos \theta^*|)^{-2}\)

Resolved sample rises strongly with \( |\cos \theta^*| \)

\(\rightarrow\) **Signature of g-exchange**

Direct sample consistent with q exchange

Evidence for resolved photon charm excitation

LO MC describe data shapes of both \(x_\gamma^{\text{OBS}} > 0.75\) and \(x_\gamma^{\text{OBS}} < 0.75\)
Charm Dijet Angular Distributions in PHP

Comparison with fixed-order NLO and with CASCADE

ZEUS

For $x_\gamma^\text{OBS} > 0.75$ NLO describe data well

For $x_\gamma^\text{OBS} < 0.75$ NLO lower than data in both proton and photon directions. Shape OK

CASCADE exceed data by $\approx 30\%$, mostly in $x_\gamma^\text{OBS} > 0.75$

Shape described reasonably well
**Charm Dijet Photoproduction**

$D^*$ dijet events enable study of the photon structure, in particular it's charm content 120 pb^{-1}; $Q^2 < 1$GeV^2; $130 < W_{\gamma p} < 280$ GeV

Require $D^*$ with $p_T^{D^*} > 3.0$ GeV, $|\eta^{D^*}| < 1.5$

2 jets with $E_T^{jet} > 5$ GeV, $|\eta^{jet}| < 2.4$,

$M_{jj} > 18$ GeV, $|\bar{\eta}| < 0.7$

Fraction of photon momentum producing the dijet:

$$x_{\gamma}^{OBS} = \frac{\Sigma_{jets} E_T \cdot e^{-\eta}}{2y E_e}$$

$x_{\gamma}^{OBS} = 1$: direct $\gamma$

$x_{\gamma}^{OBS} < 1$: resolved $\gamma$

$x_{\gamma}^{OBS} > (<) 0.75$: Enriched direct-(resolved-) $\gamma$

- Significant contribution $\approx 40\%$ from resolved photons
- Good agreement in shape between data and LO MC’s (CASCADE too high for high $x_{\gamma}^{OBS}$)
- Data compared to fixed-order NLO DGLAP calculation + hadronisation correction
- Low $x_{\gamma}^{OBS}$ tail of NLO cross section below data
Theoretical Framework

Hard scale $m_c \gg \Lambda_{QCD}$
$\Rightarrow$ pQCD calculations - valid

QCD LO contributions to open c production:
“Direct” BGF  “Resolved” photon  “Charm excitation”

$$\gamma g \rightarrow c\bar{c} \quad gg \rightarrow c\bar{c} \quad cg \rightarrow cg$$
$\Rightarrow$ probe $g$ in $p$  $\gamma$ partonic structure

Next-to-Leading order (NLO) calculations:
DGLAP evolution: Frixione et al.  Kniehl et al.

Fixed-order (“massive”)  Resummed (“massless”)

- $p, \gamma$ active flavours: $u,d,s$  $u,d,s,c$
- Scheme valid for: $Q^2, p^2_\perp \approx m_c^2$  $Q^2, p^2_\perp \gg m_c^2$

Matched (“FONLL”) calculation: Cacciari et al.
Incorporate mass effects up to NLO
resummation of $p_T$ logs up to NLL level

CASCADE MC based on CCFM evolution
At large $x$  CCFM $\rightarrow$ DGLAP $Q^2$ evolution
For $x \rightarrow 0$  CCFM $\rightarrow$ BFKL $1/x$ evolution
Precise data enable measurements of double differential cross sections

Data: Close to upper band of predictions
Significantly above FO, FONLL at medium $p_T^{D^*}$, forward $\eta^{D^*}$
(Even upper bounds below data!)
For low $p_T^{D^*}$ FONLL predictions close to FO
For large $p_T^{D^*}$ FONLL predictions below FO
Challenge for theory. Need for NNLO?
Inclusive $D^*$ Production in Photon-Photon Collisions with Massive Quarks in NLO

Photon 2003, Frascati

Three approaches $\gamma + \gamma \rightarrow D^{*\pm} + X$

NLO: $\gamma + \gamma \rightarrow c + \bar{c} + g$

direct contribution

- (i) massless approach $m_c = 0$, $N_f = 4$

$$d\sigma(\gamma\gamma \rightarrow CX) = \frac{\Delta}{2\pi} P_{c\bar{c}} d\sigma(\gamma c \rightarrow cg) \ln \frac{S}{M^2}$$

$M$ factorization scale $O(\sqrt{S})$

originates from collinear divergent piece

$$d\sigma(\gamma\gamma \rightarrow CX) = \frac{\Delta}{2\pi} \left( -\frac{1}{E} \right) \left( \frac{4\pi e^2}{S} \right) P_{c\gamma} d\sigma(\gamma c \rightarrow cg)$$

\[ \left( \frac{4\pi e^2}{M^2} \right) \left( \frac{M^2}{S} \right) \rightarrow \text{into NLO corr} \]

\[ \rightarrow \text{absorbed in } f_c^\gamma \]

distributed contribution
\[ \text{\bullet (ii) massive approach} \quad m_c \neq 0 \quad , \quad N_f = 3 \]

\[ d\sigma(\gamma\gamma \rightarrow cX) = \frac{\alpha}{x_{\gamma\gamma}} P_{c\gamma} d\sigma(yc \rightarrow cg) \ln \frac{S}{M_c^2} \]

factorization scale \( M = m_c \) \( \rightarrow \) large

charm only in final state : \( f_c^\gamma = 0 \)

\[ \text{\bullet (iii) massive approach} \quad m_c \neq 0 \quad , \quad N_f = 4 \]

\[ \ln \frac{S}{m_c^2} = \ln \frac{S}{M^2} + \ln \frac{M^2}{m_c^2} \]

\[ \uparrow \quad \uparrow \]

as in massless \quad absorbed in \( f_c^\gamma \)

charm also in initial state:

single and double resolved with charm

same procedure for second and third diagram

factorization scale \( M_f \)

need fragmentation for \( c \rightarrow D^* : \quad D_c^D(x) \)
\( m_c = 0 \) from start \((ZM - VFN)\)

- \( m_c^2 / p_T^2 \) terms neglected
  - good only for large \( p_T \)

- \( \ln \frac{M^2}{m_c^2} \) terms summed in evolved \( f_c^Y \) and \( D_c^{D^*} \)

\( m_c \neq 0 \) \((FFN)\) \( n_f = 3 \)

- no c quarks in initial state
  - \( f_c^Y = 0 \), \( D_c^{D^*} \) not evolved, fragmentation pert.
  - good for \( p_T^2 \approx m_c^2 \), \( m_c^2 / p_T^2 \) terms included

\( m_c \neq 0 \) \((Massive\ VFN)\) \( n_f = 4 \)

- c quarks in initial state
  - \( f_c^Y \neq 0 \), \( f_c^Y \) and \( D_c^{D^*} \) evolved

- \( \ln \frac{M^2}{m_c^2} \) terms summed
- \( m_c^2 / p_T^2 \) terms included

- good for \( p_T^2 \gg m_c^2 \), where \( f_c^Y \neq 0 \), \( D_c^{D^*} \neq 0 \)
- \( p_T^2 \leq m_c^2 \) transition to FFN
massless limit of (iii) neglects $m_c^2/p_t^2$ terms

(i) and $m_c \to 0$ limit of (iii) identical? 
answer: no!

(ii) and (iii) differ by finite terms
do not vanish for $m_c \to 0$

finite terms subtracted to match (i)
calculated for
direct process
single-resolved process

hep-ph/0109167

G.K. + H. Spiesberger
EPJC 22, 289 (2001)

hep-ph/0302081

direct process
finite terms = LO pert. fragmentation functions


finite terms in (iii) subtracted to match (i)

(i) is for $\overline{\text{MS}}$ factorization scheme
scheme for PDF and FF $c \to D^*$ is $\overline{\text{MS}}$
Conclusions

Resummed NLO calculation with $m_c \neq 0$ exists

Good agreement with ALEPH, L3 and OPA data
for $p_T > 2$ GeV

Matching to NLO FFV, $n_f = 3$

at small $p_T$ needs further study
$\frac{d\sigma}{dp_T}$ [pb/GeV]

ALEPH

L3

OPAL

different constraints on $\sqrt{s_{av}}$, tagging, $\eta$ range
Motivations:

- Hard production of jets is a complementary method (with respect to DIS) to study the "structure" of the photon
- It is rich test of QCD (since the beginning of history...Han-Nambu integer charges model)

Experimental Situation:

- OPAL, see talk by T. Wengler
- L3, see talk by M. Kienzle
- DELPHI, see Photon2001 proceedings
- Future Linear Collider ...

