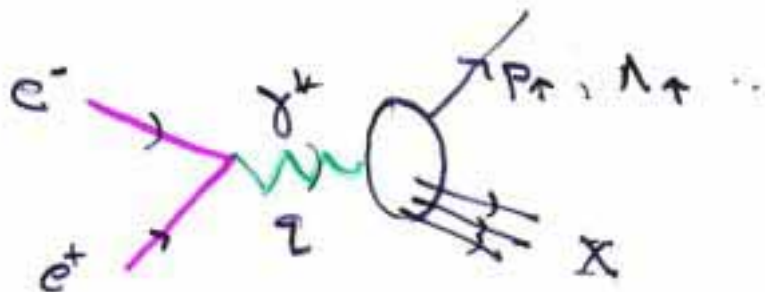
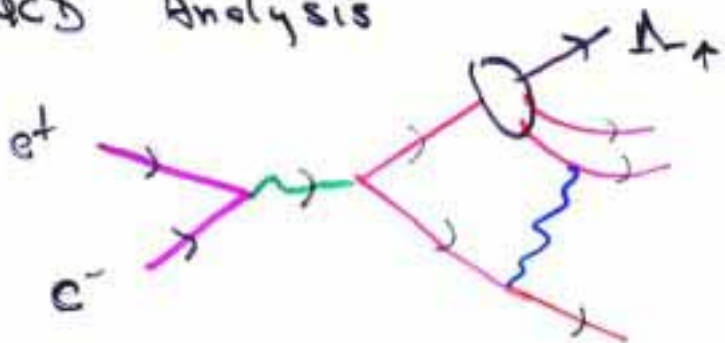


Semi-Inclusive Single-Spin Asymmetries



- PQCD Analysis



$$\vec{S}_\Lambda \cdot \vec{P}_\Lambda \times \vec{P}_e$$

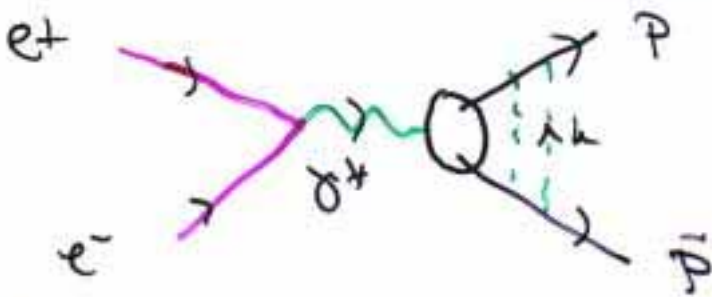
Leading Twist

- ✗ From FSI (similar to BHS "Sivers" effect)
- ✗ Requires $L=1, 0$ in Λ^+ Wave Function
- ✗ Matrix element proportional to M_{11}^*

A. Metz
Huang, Schnitt, 800
Collins

QED Coulomb Effects at Threshold

Hadron - Pair Production



Coulomb interactions
at Bohr scale
($k \sim 0(\alpha m_p)$)

Same as H^+H^-

reflects
atomic
beryonium
at $5\alpha M_p$

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

measured
form
factors

$$G_{MP}^2 \rightarrow G_{0MP}^2 \frac{x}{1-e^{-x}}$$

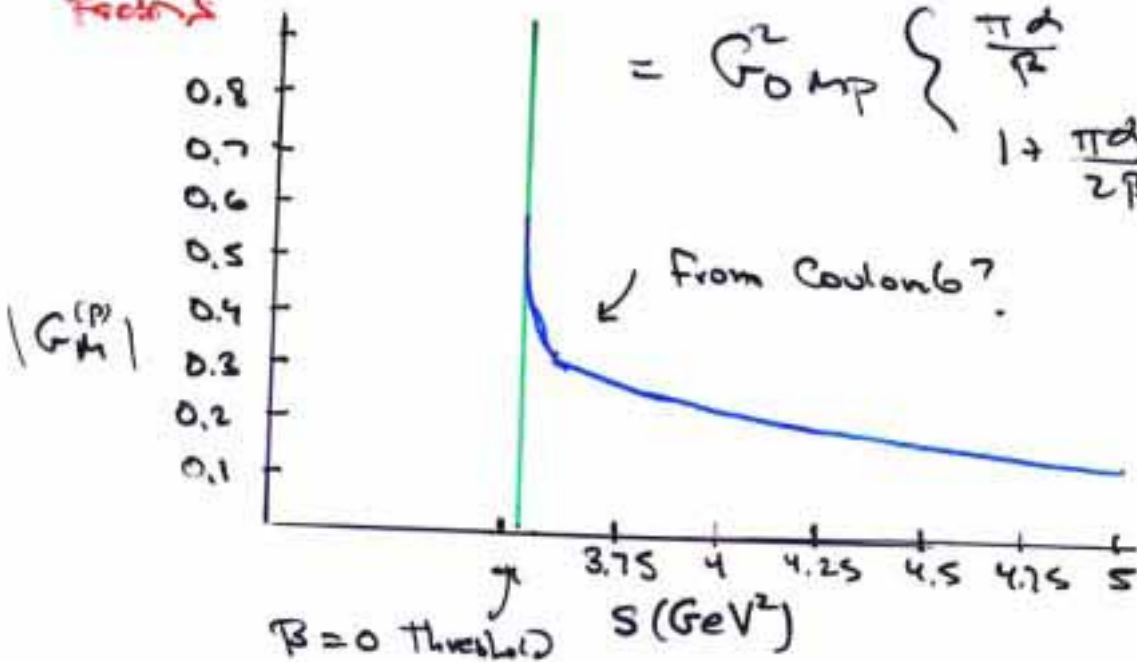
$$x = \frac{\pi\alpha^2}{\beta}$$

$$= G_{0MP}^2 \left\{ \frac{\pi\alpha}{\beta} \right.$$

$$\beta < \pi\alpha$$

$$\left. 1 + \frac{\pi\alpha}{2\beta} \right\}$$

$$\beta > \pi\alpha$$



$$\beta^2 = 1 - \frac{4M_p^2}{S}$$

$$\alpha = \alpha_0 \beta^2$$

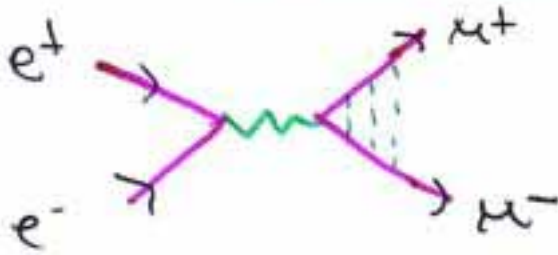
zero effect $e^+e^- \rightarrow n\bar{n}$; 4 times $e^+e^- \rightarrow \Delta^{++}\Delta^{--}$

