Explicit & Hidden Strangeness at JLab:

Selected Results & some Ideas for the future

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Dedicated to Nathan Isgur

5/25/47 – 7/24/01

Users Group Symposium

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Some things Old, some things New....

Strangeness Production

- elementary $p(e,e'K)Y = \Lambda, \Sigma$
  QHD, L,T separation, Kaon form fact
  beyond tree level
- $d(e,e'K)YN = \Lambda n, \Sigma^0 n, \Sigma^- p$
- $A(e,e'K)_Y B$ hypernuclei

Hidden Strangeness

- $\langle N|\bar{s}\Gamma s|N\rangle$, OZI violations
- $p(\gamma,\phi)p$ & $G_E^n(Q^2) \Rightarrow g_{\phi NN}$
- $p(\gamma,e^+e^-)p \Rightarrow G_E^p \quad 0 \leq -Q^2 \leq 4m_p^2$

Quark/QCD Related for $p(\gamma,K)Y$

- Quark Model
- Schwinger-Dyson

Exotic States (time permitting)

glueballs, hybrids, charmonium

Elementary Kaon Production Models

QHD Isobar Models

WJC Williams, Ji, Cotanch, PRC46, 1617 (1992)

David, Fayard, Lamot, Saghai, PRC 53, 2613 (1996)

MB Mart, Bennhold, PRC 61, 012201 (R) (2000)

Hsiao, Lu, Yang, PRC 61, 068201 (2000)

Janssen, Ryckebusch, Debruyne, Van Cauteren PRC 65, 015201 (2002)

Regge Models

Vanderhaeghen, Guidal, Laget, PRC 57, 1454 (1998)

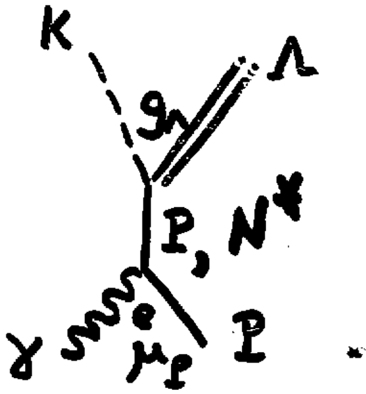
QHD for $\gamma + p \to K + \Lambda$

$$\mathcal{L}_{int} = -e(J_P^\mu + J_K^\mu)A_\mu - (\mu_P S_P^{\mu\nu} + \mu_\Lambda S_\Lambda^{\mu\nu} + \mu_T S_{\Lambda\Sigma}^{\mu\nu})F_{\mu\nu}$$
$$+ (i g_\Lambda J^5_{\Lambda P} + i g_\Sigma J^5_{\Sigma P} + \frac{g^\gamma_{K^*}}{m} \varepsilon^{\alpha\beta\mu\nu} \nabla_\alpha \phi_\beta \nabla_\mu A_\nu)\phi$$
$$+ g^V_{K^*} J^\mu_{\Lambda P} \phi_\mu + \frac{g^T_{K^*}}{m_P + m_\Sigma} S^{\mu\nu}_{\Lambda P} G_{\mu\nu}$$

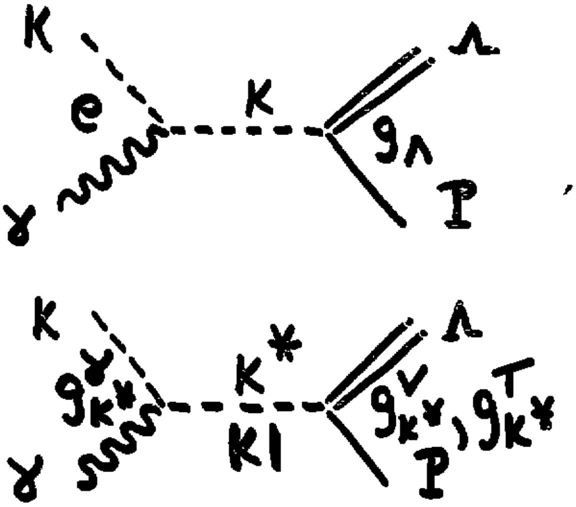
with $J^5 = \bar\psi \gamma^5 \psi$, $J^\mu = \bar\psi \gamma^\mu \psi$, $S_{\mu\nu} = \bar\psi \sigma_{\mu\nu} \psi$, $\sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu, \gamma_\nu]$

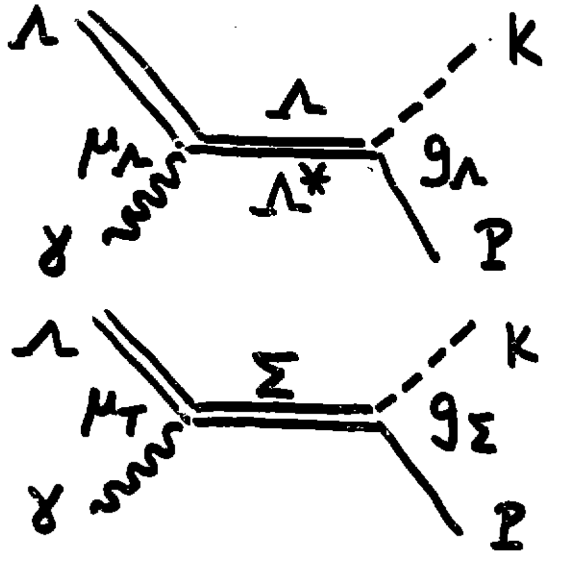
calculate
to 2nd order

$$S_{Fi} = \langle K\Lambda | T e^{i\int \mathcal{L}_{int}(x)dx} | P\gamma \rangle$$
$$\simeq \langle K\Lambda | T \int \mathcal{L}_{int}(x) \mathcal{L}_{int}(y) dx\, dy | P\gamma \rangle$$



S channel





t channel

u channel

<u>QHD</u> Analysis of $\gamma p \to K^+ Y$, $e p \to e' K^+ Y$
$Y = \Lambda, \Sigma, \Lambda^*(1405)$ $K^- p \to \gamma Y$, $K^- p \to e^+ e^- Y$

Model Strengths

Field Theory

* Relativity

Poincare Symmetry

crossing symmetry

* Gauge Invariance

[redacted]

incorporates Duality
(Regge Theory)

E&M vertex functions
from Vector Dominance

Historical legacy

Phenomenologically successful

Model Limitations

* No QCD

lacks unitarity

not renormalizable

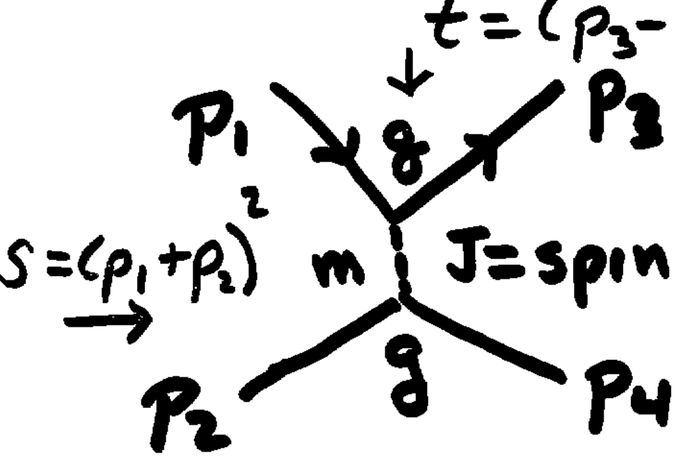
tree level approx.

constant hadronic
vertex functions
($g(s,t) \to g$)
(have included in)
$\pi^- p \to \gamma n$

* **No quarks**

* **No gluons**

Regge Poles & Duality



amplitude for exchange m, J

$$A(s,t) \sim \frac{g^2 s^J}{t-m^2} \sim \frac{g^2 P_J(\cos\theta_t)}{t-m^2}$$

$$\frac{d\sigma}{dt} \sim g^4 \frac{s^{2J-2}}{(t-m^2)^2}$$

unphysical at large s

Regge Pole hypothesis (T. Regge N.C. 14, 951 (1959))

$$A \sim g\frac{s^J}{t-m^2} \rightarrow \beta(t) \left(\frac{1-e^{-i\pi\alpha(t)}}{\sin\pi\alpha(t)}\right) s^{\alpha(t)}$$

$\alpha(t)$ = Regge trajectory $= J$ @ $t=m^2$

Duality hypothesis (Dolen, Horn, Schmid P.R. 166 1768 (1968))

used finite energy sum rules, showed cross channel Regge exchanges determined ave. direct channel amplitude

$\Rightarrow$ low energy s channel resonances are <u>dual</u> to t channel Regge trajectories

Table I

Particle	J^P	Mass (GeV)	Width (GeV)
p *	$\frac{1}{2}^+$	.93828	–
K^+ *	0^-	.49367	–
K^{*+} †	1^-	.89210	.051
Λ *	$\frac{1}{2}^+$	1.11560	–
Σ *	$\frac{1}{2}^+$	1.19246	–
Y1 *	$\frac{1}{2}^-$	1.405	.040
Y2	$\frac{1}{2}^-$	1.670	.040
Y3	$\frac{1}{2}^-$	1.800	.300
N1	$\frac{1}{2}^+$	1.470	.200
N4 *	$\frac{1}{2}^-$	1.650	.150
N6 *	$\frac{1}{2}^+$	1.710	.120
K1 †	1^+	1.280	.090

Resonances included for
$\gamma p \to K^+ \Lambda$

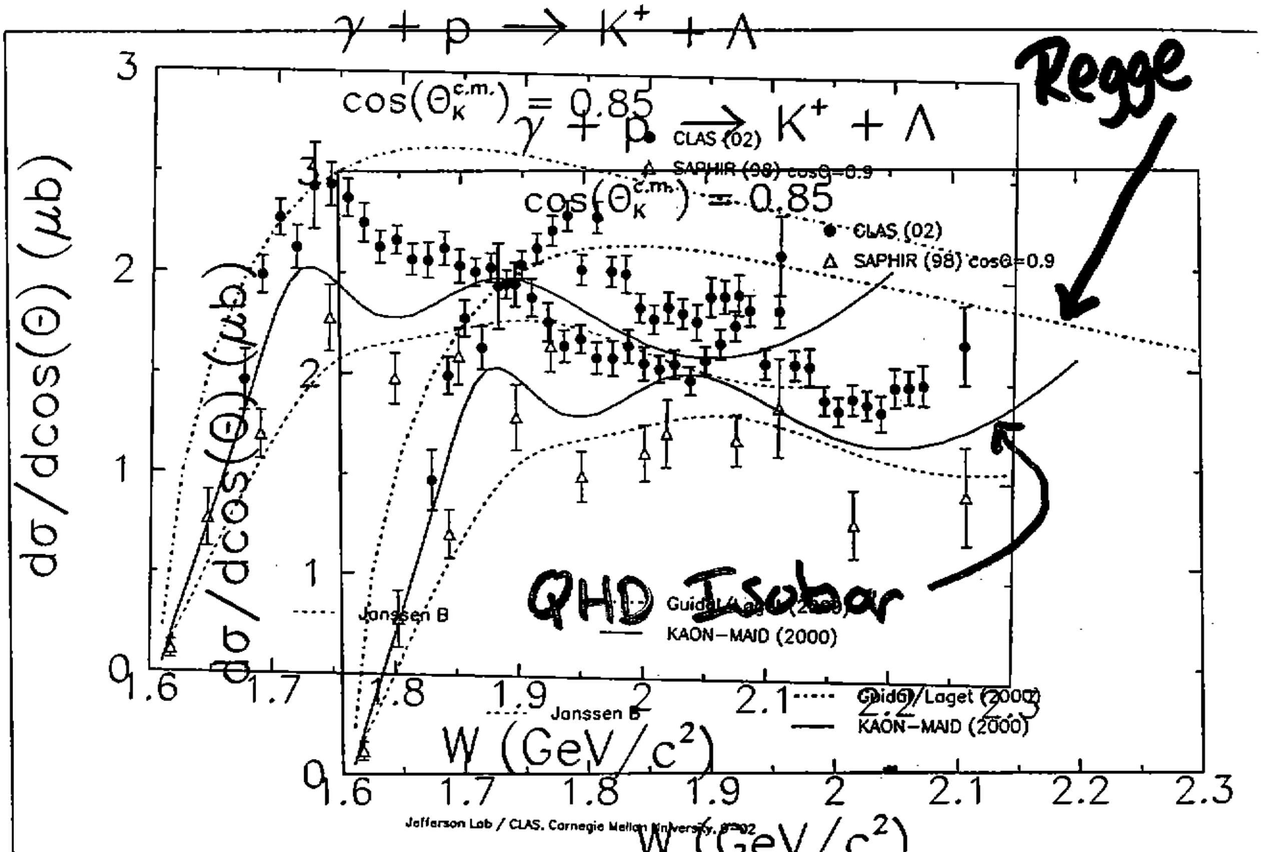
* minimal model

† duality motivated

$\gamma \to K^+\Lambda$ E 89-004

Differential Cross Section

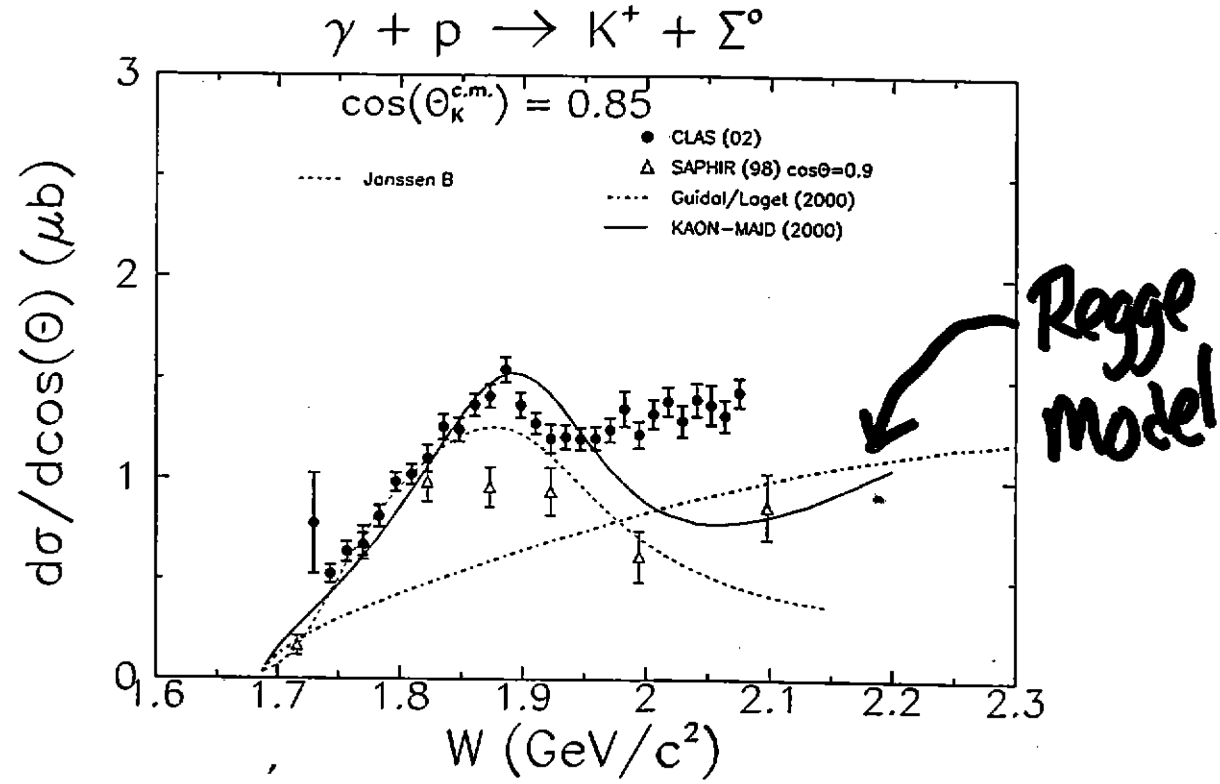
Differential Cross Section



Jefferson Lab / CLAS, Carnegie Mellon University, 9/2002
Thesis Defense: 2

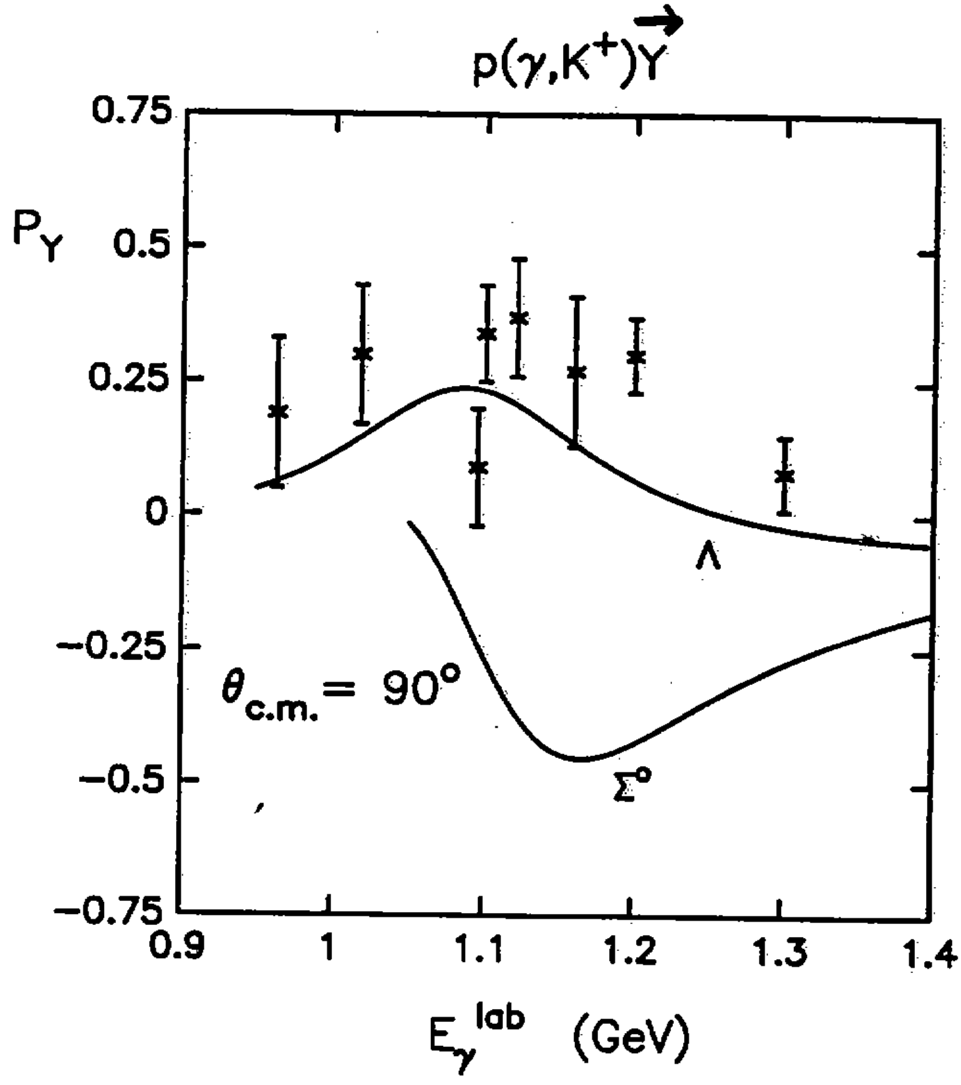
J. McNabb Thesis

Results of $\gamma\, p \rightarrow\ K^{+}\Sigma^{0}$



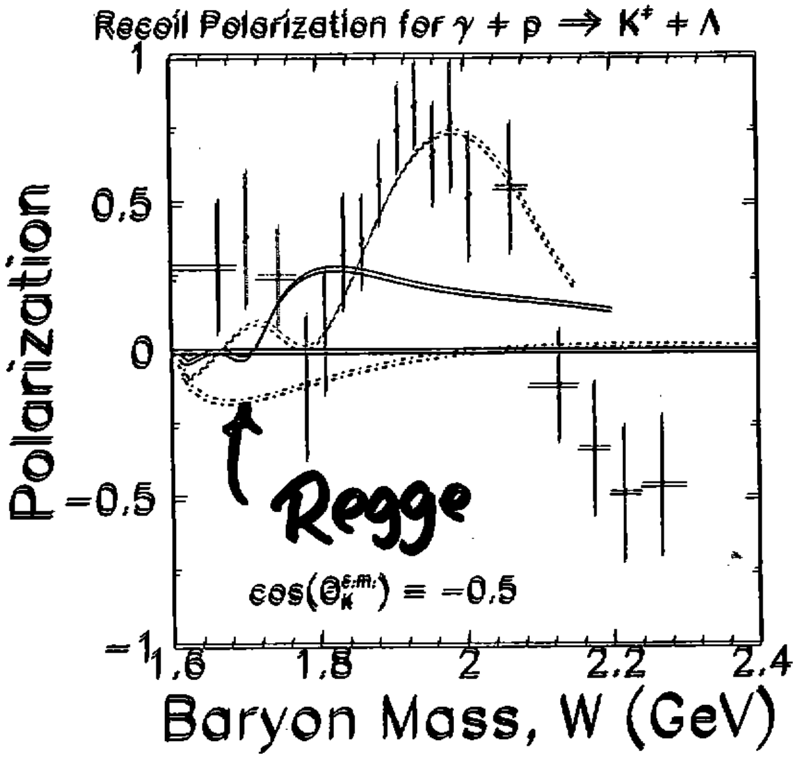
Jefferson Lab / CLAS, Carnegie Mellon University, 9–02

