Photon-Photon Physics
A brief survey

The study of light has resulted in achievements of insight, imagination and ingenuity unsurpassed in any field of mental activity; it illustrates, too, better than any other branch of physics, the Vicissitudes of theories (Sir J.J. Thomson, 1925).

Photon and its hadronic interaction

Maria Krawczyk[a]

[a]Institute of Theoretical Physics, Warsaw University,

Nuclear Physics B (Proc. Suppl.) 126 (2004) 3–4

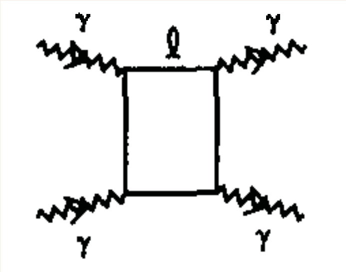
Remarkable Idea: Scatter Light on Light

Light-by-Light Scattering $(s_{\gamma\gamma} \ll 4m_\ell^2)$:

$\sigma(\gamma\gamma \to \gamma\gamma) \sim \frac{\alpha^4 s^3}{m_\ell^8}$ from QED box graph.

Derive from Dimension-8 Euler-Heisenberg Effective Lagrangian

$$\mathcal{L}_{\mathcal{EH}} \sim \frac{\alpha^2 F_{\mu\nu}^4}{m_\ell^4}$$



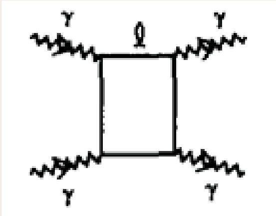
Extremely small rate in optical regime

Serbo et al.

Tested in g-2 of electron and muon

Aldins, Dufner, Kinoshita, SJB

Photon-Photon Scattering in QED



Subthreshold Light-by-Light Scattering
$(s_{\gamma\gamma} \ll 4m_\ell^2)$:

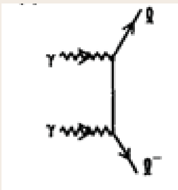
$$\sigma(\gamma\gamma \to \gamma\gamma) \sim \frac{\alpha^4 s^3}{m_\ell^8}$$ from QED box graph.

Resonant Light-by-Light Scattering
$(s_{\gamma\gamma} = 4m_\ell^2 - 4m\epsilon_n)$

$$\sigma(\gamma\gamma \to [\ell^+\ell^-]_n \to \gamma\gamma) \sim \frac{\Gamma_n^2}{(s-M_n^2)^2+M_n^2\Gamma_n^2}$$

$C = +$ states:
positronium $[e^+e^-]$, true muonium $[\mu^+\mu^-]$,
true tauonium $[\tau^+\tau^-]$

Threshold Domain Small relative velocity v
$(s_{\gamma\gamma} \simeq 4m_\ell^2)$:



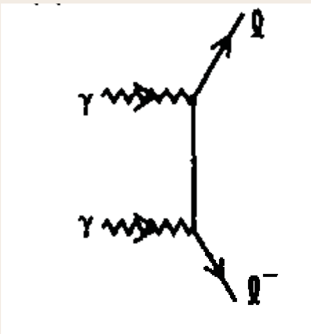
$$\sigma(\gamma\gamma \to \ell^+\ell^-) \sim \frac{\pi\alpha^2 v}{m_\ell^2} \times [1 + \frac{\pi\alpha}{v}]$$

Sommerfeld-Schwinger domain – analytically connected to Bohr spectrum

Bjorken

Photon-Photon Scattering in QED

Single pair production $(s_{\gamma\gamma} \gg 4m_\ell^2)$:

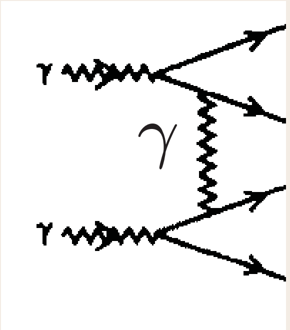


$$\sigma(\gamma\gamma \to \ell^+\ell^-) \sim \frac{\pi\alpha^2}{s} \log \frac{s}{m_\ell^2}$$

spin-$\frac{1}{2}$ exchange

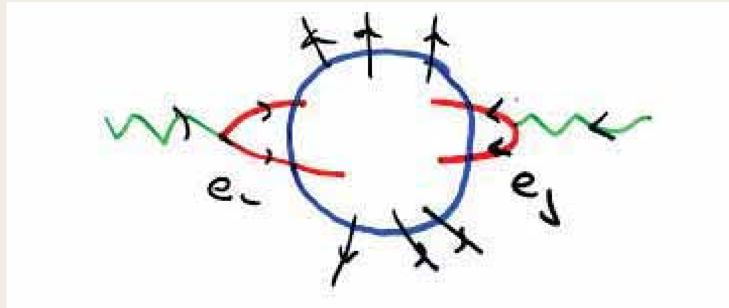
First observed at Novosibirsk, Frascati

Double pair production $(s_{\gamma\gamma} \gg 16m_\ell^2)$:



$$\sigma(\gamma\gamma \to \ell^+\ell^-\ell^+\ell^-) \sim \frac{\alpha^4}{m_\ell^2}$$

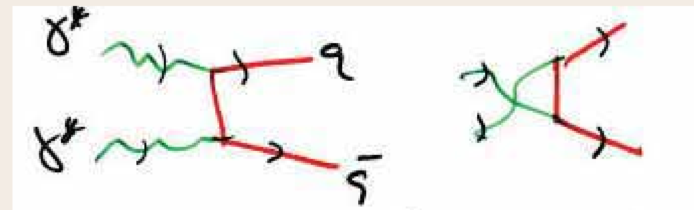
spin-1 exchange



Features of $\gamma\gamma$ Collisions

- Collisions of gauge fields

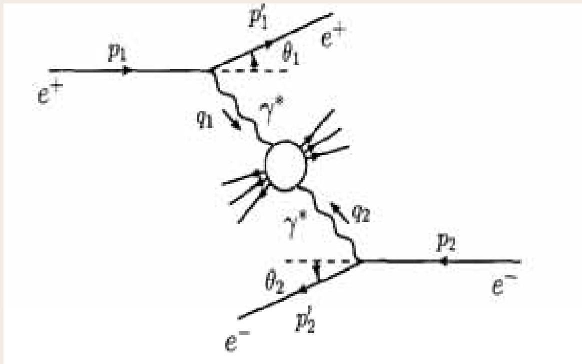
- Direct coupling to fundamental currents

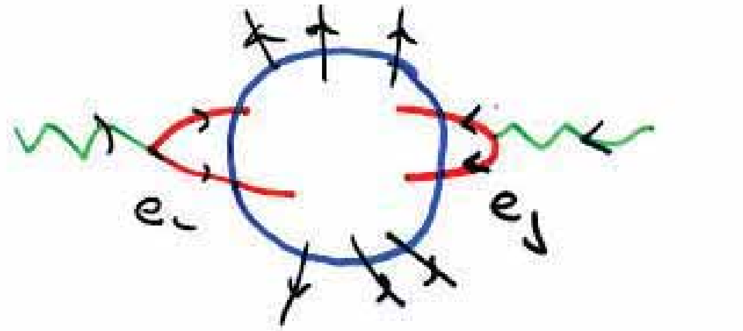


- Window to full spectrum of $C = +$ hadronic states

- No restriction on J^P

- Analog of meson-meson collisions

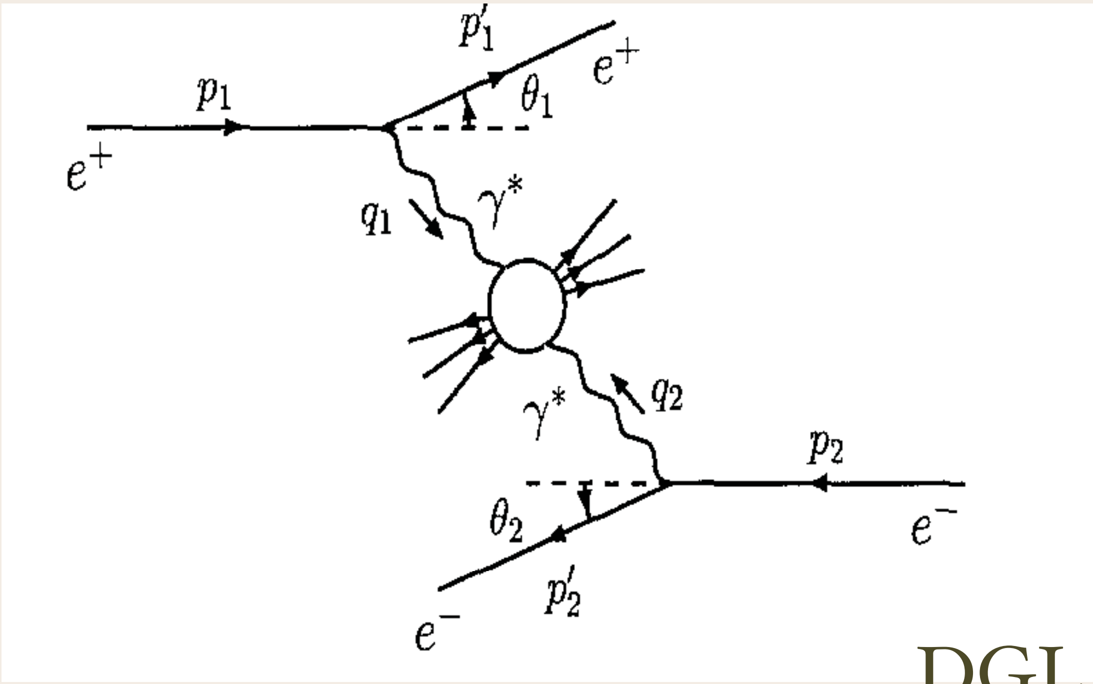




- Measure in double-tagged electron-positron collisions $e^+e^- \to e^+e^-X$

- $\sigma(\gamma^*\gamma^* \to X)(s, q_1^2, q_2^2)$

- Vary photon energy, virtuality, and polarization: longitudinal, transverse, linear (controlled by electron scattering plane)



DGLAP kernel

Two-Photon Collisions from Double Equivalent Photon Approximation

Photon-Photon Fusion: Remarkable laboratory for testing QCD

- C = + Resonances
- Heavy Quarkonium
- Photon-to-Meson Transition Form Factors
- Exclusive Two-Photon Reactions
- Timelike Compton Reactions
- Hard QCD Jets
- Photon Structure Function
- Nature of Pomeron and Odderon

γγ → Resonances

Discovery tool for Gluonium

$S = \frac{\Gamma_{gg}}{\Gamma_{\gamma\gamma}}$ "stickiness"

Chanowitz

CLEO: upper limit for Γ

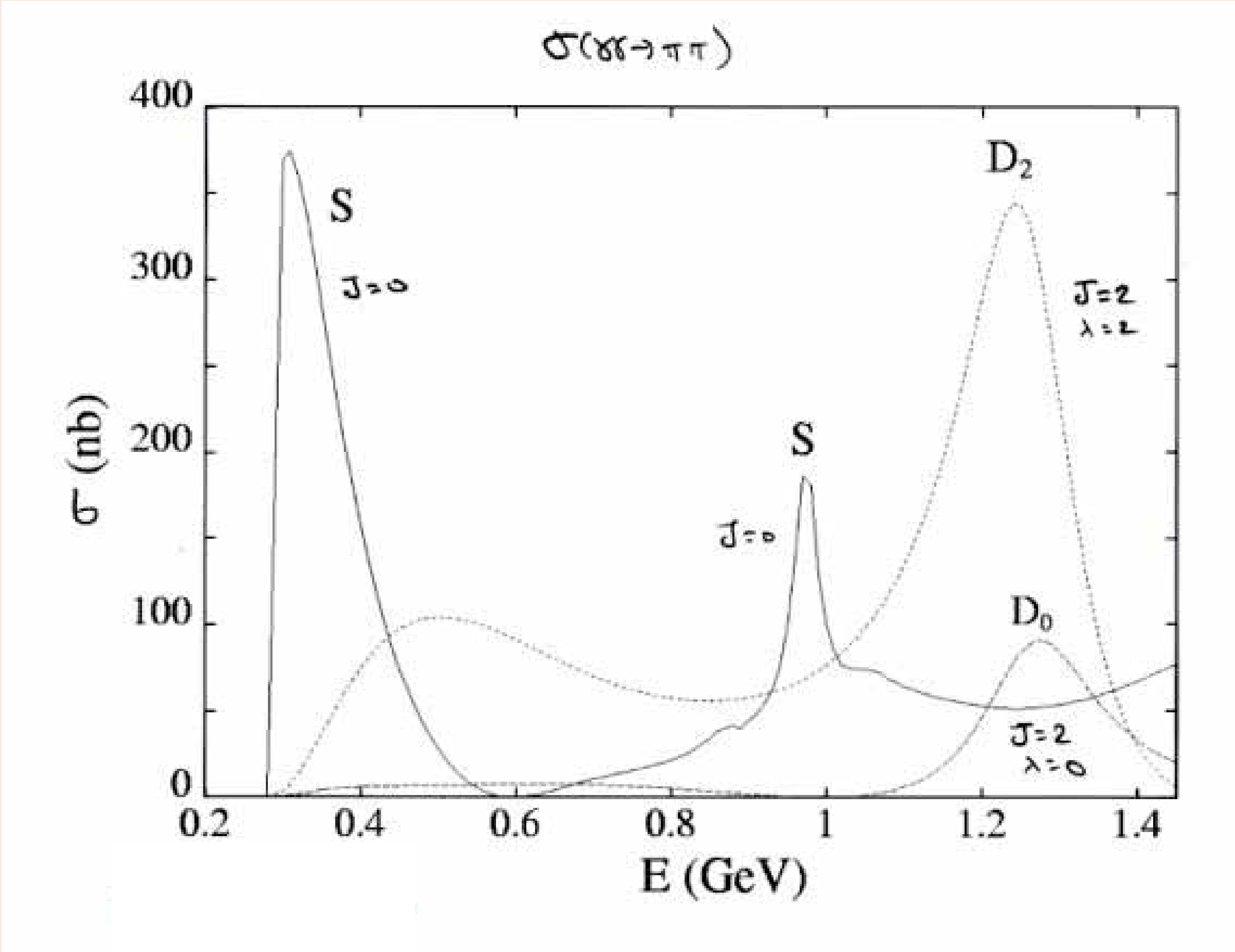
Sivertz
Poor

$\gamma\gamma \to f_0(2220)$

$\hookrightarrow K_s K_s$

$S > 82$ (95% c.l.) !

also: $J/\psi\,\gamma$
MARK III
BES



Roglioni, Pennington

Discovery of $\eta_c(2^1S_0)$ — The radial excitation of the singlet $|c\bar{c}>_{g.s.}$

- The $\eta_c(2^1S_0)$ or η_c' is known to be bound, somewhere below the triplet state $\psi(2^3S_1)$ or ψ' which has a mass of 3686.11 ± 0.03 MeV.
- In 1982 the Crystal Ball reported observation of a weak, 91 ± 5 MeV transition in the inclusive photon spectrum from the decay of $\psi(2S)$, and claimed [2] $M(\eta_c') = 3594 \pm 5$ MeV.
- Several subsequent attempts, $p\bar{p}$ (E760[3]/E835[4]), $\gamma\gamma$ fusion, (DELPHI[5], L3[6]), inclusive photon (CLEO[7]), to find η_c' were unsuccessful.

  Prior to 2002 all editions of PDG dropped η_c' from their meson summary.
- Most potential model calculations predicted $M(\eta_c') = 3594 - 3626$ MeV.

  So, where is η_c'?

The Discovery of $\eta_c'(2^1S_0)$

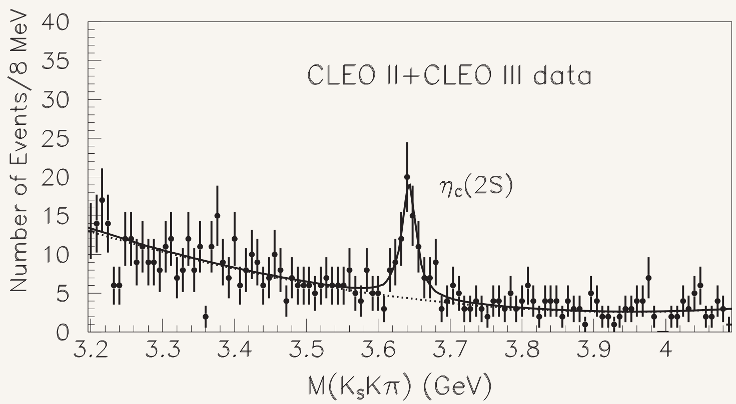
The breakthrough came, of all the places, from the observation of η_c' in B decays by Belle. It was followed by its observation in $\gamma\gamma$ fusion at CLEO and BaBar.

(in MeV)	$M(\eta_c'(2S))$	$\Gamma(\eta_c'(2S))$	events (reaction)
Belle(2002) [8]	3654 ± 10	< 55	39 ± 11 $(B \to K(K_S K \pi))$
CLEO(2004) [9]	$\mathbf{3642.9 \pm 3.4}$	$\mathbf{6.3 \pm 14.1}$	$\mathbf{61 \pm 15}$ $(\gamma\gamma \to K_S K \pi)$
BaBar(2004) [10]	3630.8 ± 3.5	17.0 ± 8.7	112 ± 24 $(\gamma\gamma \to K_S K \pi)$
BaBar(2005) [11]	3645.0 ± 5.5	22 ± 14	121 ± 27 $(e^+e^- \to J/\psi(c\bar{c}))$
Belle(2005)* [12]	3636 ± 9		311 ± 42 $(e^+e^- \to J/\psi(c\bar{c}))$

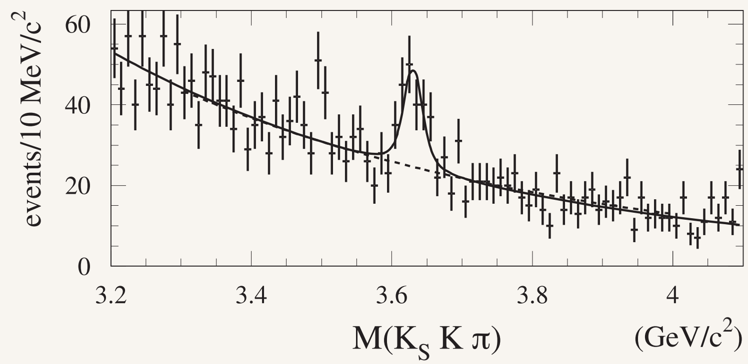
*Both η_c and χ_{c0} masses in this measurement were obtained ~ 10 MeV lower than their known values. With apologies I have therefore arbitrarily increased the η_c' mass reported by Belle by 10 MeV in the above table.

- New measurements are being made, but $M(\eta_c')$ is still not firmly anchored. The present weighted average is $M(\eta_c') = 3638.7 \pm 2.0$ MeV.
- This leads to the hyperfine splitting
  $\Delta M_{hf}(2S) = 3686.1 - 3638.7 = 47.4 \pm 2.0$ MeV.
  Recall that, **$\Delta M_{hf}(1S) = 3097 - 2980 = 117 \pm 1$ MeV.**
  Explaining this large difference is a challenge for theorists.
- Width of η_c' is essentially unmeasured so far.
- **LOTS REMAINS TO BE DONE ABOUT $\eta_c'(2^1S_0)$.**

The Discovery of $\eta_c'(2^1S_0)$



CLEO II+III: 27 fb^{-1} ($\gamma\gamma \to K_S K \pi$)



BaBar: 86 fb^{-1} ($\gamma\gamma \to K_S K \pi$)

Z(3931) observed in two photon fusion

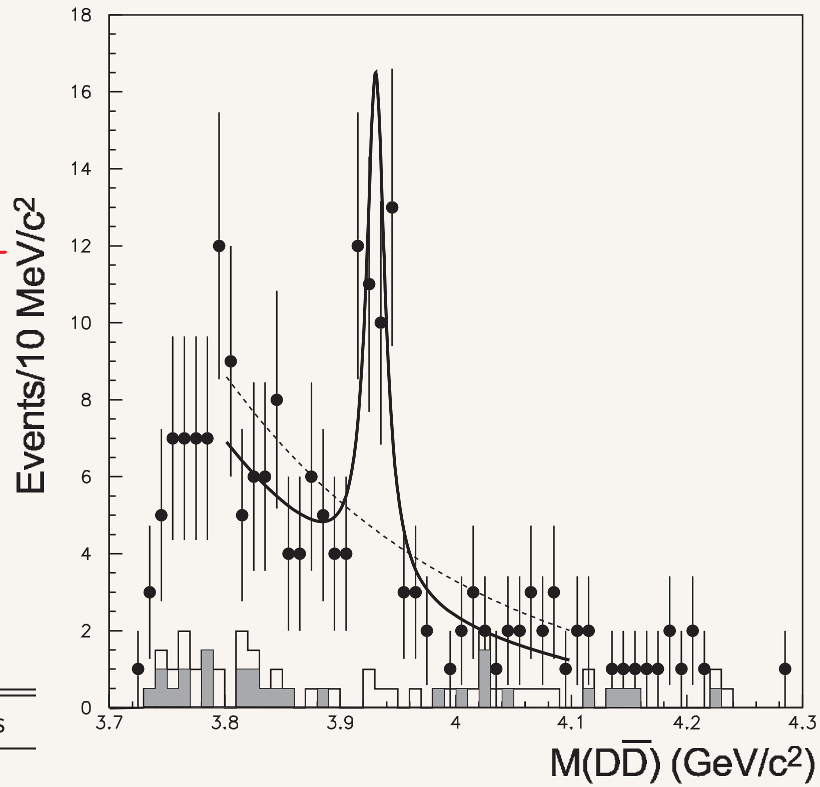
$$e^+e^- \to e^+e^-(\gamma\gamma),\ \gamma\gamma \to D\bar{D}$$

M(Z)=$3931 \pm 4 \pm 2$ MeV, significance=5.5σ

Γ(Z)=$20 \pm 8 \pm 3$ MeV

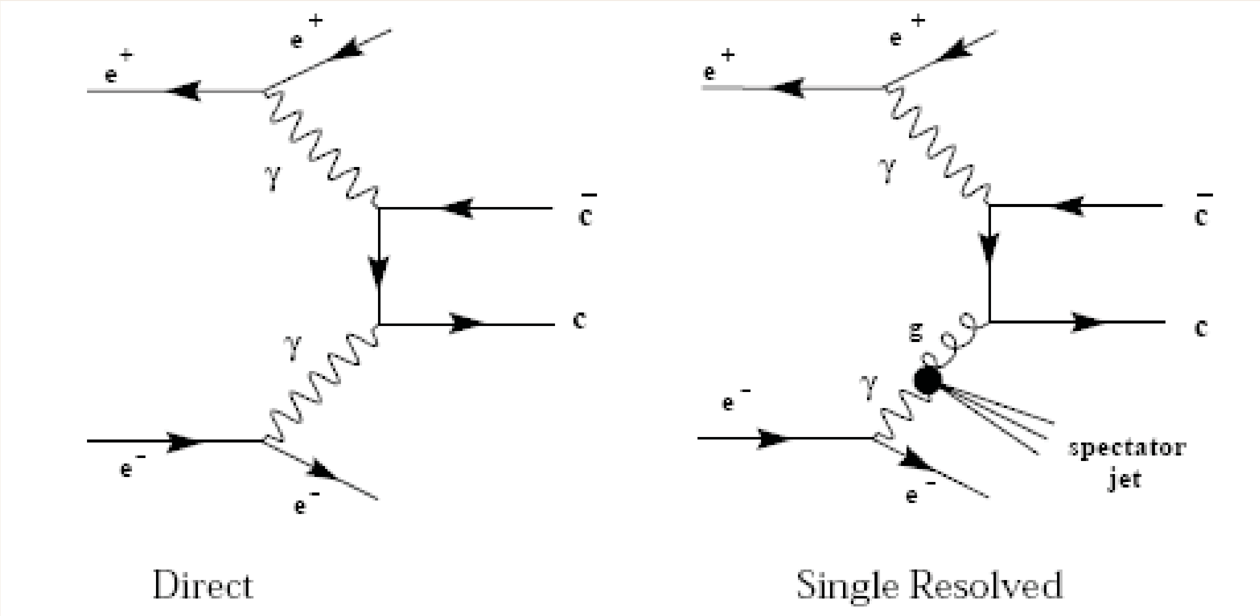
$\Gamma_{\gamma\gamma} \times \mathcal{B}(\to D\bar{D}) = 0.23 \pm 0.06 \pm 0.04$ keV

Candidate for charmonium state $\chi_2'(2^3P_2)$.



	M(MeV)	Γ(MeV)	Formed in	Decays in	not in	suggests
X	$3943 \pm 6 \pm 6$	15 ± 10	$e^+e^- \to J/\psi(c\bar{c})$	$D^*\overline{D}$	$D\overline{D}$, $\omega J/\psi$	?
Y	$3943 \pm 11 \pm 13$	87 ± 22	$B \to K(\omega J/\psi)$	$\omega J/\psi$	$D^*\overline{D}(?)$	$c\bar{c}$ hybrid?
Z	$3931 \pm 4 \pm 2$	$20 \pm 8 \pm 3$	$\gamma\gamma$ fusion	$D\overline{D}$		$\chi'_{c2}(2^3P_2)$

Inclusive Charm Production



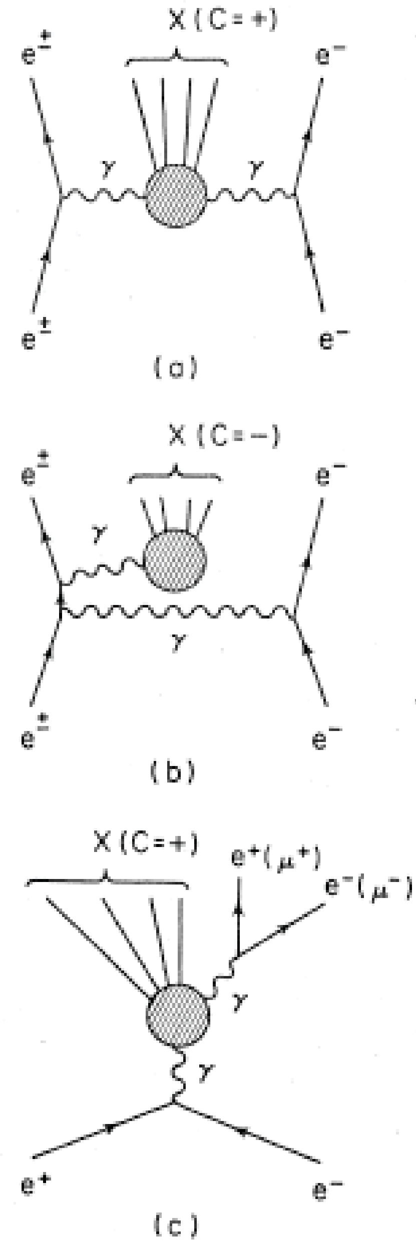


FIG. 1. The three types of diagrams which contribute to the production process $e^{\pm}+e^{-}\to e^{\pm}+e^{-}+X$ in $e^{\pm}e^{-}$ colliding-beam experiments. The product states have positive charge conjugation ($C=+$) in processes (a) and (c) and negative charge conjugation in process (b). In the case of $e^{-}e^{-}$ collisions, there is another diagram in which the two final electron lines in (a) are exchanged.

