Photon-Photon Interactions

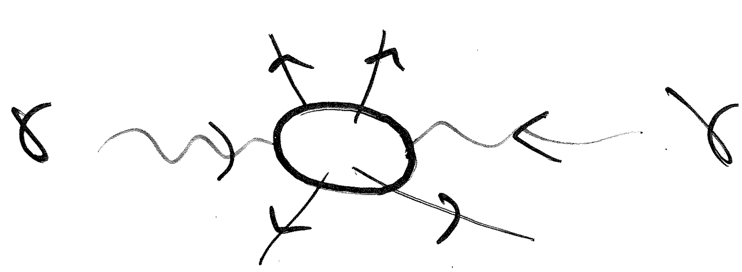
Stan Brodsky

SLAC

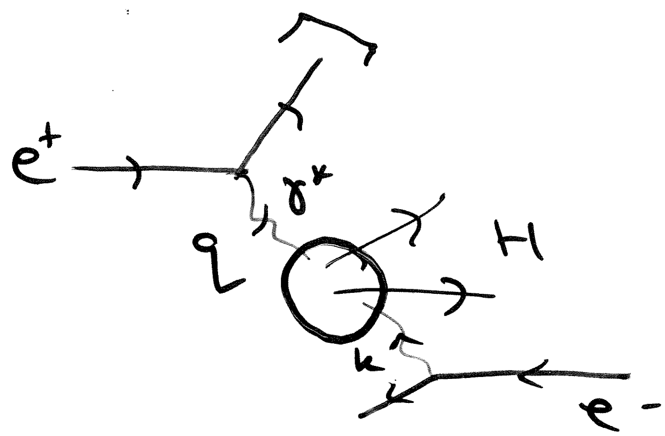
e^+e^- Physics at Intermediate Energies

P5P-N Workshop

May 2, 2001



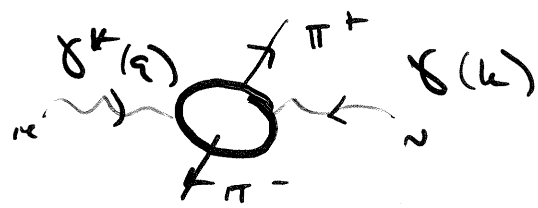
$\gamma^* \gamma \to H$ at PEP-N



tag scattered e^+

$\gamma^* \gamma \to H$

$\hookrightarrow \pi^0, \eta^0, \pi^+\pi^-, \pi^0\pi^0, K^+K^-$ ...

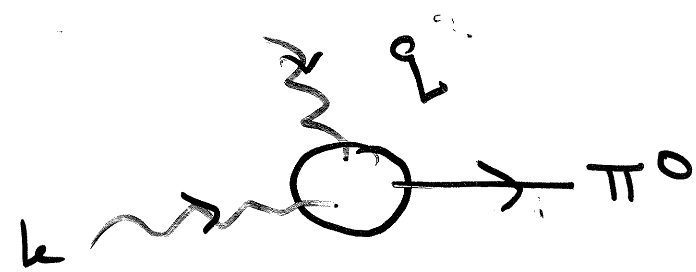
e.g. 

– $T^{\mu\nu} = i \int d^4x \, e^{-iq\cdot x} \langle \pi^+(p^+)\pi^-(p^-) | T J^\mu(x) J^\nu(0) | \gamma$

* Study real and virtual Compton scattering on π target via crossing

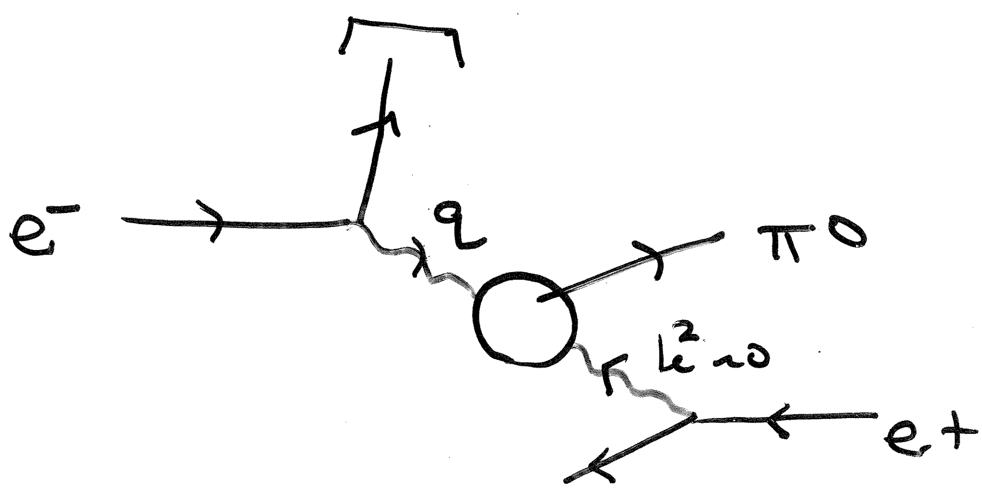
– L, T polarization
– planar correlations

Photon-to-Pion Transition Form Factor



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

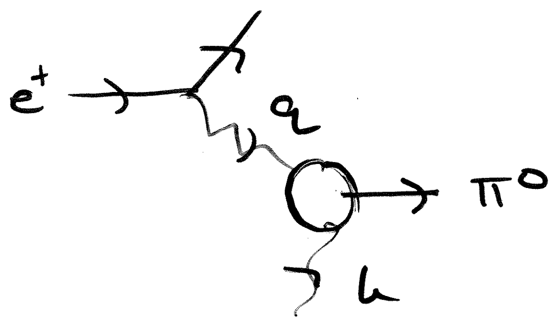
* Measure in e^+e^- colliders



CLEO

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

Simplest example of exclusive process



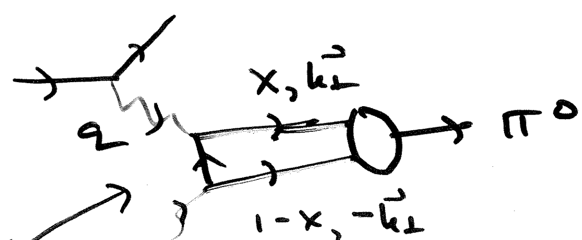
$F_{\gamma\pi^0}(q^2)$

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

$k^2 = 0$

Lepage 5.15

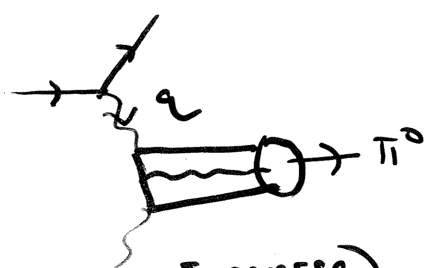
For $Q^2 \gg \Lambda^2_{QCD}$ analyze in PQCD



gives $\frac{1}{Q^2}$

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

$+$



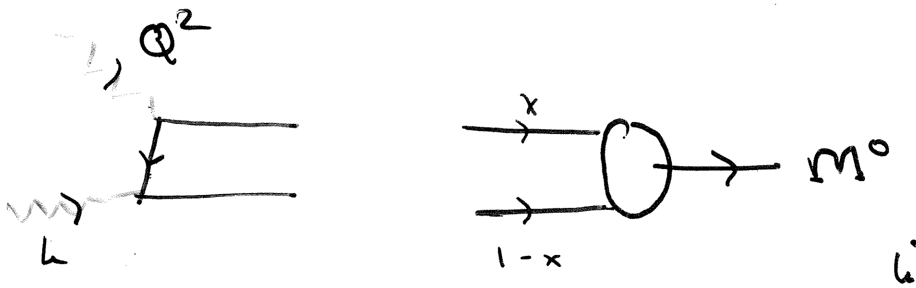
suppressed by $1/Q^2$

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

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

pion distribution amplitude

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



T_H

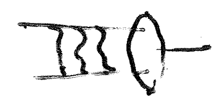
$$\phi_M(x,Q) = \int^{k_\perp^2 < \tilde{Q}^2} d^2k_\perp\, \psi_{q\bar{q}}(x,k_\perp)$$

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

$\mathcal{O}(Q)$

* 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

** <u>Small part of Fock state dominates</u>

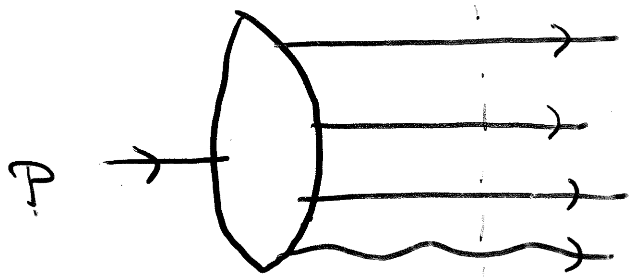
$$\phi_M \sim \psi(x, b_\perp \sim \tfrac{1}{Q})$$

Light-Cone Wavefunctions

and QCD Phenomena

Non-Perturbative QCD

$\{\Psi_n\}$: translation: hadrons $\Rightarrow q, g$



$x_1, \vec{k}_{\perp 1}, \lambda_1$

$$x_i = \frac{k_i^+}{P^+} = \frac{k_i^0 + k_i^z}{P^0 + P^z}$$

fixed $\tau = t + z/c$ Dirac

$$|\Psi\rangle = \sum_n |n\rangle \, \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

← free q, g basis

$$\sum_{i=1}^{n} x_i = 1 \, , \quad \sum_{i=1}^{n} \vec{k}_{\perp i} = 0$$

"Light-cone Fock expansion"

boost invariant Frame-indep.

$\tau = t + z/c$

Dirac
Bjorken, Kogut, Soper
Lepage + SJB
Pauli + SJB

Equation of motion

$$i \frac{\partial}{\partial \tau} |\Psi_H\rangle = P^- |\Psi_H\rangle = \frac{M_H^2 + \vec{P}_\perp^2}{P^+} |\Psi_H\rangle$$

$$H_{LC} = P^- P^+ - P_\perp^2$$

$P^+ , P_\perp$
kinemetical

$$\boxed{H_{LC} |\Psi_H\rangle = M_H^2 |\Psi_H\rangle}$$

$\Rightarrow$ eigenvalue problem for LC Hamiltonian

Insert complete set of color-singlet H_{LC}^0 eigenstates

$$\sum_n |n\rangle\langle n| = I$$

$$\sum_n \langle m | H_{LC} | n \rangle \langle n | \Psi_H \rangle = M_H^2 \langle m | \Psi_H \rangle$$

DLCQ

$\Rightarrow$ Heisenberg matrix form of eigenvalue problem

$$|\Psi_H\rangle = \sum_n |n\rangle\langle n | \Psi_H\rangle = \sum_n |n\rangle \psi_{n/H}(x_i, \vec{k}_{\perp i}, \lambda_i)$$

$\Rightarrow$ LC Fock expansion of eigenstate $|\Psi_H\rangle$

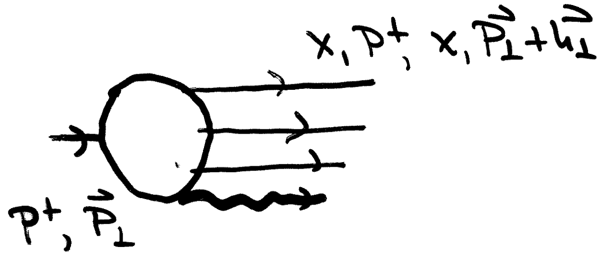
* Given $\{\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)\}$

wavefunction known for all $\underline{P^\mu}$!

relative coordinates

$$|P^+, \vec{P}_\perp\rangle = \sum_n \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) \prod_j \frac{1}{\sqrt{x_j}} \, |x_i P^+, x_i \vec{P}_\perp + \vec{k}_{\perp i}, \lambda_i\rangle$$

absolute coordinates



In equal-time theory (instant form)

boosts mix with interactions

changing $\vec{P} \to \vec{P}'$ as complicated

as solving $H|\Psi\rangle = E|\Psi\rangle$

Factorization of Exclusive Amplitudes at Large Momentum Transfer

Lepage SJB
Efremov Radyushkin
Chernyak etc

$$* \quad \mathcal{M} = \int [dx] \prod_i \phi_i(x,Q) \, T_H$$

- Accurate to leading twist $+ O\left(\frac{1}{Q}\right)^n$
- ϕ_i universal distribution amplitude
- T_H: hard scattering amplitude
  - perturbative calculable in α_s
- Hadron helicity conservation $\sum_{init} \lambda_H = \sum_{final} \lambda_H$
- Quark Counting Rules
- Color Transparency
- End-point suppression by Sudakov effect

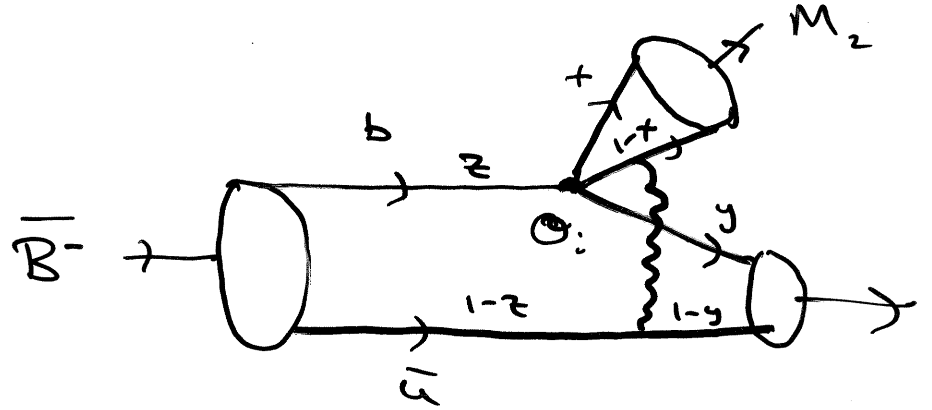
Berger + SJB

Many applications: form factors, higher twist DIS, fixed θ_{cm} scattering, heavy hadron decay

New Analyses of B → MM in PQCD

BBNS : Beneke, Buchalla, Neubert, Sachrajda

KLS : Keum, Li, Sanda



"octet"
non-factorizable

$\alpha_s(k^2)$: BLM scale

* $$\mathcal{M}_{B\to M_1 M_2} = \int_0^1 dz \int_0^1 dx \int_0^1 dy$$

$$\phi_B(z,Q)\; T_H(z,x,y;Q)\; \phi_{M_2}(x,Q)\; \phi_{M_1}(y,Q)$$

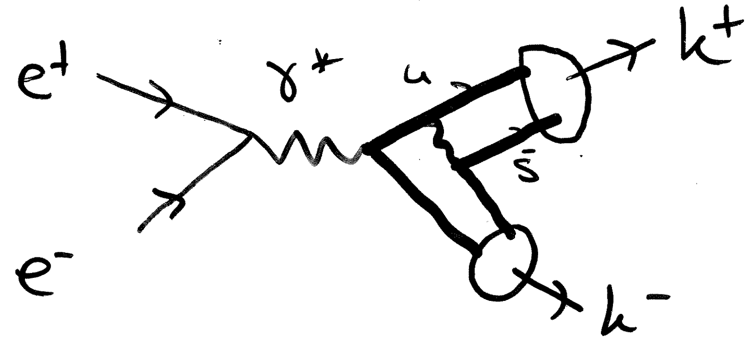
$b\bar{u} \to q\bar{q}\, q\bar{q}$

* No end-point singularities

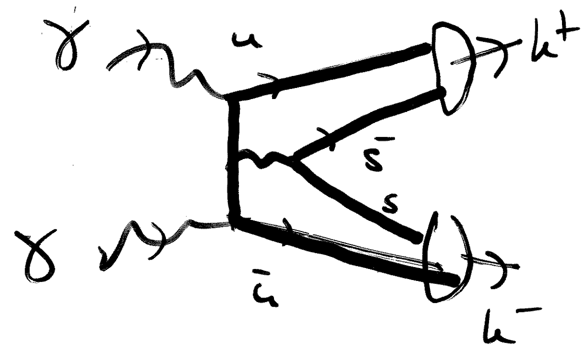
* Color Transparency

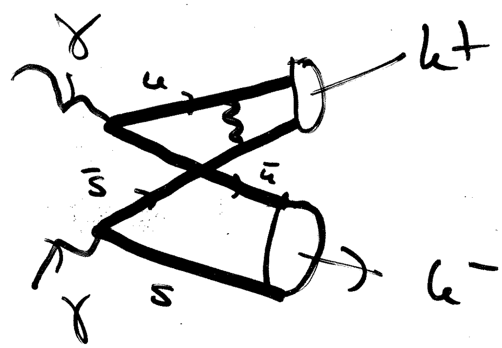
* $Q^2 = \mathcal{O}(M_B^2)$: Factorization scale

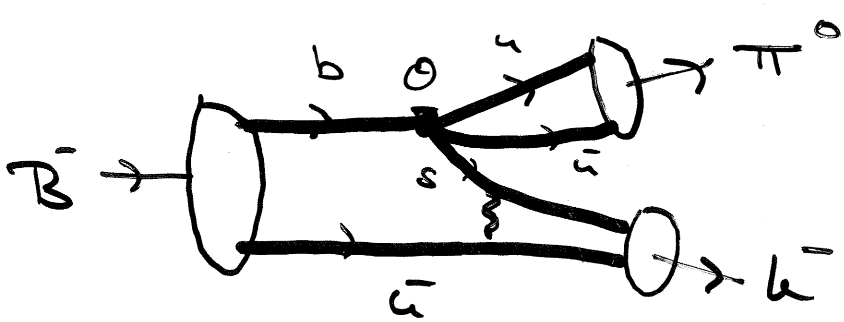
<u>Universal</u> Light-Front Wavefunctions



G. P. Lepage
SJB







Henley
Szczepaniak
SJB

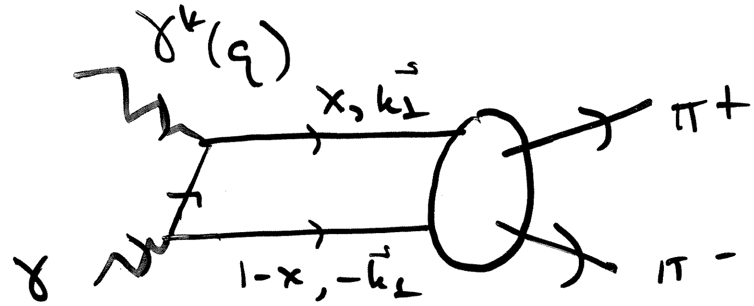
Common Ingredients: Distribution Amplitudes

* $\phi_\pi(x, Q)$, $\phi_K(x, Q)$ Amplitudes

* $\alpha_s(Q)$ at low scales

Use $\gamma^* \gamma \to M \bar{M}$

to predict B-decays

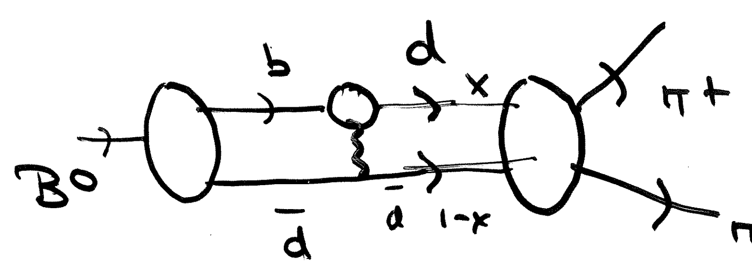


$k_\perp^2 < (1-x) Q^2$

Measures

$$\frac{1}{Q^2} \int_0^1 \frac{dx}{1-x} \; \phi_{\pi^+\pi^-}(x, k^2_{\perp max}; M^2_{\pi\pi})$$

M. Diehl et al



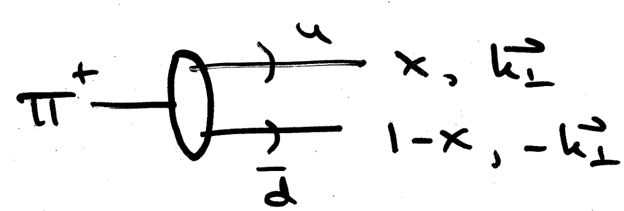
Measures $\phi_{\pi^+\pi^-}(x, k^2_{\perp max} = M_B^2, M_B^2)$

weighted by $\phi^B_{d\bar{d}}(x)$

G. P. Lepage
SSB

Pion Distribution Amplitude

$$\phi_\pi(x,Q^2) = \int \frac{d^2k_\perp}{16\pi^3}\, \psi^{(Q)}_{q\bar q/\pi}(x,\vec k_\perp)$$



$$\sim\ \psi_{q\bar q/\pi}\left(x,\, b_\perp \sim O\left(\tfrac{1}{Q}\right)\right)$$

$$\phi_\pi(x,Q) = \int \frac{dz^-\, P_\pi^+}{4\pi}\, e^{ix P_\pi^+ z^-/2}$$

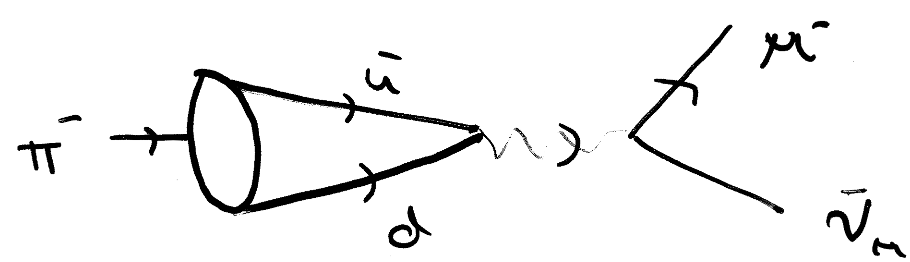
$$\langle 0|\bar\psi(0)\,\frac{\gamma^+\gamma_5}{2\sqrt{2n_c}}\,\psi(z)|\pi\rangle^{(Q)}\Big|_{z^+=\vec z_\perp=0}$$

$$P\exp\int_0^1 ds\, i g\, A(sz)\cdot z = 1 \quad \text{in } A^+=0 \text{ gauge}$$

$$= \int \frac{dk^-}{2\pi}\, \psi_{BS}(k,p)$$

obeys: OPE, RGE, Evolution Eqn.