Theoretical results:

- As of now only the theoretical prediction by Klasen, Kleinwort, Kramer (KKK) (hep-ph/9611450 and hep-ph/9712256) is available
- It is based upon slicing method
About subtraction method:

\[
\left\langle F \right\rangle_{NLO} = \frac{1}{2\varepsilon} \int_0^1 dx \delta(1-x) F(x) + \int_0^1 dx \frac{1}{(1-x)^{1+2\varepsilon}} F(x)
\]

\[
\left\langle F \right\rangle_{\text{Slicing}}^{\text{NLO}} = \int_0^{1-\delta} dx \frac{F(x)}{(1-x)} + F(1) \log(\delta)
\]

Neglected \( O(\delta) \) terms

Large-number cancellations

\[
\left\langle F \right\rangle_{R}^{\text{Sub}} = \int_0^1 dx \frac{F(x) - F(1)\theta(x-1+x_c)}{(1-x)^{1+2\varepsilon}} + \int_0^1 dx \frac{F(1)\theta(x-1+x_c)}{(1-x)^{1+2\varepsilon}} \quad 0 < x_c \leq 1
\]

\[
\left\langle F \right\rangle_{NLO}^{\text{Sub}} = \int_0^1 dx \frac{F(x) - F(1)\theta(x-1+x_c)}{(1-x)} + F(1) \log(x_c)
\]

without any approximation and large-number cancellation (beware of narrow bins)
Any prediction has to be checked!

\[ \frac{d\sigma}{dX} = \sum_{j,k} \int f_j(x_1,Q_i) f_k(x_2,Q_i) \frac{d\hat{\sigma}_{jk}(Q_i,Q_f)}{d\hat{X}} F(\hat{X} \to X; Q_i,Q_f) \]

**Factorization theorem**

- We are not able to compute differential cross section analytically
- We fight against large unphysical oscillations and computer precision
  - A general method should be adopted in order to cancel out divergences analytically, and finite reminders can be numerical (MC) integrated
  - We use subtraction method, KKK used slicing one
- ... double test: a different computation with a different method
We implemented a computer code to compute jet and di-jet observables using the subtraction method; our results are in agreement with the predictions by KKK.

The comparisons of our results with OPAL data are really satisfactory for inclusive observables. The comparison with L3 data is troublesome!

Finally, we analyzed some theoretical QCD (NLO) difficulties to describe well particular exclusive observables measured by OPAL. Theoretical uncertainties for inclusive observables are under control.
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- It is rich test of QCD
  (since the beginning of history...Han-Nambu integer charges model)

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About subtraction method:

\[
\left( \frac{d\sigma}{dx} \right)_R = \frac{1}{1-x} \quad p_{\frac{(1-x)^p}{(1-x)^p}} \quad \text{Real emission plus virtual correction} \quad \left( \frac{d\sigma}{dx} \right)_R = \frac{1}{2\varepsilon} \delta(1-x)
\]

\[
\langle F \rangle_{NLO} = \frac{1}{2\varepsilon} \int_0^1 dx \delta(1-x) F(x) + \int_0^1 dx \frac{1}{(1-x)^{1+2\varepsilon}} F(x)
\]

\[
\langle F \rangle_{\text{Slicing}}^{\text{NLO}} = \int_0^{1-\delta} dx \frac{F(x)}{(1-x)} + F(1) \log(\delta)
\]

Neglected \( O(\delta) \) terms
Large-number cancellations

\[
\langle F \rangle_R^{Sub} = \int_0^1 dx \frac{F(x) - F(1)\theta(x-1+x_c)}{(1-x)^{1+2\varepsilon}} + \int_0^1 dx \frac{F(1)\theta(x-1+x_c)}{(1-x)^{1+2\varepsilon}} \quad 0 < x_c \leq 1
\]

\[
\langle F \rangle_{NLO}^{Sub} = \int_0^1 dx \frac{F(x) - F(1)\theta(x-1+x_c)}{(1-x)} + F(1) \log(x_c)
\]

without any approximation and large-number cancellation (beware of narrow bins)
Any prediction has to be checked!

\[ \frac{d\sigma}{dX} = \sum_{j,k} \int f_j(x_1, Q_i) f_k(x_2, Q_i) \frac{d\hat{\sigma}_{jk}(Q_i, Q_f)}{d\hat{X}} F(\hat{X} \to X; Q_i, Q_f) \]

- We are not able to compute differential cross section analytically
- We fight against large unphysical oscillations and computer precision
  - A general method should be adopted in order to cancel out divergences analytically, and finite reminders can be numerical (MC) integrated
  - We use subtraction method, KKK used slicing one
- ... double test: a different computation with a different method
We implemented a computer code to compute jet and di-jet observables using the subtraction method; our results are in agreement with the predictions by KKK.

The comparisons of our results with OPAL data are really satisfactory for inclusive observables. The comparison with L3 data is troublesome!

Finally, we analyzed some theoretical QCD (NLO) difficulties to describe well particular exclusive observables measured by OPAL. Theoretical uncertainties for inclusive observables are under control.
In wide range of $\omega$ around $\omega = 0$

No sensitivity to $B_4, B_6, \ldots$

Little sens. to $B_2$

\[ F_{T\bar{c}g} = \frac{\sqrt{2} f_{c}}{3 R^2} \left[ 1 - \frac{\xi_3}{\pi} - 2.583 \left( \frac{\xi_3}{\pi} \right)^2 - 20.215 \left( \frac{\xi_3}{\pi} \right)^3 \right. \]

\[ \left. + \frac{1}{5} \omega^2 \left( 1 - \frac{5}{3} \frac{\xi_3}{\pi} \right) + \frac{12}{35} \omega^2 B_2 + \ldots \right] \]

- Gegenbauer moments appear as $\omega^n B_n (1 + \omega^2 + \ldots \omega^4 + \ldots)$

- $F_{T\bar{c}g}$ known up to corrections in $\xi_3^4, \xi_3^3, \omega^2, \omega^4, \frac{1}{\sqrt{6}}$

If given $B_2$ and one twist-4 matrix elem.,

**Constrain from data, calculate in lattice QCD**

→ An (almost) parameter-free prediction of QCD

→ Fundamental test

→ Measure $\xi_3$

Very similar to Bjorken sum rule in DIS
SUMMARY

- $\delta \delta \to \pi^+\pi^-, \pi^0\pi^0, K^+K^-, ...$

- $\gamma\gamma \to p\bar{p}, \Sigma^0\Sigma^0, ...$

SOFT "HANDBAG" MECHANISM:

TESTABLE PREDICTIONS

HOPE TO CLARIFY WHAT IS REACTION MECHANISM

- $\delta\delta^* \to \pi^0$

  AT $Q^2 \ll q^2$ SOME (THEORETICALLY CLEAN)

  EXTRA INFORMATION ON

  PION DISTRIBUTION AMPLITUDE

  AT $Q^2 \sim q^2$

  POTENTIAL FOR PRECISION TEST OF QCD

  DETERMIN. OF $\alpha_3$

PHYSICS FOR HIGH-LUMINOSITY $e^+e^-$ MACHINES
WHAT CAN WE LEARN WITH TWO OFF-SHELL PHOTONS?

$$\bar{\alpha}^2 = \frac{1}{2} (\alpha^2 + \alpha'^2) \quad w = \frac{\alpha^2 - \alpha'^2}{\alpha^2 + \alpha'^2}$$

$$F_{\pi\eta^0} \propto \frac{1}{\bar{\alpha}^2} \left[ c_0(w) + \sum_{n=2,4,\ldots} c_n(w) B_n \right]$$

AS $w$ GOES AWAY FROM $w = 1$ ...

SOMETHING FUNNY HAPPENS $\Rightarrow$ PLOTS
Data for meson pair production:

Data completely off by a factor 10 compared to the Brodsky-Lapage hard scattering model.

But

1) only LO calculation.

2) Small scales sneak in, so the hard scattering predictions not such a surprise after all.

3) $\pi^+\pi^-/\k^+\k^-$ ratio should not be taken.

3) Disagreement of $\pi^+\pi^-/\k^+\k^-$ from the prediction of Brodsky-Lapage model not a failure of hard scattering model mechanism. Result of assuming same distribution amplitudes for $\k^+\pi^-$.