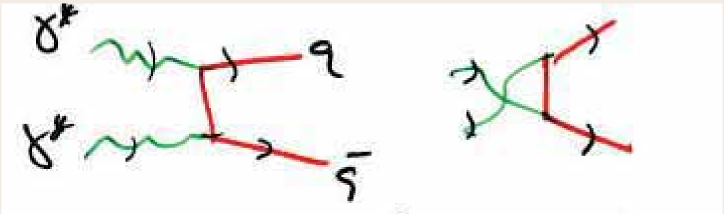
Photon-Photon Collisions

$\gamma\gamma$ **Processes**

- Direct coupling of real photons to high p_t jets

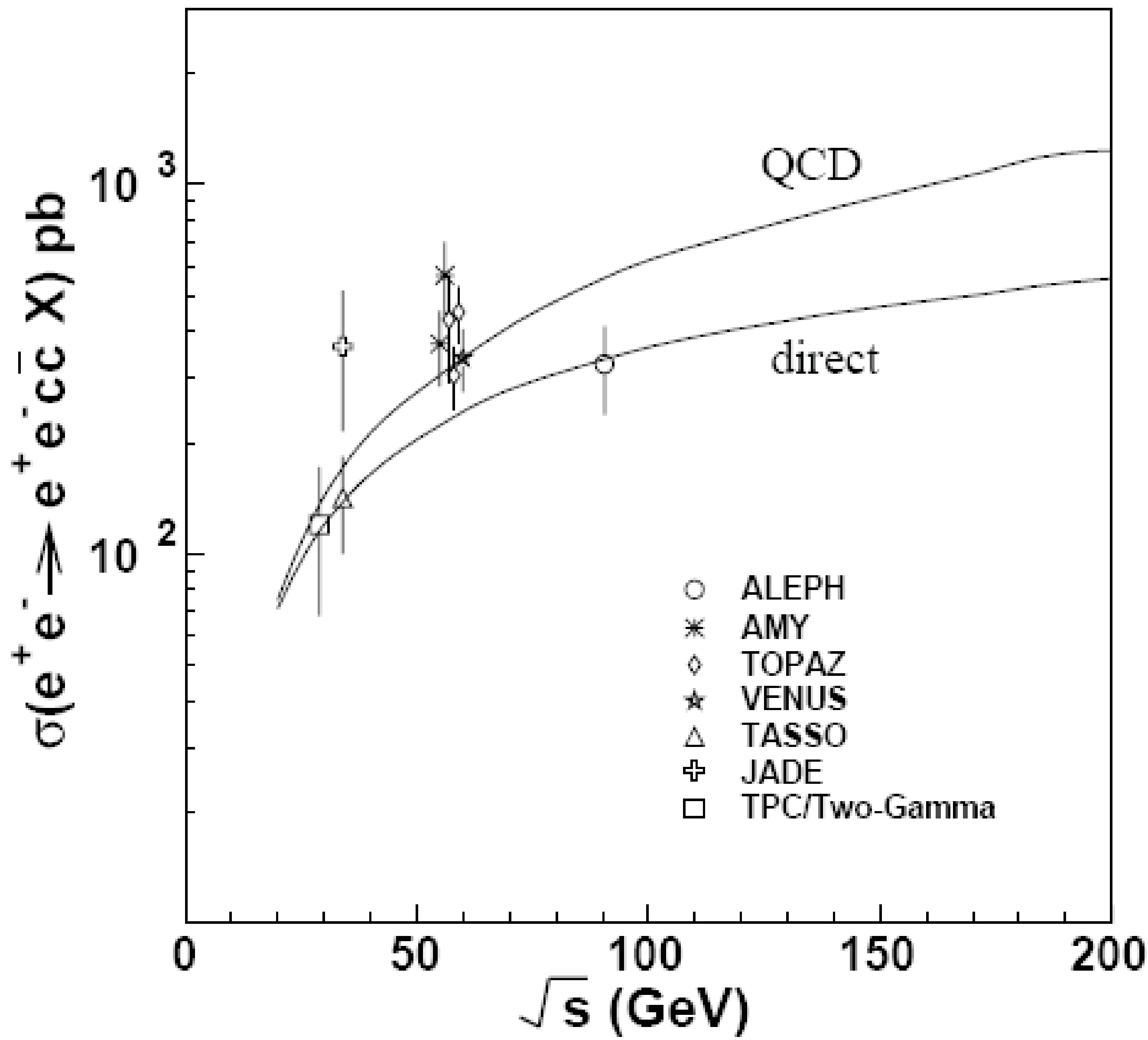
$$\sigma(\gamma\gamma \to q\bar{q}) \sim \frac{\pi\alpha^2}{p_T^2}$$

$$R_{\gamma\gamma} = \frac{\sigma(\gamma\gamma\to q\bar{q})}{\sigma(\gamma\gamma\to\mu^+\bar{\mu}^-)} = N_C \times \sum_q e_q^4$$



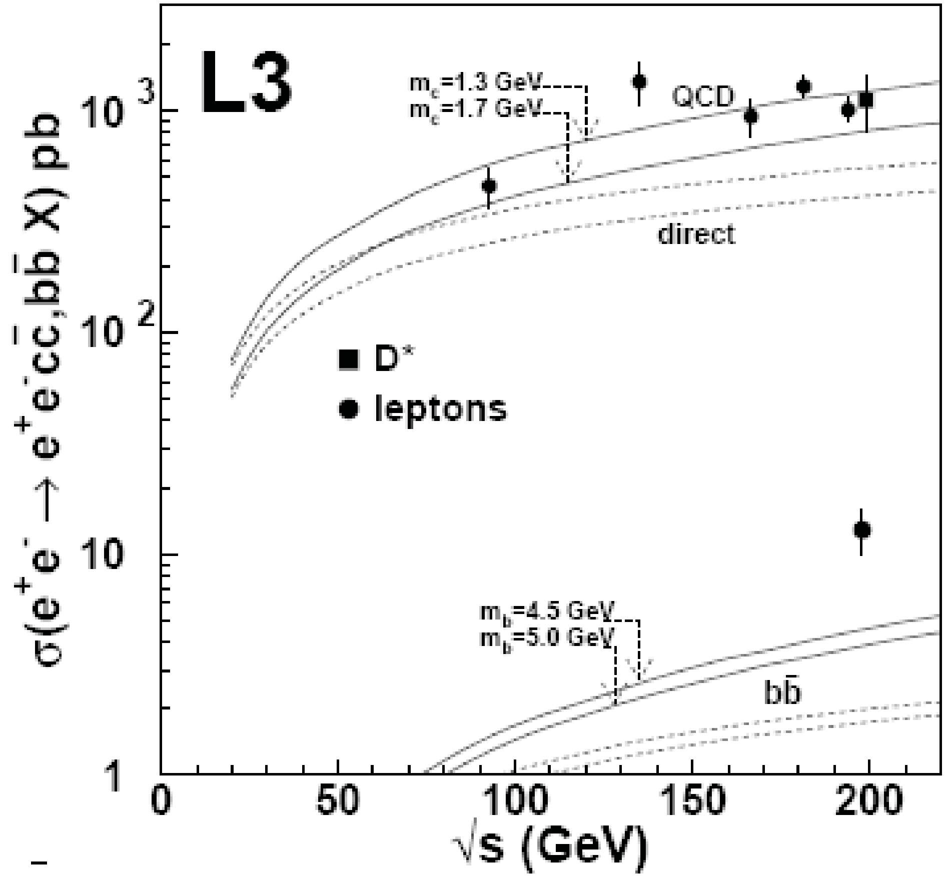
Inclusive Charm Production

A.L. Stone

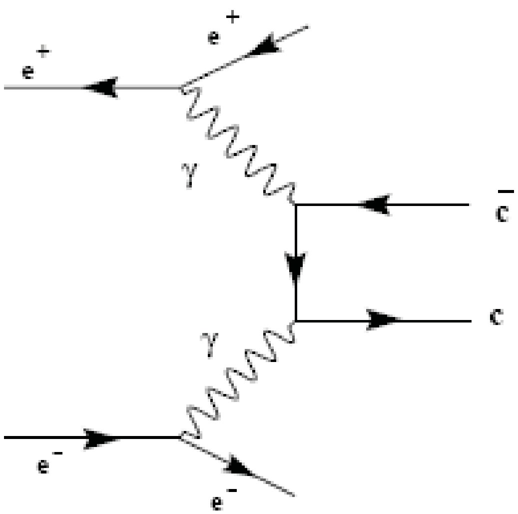


MEASUREMENT OF THE CROSS SECTION FOR OPEN-BEAUTY PRODUCTION IN PHOTON-PHOTON COLLISIONS AT LEP.
By L3 Collaboration (P. Achard *et al.*). CERN-PH-EP-2005-007, Feb 2005. 16pp.
Published in **Phys.Lett.B619:71-81,2005**
e-Print Archive: **hep-ex/0507041**

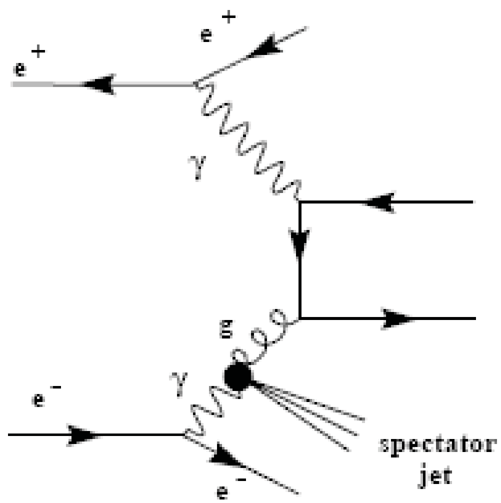
Open Bottom and Charm Production L3



TWO PHOTON PROCESSES AT VERY HIGH-ENERGIES.
By J.A.M. Vermaseren (NIKHEF, Amsterdam),. NIKHEF-H/82-15, Jul 1982. 44pp.
Published in **Nucl.Phys.B229:347,1983**



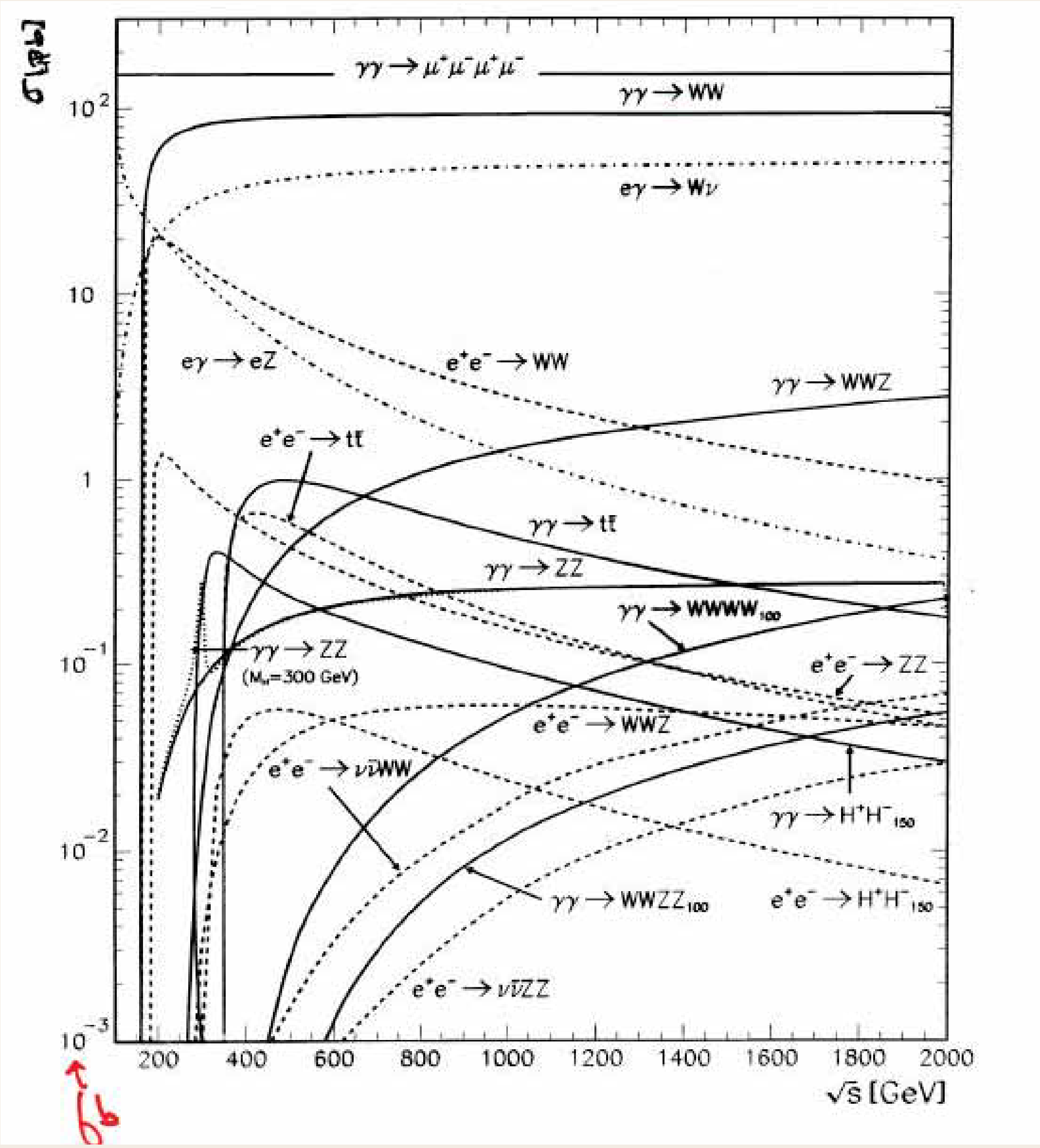
Direct

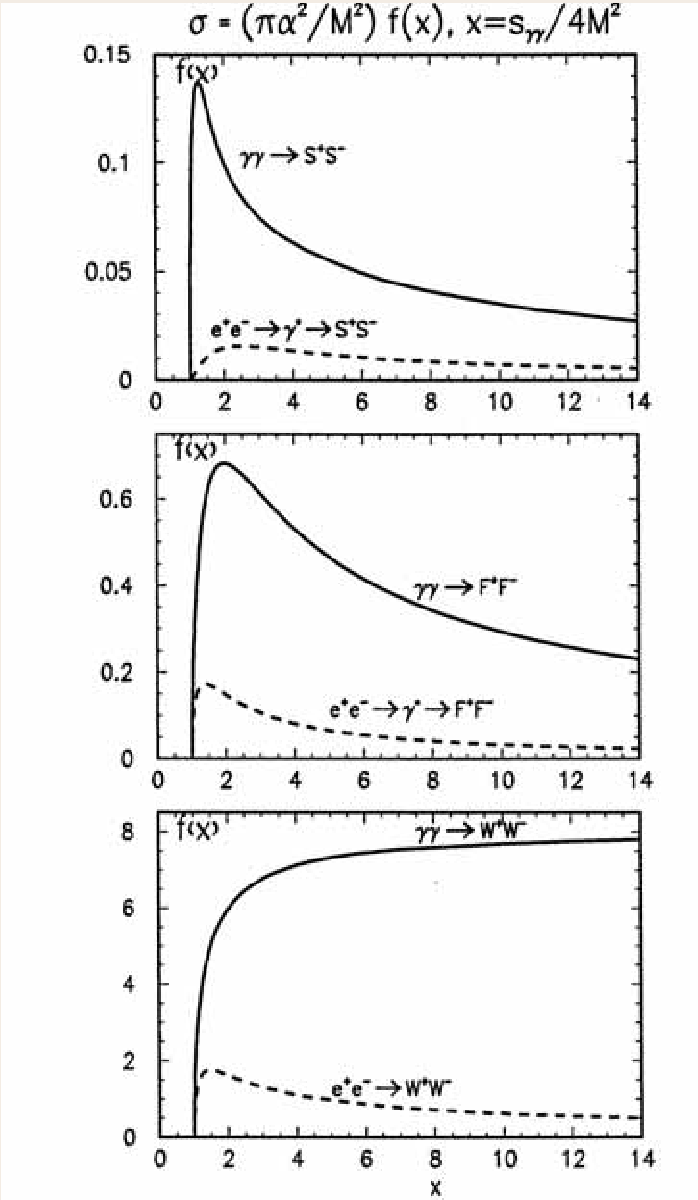


Single Resolved

• Typical cross sections measureable in $\gamma\gamma, e\gamma, ee$ collisions

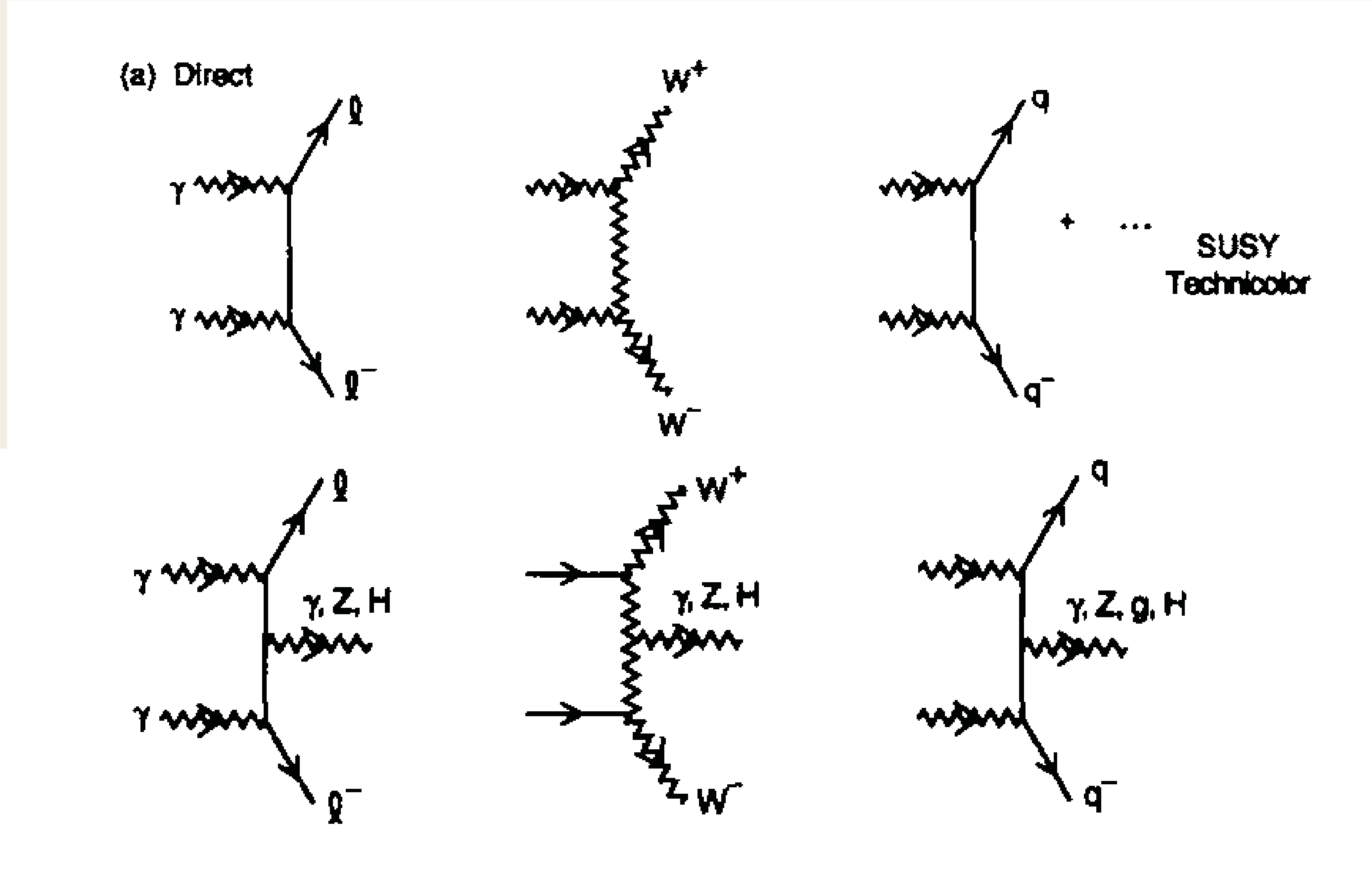
Ref: E. Boos, et al., hep/ph-1003090



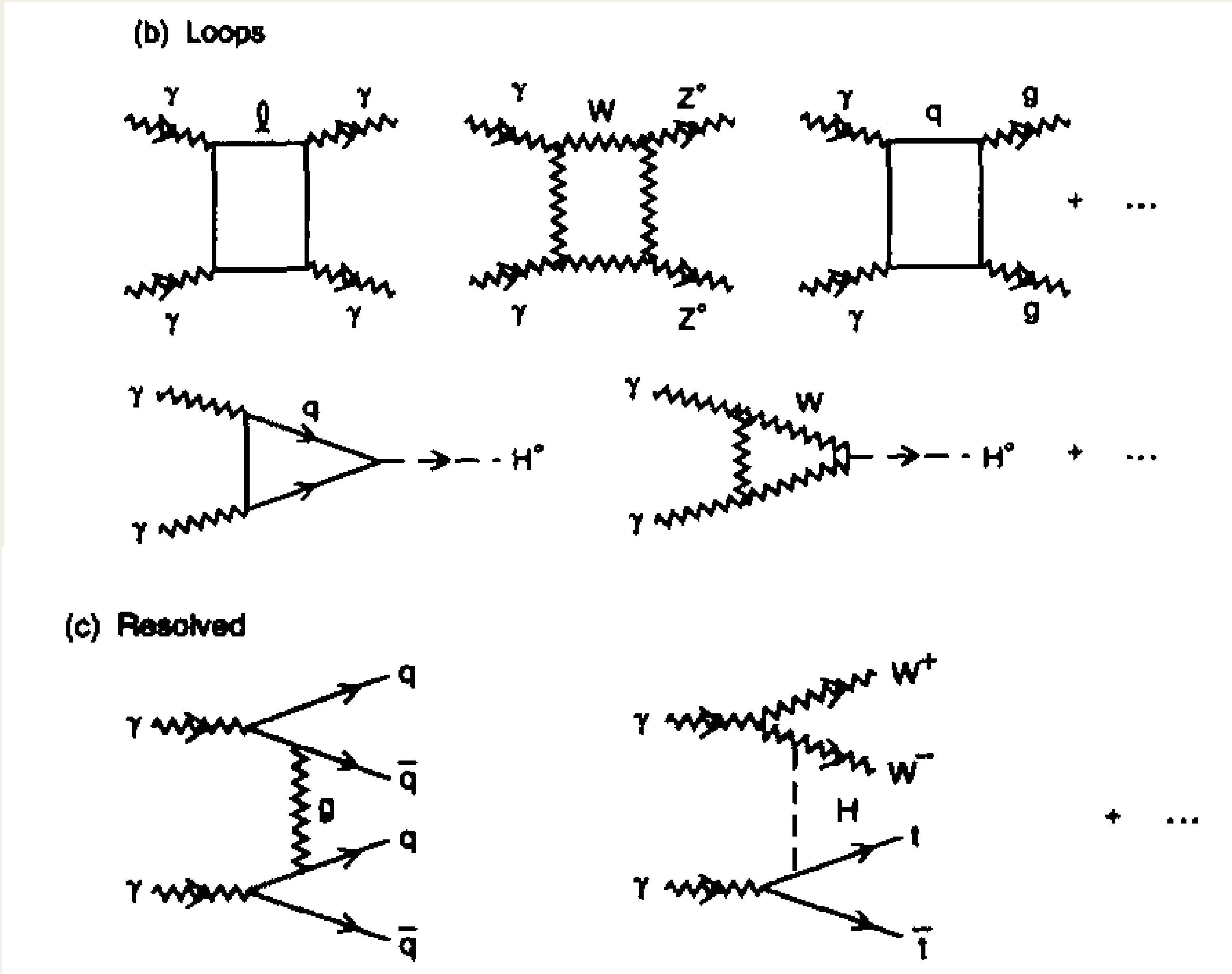


Comparison between cross sections for charged pair production in unpolarized e^+e^- and $\gamma\gamma$ collisions. S (scalars), F (fermions), W (W bosons); $\sqrt{s}$ is the invariant mass (c.m.s. energy of colliding beams). The contribution of the Z^0 boson to the production of S and F in e^+e^- collisions was not included. From Boos *et al.*

Two-Photon Collisions in the Standard Model

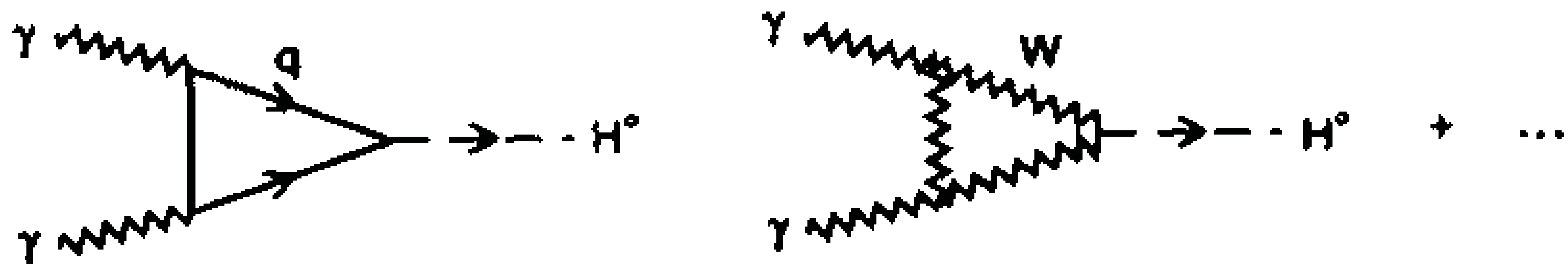


Illustrations of High-Energy Two-Photon Collisions in the Standard Model

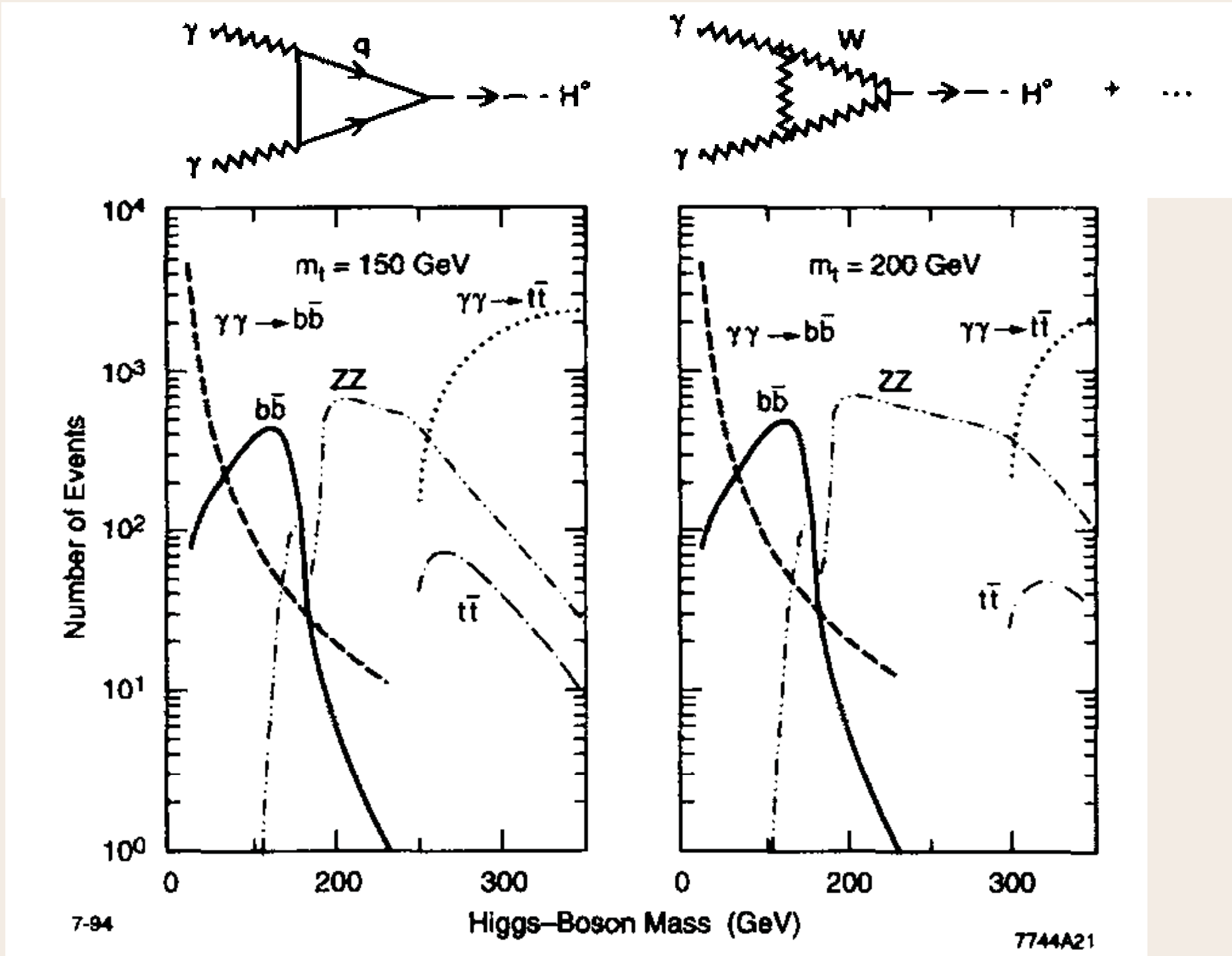


Higgs Production at a Photon Collider

$$\sigma(\gamma\gamma \to \mathrm{H}) = \frac{8\pi^2}{m_\mathrm{H}} \Gamma(\mathrm{H} \to \gamma\gamma) \frac{m_\mathrm{H}\Gamma_{\mathrm{tot}}/\pi}{(s - m_\mathrm{H}^2)^2 + (m_\mathrm{H}\Gamma_{\mathrm{tot}})^2}$$