Valence wavefunction normalized to pion decay constant



$$\int_0^1 dx \, \phi_\pi(x, Q) = \frac{f_\pi}{2\sqrt{3}}$$

Evolution Eqn. for Distribution Amplitudes

$$\phi_M(x, Q) = \int \frac{d^2k_\perp}{16\pi^3} \, \psi^{(Q)}_{q\bar{q}}(x, \vec{k}_\perp) \, \Theta\left(Q^2 - \frac{k_\perp^2}{x(1-x)}\right)$$

$$= x_1 x_2 \tilde{\phi}$$

$$\boxed{x_1 x_2 \frac{\partial}{\partial \ln Q^2} \tilde{\phi}_M(x, Q) = \frac{\alpha_s(Q^2)}{4\pi} \int_0^1 dy \, V(x,y) \, \tilde{\phi}_M(y, Q)}$$

* $$V(x,y) = 2C_F \, x_1 y_2 \, \Theta(y_1 - x_1)\left(\delta_{h_1 \bar{h}_2} + \frac{\Delta}{y_1 - x_1}\right) + (1 \leftrightarrow 2)$$

$$\Delta \tilde{\phi} = \tilde{\phi}(y_1, Q) - \tilde{\phi}(x_1, Q)$$

$$x_1 = x, \quad x_2 = 1 - x$$

$\delta_{h_1 \bar{h}_2} = 1$ for opp hel

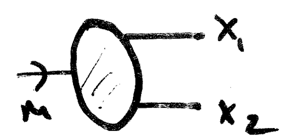
favors opp hel.

For baryons:

* $$V(x_i, y_i) = 2 x_1 x_2 x_3 \sum_{i \neq j} \Theta(y_i - x_i) \, \delta(x_k - y_k) \, \frac{y_j}{x_j} \left(\frac{\delta_{h_i \bar{h}_j}}{x_i + x_j} + \frac{\Delta}{y_i - x_i}\right)$$

$\phi_M(x_i, Q)$

Hadron Distribution Amplitude



$k_\perp^2 < Q^2$

- key non-perturbative input to hadronic exclusive processes at large momentum transfer

Rigorous results

$$\phi(x_i, Q) \equiv \left(\ln \frac{Q^2}{\Lambda^2}\right)^{-n\gamma_n/2\beta_0}$$

$$\int \prod_{i=1}^{n} \{d^2 k_\perp^{(i)}\, \Theta(Q^2 - m_n^2)\}\, \delta^{(2)}(\Sigma k_\perp^{(i)})\, \psi^{val}(x_i, \vec{k}_\perp^{(i)})$$

$$\phi_M(x_i, Q) = x_1 x_2 \sum_n a_n\, C_n^{3/2}(x_1 - x_2) \left(\ln \frac{Q^2}{\Lambda^2}\right)^{-\gamma_n/2\beta_0}$$

Lepage SJB Efremov Radyushkin

non-perturbative input

from conformal symmetry

$$\xi(Q^2) = \frac{1}{2\pi}\int^{Q^2} \frac{d\ell^2}{\ell^2}\, \alpha_s(\ell^2)$$

deviations from conformal symmetry

$$e^{-\gamma_n \xi(Q^2)} \Rightarrow \left(\ln Q^2/\Lambda^2\right)^{-\gamma_n/2\beta_0}$$

"Asymptotic" Distribution Amplitude

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

- Leading anomalous dimension in OPE
- Solution to QCD evolution eqn
  at $Q^2 \to \infty$

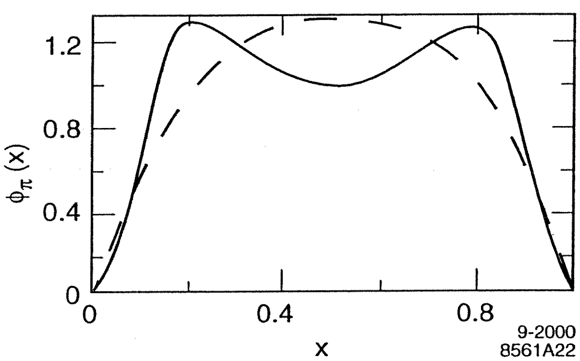
SJB + GPL

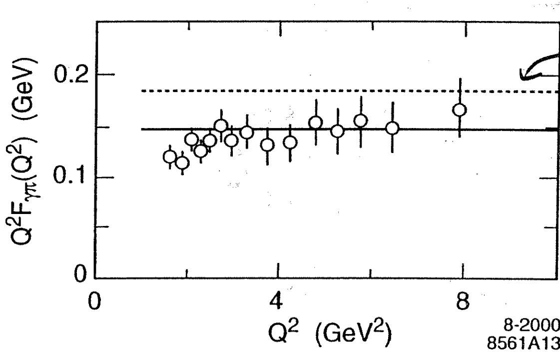
- $$\frac{\partial}{\partial \ln Q^2} \phi(x, Q^2) = \int dy\, V(x,y)\, \phi(y,Q^2)$$

- Non-perturbative methods
  DLCQ + Transverse lattice

Dalley
Burkardt

- Normalized by $\pi \to e\nu$





asympt

NLO

—— transverse lattice/DLCQ

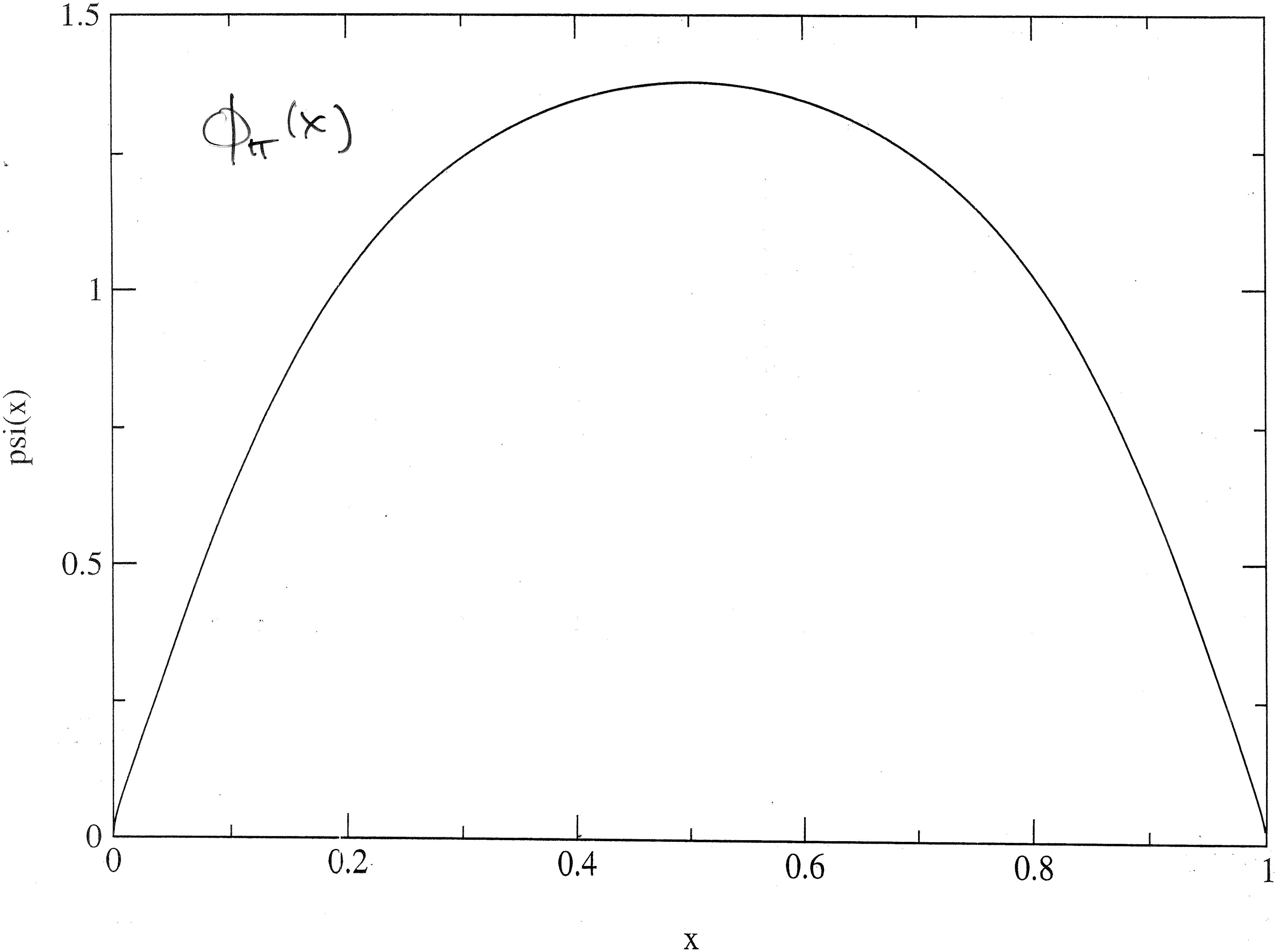
Dalley

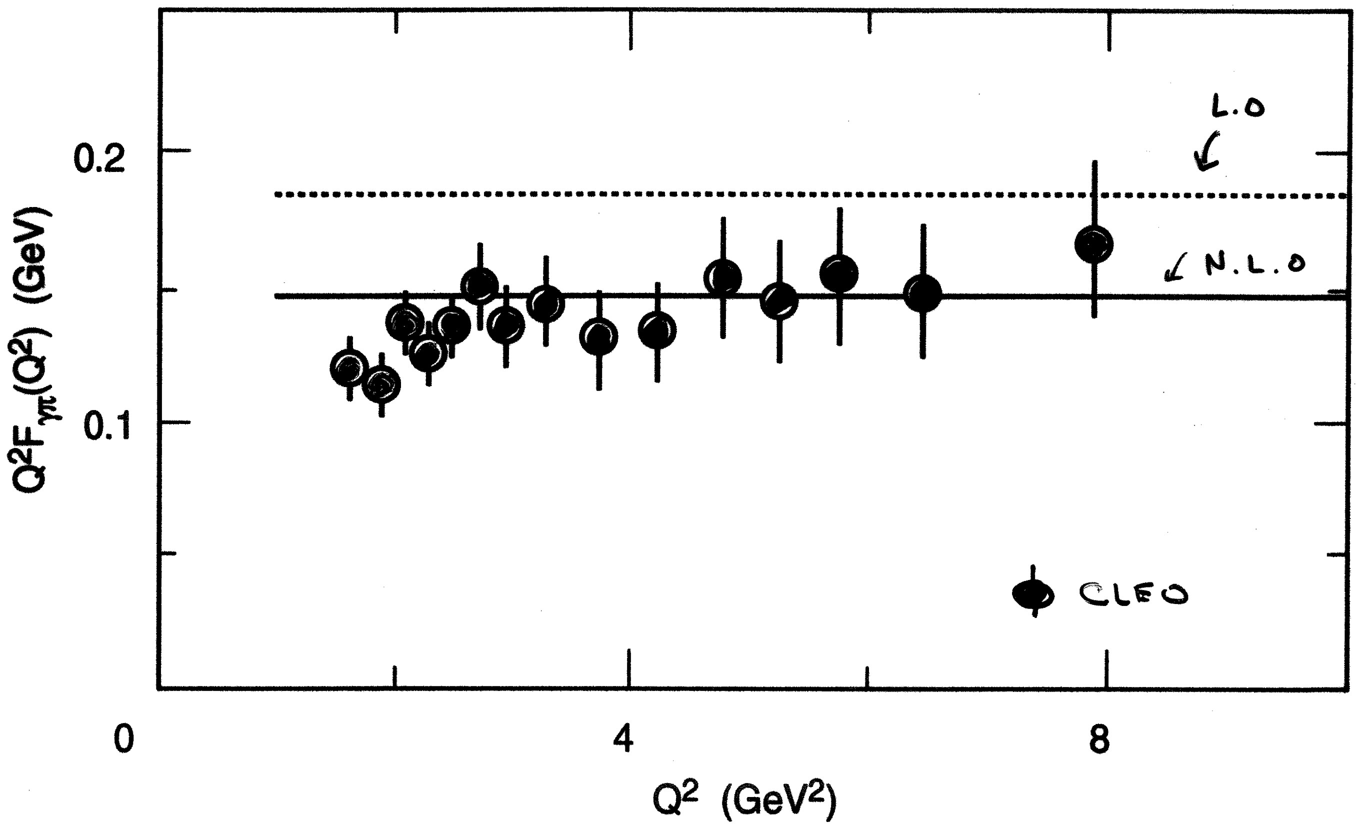
- - - Asymptotic dist. ampl.

Burkardt

Transverse Lattice + DLCQ

Burkardt + Seal





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assumes $\phi_\pi(x) = \phi_{asympt}(x)$

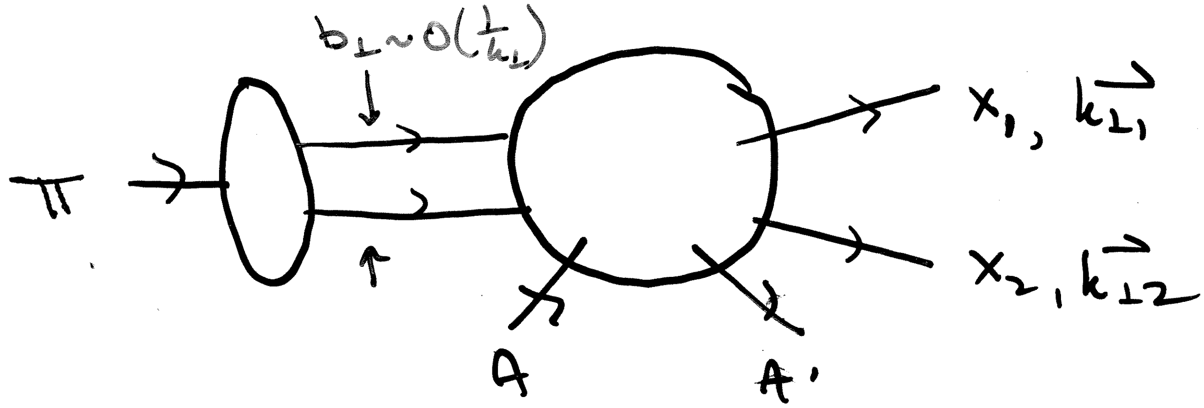
$= \sqrt{3} f_\pi\, x(1-x)$

Measure $\psi_H^{val}(x, k_\perp)$ via Diffractive Dissociation

$\boxed{\pi A \to q\bar{q} A'}$

Bertsch, Goldhaber, Gunion, SJB

Frankfort, Miller, Strikman



reconstruct jets

$$x_1 + x_2 \cong 1$$

$$\vec{q_\perp} = -\vec{k_{\perp 1}} - \vec{k_{\perp 2}} < R_A^{-1}$$

$\vec{k_\perp}$ large: color transparency $M_A \sim A^1 M_N$

$q_\perp$ small $\quad \frac{d\sigma}{dq_\perp^2} \propto e^{-q_\perp^2 R_A^2/3}$

* $\int \frac{d\sigma}{dq_\perp^2} dq_\perp^2 \sim \frac{A^2}{R_A^2} \sim A^{4/3}$

* $x, \vec{k_\perp}$ dist $\Rightarrow \left|\frac{\partial^2}{\partial k_\perp^2} \psi(x, k_\perp^2)\right|^2$

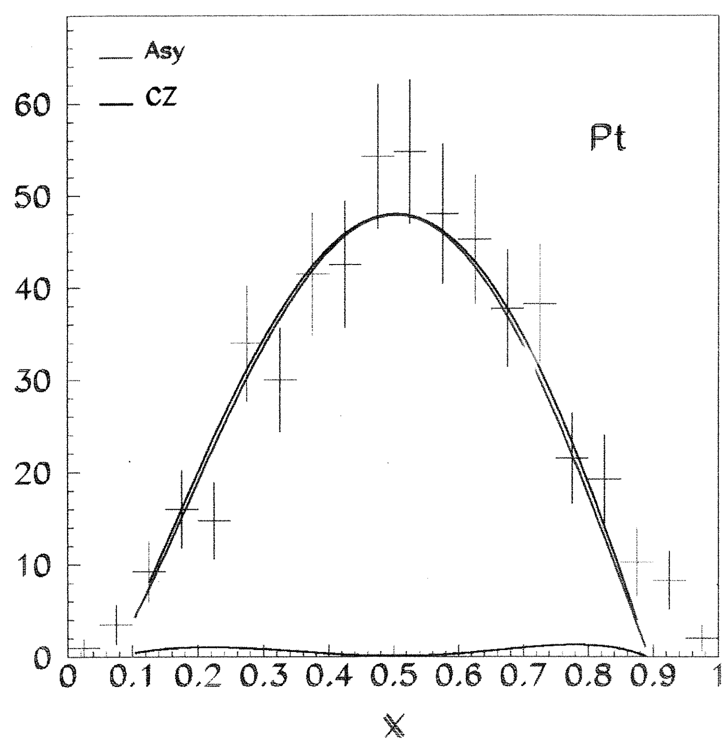
E791 DATA - THE $q\bar{q}$ MOMENTUM WAVE FUNCTION AS MEASURED BY THE DI-JETS

- Use the diffractive di-jets to extract the momentum x distribution.
- Fit to a combination of the two wave function simulations.

$$\phi^2 = \alpha\phi^2_{Asy} + \beta\phi^2_{CZ}$$

$\phi_{Asympt}(x, Q^2)$
$\Rightarrow$ for $x(1-x)$
$\sqrt{3}$
Soln to
PQCD
evol. eqn.

$$k_t > 1.5GeV/c\ ;\ Q^2 \sim 10GeV^2$$



$\phi_\pi^{Asymp} \propto x(1-x)$

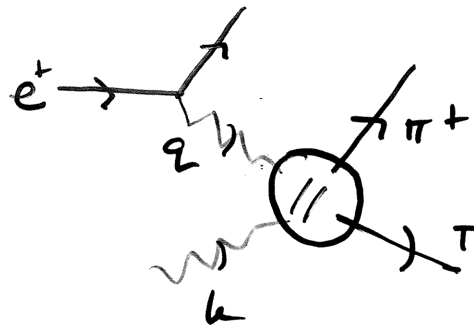
PRELIMINARY: $>$ 90% Asymptotic W.F.