4) Discriminating test for handbag mechanism

$$\sigma (\pi^+\pi^-) = \sigma (\pi^+\pi^-) \left| \begin{array}{c}
\text{hard scattering} \\
\sigma (\pi^+\pi^-) < \sigma (\pi^+\pi^-)
\end{array} \right.$$
RESULTS: MESON PAIRS

\[
\frac{d\sigma}{dt} = \frac{8\pi e^2}{s^2} \frac{1}{\sin^4 \theta} |R_{\pi\pi}(s)|^2
\]

FORM FACTOR OF QUARK ENERGY - MOMENTUM TENSOR

- CAN DESCRIBE PRELIM. ALEPH + DELPHI DATA (PHOTON '01)

\[
|R_{\pi\pi}(s)| \sim \frac{(0.75 \pm 0.07) \text{ GeV}^2}{s}
\]

FOR \( s = 6.2 \pm 3.0 \text{ GeV}^2 \)

COMPARE WITH TIMELIKE ELECTROMAG. FORM FACTOR

\[
|F_{\pi}(s)| \sim \frac{(0.93 \pm 0.12) \text{ GeV}^2}{s}
\]

FOR \( s = 4 \pm 9 \text{ GeV}^2 \)

- SOFT OVERLAP CAN MIMIC PERTURB 1/s BEHAVIOR OVER A FINITE s RANGE

[EXPLICITLY SEEN FOR MODELS IN SPACELIKE REGION]

M.O. ET AL.
PLB 460, 204

- PREDICT θ DEPENDENCE

FOR \( |\cos \theta| \not\approx 1 \)

\( s, t, u \) NOT TOO SMALL
\[ \gamma \gamma \rightarrow \pi\pi, \ K\bar{K}, \ldots \]
\[ \rightarrow \bar{p}p, \ \Lambda\bar{\Lambda}, \ldots \]

AT LARGE ENERGY

HARD SCATTERING MECHANISM (BRODSKY, LEPAGE)

\[ \gamma \gamma \rightarrow \pi\pi \]

\[ \gamma \gamma \rightarrow p\bar{p} \]

IN LIMIT \( S \rightarrow \infty \) AT \( t/s, u/s \) FIXED
- Region where yellow lines are soft (momenta ~ 100 MeV in c.m.)

  Is power suppressed

  Approximations of hard-scattering calculation break down

  For $s \sim \text{few GeV}^2 \ldots \text{few 10 GeV}^2$

  Calculation either
    - Undershoots data
    - Has substantial contribution from soft region

  Depends on wave function
The new kinds of partonic distributions (GPD) and distribution amplitudes (GDA) are arisen from

Here, \( h = \{ N, \pi, \rho, \ldots \} \); \( \ldots \rightarrow q^2 \rightarrow \infty \); \( \ldots \rightarrow q'^2 \rightarrow 0 \)

1) \( h = N \) a good subject from experimental point of view , the theoretical investigations are related to more complicated calculations than for meson case, due to spin 1/2
- \( h = \pi, \rho, \ldots \) the theoretical part is attracted thanks to relative simplicity. But the problems of experimental character certainly exist owing to the absence of \( \pi \)-target.

2) The probing the meson structure is available from both exper and theor. points of view.
- \( \gamma^8 \rightarrow \pi \pi \) CLEO Coll., J.Gonberg et al., PRD 57, 33(1998)
- Theor. \( \gamma^8 \rightarrow \pi \pi \) twist-2 and twist-3 have been considered in
  M.Diehl et al., PRL 81, 1782 (1998)
  N.Kivel & L.Mankiewicz , PRD 63, 054017
  I.V.A and O.V.Teryaev , PLB 509, 95 (2001)
Figure 3: Cross-section $d\sigma/dQ^2 [pb/GeV^2]$ in logarithmic scale. The theoretical cross-section is plotted for the best fitted parameters which are $C_1 = 1$, $W_1 = 2.9$ GeV and $W_2 = 1.2$ GeV

\[
\frac{d\sigma}{dQ^2}(ee \rightarrow ee\gamma^*) = \frac{\alpha^4}{16\pi^2} C_1 \int_0^1 dx_2 F_{\gamma\gamma}(x_2)
\]
\[
\left\{ \frac{1}{16x_2 E_2^2 Q^2} - \frac{1}{2x_2 E_2^2 Q^2 (Q^2 + \langle W_1^2 \rangle)} + \frac{2}{Q^2 (Q^2 + \langle W_2^2 \rangle)^2} \right\}
\]

The best fit correspond to

$C_1 = 1.0 \pm 0.12$ GeV$^2$  $\langle W_2 \rangle = 1.2 \pm 0.08$ GeV

$\langle W_1 \rangle = 2.9 \pm 0.8$ GeV

$\chi^2 / \text{d.o.f.} = 0.25$
Conclusion

Preliminary data seem to be in agreement with the theoretical expectation on the $Q^2$ behaviour of the cross section.

Further investigations:

- the angular dependence of the final state
- the spin structure of the final state
- $W^2$-dependence of the cross-section
- $p^+p^-$
Talking of $\psi \to \phi \phi$ : Threshold Enhancement

near the threshold

$L_3$ data [are much lower compared to Argus].

→ Please from theorists:

can we have measurements from KEK?
Conclusions

The available data on \( nn, \gamma p \) and \( \gamma \gamma \) reactions lend strong experimental support to the factorization hypotheses of

- the well-known cross section factorization theorem:
  \[
  \frac{\sigma_{nn}}{\sigma_{\gamma p}} = \frac{\sigma_{\gamma p}}{\sigma_{\gamma \gamma}}
  \]

- the lessor-known nuclear slope factorization theorem:
  \[
  \frac{B_{nn}}{B_{\gamma p}} = \frac{B_{\gamma p}}{B_{\gamma \gamma}}
  \]

- the relatively obscure requirement:
  \[
  \rho_{nn} = \rho_{\gamma p} = \rho_{\gamma \gamma}
  \]
\[ \sigma_{\gamma\gamma} = (\frac{2}{3}P_{\text{had}})^2 \sigma_{\text{nn}}, \]

L3 and OPAL data, uncorrected with PYTHIA and PHOJET
\[ \sigma_{\gamma\gamma} = \left( \frac{2}{3} P_{\text{had}} \right)^2 \sigma_{nn}, \]

L3 and OPAL data, uncorrected with PYTHIA and PHOJET
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Fit 1: no $\sigma_{\gamma\gamma}$</th>
<th>Fit 2: $\sigma_{\gamma\gamma}$, PHOJET</th>
<th>Fit 3: $\sigma_{\gamma\gamma}$, PYTHIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$(mb)</td>
<td>37.2 ± 0.81</td>
<td>37.1 ± 0.87</td>
<td>37.3 ± 0.77</td>
</tr>
<tr>
<td>$\beta$(mb)</td>
<td>0.304 ± 0.023</td>
<td>0.302 ± 0.024</td>
<td>0.307 ± 0.022</td>
</tr>
<tr>
<td>$s_0$((GeV)$^2$)</td>
<td>34.3 ± 14</td>
<td>32.6 ± 16</td>
<td>35.1 ± 14</td>
</tr>
<tr>
<td>$D$(mb(GeV)$^2(1-\alpha)$)</td>
<td>$-35.1 ± 0.83$</td>
<td>$-35.1 ± 0.85$</td>
<td>$-35.4 ± 0.84$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$c$(mb(GeV)$^2(1-\mu)$)</td>
<td>55.0 ± 7.5</td>
<td>55.9 ± 8.1</td>
<td>54.6 ± 7.3</td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$P_{\gamma\text{had}}^\gamma$</td>
<td>$1/(233.1 ± 0.6)$</td>
<td>$1/(233.1 ± 0.6)$</td>
<td>$1/(233.1 ± 0.6)$</td>
</tr>
<tr>
<td>$N_{\text{OPAL}}$</td>
<td></td>
<td>0.929 ± 0.037</td>
<td>0.861 ± 0.050</td>
</tr>
<tr>
<td>$N_{\text{L3}}$</td>
<td></td>
<td>0.929 ± 0.025</td>
<td>0.808 ± 0.020</td>
</tr>
<tr>
<td>$\chi^2$/d.f.</td>
<td>1.62</td>
<td>1.49</td>
<td>1.87</td>
</tr>
<tr>
<td>d.f.</td>
<td>68</td>
<td>78</td>
<td>78</td>
</tr>
<tr>
<td>total $\chi^2$</td>
<td>110.5</td>
<td>115.9</td>
<td>146.0</td>
</tr>
</tbody>
</table>

**Notes:**
- **GOOD:** Fits 1 and 2
- **BAD:** Fit 3
But L3 paper had fitted
\[ \sigma(s) = a s^l + b s^e \]

for PHOJET and PYTHIA nos.-separately
always yielding \( \sigma > 0.08 \).

