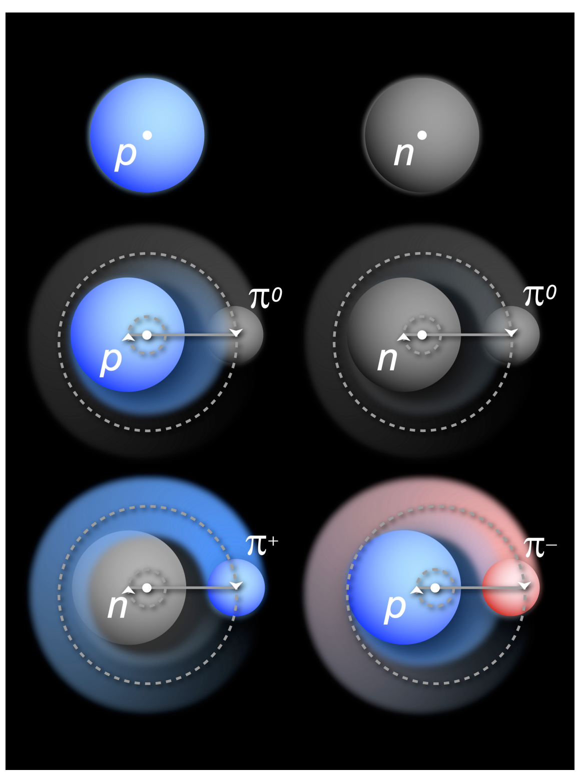
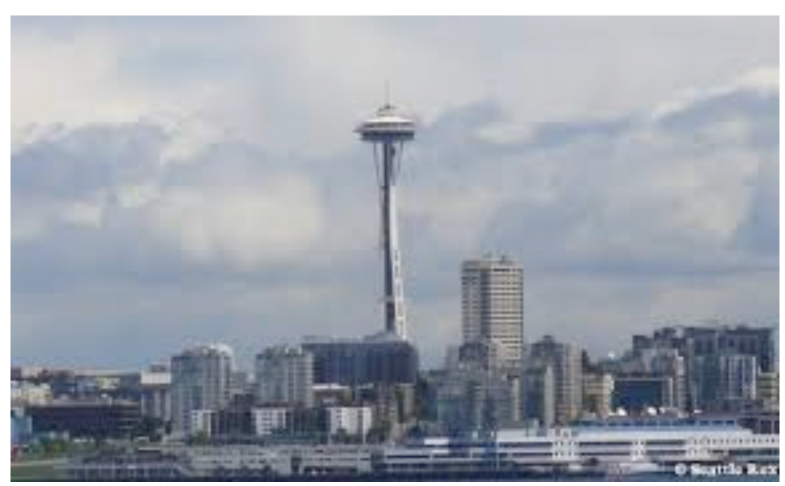
Taming the pion cloud

Gerald A. Miller, UW
Mary Alberg, Seattle U, UW





vs

Arrington arXiv:1208.4047

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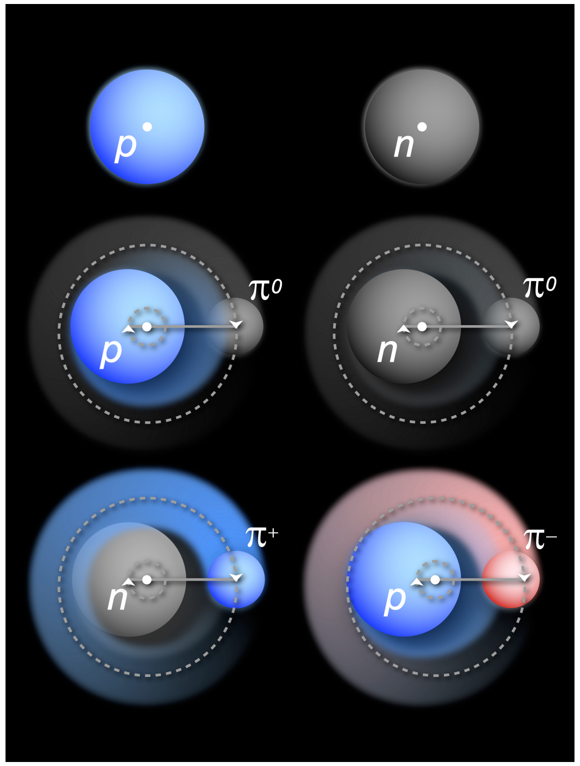

