Observing Flavor Dependence of the EMC Effect through Parity Violation

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U.S. DEPARTMENT OF ENERGY
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Argonne NATIONAL LABORATORY

SoLID SOLENOIDAL LARGE INTENSITY DEVICE

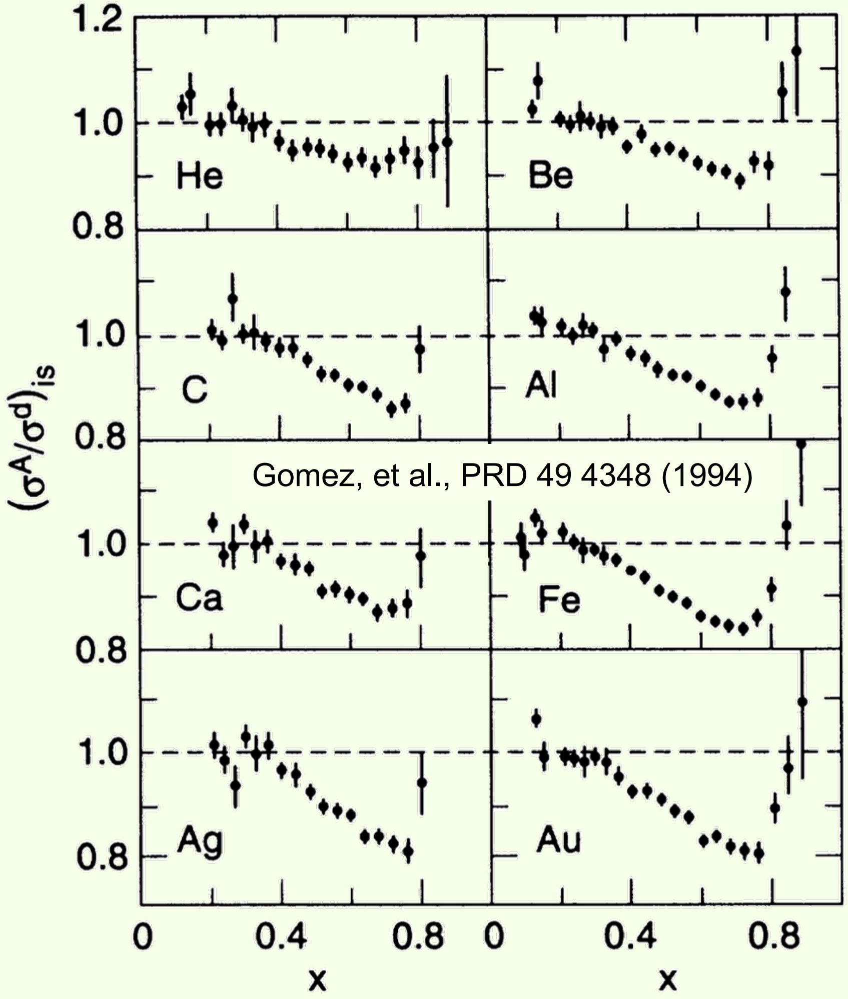
PROBING THE EMC EFFECT

What we know: (See T. Hague's talk)

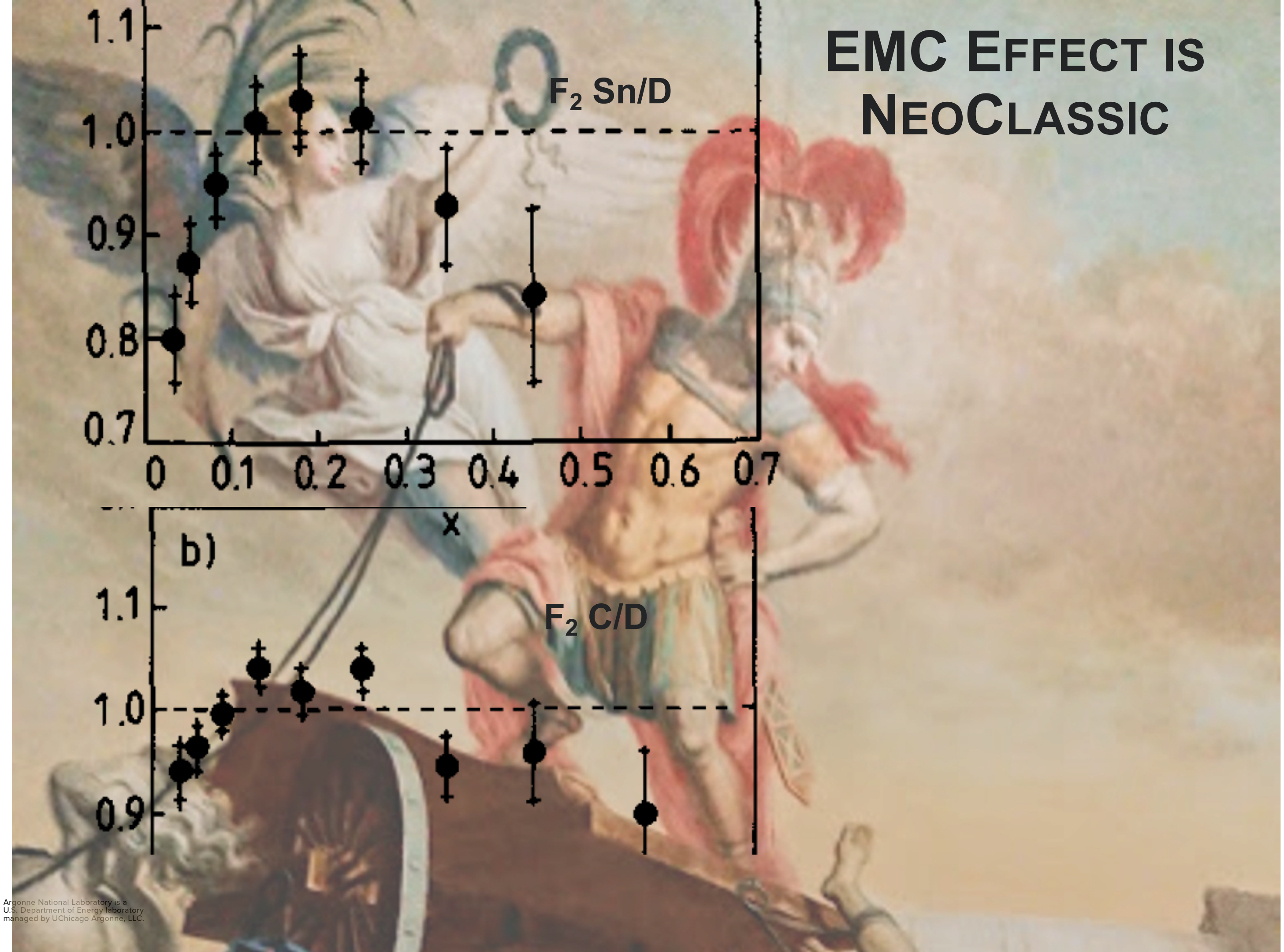
- Parton distributions in nuclei are different

$$R^A(x,Q^2) = \frac{F_2^A(x,Q^2)}{ZF_2^p(x,Q^2)+NF_2^n(x,Q^2)} \neq 1$$

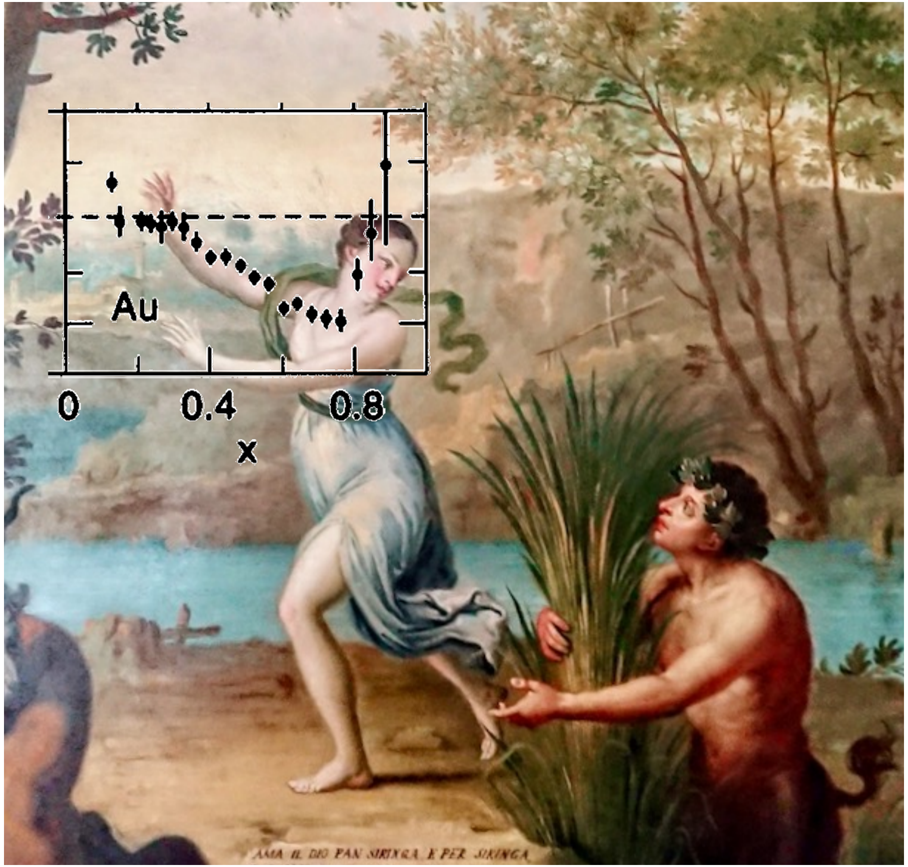
- Local density and SRC appear to be important
- Appears to follow a universal curve