\( \gamma \) Photon does have its own event hadronic 'natur' in part to a 'hard' \( q\bar{q}Y \) vertex.

\( \gamma \) should one be surprised if \( \sigma p/\sigma Y \)
cross-sections show a diff't. behaviour ?

\( \gamma \) measured parton densities in 'Y' quite a bit diff't. form that in a proton.

\( \gamma \) Newer measurements from existing data expected from OPAL, H1
\[ \sigma_{\gamma p} / \sigma_{\gamma p}^{\text{tot}} \]

We look forward to that
The Fall & Rise of Total X-sections

Yogendra Srivastava
Perugia + Northeastern

Photon 03 Frascati
April 8, 2003

Work in Collaboration with:

* A. Gran (Granada)
* R. Godbole (Bangalore)
* G. Pancheri (Frascati)
* S. Pacetti (Perugia)
* A. Widom (Northeastern)
Instability of the AF vacuum
Confinement
Analytic $\alpha_s$
Applications

- In QCD, the 1-loop AF gives
  \[ \alpha_{\text{1-loop}}(s) = \frac{1}{b \ln(-s/\Lambda^2)} \]
  has a pole at $s = -\Lambda^2$ (space-like value). Higher loops suffer from a similar disease.

- Of course, analyticity – derived from unitarity – forbids any singularity in the space-like region. Absorptive part of the

- Also, the AF $\alpha_s$ has the "wrong" sign for stability. The physics behind this mysterious statement is very simple.

  Consider the (static) Coulomb potential for a charged particle

  - In vacuum \[ \frac{\alpha_0}{r} \]
  - In a medium \[ \frac{\alpha_0}{\varepsilon r} \quad \varepsilon \to \text{dielectric constant} \]

  The $s$-dependent (i.e., dynamical)

  \[ \varepsilon(s) = \frac{1}{\alpha(s)} \]
The problem with this model is that it is too singular, so that integrals—which routinely occur in soft-gluon summations—of the type

\[ \alpha_{av}(s) = \frac{i}{8} \int_0^\infty ds' \alpha_s(s') \]

are not convergent.

Taking our cue from the above, we have developed a general class of models, for which \( \alpha_1 \) & \( \alpha_2 \) are limiting cases.

A simpler function to disperse is the color dielectric function \( \varepsilon(s) = \frac{1}{\alpha_s(s)} \)

\[ \varepsilon(s) = \left( \frac{s}{\pi} \right) \int_0^\infty ds' \frac{\text{Im} \varepsilon(s')}{s' (s'-s-i\delta)} \]

with

\[ \text{Im} \varepsilon(s) = -\frac{\pi \delta}{[1+(\lambda^2 s)^p]} \quad (0 < p \leq 1) \]

In this form, confinement is automatic provided \( \varepsilon(0) = 0 \)

If \( p = 1 \) \( \rightarrow \alpha_2(s) \)
Applications:

1. Intrinsic transverse momentum:

Some time ago [NPS], analytic $\alpha_s$ of this type were used for the transverse momentum distribution of lepton pairs, $W$ & $Z$. Good agreement with data were obtained without any need of an additional intrinsic transverse momentum term.

2. Inclusive $\tau$ Decays:

- The ratio of hadronic to leptonic $\tau$ decay widths

$$R_\tau = \frac{\Gamma(\tau \rightarrow \nu_\tau + \text{hadrons})}{\Gamma(\tau \rightarrow \nu_\tau e^- \bar{\nu}_e)}$$

allows one to compute, with some accuracy, the value of $\alpha_s(s)$ at $\tau$-mass: $s = M_\tau^2 \approx (1.78 \text{ GeV})^2$

- For massless quarks

$$R_\tau = 2 \sum_q \left( \frac{M_q^2}{M_\tau^2} \right) \left[ 1 - \frac{s}{M_\tau^2} \right]^2 \left( 1 + \frac{s}{M_\tau^2} \right) \tilde{R}(s)$$

$\tilde{R}(s)$ is proportional to the hadronic correlator

$$\Pi(s) = \sum_q |V_{uq}|^2 \left[ \Pi_{uq,V}(s) + \Pi_{uq,A}(s) \right]$$
Ratios of slopes & intercepts of (\(q\bar{q}\)) & (gg)

Regge Trajectories:

- A Pomeron structure (P) in QCD is believed to be generated by 2 gluons, just as the quasi-degenerate \(S, W, f_0, A_2\) (R) trajectories are generated by a (quasi-massless) \(q\bar{q}\) pair. A partial understanding between P & R trajectories may be obtained through the following simple hadronic string picture.

\[ q \leftrightarrow \gamma \rightarrow \bar{q} \]

\[ g \leftrightarrow \gamma \rightarrow g \]

\[ \text{massless } q\bar{q} \text{ pair } (R) \]

\[ \text{a } gg' \text{ pair } (R) \]

\[ E_{cm} = \text{Angular Mom + Coulomb + Tension terms} \]

\[ M_i(J) = \min_r \left[ \frac{2(2 - C_i \kappa_0)}{\gamma} + C_i \tau_0 \gamma \right] \]

\[ i = R \rightarrow C_F = \frac{4}{3} \]
\[ i = P \rightarrow C_P = 3 \]

\[ \alpha_i(s) = C_i \alpha_i(0) + \left( \frac{1}{g C_i \tau_0} \right) s \]
\[ \alpha_R(0) = \frac{4}{g} \alpha_P(0) \]
\[ \alpha_P' = \frac{4}{g} \alpha_R' \]

Both are reasonable results

This gives - to the zeroth order - why the R-intercept is near a half if the Pomeron intercept is near 1 and why the P-intercept is about \( \alpha_P' \sim 0.4 \text{ GeV}^{-2} \) if \( \alpha_R' \sim 0.9 \text{ GeV}^{-2} \).

A posteriori, it also strengthens the case for a predominantly 2-gluon makeup of the Pomeron.
The procedure for \( \mathbf{pp} \) and \( \mathbf{p\bar{p}} \):

- \( \chi_{\text{soft}} = \mathcal{A}_{BN}(6) \sigma_{\text{soft}} \rightarrow \sigma_0 \left( 1 + \frac{2}{\sqrt{s}} \right) \mathbf{pp} \)
- \( \chi_{\text{hard}} = \mathcal{A}_{BN}(6,5) \sigma_{\text{jet}} \)
- \( \mathcal{A}_{BN} \rightarrow \alpha_s(k_F) \left( \frac{g}{k_F^2} \right) \triangleleft \mathbf{p, \bar{p}} \)

\[ \sigma_0, p_{\text{min}}, \text{density, } \mathbf{p, \bar{p}} \]

\[ \text{soft scale parameter: } \frac{2}{3} \sum_{\nu} \frac{4\pi\alpha_s}{f_{\nu}^2} \]

\[ \left( \frac{2}{3} \sum_{\nu} \frac{4\pi\alpha_s}{f_{\nu}^2} \right)^2 \]
A good description is obtained with a soft part given by

$$\sigma_{soft}^{pp} = \sigma_0 A_{BN}^{soft}(b, s) \quad \sigma_0 = 48 \text{mb}$$

and

$$\sigma_{soft}^{p\bar{p}} = \sigma_0 (1 + \frac{2}{\sqrt{s}}) A_{BN}^{soft}(b, s)$$
\[ \Rightarrow \text{for} \quad Y \quad \Rightarrow \quad \text{needs} \]
\[ \chi_{\text{soft}} = \chi_s \times \frac{2}{3} \]

\[ \text{Gry, GRS, CJKL} \]
\[ p_{\text{tmin}} = \left\{ 1.2 \div 2 \right\} \]

\[ \Rightarrow \quad \Box \quad \Rightarrow \quad \chi_{\text{soft}} \left( \frac{2}{3} \right)^2 \frac{\chi_{pp} \chi_{pp}}{2} \]

\[ \Rightarrow \quad \text{present L3 /opal} \]
\[ \text{normalization at low energy} \]

\[ \text{Gry, GRS, CJKL} \]
\[ p_{\text{tmin}} = \left\{ 1.3 \div 2 \right\} \]
soft from pp (no pp) x scaling factor
\( \frac{2}{3} \frac{\pi}{v^2} \)
rise from minijets + resummation

- Photoproduction data before HERA
- ZEUS 96 Preliminary
- H1 94
- ZEUS 92 and 94
- ZEUS BPC 95

with BN resummation

GRV \( p_{\text{min}} = 1.4, 1.6, 1.8 \) GeV

Soft from pp soft eikonal times 2/3

April 8th, 2003
Photon 2003, Frascati

Photon Total Cross-Sections (page 14)

Giulia Pancheri
INFN Frascati National Laboratories
should $p_{t\text{min}}$ be same for all?

