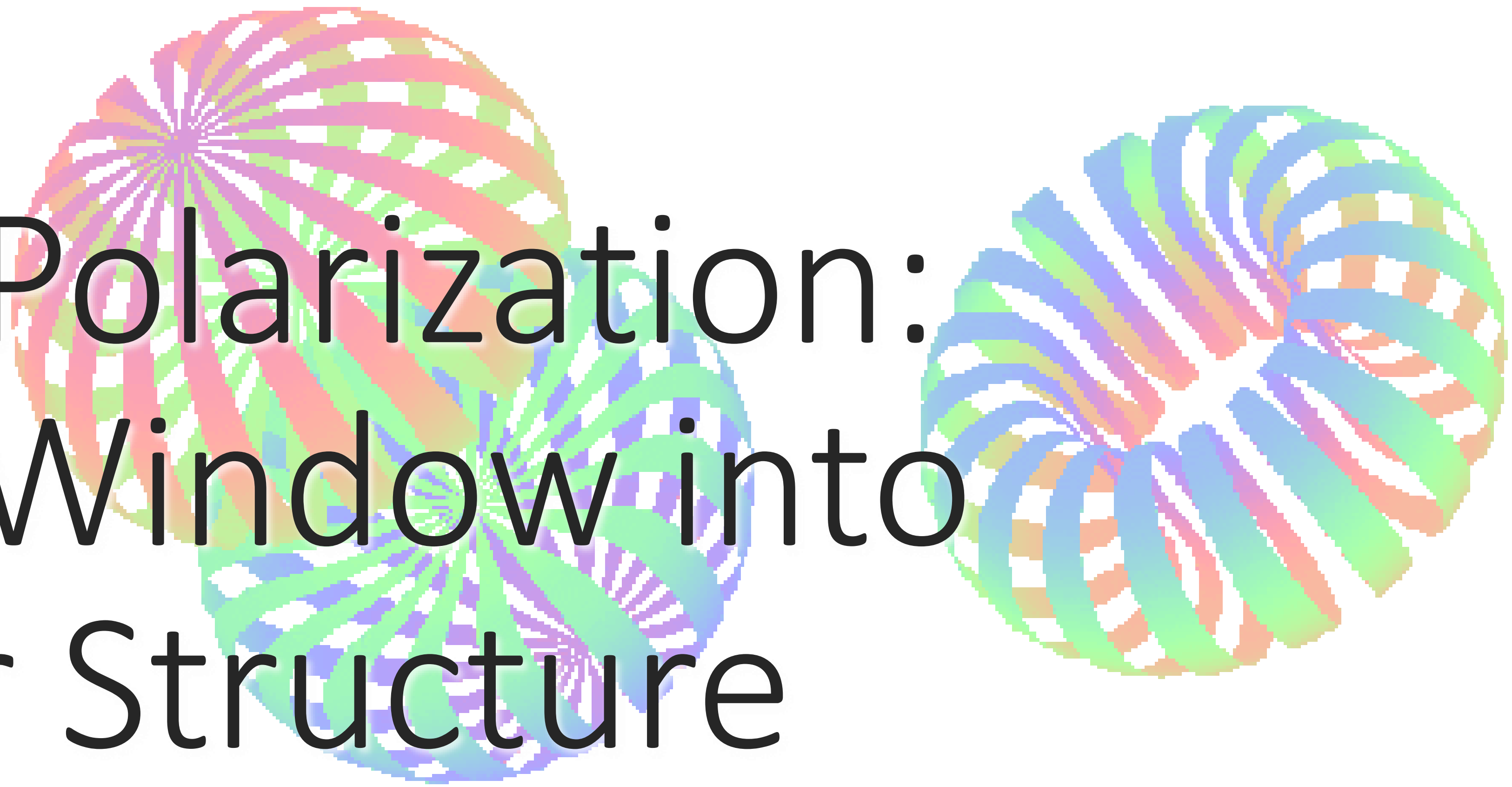
Tensor Polarization: A New Window into Nuclear Structure



Dr. Elena Long

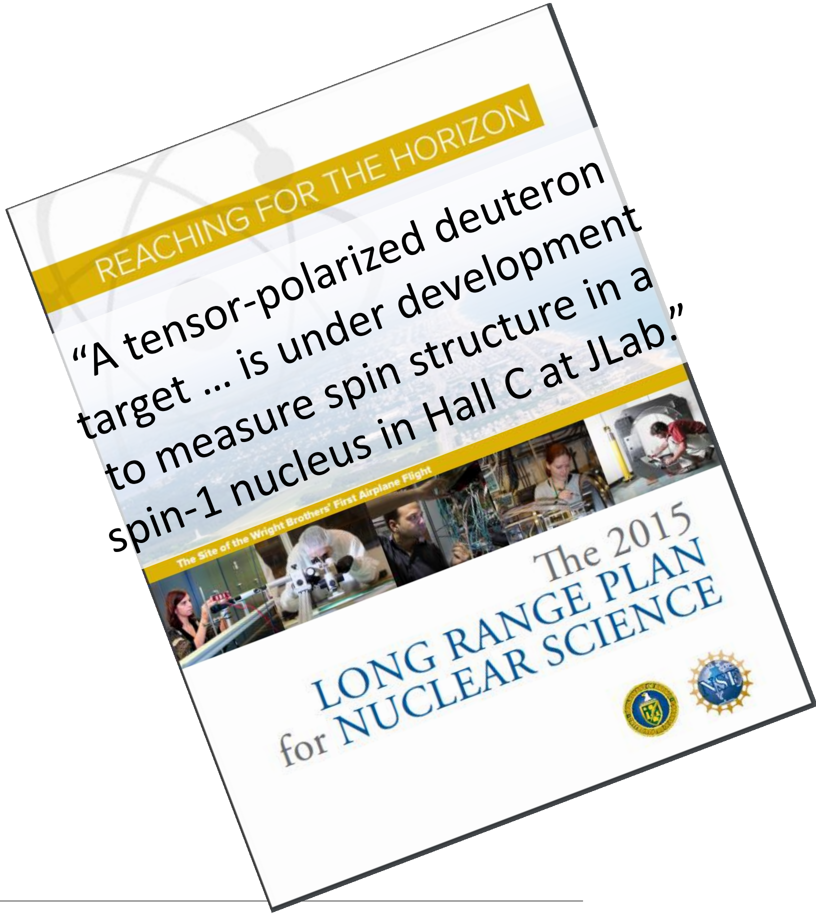
SPIN 2018

University of Ferrara

September 8th, 2018

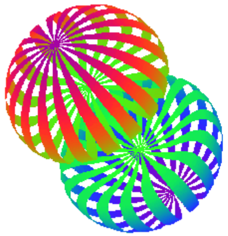
University of New Hampshire

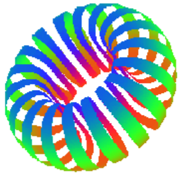
Long Lab



Where Do We Go From Here?

New Degree of Freedom: Tensor Polarization

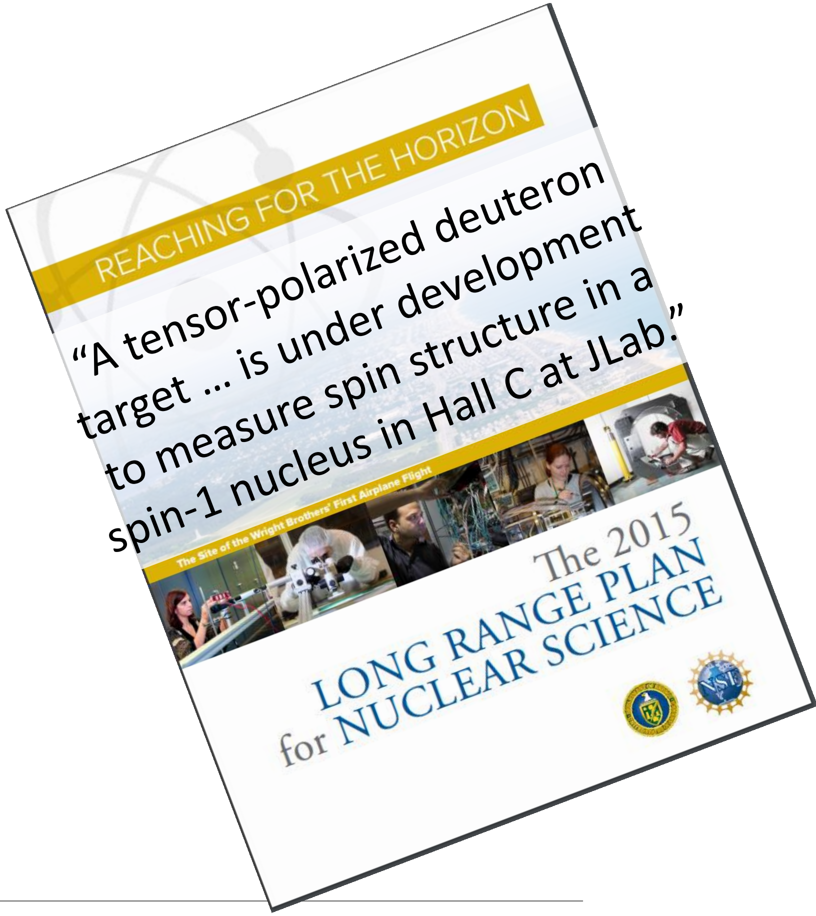




"The proton, **deuteron**, and α particle are most interesting to study because they are among the simplest nuclear structures."

RW McAllister, R Hofstadter, Phys.Rev. **102** 851 (1956)

Shout out to Eva Weiner, Mother of Modern Nuclear Physics Targets. She built Hofstadter's Nobel Prize winning target but tragically died in a 1953 car crash.



"A tensor-polarized deuteron target … is under development to measure spin structure in a spin-1 nucleus in Hall C at JLab."

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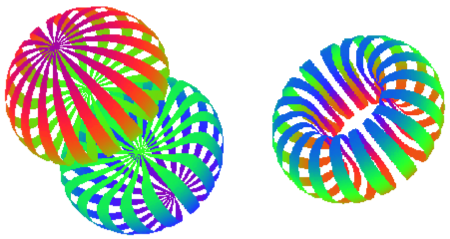

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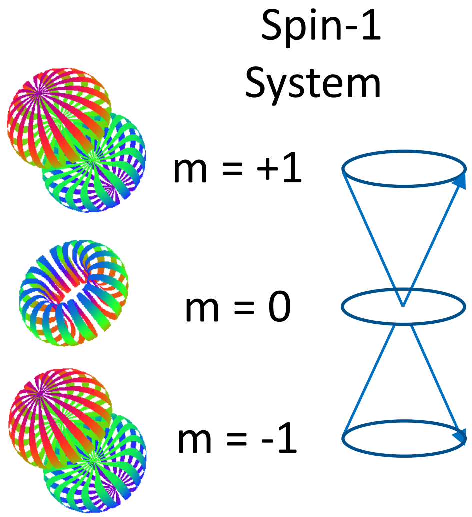
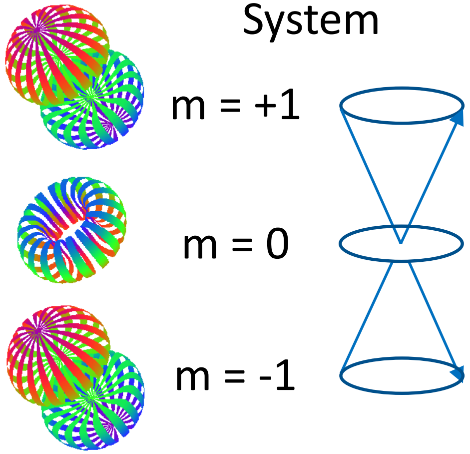
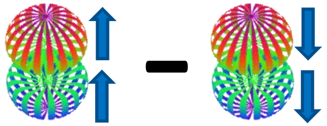


J Forest, *et al*, PRC **54** 646 (1996)

What is Tensor Polarization?

Spin-1
System





"Normal" Polarization:
Vector $P_z = p_+ - p_-$

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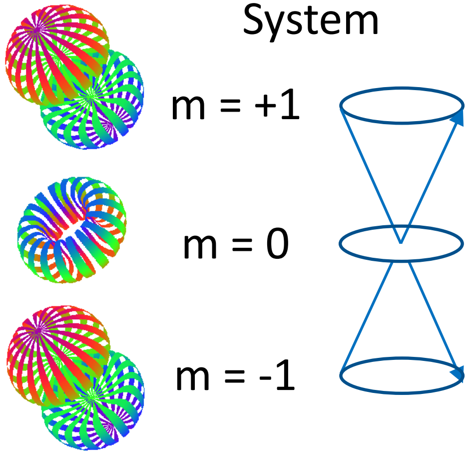

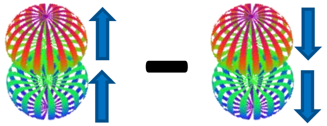

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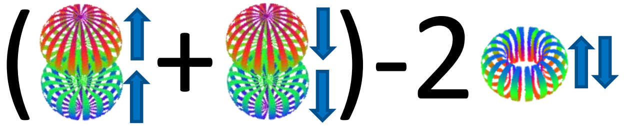

Tensor $P_{zz} = (p_+ + p_-) - 2p_0$

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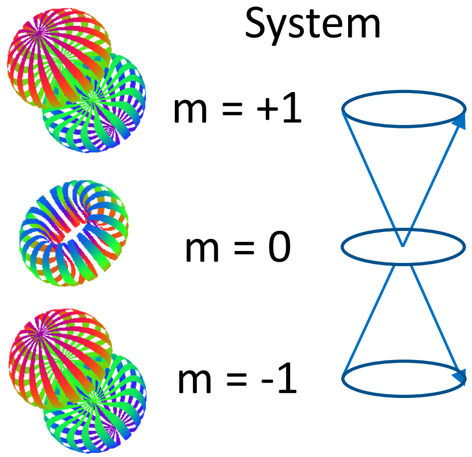

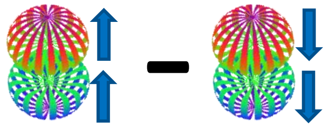

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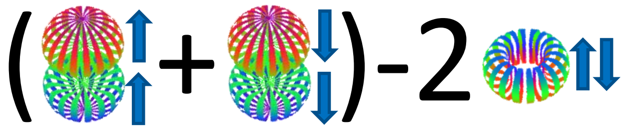

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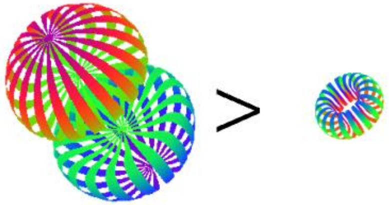
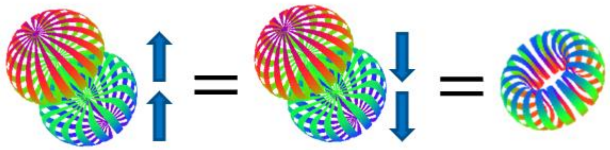
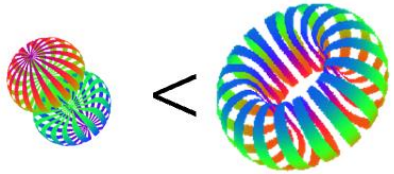


$\rightarrow 0 < P_{zz} \leq 1$



$\rightarrow P_{zz} = 0$



$\rightarrow -2 \leq P_{zz} < 0$

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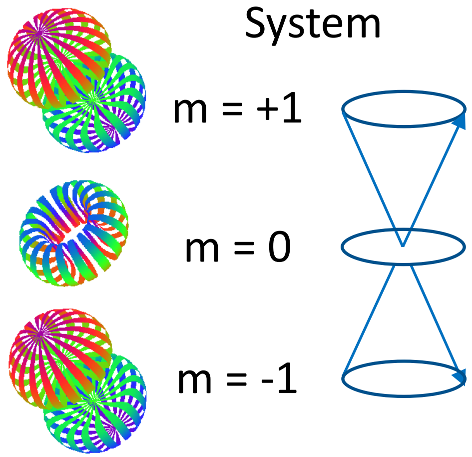
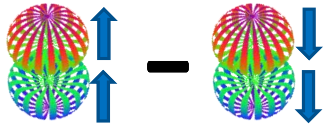
What is Tensor Polarization?

A high-luminosity tensor-polarized target has promise as a **novel probe of nuclear physics**

Spin-1 System





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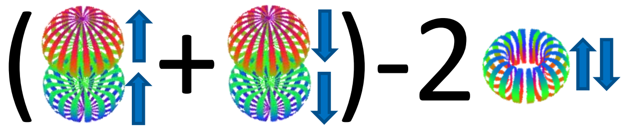

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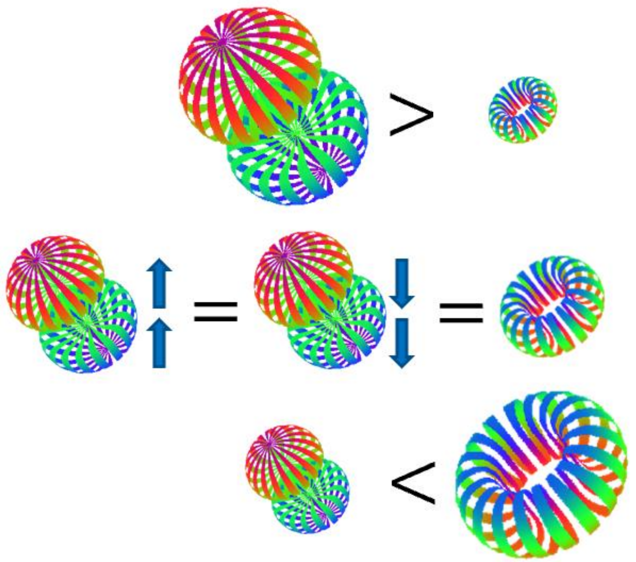

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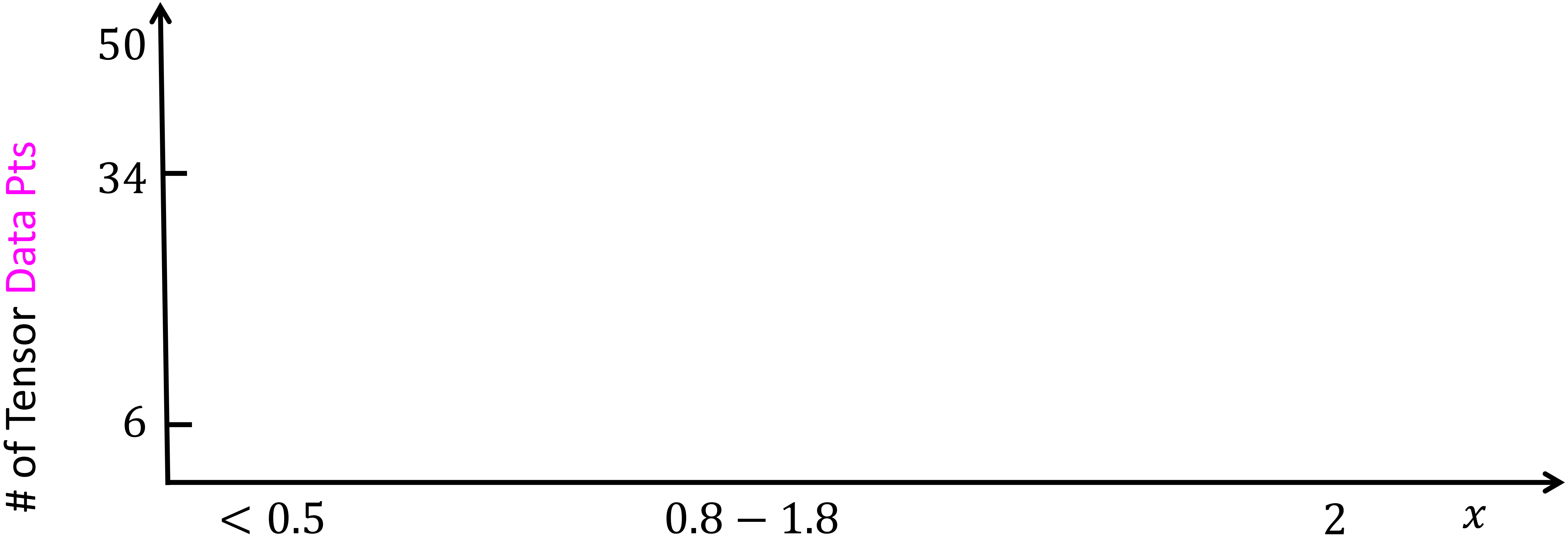
Current Landscape of Tensor Observables



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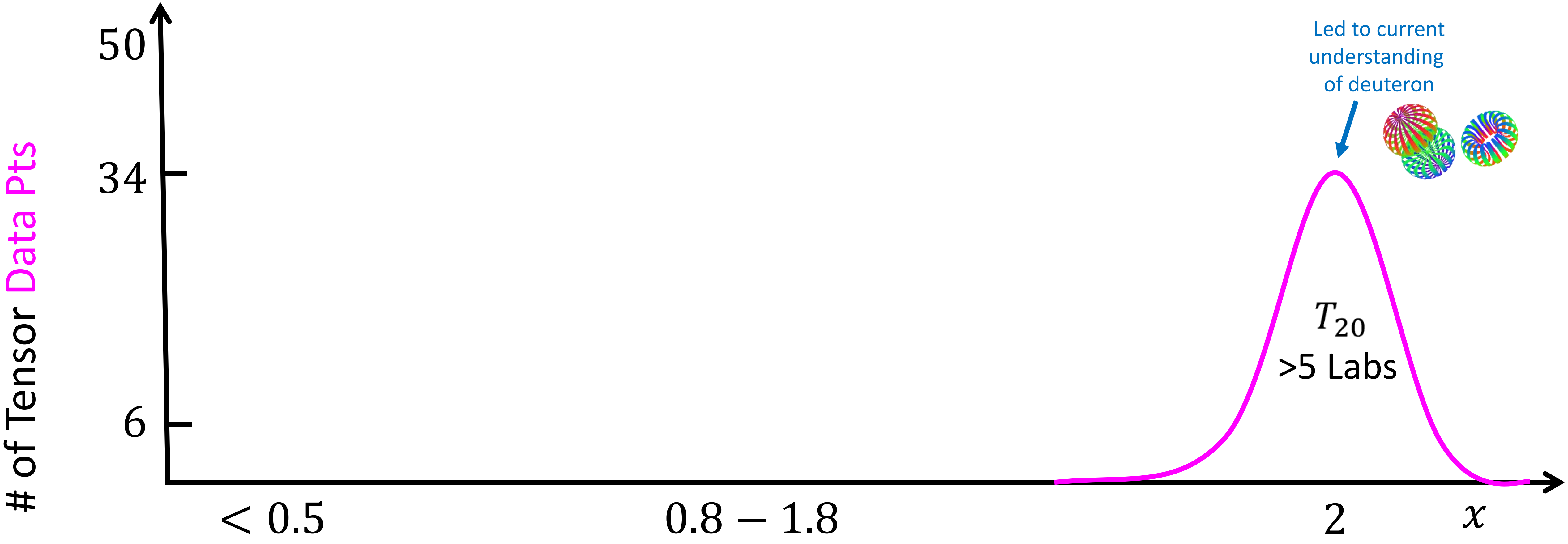
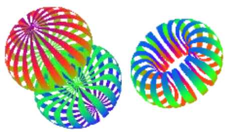
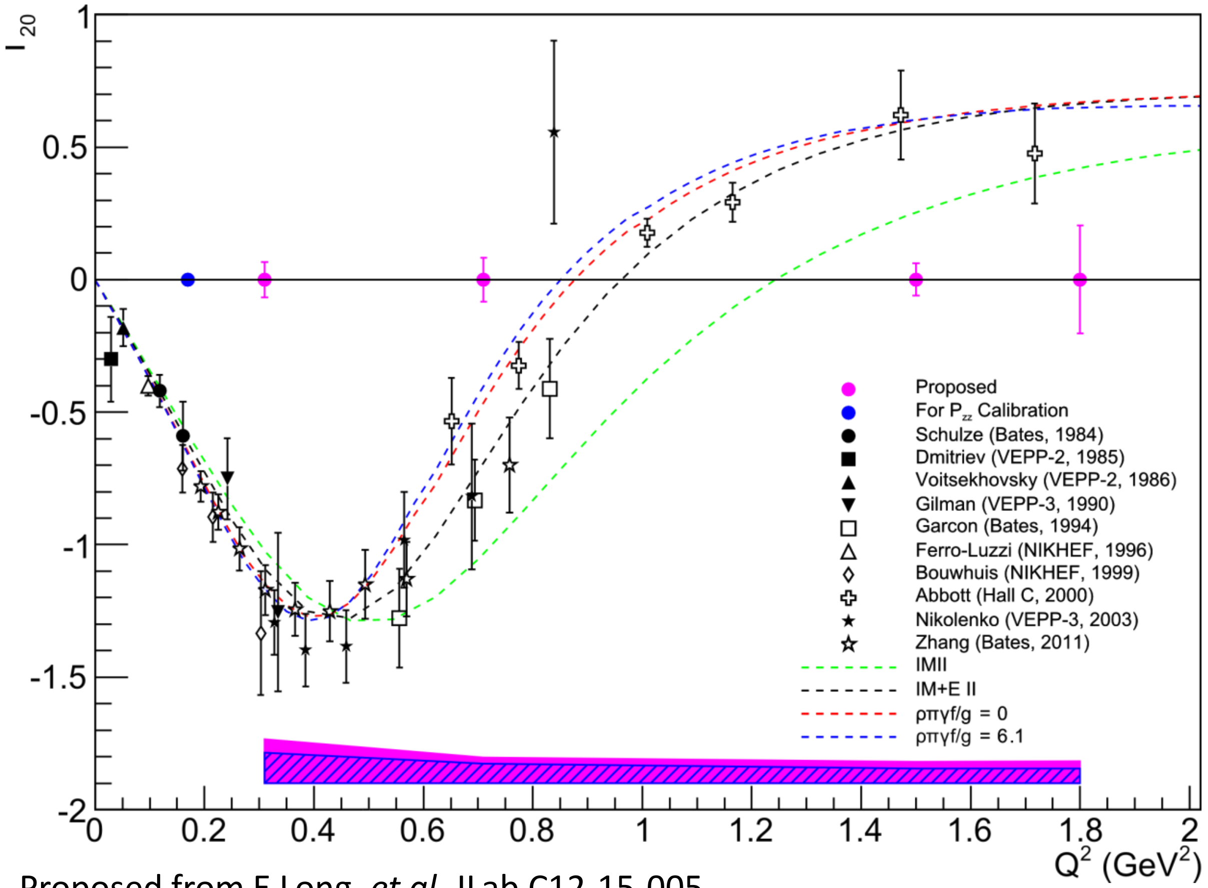


