Exploring the Role of Pions in the Nucleus

Dave Gaskell

Jefferson Lab

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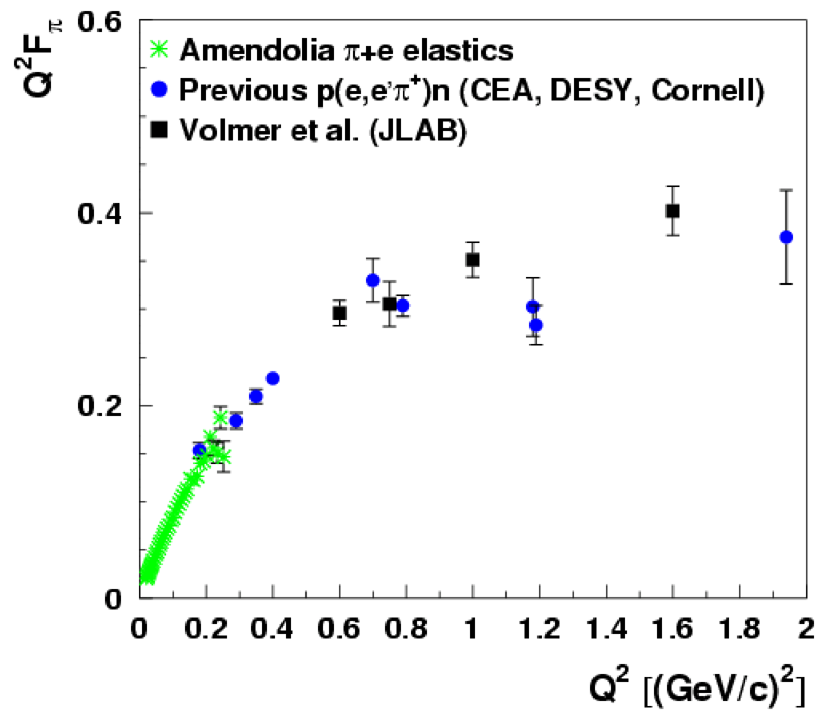
- Nuclear forces and "excess" pions
- The ambiguous experimental landscape
    - -> DIS and Drell-Yan results
    - -> (p,n) Reactions
    - -> Pion electroproduction
- New Directions

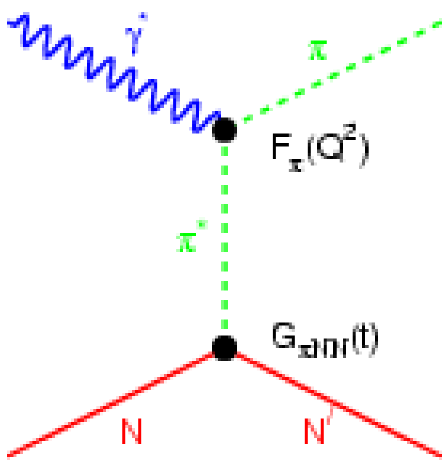
Pions as Constituents

- QCD describes strong interactions at the most fundamental level
  - hadrons (nucleons) are made of quarks and gluons
- However, cannot generate nucleon parton distributions from 3 quarks + Q^2 evolution
- A meson cloud is required to understand the structure of the nucleon
  - Nucleon axial current partially conserved
  - Ability to extract pion form factor from $H(e,e'\pi^+)$
  - Asymmetry of nucleon sea -> $\bar{d}/\bar{u}$

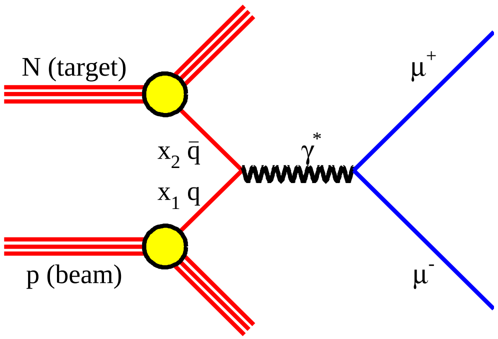
Charged Pion Form Factor from Pion Electroproduction

- No "free pion" target -> extraction of pion form factor at large Q2 requires use of "virtual pion" content of the proton
- Excellent agreement between π+e elastic data and $p(e,e'\pi^+)n$