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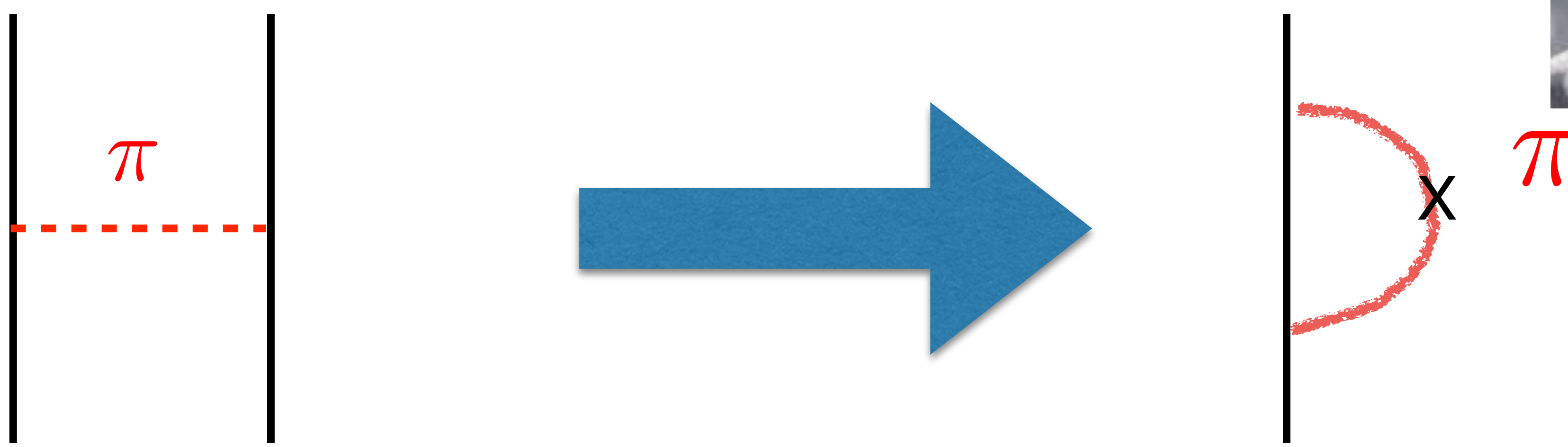
Arrington arXiv:1208.4047

Ancient History

NN force

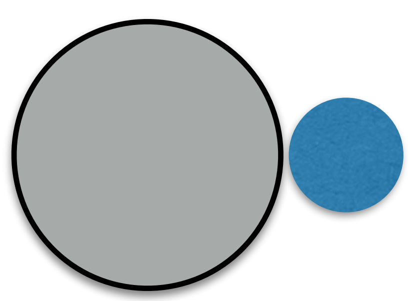


H. Yukawa

Longest range component

Pion cloud

Fundamental Question: meson cloud or $4q\bar{q}$

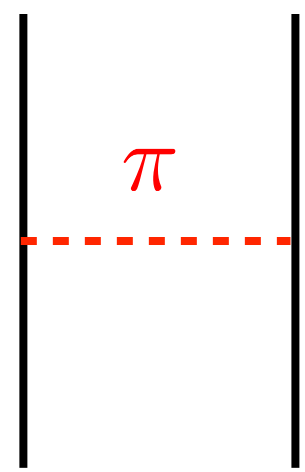


Hidden color

Important implications for nuclear force and nuclear structure if meson cloud picture is shown to fail

Ancient History

NN force



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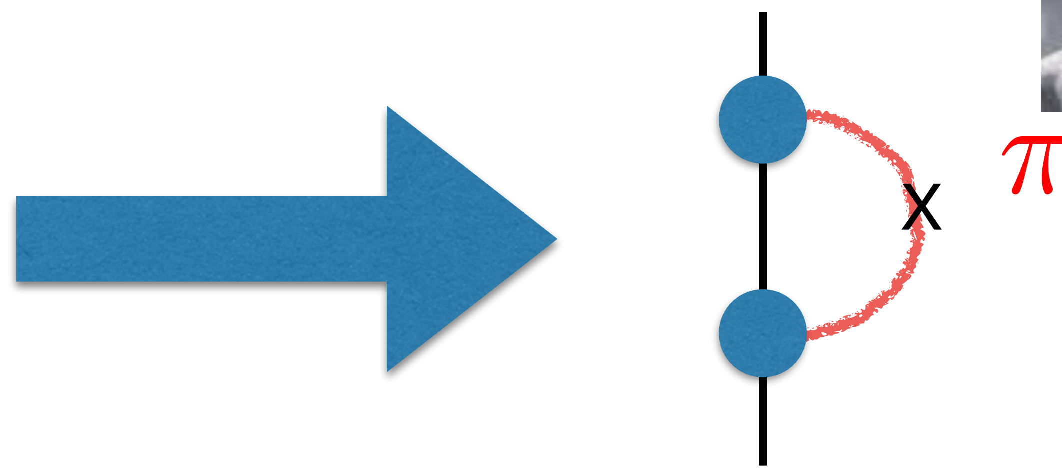


Pion cloud

H. Yukawa

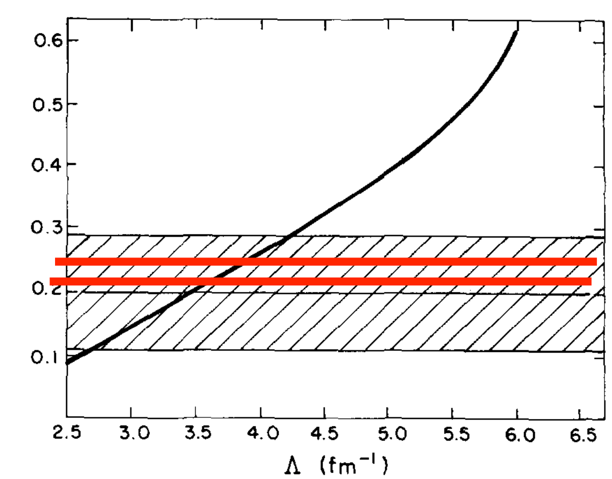
A W Thomas PLB 126, 97 (1983)

Wandmolders et al PRL 66,2712 (1991)

$$D \equiv \int_0^1 [\bar{d}(x) - \bar{u}(x)]\,dx = 0.136 \pm 0.060 \,. \quad 0.16 \pm 0.01$$

Henley & Miller PLB 251, 453 (1990)

