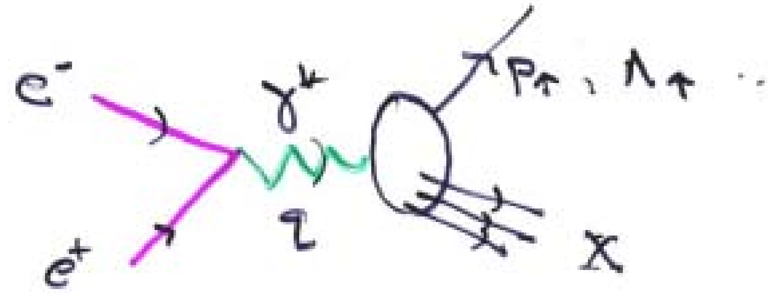
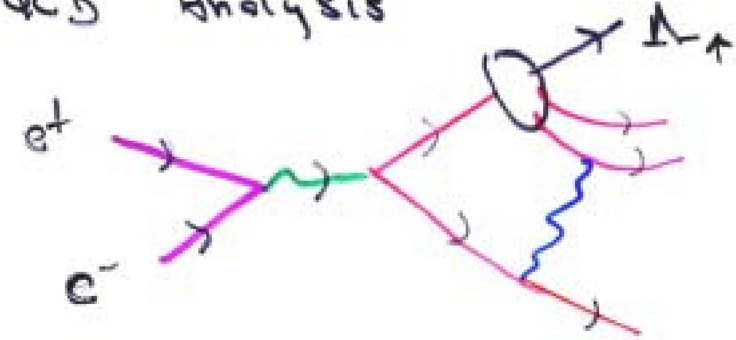
Semi-Inclusive Single-Spin Asymmetries



– PQCD Analysis



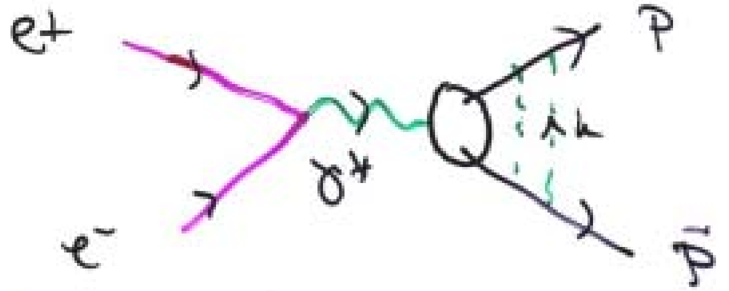
$\vec{S}_\Lambda \cdot \vec{p}_\Lambda \times \vec{p}_{e^-}$

Leading Twist

- From FSI (similar to BHS "Sivers" Effect)
- Requires $L = 1, 0$ in $\Lambda_\uparrow$ Wave Function
- Matrix element proportional to μ^*_Λ

A. Metz
Hwang, Schmidt, SJB
Collins

QED Coulomb Effects at Threshold Hadron-Pair Production



Coulomb interactions at Bohr scale $|\vec{k}| \sim O(\alpha m_p)$

same as $\mu^+\mu^-$

reflects atomic baryonium at $s < 4m_p^2$

$$\sigma(e^+e^- \to p\bar{p}) = \sigma_0(e^+e^- \to p\bar{p}) \frac{x}{1-e^{-x}}$$

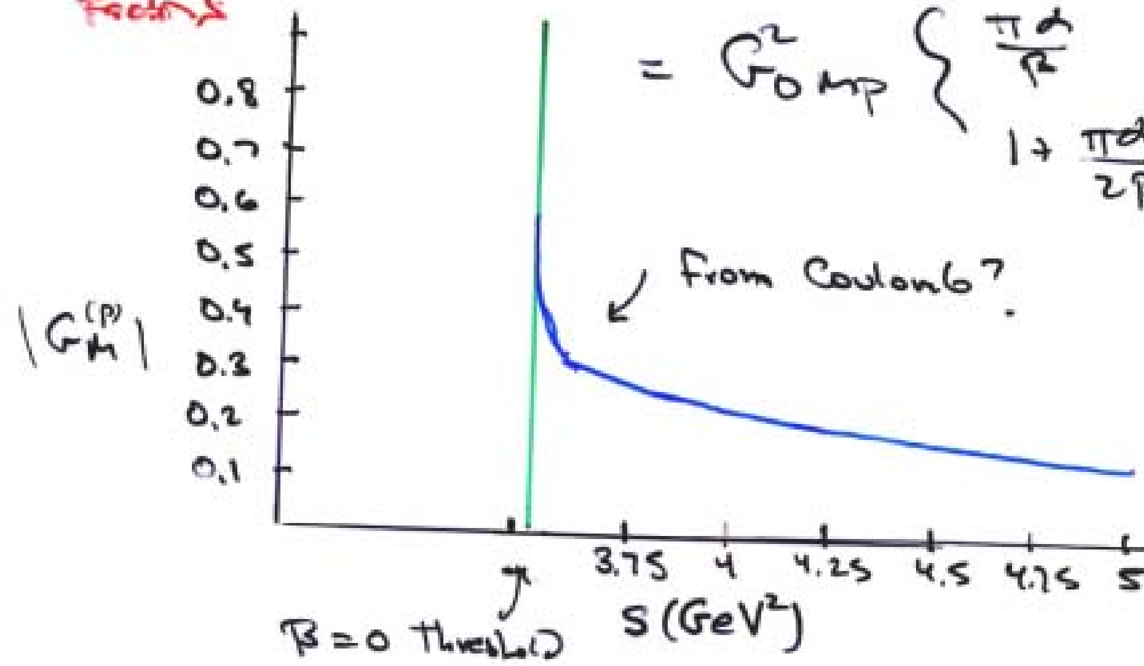
measured form factors $\rightarrow$

$$G^2_{M(p)} = G^2_{0\,M\,p} \frac{x}{1-e^{-x}} \qquad x = \frac{\pi\alpha Q_p^2}{\beta}$$

$$= G^2_{0\,M\,p} \begin{cases} \frac{\pi\alpha}{\beta} & \beta \ll \pi\alpha \\ 1 + \frac{\pi\alpha}{2\beta} & \beta \gg \pi\alpha \end{cases}$$