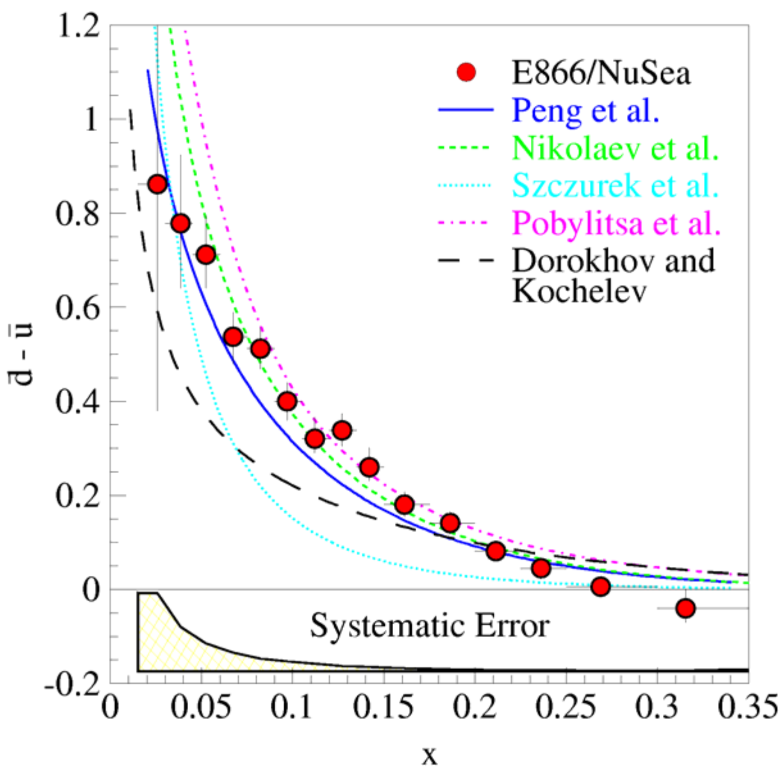




Sea-Quark Asymmetry from Drell-Yan



- Fermilab E866 measured D-Y cross section ratios $\sigma(p+d)/\sigma(p+p)$
- Extracted results for $\bar{d}-\bar{u}$ favor pion cloud models



J.C. Peng et al., Phys. Rev. **D58**, 092004 (1998)

Pions in "Conventional" Nuclear Physics

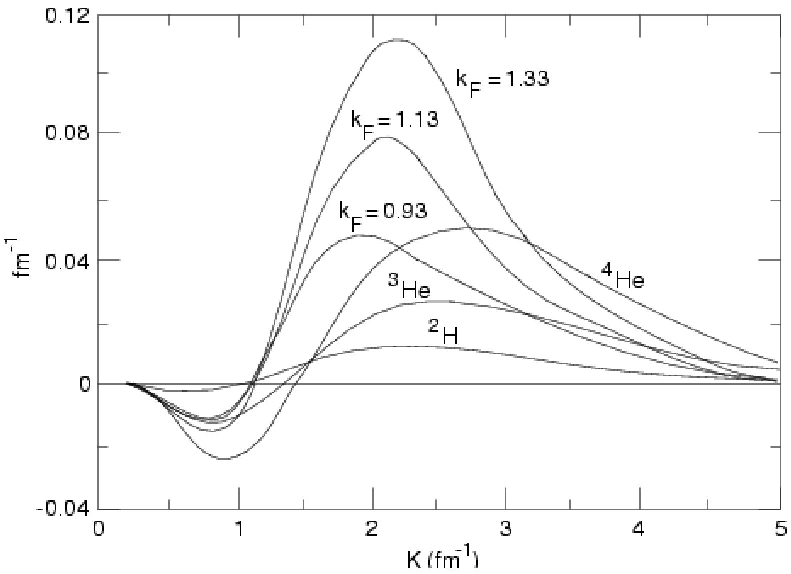
- Yukawa's initial insight -> π as carrier of strong force has proved remarkably durable
- Modern effective NN forces (Bonn, Argonne V-18) are significantly more complex, but the fundamental principle is the same
  - Employ additional mesons (ρ, etc.)
  - Form factors control pion contributions at short distances
  - 3N interactions?
- Effective NN forces work!
  - Green's Function Monte Carlo calculations accurately reproduce nuclear properties up to ^{12}C
  - Only limited by CPU
- These effective theories predict that there should be "extra" virtual pions in the nucleus

The Pion Excess and Pions in the Nucleus

- Using either mean field calculations or detailed N-N forces one can calculate a "pion excess" ->

$$\delta n_\pi^A(k) = n_\pi^A(k) - n_\pi^N(k)$$

- Friman et al. used Argonne v28 and found about 0.18 extra pions per nucleon in nuclear matter
- A significant portion of the excess arises from the $\pi N \Delta$ coupling -> with no Δ states only 0.04 "extra" pions



Pion excess $k^2\langle\delta n_\pi(k)\rangle / 2\pi A$
as a function of virtual pion momentum

Friman, Pandharipande, and Wiringa, PRL **51** 763 (1983)

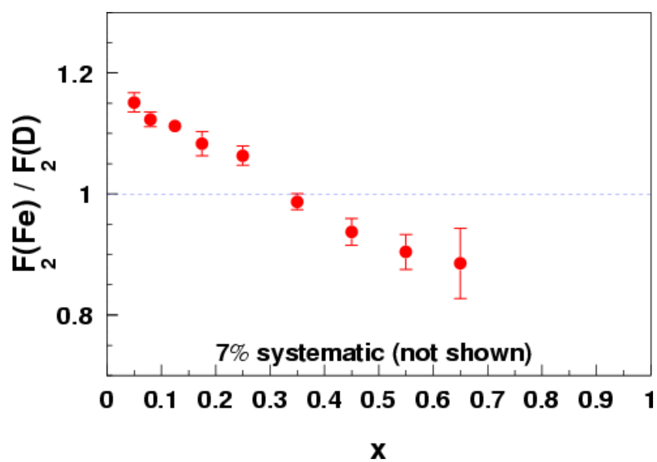
Accessing Pions in the Nucleus

- There is a clear indication that the pion cloud of the nucleon is real
- If we are able to access the nucleon pion cloud, we should also be able to access the nuclear pion cloud
- Experimental access to virtual pions in the nucleus
  - Deep Inelastic Scattering (EMC Effect)
  - Drell-Yan Reaction (antiquark distributions in the nucleus)
  - $(\vec{p},\vec{n})$ scattering (Nuclear Longitudinal Response)
  - Pion electroproduction (virtual pion knockout)