$\frac{3}{2} D$



Implications for sea

$$p \to n\pi^+,\, p \to \Delta^{++}\pi^-, \cdots$$

$$\pi^+ \sim u\bar{d},\, \pi^- \sim d\bar{u}$$

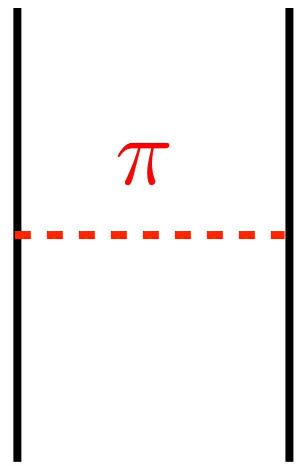
$$\text{Thus } \bar{d}(x) \neq \bar{u}(x)$$

Form factor $\exp\left(-k^2/\Lambda^2\right)$

Ancient History

H. Yukawa

NN force



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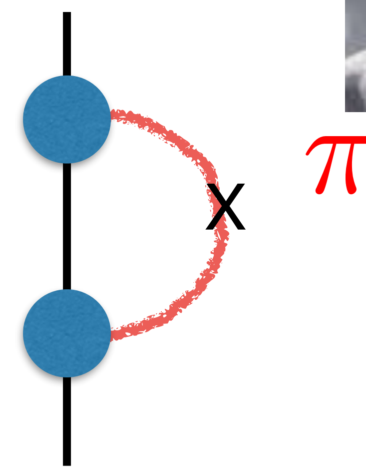

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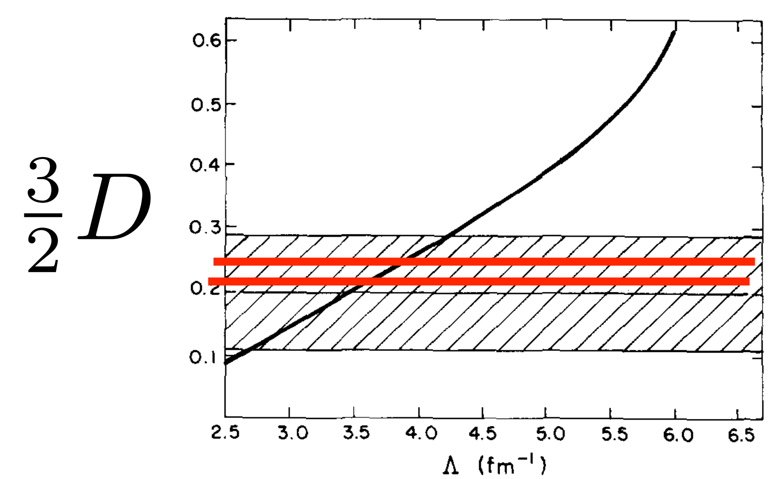
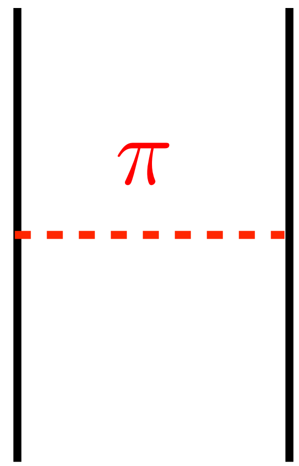


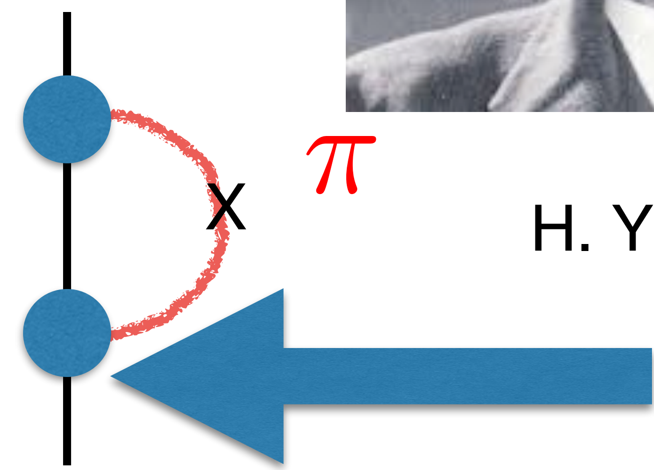
Form factor $\exp\left(-k^2/\Lambda^2\right)$

$$\Lambda \to R_{\pi N} = R_{\pi N}^{\text{experiment}} = 0.66 \text{ fm}$$

Ancient History

NN force





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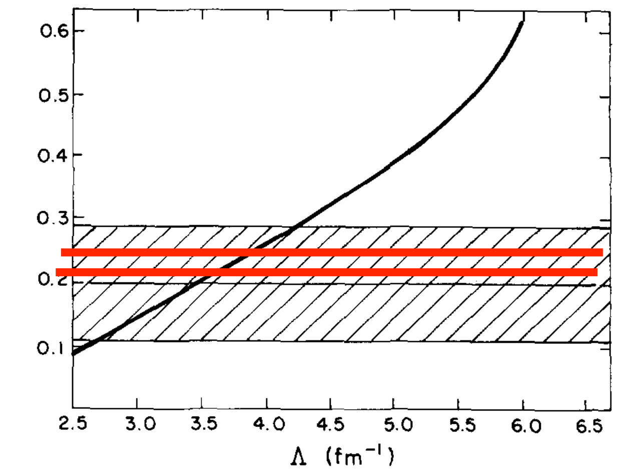

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Experimental Progress Drell-Yan

- NMC measured integral quantity for Gottfried sum
- E866 FermiLab measured x-dependence

