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

PR12-26-008 – PAC 54

July 6, 2026

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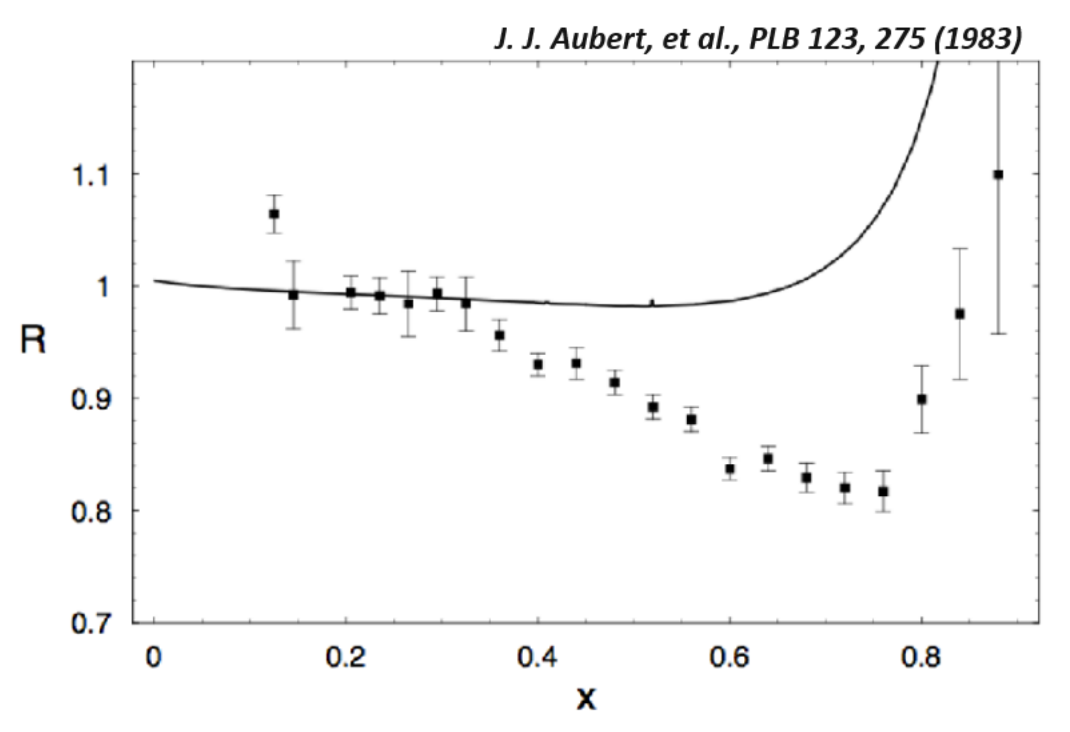
Motivation

The EMC Effect

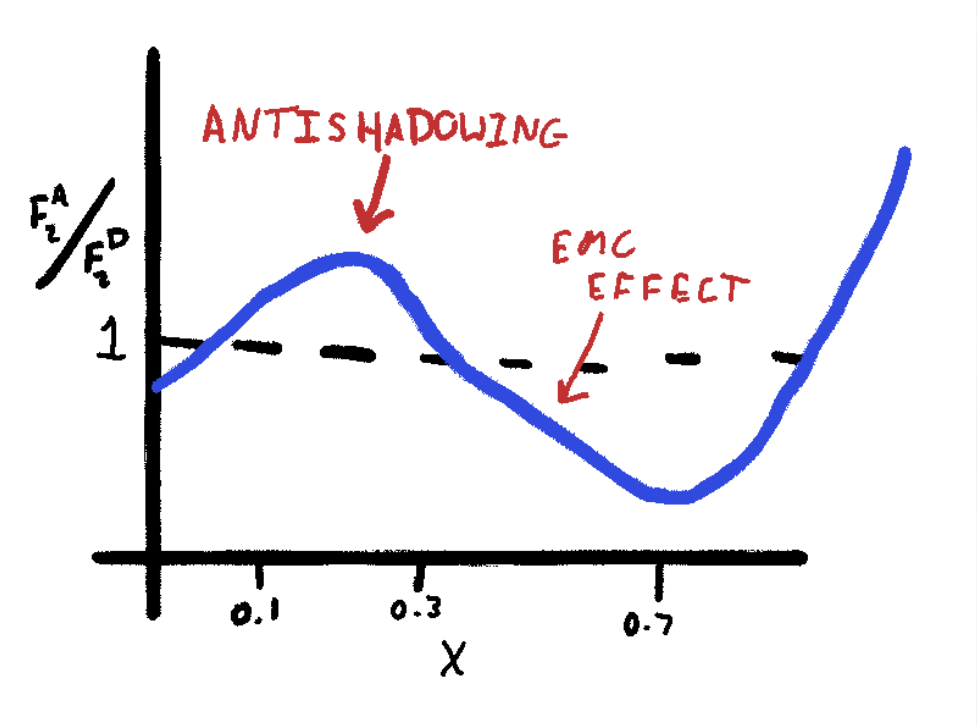
- First seen by the European Muon Collaboration (EMC)
- Partonic structure of nucleons is modified in nuclei
- Studied through ratios of nuclear F_2 structure functions to deuterium



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

The EMC Effect

- Target ratios are generally characterized by universal features:
  - Shadowing
  - Antishadowing
  - EMC Effect
  - Fermi Smearing
- Antishadowing and the EMC Effect are relevant to this discussion



The Problem of Helium-3

Helium-3 DIS Data

- There are three world data sets of DIS on Helium-3, all of which deviate from the "universal" picture

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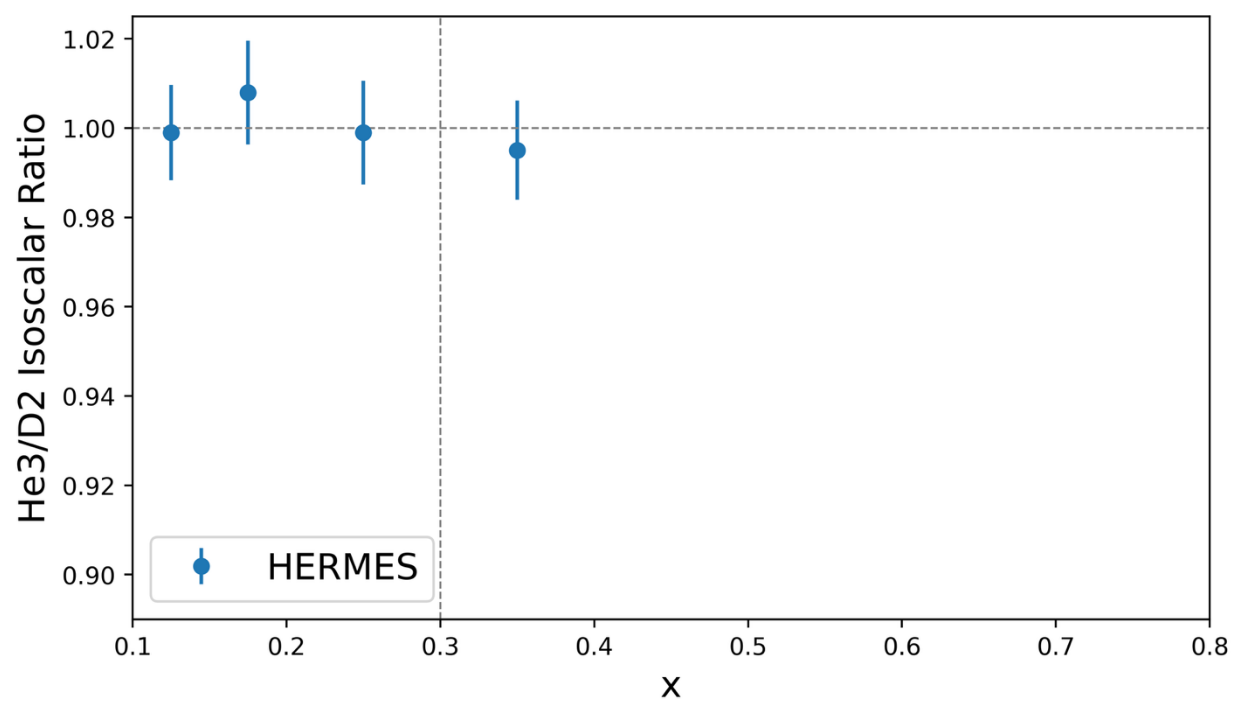

Helium-3 DIS Data

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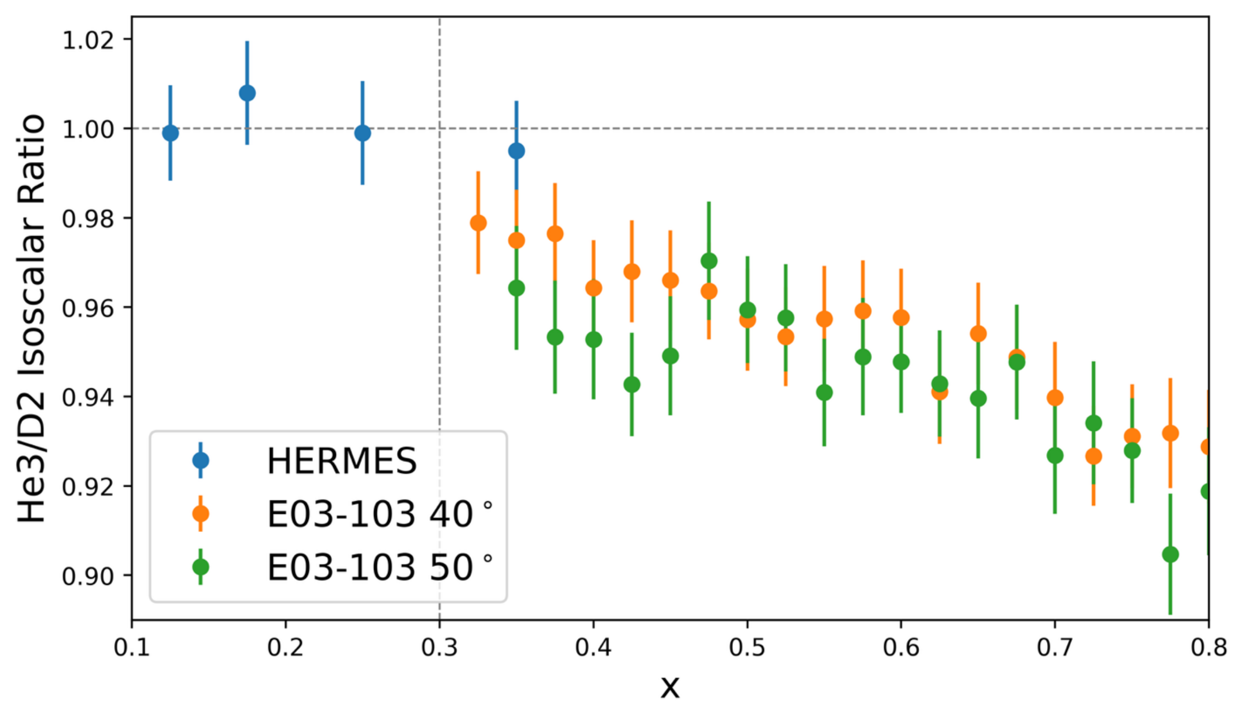
  - Twice is a coincidence