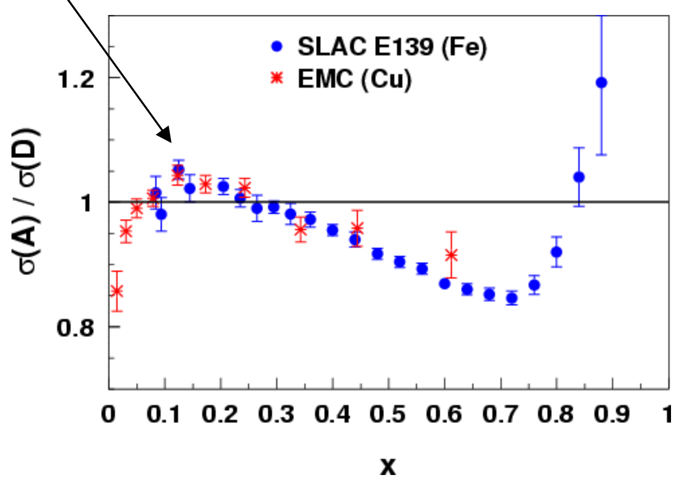
Deep Inelastic Scattering – the EMC Effect

- At large Q^2, $F_2(x,Q^2)$-> $F_2(x)$: scattering from constituents
- In pion model one can also scatter from constituents in pions exchanged between nucleons
- Original EMC result (1983) was initially interpreted in this manner
- Enhancement at x<0.2 is significantly smaller in later data

J. Aubert *et al*., Phys. Lett. B **123**, 275 (1983)



J. Ashman *et al*., Z. Phys. **C57**, 211 (1993)
J. Gomez *et al*., Phys. Rev. **D49**, 4348 (1994)



Berger-Coester Model of EMC Effect

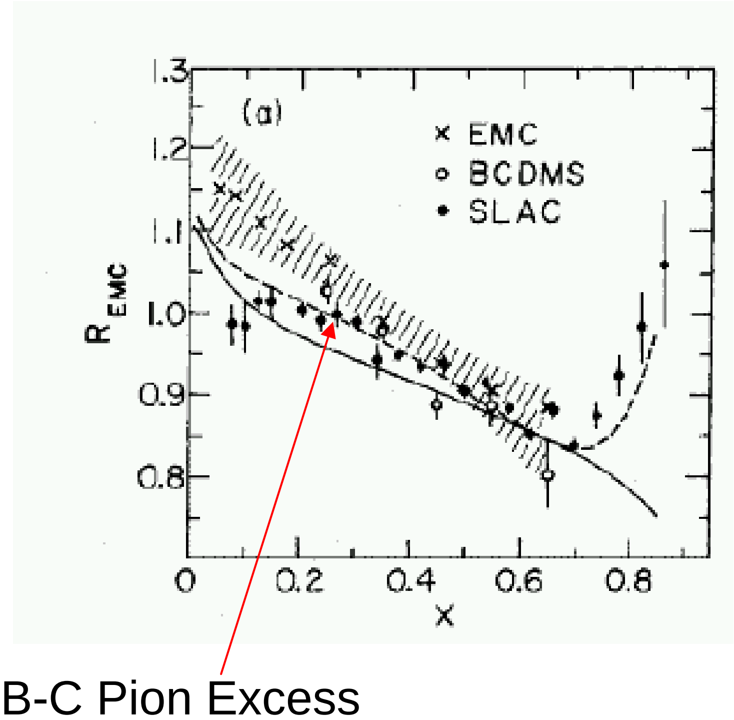
- Ericson and Thomas:
  - Pion distribution in nucleus, $f_\pi^A(y)$, calculated in terms of $R_L(q,\omega)$

$$f_\pi^A(y) = \frac{3g^2}{16\pi^2} y \int_{M_N^2 y^2}^{\infty} dk^2 \int_0^{k - M_N y} d\omega \frac{k^2 |G_{\pi NN}(k^2)|^2}{(t + m_\pi^2)^2} R_L(k,\omega)$$

- B-C calculations links $f_\pi^A(y)$ directly to pion excess

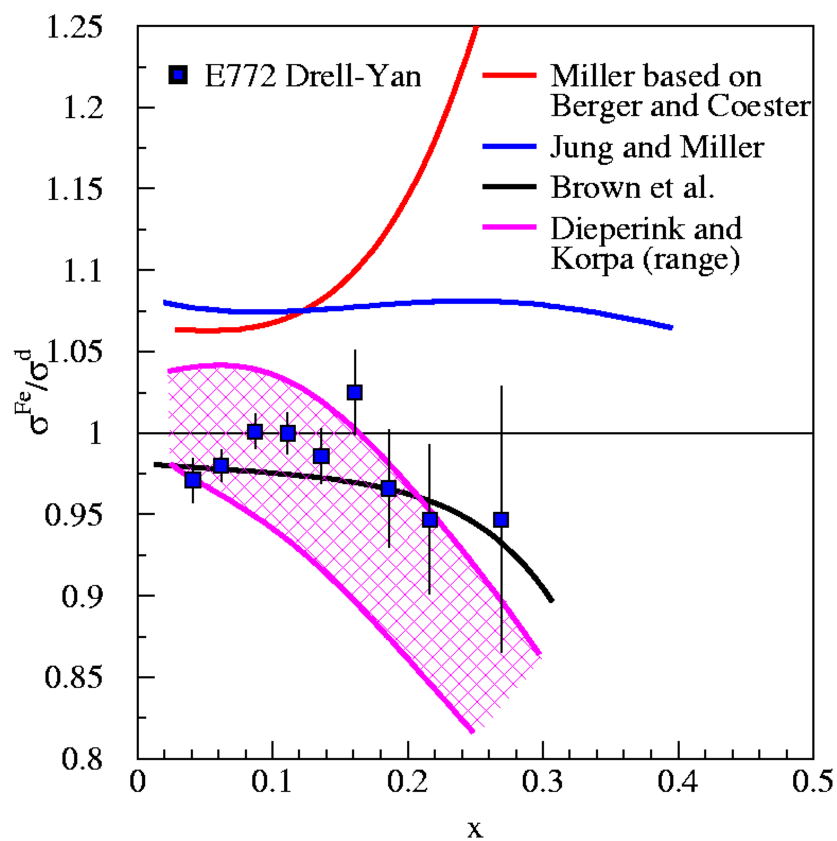
- Results agrees well with later EMC ratio results down to x~0.2