J. C. PENG *et al.* PHYSICAL REVIEW D **58** 092004

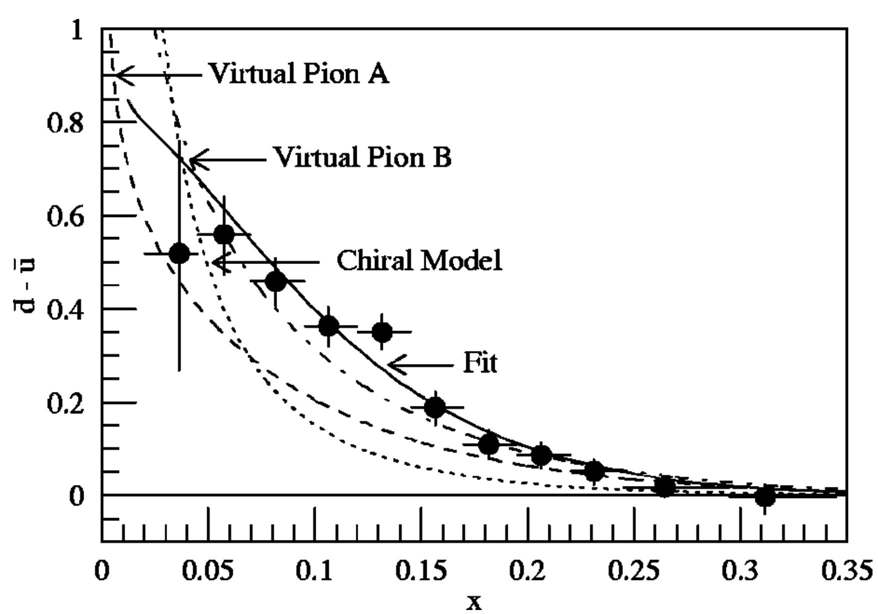
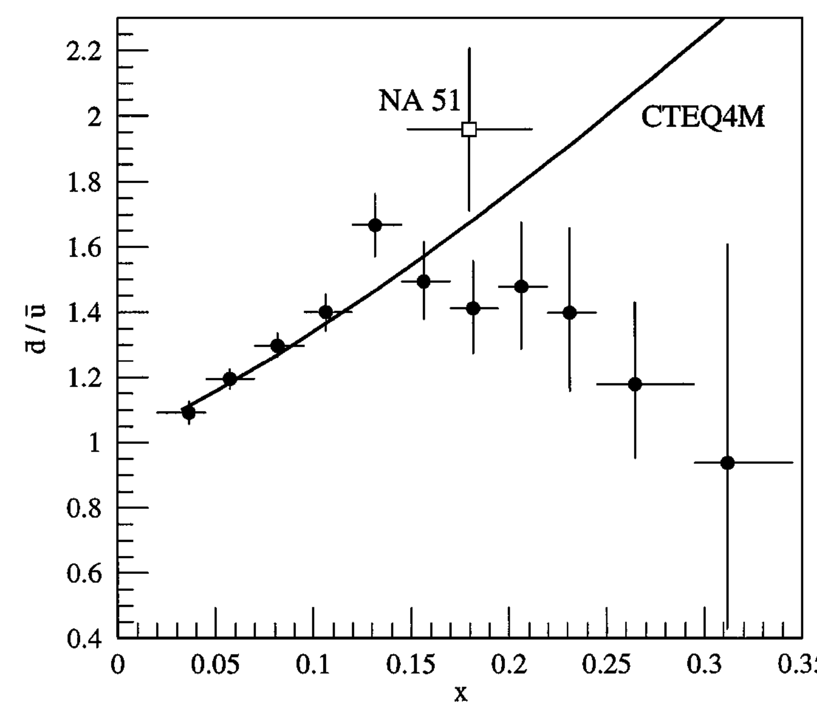


FIG. 1. Comparison of the E866 $\bar{d}-\bar{u}$ results at $Q=7.35$ GeV with the predictions of various models as described in the text.

$$\bar{d}(x) > \bar{u}(x) \text{ what about } \bar{d}/\bar{u}?$$

Expect large ratio at large x

Hawker et al PRL 80, 3715



More data- E866 (1999)

Drell-Yan Measured $\bar{d} - \bar{u}$ **and** $\frac{\bar{d}}{\bar{u}}$

Form factor

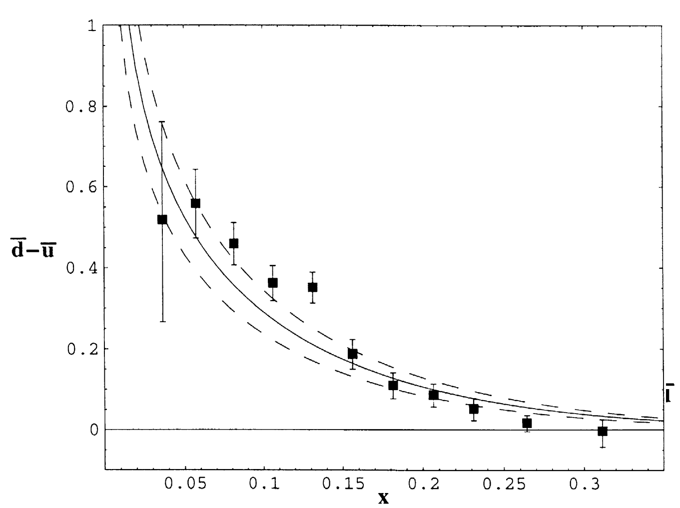
$$G_M(t,u) = \exp\left(\frac{t - m_M^2}{2\,\Lambda_M^2}\right)\exp\left(\frac{u - m_B^2}{2\,\Lambda_M^2}\right),$$