$\Rightarrow \gamma p \& \gamma \gamma$

cJKL 1.8 GeV

$p_{t\text{min}} \equiv \text{onset of } \mathcal{QCD}$

$\Rightarrow \text{soft with } \frac{p_{t} + \overline{p}_{t}}{2} \text{ O.K. with present data}$
Problem with this approach:

The elastic cross-section is off by 10%.

May be modelling of $A(0,s)$ needs to be improved.

- Only LO
- Abelian Approximation.
Photoproduction of a vector meson

The Amplitude $\gamma p \rightarrow V p$

\[ A(s, t)_{s \rightarrow \infty} \approx if(t) \left( -i \frac{s}{s_0} \right)^{\alpha_F(t)} \left[ \ln \left( -i \frac{s}{s_0} \right) + g(t) \right] \]

$s \equiv W^2$

\[ f(t) = (\alpha_p(t) - 1)f_1(t) + (\alpha_p(t) + 1)f_2(t) \]

EPJ direct C 4 (2002) 1

\[ f(t) = a e^{bt} + ct e^{dt} ; g(t) \equiv g. \]
The Dipole Pomeron

\[ \alpha_{IP}(t) = 1 + \gamma(\sqrt{t_0} - \sqrt{t_0 - t}) \]

\[ t_0 = 4m^2_\pi, \gamma = m_\pi/1 \text{ GeV}^2 \]

\[ \alpha_{IP}(0) = 1 \]

\[ \alpha'_{IP}(0) \approx 0.25 \text{ GeV}^{-2} \]


The cross section \( \gamma^* p \rightarrow J/\psi p \)

\[ \sigma_{tot}^{\gamma^* p \rightarrow J/\psi p} \propto \frac{1}{(1 + Q^2/M^2_{J/\psi})^n}, \]

\( n \approx 1.75 \) ZEUS Eur. Phys. J. C 6, 603 (1999),


\[ \frac{d\sigma}{dt} = 4\pi \left( 1 + \frac{Q^2}{M^2_{J/\psi}} \right)^{-\beta} \left[ a e^{bt} + c t e^{dt} \right]^2 \left( \frac{s}{s_0} \right)^{2\alpha_{IP}(t)-2} \times \left( \ln \left( \frac{s}{s_0} \right) + g \left[ 1 + Q^2/(Q^2 + M^2_{J/\psi}) \right]^{\gamma} \right)^2 + \frac{\pi^2}{4} \]

\( J/\psi \) and \( \phi(1020) \rightarrow \) only the Pomeron exchange.
The slope of differential cross section of $\bar{p}p$ scattering.

$$B(W) = \frac{d}{dt} \left( \ln \frac{d\sigma}{dt} \right)$$
Differential cross section of exclusive $J/\psi$ photoproduction for $100 \leq W \leq 140$ GeV.
As a result one obtains the sum rule of the following form

\[ \frac{1}{3} \left[ 4 \left( r_{1He^3}^2 \right) - \left( r_{1H^3}^2 \right) \right] - \frac{\mu^2_{He^3}}{4M^2_{He^3}} + \frac{\mu^2_{H^3}}{4M^2_{H^3}} = \]

\[ = \frac{1}{2\pi^2\alpha} \int_{\omega_{th}}^{\infty} \frac{d\omega}{\omega} \left[ \sigma_{tot}^{He^3 \to X}(\omega) - \sigma_{tot}^{H^3 \to X}(\omega) \right] \]  

(15)

**Conclusions**

Starting from:

- very high-energy elastic and inelastic electron nucleon (or electron-trinucleon) scattering with a production of a hadronic state X moving closely to the direction of initial hadron

- utilizing analytic properties of the forward Compton scattering amplitude on nucleons (or trinucleons)

- then for the case of small transferred momenta one can derive new sum rules relating Dirac radii and anomalous magnetic moments of the considered objects to the integral over a difference of the total proton and neutron (or $He^3$ and $H^3$) photoproduction cross-sections
\[
\frac{1}{3} \langle r_{1p}^2 \rangle - \frac{\mu_p^2}{4M_p^2} + \frac{\mu_n^2}{4M_n^2} = \frac{1}{2\pi^2 \alpha} \int_{\omega_N}^{\infty} \frac{d\omega}{\omega} \left[ \sigma_{\gamma p \rightarrow X}^{\gamma p \rightarrow X}(\omega) - \sigma_{\gamma n \rightarrow X}^{\gamma n \rightarrow X}(\omega) \right]
\] (14)

with \( \omega_N = m_\pi + m_\pi^2 / 2M_N \), in which just a mutual cancellation of the rise of these total proton and neutron photoproduction cross-sections for \( \omega \rightarrow \infty \), created by the Pomeron exchanges, is achieved.

Here we would like to note, that the sum rule following from (11) by a derivation of both sides according to \( Q^2 \) and an application of the relation (6), is the known Gottfried sum rule \(^1\)

\[ K. Gottfried, Phys. Rev. Lett. 18 (1967) 1174 \]

under the assumption that one neglects a contribution of \( LCC_p \).
The Gottfried sum rule, however, suffers from a divergence of the corresponding integral due to the well known rise of the total proton photoproduction cross-section at high energies created by the Pomeron exchanges at the competent amplitude.

If we consider instead of the proton and neutron, \( He^3 \) and \( H^3 \), which belong to the same isodoublet with spin 1/2; then all previous procedure can be repeated with the latter nuclei.

\(^1\) We would like to thank S.Gerasimov for giving us this reference
Potential Models result; BBL approach with input from $\Upsilon$ decay data;
Lattice evaluation of $G_1$ and $F_1$ factors; Singlet picture with $G_1$
obtained from $\Upsilon \to e^+ e^-$ and $\Upsilon \to LH$ processes respectively.
The last point refers to a $\mathcal{O}(\alpha_s^2)$ correction to the decay rate.
Conclusions

- The $\Gamma(\eta_b \rightarrow \gamma\gamma)$ decay width prediction of potential models considered gives the value:
  
  $$466 \pm 101 \text{ eV}$$

- This result is in agreement with the naive estimate from the $Y$ decay.

- Prediction of the BBL procedure are consistent with the potential model results, for both the long distance terms $G_1$ and $F_1$ extracted from the $Y$ experimental decay widths and the one evaluated from lattice calculations.

- The results from the singlet picture are also consistent with the potential model results.
Talking of virtual $\pi^0$:

**effective parton density in annelacm** 

$\left( e^{i \pi^0 \cdot p_\perp}\right)$

a small comment:

$$f_{p_{1/2}}(x, q^2) = \int \frac{dx}{y} \left[ \frac{p_{\text{max}}^2}{p_{\text{min}}^2} \int \frac{dp^2}{p^2} f_{p_{1/2}}(x, q^2) \right]$$

1. $P^2$ dependence of the flux factor as well as densities in photon

2. $q^2 > P^2$: concept of partons in $\sigma'$ to make sense

3. We had made a simple model for $P^2$ dependence of $f_{p_{1/2}}(x, q^2, P^2)$.

Drees, Godbole (PRD, 94)

Sheffield 95
Transversity measurement at HERMES

Delia Hasch
on behalf of the HERMES collaboration

INFN Frascati

International Conference on the Structure and Interactions of the Photon
April 7-11, 2003; LNF-INFN, Frascati, Italy

- how to measure transversity in sidis
- target-spin + beam-spin azimuthal asymmetries
- outlook
transversity

how to measure in SIDIS

→ chiral odd
→ observed only in combination with another chiral odd structure:

\[ \sigma^{lH \rightarrow lhX} = \sum_q f^{H \rightarrow q} \otimes \sigma^{lq \rightarrow lq} \otimes D^{q \rightarrow h} \]

↓
chiral-odd DF

↓
chiral-odd FF

→ interference fragmentation: \( ep^\uparrow \rightarrow e'\pi\pi X \)

→ final state polarisation:
  spin-1/2 (\( \Lambda \)) fragmentation: \( ep^\uparrow \rightarrow e'\Lambda^\uparrow X \)

→ Collins effect:

\[ A_T = \langle \sin \phi \rangle_{UT} \propto h_1(x) \otimes H_1^\perp(z, k_T) \]