$\beta^2 = 1 - \frac{4m_p^2}{s}$

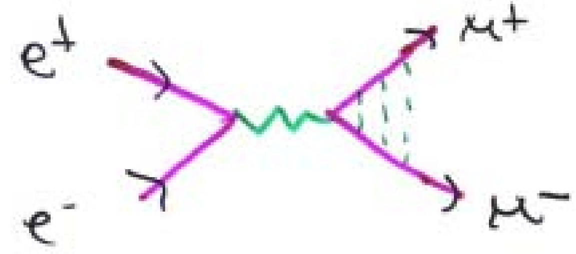
$\alpha = \alpha Q_p^2$



zero effect $e^+e^- \to n\bar{n}$; 4 times $e^+e^- \to \Delta^{++}\Delta^{--}$

$\boxed{\text{Coulomb Effects at Threshold}}$

Hoang, Kühn, Teubner, 89



Sommerfeld Factor

$$\beta = \sqrt{1 - \frac{4m_\mu^2}{s}}$$

reflects $(\mu^+\mu^-)$ Bound States

$$\boxed{\sigma = \sigma_0 \frac{x}{1-e^{-x}}} \qquad \boxed{x = \frac{\pi\alpha}{\beta}}$$

For $\beta \to 0$, $x \to \infty$, $\frac{x}{1-e^{-x}} \Rightarrow x = \frac{\pi\alpha}{\beta}$

σ finite for $\beta \to 0$ $\quad (\beta \ll \pi\alpha)$
since $\sigma_0 \propto \beta$

For $x \ll 1$, $\frac{x}{1-e^{-x}} \simeq 1 + \frac{x}{2}$

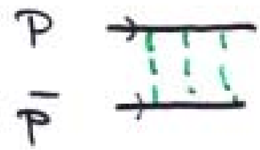
$$\sigma \simeq \sigma_0 \left[1 + \frac{\pi\alpha}{2\beta} \right] \qquad (\beta \gg \pi\alpha)$$

In terms of Form Factors

$$\frac{d\sigma_0}{d\Omega} = \frac{\alpha^2\beta}{4s}\left[|G_M^2|(1+\cos^2\theta) + \frac{4m^2}{s}|G_E^2|\sin^2\theta \right]$$

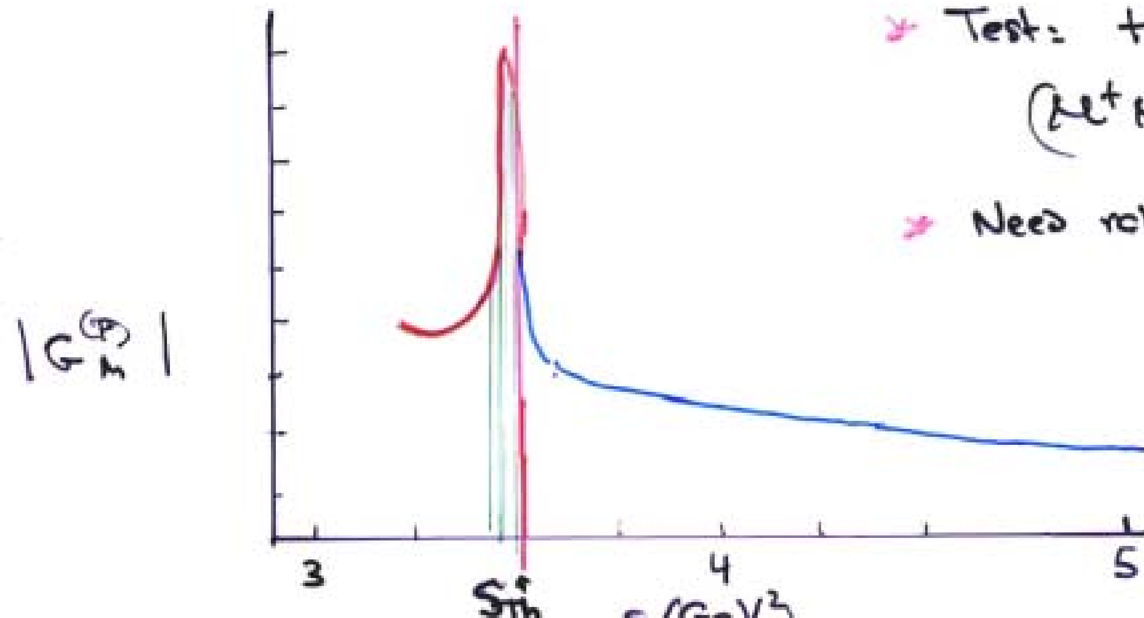
$$G_M^2 \to G_M^2 \frac{x}{1-e^{-x}} = \begin{cases} G_M^2 \frac{\pi\alpha}{\beta} & \beta \ll \pi\alpha \\ G_M^2\left(1 + \frac{\pi\alpha}{2\beta}\right) \end{cases}$$

Atomic Baryonium



Coulomb-bound

- Decays to $\ell=0$ multipions, e^+e^-, $\gamma\gamma\gamma$
- Radiative transitions $(B\bar{B})' \to \gamma\,(B\bar{B})$
- Delayed decay for $\ell \neq 0$.



- Test: true muonium ($\mu^+\mu^-$)
- Need rate calculation

Atomic Baryonium ($p\bar{p}$) below threshold?

Accumulation of Bohr levels: $M_n = 2M_p - \frac{\alpha^2 M_p}{4n^2}$

$$m_r = \frac{1}{2} M_p$$

See sum of states within (e^+e^-) energy resolution

Search for Exotica

$e^+e^- \to \gamma X \qquad C=+,\ I=0,1,2$

$(q\bar{q}q\bar{q}),\ (q\bar{q}g),\ (gg)$

$e^+e^- \to \phi X$ Glue-Rich

πX

ηX

New Atoms:

$(\mu^+\mu^-)$

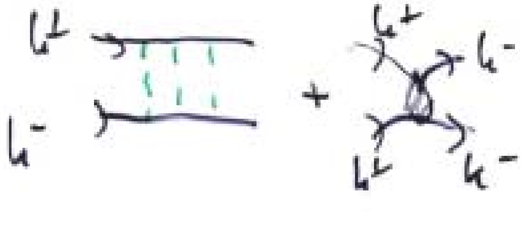
$e^+e^- \to (\pi^+\pi^-)$ ← hadronic stability

(K^+K^-)