Same as
seen in
$F_{\gamma\to\pi^0}(Q^2)$

Diehl

D. Müller Goussset

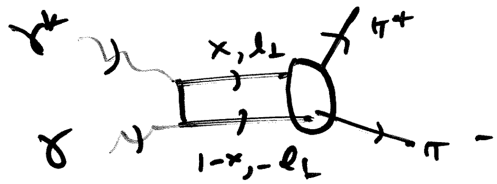
Pire



Analyze in PQCD

for fixed $W^2 = m^2_{\pi\pi}$

and $Q^2 \gg \Lambda^2_{QCD}$



$$T^{\mu\nu} = -g_T^{\mu\nu} \sum_q \frac{e_q^2}{2} \int_0^1 dx \left[\frac{1}{1-x} - \frac{1}{x}\right] \Phi^{\pi\pi}_{q\bar{q}}(x, \zeta, W^2)$$

$$\Phi^{\pi\pi}_{q\bar{q}}(x, \zeta, W^2) = \int \frac{dx^-}{2\pi} e^{-ixP^+ \cdot x^-}$$

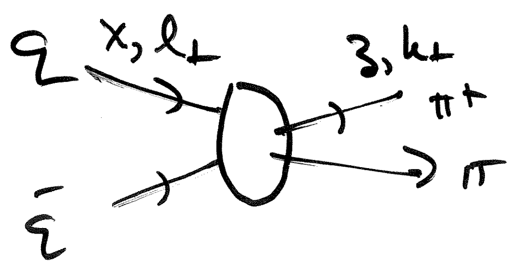
generalized distribution amplitude

$$\langle \pi(p^+)\pi(p^-) | \bar{q}(x^-)\gamma^+ q(0) | 0 \rangle$$

(l.c.g.)

$$W^2 = \frac{k_\perp^2 + m_\pi^2}{\zeta(1-\zeta)}$$

also gg component.



$q\bar{q}$ wavefunction of $\pi\pi$ system

$$\psi^{\pi\pi}_{q\bar{q}}(x, \ell_\perp, \lambda)$$

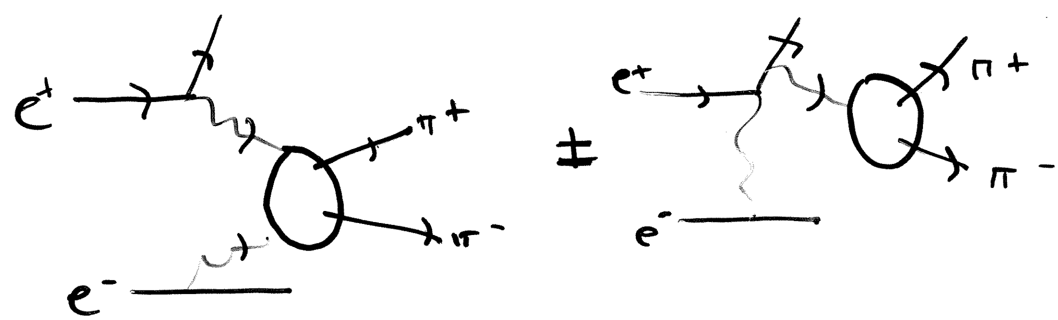
Diehl et al: $\gamma^*\gamma \to \pi^+\pi^-, \pi^0\pi^0$

Dominance of A_{++} amplitude

Model estimate for dist. amp., rates

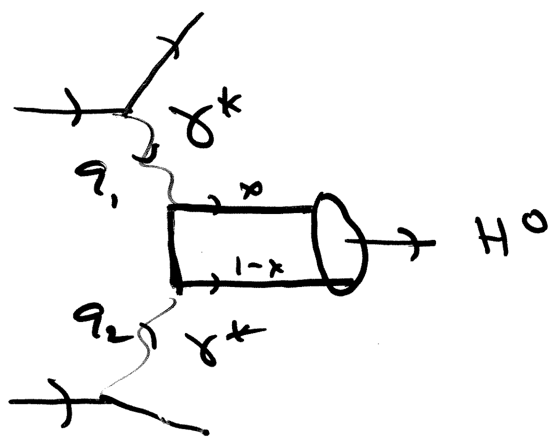
Cross sections $\sigma \sim \frac{1}{2}$ nb at Babar Belle

Interference with bremstrahlung amplitude



π^+ vs π^- asymmetry

Extension to double-tagged

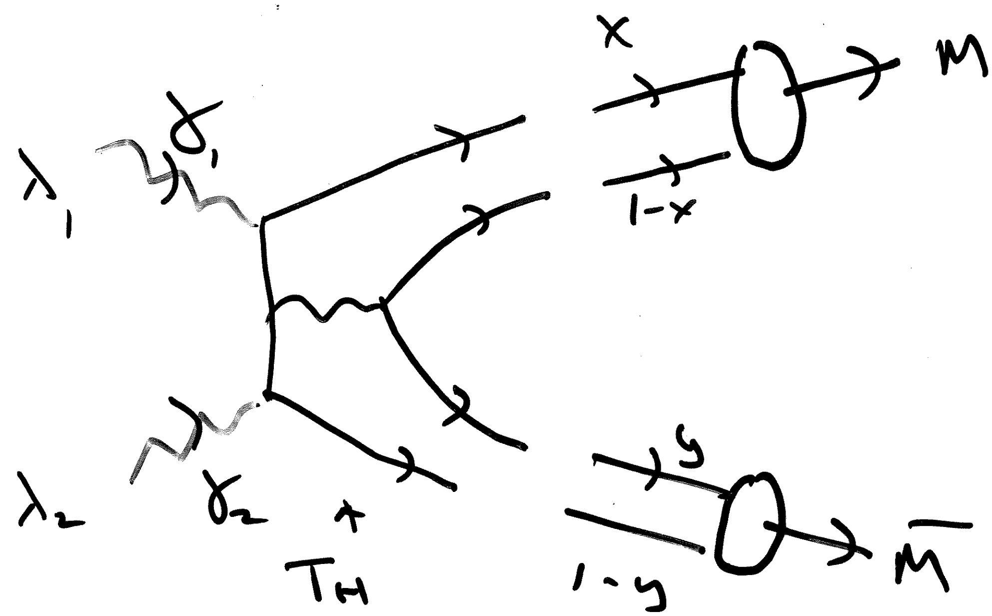


$$\frac{1}{(1-x)Q^2} \Rightarrow \frac{1}{(1-x)Q_1^2 + x\,Q_2^2}$$

Ong
Walsh, et al
Vogt, et al

G.P. Lepage + SJB
Vogt et al
Chernyak

PQCD Factorization at large s, t

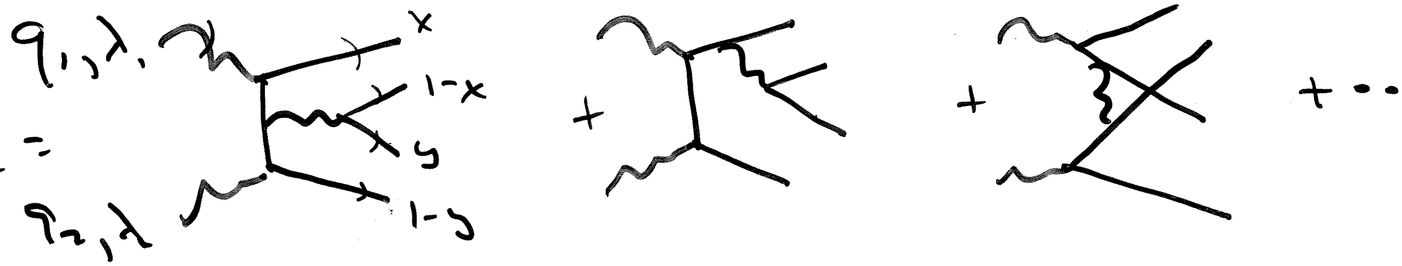


no FSI!

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

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

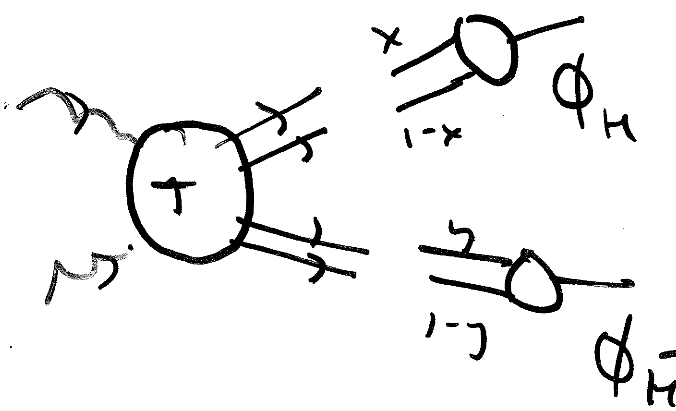
$T_{\lambda_1\lambda_2} =$



$$\mathcal{M}_{\lambda_1\lambda_2}(s,\theta_{cm}) = \int_0^1 dx \int_0^1 dy \; \phi_H^*(x,Q)\, \phi_{\bar{H}}^*(y,Q)\, T_{\lambda_1\lambda_2}(x,y;s,\theta_{cm})$$

<u>Factorization theorem</u>

* Separates perturbative $T_{\lambda_1\lambda_2}$ from non-perturbative $\phi_H(x,Q)$



* ϕ_H universal; no FSI!

SJB

$$\boxed{T_{\lambda_1\lambda_2} \text{ for } \gamma_1\gamma_2 \to M\bar{M}}$$

helicity zero mesons

leading twist

$$T_{++} = T_{--} = \frac{16\pi\alpha_s}{3s} \frac{32\pi\alpha}{x(1-x)y(1-y)} \frac{e_M^2 a}{1-\cos^2\theta_{cm}}$$

$$T_{+-} = T_{-+} = \quad '' \quad \left[\frac{e_M^2(1-a)}{1-\cos^2\theta_{cm}} + \frac{e_1 e_2 c}{a^2-b^2\cos^2\theta_{cm}}\right]$$

$$a = (1-x)(1-y) + xy$$

$$b = (1-x)(1-y) - xy$$

$$c = (1-a)[y(1-y) + x(1-x)]$$

$$e_M = e_1 - e_2$$

Compare

$$T_{\gamma^*\to q\bar{q}} = \frac{16\pi\alpha_s}{3s} \frac{1}{x(1-x)} \frac{1}{y(1-y)}$$

$$\therefore \quad \mathcal{M}_{++} = \mathcal{M}_{--} = 16\pi\alpha\, F_M(s) \frac{e_M^2}{1-\cos^2\theta_{cm}}$$

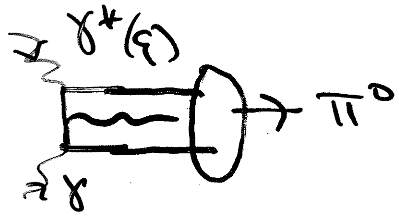
$$\mathcal{M}_{+-} = \mathcal{M}_{-+} = 16\pi\alpha\, F_M(s) \left[\frac{e_M^2}{1-\cos^2\theta_{cm}} + 2e_1e_2\, g(\theta_{cm})\right]$$

if $\phi(x) = \phi(1-x)$

Proof of PQCD Factorization

Lepage + SJB
H.N. Li
Mueller, Duncan
⋮

- 1. Decoupling of soft gluons to hard lines (simplest in l.c.g.)



- 2. Decoupling of soft gluons to states with small color dipole moment

⇒ color transparency — Mueller, SJB

⇒ suppression of FSI

(no violation of Watson's Theorem) — Wolfenstein

- 3. End-point suppression (Feynman region)

$x \to 1$, $k_\perp$ fixed

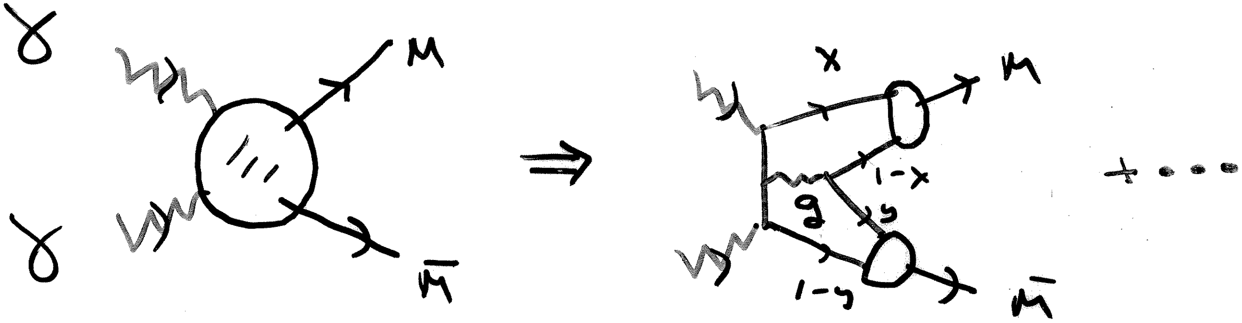
from dynamical suppression of w.f.

and Sudakov suppression

Issues in $\gamma\gamma$ Hard-Scattering

Exclusive Processes

SJB
G.P. Lepage



* $$\frac{d\sigma}{dt} = \frac{\alpha^2 \alpha_s^2}{s^4} F\left(\frac{p_T^2}{s}, \ln p_T\right).$$

$(\lambda_M + \lambda_{\bar{M}} = 0)$

* $$\frac{\frac{d\sigma}{dt}(\gamma\gamma \to M\bar{M})}{\frac{d\sigma}{dt}(e^+e^- \to M\bar{M})} \cong F_{M\bar{M}}(\theta_{cm})$$

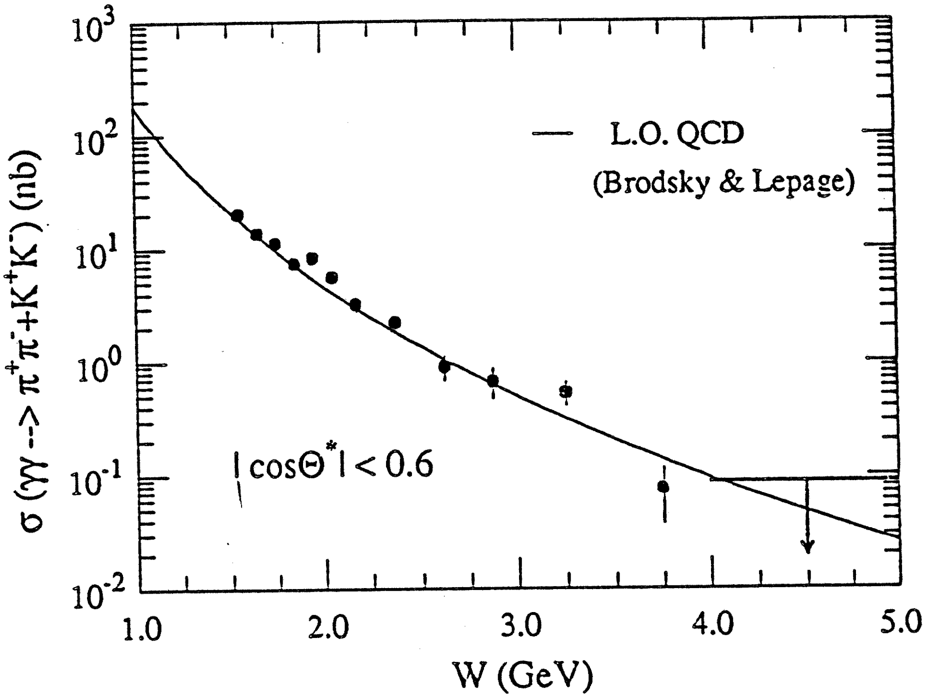
$$\Rightarrow \phi_M(x, \tilde{Q})$$

* $\alpha_s(\mu) \Rightarrow \alpha_V(Q^*)$ Commensurate Scale Relns

SJB, Ji, Pang, Robertson

$\gamma\gamma \to \pi^+\pi^-, K^+K^-$

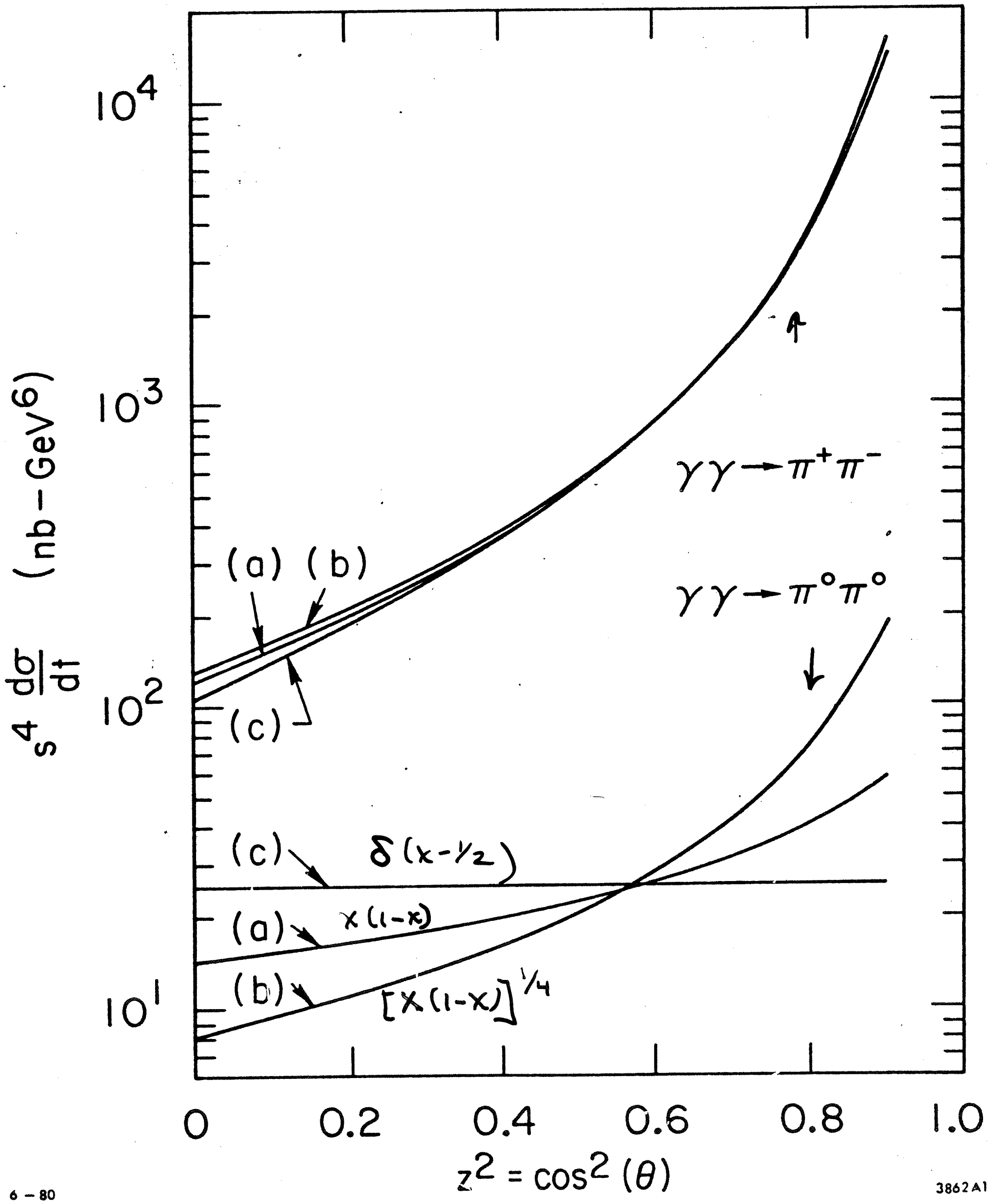
CLEO



$W_{\gamma\gamma}$

HPP

BHL



insensitive to $\phi_{\pi^\pm}(x)$!

strong sensitivity to $\phi_{\pi^0}(x)$!