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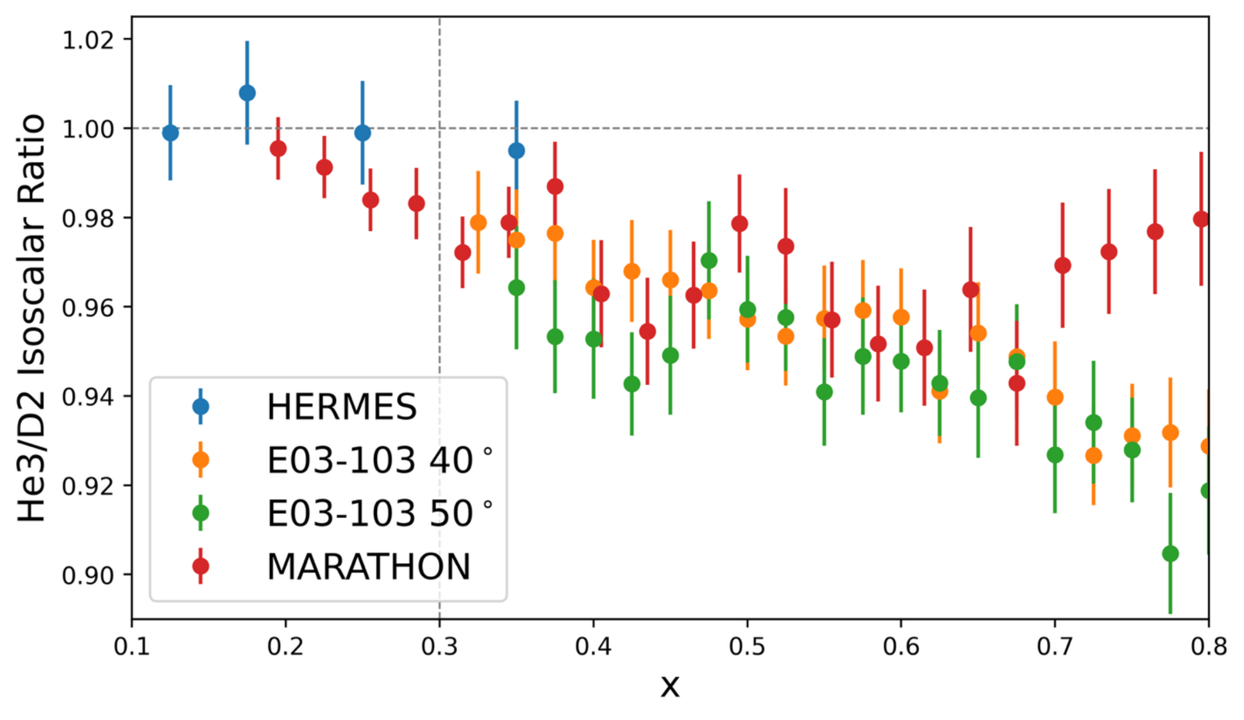

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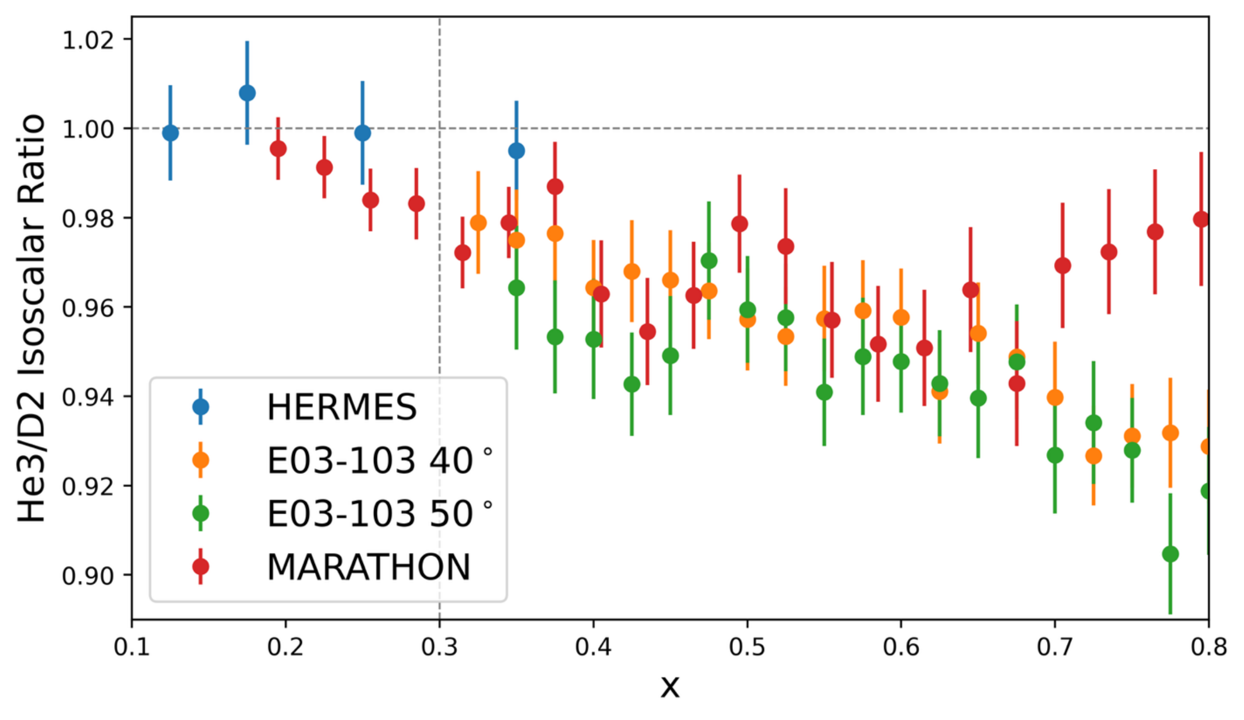
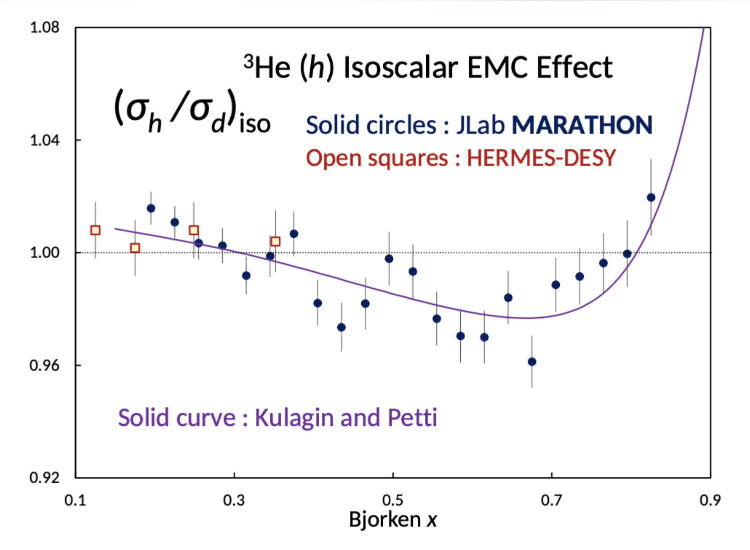


None of these data sets show the expected unity crossing at x=0.3!*

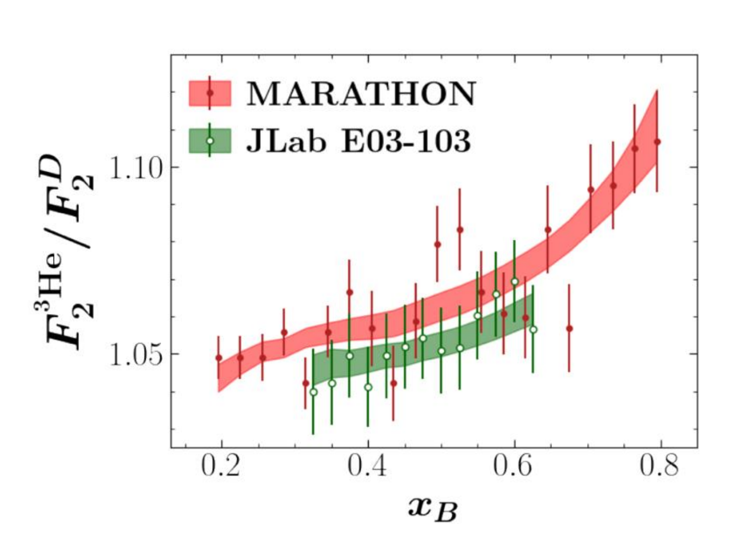
*HERMES and MARATHON were both normalized to "correct" for this. All normalizations are removed in this figure.