Elastic T_{20}



T_{20}, along with unpol. A & B form factors, gave rise to current deuteron understanding

$T_{20} = \dfrac{A_{zz}}{d_{20}\sqrt{2}}$ on elastic peak $\quad d_{20} = \dfrac{3\cos^2\theta^* - 1}{2}$



Proposed from E Long, *et al*, JLab C12-15-005

World Data from R Holt, R Gilman, Rept.Prog.Phys. **75** 086301 (2012)

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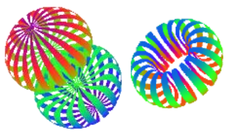

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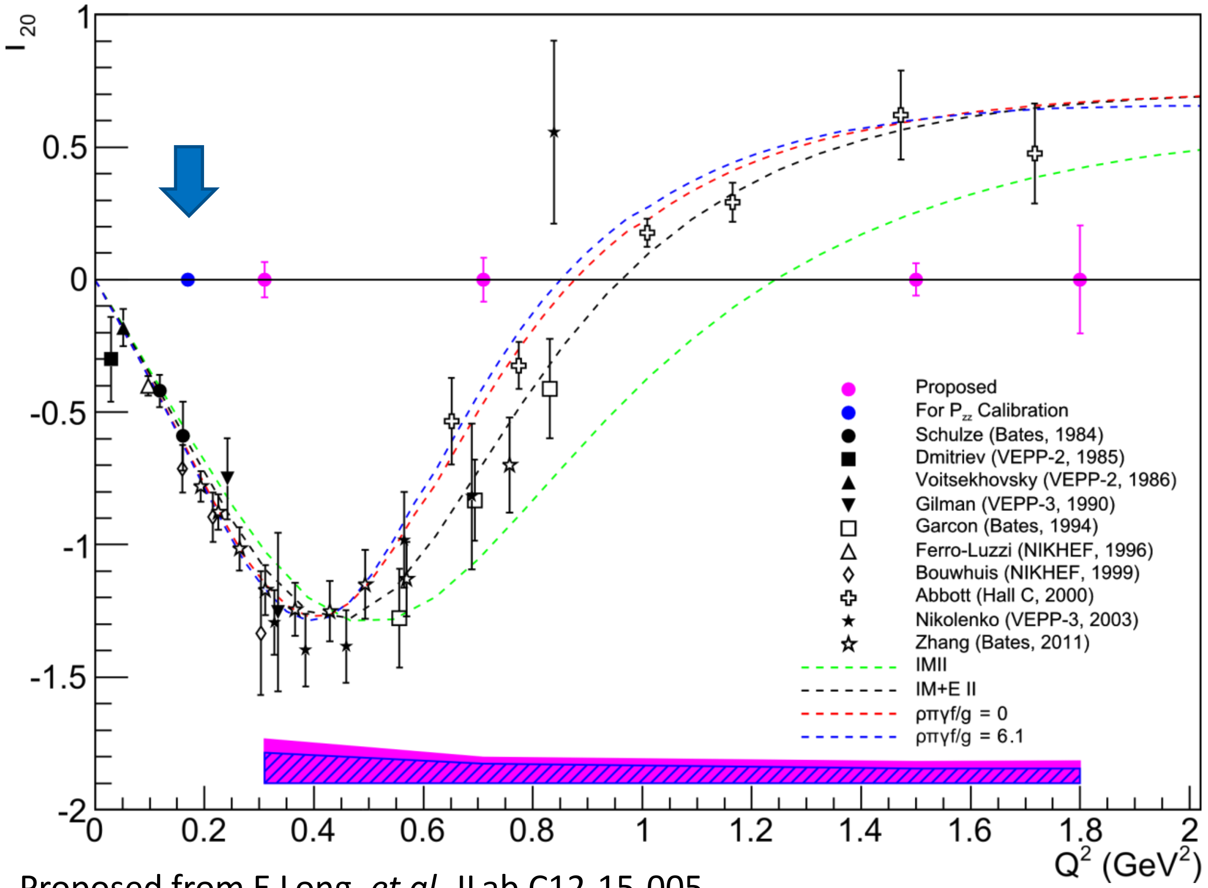
At low Q^2:

- T_{20} well known
- P_{zz} can be extracted from T_{20}
- Completely independent P_{zz} measurement from NMR line-shape P_{zz}



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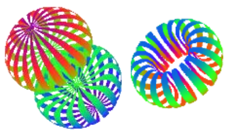

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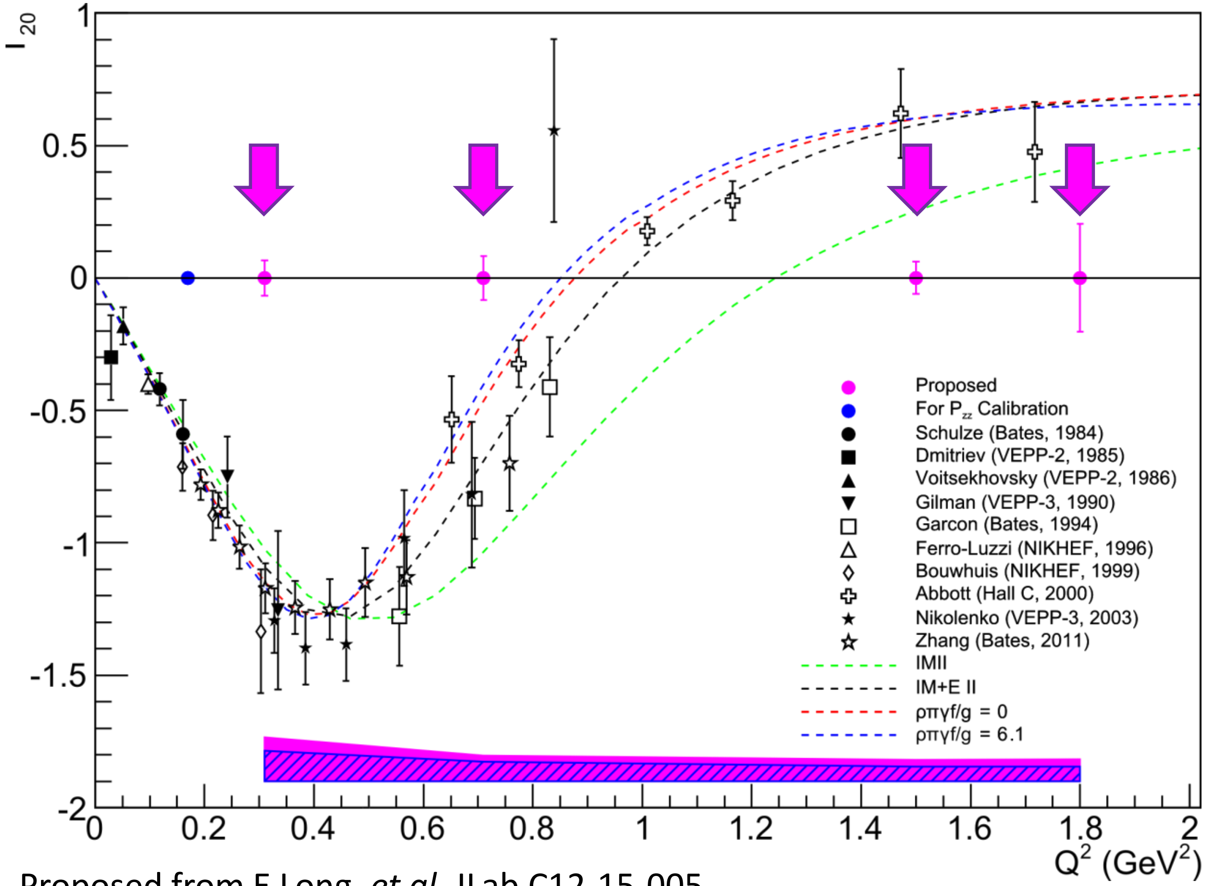
JLab E12-15-005 will measure T_{20} over the largest & highest Q^2 range

- Important cross-check of Hall C high Q^2 data



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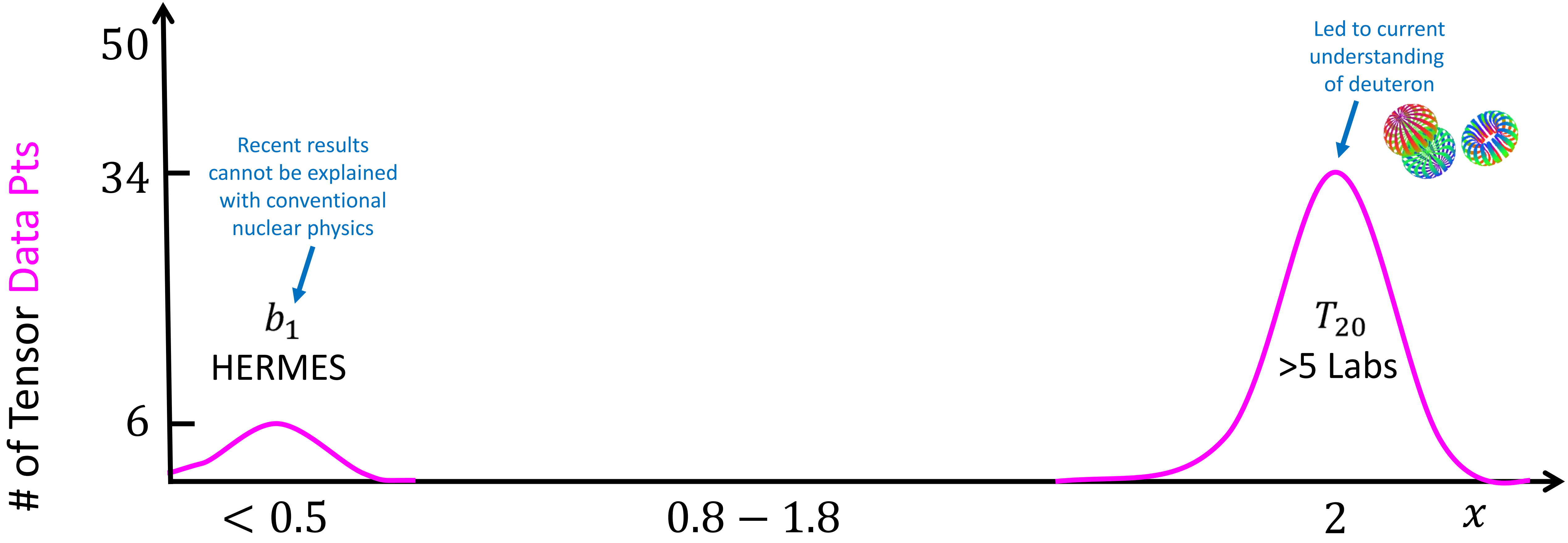
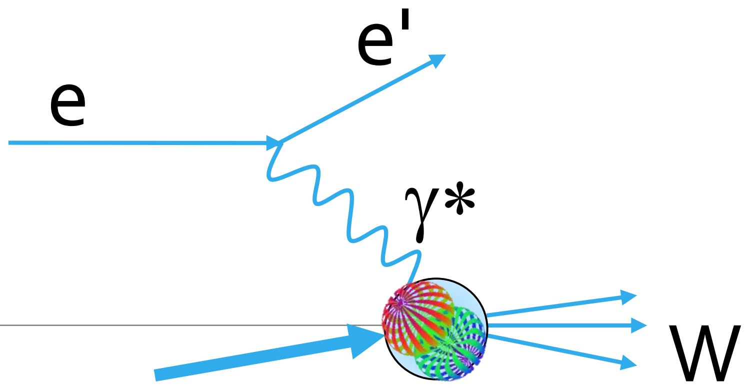


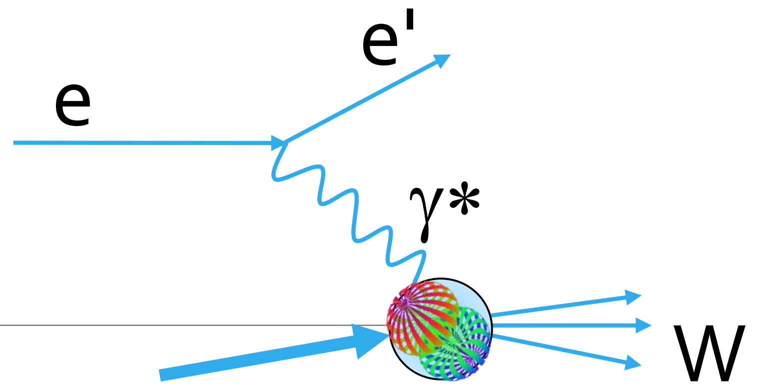
Structure Functions



Scattering on:

- Unpolarized Targets $W_{\mu\nu} = -\alpha F_1 + \beta F_2$

Existence of quarks & quark spin!



Structure Functions

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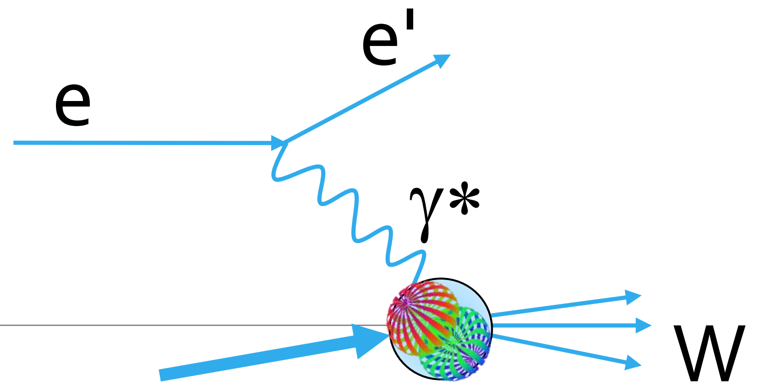
Spin crisis! (Solving proton radius?)



Structure Functions

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- Tensor Polarized Targets

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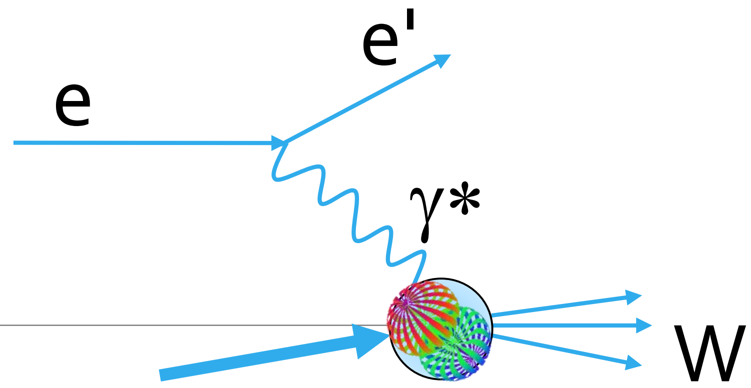
Spin crisis! (Solving proton radius?)

$$-\varepsilon b_1 + \zeta b_2 + \eta b_3 + \kappa b_4$$

Four New SFs to Explore!!

Structure Functions



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Four New SFs to Explore!!

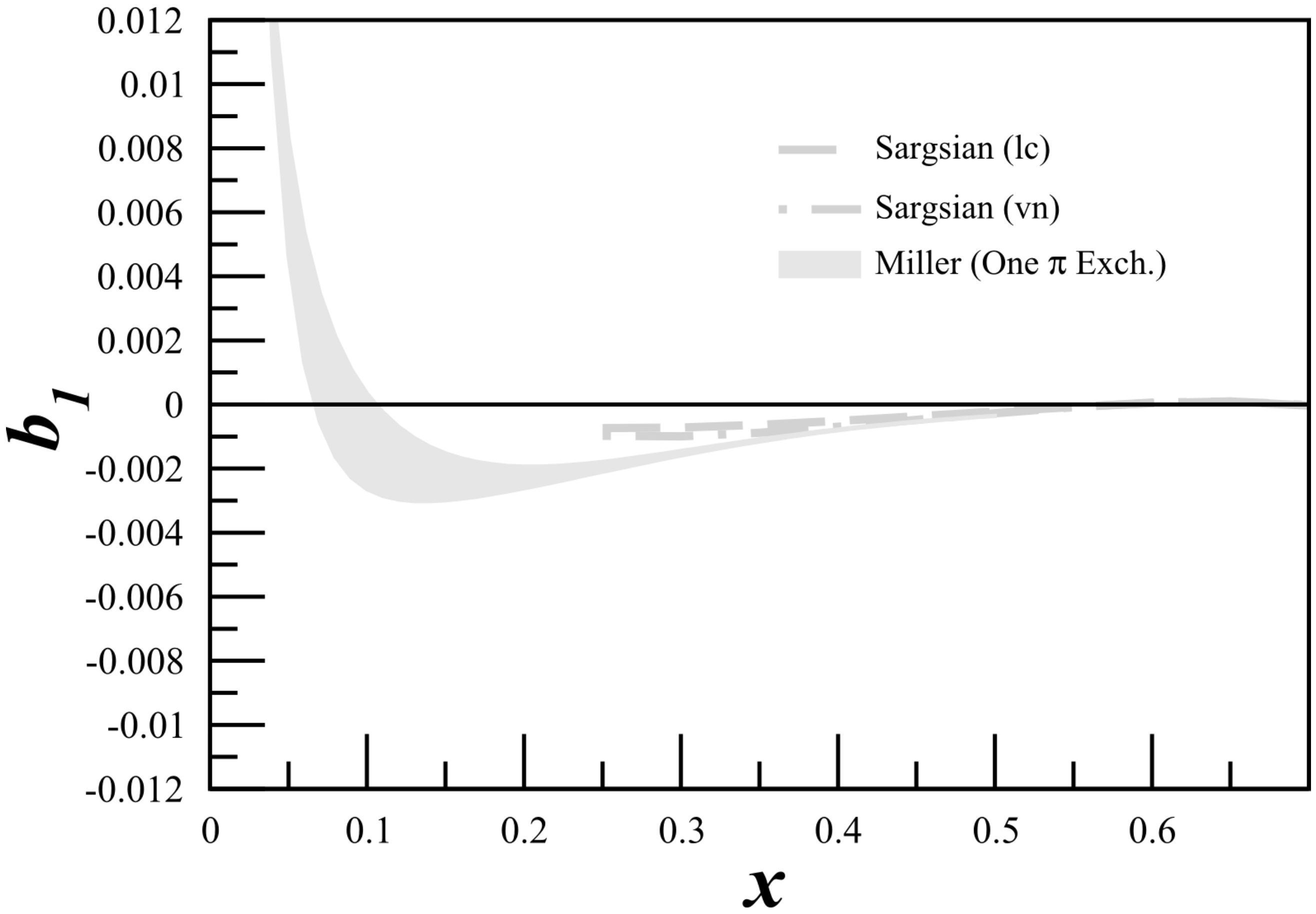
Hidden color? Quark OAM? Sea polarization? Solving the Spin Crisis?

b_1 probes nuclear effects at quark resolution!

$$b_1(x) = \frac{q^0(x) - q^{\pm 1}(x)}{2}$$

Tensor Structure Function, b_1

- All conventional **models predict small or vanishing values of b_1**



A Airapetian, *et al*, PRL **95** 242001 (2005)
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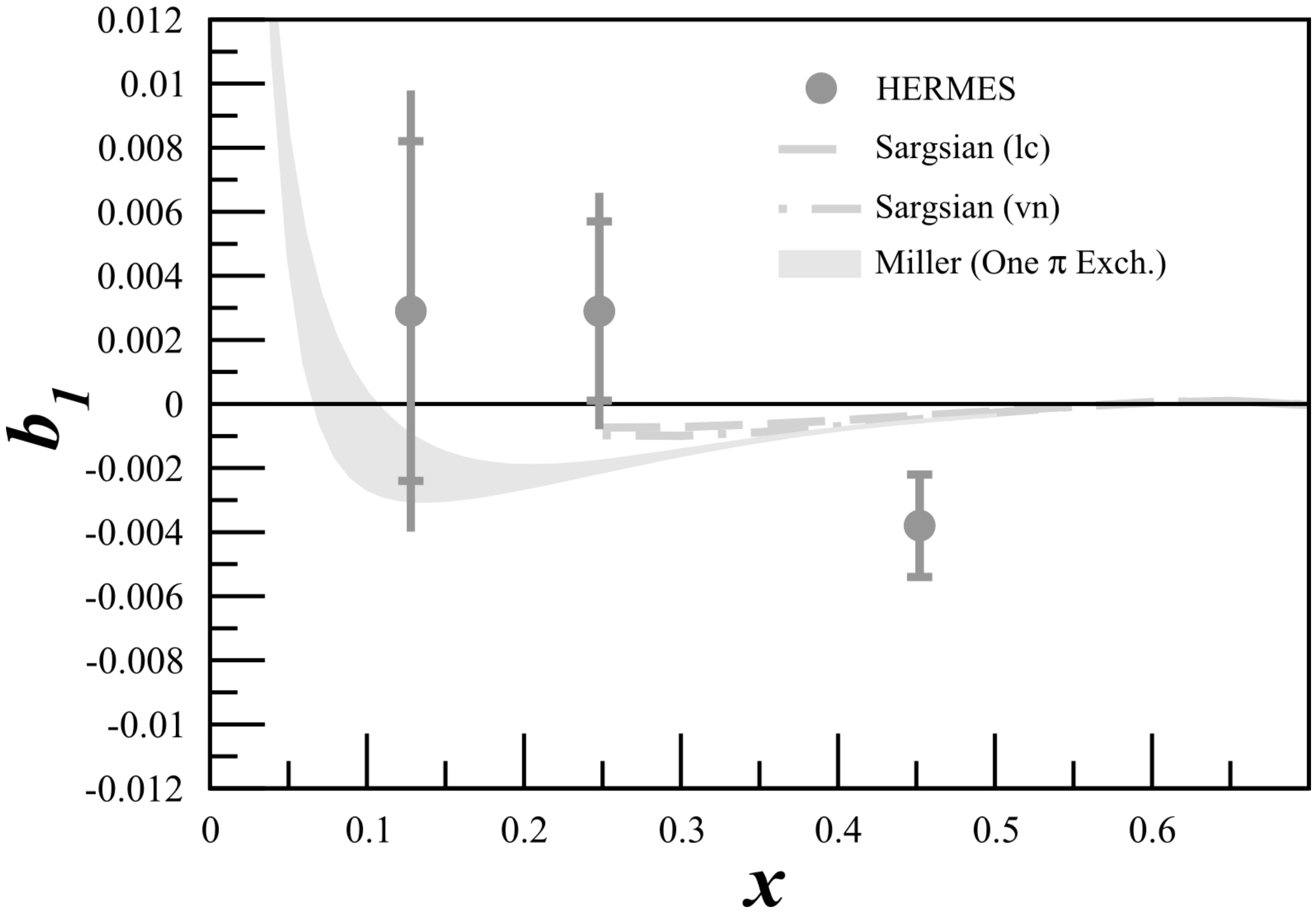