Λ, Σ^0 Polarization



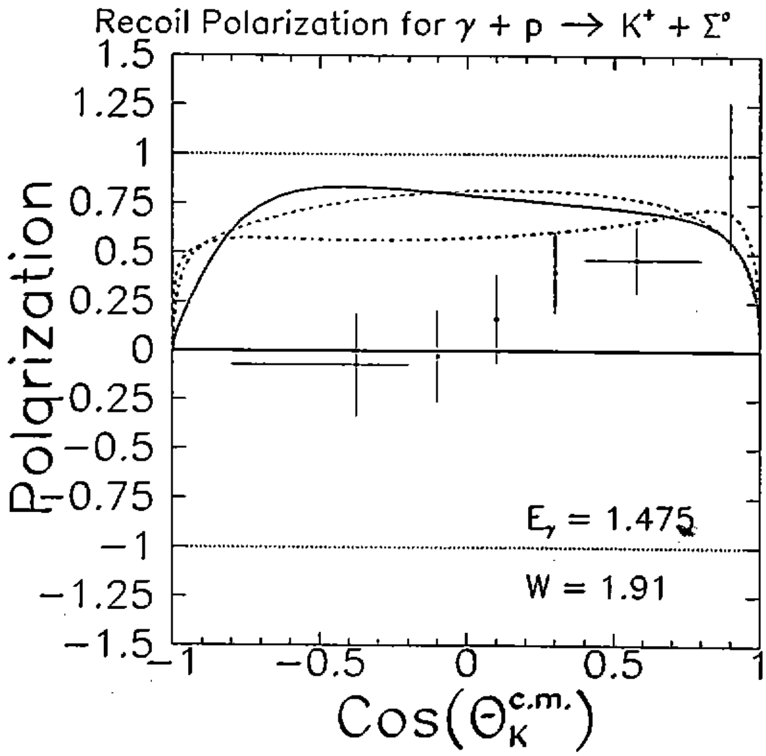
no good $\vec{\Sigma}^0$ data available
(some Σ^0 hadronic production data)

Results of $\gamma\, p \rightarrow\ K^+\Lambda$



$\vec{\Lambda}$ polarization

Results of $\gamma\, p \rightarrow\ K^+\Sigma^0$



$\vec{\Sigma}^0$ polarization

Rosenbluth Decomposition $ep \to e'KY$

$$\sigma = \sigma_T + \varepsilon\sigma_{TT}\cos 2\phi + \varepsilon\sigma_L + \sqrt{2\varepsilon(\varepsilon+1)}\,\sigma_{LT}\cos\phi$$

isolate σ_T, σ_L by measuring $\sigma(\varepsilon,\phi)$

for fixed $q^2 = -Q^2 = (p_e - p_e')^2$, $s = W^2 = (q + p_N)^2$

$\boxed{\sigma_T}$ verify $\dfrac{\sigma_T(K\Sigma)}{\sigma_T(K\Lambda)}$ rapidly declines with Q^2

Nachtmann
N.P.B 74 (1974)
$$\frac{F_2^n(x)}{F_2^p(x)} \to \frac{1}{4} \quad \text{for } x = \frac{Q^2}{2M\nu} = 1$$

$\Rightarrow$ ud quarks have isospin=0 $\Rightarrow \sigma(K\Lambda) > \sigma(K\Sigma)$

$\boxed{\sigma_L}$ Extract K form factor from σ_L

Chew-Low extrapolation
$$\lim_{t \to m_K^2} \left(N(t)[t - m_K^2]\sqrt{\sigma_L} \right) = F_K(Q^2)$$

K^* complicates low Q^2

for high Q^2 extract F_K to 10%

Hall C

E93018 PRC 67, 055205 (2003)

— WJC

---- Mart et al.

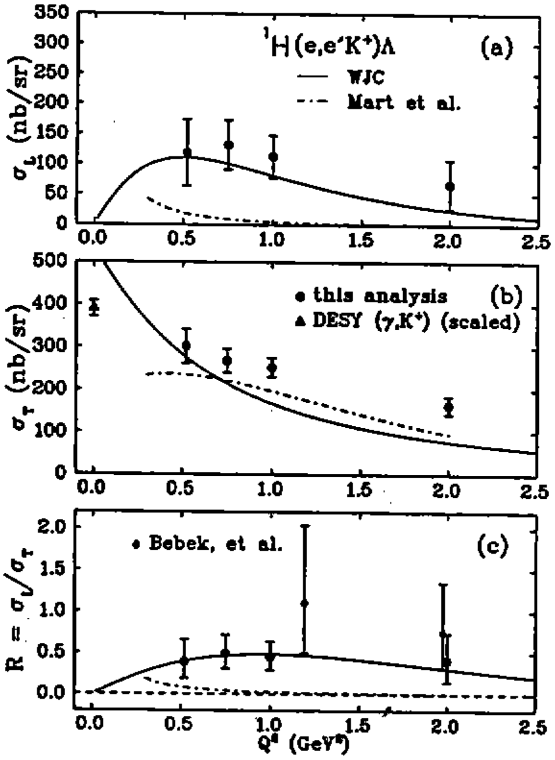
$ep \to e'K^+\Lambda$

$ep \to e'K^+\Sigma^0$

σ_L

σ_T

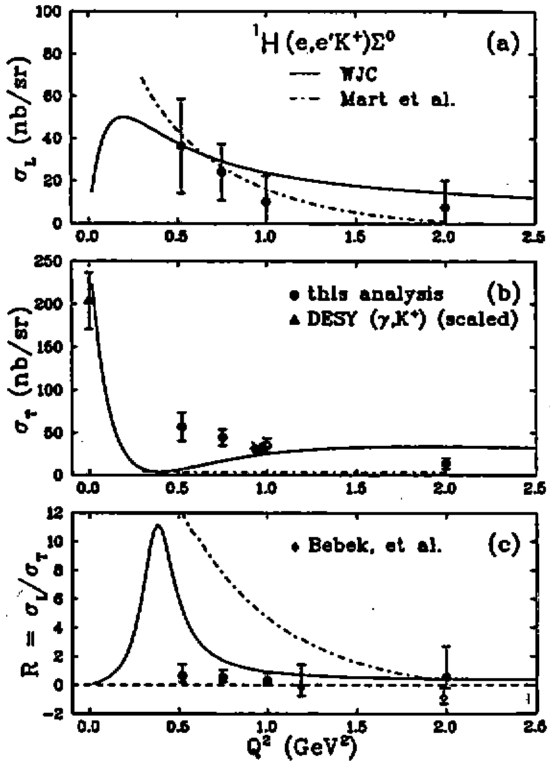
σ_L/σ_T



σ_L

σ_T

σ_L/σ_T

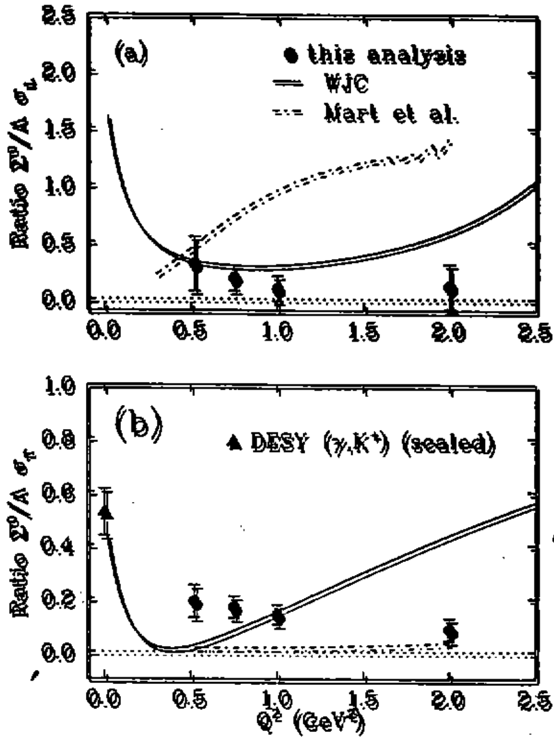


$\sqrt{s} = W = 1.84$ GeV

Ratio of Σ^0 to Λ

$$\frac{\sigma_L^{\Sigma^0}}{\sigma_L^{\Lambda}}$$

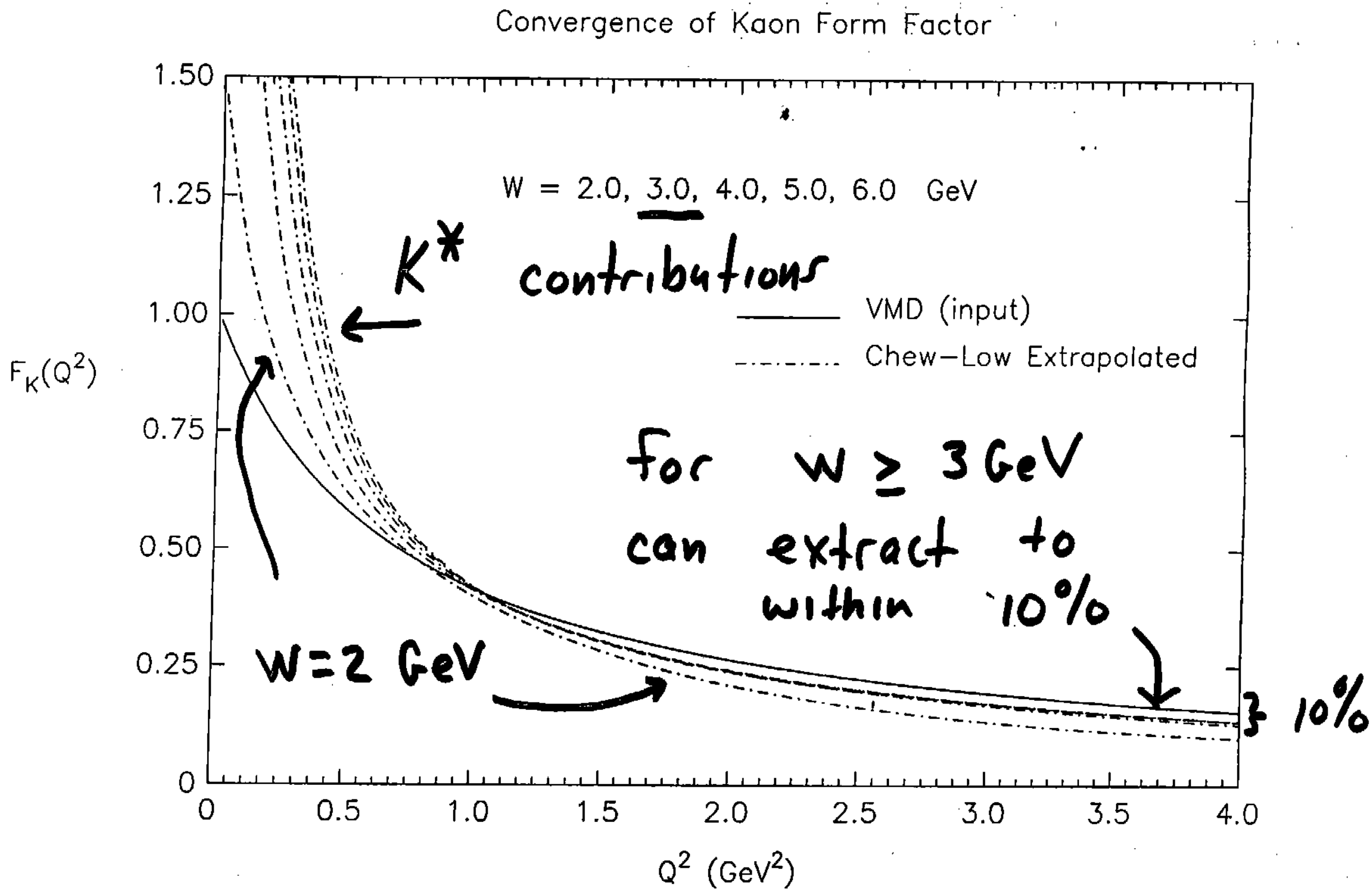
$$\frac{\sigma_T^{\Sigma^0}}{\sigma_T^{\Lambda}}$$



note fall off with Q^2

Q^2

Simulation of Kaon Form Factor Chew-Low Extrapolation

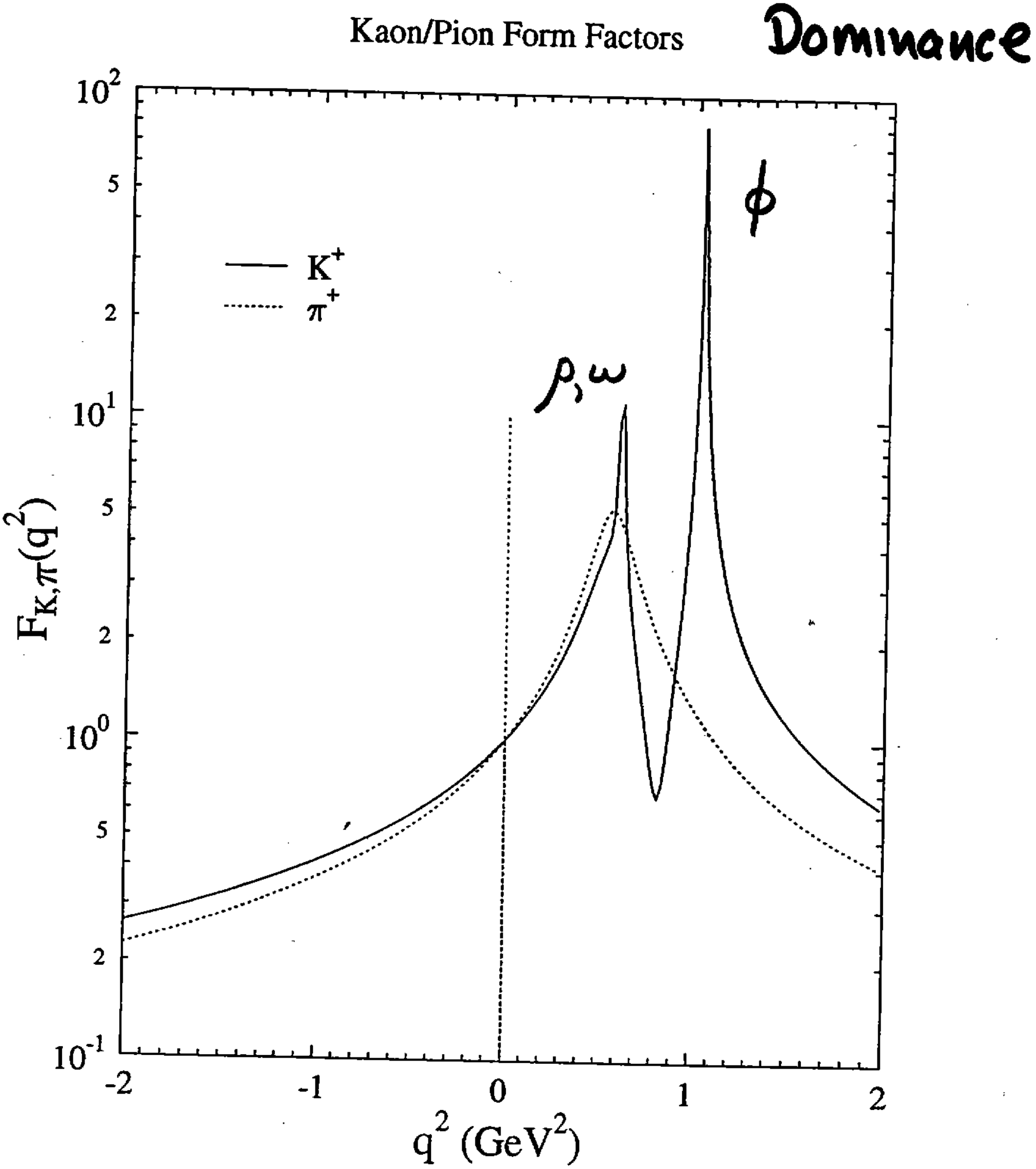


Meson Form Factors

K^+ solid curve

π^+ dashed curve

Vector Meson Dominance

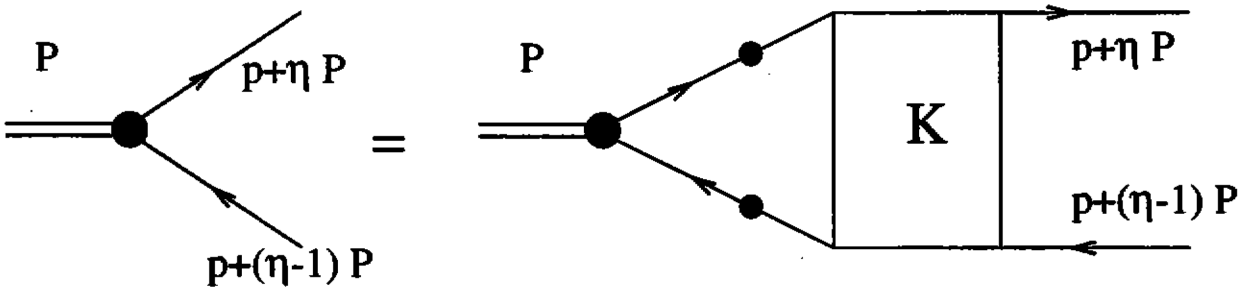


- MESONS bound states of a quark and anti-quark

HOMOGENEOUS BETHE–SALPETER EQN

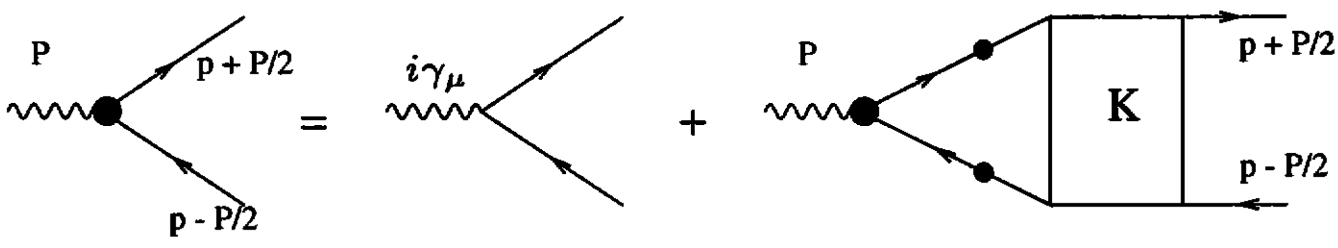
at mass pole $P^2 = -m^2_{\text{meson}}$

$$\Gamma_H(p;P) = -\int^\Lambda \frac{d^4q}{(2\pi)^4}\, \mathrm{K}(p,q;P) \times \left[S(q_+)\Gamma_H(q;P)S(q_-)\right]$$