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, 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)

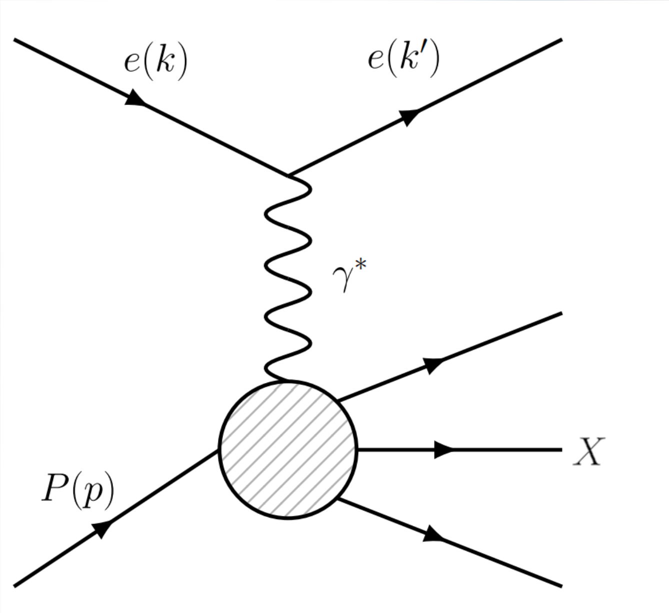


C. Cocuzza, TJH, *et al*, arXiv: 2602.16589 (2026)

A brief look at equations

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)



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

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

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 $R=\sigma_L/\sigma_T$

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

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

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

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

Getting F_2 Ratios

- From a cross section ratio, we can see that they are equal to the F_2 ratio multiplied by a set of kinematic factors
- If, and only if, $R_A = R_D$ we can then completely cancel those terms so long as the data were taken at the same kinematics
- This is the standard assumption made

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

If $R_A = R_D$:

$$\frac{\sigma_A}{\sigma_D} = \frac{F_2^A}{F_2^D}$$

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- How well do we know it?

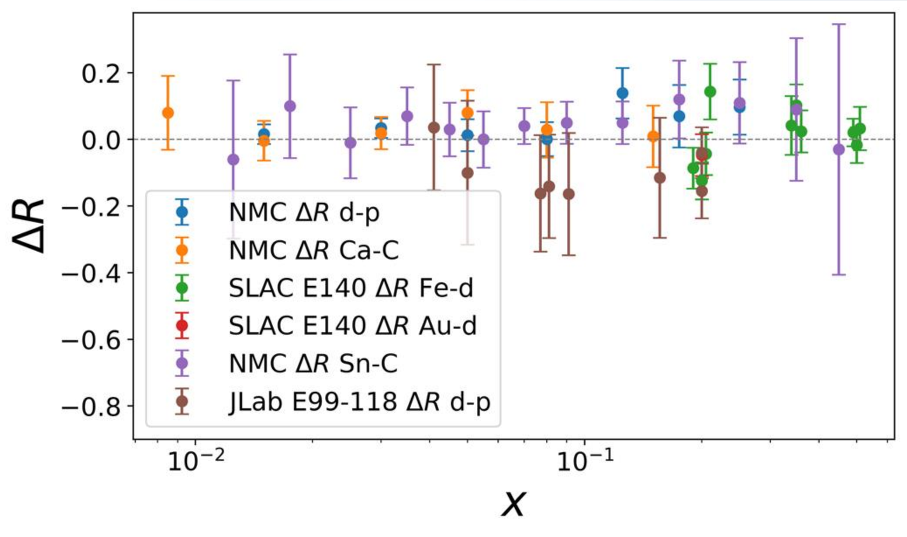
$$\frac{\frac{d^2\sigma_A}{d\Omega dE'}}{\frac{d^2\sigma_D}{d\Omega dE'}} = \frac{\sigma_A}{\sigma_D} = \frac{F_2^A\left[\frac{1}{\nu} + \frac{(1+Q^2/\nu^2)}{xM(1+R_A)}\tan^2\left(\frac{\theta}{2}\right)\right]}{F_2^D\left[\frac{1}{\nu} + \frac{(1+Q^2/\nu^2)}{xM(1+R_D)}\tan^2\left(\frac{\theta}{2}\right)\right]}$$

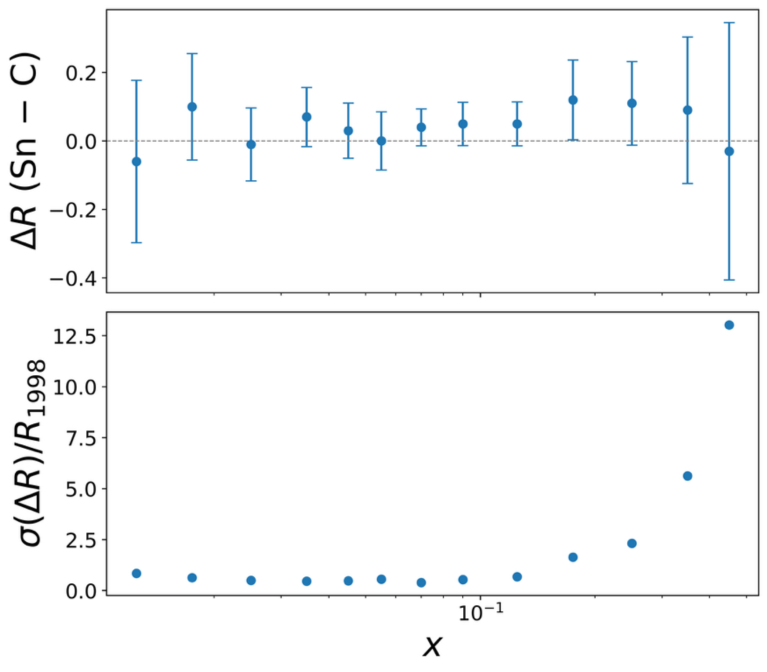
If $R_A = R_D$:

$$\frac{\sigma_A}{\sigma_D} = \frac{F_2^A}{F_2^D}$$

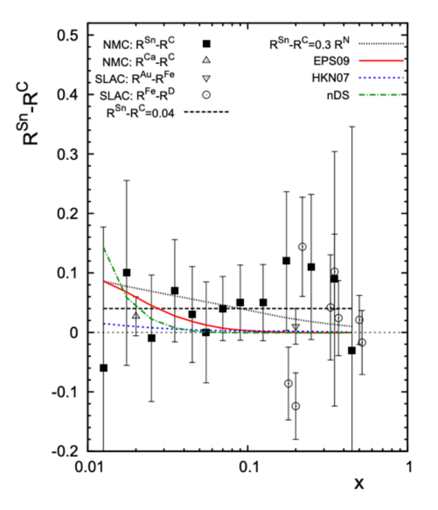
Universality of R

- 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





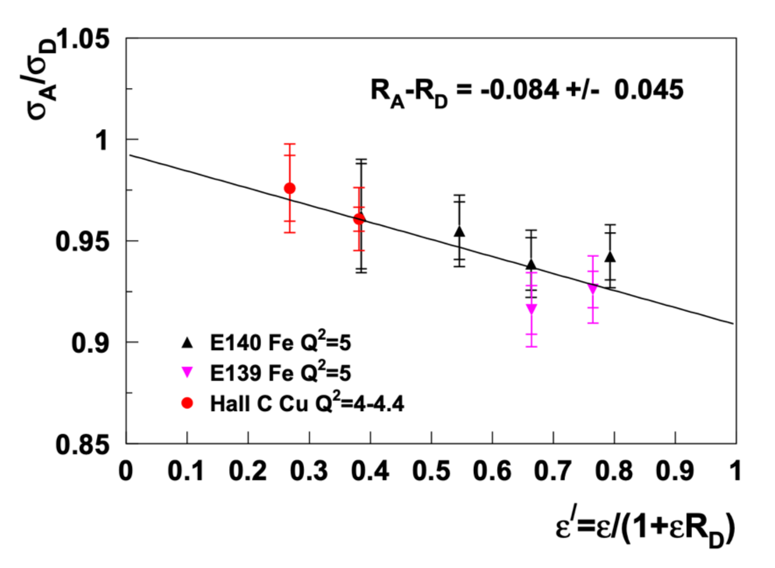
An example of precision of ΔR=0
Data from M. Arneado *et al*, NPB 481 (1996)
R1998 from K. Abe *et al*, PLB 452 (1999)