Coulomb Effects at Threshold

Hoang, Kühn, Tüchler, 2009

Sommerfeld Factor

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



reflects
($\mu^+\mu^-$)
Born
Stabs

$$\sigma = \sigma_0 \frac{x}{1 - e^{-x}}$$

$$x = \frac{\pi\alpha}{\beta}$$

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

σ finite for $\beta \rightarrow 0$ since $\sigma_0 \propto \beta$ ($\beta \ll \alpha$)

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

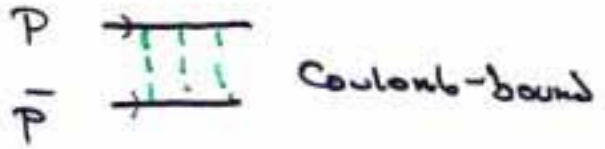
$$\sigma \approx \sigma_0 \left[1 + \frac{\pi\alpha}{2\beta} \right] \quad (\beta \gg \alpha)$$

In terms of Born Factor:

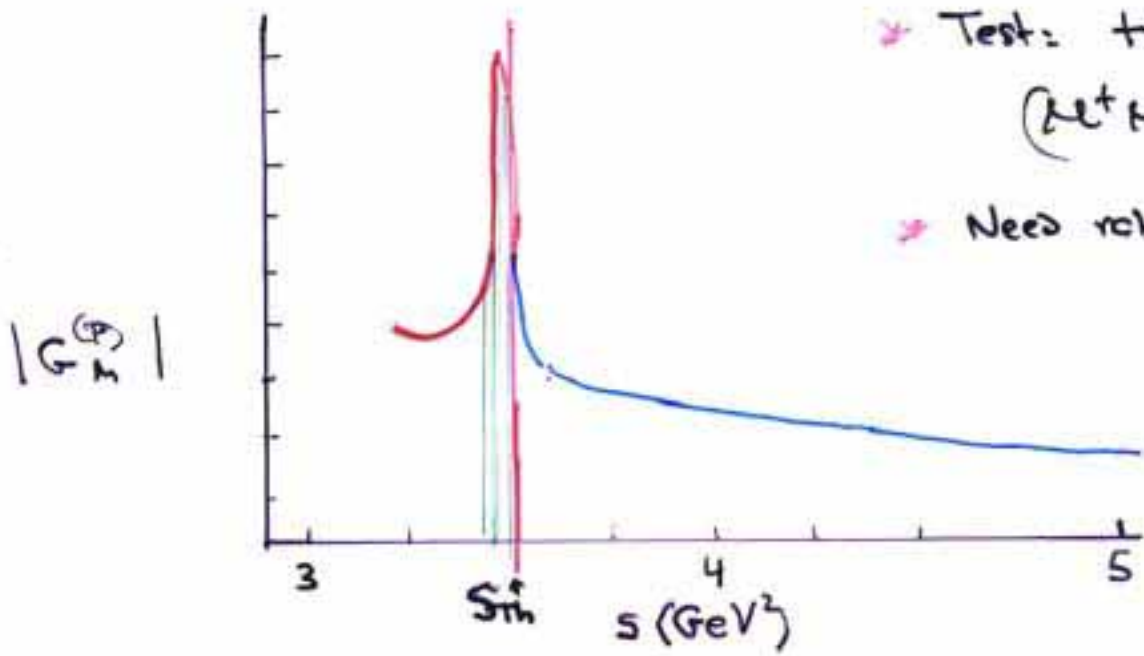
$$\frac{d\sigma_0}{d\Omega} = \frac{\alpha^2 \beta}{4s} \left[|G_M^2| (1 + \cos^2 \theta) + \frac{4}{3} |G_E^2| \sin^2 \theta \right]$$

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

Atomic Baryonium



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



- * 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 Exotics

$$e^+e^- \rightarrow \gamma X \quad C=+, \quad \mathbb{P}=0, 1, 2$$

$$(q\bar{q}q\bar{q}), (q\bar{q}q), (qq)$$

$$e^+e^- \rightarrow \begin{matrix} \phi X \\ \pi X \\ \eta X \end{matrix} \quad \text{Glue-Rich}$$

New Atoms:

$$e^+e^- \rightarrow \begin{matrix} (e^+e^-) \\ (\pi^+\pi^-) \\ (K^+K^-) \\ (p\bar{p}) \end{matrix}$$