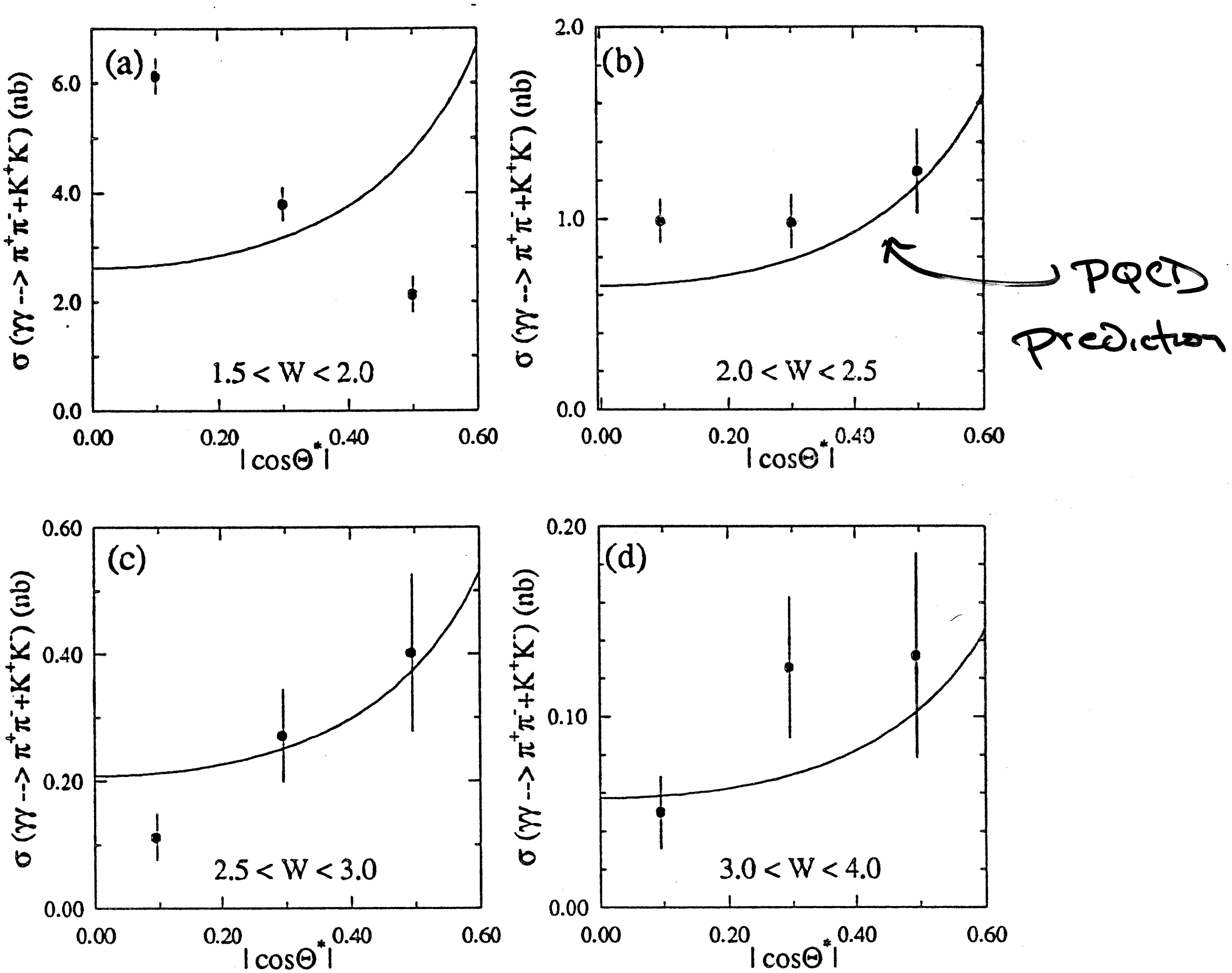
Fig. 3

Strong suppression of $\gamma\gamma \to \pi^0\pi^0$

not true if only

$\gamma\gamma \to \pi^+\pi^-, K^+K^-$
(θ^* dep)

CLEO

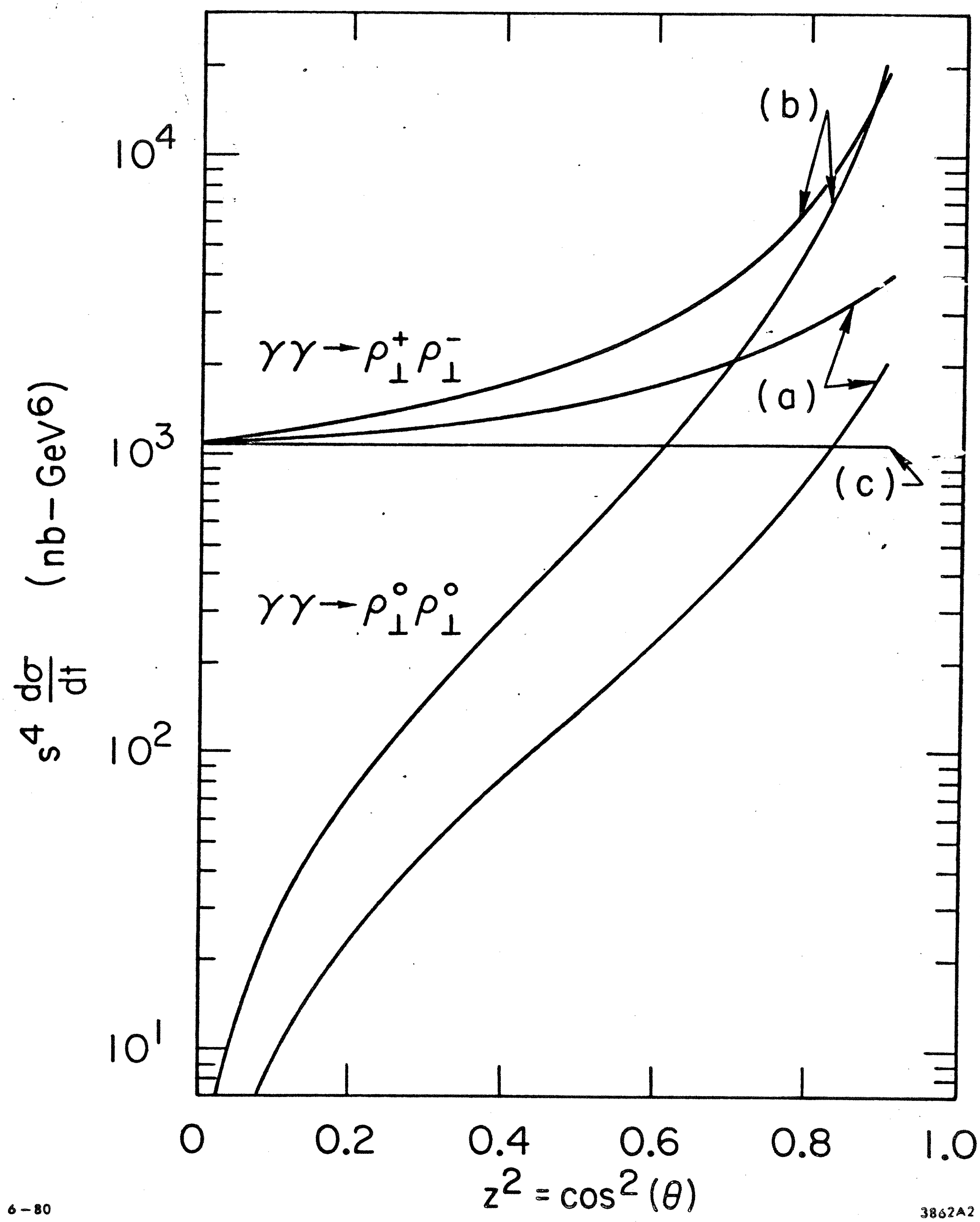


$|\cos\theta^*|$

Evidence for PQCD at $W_{\gamma\gamma} \gtrsim 2.5$ GeV

HPP

DRC



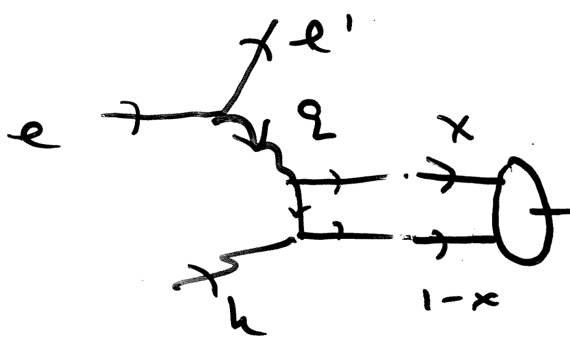
$s^4 \frac{d\sigma}{dt}$ (nb-GeV6)
10^4
10^3
10^2
10^1
(b)
$\gamma\gamma \to \rho_\perp^+ \rho_\perp^-$
(a)
(c)
$\gamma\gamma \to \rho_\perp^\circ \rho_\perp^\circ$
0
0.2
0.4
0.6
0.8
1.0
$z^2 = \cos^2(\theta)$
6-80
3862A2

Fig. 5

Exclusive Two-Photon Reactions

measure $\phi_H(x, Q)$

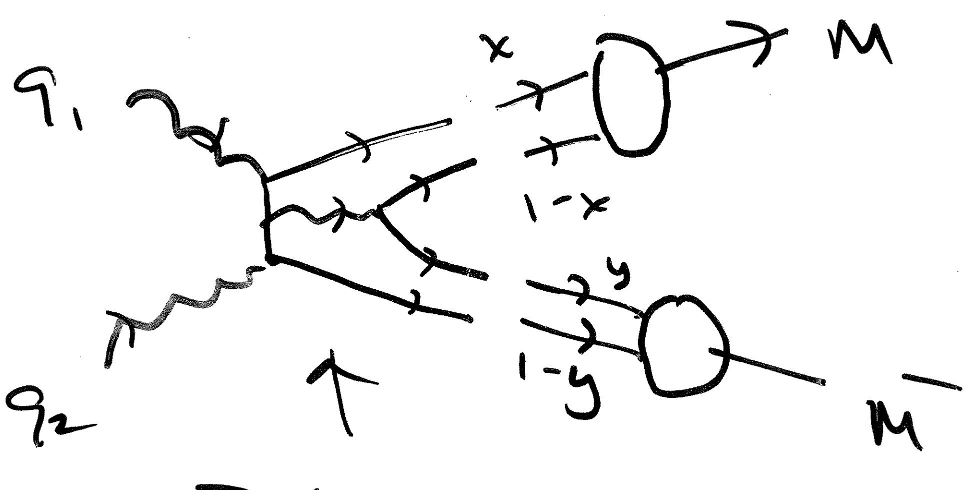
distribution amplitude



π^0, η, η', η_c

$\pi^+\pi^-$ . . .

$k^2 \sim 0$, $-q^2 \gg \Lambda_{QCD}^2$



$\phi_M(x, Q)$

$\phi_{\bar{M}}(y, Q)$

$T_H(x, y; s, \theta_{cm})$

s, t, u large (fixed θ_{cm})

For $\gamma\gamma \to \pi^+\pi^-$: DHL

$$\boxed{\frac{\frac{d\sigma}{dt}(\gamma\gamma \to \pi^+\pi^-)}{\frac{d\sigma}{dt}(\gamma\gamma \to \mu^+\mu^-)} = \frac{4 F_\pi^2(s)}{1-\cos^2\theta_{cm}}}$$

nearly insensitive to slope of $\phi_\pi(x, Q)$

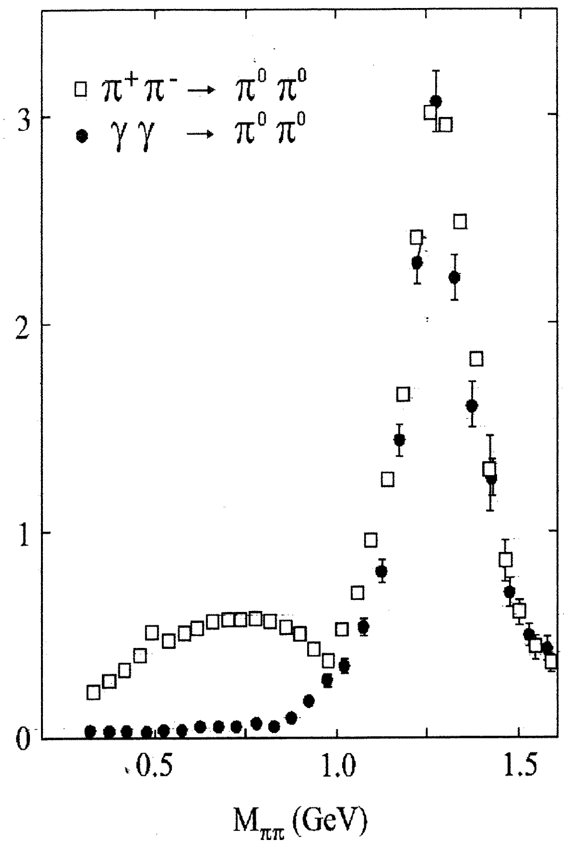
$$\int_0^1 dx\, \phi_M(x, Q) = \frac{f_M}{2\sqrt{3}}$$

$$\frac{d\sigma}{dt}(\gamma\gamma \to K^+K^-) \cong 2\, \frac{d\sigma}{dt}(\gamma\gamma \to \pi^+\pi^-)$$

$$K_L K_S \cong 0.3 \qquad \pi^0\pi^0$$

$$\underset{\lambda=0}{\rho^+}\,\underset{\lambda=0}{\rho^-} \cong 7.5 \qquad \pi^+\pi^-$$

Many such predictions of similar ϕ_M

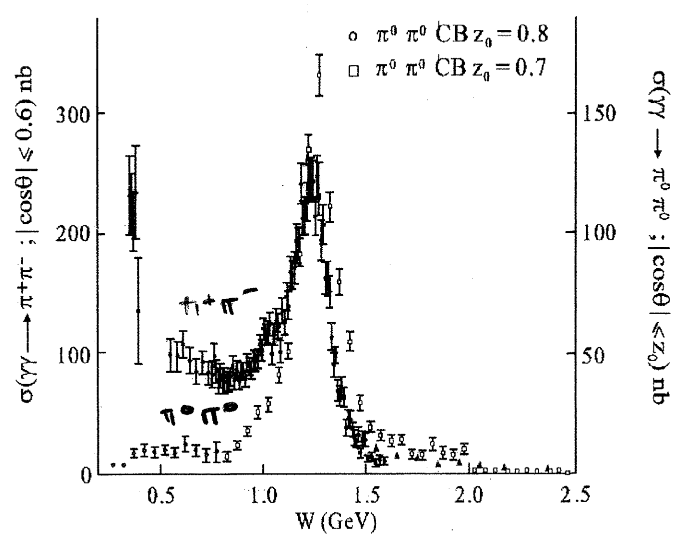


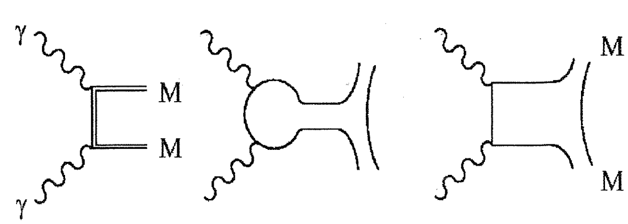
Pennington

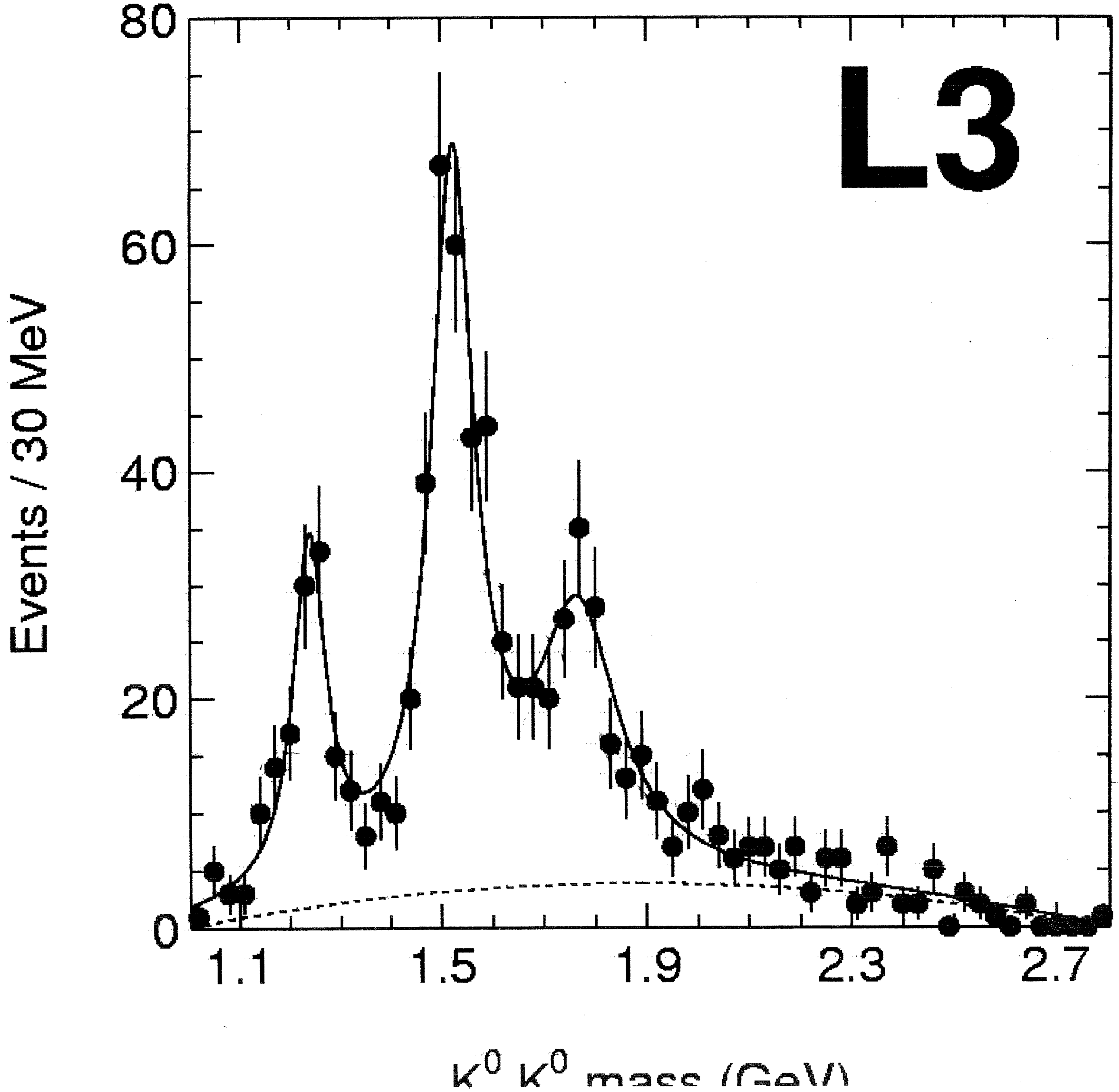
σ resonance $\Rightarrow$ glueball?

or gauge suppression?