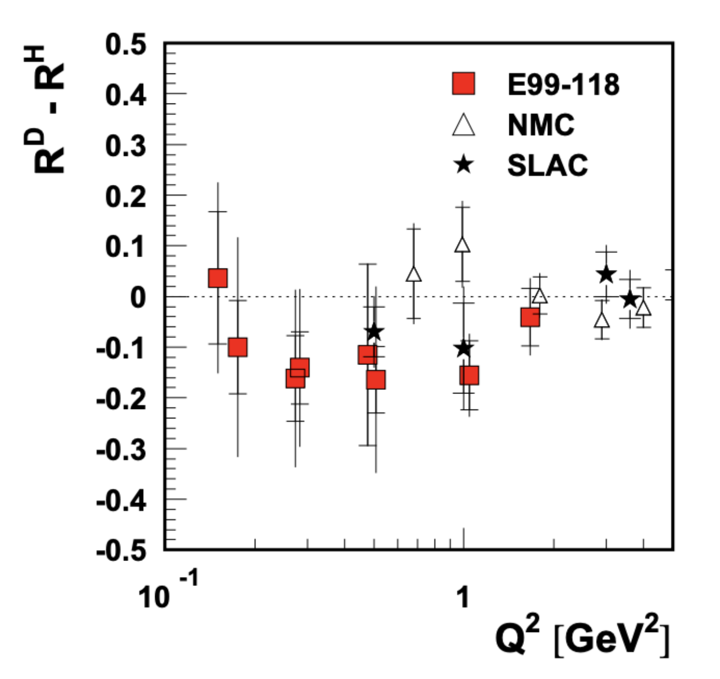


V. Guzey *et al,* PRC 86 (2012)

Cracks in the Picture

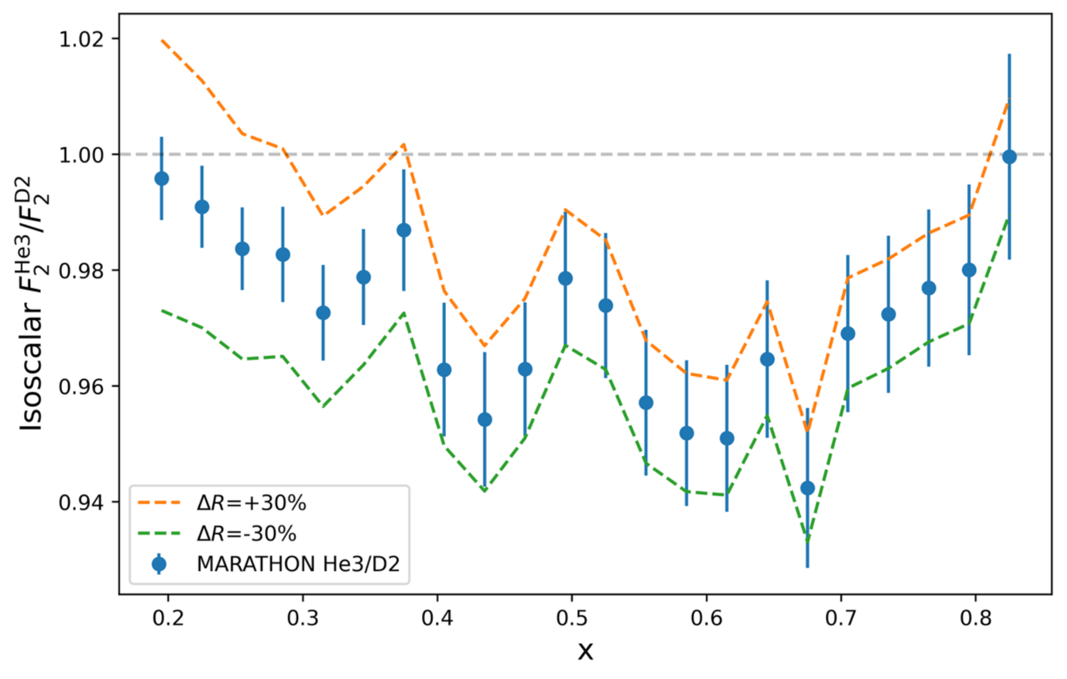
- Analyses in the E12-14-002 proposal and V. Tvaskis *et al.*, PRL 98 (2007) hint that R may not be universal in the DIS regime
- Model independent analyses find that R_D trends smaller than R_p
- Model independent analyses find that R_A trends smaller than R_D
  - The nuclear targets studied are iron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





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

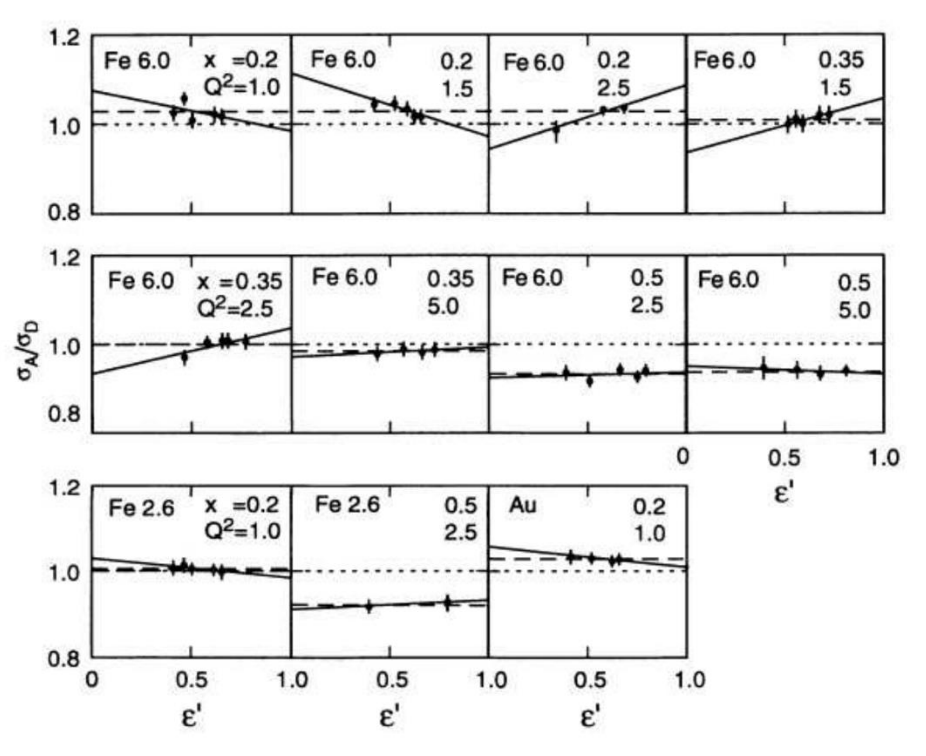


30% selected to match an example in V. Guzey *et al*. The value is well within the uncertainty at which R is measured to be universal

Model independent extraction of R and 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

$$\frac{\sigma\_A}{\sigma\_D} = \frac{F_1^A}{F_1^D}[1 + \epsilon`\Delta R] \qquad \sigma = \Gamma\sigma_T(1 + \epsilon R)$$



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

Can data tell us anything?

Let’s check

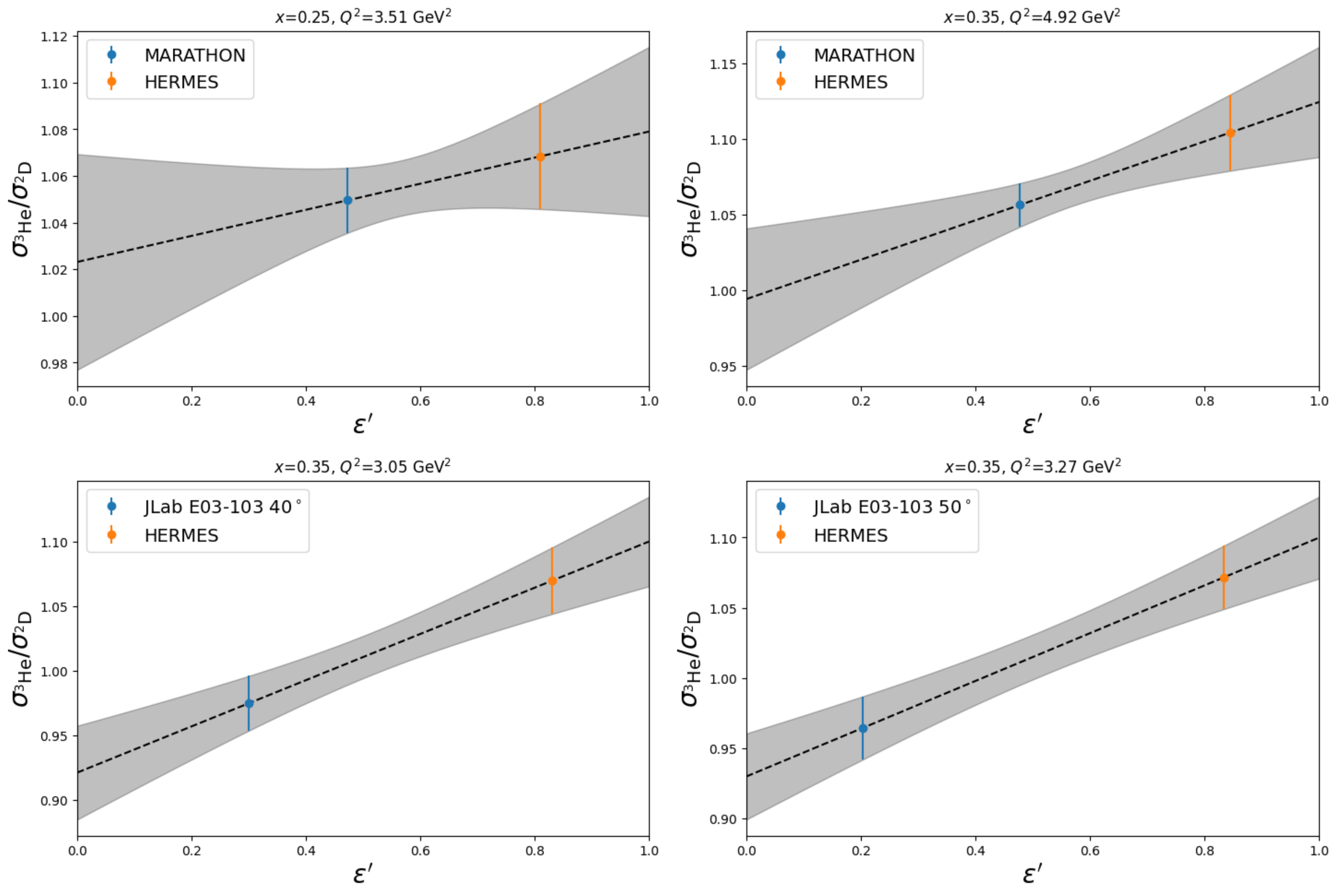
Data used

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))