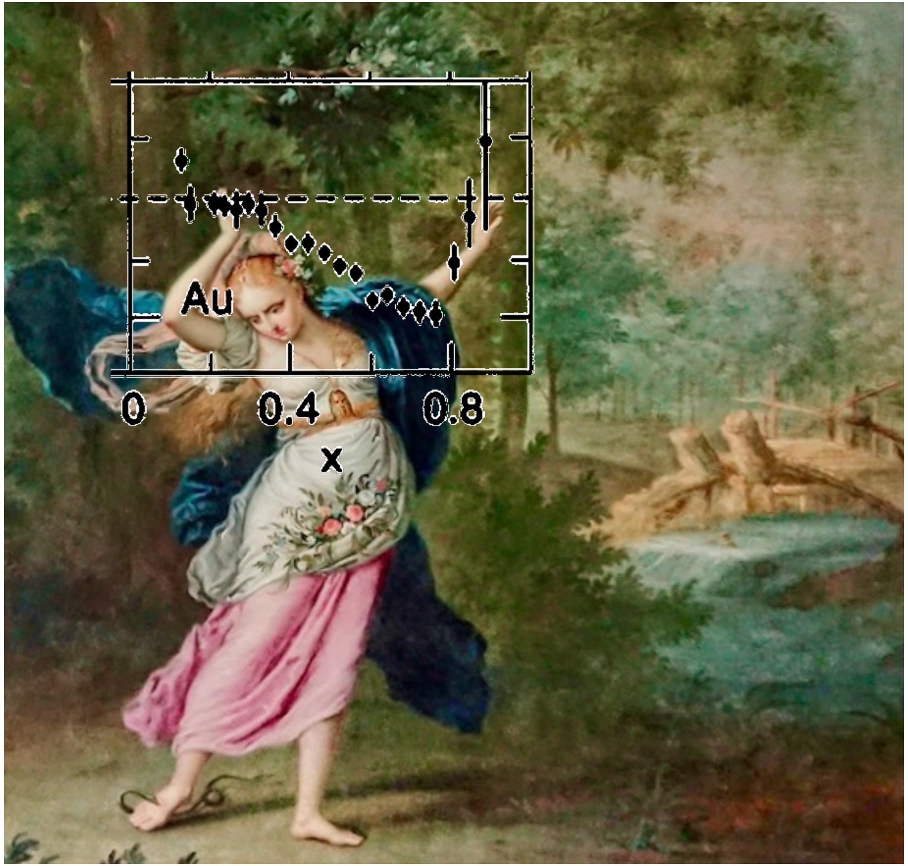


EMC Effect is NeoClassic



EMC Shape Predicted in Art at ECT*





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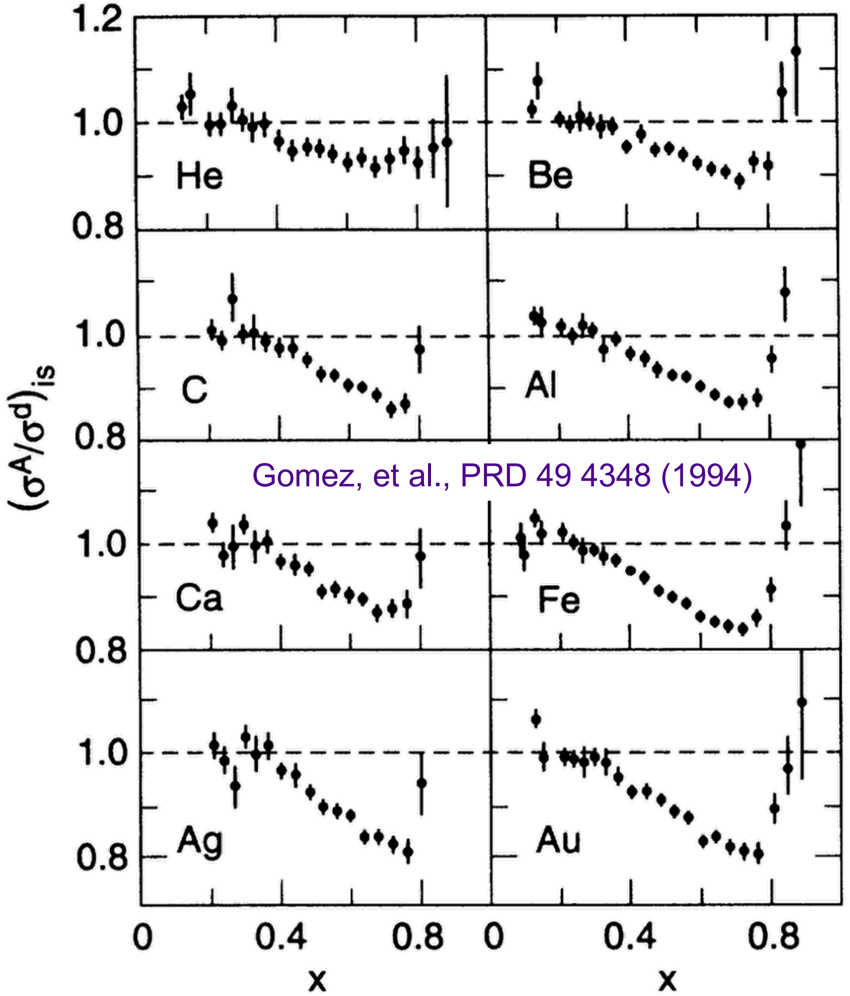
- **Why** does the effect exist at all?
  Strongly interacting particles in residual strong field



Gomez, et al., PRD 49 4348 (1994)

Probing the EMC Effect

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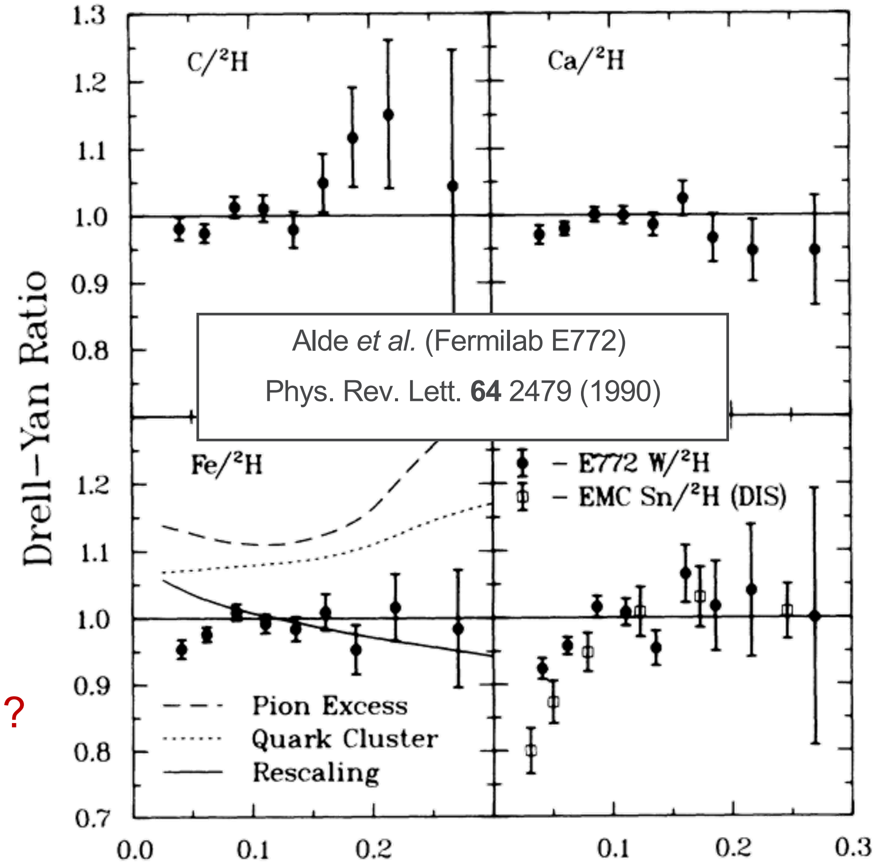
- Is the effect in **sea quarks** absent? Or enhanced?



Alde *et al.* (Fermilab E772)

Phys. Rev. Lett. **64** 2479 (1990)

Probing the EMC Effect

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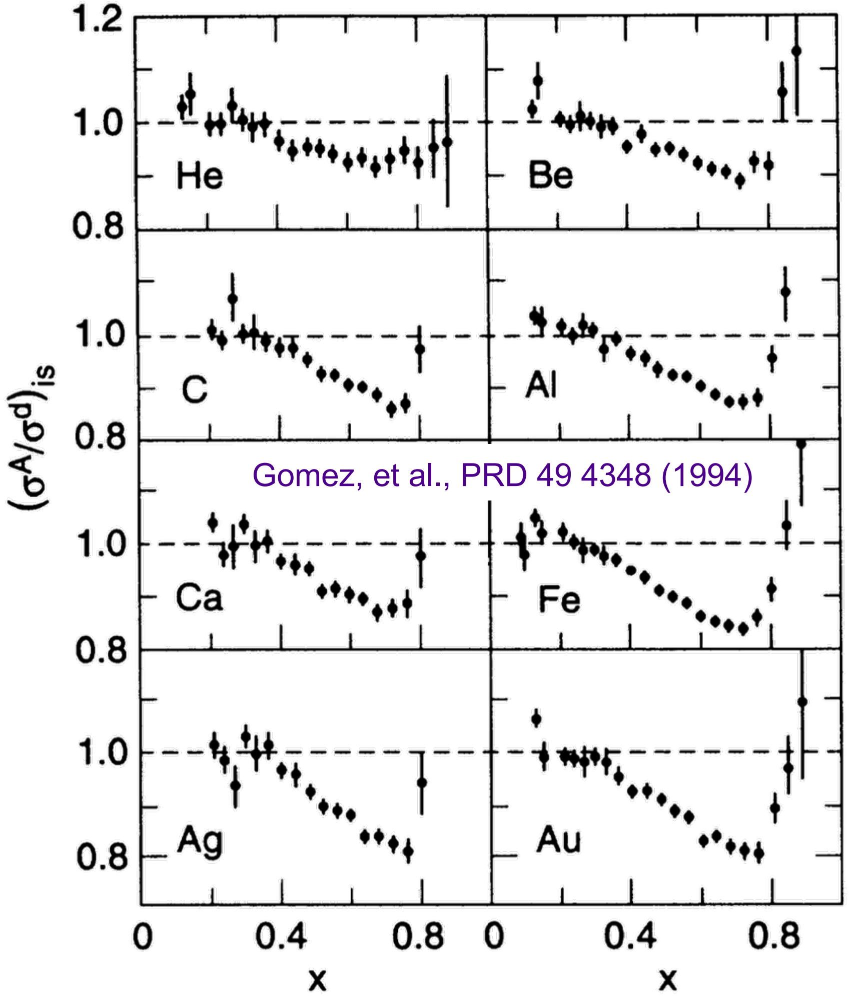
What we don't know:

- **Why** does the effect exist at all?
  Strongly interacting particles in residual strong field
- Is the effect in **sea quarks** absent? Or enhanced?
- Is it **flavor** dependent?
  c.f. Cloët, Bentz, and Thomas
- . . .



Flavor Dependent EMC

- Most models of the EMC effect assume that the effect is flavor blind:

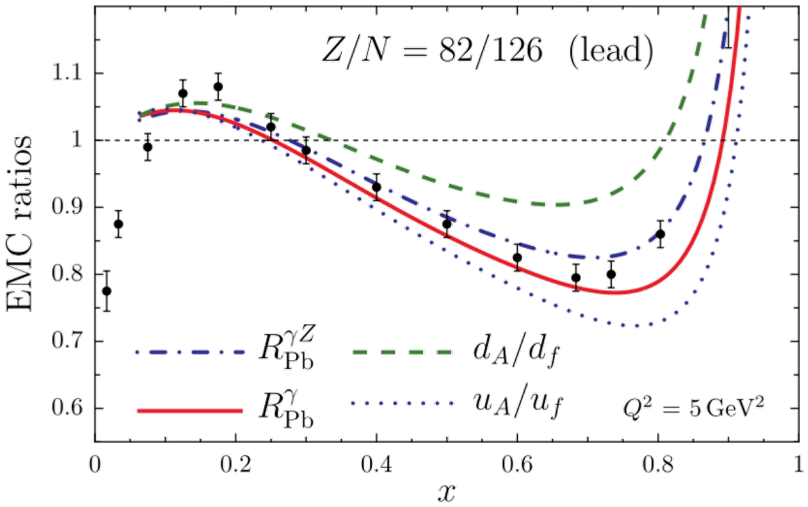
$$\frac{u_A(x)}{u_f(x)} \equiv \frac{d_A(x)}{d_f(x)}$$