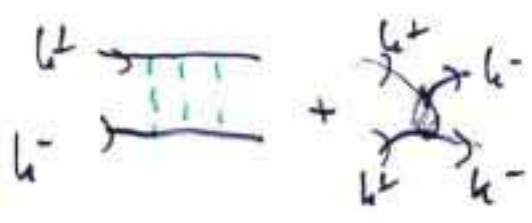
← hadronic stability

Search ^{just} below threshold

associated with $\frac{11\pi}{\beta}$



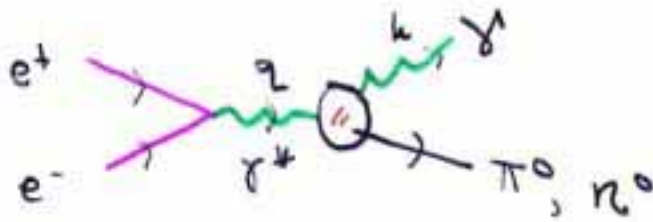
Singular behavior



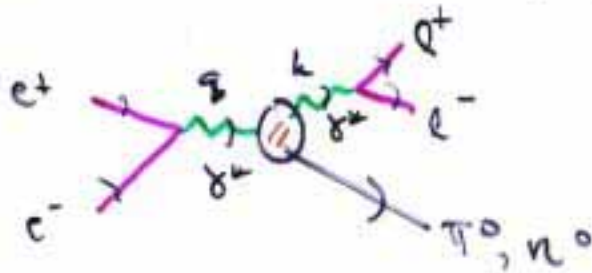
s-wave contact term

Use radiative processes
to probe QCD

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

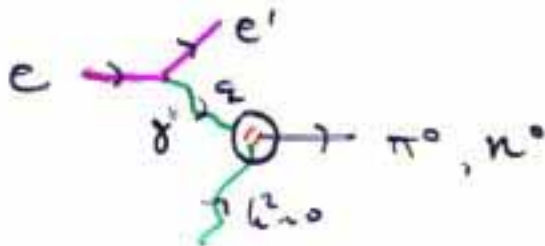


$q^2 > 0$ $F_{\gamma\pi}(q^2)$



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

Extension of spacelike pion transition form factor

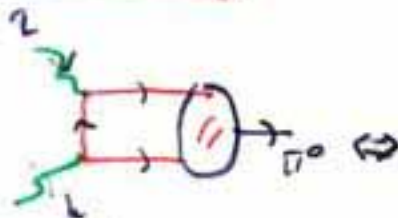


$q^2 < 0$ $F_{\gamma\pi}(q^2)$

same function
evaluated for spacelike q

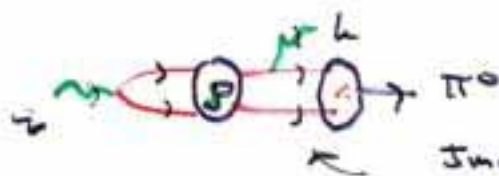
Primary test of QCD!

PEP
Lepage, SJS

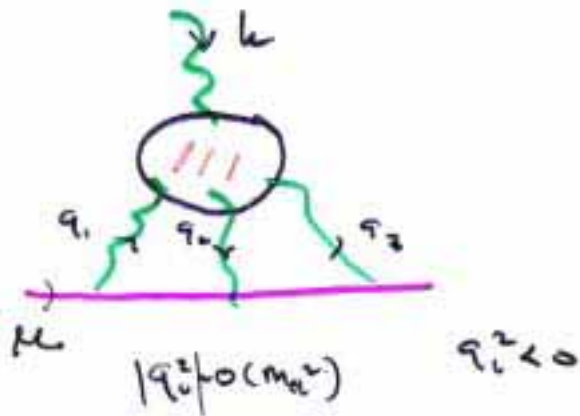


Crossing
+ dispersion rel.

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



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

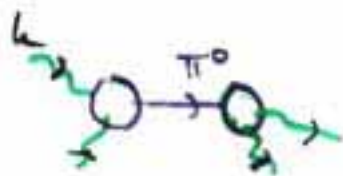


Light-by-light $O(\alpha^2)$

contribution to

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

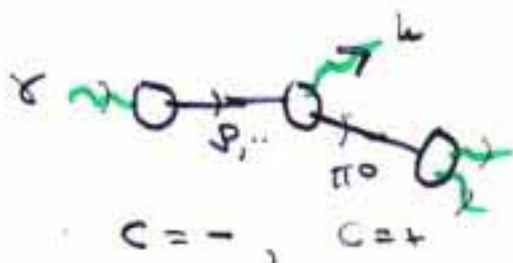
Estimate from chiral theory (elementary pions)



$C=+$
Selection

Sends et al
Knecht et al

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

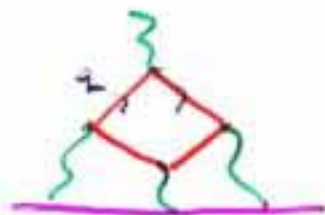


Determine
From dispersive part

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

* Free quark estimate: (duality)

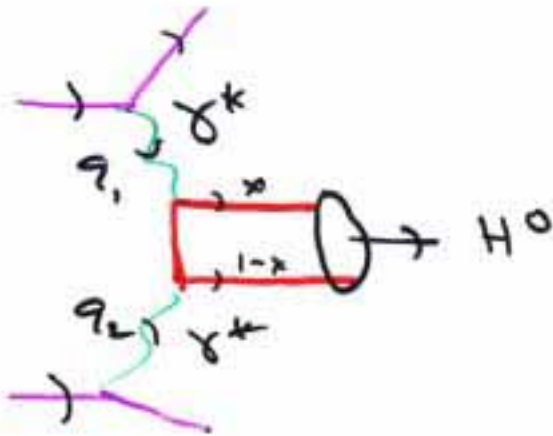
$m_2(k^2) ?$



$$a_{\mu}^{\gamma\gamma}(\text{hadron}) = \sum_q e_q^4 Q_{\mu}(\text{hadron})$$

Aldins, Dutta, Knecht
SJB

Extension to double-tagged



$$\frac{1}{(1-x)Q^2} \Rightarrow \frac{1}{(1-x)Q_1^2 + xQ_2^2}$$

Insensitive to shape of $\phi_{H_0}(k, Q)$

SIS + GPL

Chng

Walsh, et al

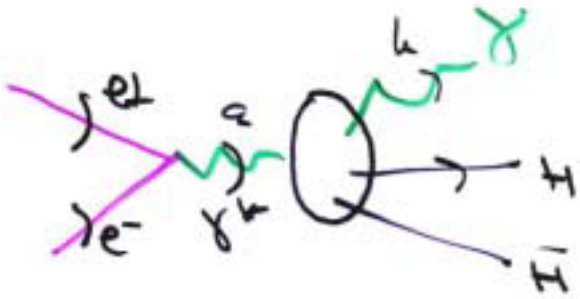
Vogt, et al

Measure ratio of

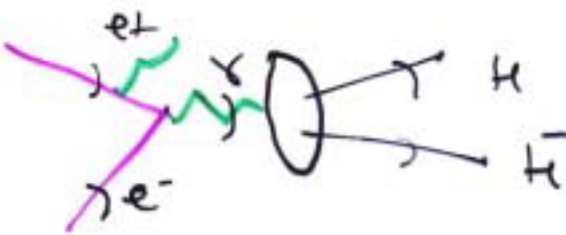
$$\frac{\lambda^* \lambda^* \rightarrow H_0}{\lambda^* \lambda^* \rightarrow H_0}$$

New Physics Areas

Timelike Virtual Compton Scattering



timelike
DVCS



ISR

Interference:

H vs H̄

Charge Asymmetry

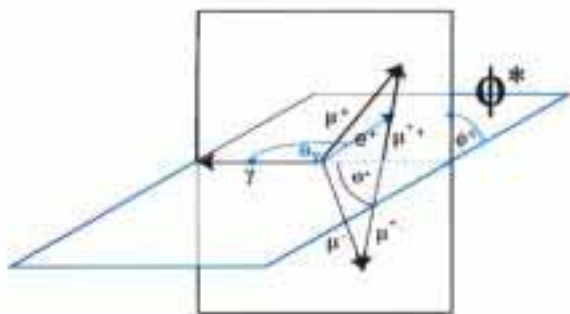
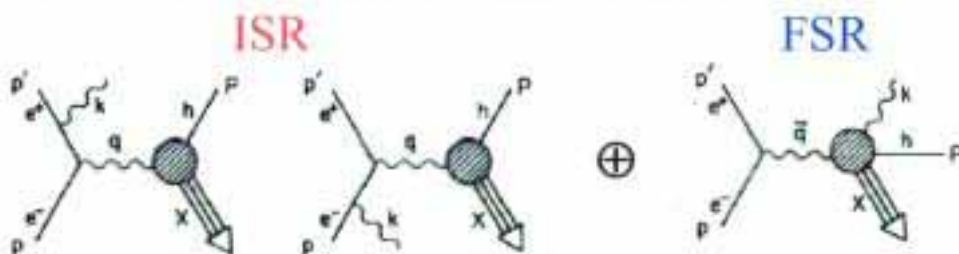
$$\text{Re}(F_H^+ T_{HV})$$

Single-Spin Asymmetry

$$\text{Im}(F_H^+ T_{HV})$$

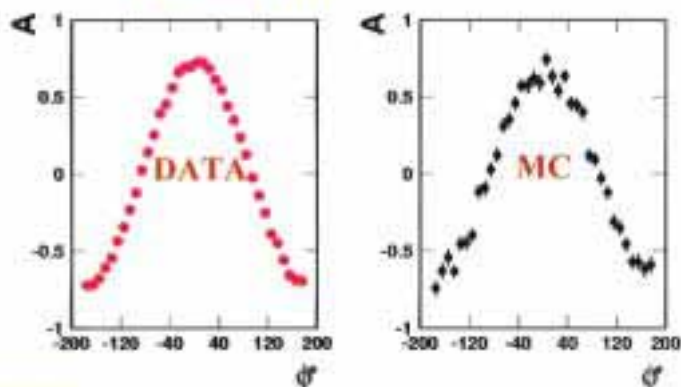


Initial and Final State Interference



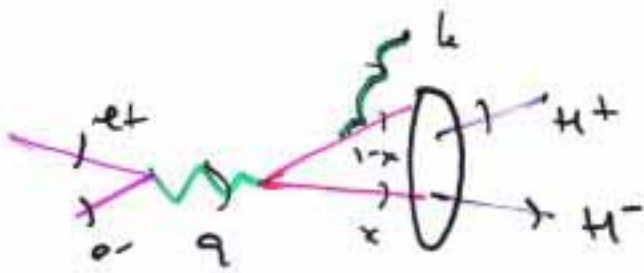
⇒ QED charge asymmetry observed in the $\mu\mu\gamma$ channel

ISR-FSR interference



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



$$Q^2 \gg m_{H\bar{H}}^2$$

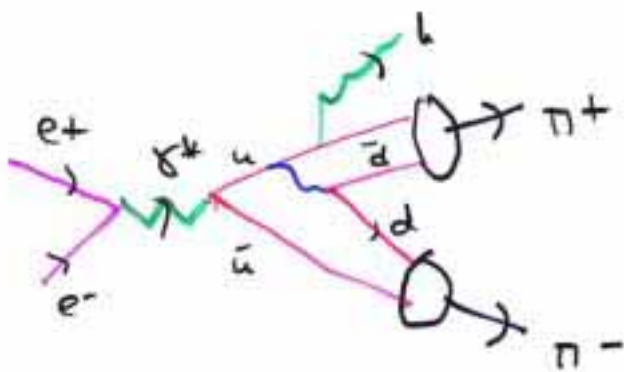
$$M_{\gamma\gamma \rightarrow H\bar{H}} \sim \frac{E \cdot E}{Q^2} \int_0^1 \frac{dx}{x} \sum e_f^2 \phi_{H\bar{H}}(x, m^2, Q^2)$$

Measures two-hadron distribution amplitude

A. Diehl et al

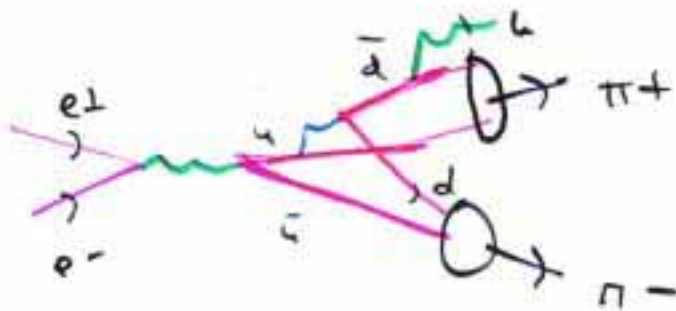
Lepos, 823

Timelike Virtual Compton



$$M_{\pi\pi}^2 > q^2$$

$$\sum e_q^2$$



$$e_u e_d$$

no "handles"

approximation possible

$$M_{\gamma^* \rightarrow \pi^+ \pi^- \gamma}$$

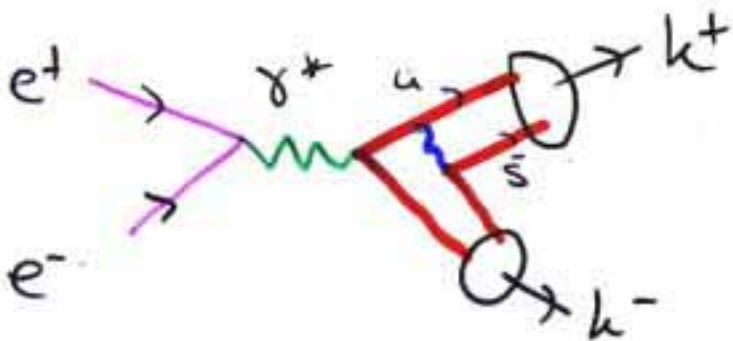
$$= \int_0^1 dx \int_0^1 dy T_H(x, y, q^2) \phi_\pi(x, q^2) \phi_\pi(y, q^2)$$