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

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



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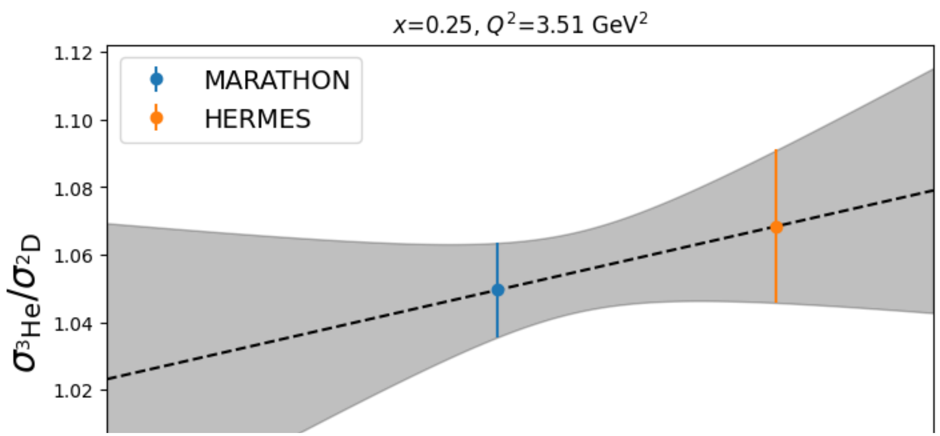
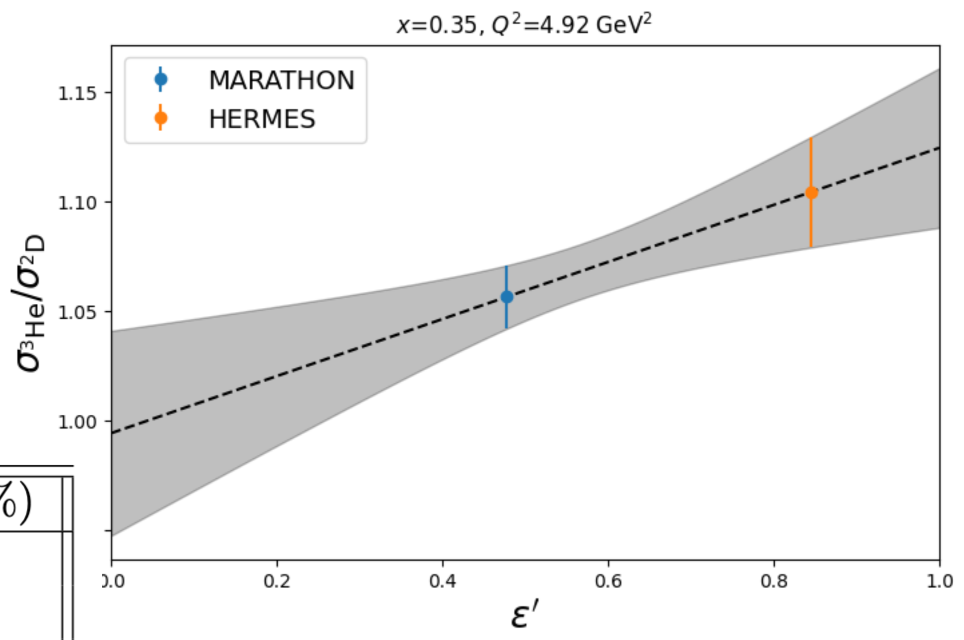
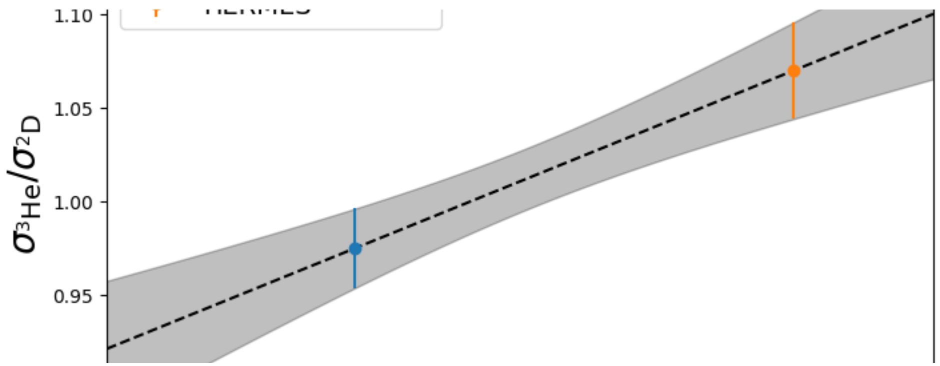
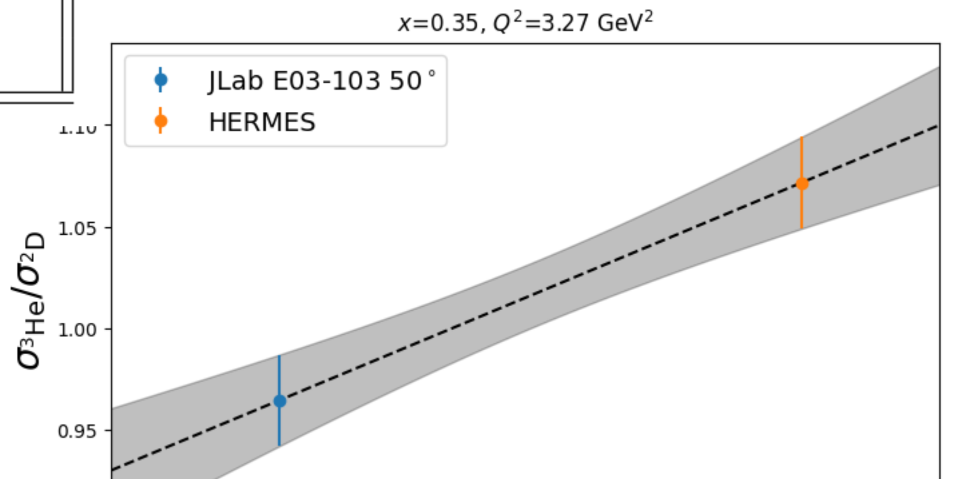




Data Sets	x	Q^2	ΔR	$\sigma_{\Delta R}$	$\Delta R/R_D$ (%)
HERMES + MARATHON	0.25	3.51	0.0554	0.0853	30.8%
HERMES + MARATHON	0.35	4.92	0.1318	0.0939	103%
HERMES + E03-103	0.35	3.0456	0.1947	0.0781	105%
HERMES + E03-103	0.35	3.2663	0.1834	0.0607	104%

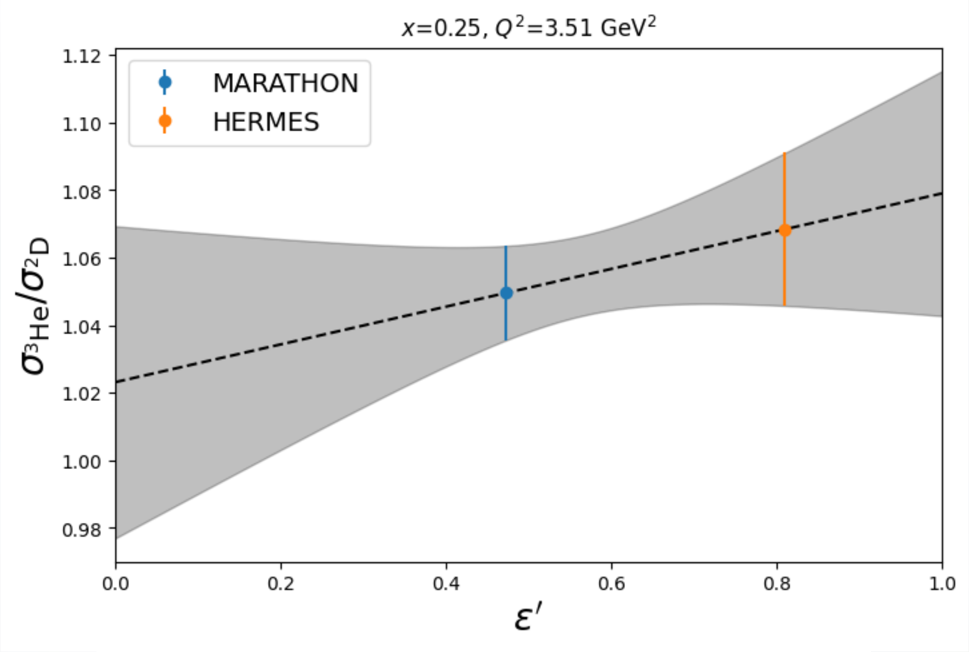


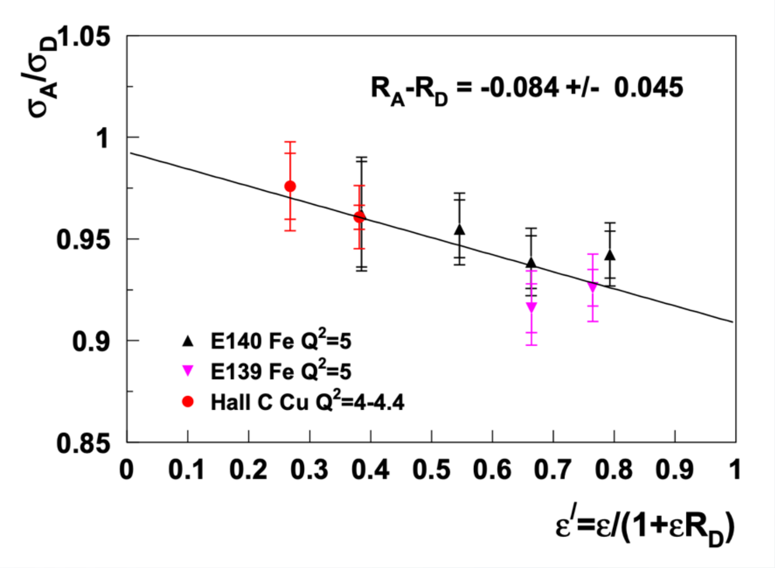


** Note larger uncertainties on ΔR than in proposal. Previously used covariance matrix. Newly reevaluated with MC resampling.*
Error band in figure is from covariance matrix, not the MC resampling.
MC resampling uses each experiments statistical, systematic, and scale uncertainties added in quadrature for smearing