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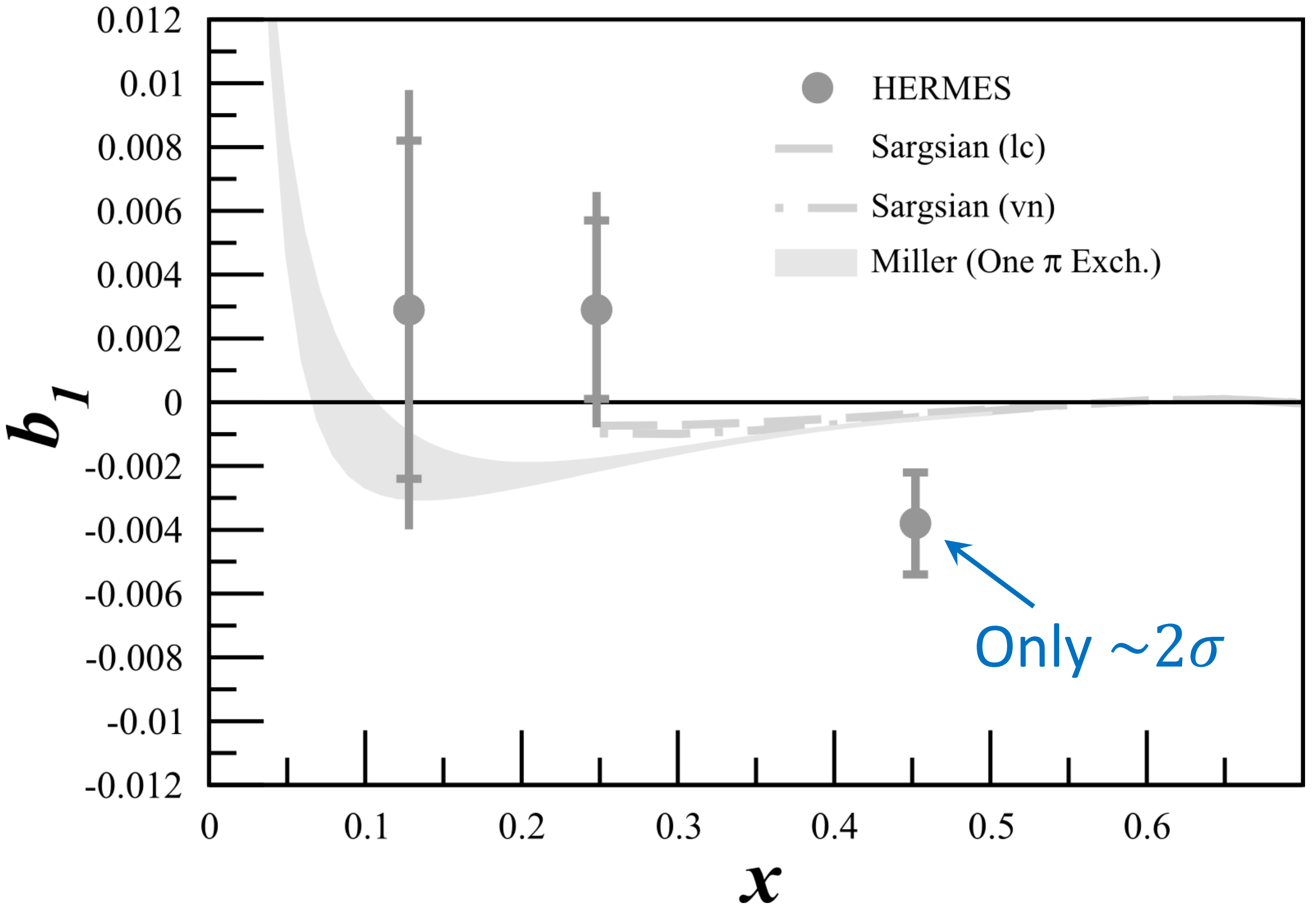

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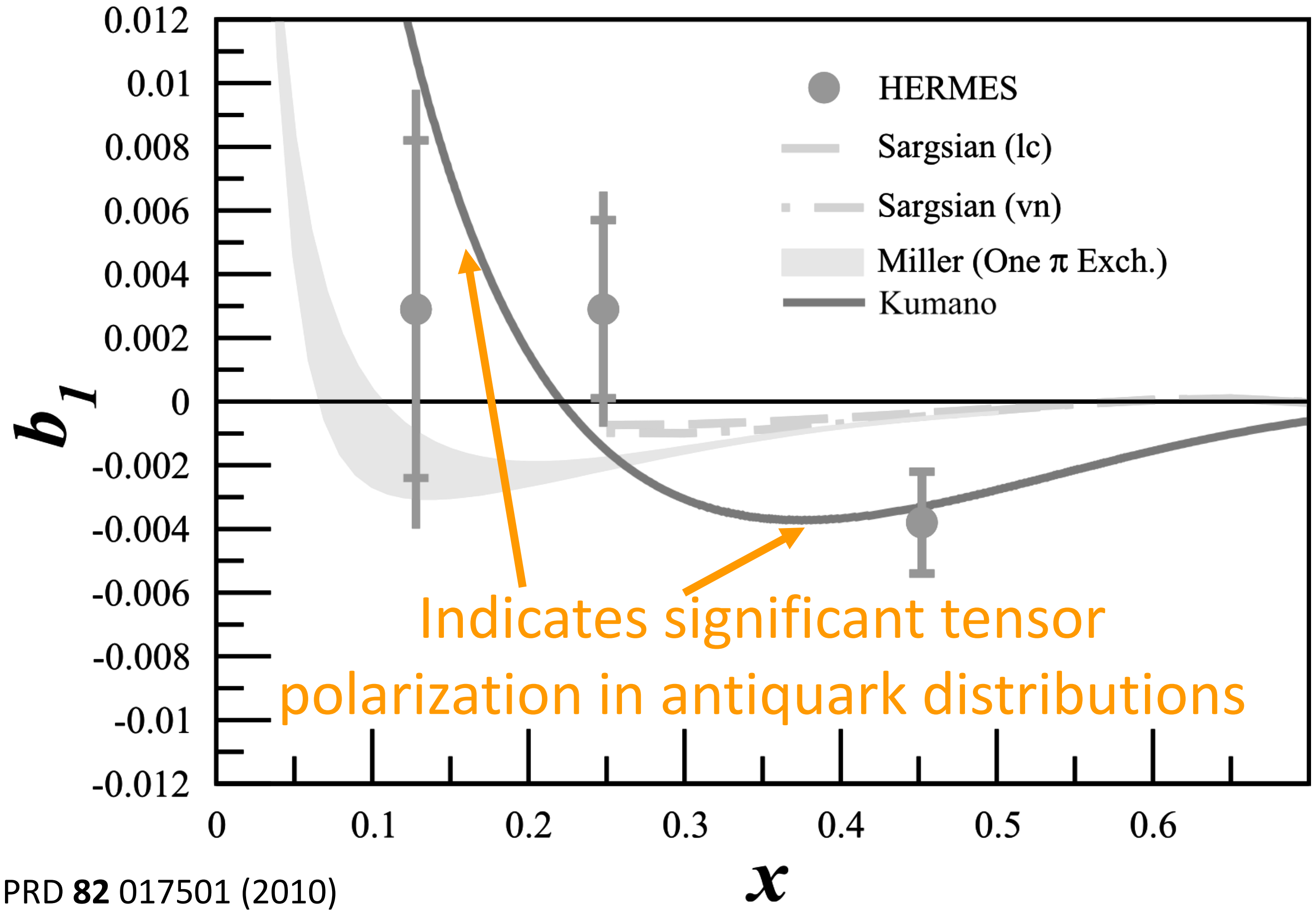

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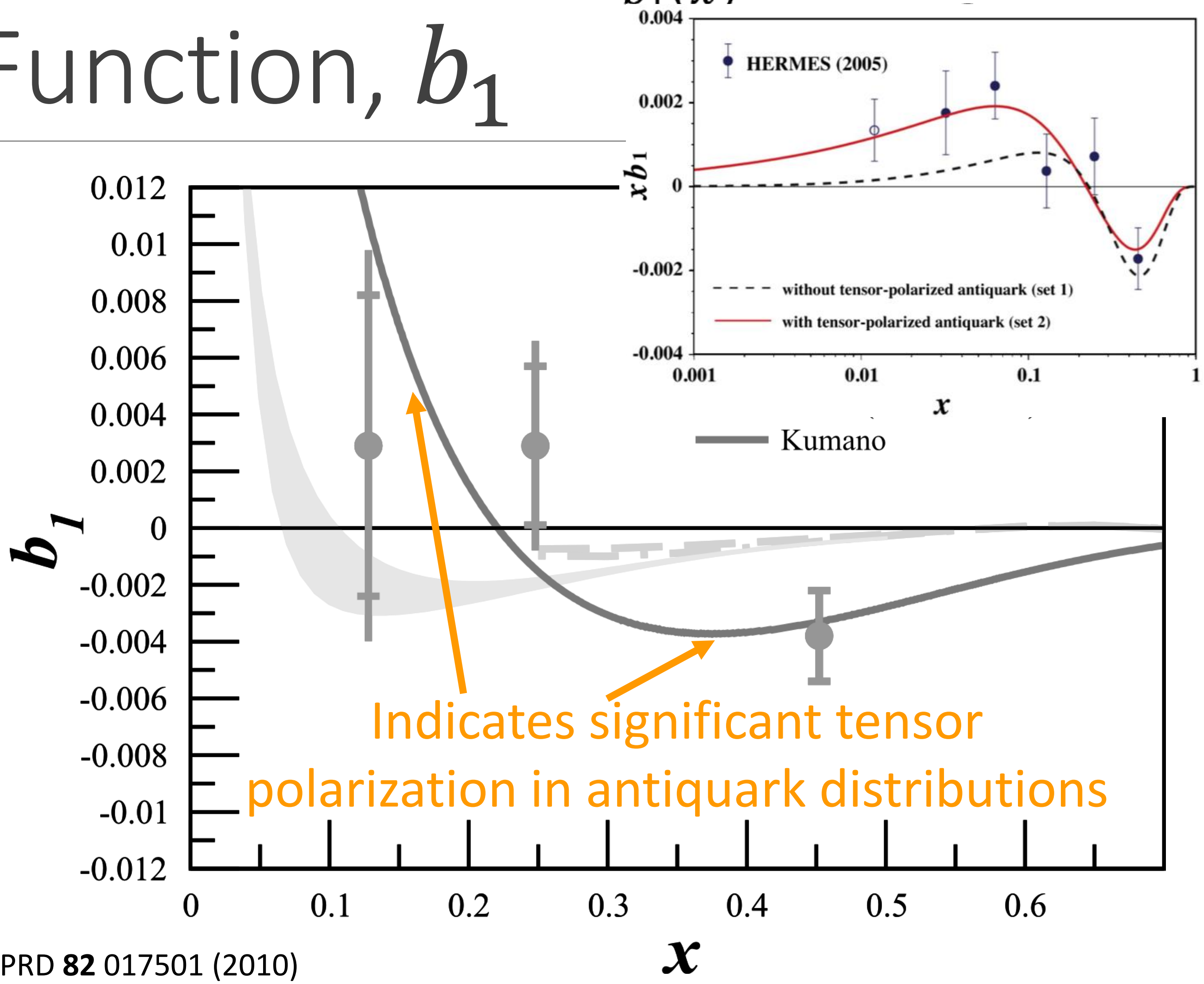

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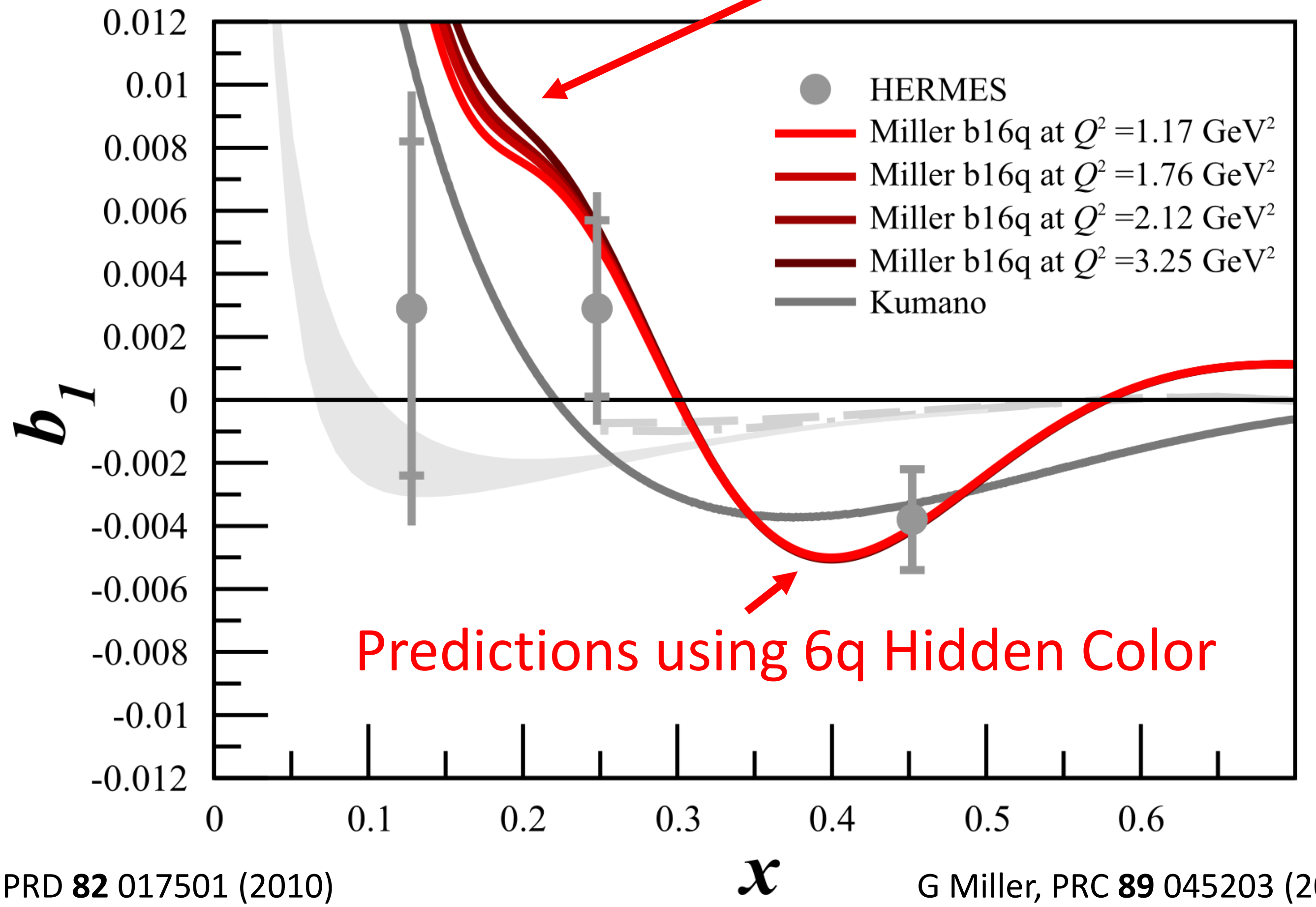

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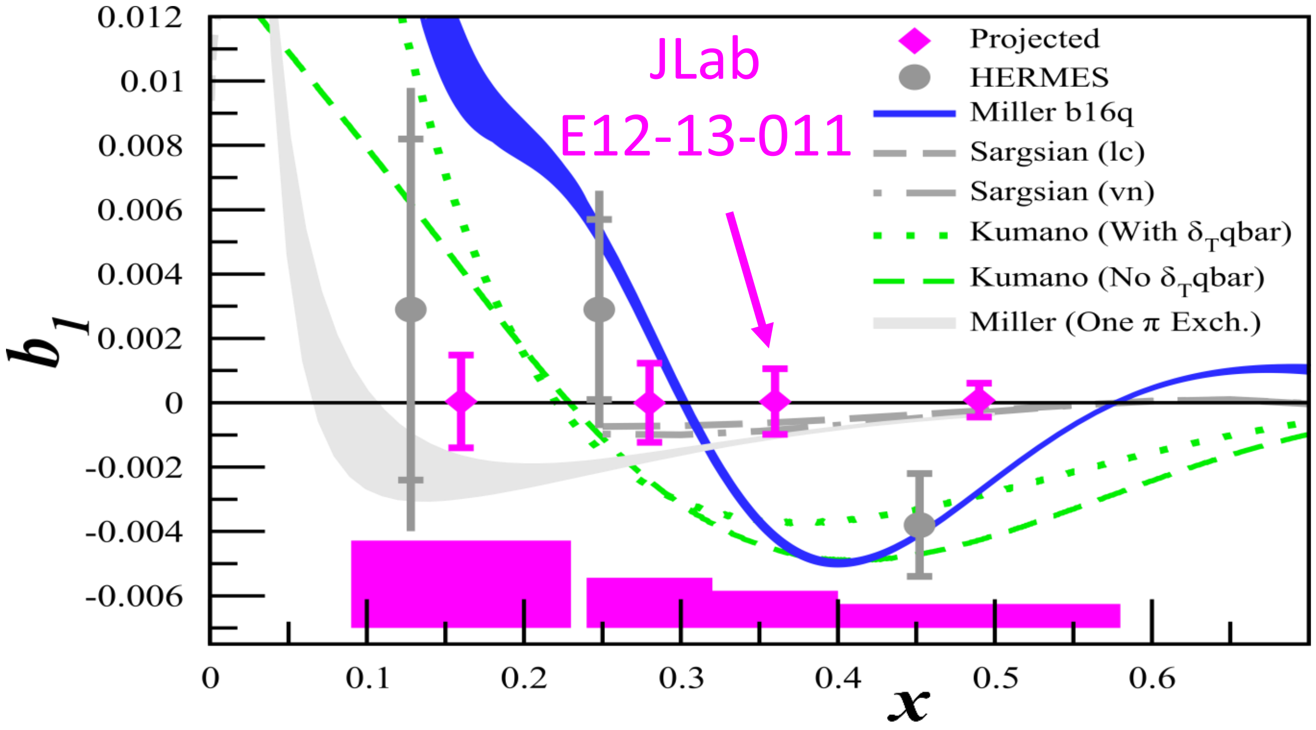

+ Insight in Close-Kumano Sum Rule & Quark Orbital Angular Momentum

FE Close, S Kumano, PRD **42** 2377 (1990)
SK Taneja *et al*, PRD **86** 036008 (2012)
A Airapetian, *et al*, PRL **95** 242001 (2005)
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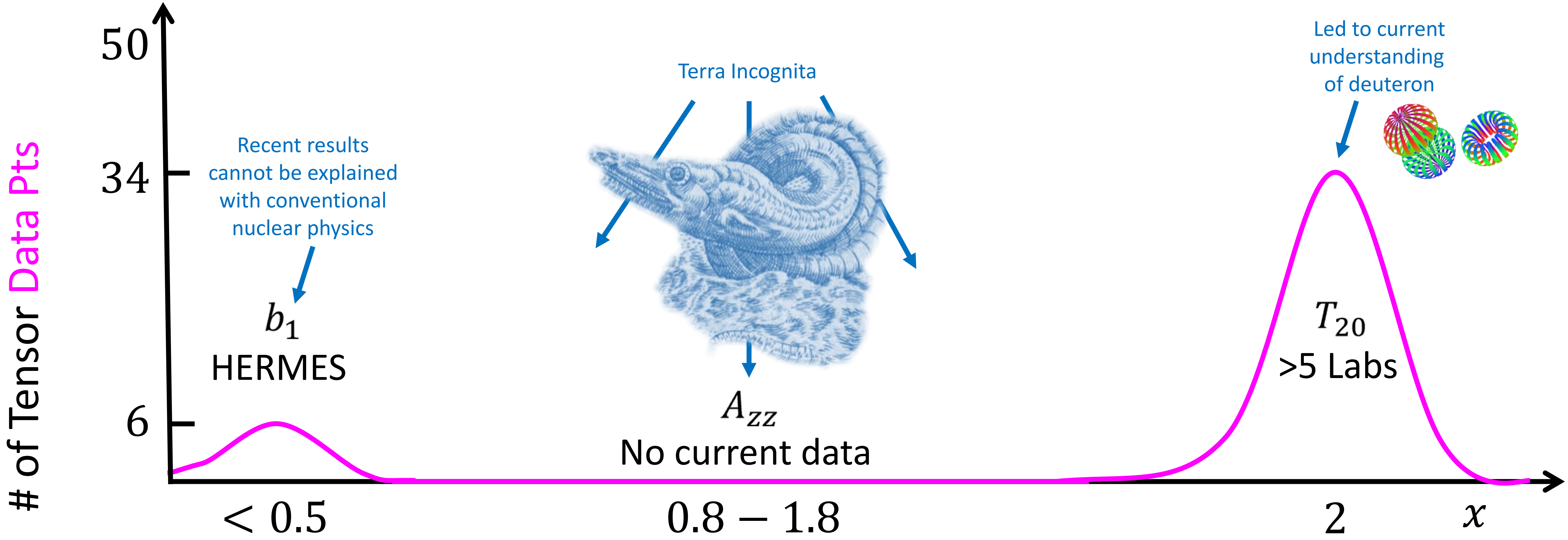

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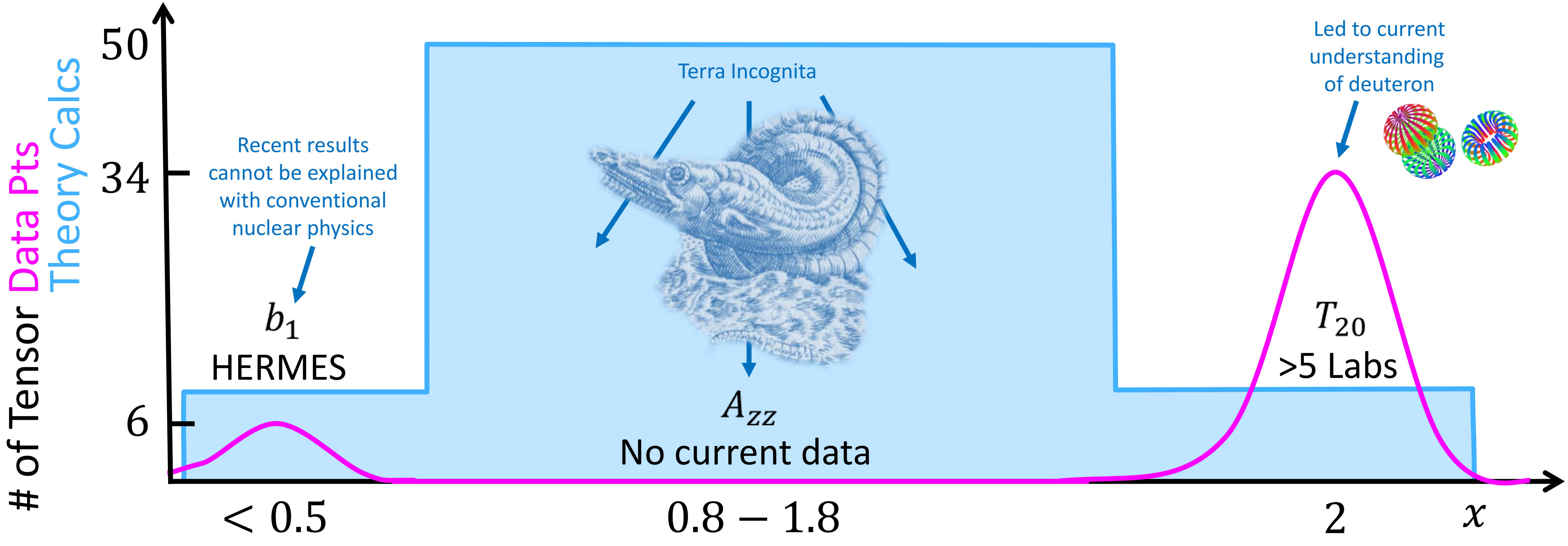
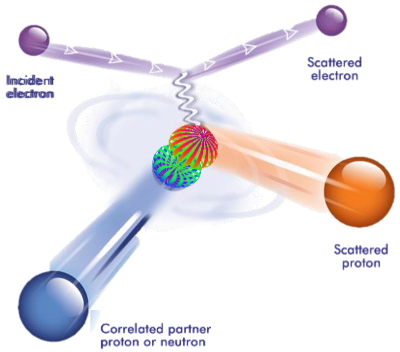


Matter at Small Distances & High Momentum

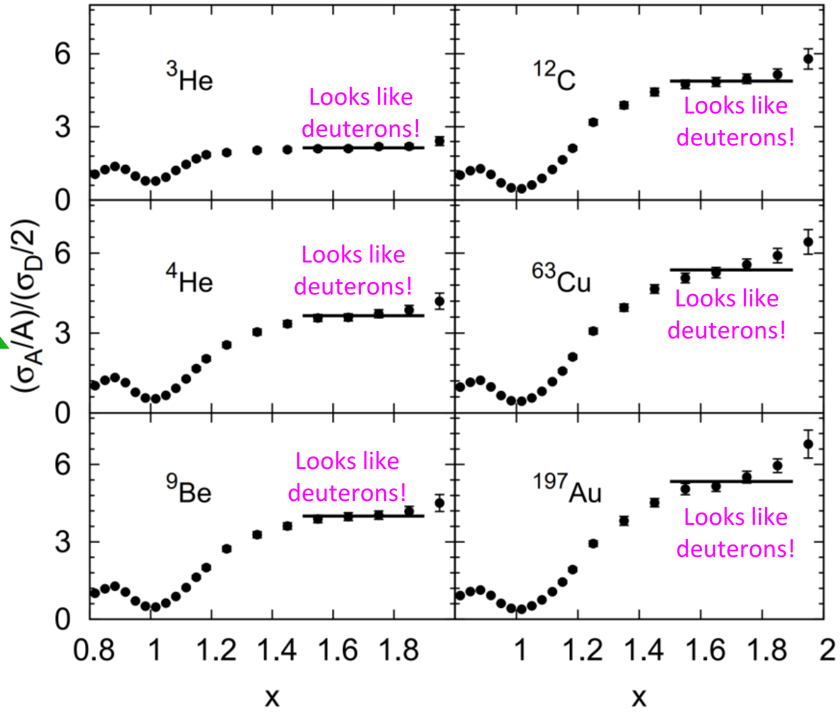


- Short-Range Correlations:

  Everything looks like deuterons!