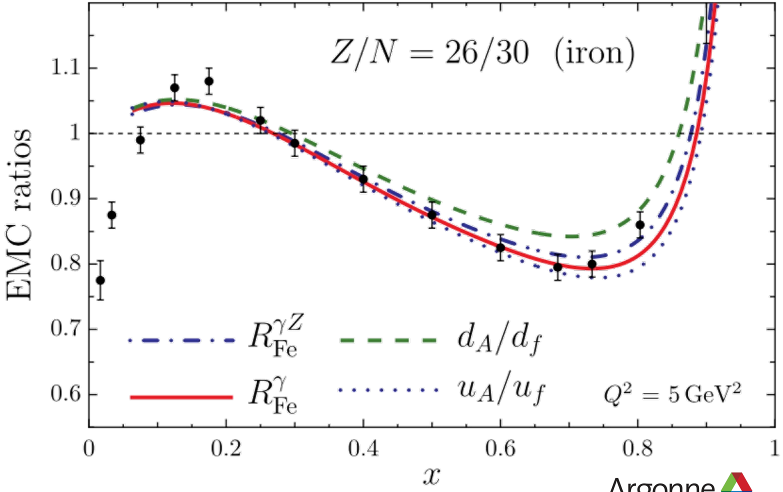
- **This symmetry is not demanded by any underlying physics!**

Flavor Dependent EMC—Cloët, Bentz, and Thomas

General idea

- For N ≠ Z there is a small **isovector-vector** mean field, ρ^0
- Additional vector
  - attraction for u-quarks
  - repulsion for d-quarks





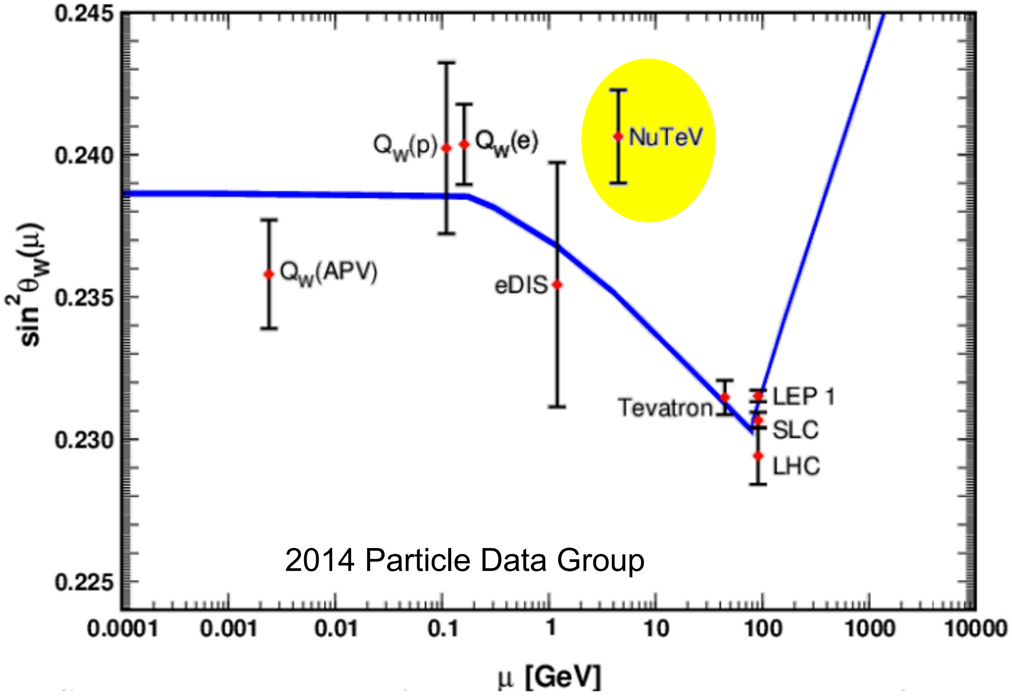
Cloët et al., PRL 109, 182301 (2012)
Cloët et al., PRL 102, 252301 (2009)

NuTeV

Standard Model test

- Pachos-Wolfenstein (PW) relationship

$$R_{PW} = \frac{\sigma_{NC}^{\nu A} - \sigma_{NC}^{\bar{\nu} A}}{\sigma_{CC}^{\nu A} - \sigma_{CC}^{\bar{\nu} A}} \xrightarrow{N=Z} \frac{1}{2} - \sin^2\theta_W$$



- Extremely difficult experiment
- Fe target (needed high density since ν's don't interact).
- This flavor dependent EMC (*if it exists*) can explain about 1.5σ of the observed approx. 3σ discrepancy

Cloët et al., PRL 109, 182301 (2012)
Cloët et al., PRL 102, 252301 (2009)

Parity NonConservation and Electron Scattering

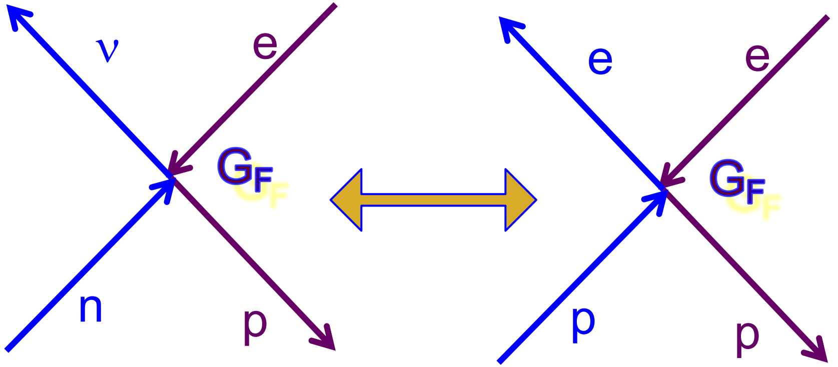
LETTERS TO THE EDITOR

PARITY NONCONSERVATION IN THE FIRST ORDER IN THE WEAK-INTERACTION CONSTANT IN ELECTRON SCATTERING AND OTHER EFFECTS

Ya. B. ZEL' DOVICH

Submitted to JETP editor December 25, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) 36, 964-966 (March, 1959)

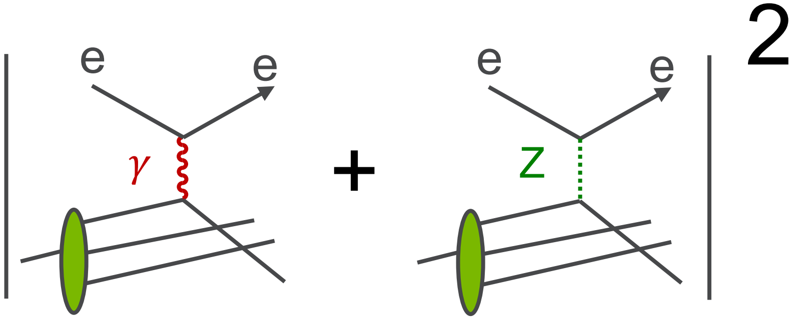


Proposes that electron scattering should have measurable parity violating asymmetry

- Proposes interaction like that responsible for β decay to occur in electron scattering
- Argues cross sections for scattering left- and right-handed electrons *could* differ

ZEL'DOVICH

$\sigma =$

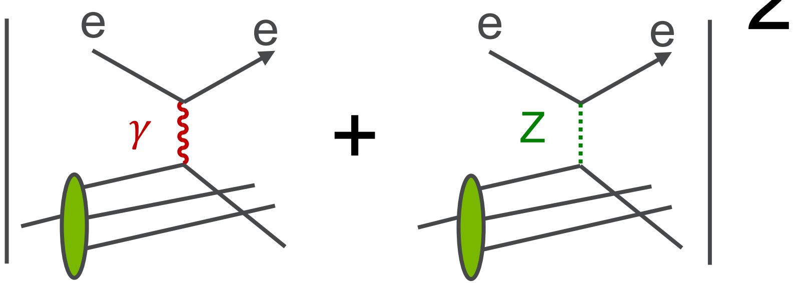


$$\sigma^l \propto \left|\mathcal{M}_{\rm em} + \mathcal{M}^l_{\rm weak}\right|^2 \qquad \sigma^r \propto \left|\mathcal{M}_{\rm em} + \mathcal{M}^r_{\rm weak}\right|^2$$

$$\approx \left|\mathcal{M}_{\rm em}\right|^2 + 2\mathcal{M}_{\rm em}\mathcal{M}^l_{\rm weak} + \left|\mathcal{M}^l_{\rm weak}\right|^2$$

ZEL'DOVICH

$$\sigma =$$



$$\sigma^l \propto |\mathcal{M}_{\text{em}} + \mathcal{M}^l_{\text{weak}}|^2 \approx |\mathcal{M}_{\text{em}}|^2 + 2\mathcal{M}_{\text{em}}\mathcal{M}^l_{\text{weak}} + |\mathcal{M}^l_{\text{weak}}|^2$$

$$\sigma^r \propto |\mathcal{M}_{\text{em}} + \mathcal{M}^r_{\text{weak}}|^2$$

Large, but equal

Tiny

$$A_{\text{PV}} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \approx \frac{\mathcal{M}^l_{\text{weak}} - \mathcal{M}^r_{\text{weak}}}{\mathcal{M}_{\text{EM}}}$$

PVEMC

$$A_{PV} \approx -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left[\boldsymbol{a_1}(x) + \frac{1-(1-y)^2}{1+(1-y)^2}\boldsymbol{a_3}(x)\right]$$

$$\boldsymbol{a_1}(x) = g_A^e \frac{F_1^{\gamma Z}}{F_{1A}^{\gamma}} = 2\frac{\sum e_i\, g_i^V [q_i(x) + \bar{q}_i(x)]}{\sum e_i^2 [q_i(x) + \bar{q}_i(x)]}$$

$$\boldsymbol{a_3}(x) = g_A^e \frac{F_3^{\gamma Z}}{F_1^{\gamma}} = 2\frac{\sum e_i\, g_i^V [q_i(x) - \bar{q}_i(x)]}{\sum e_i^2 [q_i(x) + \bar{q}_i(x)]}$$

$$e_u g_{1u}^V = \frac{2}{3}\left(\frac{1}{2} - \frac{4}{3}\sin^2\theta_W\right)$$

$$e_d g_{1d}^V = \frac{1}{3}\left(-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W\right)$$