$$\sim \frac{\alpha_s f_\pi^2}{m_{\pi\pi}^2}$$

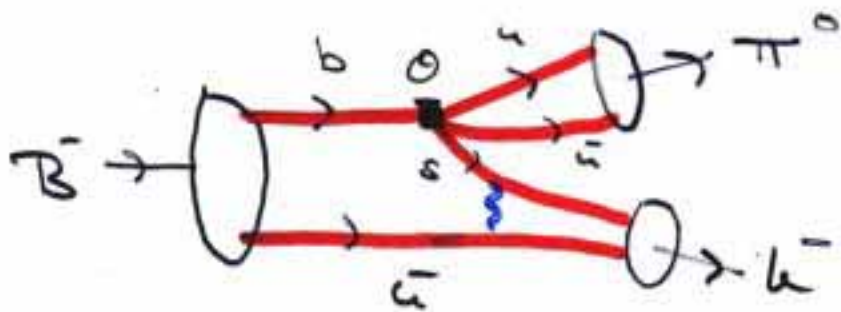
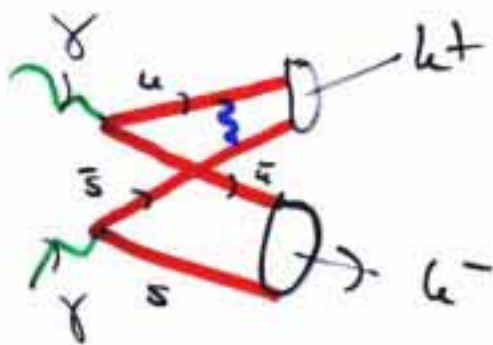
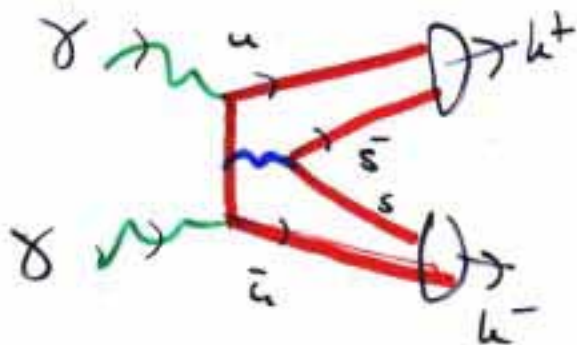
large QCD

Strong cancellations for $\pi^0 \pi^0$

Universal Light-Front Wavefunctions



G. P. Lepage
SJB



Henry
Sapoznik
SJB

Li, Keum
Sander

BBNS

Common Ingredients:

* $\phi_{\pi}(x, Q)$, $\phi_{K}(x, Q)$

Distribution
Amplitudes

* $\alpha_s(Q)$ at low scales

Exclusive channels

dimensional
Scaling

BF, MMT
Poleinst. + Strasser
ADS corresp.



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

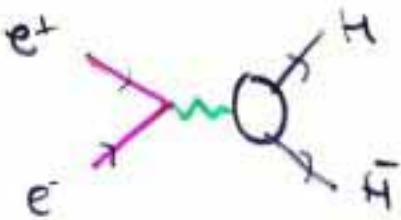
$$\Delta = \sum n_q + n_g + 1$$

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

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

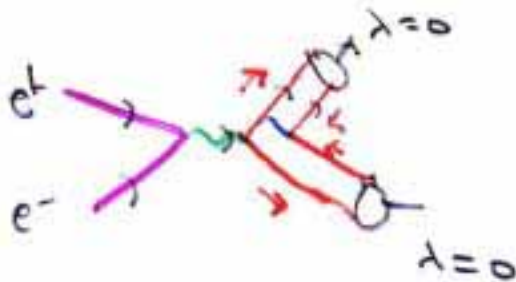
Helicity conservation

Lepage, 82



$$\frac{d\sigma}{d\Omega} \propto \begin{matrix} \sin^2\theta & M\bar{M} \\ 1+\cos^2\theta & B\bar{B} \end{matrix}$$

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



quark helicity conservation
 $\pm \frac{1}{2} = \pm 1$ only

test in $e^+e^- \rightarrow p^+p^-, p\pi, N, N^+$

Exclusive Final States : power-law, Eng. dist

ADS/CFT Near Conformal QCD

FW
Dec

* $\sigma(\gamma^* \rightarrow n\pi) \sim \frac{1}{s^{\Delta-1}}$ $\Delta = \pm 9, 5, 1$

* $\gamma^* \rightarrow p\pi$ Test hadron helicity conserv.

* $\gamma^* \rightarrow p\bar{p}, n\bar{n}, \Lambda\bar{\Lambda}, pD, \Delta\bar{\Delta}, \dots$

* $\gamma^* \rightarrow (\rho\pi)\bar{p}$
 \uparrow
 low β

Near-threshold chiral dynamics

* $\gamma^* \rightarrow \gamma \pi^+ \pi^-$
 $\gamma \pi^0 \pi^0$

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

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

Fundamental test.