Everything / Deuteron

N Foman, *et al*, PRL **108** 092502 (2012)



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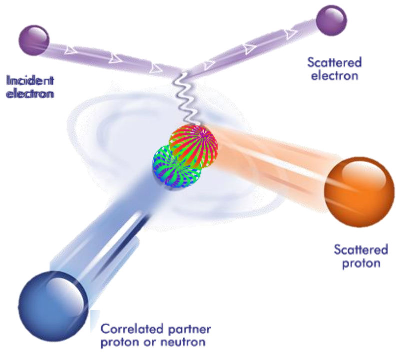
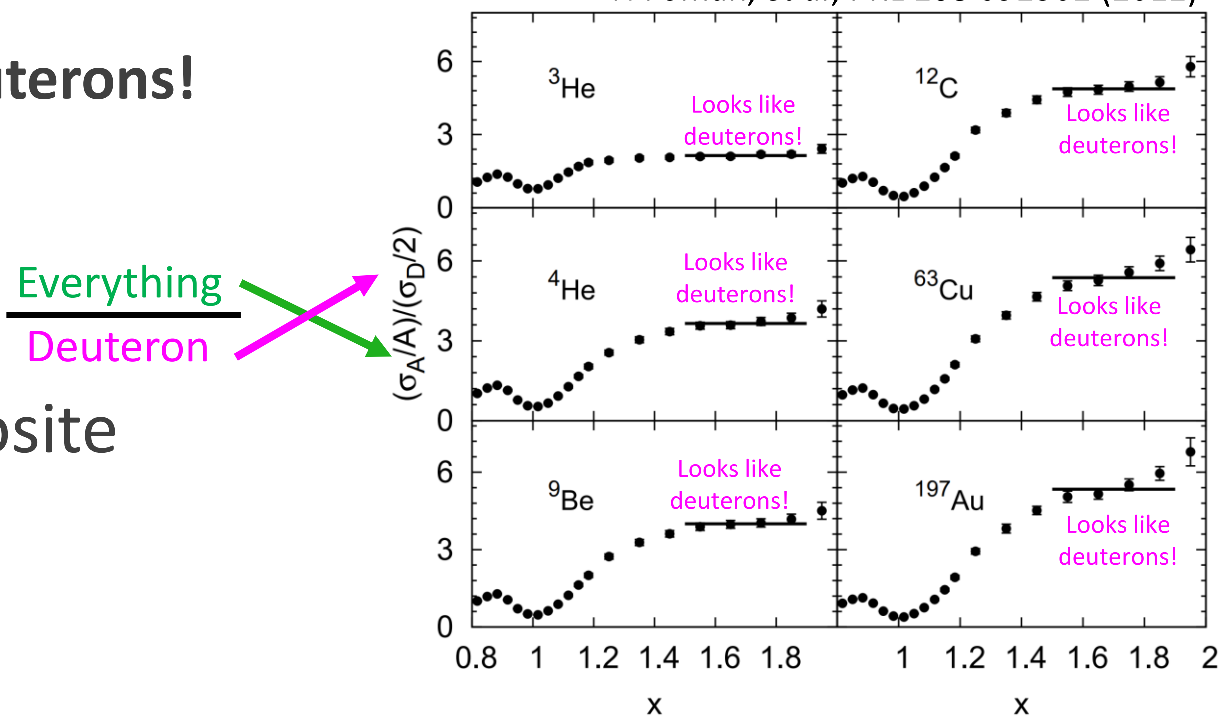


Look @ Deuteron: Simplest composite nuclear system

N Foman, *et al*, PRL **108** 092502 (2012)



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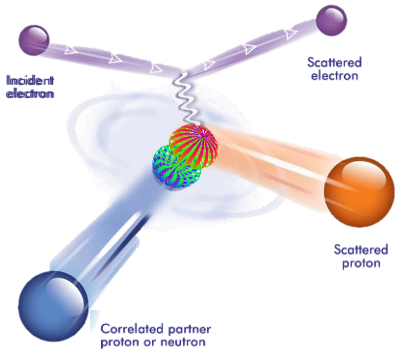

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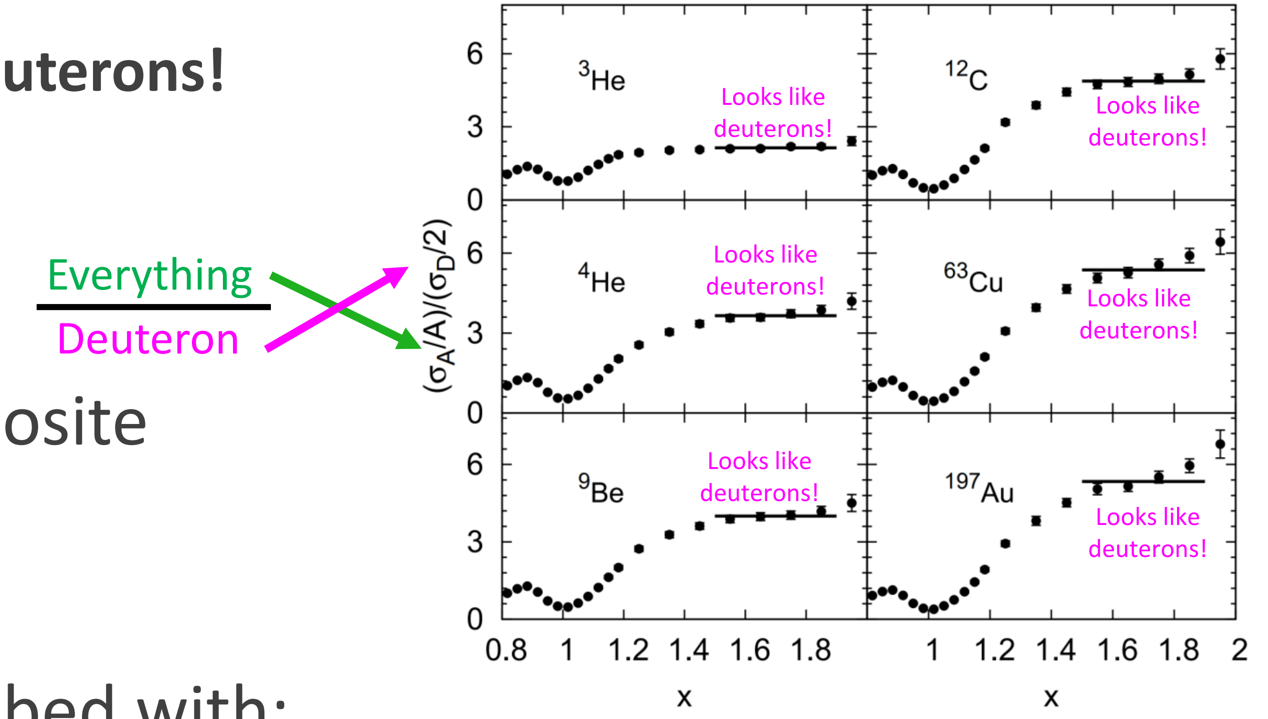


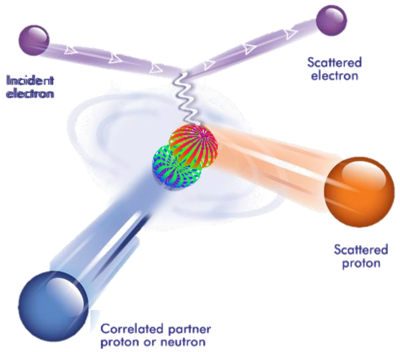
Look @ Deuteron: Simplest composite nuclear system

Short-range, high *p* structure probed with:

- $x > 1$ kinematics
- Enhancing tensor polarization

We combine both techniques

Matter at Small Distances & High Momentum



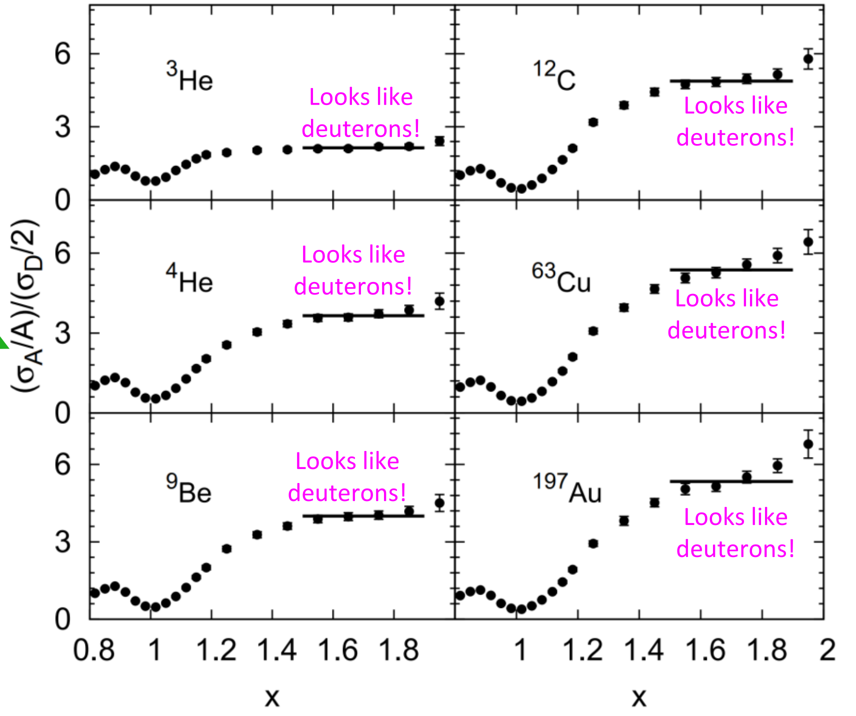
- Short-Range Correlations:

Everything looks like deuterons!

Probe the tensor force with tensor polarization!

$\frac{\text{Everything}}{\text{Deuteron}}$

N Foman, *et al*, PRL **108** 092502 (2012)



Look @ Deuteron: Simplest composite nuclear system

Short-range, high *p* structure probed with:

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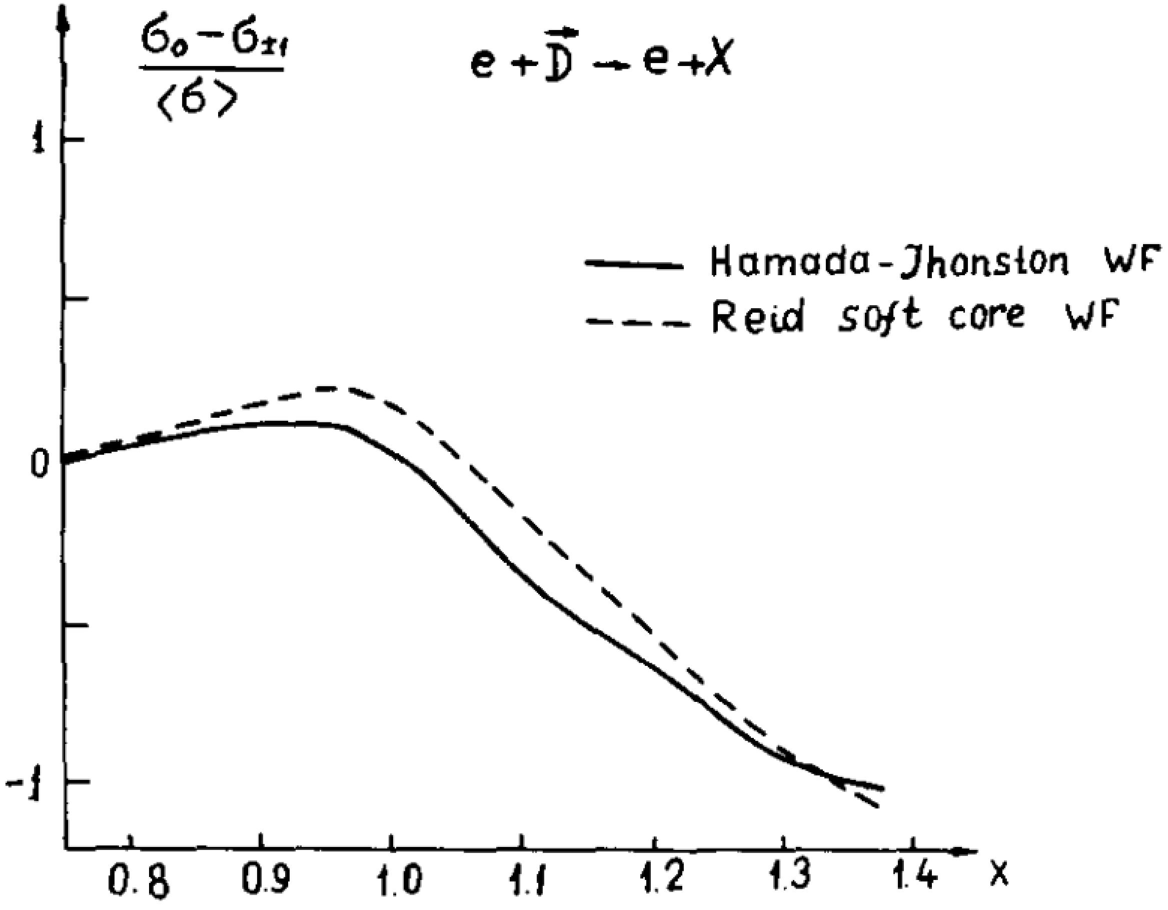
"There is a strong need for models of the deuteron wave function that are both **realistic** and relativistic." - J. Terry, G. Miller, arXiv:1603.07032 (2016)

Deuteron Wavefunction

First calculated in the '70s, A_{zz} can be used in to discriminate between hard and soft wave functions

$$A_{zz} = \frac{2}{f \cdot P_{zz}} \left(\frac{\sigma_p - \sigma_u}{\sigma_u} \right)$$



LL Frankfurt, MI Strikman, Phys. Rept. **76** 215 (1981)

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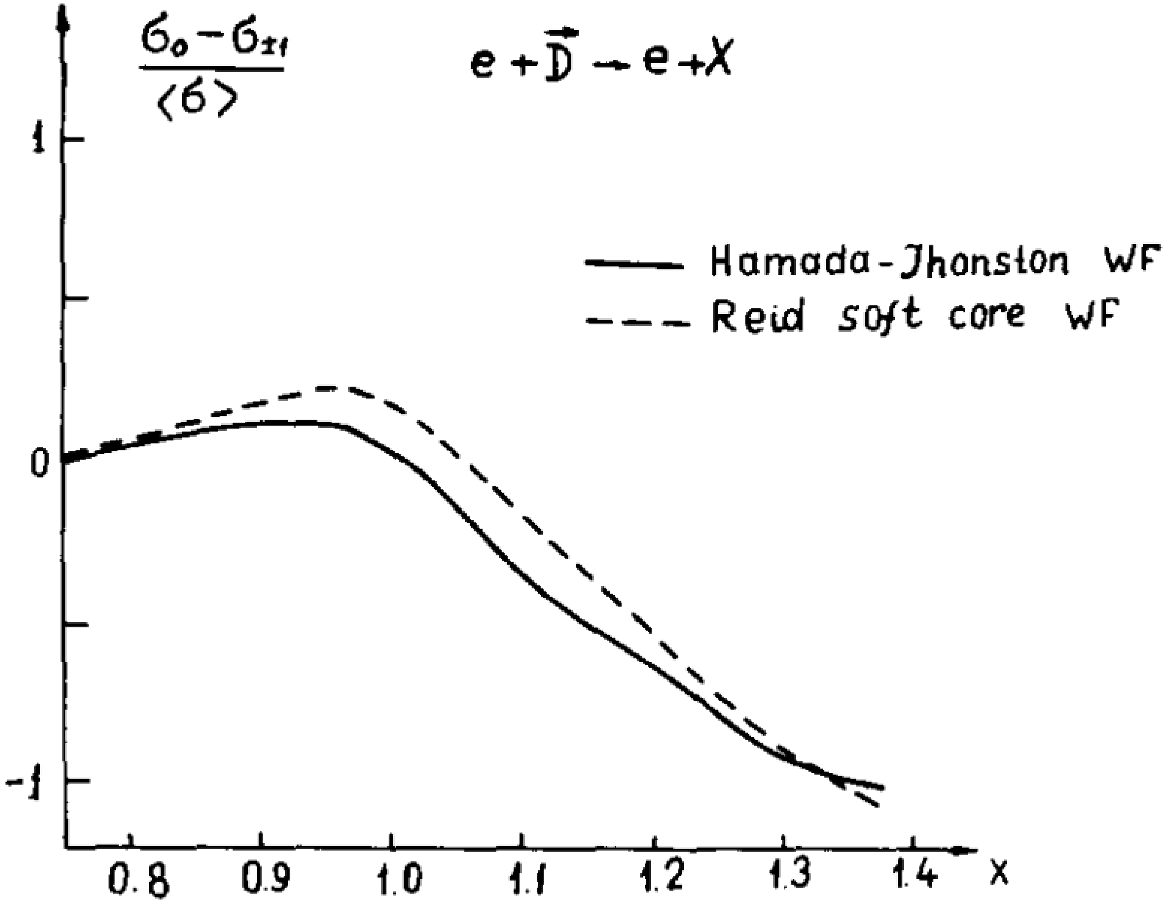
$S \to u(k)$
$D \to w(k)$

$$A_{zz} \propto \frac{\frac{1}{2}w^2(k) - u(k)w(k)\sqrt{2}}{u^2(k) + w^2(k)}$$



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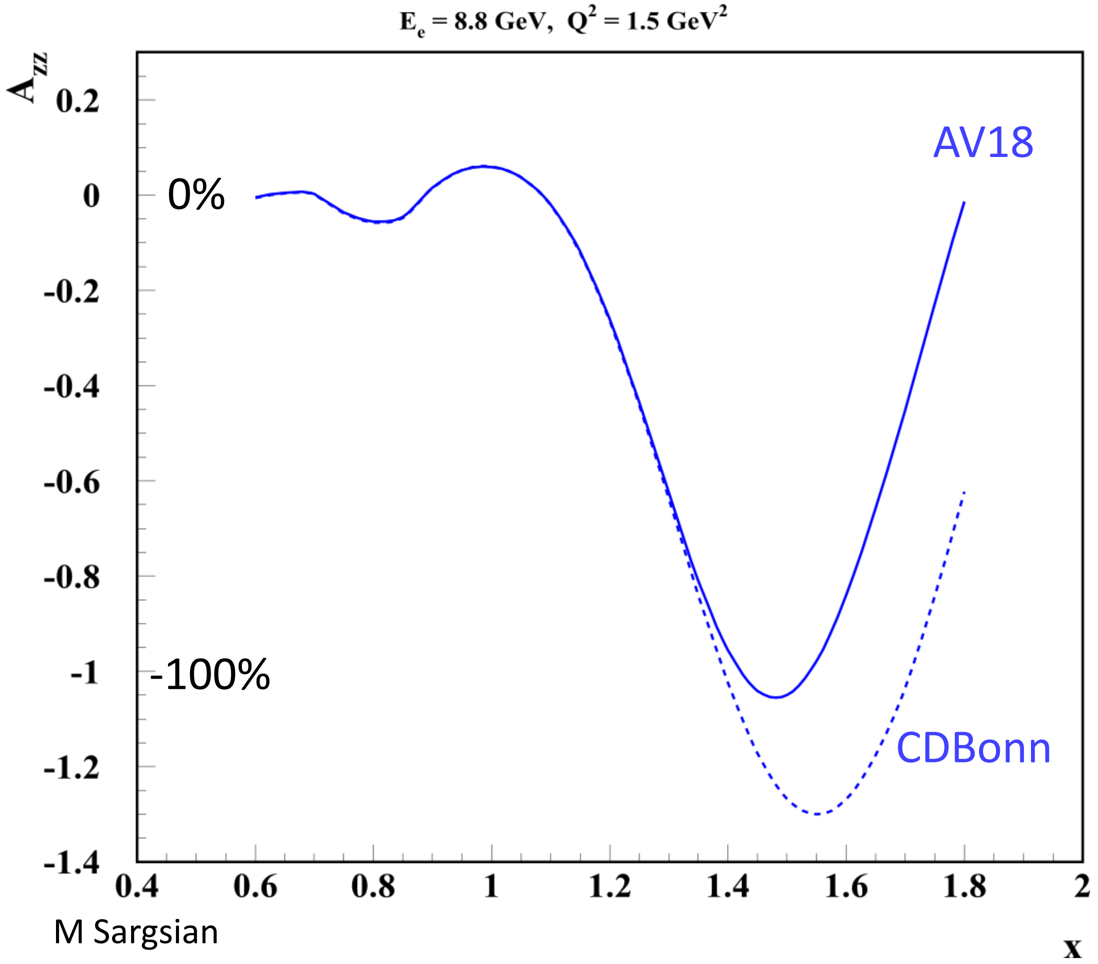

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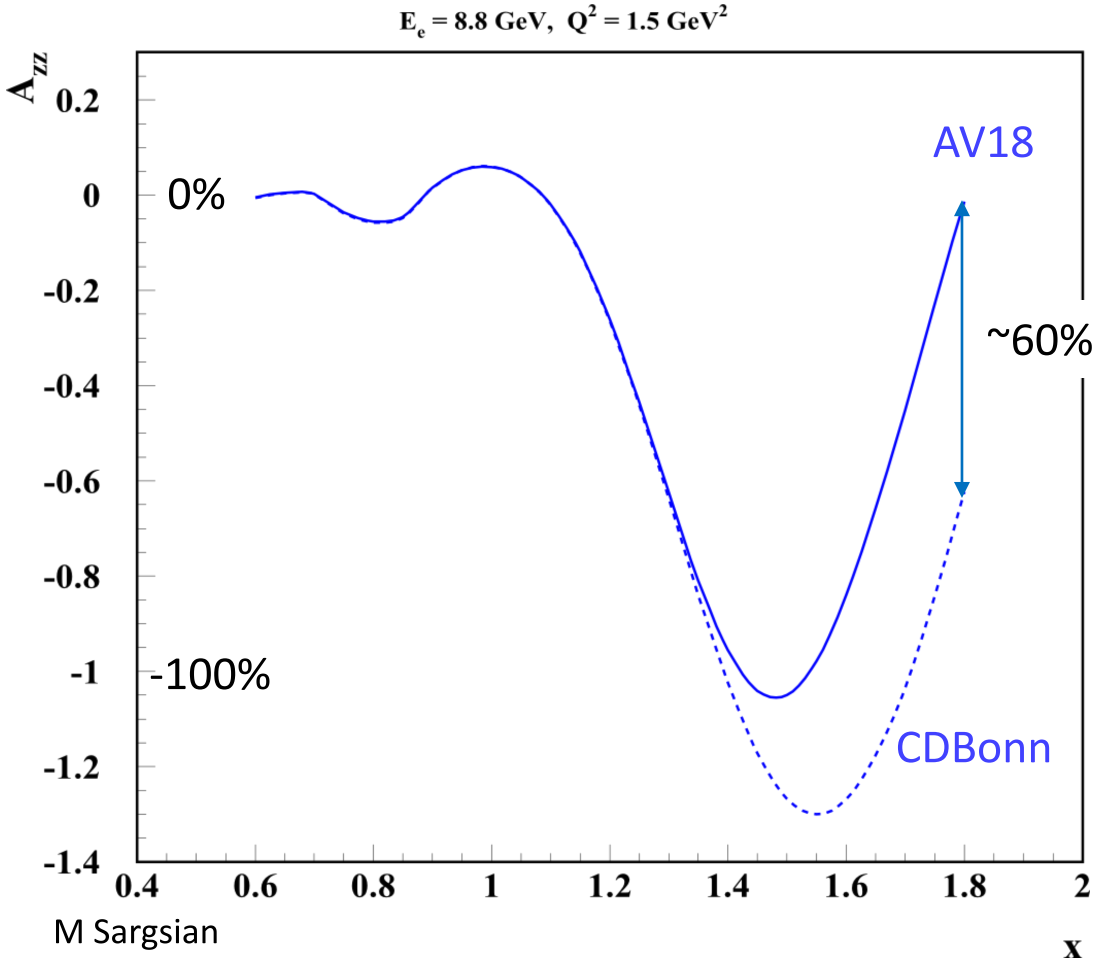