... azimuthal asymmetries
target single-spin azimuthal asymmetry

\[
S_T = |S| \sin \theta_\gamma \approx |S| \frac{2Mx}{Q^2} \sqrt{1 - y} \sim 0.15
\]

\[
A(\phi)_{UL} = \frac{1}{\langle P \rangle} \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}
\]

\[
\langle x \rangle = 0.09, \langle y \rangle = 0.57, \langle z \rangle = 0.48, \langle P_\perp \rangle = 0.44, \langle Q^2 \rangle = 2.4 \text{ GeV}^2
\]
**Remarks on Model Calculations**

\[ \sin \phi \text{ moments from proton + deuteron targets well described by various model calculations based on Collins effect } \sim h_1 \otimes H_1^\perp \]

**BUT**

\[ \Rightarrow \text{ @ longitudinally polarised target: } S_T \text{ w.r.t. } \gamma^* \propto 1/Q \]

\[ A_{UL}^{\sin \phi} \sim \text{ twist-3: } h_L H_1^{(1)} \text{ contribution } \approx 75\% \leftarrow \text{ opposite sign} \]

\[ \text{while } h_1 H_1^{(1)} \text{ contribution } \approx 25\% \checkmark \quad [\text{K. Oganessyan}, \text{Efremov, Goeke, Schweitzer}] \]

\[ \Rightarrow \text{ SSA from final state interaction (gluon exchange)} \]

\[ \equiv \text{ Sivers effect } \sim f_{1T}^\perp \otimes D_1 \]

\[ \cdots \text{ Collins + Sivers effect show different dependence on } \alpha \]

---

[Diagram of polarization and scattering process]
transversely polarised target

\[ A_{UT}(\Phi) = \frac{1}{(P_t)} \cdot \frac{N^+(\Phi) - N^-(\Phi)}{N^+(\Phi) + N^-(\Phi)} \]

\[ \Phi = \phi + \phi_s \]

\[ \Phi = \phi - \phi_s \]

\[ \cdots [\text{Collins type}] \]

\[ \cdots [\text{Sivers type}] \]

\[ \circ \circ \circ \text{HERMES measurements in 2002++} \]
summary & outlook

single-target + single-beam spin azimuthal asymmetries measured in $\pi(K)$ electroproduction with longitudinally polarised target and beam

$A_{UL}^{\sin \phi}$ well described by model calculations based on Collins effect

$\Rightarrow$ non-ambiguous measurement of transversity will be possible with transversely polarised target:

$\rightarrow$ HERMES run-II 2002++

mapping transversity:

sidis: $ep^\uparrow \rightarrow \pi X$  Hermes, Compass, JLab
annihilation: $e^+e^- \rightarrow \pi\pi X$  Delphi, Belle
inclusive pion: $p^\uparrow p \rightarrow \pi X$  E704, RHIC
Drell Yan: $p^\uparrow p^\uparrow \rightarrow llX$  RHIC (after lumi upgrade)
Charge asymmetry in

\[ \gamma\gamma \rightarrow \mu^+\mu^- \quad W^\pm \mu^\mp + \text{neutrals} \]

with polarized photons

D.A. Anipko, M. Cannoni,
I.F. Ginzburg, O. Panella, A.V. Pak,

Sobolev Institute of Mathematics &
Novosibirsk State University,
Novosibirsk, Russia,
Perugia University, Perugia, Italy

Two series of observable phenomena:
- The difference in distributions of \( \mu^+ / \mu^- \) (e.g. in \( \gamma\gamma \rightarrow W^+\mu^-+\text{neutrals} / \gamma\gamma \rightarrow W^-\mu^++\text{neutrals} \)).
- The violation of symmetry in distributions of \( \mu^+ \) and \( \mu^- \) in \( \gamma\gamma \rightarrow \mu^+\mu^-+\text{neutrals} \) in each event

(smaller cross sections).

At Photon Colliders high energy photons will be prepared mainly in the states with definite helicity \( \lambda_i \approx \pm 1 \).
For oral discussion, we distinguish the initial states with \( \lambda_1, \lambda_2 = \pm 1 \).
Double resonant.  
3 diagrams,  
\[ \sigma_d \sim \frac{\alpha^2}{M_W^2} \text{Br}^2(W \rightarrow \mu\nu) \]  
- numerically 70%.

Single resonant 1.  
\[ \gamma_1 \leftrightarrow \gamma_2, \mu^+ \leftrightarrow \mu^- \rightarrow 4 \text{ diagrams}, \]
\[ \sigma_{s1} \sim \frac{\alpha^3}{M_W^2} \text{Br}(W \rightarrow \mu\nu) \]  
- numerically 30%.

Single resonant 2.  
2 basic diagrams \( \times \mu^+ \leftrightarrow \mu^- \rightarrow 4 \) diagrams,  
\[ \sigma_{s2} \sim \frac{\alpha^3}{s} \text{Br}(W \rightarrow \mu\nu) \]  
- small.

Z pole.  
2 basic diagrams with 3 points for Z in each  
- 6 diagrams,  
\[ \sigma_Z \sim \frac{\alpha^3}{s} \text{Br}(Z \rightarrow \nu\bar{\nu}) \]  
- small.

Nonresonant.  
\[ \gamma_1 \leftrightarrow \gamma_2 \rightarrow 2 \text{ diagrams}, \]
\[ \sigma_n \sim \frac{\alpha^4}{M_W^2} \]  
- small.
Momentum distributions of negative (left) and positive (right) muons

Initial photon state --

Initial photon state ++

Initial photon state --+

Qualitative interpretation

Main contribution is given by double resonant process with W's flying forward.
In this case helicities of W± coincide with those of initial photons.
W⁻ decay: muons fly opposite to W spin
W⁺ decay: muons fly along W spin.

Comment: CP conservation.
Formalism: production/decay vertices.

Process we calculate

\[ \mathcal{V}_{t\bar{t}\phi} = -ie \frac{m_t}{M_W} (S_t + i\gamma^5 P_t), \]
\[ \mathcal{V}_{\gamma\gamma\phi} = \frac{i\sqrt{s}\alpha}{4\pi} \left[ S_\gamma(s) \left( \epsilon_1 \cdot \epsilon_2 - \frac{2}{s}(\epsilon_1 \cdot k_2)(\epsilon_2 \cdot k_1) \right) 
- P_\gamma(s) \frac{2}{s} \epsilon_{\mu\nu\alpha\beta} \epsilon_1^\mu \epsilon_2^\nu k_1^\alpha k_2^\beta \right] \]

- \( k_1 \) and \( k_2 \) are the four-momenta of colliding photons \( \epsilon_{1,2} \) are photon polarisation vectors.

- \( S_t, P_t \): real constants \( S_\gamma, P_\gamma \) complex form factors.

- Simultaneous presence of \( P_t \) and \( S_t \) and/or \( S_\gamma \) and \( P_\gamma \) implies CP violation.
Asymmetries:

For defining asymmetries, we choose two polarised cross-section at a time out of four available, and can define six asymmetries as,

\[
\begin{align*}
A_1 &= \frac{\sigma(++,\sigma(-,-)}{\sigma(++,\sigma(-,-) + \sigma(+-,-)} \\
A_2 &= \frac{\sigma(+-,-)}{\sigma(++,\sigma(-,-) + \sigma(+-,-)} \\
A_3 &= \frac{\sigma(++,\sigma(-,-)}{\sigma(++,\sigma(-,-) + \sigma(+-,-)} \\
A_4 &= \frac{\sigma(++,\sigma(-,-)}{\sigma(++,\sigma(-,-) + \sigma(+-,-)} \\
A_5 &= \frac{\sigma(++,\sigma(+,-)}{\sigma(++,\sigma(+,-) + \sigma(-,-)} \\
A_6 &= \frac{\sigma(++,\sigma(+,-)}{\sigma(++,\sigma(+,-) + \sigma(-,-)}
\end{align*}
\]

- the \( \sigma' \) s are calculated with a cut off on the lepton angle \( \theta_0 \), to be optimised to increase sensitivity to \( CP \) violating couplings.

\( \triangleright \) \( A_1 \) and \( A_2 \) are purely \( CP \) violating.

\( \triangleright \) \( A_3 \) and \( A_4 \) are polarisation asymmetries for a given lepton charge.

\( \triangleright \) \( A_5 \) and \( A_6 \) are charge asymmetries for a given polarisation. Will be zero if \( \theta_0 \rightarrow 0 \).