- QUARK-PHOTON VERTEX

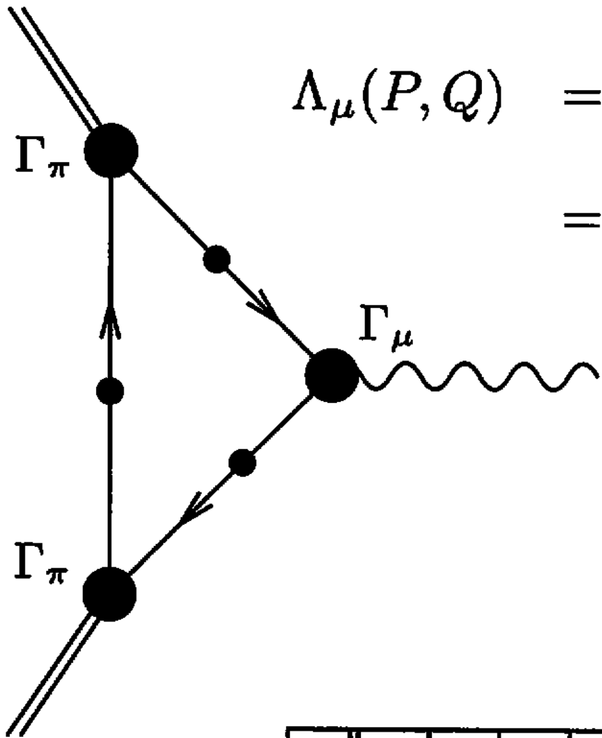
INHOMOGENEOUS BETHE–SALPETER EQN



with the same kernel K as the meson BSE

Pion Electromagnetic Form Factor

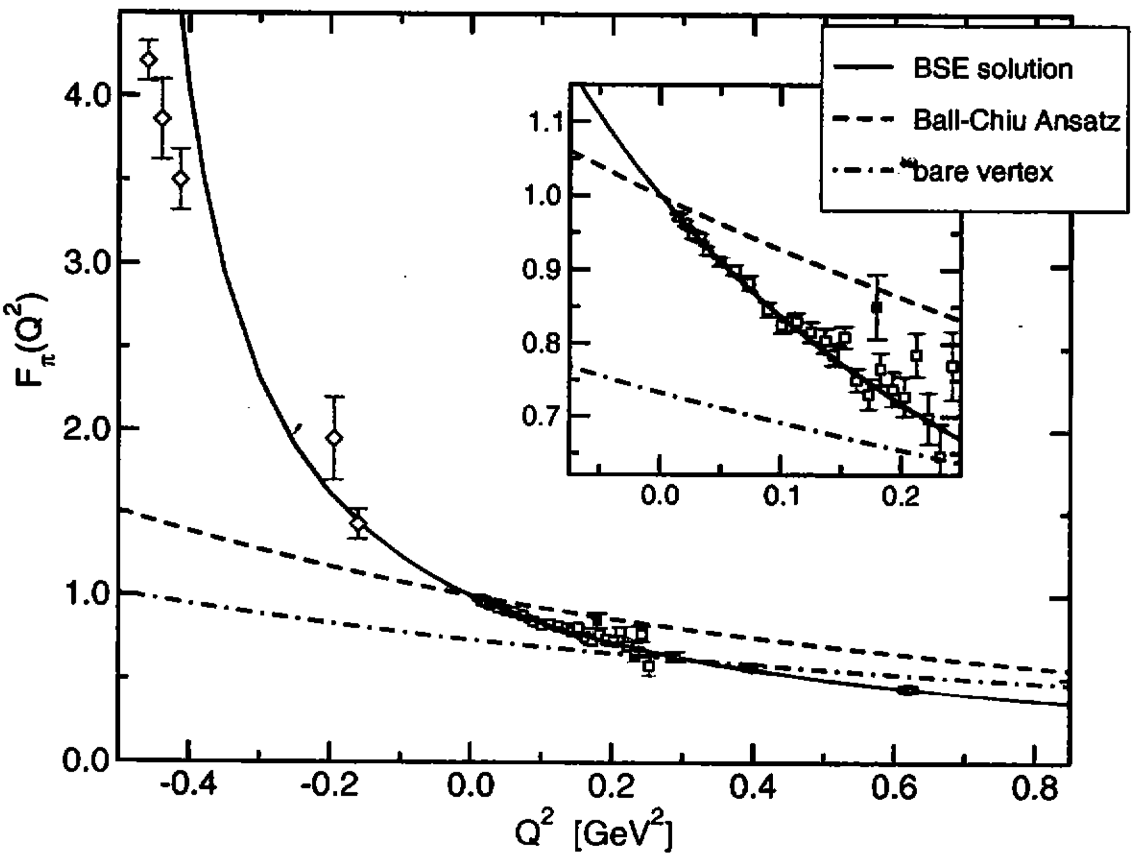
(PM & PCT, PRC61, 045202 (2000))



$$\begin{aligned}\Lambda_\mu(P,Q) &= 2\,P_\mu\,F_\pi(Q^2)\\ &= N_c\int\frac{d^4q}{(2\pi)^4}\,\mathrm{Tr}\big[\bar\Gamma^\pi\,S\,i\Gamma_\mu\,S\,\Gamma^\pi\,S\big]\end{aligned}$$

BSE vertex: $r_\pi = 0.68$ fm

expt.: $r_\pi = 0.663 \pm .006$



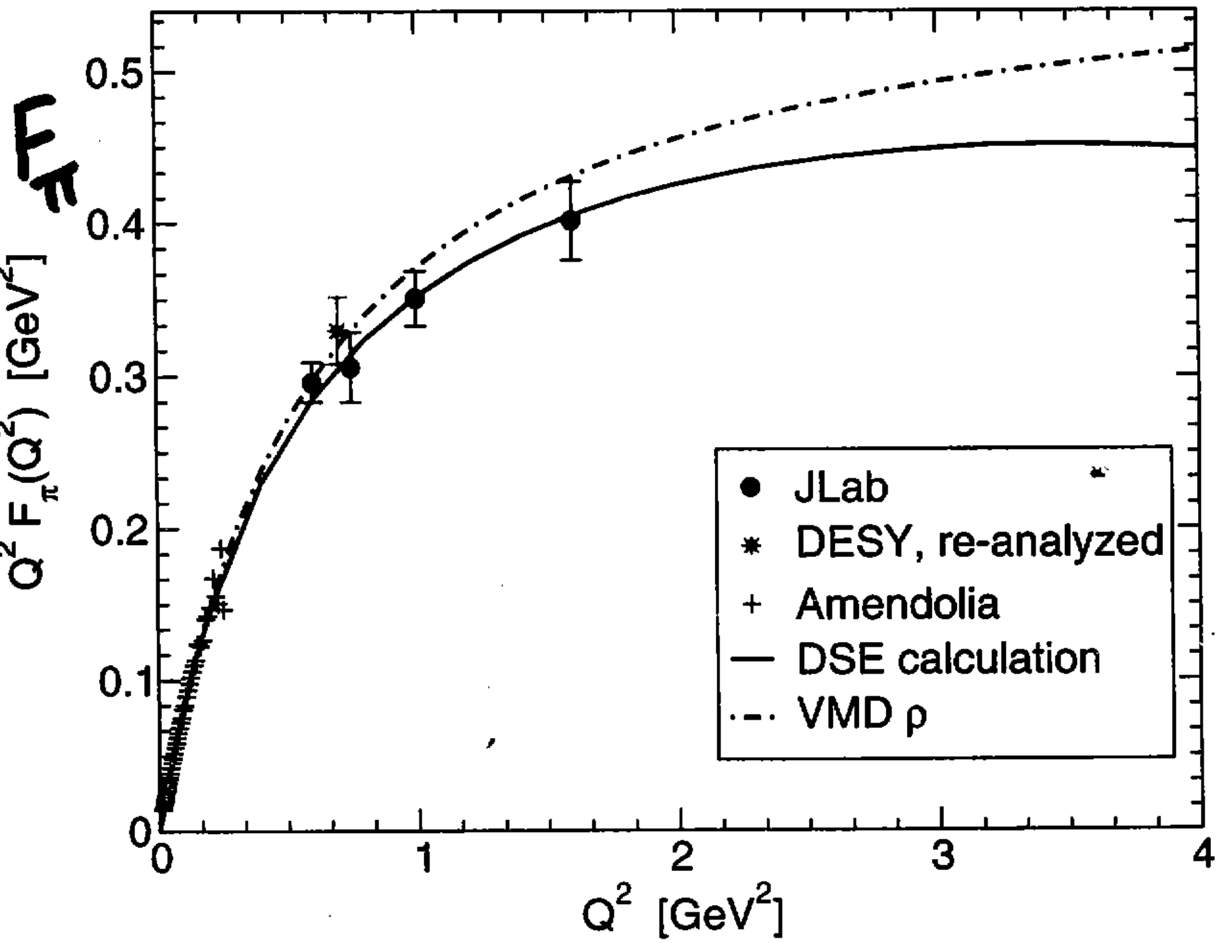
Behavior of $Q^2 F_\pi(Q^2)$ at intermediate Q^2

New data from JLab E93-021 and extension

(Volmer et al. PRL86, 1713 (2001),
see also J. Volmer, The pion charge form factor via pion electroproduction on the proton, PhD thesis, Amsterdam, 2000)

π Form Factor

$Q^2 F_\pi$



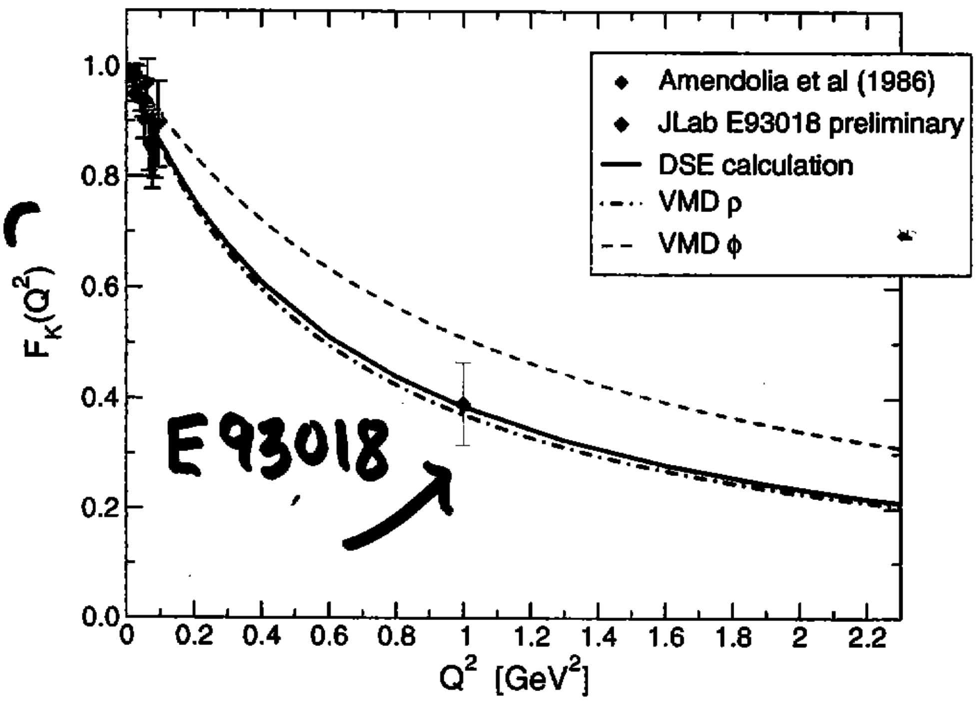
(PM & Tandy, PRC62, 055204)

- Results for charge radii $r^2 = -6F'(0)$

charge radii	experiment	calculated
r_π^2	0.44 ± 0.01 fm^2	0.45 fm^2
r_{K+}^2	0.34 ± 0.05 fm^2	0.38 fm^2
$r_{K^0}^2$	-0.054 ± 0.026 fm^2	-0.086 fm^2

- Results for larger Q^2, together with preliminary results from JLab (E93018, spokesperson K. Baker)

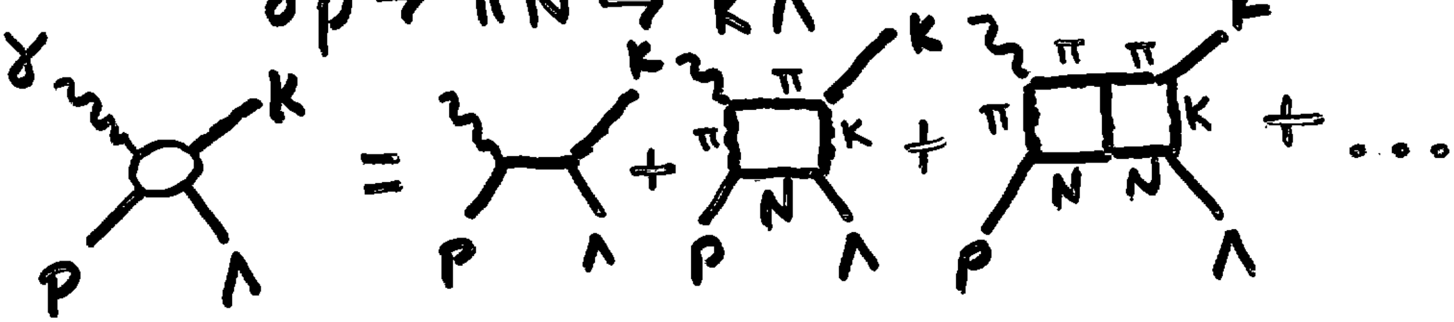
Kaon Form Factor F_K



Q^2

(G. Niculescu, First measurement of the longitudinal and transverse cross sections in $^1H(e, e'K^+)\Lambda$, PhD thesis, Hampton U., 1998)

$\gamma p \to \pi N \to K\Lambda$



Chiang, Tabakin, Lee, Saghai, PLB 517, 101 (2001)

include coupled channels & FSI effects

Beyond tree level

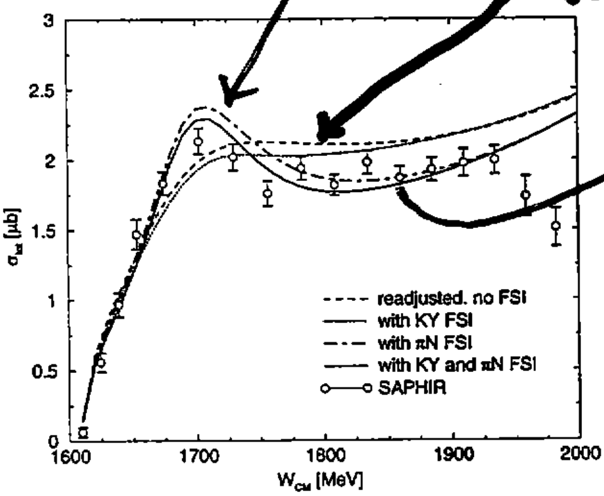
with πN intermediary states

without

15% effect

SAPHIR Data

σ_T



W

Calculations for A > 1

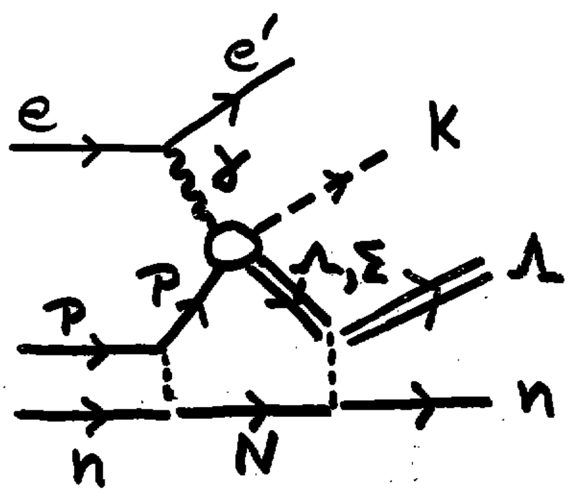
H. Yamamura et al PRC 61, 14001
$d(\gamma, K^+)YN$

T. Mart et al nucl-th/9708012
$^3He(\gamma, K^+)^3_\Lambda H$

Lee et al nucl-th/9907119
$A(\gamma, K^+Y)B$ quasifree
also Bennhold et al nucl-th/9712075

Motoba see PRL in press June, 2003
$^{12}C(e\gamma, K^+)^{12}_\Lambda B$

Include ΣN Channels in $d(e,e'K)\Lambda n$



See $d(K^-,\pi^-)\Lambda p$ study

Dalitz, Nucl. Phys. A354 (1981)

Mizuno, Prog. Theor. Phy 62 (1979)

Solve coupled channels problem for YN system

$$\Lambda n \to \Lambda n$$
$$\to \Sigma^0 n$$
$$\to \Sigma^- p$$

$$(H_{YN} - E)\Psi_{YN} = 0$$

$$\Psi_{YN} = \chi_{\Lambda n}|\Lambda n\rangle + \chi_{\Sigma^0 n}|\Sigma^0 n\rangle + \chi_{\Sigma^- p}|\Sigma^- p\rangle$$

