



Studying Possible Isospin Dependence of $R = \sigma_L / \sigma_T$

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Introduction and Formalism

Deep Inelastic Scattering

- DIS allows us to probe the partonic structure of nuclei and nucleons
- With this technique, we extract F_2 (and occasionally F_1) which encodes this structure
- In the naïve quark-parton model, these directly map to the quark parton distribution functions (PDFs)
- PDFs encode the probability of finding a quark flavor with nucleon momentum fraction x (also known as Bjorken x)

DIS DIAGRAM HERE

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2}{Q^4} \cos^2 \frac{\theta}{2} \left(\frac{F_2(x, Q^2)}{\nu} + \frac{2F_1(x, Q^2)}{M} \tan^2 \frac{\theta}{2} \right)$$

$$F_2(x) = 2xF_1(x) = x \sum_q e_q^2 (q(x) + \bar{q}(x))$$

Virtual Photon Exchange

- The cross section can also be written in terms of the virtual photon helicity
- σ_L and σ_T are the cross sections for absorption of a longitudinal and transverse virtual photon, respectively
- By equating this cross section formalism with the formalism on the previous slide, we can rewrite the cross section in terms of F_2 and $R = \sigma_L / \sigma_T$

$$\frac{d^2\sigma}{d\Omega dE'} = \Gamma(\sigma_T + \epsilon\sigma_L) = \Gamma\sigma_T(1 + \epsilon R)$$

$$\Gamma = \frac{\alpha}{2\pi^2 Q^2} \frac{E' \nu(1-x)}{E(1-\epsilon)}$$

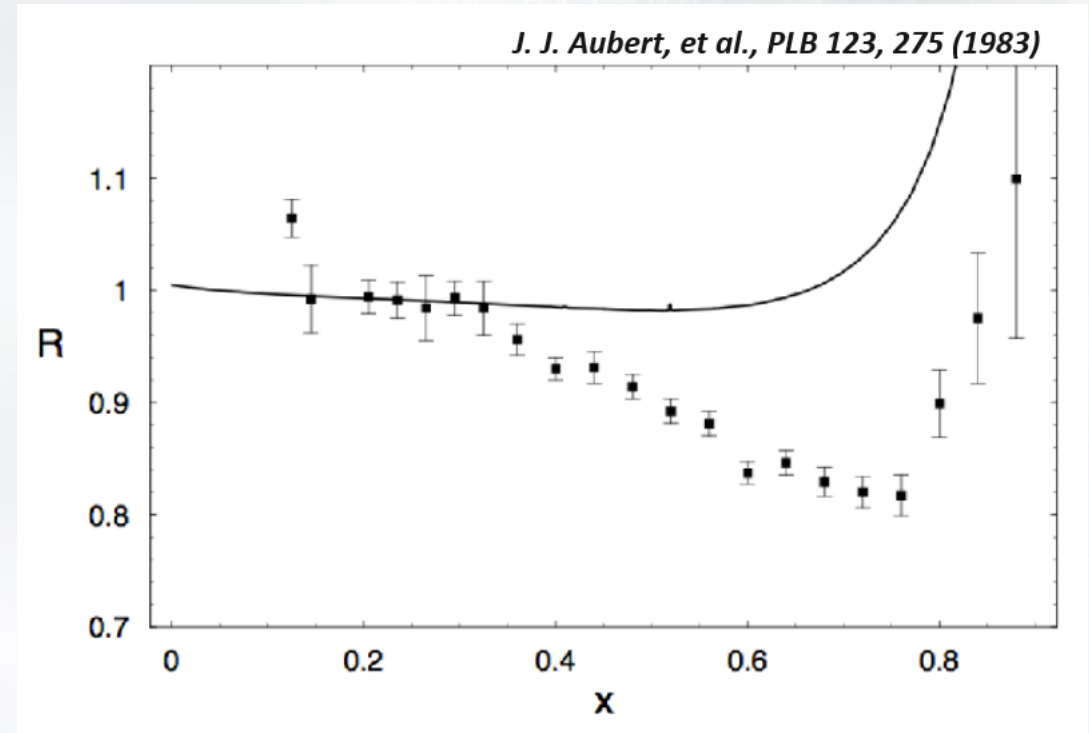
$$\epsilon = \left[1 + 2 \left(1 + \frac{\nu^2}{Q^2} \right) \tan^2 \frac{\theta}{2} \right]^{-1}$$

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'}{Q^4} \cos^2 \left(\frac{\theta}{2} \right) F_2 \left[\frac{1}{\nu} + \frac{(1 + Q^2/\nu^2)}{xM(1 + R)} \tan^2 \left(\frac{\theta}{2} \right) \right]$$

The EMC Effect

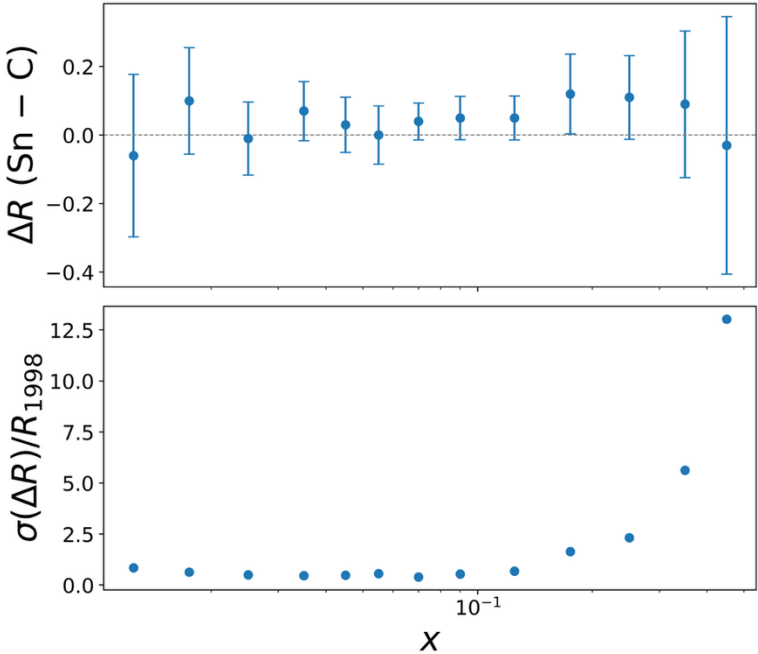
- First seen by the European Muon Collaboration (EMC)
- Characterized by modification of partonic structure in nuclei
- Studied through ratios of nuclear F_2 structure functions to deuterium

$$\frac{\frac{d^2\sigma_A}{d\Omega dE'}}{\frac{d^2\sigma_D}{d\Omega dE'}} = \frac{\sigma_A}{\sigma_D} = \frac{F_2^A \left[\frac{1}{\nu} + \frac{(1 + Q^2/\nu^2)}{xM(1 + R_A)} \tan^2\left(\frac{\theta}{2}\right) \right]}{F_2^D \left[\frac{1}{\nu} + \frac{(1 + Q^2/\nu^2)}{xM(1 + R_D)} \tan^2\left(\frac{\theta}{2}\right) \right]}$$