$(p\bar{p})$

search just below threshold

associated with $\frac{\pi\alpha}{\beta}$ singular behavior

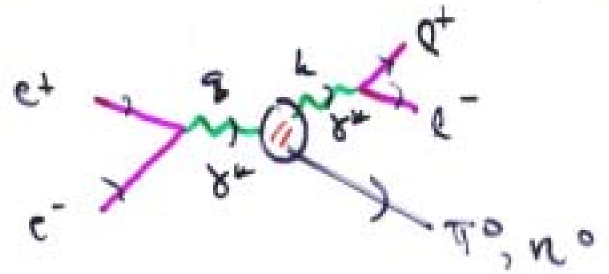


s-wave contact term

Use radiative processes
to probe QCD

$F_{\gamma\pi}(0)$: $\pi^0 \to \gamma\gamma$ decay constant

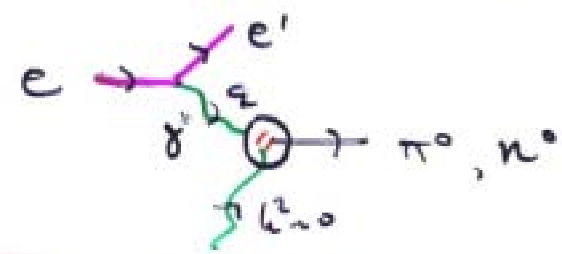
$q^2 > 0$ $\quad F_{\gamma\pi}(q^2)$



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

$q^2 > 0$, $k^2 > 0$

Extension of spacelike pion transition form factor

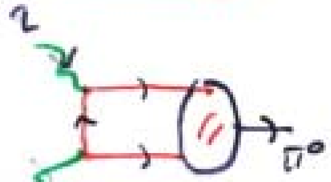


$q^2 < 0 \quad F_{\gamma\pi}(q^2)$

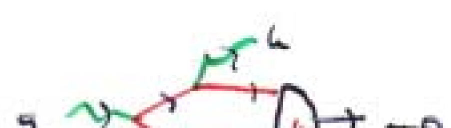
same function
evaluated for spacelike q

Primary test of QCD!

PQCD
Lepage, SJB



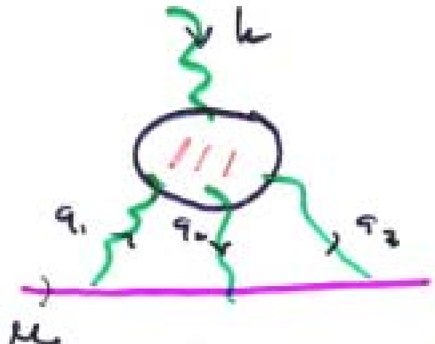
$\Leftrightarrow$



crossing
+
dispersion rel.

$$F_{\gamma\pi}(q^2) \sim \frac{1}{q^2}\int_0^1 \frac{dx}{x}\, \phi_\pi(x, Q)$$

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

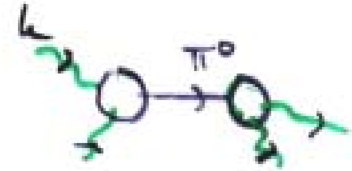


$|q_i^2| \sim O(m_\mu^2)$ $q_i^2 < 0$

Light-by-Light $O(\alpha^3)$ contribution to

$$a_\mu = \left(\frac{g-2}{2}\right)_\mu$$

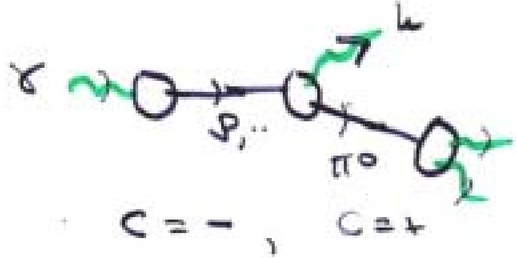
Estimates from chiral theory (elementary pions)



C = + saturation

Sanda et al
Kinoshita et al

* Test input using measurements of $\gamma^* \to \pi^0 \gamma$
$F_{\gamma\pi}(q^2)$: $\gamma^* \gamma \to \pi^0$

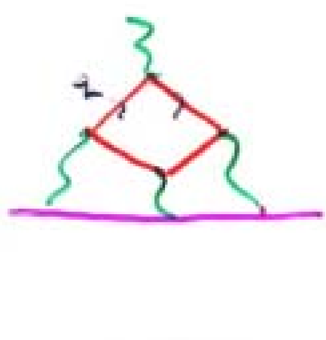


C = − , C = +

Determine
From dispersive part
of $F_{\gamma\pi}(q^2)$

* Free quark estimate: (duality)

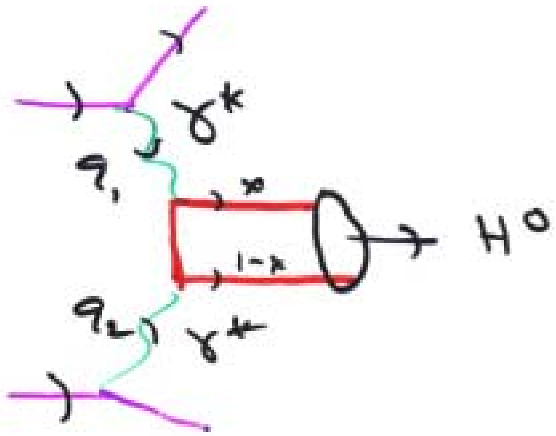
$m_q(k^2)$?



$$a_\mu^{\gamma\gamma}(\text{hadronic}) = \sum_q e_q^4 \, a_\mu(\text{leptonic})$$

Aldins, Dufner, Kinoshita
SJB

Extension to double-tagged



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

Insensitive to shape of $\phi_{H^0}(x,Q)$

SJB + GPL

Ong

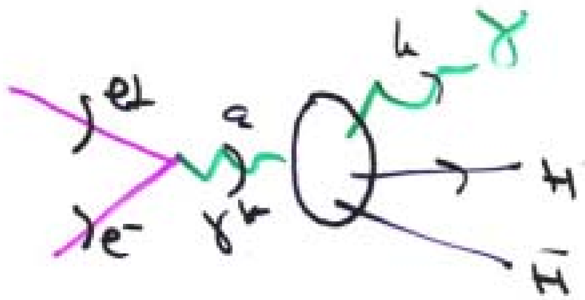
Walsh, et al

Vogt, et al

Measure ratio of $\dfrac{\gamma^*\gamma \to H^0}{\gamma^*\gamma^* \to H^0}$

New Physics Arena

$\boxed{\text{Timelike Virtual Compton Scattering}}$



timelike
DVCS

ISR

Interference: H vs $\bar{H}$

Charge Asymmetry

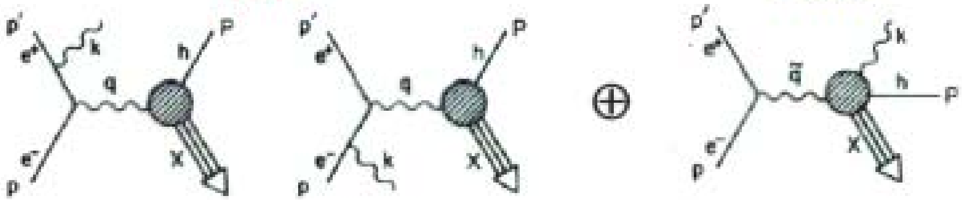
$$\mathrm{Re}\left(F_H^{+}\, T_{\mu\nu}\right)$$

