

The 12 GeV Science at the upgraded JLab: the first results

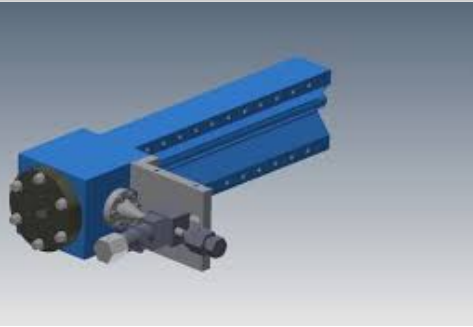


Dipangkar Dutta
Mississippi State
University



SESAPS 2019
Nov 8, 2019
Wilmington, NC

Outline



1. Introduction

2. Early results from

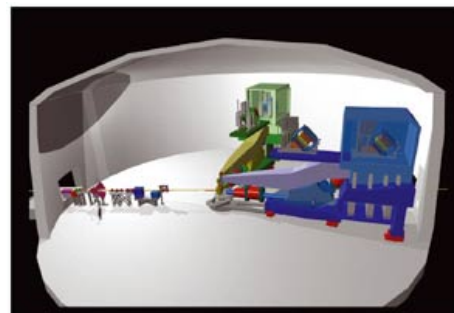
- Hadrons and cold nuclear matter
- Transverse & Longitudinal structure of hadrons
- 3D structure of hadrons
- Hadron spectra to probe QCD
- Low-energy tests of SM



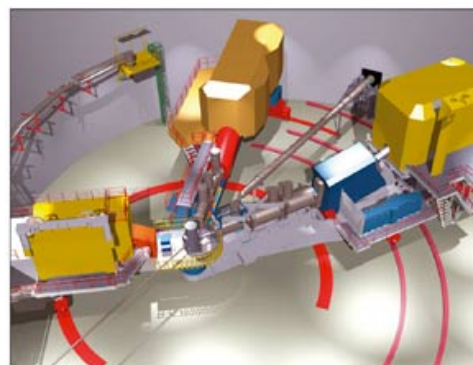
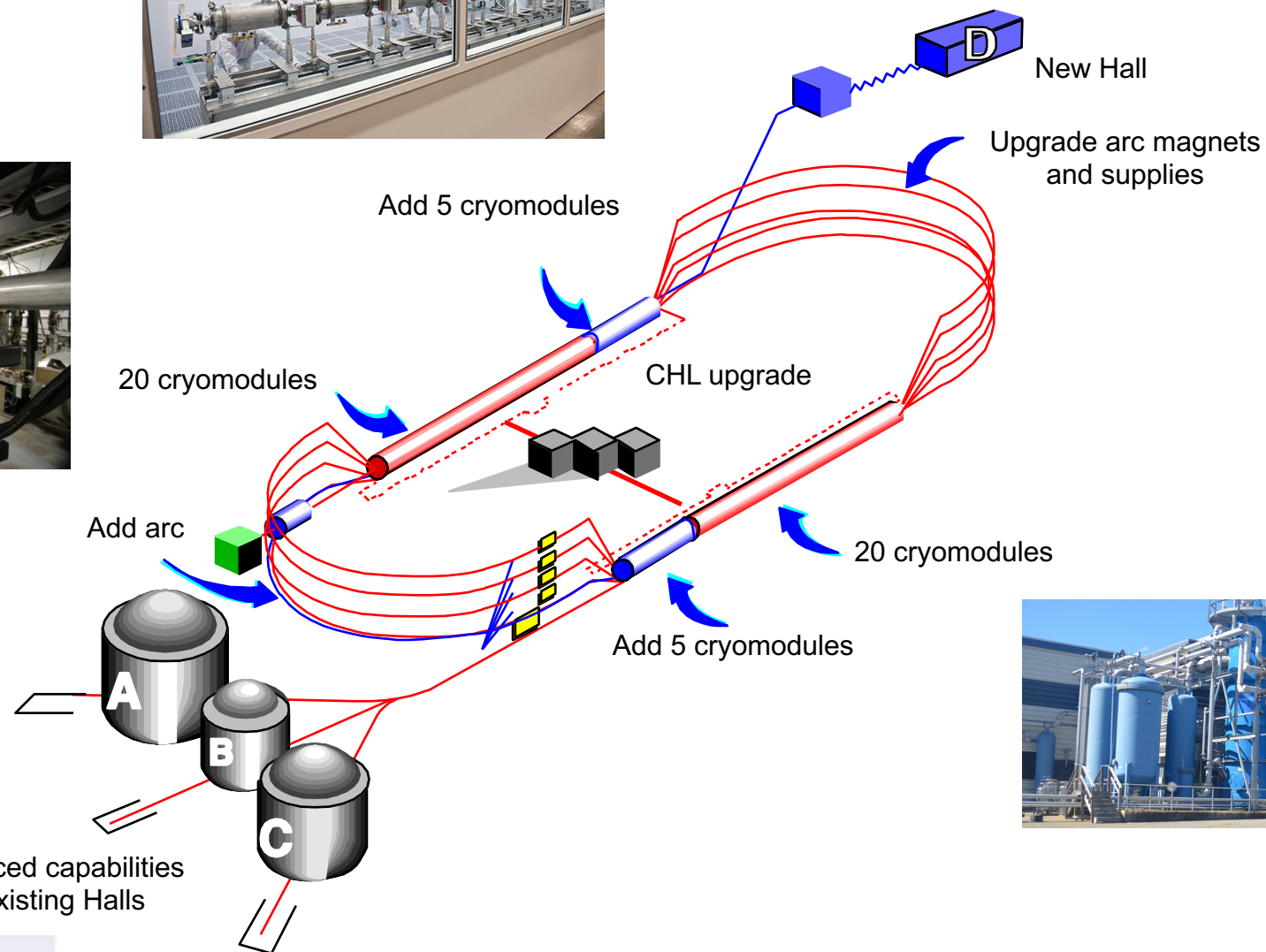
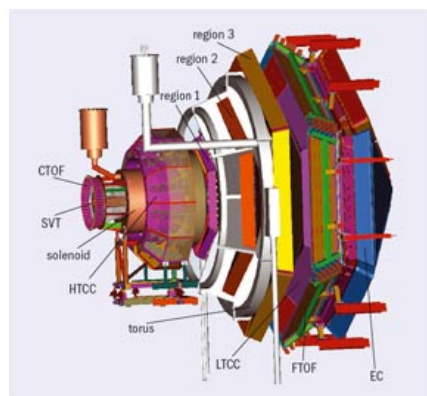
3. Summary



The Jefferson Lab 12 GeV upgrade project was declared completed on September 27, 2017.

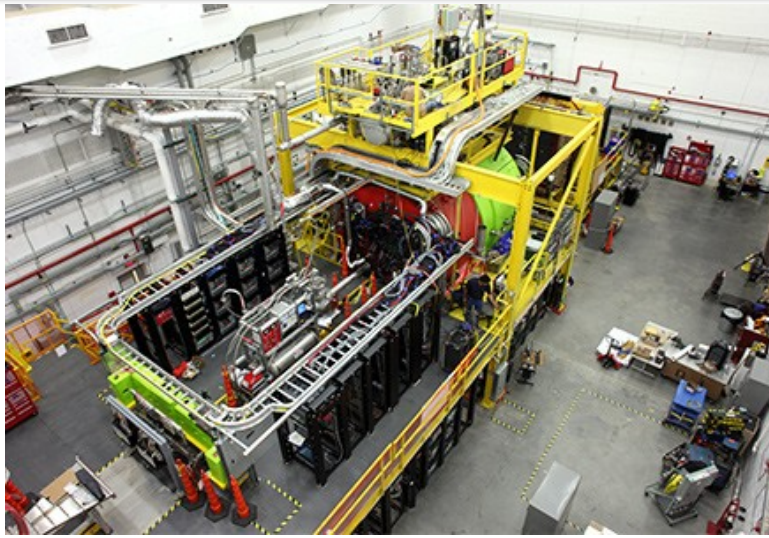


Enhanced capabilities
in existing Halls



**The last 6 GeV era experiments
completed in May 2012.**

To date, over 23 experiments (~1/3) have already been completed using the upgraded JLab.



Hall-D

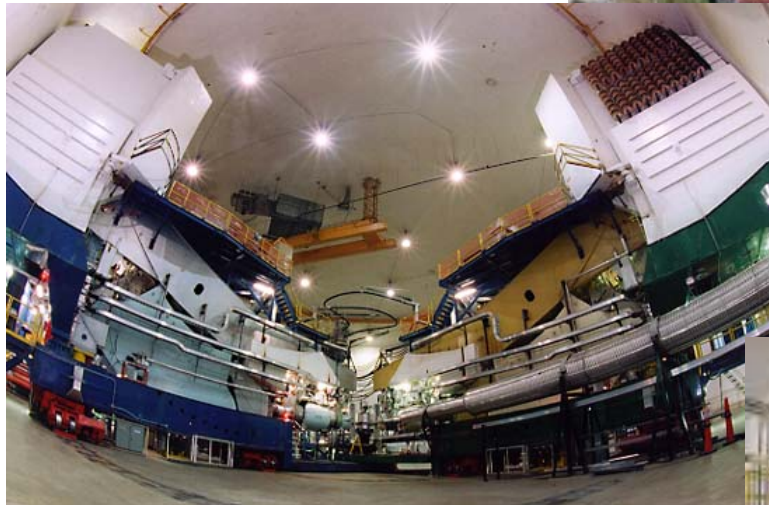
First beam May 2014,
1.2 experiments completed



4-Hall operation
since Jan. 2018

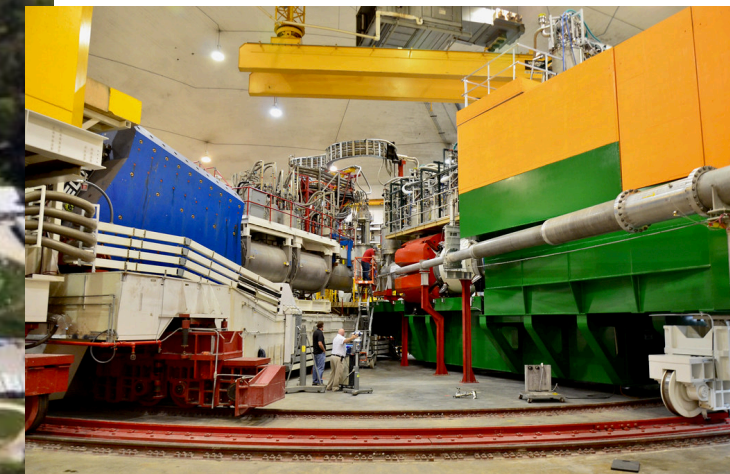
Hall-A

First beam
April 2014,
8 experiments
completed



Hall-B

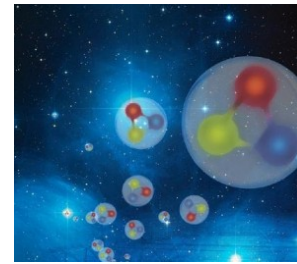
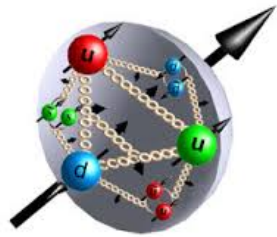
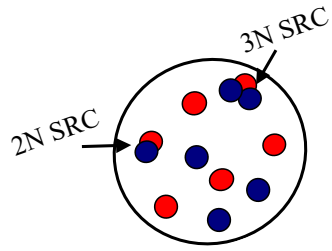
First beam Dec. 2014,
8.6 experiments completed



Hall-C

First beam Sept. 2017,
5.9 experiments
completed

These early experiments address a wide range of basic nuclear physics questions.



1. What is the nature of short range forces in nuclei?
2. How do we reveal the quark structure of nuclei?
3. What is the neutron density in heavy nuclei?
4. Why & how are the quark distributions inside nuclei modified?
5. What NP phenomena are critical for neutrino experiment?
6. How do we reveal the quark structure of nucleons and their excited states?
7. How do quarks and gluons create nucleon structure and properties?
8. What does the quark/gluon orbital angular momentum contribute to the proton's spin?
9. What is the role of glue in the spectroscopy of light mesons and baryons?
10. Is there evidence for physics beyond the standard model of particle physics at low energies?

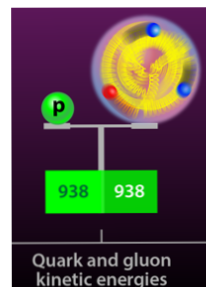
hadrons and cold nuclear matter

transv. & long. hadron structure

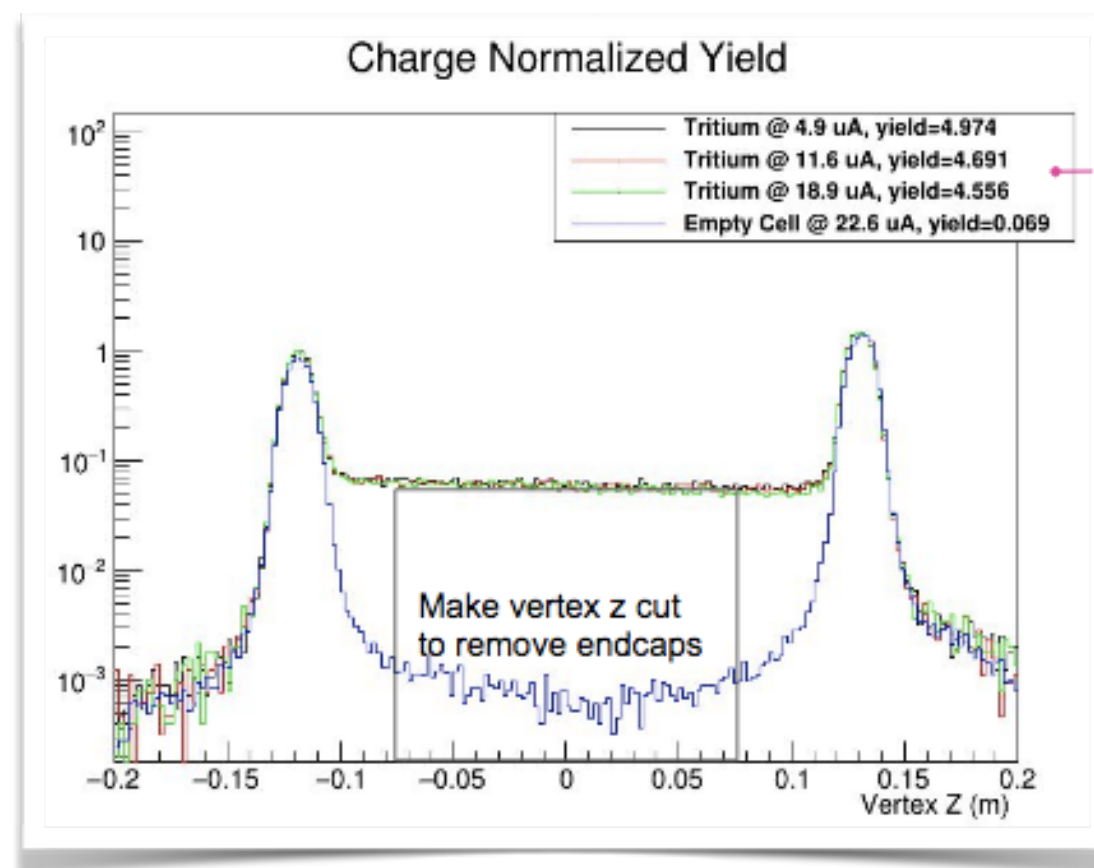
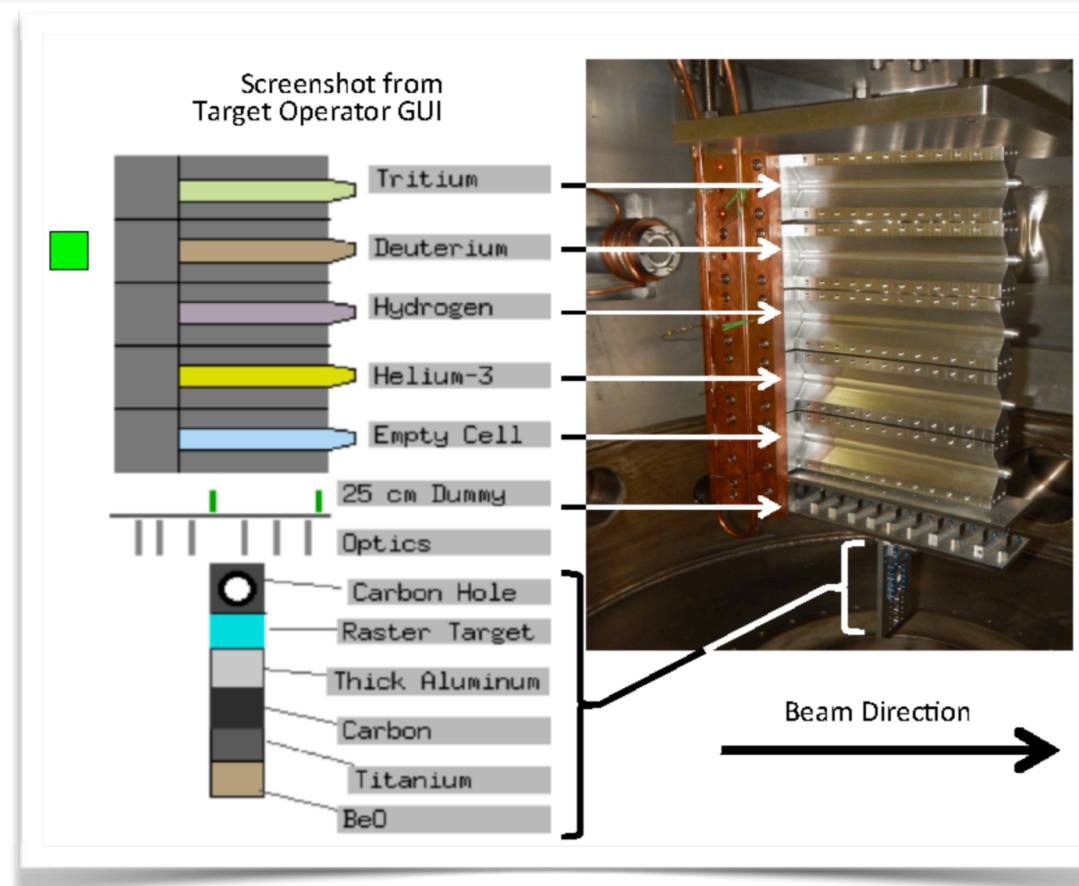
3D structure of hadrons

hadron spectra

SM tests & fund. symmetries

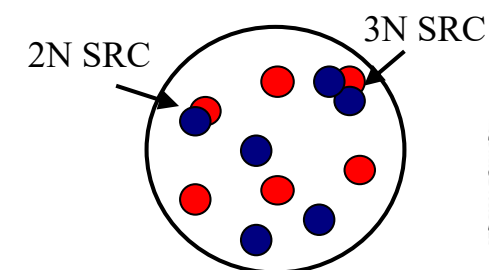


Completed “hadrons and cold nuclear matter” experiments include a unique Tritium program in Hall A.

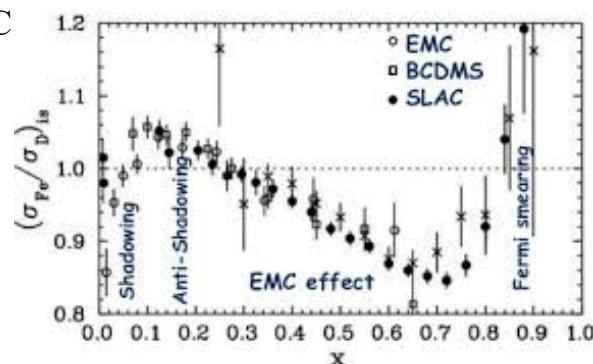


Low activity (~ 1 kCi); High-pressure sealed cell @ 40K; Beam current $< 22.5\mu\text{A}$

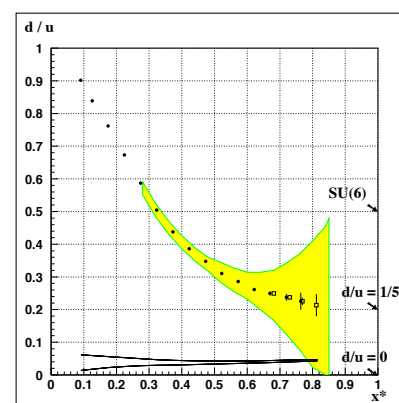
Used for a broad physics program with mirror nuclei (^3H , ^3He)