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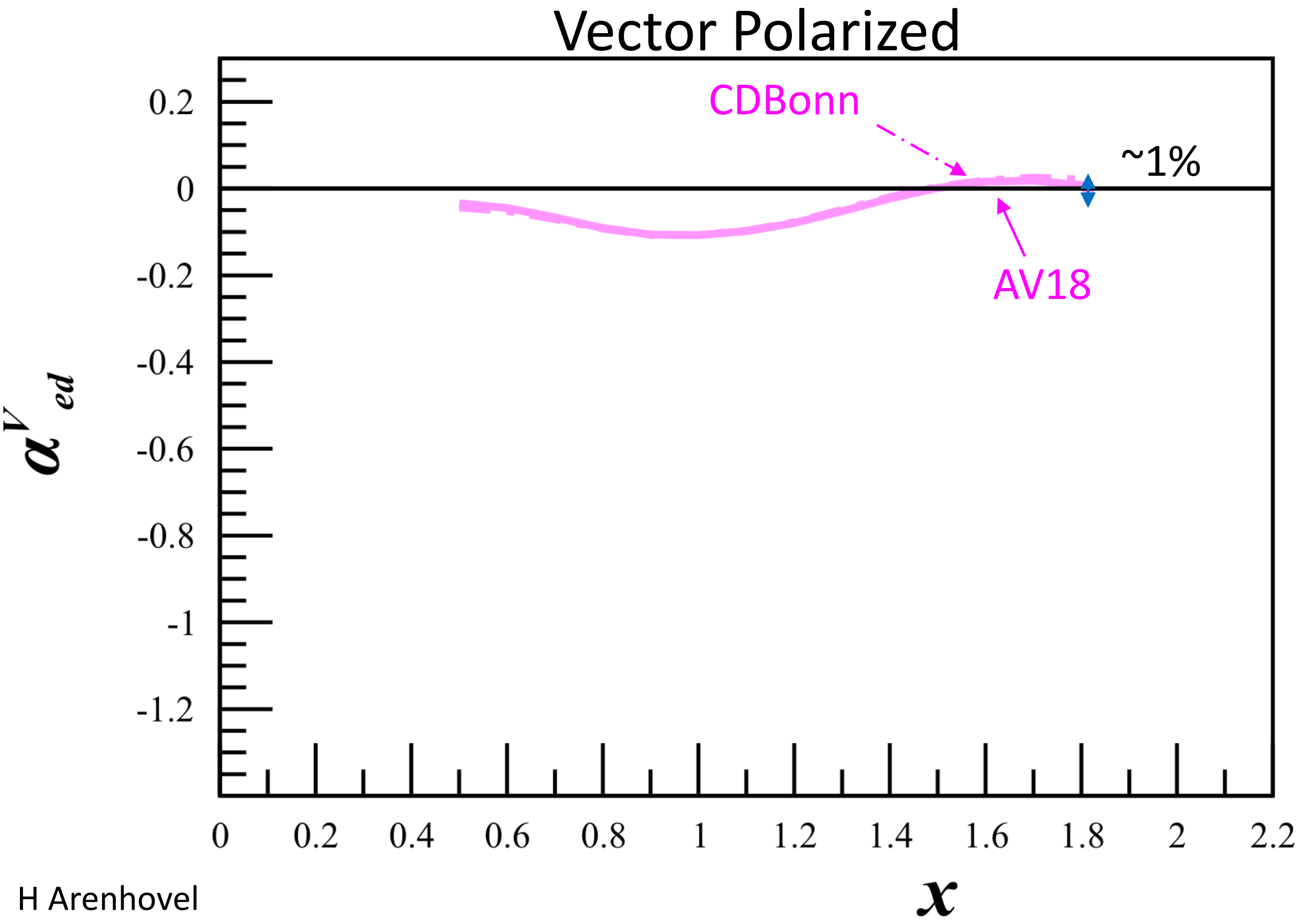
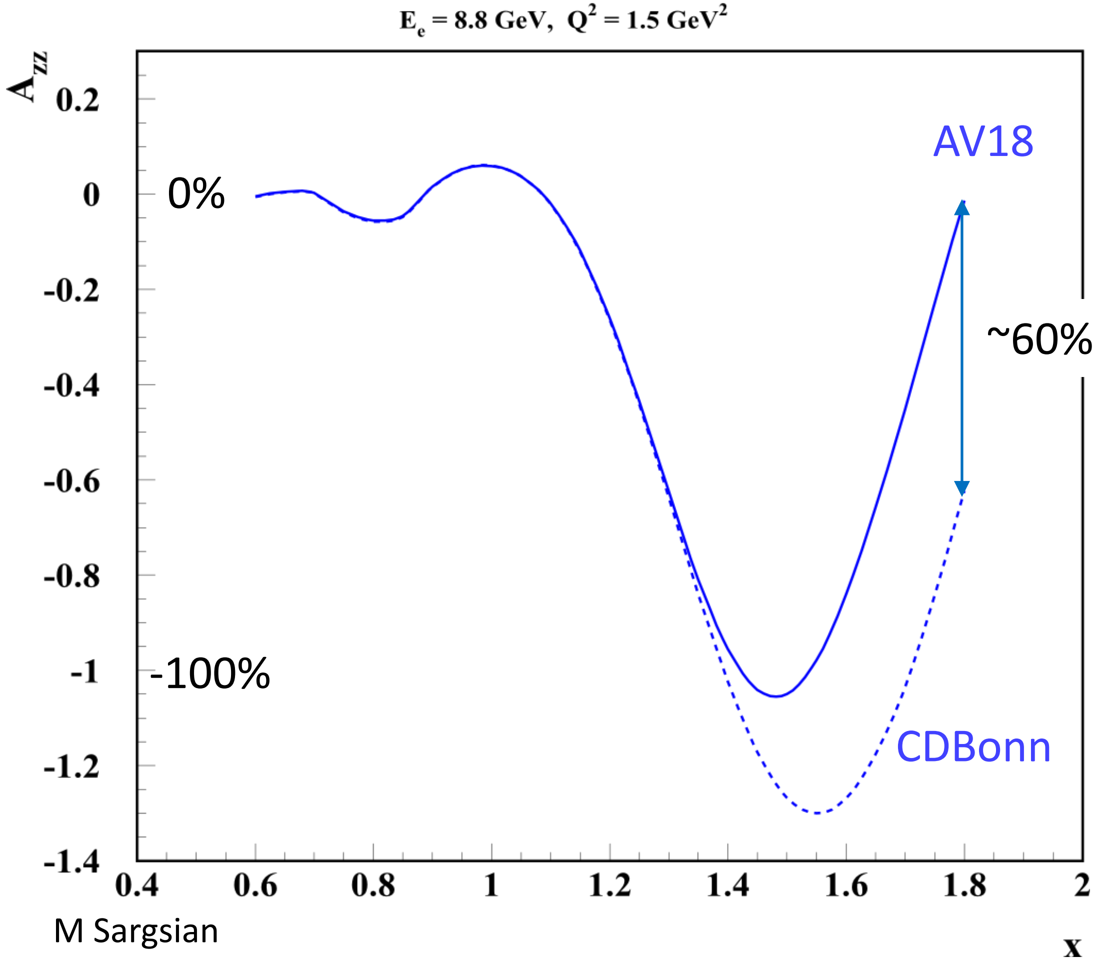


H Arenhovel



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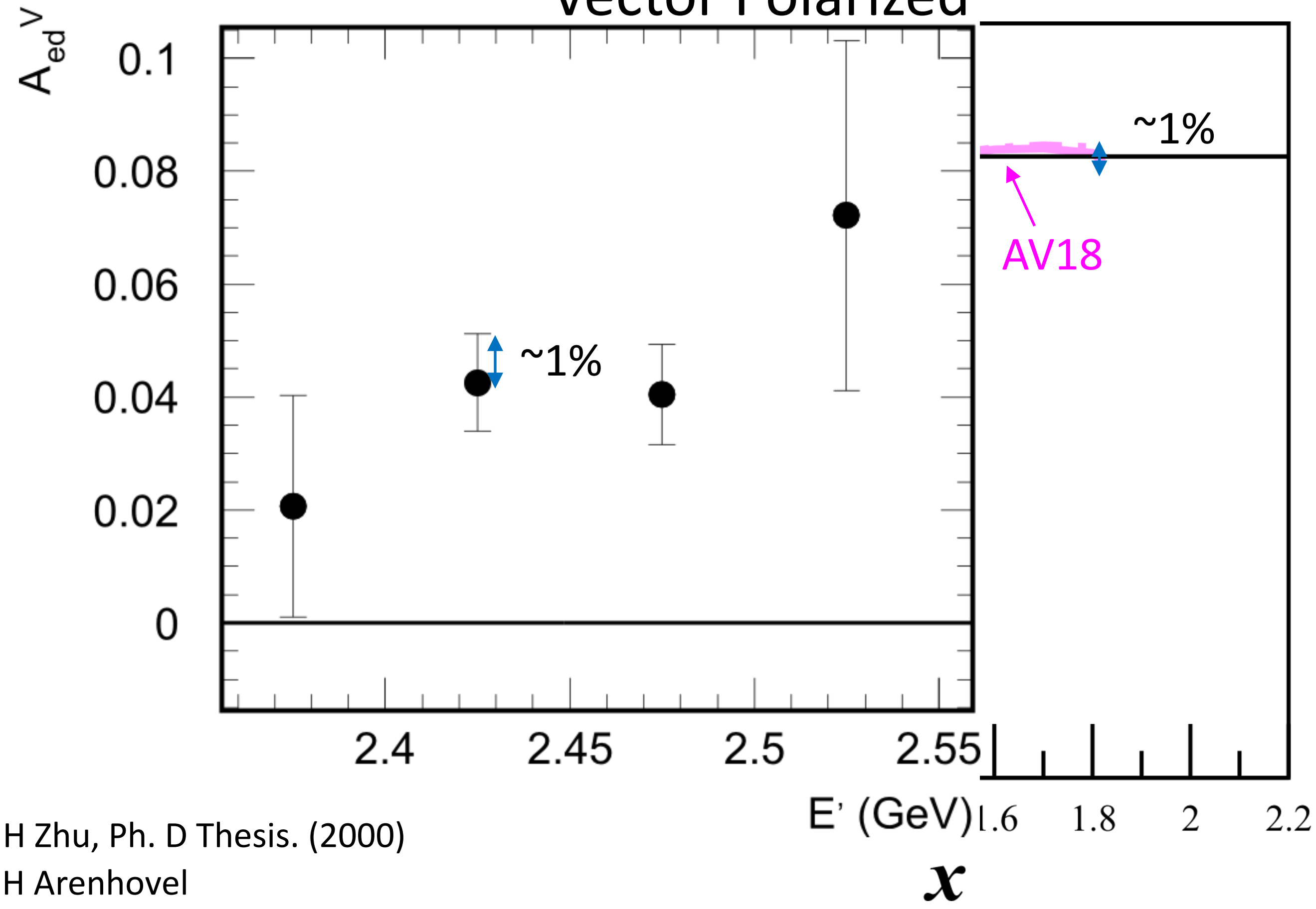
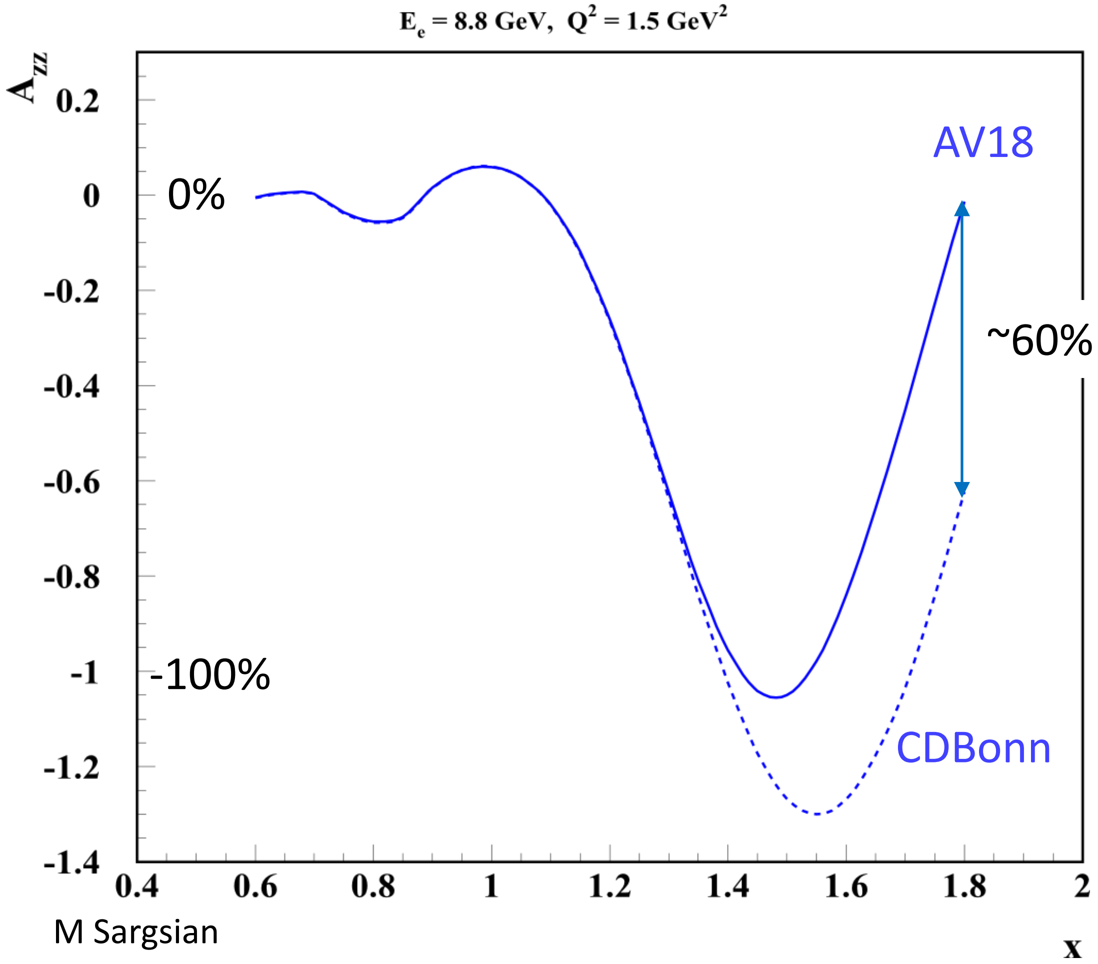


H Zhu, Ph. D Thesis. (2000)
H Arenhovel



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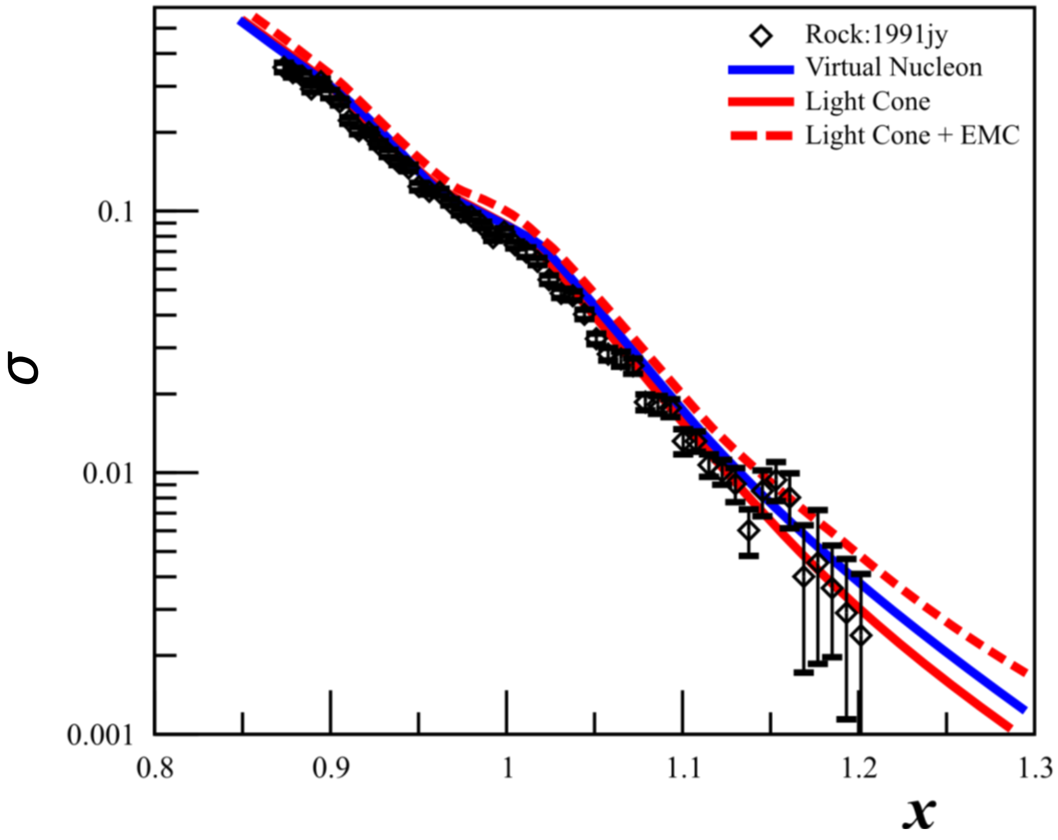
Relativistic *NN* Bound System

Unpolarized



Understanding SRCs requires relativistic calculations at high *p*

Currently two methods:

- Light Cone (LC)
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Large $p > 500\ \mathrm{MeV}/c$ needed to discriminate with unpolarized deuterons

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M Sargsian, Tensor Spin Observables Workshop (2014)

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Relativistic *NN* Bound System

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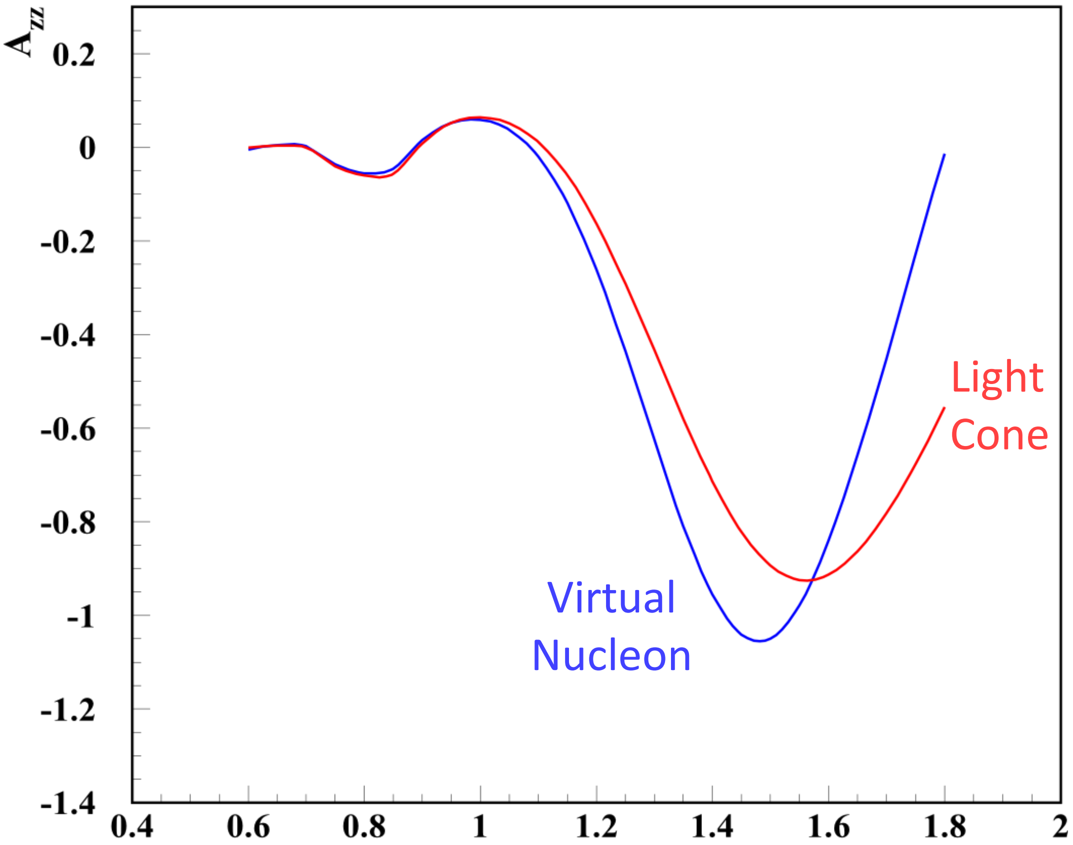

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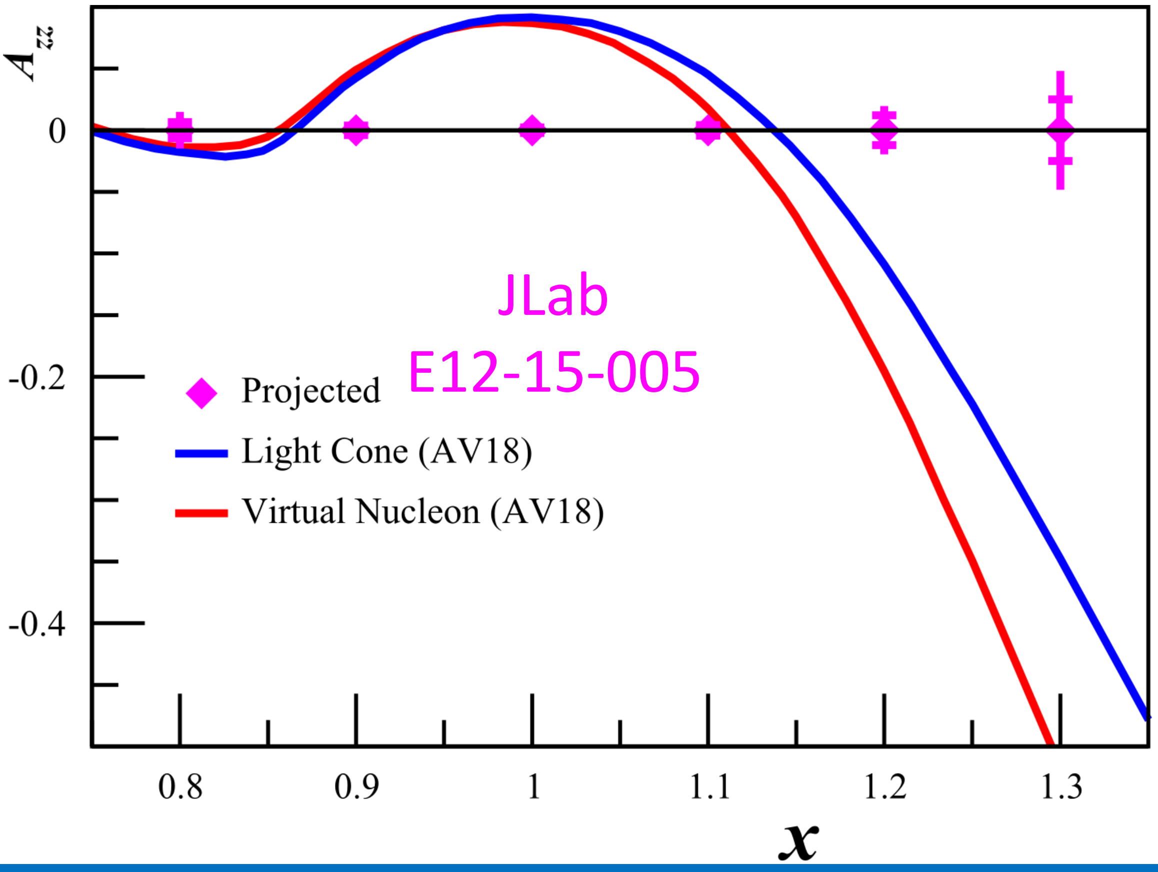