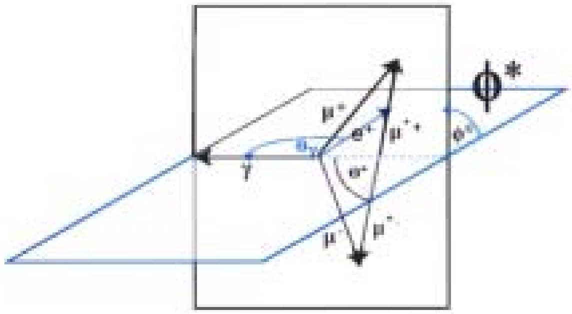
Single-Spin Asymmetry

$$\mathrm{Im}\left(F_H^{+}\, T_{\mu\nu}\right)$$

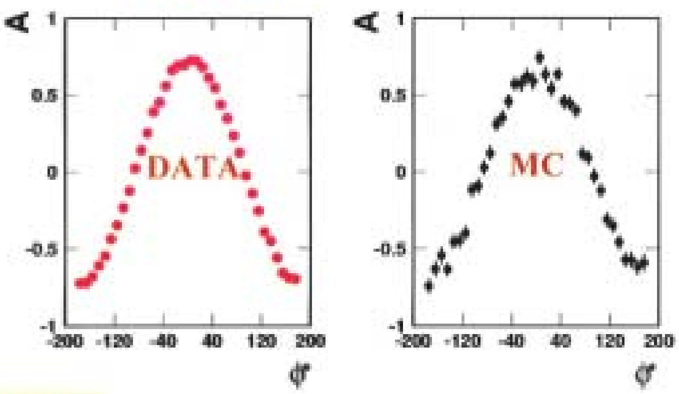
Initial and Final State Interference

ISR FSR





ISR-FSR interference

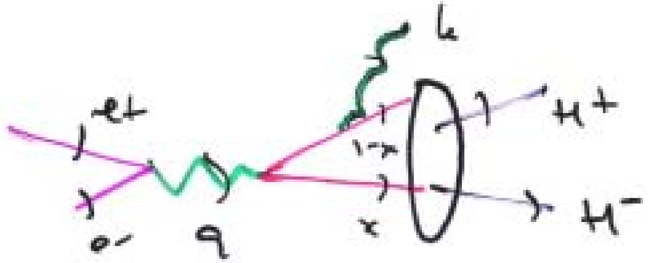


⇒QED charge asymmetry observed in the $\mu\ \mu\ \gamma$ channel

What does *A* look like for $\pi^+\pi^-\gamma$ or $K^+K^-\gamma$?

→ measurement of QCD phases

ϕ^* - is an angle between production plane and decay plane



$q^2 \gg M^2_{H\bar{H}}$

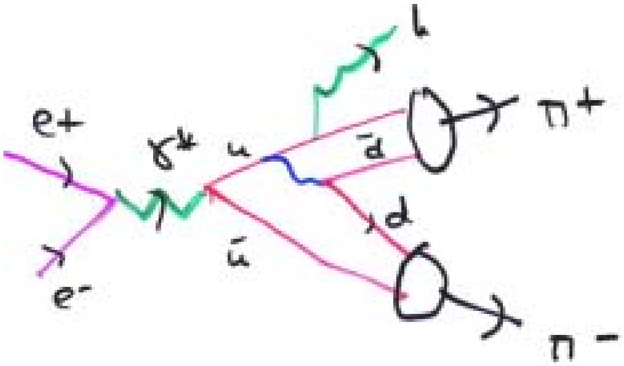
$$\mathcal{M}_{\gamma^* \to H\bar{H}\gamma} \sim \frac{\epsilon \cdot \epsilon}{q^2} \int_0^1 \frac{dx}{x} \sum e_q^2 \, \phi_{H\bar{H}}(x, M^2, Q^2)$$

Measures two-hadron distribution amplitude

M. Diehl et al

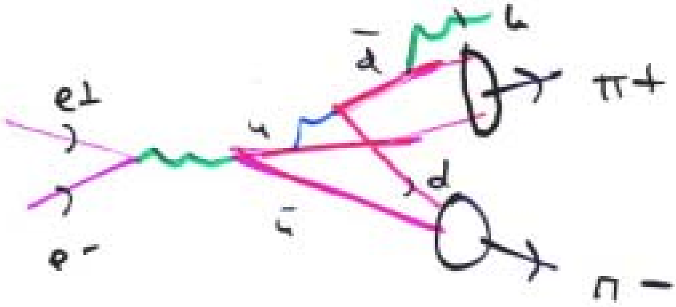
Lepage, SJB

$\boxed{\text{Timelike Virtual Compton}}$



$\mathcal{M}_{\pi\pi}^2 > q^2$

Σe_q^2



$e_u e_{\bar{d}}$

no "handbag" approximation possible

$$\mathcal{M}_{\gamma^* \to \pi^+\pi^-\gamma}$$

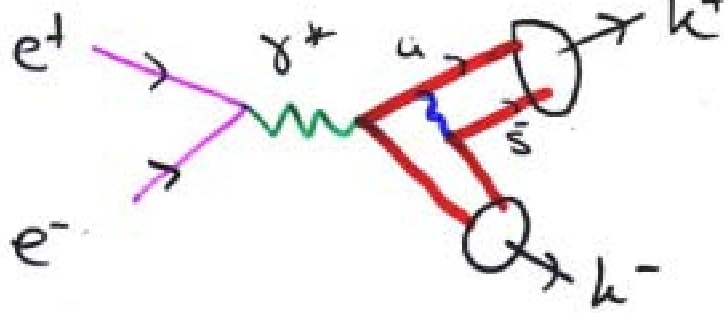
$$= \int_0^1 dx \int_0^1 dy \, T_H(x, y, Q^2) \, \phi_\pi(x, Q^2) \, \phi_\pi(y, Q^2)$$