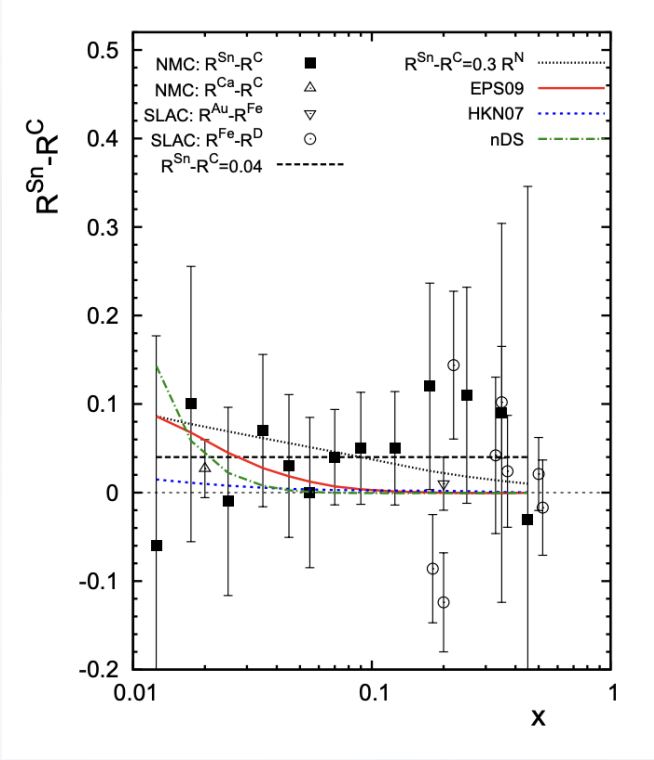


Universality of R

- In studies of the EMC effect, it is standard procedure to assume that R is universal for all nuclei
- That is, $R_A = R_D$ which allows kinematic quantities in the ratio to cancel making the cross section ratio equal to the F_2 ratio



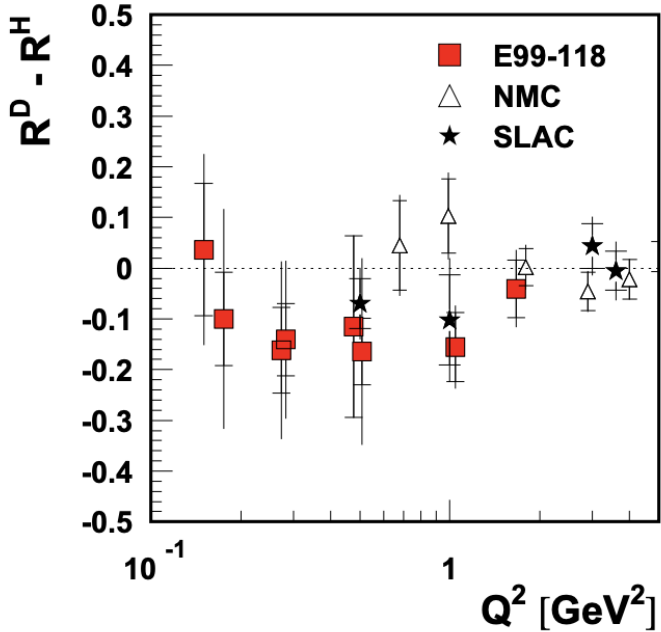
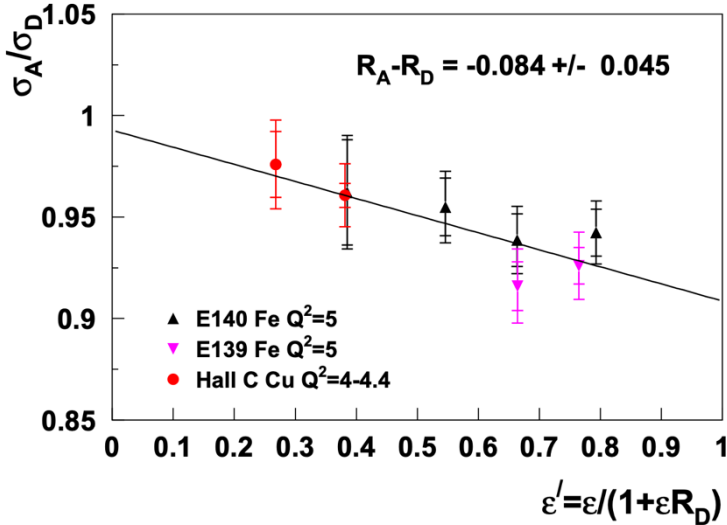
An example of precision of $\Delta R=0$
 Data from M. Arneado *et al*, NPB 481 (1996)
 R1998 from K. Abe *et al*, PLB 452 (1999)



V. Guzey *et al*, PRC 86 (2012)

Cracks in the Picture

- Analyses in the E12-14-002 proposal and V. Tvaskis et al, Phys. Rev. Lett. 98, 142301 (2007) hint that R may not be universal in the DIS regime
- Model independent analyses find that R_D trends smaller than R_p
- Model independent analyses find that R_A trends smaller than R_D
 - The nuclear targets studied are iron and copper

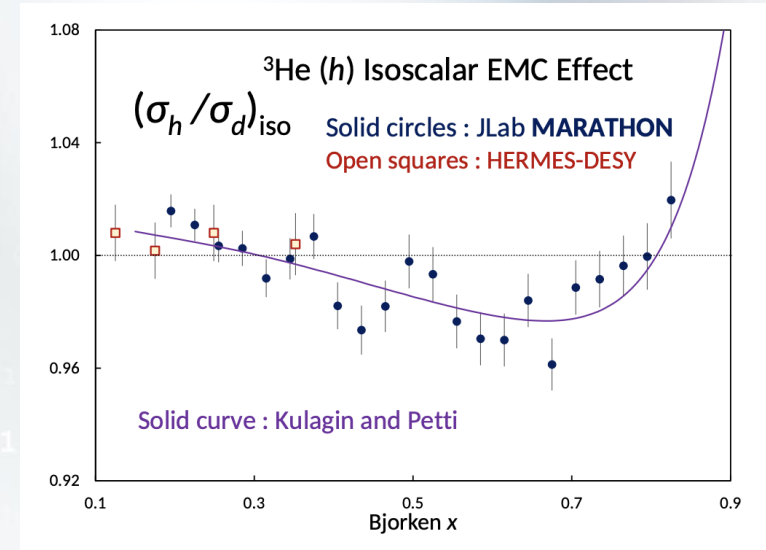


The Problem of Helium-3

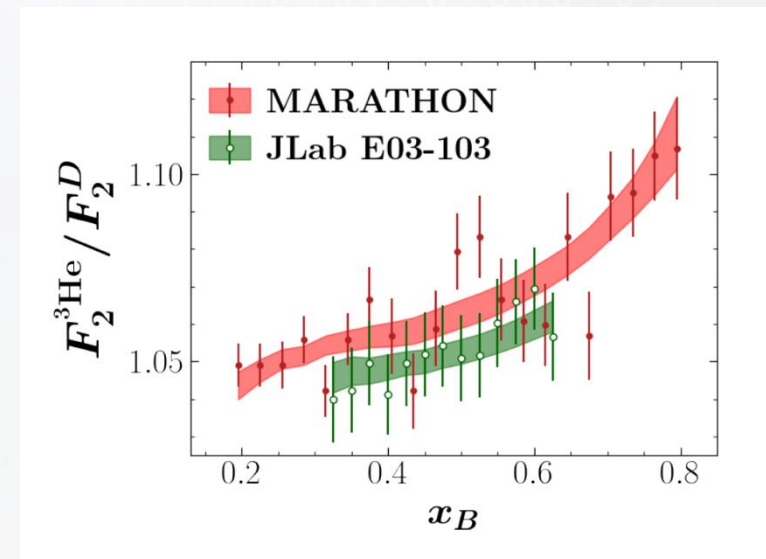


MARATHON

- MARATHON extracted F_2 ratios for He3/H3, D/p, He3/D, and H3/D
- The Helium-3 data was normalized up by 2.1% and the Tritium data was normalized down by 0.4%
- These were determined to enforce the cancellation of nuclear effects in the vicinity of $x=0.31$, most readily observed by a unity crossing in the EMC ratio
- The He3 normalization is much larger than the target normalization uncertainty
- Is there a physics observable that could explain this normalization?