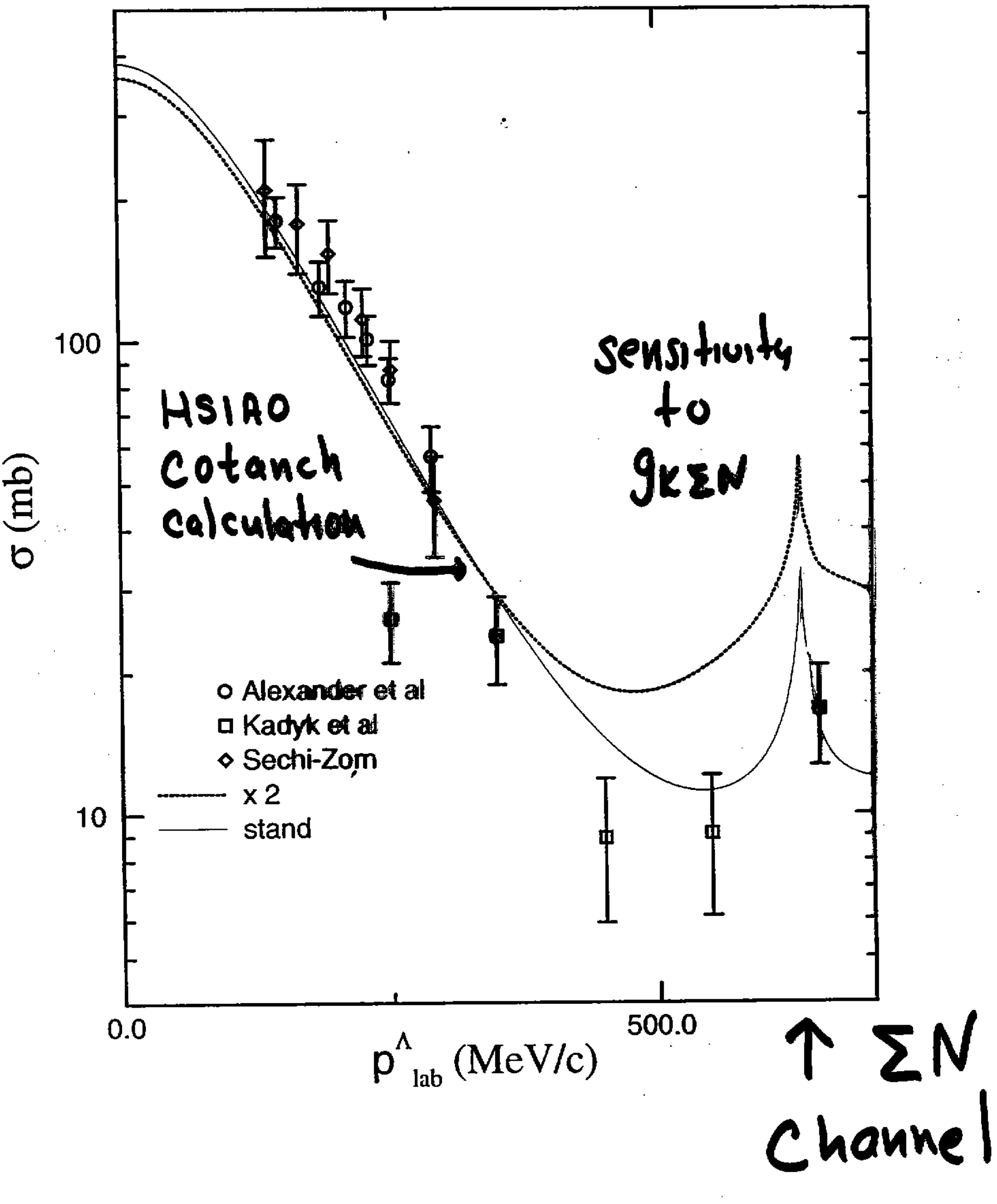
Use Nagels & de Swart YN Potential D P.R. 15 2547 (1977) with hard cores & tensor interaction

$$T_\lambda = \int e^{i\vec{k}_n \cdot \vec{r}} \Psi^\dagger_{YN} (a_\lambda + i\vec{b}_\lambda \cdot \vec{\sigma}) \phi_d(\vec{r})\, d\vec{r}$$

$$\Psi_{YN} = \sum_{J^\pi} \Psi^{J^\pi}_{YN}$$

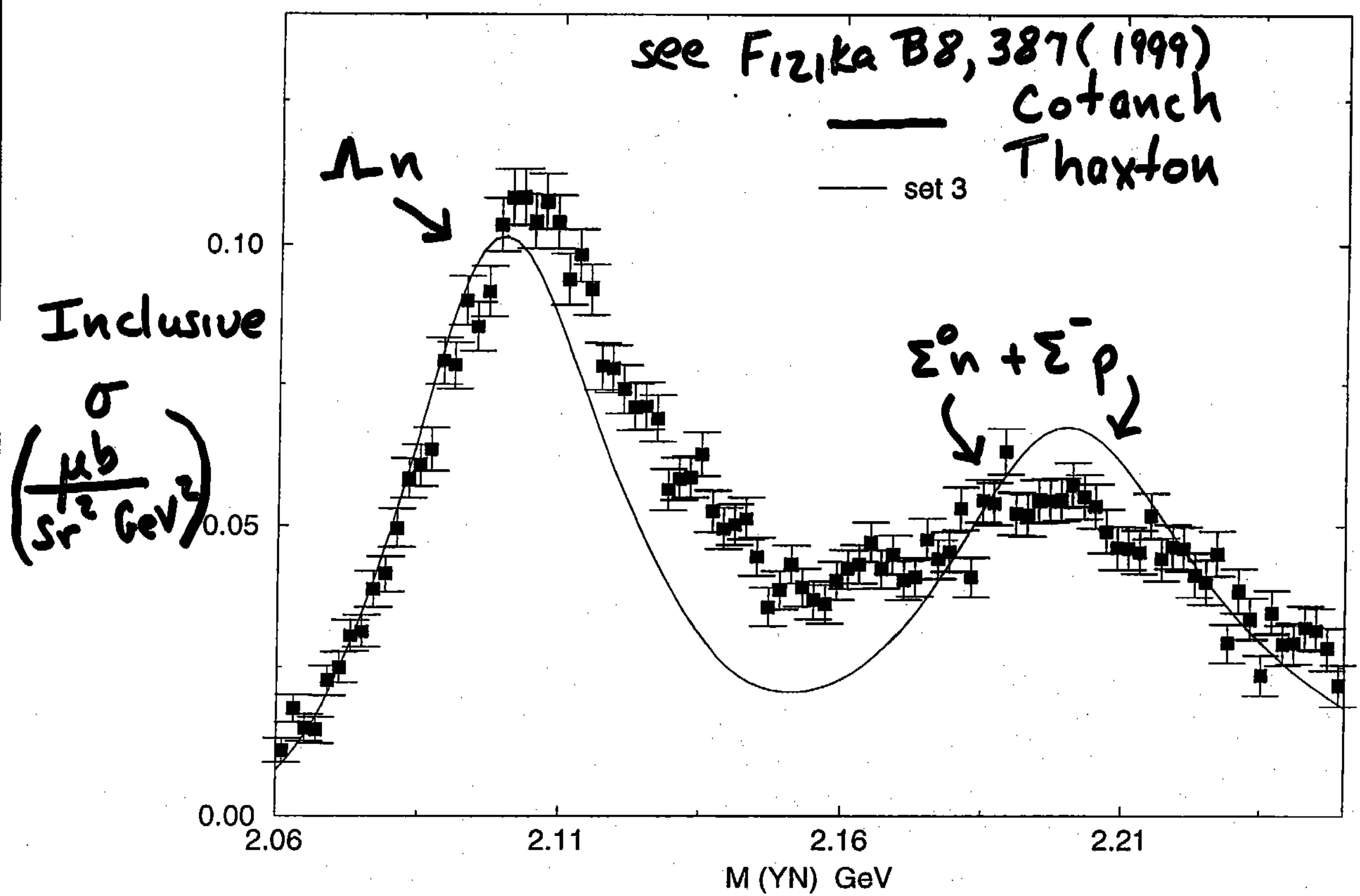
Solve 6 coupled eqs. for each J^π

ΛP --> ΛP cross section

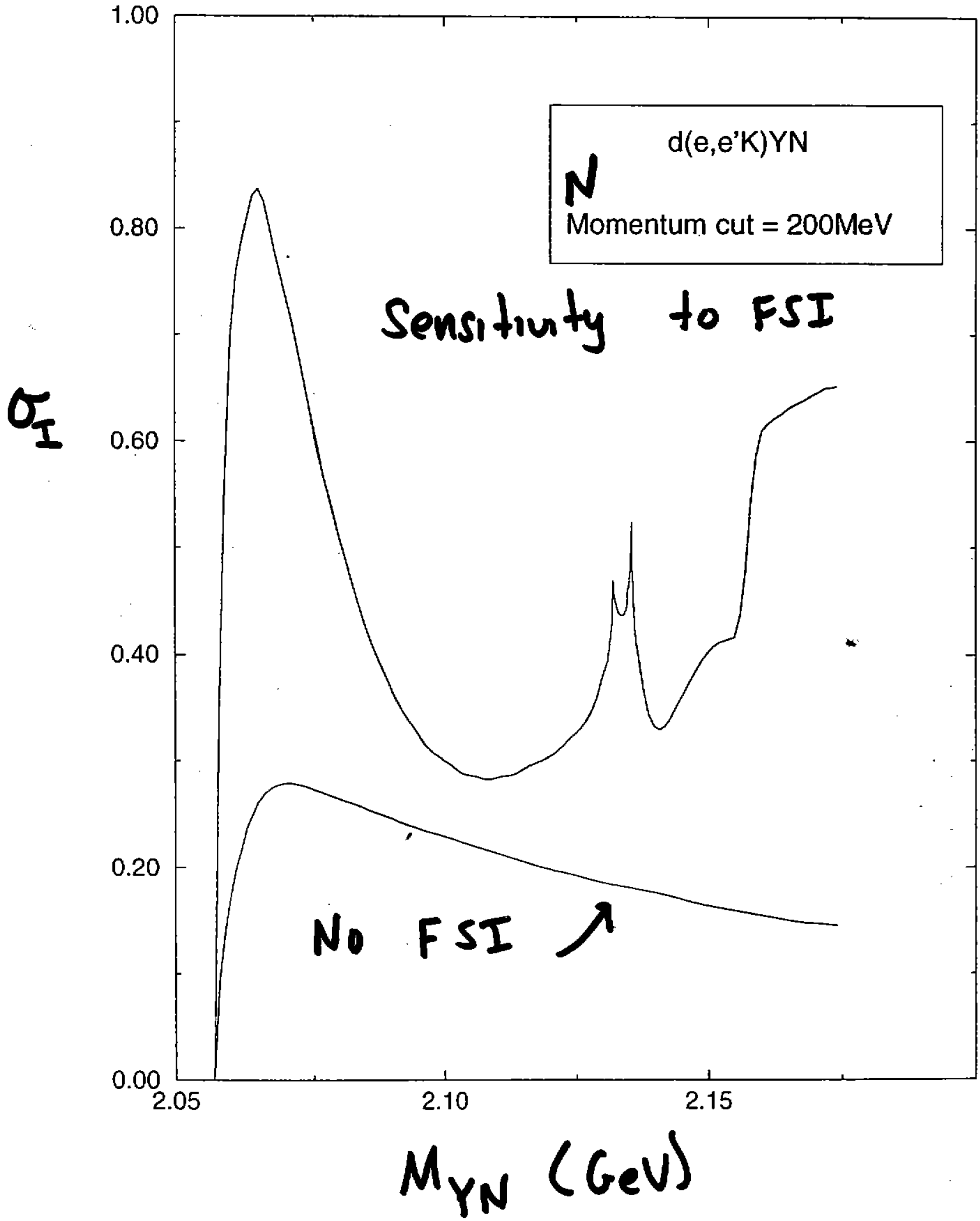


New $d(e,e'K^+)YN = \Lambda n, \Sigma^0 n, \Sigma^- p$ JLAB Data

E91-016 Hall C (J. Reinhold)



YN Invariant Mass



1.00
0.80
0.60
0.40
0.20
0.00
2.05
2.10
2.15
d(e,e'K)YN
N
Momentum cut = 200MeV
Sensitivity to FSI
No FSI
σ_I
M_{YN} (GeV)

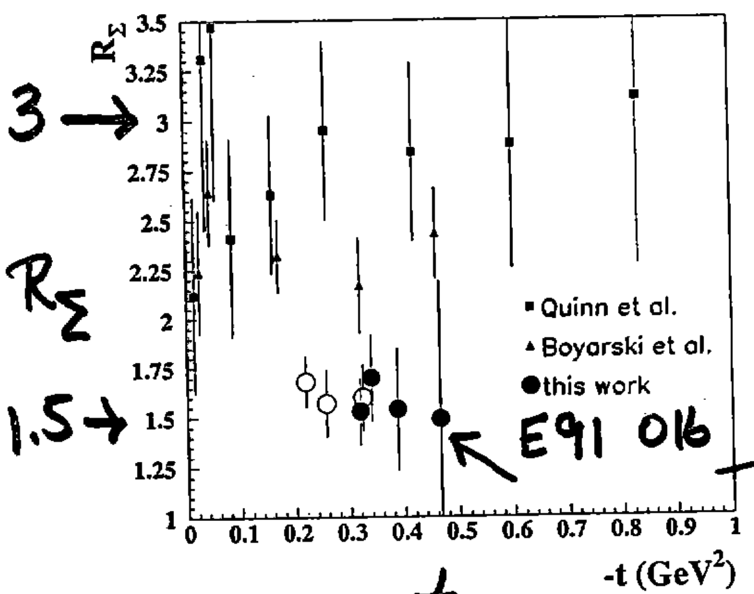
Isospin Decomposition

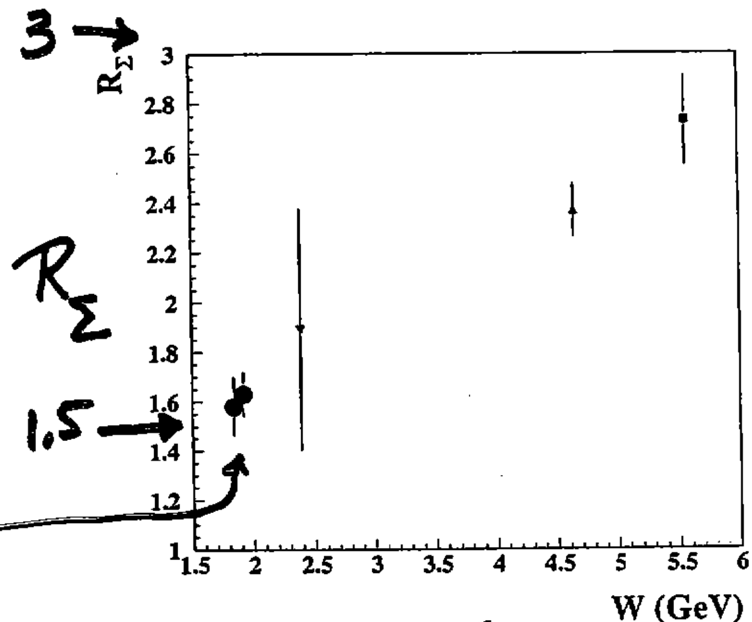
$$R_\Sigma \equiv \frac{\sigma(\gamma d \to K^+\Sigma^0 + K^+\Sigma^-)}{\sigma(\gamma p \to K^+\Sigma^0)}$$

$\longrightarrow$ 3 pure t channel (high s)

$\longrightarrow$ 1.5 pure s channel (high t)

evolution of s to t channel physics





t $\sqrt{s}$

need low t and high data

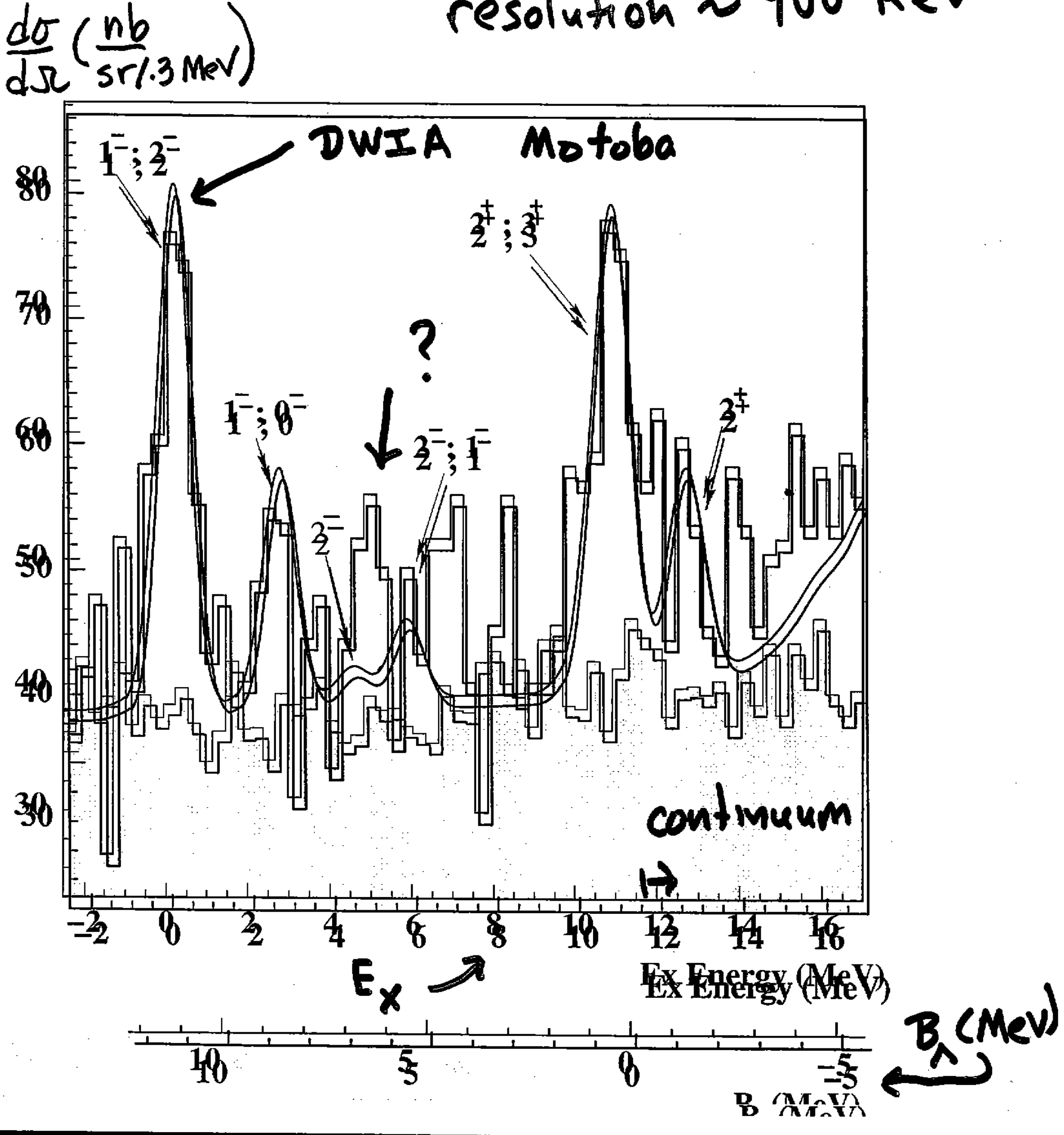
$E_e = 11$ GeV $\Rightarrow$ $W = 3.6$ GeV

E89-009

PRL (June, 2003)

extracted $^{12}C(\gamma, K^+)^{12}_{\Lambda}B^*$

resolution ~ 900 keV



Hidden Strangeness

Vacuum $\langle 0|\bar{s}s|0\rangle \simeq \langle 0|\bar{u}u|0\rangle \sim -\Lambda^3_{QCD}$

Nucleon $\langle N|\bar{s}\Gamma_i s|N\rangle \quad i=1,2,\ldots 16$
& N^*

Vector $\langle N|\bar{s}\gamma_\mu s|N\rangle \simeq g^V_{\phi NN}$

$\phi \approx \bar{s}s$

Tensor $\langle N|\bar{s}\sigma_{\mu\nu}s|N\rangle \simeq g^T_{\phi NN}$

$$\mathcal{L}_{\phi NN} = g^V_{\phi NN}\bar{N}\gamma_\mu N\phi^\mu + g^T_{\phi NN}\bar{N}\sigma_{\mu\nu}N(\nabla^\mu\phi^\nu - \nabla^\nu\phi^\mu)$$

Axial Vector $\langle N|\bar{s}\gamma_5\gamma_\mu s|N\rangle = 2S_\mu\Delta s$

$\Delta s(x) = s_\uparrow(x) - s_\downarrow(x)$ parton helicity density

Scalar $\langle N|\bar{s}s|N\rangle$

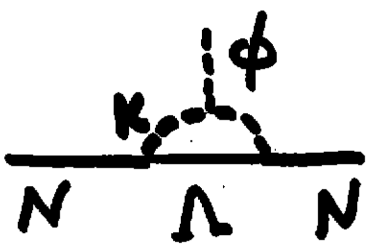
πN Σ term, OZI violations

Kaon Loop Studies / Calculations :

$|N\rangle = |qqq\rangle + |K\Lambda\rangle$

compute

$\langle N|\bar{s}\Gamma_\mu s|N\rangle$



→ Geiger, Isgur P.R.D$\underline{55}$, 299 (97)
$\Delta s = -.13$, $r_p^{(s)}$, $\mu_p^{(s)}$ small effects
Loop cancel.