E. Berger and F. Coester, Phys. Rev. D32, 1071 (1985)



Nuclear Dependence of Drell-Yan

- Drell-Yan samples antiquark distributions in target
  - should be more sensitive than DIS to pion contributions
- E-772 (FNAL) measured the A dependence of Drell-Yan
- No apparent nuclear dependence
- Appears to rule out models that predict a significant pion excess

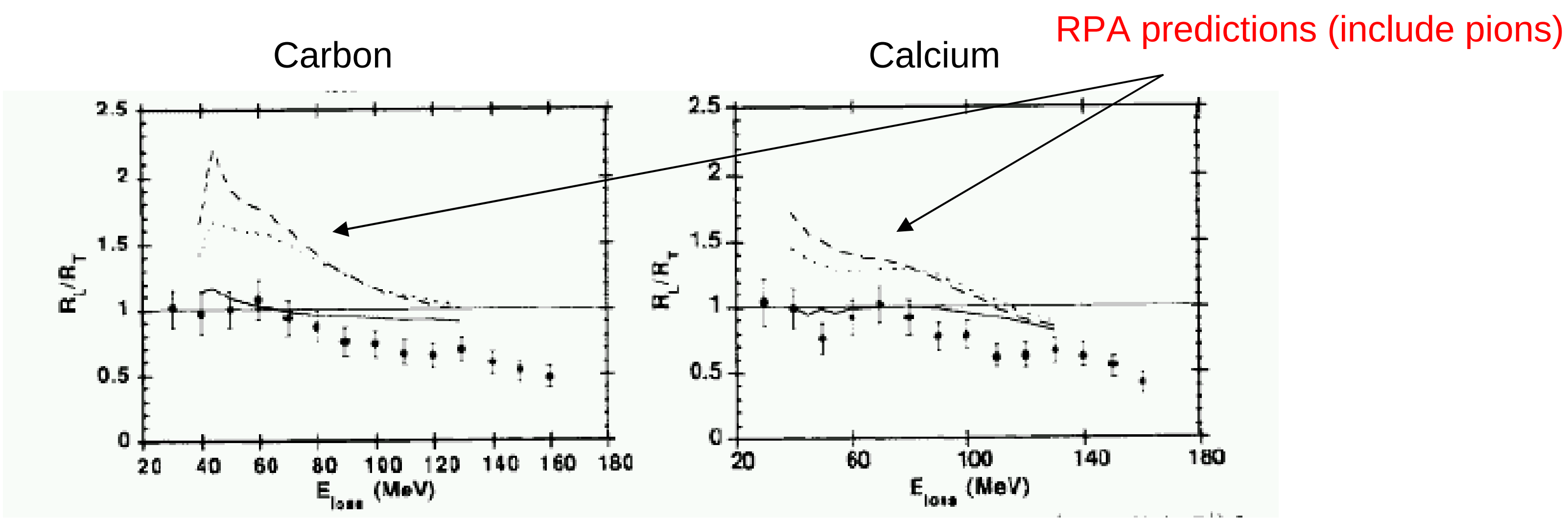


D.M. Alde *et al*., PRL **64** 2479 (1990)

Polarization Transfer Reactions

- Pion excess effects on F_2 and D-Y come about from enhancement of $R_L(q,\omega)$
- Rather than trying to extract pion excess effects via convolution integral, maybe simpler to measure $R_L(q,\omega)$ directly
- $(\vec{p},\vec{n})$ scattering directly sensitive to the isovector part of the nuclear response