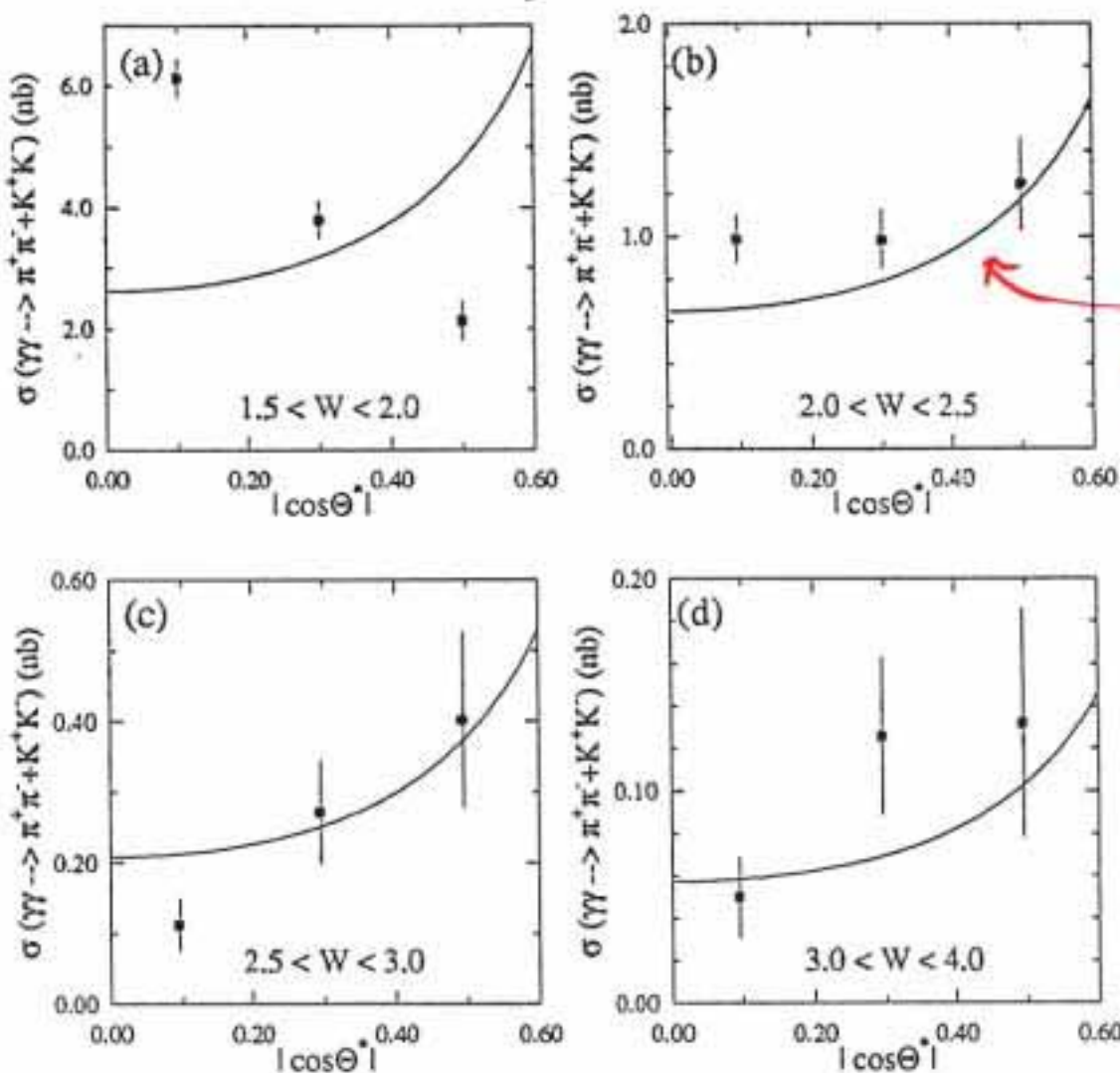
↓ PQCD Factorization.

* Critical ^{NP} input for B, h decays

$$\underline{\gamma\gamma \rightarrow \pi^+\pi^-, K^+K^-}$$

$$(\theta^* \text{ dep})$$

CLEO



PQCD prediction

$|\cos\theta^*|$

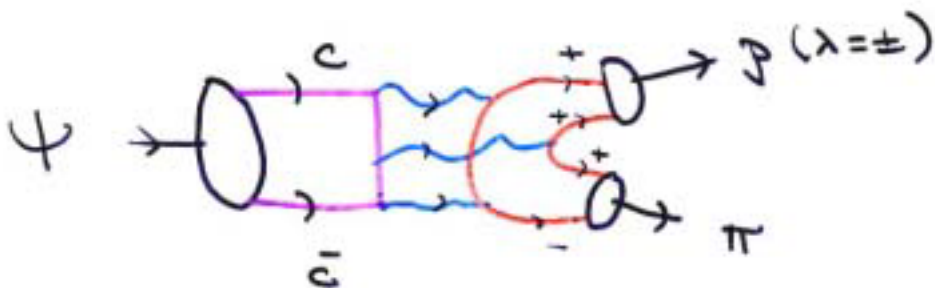
Evidence for PQCD at $W_{\gamma\gamma} \gtrsim 2.5$ GeV

The "J/ψ → P π" Puzzle
 and Intrinsic Charm

SJB + M. Karliner

$$B [J/\psi \rightarrow P \pi] = 1.28 \pm 0.10 \%$$

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



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

$Q \bar{Q} \rightarrow P \pi$ suppressed by "hadron helicity cons."

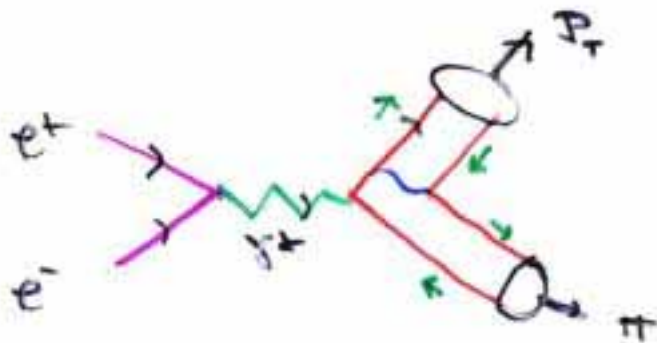
Same problem: kh^*

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

Important test of QED dynamics:

$$\frac{\frac{d\sigma}{d\Omega} (e^+e^- \rightarrow \mathcal{P}_T \pi)}{\frac{d\sigma}{d\Omega} (e^+e^- \rightarrow \pi \pi)} \sim \frac{\lambda_p^2}{s} \left(\frac{1 + \cos^2\theta}{\sin^2\theta} \right)$$

* Tests: presence of $(\rho \bar{\rho})$ Fock state
 or $L_z = 1$ in $\mathcal{P}(E)$
 wavefunction!



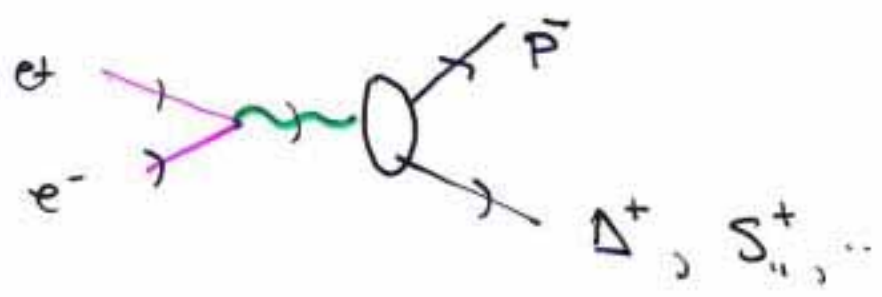
* Must have $\mathcal{P}_T: E_{\mu\nu\sigma\tau} E_{\mu}^{(\rho)} P_{\nu}^{(\rho)} P_{\sigma}^{(\pi)} E_{\tau}^{(\pi)}$

