Closing Talk

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

Australian Government
Australian Research Council

Anthony W. Thomas

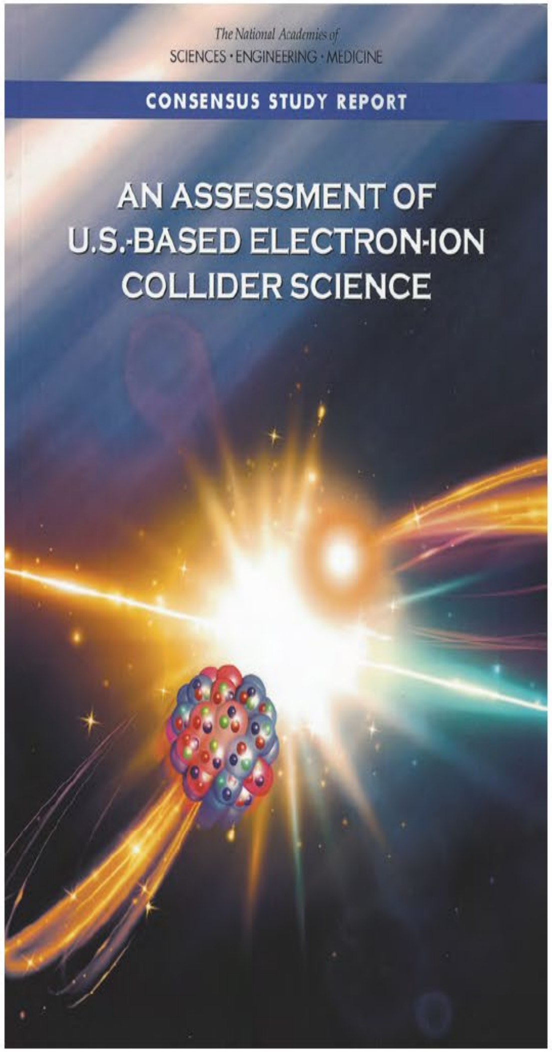
HiX

Kolympari : 17th August 2019

ADELAIDE UNIVERSITY AUSTRALIA

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

New Facilities & Apparatus



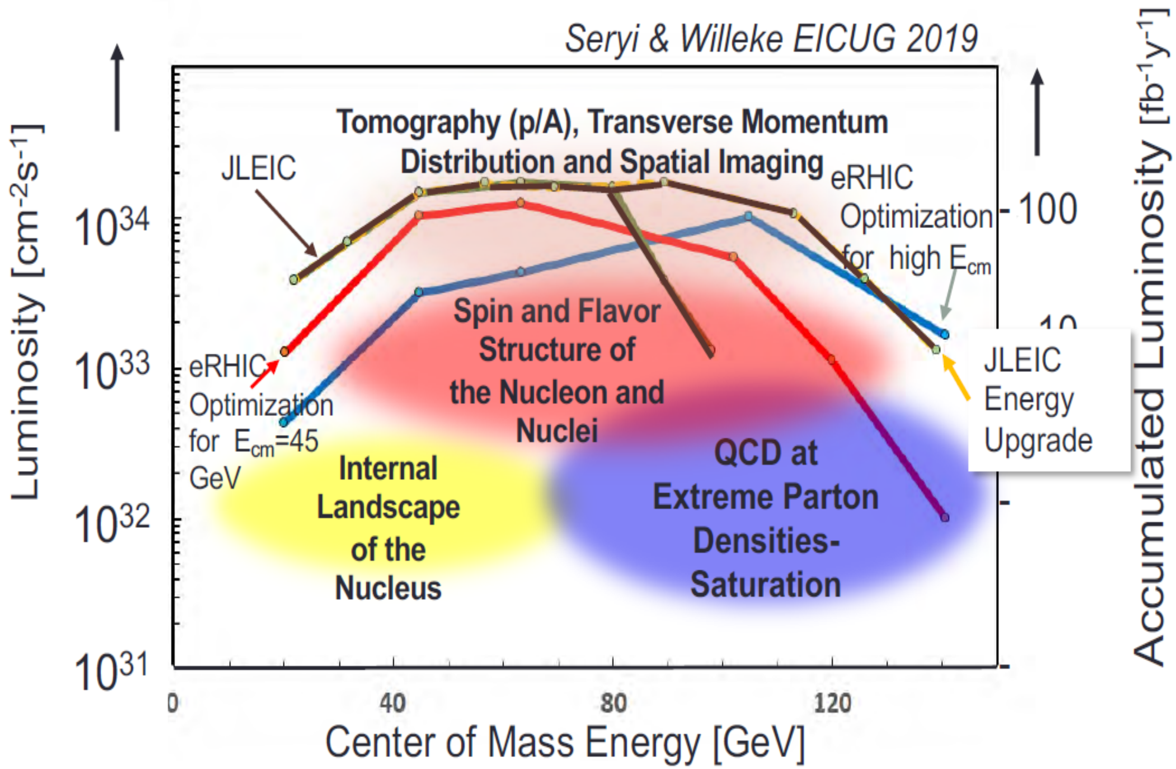
Consensus Study Report on the US based Electron Ion Collider