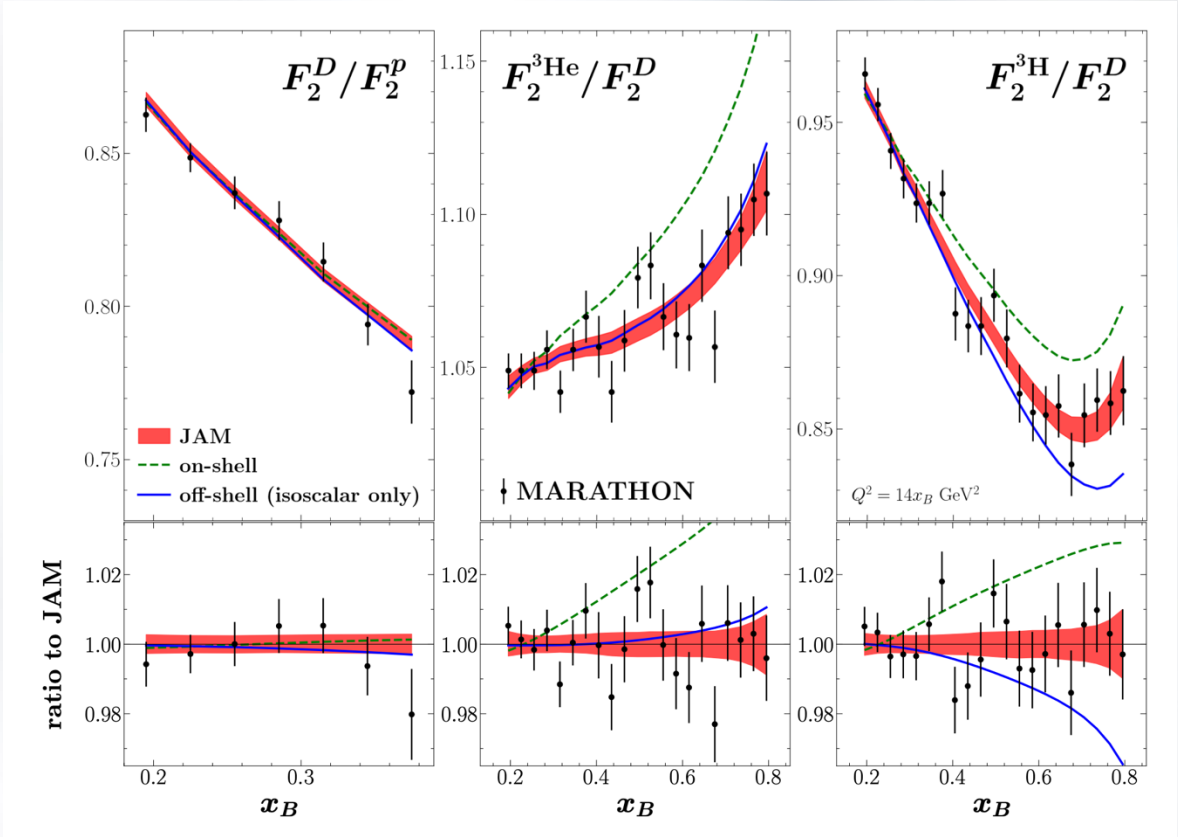
D. Abrams *et al*, PRL 135 (2025)



C. Cocuzza, TJH, *et al*, arXiv: 2602.16589 (2026)

JAM Analysis 2026

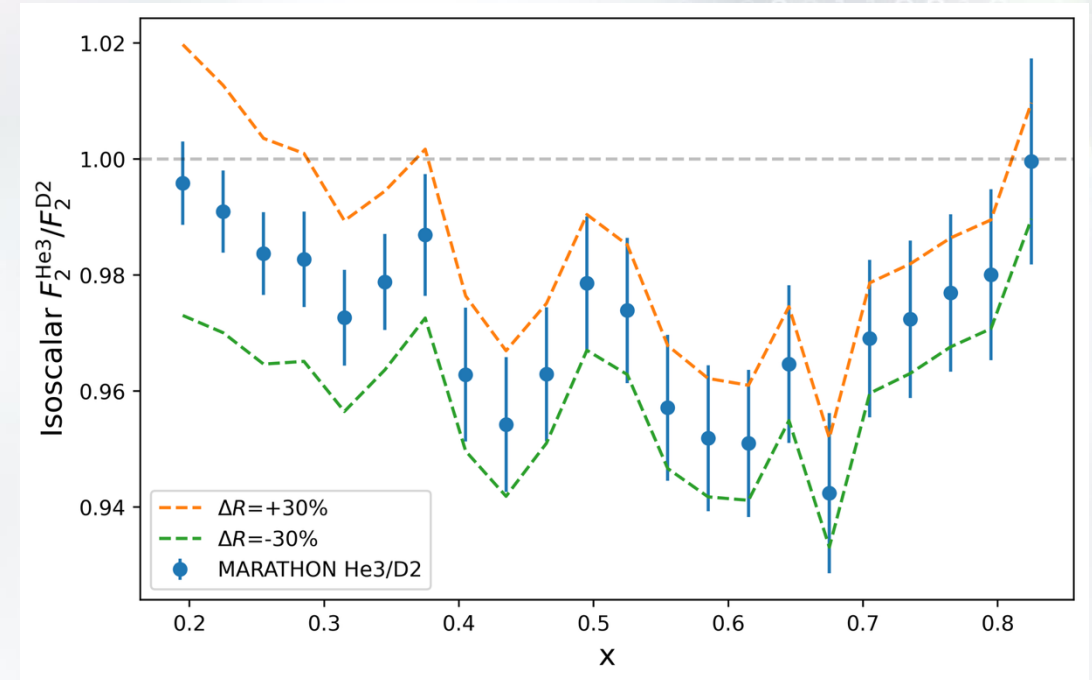
- JAM recently added the MARATHON EMC data to their global analysis
- This analysis finds that the He3 EMC effect is particularly sensitive to isospin-dependent effects
- The data suggests large isoscalar and isovector off-shell effects are necessary
- As an experimentalist, off-shell effects are hard to study. The sensitivity to isospin-dependent effects got me thinking...



C. Cocuzza, TJH, *et al*, arXiv: 2602.16589 (2026)

What if R is isospin dependent?