• $\pi^+\pi^-$ Mark II, CLEO

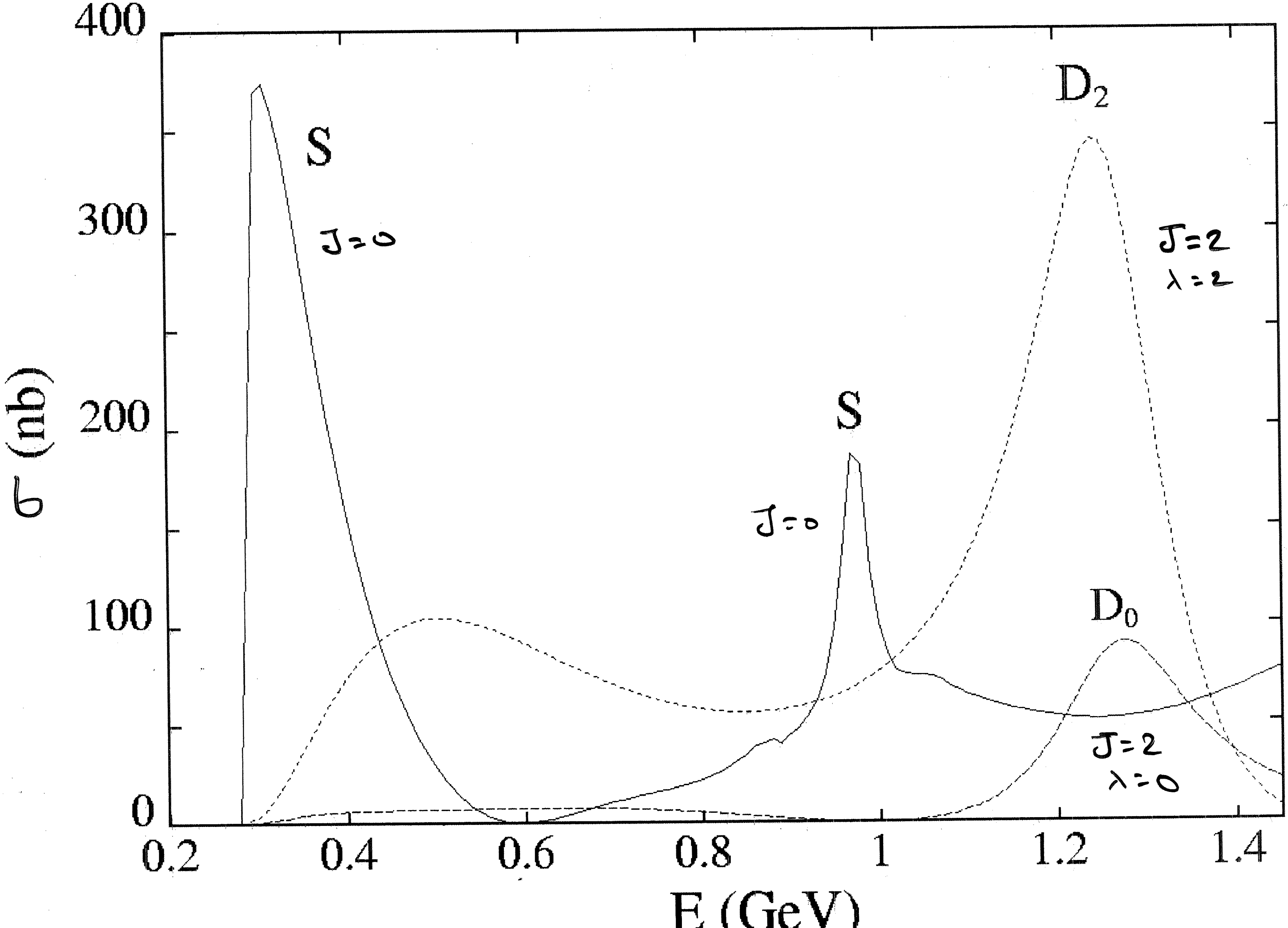






L3
Events / 30 MeV
0
20
40
60
80
1.1
1.5
1.9
2.3
2.7
K0 K0 mass (GeV)

$\sigma(\gamma\gamma \to \pi\pi)$

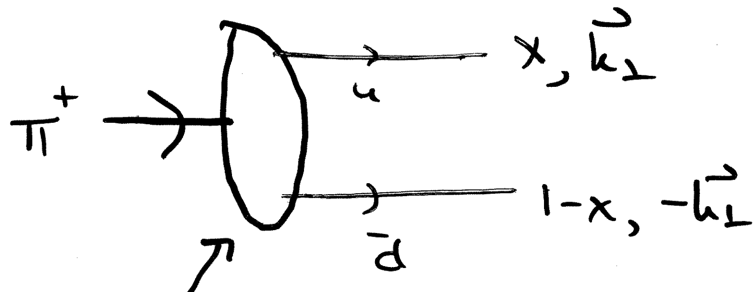


Boglione + Pennington

Ingredients

$*$ $$\phi_\pi(x,Q) = \int^Q d^2k_\perp \, \psi^\pi_{q\bar q}(x,\vec k_\perp)$$

G.P.L.
SJB



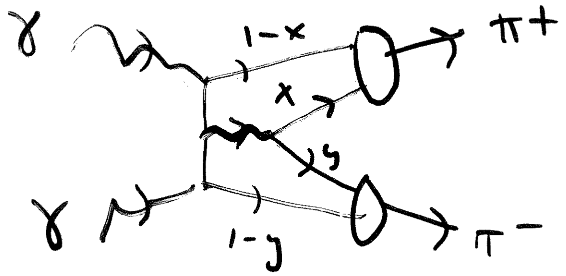
$\psi^\pi_{q\bar q}(x,\vec k_\perp)$ $\quad (\tau = t - z/c = 0)$

$$x = \frac{k^+}{P^+_\pi} = \frac{k^0+k^z}{P^0_\pi+P^z_\pi}$$

$*$ $\alpha_s(Q^2)$ at low scales

e.g.: $Q^2 = \hat s = xys \sim \dfrac{s}{4}$

$*$



$*$ Color Transparency
(suppressed F.S.I.)

A.H. Mueller
SJB

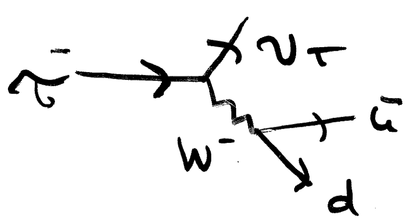
Effective Charges:

Define $\alpha_s(Q^2)$ from single observable
Elim $\overline{MS}$: relate observables

e.g.:

$$R_{e^+e^-}(s) \equiv R_0(s)\left[1+\frac{\alpha_R(s)}{\pi}\right]$$

* $BR(\tau \to \text{hadrons} + \nu_\tau) = (BR)_0\left[1+\frac{\alpha_\tau(m_\tau^2)}{\pi}\right]$



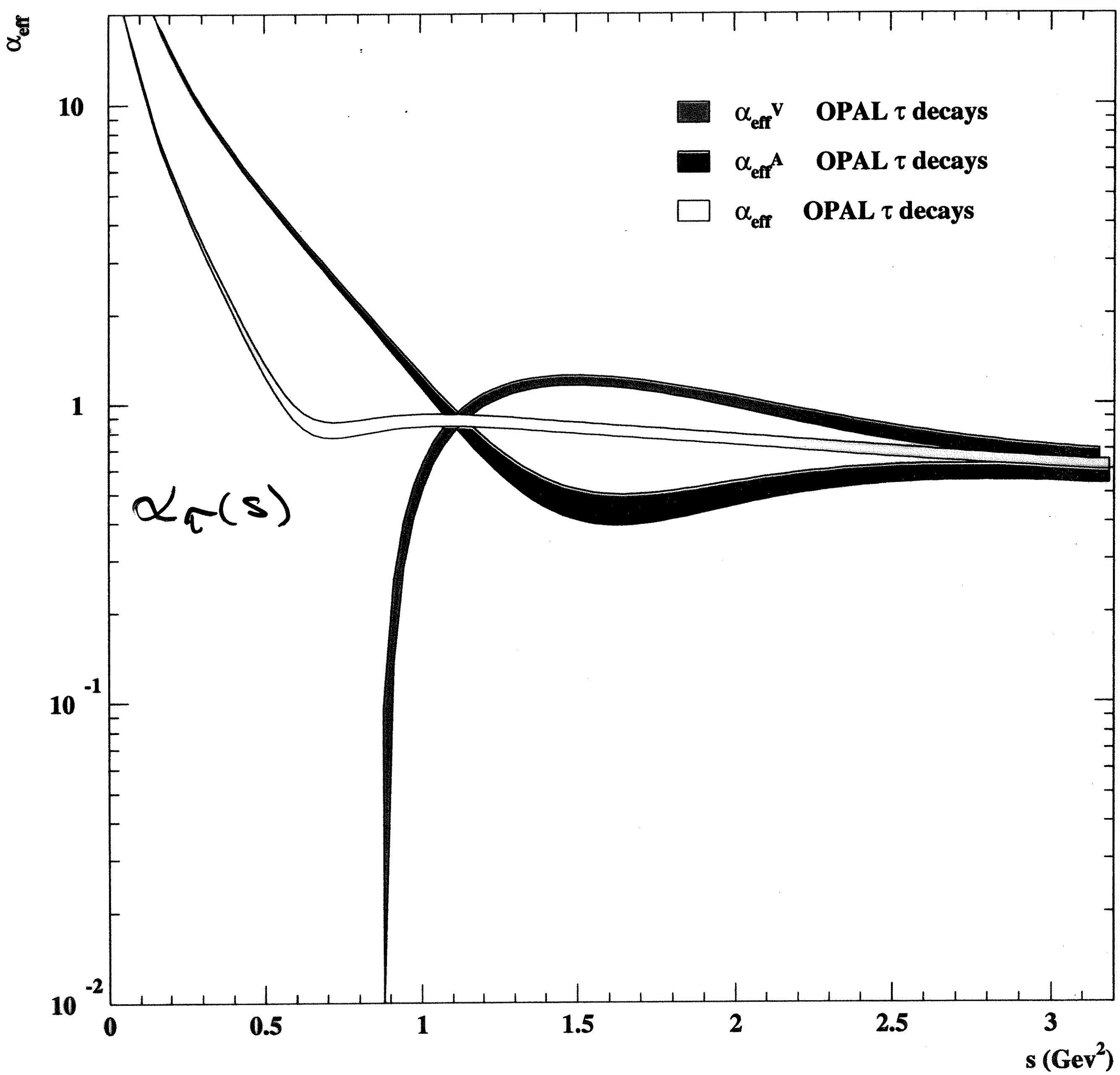
→ hadrons (V, A)

S. Menke: Isolate all channels
(OPAL) Separate V, A, $s\bar{u}$

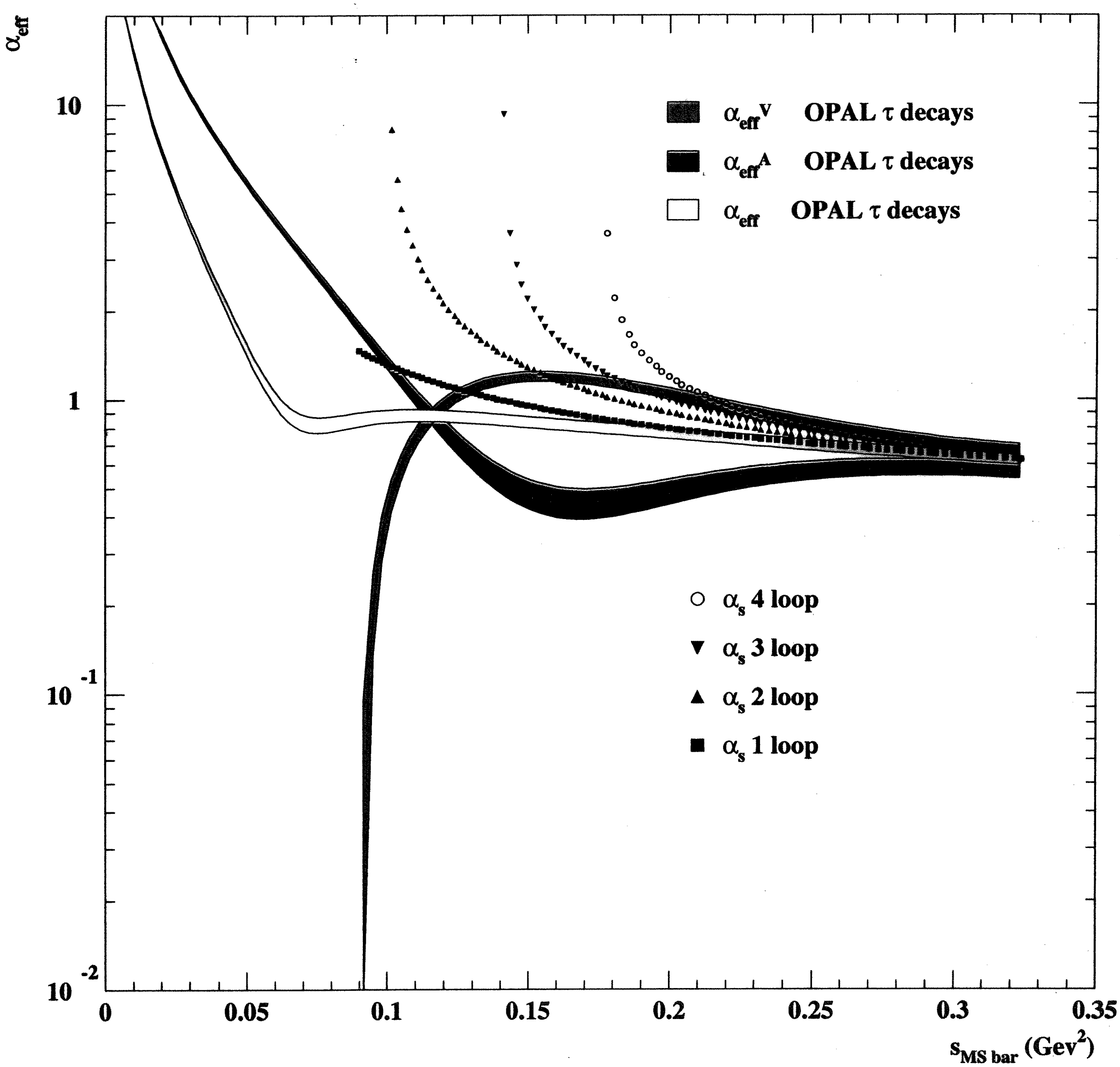
* $\alpha_\tau(s)$ obeys standard RGE
β_τ : known to 3-loops

Menke, Merino, SJB

S. Menke
(prelim)



α_τ ~ flat
~ 1
not .3 to .4



α_{eff}
α_{eff}^V OPAL τ decays
α_{eff}^A OPAL τ decays
α_{eff} OPAL τ decays
α_s 4 loop
α_s 3 loop
α_s 2 loop
α_s 1 loop
10
1
10^{-1}
10^{-2}
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
$s_{MS\ bar}$ (Gev^2)

high $Q^2 = -q^2$

$Q^2 \gg \langle k_\perp^2 \rangle$

T_H

ϕ

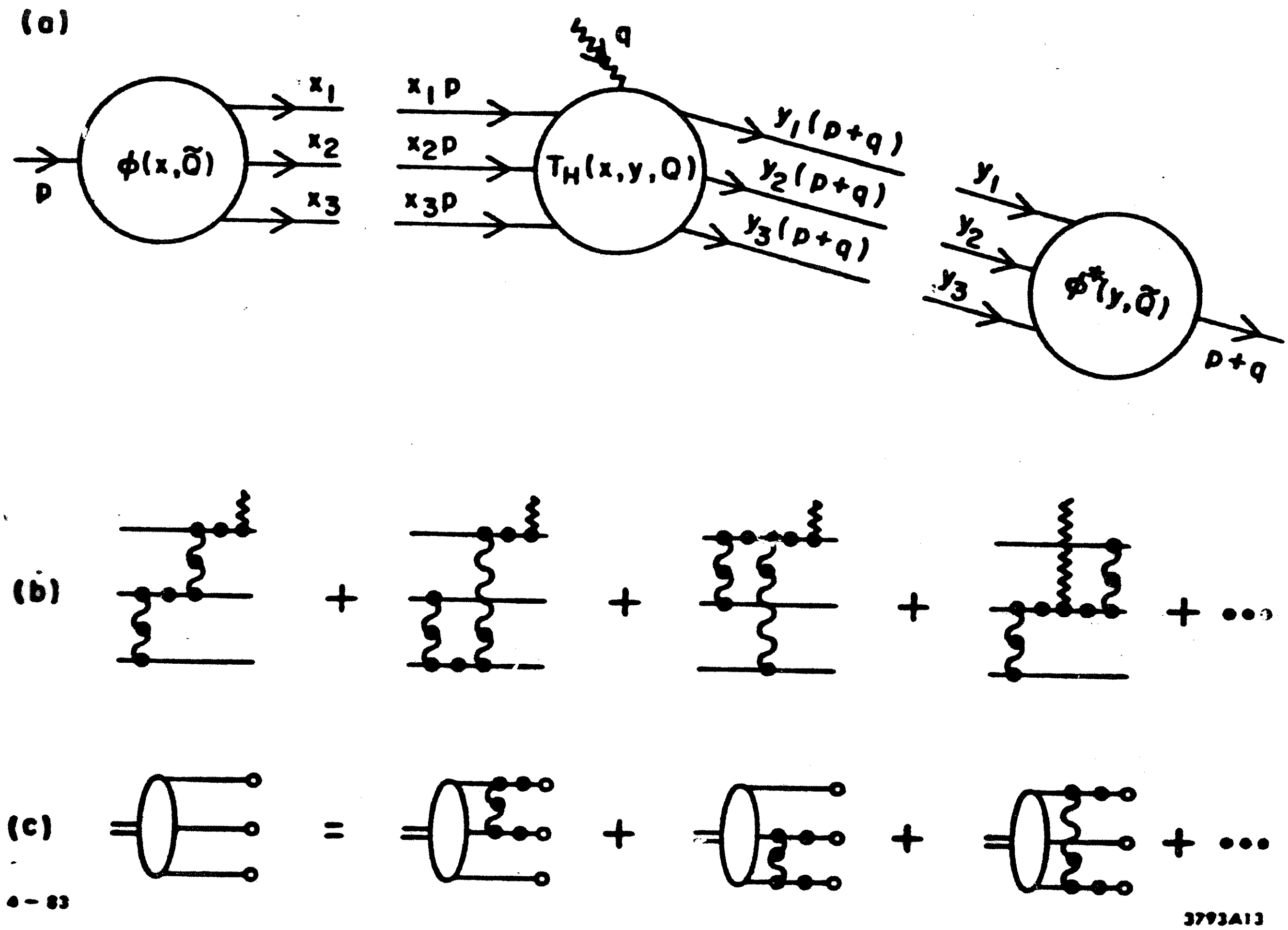


Figure 19. (a) Factorization of the nucleon form factor at large Q^2 in QCD. (b) The leading order diagrams for the hard scattering amplitude T_H. The dots indicate insertions which enter the renormalization of the coupling constant. (c) The leading order diagrams which determine the Q^2 dependence of the distribution amplitude $\phi(x, Q)$.