P.M. Zerwas and SJB



Higgs Production at a Photon Collider

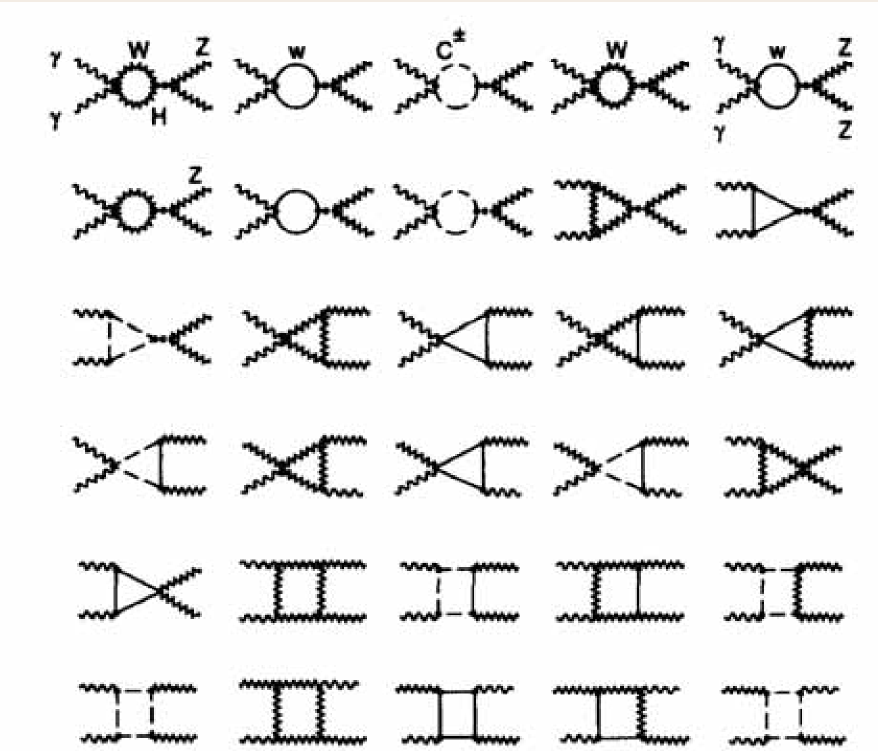
Number of Events per year for $\gamma\gamma \to H$ for various final states and QCD backgrounds

Backscattered laser bea

$\sqrt{s_{ee}} = 500$ GeV

$\mathcal{L}_{eff} = 20 nb^{-1}$

J.F. Gunion and H.E. Haber, Phys. Rev. D 48 (1993) 5109.



Standard Model contributions to the reaction

$$\gamma\gamma \to Z^0 Z^0$$

including ghost c^* and scalar w contributions in the nonlinear background gauge.

G. Jikia, Nucl. Phys. B 405 (1993) 24;

Early History of Photon-Photon Collisions

- Surprisingly large $e^+ e^-$ hadronic cross sections observed at CEA by BOLD detector in 1969, increasing with cm energy.
- Speculations by Richter on new hadronic physics of electron!
- Kinoshita and SJB at Cornell Faculty Club 1969
- Cross section for $e^+ e^- \to e^+ e^- X$ logarithmically increasing with electron-positron energy
- BOLD detector did not measure final state energy.
- Maybe Two-Photon Collisions

Hadron Production by Electron-Positron Annihilation at 4-GeV Center-of-Mass Energy*

A. Litke,† G. Hanson, A. Hofmann, J. Koch, L. Law, M. E. Law, J. Leong, R. Little, R. Madaras, H. Newman, J. M. Paterson, R. Pordes, K. Strauch, G. Tarnopolsky, and Richard Wilson

Harvard University, Cambridge, Massachusetts 02138, Cambridge Electron Accelerator, Cambridge, Massachusetts 02138, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, Southeastern Massachusetts University, North Dartmouth, Massachusetts 02747, and Technion–Israel Institute of Technology, Haifa, Israel

(Received 13 April 1973)

We have measured the total cross section for electron-positron annihilation into three or more hadrons, with at least two charged particles in the final state. The measurement was made at a center-of-mass energy of 4 GeV with a 2π-sr nonmagnetic detector. With 88 events detected, we obtain a model-independent lower limit on the hadron production cross section of 9.6 ± 1.4 nb; a calculation of detection efficiency based on invariant phase-space production of pions leads to a total cross section of 26 ± 6 nb. This cross section is 4.7 ± 1.1 times the theoretical total cross section for $e^+e^- \to \mu^+\mu^-$. The average charged multiplicity is $\bar{n} = 4.2 \pm 0.6$.

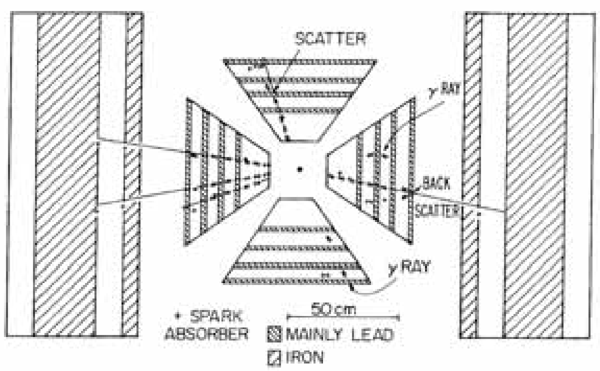


FIG. 1. A view along the beam line of a five-prong event in BOLD. Clearly seen are a backward scatter, a large-angle scatter, a γ conversion, and particles stopping in the iron absorber.

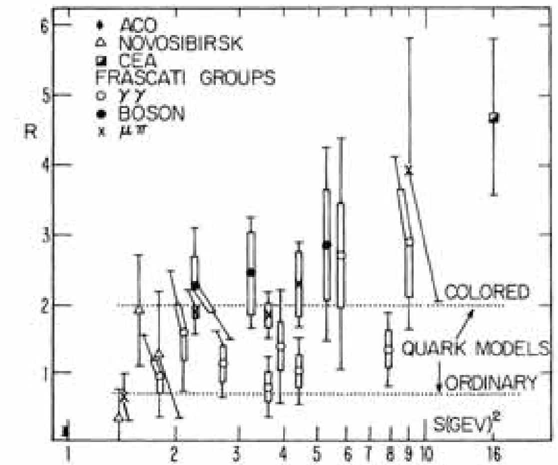


FIG. 2. $R = \sigma(e^+e^- \to \text{multibody hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ versus the square of the center-of-mass energy s in GeV^2. The dotted lines give the asymptotic predictions of parton models assuming ordinary and colored quarks.

At the time, there were already many what-proved-to-be wrong papers trying to interpret the electron–positron experiments, and the SLAC experiment leader, Burt Richter, was touring the country explaining that he had made the monumental discovery that the electron was actually a little hadron, i.e., a strongly interacting particle like the proton, only much smaller in diameter. (This discovery, or at least the same experimental results, had been observed a few years earlier at the Cambridge Electron Accelerator, a joint Harvard–MIT venture. But no one believed it, and the machine was decommissioned.)

H. David Politzer – Nobel Lecture

The Dilemma of Attribution

H. David Politzer held his Nobel Lecture December 8, 2004, at Aula Magna, Stockholm University.

DOMINANT COLLIDING-BEAM CROSS SECTIONS AT HIGH ENERGIES*

Stanley J. Brodsky†
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850, and Stanford Linear Accelerator Center,‡ Stanford, California 94305

and

Toichiro Kinoshita and Hidezumi Terazawa
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850
(Received 11 August 1970)

We report on our calculation of the energy and angular dependence of the cross sections for the production of various particles by two-photon annihilation processes in e^+e^- and e^-e^- colliding beams. For beam energy E of more than 1 GeV, these cross sections $[\sigma \propto \alpha^4(\ln E)^3]$ become increasingly more important than the usual one-photon cross sections $[\sigma \propto \alpha^2(E)^{-2}]$ for hadron production.

Although the study of hadron production by electron-positron collision is of intense experimental and theoretical interest,[1] it is not generally appreciated that the most frequent events at energies $E_{\text{c.m.}} = (s_{\text{c.m.}}/4)^{1/2}$ above 1 GeV occur via a two-photon annihilation process.[2,3] In fact two-photon cross sections for processes of the type

$$e + e \to e + e + N,$$

where $N = \pi^+\pi^-,\ \pi^+\pi^-\pi^0,\ \pi^0,\ \eta^0$, etc., are rather large and increase logarithmically at high energies. For example

$$\sigma_{ee\to ee\pi^+\pi^-} \sim \frac{8\alpha^4}{3\pi}\frac{1}{m_\pi^2}\left(\ln\frac{E}{m_e}\right)^2\left(\ln\frac{E}{m_\pi}\right). \quad (1)$$

If the scattered leptons are not observed, then to leading order in $\ln(E/m_e)$ each lepton (e^+ or e^-) is equivalent to a beam of real transversely polarized photons (the energy k) with a spectrum[4]

$$\frac{\alpha}{\pi}\frac{E^2+(E-k)^2}{E^2}\ln\left(\frac{E}{m_e}\right)\frac{dk}{k}. \quad (2)$$

$$d\sigma^N = \left(\frac{2\alpha}{\pi}\right)^2\left(\ln\frac{E}{m_e}\right)^2\int\frac{dk_1}{k_1}\frac{dk_2}{k_2}\frac{[E^2+(E-k_1)^2][E^2+(E-k_2)^2]}{4E^4}d\sigma_{\gamma\gamma}{}^N(k_1,k_2).$$

DOMINANT COLLIDING-BEAM CROSS SECTIONS AT HIGH ENERGIES*

Stanley J. Brodsky†
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850, and Stanford Linear Accelerator Center,‡ Stanford, California 94305

and

Toichiro Kinoshita and Hidezumi Terazawa
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850
(Received 11 August 1970)

$s_0 = 4E^2$

$s = 4k_1 k_2 \quad (4\mu^2 \leq s \leq s_0)$

$\omega = k_1 + k_2$

$q = k_1 - k_2 \quad (|q| \leq q_m = E - s/4E)$

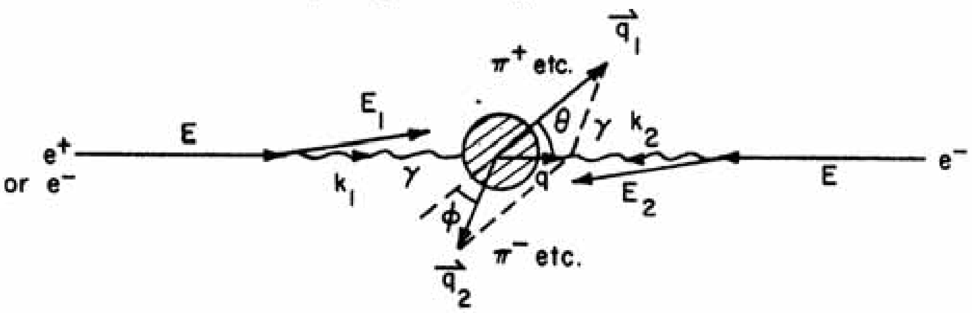


FIG. 1. Notation and geometry for the pair production of various particles by two-photon annihilation.

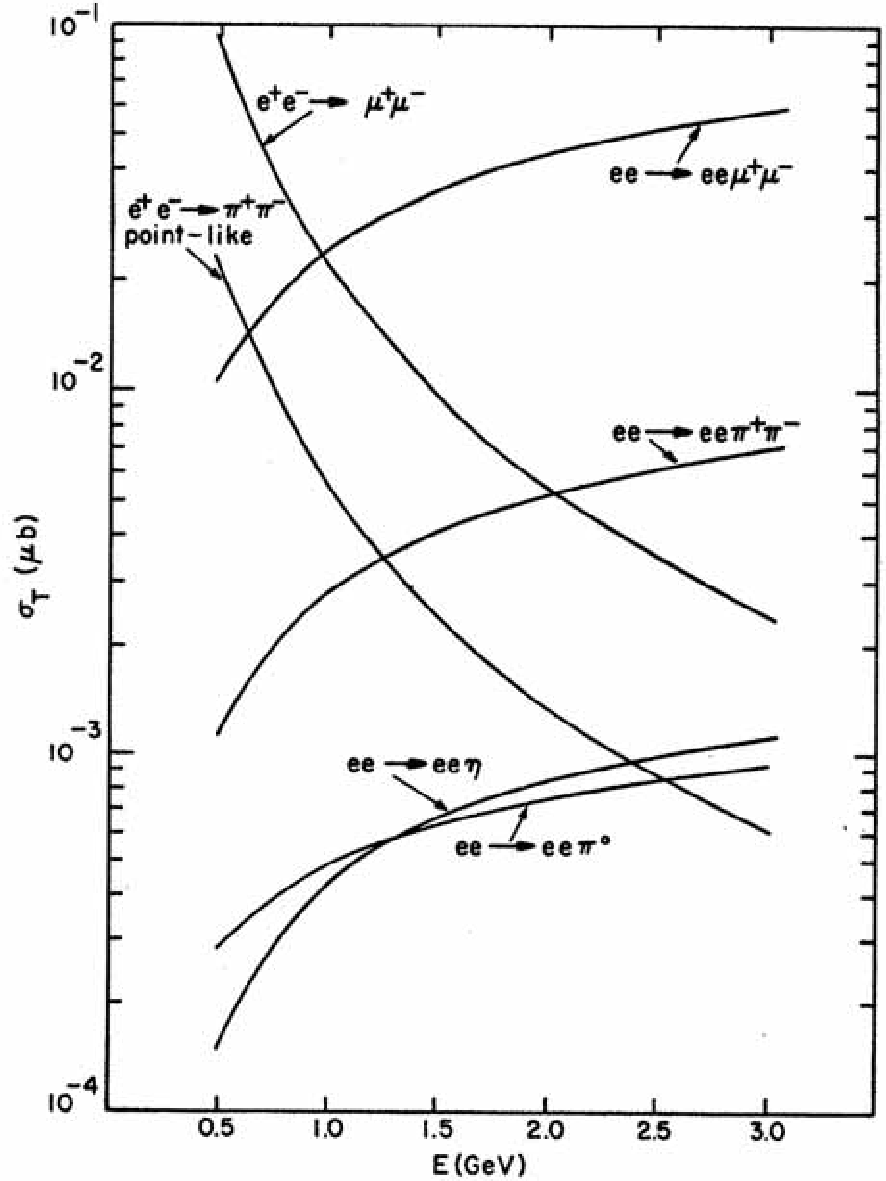


FIG. 2. The total cross sections for the colliding beam production of various particles.

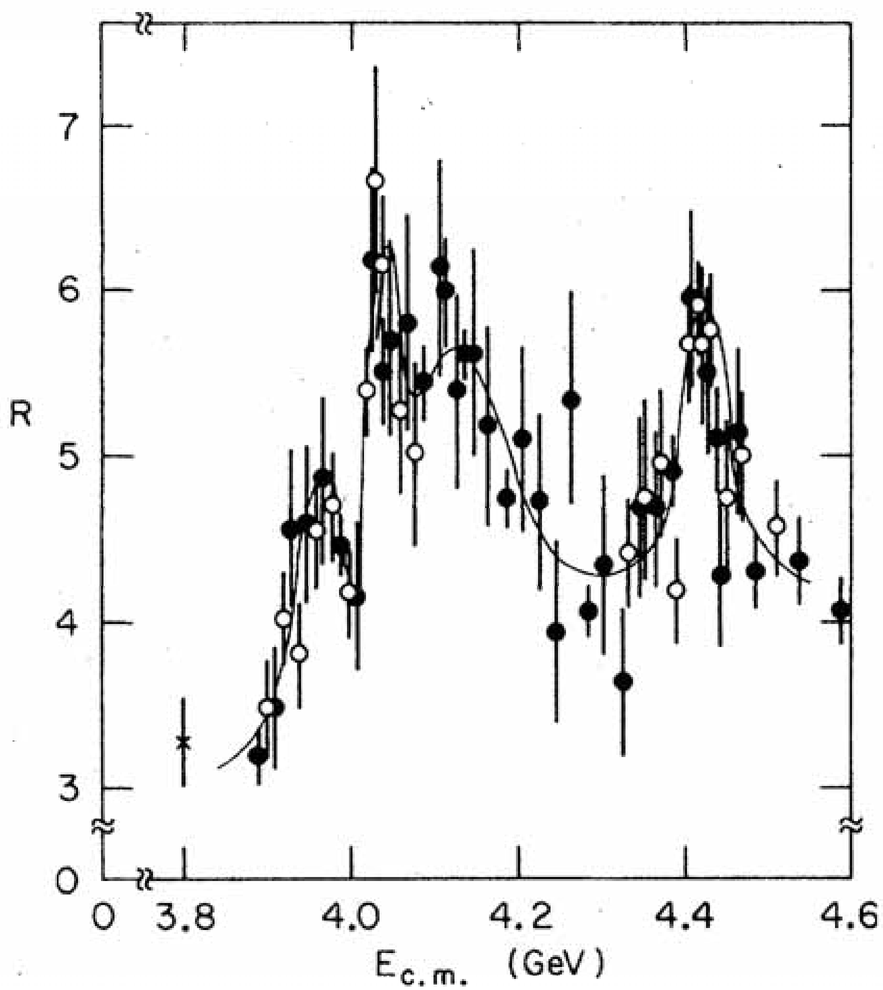


FIG. 14. An expanded view of R in the transition region around 4 GeV.

From the psi to charm: The experiments of 1975 and 1976

Burton Richter

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

Rev. Mod. Phys. 49, 251–266 (1977)

Charm Production not Photon-Photon Collisions!

DOMINANT COLLIDING-BEAM CROSS SECTIONS AT HIGH ENERGIES*

Stanley J. Brodsky†
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850, and Stanford Linear Accelerator Center,‡ Stanford, California 94305

and

Toichiro Kinoshita and Hidezumi Terazawa
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850
(Received 11 August 1970)

[3]This process has also been considered by several authors but a clear presentation of the energy dependence and angular distribution has not been given. Besides articles quoted in F. E. Low, Phys Rev. 120, 582 (1960), and in P. C. De Celles and J. F. Goehl, Jr. Phys. Rev. 184, 1617 (1969), see F. Calogero and C. Zemach, Phys. Rev. 120, 1860 (1960), and N. A-Romero, A. Jaccarini, and P. Kessler, C. R. Acad. Sci., Ser. B 296, 153, 1133 (1969). The elaborate work recently done by Cheng and Wu has influenced our thought about this process. See H. Cheng and T. T Wu, Phys. Rev. Lett. 23, 1311 (1969), and Phys. Rev. D 1, 2775 (1970), and references therein.

Independent Theoretical Physics Studies of Two-Photon Processes, especially Novosibirsk

THE TWO PHOTON PARTICLE PRODUCTION MECHANISM. PHYSICAL PROBLEMS. APPLICATIONS. EQUIVALENT PHOTON APPROXIMATION.
By V.M. Budnev, I.F. Ginzburg, G.V. Meledin, V.G. Serbo (Sobolev IM, Novosibirsk),. 1974. 101pp.
Published in **Phys.Rept.15:181-281,1974**

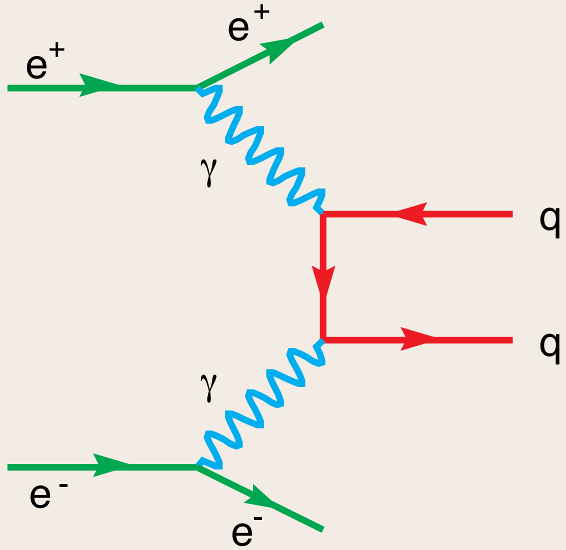
- **APPLICABILITY OF THE WEIZSAECKER-WILLIAMS APPROXIMATION FOR TWO-PHOTON PARTICLE PRODUCTION.** (In Russian)
  By V.M. Budnev, I.F. Ginzburg, G.V. Meledin, V.G. Serbo. 1972.
  Published in **Yad.Fiz.16:362-366,1972**

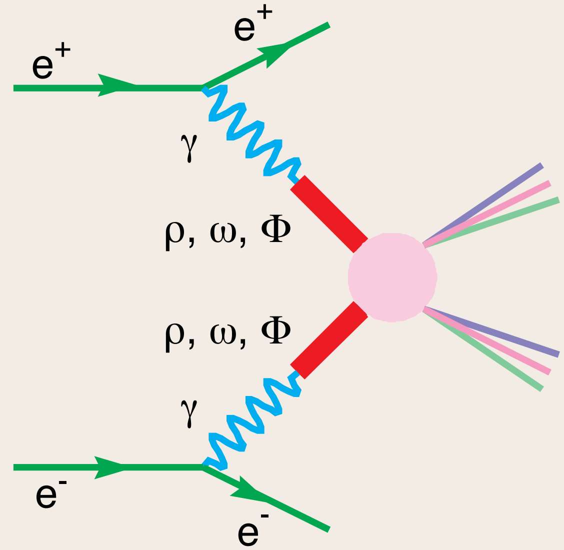
- **HADRON PRODUCTION BY HIGH ENERGY ELECTRON COLLIDING BEAMS.**
  By V.M. Budnev, I.F. Ginzburg (Sobolev IM, Novosibirsk),. 1972.
  Published in **Phys.Lett.B37:320-325,1971**
- **INVESTIGATION OF HIGH-ENERGY GAMMA GAMMA SCATTERING WITH COLLIDING ELECTRON BEAMS. KINEMATICS AND ESTIMATES OF THE CROSS SECTIONS.** (In Russian)
  By V.M. Budnev, I.F. Ginsburg. 1971.
  Published in **Yad.Fiz.13:353-362,1971**
- V.E. Balakin, V.M. Budnev and I.F. Ginzburg *JETP Letters (USSR)* **11** (1970), p. 559. Abstract-INSPEC
  V.M. Budnev and I.F. Ginzburg *Yad. Fiz.* **13** (1971), p. 353. Abstract-INSPEC
- **PHOTON-PHOTON COLLISIONS, A NEW AREA OF EXPERIMENTAL INVESTIGATION IN HIGH-ENERGY PHYSICS.**
  By N. Arteaga-Romero, A. Jaccarini, P. Kessler (College de France), J. Parisi. 1971. 10pp.
  Published in **Phys.Rev.D3:1569-1579,1971**

- **TWO PHOTON PROCESSES IN COLLIDING BEAM EXPERIMENTS.**
  By C.E. Carlson (Chicago U., EFI), Wu-Ki Tung (Chicago U., EFI & Chicago U.),. 1971. 11pp.
  Published in **Phys.Rev.D4:2873-2884,1971, Erratum-ibid.D6:402,1972**