- Previously we noted that data suggests that R_D is smaller than R_p and that R_{Fe} and R_{Cu} is smaller than R_D
- Deuterium adds a neutron to proton
- Iron and copper have neutron excess
- Helium-3 has *proton* excess
- On the right is the MARATHON He3 EMC ratio, sans normalization, with a band showing the shift in the ratio if R is 30% different from deuterium, using the R1998 parameterization for R_D
- A shift of +30% (that is, larger R) is fairly close to the normalization applied



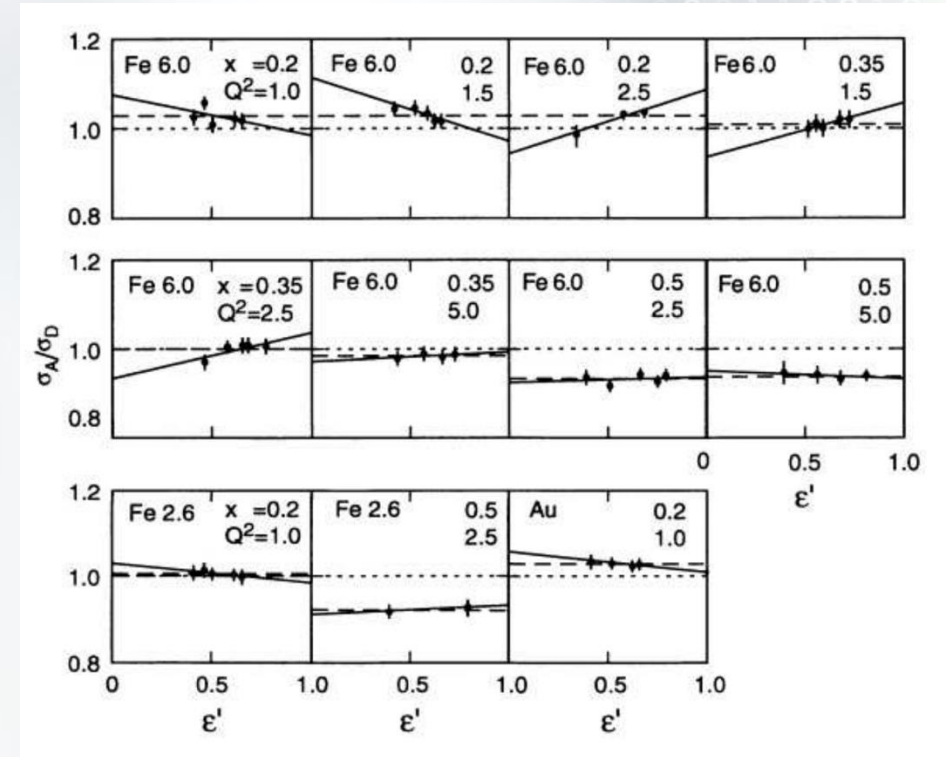
30% selected to match an example in V. Guzey *et al.*
The value is well within the uncertainty at which R is measured to be universal

Can data tell us anything?

Let's check

Model independent extraction of ΔR

- Requires an L-T separation by taking data at the same x and Q_2 with different beam energies to get a spread in ϵ (ϵ' for ΔR)
- For cross sections, a linear fit gives σ_T for the intercept and $\sigma_T * R$ for the slope
- For cross section ratios, a linear fit gives F_1^A/F_1^D for the intercept and $\Delta R * F_1^A/F_1^D$ for the slope




S. Dasu *et al.*, PRD 49 (1994)

Data used

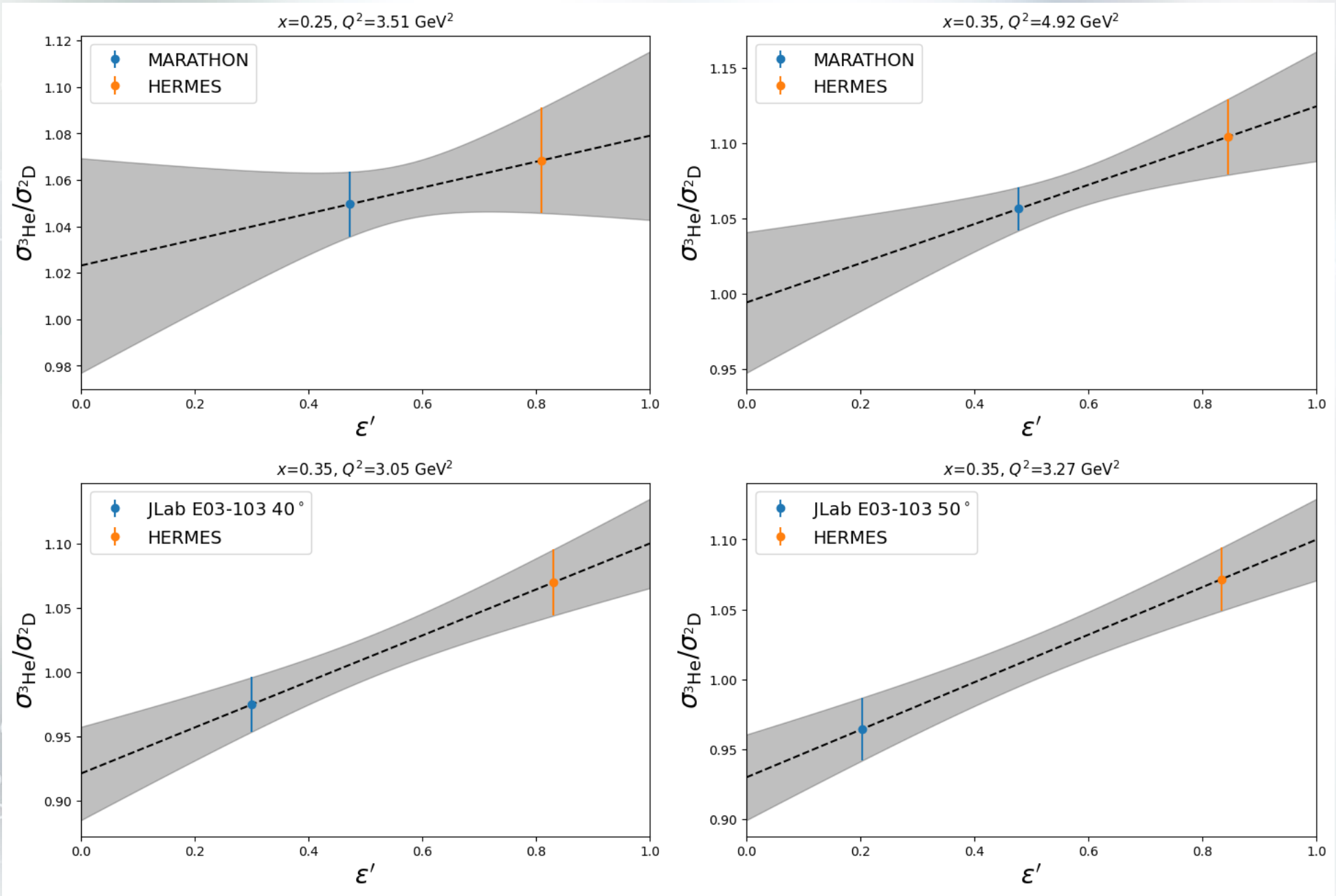
Data used:

- HERMES
 - Data tables include finely binned in Q^2 which allowed matching with JLab measurements
 - Data reported with 0.9% normalization to match Helium-4 data. This has been removed
 - Data reported isoscalar corrected, removed with cited NMC extraction
- JLab E03-103
 - 6 GeV data in Hall C
- MARATHON
 - Model dependent 2.1% normalization removed
- Used R1998 for R_D (K. Abe *et al*, PLB 452 (1999))