→ Melnitchouk, Malheiro, P.R.C$\underline{55}$, 431(97)
Light cone, $\Delta s < .003$ very small effects

Savage, Walden P.R.D$\underline{55}$, 5376 (97)
K, η, π Loops $-.35 \leq \Delta s \leq 0$ larger effects

Musolf, Hammer P.R.D$\underline{55}$, 2741 (97)
dispersion analysis, find loops violate unitary ⇒ theoretical uncertainty

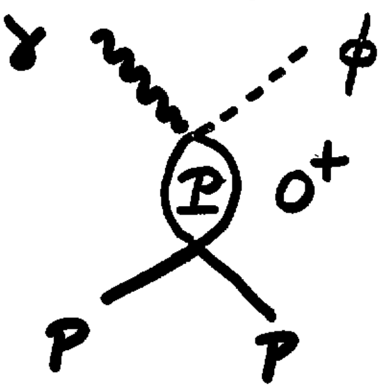
Kaon Loops importance is open question

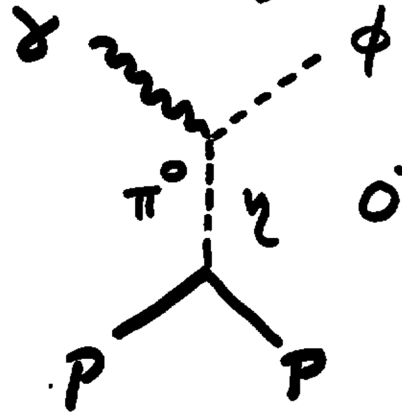
Meißner, Mull, Speth, Van Orden
phen. dispersion analysis of $F_N^{I=0}(q^2)$
small effects, loop cancellation ⇒ $g_{\phi NN} = .2$

ϕ Photoproduction $\quad \gamma p \to \phi p$

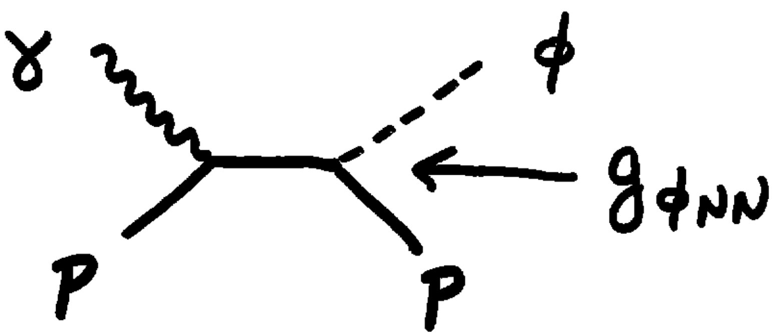
R. Williams, P.R.C $\underline{57}$, 223(199

t channel: Pomeron + π^0, η exchange

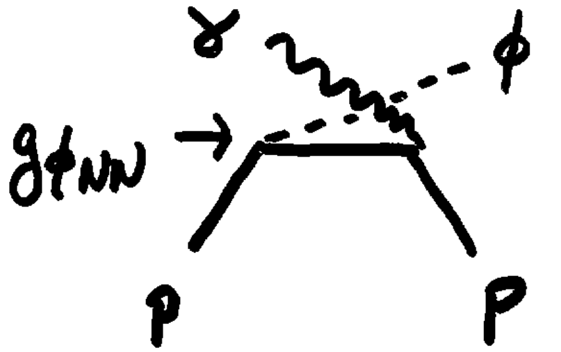




s channel:

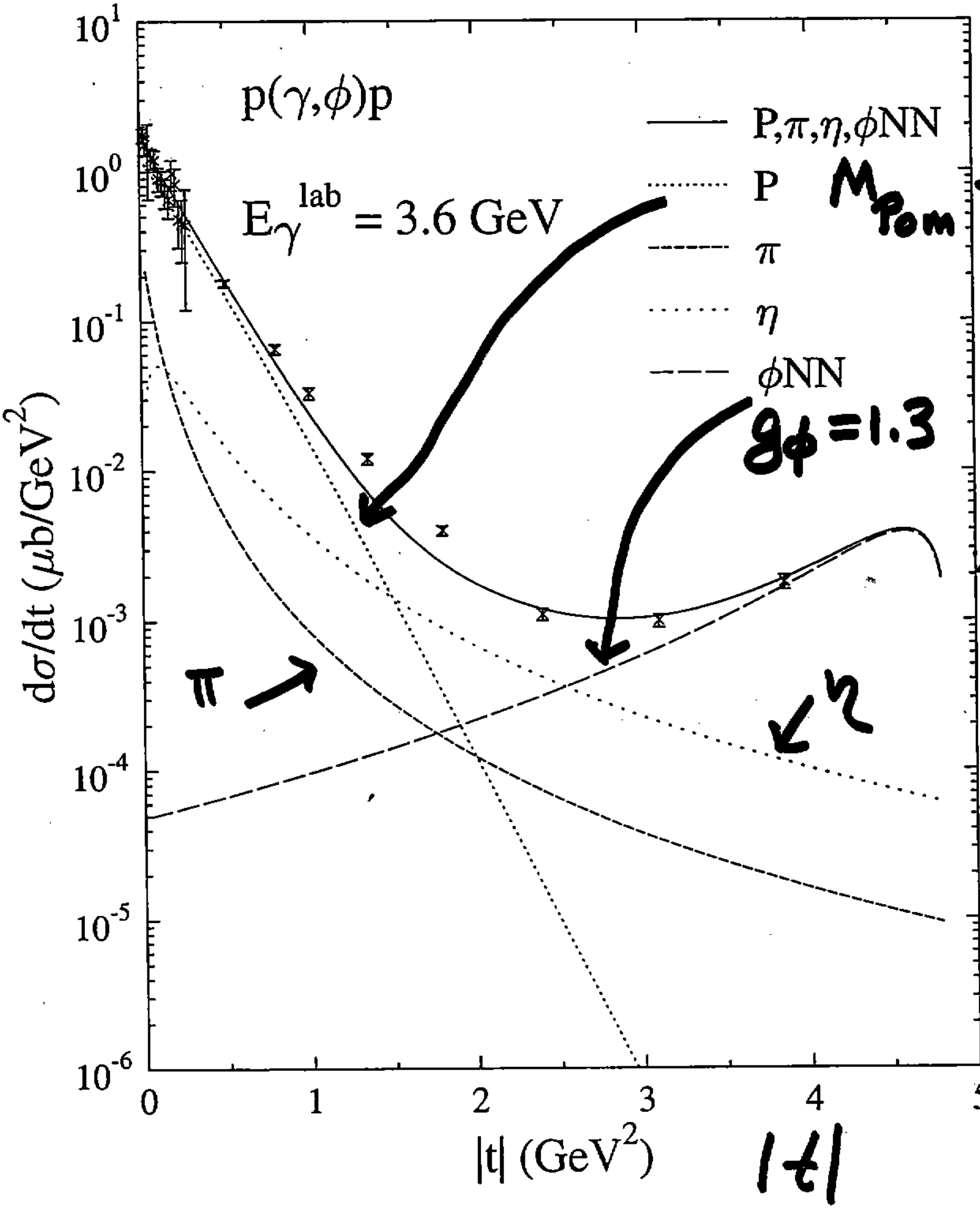


u channel:



PLB 549, 85 (2002)

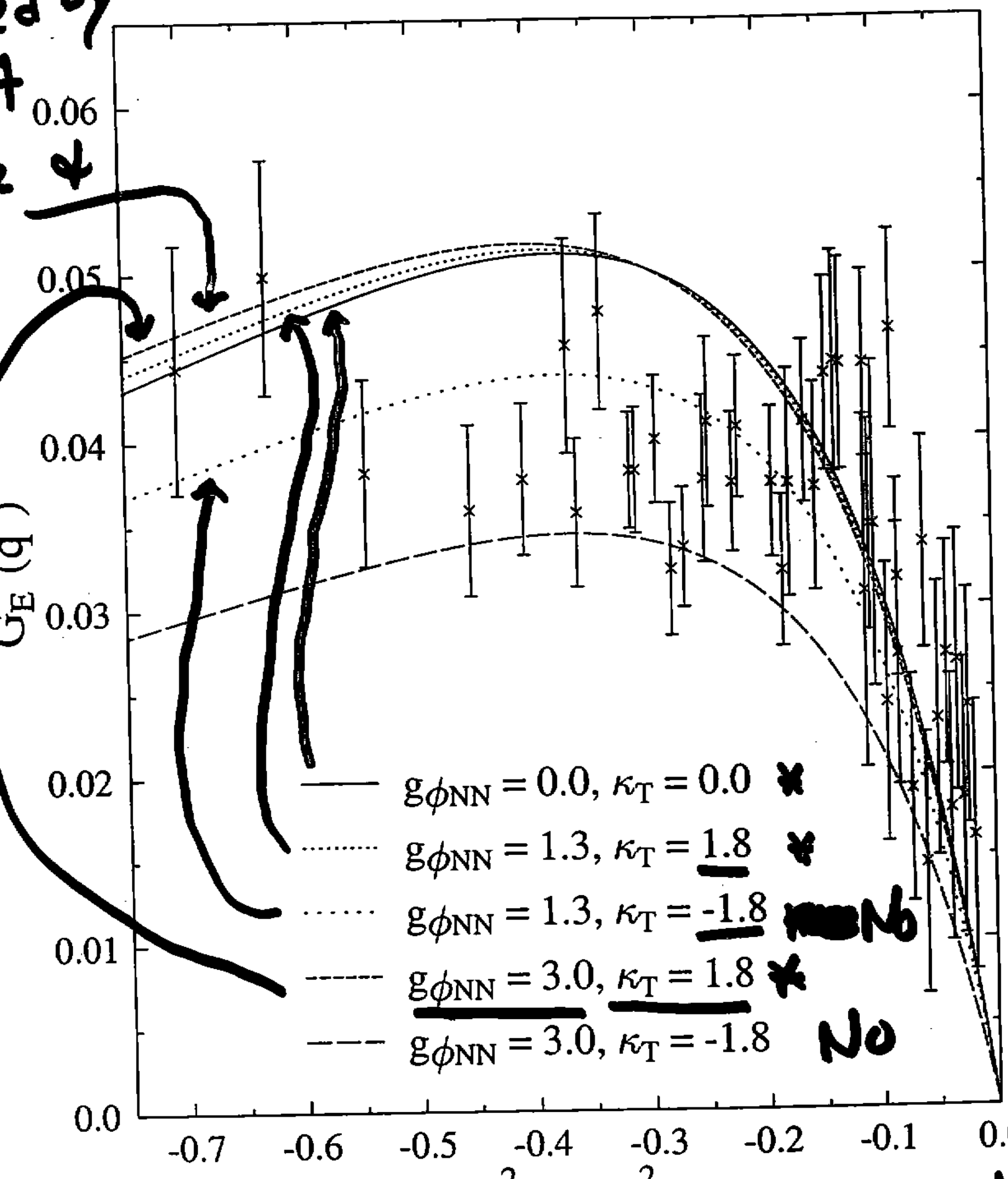
ϕ photo production versus $|t|$



Data E93 031 CLASS PRL 85 4689 (2000)

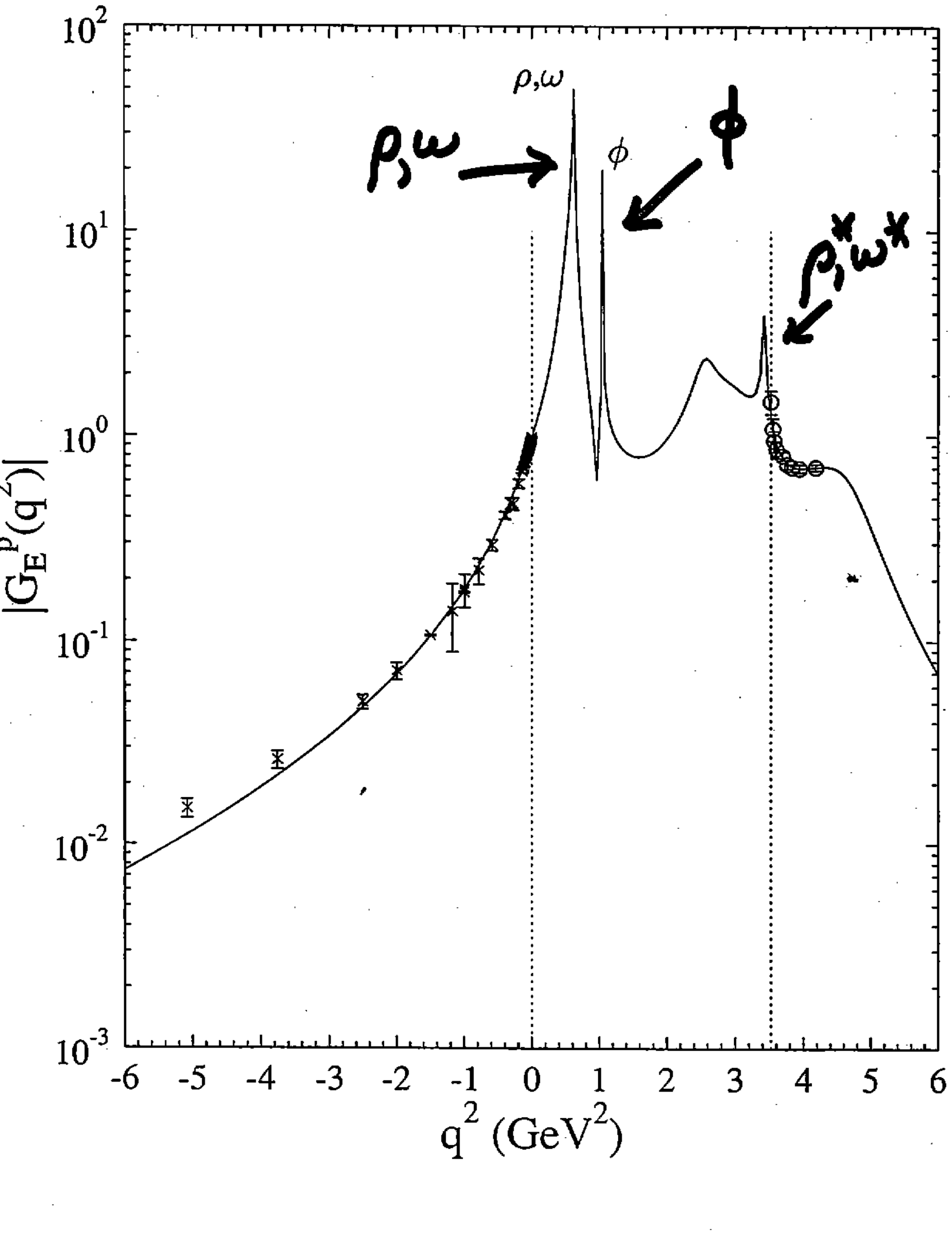
neutron Electric Form Factor sensitivity to $g_{\phi NN}^{V,T}$

favored by recent Mainz & JLab data



* possible

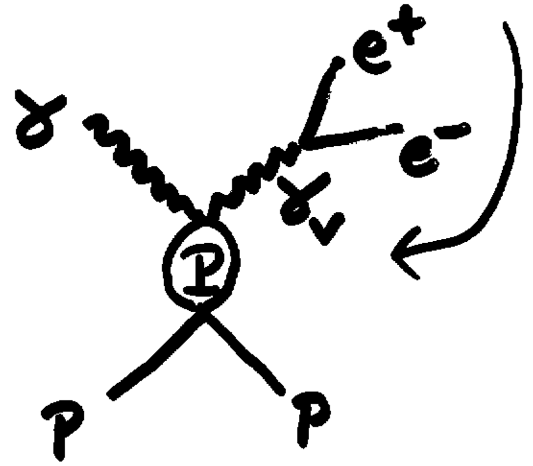
Proton Electric Form Factor

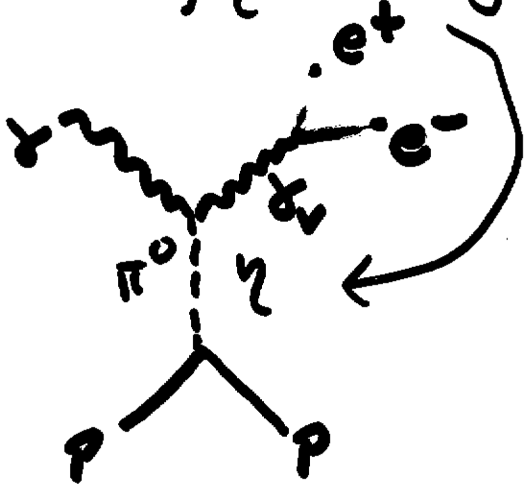


Time-Like Compton Scattering $p(\gamma, e^+e^-)p$

$C_{e^+e^-} = -1$

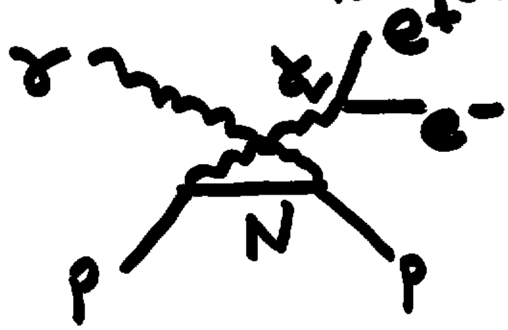
t channel Pomeron + π^0, η exchange



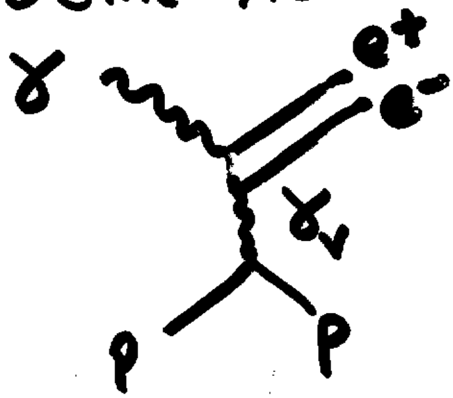


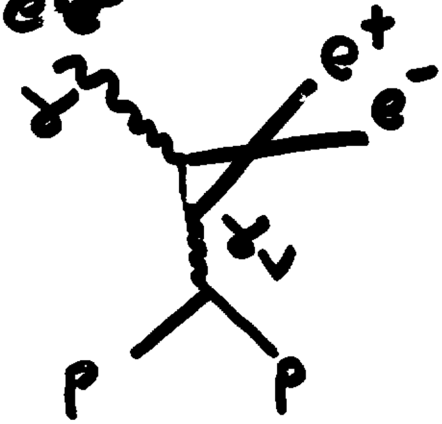
s channel

u channel



Bethe-Heitler $C_{e^+e^-} = +1$





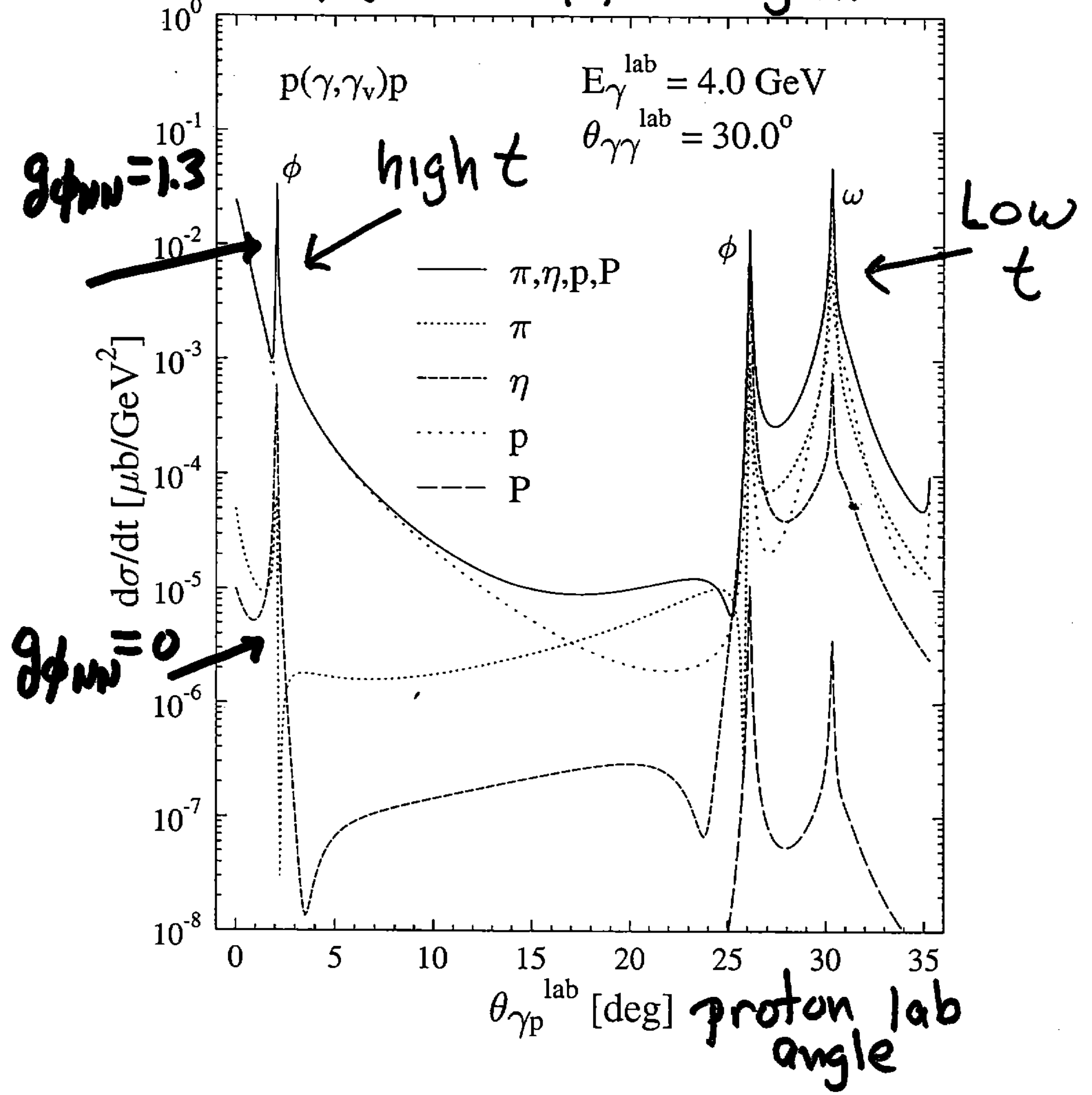
$$A = \frac{\sigma_{e^+e^-} - \sigma}{\sigma_{e^+e^-} + \sigma}$$