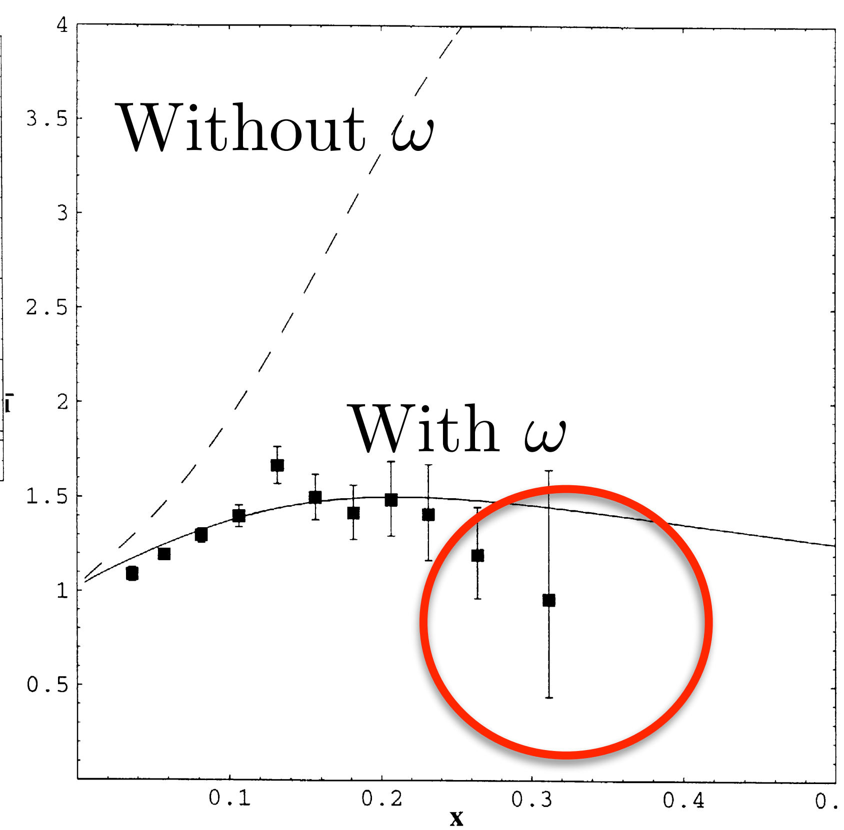
J. Speth, A.W. Thomas, Advances in Nuclear Physics, vol. 24, J.W. Negele, E.W. Vogt (Eds.), Plenum Press, New

Alberg, Henley and Miller PLB 471, 396 (2000)

With pions get too large a ratio $\frac{\bar{d}}{\bar{u}}$

Is there an isoscalar non-perturbative sea (omega meson)?





The omega represents any non-perturbative isoscalar sea

What's going on at high x?

SeaQuest aims at better measurement, so we try to improve

Theory problems

- Results depend on form factor parameter Λ
- form factors enter as three dimensional functions even though expressed in terms of t and u
- how to derive ????
- Why do we need form factors? Form factors oppose chiral perturbation theory

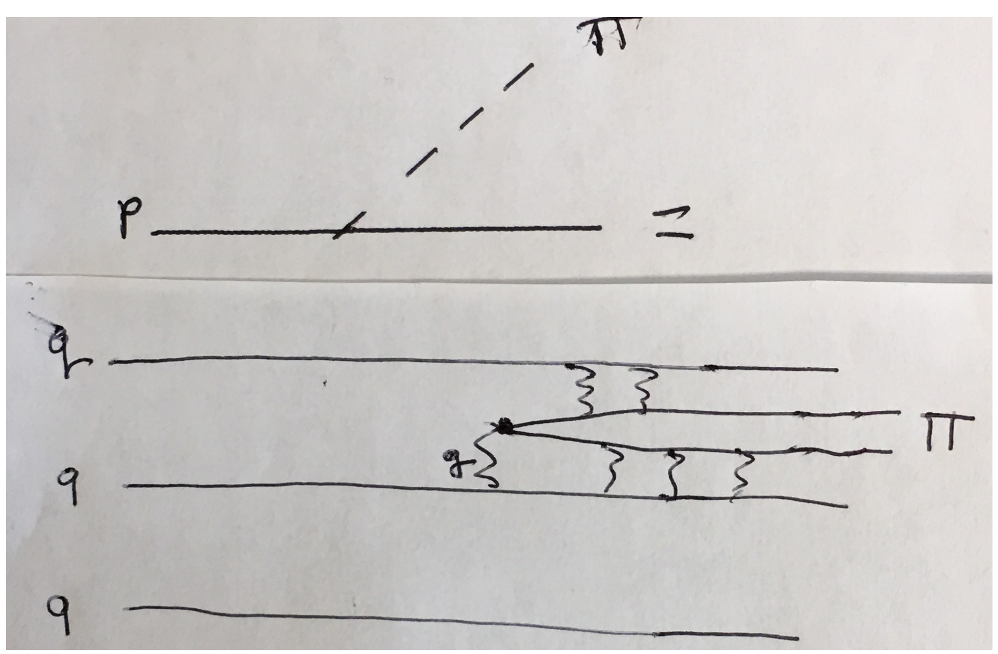
Why do we need form factors?