$$\sim \frac{\alpha_s f_\pi^2}{\mathcal{M}_{\pi\pi}^2}$$

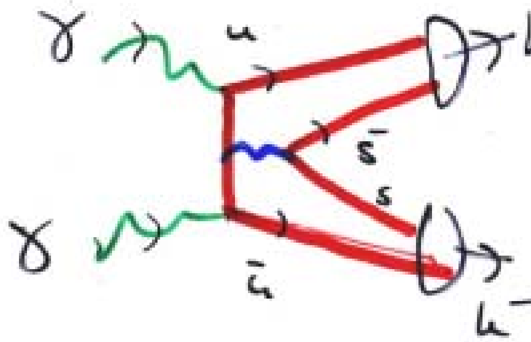
Lepage SJB

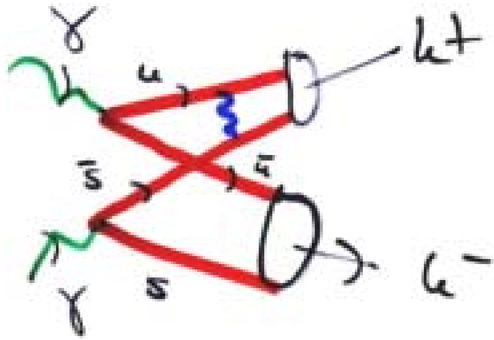
Strong cancellation for $\pi^0\pi^0$

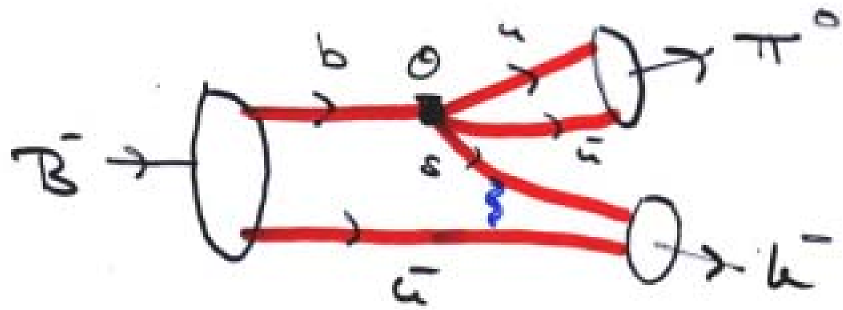
Universal Light-Front Wavefunctions



G. P. Lepage
SJB







Henley
Szepaniak
SJB

Li, Keum
Sanda

BBNS

Common Ingredients:

Distribution Amplitudes

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

* $\alpha_s(Q)$ at low scales

Exclusive channels

dimensional scaling

BF, MMT

Polchinski - Strassler

ADS corresp.

$$\sigma_{\text{fixed } \theta_{cm}} \sim \frac{1}{s^{\Delta - 1}}$$

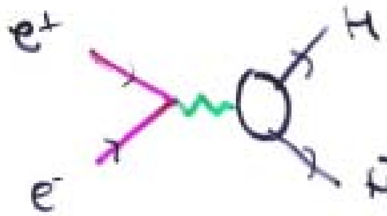
$$\Delta = \sum n_q + n_g + \ell$$

e.g. $\sigma_{e^+e^- \to B\bar{B}}$: $\Delta = 6$, $F_1^B(s) \sim \frac{1}{s^2}$

$\sigma_{e^+e^- \to B\bar{B}\pi}$: $\Delta = 8$

Hadron helicity conservation

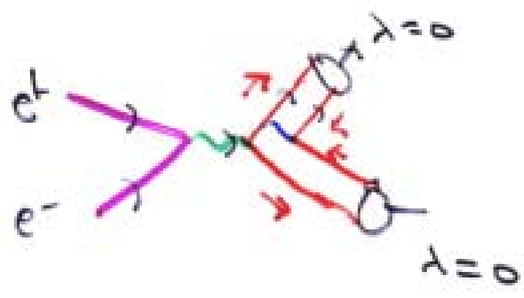
Lepage, SJB



$$\frac{d\sigma}{d\Omega} \propto \sin^2\theta \qquad M\bar{M}$$

$$1 + \cos^2\theta \qquad B\bar{B}$$

H and $\bar{H}$ have opposite helicity for leading power



quark chirality conservation

$+ J_z^\gamma = \pm 1$ only

test in $e^+e^- \to \rho^+\rho^-$, $\rho\pi$, N, N^*..

Exclusive Final States : power-law, ang. dist

ADS/CFT Near Conformal QCD

Few Body

* $\sigma(\gamma^* \to n\pi) \sim \frac{1}{s^{\Delta-1}}$ $\Delta = \#\, q, g, l$

* $\gamma^* \to \rho\pi$ Test hadron helicity conserv.

* $\gamma^* \to p\bar{p},\ n\bar{n},\ \Lambda\bar{\Lambda},\ p\Delta,\ \Delta\bar{\Delta}, \ldots$