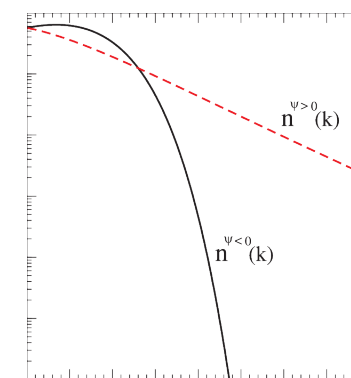
Short range correlations,



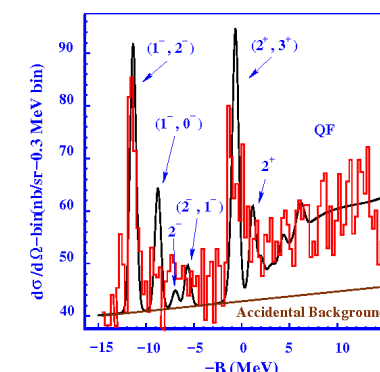
EMC effect,



$F_2^n/F_2^p \rightarrow d/u$,



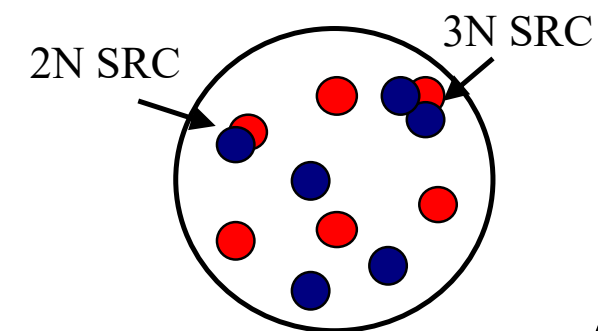
p & n momentum distributions,



Λ hypernuclear spectroscopy,

+ form factors
+

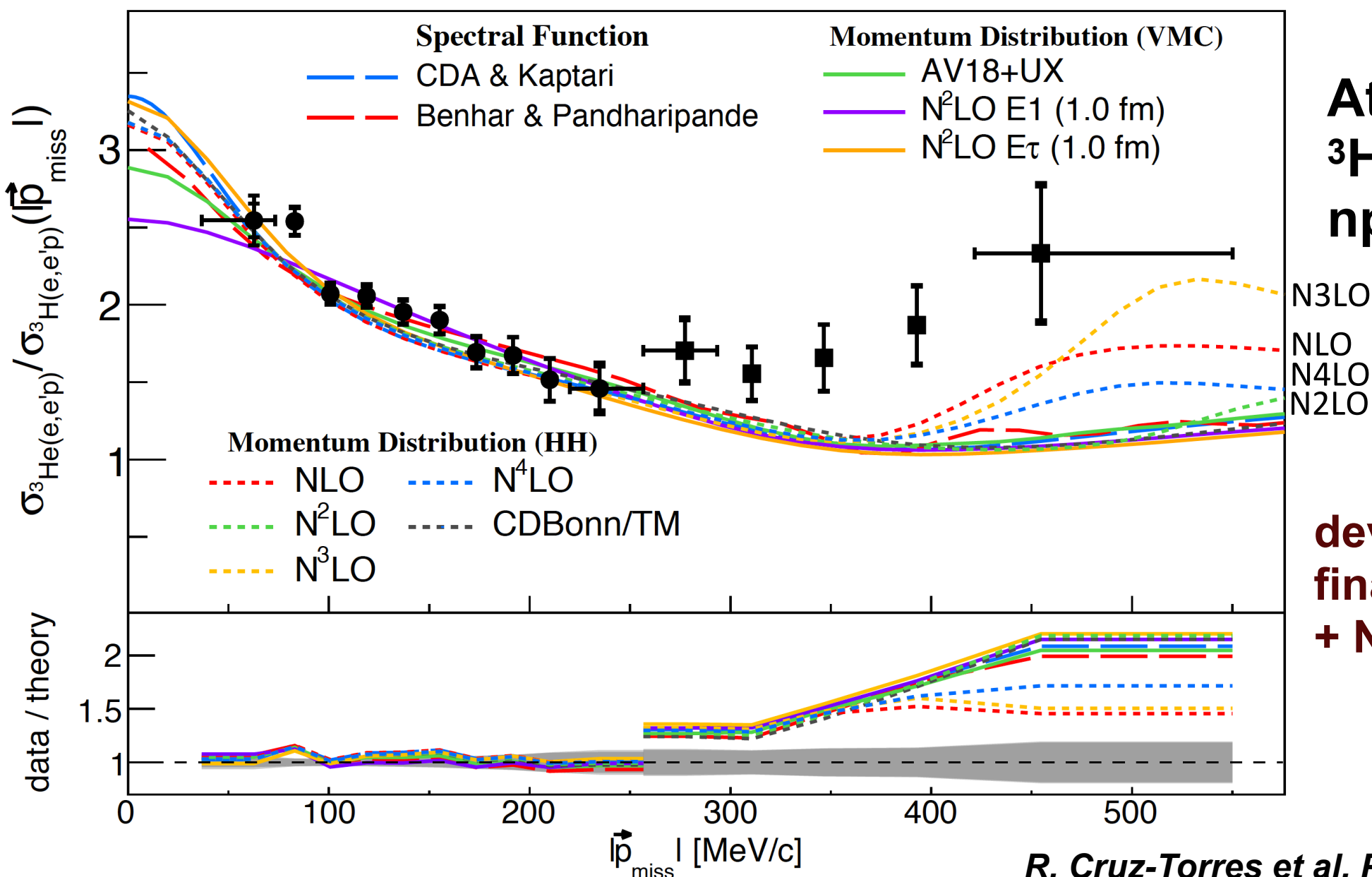
A study of short range correlations with exclusive scattering from $^3\text{H}/^3\text{He}$ was the first publication from the Tritium program in Hall A.



Short Range Correlations in $^3\text{H}/^3\text{He}$

using proton and neutron momentum distributions in $A = 3$ asymmetric nuclei

$A(e,e'p)$ yields at $x > 1$ vs Missing Momentum $|\vec{P}_m|$

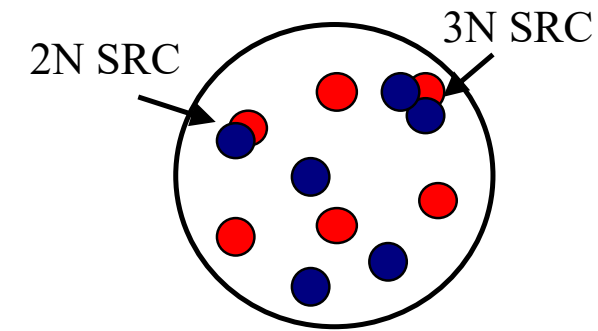


At large $|\vec{P}_m|$,
 $^3\text{He}/^3\text{H}$ ratio ~ 1 in
np dominance picture

deviations due to
final state interactions (FSI)
+ NN potential?

R. Cruz-Torres et al, Phys.Lett. B797 (2019) 134890

The Tritium program includes studies of short range correlations with inclusive scattering from $^3\text{H}/^3\text{He}$.

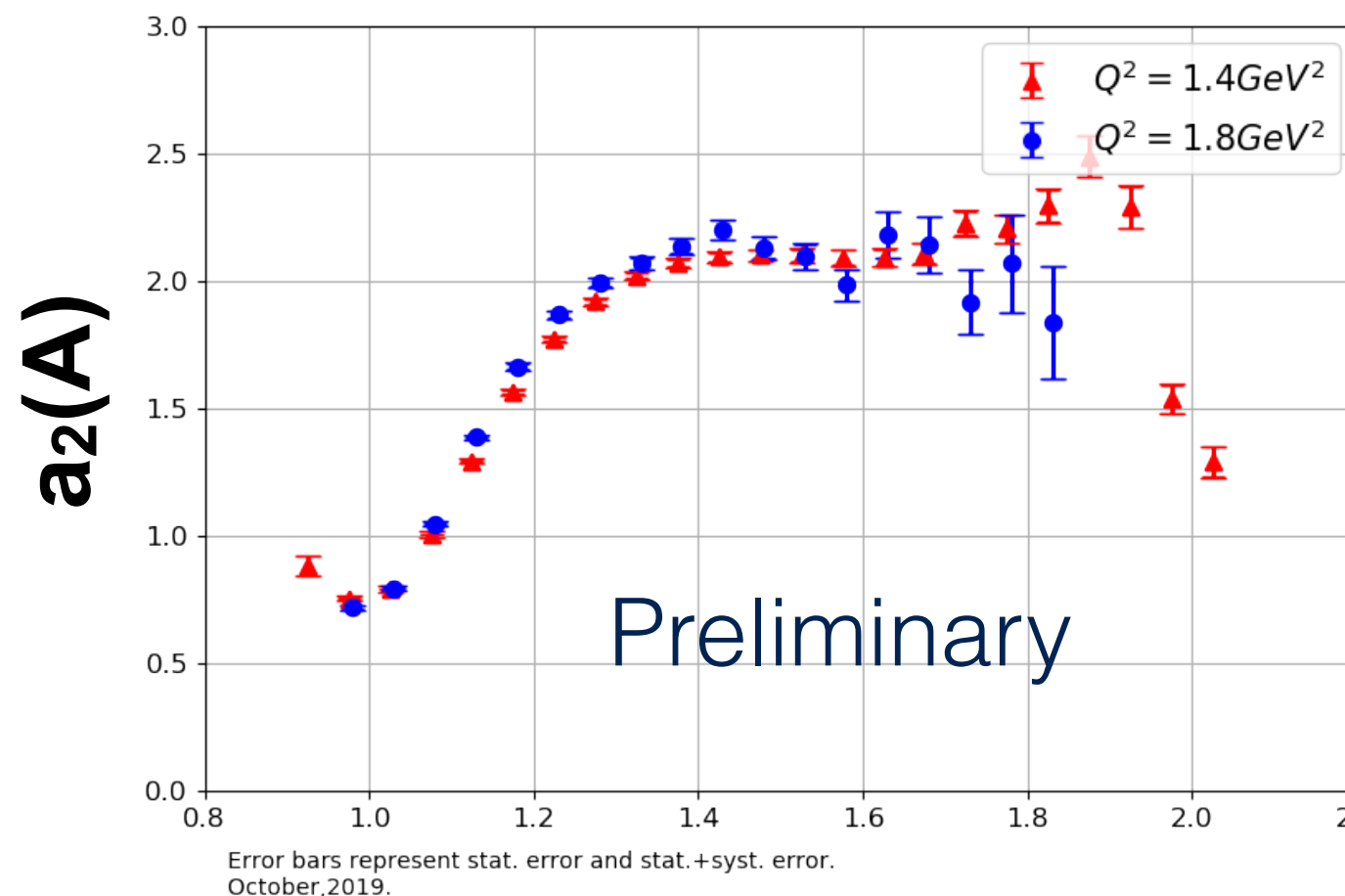


$$\frac{2}{A} \frac{\sigma_A}{\sigma_D} = a_2(A)$$

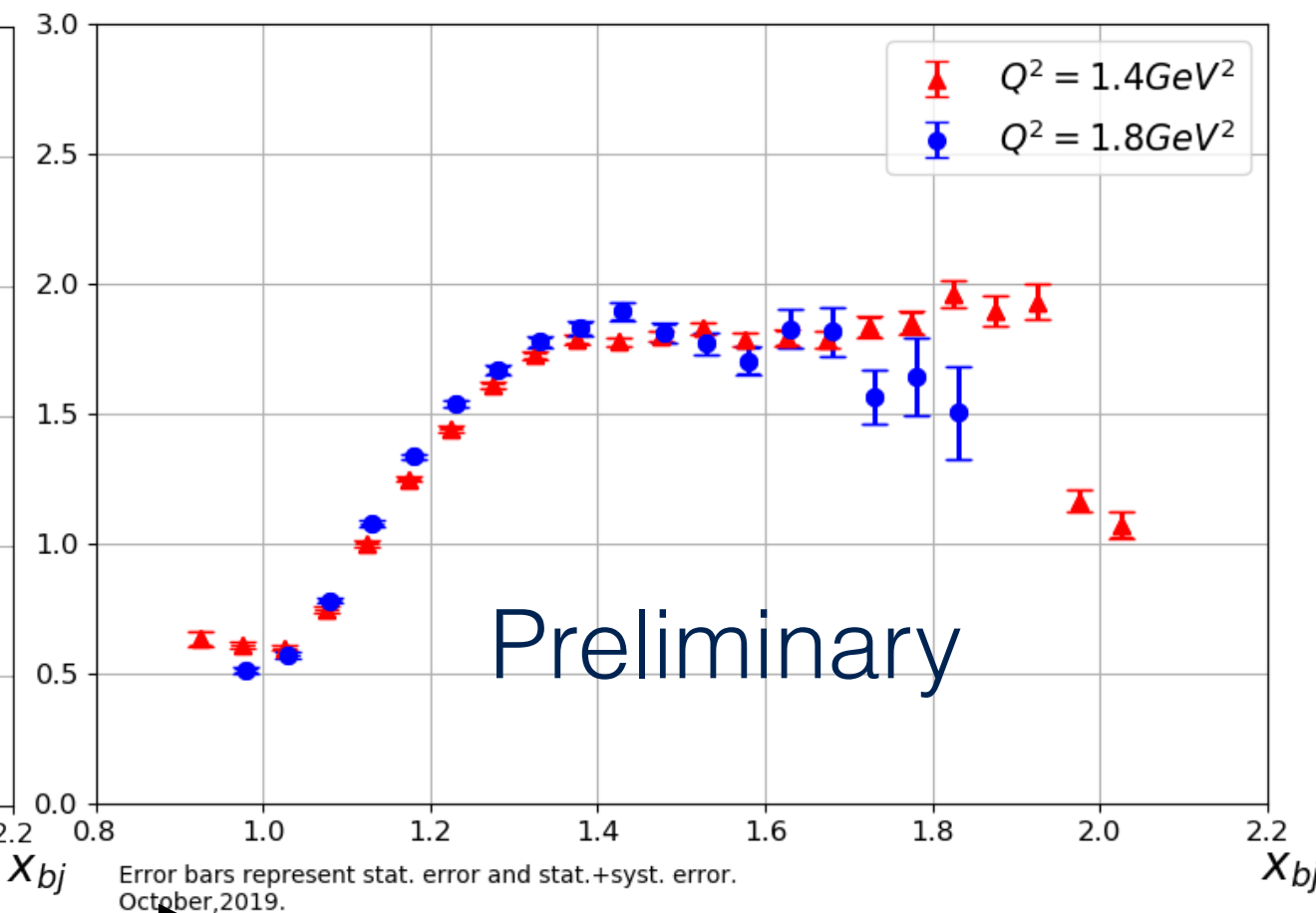
(A/D) ratio of inclusive cross section at $x > 1$
 \propto probability of scattering from a SRC pair

Compare ^3He to ^3H to study the composition of SRCs

Helium-3/Deuterium ratio



Tritium/Deuterium ratio



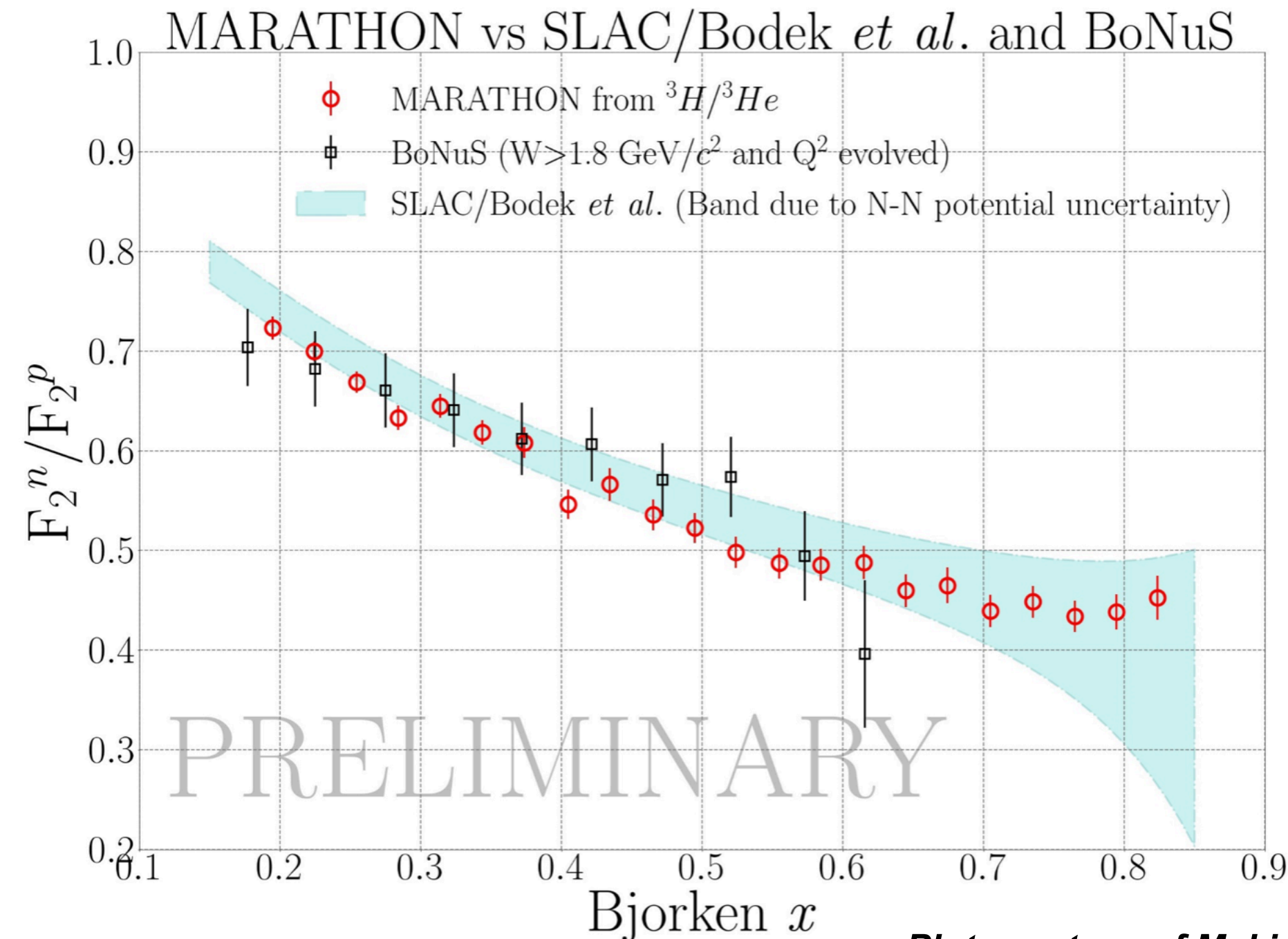
X_{Bj}

Plots courtesy of Shujie Li, UNH

The Tritium program also measured F_2^n/F_2^p , d/u , $A=3$ EMC effect and form factors in ^3H & ^3He .

Measurement of the F_2^n/F_2^p , d/u Ratios and $A=3$ EMC Effect in Deep Inelastic Electron Scattering Off the Tritium and Helium Mirror Nuclei (MARATHON)

Experiment ran in Hall A in 2018



F_2^n/F_2^p is extracted from the ^3H and ^3He cross sections using the knowledge of the difference in their nuclear effects

$$\frac{F_2^n}{F_2^p} = \frac{2R^* - \sigma^{^3\text{He}} / \sigma^{^3\text{H}}}{2\sigma^{^3\text{He}} / \sigma^{^3\text{H}} - R^*}$$

where

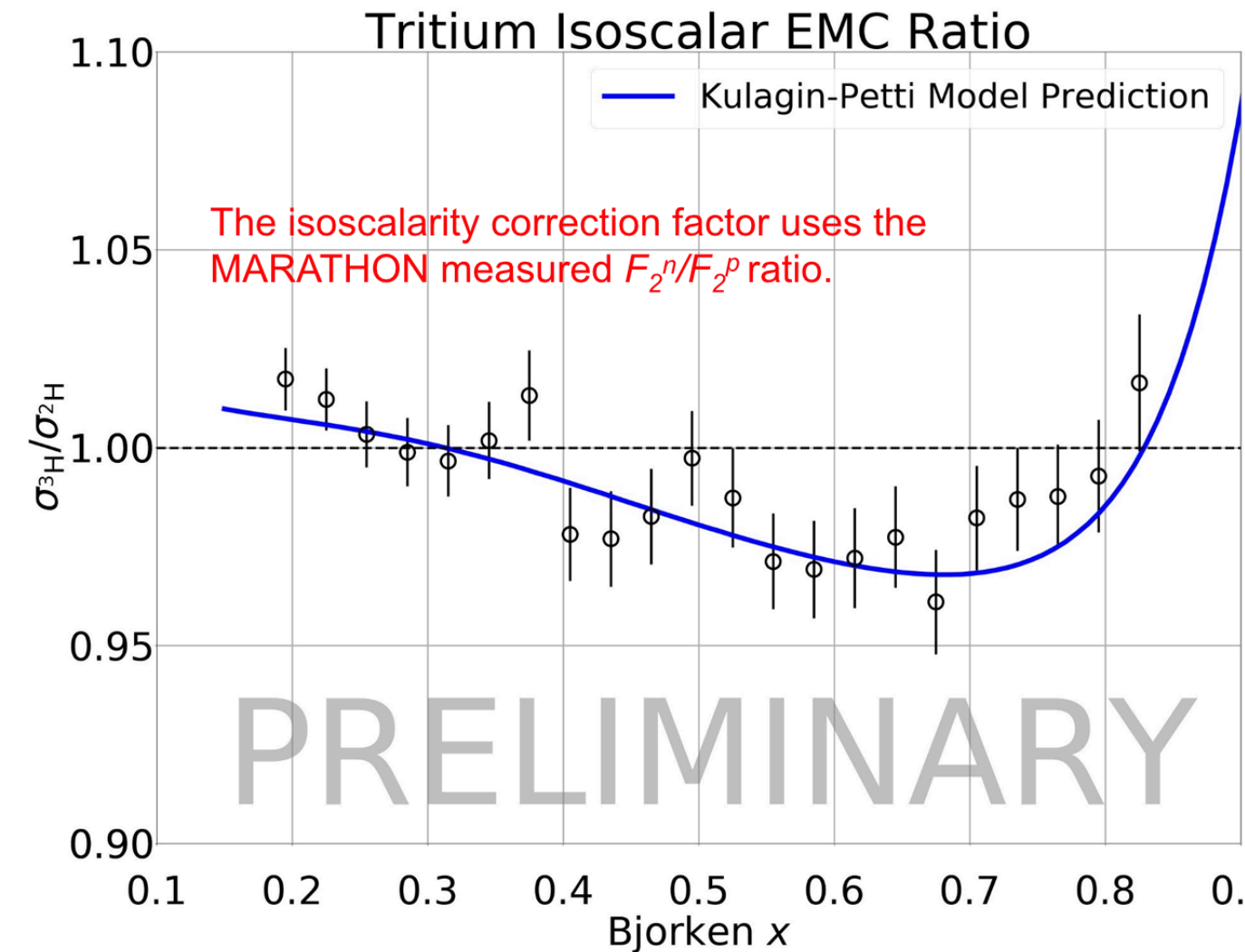
$$R^* = \frac{R(^3\text{He})}{R(^3\text{H})} \quad \text{and}$$

$$R(^3\text{He}) = \frac{F_2^{^3\text{He}}}{2F_2^p + F_2^n}$$

$$R(^3\text{H}) = \frac{F_2^{^3\text{H}}}{F_2^p + 2F_2^n}$$

Plot courtesy of Makis Petratos

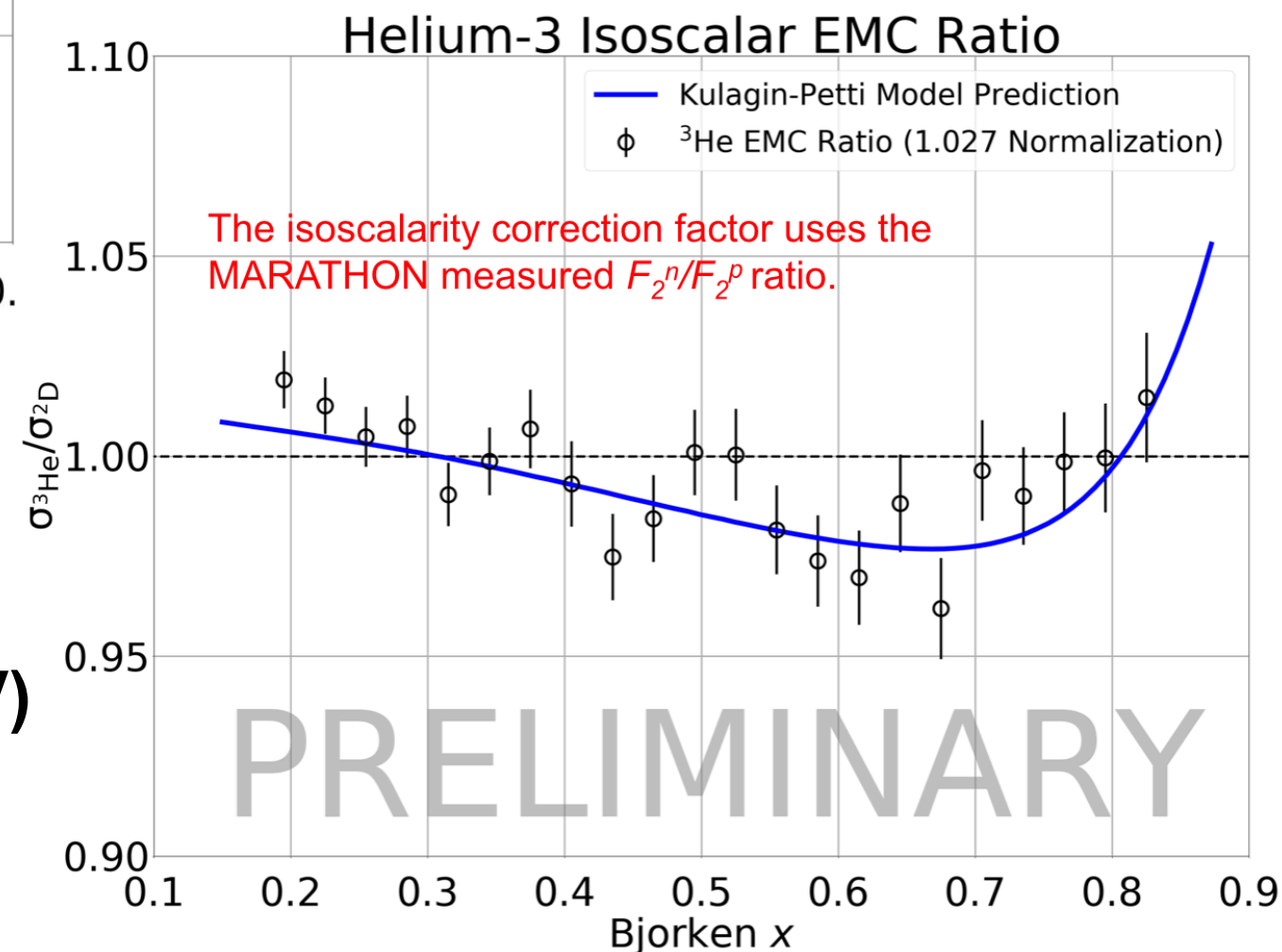
MARATHON measured the EMC effect in Tritium and Helium-3