Summary:

The science questions that an EIC will answer *are central* to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today. In addition, the development of an EIC would *advance accelerator science and technology* in nuclear science; it would as well *benefit other fields of accelerator based science and society*, from medicine through materials science to elementary particle physics

Luminosity EIC at BNL (& JLab)

IR Designs can be adjusted to obtain peak luminosity at different center of mass energies. The curves below show luminosity vs E_{cm} with IRs optimized for high or low center of mass energy. *With two IRs, in principle both optimization can coexist in the same machine*



For e-A collisions, the E_{cm} scale needs to be reduced by a factor $(Z/A)^{1/2}$

EIC @ JLab & Energy Upgrade

EIC @ BNL High energy optimization

EIC @ BNL Low energy optimization *(Motivated by interest of EICUG intermediate to high-x)*

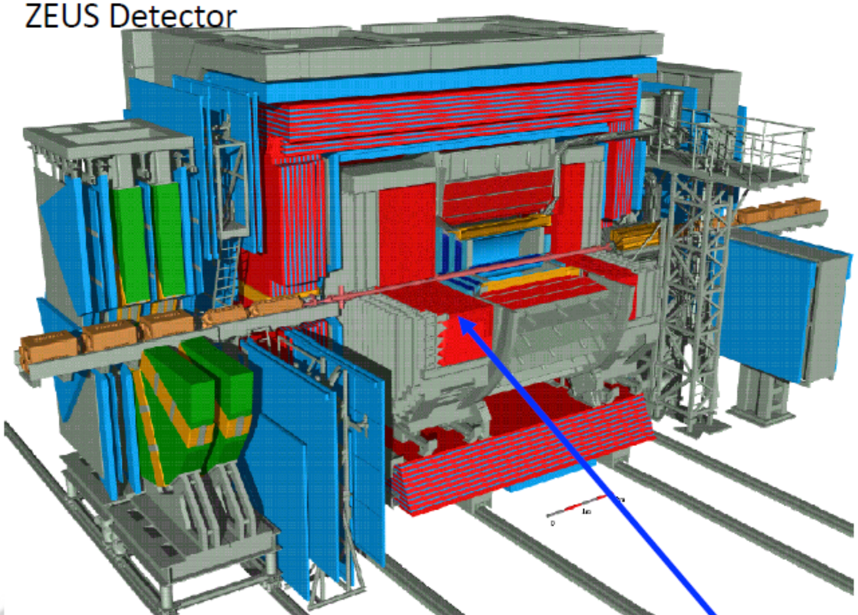
- Increased crossing angle to 50mrad
- Electron quads brought in closer: small β^*
- Increase number bunches