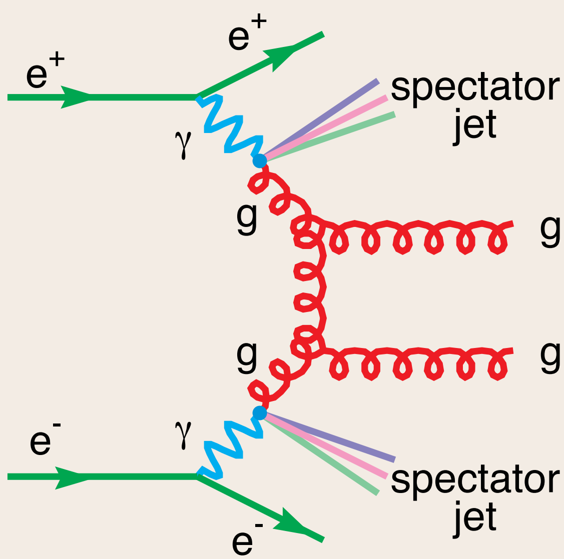
Early Two-Photon Papers

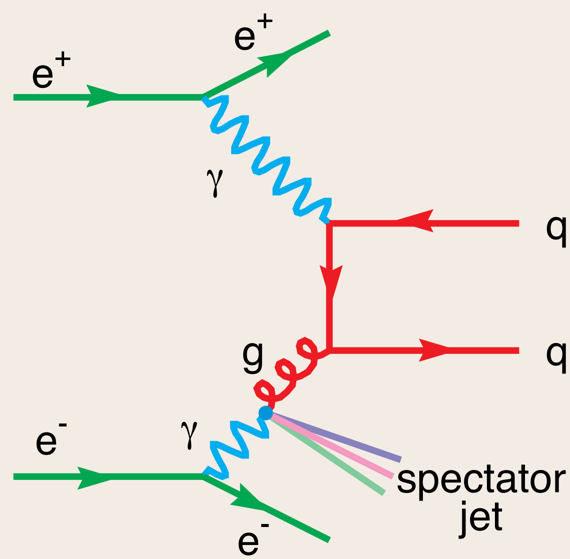
- **PRODUCTION OF ELECTRONS AND POSITRONS BY A COLLISION OF TWO PARTICLES.**
  By L.D. Landau, E.M. Lifschitz. 1934.
  Published in **Phys.Z.Sowjetunion 6:244,1934**
- **PROPOSAL FOR MEASURING THE PI0 LIFETIME BY PI- PRODUCTION IN ELECTRON ELECTRON OR ELECTRON - POSITRON COLLISIONS.**
  By F.E. Low (MIT, LNS),. Jun 1960.
  Published in **Phys.Rev.120:582-583,1960**
- **TWO - PHOTON CROSS-SECTION FOR W - PAIR PRODUCTION BY COLLIDING BEAMS.**
  By Peter D. Pesic (SLAC),. SLAC-PUB-1188, Feb 1973. 21pp.
  Published in **Phys.Rev.D8:945,1973**
- **A METHOD FOR MEASURING THE PHOTON - PHOTON TOTAL CROSS-SECTION.**
  By Leo Stodolsky (SLAC),. SLAC-PUB-0825, Oct 1970. 11pp.
  Published in **Phys.Rev.Lett.26:404,1971**



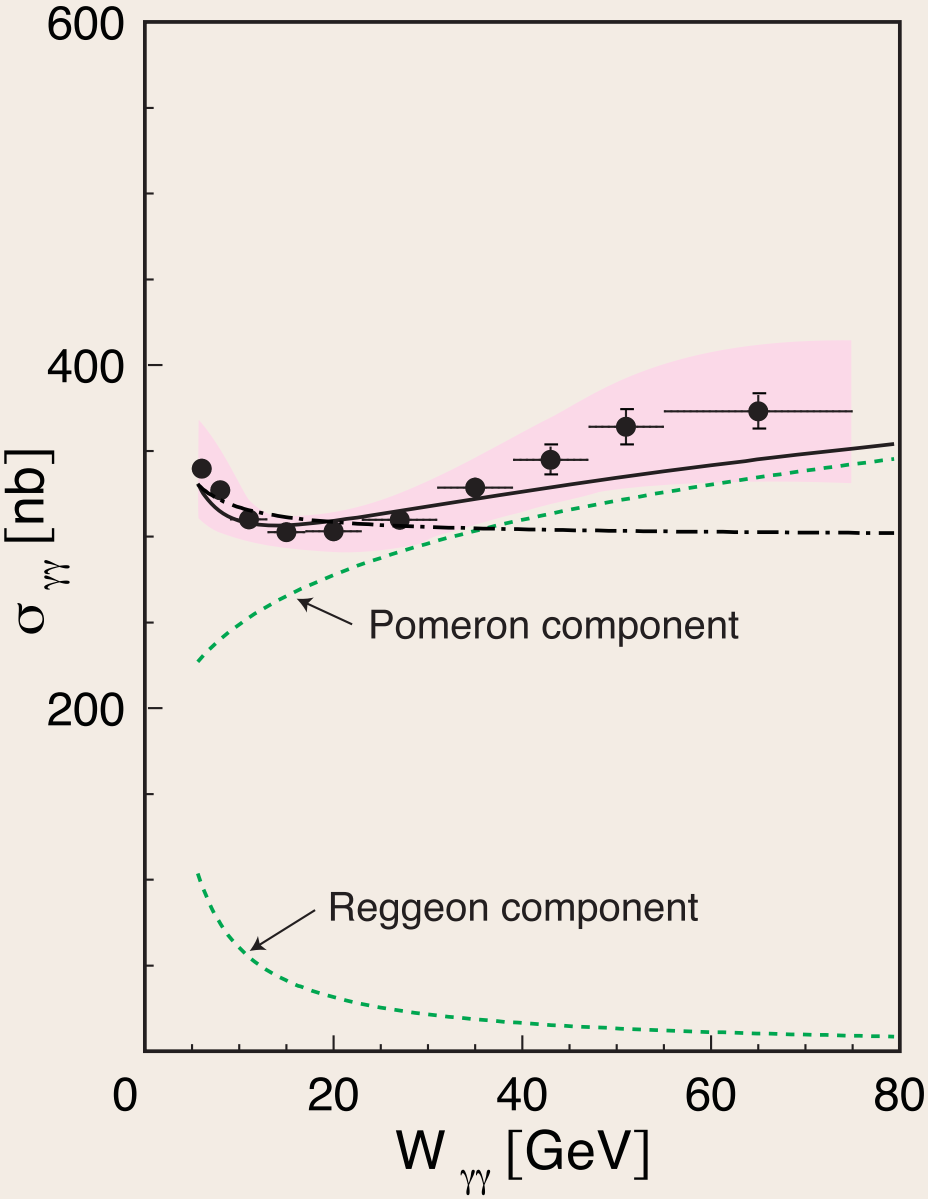


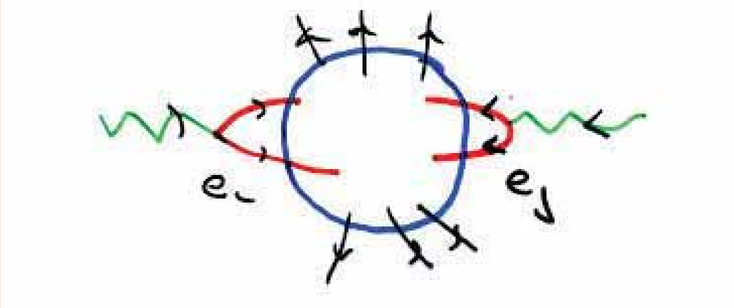
Contributions to to Total Two-Photon Cross Section





Total Two-Photon Annihilation Cross Section





- Remarkable test of BFKL hard pomeron dynamics at $s \gg -q_1^2, -q_2^2$

- Collisions of QCD color dipoles of variable transverse size

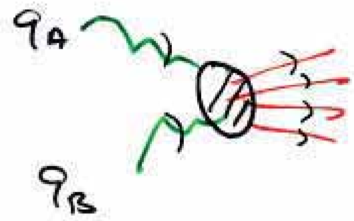
- Exclusive double-diffractive vector meson production $\sigma(\gamma^*\gamma^* \to VV)(s, q_1^2, q_2^2, t_1, t_2)$

- Singly diffractive vector meson production $\sigma(\gamma^*\gamma^* \to XV)(s, q_1^2, q_2^2, t)$

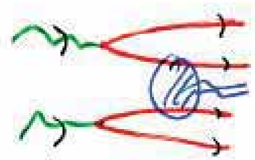
The behavior of high energy cross sections

$$\sigma_{AB\to X}(s)\ ,\quad \frac{d\sigma}{dt}(s,t)\ \ldots$$

challenge to QCD



$$\sigma_{\gamma^*\gamma^*}(\hat{s}, Q_A^2, Q_B^2)$$



QCD: Interaction of small color dipoles

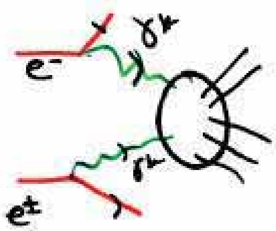
$$R_A \sim \frac{1}{Q_A}\ ,\quad R_B \sim \frac{1}{Q_B}$$

- * perturbatively calculable? { BFKL, Mueller }
- * polarization tests: $\sigma_{TT} \gg \sigma_{LL} \gg \sigma_{LT}$
- * breaking of factorization

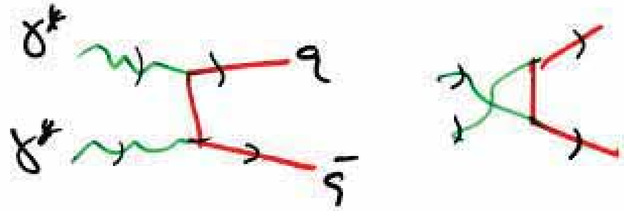
$$\sigma_{\gamma^*\gamma^*} \neq F(Q_A^2)\, F(Q_B^2)\, \hat{\sigma}$$

Total Cross-Section

$$\gamma^*(Q_1)\,\gamma^*(Q_2) \to X$$

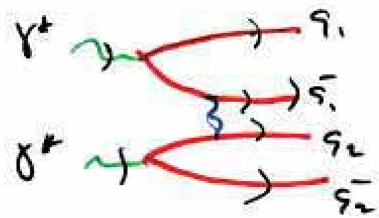


QCD :



$$\sigma(s_{\gamma\gamma}) \sim \frac{\pi\alpha^2}{s_{\gamma\gamma}} \sum e_q^2$$

High energy dominated by spin 1 exchange



$$\sigma(s_{\gamma\gamma}) \sim \sum e_1^2 \sum e_2^2\, \alpha^2 \alpha_s^2 \times \frac{\left[\log s/(Q_1^2+Q_2^2)\right]^{n-1}}{Q_1^2+Q_2^2}$$

"Color dipole" Scattering

ref: Hautmann, Soper, SJB, Bartels, et al — PRD D56 6957 (1997)

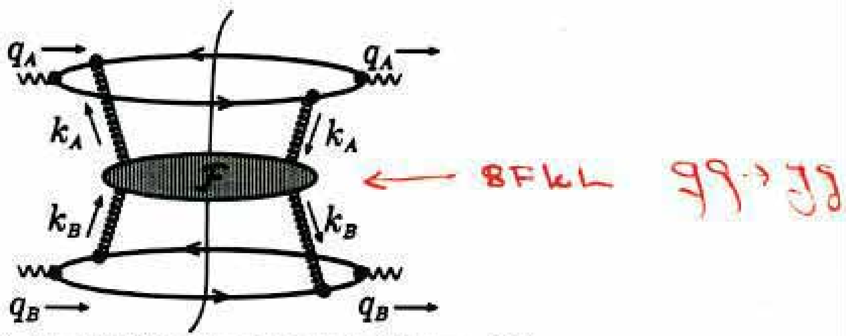


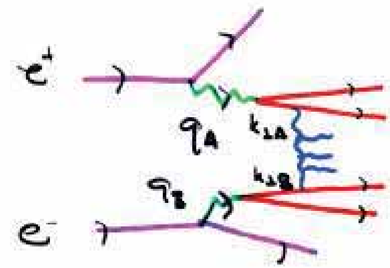
FIGURE 1. The virtual photon cross section in the high energy limit.

Balitski
Fadin
Kuraev
Lipatov
} BFKL

SJB, F. Hautmann, D.E. Soper
Bartels, DeRoeck, Lotter
} $\gamma^* \gamma^*$

BFKL Pomeron and $\sigma_{\gamma^*\gamma^* \to X}(s)$

Hautmann, Soper
S&B



$L = \ln s/Q^2$

$$\sigma_{\gamma^*\gamma^*} = \sigma^{(0)}\left[1 + \sum_{k=1}^{\infty} a_k (\alpha_s L)^k \ldots\right]$$

$$\sigma(s, Q_A^2, Q_B^2) = \int_{a-i\infty}^{a+i\infty} \frac{dN}{2\pi i}\, e^{NL}\, \sigma_N(Q_A^2, Q_B^2)$$

Mellin-Fourier moments

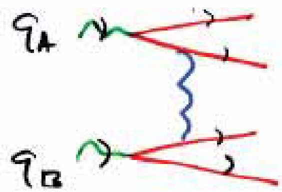
$$\sigma_N = \int_0^\infty \frac{ds}{s}\left(\frac{s}{Q^2}\right)^{-N} \sigma(s)$$

leading log:

$$\sigma_N(Q_A^2, Q_B^2) = \int \frac{d^2k_{\perp A}}{\pi k_{\perp A}^2} \int \frac{d^2 k_{\perp B}}{\pi k_{\perp B}^2} G_1(k_{\perp A}^2/Q_A^2)\, G_1(k_{\perp B}^2/Q_B^2) \cdot F_N(k_{\perp A}^2, k_{\perp B}^2)$$

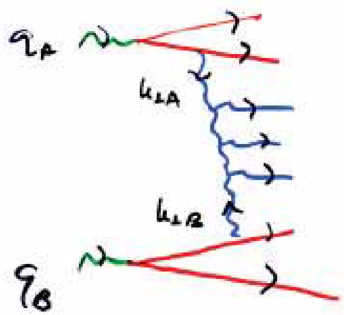
Born: $F_N^{(0)} = \frac{1}{2N}\frac{1}{\pi}\,\delta(k_{\perp A}^2 - k_{\perp B}^2)$

PQCD Analysis of $\sigma_{\gamma^*\gamma^*}(\hat{s}, Q_A^2, Q_B^2)$



$$\sigma^{0}_{\gamma^*\gamma^*} = \alpha^2 \alpha^2_{\overline{MS}}(e^{-5/3}Q^2) \frac{F(Q_A^2, Q_B^2}{Q^2}$$

$$Q^2 = Q_A Q_B$$



$$\sigma_{\gamma^*\gamma^*} = \sigma^{(0)}_{\gamma^*\gamma^*}\left[1 + \sum_{k=1}^{\infty} a_k (\alpha_s L)^k\right.$$

$$L = \ln \frac{\hat{s}}{Q^2}$$ From dy

$$\Rightarrow \boxed{\sigma_{\gamma^*\gamma^*} \sim \left(\frac{\hat{s}}{Q^2}\right)^{\lambda} \sigma^{(0)}_{\gamma^*\gamma^*}}$$

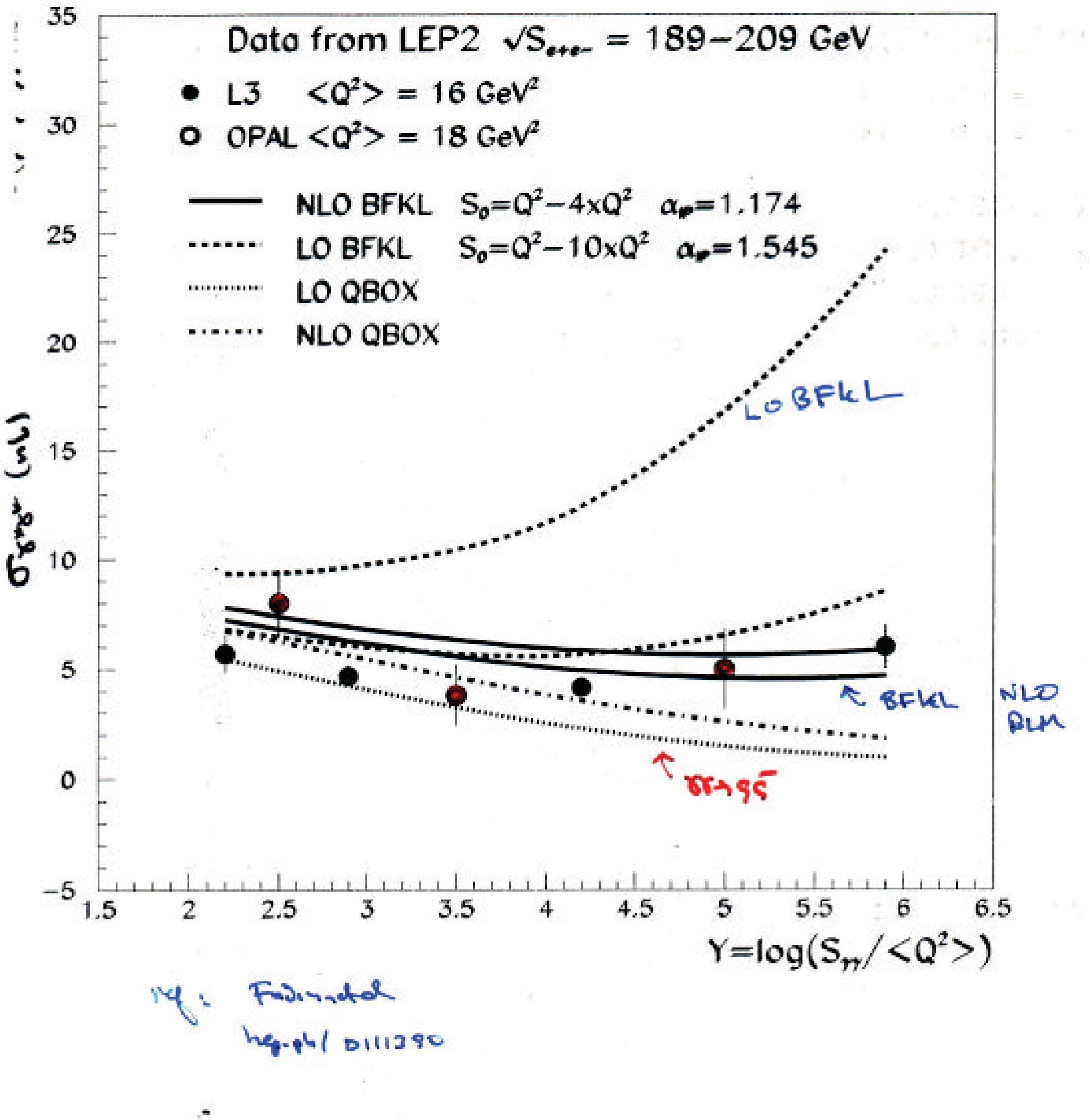
BFKL:

* $\lambda = \bar{\alpha}_s \chi(\gamma) \cong \bar{\alpha}_s \chi(\tfrac{1}{2}) = 2.77$

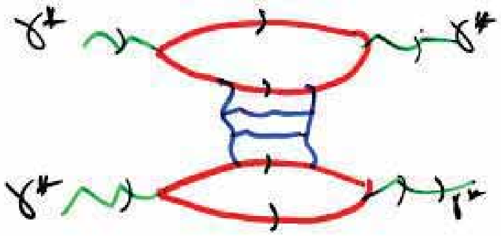
where $\bar{\alpha}_s = \alpha_s(\mu) \frac{N_c}{\pi}$, $\mu = O(Q)$

(Huge NLO correction (Fadin & Lipatov))

BFKL intercept stabilized at NLO by BLM



Exchange multiple gluons : BFKL Pomeron



$\sigma_{\gamma^*\gamma^*\to X} = \frac{1}{s}\,\mathrm{Im}\,M_{\gamma\gamma\to}$

$s^0 \log s \Rightarrow s^{\alpha(0)-1}$

$\alpha_{LO}(0) = 1 + \omega_{LO} = 1 + 12\ln 2\,\frac{\alpha_s}{\pi}$

Need to fix scale of α_s ! Need NLO

BLM : preserve conformal coefficients

$\omega_{NLO} \Rightarrow 0.13$ to 0.18

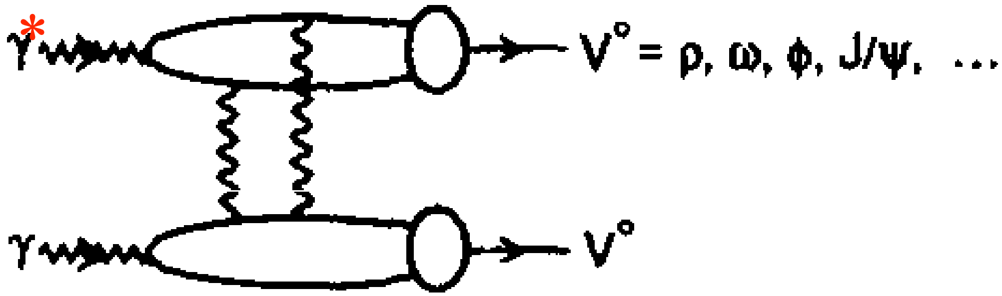
ref: Fadin, Kim, Lipatov, Pivovarov, SJB hep-ph/0111390

Data from L3 and OPAL at LEP 2
Need tests in Q_1^2, Q_2^2

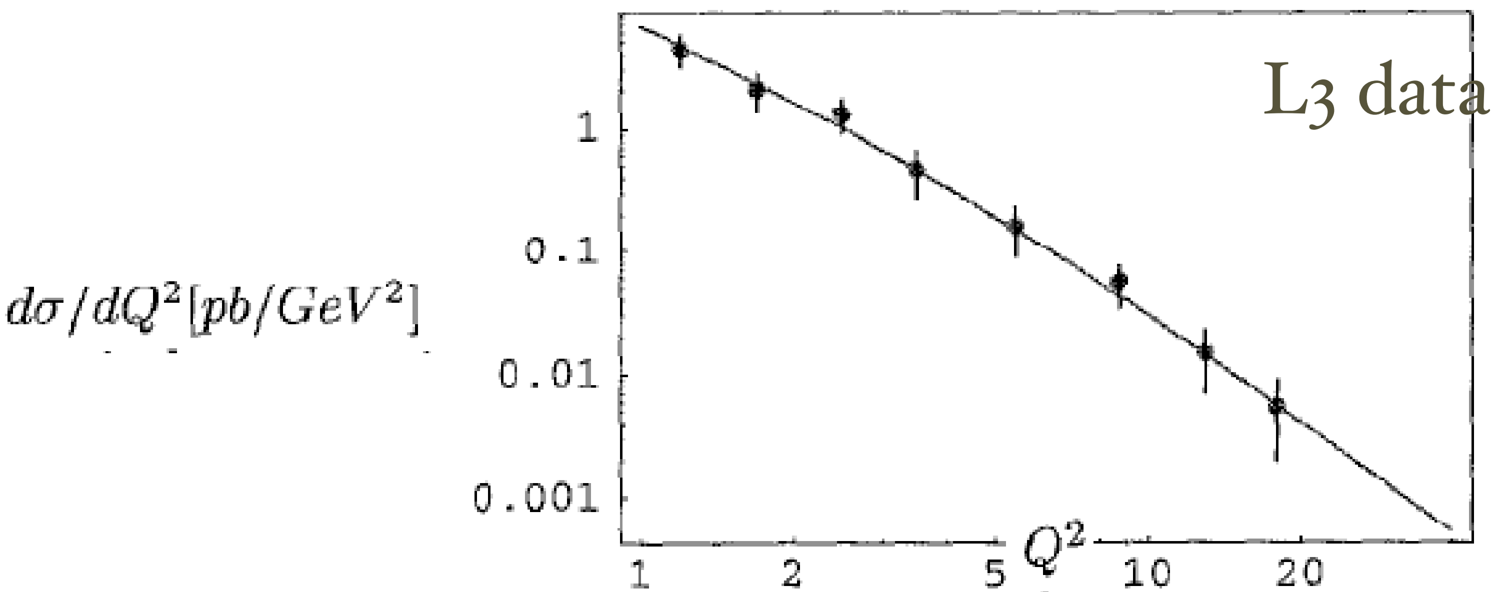
Exclusive two ρ^0-mesons production in $\gamma\gamma^*$ collision

I.V. Anikin[a], B. Pire[b] and O. V. Teryaev[c]

Nuclear Physics B (Proc. Suppl.) 126 (2004) 277–282



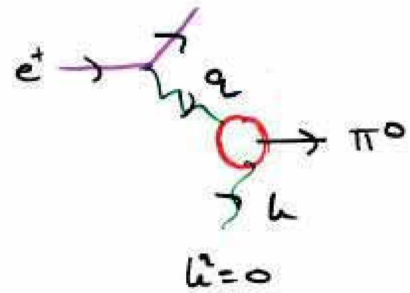
BFKL Analysis:
Enberg, Wallon



$\gamma\gamma^* \to \rho^0\rho^0$ at $Q^2 \geq 1.2\,\mathrm{GeV}^2$ and $W \leq 3.0\,\mathrm{GeV}$.

$\gamma^* \gamma \to \pi^0, \eta, \eta', \eta_c \cdots$

Simplest example of exclusive process

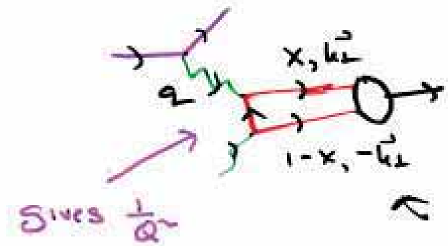


$F_{\gamma\pi^0}(q^2)$

$\pi^0 \to \gamma\gamma$ at $q^2 = 0$.

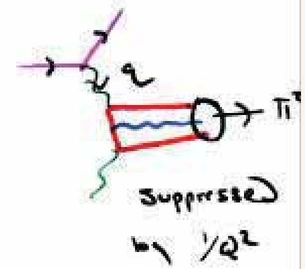
For $Q^2 \gg \Lambda^2_{QCD}$ analyze in PQCD

Lepage SJB



$\leftarrow \psi^\pi_{q\bar{q}}(x, \vec{k}_\perp)$

+



* $F_{\gamma\pi^0}(Q^2) = \frac{1}{Q^2} 2\sqrt{n_c} (e_u^2 - e_d^2) \int_0^1 dx \left(\frac{1}{x} + \frac{1}{1-x}\right) \phi_\pi(x, Q$

* $\phi_\pi(x, Q) = \int^Q \frac{d^2 k_\perp}{16\pi^3} \psi_{q\bar{q}}(x, \vec{k}_\perp)$ pion distribution amplitude

Photon-to-Meson Transition Form Factors

$$\Gamma_\mu = -ie^2 F_{M\gamma}(Q^2)\epsilon_{\mu\nu\rho\sigma} P_M^\nu \epsilon^\rho q^\sigma$$

Simplest hadron form factor in QCD

$$F_{\pi\gamma}(Q^2) = \frac{2}{\sqrt{3}Q^2}\int_0^1 dx \frac{\phi_\pi^*(x,\tilde{Q})}{x(1-x)}\left[1+O\left(\alpha_s,\frac{m^2}{Q^2}\right)\right]$$

Measure in $e^- e^+ \to e^- e^+ \pi^0$
single tagged virtual photon

G. P. Lepage, SJB

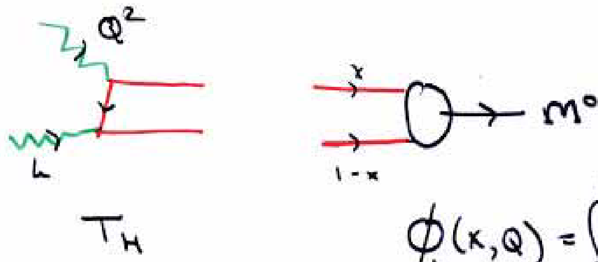
Phys.Rev.D22:2157,1980

Phys.Rev.D24:1808,1981

$$F_{\pi\gamma} \to \frac{2f_\pi}{Q^2} \quad \text{as } Q^2 \to \infty$$

Zerwas, Walsh

PQCD: $F_{\gamma \to M^0}(Q^2) \sim \frac{1}{Q^2}\int_0^1 \frac{dx}{1-x}\,\phi_M(x,\tilde{Q})$



$$\phi_M(x,Q) = \int^{k_\perp^2 < \tilde{Q}^2} d^2k_\perp\, \psi_{q\bar{q}}(x,k_\perp)$$

* $T_H(\gamma^*\gamma \to q\bar{q}) \sim \frac{1}{Q^2(1-x)}$

  $\mathcal{O}(Q)^*$ — collinear

* Higher Fock states: $\frac{1}{Q^4}$ 

  Other diagrams $\mathcal{O}(\alpha_s(Q^2))$!