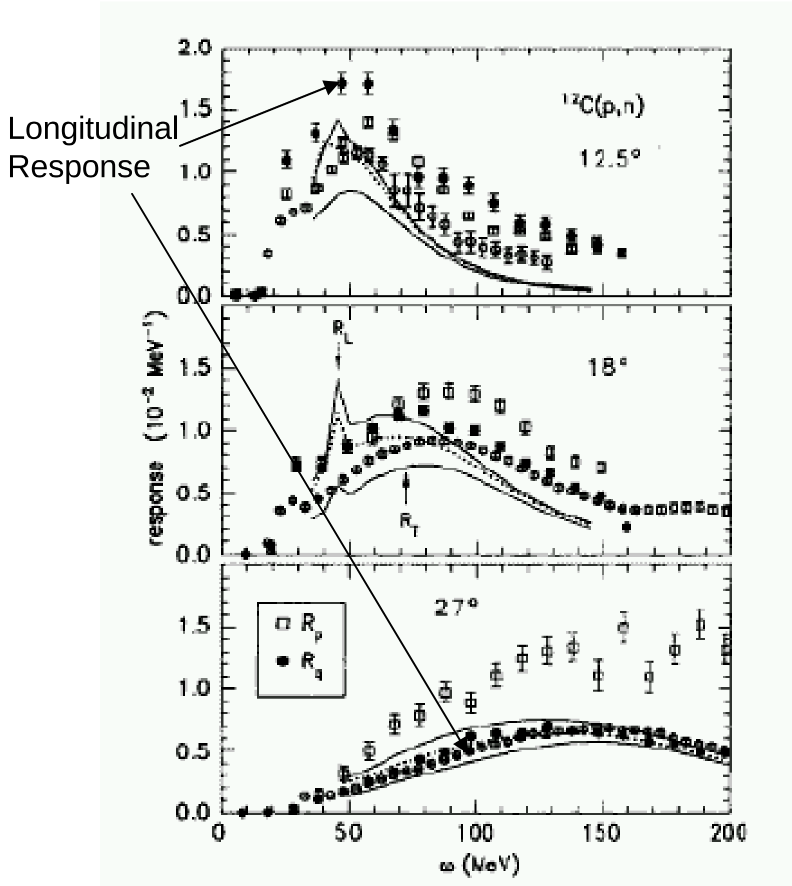
$$\frac{R_L}{R_T}$$



J. B. McClelleland et al., PRL **69** 582 (1992)

Separated Response Functions in Polarization Transfer

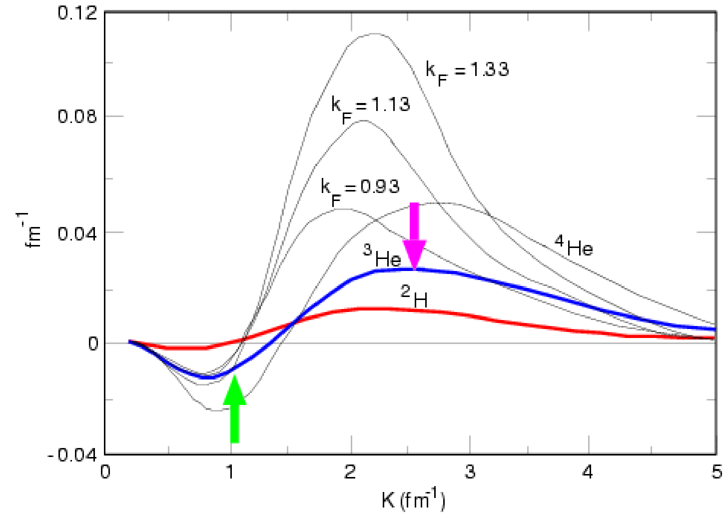
- Initial polarization transfer results inconsistent with RPA calculations that included pion excess effects
  - Only reported ratio of responses
  - No effect expected on R_T
- A later extraction of the separated response functions (R_L and R_T) hinted at an enhancement of both, but with large systematic errors

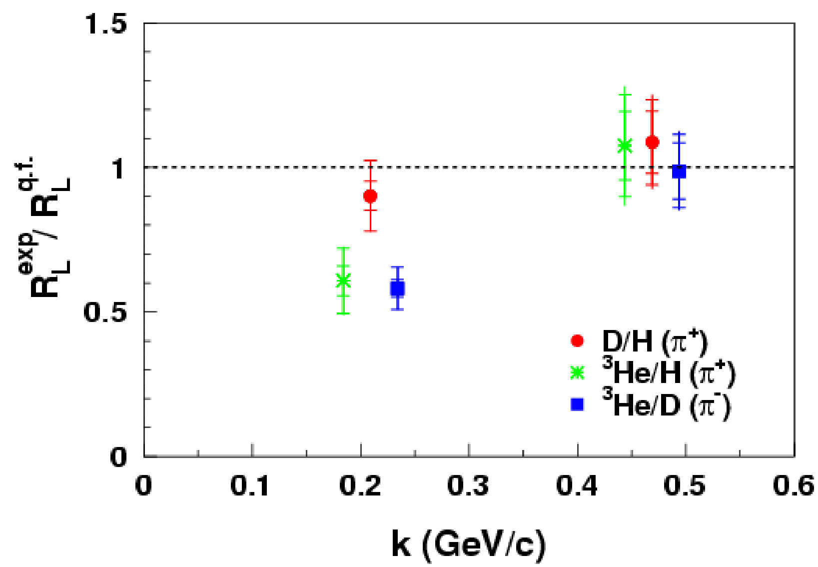


Taddeucci *et al.*, PRL **73** 3516 (1994)

Quasifree Pion Electroproduction

- Pole process dominates longitudinal cross section
  - Charged π production = virtual pion knockout
- JLab exp. E91003 measured charged π electroproduction from H,D and ^{3}He (^{4}He)
  - Extracted σ_L mass dependence
  - 2 values of virtual pion momentum sampled: k=200, 470 MeV/c
- Based on Friman et al. calculations, might expect up to 15% effects (25% for ^{4}He)
- Uncertainties are too large to confirm or rule out effects from excess pions