* $\gamma^* \to (p\pi)\ \bar{p}$

low B

Near-threshold chiral dynamics

* $\gamma^* \to \gamma\ \pi^+\pi^-$

$\gamma\ \pi^0\pi^0$

* $\gamma\gamma \to \pi^+\pi^-,\ \pi^0\pi^0$

PQCD: $\sigma(\pi^0\pi^0) \ll \sigma(\pi^+\pi^-)$

Fundamental test

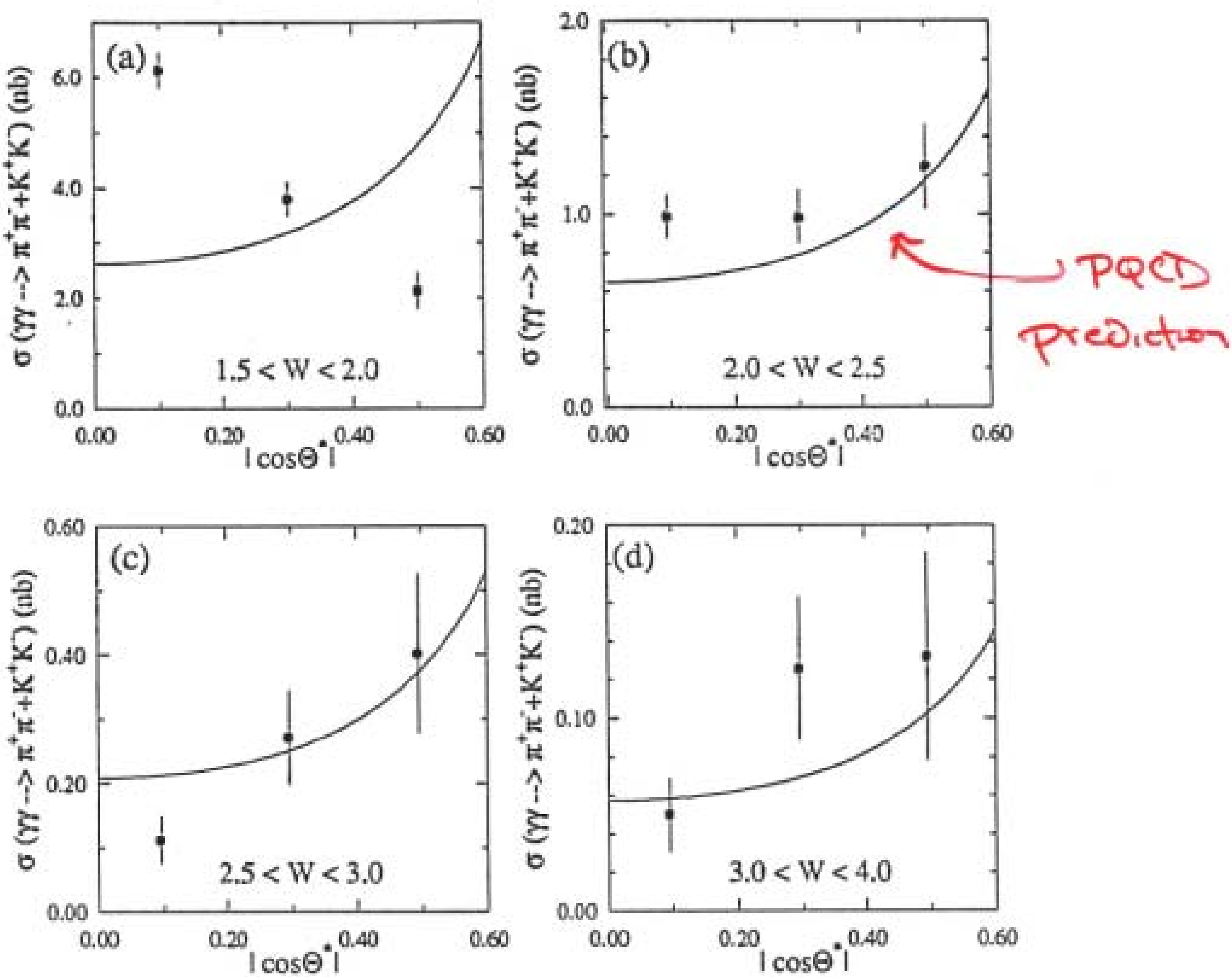
of PQCD Factorization.

* Crucial NP input for B, h decays

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

(θ^* dep)

CLEO



$|\cos\theta^*|$

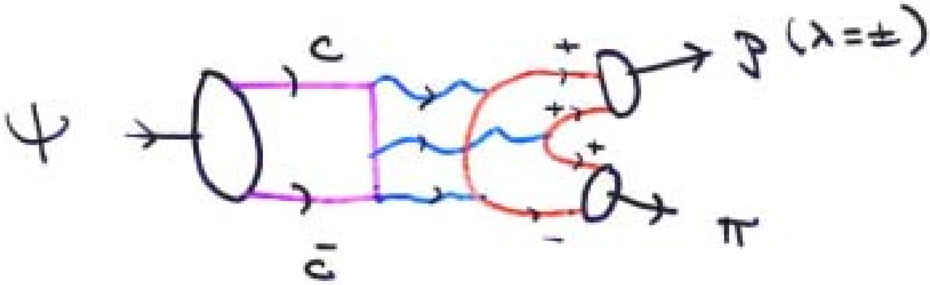
Evidence for PQCD at $W_{\gamma\gamma} \gtrsim 2.5$ GeV

The "$J/\psi \to \rho\pi$" Puzzle and Intrinsic Charm

SJB + M. Karliner

$$B[J/\psi \to \rho\pi] = 1.28 \pm 0.10 \%$$

$$B[\psi'(2S) \to \rho\pi] < 3.6 \times 10^{-5}$$



PQCD: $B[\psi' \to \rho\pi] < \frac{1}{50}$ expected rate

$Q\bar{Q} \to \rho\pi$ suppressed by "hadron helicity cons."

Same problem: KK^*

SJB, G.P. Lepage
S.F. Tuan

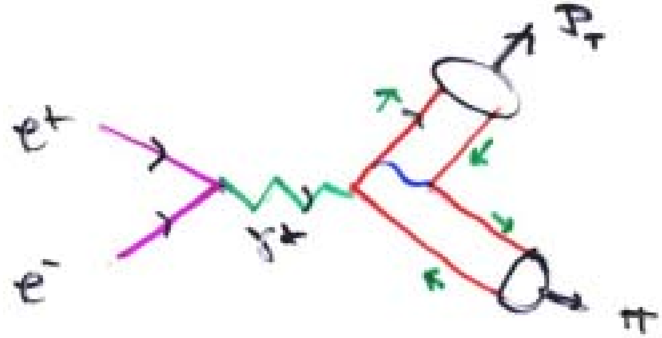
Important test of QCD dynamics:

$$\frac{\frac{d\sigma}{d\Omega}(e^+e^- \to \rho_T \pi)}{\frac{d\sigma}{d\Omega}(e^+e^- \to \pi \pi)} \sim \frac{\lambda_\rho^2}{s} \cdot \left(\frac{1+\cos^2\theta}{\sin^2\theta}\right)$$

* Tests: presence of $|q\bar{q}g\rangle$ Fock state

or $L_z = 1$ in ρ $|q\bar{q}\rangle$

wavefunction !