The First measurement of EMC Effect in Tritium

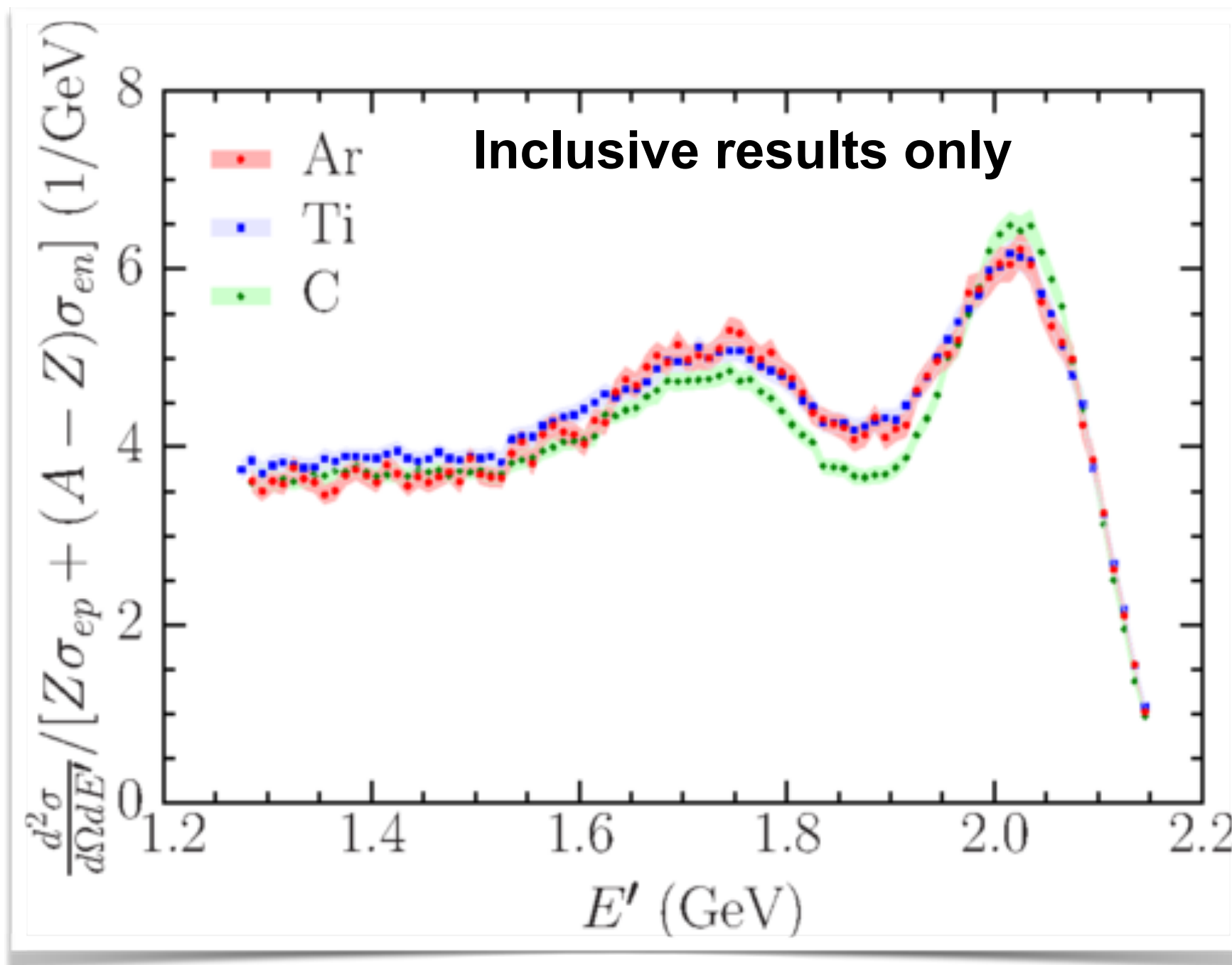
^3He result agrees with 6 GeV measurement in DIS region ($W > 2$ GeV)

Plots courtesy of Makis Petratos



Hall-A experiment measured spectral function of ^{40}Ar useful for future neutrino experiments.

Exhaustive electron scattering measurements on ^{40}Ar has been completed to study the detailed spectral functions and nuclear structure of Argon.



Upcoming neutrino experiments will make use of liquid Argon detectors.

Monte Carlos used for event reconstruction need detailed knowledge of nuclear structure to control uncertainties

H. Dai et al., PRC 99, 054608 (2019)

The deuteron electro-disintegration experiment in Hall-C is the simplest for access to short distance structure.

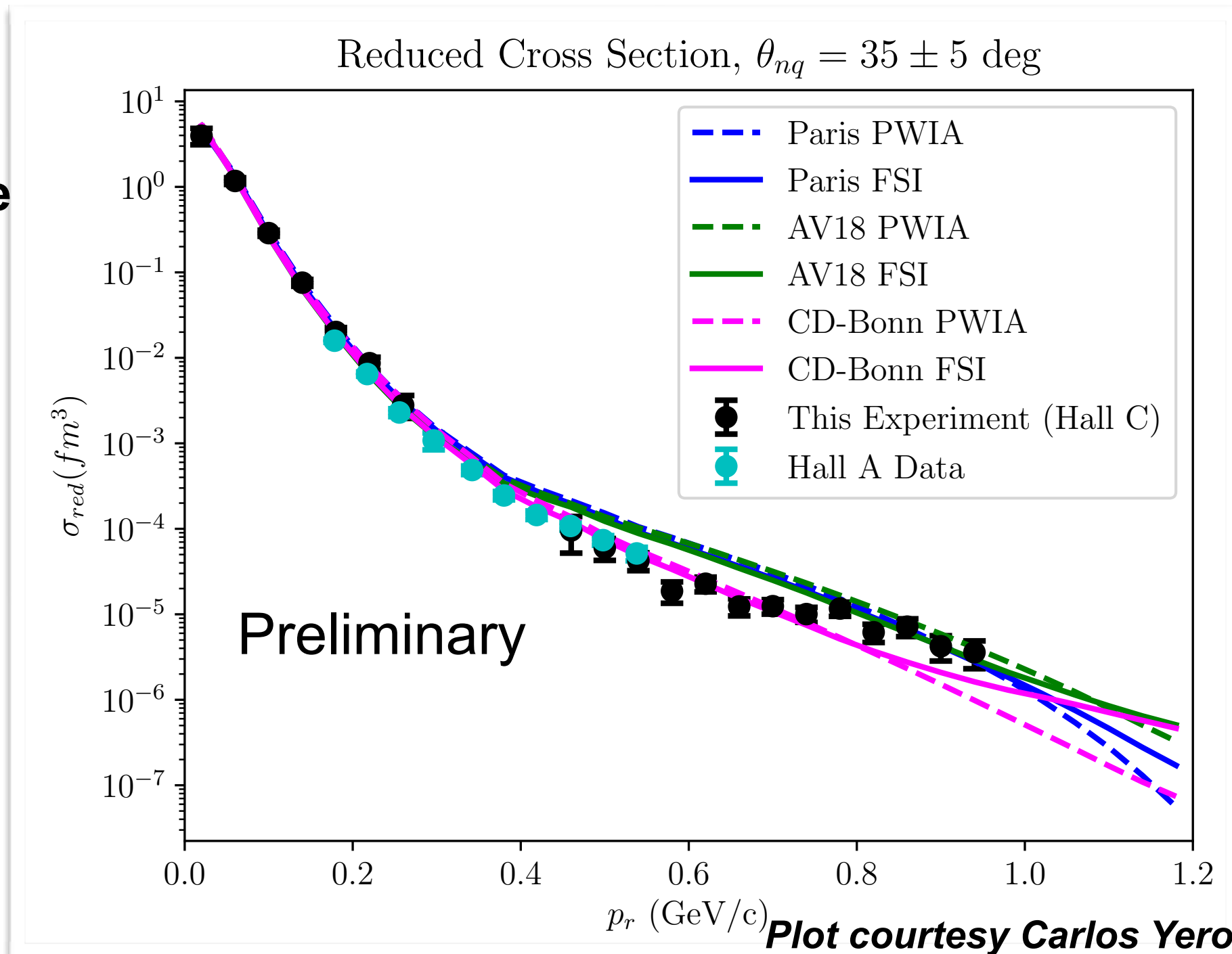
$D(e,e'p)n$ provides details about the high-momentum or short distance structure (direct access compared to inclusive/exclusive ratios which give the relative number of SRC).

The Hall C experiment extends the reach to the highest $|P_m|$ to date.

$|P_m| \sim 1 \text{ GeV}/c$

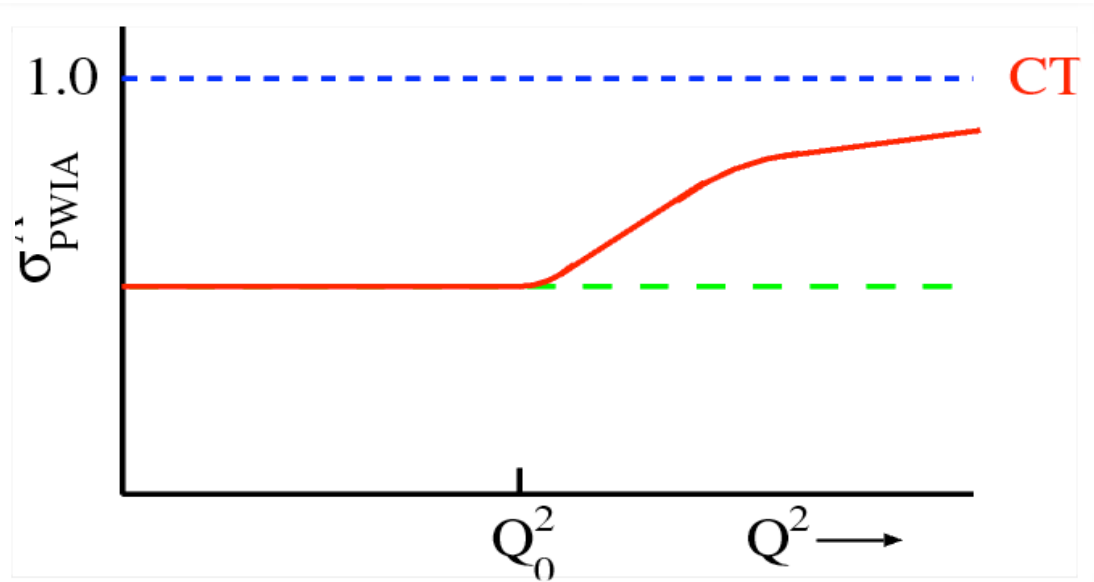
Theory input was crucial for this experiment to help select the kinematics with small FSI

Preliminary results show deviations from models above $|P_m| > 700 \text{ MeV}/c$



One of the commissioning experiments in Hall-C looked for onset of color transparency in protons.

QCD predicts that exclusive hadrons at high momentum transfers have reduced final state interactions also called color transparency (CT).



CT is well established at high energies (DIS data cannot be described without assuming CT).

CT is closely linked to soft-hard factorization in exclusive processes.

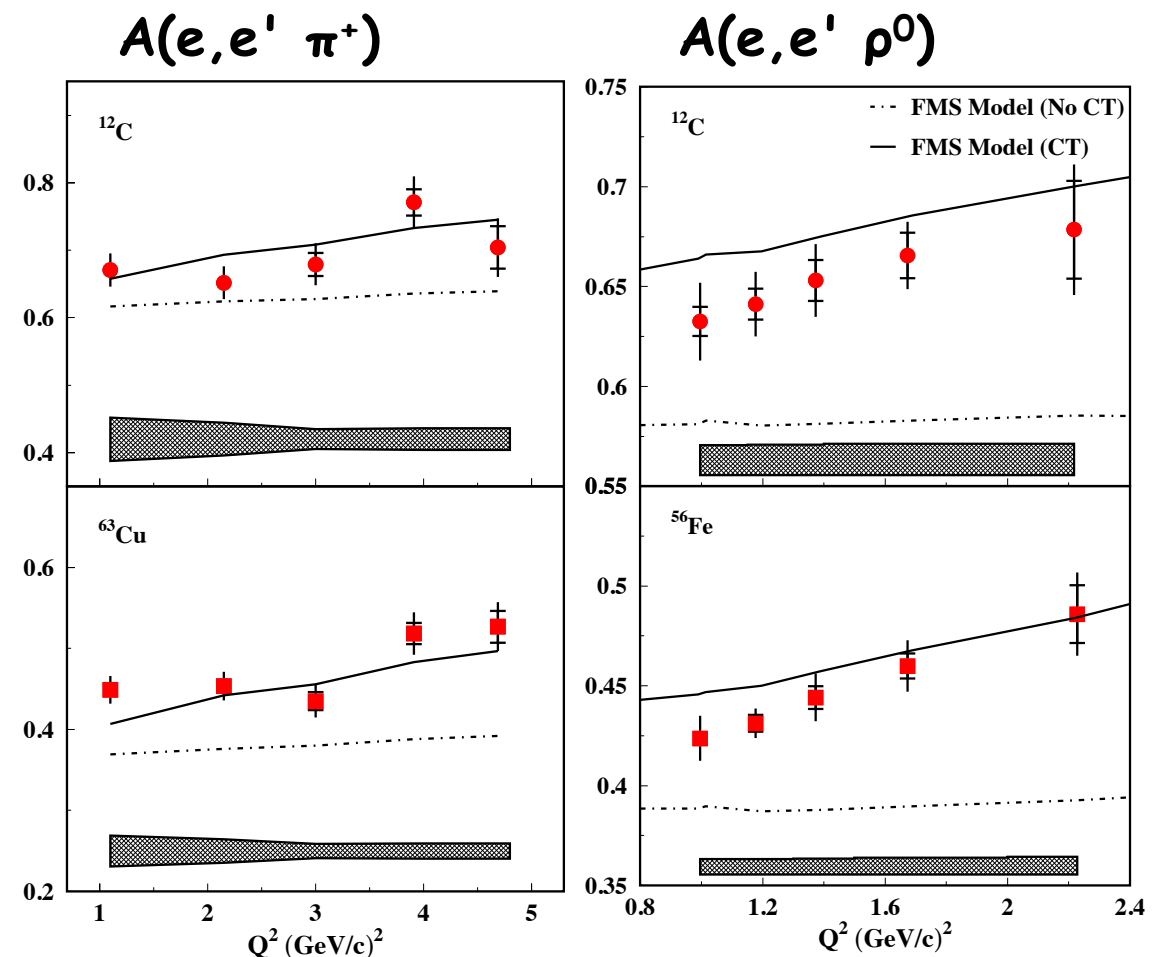
The onset of CT is of primary interest.

The onset of CT is a signature of QCD degrees of freedom in nuclei.

JLab 6 GeV experiments established the onset of CT in mesons.

X. Qian et al., PRC81:055209 (2010), $A(e, e' \pi^+)$
B. Clasie et al, PRL99:242502 (2007)

L. El-Fassi, et al., PLB 712, 326 (2012) $A(e, e' \rho^0)$



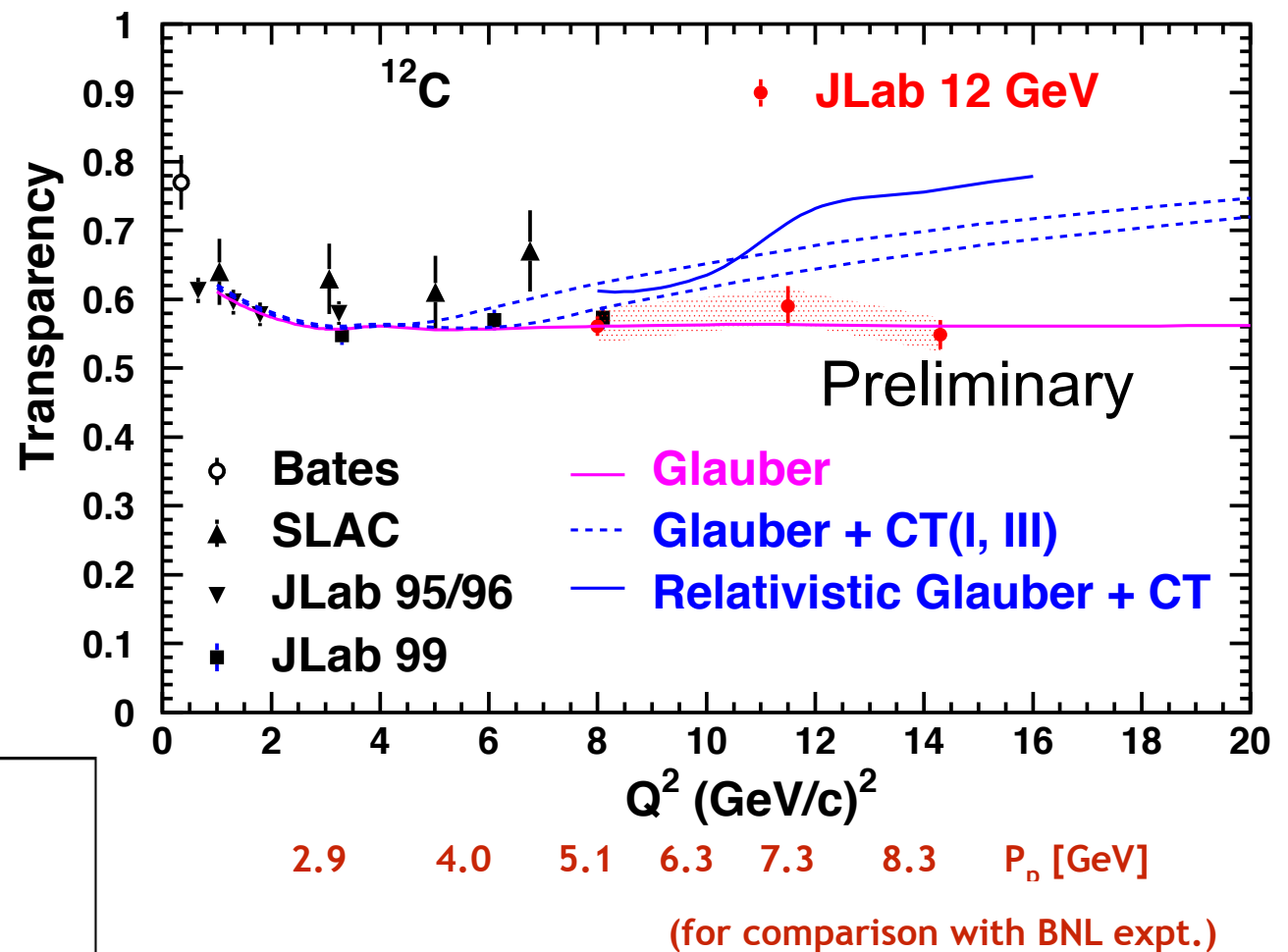
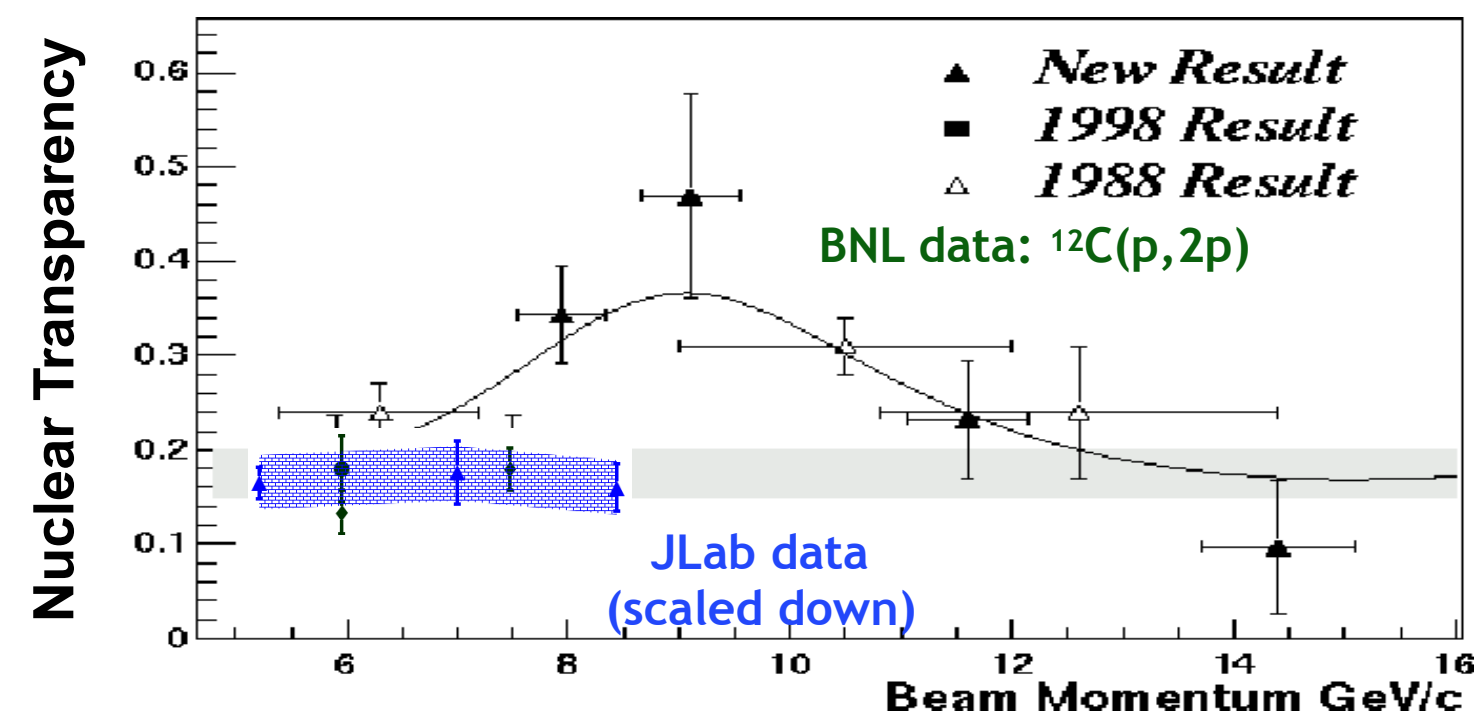
FMS: Frankfurt, Miller and Strikman, Phys. Rev., C78: 015208, 2008

Preliminary results do not show any signs of the onset of color transparency in protons.