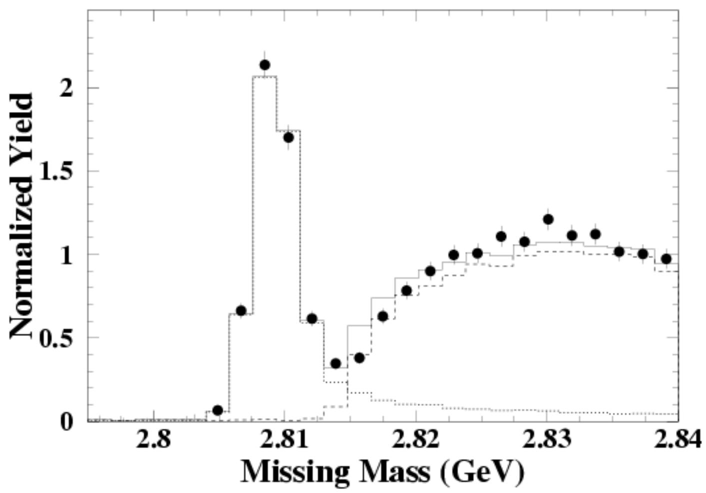


Coherent Pion Electroproduction

- Coherent $^3He(e,e'\pi^+)^3H$ process can also be used to probe pion field of nucleus
  - In a factorized approximation:

$$\sigma(^3H) = \rho F^2(k)\sigma(H)$$

  - F(k) is ^3He form-factor, ρ is kinematic factor
- Results from Mainz and Jlab E91003 hint at an enhancement of the longitudinal strength
  - E91003 compared directly ^3He to H directly
  - Mainz compared to DWIA calculation using MAID



E91003 $\sigma_L(^3H)/\sigma_L(H)$:
Prediction -> 0.42
Result -> 0.50 +/- 0.08

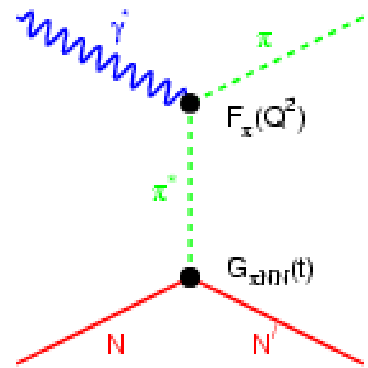
Mainz: σ_L 2x larger than DWIA calculation

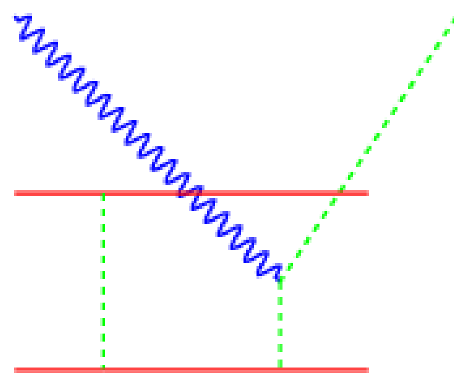
Nuclear Pion Scorecard

1. EMC effect: maybe
   - Calculations including pion excess can do a good job down to x ~ 0.2
   - These models predict significant effects in Drell-Yan scattering
2. Drell-Yan: no
   - All models including significant pion effects inconsistent with E772 data
   - A reduced pion content is allowed (G. Miller), but then convolution EMC calculations suffer
   - Not a problem if we're happy to introduce more exotic physics at moderate x (~0.2-0.6)
3. Polarization transfer: maybe
   - Separated response functions consistent with pion excess calcs., but large error bars
4. Pion Electroproduction: maybe
   - Quasifree production needs smaller errors and ^{4}He
   - Coherent production tantalizing, but not really conclusive

Pions are in Nucleons – What About Nuclei?

- There are experimental indications that the pion cloud plays a significant role in nucleon structure
- Why can we not see similar effects in nuclei?
- Either we need totally new probes, or we're misusing the probes we have