∴ must have L_z or extra gluon

⇒ extra mass dimension λ_p

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

Critical Measurement



POOD: Expect same behavior as

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

- Spacelike $e p \rightarrow e \Delta(1230) \sim \frac{1}{s^3}$
- $e p \rightarrow e \Sigma_{11}(1535) \sim \frac{1}{s^2}$
- $e p \rightarrow e p \sim \frac{1}{s^2}$

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

Covison

asymptotic form
accidental suppression of

$$\int \phi_{\Delta}^{\dagger} T_H \phi_p$$

check $e^+e^- \rightarrow \Delta\Delta, \dots$

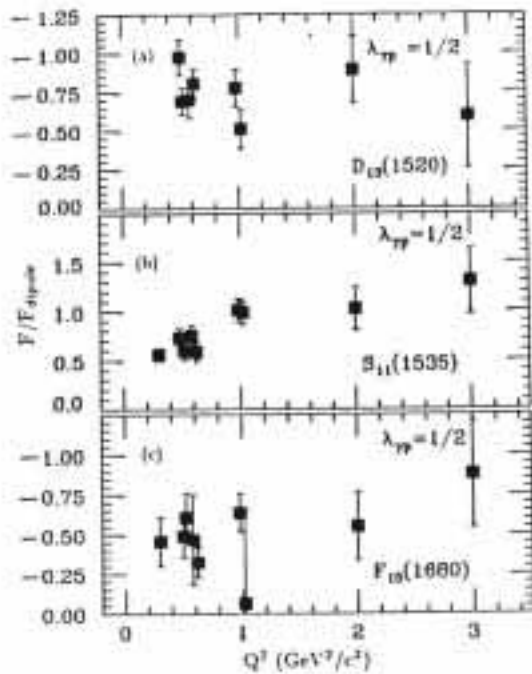
HNC: $\lambda_{\bar{p}} + \lambda_{N^+} = 0$

Test of Hadron Helicity Conservation

$\lambda = 1/2$

$CP \rightarrow C' N^*$

$\lambda = 3/2$



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

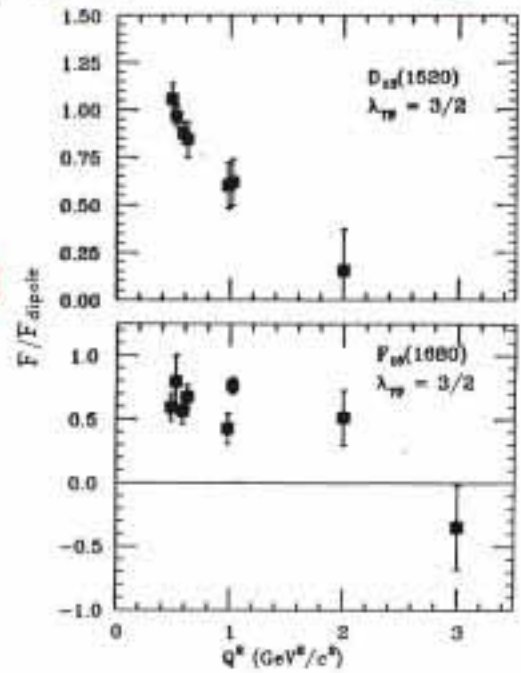
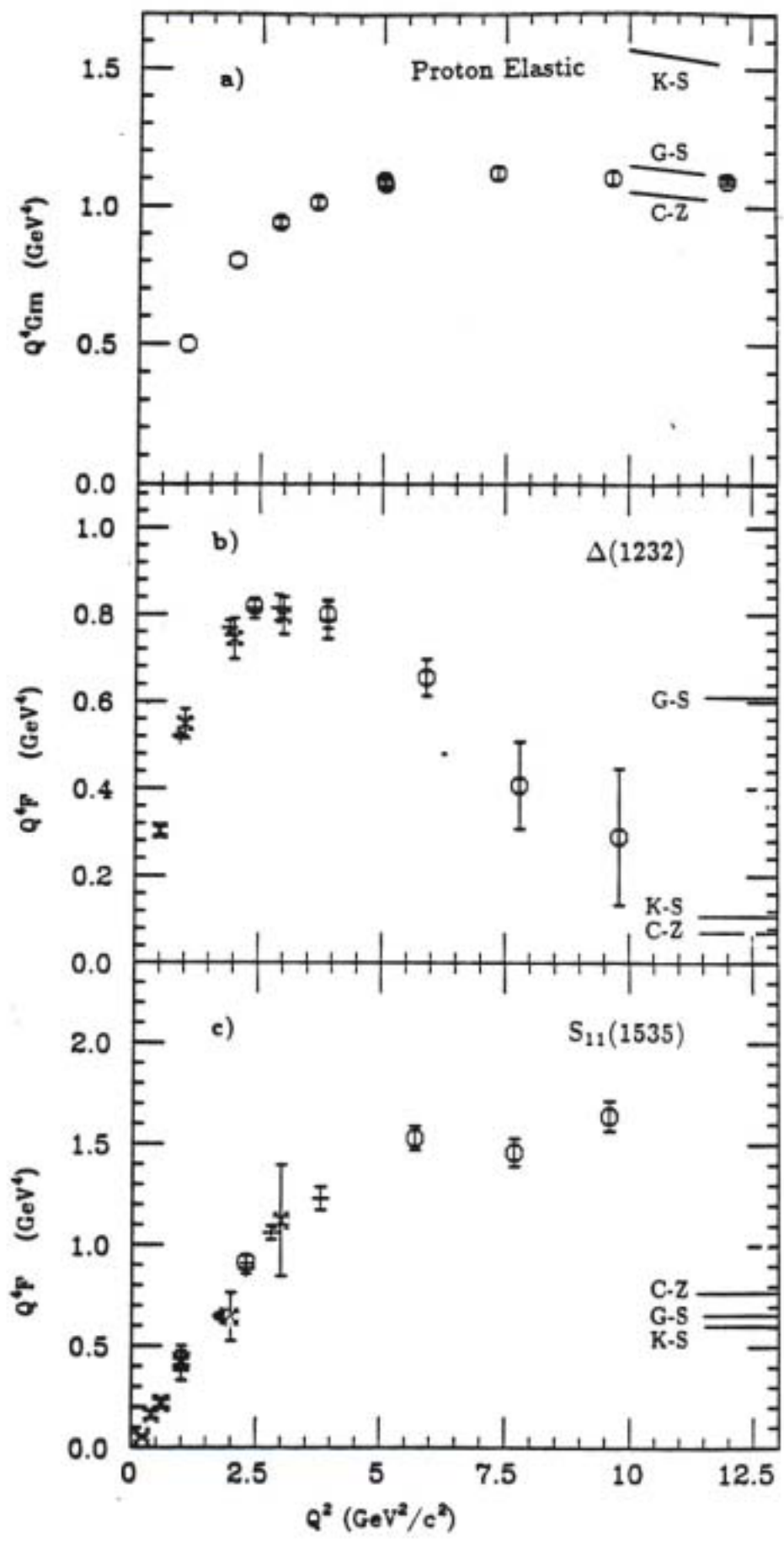