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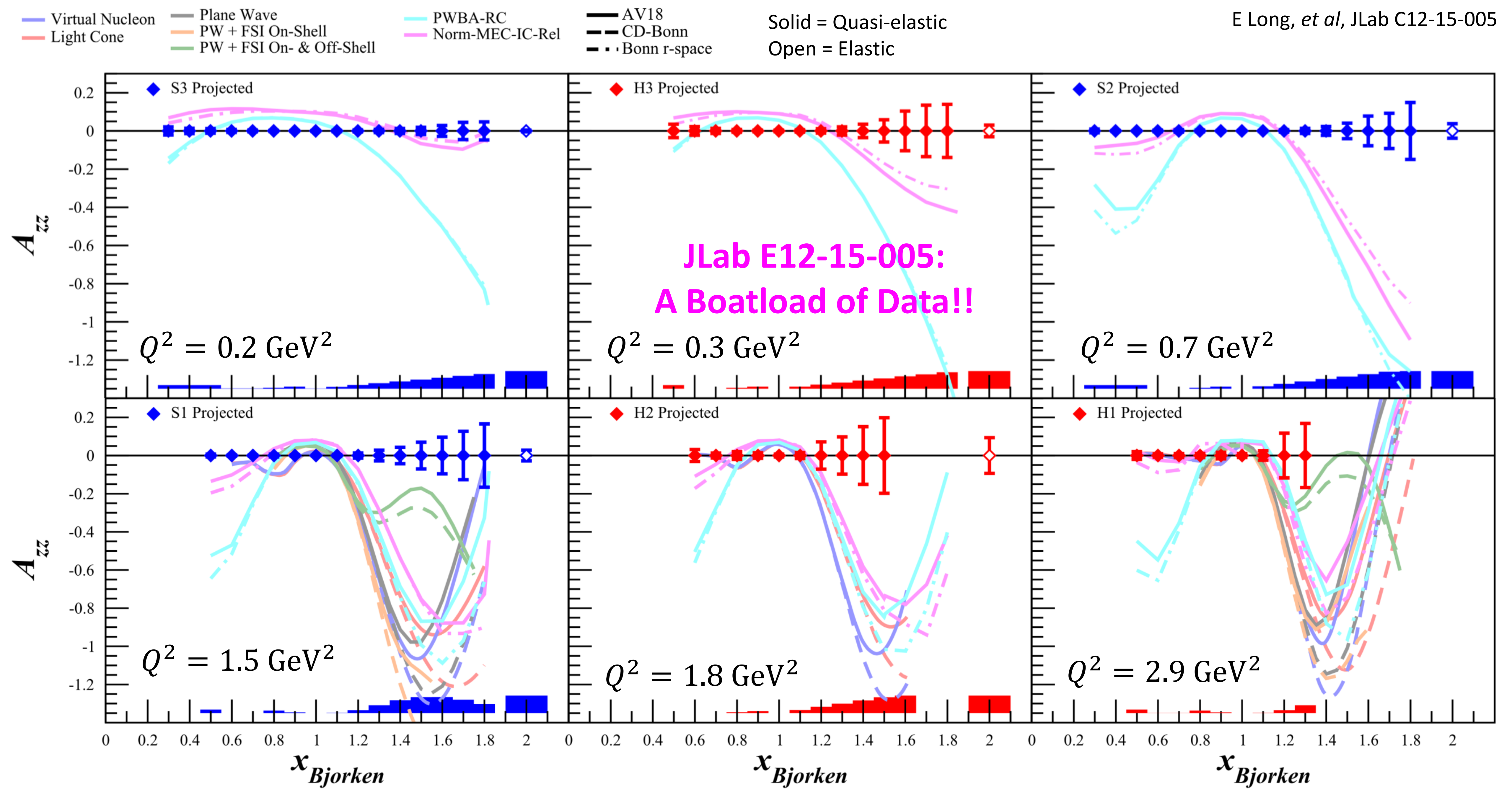
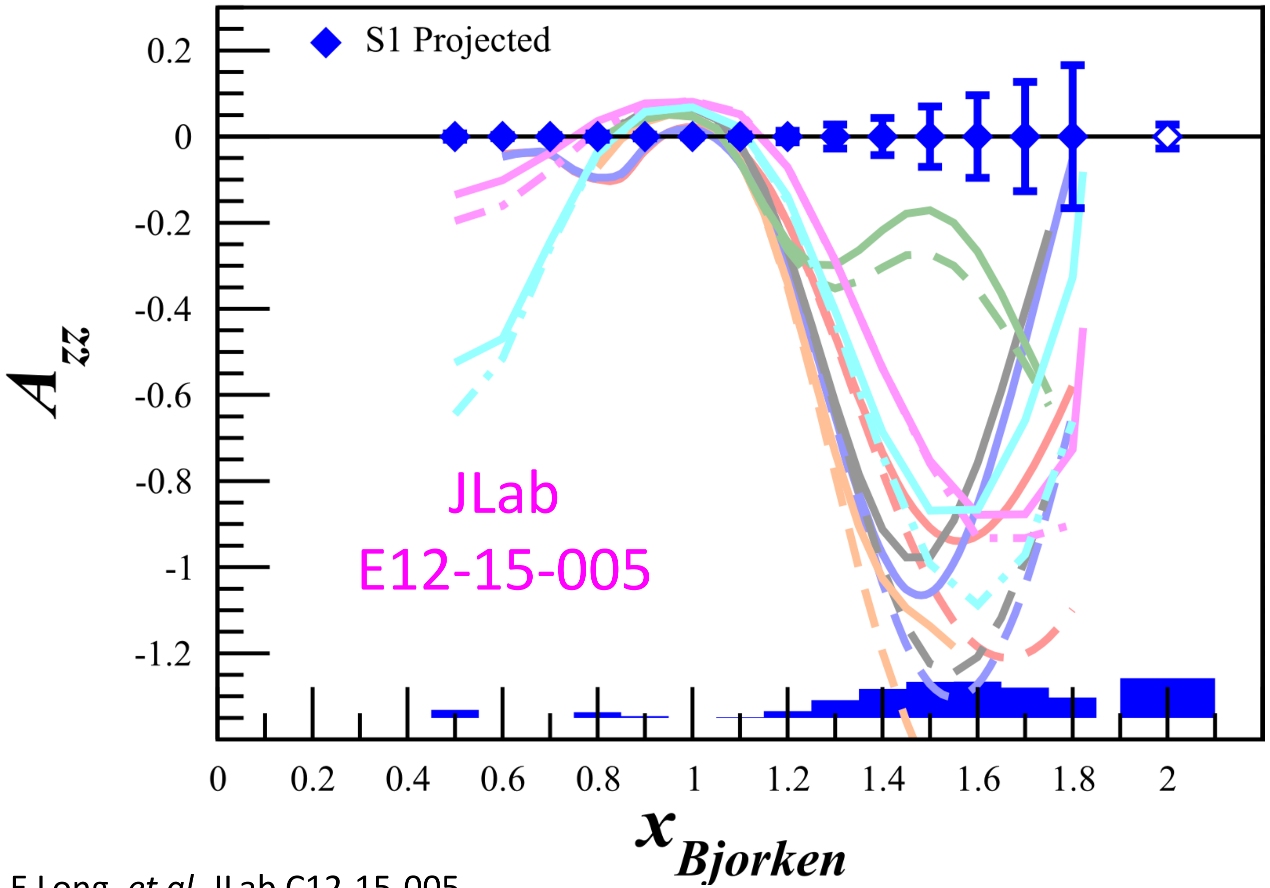


Virtual Nucleon
Light Cone
Plane Wave
PW + FSI On-Shell
PW + FSI On- & Off-Shell
PWBA-RC
Norm-MEC-IC-Rel
AV18
CD-Bonn
Bonn r-space
Solid = Quasi-elastic
Open = Elastic
E Long, et al, JLab C12-15-005
S3 Projected
H3 Projected
S2 Projected
S1 Projected
H2 Projected
H1 Projected
JLab E12-15-005:
A Boatload of Data!!
$Q^2 = 0.2$ GeV^2
$Q^2 = 0.3$ GeV^2
$Q^2 = 0.7$ GeV^2
$Q^2 = 1.5$ GeV^2
$Q^2 = 1.8$ GeV^2
$Q^2 = 2.9$ GeV^2
A_{zz}
$x_{Bjorken}$

First Measurement of Quasi-Elastic A_{zz}



E Long, *et al*, JLab C12-15-005

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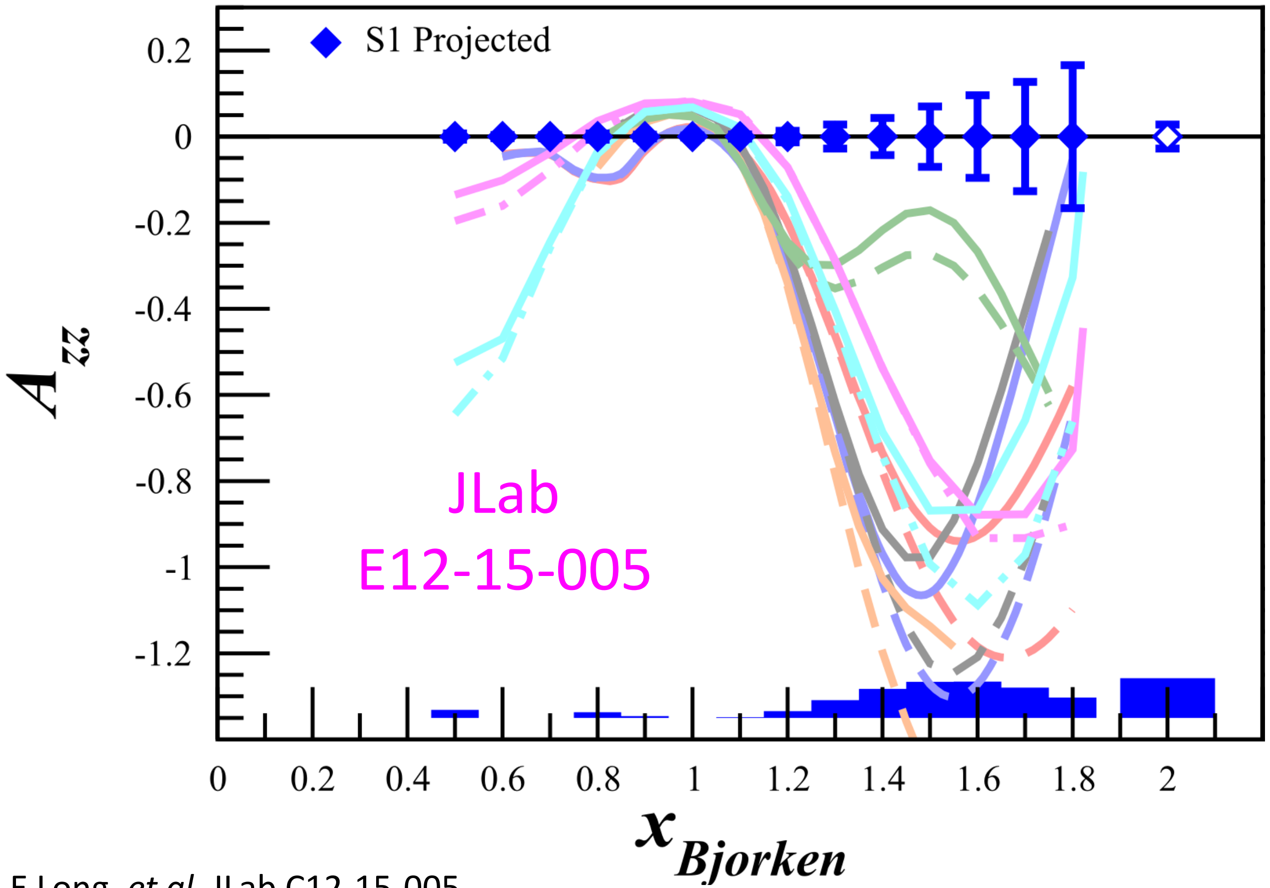

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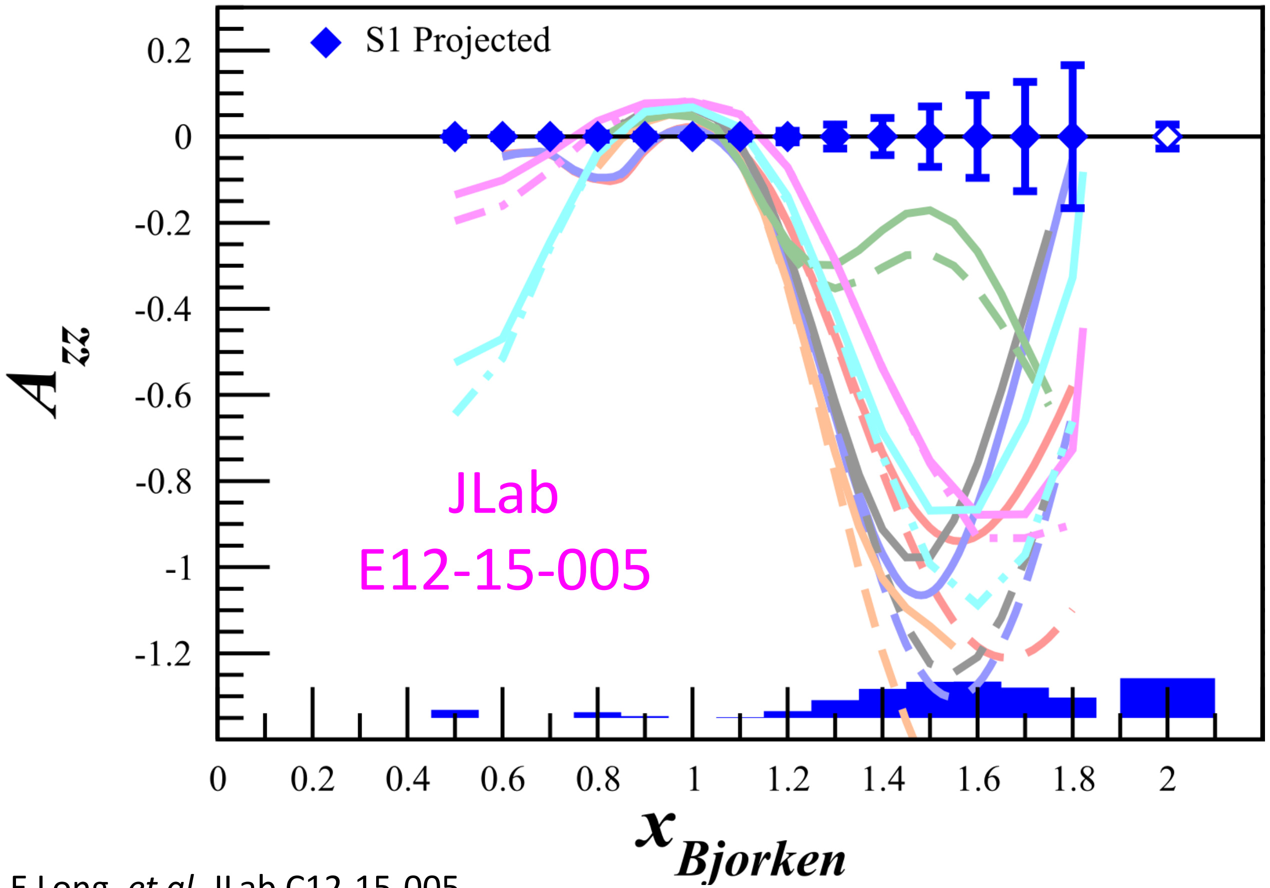

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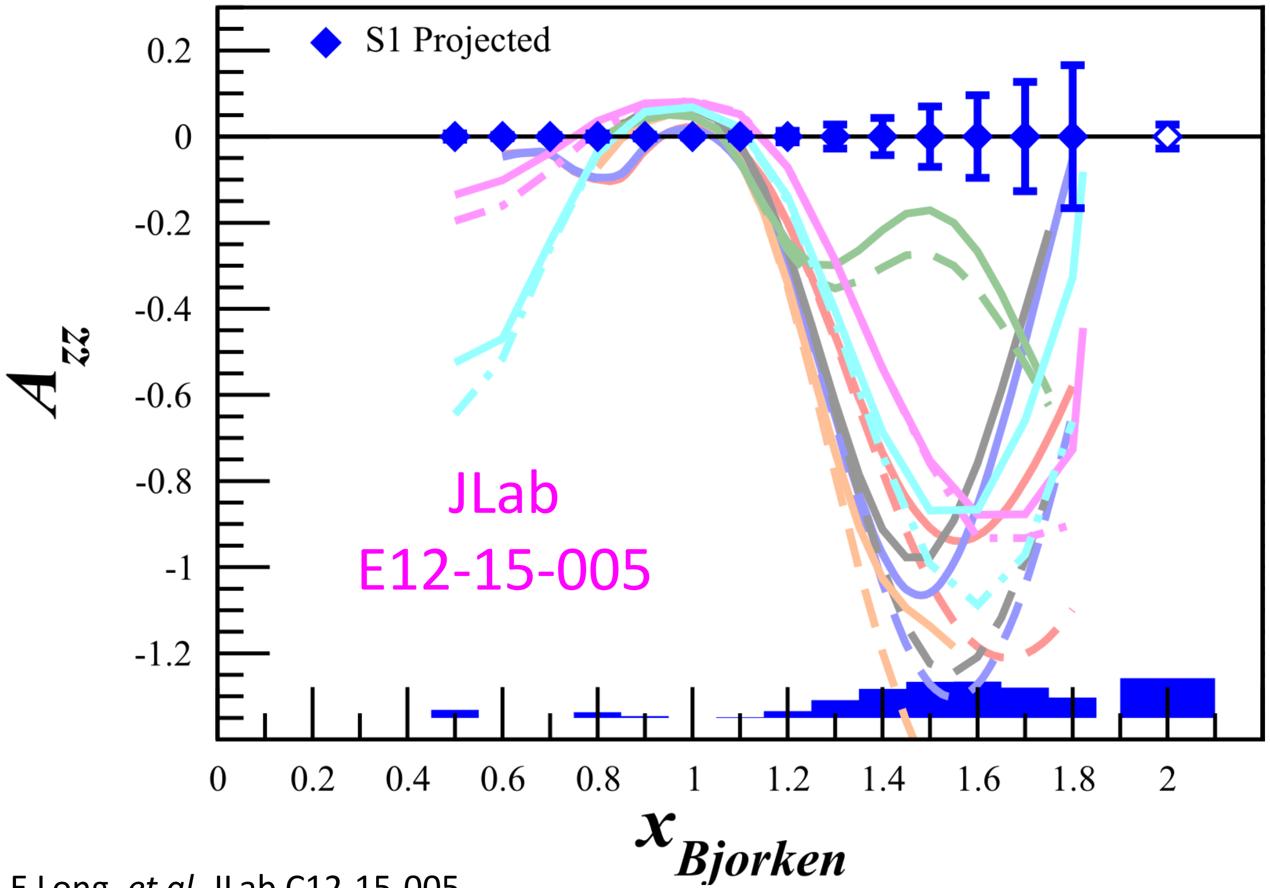

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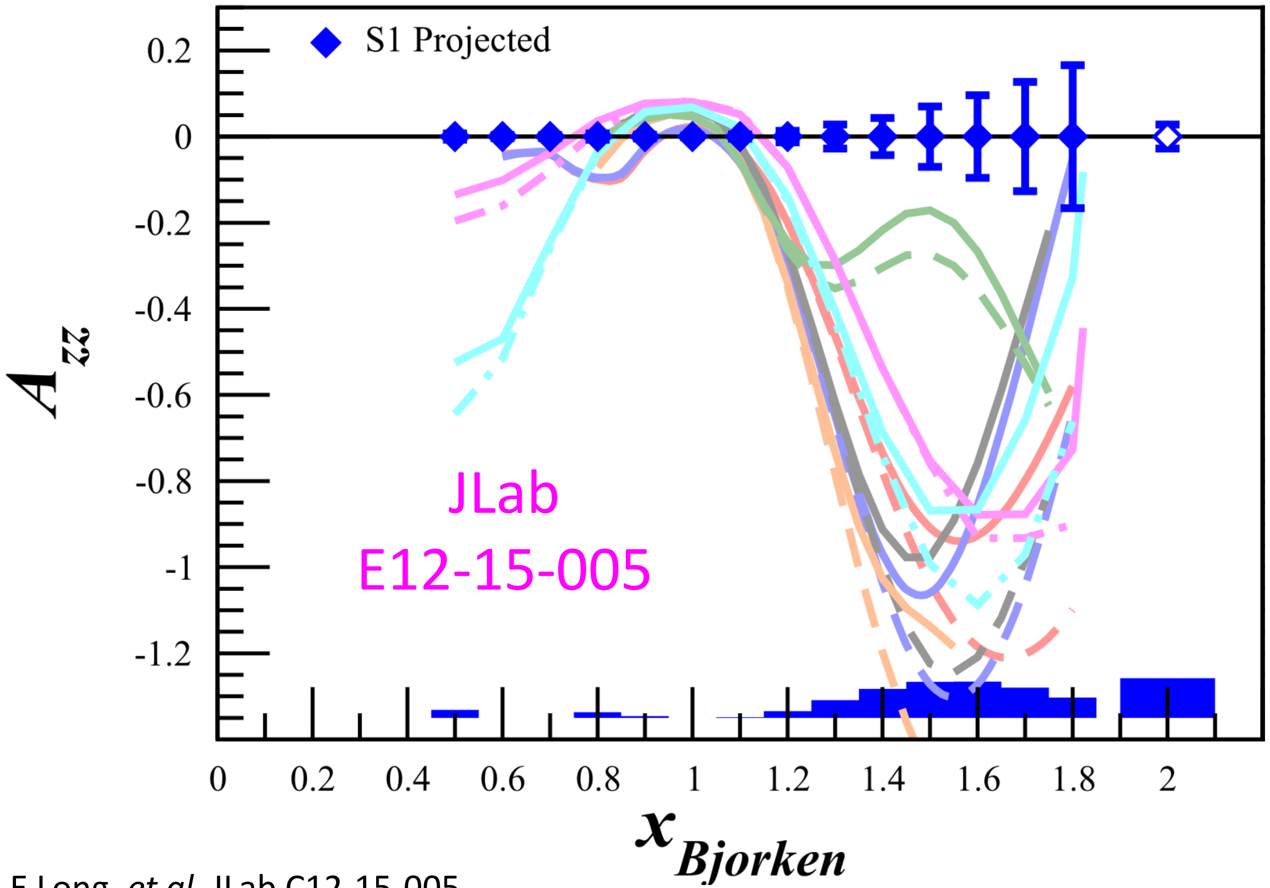

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Importance ranges from understanding **short-range correlations** to the **equations of state of neutron stars**

J. Phys.: Conf. Ser. 543 011001-012015 (2014)
http://iopscience.iop.org/1742-6596/543/1

[1] A. Bacchetta, Ph.D. Thesis (2002) arXiv:0212025

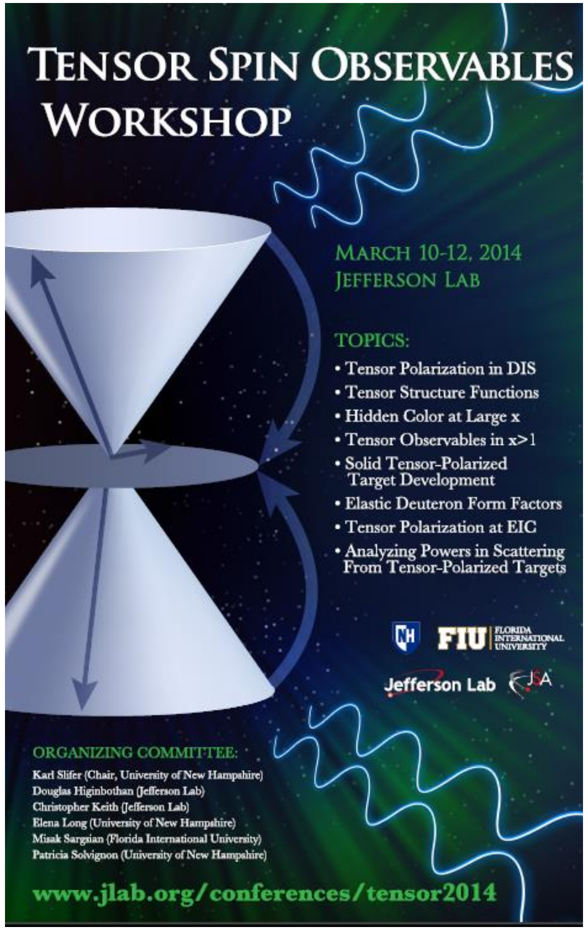
And That's Just the Beginning!

Growing tensor program:

- DIS b_1: Approved (C12-13-011)
- QE and Elastic A_{zz}: Approved (C12-15-005)
- Exotic gluon states through Δ (LOI12-16-006)

Physics accessible with a tensor polarized target:

- Orbital Angular Momentum & Spin Crisis
- Gravitomagnetic Form Factors
- Pionic Effects
- Polarized Sea Quarks
- Tensor polarized antiquarks
- Linking traditional nuclear physics and quark-gluon picture
- Final State Interactions
- Gluonic Effects
- **Tensor structure functions → b_2, b_3**
- **Tensor DVCS → Test sum rules, new helicity term**
- **Tensor Drell-Yan → 60 new structure functions**
- **Tensor TMD → Directly measure a T-odd function[1]**
- **Tensor EIC → Many calculations simplified**
- …and more!



So, How Much Longer?