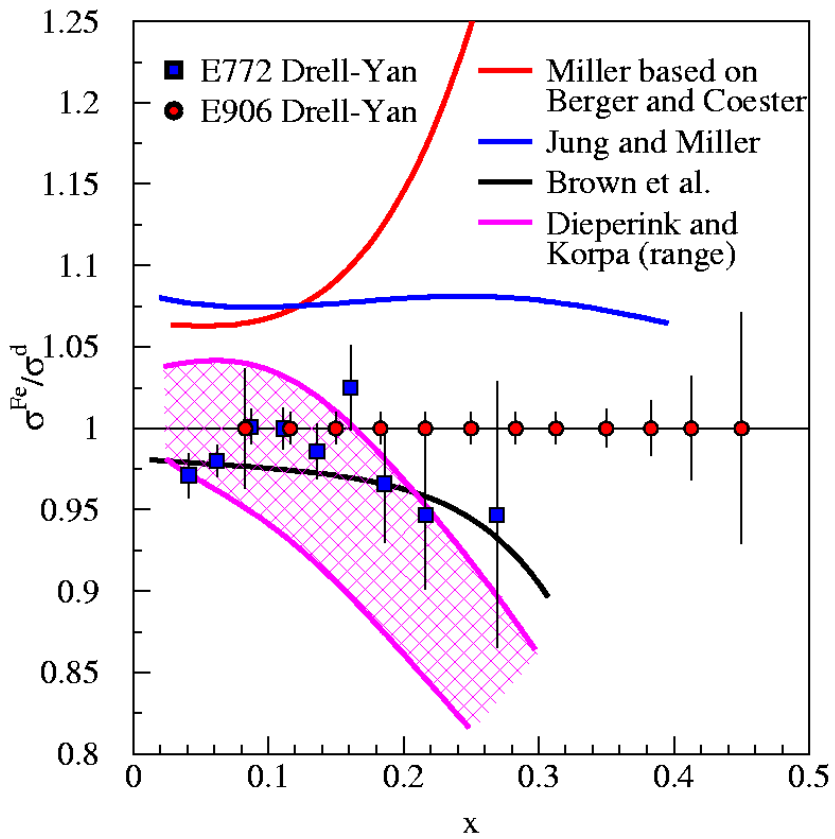


New Directions

- If pion excess leads to enhancement of antiquark distributions and we can't see that at low x, maybe we need to go higher?
  - Drell-Yan at higher x
    - Fermilab E906 will measure Drell-Yan at larger x
  - Separated inclusive cross sections
    - G. Miller predicts large effects for the A-dependence of σ_L at moderate x (~0.4)
- JLab at 12 GeV
  - (EMC Effect at large x)
  - Semi-inclusive production
  - More exclusive and semi-exclusive pion electroproduction

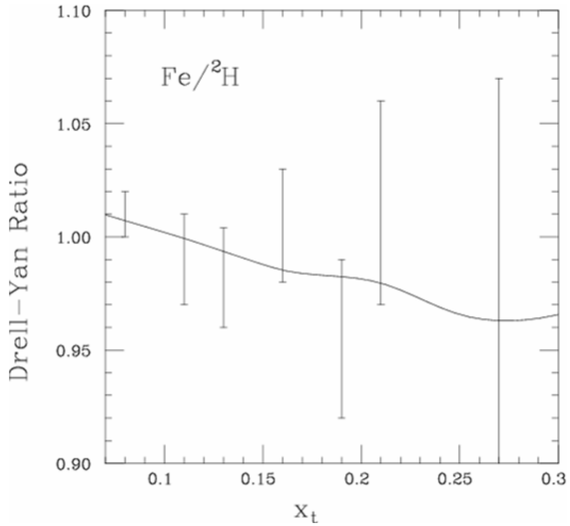
Fermilab E906

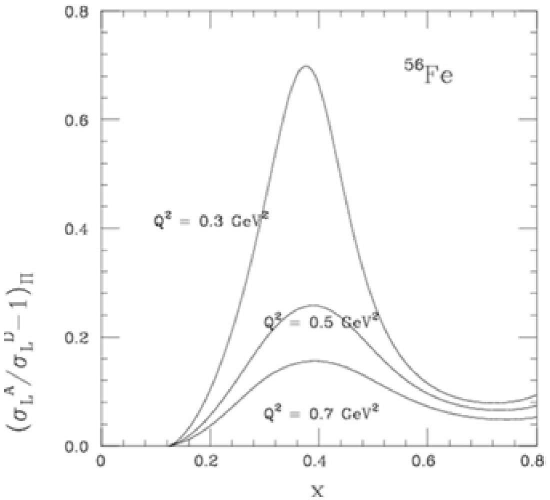
- Approved Fermilab E906 will extend precision and x-range of E772 Drell-Yan measurements
- If B-C model has correct trend but wrong absolute value, should be able to discern by going to larger x
- Date of E906 run still TBD



Inclusive Electron Scattering

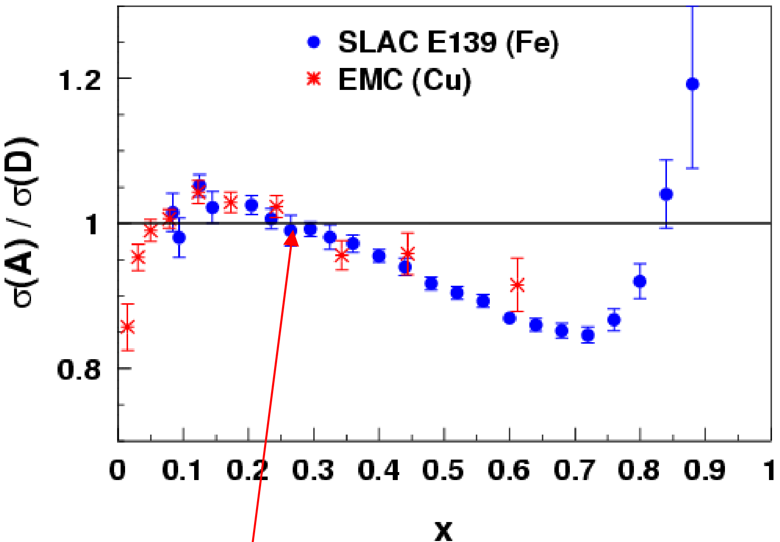
- G. Miller light front calculation predicts large effects in the inclusive, longitudinal cross section
- Accurately reproduces existing D-Y data -> requires rather modest pion excess (~0.05/nucleon)
- JLab E02-109 and E04-001 will measure L-T separated cross sections where effect predicted to be large
- E91003 measured exclusive pion production at Q2=0.4, x=0.48 and saw no indication of such large effects – ^{3}He not heavy enough?