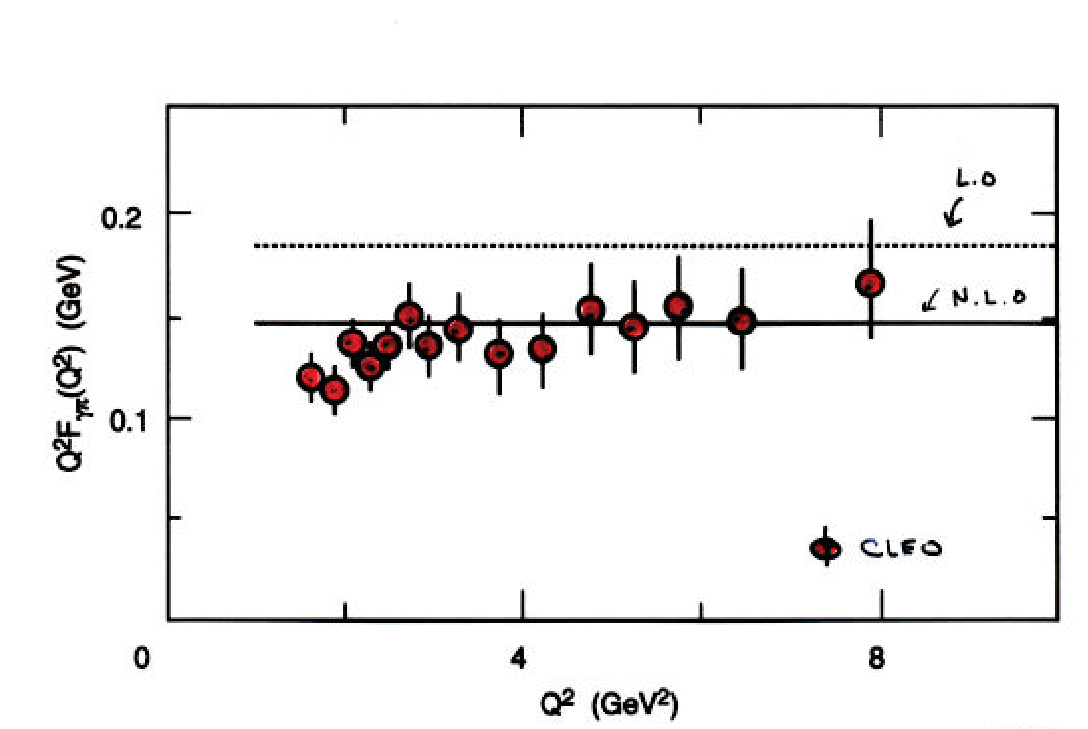
* $\phi_M(x,Q) = \sum_{n=0}^{\infty} a_n P_n(x)\left(\ln\frac{Q^2}{\Lambda^2}\right)^{-\gamma_n}$ 

  log evolution

* $\lambda_M = \lambda_q + \lambda_{\bar{q}} = 0.$ HHC — test in ρ^0

** Small part of Fock state dominates

$$\phi_M \sim \psi(x, b_\perp \sim \tfrac{1}{Q})$$



CLEO, Savinov et al.

Assumes

$$\phi_\pi(x,Q) = \phi_\pi^{asymptotic}(x) = \sqrt{3} f_\pi \; x(1-x)$$

Lepage, sjb

- PQCD prediction at NLO

$$Q^2 F_{\gamma\to\pi}(Q^2) = 2 f_\pi \; [1 - \frac{5}{3\pi} \frac{\alpha_V(e^{-3}Q^2)}{\pi}]$$

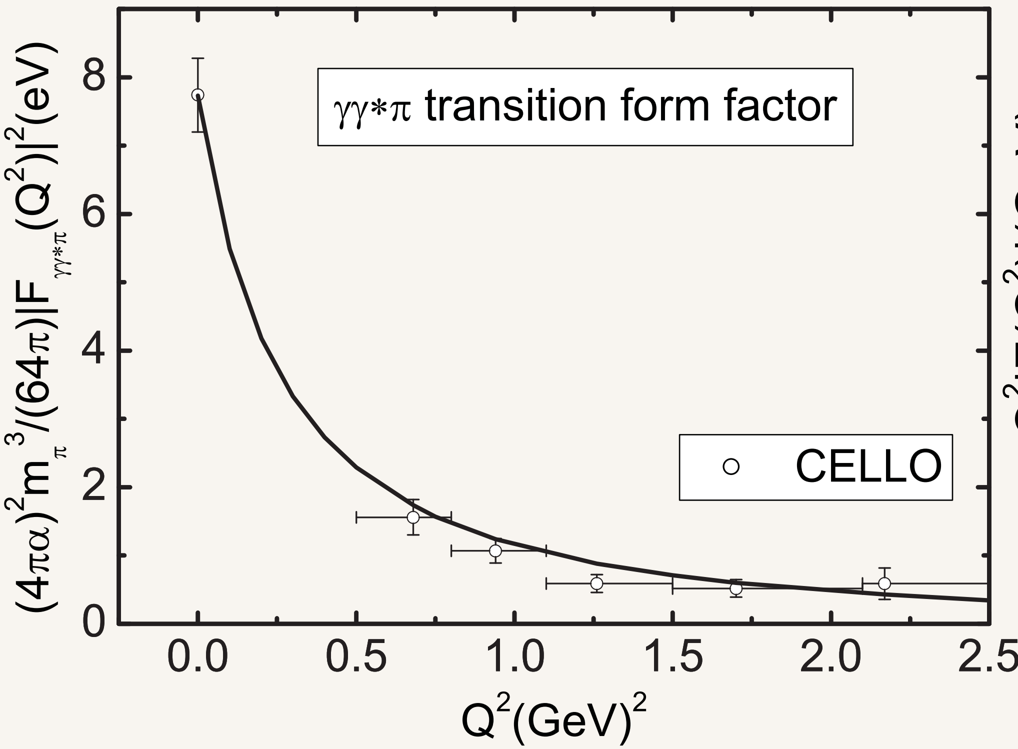
Radyushkin, Braaten, Chase

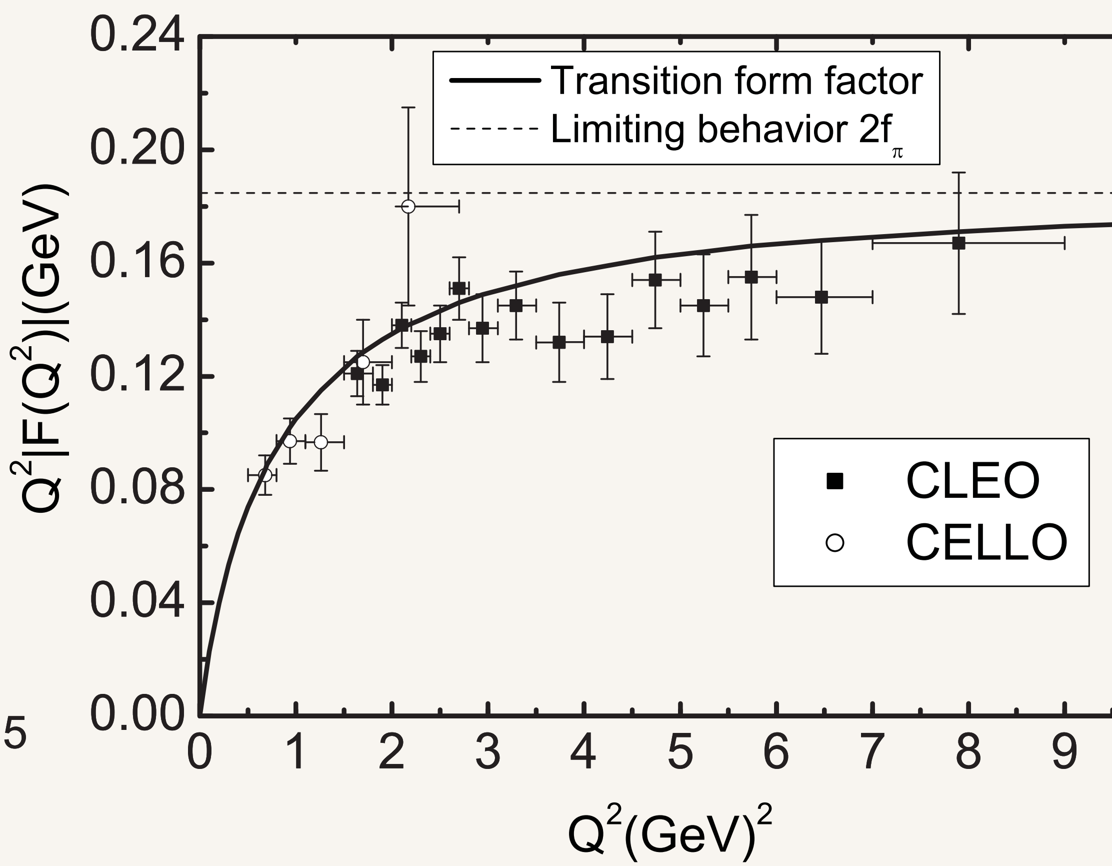
PHOTON-MESON TRANSITION FORM-FACTORS OF LIGHT PSEUDOSCALAR MESONS.

Bo-Wen Xiao Bo-Qiang Ma

Phys.Rev.D71:014034,2005

$$F_{\pi\gamma} \to \frac{2f_\pi}{Q^2} \quad \text{as } Q^2 \to \infty$$



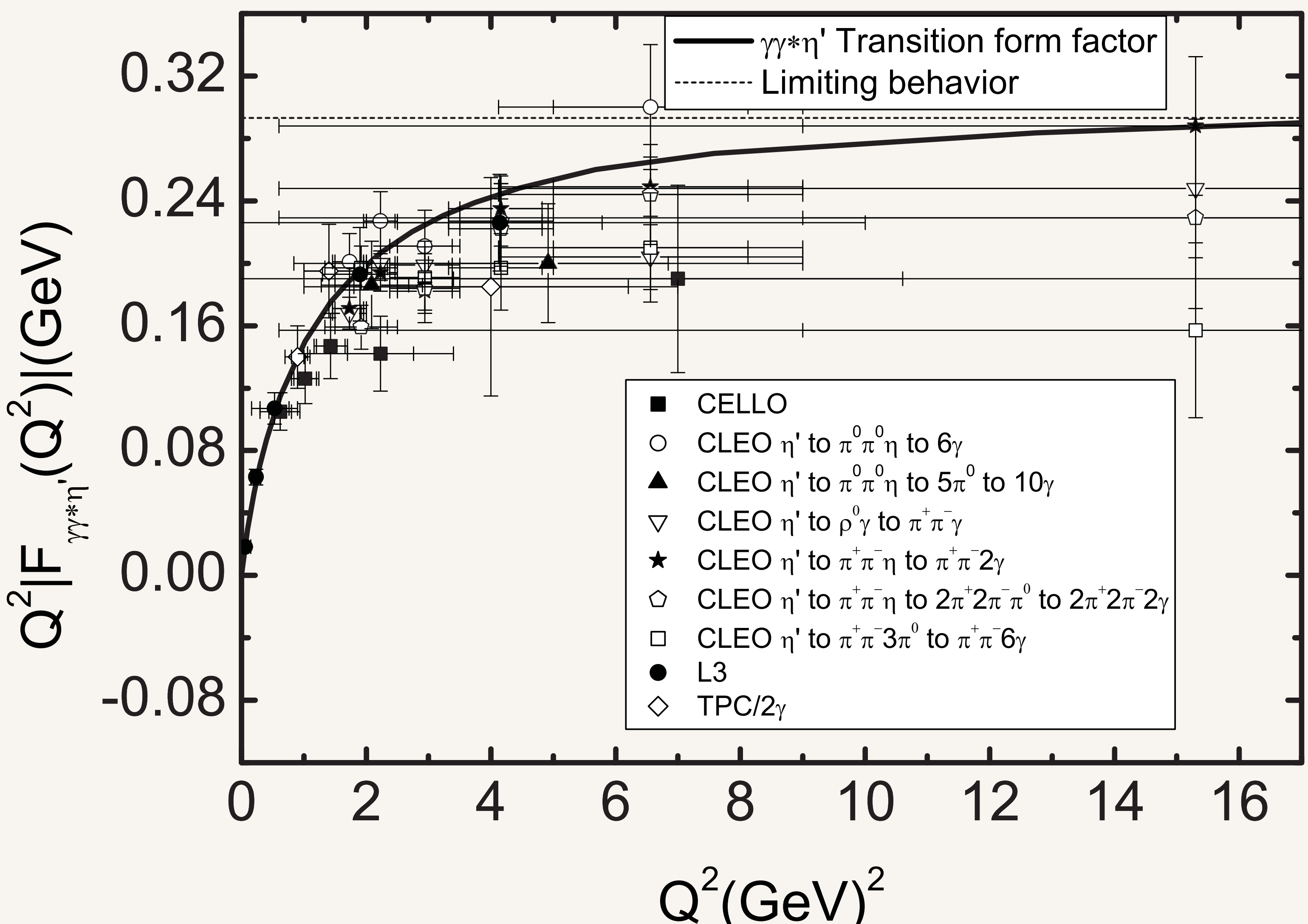


QCD Phenomena - AdS/CFT

PHOTON-MESON TRANSITION FORM-FACTORS OF LIGHT PSEUDOSCALAR MESONS.

Bo-Wen Xiao Bo-Qiang Ma

Phys.Rev.D71:014034,2005

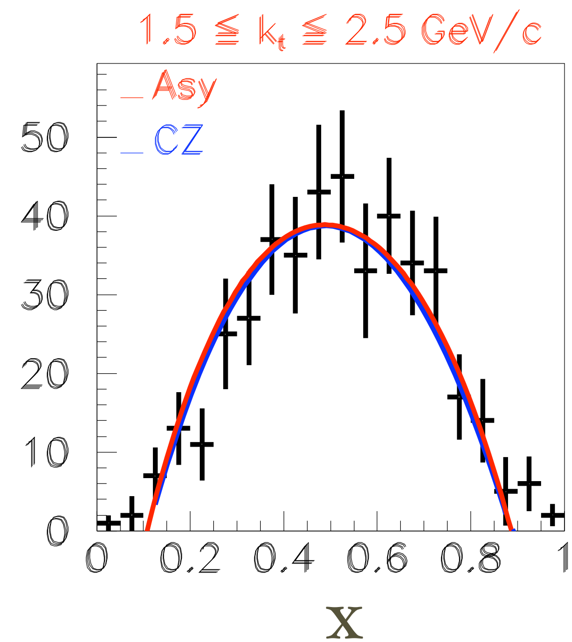


Diffractive Dissociation of a Pion into Dijets

$$\pi A \rightarrow Jet\,Jet\,A'$$

- E789 Fermilab Experiment Ashery et al
- 500 GeV pions collide on nuclei keeping it intact
- Measure momentum of two jets
- Study momentum distributions of pion LF wavefunction

$$\psi^{\pi}_{q\bar{q}}(x, \vec{k}_{\perp})$$



Diffractive Dissociation of Pion into Di-Jets

- Verify Color Transparency
- Pion Interacts coherently on each nucleon of nucleus !

$$M \propto A, \ \sigma \propto A^2$$

- Pion Distribution similar to Asymptotic Form
- Scaling in transverse momentum consistent with PQCD

$$\psi(x, k_\perp) \propto x(1-x)$$

Consistent with:

AdS/CFT Holographic Model
de Teramond, SJB

Transverse Lattice
Dalley, Burkardt

Lattice Gauge Theory Moments
Sachrajda

Holographic LFWF

AdS/CFT

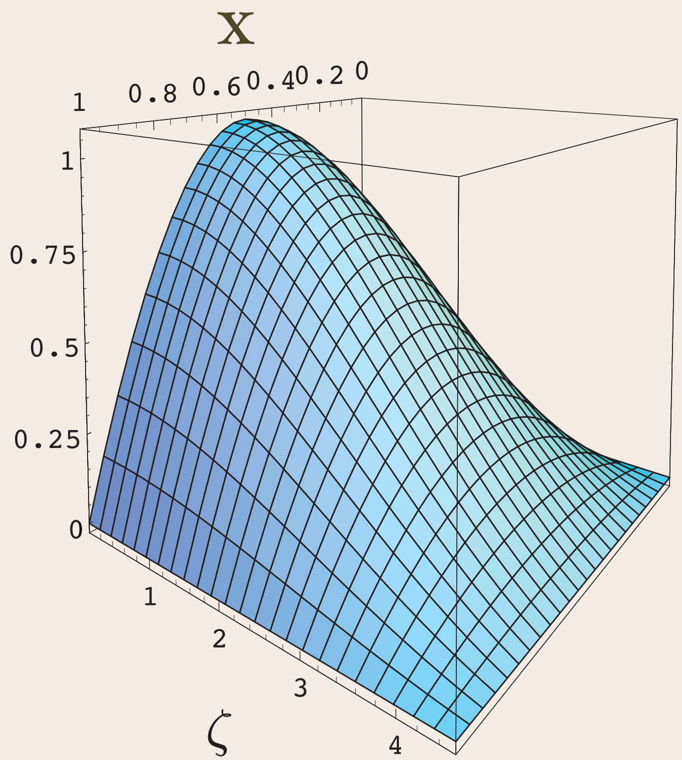


Figure 1: Ground state light-front wavefunction in impact space $\psi(x, b)$ for a two-parton state in a holographic QCD model for $n = 2, \ell = 0, k = 1$.

$$z \to \zeta$$

G. de Teramond & Sjb

$$\zeta = b\sqrt{x(1-x)}$$

G.P. Lepage, sjb

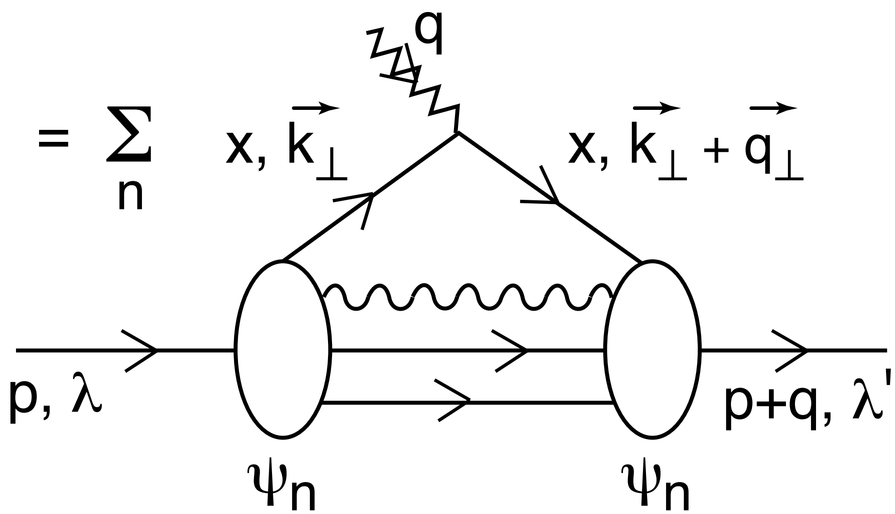
PQCD and Exclusive Processes

$$M = \int \prod dx_i dy_i \phi_F(x, \tilde{Q}) \times T_H(x_i, y_i, \tilde{Q}) \phi_I(y_i, Q)$$

- Iterate kernel of LFWFs when at high virtuality; distribution amplitude contains all physics below factorization scale
- Rigorous Factorization Formulae: Leading twist
- Underly Exclusive B-decay analyses
- Distribution amplitude: gauge invariant, OPE, evolution equations, conformal expansions
- BLM scale setting: sum nonconformal contributions in scale of running coupling
- Derive Dimensional Counting Rules/ Conformal Scaling

Form Factors $\ell p \rightarrow \ell' p'$ $\langle p' \lambda' | J^+ (0) | p \lambda \rangle$

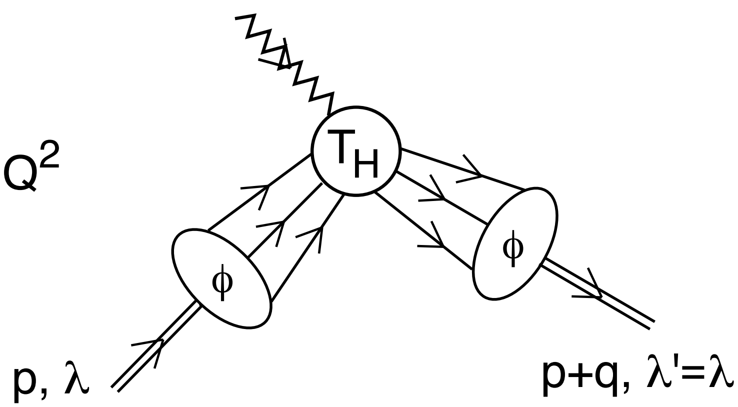
$F_{\lambda\lambda'}(Q^2) = \sum_n$



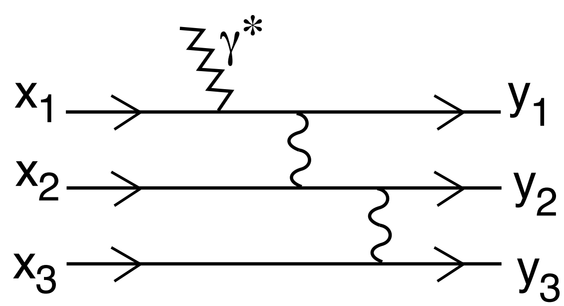
Lepage, Sjb
Efremov
Radyushkin

QCD Factorization

⇨ Large Q^2



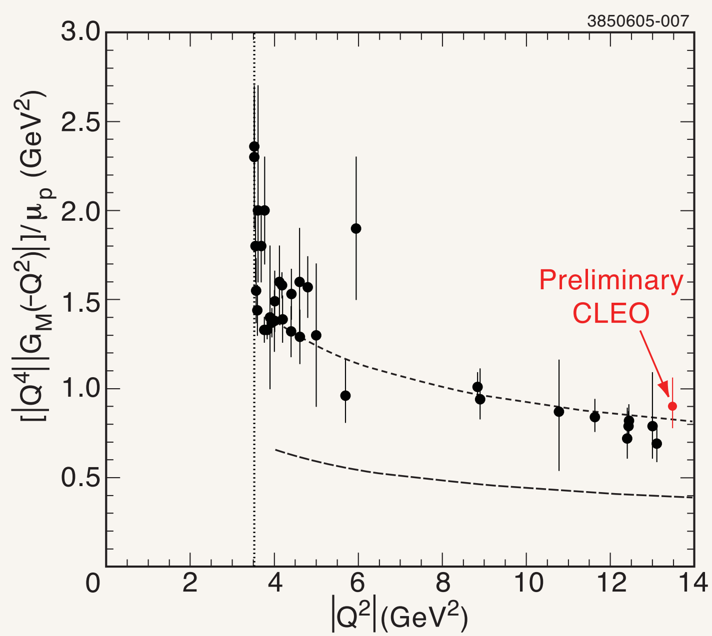
$T_H = \sum$



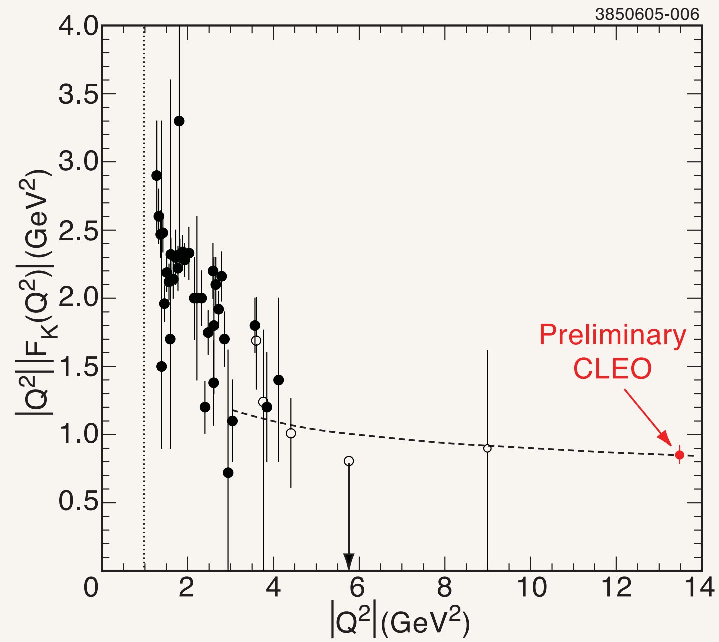
$+ \cdots$

$$= \frac{\alpha_s^2}{Q^4} f(x_i, y_i,)$$

Scaling Laws from PQCD or AdS/CFT



Proton timelike form factor.



Kaon timelike form factor.