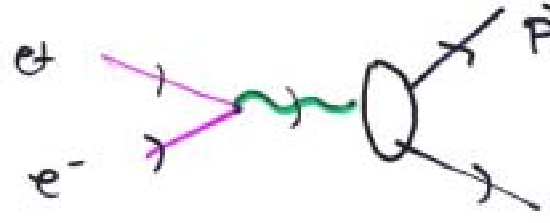
* Must have ρ_T: $\epsilon^{\mu\nu\sigma\tau}\, \epsilon_\mu^{(\rho)}\, P_\nu^{(\rho)}\, P_\sigma^{(\pi)}\, \epsilon_\tau^{(\gamma)}$

$\therefore$ must have L_z or extra gluon

$\Rightarrow$ extra mass dimension λ_ρ

* Same result for any $V = \rho, \omega, \phi$

Critical Measurement



PQCD: Expect same behavior as

$$e^+e^- \to p\bar{p} \qquad G_M \sim \frac{1}{s^2}$$

Spacelike

$$e\,p \to e\,\Delta(1230) \qquad \sim \frac{1}{s^3}$$

$$e\,p \to e\,S_{11}(1535) \qquad \sim \frac{1}{s^2}$$

$$e\,p \to e\,p \qquad \sim 1/s^2$$

Possible explanation: $\phi_\Delta(x_1, x_2, x_3) \sim x_1 x_2 x_3$

Carlson

asymptotic form

accidental suppression of

$$\int \phi_\Delta^\dagger\, T_H\, \phi_p$$

Check $e^+e^- \to \Delta\bar{\Delta}, \ldots$

HHC: $\lambda_{\bar{p}} + \lambda_{N^*} = 0$

Test of Hadron Helicity Conservation

$\lambda = 1/2$

$ep \to e' N^*$

$\lambda = 3/2$

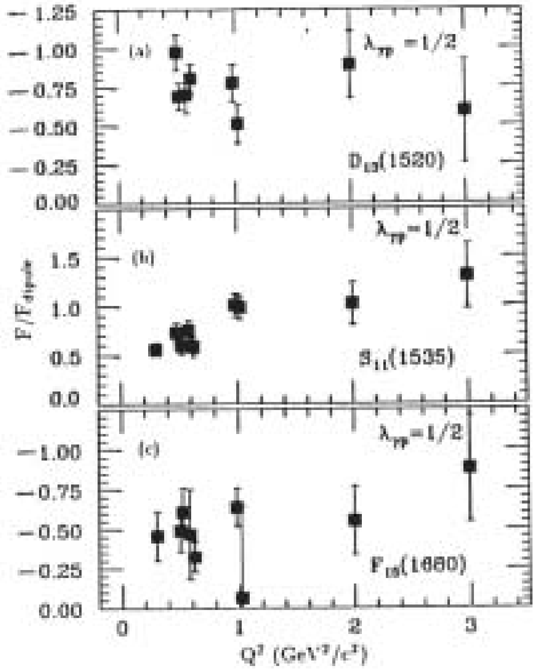


FIG. 6. The helicity-$\frac{1}{2}$ form factors F/F_{dipole} vs Q^2, constructed from helicity amplitudes given in Ref. [31]. (a): $D_{13}(1520)$. (b): $S_{11}(1535)$. (c): $F_{15}(1680)$.

$\frac{F(Q^2)}{F_{dipole}(Q^2)}$

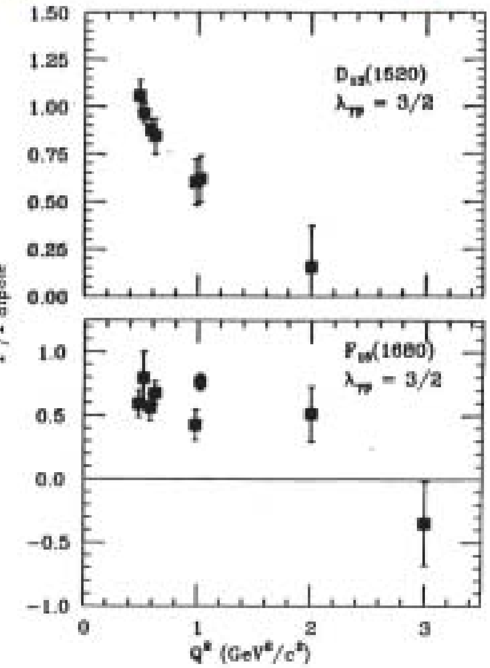
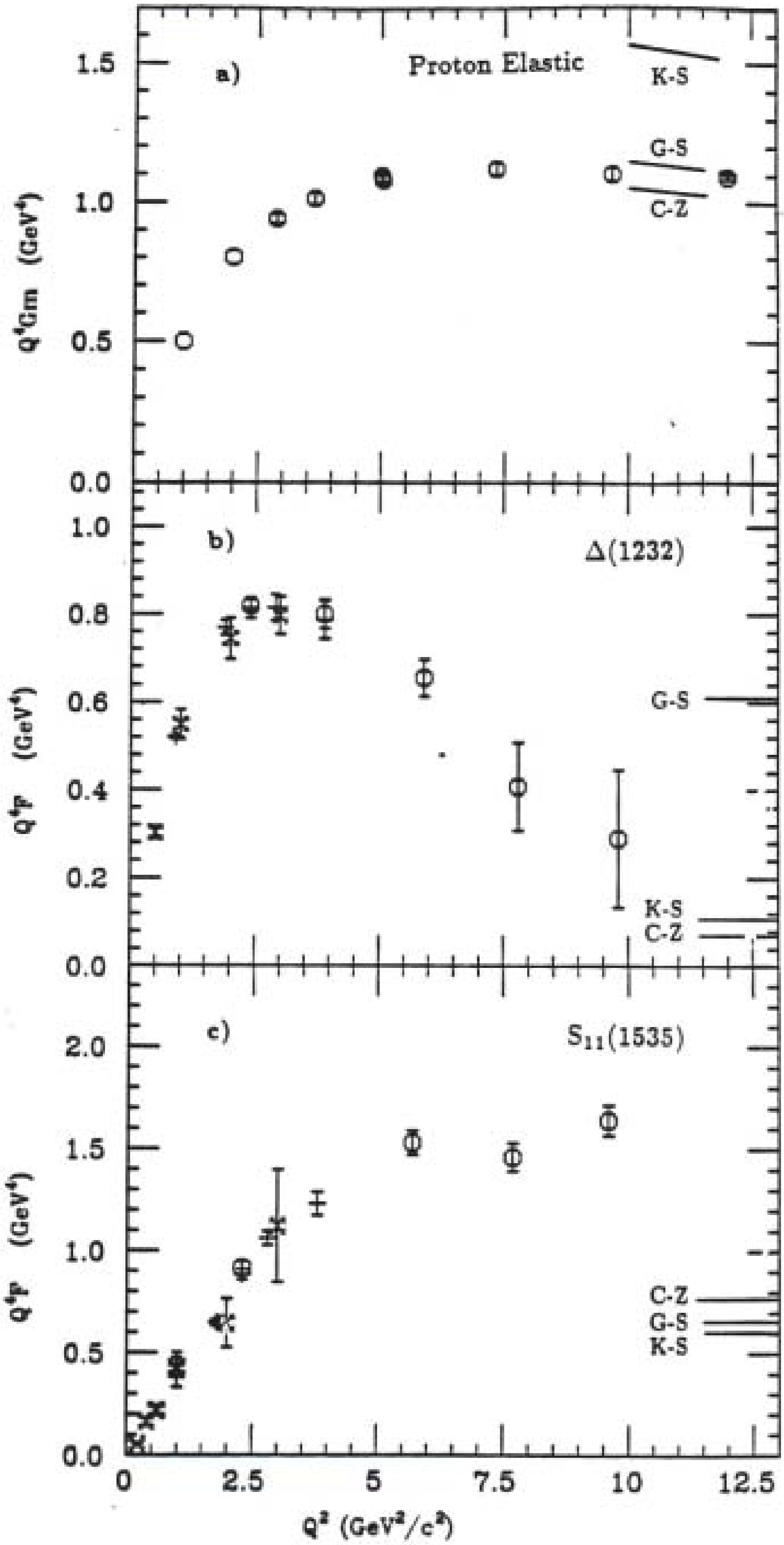