Time-Like Virtual Compton Scattering [TVCS]

PLB 549, 85 (2002)

vs proton lab angle

note dual ϕ peak signature



$\gamma p \to K^* \Sigma$

Quark Model s, u channel Approach

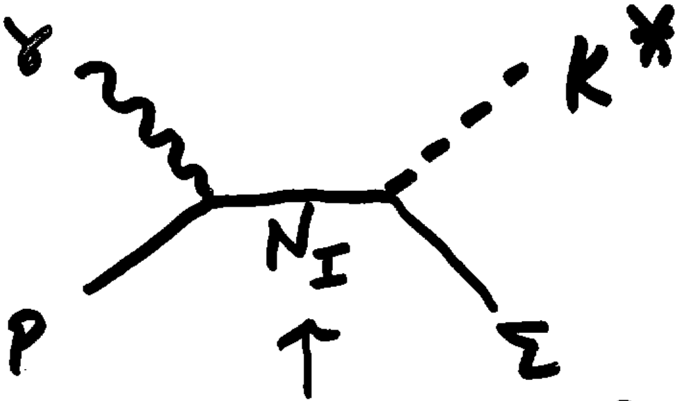
Zhao, Al-Khalili, Bennhold
PRC 64, 052201 (2001)

$$T^s_{fi} = \sum_I \langle K^* \Sigma | H_{qK^*} | N_I \rangle \langle N_I | \frac{H_{em}}{E_I - E_\gamma - E_i} | p \gamma \rangle$$

$$H_{qK^*} = \bar{\psi}_q \left(a\gamma_\mu + \frac{i b}{2m_q} \sigma_{\mu\nu} q^\nu \right) \psi_q K^{*\mu}$$

s Channel

$$H_{em} = e_q \bar{\psi}_q \gamma_\mu \psi_q A^\mu$$



same for u channel

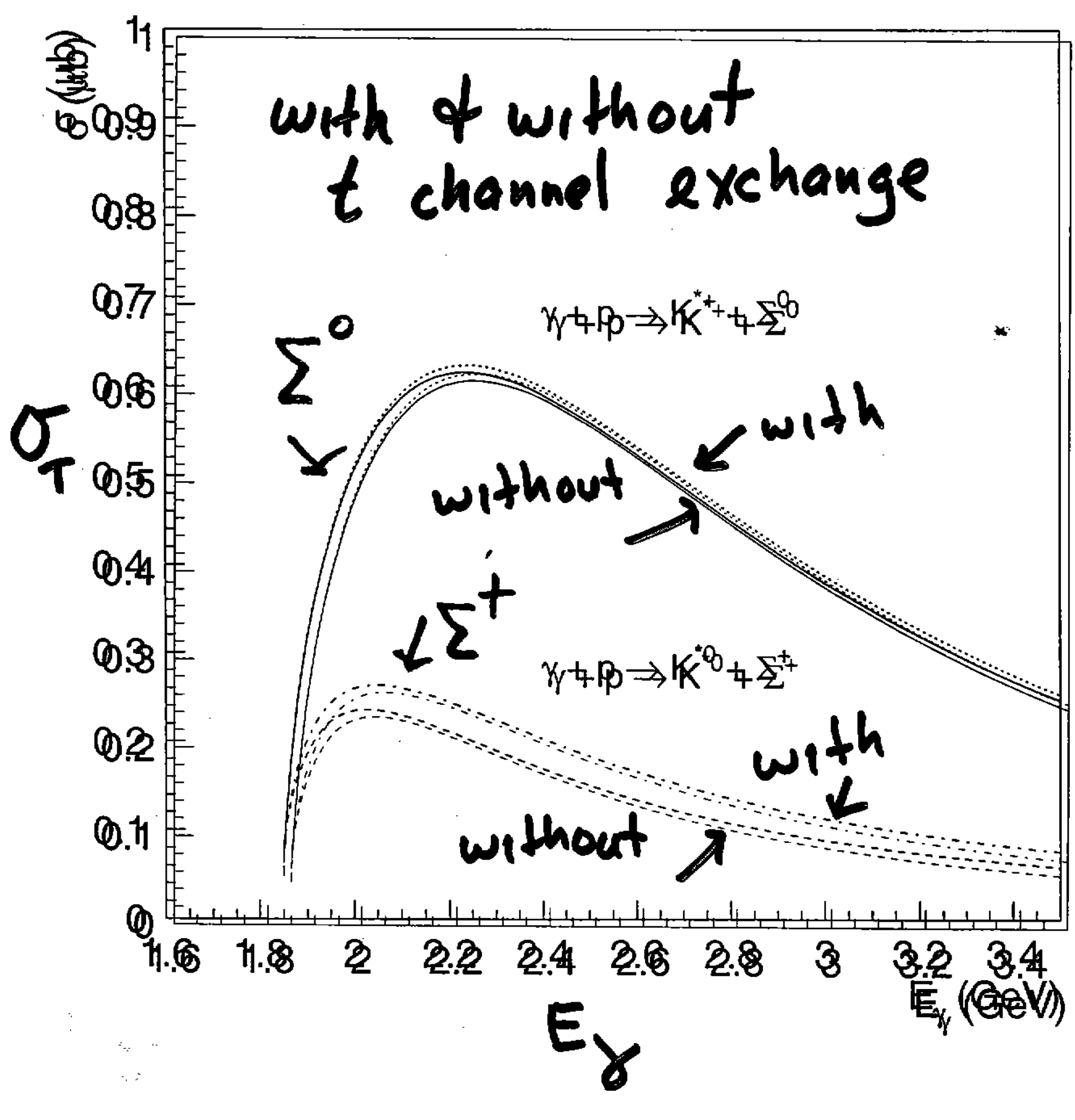
Use quark Model for $|N_I\rangle, |p\rangle, |\Sigma\rangle$

quark model for s & u channels
K, K* exchange for t channel

modeled

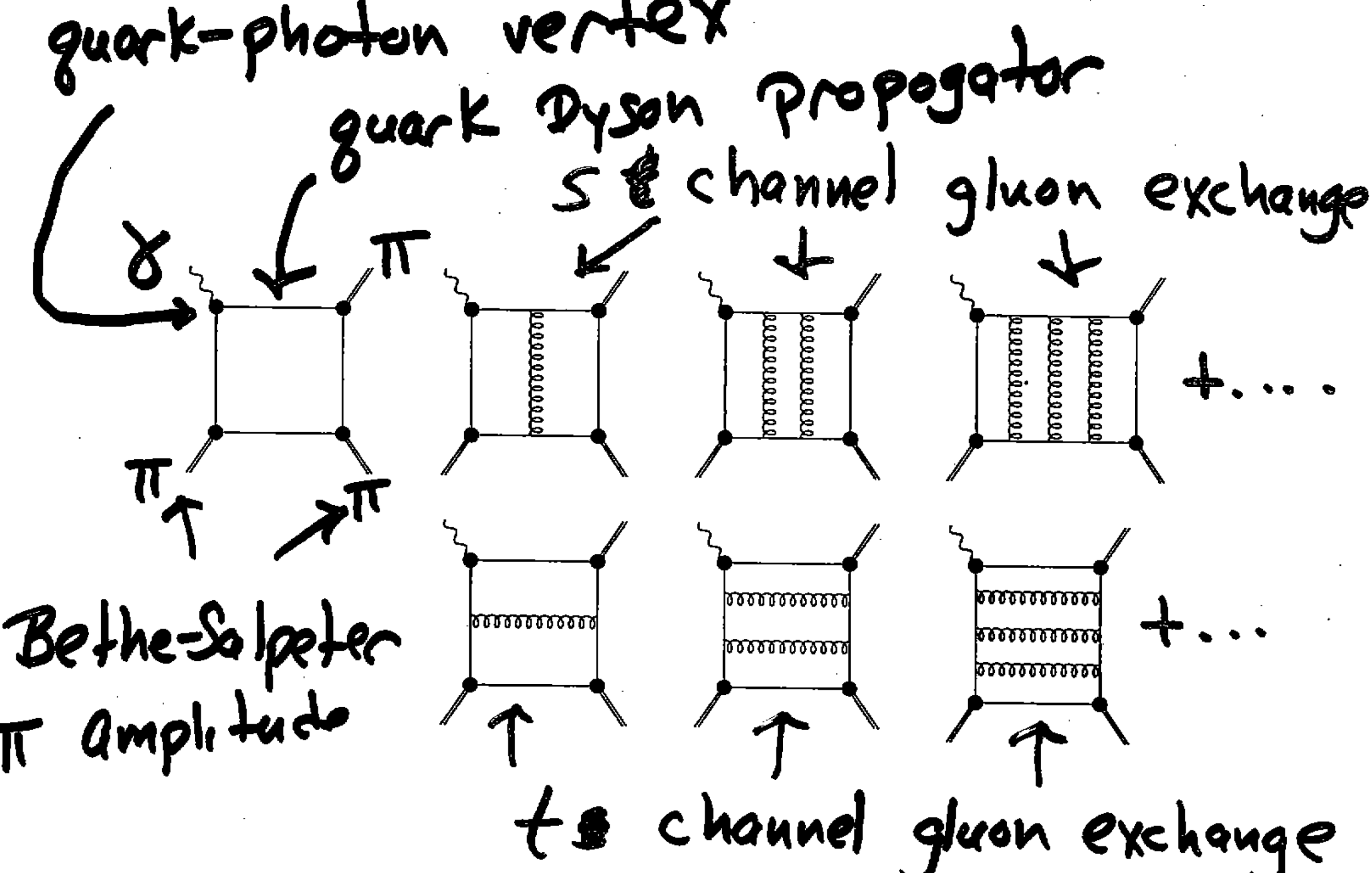
$\gamma p \to K^* \Sigma$

$g_{K^*\Sigma N^*}$



Quark Dyson-Schwinger for $\gamma\pi \to \pi\pi$

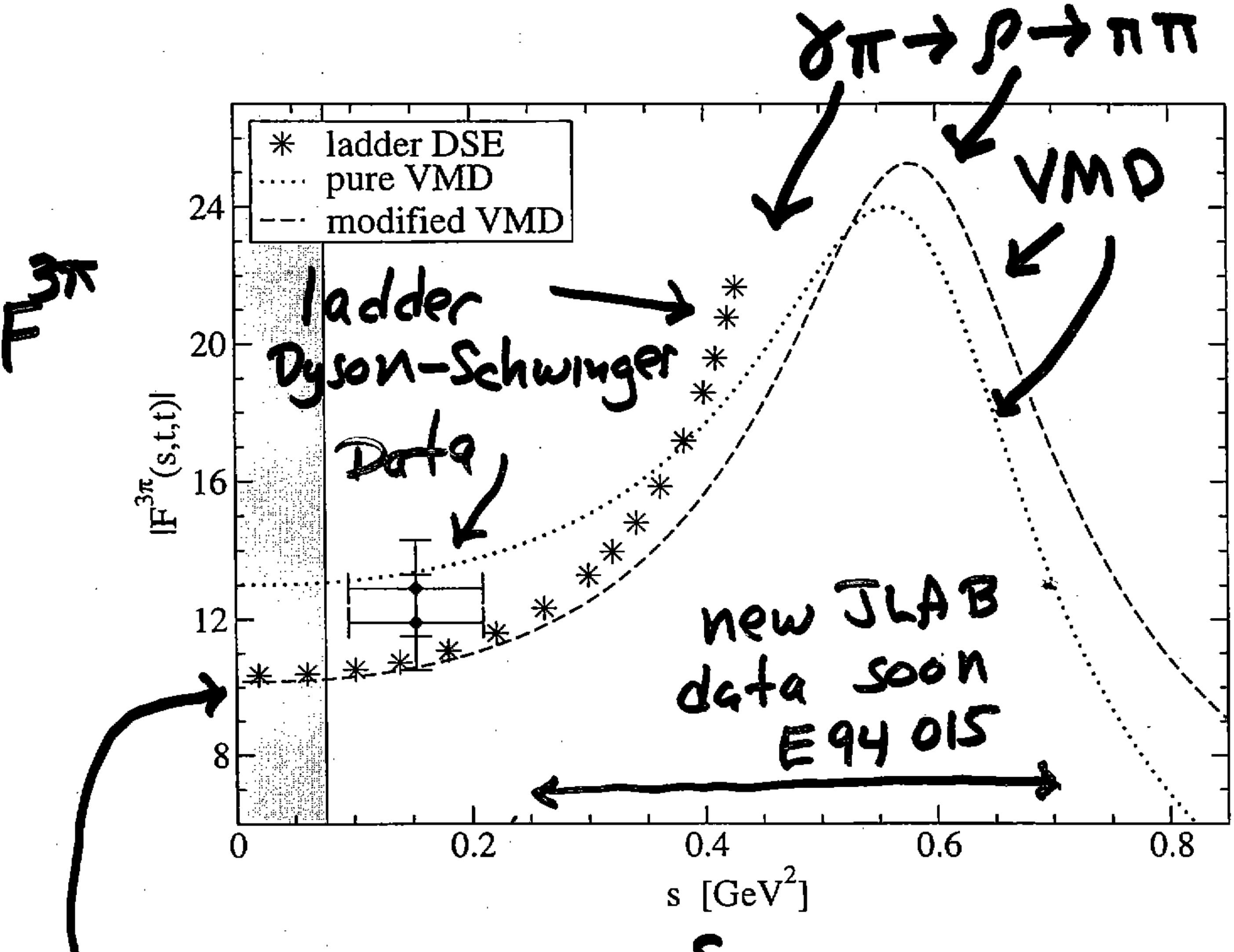
Cotanch, Maris PRD 66, 116010 (2002)



Sum all s, t, u ladder diagrams

$\gamma\pi \to \pi\pi$ & $\gamma \to \pi^+\pi^-\pi^0$

anomalous form factor $F^{3\pi}(s,t,u)$



reproduce low energy theorem

$$F^{3\pi}(0,0,0) \to \frac{e}{4\pi^2 f_\pi^3}$$

Coulomb Gauge Hamiltonian $\vec{\nabla}\cdot\vec{A}^a = 0$

Legendre transformation of $\mathcal{L}_{QCD}$

$$H = \frac{1}{2}\int d\vec{x}\left[J^{-1}\vec{E}^a(\vec{x})\cdot J\vec{E}^a(\vec{x}) + \vec{B}^a(\vec{x})\cdot\vec{B}^a(\vec{x})\right]$$

$$+ \int d\vec{x}\,\psi^\dagger(\vec{x})\left[-i\vec{\alpha}\cdot\vec{\nabla} + g\frac{\lambda^a}{2}\vec{\alpha}\cdot\vec{A}^a(\vec{x}) + \beta m_q\right]\psi(\vec{x})$$

$$+ \frac{g^2}{2}\iint d\vec{x}\,d\vec{y}\,J^{-1}\rho^a(\vec{x})\,V_{ab}(\vec{x},\vec{y})\,J\rho^b(\vec{y})$$

where $J = \det(\nabla_i D_i)$ Fadeev-Popov determ.

$D_i^{ac} = \nabla_i\delta_{ac} + g f^{abc} A_i^b$ covariant deriv.

$\rho^a(\vec{x}) = \psi^\dagger(\vec{x})\frac{\lambda^a}{2}\psi(\vec{x}) + f^{abc}\vec{A}^b(\vec{x})\cdot\vec{E}^c(\vec{x})$

color charge density

$$V_{ab}(\vec{x},\vec{y}) = -\langle\vec{x},a|(\nabla_i D_i)^{-1}\nabla^2(\nabla_i D_i)^{-1}|\vec{y},b\rangle$$

Solve Simpler H_{eff}

$$H = K - \frac{1}{2}\int d\vec{x}\, d\vec{y}\, \rho^a(\vec{x})\, V(\vec{x},\vec{y})\, \rho^a(\vec{y})$$

$$K = \begin{cases} \frac{1}{2}\int d\vec{x} \left(\vec{E}^a(\vec{x})^2 + \vec{B}^a(\vec{x})^2 \right) & \text{gluon} \\ \int d\vec{x}\, \Psi^\dagger(\vec{x}) \left(-i\vec{\alpha}\cdot\vec{\nabla} + \beta m \right) \Psi(\vec{x}) & \text{quark} \end{cases}$$

$$\rho^a(\vec{x}) = \begin{cases} f^{abc} \vec{A}^b(\vec{x}) \cdot \vec{E}^c(\vec{x}) & \text{gluon} \\ \Psi^\dagger(\vec{x}) \frac{\lambda^a}{2} \Psi(\vec{x}) & \text{quark} \end{cases}$$

$$V(\vec{x},\vec{y}) = \sigma |\vec{x} - \vec{y}|$$

$\sigma = .18\ \text{GeV}^2$ from lattice

$m = 5$ MeV for u & d

$= 150$ MeV for s

$= 1200$ MeV for c

non-linear, non-local quark gap eq.