FIG. 6. The helicity- $\frac{1}{2}$ form factors F/F_{dipole} vs Q^2 , constructed from helicity amplitudes given in Ref. [31]. (a): $D_{13}(1520)$. (b): $S_{11}(1535)$. (c): $F_{13}(1680)$.

FIG. 7. The helicity- $\frac{3}{2}$ form factors F/F_{dipole} vs Q^2 , constructed from helicity amplitudes given in Ref. [31]. (a) $D_{13}(1520)$. (b) $F_{13}(1680)$.

ref: P. Stoler, Phys. Rev. D, 13 (1976)

P. Stolar
Carlson

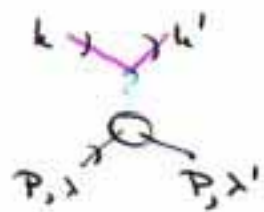


P → P

P → Δ

Suppression
for
C-Z v.s.

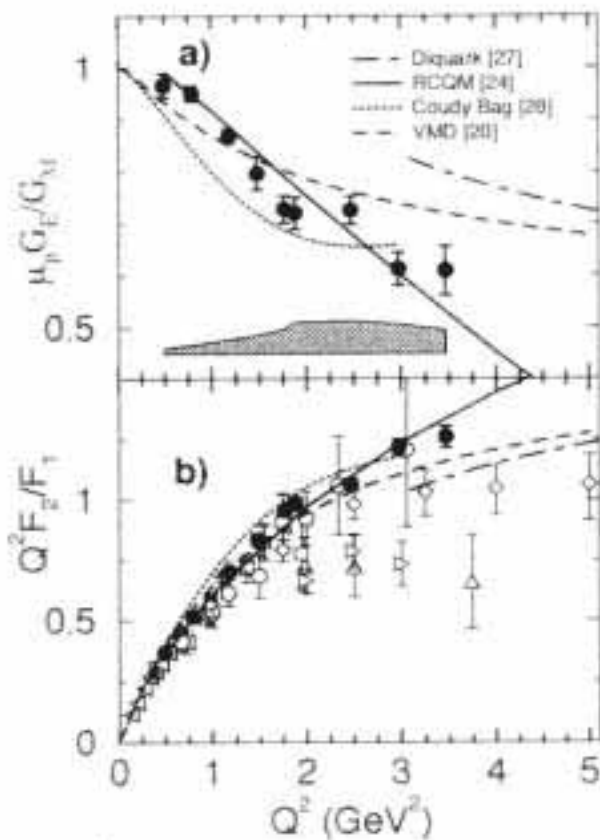
P → S₁₁



JLab uses polarization transfer to recoil proton

$$\langle P', \lambda' | j_\mu | P, \lambda \rangle \propto G_E, G_M$$

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



Jefferson Lab

PQCD

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

diquark model?

Measurements of

$$\Phi_H(x_i, Q)$$

Central problem of QCD

$$\frac{d\sigma}{dt} \left[\gamma\gamma \rightarrow H \bar{H} \right]_{\lambda_1 \lambda_2 \lambda_3 \lambda_4}$$

Scaling, helicity, angular structure

Retros critical [$\alpha_s \sim \text{cancels}$]

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

$$\frac{\gamma\gamma \rightarrow n \bar{n}}{\gamma\gamma \rightarrow p \bar{p}} \Rightarrow \Phi_N(x, Q)$$

CLEO, Babar, Belle, LEP, ...

opportunities for fundamental physics

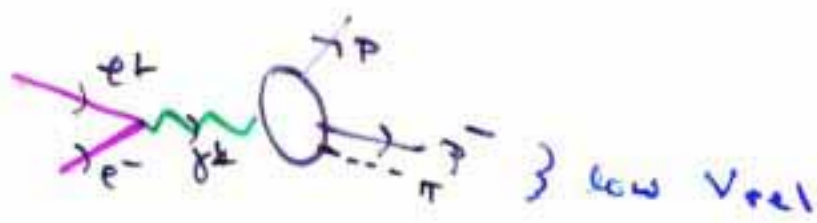
Near-Threshold Pion Production

"Soft-pion theorems for hard processes"

Pobylitsa
Polyskov
Strikner

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

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



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

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

$$m \sim \langle 0 | J^A | N\bar{N}\pi \rangle \sim \frac{i}{F_\pi} \langle 0 | [Q_5, J^A] | N\bar{N} \rangle$$

↑ chiral rot

$$\sim \frac{i}{F_\pi} \langle 0 | J^A | N\bar{N} \rangle$$

Same scaling as $N\bar{N}$

QCD Physics -

New topics in low energy $e^+e^- \rightarrow X$

$$\sqrt{s} \lesssim 2.5 \text{ GeV}$$

* $e^+e^- \rightarrow P \uparrow \bar{P}$ Polarization
Timelike Form Factors, $\text{Im } G_N^+ G_N^-$

* $e^+e^- \rightarrow \gamma \pi^+ \pi^-$, $\gamma k^+ k^-$, $\gamma P \bar{P}$
Timelike DVCS, Real + Im part

* $e^+e^- \rightarrow \pi^+ \pi^-$, $k^+ k^-$, $P \bar{P}$
Charge & symmetry
resolve Rosenbluth / Pol. Trans
discrepancy G_E/G_M
 $\gamma^* \gamma^* \rightarrow \pi \pi$

* $e^+e^- \rightarrow \pi^0, \eta^0 \gamma$ ($\gamma^* \rightarrow \pi^0 \gamma$)
 $(G_A^2)_{LL}$, Fundamental QCD physics