Calculation of proton form factor in PQCD

Lepage + SJB

Chernyak + Zhitnitsky

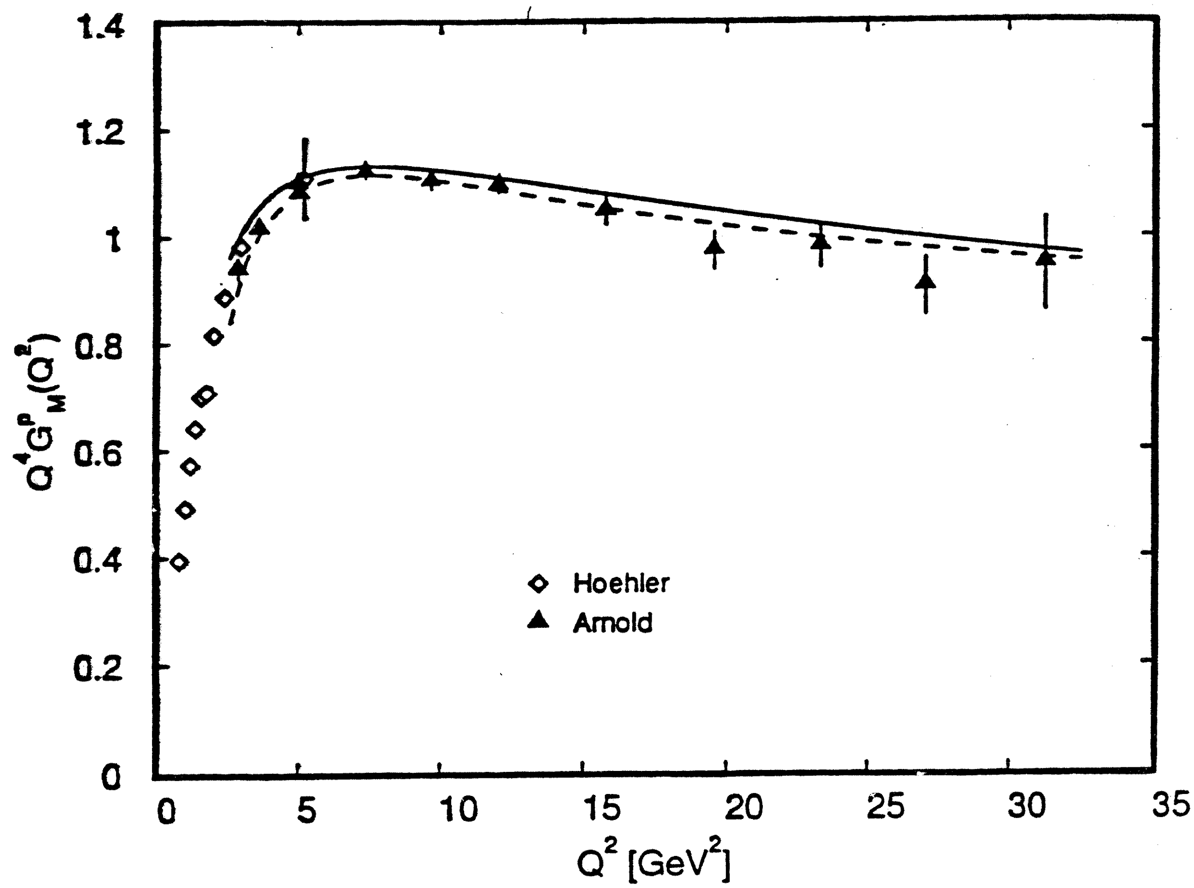
Radyushkin

Mueller + Duncan

Feynman

endpoint: Kroll et al

Fig from Kroll et al



$\sim \alpha_s^2(Q^2)$

Fig. 4

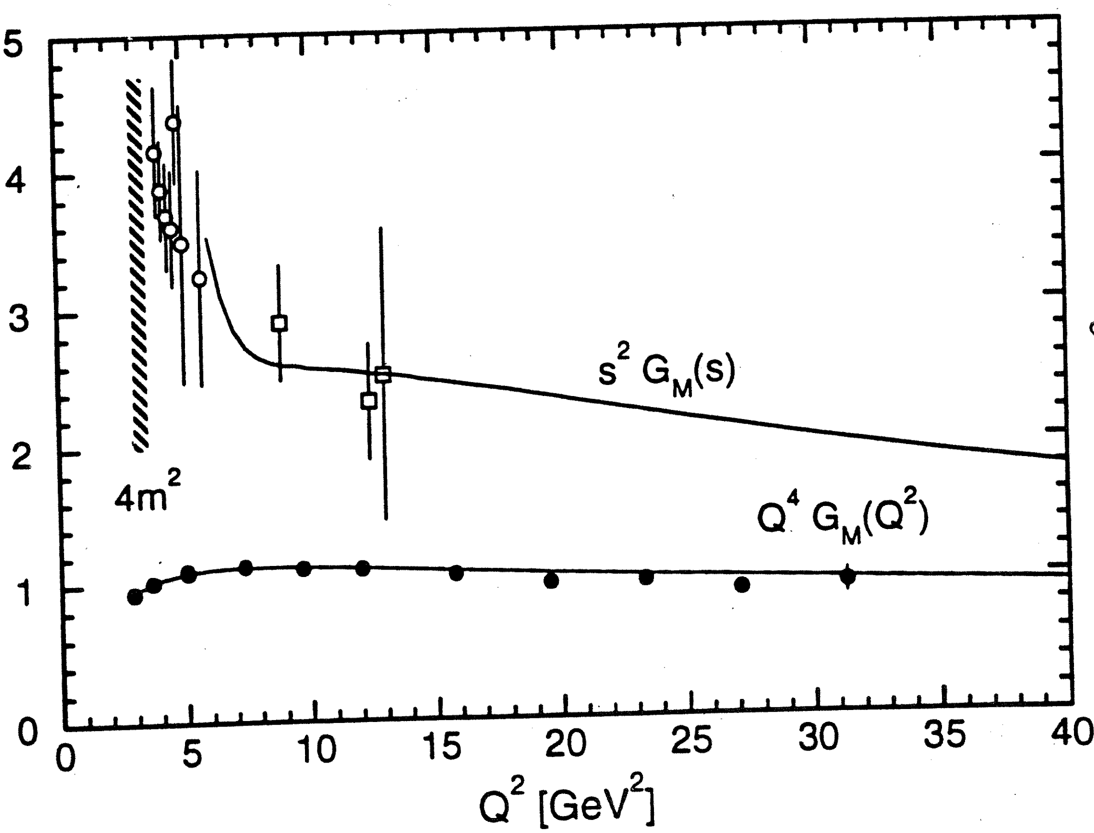
PQCD predicts $\frac{1}{Q^4}$!

Consistent with

$$F_1(Q^2) \sim \frac{\alpha_s^2(Q^2)}{Q^4}$$

Kroll, Pilsner, Schürmann, Schweiger

$q + (qq)$

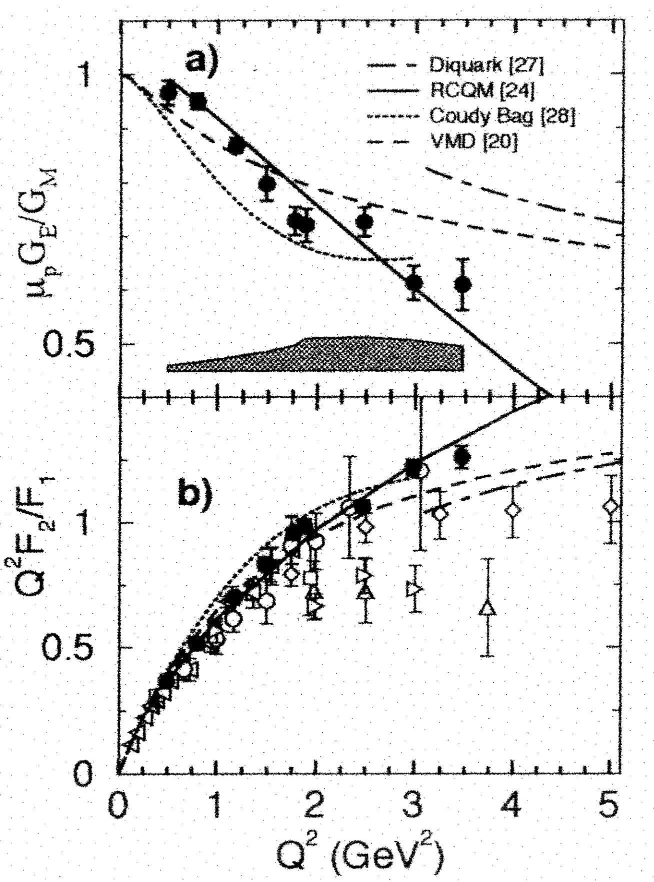


$p\bar{p} \to \ell^+\ell^-$
E760

Fig. 1

Ji, Pang, Robertson, SJB:

Little room for variation of $\alpha_V\left(\frac{Q^2}{9}\right)$!



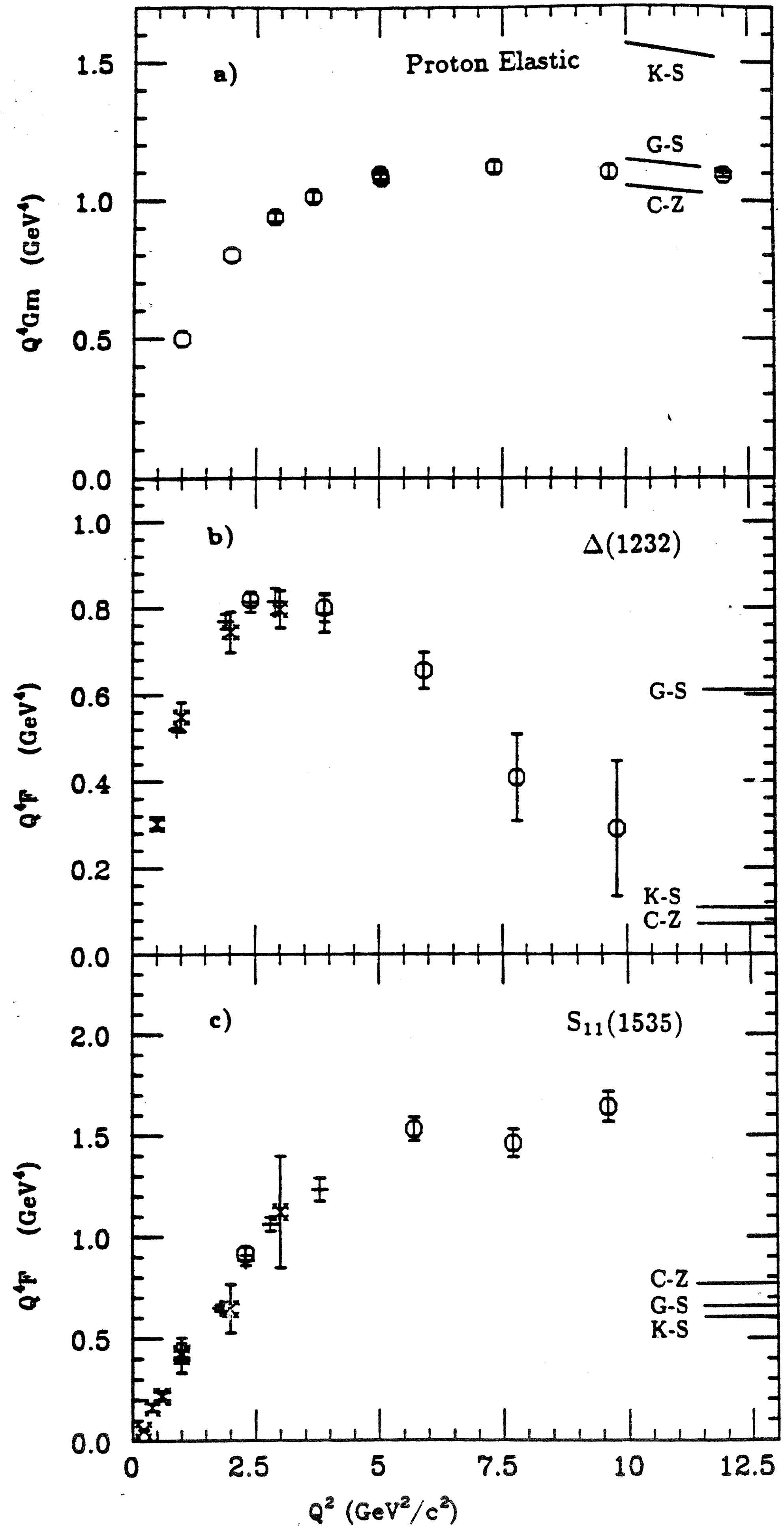
Jefferson Lab

diquark model?

PQCD $\frac{F_2}{F_1} \sim \frac{1}{Q^2}$

4/38

P. Stoler
Carlson



p → p

p → Δ

Suppression from C-Z s.r.

p → S_{11}

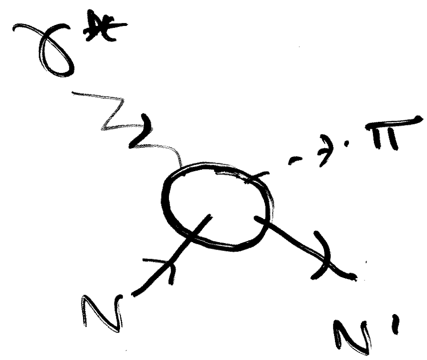
Near-Threshold Pion Production

P.V. Pobylitsa
M.V. Polyakov
M. Strikman

"Soft pion theorems for hard processes"

Example: $\gamma^* N \to (\pi N')$

$$W - W_{Th} < m_\pi$$



$$W_{Th} = m_N + m_\pi$$

Also applicable to

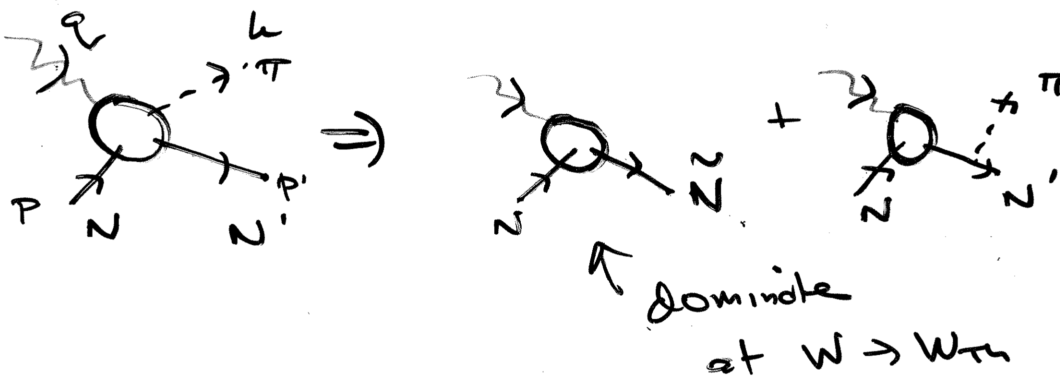
$\gamma\gamma,\ e^+e^- \to B(\bar{B}\pi)$ continuum near threshold

$$m_{\bar{B}\pi} - m_B - m_\pi < m_\pi$$

Weak decays, meson processes.