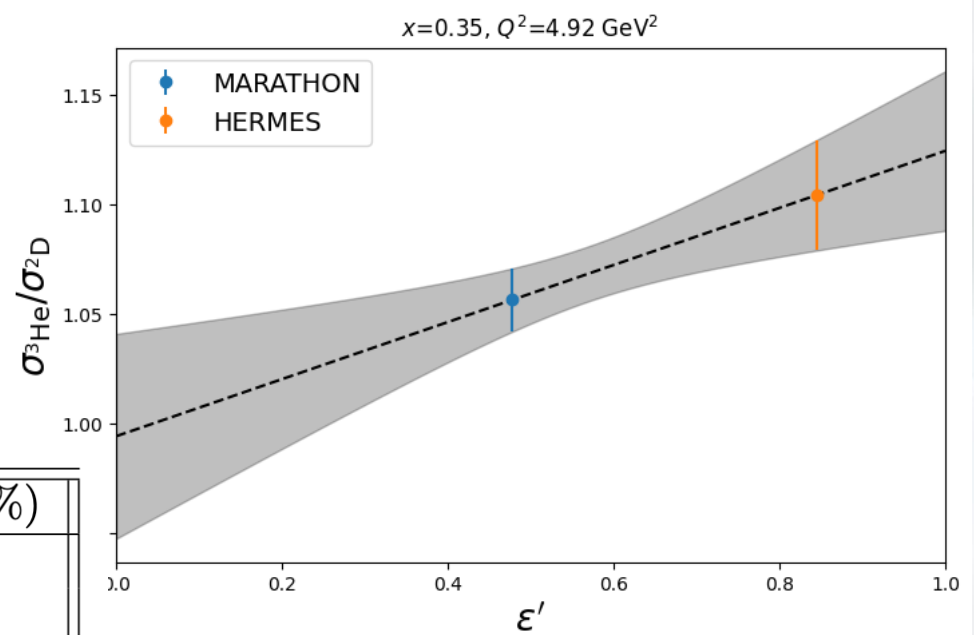
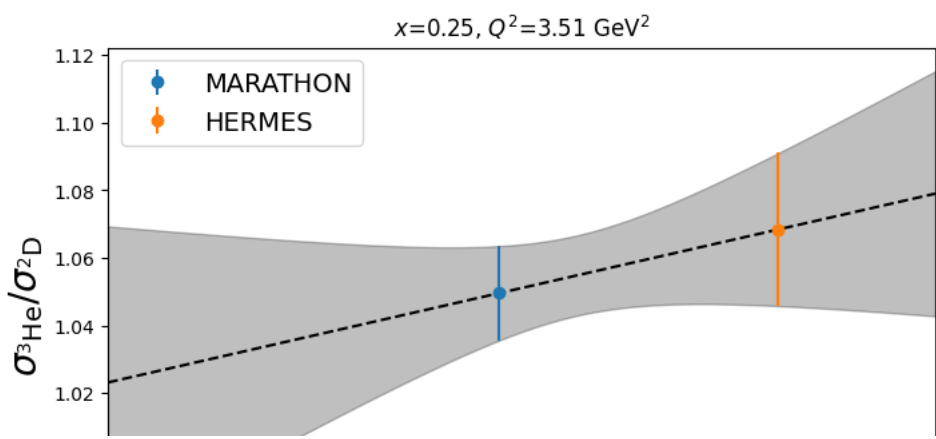
A small, semi-transparent molecular model is located in the upper left quadrant of the slide. It consists of three spheres: a green one at the top, a blue one at the bottom right, and an orange one at the bottom left, all connected by thin lines representing bonds. The background of the slide is a light blue gradient with faint, scattered binary code (0s and 1s) and other molecular models.

Caution!
**The following combines data from
very different experiments!**
**It suggests interesting physics but is
not conclusive!**

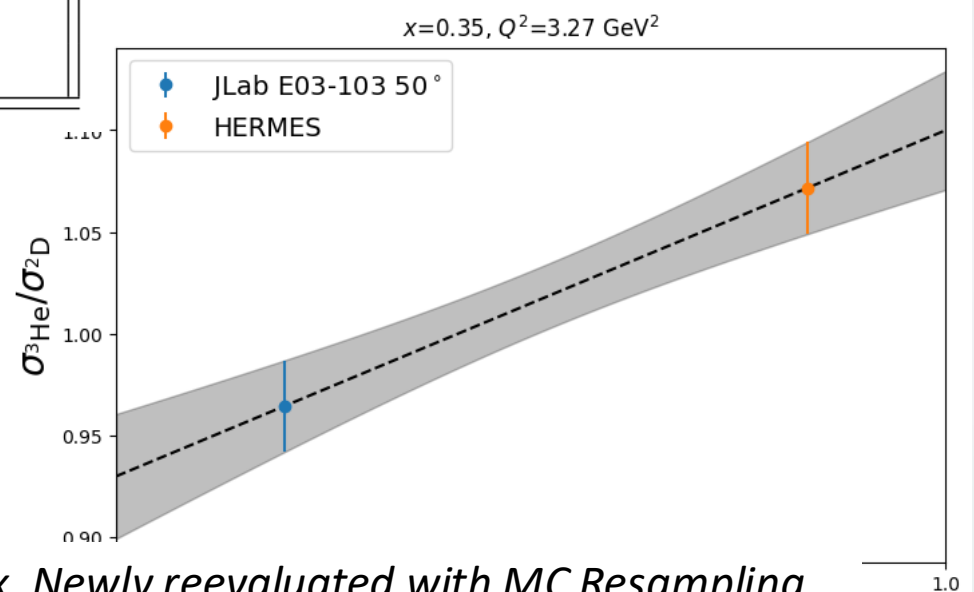
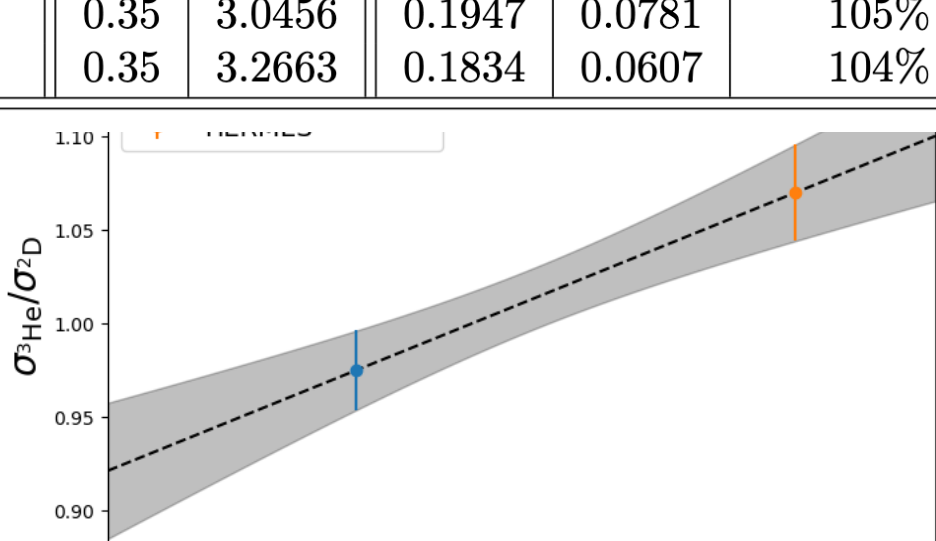
$$\Delta R = R_{\text{He3}} - R_{\text{D}}$$