Using form factors opposes chiral perturbation theory

$$\mathcal{L}_N^{(1)} = \bar{\psi}(i\gamma \cdot \partial - M)\psi - \frac{g_A}{2f_\pi}\bar{\psi}\gamma_\mu\gamma_5\tau^a\psi\,\partial_\mu\pi^a - \frac{1}{f_\pi^2}\bar{\psi}\gamma_\mu\tau^a\psi\;\epsilon^{abc}\pi^b\partial_\mu\pi^c$$

Non-renormalizable $\mathcal{L}$, expand in powers of momentum
add counter terms order-by order -LECs.
results **INDEPENDENT OF CUTOFF** Not sufficient for DIS, IMHO because momenta $\mathcal{O} \sim m_N$

Form factor relates the LECs in a very specific way
different philosophy
Comment talk last week titled "$\cdots$ with chiral perturbation theory"
is **NOT** – no LEC's, but yes to cutoff dependence



pion-nucleon
Form factor takes composite nature of pion and nucleon into account

Taming I -Alberg & Miller PRL 108 (2012) 172001

Constrain form factor using experimental input info from Thomas and Weise book

$$q_\mu \langle p(P')|A_+^\mu(0)|n(P)\rangle = 2\bar{u}_p(P')\left[MG_A(Q^2) - \frac{Q^2 f_\pi g_{\pi NN}(Q^2)}{Q^2+m_\pi^2}\right]\gamma_5 u_n(P).$$

Thus the matrix element of the divergence of the axial current vanishes as $m_\pi^2 \to 0$ if $G_A(Q^2)$ and the pion-nucleon form factor $g_{\pi NN}(Q^2)$ are related by

$$MG_A(Q^2) = f_\pi g_{\pi NN}(Q^2). \qquad (3.10)$$

At $Q^2 = 0$ this is known as the Goldberger-Treiman relation and it is satisfied at the level of 3 % (with $g_A = G_A(0) = 1.267 \pm 0.004$, $g_{\pi NN} = g_{\pi NN}(0) = 13.2 \pm 0.1$ and $M =$

$$G_A(Q^2) = \frac{G_A(0)}{\left(1+\frac{Q^2}{M_A^2}\right)^2},$$

Exp.	M_A [GeV]
BNL	1.07 ± 0.06
ZGS	1.00 ± 0.05
Fermilab	$1.05\ ^{+0.12}_{-0.16}$
Average:	1.03 ± 0.04

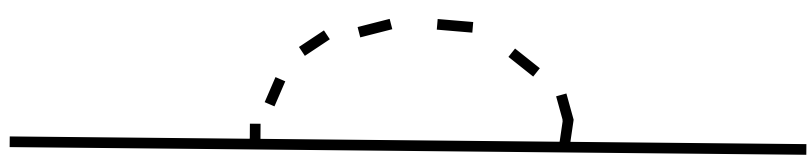
Pion-Nucleon form factor determined for on-mass-shell nucleons, off shell pion

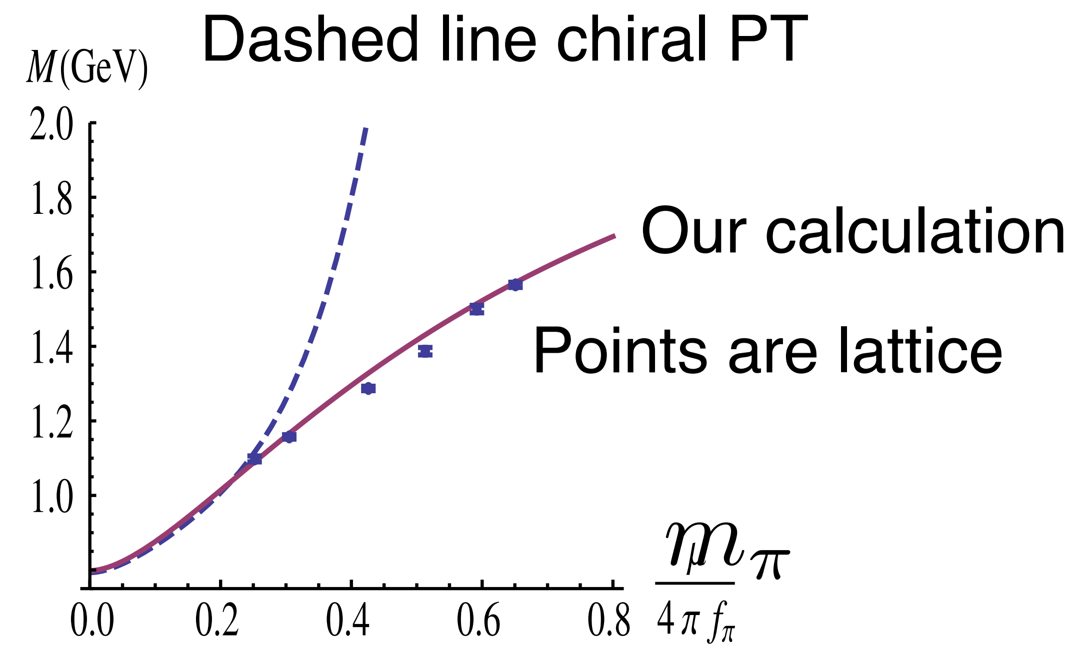
Taming I -Alberg & Miller PRL 108 (2012) 172001

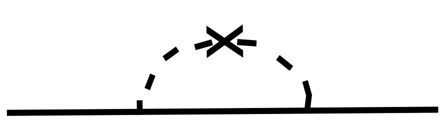
$$g_{\pi NN}(Q^2) \propto G_A(Q^2) = \frac{G_A(0)}{(1+\frac{Q^2}{M_A^2})^2}$$