New results from CLEO

$$Q^2|F_K(13.48\ \mathrm{GeV}^2)| = 0.85 \pm 0.05(\mathrm{stat}) \pm 0.02(\mathrm{syst})\ \mathrm{GeV}^2$$
$$Q^4|G_M^p(13.48\ \mathrm{GeV}^2)| = 2.54 \pm 0.36(\mathrm{stat}) \pm 0.16(\mathrm{syst})\ \mathrm{GeV}^4$$

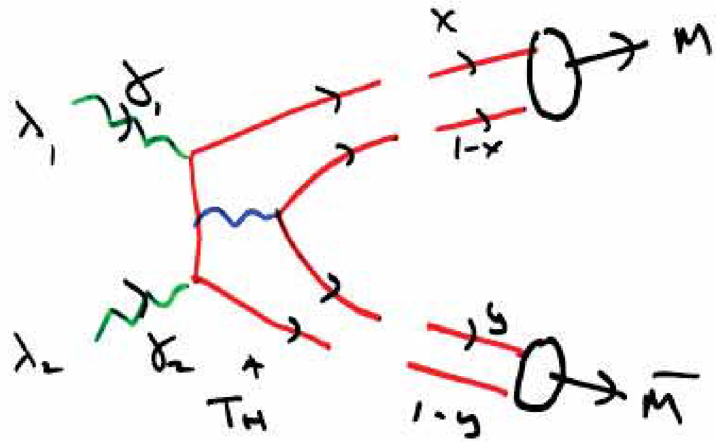
The proton magnetic form factor result agrees with that measured in the reverse reaction $p\bar{p} \to e^+e^-$ at Fermilab. **The kaon form factor measurement is the first ever direct measurement at $|Q^2| > 4$ GeV^2.**

PQCD Factorization at large s, t

G.P. Lepage + SJB

Vogt et al

Chernyak



no FSI!

$$\mathcal{M}(\gamma_1, \gamma_2 \to M \bar{M}) = \int_0^1 dx \int_0^1 dy \, T_H(x, y; s, \theta_{cm}) \, \phi_M(x, \tilde{Q}) \, \phi_{\bar{M}}(y, \tilde{Q})$$

$$\phi_M(x, \tilde{Q}) = \int^{\tilde{Q}} d^2k_\perp \, \psi_{q\bar{q}/M}(x, \vec{k_\perp})$$

Two-Photon Exclusive Amplitudes

$$F_M(s)=\frac{16\pi\alpha_s}{3s}\int_0^1 dx\,dy\,\frac{\phi_M^*(x,\tilde{Q}_x)\phi_M^*(y,\tilde{Q}_y)}{x(1-x)y(1-y)}$$

when $\phi_M(x,Q)=\phi_M(1-x,Q)$ is assumed.[7] Thus much of the dependence on $\phi(x,Q)$ can be removed from $\mathcal{M}_{\lambda\lambda'}$ by expressing it in terms of the meson form factor—i.e.,

Lepage, SJB

$$\left.\begin{matrix}\mathcal{M}_{++}\\ \mathcal{M}_{--}\end{matrix}\right\}=16\pi\alpha F_M(s)\left[\frac{\langle(e_1-e_2)^2\rangle}{1-\cos^2\theta_{\rm c.m.}}\right],$$

$$\left.\begin{matrix}\mathcal{M}_{+-}\\ \mathcal{M}_{-+}\end{matrix}\right\}=16\pi\alpha F_M(s)\left[\frac{\langle(e_1-e_2)^2\rangle}{1-\cos^2\theta_{\rm c.m.}}+2\langle e_1e_2\rangle g[\theta_{\rm c.m.};\phi_M]\right],$$

up to corrections of order α_s and m^2/s. Now the only dependence on ϕ_M, and indeed the only unknown quantity, is in the θ-dependent factor

$$g[\theta_{\rm c.m.};\phi_M]=\frac{\displaystyle\int_0^1 dx\,dy\,\frac{\phi_M^*(x,\tilde{Q})\phi_M^*(y,\tilde{Q})}{x(1-x)y(1-y)}\,\frac{a[y(1-y)+x(1-x)]}{a^2-b^2\cos^2\theta_{\rm c.m.}}}{\displaystyle\int_0^1 dx\,dy\,\frac{\phi_M^*(x,\tilde{Q})\phi_M^*(y,\tilde{Q})}{x(1-x)y(1-y)}}.$$

The spin-averaged cross section follows immediately from these expressions

$$\frac{d\sigma}{dt}=\frac{2}{s}\frac{d\sigma}{d\cos\theta_{\rm c.m.}}=\frac{1}{16\pi s^2}\frac{1}{4}\sum_{\lambda\lambda'}|\mathcal{M}_{\lambda\lambda'}|^2$$

$$=16\pi\alpha^2\left|\frac{F_M(s)}{s}\right|^2\left\{\frac{\langle(e_1-e_2)^2\rangle^2}{(1-\cos^2\theta_{\rm c.m.})^2}+\frac{2\langle e_1e_2\rangle\langle(e_1-e_2)^2\rangle}{1-\cos^2\theta_{\rm c.m.}}g[\theta_{\rm c.m.};\phi_M]+2\langle e_1e_2\rangle^2g^2[\theta_{\rm c.m.};\phi_M]\right\}.$$

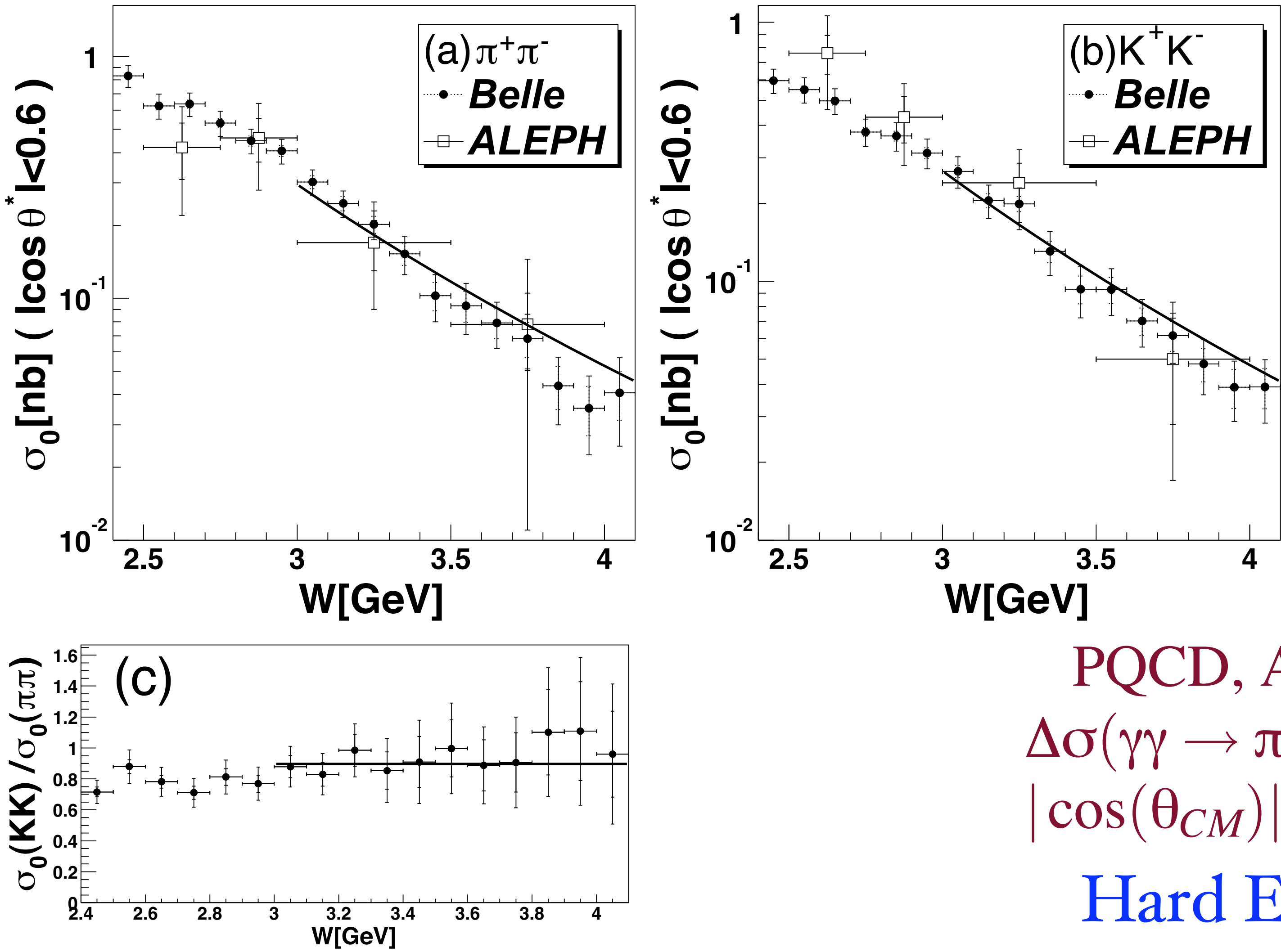


Fig. 5. Cross section for (a) $\gamma\gamma\to\pi^+\pi^-$, (b) $\gamma\gamma\to K^+K^-$ in the c.m. angular region $|\cos\theta^*| < 0.6$ together with a W^{-6} dependence line derived from the fit of $s|R_M|$. (c) shows the cross section ratio. The solid line is the result of the fit for the data above 3 GeV. The errors indicated by short ticks are statistical only.

PQCD, AdS/CFT:

$$\Delta\sigma(\gamma\gamma \to \pi^+\pi^-, K^+, K^-) \sim 1/W^6$$

$$|\cos(\theta_{CM})| < 0.6$$

Hard Exclusive Processes: Fixed angle

PQCD: $$\frac{d\sigma}{d|\cos\theta^*|}(\gamma\gamma \to M^+M^-) \approx \frac{16\pi\alpha^2}{s}\frac{|F_M(s)|^2}{\sin^4\theta^*},$$

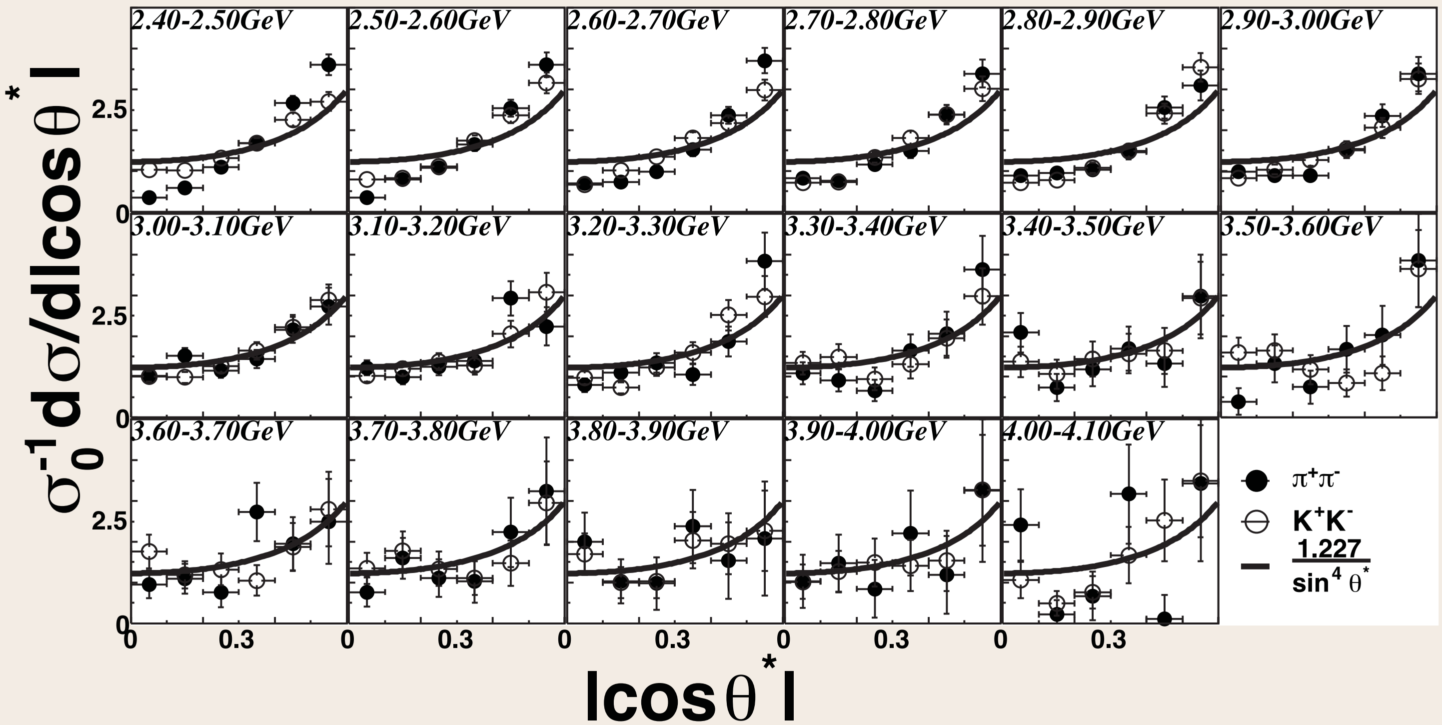
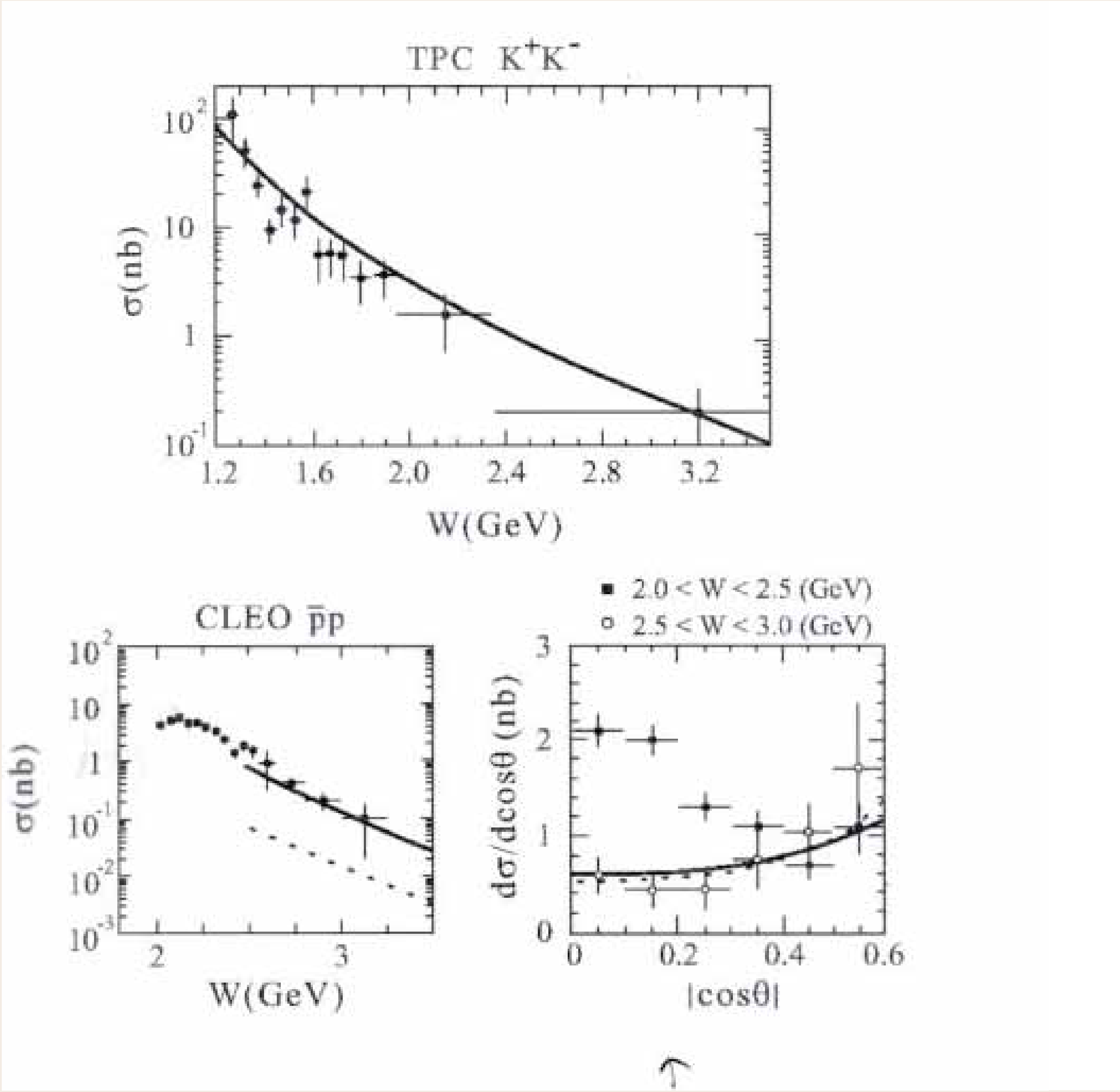


Fig. 4. Angular dependence of the cross section, $\sigma_0^{-1} d\sigma/d|\cos\theta^*|$, for the $\pi^+\pi^-$(closed circles) and K^+K^-(open circles) processes. The curves are $1.227 \times \sin^{-4}\theta^*$. The errors are statistical only.

Measurement of the $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to K^+K^-$ processes at energies of 2.4–4.1 GeV

Belle Collaboration


TPC K⁺K⁻
σ(nb)
W(GeV)
CLEO p̄p
σ(nb)
W(GeV)
2.0 < W < 2.5 (GeV)
2.5 < W < 3.0 (GeV)
dσ/dcosθ (nb)
|cosθ|

Two Regimes

$$\frac{\Delta\sigma(\gamma\gamma \to \pi^0\pi^0)}{\Delta\sigma(\gamma\gamma \to \pi^+\pi^-)}$$

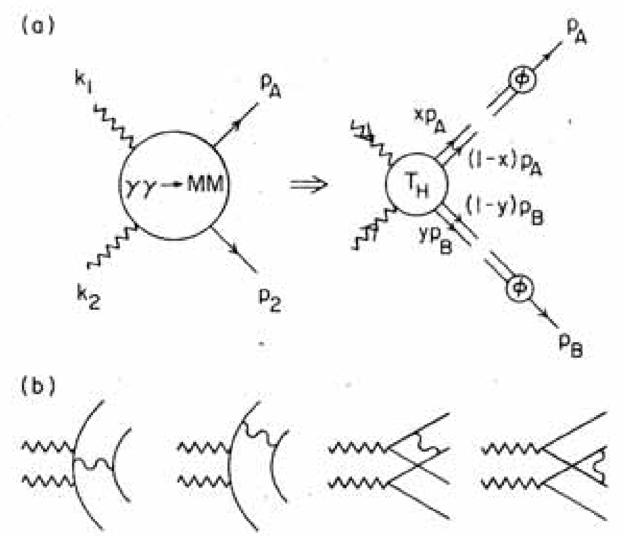


FIG. 1. (a) Factorized structure of the $\gamma\gamma \to M\overline{M}$ amplitude in QCD at large momentum transfer. The T_H amplitude is computed with quarks collinear with the outgoing mesons. (b) Diagram contributing to T_H ($\gamma\gamma \to M\overline{M}$) to lowest order in α_s.

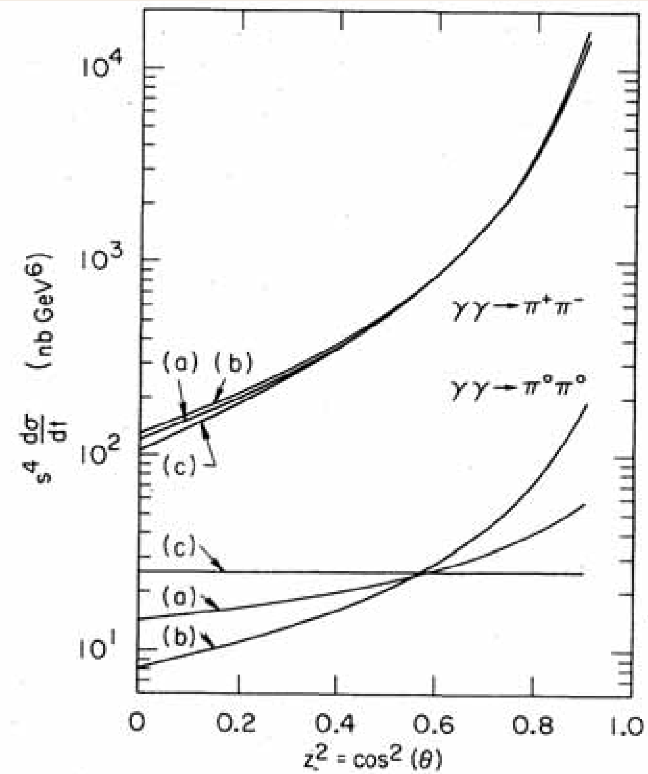
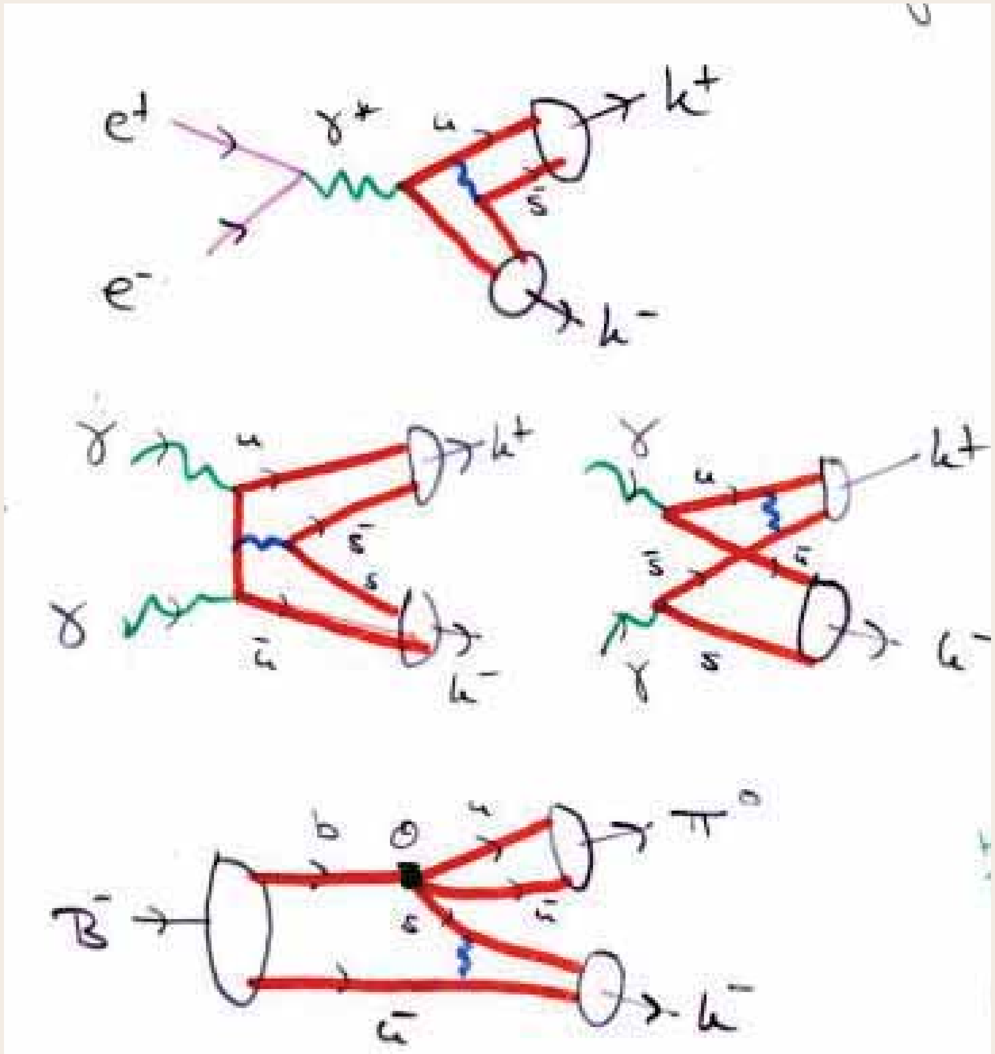


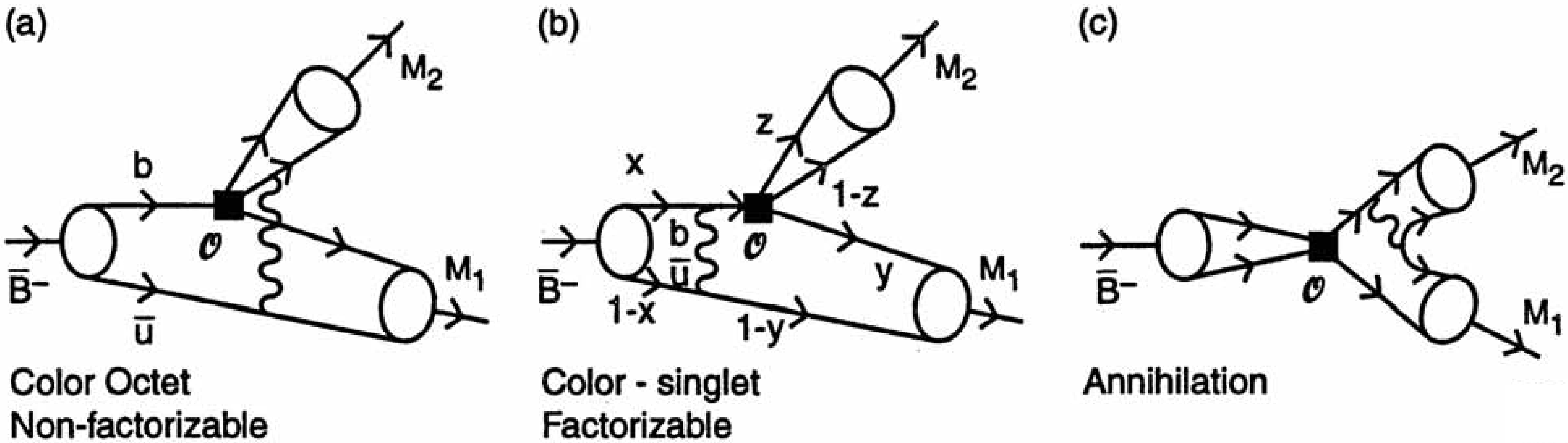
FIG. 3. QCD predictions for $\gamma\gamma \to \pi\pi$ to leading order in QCD. The results assume the pion-form-factor parametrization $F_\pi(s) \sim 0.4\ \mathrm{GeV}^2/s$. Curves (a), (b), and (c) correspond to the distribution amplitudes $\phi_M = x(1-x)$, $[x(1-x)]^{1/4}$, and $\delta(x-\frac{1}{2})$, respectively. Predictions for other helicity-zero mesons are obtained by multiplying with the scale constants given in Table I.

Handbag model (Diehl, Kroll et al) neglects $e_1 \times e_2$ cross terms -- Equal charged and neutral rate

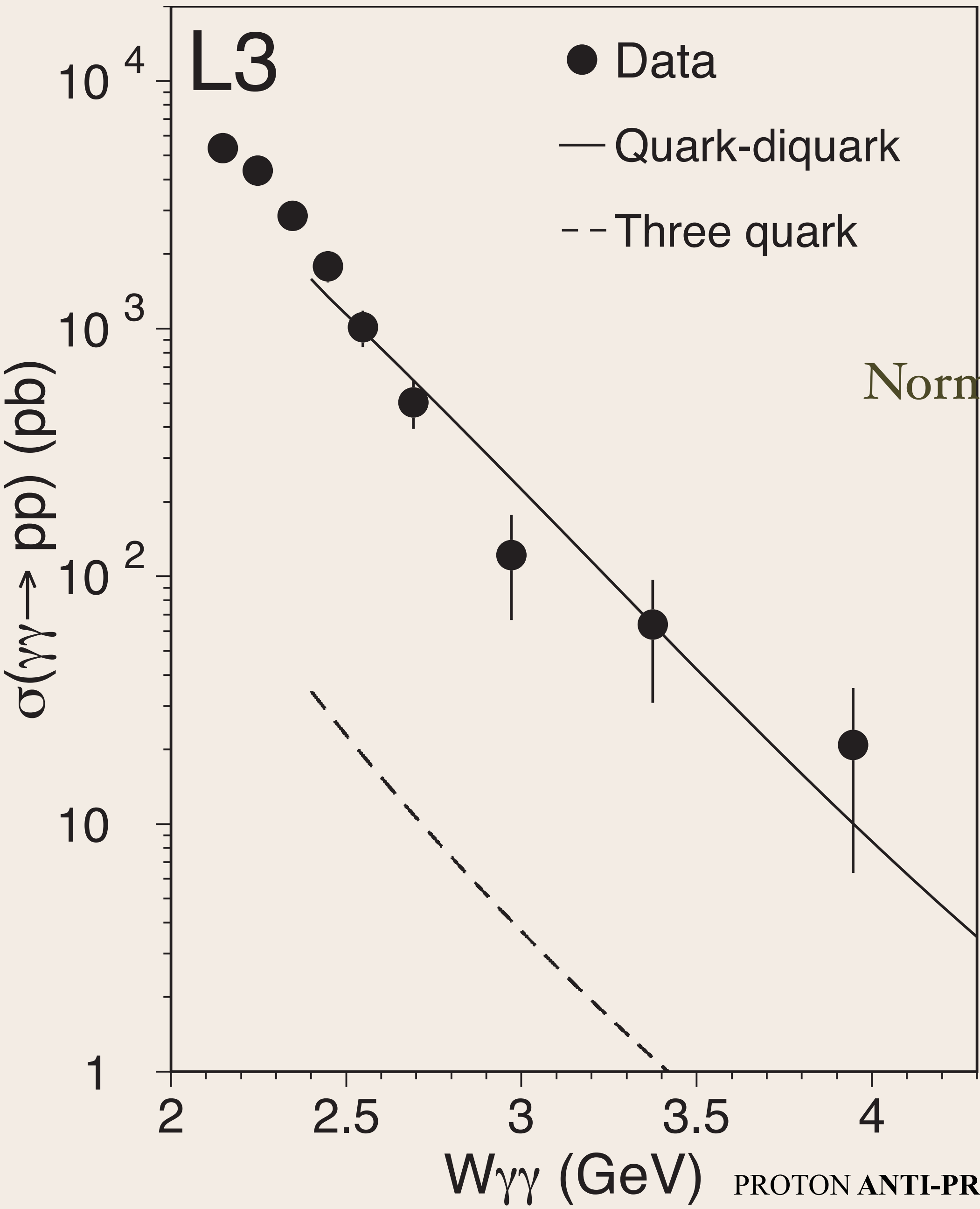
Common Ingredients:
Universal LFWFS, Distribution Amplitudes



Meson Distribution Amplitudes and Exclusive B decays



Three representative contributions to exclusive B decays to meson pairs in PQCD. The operators $\mathcal{O}$ represent the QCD-improved effective weak interaction.