QCD predicts that exclusive hadrons at high momentum transfers have reduced final state interactions also called color transparency (CT).

Kinematics comparable to BNL (p,2p) results which can be interpreted as a sign of CT + other mechanisms.

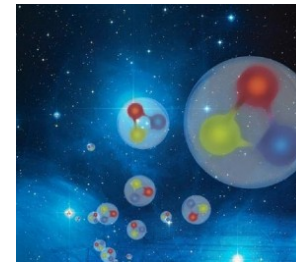
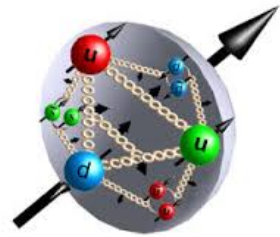
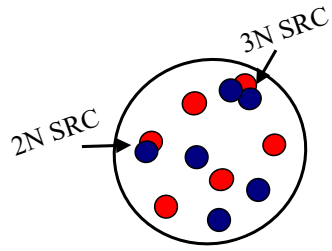
preliminary



BNL observations unlikely to be because of CT

Will place very stringent constraints on all existing CT models

These early experiments address a wide range of basic nuclear physics questions.



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2. How do we reveal the quark structure of nuclei?
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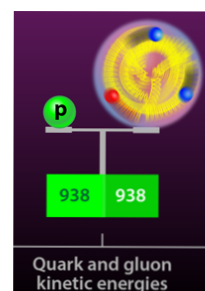
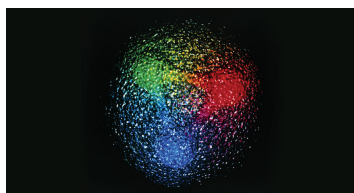
hadrons and cold nuclear matter

transv. & long.
hadron structure

3D structure
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hadron spectra

SM tests &
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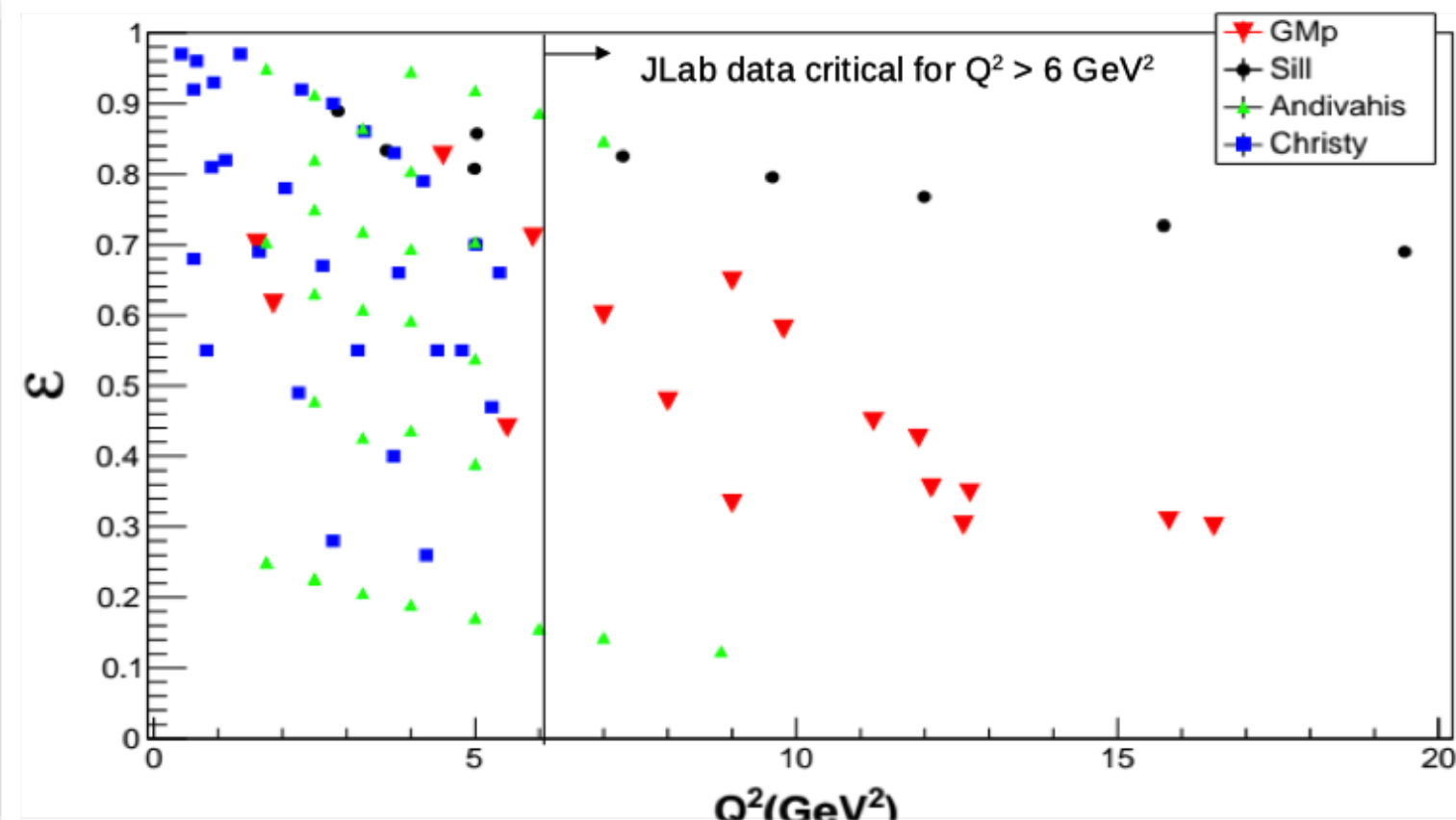
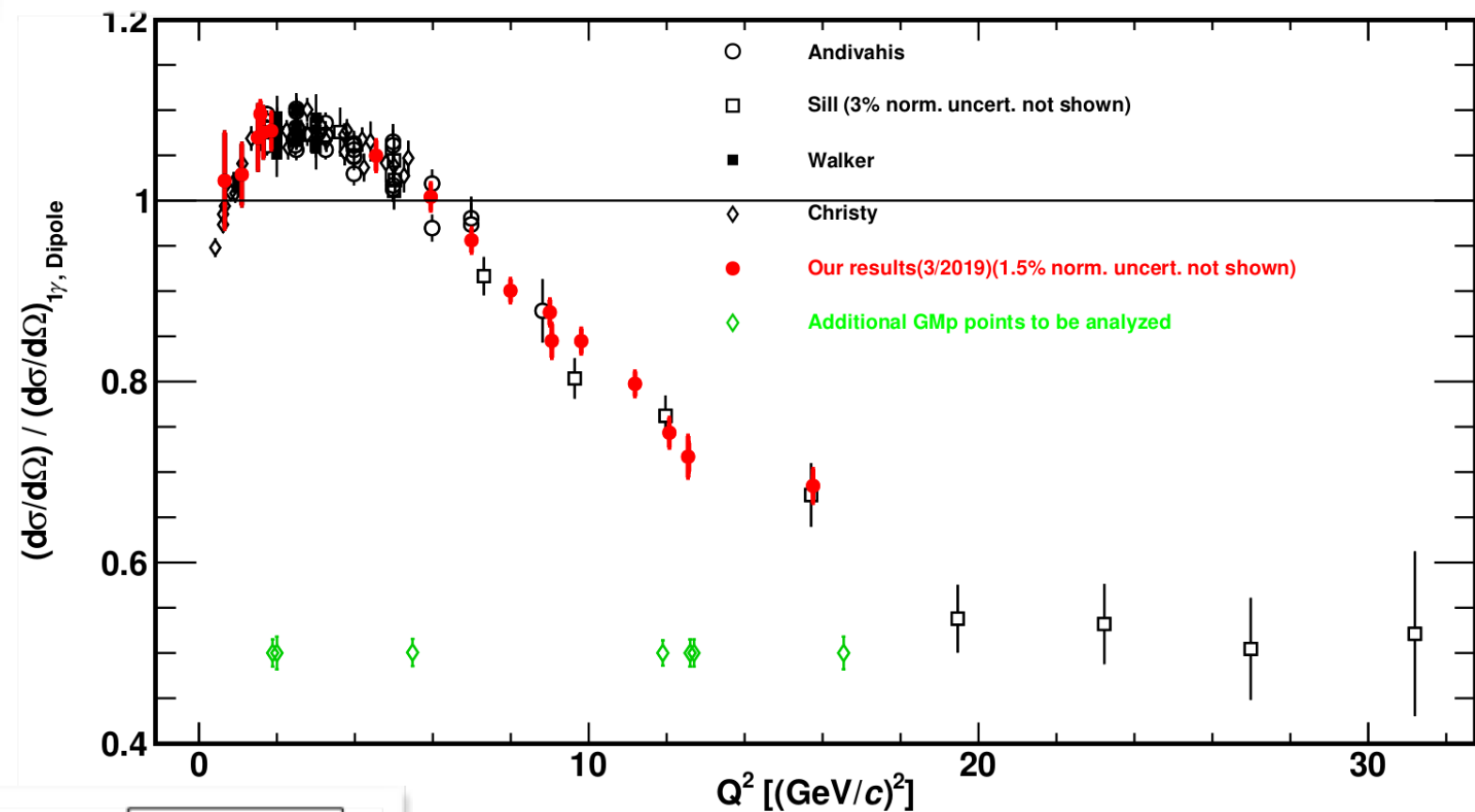


The JLab 12 GeV program includes extensive nucleon and meson form factor measurement experiments.

Preliminary cross sections from the G_M^p experiment in Hall A (Ran in 2015-2016)

Relative to one-photon exchange cross section with $G_E^p = \text{dipole}$

Significant improvement in precision for $Q^2 > 6 \text{ GeV}^2$



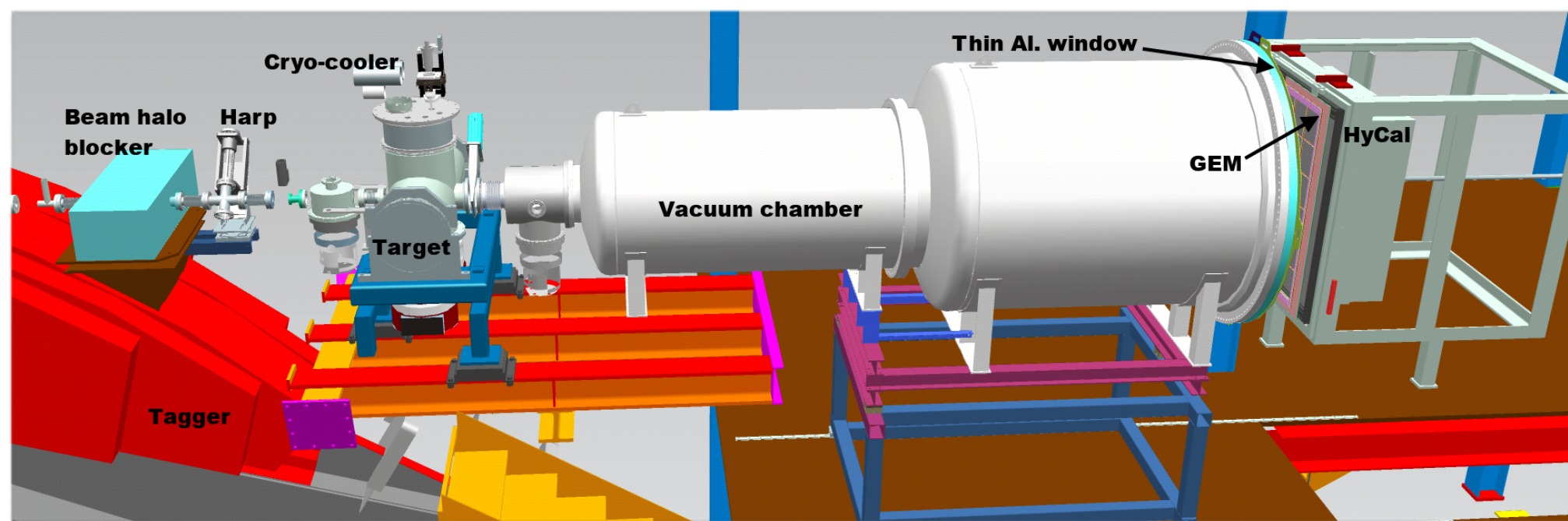
$$\frac{d\sigma}{d\Omega} = \sigma_{\text{Mott}} \frac{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}{\epsilon (1 + \tau)},$$

Hall-A G_M^p data covers wide range in ϵ , hence less sensitivity of G_E

The large lever arm in ϵ will help extract 2-photon contribution.

Plots courtesy Eric Christy

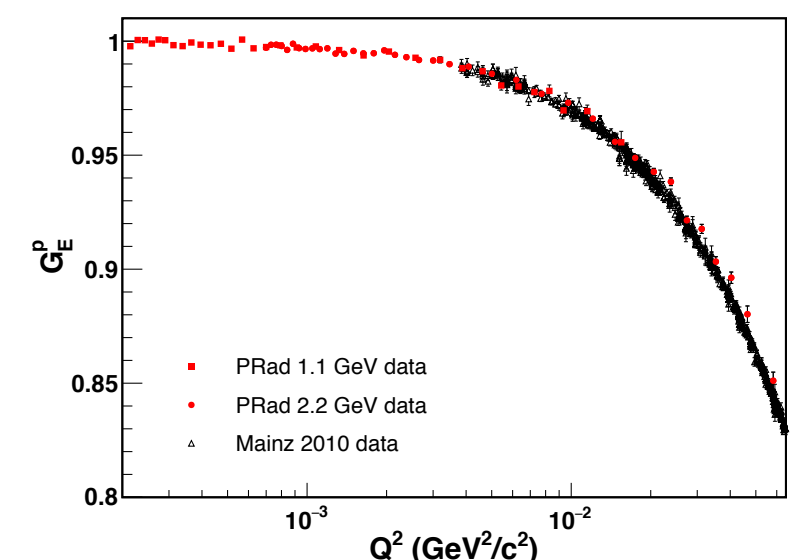
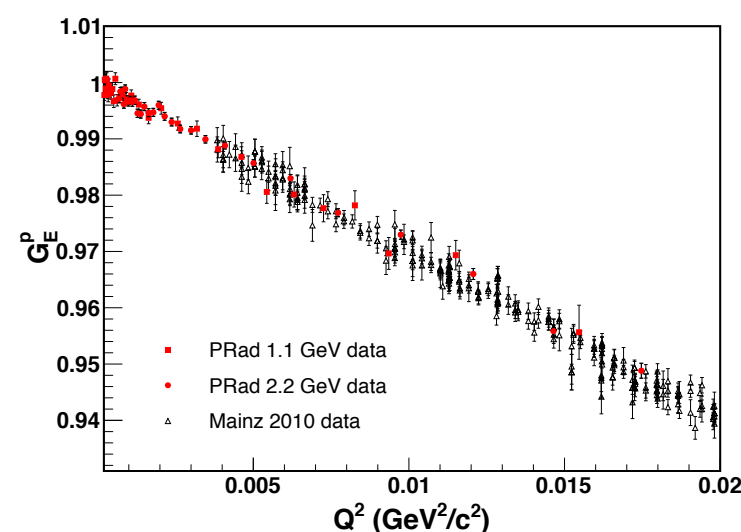
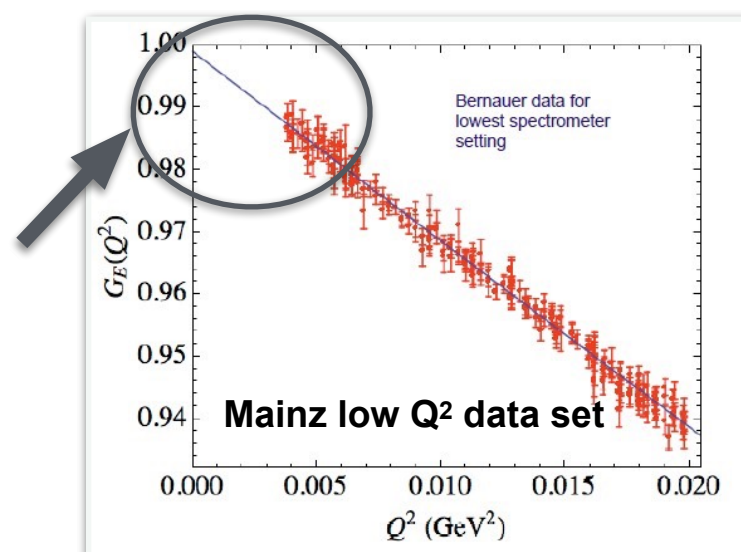
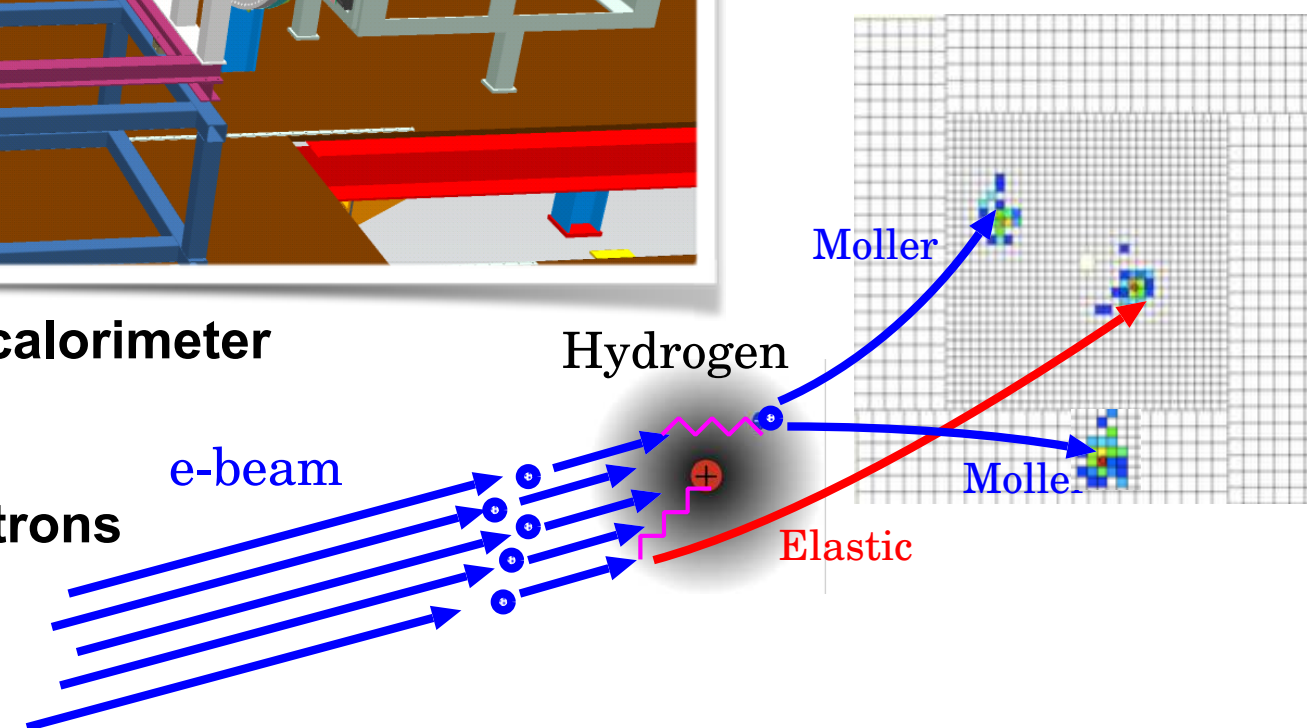
One of the early Hall-B (non-CLAS) experiments was a novel experiment to measure the proton charge radius.