$$\Delta R = R_{\text{He3}} - R_D$$



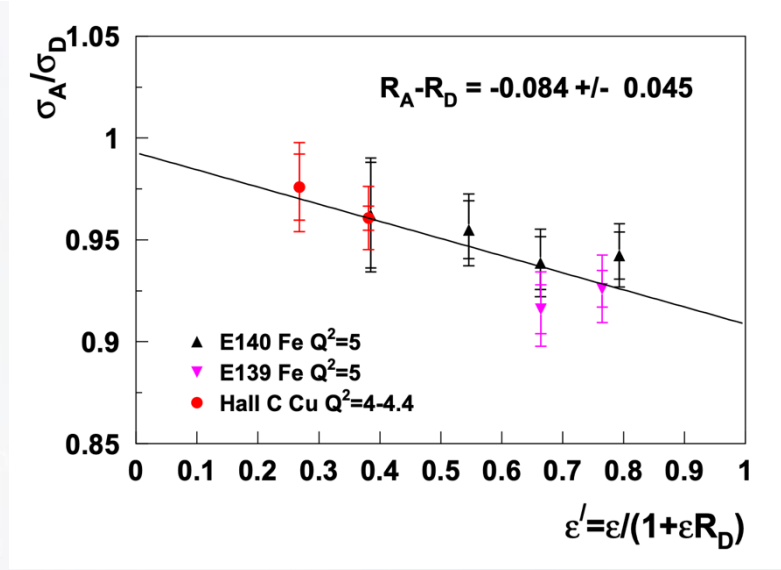
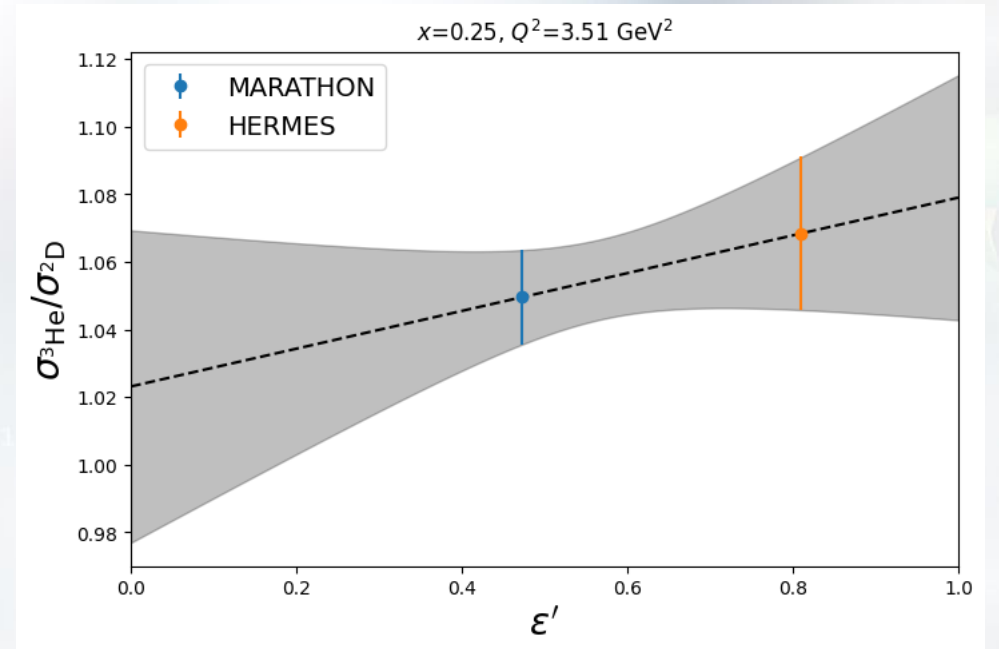
Data Sets	x	Q^2	ΔR	$\sigma_{\Delta R}$	$\Delta R/R_D$ (%)
HERMES + MARATHON	0.25	3.51	0.0554	0.0853	30.8%
HERMES + MARATHON	0.35	4.92	0.1318	0.0939	103%
HERMES + E03-103	0.35	3.0456	0.1947	0.0781	105%
HERMES + E03-103	0.35	3.2663	0.1834	0.0607	104%



* Note larger uncertainties than in proposal. Previously used covariance matrix. Newly reevaluated with MC Resampling. Error band in figure is from covariance matrix.

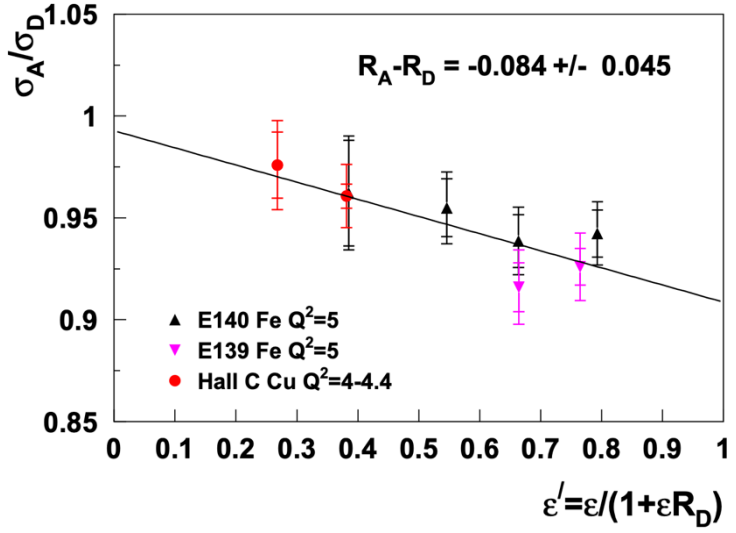
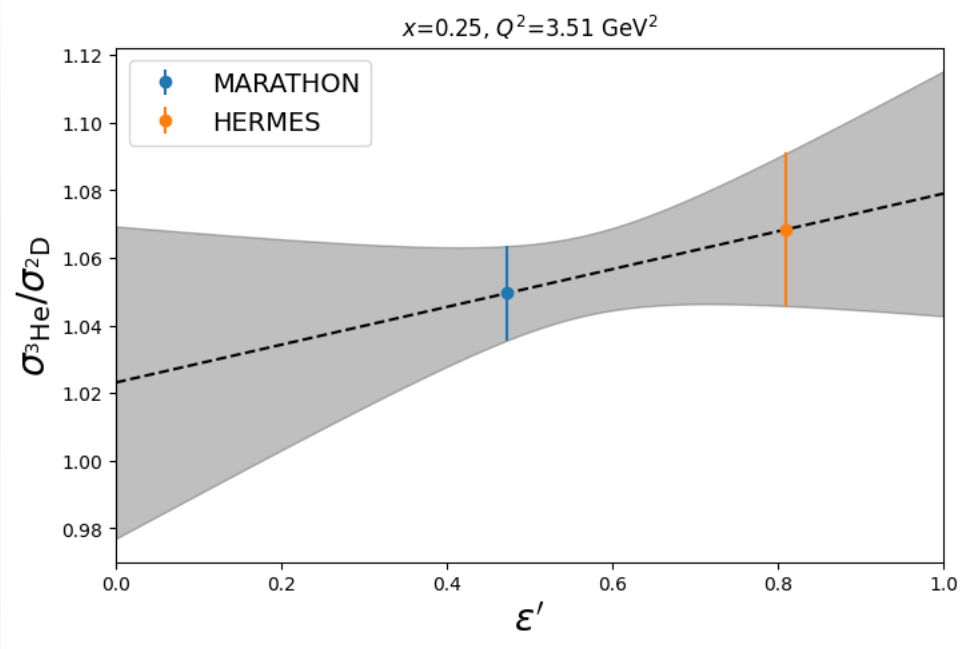
Discussion

- The slope is opposite that of the previously shown ΔR plots
- The slope indicates a larger value of R for Helium-3 than Deuterium
- How can we test this?