$\gamma\gamma^* \to (\pi\pi)$ (Terayev)

Soft pion reduction

$W \to W_{th}$: 

$$\mathcal{M} = \langle \pi N' | J^\mu(0) | N \rangle$$

$$\Rightarrow \frac{i}{f_\pi} \langle N' | [Q_5, J^\mu(0)] | N \rangle$$

$$+ \frac{i g_A}{4 f_\pi\, p' \cdot k} \bar{u}(p') \not{k} \gamma_5 \tau u(p) \langle N' | J^\mu(0) | N \rangle$$

where $2p' \cdot k = W^2 - m_p^2 - m_\pi^2 = (W - W_{th})^2 + 2 m_\pi m_p$

* First term dominates at small β:

$$\beta = \sqrt{1 - \frac{(m_N + m_\pi)^2}{W^2}}$$

$[Q_5, J^\mu(0)]$: chiral rotation of J

$N \to \tilde{N}$

Distribution amplitude of proton:

$$|p\uparrow\rangle = \frac{\phi_S(x_i)}{\sqrt{6}}\left[2u_\uparrow d_\downarrow u_\uparrow - u_\uparrow u_\downarrow d_\uparrow - d_\uparrow u_\downarrow u_\uparrow\right]$$

$$+ \frac{\phi_A(x_i)}{\sqrt{2}}\left[u_\uparrow u_\downarrow d_\uparrow - d_\uparrow u_\downarrow u_\uparrow\right]$$

$$\phi_S(x_1,x_2,x_3) = \phi_S(x_3,x_2,x_1)$$
$$\phi_A(x_1,x_2,x_3) = -\phi_A(x_3,x_2,x_1)$$

Chiral rotation:

$$|p\uparrow\pi^0\rangle = \frac{\phi_S(x_i)}{2\sqrt{6}\,f_\pi}\left[6u_\uparrow d_\downarrow u_\uparrow + u_\uparrow u_\downarrow d_\uparrow + d_\uparrow u_\downarrow u_\uparrow\right]$$

$$- \frac{\phi_A(x_i)}{3\sqrt{2}\,f_\pi}\left[u_\uparrow u_\downarrow d_\uparrow - d_\uparrow u_\downarrow u_\uparrow\right]$$

$$|n\uparrow\pi^+\rangle = \frac{\phi_S(x_i)}{\sqrt{12}\,f_\pi}\left[2u_\uparrow d_\downarrow u_\uparrow - 3u_\uparrow u_\downarrow d_\uparrow - 3d_\uparrow u_\downarrow u_\uparrow\right]$$

$$- \frac{\phi_A(x_i)}{2f_\pi}\left[u_\uparrow u_\downarrow d_\uparrow - d_\uparrow u_\downarrow u_\uparrow\right]$$

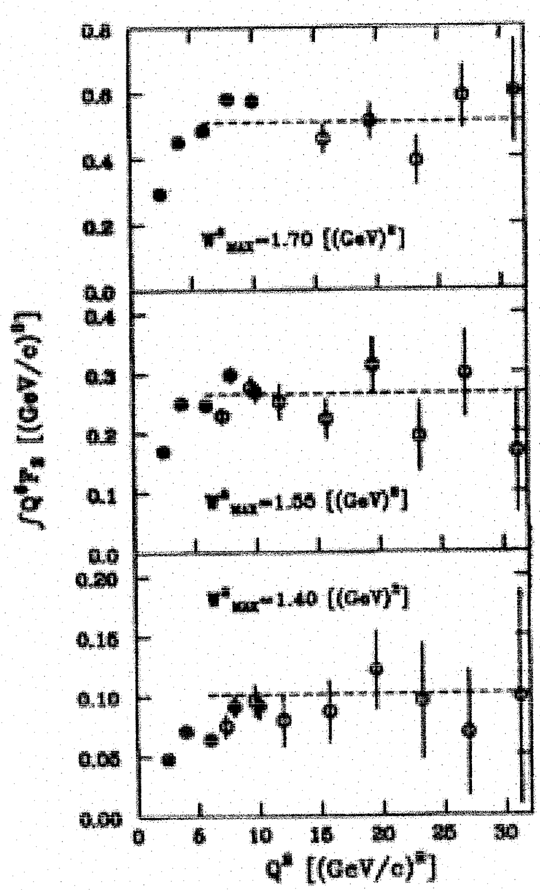
* ∴ Distribution amplitudes of (πN) system determined!

Chiral Dynamics in Hard Processes

Polyakov, M

E136

$$\int_{W_{th}^2}^{W_{MAX}^2} dW^2 \, Q^6 \, F_2(W, Q^2)$$



PQCD prediction
+ soft pion theorem
$\phi_A = 0$.

$\Leftarrow W_{MAX} - W_{th} \sim m_\pi$

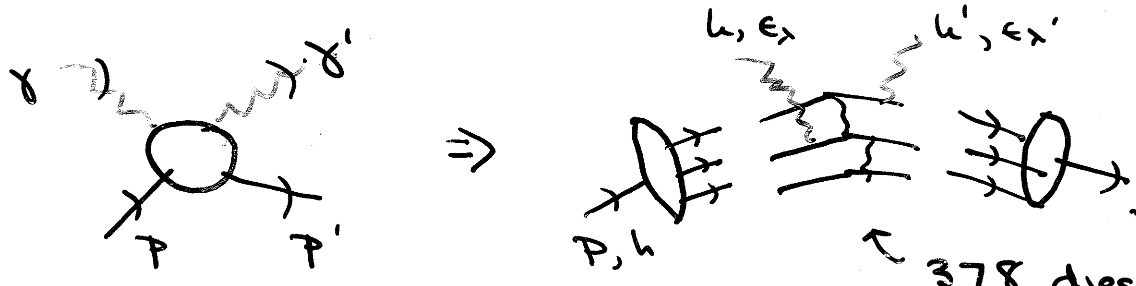
Fig. 6

Compton Scattering at Large Momentum Transfer

SJB
G.P. Lepage

Nizic
Kronfeld

Brooks
Dixon



↖ 378 diagrams in T_H

$$\mathcal{M}_{hh'}^{\lambda\lambda'}(s,t) = \sum \int [dx][dy]\, \phi(x_i,Q)\, T_H(x_i;y_i;Q)\, \phi(y_j,Q)$$

$*$ $\quad \frac{d\sigma}{dt}(\gamma_\lambda p_h \to \gamma'_{\lambda'} p'_{h'}) \cong \frac{f_{hh'}^{\lambda\lambda'}(\theta_{cm})}{s^6}$ PQCD scaling

$\boxed{h = h'}$ Hadron Helicity Conservation

Detailed predictions for each helicity amplitude, phase

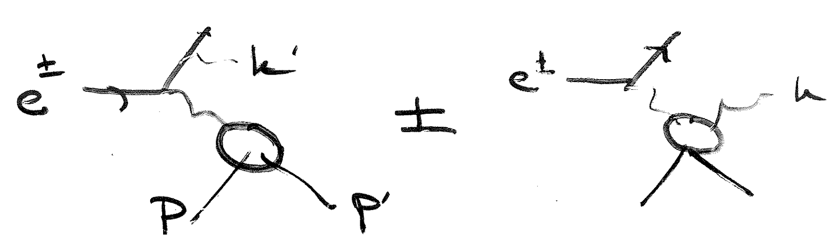
$*$ $\quad F_{hh'}^{\lambda\lambda'}(\theta_{cm})$ depends on $\phi(x_i,Q)$ shape

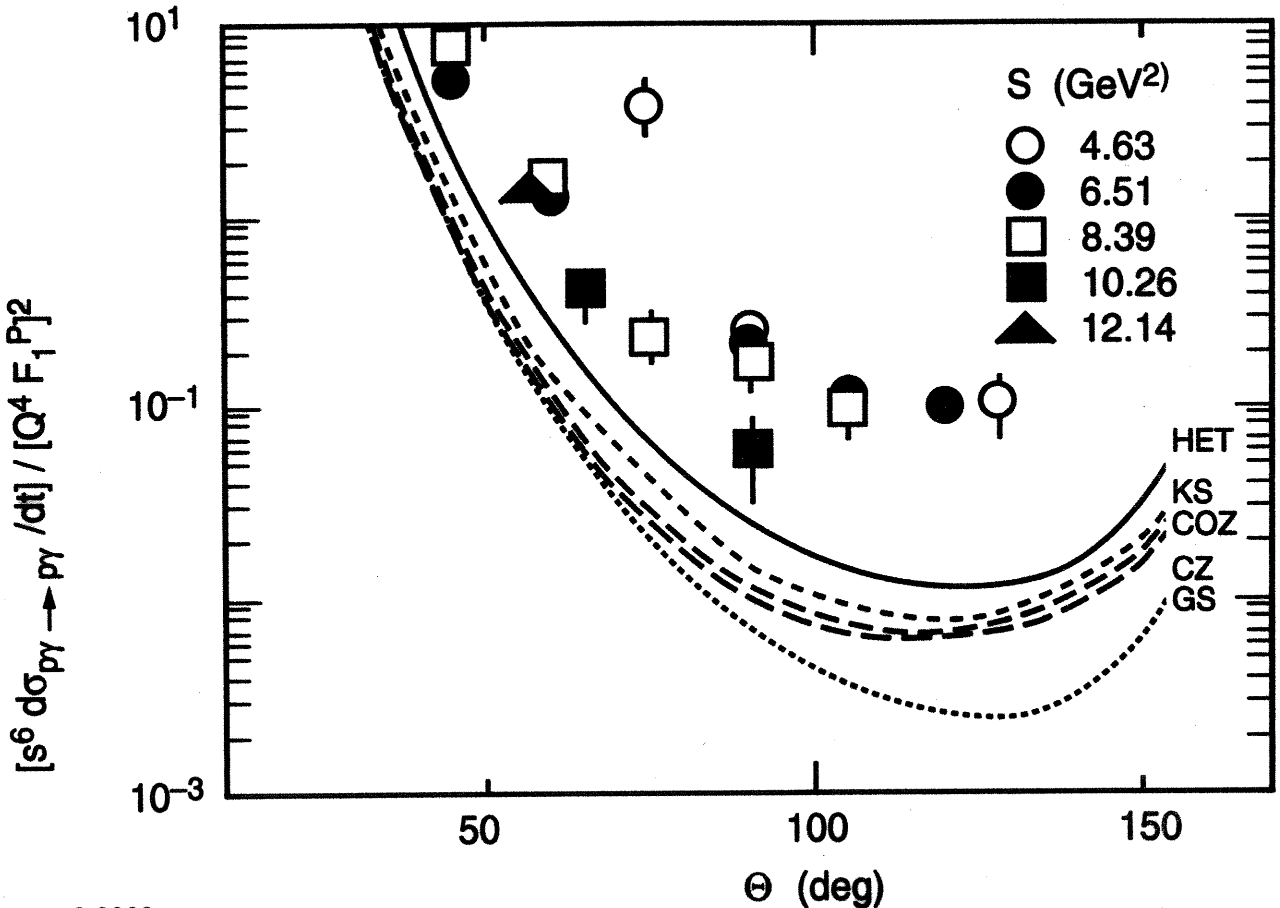
Use backscattered laser beam $\gamma_\uparrow p_\uparrow \to \gamma p$

Measure phase in $e^\pm p \to e^\pm p \gamma$

Virtual Compton

Close





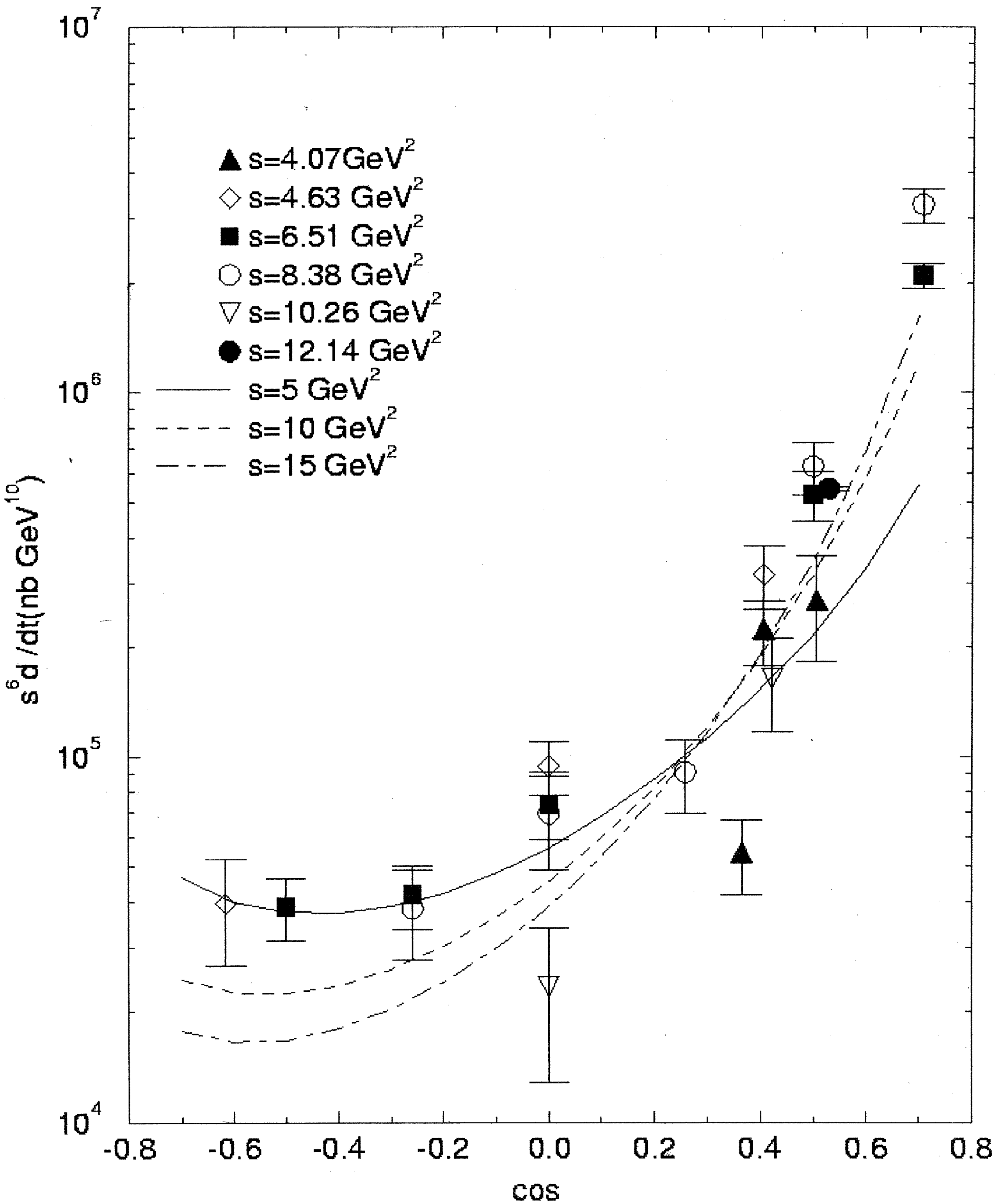
8-2000
8561A15

Brooks + Dixon

$\alpha_S = .3$

diquark model kroll et al

Real compton Scattering



Timelike Compton Processes

$\gamma\gamma \to p\bar{p},\ n\bar{n},\ \ldots$

E760
$p\bar{p} \to \gamma\gamma$

$\to \Delta^+\Delta^-,\ S_1,\ S_1^*\ \ldots$

$\to \Delta^{++}\Delta^{--}$

$\to p,\ \Delta^-\ \ldots$

- Important QCD Laboratory

- PQCD $\Rightarrow$ $\phi_N(x_i, Q)$

  Farrar + Huang, Hyer

  from ratios, angular distributions, crossing

  diquark model

- Threshold regime $\Rightarrow$ novel physics?

  Skyrmion - Anti-Skyrmion.

- $\gamma^*\gamma \to \bar{p}p$ at fixed M^2

- Virtual Compton amplitude

- Generalized distribution amplitudes

* Normalization uncertainties cancel in

$$R_{\gamma/e} = \frac{\frac{d\sigma}{dt}(\gamma p \to \gamma p)}{\frac{d\sigma}{dt}(ep \to ep)} = F(\cos\theta_{cm})$$

Ti Hyer

* Ratio highly sensitive to $\phi_p(x_i)$ since

$$G_{M_p} = 0 \quad \text{for} \quad \phi_p = x_1 x_2 x_3$$
(leading twist)

— Take:

$$\phi^{p}_{u_\uparrow u_\downarrow d_\uparrow}(x_1, x_2, x_3)$$

$$= A\left[x_1 x_2 x_3 + c_1(1-3x_3) + c_2(x_1 - x_2)\right]$$

fit ratio to c_1, c_2

Brooks Dixon

Conformal Symmetry and Baryon Distribution Amplitudes

V. Braun, S. Derkachov,
A. Manashov, G. Korchemsky

$$q\uparrow q\uparrow q\uparrow \Rightarrow \phi_\Delta^{\lambda=3/2}(x_i, \mu^2)$$

$$q\uparrow q\downarrow q\uparrow \Rightarrow \begin{cases} \phi_N^{\lambda=1/2}(x_i, \mu^2) \\ \phi_\Delta^{\lambda=1/2}(x_i, \mu^2) \end{cases}$$

$$\sum_{i=1}^{3} x_i = 1$$

$$\phi_{N,\Delta}^{\lambda=1/2}(x_i, \mu^2) = x_1 x_2 x_3 \sum_{N=0}^{\infty} \varphi_N^{\mu_0} \left[\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\right]^{\gamma_N}$$

scalar diquark

$$(\uparrow \downarrow) \quad \uparrow$$

$$1 \quad 2 \qquad 3$$

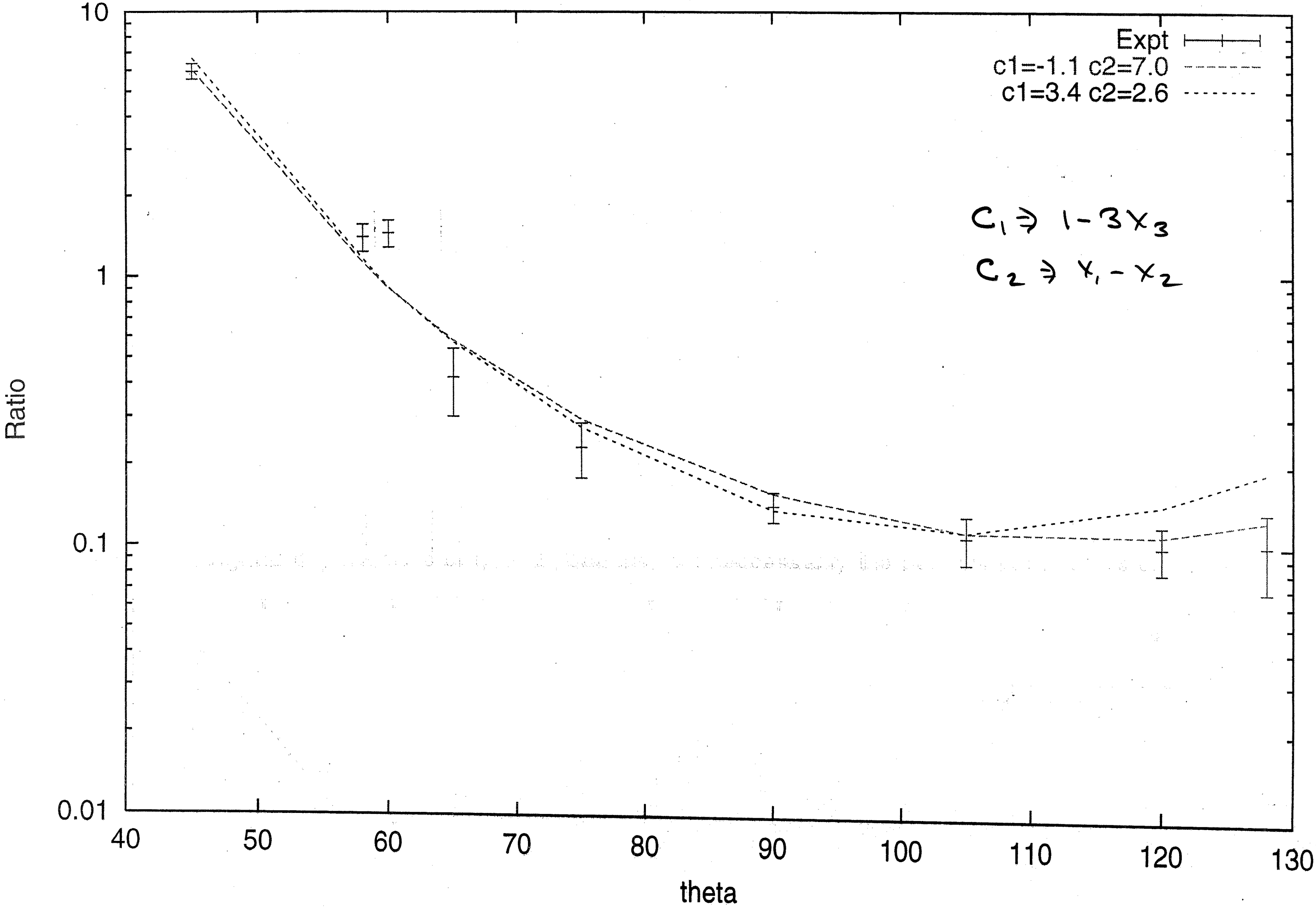
$$\times \left\{ P_N(1-2x_3) \pm P_N(1-2x_1) \right\}$$