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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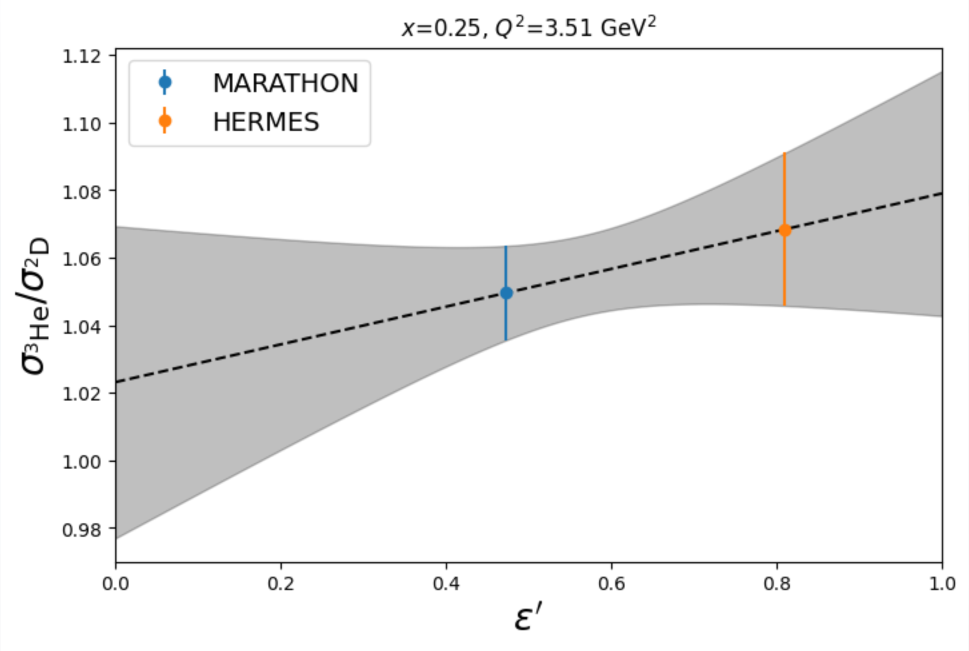
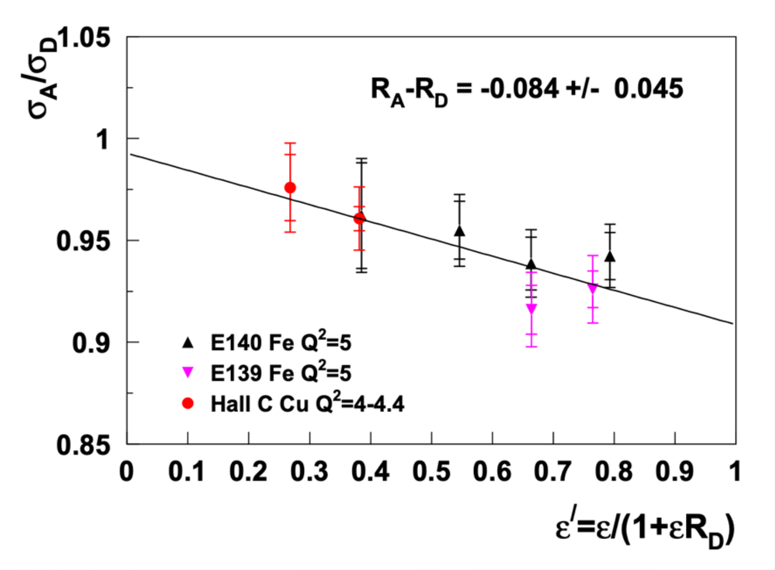
- Helium-3 target
    - But when?





Discussion

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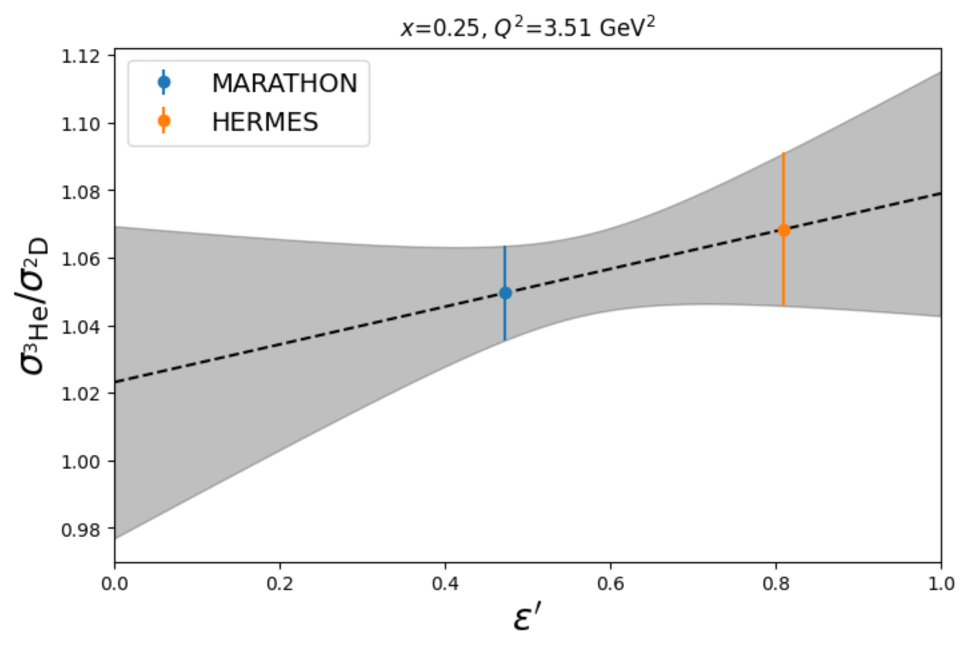
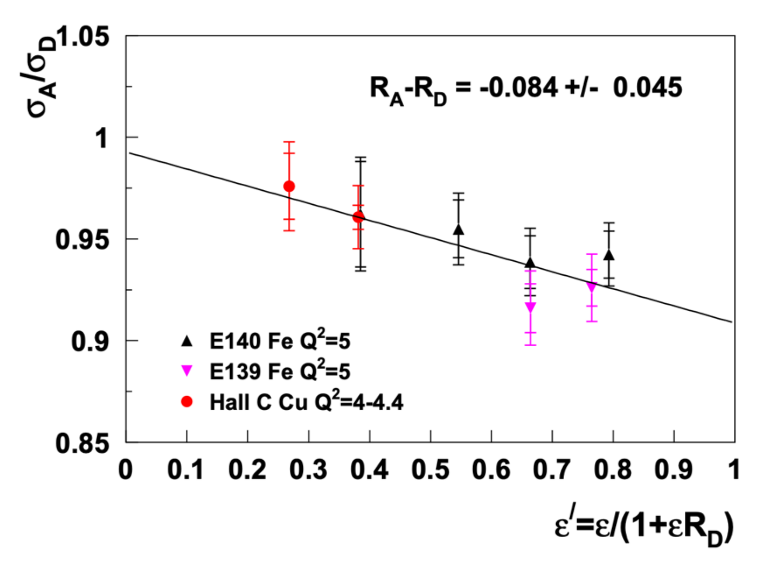
- The slope indicates a larger value of R for Helium-3 than Deuterium
- How can we test this?
- Helium-3 target
  - But when?
- E12-14-002 is scheduled for next year to test the A dependence of R
  - Could we add a Helium-3 target to the ladder?





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	67
Target Changes	39
Target Boiling Studies	2
Charge Symmetric Background Studies	7
Total	115 hours (5 days)

*Time budget has changed from proposal text to reflect changes necessary based on new information that became known from discussions that occurred about TAC comments and PAC reader questions. See backup slides for further details of these changes.

The Proposed Helium-3 Target

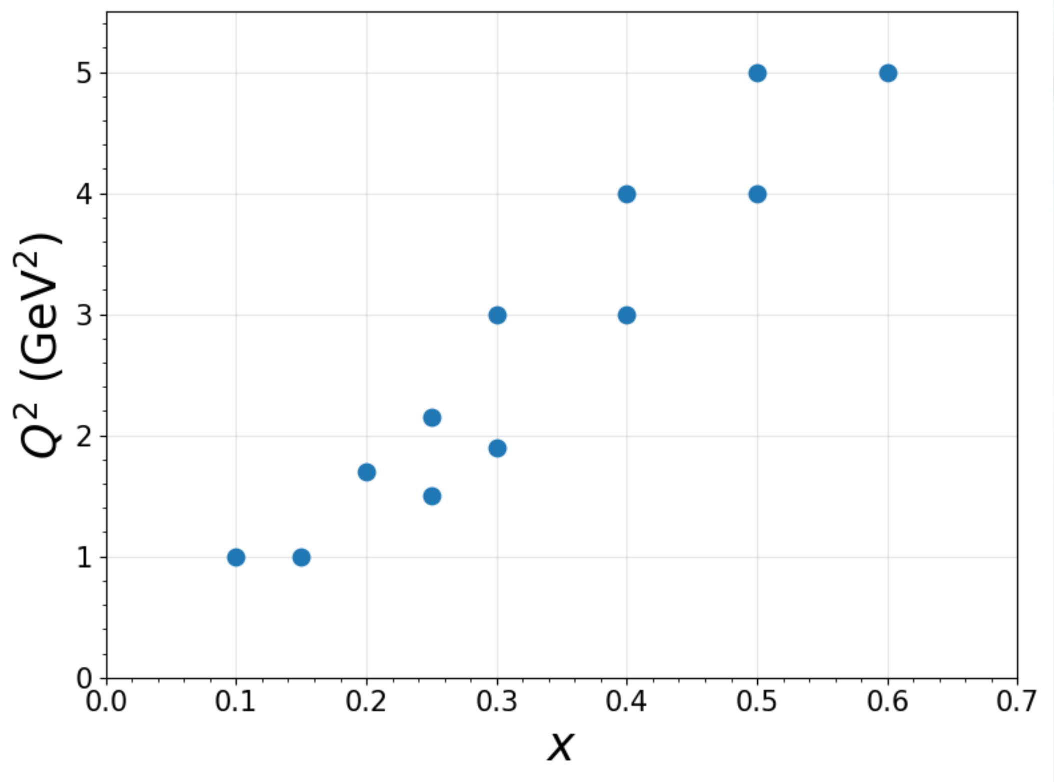
- E12-14-002 has two cryotargets already, LH2 and LD2
- Any additional cryotarget would use the third loop
- The high pressure target cells will be in use for LH2 and LD2, so we would use a low pressure cell
- For compatibility with the LH2 and LD2, we would use the 15K coolant as opposed to 4K
- Ventilation 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

A note on scheduling

- We propose to run with E12-14-002, Precision Measurements and Studies of a Possible Nuclear Dependence of $R=\sigma L/\sigma T$
- The TAC and PAC readers informed us that the FY27 run period begins with a large number of solid targets on the target ladder, leaving no space for a third loop
- The schedule has 2 weeks for the machine to rescale from 1.1 GeV/pass to 2.2 GeV/pass
- Speaking with target experts, this is enough time for the target group to remove the solid targets from the ladder and install the third loop for this proposal
- This makes the 5.5 GeV beam energy unavailable for us, this solution is acceptable and still allows for us to make a very good measurement with slightly adjusted kinematics within the requested beam time
- Figures in this presentation use adjusted kinematics based on an assumed unavailability of 5.5 GeV and 7.7 GeV. Projected uncertainties are also recalculated in the absence of these energies.