Berger-Schweiger

Farrar-Maina-Neri

Normalization: Large uncertainties

$$\sigma(\gamma\gamma \rightarrow p\overline{p})$$

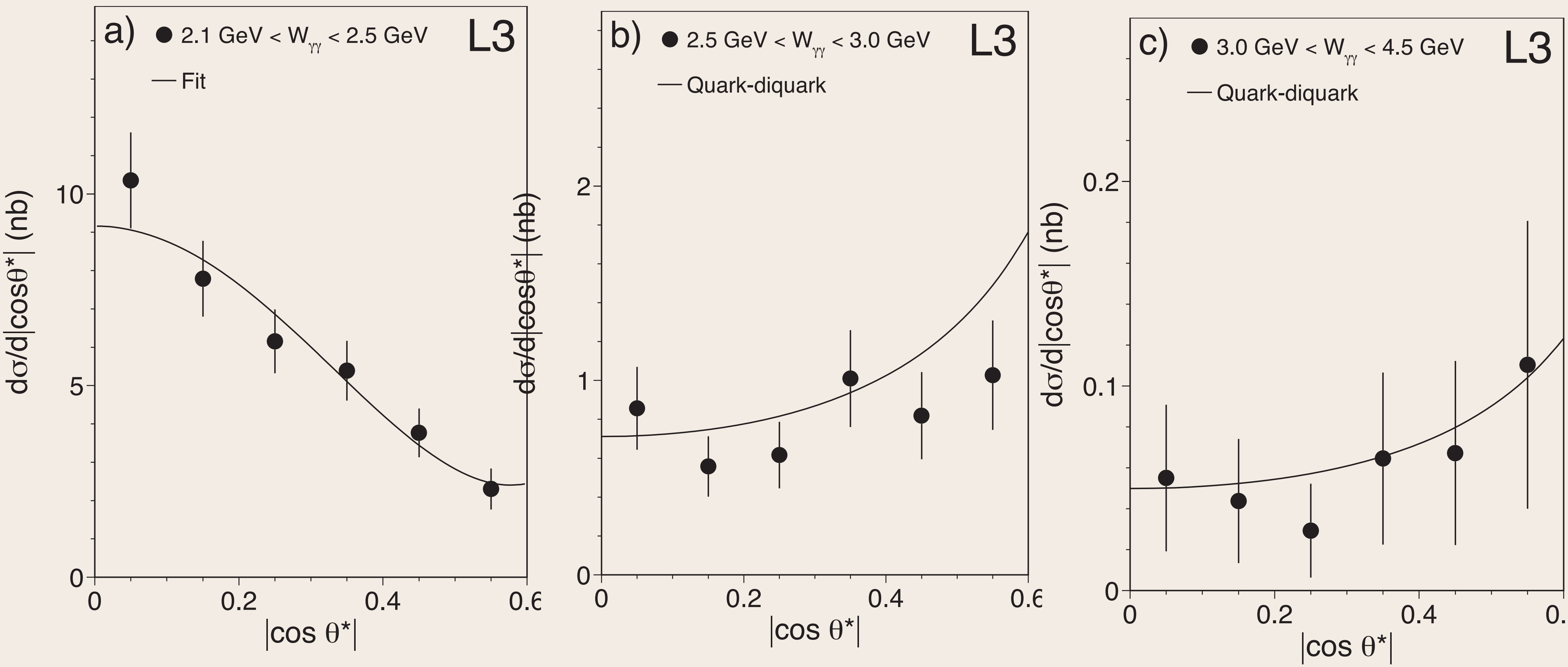
$$|cos\theta_{cm}| < 0.6$$

PROTON **ANTI-PROTON PAIR PRODUCTION IN TWO PHOTON COLLISIONS AT LEP.**
By L3 Collaboration (P. Achard *et al.*). CERN-EP-2003-014, Mar 2003. 17pp.
Published in **Phys.Lett.B571:11-20,2003**
e-Print Archive: **hep-ex/0306017**

Normalization of Hard Exclusive Amplitudes in PQCD

$$\frac{d\sigma}{dt}(\gamma\gamma \to B\overline{B})$$

- Decay constant f_N of nucleon unknown
- Running QCD coupling evalated at small scales
- Non-Abelian ggg coupling at higher orders



PROTON **ANTI-PROTON PAIR PRODUCTION IN TWO PHOTON COLLISIONS AT LEP.**
By L3 Collaboration (P. Achard *et al.*). CERN-EP-2003-014, Mar 2003. 17pp.
Published in **Phys.Lett.B571:11-20,2003**
e-Print Archive: **hep-ex/0306017**

The Photon Structure Function

VOLUME 27, NUMBER 5 PHYSICAL REVIEW LETTERS 2 AUGUST 1971

S. J. Brodsky
Stanford Linear Accelerator Center, Stanford, California 94305

and

Toichiro Kinoshita and Hidezumi Terazawa†
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850
(Received 27 April 1971)

Volume 36B, number 2 PHYSICS LETTERS 23 August 19

INELASTIC ELECTRON-PHOTON SCATTERING

T. F. WALSH
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

Received 19 March 1971

Nuclear Physics B41 (1972) 551–556.

SCALING BEHAVIOUR IN OFF-SHELL PHOTON-PHOTON SCATTERING

T.F. WALSH
II. Institut fur Theoretische Physik der Universitat Hamburg

P.ZERWAS ‡
Deutsches Elektronen-Synchrotron DESY, Hamburg

Received 14 February 1972

Nuclear Physics B120 (1977) 189–202

ANOMALOUS CROSS SECTION FOR PHOTON-PHOTON SCATTERING IN GAUGE THEORIES *

Edward WITTEN **
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540

Received 12 July 1976

We consider the deep inelastic structure functions of the photon in an asymptotically free gauge theory. In contrast to the case of a hadronic target, we find that the short-distance analysis determines the shape and magnitude and not merely the Q^2 dependence of the structure functions. The structure functions of the free quark theory are renormalized by finite, calculable factors. For example, at $x = 0.1$, we find that F_2 will, at large Q^2, exceed the free quark result by a factor 1.751, while for $x = 0.5$, F_2 is suppressed asymptotically, relative to the free quark theory, by a factor 0.964, and at $x = 0.8$, by a factor 0.611.

Deep Inelastic Scattering of Electrons on a Photon Target*

S. J. Brodsky
Stanford Linear Accelerator Center, Stanford, California 94305

and

Toichiro Kinoshita and Hidezumi Terazawa†
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850
(Received 27 April 1971)

BKT: Assume Bjorken Scaling

$$\frac{d\sigma(e+B\to e+\text{anything})}{dQ^2d\nu}=-\frac{2\pi\alpha^2}{(Q^2)^2}\left[W_2(Q^2,\nu)\left(1-y-\frac{y^2Q^2M^2}{4\nu^2}\right)+W_1(Q^2,\nu)\frac{y^2Q^2}{2\nu^2}\right], \tag{2}$$

where $P^2=M^2$ and $y=\nu/p\cdot P$. We have neglected the electron mass compared with the incident energy. We have defined W_1 and W_2 in such a way that we do not encounter any difficulty in passing to the limit $M=0$. From now on we shall regard B as a real photon. Of course in this case the rest system of the target no longer exists.

We now consider large-Q^2 and large-ν regions and assume that the Bjorken scaling limit[5] exists for the hadronic structure functions of the *photon*:

$$\lim_{\substack{\nu\to\infty\\ \omega\text{ fixed}}} W_1(Q^2,\nu)=F_1{}^{\gamma}(\omega),\qquad \lim_{\substack{\nu\to\infty\\ \omega\text{ fixed}}} \nu W_2(Q^2,\nu)=F_2{}^{\gamma}(\omega), \tag{3}$$

where $\omega=2\nu/Q^2$ $(\geq 1+m_\pi{}^2/Q^2)$, and $F_1{}^\gamma$ and $F_2{}^\gamma$ are dimensionless functions of ω and are implicitly of order α. Then for large ν and fixed ω we have the simple formula

$$\frac{d\sigma(e+\gamma\to e+\text{anything})}{dQ^2d\nu}=-\frac{2\pi\alpha^2}{\nu(Q^2)^2}\left[F_2{}^{\gamma}(\omega)(1-y)+F_1{}^{\gamma}(\omega)\frac{y^2}{\omega}\right]. \tag{4}$$

This shows clearly that electron-photon scattering experiments in the deep inelastic kinematical region will give us information on the hadronic structure functions $F_1{}^\gamma$ and $F_2{}^\gamma$ of the photon.

Nuclear Physics B120 (1977) 189–202

ANOMALOUS CROSS SECTION FOR PHOTON-PHOTON SCATTERING IN GAUGE THEORIES *

Edward WITTEN **
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540

Received 12 July 1976

$$\int_0^1 \mathrm{d}x\, x^{n-2} F(x, q^2) = \sum_i (M(q^2/\mu^2, g, \alpha)\, \hat{C}(1, \bar{g}^2, \alpha))_i \langle \gamma | \hat{O}_i | \gamma \rangle + \sum_i \left(\frac{e^2 r}{2b\bar{g}^2} \sum_k \frac{P_k}{1 + \lambda_k/2b} \right)_i \hat{C}_i(1, \bar{g}^2, \alpha) + D(1, \bar{g}^2, \alpha)\,. \qquad (8)$$

What are the scaling properties of the various terms?

We consider first the transverse structure function F_2. For F_2, $\hat{C}$ and D approach constant limits as $Q^2 \to \infty$. Therefore, the third term in (8) is Q^2 independent for large Q^2. The second term, however, will grow like $\ln Q^2$, because of the factor $1/\bar{g}^2$. In the first term, M will scale with the usual anomalous dimensions for hadron targets (see eq. (5)), which means that the first term is asymptotically Q^2 independent for $n = 2$, and logarithmically suppressed for $n > 2$. Therefore, the dominant term is the logarithmically growing second term, and each moment of F_2 will grow like $\ln Q^2$.

Ed Witten: Inhomogeneous Evolution Equation for the Photon Structure Function

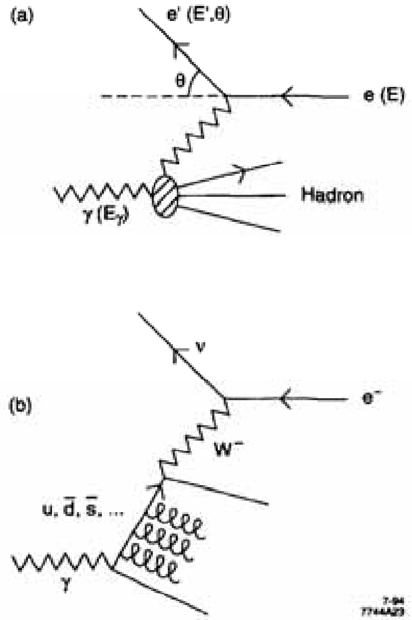


Fig. 16. (a) Deep-inelastic electron-photon scattering $e\gamma \to eX$. (b) The charged current process $e\gamma \to \nu X$ in deep-inelastic $e\gamma$ scattering.

S.J. Brodsky, P.M. Zerwas / Nucl. Instr. and Meth. in Phys. Res. A 355 (1995) 19–41

$$\frac{\partial q}{\partial t} = e_q^2 d_B + \frac{\alpha_s(t)}{2\pi}\left[A_{qq} * q + A_{qg} * G\right],$$

$$\frac{\partial G}{\partial t} = \frac{\alpha_s(t)}{2\pi}\left[A_{gq} * q + A_{gg} * G\right],$$

where $t = \log Q^2/\Lambda^2$ and $\alpha_s(t) = 1/bt$ [76].

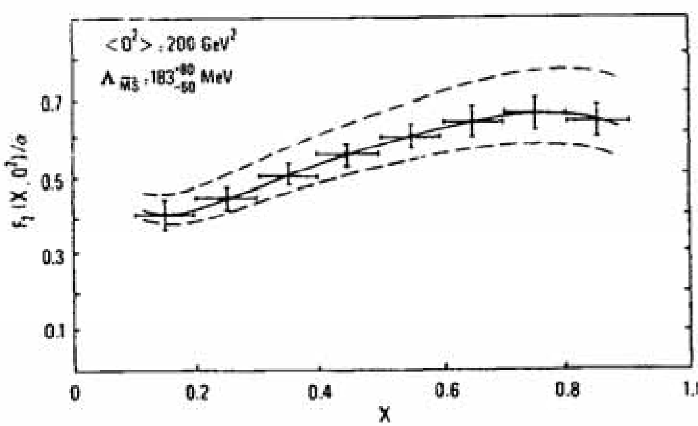


Fig. 18. QCD prediction for the photon structure $F_2^\gamma(x, Q^2)$ at $Q^2 = 200$ GeV^2 and sensitivity to the QCD Λ parameter. Error bars correspond to an integrated luminosity of 500 pb^{-1} at LEP200 and the range $100 < Q^2 < 500$ GeV^2 (from Ref. [85]).

The cross section for deep-inelastic scattering $e + \gamma \to e + X$ is parametrized by the transverse F_T^γ and the longitudinal F_L^γ structure functions (Fig. 16a),

$$\frac{d\sigma}{dx\,dy} = \frac{2\pi\alpha^2 s_{e\gamma}}{Q^4}\left[1 + (1-y)^2\right] \times \left[2xF_T^\gamma(x, Q^2) + \epsilon_y F_L^\gamma(x, Q^2)\right].$$

The transverse structure function can be substituted by the more familiar structure function $F_2^\gamma = 2xF_T^\gamma + F_L^\gamma$. The

Bjorken variable x and y can be expressed in terms of the momentum transfer Q^2, the invariant hadronic energy W, and the laboratory energies and electron scattering angle,

$$x = \frac{Q^2}{2qp_\gamma} = \frac{Q^2}{Q^2 + W^2}$$

$$= 1 - \frac{E'}{E}\cos^2\frac{\vartheta}{2}.$$

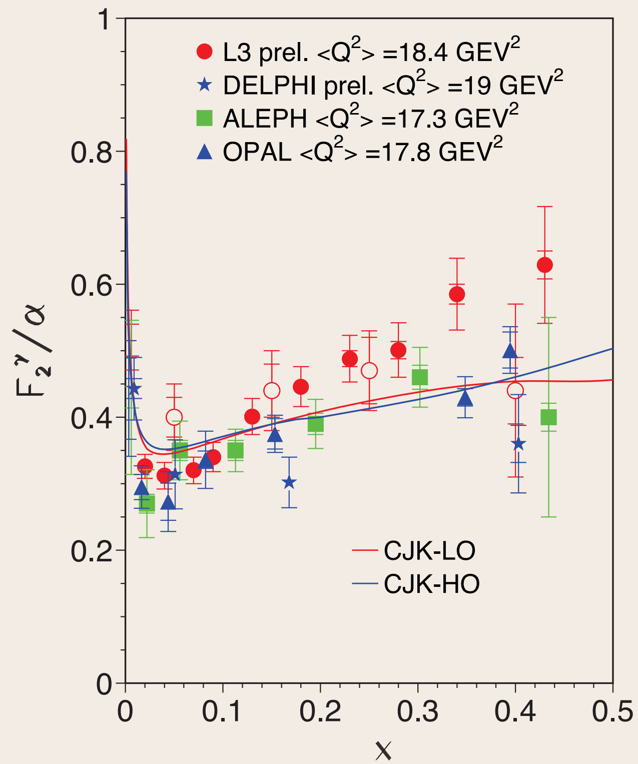
$$q(t) = q(t_0)\left[\frac{\alpha_s(t)}{\alpha_s(t_0)}\right]^{d_{NS}} + \frac{1}{3}\frac{d_B}{1+d_{NS}}\left\{t - \left[\frac{\alpha_s(t)}{\alpha_s(t_0)}\right]^{d_{NS}} t_0\right\}$$

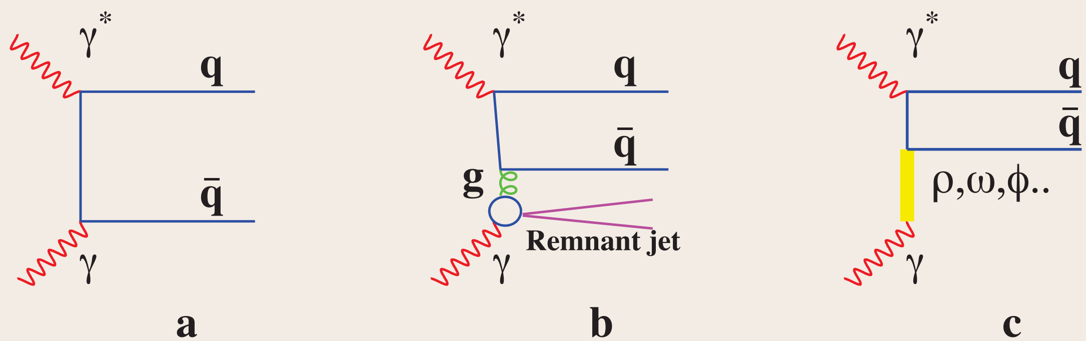
$$= \left\{q(t_0) - q_{pt}(t_0)\right\}\left[\frac{\alpha_s(t)}{\alpha_s(t_0)}\right]^{d_{NS}} + \frac{1}{3}\frac{d_B}{1+d_{NS}}\frac{2\pi/b}{\alpha_s(t)}.$$

The last term

$$q_{pt}(t) = \frac{1}{3}\frac{d_B}{1+d_{NS}}\frac{2\pi/b}{\alpha_s(t)}$$

Contributions to the Photon Structure Function





M. N. Kienzle-Focacci

Measurement of the Photon Structure Function F_2^γ with the L3 Detector at LEP

L3 Collaboration

CERN-PH-EP/2005-004
February 15, 2005

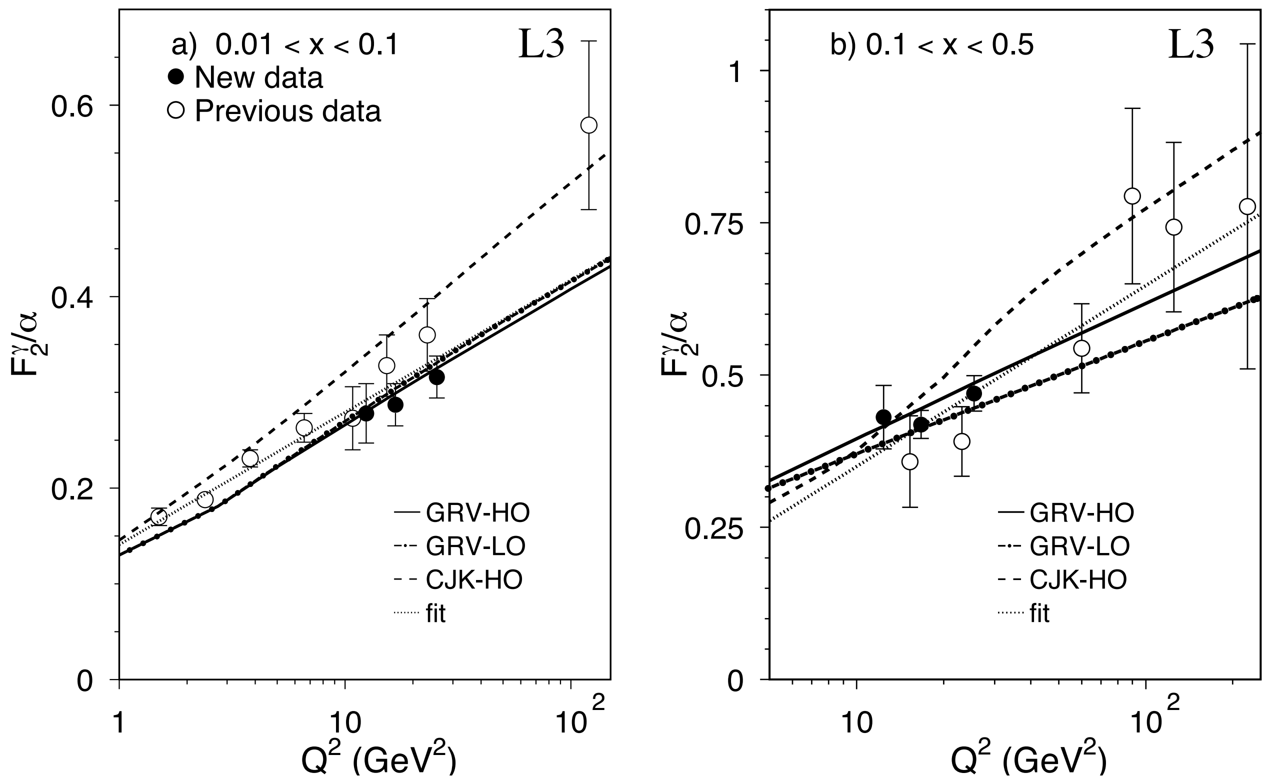


Figure 7: Evolution of the photon structure function F_2^γ/α as a function of Q^2 for two x intervals. The results of a fit to the data of the function $a + b(\ln Q^2/\text{ GeV}^2)$ are shown together with the predictions of the higher-order parton density functions GRV and CJK as well as the leading-order predictions of GRV.

Measurement of the Photon Structure Function F_2^γ with the L3 Detector at LEP

L3 Collaboration

CERN-PH-EP/2005-004
February 15, 2005

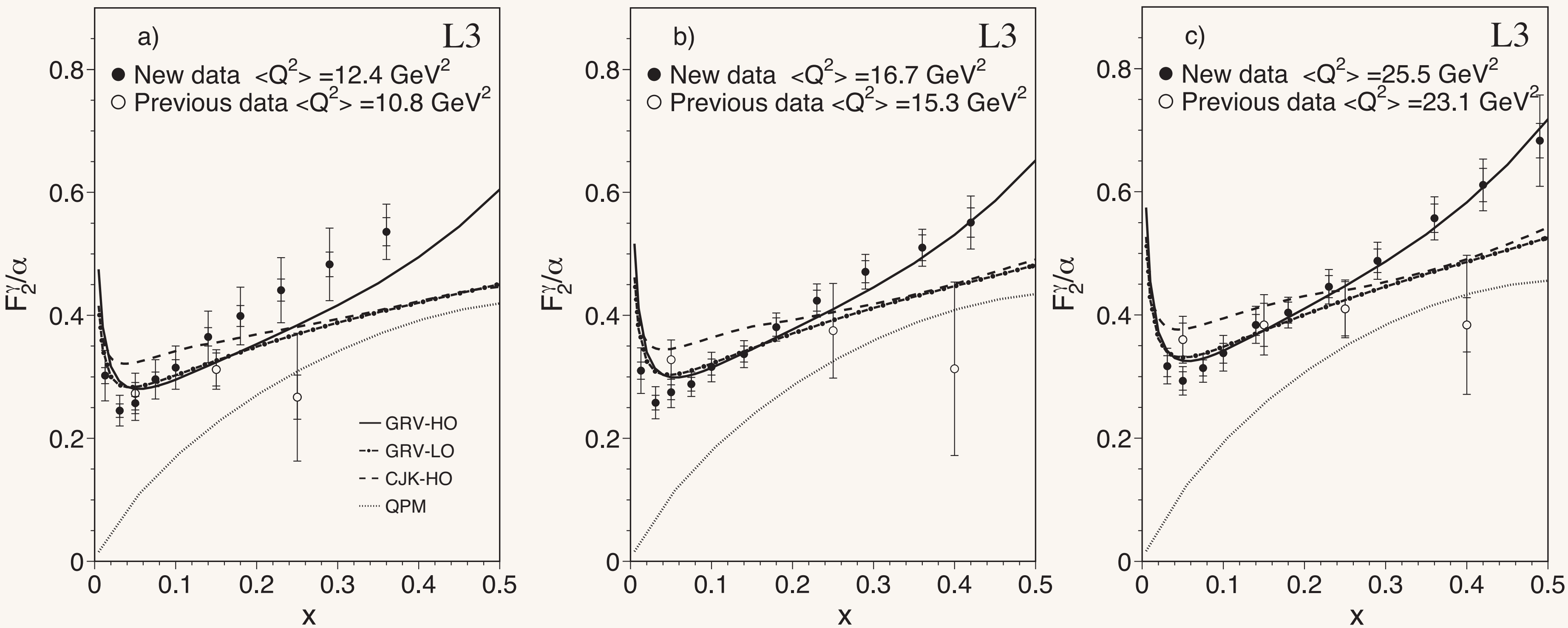


Figure 6: The photon structure function F_2^γ/α as a function of x for the three Q^2 intervals, with statistical and systematic uncertainties. The former are indicated by the inner error bars. The new data are presented together with the previous results at $\sqrt{s} = 183$ GeV [6]. The predictions of the higher-order parton density functions GRV and CJK are shown as well as the leading-order predictions of the GRV. The changes in slope of the CJK predictions are due to the c-quark threshold. The QPM predictions for $\gamma\gamma \rightarrow q\bar{q}$ are also shown.