Completed
July 2016

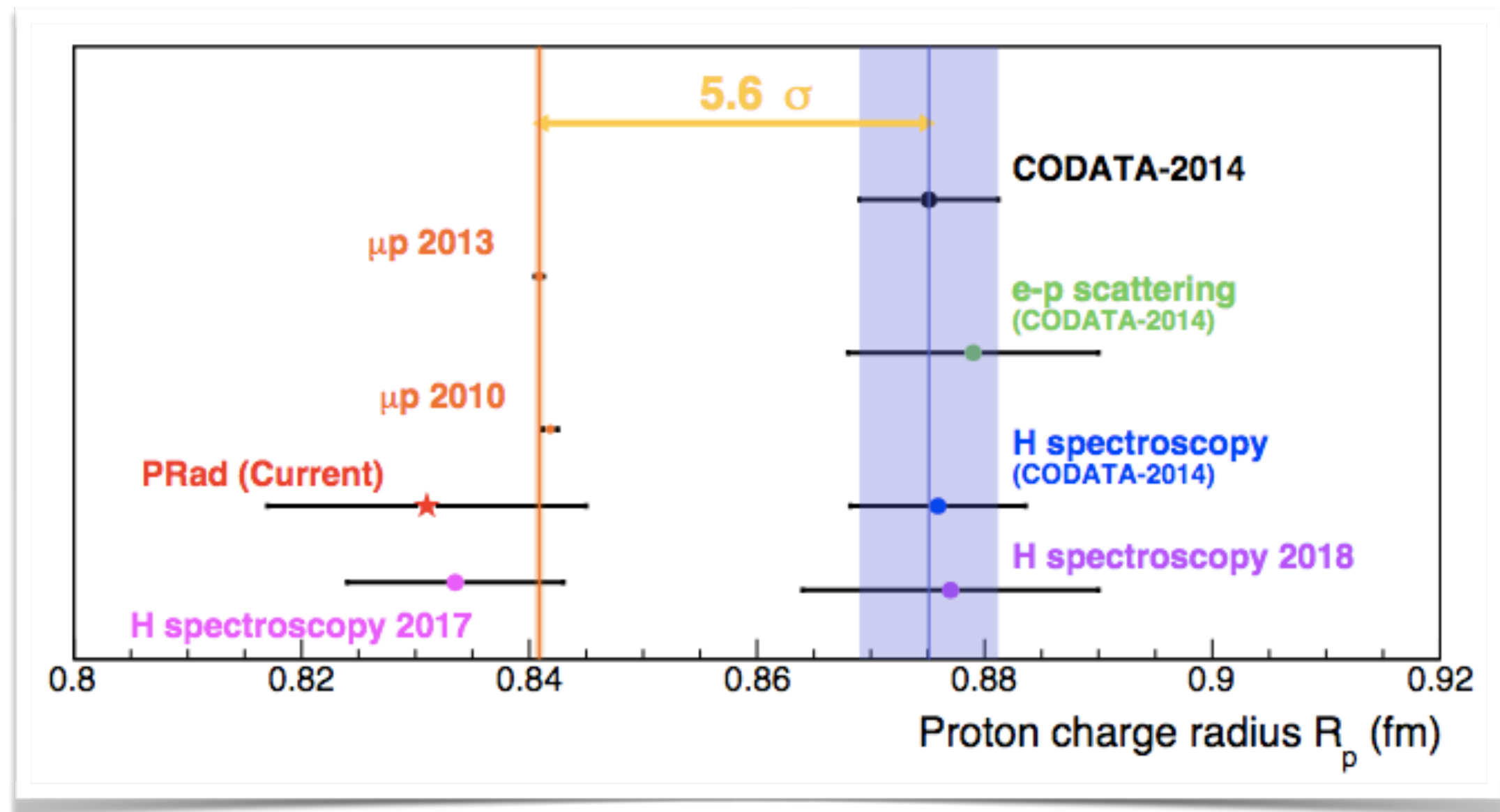
HyCal + GEM

- High resolution, large acceptance, hybrid HyCal calorimeter (PbWO₄ and Pb-Glass)
- Windowless H₂ gas flow target
- Simultaneous detection of elastic and Møller electrons
- Q^2 range of $2 \times 10^{-4} - 0.06 \text{ GeV}^2$
- XY – veto counters replaced by GEM detector
- Two section 5m vacuum chamber



The PRad collaboration measured a small proton charge radius using the first new electron scattering method in half a century.

PRad result: 0.831 ± 0.007 (stat.) ± 0.012 (syst.) fm



Appeared yesterday in Nature - W. Xiong et al., Nature 575, 147 (2019)

Recently, CODATA released their revised value of r_p (online only)

CODATA has also shifted the value of the Rydberg constant.

A whole session (session H01) dedicated to the proton radius puzzle is scheduled for tomorrow morning.

86th Annual Meeting of the APS Southeastern Section

Thursday–Saturday, November 7–9, 2019; Wrightsville Beach, North Carolina

Session Index

Session H01: Puzzle of Proton Charge Radius

[Show Abstract](#)

Chair: Ashot Gasparlan, North Carolina A&T State University

Room: *Holiday Inn Resort Causeway/Masonboro*

Saturday, November 9, 2019
8:00AM - 8:30AM

[H01.00001: Status of the MUSE Experiment at PSI](#)
Invited Speaker: Lin Li

[Preview Abstract](#)

Saturday, November 9, 2019
8:30AM - 9:00AM

[H01.00002: Proton Radius from Jefferson Lab PRad Experiment](#)
Invited Speaker: Xinzhan Bai

[Preview Abstract](#)

Saturday, November 9, 2019
9:00AM - 9:30AM

[H01.00003: Deuterium Charge Radius Experiment \(DRad\) at Jefferson Lab](#)
Invited Speaker: Jingyi Zhou

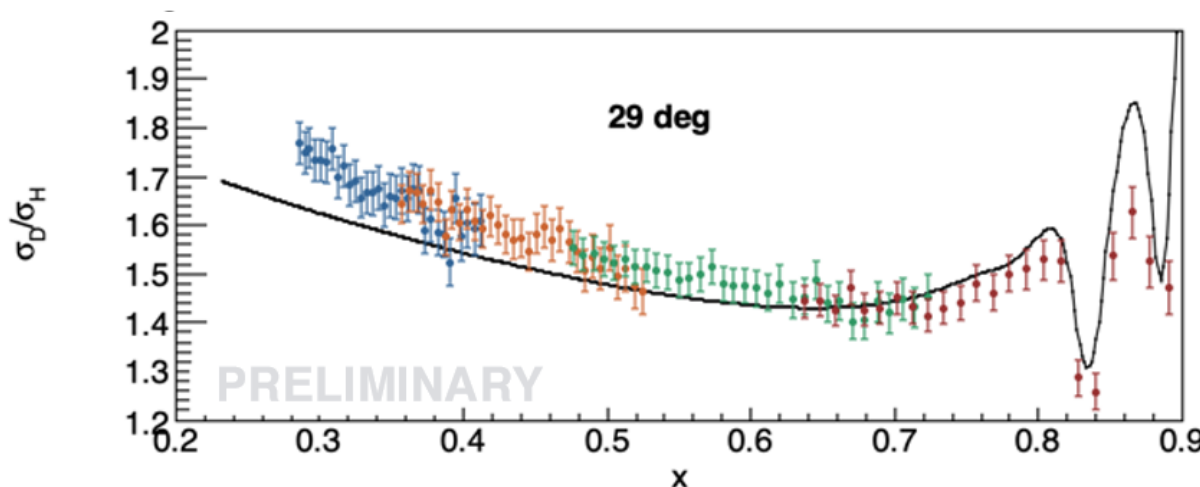
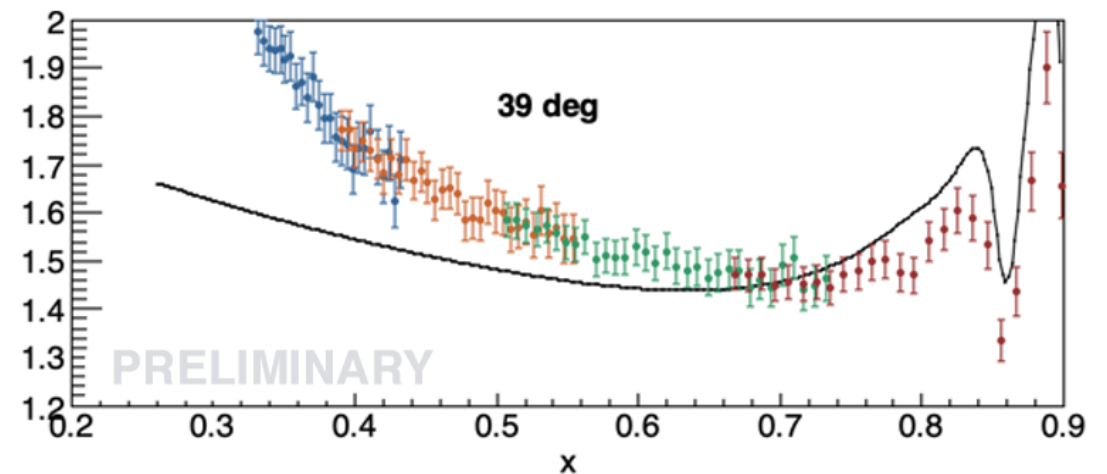
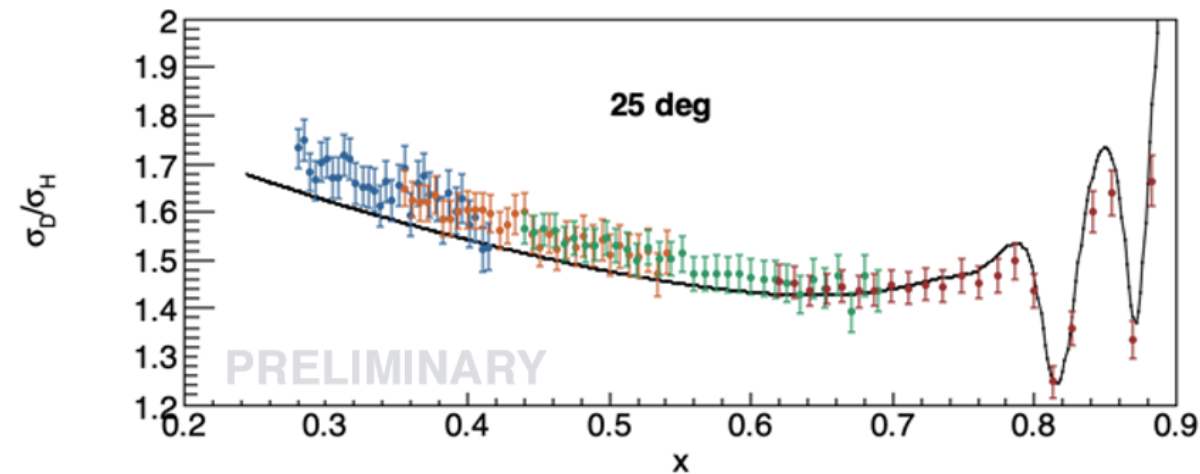
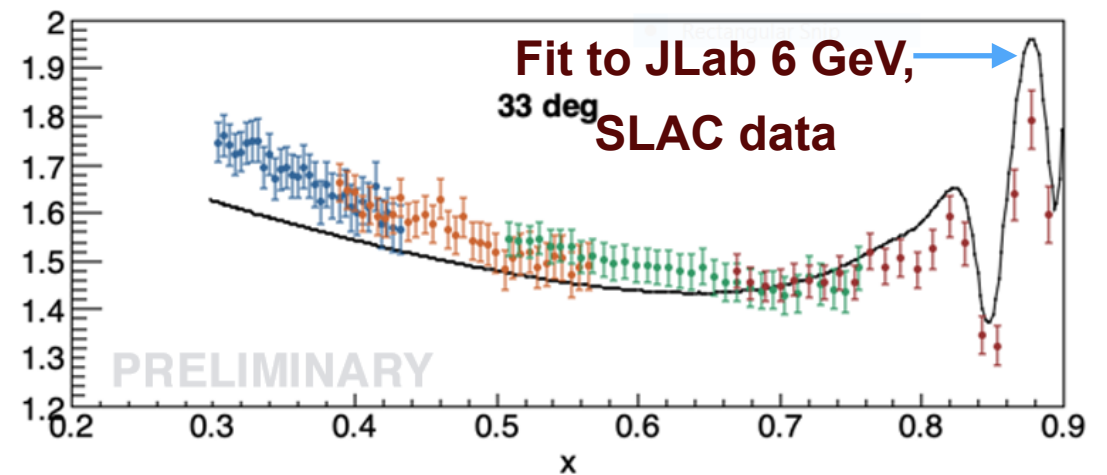
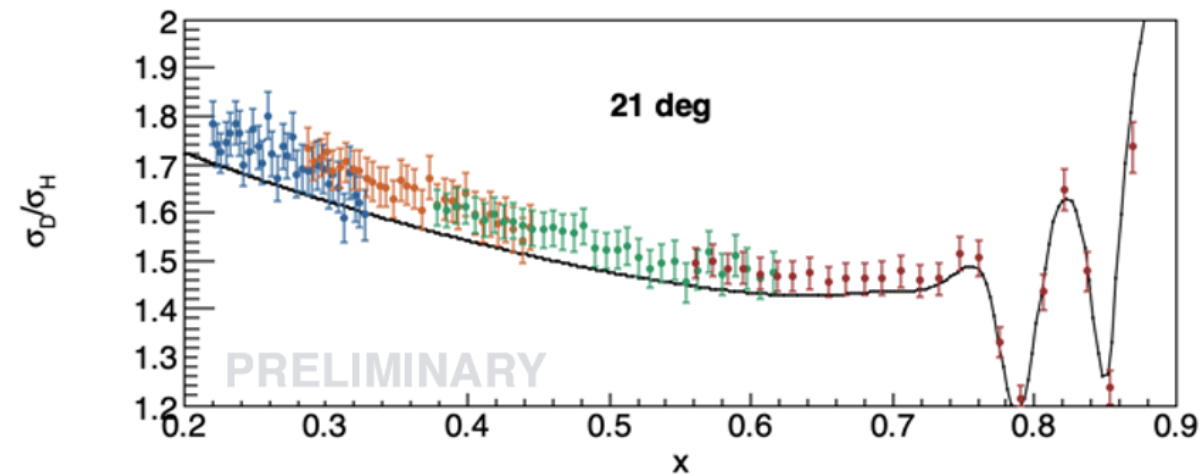
[Preview Abstract](#)

Saturday, November 9, 2019
9:30AM - 10:00AM

[H01.00004: New Instrumentation for Future High Precision Proton and Deuteron Radius Experiments](#)
Invited Speaker: Kondo Gnanvo

Among the completed experiments several conducted extensive measurements of structure functions and PDFs.

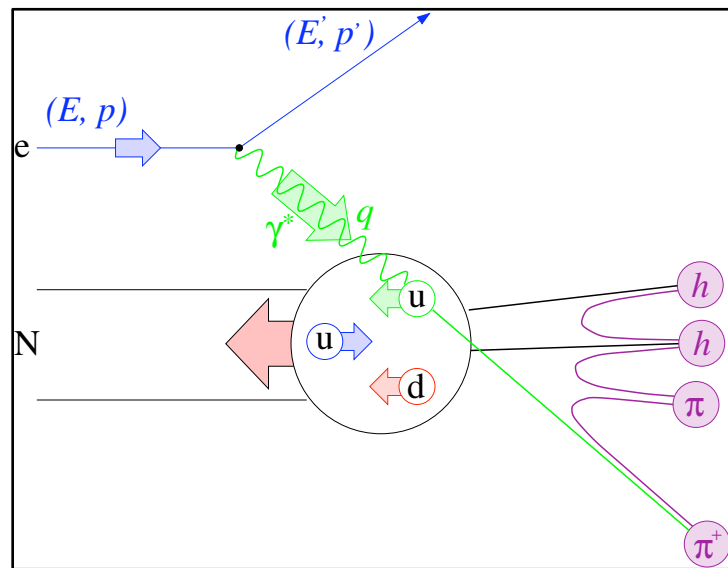
One of the Hall-C commissioning experiments measured $H(e,e')$ and $D(e,e')$ cross section to: i) constraints PDFs, ii) study quark-hadron duality, iii) compare moments of the F_2 structure function to Lattice calculations and iv) model nucleon resonances



**Preliminary D/H ratios
(not yet corrected for charge
symmetric backgrounds)**

Plots courtesy Abel Sun

A comprehensive study of the 3D structure of nucleons is a key-stone of the JLab 12 GeV program.



N/q	U	L	T
U	f_1		h_1^\perp
L		g_1	h_{1L}^\perp
T	f_{1T}^\perp	g_{1T}	$h_1 h_{1T}^\perp$

quark

nucleon

U=unpolarized
L=long. polarized
T=trans. polarized

SIDIS programs will measure:

Transversity distribution

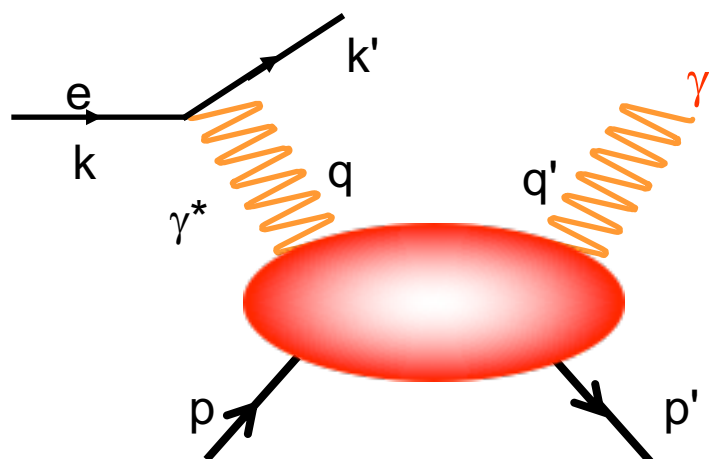
**Transverse Momentum Distributions (TMDs),
and perform high precision L/T separations**

These experiments explore k_T dependence of quarks to
access quark orbital angular momentum
and validation of SIDIS factorization framework

$$f^a(x, k_T^2; Q^2)$$

$f_{1T}^\perp \rightarrow$ Siverts function, describes unpolarized quark in trans. pol. nucleon

$h_1^\perp, h_{1L}^\perp, h_{1T}^\perp \rightarrow$ Boer-Mulders functions describe transversely polarized quarks in un/long./trans./polarized nucleon



Deep exclusive channels:

DVCS ($\vec{e}p \rightarrow e'p\gamma$),

vector and pseudo-scalar mesons production (DVMP)

allow access to GPDs that provide another handle for 3-D mapping of quark structure.

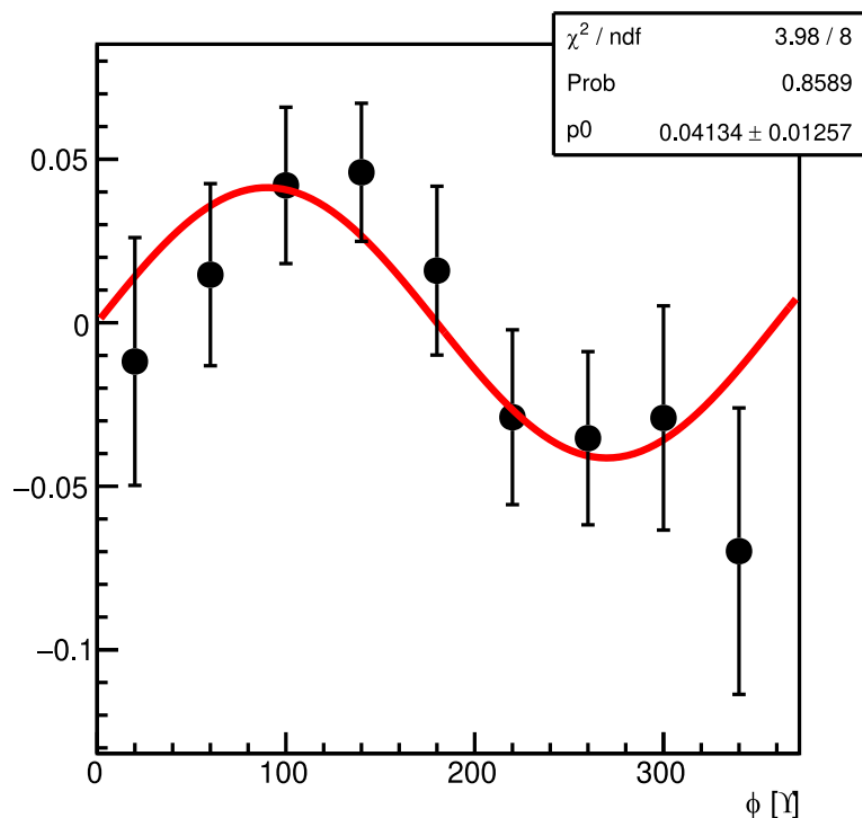
The CLAS12 commissioning experiment was a group of 13 experiments (Run Group A).

Includes an extensive SIDIS program and a DVMP program with polarized electrons on hydrogen.

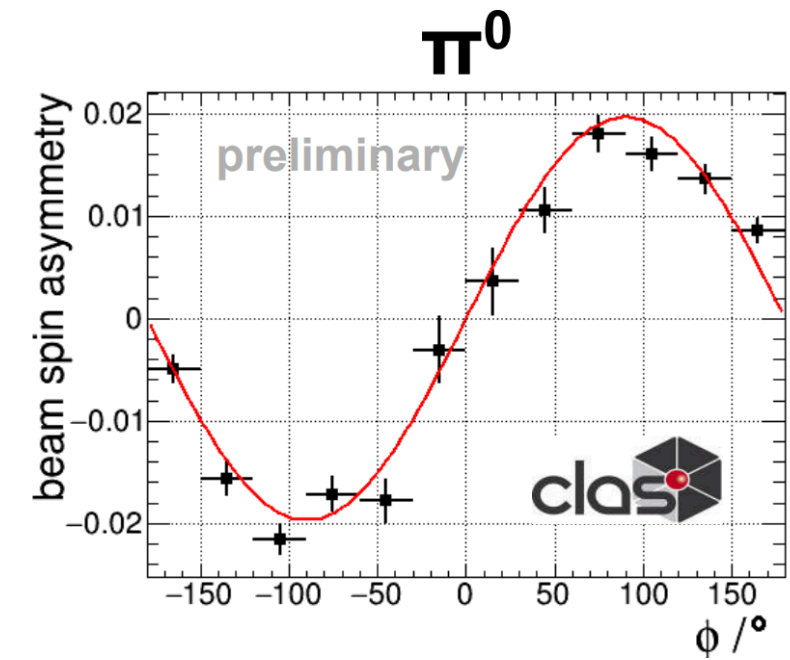
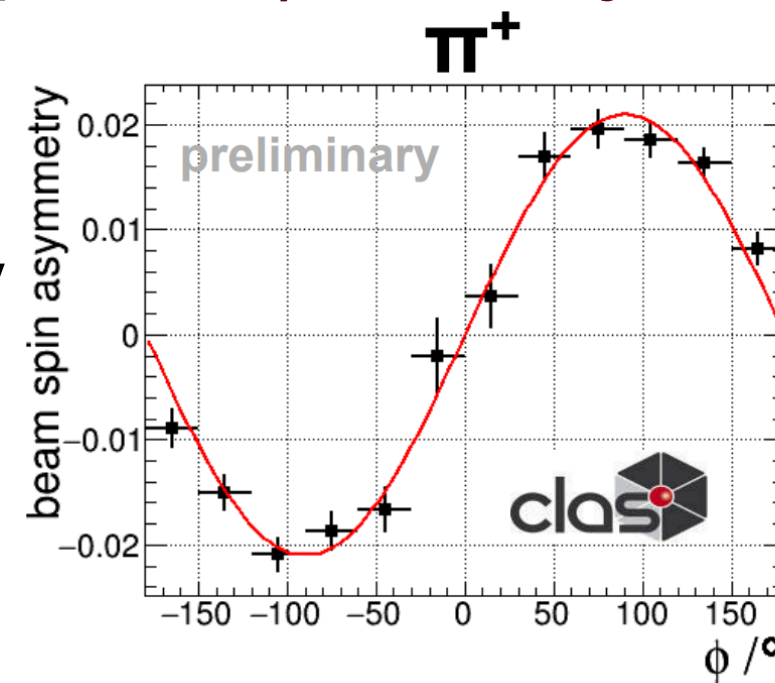
Large acceptance of CLAS12 allows studies of P_T and Q^2 -dependence of SSAs in a wide kinematic range

The preliminary results on ($\vec{e}p \rightarrow e'\pi X$) are from just a few % of the acquired statistics.