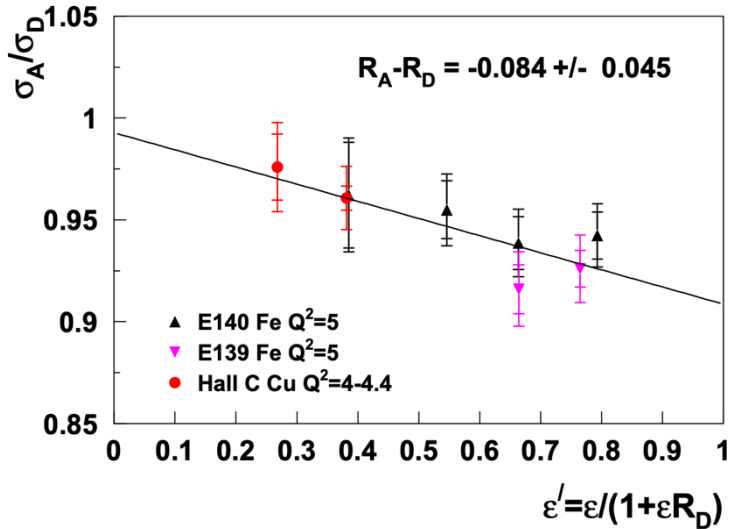
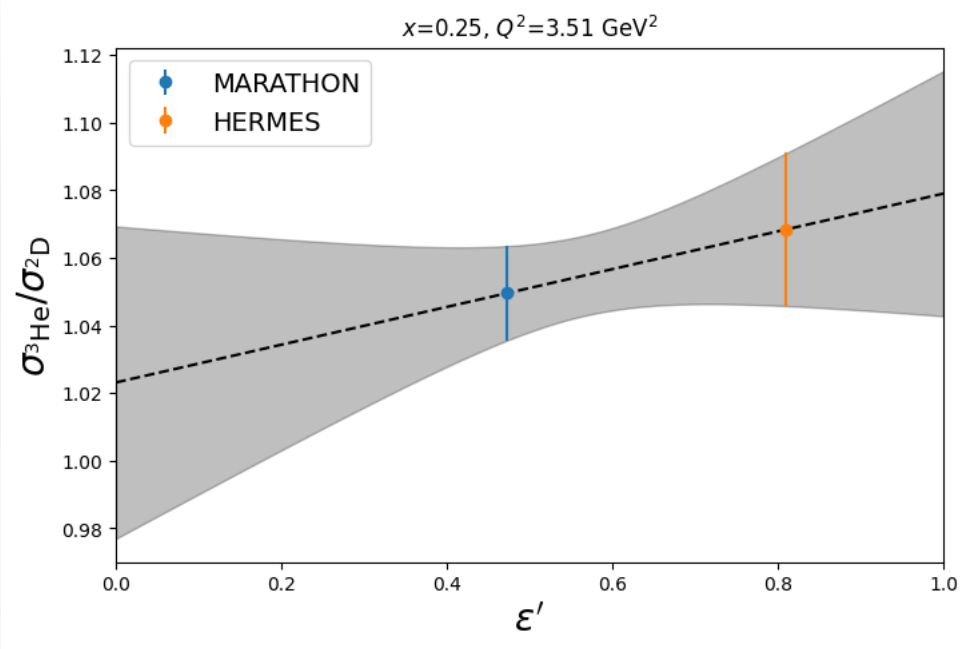
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- Helium-3 target
 - But when?



Discussion

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- The slope indicates a larger value of R for Helium-3 than Deuterium
- How can we test this?
- Helium-3 target
 - But when?
- E12-14-002 is scheduled for next year to test the A dependence of R
 - Could we add a Helium-3 target to the ladder?





PR12-26-008
Studying Possible Isospin
Dependence of $R = \sigma_L/\sigma_T$

The Proposal

- Add a Helium-3 target to the target ladder with E12-14-002
- Record data at a subset of the kinematic points
- Focus on broad x coverage to maximize potential impact on the EMC effect
- Extract R , F_1 , F_2 , F_L , and ΔR
- Uses HMS and SHMS in Hall C to record data

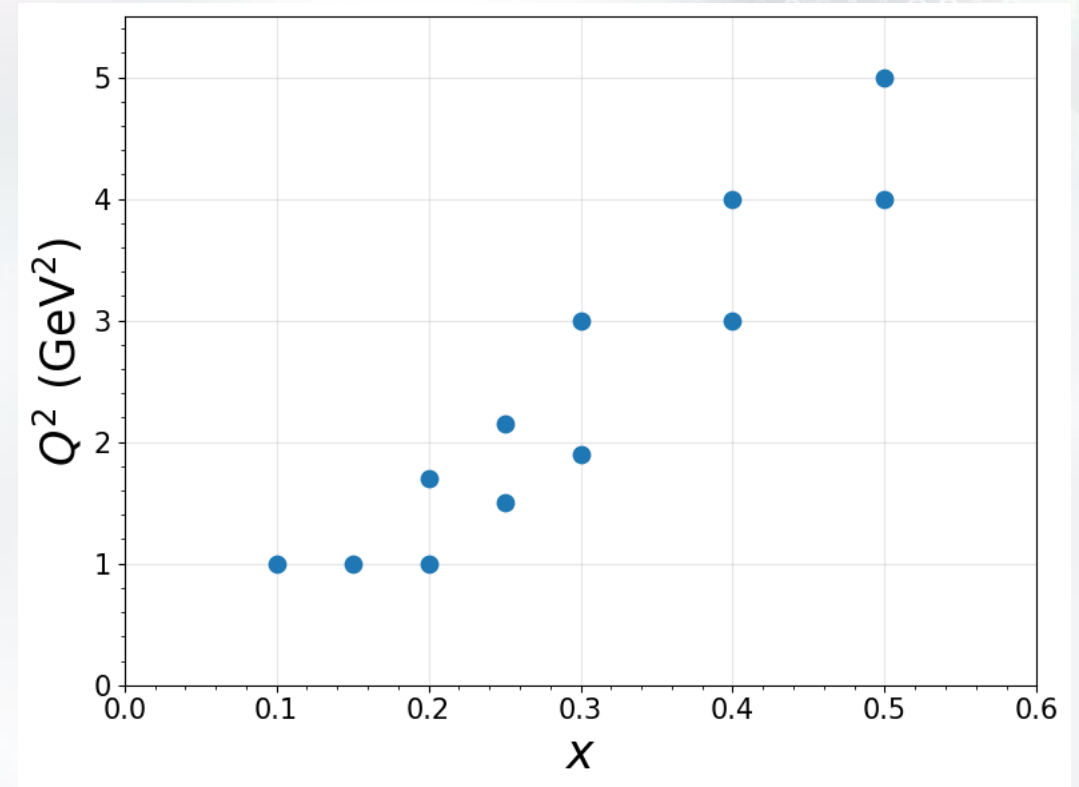
Activity	Time (hrs)
Production on Helium-3	88
Target Changes	6
Target Boiling Studies	2
Charge Symmetric Background Studies	9
Total	105 hours (5 days)

The Proposed Helium-3 Target

- E12-14-002 has two cryotargets already, LH2 and LD2
- Any additional cryotarget would use the third loop
- The high pressure target cells will be in use for LH2 and LD2, so we would use a low pressure cell
- For compatibility with the LH2 and LD2, we would use the 15K coolant as opposed to 4K
- Ventilation design is non-trivial
 - Discussions with target expert suggest that it's possible but hard
- The target will be quite thin
 - We estimate about 0.12% RL