Approximate $\boldsymbol{a_1}(x)$ around symmetric nucleus

$$\boldsymbol{a_1}(x) \simeq \frac{9}{5} - 4\,\sin^2\theta_W - \left(\frac{12}{25}\right)\frac{\boldsymbol{u_A^+} - \boldsymbol{d_A^+}}{\boldsymbol{u_A^+} + \boldsymbol{d_A^+}}$$

$$q^{\pm}(x) = q(x) \pm \bar{q}(x)$$

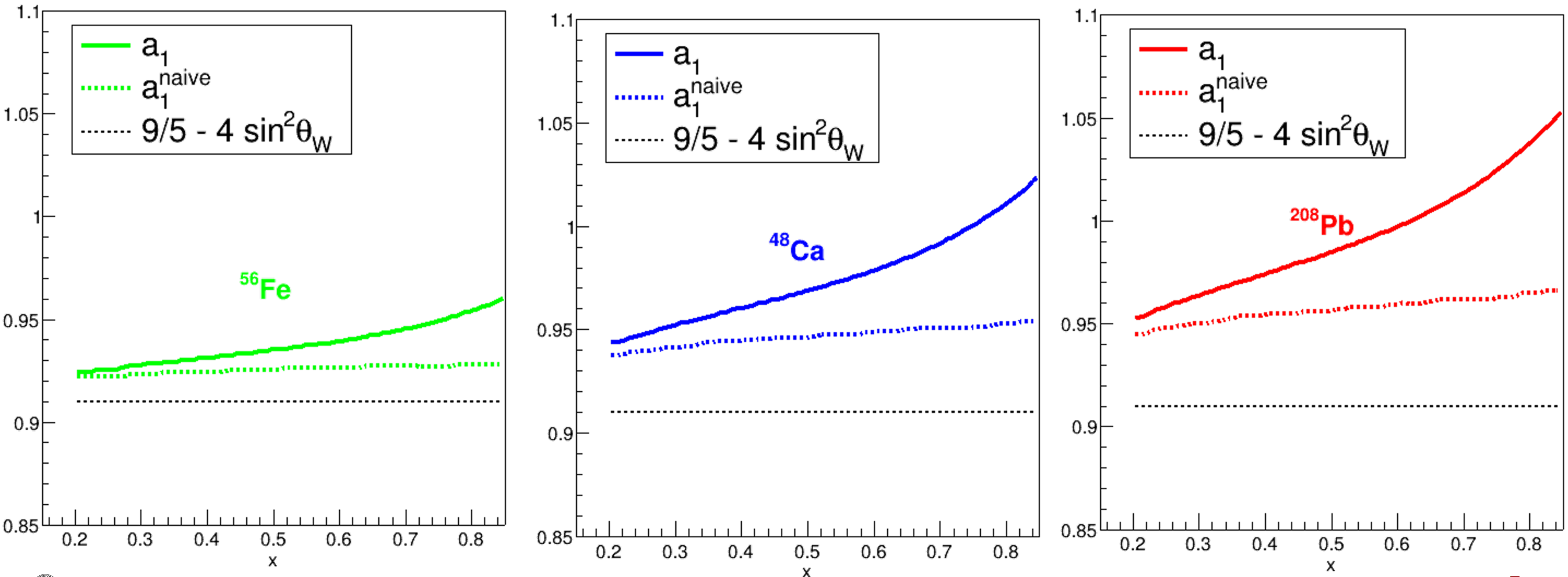
Measures flavor differences!

Cloët et al., PRL 109, 182301 (2012)
Cloët et al., PRL 102, 252301 (2009)

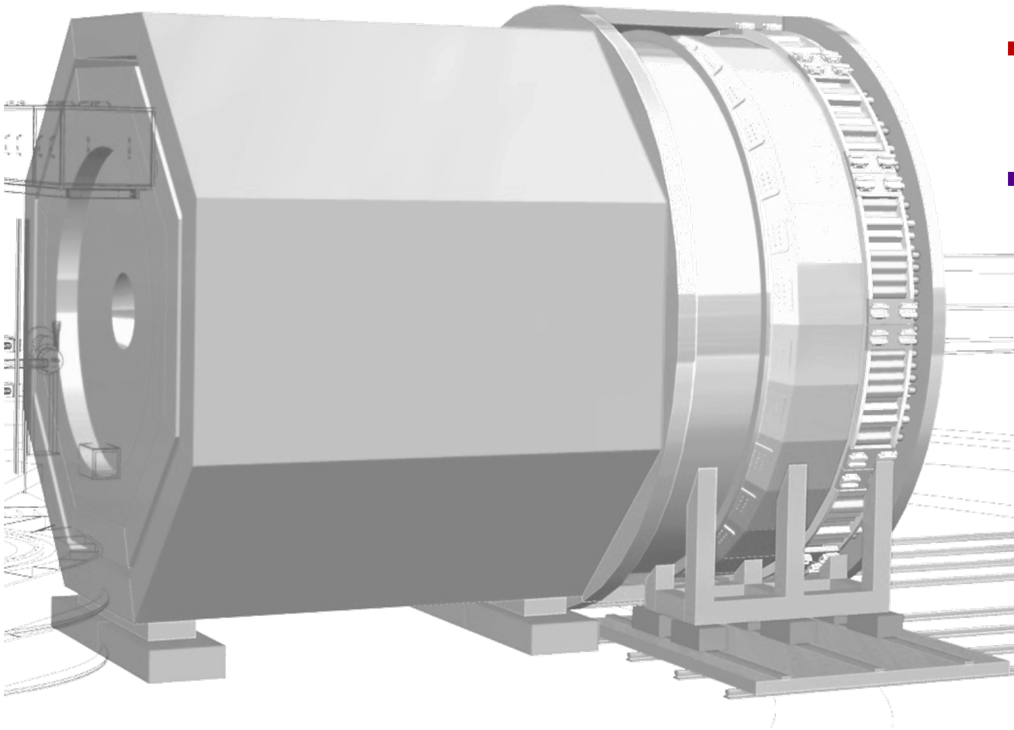
$a_1(x)$ for Nuclei

Cloët et al., PRL 109, 182301 (2012)
Cloët et al., PRL 102, 252301 (2009)

$$a_1(x) \simeq \frac{9}{5} - 4\sin^2\theta_W - \left(\frac{12}{25}\right)\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+}$$



SoLID – The Next-Gen Spectrometer at JLab



- Solid
  Solenoidal Large Intensity Device
- Rich physics program including
  - SIDIS
  - J/ψ production
  - **Parity Violation**

For an overview, see

White Paper arXiv:2209.13357

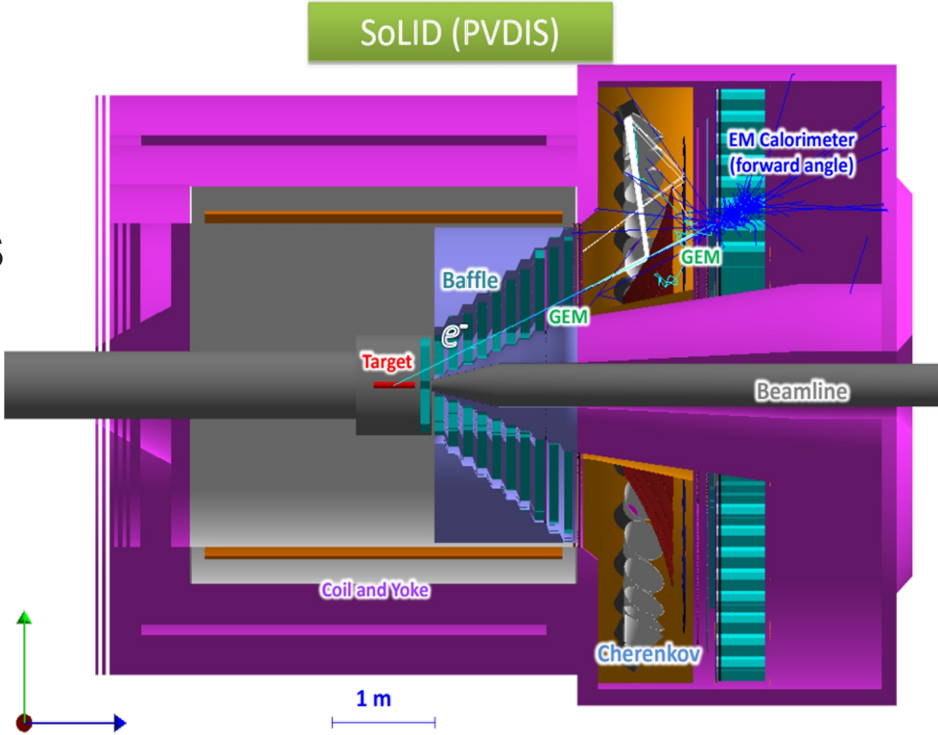
SoLID Apparatus for PVDIS

What do you need for to measure parity violation in DIS?

- DIS experiment: $W^2 > 4\ GeV^2$ Isolate DIS events. Only electron is detected.
- PV experiment: High Luminosity, E ~ 11 GeV, stable systematics

What do you need to address the physics?

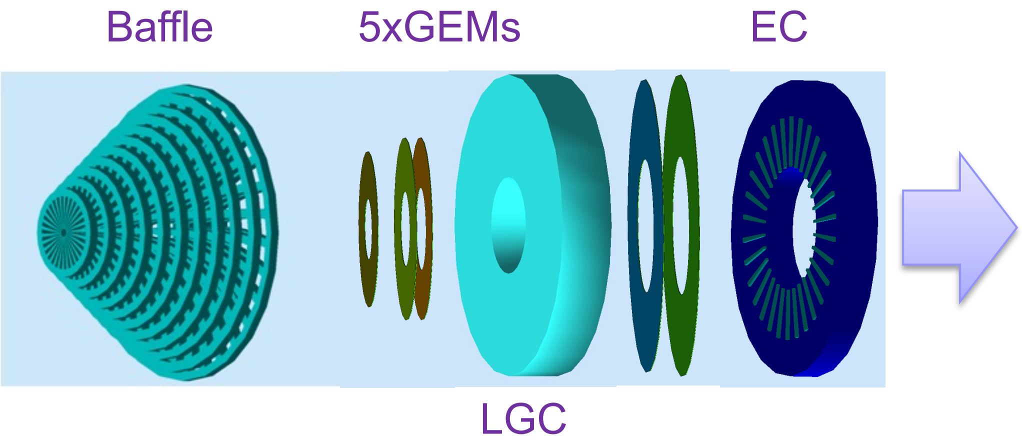
- Wide x-range: 0.25-0.75
- Large azimuthal acceptance.
- Better than 1% statistical errors for small bins
- 2 GeV < E'< 6 GeV: Low background

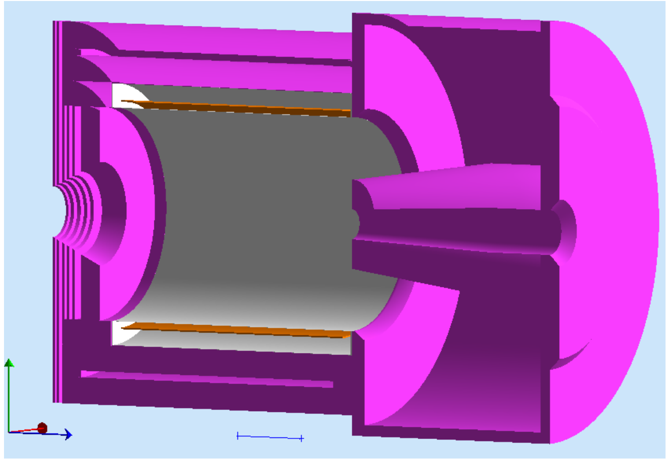


- Around 2% Momentum resolution

SoLID Apparatus

- Baffles to reject wrong momentum background
- Light Gas Cerekkov: identify electrons for trigger; reject pions.
- Shashlyk electromagnetic calorimeter (Ecal) : coincident trigger and further particle identification.
- With tracking, tight E/p cuts reduce pion backgrounds.