Preliminary SIDIS
beam spin asymmetry



Preliminary beam spin asymmetry from
DVMP ($\vec{e}p \rightarrow e'p\pi^0$)

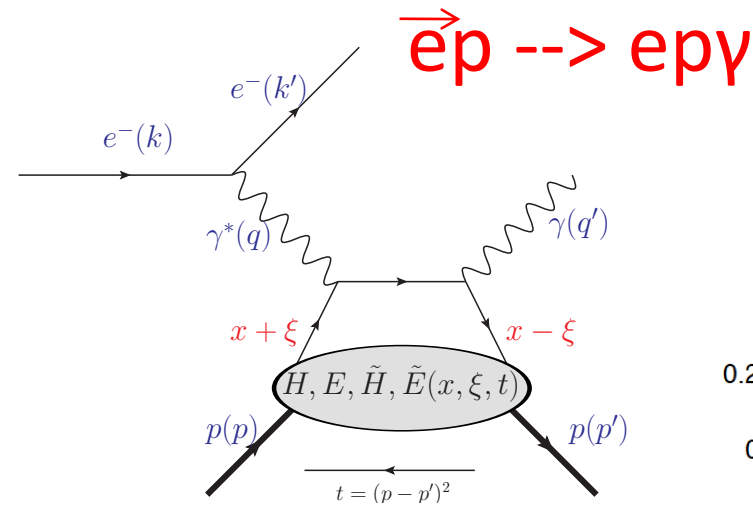


Plots courtesy of S. Diehl / A. Kim / N. Markov

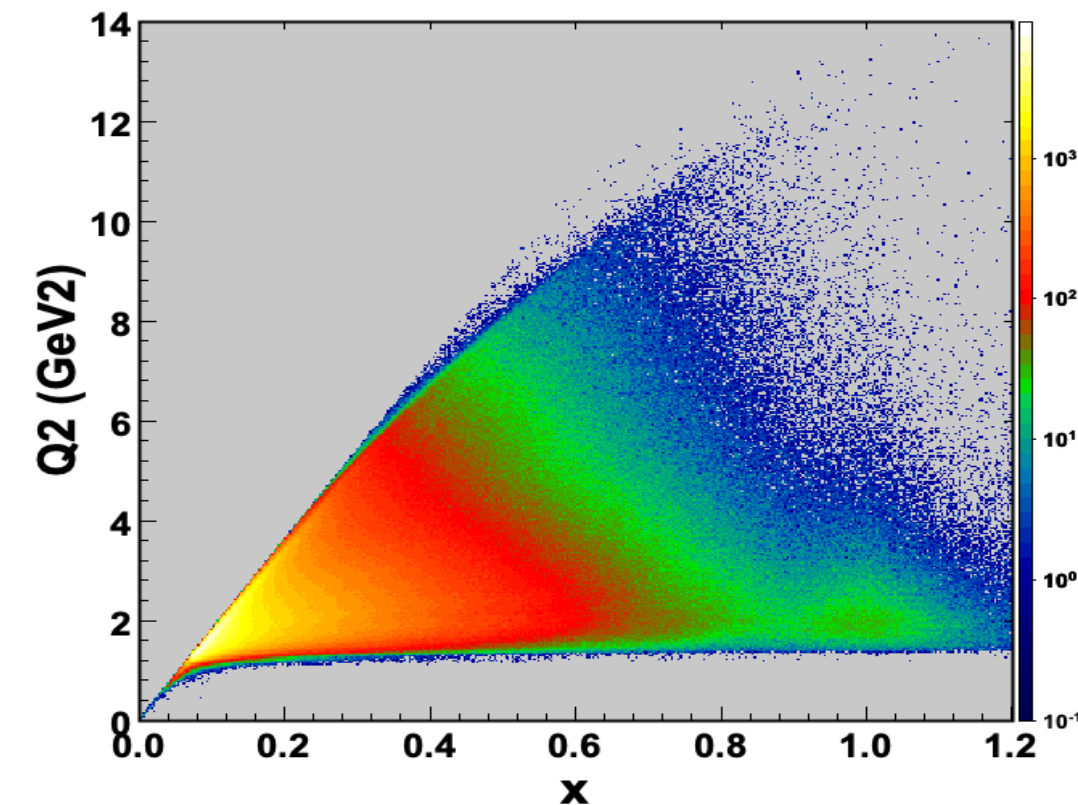
SESAPS, Nov 8, 2019

The Run Groups A and K measured DVCS over wide range of x , Q^2 and $-t$, and at different beam energies.

$$\Delta\sigma_{LU} \sim \sin\phi \{F_1 \mathbf{H} + \xi(F_1+F_2) \mathbf{H} + kF_2 \mathbf{E}\} d\phi$$



DVCS beam spin asymmetry at 10.6 GeV



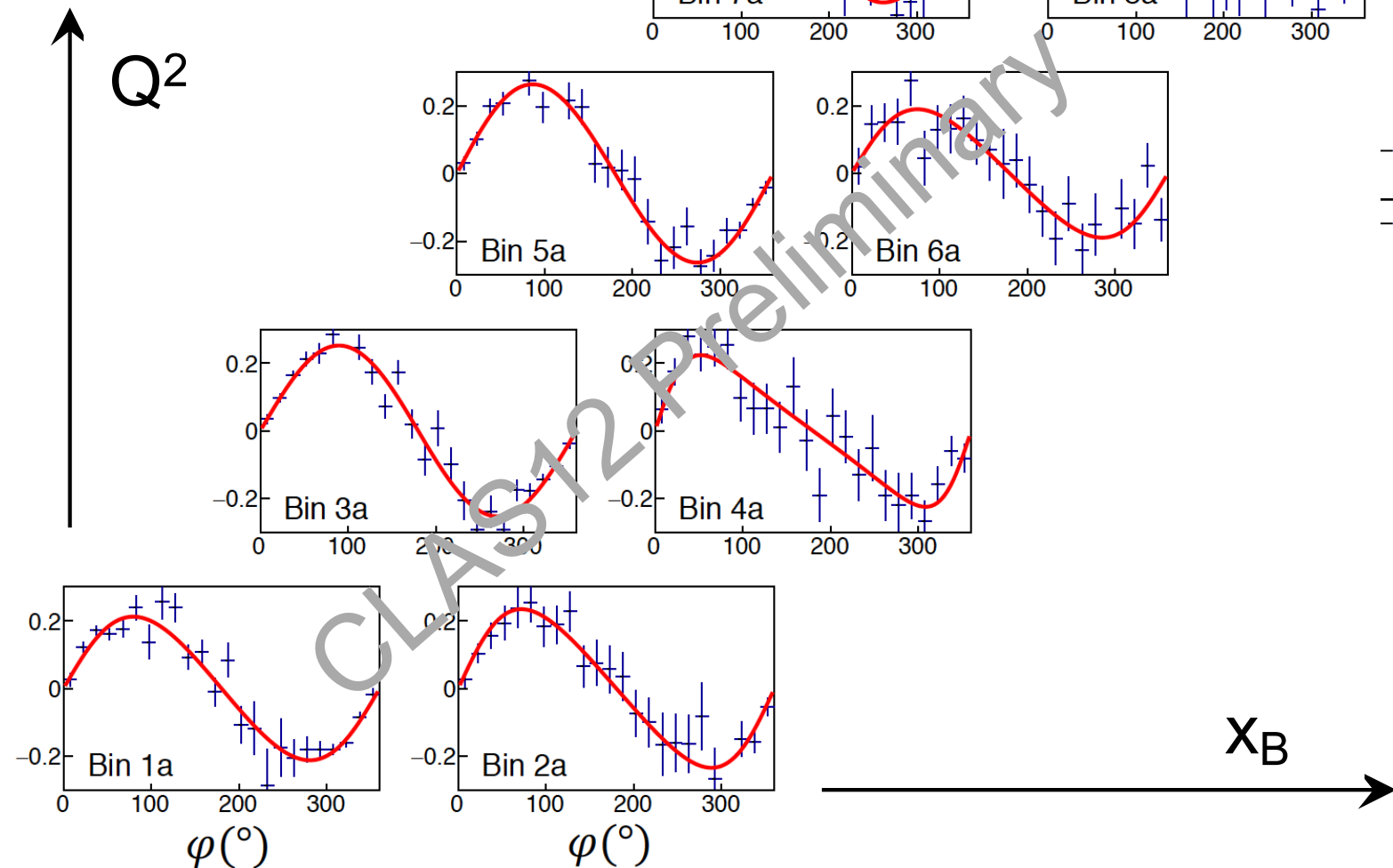
Run Group A

~54% of planned data collected

Run Group K

~12% of planned data collected

Plots courtesy of L. Elouadrhiri

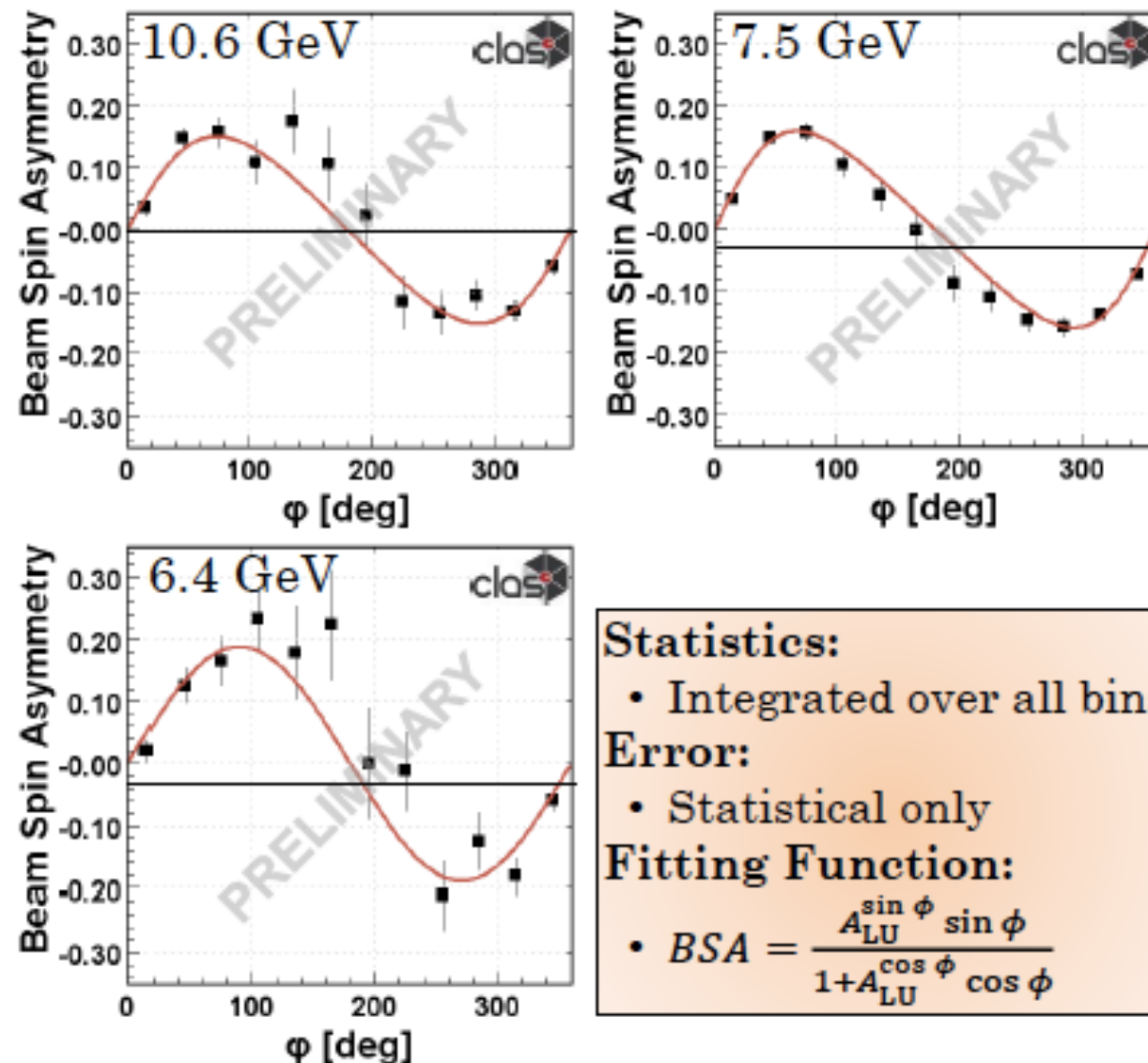


First results based on few % of the expected statistics

The Hall-B DVCS experiments explore confinement via measurement of pressure and shear force distributions.

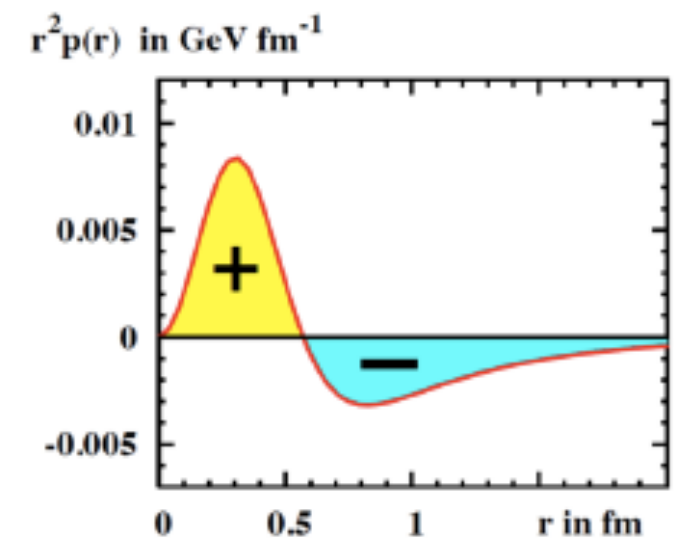
Study GPDs and their moments from DVCS

BEAM SPIN ASYMMETRY $A_{LU}^{\sin \phi}$



DVCS at different beam energies allow the extraction of Compton form factors \mathcal{H} , $\tilde{\mathcal{H}}$ and \mathcal{E} : which allows access to the pressure and shear force distributions.

Nucleon Pressure Distribution

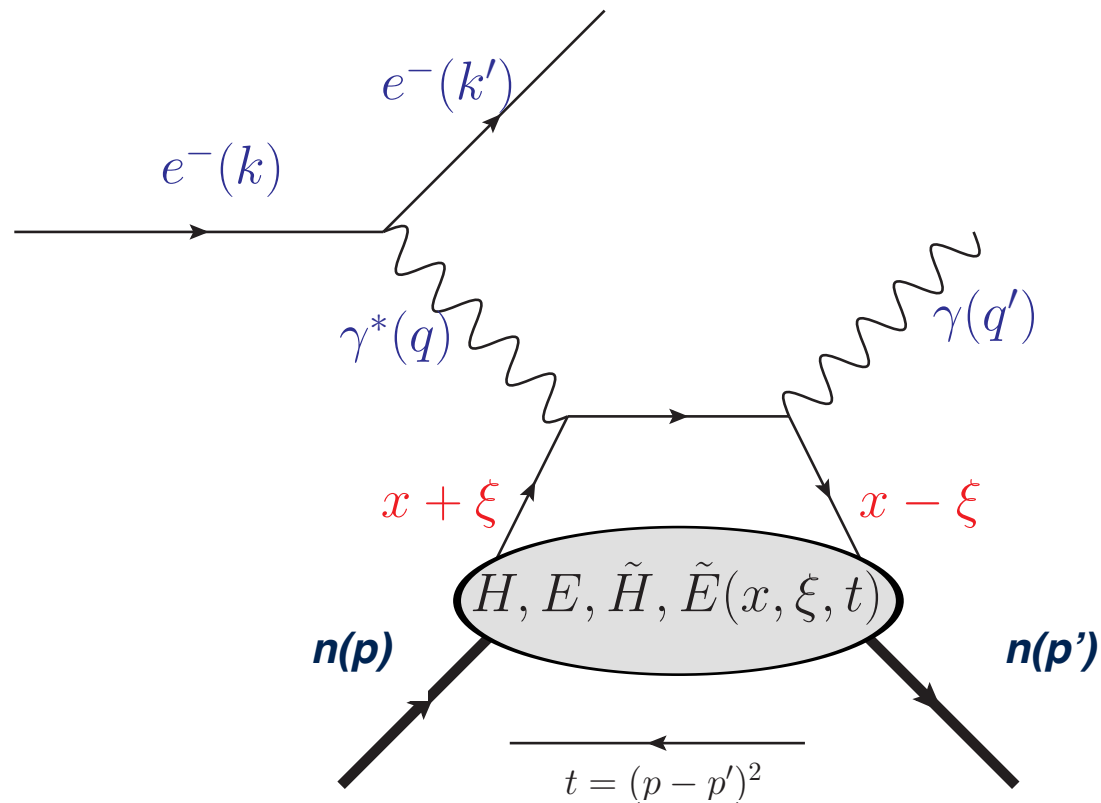


Beam spin asymmetry fits with $Q^2 > 1 \text{ GeV}^2$, $W > 2 \text{ GeV}$, $|\vec{q}'| > 2 \text{ GeV}$, $\Delta\theta_{\text{cone}(\gamma)}$ cut, and $E_{X_{e'p'\gamma}}$ cut is qualitatively in agreement with the previous CLAS DVCS results.

Plots courtesy of J. Tan

CLAS12 has also measured nDVCS with polarized electrons on deuterium.

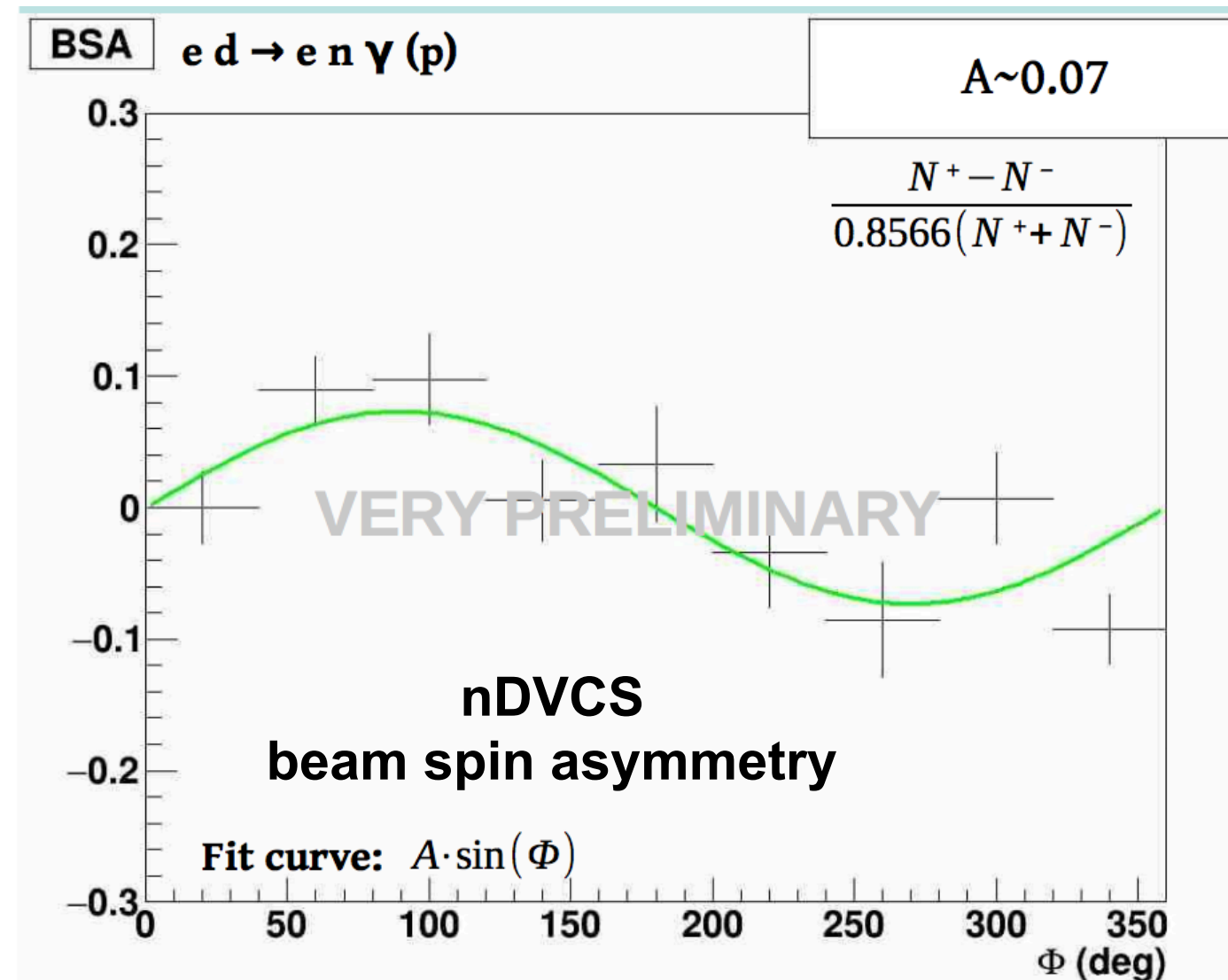
Run Group B - 7 different experiments
(~ 20% of planned data collected)