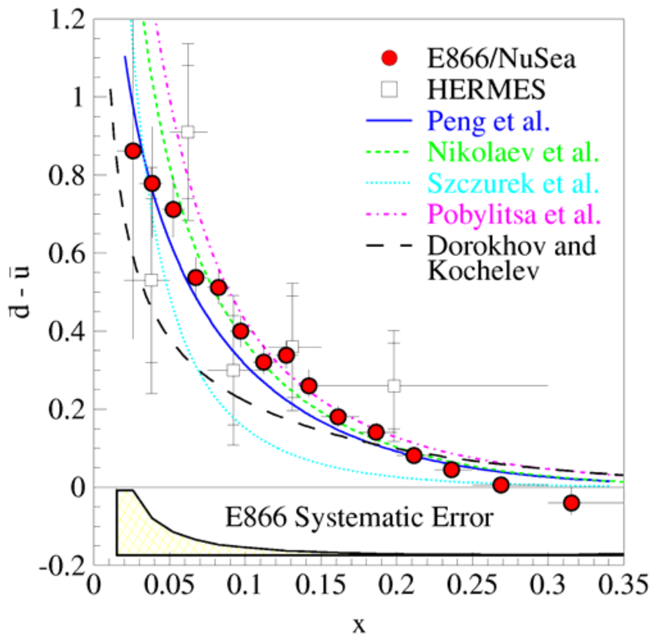




G. Miller, Phys. Rev. C64, 022201 (2001)

Semi-inclusive Production from Nuclei





- Explore ν and z dependence of hadronization effects at x ~0.3 (no EMC effect)
- Use semi-inclusive meson production to explore flavor specific EMC effect or nuclear dependence of sea asymmetry

Nuclear Response at Large Virtual Pion Energies

- Size of the pion excess can be related to the spin-isospin longitudinal nuclear response

$$\delta n_\pi^A(k) = \frac{f^2 F^2(k)}{2\varepsilon_k} \int_0^\infty d\omega \frac{R_L(k,\omega)}{[\varepsilon_k + \omega]^2} - n_\pi^N(k)$$

- In NN correlated theory, much of the excess pion strength appears at large virtual pion energy, ω -> D. Koltun, Phys. Rev. C **57**, 1210 (1998)
- Large ω contributions suppressed in the convolution integrals used for calculating light-cone pion distribution in nuclei

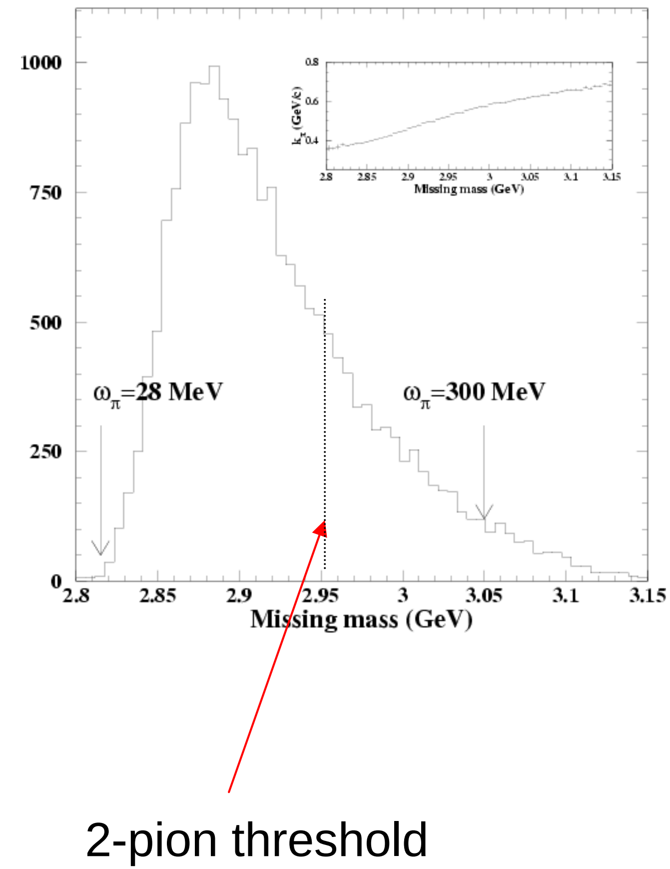
$$f_\pi^A(y) = \frac{3g^2}{16\pi^2} y \int_{M_N^2 y^2}^{\infty} dk^2 \int_0^{k - M_N y} d\omega \frac{k^2 |G_{\pi NN}(k^2)|^2}{(t + m_\pi^2)^2} R_L(k,\omega)$$

- Pion electroproduction at large missing mass (z<1) can probe the longitudinal response at large ω

(Semi-) Exclusive Pion Electroproduction

- In parallel kinematics, exclusive pion electroproduction from nuclei samples a contour in virtual pion energy and momentum space
- If restricted to exclusive production (below 2-pion threshold) will never measure large ω
- Must map out transition between semi-inclusive and exclusive nucleon/deuterium (longitudinal and transverse!)
- Compare z<1 in nuclei to calculations that include
  1. Quasifree pion production
  2. z<1 pion production from nucleon

Missing mass spectrum for (quasifree) π^- production from ^{3}He



Pion Electroproduction at 12 GeV

- Advantages of 12 GeV JLab for pion electroproduction search for nuclear pions
  - At z<1, higher energies will reduce resonance effects in residual system -> simplify model calculation of quasifree+fragmentation(?) components of electroproduction cross section in nuclei
  - At higher energies, color transparency may allow us to use heavier nuclei. Currently limited to light nuclei (^3He, ^4He) because of pion re-scattering effects

Summary

- Pions seem to be an intrinsic, non-perturbative part of nucleon structure
- Conventional pictures of the strong force at large and medium distance scales require pions to be the force "carrier"
- These theories predict that there should be "extra" pions in the nucleus
- To date, there is no convincing experimental evidence these "nuclear pions" have been observed
- JLab at 12 GeV
  - EMC Effect at large x
  - Semi-inclusive studies
  - L-T separated exclusive and semi-inclusive cross sections