Pion-Nucleon form factor determined for on-mass-shell nucleons, off shell pion

Nucleon self energy -intermediate nucleon and Delta







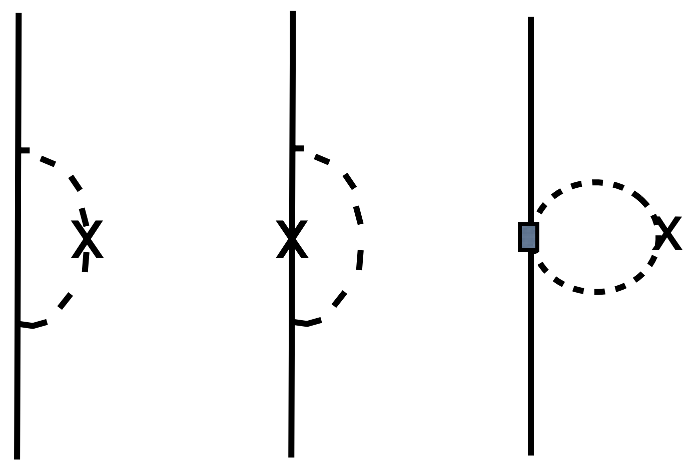
$$D \equiv \int_0^1 [\bar{d}(x) - \bar{u}(x)]dx = 0.118 \pm 0.012.$$

Ours 0.109

Parameter free calculation!
So what's the problem?

Taming II- recent

To get $\bar{u}$ and $\bar{d}$ need to calculate the graphs:



Both pion and nucleon are off-shell in the Feynman graphs
need to reconsider the formalism

$$q_N^f(x) = Z_2 q_{N0}^f(x) + \sum_{B,M} \int_x^1 \frac{dy}{y} f_{MB}(y) q_M^f(\tfrac{x}{y}) + \sum_{B,M} \int_x^1 \frac{dy}{y} f_{BM}(y) q_B^f(\tfrac{x}{y})$$

$$Z_2^{-1} - 1 = \sum_{B,M} \int dy f_{BM}(y),$$

Brodsky-Lepage Fock space representation:

$$|\pi N\rangle \propto \int_0^1 \frac{dy}{\sqrt{y}} d^2k_{\perp\pi} \int_0^1 \frac{dy_N}{\sqrt{y_N}} d^2k_{\perp N} \delta(1-y-y_N)\delta(\vec{k}_{\perp\pi}+\vec{k}_{\perp N})\psi_{\pi N}(y,\vec{k}_{\perp\pi};y_N,\vec{k}_{\perp N})|\cdots\rangle$$

$$f_{\pi N}(y) = \int d^2k_{\perp\pi} \left|\psi_{\pi N}(y,\vec{k}_{\perp\pi};1-y,-\vec{k}_{\perp\pi})\right|^2 = f_{N\pi}(1-y)$$

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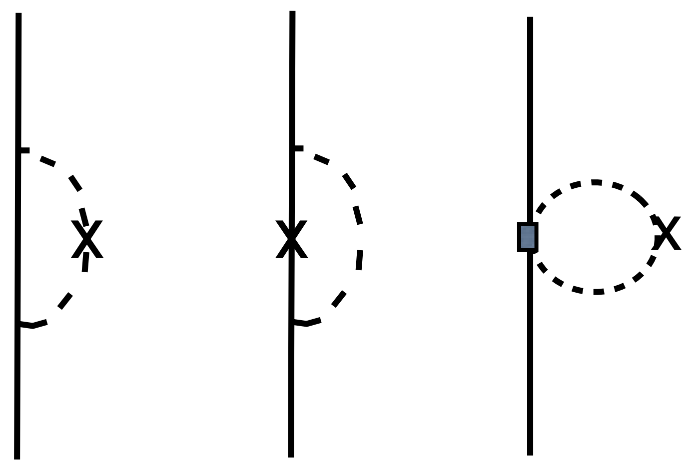

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$$Z_2^{-1} - 1 = \sum_{B,M} \int dy f_{BM}(y),$$

If f_{MB} has $\delta(y)$
Z_2 would change,
but **NO** delta functions here!

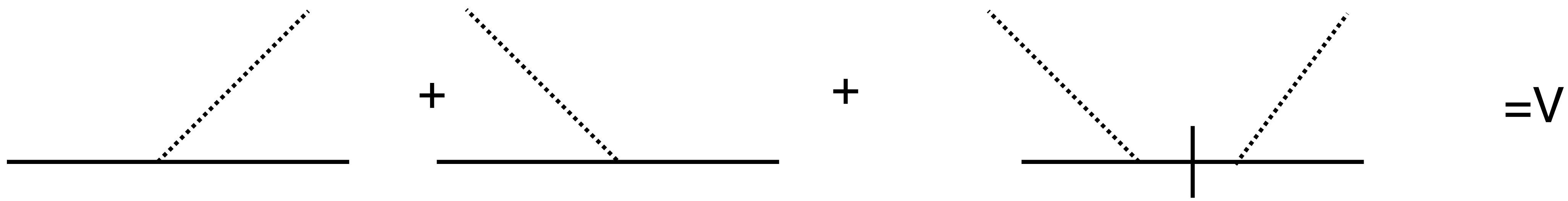
Brodsky-Lepage Fock space representation:

$$|\pi N\rangle \propto \int_0^1 \frac{dy}{\sqrt{y}} d^2k_{\perp\pi} \int_0^1 \frac{dy_N}{\sqrt{y_N}} d^2k_{\perp N} \delta(1-y-y_N) \delta(\vec{k}_{\perp\pi}+\vec{k}_{\perp N}) \psi_{\pi N}(y, \vec{k}_{\perp\pi}; y_N, \vec{k}_{\perp N}) | \cdots \rangle$$

$$f_{\pi N}(y) = \int d^2k_{\perp\pi} \left| \psi_{\pi N}(y, \vec{k}_{\perp\pi}; 1-y, -\vec{k}_{\perp\pi}) \right|^2 = f_{N\pi}(1-y)$$