CLAS12 DVCS experiments have very wide kinematic coverage and will concentrate on beam spin asymmetries (not absolute cross sections)

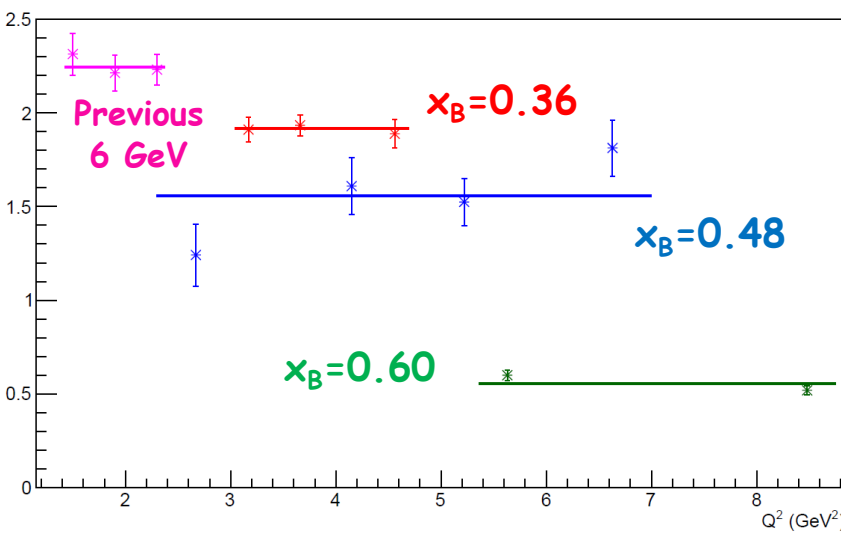
$$\vec{e}d \rightarrow e'n\gamma(p)$$

10.6 GeV polarized electrons on deuterium.



Plots courtesy of K. Price / N. Markov

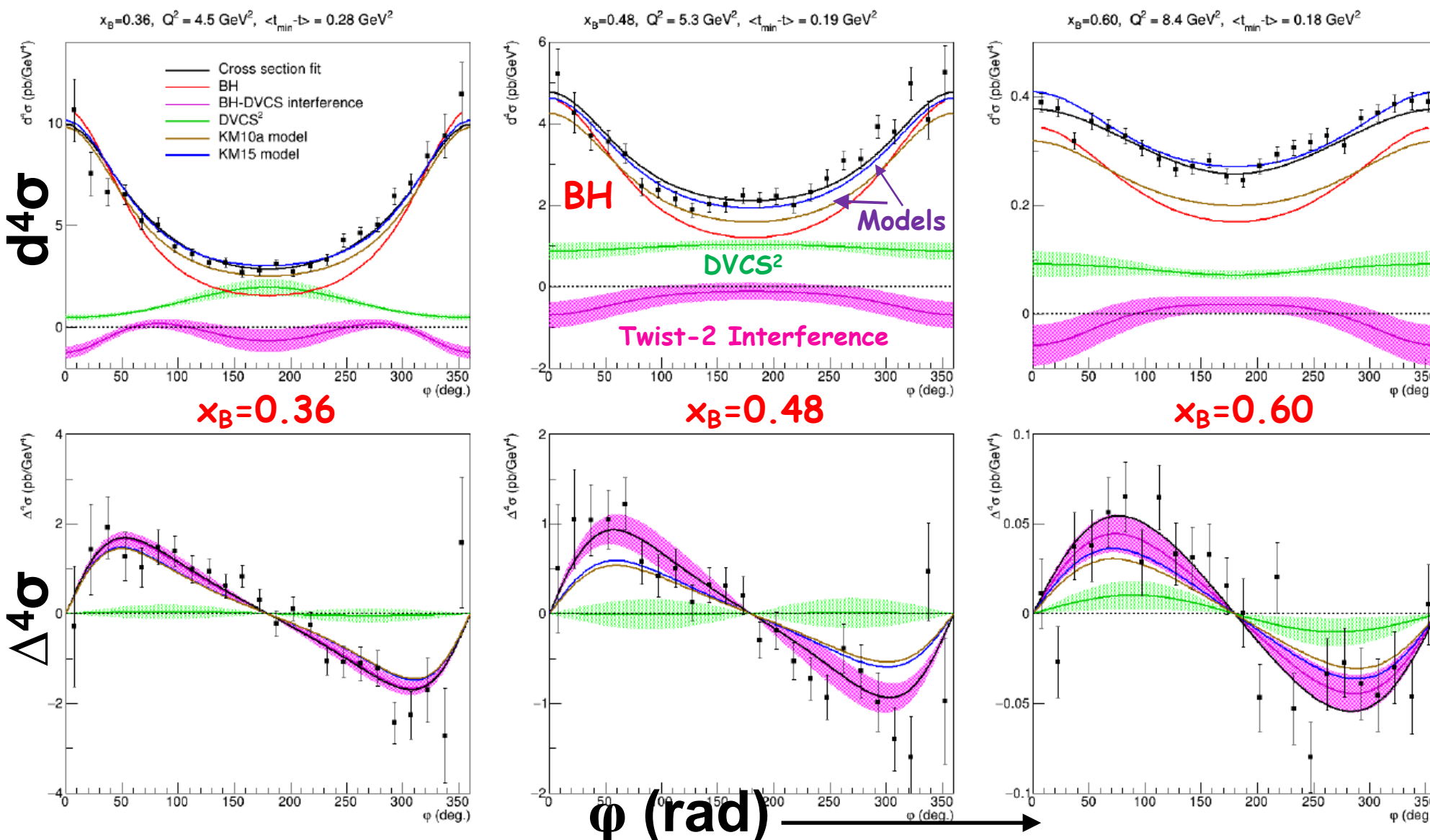
The Hall-A DVCS experiment has collected data to explore the high x_B regions for the first time.



50% data collected in 2014 and 2016.
High precision scaling tests of the DVCS cross section at fixed x_B

Analysis of DVCS cross sections completed for *all 9 kinematic settings* (limited coverage)

Sample of preliminary cross-section results



Helicity-independent cross section

Publication forthcoming in 2019

Helicity-dependent cross section

Plots courtesy of Carlos Munoz Camacho

The 3D structure of hadrons has one whole session (session K01) with several talks on new JLab results.

[Show Abstracts](#)

Session K01: The 3D Structure of the Hadrons

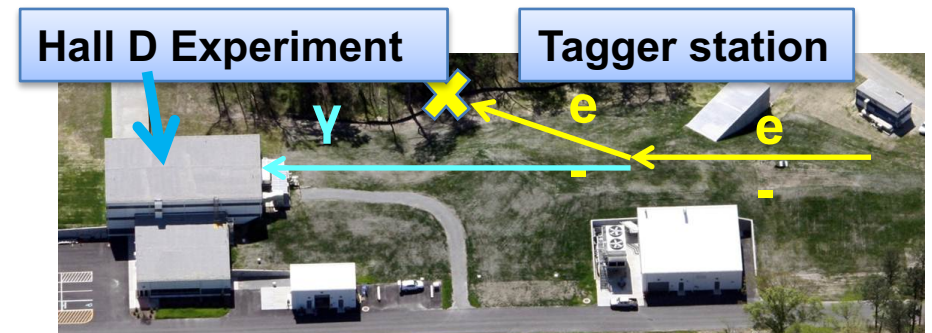
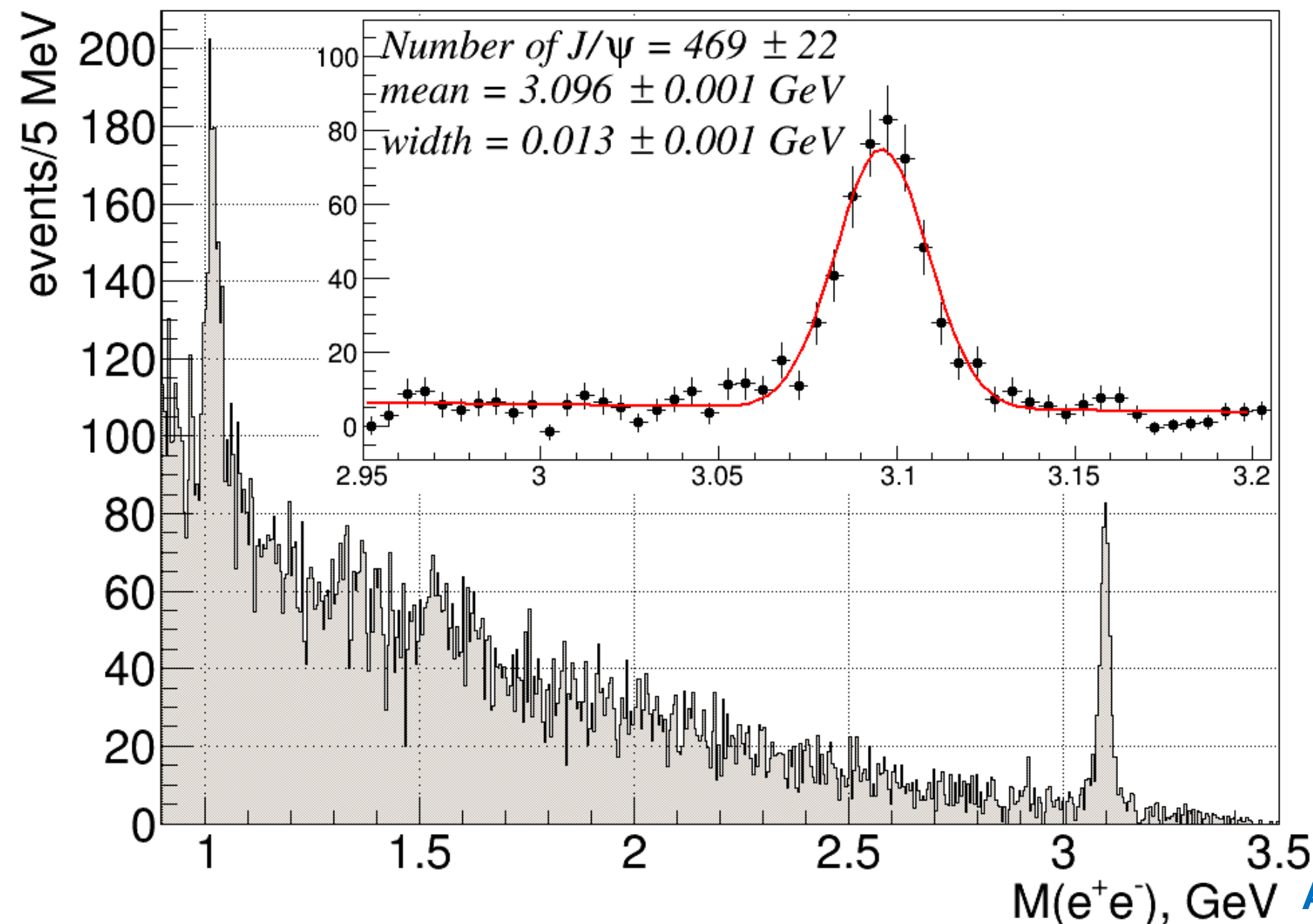
Chair: Harut Avakian, Jefferson Laboratory
Room: *Holiday Inn Resort Causeway/Masonboro*

Saturday, November 9, 2019 2:00PM - 2:30PM	K01.00001: Augmented reality: a 3D-look inside matter to understand how it comes about from QCD quarks and gluons Invited Speaker: Marco Radici Preview Abstract
Saturday, November 9, 2019 2:30PM - 3:00PM	K01.00002: 3-D Nucleon Structure Studies at JLab Hall A and C. Invited Speaker: Jian-ping Chen Preview Abstract
Saturday, November 9, 2019 3:00PM - 3:30PM	K01.00003: SIDIS with CLAS12 Invited Speaker: Giovanni Angelini Preview Abstract
Saturday, November 9, 2019 3:30PM - 4:00PM	K01.00004: The study of chiral-odd GPDs using deeply virtual π^0 electroproduction with CLAS12 at Jefferson Lab. Invited Speaker: Andrev Kim

First results from the GlueX collaboration probes gluon fields in the nucleon at high x, via J/Ψ production.

- ~ 9 GeV Linearly polarized photon beam
- Search for gluonic excitations in light meson spectra (data collected in 2017 and 2018)

Exclusive reaction $\gamma p \rightarrow J/\Psi p \rightarrow e^+e^-p$



Large-acceptance spectrometer

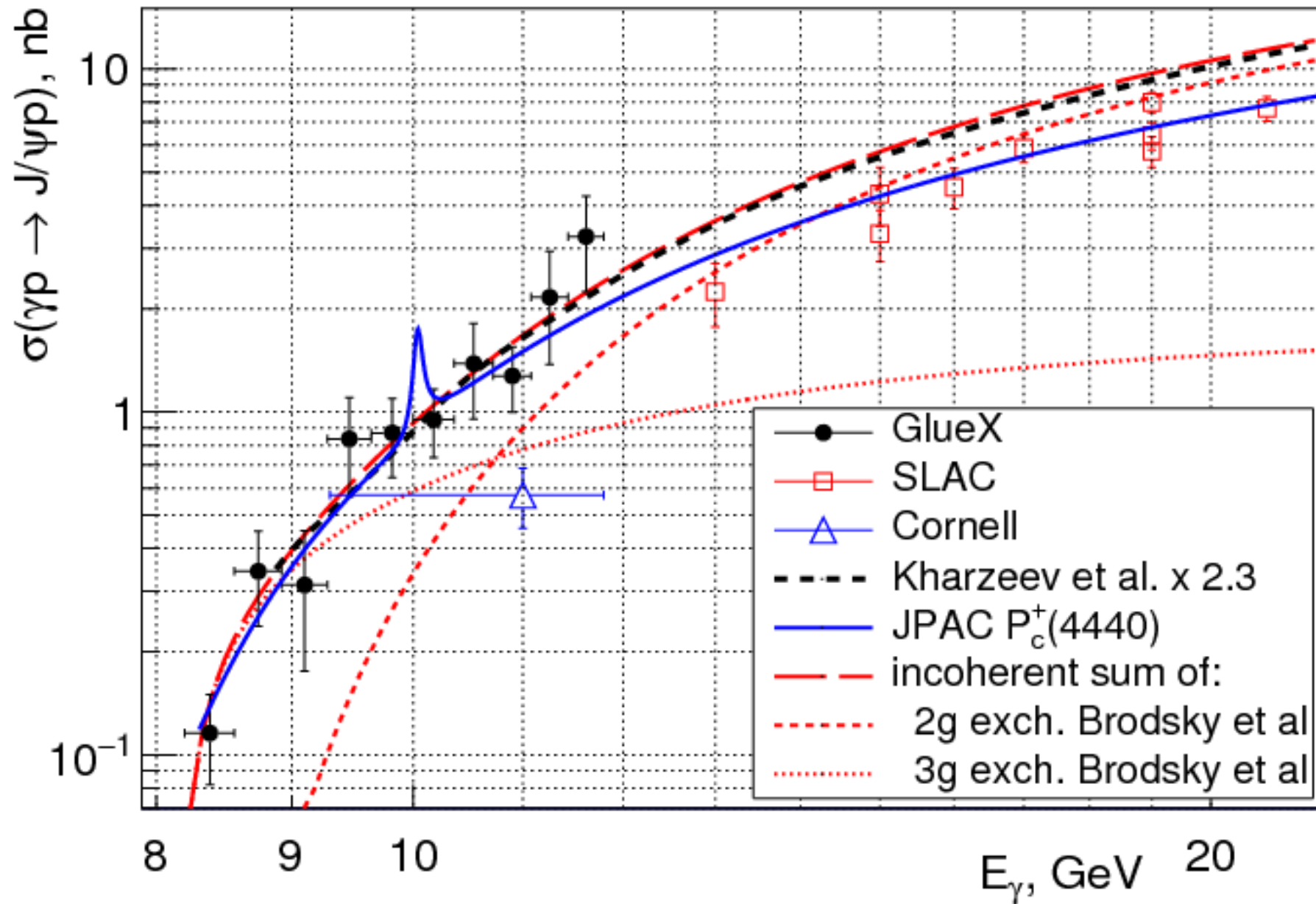


this represents ~30% of the GlueX J/Ψ events

A.Ali et al PRL 123, 072001 (Aug 2019)

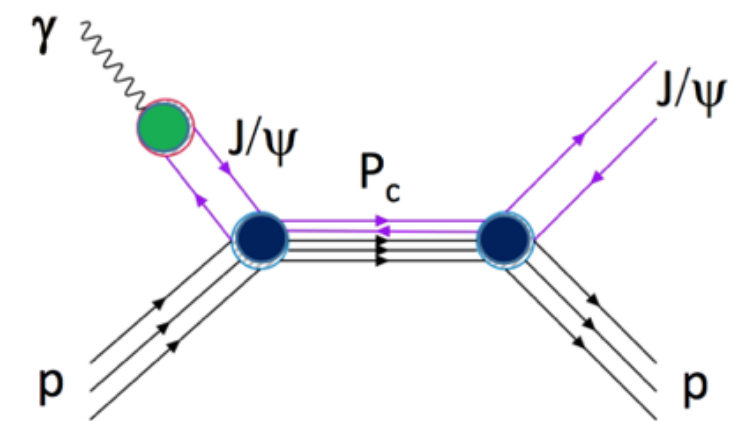
The GlueX collaboration did not find evidence for the LHCb pentaquark in s-channel production at $E_\gamma \simeq 10$ GeV.

A.Ali *et al* PRL 123, 072001 (Aug 2019)



measured cross section indicates large gluonic contribution to the mass of the proton (larger than expected from two-gluon exchange models)

this represents ~30% of the GlueX J/ Ψ events

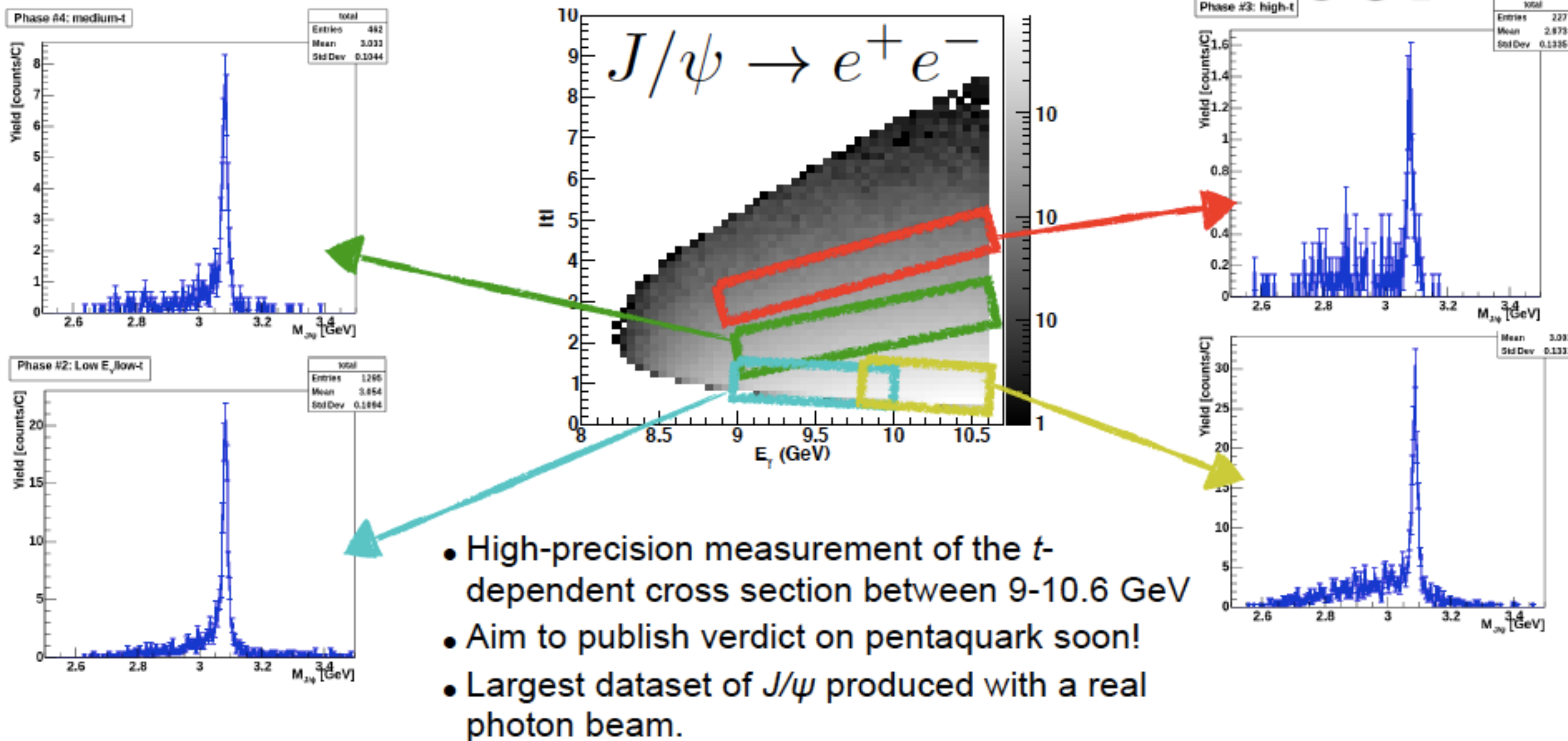


no evidence for LHCb pentaquark P_c , model-dependent upper limits on $\text{Br}(P_c \rightarrow J/\psi p)$ of 2 - 4% at 90%CL

A Hall-C experiment looking for the same pentaquark has collected J/ψ s with very high statistics.