$s_k \equiv \sin\phi(k) \qquad c_k \equiv \cos\phi(k)$

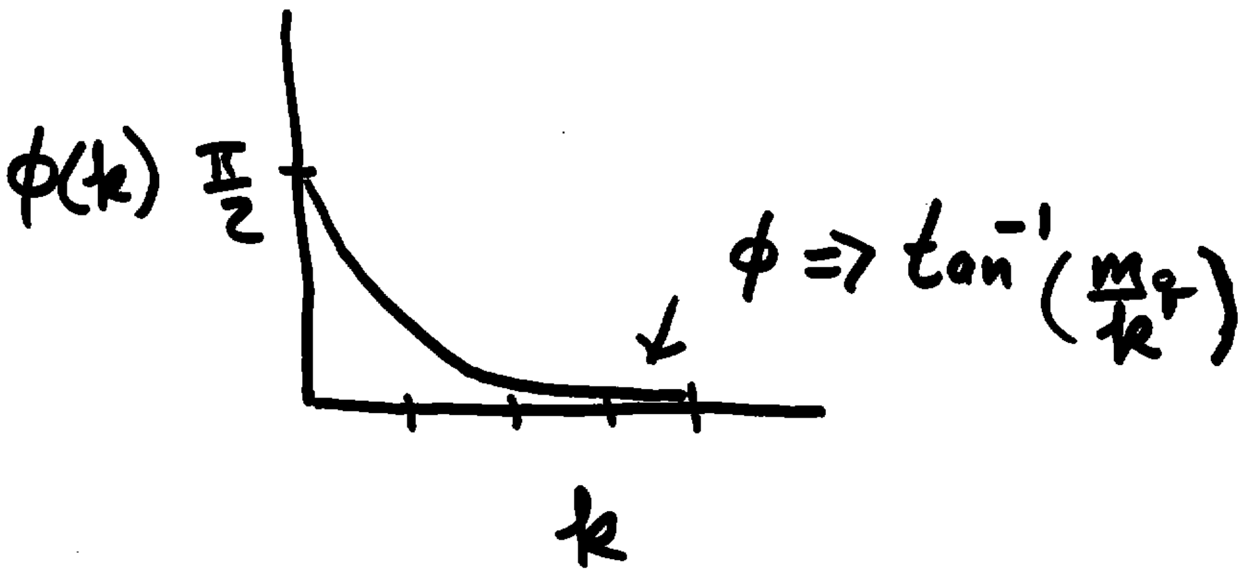
$$k s_k - m_q c_k = \frac{2}{3}\int \frac{d\vec{p}}{(2\pi)^3}\hat{V}(\vec{k},\vec{p})\left[s_k c_p \hat{k}\cdot\hat{p} - s_p c_k\right]$$

for linear confinement $\rightarrow \sigma|\vec{x}-\vec{y}|$

$$\hat{V} = -\frac{8\pi\sigma}{|\vec{k}-\vec{p}|^4}$$

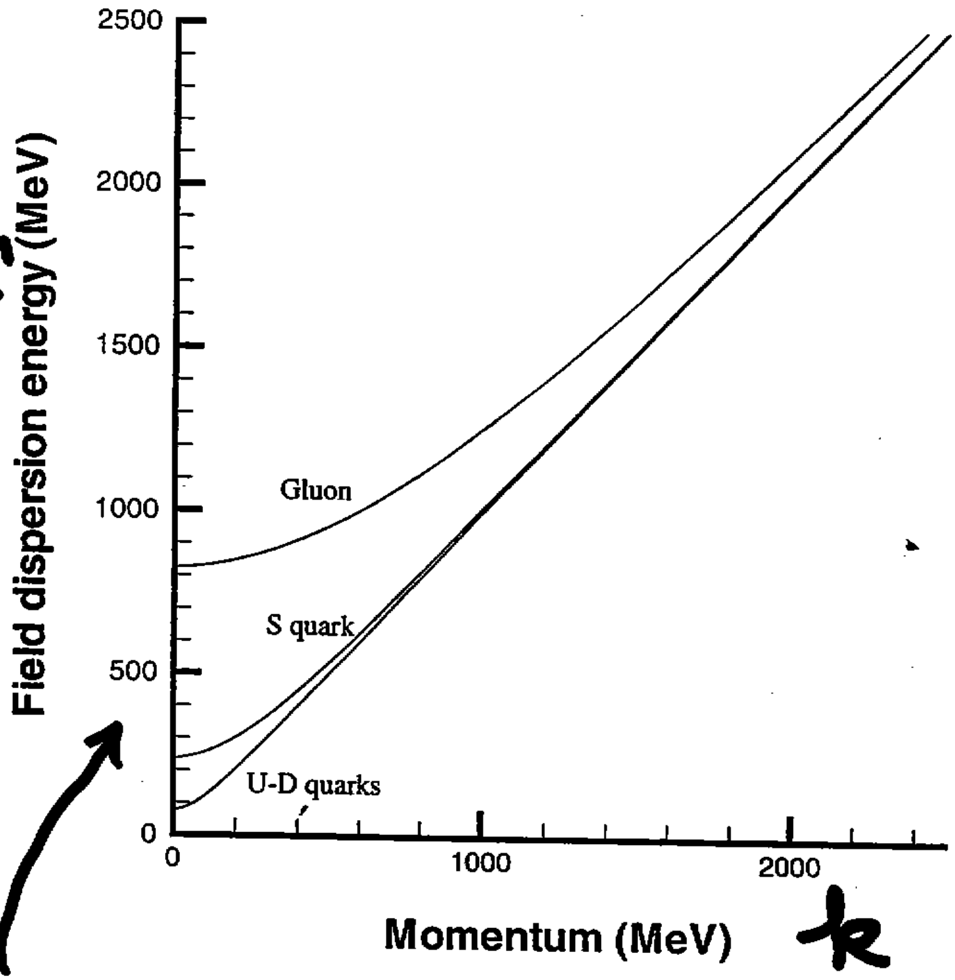
$\sigma = .18 \text{ GeV}^2$

from lattice



quasi-particle dispersion relation

$\sqrt{\hat{m}^2(k)+k^2}$



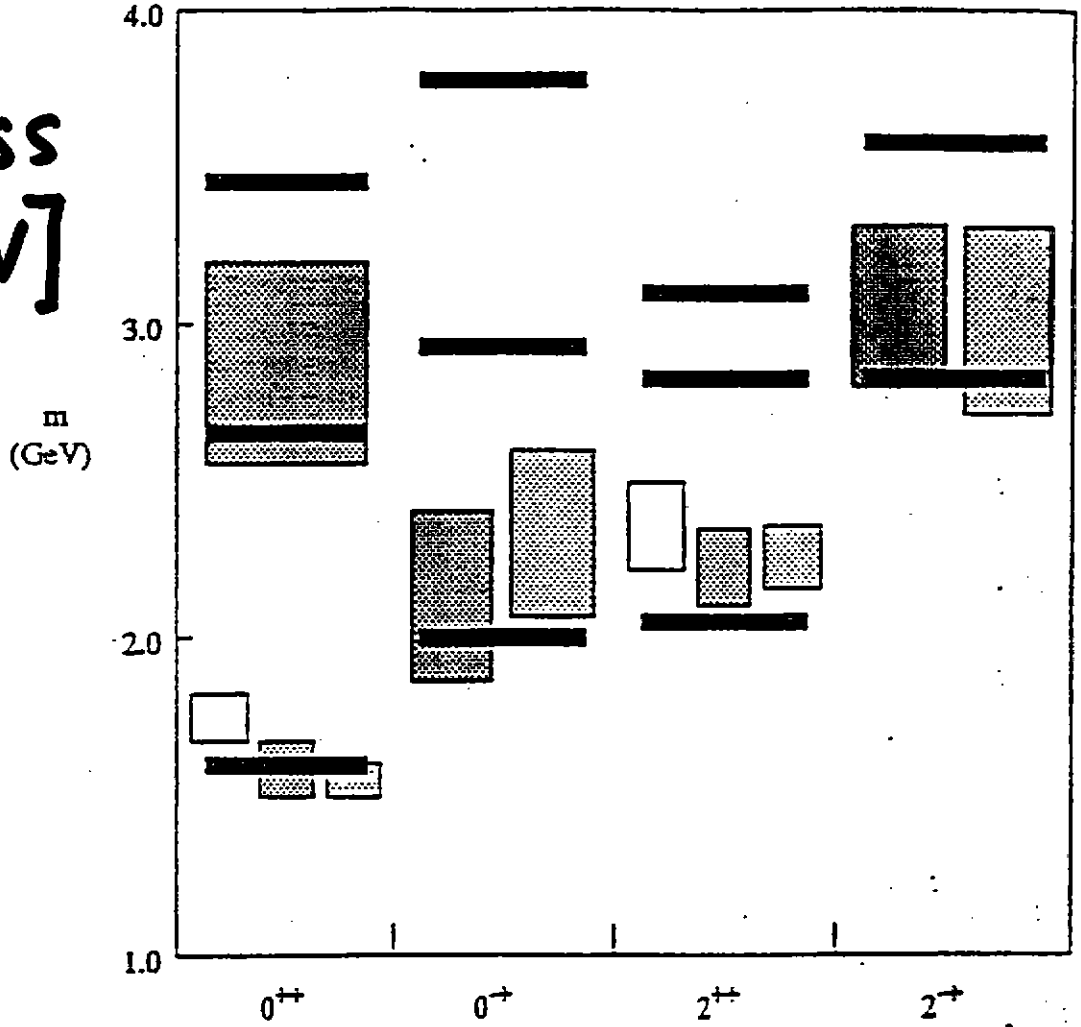
k

$\hat{m}(0) \approx m^{dynam} \cong \begin{cases} 850 \text{ MeV gluon} \\ 250 \text{ s quark} \\ 80 \text{ u/d quark} \end{cases}$

TDA Glueball Spectrum

Phys. Rev. Lett. <u>76</u>, 2011 (1996)

mass [GeV]



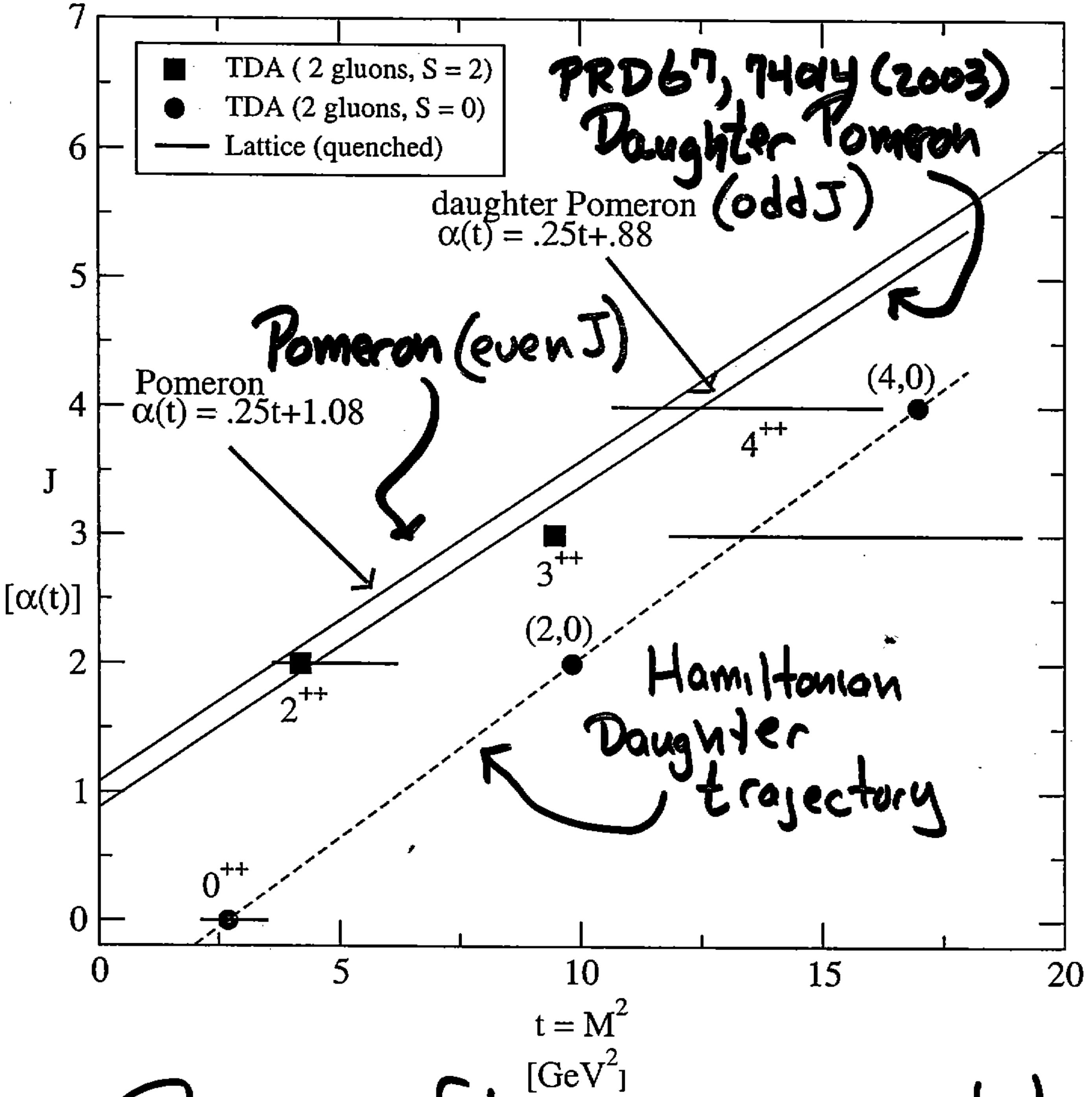
$J^{\pi C} \rightarrow$ 0^{++} 0^{-+} 2^{++} 2^{-+}

this work 2 gluons

Lattice Gauge (quenched)

Nucl. Phys. A710, 45 (2002)

Glueball Regge Trajectories



Pomeron fits high energy data

$\sigma_{Total} \sim s^{\alpha(0)-1} \sim$ constant

Cotanch Maris 1

PRD 66, 116010 (2002)

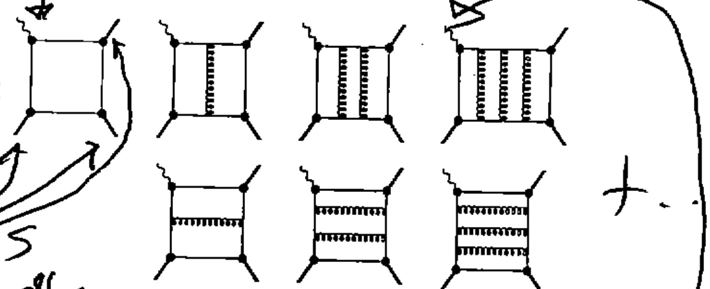
Bethe quark-photon vertex

Dyson-Schwinger quark propagator

Bethe Salpeter π amp

t channel

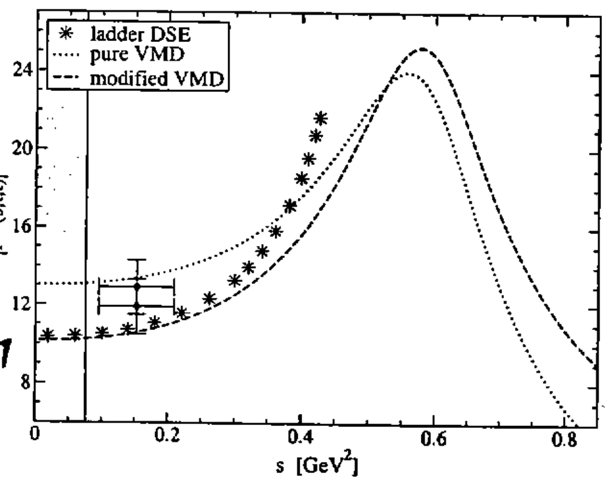
s chan



gluon s & t exchange

$\gamma\pi \to \pi\pi$ & $\gamma \to \pi^+\pi^-\pi^0$ Form Factor $F^{3\pi}$

$F^{3\pi}$



reproduces the anomalous Form Factor $\gamma \to \pi^+\pi^-\pi^0$

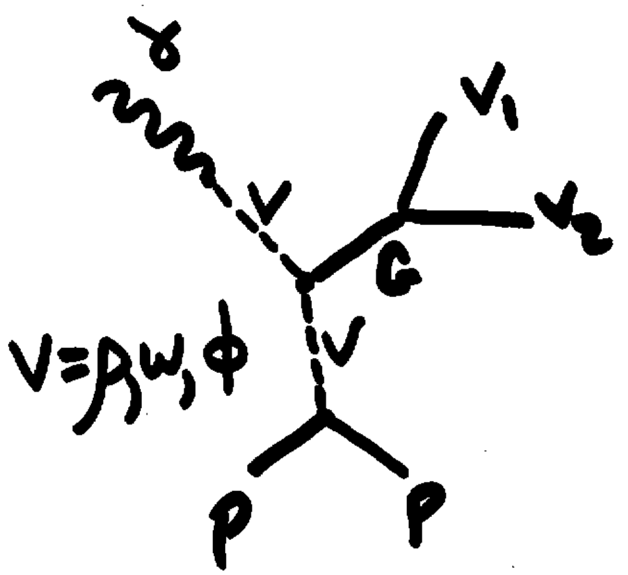
$$F^{3\pi}(0,0,0) = \frac{e}{4\pi^2 f_\pi^3} \leftarrow \text{low energy Theorem}$$

E

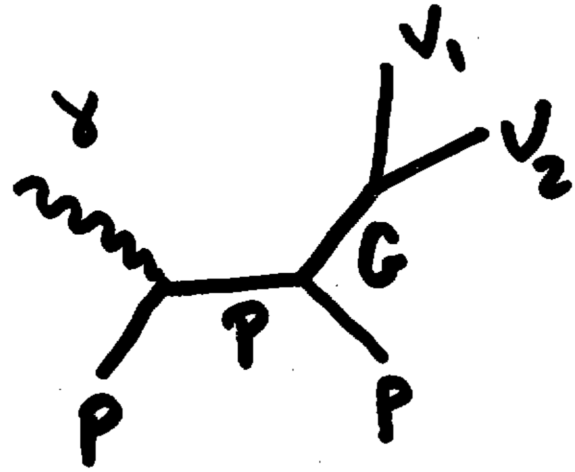
Glueball Photoproduction with two vector meson decay

$$\gamma + p \to G + p \to V_1 + V_2 + p$$

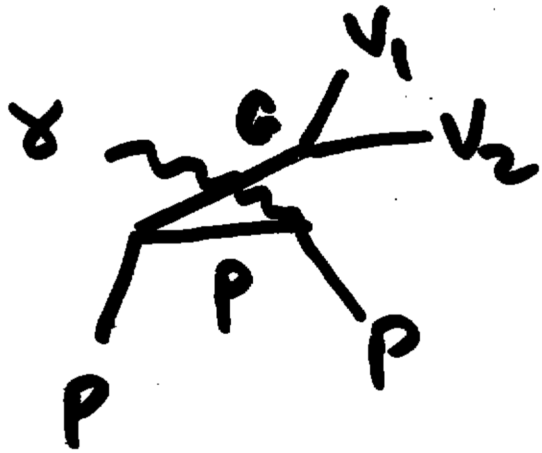
use vector meson Dominance



+



+



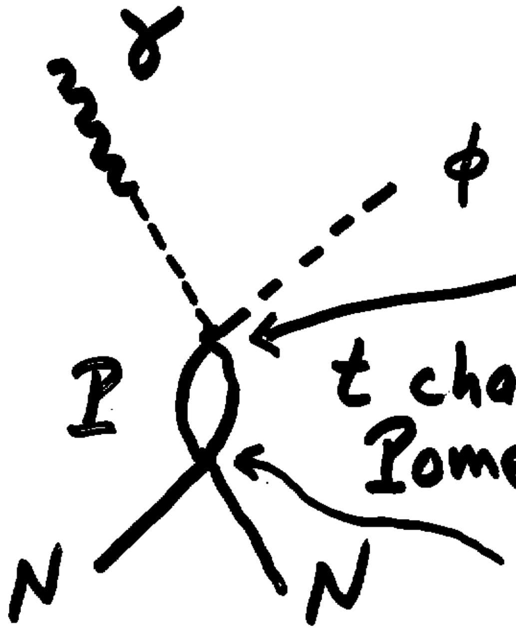
need

g_{GVV}

&

g_{GNN}

use VMD, fit $\gamma N \to \phi N$ @ low t



$\frac{e K_{\phi P \gamma}}{m_\phi}$

$K_{\phi P \gamma} = .62$

t channel
Pomeron exchange

$g_{PNN} = 44$

VMD $\Rightarrow$ $K_{\phi P \gamma} = \frac{g_{P\rho\rho}}{f_\rho} + \frac{g_{P\omega\omega}}{f_\omega} + \frac{g_{P\phi\phi}}{f_\phi}$