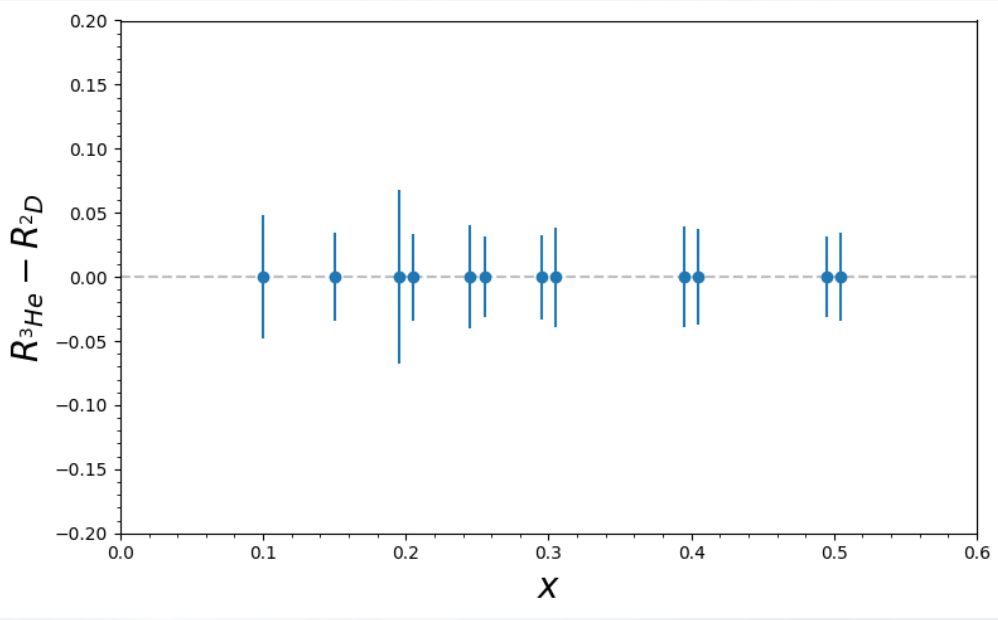
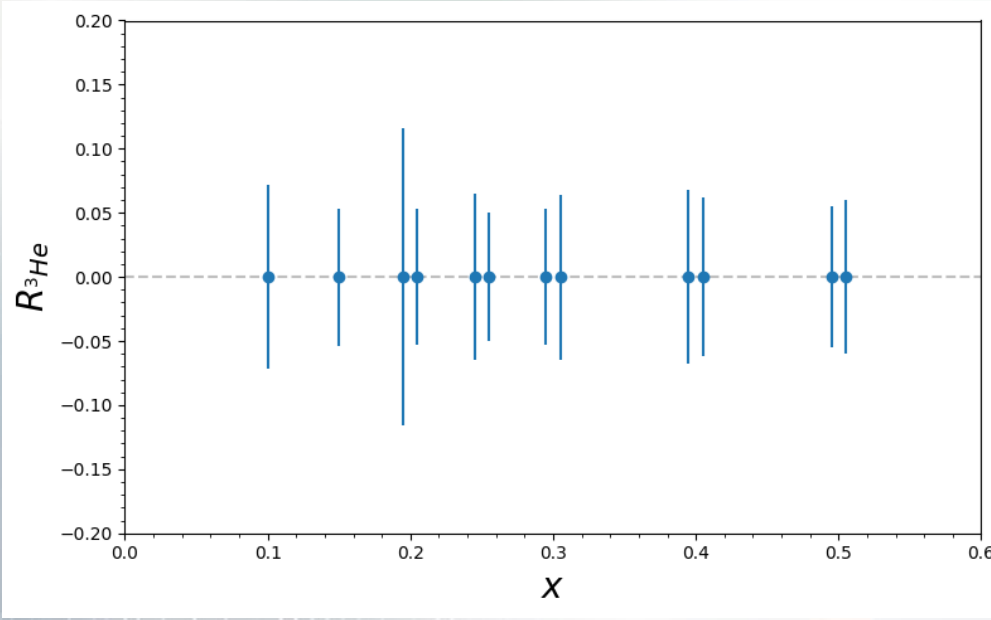
Kinematics Planned

- 0.5% Statistics goal
- 1.5% estimated target thickness uncertainty
- 1.8% estimated point-to-point systematics on He3 cross section
- 0.8-1.3% estimated point-to-point systematics on He3/D2 ratio



Projections

- Uncertainties on R and ΔR determined by 10000 Monte Carlo resampling trials
- Using 1.8% systematics for He3 cross section and 1.1% systematics for He3/D2 ratio



Summary

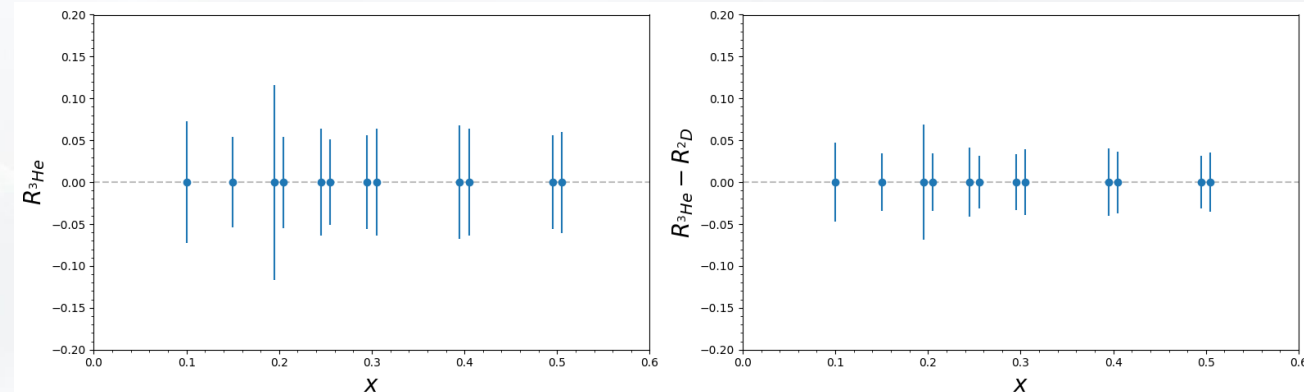
- There are hints of a nuclear dependence of $R = \sigma_L / \sigma_T$ in deuterium, iron, and copper
- This hint is also seen in Helium-3, but with opposite effect
 - Could this be a hint of isospin dependence of R ?
- PR12-26-008 proposes to make an exploratory measurement of R , F_1 , F_2 , FL , and ΔR on Helium-3 to test this hypothesis
- If this is the case, it could be a potential explanation for the perceived lack of unity crossing in world Helium-3 EMC measurements
- Any A or isospin dependence could have a dramatic impact on our current understanding of the EMC effect

QUESTIONS?

Backup

Runplan Contingencies

- It is a reasonable expectation that 7.7 GeV beam will not be available
- Only a small subset of our kinematics use this
- It is never the lowest or highest ϵ point
- Dropping these data points has minimal impact on the expected precision, based on running the same Monte Carlo resampling technique
- Would save ~ 8 hours
- Recent discussions surrounding the target ladder next year suggest that we may not be able to install until machine rescaling, losing 5.5 GeV
- We are actively investigating how we could adjust the runplan in that case, would likely change a few chosen x , Q^2 points



Why put Helium-3 on the same ladder?

- Plan is to use LD2 data from E12-14-002 to extract ΔR
- If they are not taken at the same time, systematics become large very quickly, as not all will cancel in the ratio
- On a different ladder, we would have to do every momentum, angle, and energy setting all over again
- The time savings from a thicker target are vastly overshadowed by the time increase from repeating kinematics