Latest – CLEO-II Magnet Cold Test at JLab

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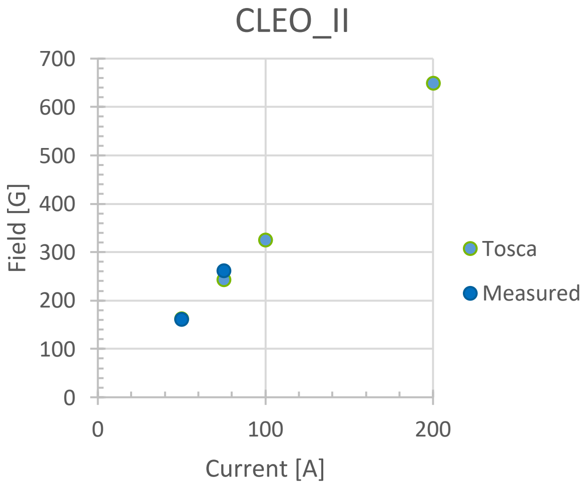
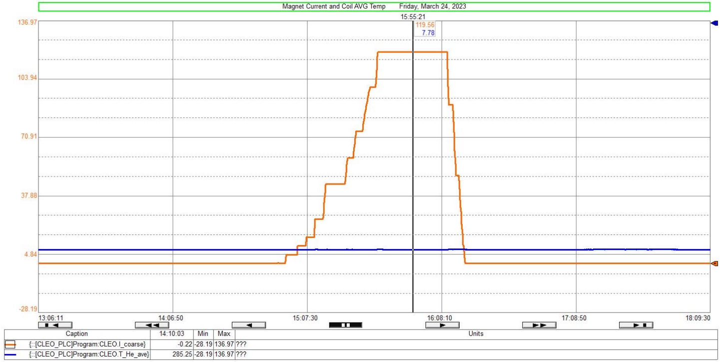
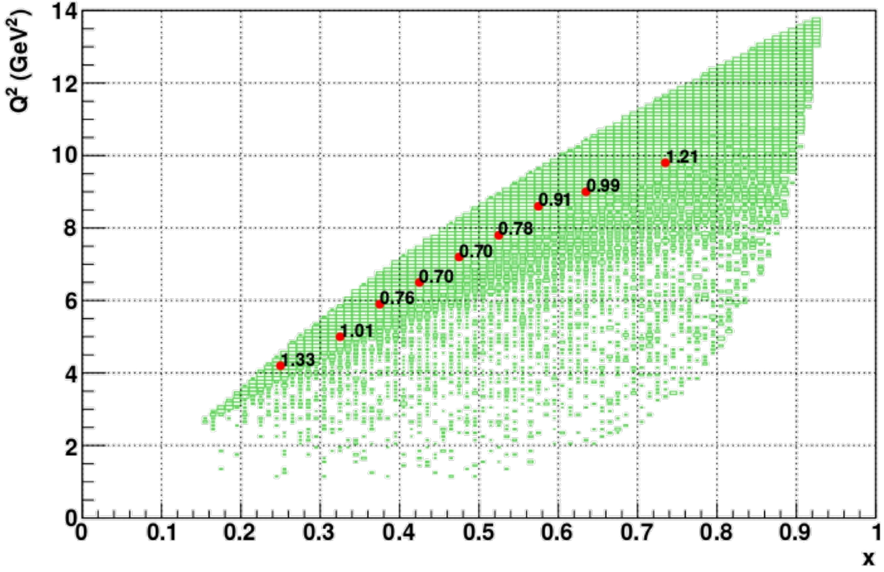
- A low current test on March 24th.
- 3-axis Hall probe data matched TOSCA model well.
- Coil average temperature remained constant during test.
- Success!!

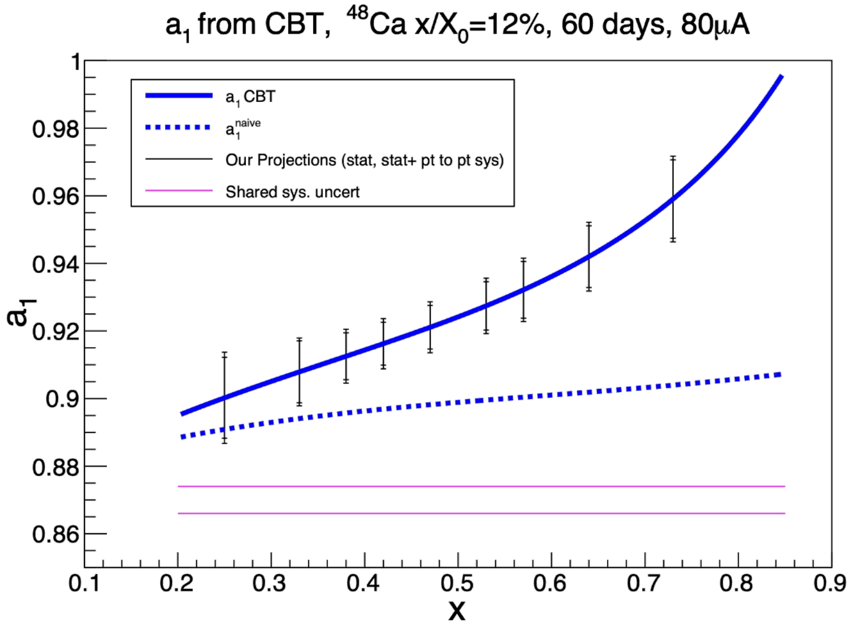




content from W. Seay and X. Zheng

Expected Results





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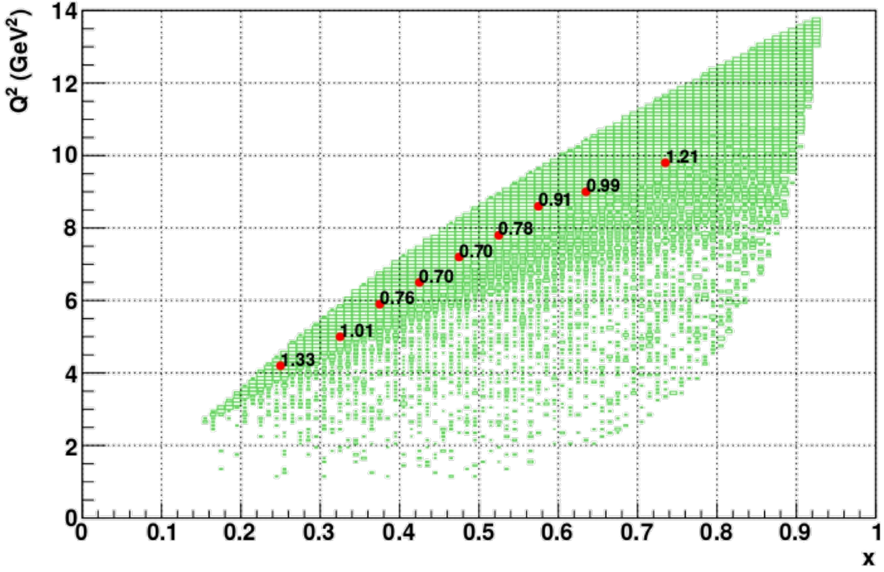
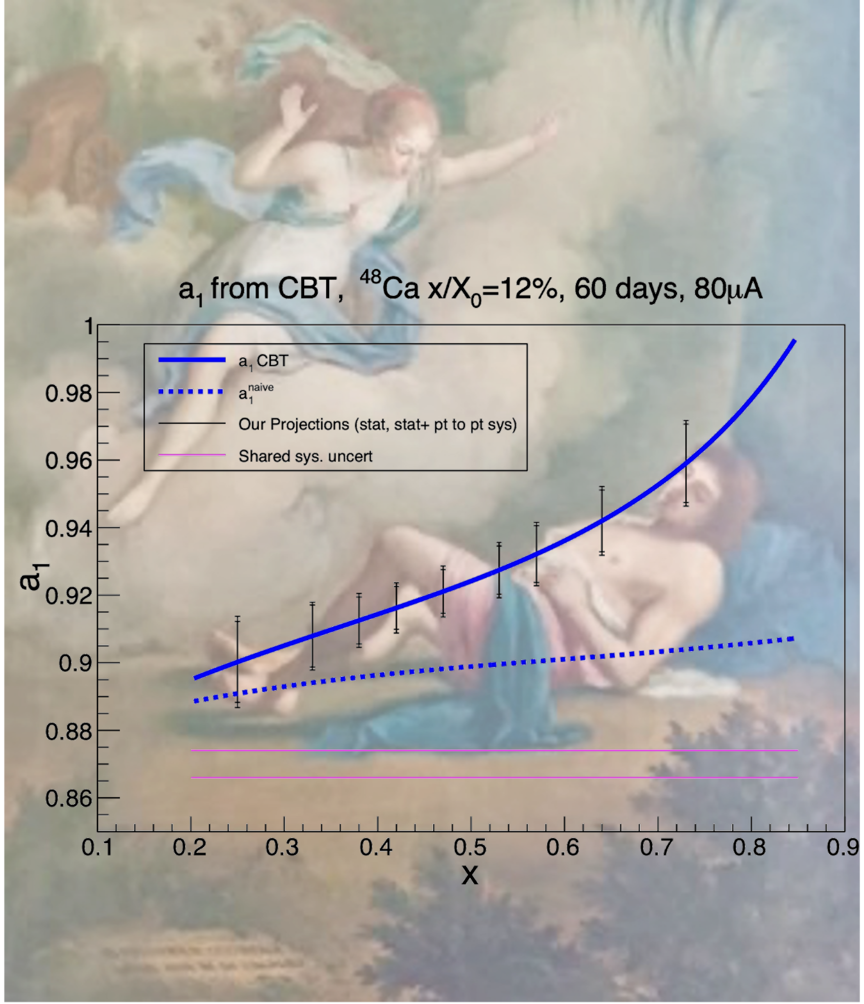




Probing the EMC Effect

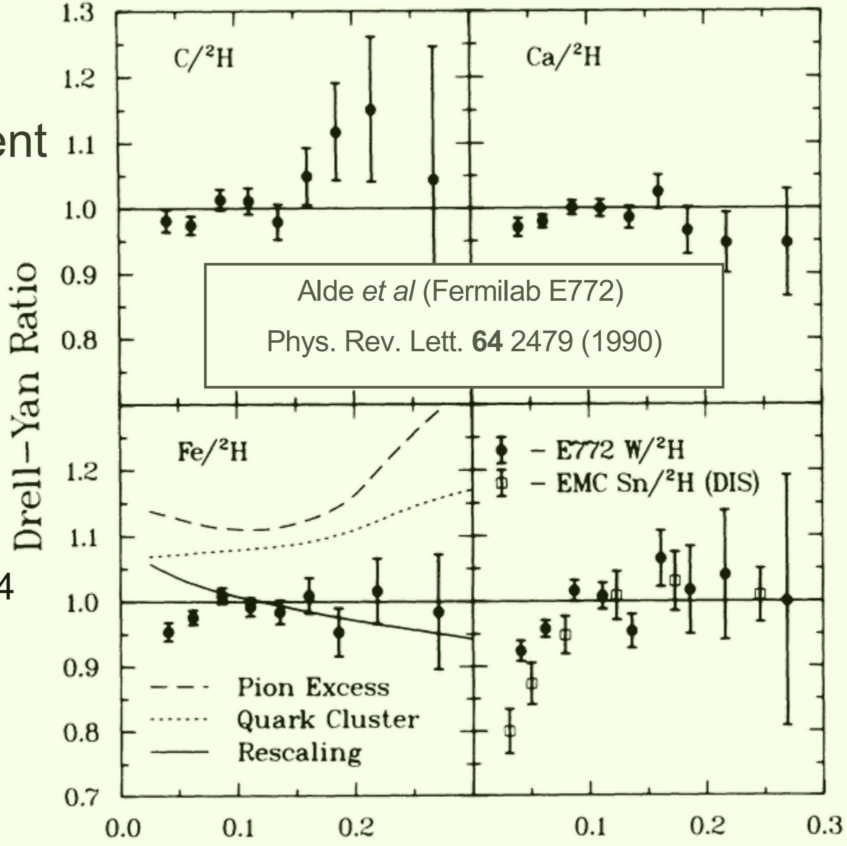
What we know:

- Parton distributions in nuclei appear different than those in nucleons

$$R_A(x,Q^2) = \frac{F_{2A}(x,Q^2)}{ZF_{2p}(x,Q^2) + NF_{2n}(x,Q^2)} \neq 1$$

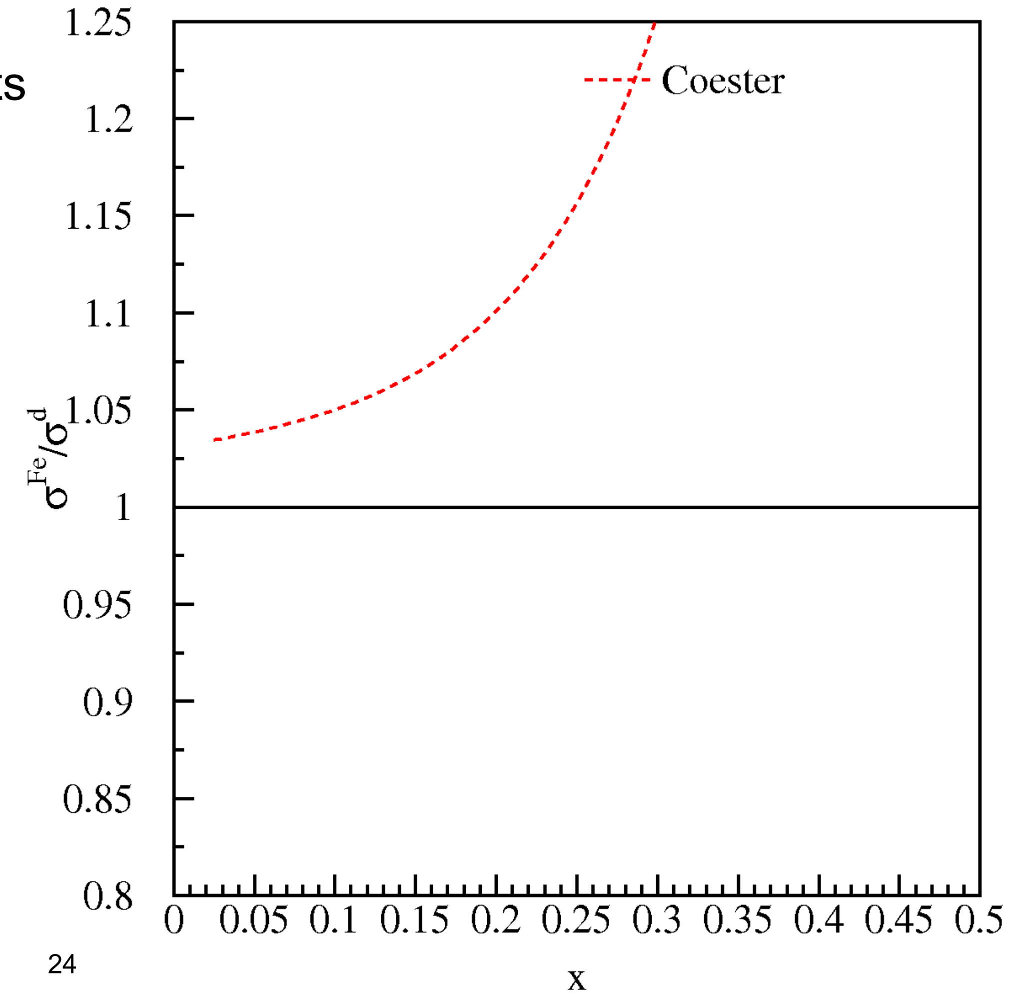
What we don't know:

- **Why** does the effect exist at all?
- Is the sea quark effect absent?
  - c.f. Alde et al., (Fermilab E772) Phys. Rev. Lett. 64 2479 (1990),
  - SeaQuest D-Y data
  - Alvioli, Strikman, Phys.Lett.B 841 (2023) 137935



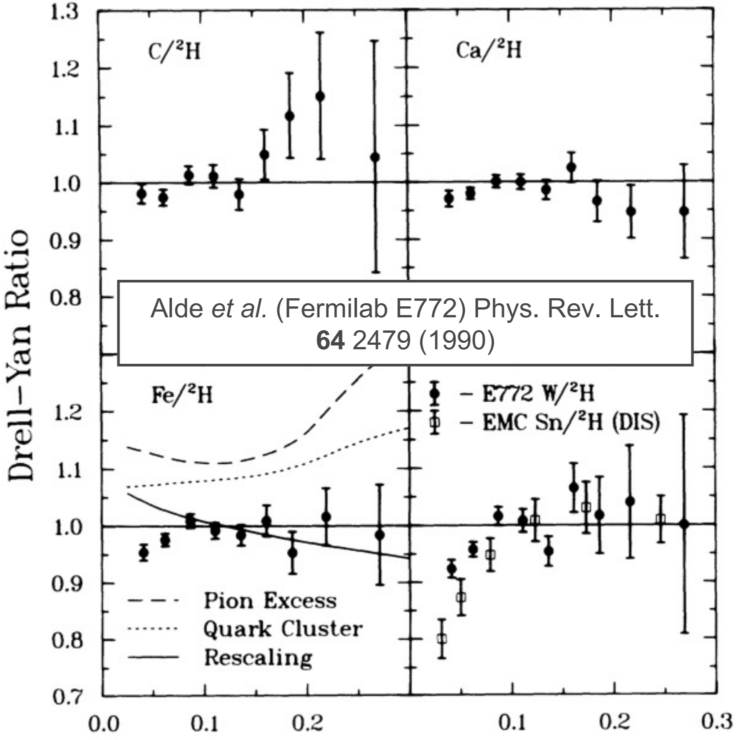
EMC Effect With Anti Quarks?

- Expectations of large antiquark effects



EMC Effect With Anti Quarks?

- Expectations of large antiquark effects
- **No effects were seen in Drell-Yan**



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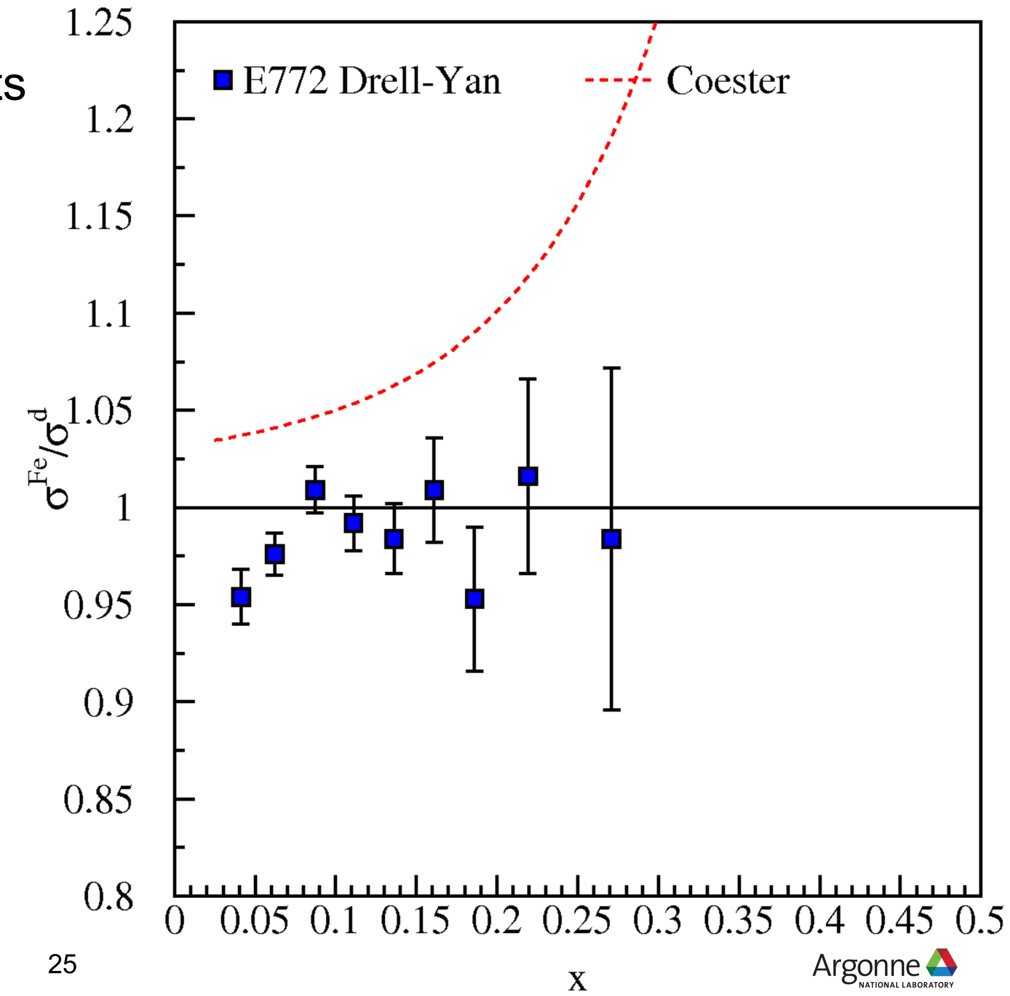
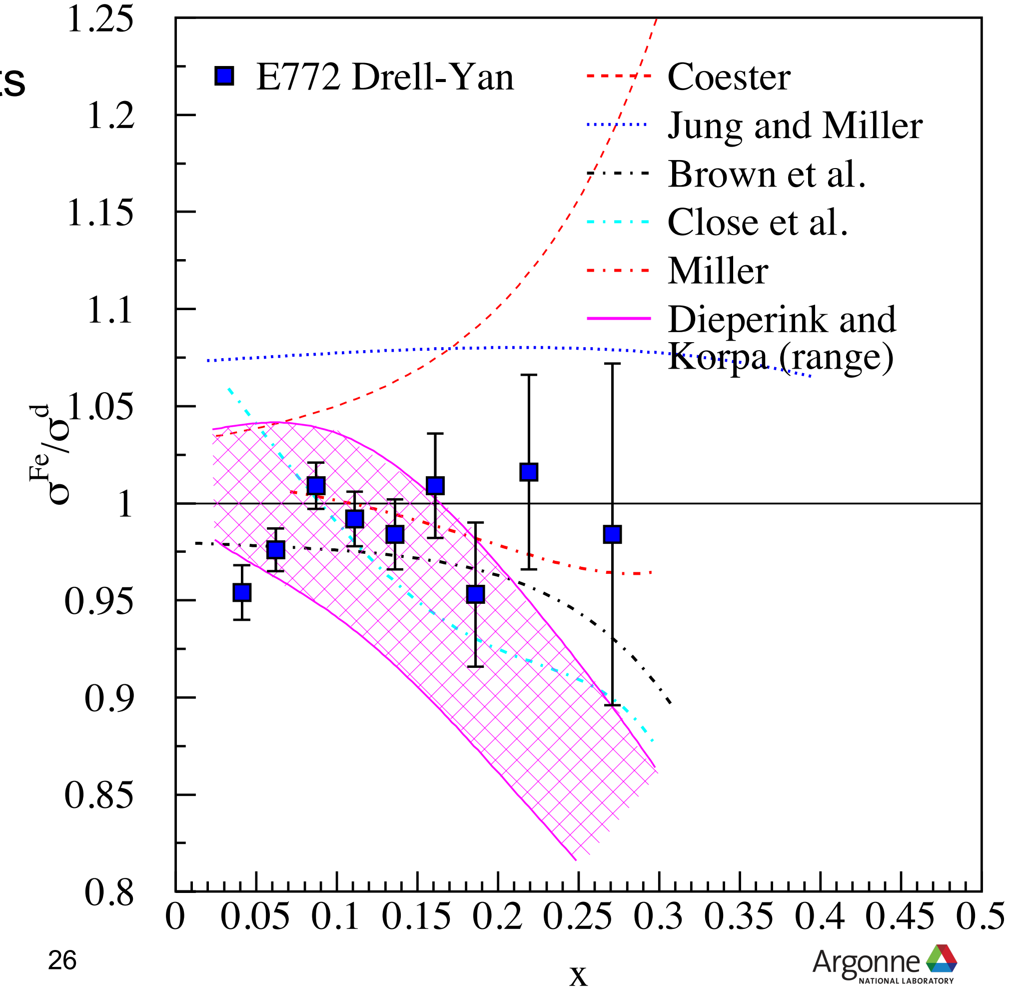
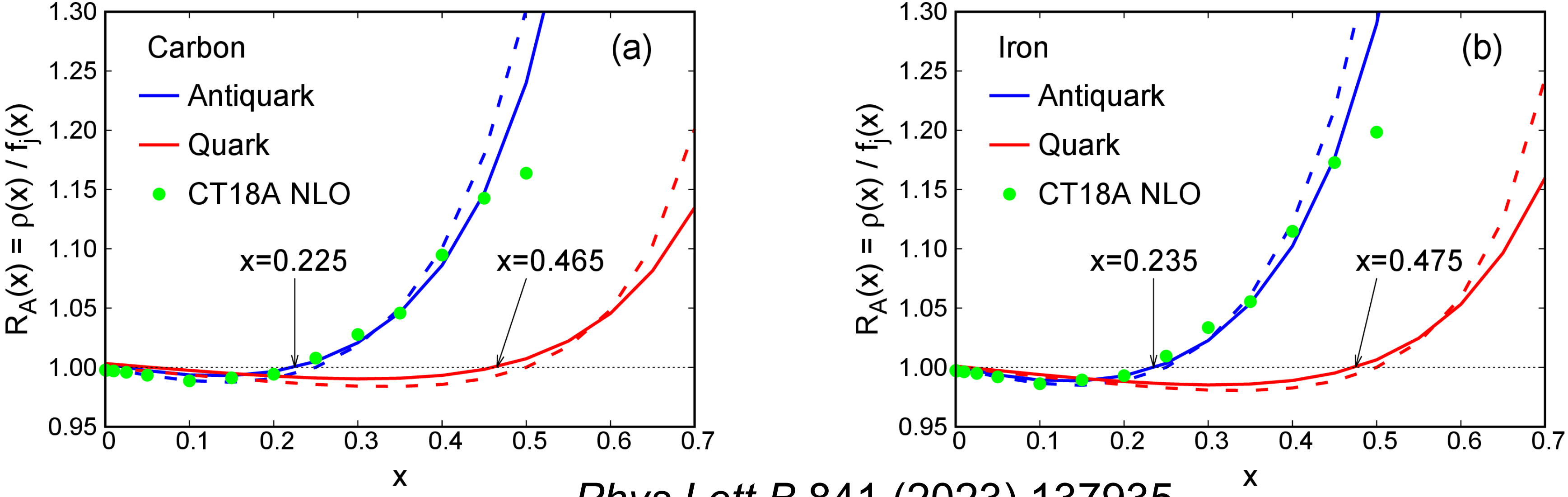