FIG. 7. The helicity-$\frac{1}{2}$ form factors F/F_{dipole} vs Q^2, constructed from helicity amplitudes given in Ref. [31]. (a) $D_{13}(1520)$. (b) $F_{15}(1680)$.

ref: P. Stoler, Phys. Rev. D 44, 73 (1991)

4/3x



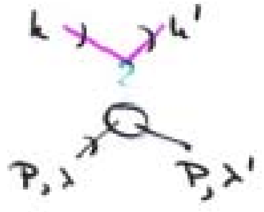
P. Stoler
Carlson

$p \to p$

$p \to \Delta$

Suppression
from
CZ s.r.

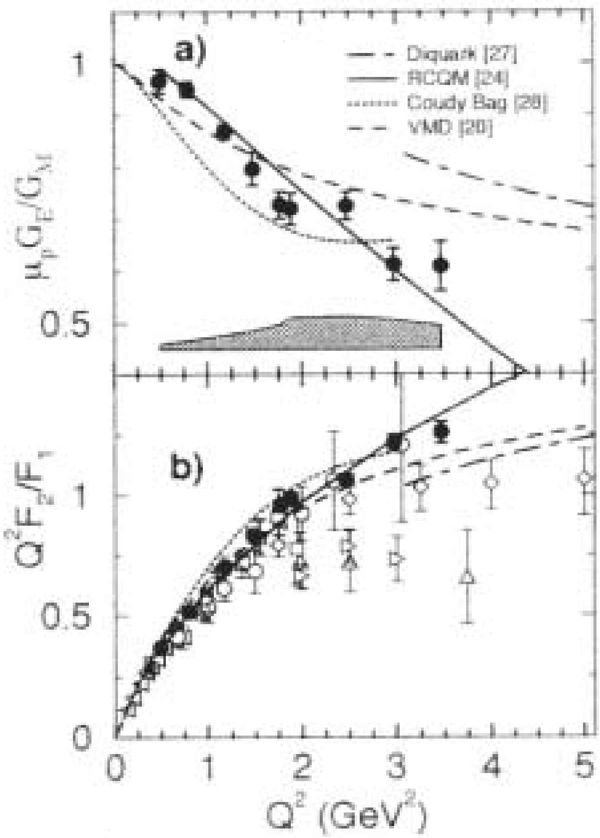
$p \to S_{11}$



JLab uses polarization transfer to recoil proton

$\ell^\mu \langle P',\lambda' | J_\mu | P,\lambda \rangle \propto G_E, G_M$

$$\frac{P_x}{P_y} = \frac{G_E}{G_M} \frac{2M}{(k+k')\tan\frac{\theta}{2}}$$



Jefferson Lab

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

diquark model?

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

$$\frac{d\sigma}{dt}\left[\gamma_{\lambda_1}\gamma_{\lambda_2} \to H_{\lambda_3}\bar{H}_{\lambda_4}\right]$$ 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

Near-Threshold Pion Production

"Soft-pion theorems for hard processes"

{ Pobylitsa, Polyakov, Strikman

Example: $\gamma^* \to N(\bar{N}\pi)$

$$W_{\pi N} - W_{\pi N}^{\text{Threshold}} < m_\pi$$

} low V_{rel}

Also $\gamma\gamma \to N(\bar{N}\pi)$, $\gamma^* N \to (\pi N)$

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

$$\mathcal{M} \sim \langle 0 | J^\mu | N\bar{N}\pi \rangle \sim \frac{i}{f_\pi} \langle 0 | [Q_5, J^\mu] | N\bar{N} \rangle$$

chiral rot

$$\sim \frac{i}{f_\pi} \langle 0 | J^\mu | N\tilde{\bar{N}} \rangle$$

Same scaling as $N\bar{N}$

QCD Physics -

$\boxed{\text{New topics in low energy } e^+e^- \to X}$

$\sqrt{s} \lesssim 2.5$ GeV

- $e^+e^- \to p\uparrow \bar{p}$ Polarization
  Timelike Form Factors, $\mathrm{Im}\, G_M^* G_E$

- $e^+e^- \to \gamma \pi^+\pi^-$, γK^+K^-, $\gamma p\bar{p}$
  Timelike DVCS, Real + Im part

- $e^+e^- \to \pi^+\pi^-$, K^+K^-, $p\bar{p}$
  charge asymmetry
  resolve Rosenbluth / Pol. Trans
  discrepancy G_E/G_M
  $\gamma^*\gamma^* \to H\,H$

- $e^+e^- \to \pi^0, \eta^0\, \gamma$ $(\gamma^* \to \pi^0\gamma)$
  $(g-2)_{\mu\,LL}$, fundamental QCD physics