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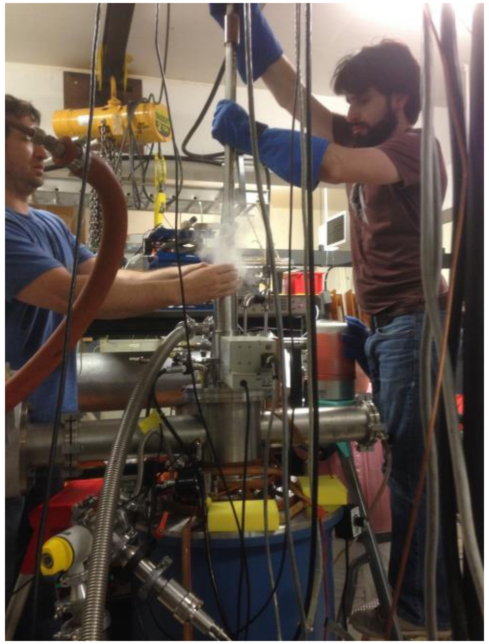

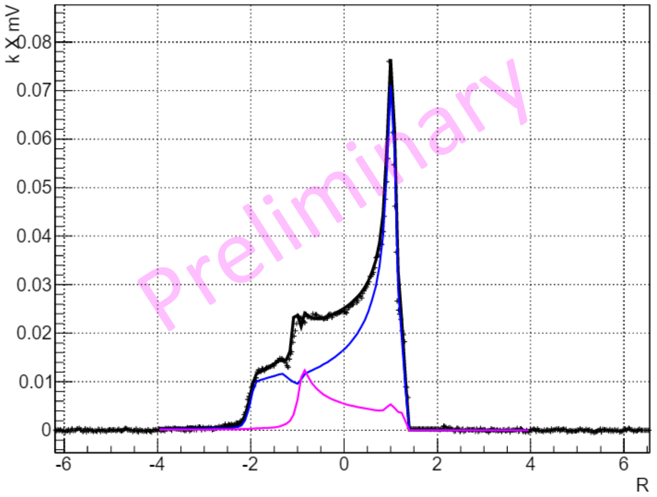

D Keller, Eur.Phys.J.A., in review (2016)
D Keller, PoS, PSTP2015:014 (2016)
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D Keller, Int.J.Mod.Phys.Conf.Ser., **40**(1):1660105 (2016)

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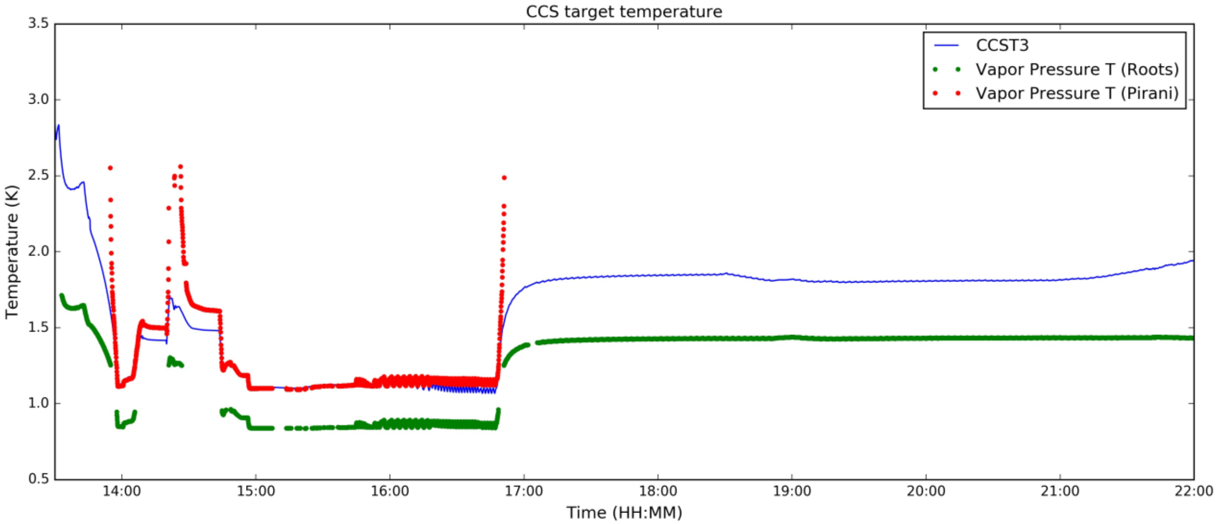

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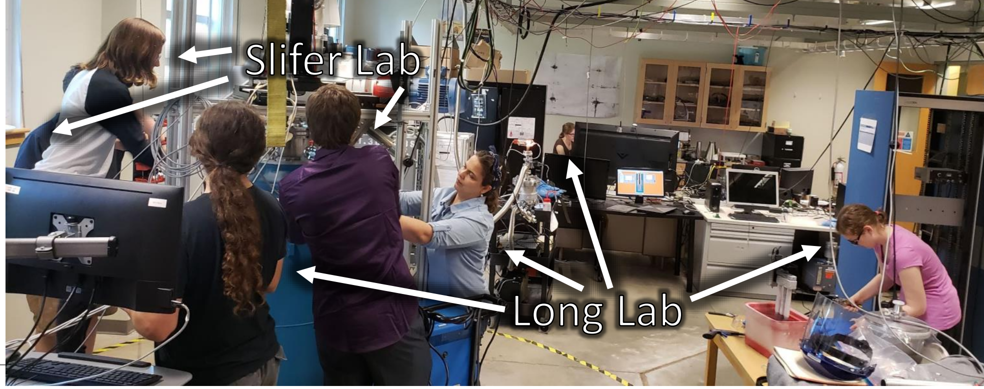

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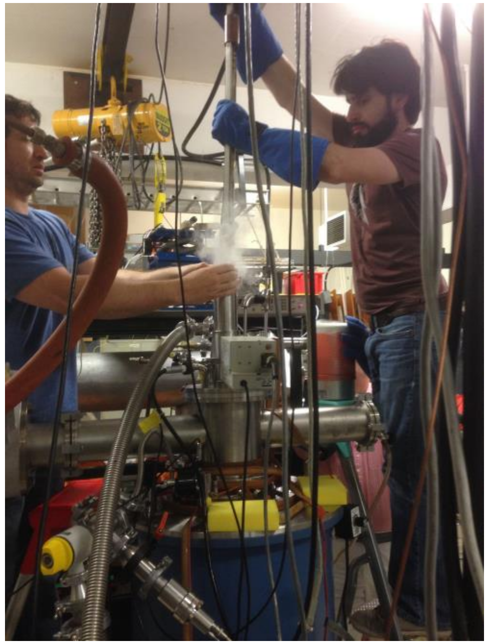

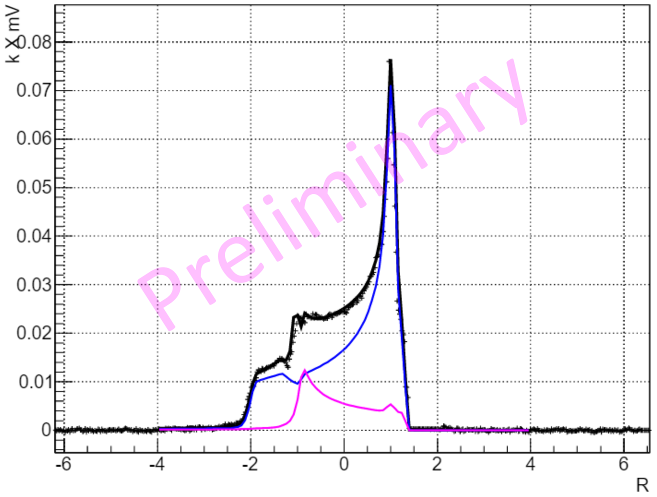

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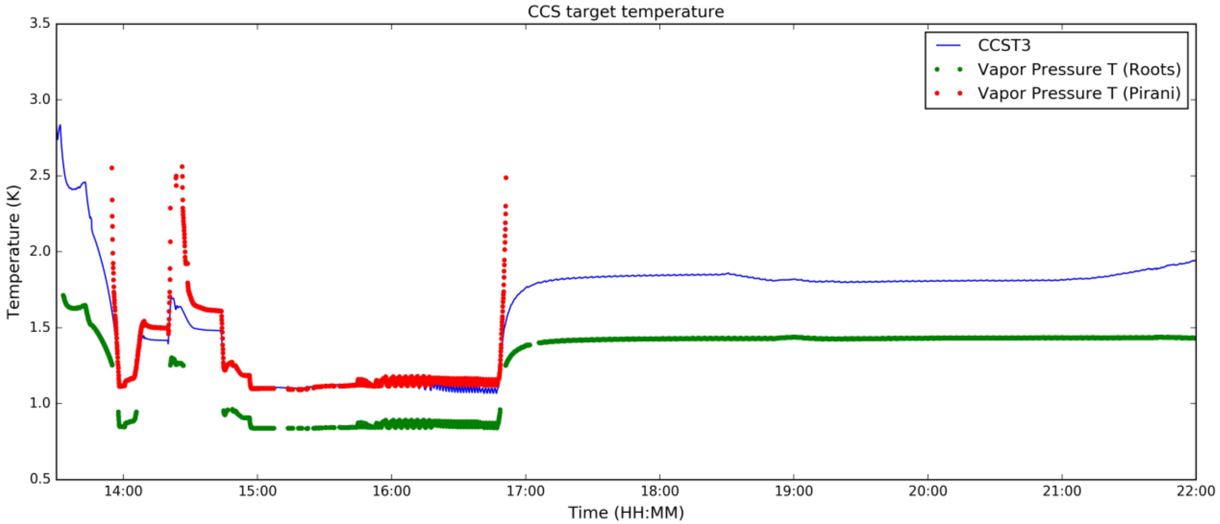

nuclear.unh.edu/~elong

Long Lab

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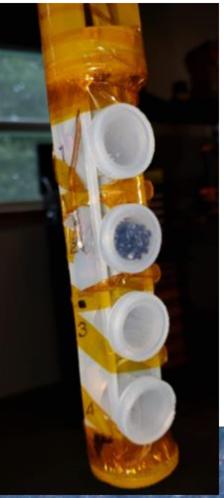
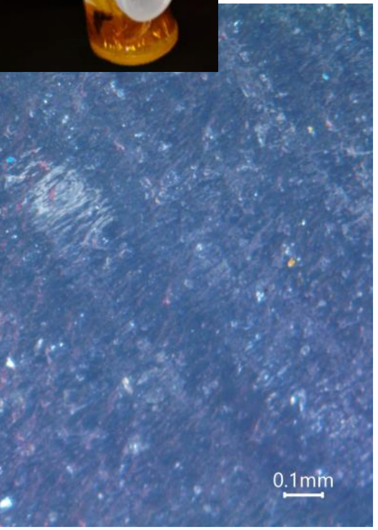
After 1K





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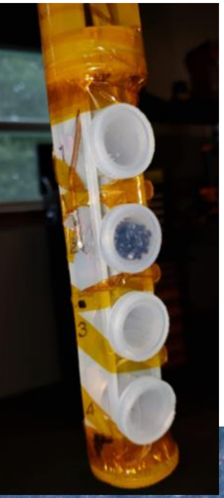

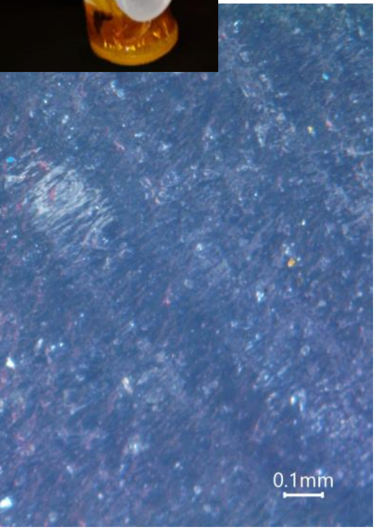

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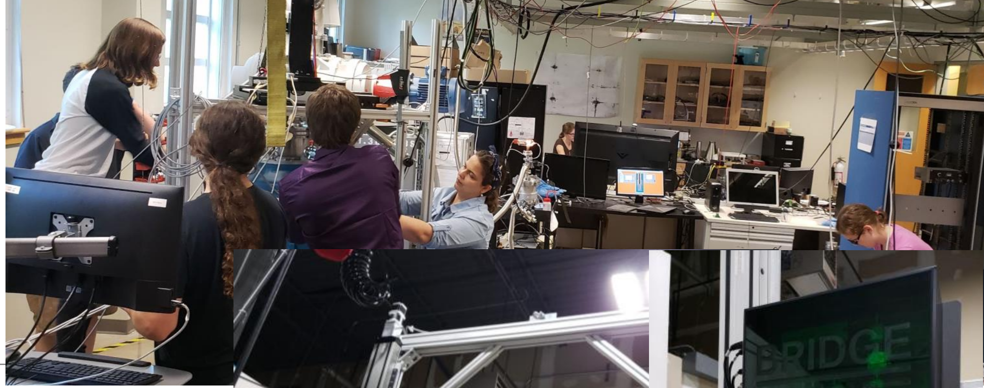

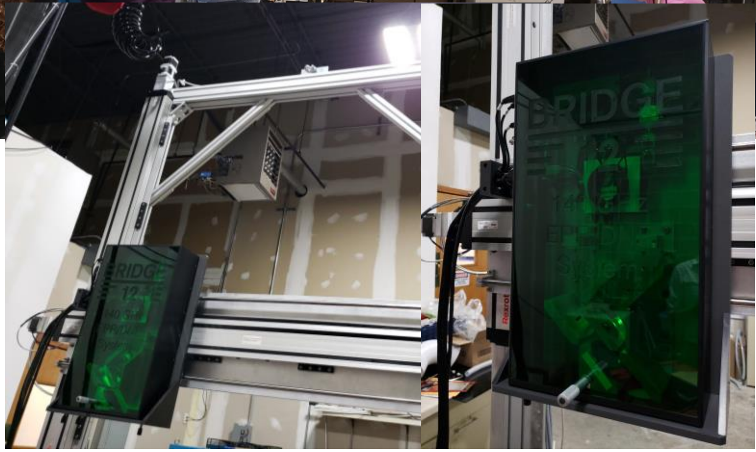

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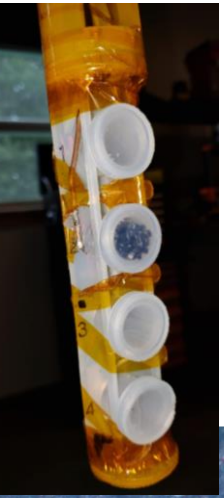

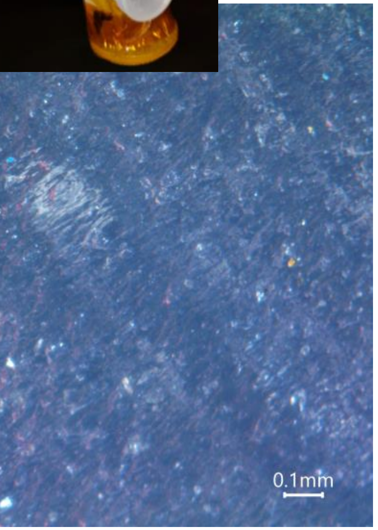

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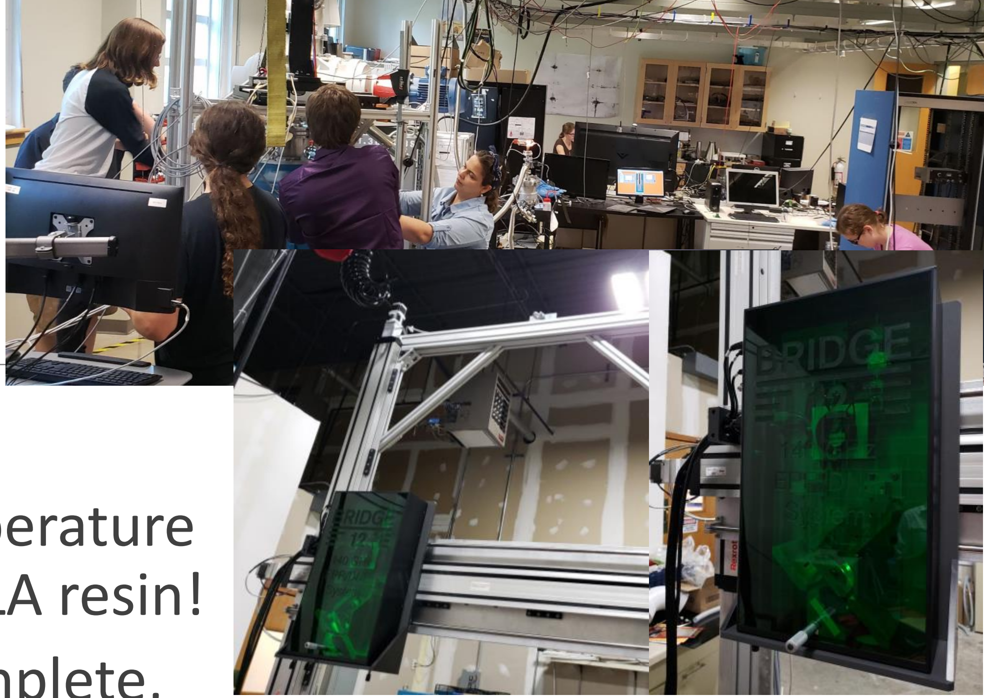

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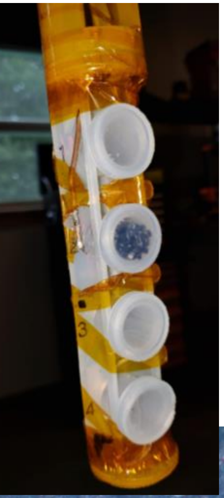

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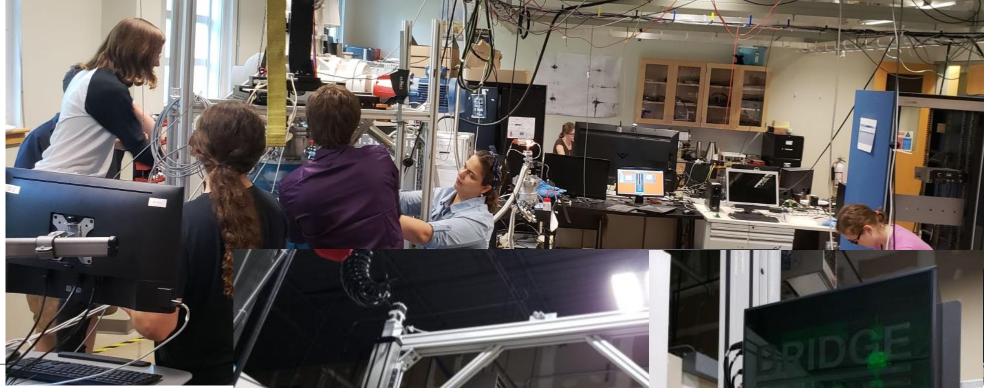

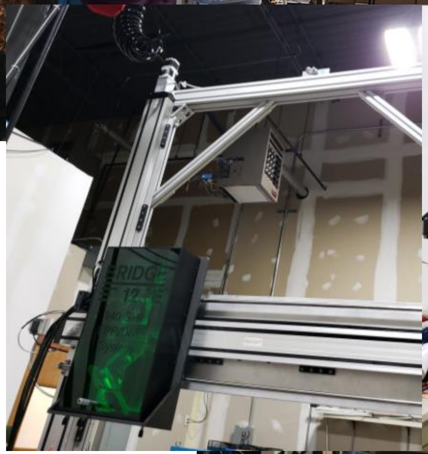

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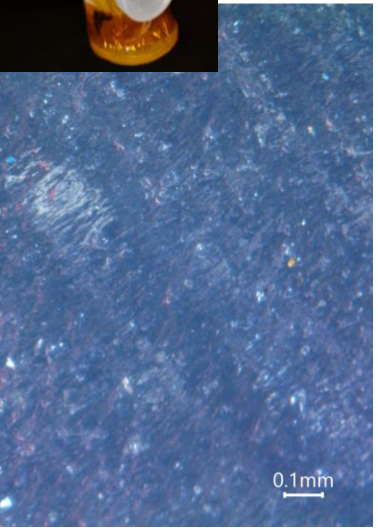

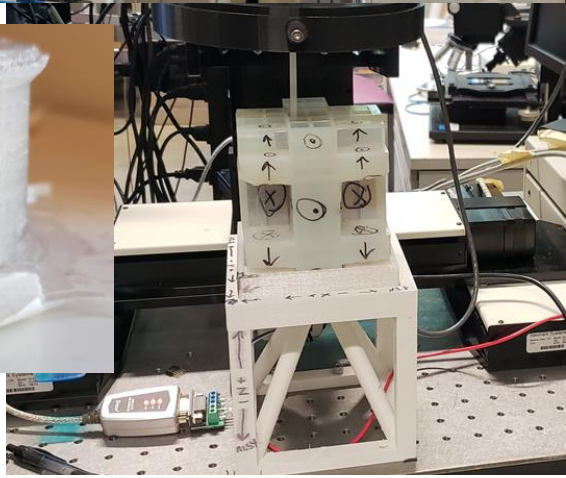

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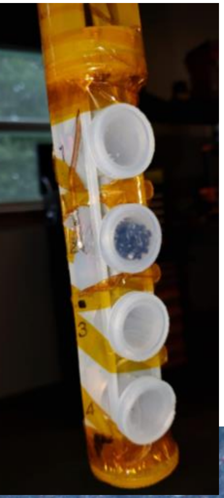

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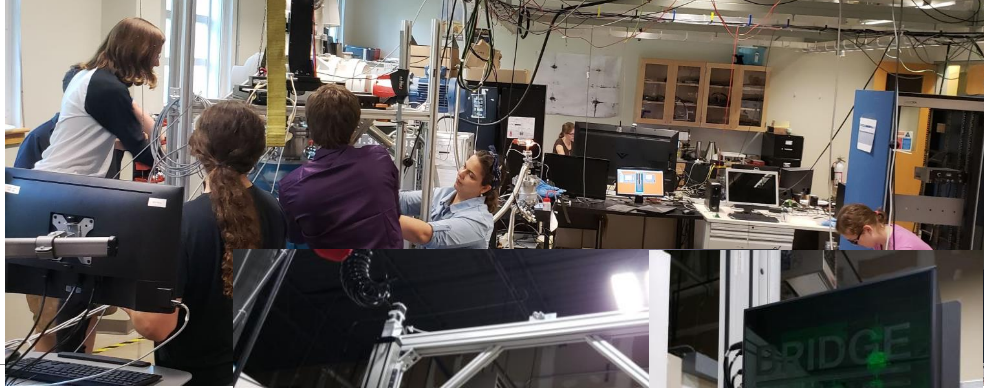

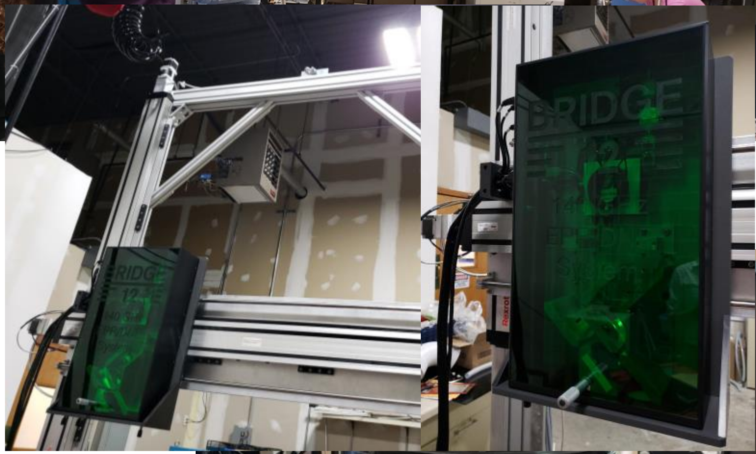

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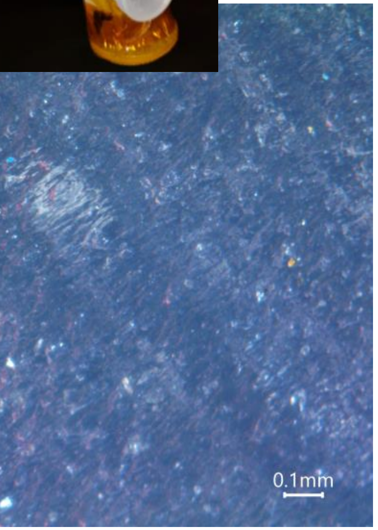
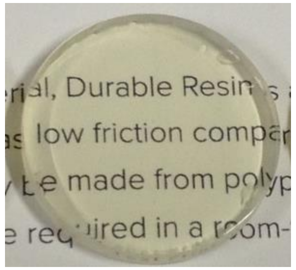
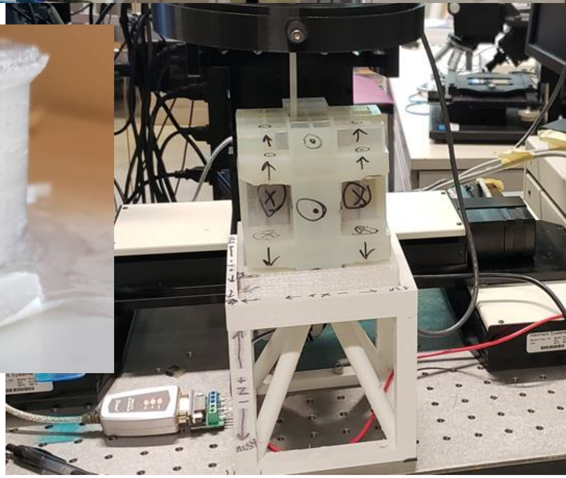
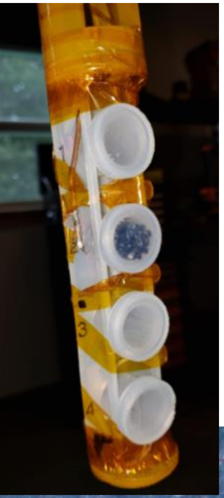
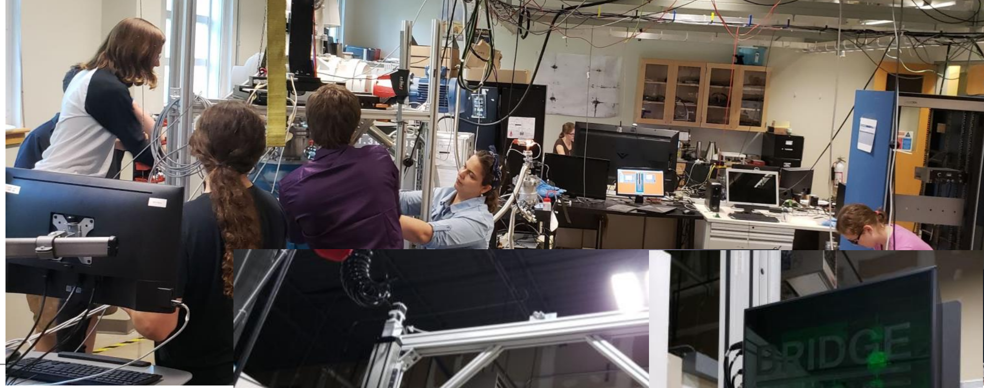






After 1K





So, How Much Longer?