- Only three of these asymmetries are linearly independent of each other.
New method for calculating helicity amplitudes of jet–like QED processes

Valeri G. Serbo
Novosibirsk State University, Novosibirsk, Russia

Based on papers
C. Carimalo, A. Schiller, V.G. Serbo

European Physical Journal
C 23 (2002) 633-649

and hep-ph/0303257
Jet-like processes

These reactions have the form of a two-jet process with the exchange of a virtual photon γ* in the t-channel:

\[ \rho_1 \rightarrow M_1 \rightarrow \rho_i \rightarrow \text{jet}_1 \]

\[ \rho_2 \rightarrow M_2 \rightarrow \rho_i \rightarrow \text{jet}_2 \]

Fig. 1

The subject of our consideration is the jet-like process of Fig. 1 at high energy

\[ s = 2p_1p_2 = 4E_1E_2 \gg m_i^2 \]  \hspace{1cm} (1)

for arbitrary helicities of leptons \( \lambda_i = \pm 1/2 \) and photons \( \Lambda_i = \pm 1 \).

The emission and scattering angles \( \theta_i \) are:

\[ \frac{m_i}{E_i} \lesssim \theta_i \ll 1, \quad m_i \lesssim |p_{i\perp}| \ll E_i \]  \hspace{1cm} (2)
The form of “the final result”

At high energies the region of scattering angles (2) gives the dominant contribution to the cross sections of all QED jet–like processes. In this region we obtain all helicity amplitudes with high accuracy, omitting only terms of the order of

$$\frac{m_i^2}{E_i^2}, \quad \theta_i^2, \quad \theta_i \cdot \frac{m_i}{E_i}$$

or smaller.

The amplitude $M_{fi}$ has a simple factorized form

$$M_{fi} = \frac{s}{q^2} J_1 J_2$$

where the impact factors $J_1$ and $J_2$ do not depend on $s$.

We give analytical expressions for $J_1$ and $J_2$. 
They are not only **compact** but are also very **convenient** for numerical calculations, since **large compensating terms** are already canceled.

It is well known that this problem of **large compensating terms** is very difficult to manage in all computer packages like **CompHEP**.

The discussed approximation **differs considerably** from the known approach of the **CALCUL** group and others (in which terms of the order of $m_i/|p_{i\perp}|$ are neglected).
Vertices instead of spinor lines

Let us consider a virtual electron in the amplitude $M_1$ with $p = (E, p)$, $E > 0$ and virtuality $p^2 - m^2$. Due to jet kinematics, $|p^2 - m^2| \ll E^2$. We introduce an artificial energy

$$E_p = \sqrt{m^2 + p^2}$$

and the bispinors $u_p^{(\lambda)}$ and $v_p^{(\lambda)}$ corresponding to a real electron and a real positron with 3-momentum $p$ and energy $E_p$. In the high-energy limit

$$\frac{E - E_p}{E + E_p} = \frac{p^2 - m^2}{(E + E_p)^2} \approx \frac{p^2 - m^2}{4E^2}. \quad (22)$$

There is an exact identity:

$$\hat{p} + m = \frac{E + E_p}{2E_p} u_p^{(\lambda)} u_p^{(\lambda)} + \frac{E - E_p}{2E_p} v_p^{(\lambda)} v_p^{(\lambda)} \quad (23)$$

or

$$\hat{p} + m \approx u_\lambda^{(\lambda)} \bar{u}_p^{(\lambda)} + \frac{p^2 - m^2}{4E^2} v_p^{(\lambda)} \bar{v}_p^{(\lambda)}. \quad (24)$$
Test of non-commutative QED

in $e^+ e^- \rightarrow \gamma \gamma$ at LEP

Tatsuo Kawamoto
University of Tokyo, OPAL

10. April 2003
Photon 2003

• What is NCQED ?
• NCQED in $e^+ e^- \rightarrow \gamma \gamma$
• What we (don’t) see in the OPAL data
Non-commutative geometry

\[ [x_\mu, x_\nu] = i\theta_{\mu\nu} \]

- \( \theta_{\mu\nu} \): antisymmetric, constant, frame independent \( \sim \text{length}^2 = 1/\text{energy}^2 \sim 1/\Lambda^2 \).
  Analog of Planck constant \( h \) in ordinary Quantum Mechanics. \( [x_\mu, p_\nu] = i\hbar \delta_{\mu\nu} \)

- In string theory, noncommutative geometry may arise through quantisation of string in the presence of background fields. (Connes, Douglas, Schwarz, Seiberg, Witten, ...)

- \( \Lambda \) is perhaps \( \sim \) the Planck scale.

- \( \Lambda \) might be at TeV scale \( \Leftarrow \) large extra dimension, D-brane, ... : TeV scale gravity

- Possible experimental signatures?
Non-commutative QED

Non-commutative quantum field theory is not well known.

Non-commutative QED exists (NCQED). Renormalizable, U(1) gauge symmetry, ...

- $e e \gamma$ vertex contains a kinematic phase: $e^{i \frac{1}{2} p^\mu \theta_{\mu \nu} p^\nu}$
  Dependence on momenta and $\theta_{\mu \nu}$.
  $\rightarrow$ Unique direction.
  Violation of Lorentz invariance.

- Nonabelian-like $3\gamma, 4\gamma$ self couplings,
  also dependent on $p^\mu \theta_{\mu \nu} p^\nu$

- Relevant high energy processes:
  $\gamma e \rightarrow \gamma e, \gamma \gamma \rightarrow \gamma \gamma, e^+ e^- \rightarrow \gamma \gamma, ...$

- Low energy experiments:
  limits from Lamb shift, Aharonov-Bohm effect, clock comparisons, ...
\[ e^+ e^- \rightarrow \gamma \gamma \] in NCQED

\[ e^+ e^- \rightarrow \gamma \gamma \] is sensitive only to \( \theta_{0i} = \frac{1}{\Lambda_{NC}^2} c_{0i} \) \( (i = 1, 3) \)

**space-time noncommutativity.**

\( c_{0i} : \) Unit space vector pointing to the 'unique direction'

\( \Lambda_{NC} : \) Energy scale of non-commutativity

**Differential cross-section for** \( e^+ e^- \rightarrow \gamma \gamma \) **(in the c.m. frame of** \( e^+ e^- \) **collision):**

\[
\frac{d\sigma}{d \cos \theta d\phi} = \frac{\alpha^2}{s} \frac{1 + \cos^2 \theta}{1 - \cos^2 \theta} (1 - \sin^2 \theta \sin^2 \Delta_{NC})
\]

\[ \Delta_{NC} = \frac{s}{4 \Lambda_{NC}^2} (c_{01} \sin \theta \cos \phi + c_{02} \sin \theta \sin \phi + c_{03} \cos \theta) \]

Dependence on \( \phi \) as well as \( \theta \).
**OPAL data**

**OPAL $e^+e^- \rightarrow \gamma\gamma$ sample**

- $\sqrt{s} = 181 - 209$ GeV
- Collected in 1997-2000
- $L = 672$ pb$^{-1}$
- 5235 events $|\cos \theta| < 0.93$

\[
\frac{d\sigma}{d \cos \theta d\phi}(\Lambda, \eta, \xi; \zeta = \omega t)
\]

Consider 3 cross-sections

- $\frac{d\sigma}{d \cos \theta}$: $\phi$ integrated, time averaged
- $\frac{d\sigma}{d\phi}$: $\cos \theta$ integrated, time averaged
- $\sigma(t)$: $\cos \theta$ integrated (0.0-0.6), $\phi$ integrated
Time averaged, $\cos \theta$ integrated $\phi$ distribution

$\phi$ structure, depending on $\eta$
Amplitude depends on $\Lambda$
Introduction

Non-perturbative hadronic effects in electroweak precision observables, main effect via effective fine structure "constant" $\alpha(E)$

(charge screening by vacuum polarization)

Of particular interest:

$$\alpha(M_Z) \text{ and } a_\mu \equiv (g - 2)_\mu / 2$$

- electroweak effects (leptons etc.) calculable in perturbation theory
- strong interaction effects (hadrons/quarks etc.) perturbation theory fails

$$\Rightarrow \text{ Dispersion integrals over } e^+e^-\text{--data}$$

encoded in

$$R_\gamma(s) \equiv \frac{\sigma(e^+e^-\rightarrow \gamma^*\rightarrow \text{hadrons})}{\sigma(e^+e^-\rightarrow \gamma^*\rightarrow \mu^+\mu^-)}$$

Errors of data $\Rightarrow$ theoretical uncertainties !!!