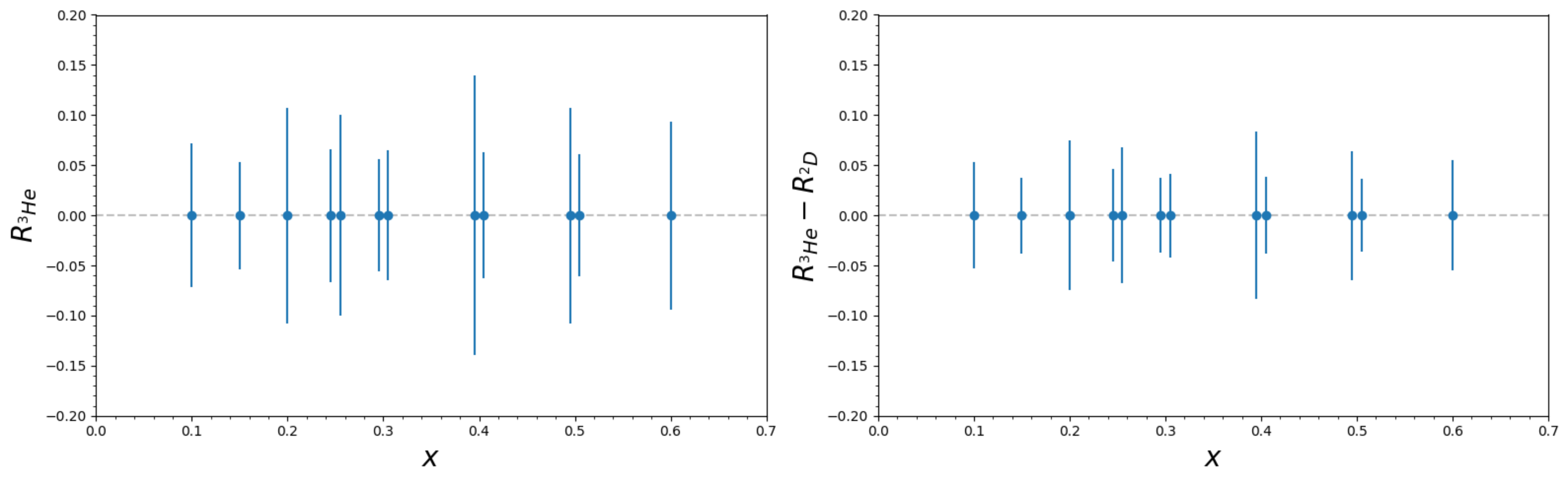
Kinematics Planned

- 0.5% Statistics goal
- 2.55% estimated target thickness uncertainty
  - Note that target thickness uncertainty cancels in the extraction of R and ΔR
- 1.8% estimated point-to-point systematics on He3 cross section
- 0.8-1.3% estimated point-to-point systematics on He3/D2 ratio