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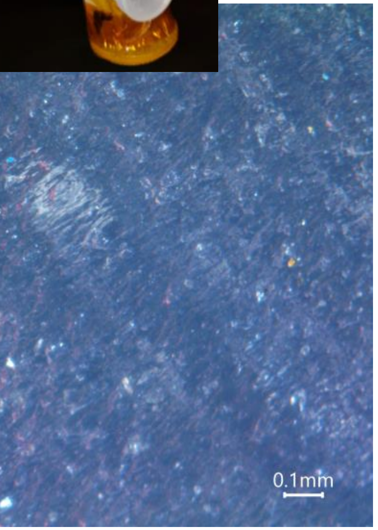
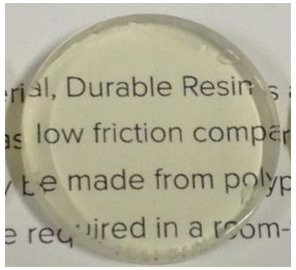
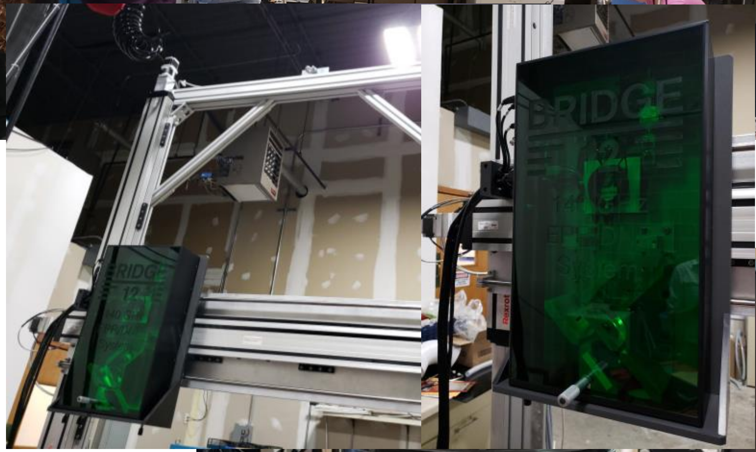
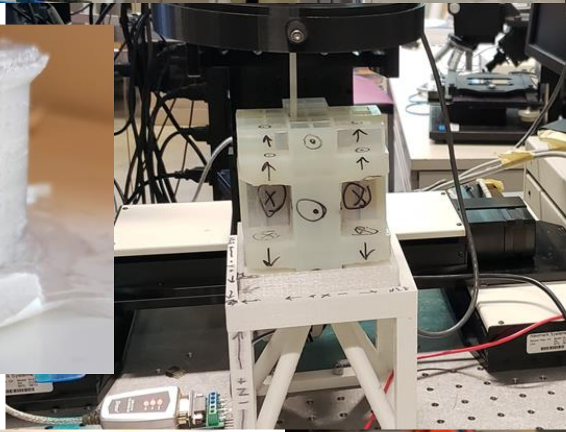
  - Attempting to 3D print 10 MeV beamline for target material pre-irradiation with <$4k printer

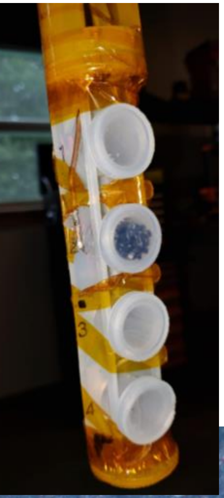








After 1K



nuclear.unh.edu/~elong

All This in ~ 1 Year

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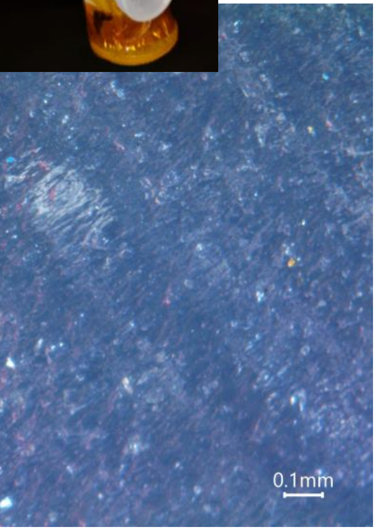
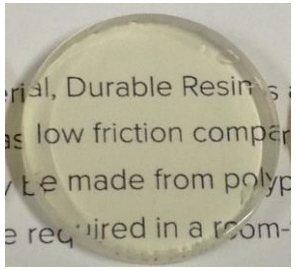
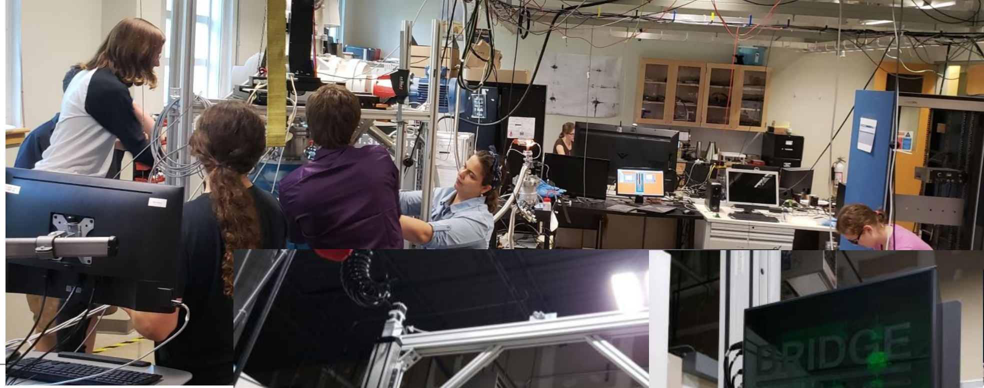
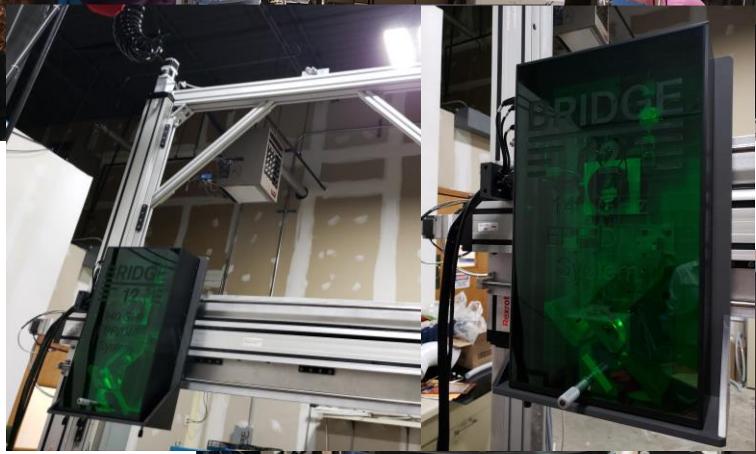
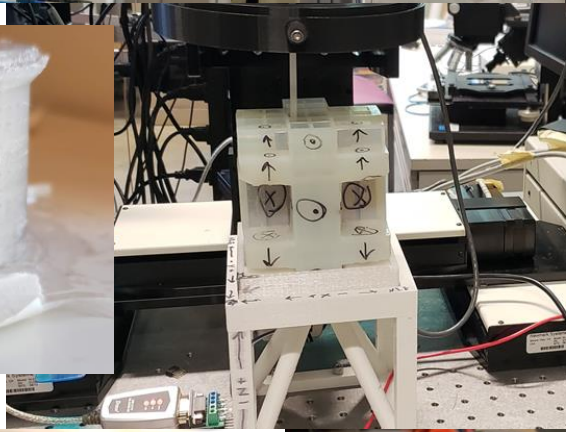


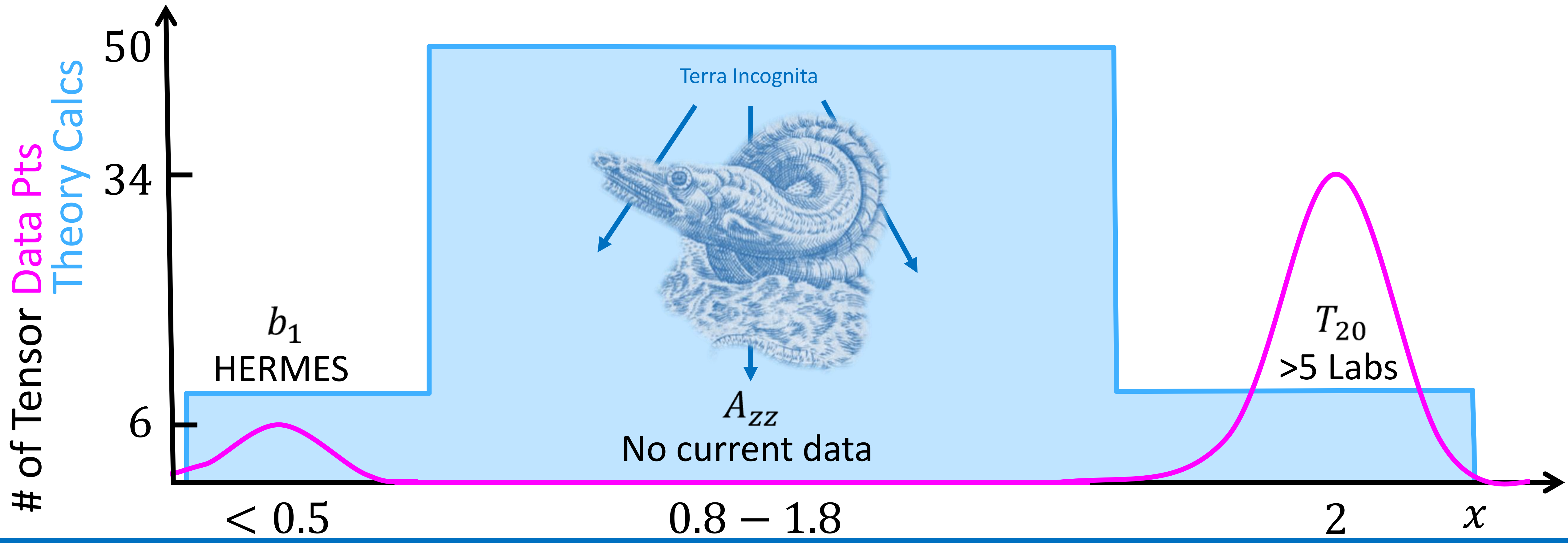




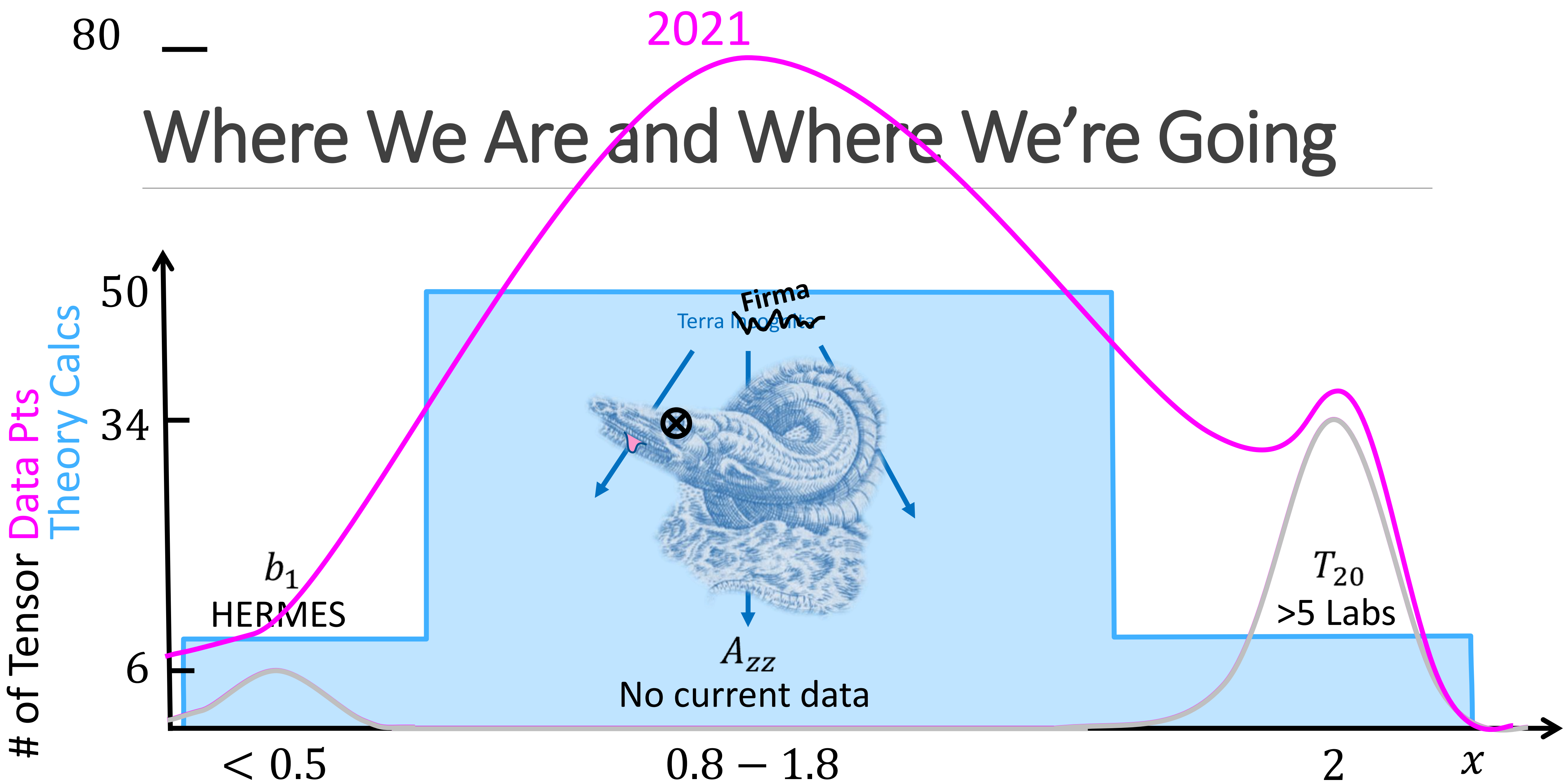




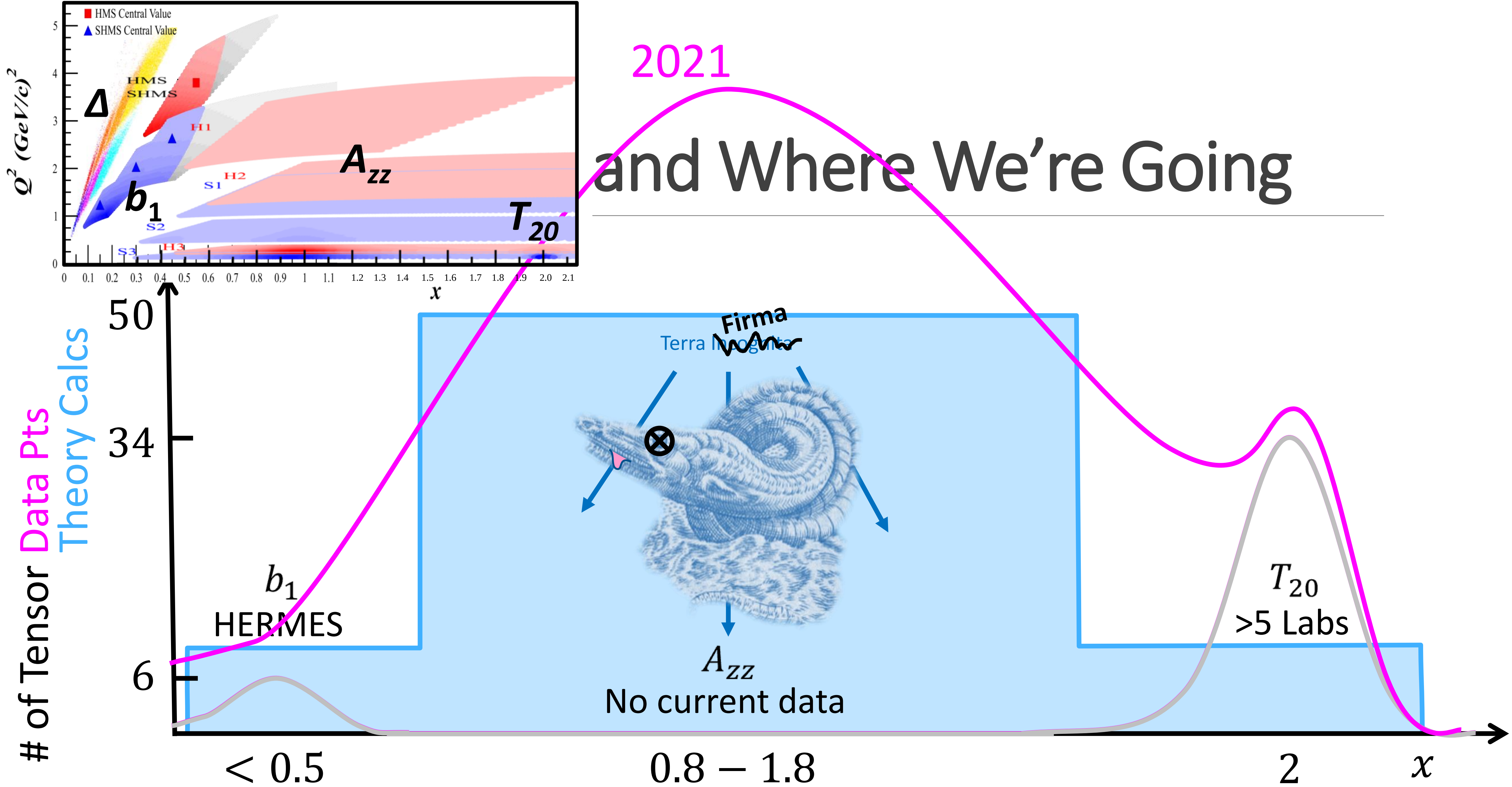
Where We Are and Where We're Going



Where We Are and Where We're Going



and Where We're Going




E. Granok
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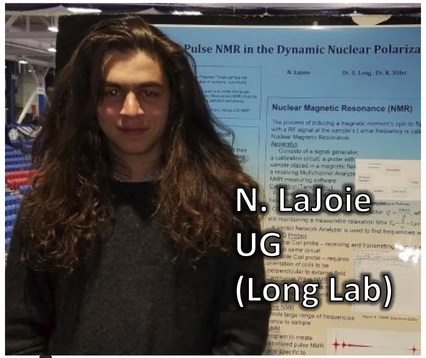
(Long Lab)


K. McGuire
UG
(Long Lab)


Nuclear Magnetic Resonance (NMR)
N. LaJoie
UG
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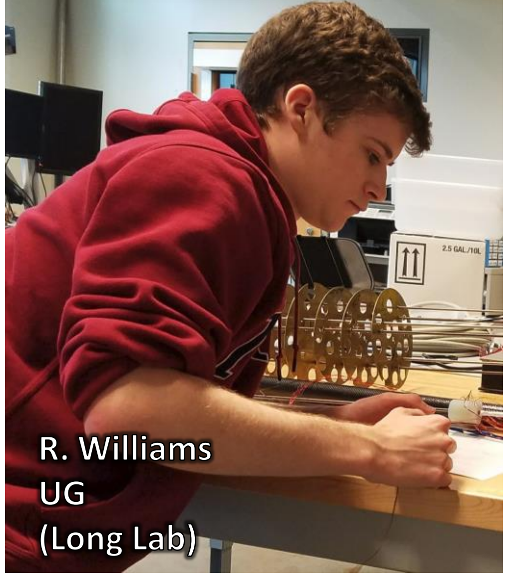
R. Williams
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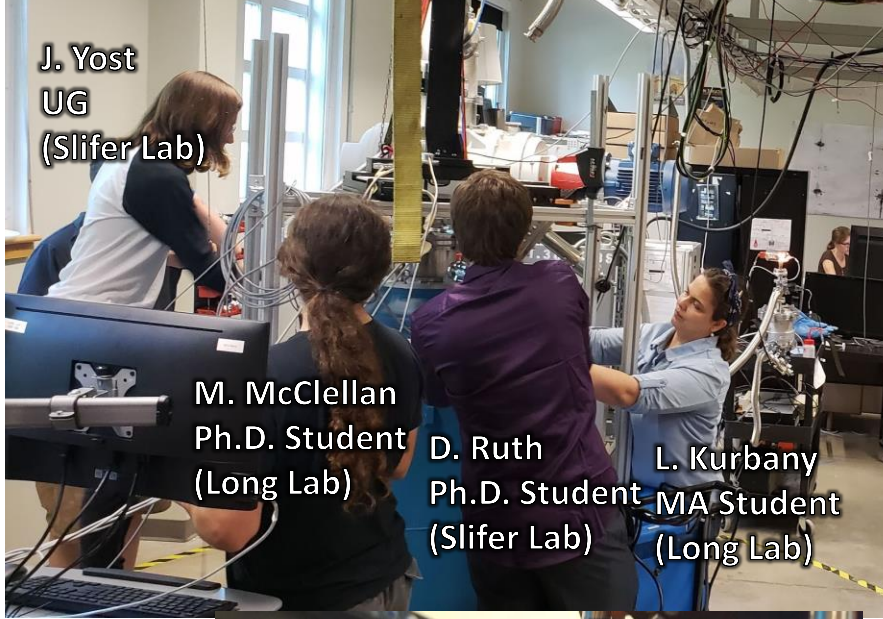
J. Yost
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M. McClellan
Ph.D. Student
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D. Ruth
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(Slifer Lab)
L. Kurbany
MA Student
(Long Lab)

Thank you!


K. Slifer


N. Santiesteban
Ph.D. Student
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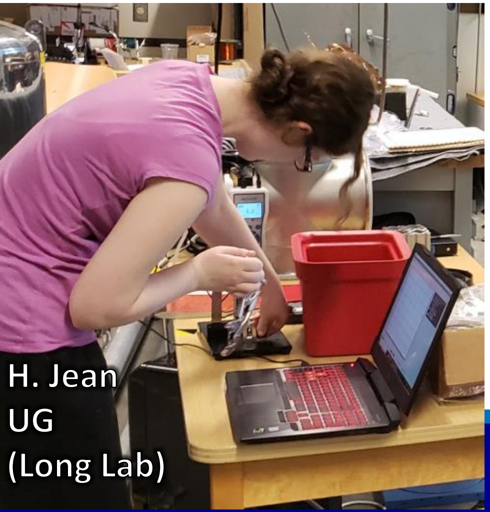
H. Jean
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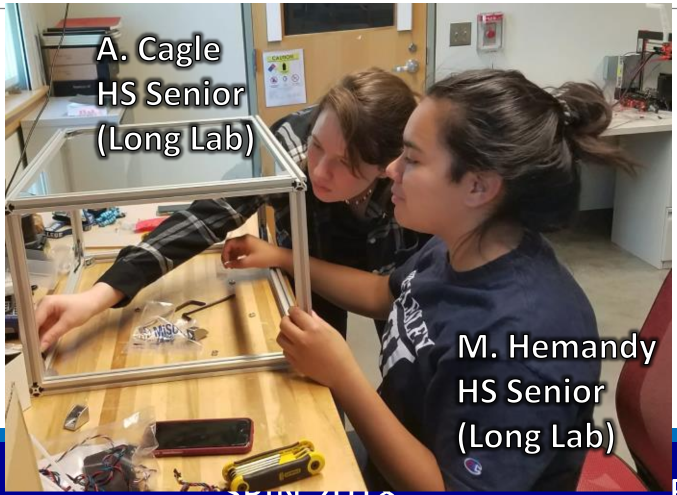
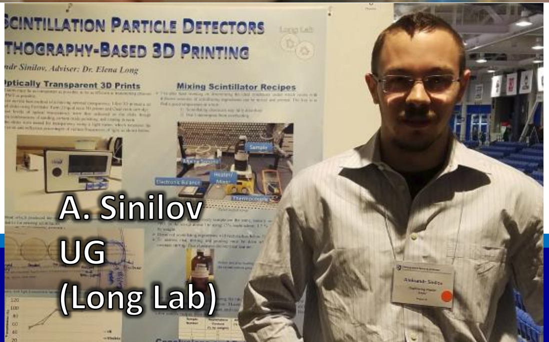

A. Cagle
HS Senior
(Long Lab)
M. Hemandy
HS Senior
(Long Lab)


A. Sinilov
UG
(Long Lab)