Study Effects of Final-State Interactions in Deep Inelastic Scattering on a Photon Target

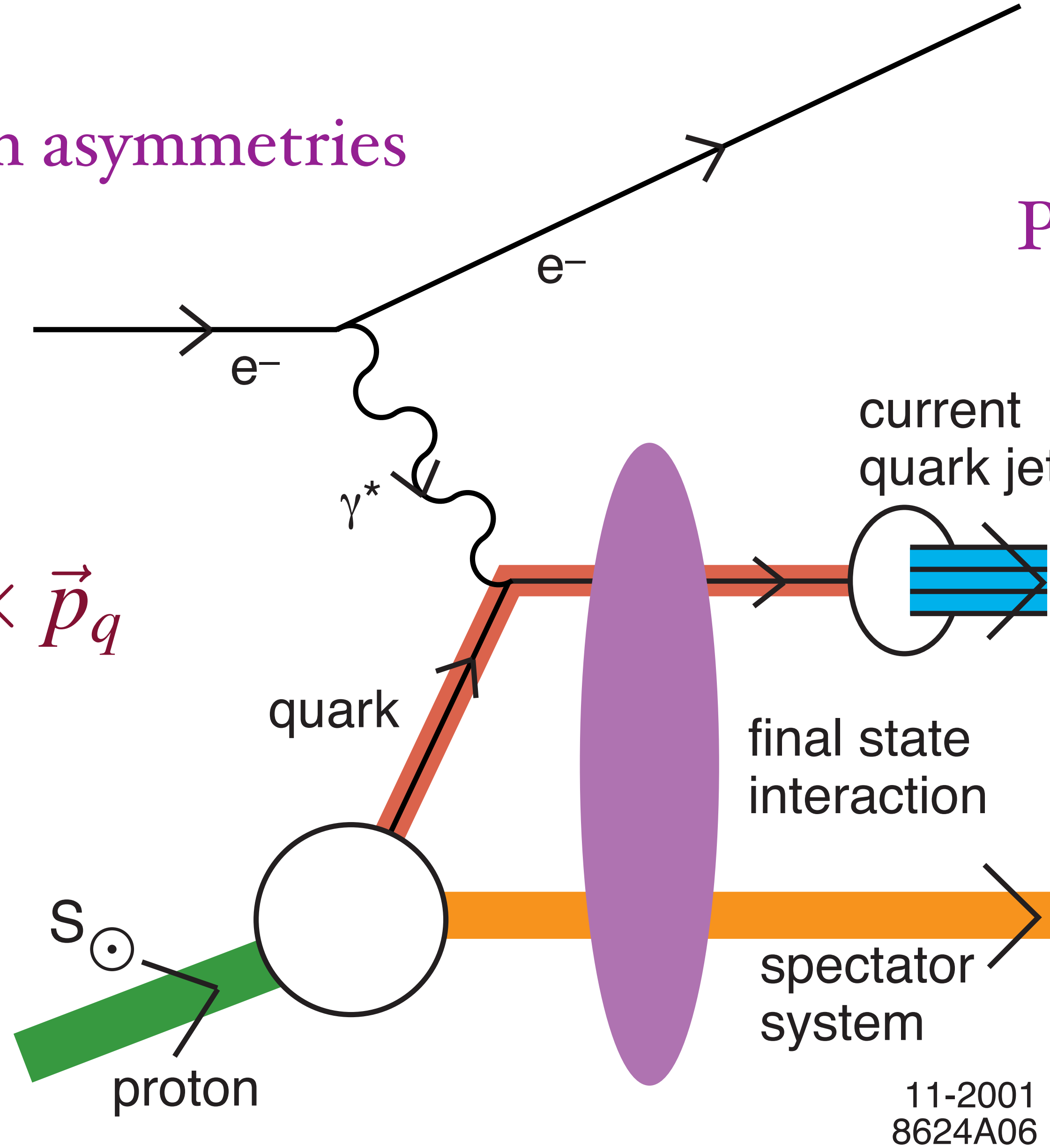
- Leading Twist Single-Spin Asymmetry:
  "Photonic Sivers Effect" — Hwang, Sivers, sjb; Collins

- Bjorken-Scaling Diffractive Contribution to the Photon Structure Function — Hoyer, Marchal,Peigne, Sannino, sjb

Single-spin asymmetries

Sivers Effect in Photon Structure Function

$\vec{S}_p \cdot \vec{q} \times \vec{p}_q$

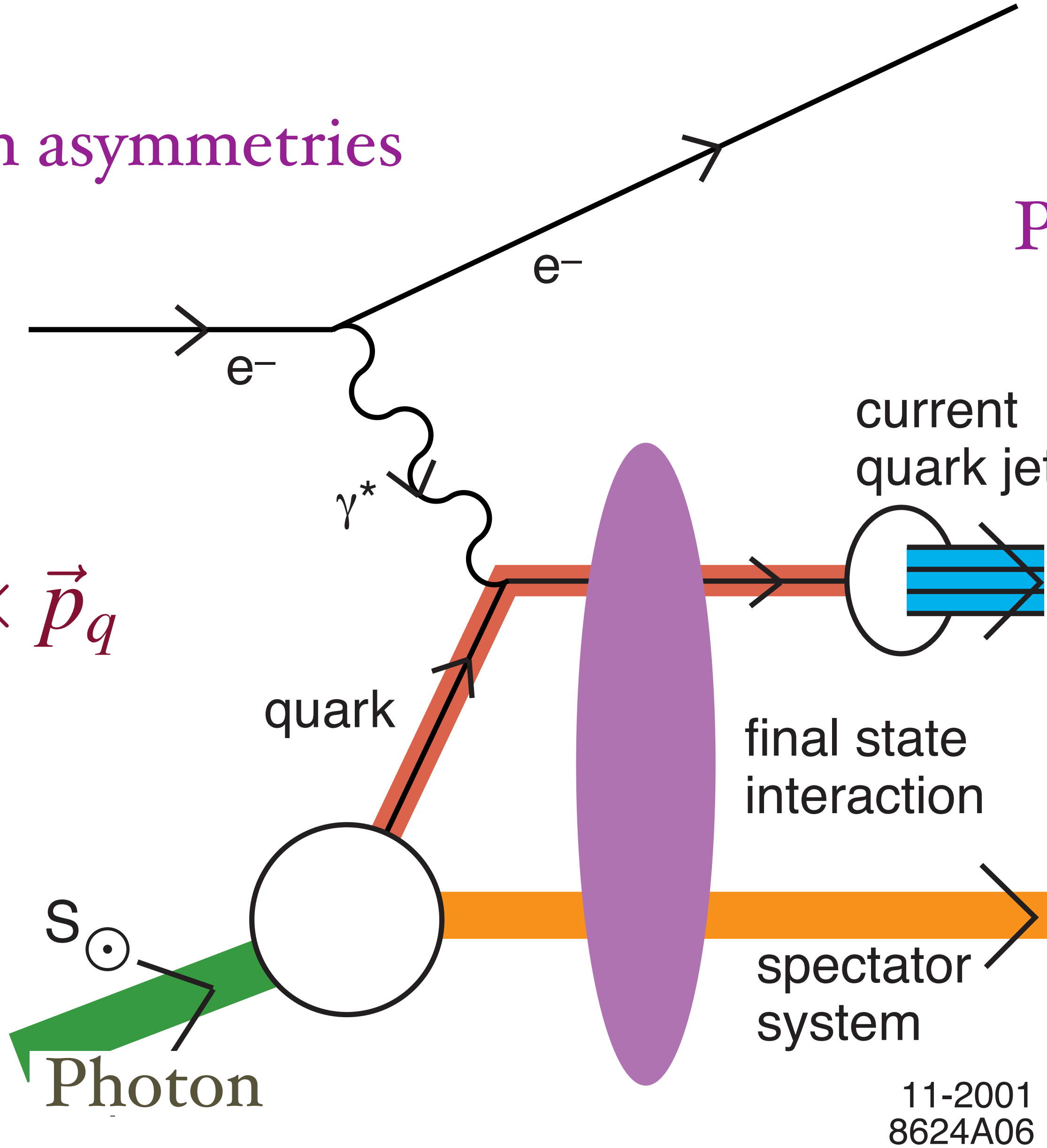


Replace by photon!

Single-spin asymmetries

Sivers Effect in Photon Structure Function

$$\vec{S}_\gamma \cdot \vec{q} \times \vec{p}_q$$



Final State Interactions Produce T-Odd (Sivers Effect)

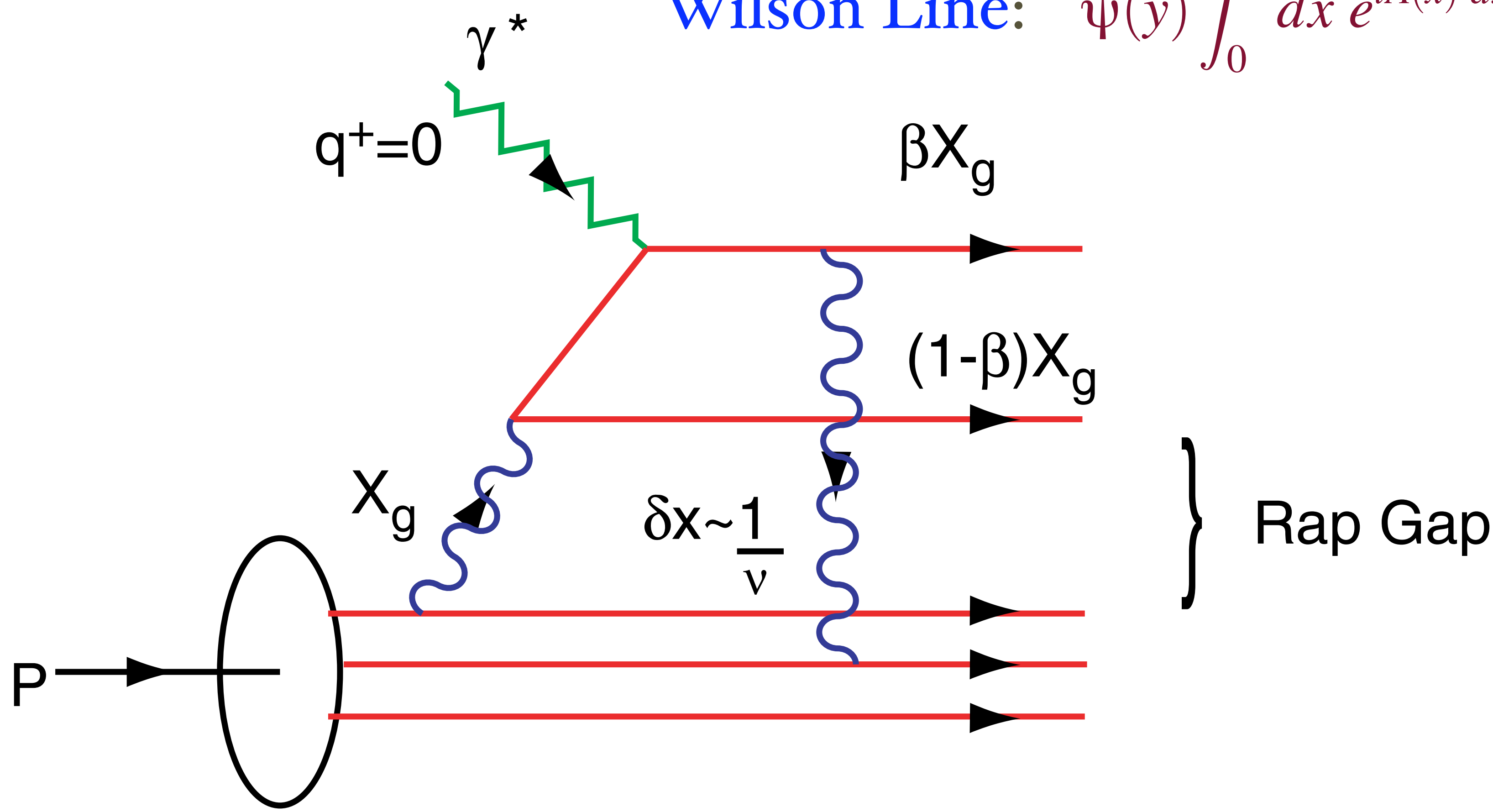
- Bjorken Scaling!
- Arises from Interference of Final State Coulomb Phase in S and P waves
- Orbital Angular Momentum in Photon!
- Relate to the quark contribution to the analog of the anomalous magnetic moment
- Sum of Sivers Functions for all quarks and gluons vanishes. (Zero gravito-anomalous magnetic moment

$$\vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$

Photon polarization from polarized electron

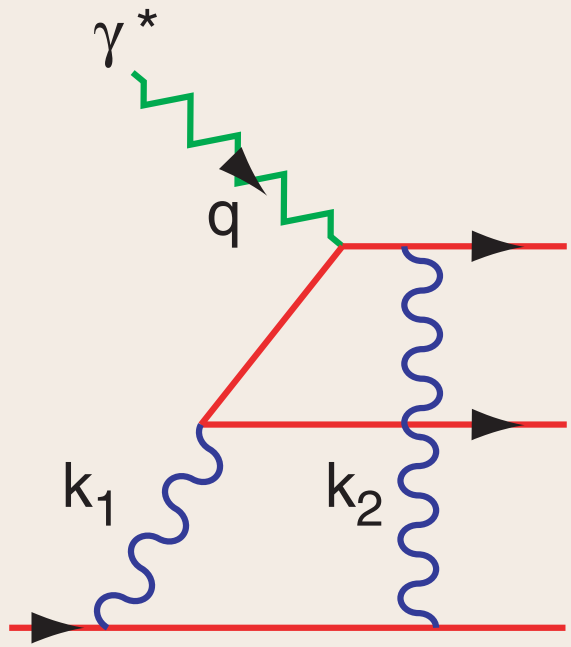
QCD Mechanism for Rapidity Gaps

Wilson Line: $\overline{\psi}(y) \int_0^y dx\, e^{iA(x)\cdot dx}\, \psi(0)$

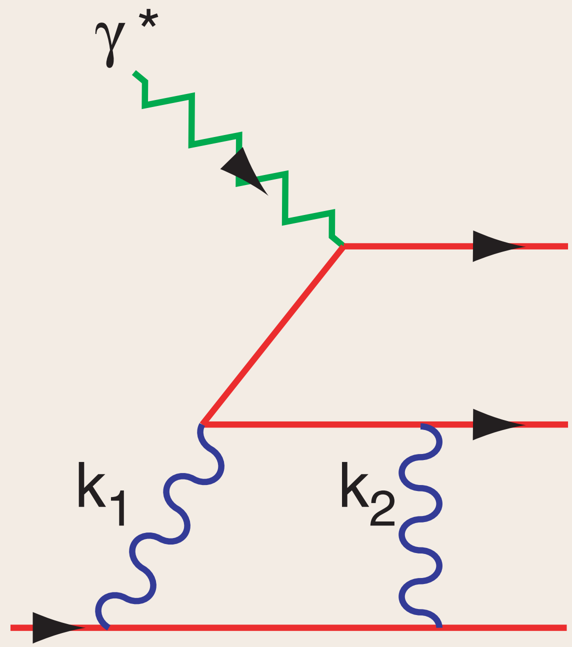


Produces Diffractive DIS at HERA

Final State Interactions in QCD



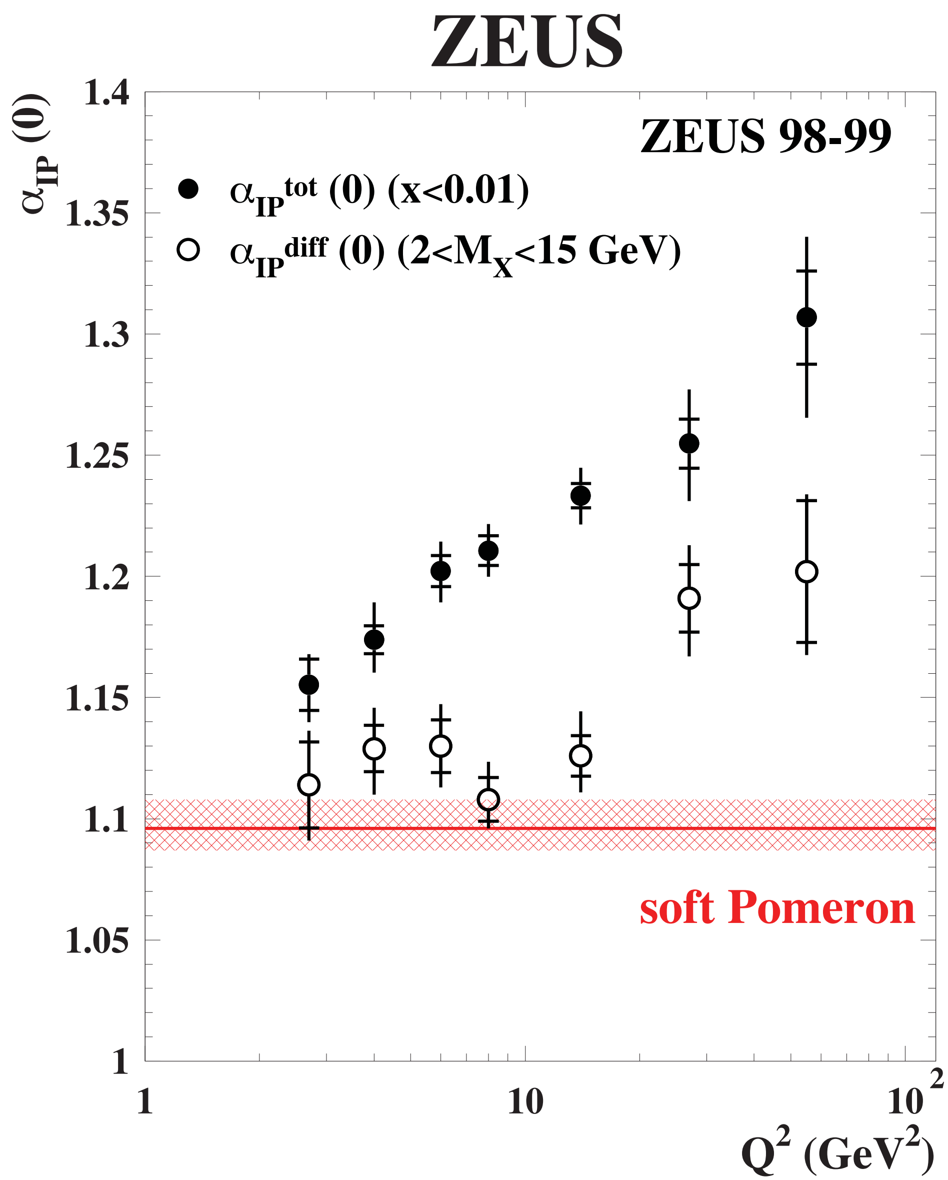
Feynman Gauge



Light-Cone Gauge

Result is Gauge Independent

Measure in $\gamma^*\gamma \to XV^0$



$$\sigma_{tot} \propto s^{\alpha_{tot}-1}$$

$$\sigma_{diff} \propto s^{2\alpha_{diff}-2}$$

No factorization of hard pomeron

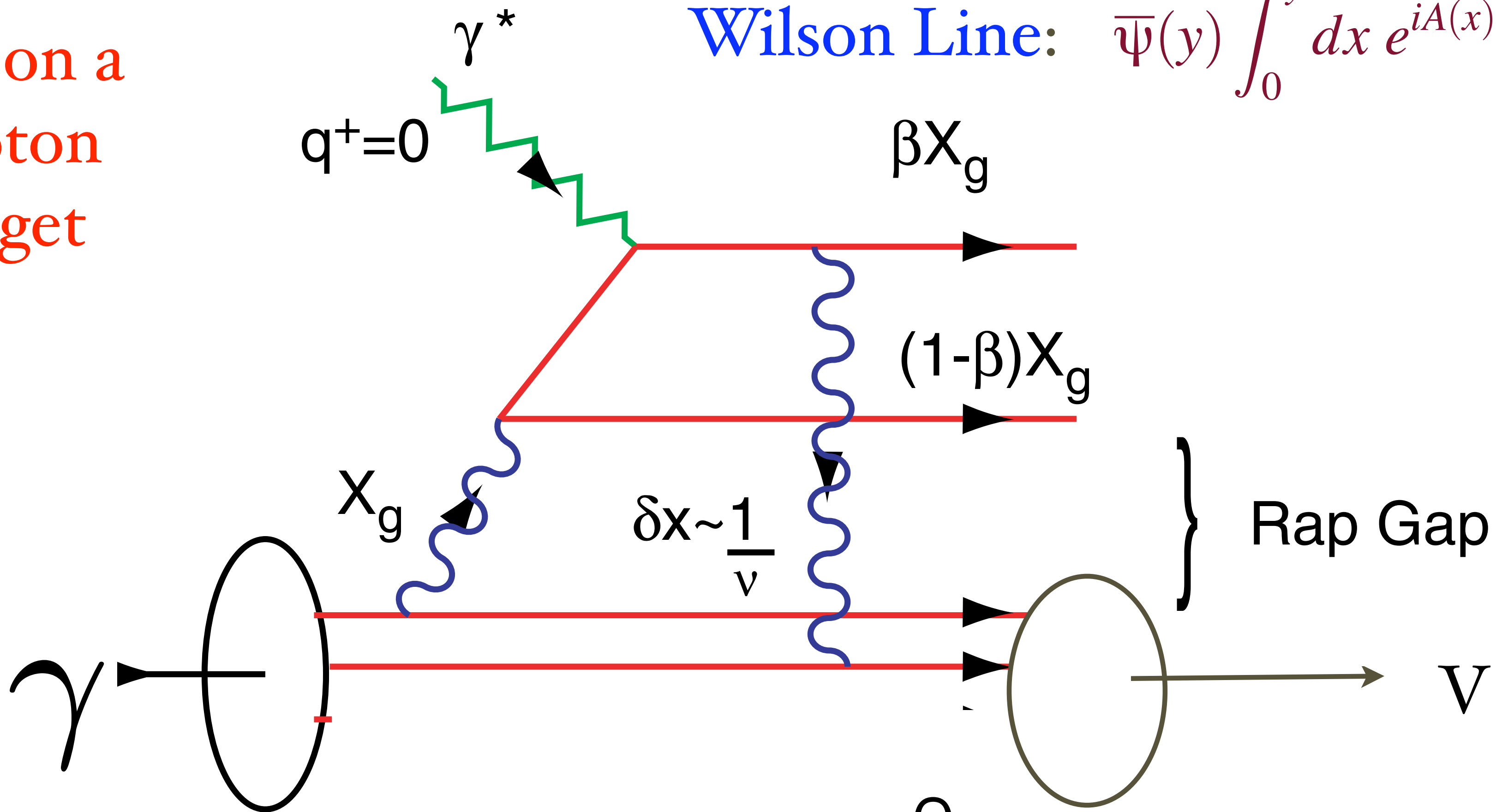
S. J. Brodsky, P. Hoyer, N. Marchal, S. Peigne and F. Sannino, Phys. Rev. D 65, 114025 (2002) [arXiv:hep-ph/0104291].
S. J. Brodsky, R. Enberg, P. Hoyer and G. Ingelman, arXiv:hep-ph/0409119.

DESY 05-011 hep-ex/0501060 January 2005
Study of deep inelastic inclusive and diffractive scattering with the ZEUS forward plug calorimeter
ZEUS Collaboration

QCD Mechanism for Rapidity Gaps

Diffractive DIS on a Photon Target

Wilson Line: $\overline{\psi}(y) \int_0^y dx\, e^{iA(x)\cdot dx}\, \psi(0)$

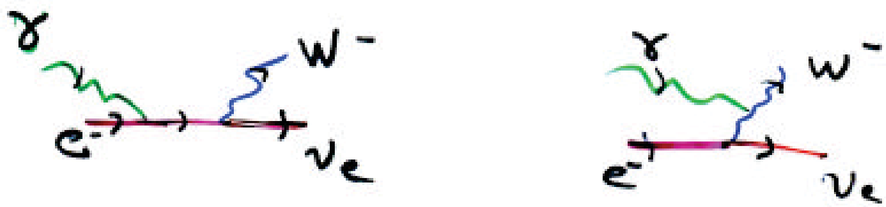


$$\gamma^*\gamma \to XV^0$$

γe Collisions:

Study Basic EW Interaction

$$\gamma e^- \to W^- \nu_e$$



DHG Sum rule
$$\int_0^1 \frac{d\nu}{\nu}(\sigma_P - \sigma_A) = O(\alpha^3)$$

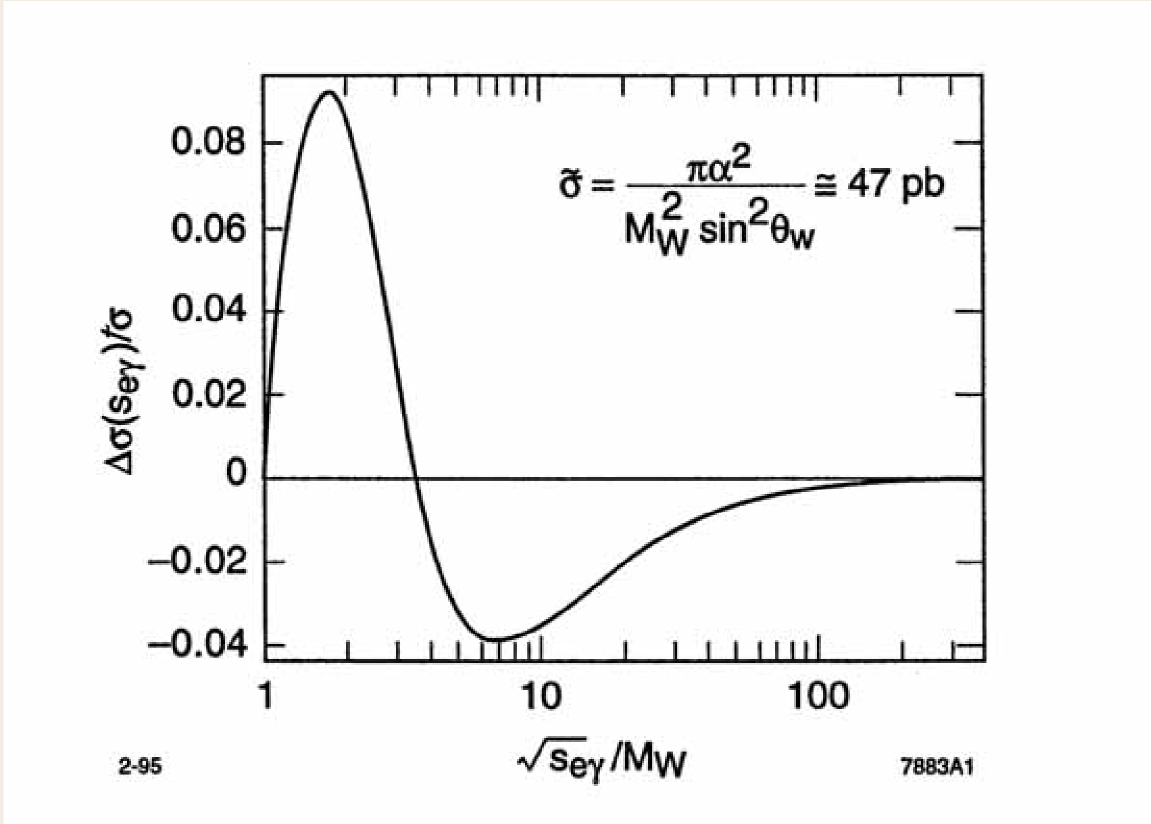
zero contribution at tree level
Miami et al

must be crossing point!
Rizzo et al

ν_e Highly sensitive to anomalous couplings W
$\Delta\kappa$, ΔQ

ref: Rizzo, Schmidt, SJB PRD 52, 4925 (9

Location of Zero Measures W anomalous moment



The Born cross section difference $\Delta\sigma$ for the Standard Model process $\gamma e \to W\nu$ for parallel minus antiparallel electron/photon helicities as a function of $\log \sqrt{s}_{e\gamma}/M_W$ The logarithmic integral of $\Delta\sigma$ vanishes in the classical limit.

Schmidt, Rizzo, sjb

Photon-Photon Collisions

- Remarkably Sensitive Tests of QCD: Hard Pomeron, Odderon, Hard Exclusive Reactions, Distribution Amplitudes, Photon-to-Meson Transition Form Factors, Double Distribution Amplitudes, Timelike Compton, Hard QCD Jets, C=+ Resonances, Jets, Top Production, Quark charge-cube test, Photon Structure Function, Novel Final-State Interaction Effects, Heavy Quarkonium

- Higgs and Electroweak Boson Production, W anomalous moment in photon-electron collisions

- SUSY, beyond the Standard Model Photon Structure Function

- Peripheral Heavy Ion Collisions

- Essential part of ILC!