Jacobi Polynomials $P_N^{(1,3)}$

expansion in conformal polynomials

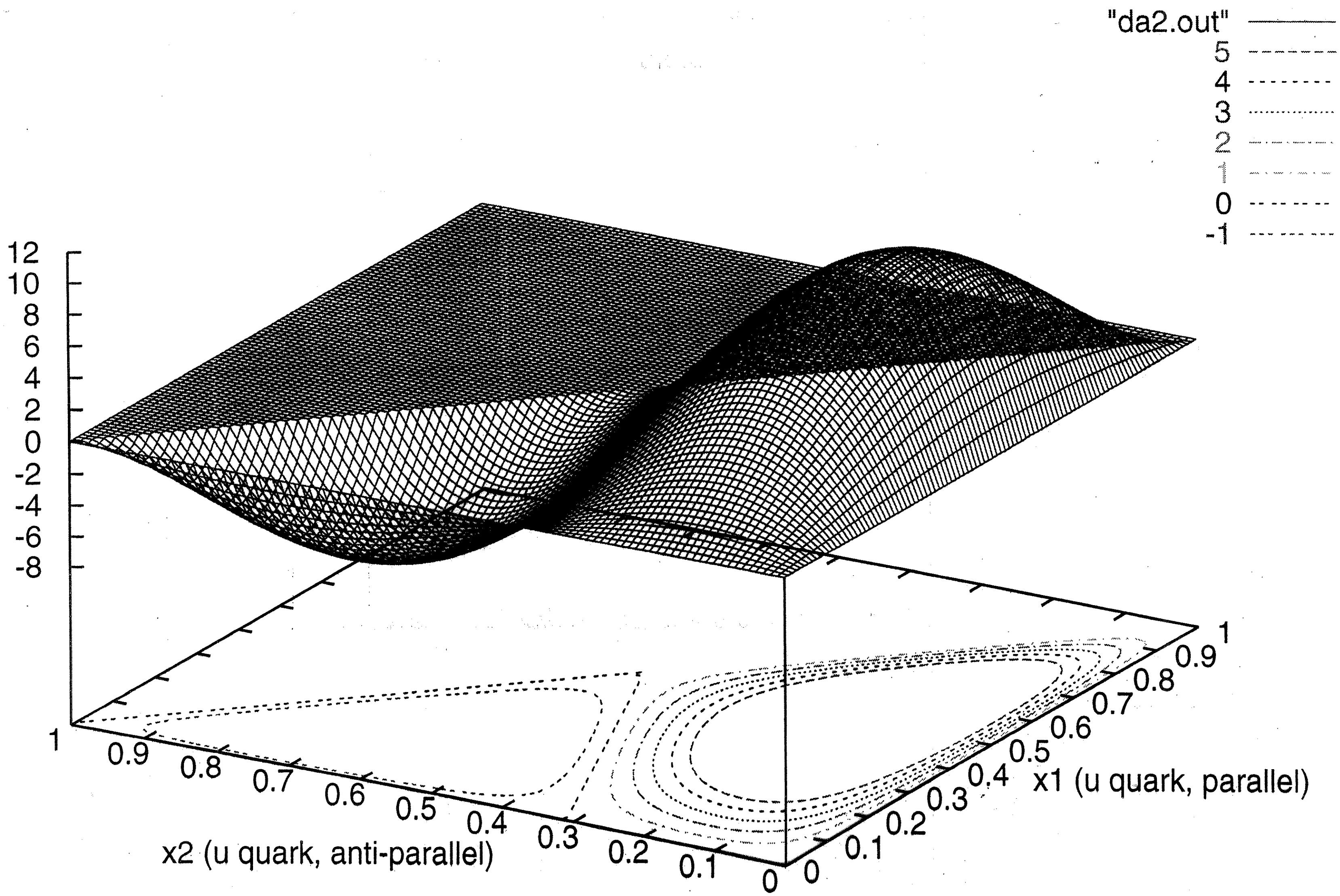
(Prelim) Brooks + Dixon

Angular dependence of typical good fits, not neccessarily the best fits in the c1 vs c2 plane

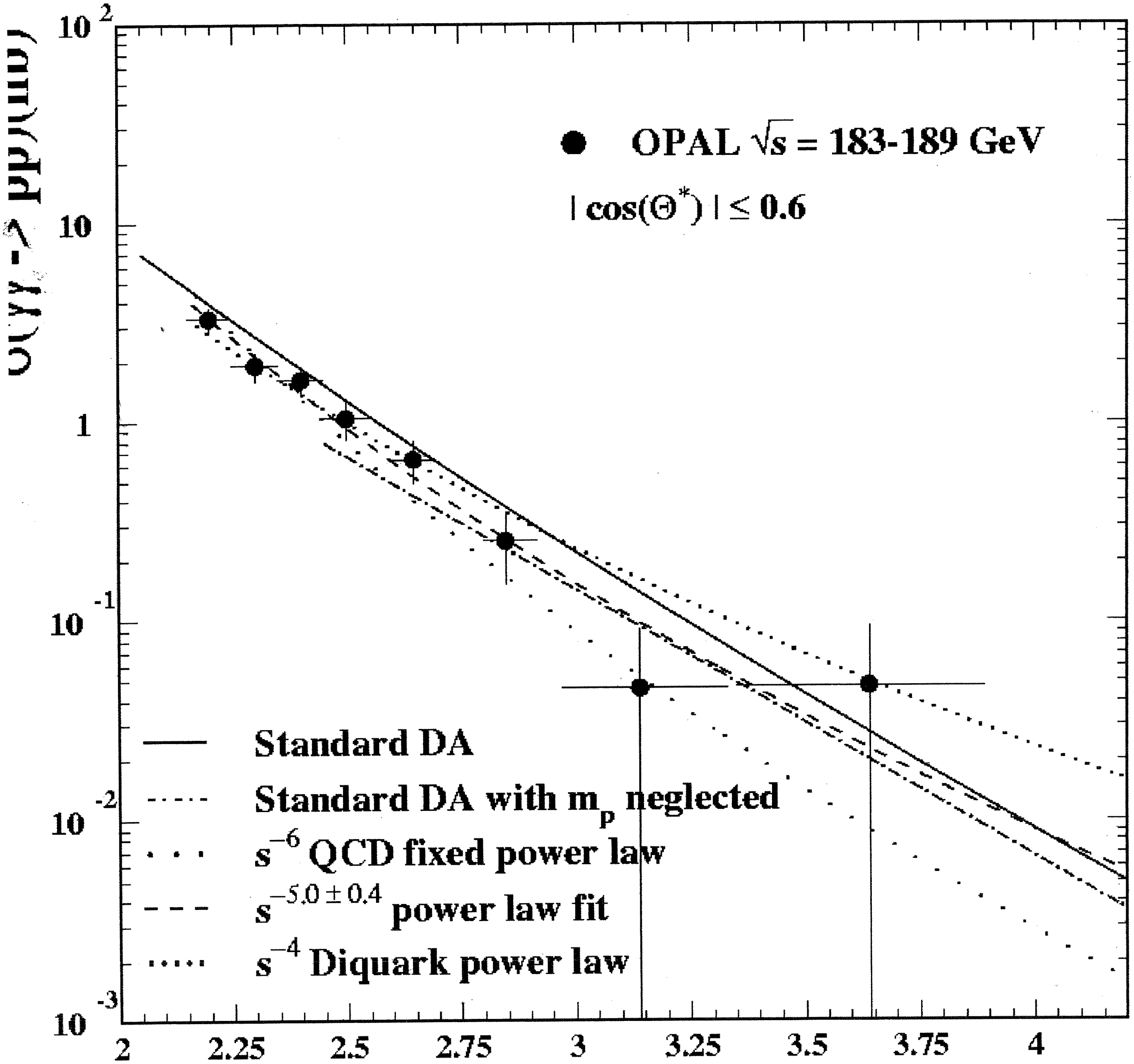


Brooks + Dixon

Typical Distribution Amplitude c1=-1.1 c2=7.0

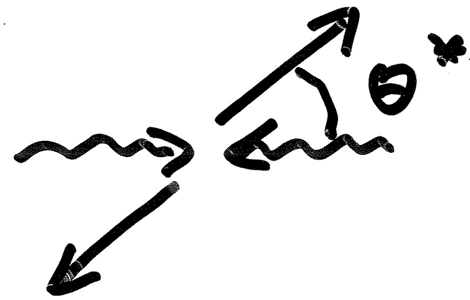


$\gamma\gamma \to p\bar{p}$

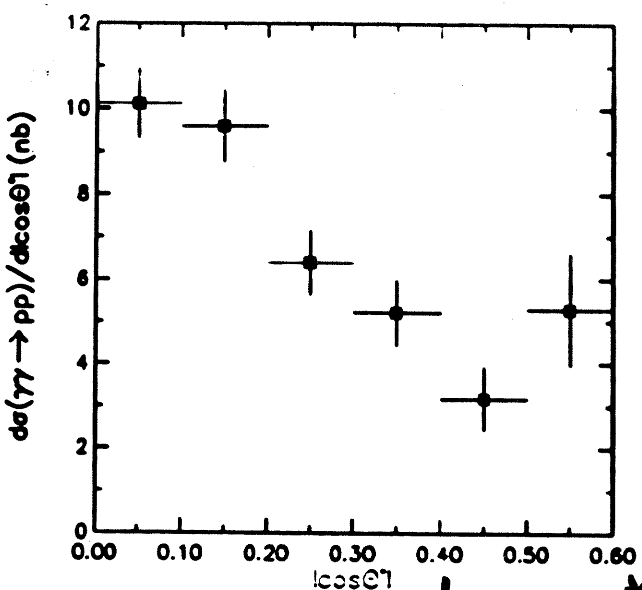


$\underline{\gamma\gamma \to p\bar{p}}$

θ^* :
(in $\gamma\gamma$ CM)



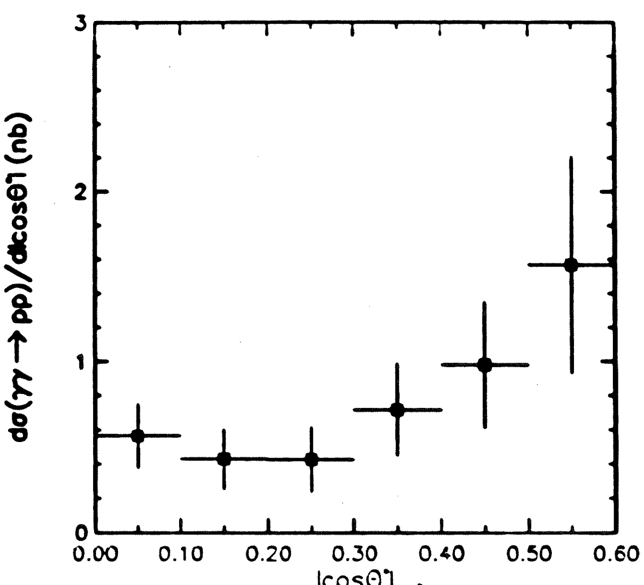
CLEO



$2 \leq W \leq 2.5$ GeV

$|\cos\theta^*|$

CLEO



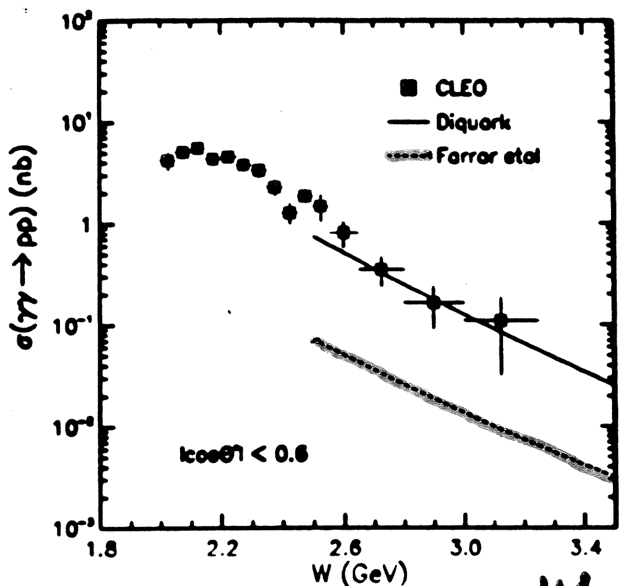
$W > 2.5$ GeV

$|\cos\theta^*|$

HPP

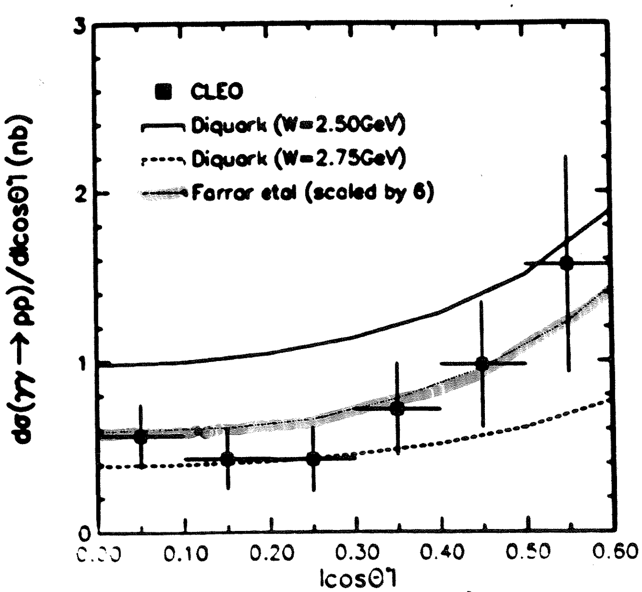
$\gamma\gamma \rightarrow p\bar{p}$

CLEO



$W_{\gamma\gamma}$

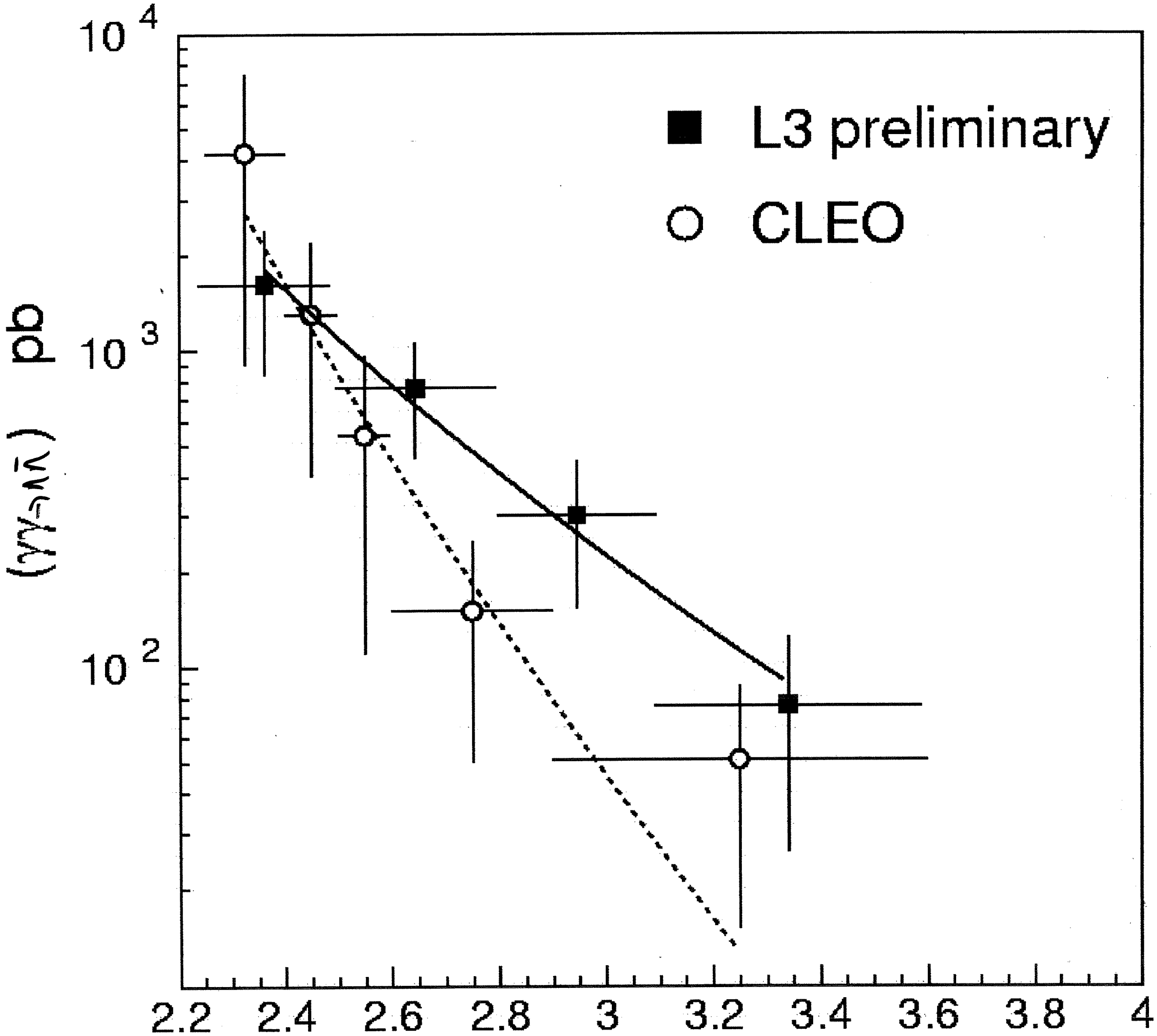
CLEO



$|\cos\theta^*|$

HPP

$\gamma\gamma \to \Lambda\bar{\Lambda}$



$$\boxed{\begin{array}{l}\text{Measurements of} \\ \qquad \phi_H(x_i, Q) \\ \text{Central problem of QCD}\end{array}}$$

$$\frac{d\sigma}{dt}\left[\gamma\gamma \to H\bar{H}\right]_{\lambda_1\lambda_2 \;\; \lambda_3\lambda_4}$$ scaling, helicity, angular structure

Ratios critical [α_s ~ cancels]

$$\frac{\gamma\gamma \to \pi^0\pi^0}{\gamma\gamma \to \pi^+\pi^-} \Rightarrow \phi_{\pi^0}(x, Q)$$

$$\frac{\gamma\gamma \to n\bar{n}}{\gamma\gamma \to p\bar{p}} \Rightarrow \phi_N(x, Q)$$

CLEO, Babar, Belle, LEP, ..

opportunity for fundamental physics

<u>Summary</u>

$\gamma\gamma \to$ Exclusive Channels

Experiment sees transition to
angular distributions pred. by PQCD

Connections to Soft-physics

analyticity
soft-pion theorems
soliton-anti-soliton formation at $W = W_{th}$
low energy theorems

Resonance phenomena

Compare $\gamma\gamma \to X$ with $J/\psi \to \gamma X$
for glueball search

PQCD : $\gamma\gamma$, $\gamma^*\gamma$, $\gamma^*\gamma^*$
window to distribution amplitudes

$\Rightarrow$ critical for B-physics