ONLINE RESULTS: INVARIANT MASS

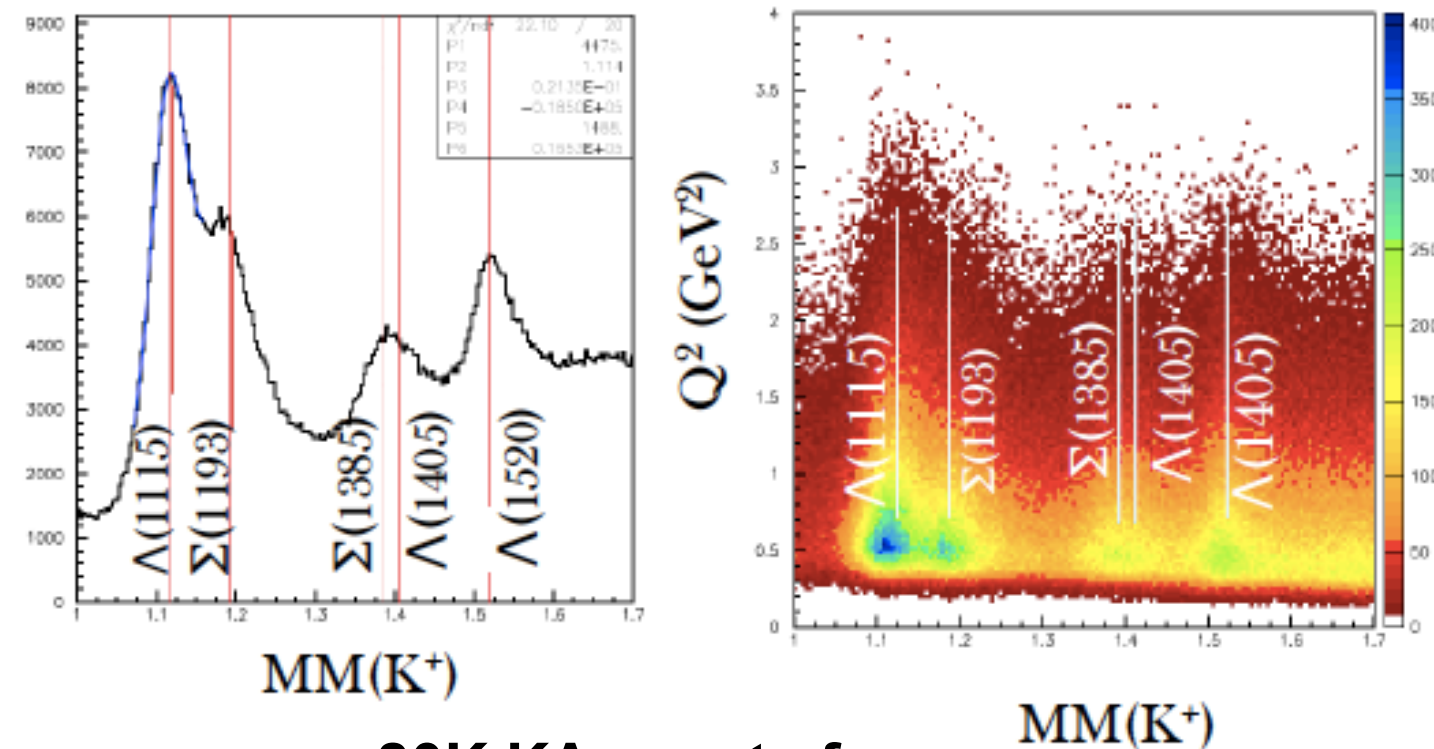
007 J/ψ



Plots courtesy of Sylvester Joosten

Hall-B has collected data to study nucleon resonances via $K\Lambda$ electroproduction & search for hybrid baryons.

$p(e,e'K^+)$

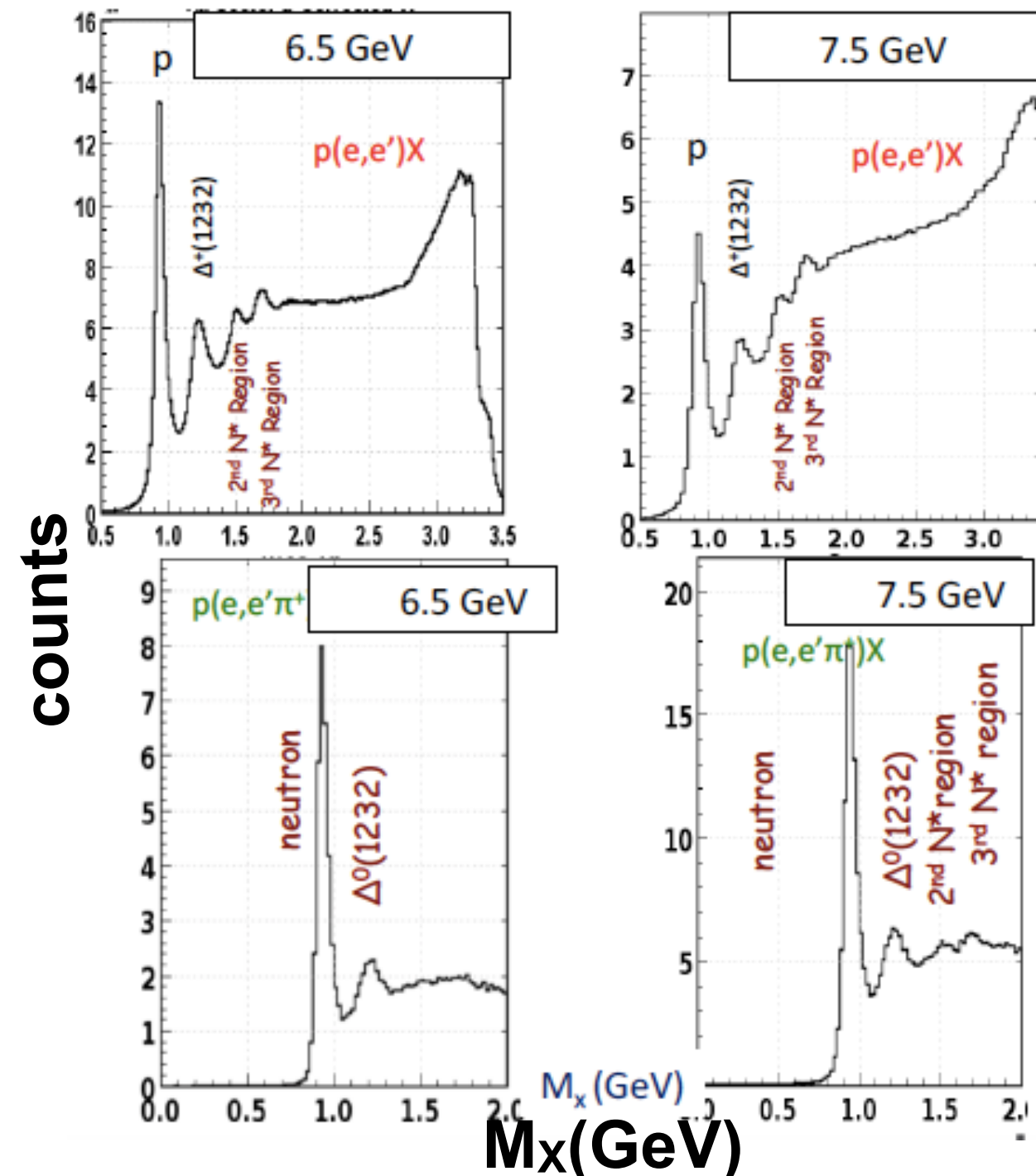


Measure the Q^2 dependence of
electrocoupling amplitudes

Unique search for hybrid
baryons: baryons with glue as a
structural component $|qqqg\rangle$

Plots courtesy of Annalisa D'Angelo

inclusive and semi-inclusive
invariant mass distributions



There are several talks on new results and other planned measurements at GlueX.

Thursday, November 7, 2019 [A03.00003: Recent Results From GlueX](#)
9:30AM - 10:00AM Invited Speaker: Colin Gleason

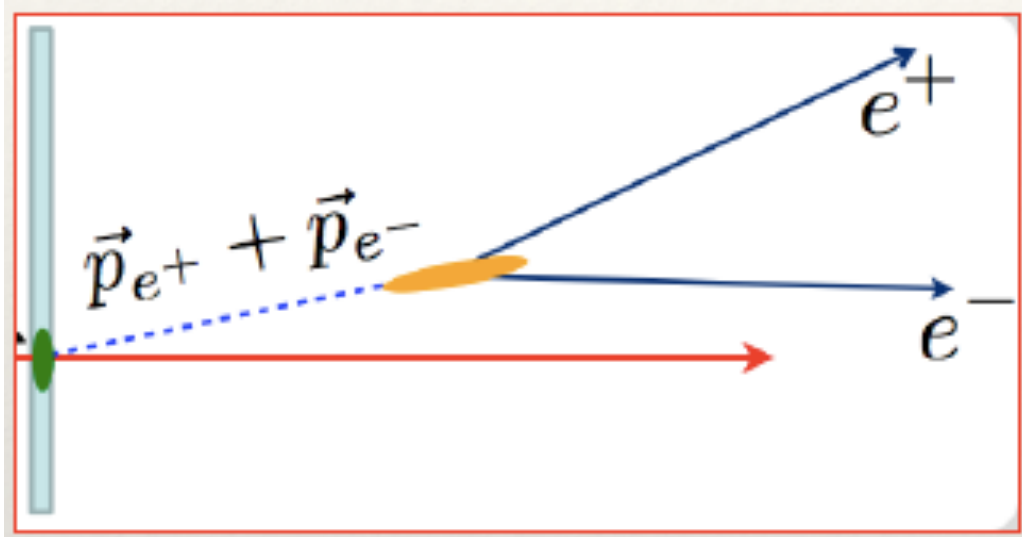
Friday, November 8, 2019 [G02.00004: Plans for a Measurement of Charged and Neutral Pion Polarizabilities with GlueX](#)
3:30PM - 4:00PM Invited Speaker: Mark Ito

Friday, November 8, 2019 [G03.00003: Prospects for Studying Photoproduction on Nuclear Targets with the GlueX Detector](#)
3:00PM - 3:30PM Invited Speaker: Alexander Somov

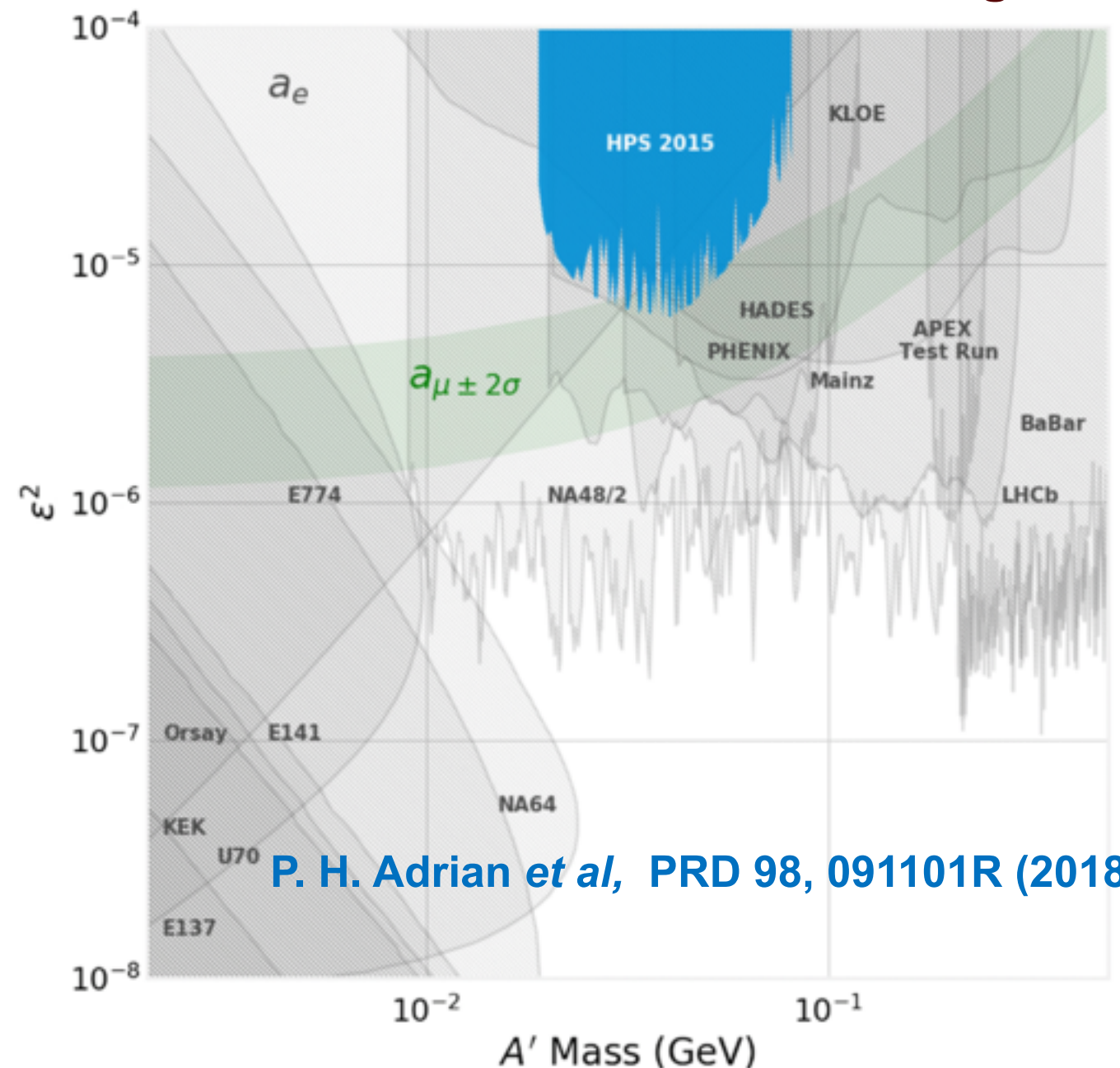
The first experiment to run in Hall-B was a “new physics” search experiment, looking for the A' heavy photon.



HPS experiment searches for A' in elctroproduced e^+e^- pairs
 $m_{A'} = 50 - 500 \text{ MeV}/c^2$ range for coupling strengths $\epsilon^2 \sim 10^{-6} - 10^{-10}$



Results from engineering run of 2015,
50 nA, 1.1 GeV beam on W target



[P. H. Adrian et al, PRD 98, 091101R \(2018\)](#)

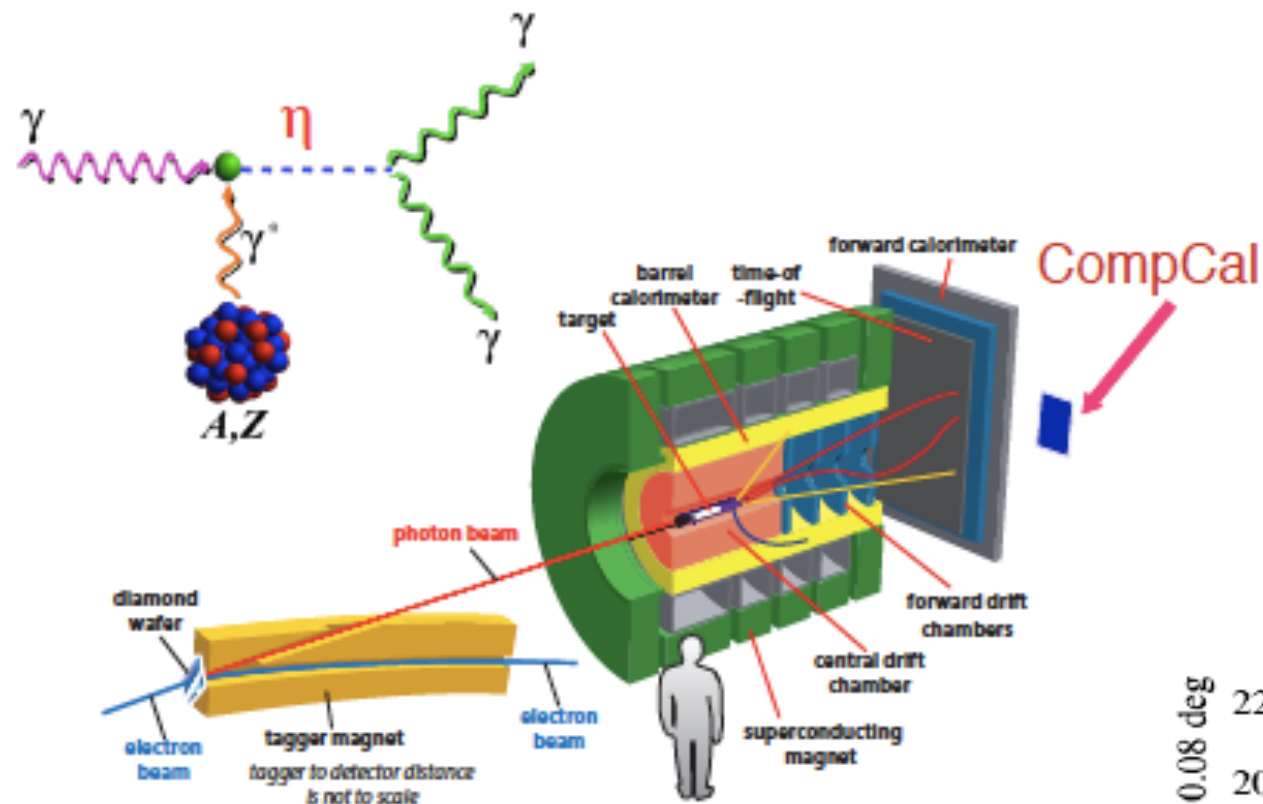
The Summer 2019, 4.56 GeV run will cover new, as yet unexplored territory (using the displaced vertex technique)

More information:

Session A04: Thursday 10:00 AM
Rafayel Paremuzyan on HPS Expt.

Session G03: Friday 2:00 PM
Alexandre Camsonne on the APEX Expt.

GlueX has also completed the Primakoff measurement of $\Gamma(\eta \rightarrow \gamma\gamma)$ with a ^4He target.



The GlueX detector with a new calorimeter CompCal.

$\eta \rightarrow \gamma\gamma$ yield [$8.0 \text{ GeV} < E_\gamma < 11.2 \text{ GeV}$]

Physics impact:

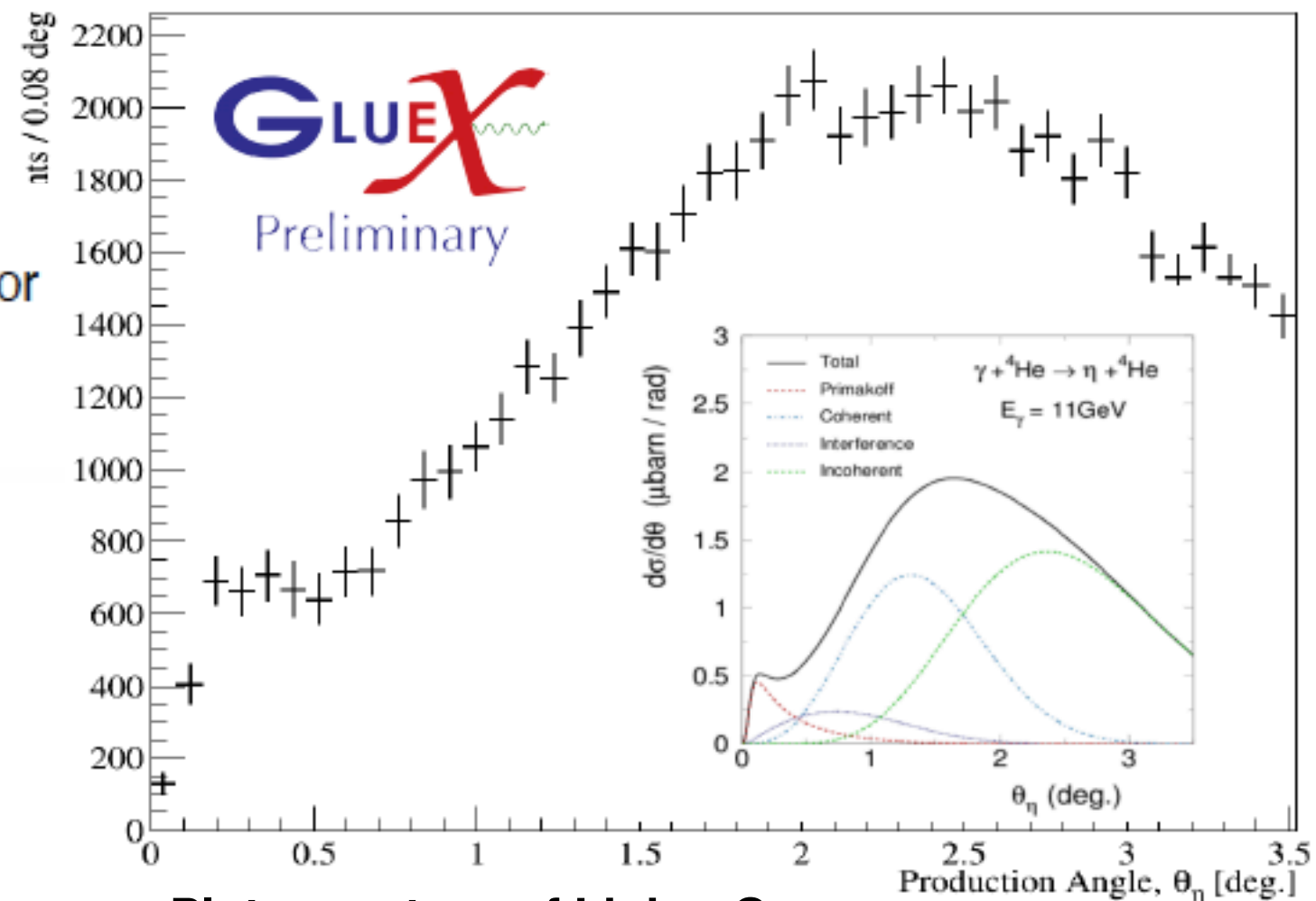
- improves all decay widths in the η -sector
- light quark mass ratio
- η - η' mixing angle

More information:

Session A04: Thursday 8:30 AM
Simon Taylor on JEF Experiment

Session G02: Friday 2:30 PM
Liping Gan on the Primakoff program

Poster: D04: Wolfgang Irrig



Plots courtesy of Liping Gan

Other completed experiments that will have preliminary results soon.

**EMC effect and SRC (at $x > 1$) measured on light nuclei:
C, ^{10}B and ^{11}B data collected in 2018 in Hall C, other targets to be completed.**

**Charge symmetry violation in quark distributions:
Measured SIDIS ratio of π^+/π^- on Deuterium, data collected in 2018 and 2019 in Hall C.**

**SIDIS pion electroproduction scans in (x, z, P_T) and Q^2 at fixed x ,
data collected in 2018 and 2019 in Hall C.**

**L-T separated cross sections for exclusive kaon electroproduction at high Q^2 ,
data collected in 2018 and 2019 in Hall C.**

**Determining the Λ -n interaction via study of Λ -nn resonance,
data collected as part of the Tritium program in 2018 in Hall A.**

**Measurement of the neutron distribution in ^{208}Pb using parity violating
electron scattering, data collected in Fall 2019.**

Summary

- **The upgraded accelerator at JLab is fully operational and the extensive experimental program is underway in earnest.**
- **Almost 30% of the approved experiments have already been completed.**
- **Exciting new results are trickling in and some have already been published.**
- **Look out for the deluge about to come.....**