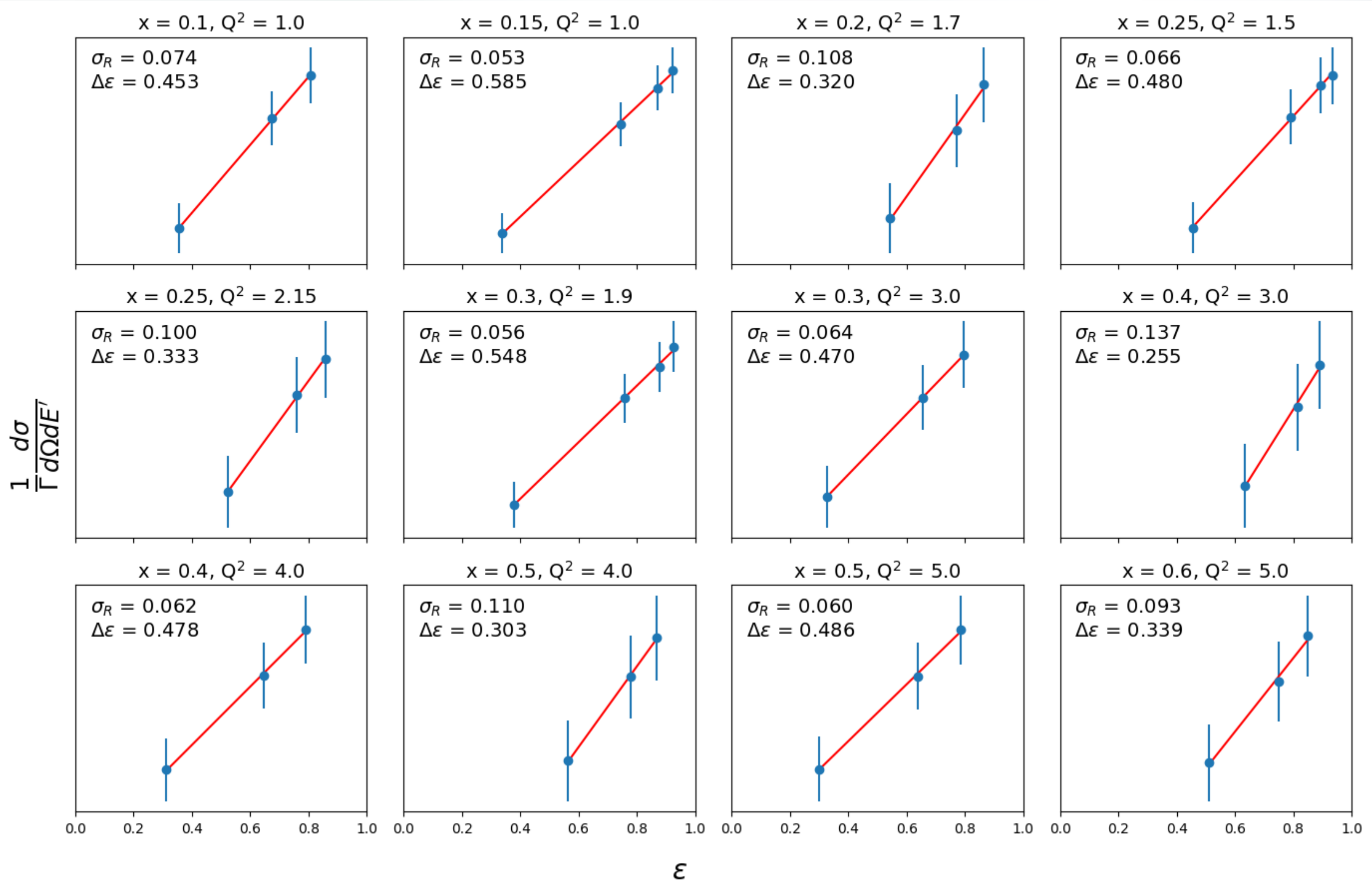


Projections

- 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



Projections



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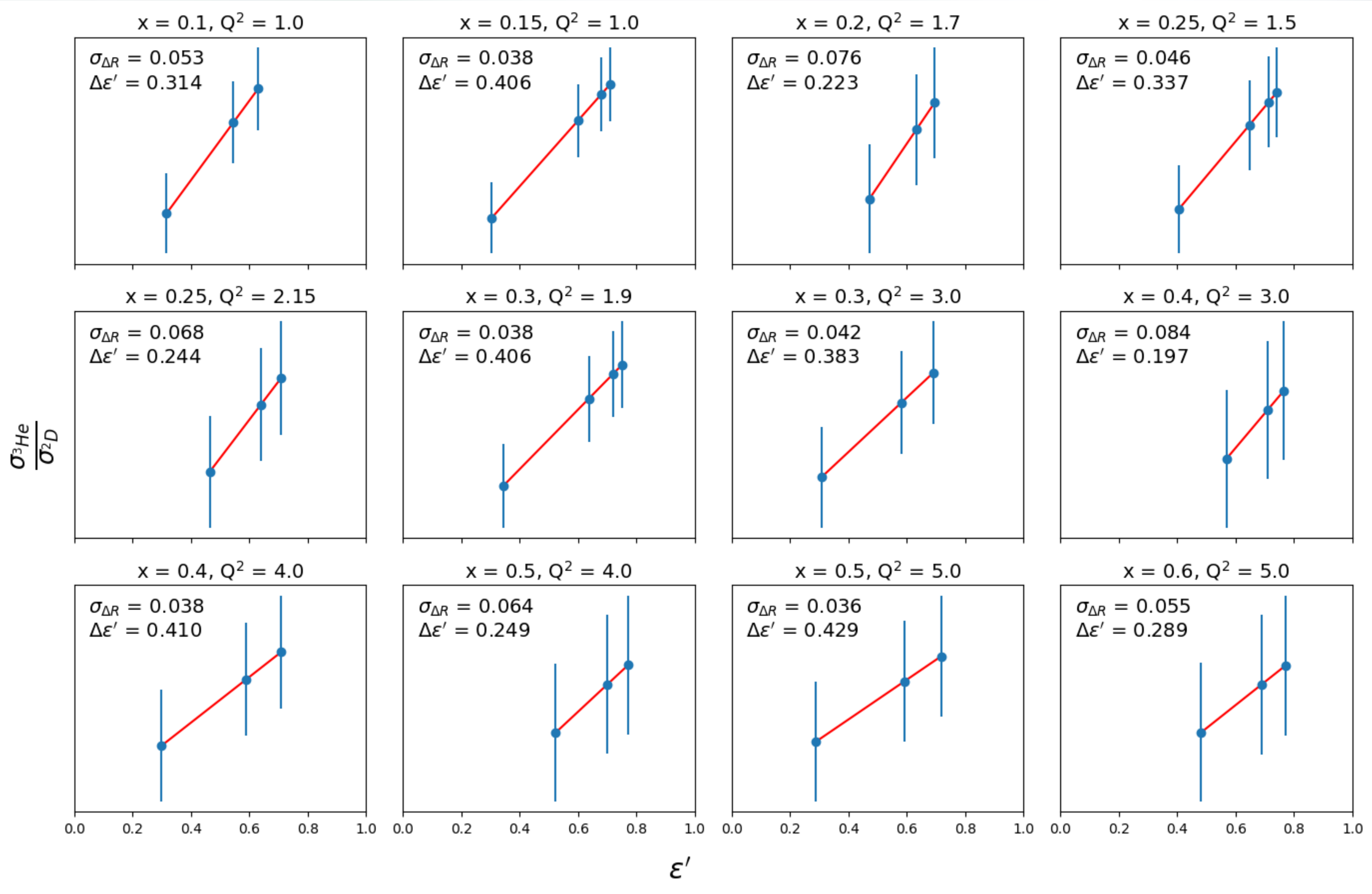
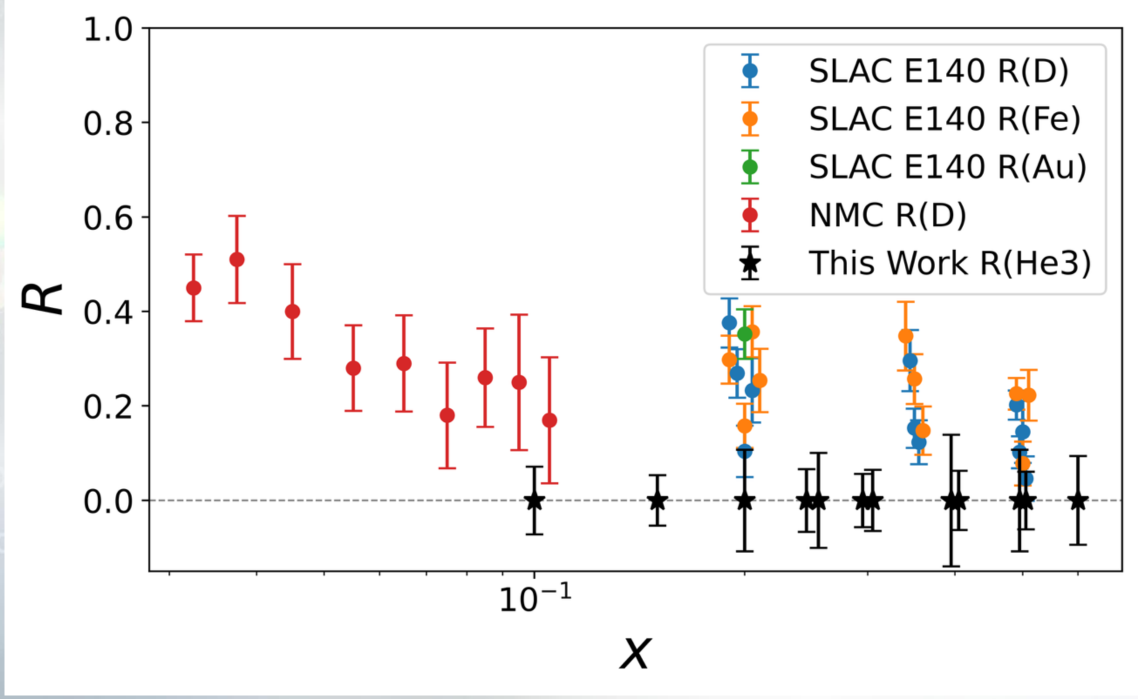
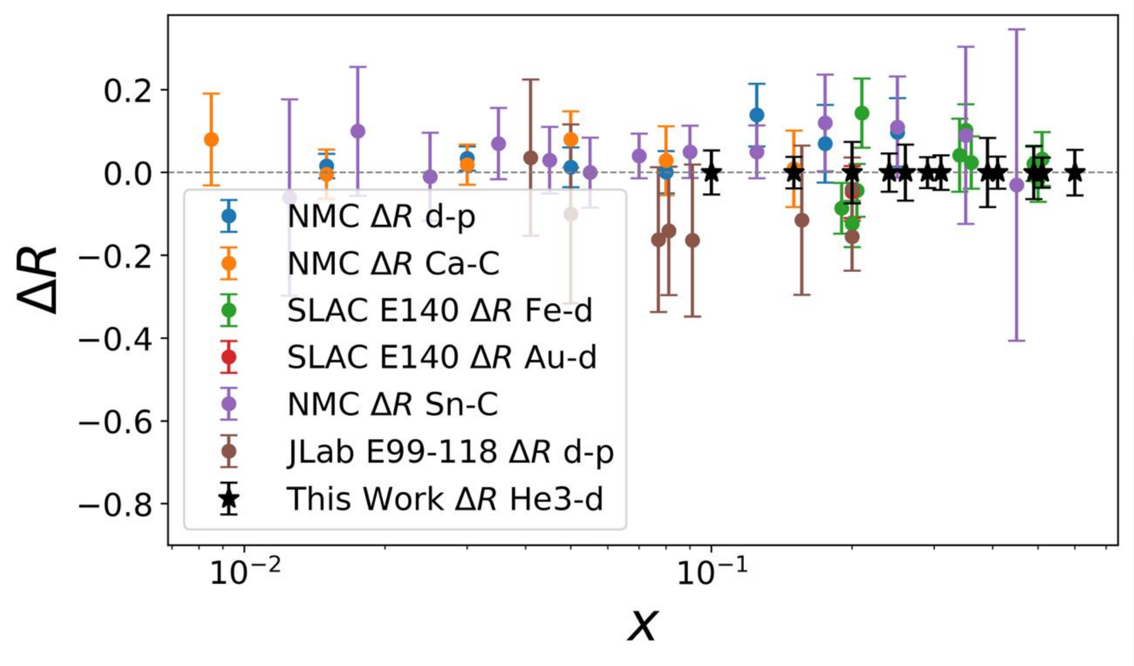


Projections





Summary

- There are hints of a nuclear dependance 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, F_L, and ΔR on Helium-3 to test this hypothesis
- If this is the case, it is 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
- We request 5 PAC days to record DIS data on Helium-3 for performing LT separations to test and constrain the impact of a potential non-zero ΔR

QUESTIONS?

Backup

Runplan Adjustments

- There is no plan for 7.7 GeV beam to be available next year for any experiment
- Due to target ladder constraints, there is no room to add the Helium-3 target to the ladder during the 1.1 GeV/pass running, making 5.5 GeV unavailable
  - There are 4 kinematics for which this was the lowest epsilon setting, which impacted the projected uncertainties
  - Due to comparable uncertainties after this change, we opted to exchange one x=.2 point for an x=0.6 point to cover more range
- The production beam time request decreased due to these energies being unavailable
- Further discussions with target experts indicated that while three cryotargets can be kept cold, only two can be ready for beam. The third must be parked.
  - Making the parked target ready requires adjusting the JT valves, we estimate 15 minutes for the change
  - We then double this to account for adjusting back to being ready for E12-14-002
- Charge symmetric background studies are still estimated at 10% of the production time. However, given the significant increase in target change time accounting, we have opted to double the target change time estimate to account for target changes during these studies.
- In total, each setting contributes 1 hour to target changes to account for readying the target, returning to the previous setting, and ensuring there is sufficient time for CSB studies.

Updated Kinematics Table

x	Q^2	E_{Beam}	E'	θ	ϵ	HMS/SHMS Rate (Hz)	HMS/SHMS Prescale	Time (h)
0.1	1	6.6	1.271	19.881	0.356	714 /	1 /	0.5
		8.8	3.471	10.381	0.673	7145 / 8891	3 / 3	0.1
		11	5.671	7.259	0.809	25410 / 34214	9 / 17	0.2
Kinematic Subtotal:								0.8
0.15	1	4.4	0.847	30.015	0.338	286 /	1 /	0.6
		6.6	3.047	12.802	0.745	6015 / 7395	3 / 3	0.1
		8.8	5.247	8.439	0.871	26011 / 34832	9 / 17	0.2
		11	7.447	6.333	0.923	/ 103510	/ 65	0.7
Kinematic Subtotal:								1.6
0.2	1.7	6.6	2.07	20.315	0.544	674 / 791	1 / 1	0.2
		8.8	4.27	12.209	0.77	4184 / 5093	2 / 2	0.2
		11	6.47	8.864	0.864	12883 / 16607	5 / 9	0.2
Kinematic Subtotal:								0.6
0.25	1.5	4.4	1.203	30.877	0.456	241 /	1 /	1
		6.6	3.403	14.849	0.79	3317 / 3963	2 / 2	0.1
		8.8	5.603	10.006	0.893	13055 / 16410	5 / 9	0.2
		11	7.803	7.58	0.936	/ 44416	/ 17	0.4
Kinematic Subtotal:								1.7
0.25	2.15	6.6	2.017	23.183	0.525	355 / 409	1 / 1	0.5
		8.8	4.217	13.824	0.759	2276 / 2674	1 / 1	0.1
		11	6.417	10.012	0.858	7085 / 8647	3 / 3	0.2
Kinematic Subtotal:								0.8
0.3	1.9	4.4	1.025	37.874	0.378	90 /	1 /	2.6
		6.6	3.225	17.183	0.758	1534 / 1766	1 / 1	0.2
		8.8	5.425	11.449	0.877	6334 / 7520	3 / 3	0.2
		11	7.625	8.632	0.926	/ 20340	/ 9	0.4
Kinematic Subtotal:								3.4

0.3	3	6.6	1.271	34.795	0.327	53 /	1 /	5.6
		8.8	3.471	18.03	0.655	565 / 640	1 / 1	0.5
		11	5.671	12.59	0.797	2031 / 2367	1 / 1	0.2
Kinematic Subtotal:								6.3
0.4	3	6.6	2.603	24.119	0.634	229 / 249	1 / 1	0.9
		8.8	4.803	15.309	0.814	1158 / 1242	1 / 1	0.3
		11	7.003	11.325	0.889	/ 3522	/ 2	0.4
Kinematic Subtotal:								1.6
0.4	4	6.6	1.271	40.395	0.313	21 /	1 /	15.9
		8.8	3.471	20.848	0.646	224 / 242	1 / 1	0.6
		11	5.671	14.547	0.791	813 / 874	1 / 1	0.3
Kinematic Subtotal:								16.8
0.5	4	6.6	2.337	29.503	0.565	62 / 64	1 / 1	1.7
		8.8	4.537	18.212	0.778	349 / 351	1 / 1	0.5
		11	6.737	13.342	0.868	/ 1023	/ 1	0.4
Kinematic Subtotal:								2.6
0.5	5	6.6	1.271	45.413	0.299	8 /	1 /	16.5
		8.8	3.471	23.342	0.637	92 / 94	1 / 1	1.9
		11	5.671	16.276	0.785	336 / 334	1 / 1	0.7
Kinematic Subtotal:								19.1
0.6	5	6.6	2.159	34.455	0.512	19 / 19	1 / 1	8.8
		8.8	4.359	20.799	0.75	116 / 109	1 / 1	1.9
		11	6.559	15.127	0.851	359 / 326	1 / 1	0.8
Kinematic Subtotal:								11.5