Light front perturbation theory for chiral lagrangian G A Miller PR C56, 2789 **1997**

$\hat{P}^-$ is Hamiltonian operator, construct from energy-momentum tensor $T^{+-}=$ free particle kinetic energy M_0^2 plus interactions V



Schroedinger eq: $(\hat{P}^-\hat{P}^- - \hat{P}_\perp^2)|p\rangle = M_p^2|p\rangle = (M_0^2 + V)|p\rangle$

$$|p\rangle \approx Z_2\left(|p\rangle_0 + \frac{1}{M^2 - M_0^2} V|p\rangle_0\right)$$

$|\pi N\rangle$ component

$$\mathcal{L}_N^{(1)} = \bar{\psi}(i\gamma\cdot\partial - M)\psi - \frac{g_A}{2f_\pi}\bar{\psi}\gamma_\mu\gamma_5\tau^a\psi\,\partial_\mu\pi^a - \frac{1}{f_\pi^2}\bar{\psi}\gamma_\mu\tau^a\psi\;\epsilon^{abc}\pi^b\partial_\mu\pi^c$$

Form factors absent

Form factors

- Including form factors goes beyond usual LF treatment
- Need form factors in frame independent manner (4-space)
- Maintain momentum conservation, unique LF wave function
  Keep experimental input
- For use in light front wave function-virtual N, π
- Product of pion and nucleon form factors:

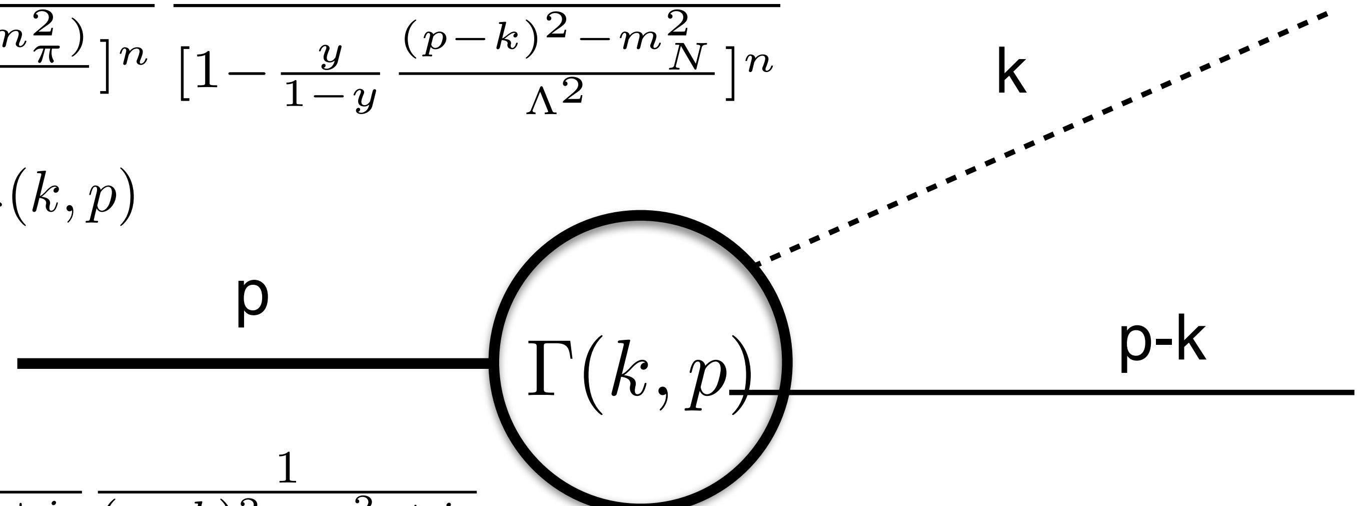
~Pauli-Villars reg.

$n =$ integer

$$F(k,p,y) = \frac{1}{[1-\frac{(k^2-m_\pi^2)}{\Lambda^2}]^n} \frac{1}{[1-\frac{y}{1-y}\frac{(p-k)^2-m_N^2}{\Lambda^2}]^n}$$

$$\psi_{LF} \propto \int_{-\infty}^{\infty} dk^- \psi_{\mathrm{Bethe-Salpeter}}(k,p)$$

$$\psi_{\mathrm{Bethe-Salpeter}}(k,p) =$$



$$\psi_{LF} \propto \int dk^- \Gamma(p,k) \frac{1}{k^2-m_\pi^2+i\epsilon} \frac{1}{(p-k)^2-m_N^2+i\epsilon}$$

Γ contains form factor.

Integrate over UH k^- plane = integrate over LH k^- plane w. stated form factor

$n = 1$ gives form factor very close to dipole, maintain experimental input!

Summary

- Have formalism to get light front wave functions and meson distribution functions needed for light flavor nucleon sea
- Meson-nucleon coupling constants are known
- Form factors included in frame independent manner that incorporates experimental input
- Given the meson cloud model can make calculations with reasonably-well understood uncertainties
- True test of meson cloud model!
- See Alberg's talk