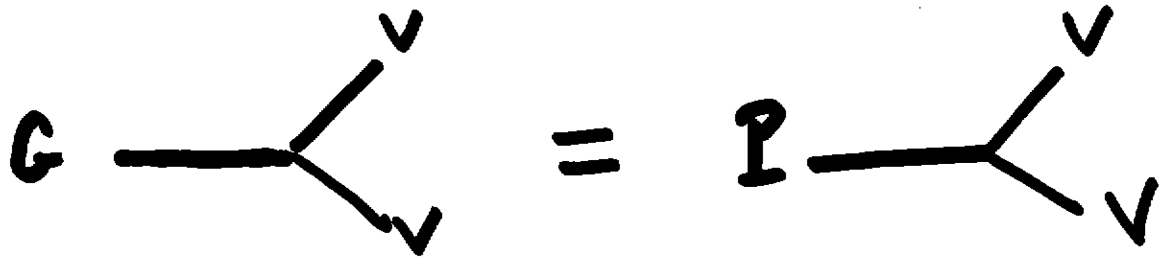
gluon coupling
flavor independent

$f_\rho = 5 \quad f_\omega = 17 \quad f_\phi = -13$

$\Rightarrow g_{P\rho\rho} = g_{P\omega\omega} = g_{P\phi\phi} = g_{PVV} = 3.43$

use generalized VMD
to estimate g_{GVV} + g_{GNN}

assume Glueball + Pomeron
couplings are the same



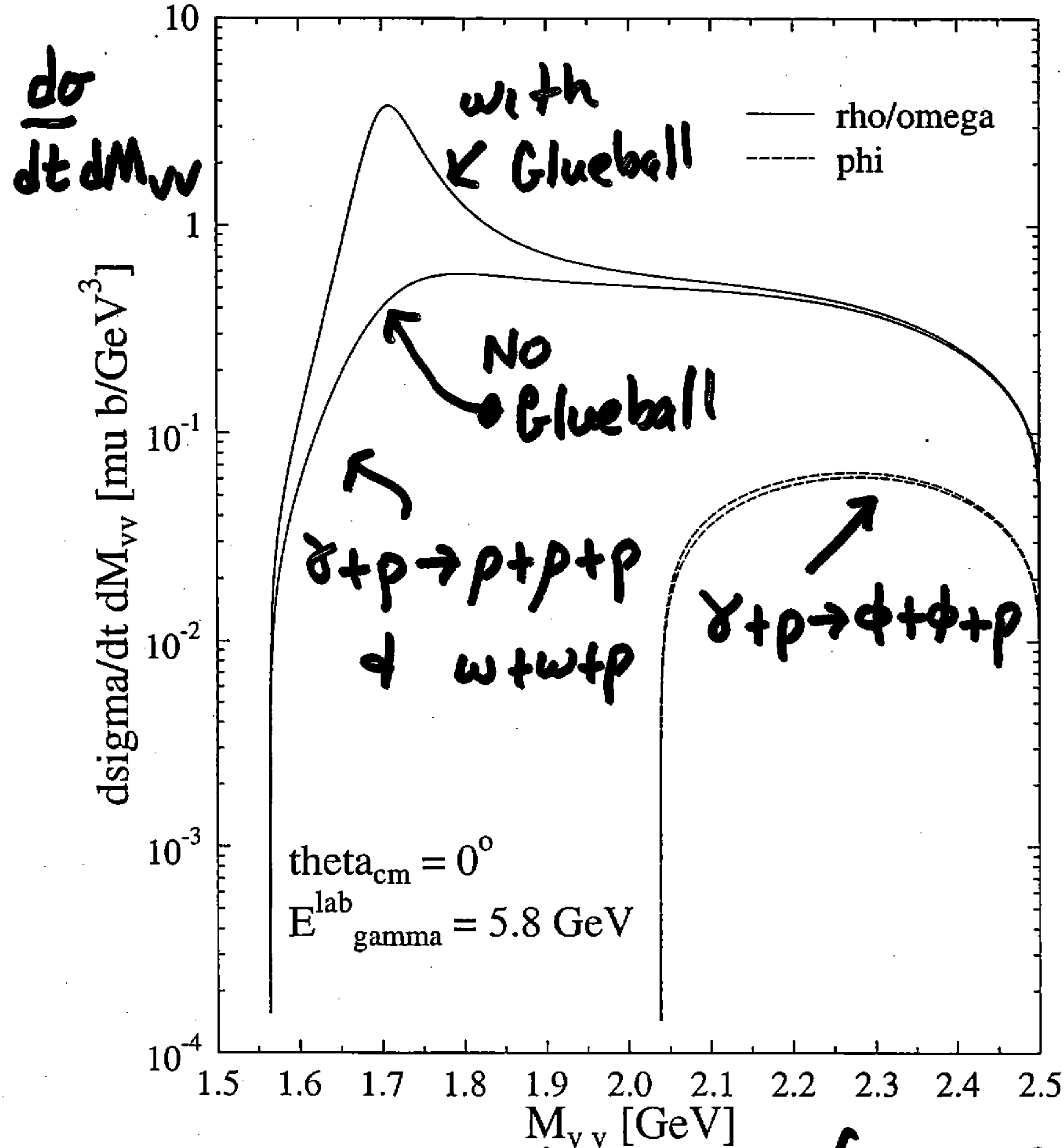
	Decay	Γ	
$G \to$	$\rho\rho$	44.4 MeV	$\Leftrightarrow g_{GVV} = 3.43$
	$\omega\omega$	34.6 MeV	
	$\rho\gamma$	.866 keV	
	$\omega\gamma$	.844 keV	
	$\phi\gamma$	.454 keV	
	$\gamma\gamma$	2.6 eV	

0^{++} Glueball photoproduction

$\gamma + p \to G + p \to V + V + p$

$V = \rho, \omega, \phi$

p(gamma,G(0^{++})->V V)p

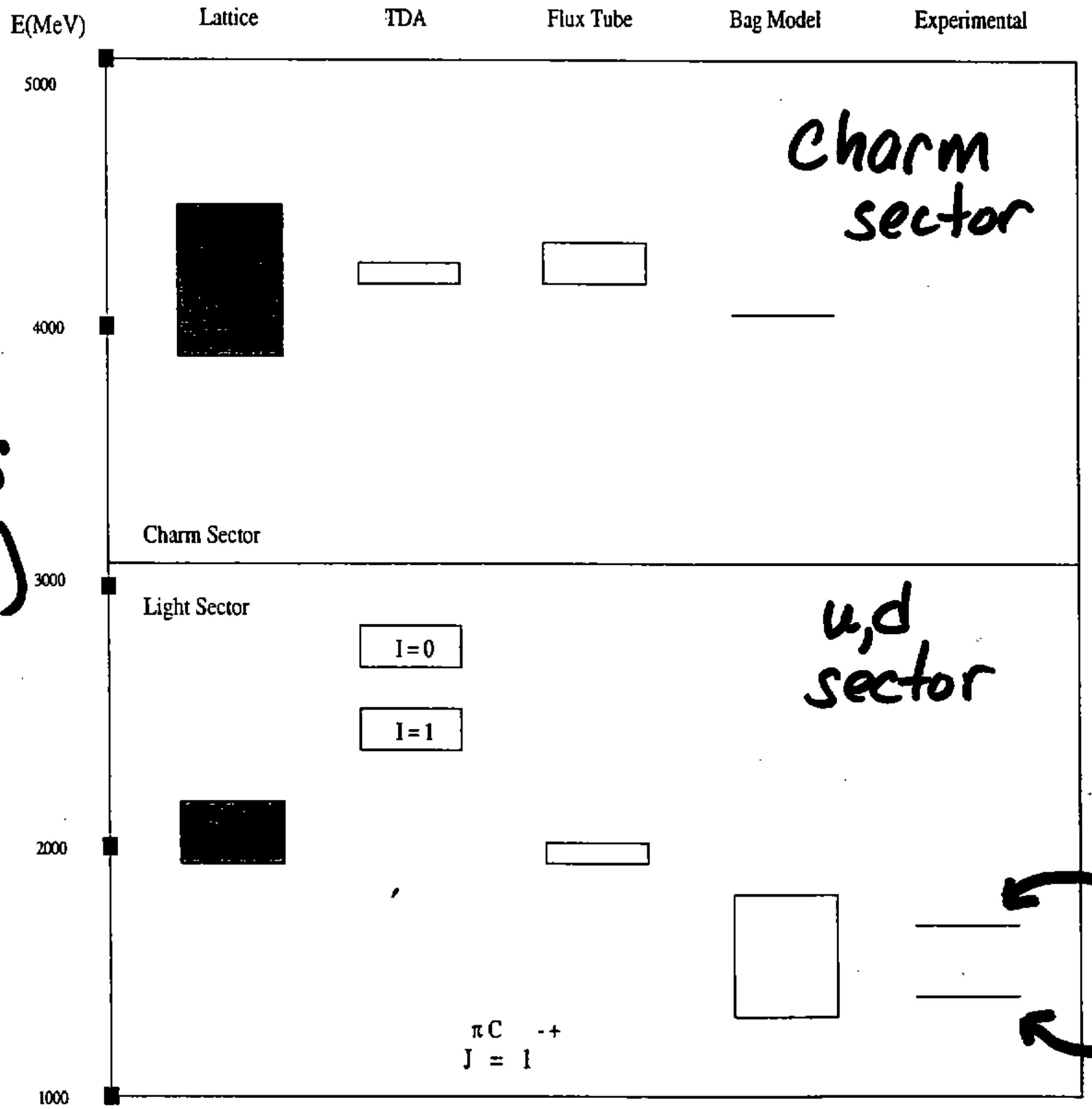


Invariant Mass of 2 vector mesons

Exotic $J^{\pi C} = 1^{-+}$ hybrids

Phys. Lett. B504, 15 (2001)

Mass (MeV)



observed I=1 states E852

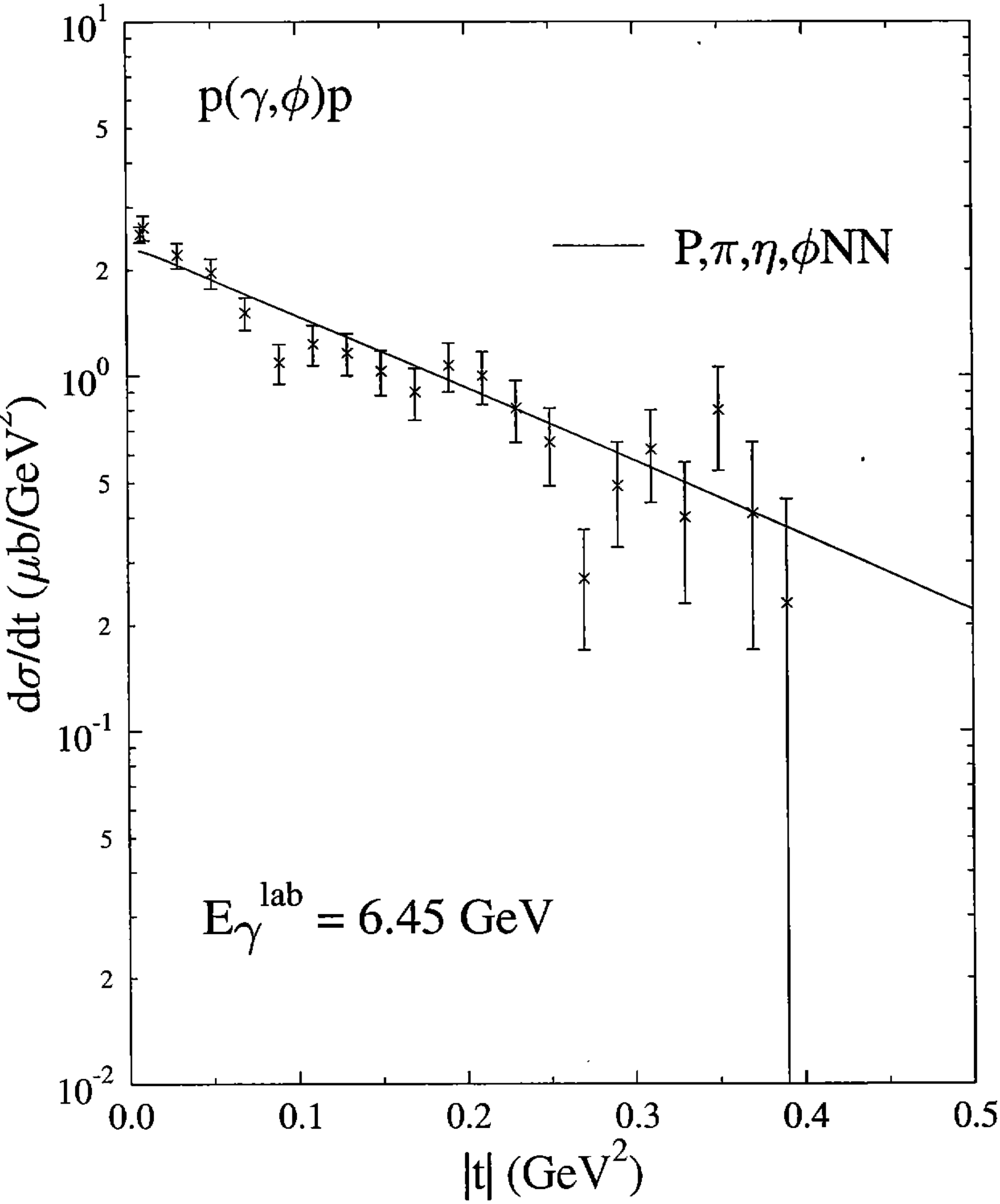
1.4 & 1.6 GeV

lattice (extrapolate)

TDA this work

flux tube

bag model

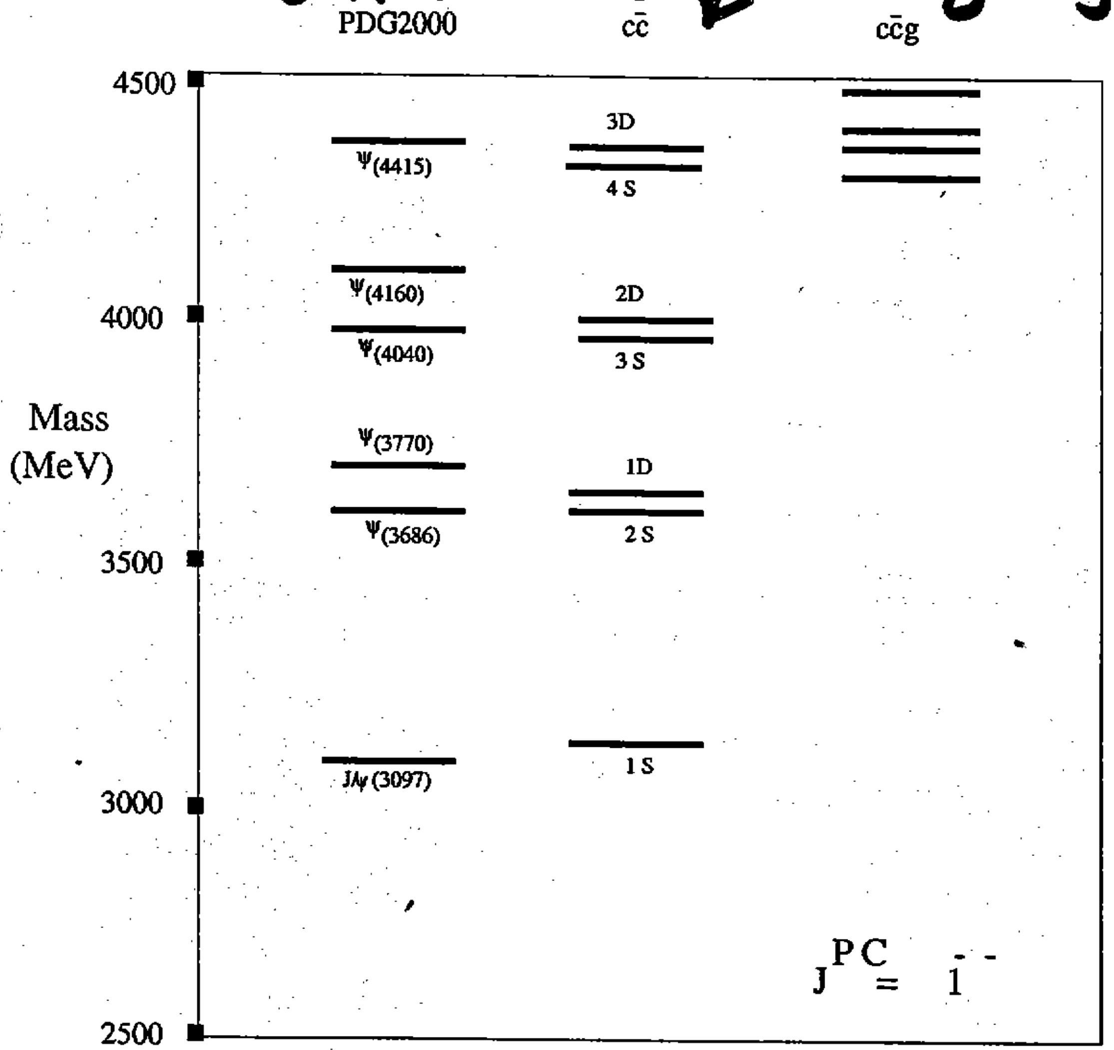


p(γ,φ)p
P,π,η,φNN
E_γ^lab = 6.45 GeV
dσ/dt (μb/GeV²)
|t| (GeV²)
10^1
5
2
10^0
5
2
10^-1
5
2
10^-2
0.0
0.1
0.2
0.3
0.4
0.5

Charmonium J/ψ Spectrum

include D waves & glue

Data cc̄ cc̄g hybrids



resolves "overpopulation" of states problem

Outlook

$p(e,e'K)Y$ Improve models effec field th, lattice $\mathcal{L}_{QHD}$, quark, Schw-Dys, PQCD @ high E

Extract $F_K(Q^2)$, g_{KYN}, N^*, Δ^*, Y^* properties

$d(e,e'K)YN$ Extract $\gamma n \to KY$ & rel. phase of $\gamma p \to K\Lambda$ to $K\Sigma$

Study $R_\Sigma = \sigma(\gamma d \to K\Sigma N) / \sigma(\gamma p \to K^+\Sigma^0)$

Study V_{YN} via FSI

$A(e,e'K)_Y B$ Improve resolution, study excited states need DWIA, continuum SM w V_{YN}, $V_{K_Y B}$

Energy upgrade / Hall D

$p(\gamma, \phi_{e^+e^-})p$ Study $\langle N|\bar{s}\Gamma s|N\rangle$, extract $g_{\phi N}$, $G^N_{E,M}(Q^2)$

$\left.\begin{array}{l} p(\gamma, G\to \nu\nu)p \\ p(\gamma, J/\psi)p \end{array}\right\}$ study exotic states glueballs, hybrids, charmonium