EMC Effect With Anti Quarks?

- Expectations of large antiquark effects
- **No effects were seen in Drell-Yan**
- Contemporary models predict more modest effects at large x_{Bj}



Effects of Fermi Motion (See M. Strikman—Tuesday)



Phys.Lett.B 841 (2023) 137935

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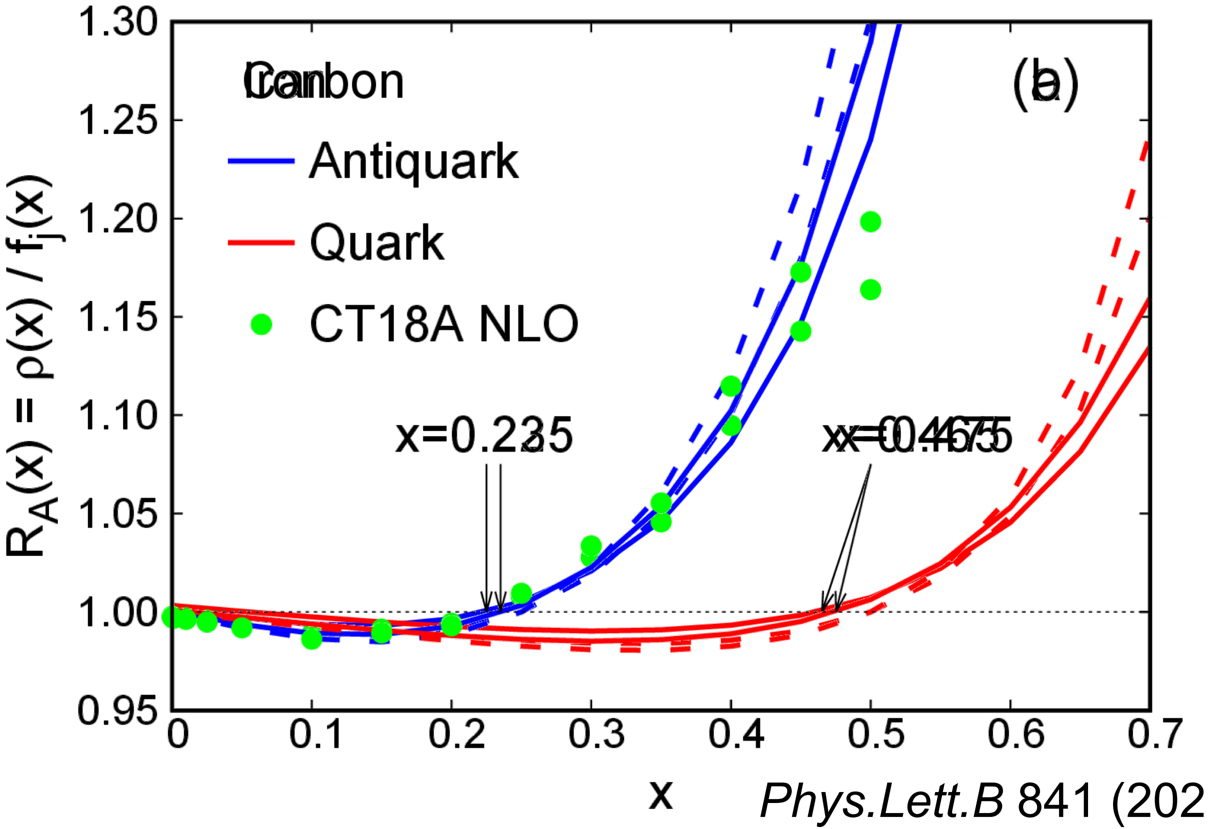

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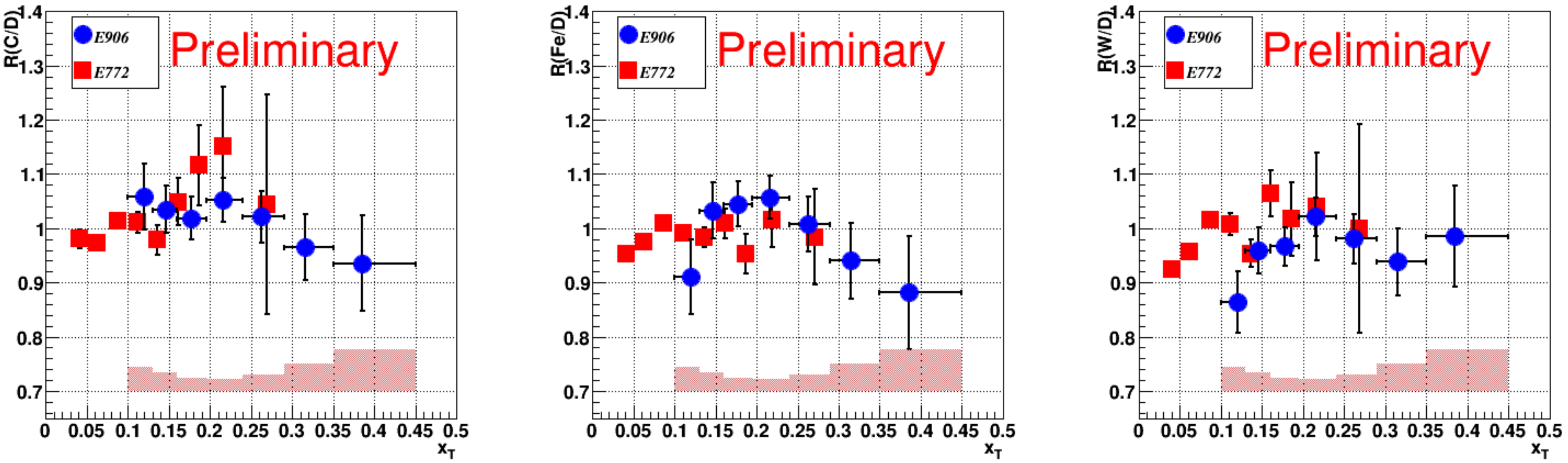
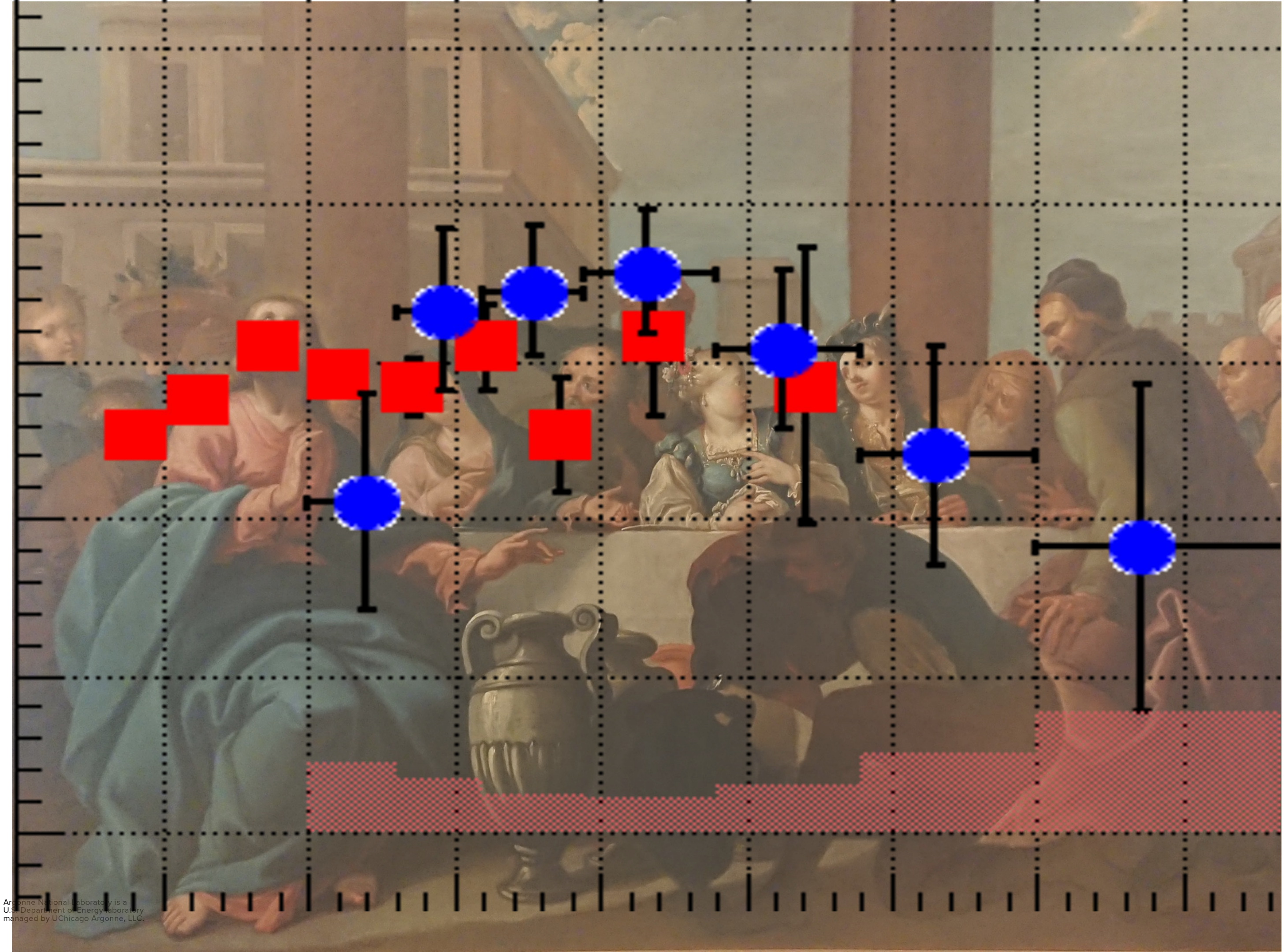
SeaQuest EMC Nuclear Dependence