The art of getting precise results from non-precision measurements !

New challenge for precision experiments on $\sigma(e^+e^- \rightarrow \text{hadrons})$ KLOE, BABAR, ....

(S. Müller's next talk)
\( a_\mu \) Summary: experiment vs. theory

- CERN (79)
- KNY (85)
- E821 (98)
- E821 (99)
- E821 (00)
- World
- E821 (01)
- E821 goal

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EJ 95 ((e^+e^-))</td>
<td>181.3 ± 16.0</td>
</tr>
<tr>
<td>DEHZ 03 ((e^+e^-))</td>
<td>169.3 ± 07.8</td>
</tr>
<tr>
<td>DEHZ02 (\tau)</td>
<td>193.6 ± 06.9</td>
</tr>
<tr>
<td>FJ 02 ((e^+e^-))</td>
<td>168.3 ± 09.3</td>
</tr>
<tr>
<td>HMNT02 ((e^+e^-))</td>
<td>166.9 ± 07.4</td>
</tr>
<tr>
<td>NAR03 ((e^+e^- + S\gamma))</td>
<td>179.9 ± 11.1</td>
</tr>
<tr>
<td>NAR03 (\tau + S\gamma)</td>
<td>202.3 ± 11.3</td>
</tr>
</tbody>
</table>

\((a_\mu -11659000)\times 10^{-10}\)

Given theory results only differ by \(a_\mu^{\text{had}(1)}\)!
Contributions to
\[ \tilde{\alpha}_\mu^{\text{had}} = \alpha_\mu^{\text{had}} \times 10^{10} \]
from exclusive channels

Theoretical work with the aim
to calculate radiative corrections
at the level of precision as indicated
in the Table is in progress.

\[ \downarrow \]
\[ \delta\alpha_\mu^{\text{had}} \lesssim 26 \times 10^{-11} \]
from
\[ \sqrt{s} \lesssim 2 \text{ GeV}. \]

<table>
<thead>
<tr>
<th>channel</th>
<th>( \tilde{\alpha}_\mu^{\text{had}} )</th>
<th>acc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho, \omega \rightarrow \pi^+\pi^- )</td>
<td>506</td>
<td>0.3%</td>
</tr>
<tr>
<td>( \omega \rightarrow 3\pi )</td>
<td>47</td>
<td>( \sim 1% )</td>
</tr>
<tr>
<td>( \phi )</td>
<td>40</td>
<td>( \downarrow )</td>
</tr>
<tr>
<td>( \pi^+\pi^-\pi^0\pi^0 )</td>
<td>24</td>
<td>( \downarrow )</td>
</tr>
<tr>
<td>( \pi^+\pi^-\pi^+\pi^- )</td>
<td>14</td>
<td>( \downarrow )</td>
</tr>
<tr>
<td>( \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0 )</td>
<td>5</td>
<td>10%</td>
</tr>
<tr>
<td>( 3\pi )</td>
<td>4</td>
<td>( \downarrow )</td>
</tr>
<tr>
<td>( K^+K^- )</td>
<td>4</td>
<td>( \downarrow )</td>
</tr>
<tr>
<td>( K_SK_L )</td>
<td>1</td>
<td>( \downarrow )</td>
</tr>
<tr>
<td>( \pi^+\pi^-\pi^+\pi^-\pi^0 )</td>
<td>1.8</td>
<td>( \downarrow )</td>
</tr>
<tr>
<td>( \pi^+\pi^-\pi^+\pi^-\pi^- )</td>
<td>0.5</td>
<td>( \downarrow )</td>
</tr>
<tr>
<td>( pp )</td>
<td>0.2</td>
<td>( \downarrow )</td>
</tr>
<tr>
<td>( 2 \text{ GeV} \leq E \leq M_{J/\psi} )</td>
<td>22</td>
<td>( \downarrow )</td>
</tr>
<tr>
<td>( M_{J/\psi} \leq E \leq M_T )</td>
<td>20</td>
<td>( \downarrow )</td>
</tr>
<tr>
<td>( M_T &lt; E )</td>
<td>( \lesssim 5 )</td>
<td>( \downarrow )</td>
</tr>
</tbody>
</table>
Hadronic effects in $(g - 2)_\mu$ and $\alpha(M_Z)$ – theoretical uncertainties

- Needs for linear collider (like TESLA): requires $\sigma_{\text{had}}$ at 1% level up to the $\gamma \rightarrow \delta \alpha(M_Z)/\alpha(M_Z) \sim 5 \times 10^{-5}$. At present would allow to get better Higgs boson mass limits.

- Future precision physics requires dedicated effort on $\sigma_{\text{had}}$ experimentally as well as theoretically (radiative corrections, final state radiation from hadrons etc.)

Maximum confusion! Likely only new experiments can settle the problems

Photon tagging experiments at KLOE, BARAR

---

---
Photon structure function reach at a photon collider

\[ 6 \cdot 10^{-5} < x \]
\[ Q^2 < 10^5 \text{ GeV}^2 \]

Also information from jets, charm
The precise measurement of the 2-photon width of the Higgs is very important. It is affected by all charged particles that can occur in the loop.

⇒ Very sensitive to new physics

\[ \gamma \stackrel{t,W}{\longrightarrow} H \stackrel{b, \text{Landau-Yang}}{\longrightarrow} \bar{b} \]

QCD \( bb \) in \( \gamma \gamma \) suppression: V. Khoze, ...

Measure \[ \Gamma(h \rightarrow \gamma \gamma) = \frac{[\Gamma(h \rightarrow \gamma \gamma)BR(h \rightarrow b\bar{b})]}{[BR(h \rightarrow b\bar{b})]} \]

Note: \( BR(h \rightarrow bb) \) measured to 1-2%

Example: 2HDM SM-like versus SM (Ginzburg, Krawczyk, Osland)
SM Higgs Analysis

- New detailed analyses for Light SM Higgs
  - Realistic photon spectra
  - NLO QCD backgrounds (Jikia)
  - B-tagging via ZVTOP
  - Mass corrected for neutrinos
  - Overlap events (~1 per B.C.)
- 2 independent analyses

$$\frac{\Delta \Gamma(h \to \gamma\gamma)BR(h \to bb)}{\Gamma(h \to \gamma\gamma)BR(h \to bb)} \approx 1.6-1.9\%$$

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>120</th>
<th>130</th>
<th>140</th>
<th>150</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \frac{\sigma}{\sigma}$ (%)</td>
<td>1.8</td>
<td>1.9</td>
<td>2.2</td>
<td>3.0</td>
<td>6.8</td>
</tr>
</tbody>
</table>
For illustration purposes use a specific MSSM prediction for the form factors of the scalar (Askawa et al):

\[
\begin{align*}
m_\phi &= 500\text{GeV}, & \Gamma_\phi &= 1.9\text{GeV}, \\
S_i &= 0.33, & P_i &= 0.15, \\
S_\gamma &= -1.3 - 1.2i, & P_\gamma &= -0.51 + 1.1i.
\end{align*}
\]

Choose the MSSM point given above, calculate \( x_i, y_j \) for that choice of CP violating parameters.

Find regions in the \( x_i, y_j \) planes around this point outside which measurements of asymmetries can test the hypothesis of this being the correct model.

Do the same for the SM meaning \( x_i, y_j = 0 \) in our parametrisation.

The asymmetries have sensitivity to loop induced CP violation in the Higgs sector of the MSSM.

---

R. Godbole et al.
hep-ph/021136 & LCWS02

Exciting possibility to analyse CP structure of the scalar

Construct combined asymmetries from initial lepton polarization and decay lepton charge

Done with Compton spectra
Using COMPANZ reduces sensitivity with factor 2

Needs detector simulation
**Extra Dimensions**

ADD type extra dimensions

Sensitivity to mass $M_s$

γγ → tt

Realism reduces sensitivity: $M_s = 1.7$ TeV to 1.4 TeV

- $\lambda = -1, \sqrt{s_{ee}} = 500$ GeV
- SM + 2σ
- SM - 2σ

Ideal Compton spectrum

COMPAZ spectrum
Non-commutative theories

Breakdown in QED due to preferred direction in space: azimuthal effects

Pair-Production ($\gamma\gamma$):
- space-time non-commutivity

Compton-Process ($e\gamma$):
- space-space and space-time non-commutivity

$\Lambda_{\text{NC}}$ sensitivity similar to Bhabha process but different combination of NC matrix elements tested

$p_T > 10$ GeV, $10^\circ < \theta < 170^\circ$, $L = 500$ fb$^{-1}$