- **Data are subject to revision—Preliminary!**
- No enhancement seen as in the case of a pion excess model
- In agreement with E772 results in the overlap region

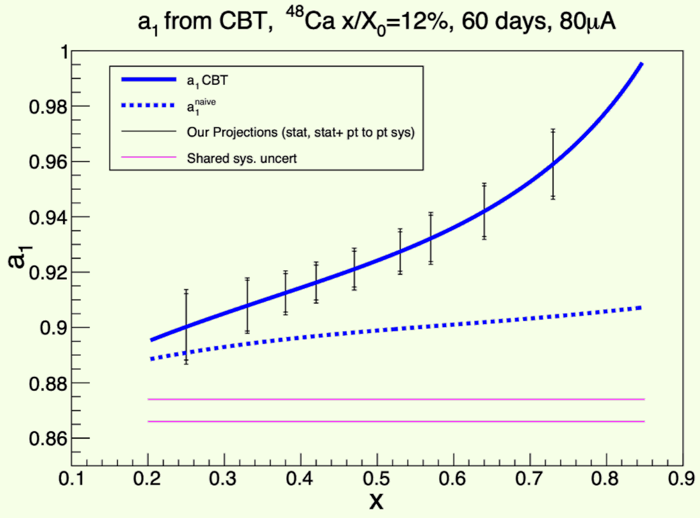


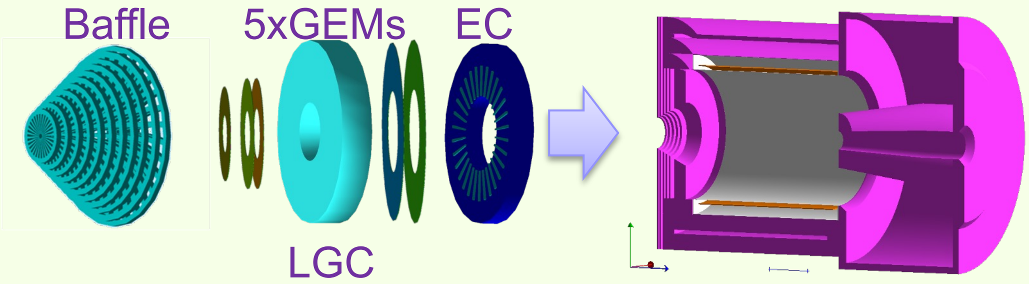
Recap

- Parity violation in DIS enables electroweak and QCD exploration

$$A_{\mathrm{PV}} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \approx \frac{\mathcal{M}^l_{\mathrm{weak}} - \mathcal{M}^r_{\mathrm{weak}}}{\mathcal{M}_{\mathrm{EM}}}$$

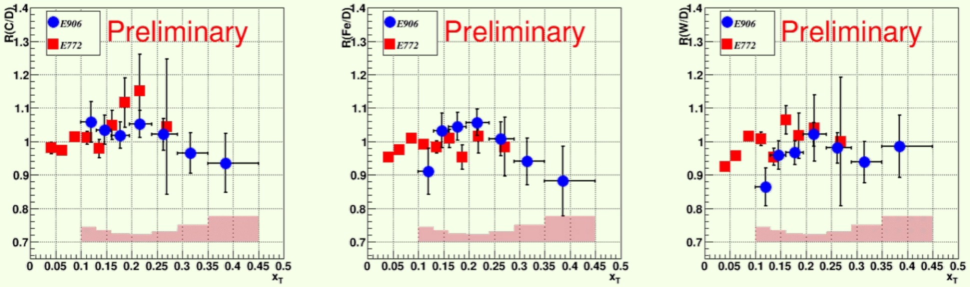
$$a_1(x) \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12u_A^+ - d_A^+}{25u_A^+ + d_A^+}$$



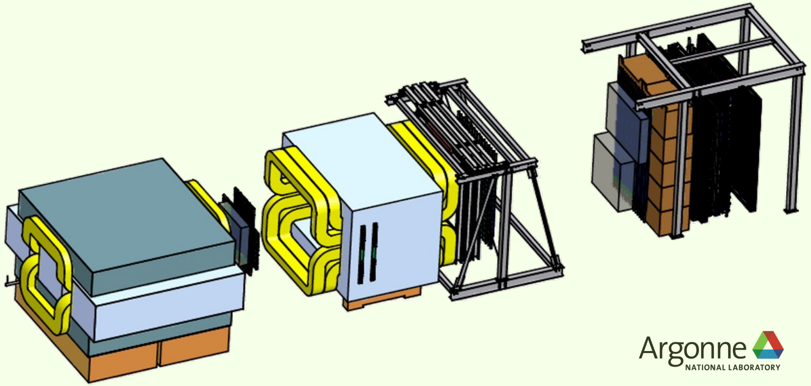


Recap

- Drell-Yan looking for Sea Quark nuclear effects



- Can different nuclear effects be resolved:
  - quark energy loss
  - EMC
  - Fermi motion



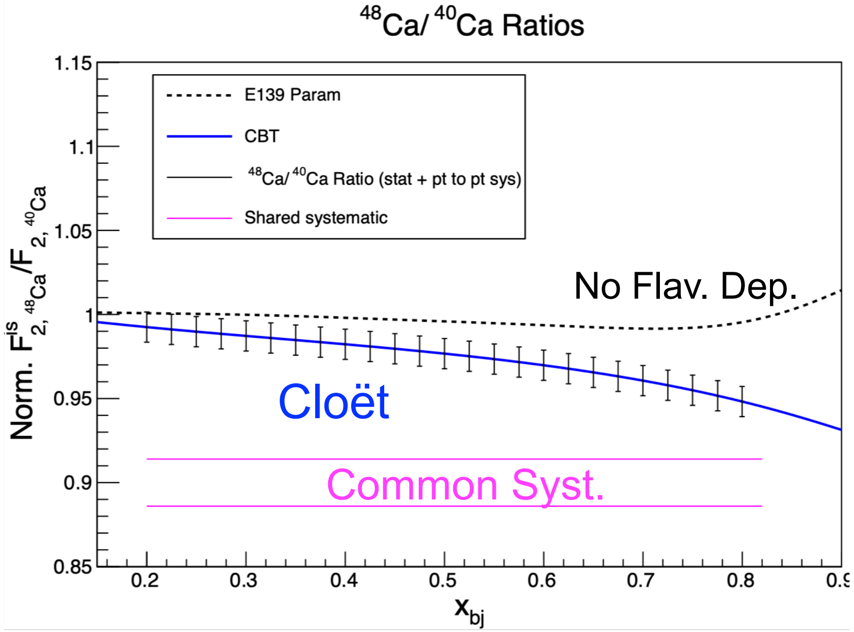
$$A_{PV}^{eDIS} = \frac{\sigma^e - \sigma^l}{\sigma^e + \sigma^l}$$

$$= 2\,\frac{sy}{M_Z^2}\,\frac{g_A^e \sum Q_A^q g_V^q [q(x)+\bar{q}(x)]\left[1+(1-y)^2\right]+g_V^e \sum Q_A^q g_A^q [q(x)-\bar{q}(x)]\left[1-(1-y)^2\right]}{Q_A^e \sum\left(2Q_A^q\right)^2 [q(x)+\bar{q}(x)][1+(1-y)^2]}$$

$$\approx \frac{3}{20\pi\alpha(Q)}\,\frac{Q\char`^2}{\nu}\left[\left(2g_{AV}^{eu} - g_{AV}^{ed}\right) + \left(2g_{VA}^{eu} - g_{VA}^{ed}\right)\left(\frac{1-(1-y)^2}{1+(1-y)^2}\right)\right]$$

Why use Parity Violation?

- $^{48}Ca/^{40}Ca$ ratio (E12-10-008)
- $^{3}H/^{3}He$ (MARARHON)
  - more sensitive to neutron structure function than flavor dependence
- π^+/π^- from $^{3}H/^{3}He$ (12-21-004 Hall B)
  - Conditional approval
  - PAC "The physics programme is very rich, but the extraction of the underlying physics observables is very challenging"



Possible Lepto-Phobic Z'; Example at lower energy

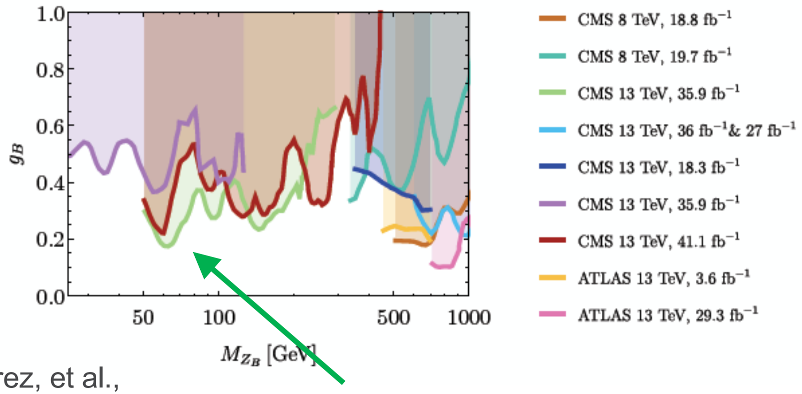
Motivation for introducing new particle:

C2

Baryon number is a global symmetry in the SM (bad).
Theories of local baryon number symmetry are attractive.
They predict a lepto-phobic boson.
They also predict a dark matter candidate.

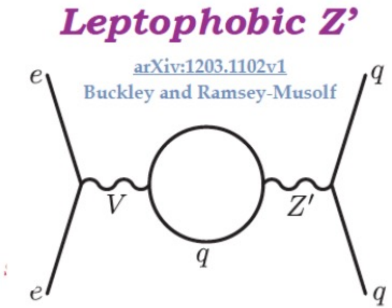
$$A \sim \frac{(gB)2}{(M_{Z'})^2}$$

Perez, Phys. Rept. 597, (2015) 1-30



Perez, et al.,
JHEP 07 (2020) 087

Limits depend on branching ratios.



Modifies mainly C_2's in PVES

Plot shows that the LHC is interested in Leptophobics