Choosing how to reconstruct x and Q^2

From R. Yoshida

Depends on the detector and its characteristics

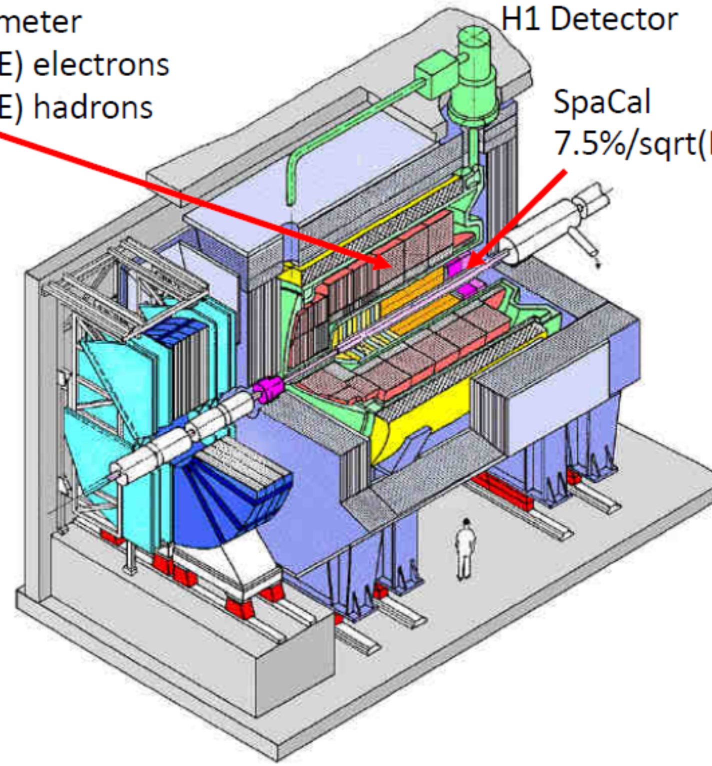
ZEUS Detector



LAr Calorimeter
12%/sqrt(E) electrons
50%/sqrt(E) hadrons

H1 Detector

SpaCal
7.5%/sqrt(E) electrons



U-Scintillator Calorimeter
18%/sqrt(E) electrons
35%/sqrt(E) hadrons

Many other differences: segmentation, tracking…

Best Collider DIS Kinematics Reconstruction Depends on Detector

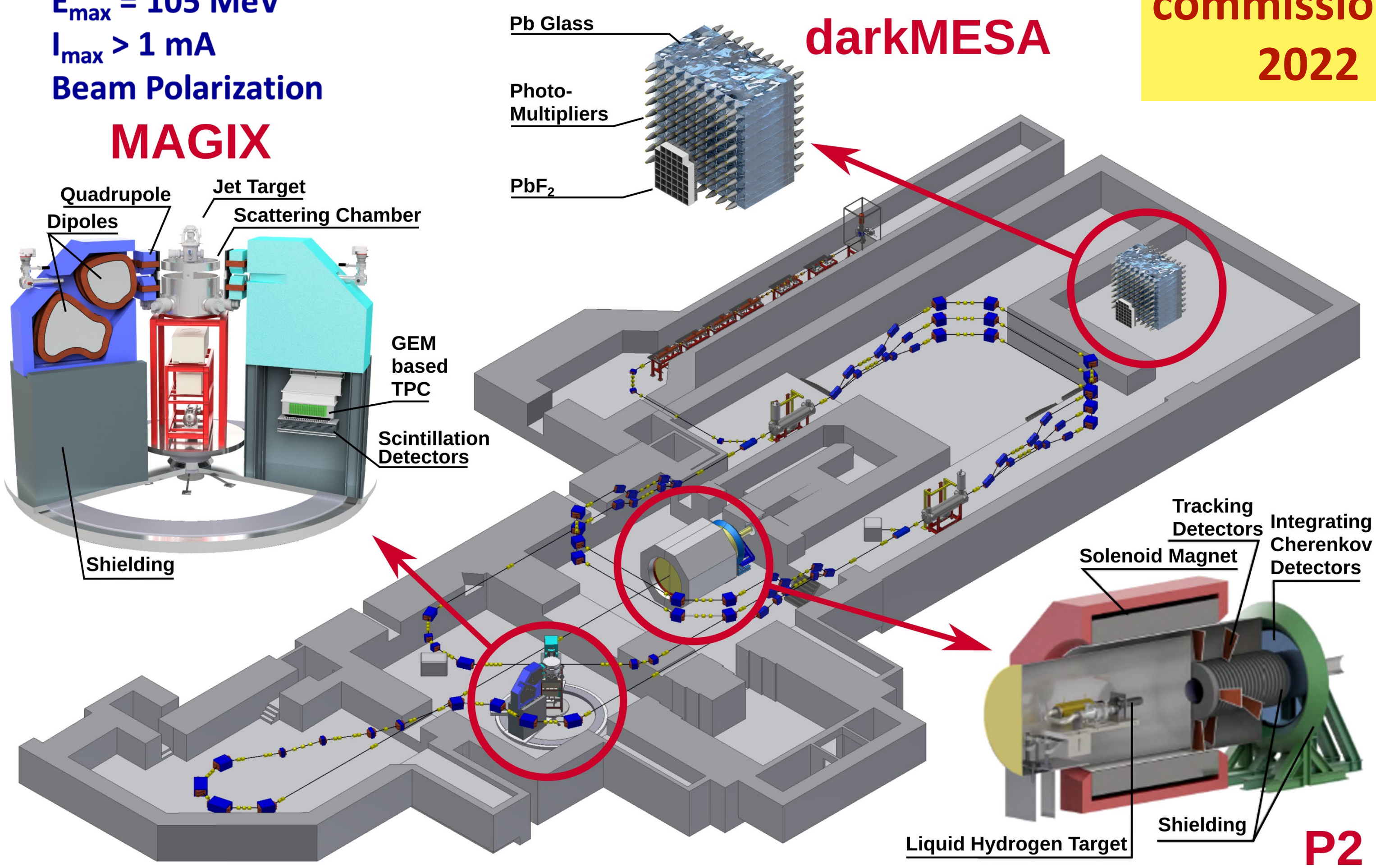
MESA at Mainz

New facility *MESA*

Mainz Energy-Recovering Superconducting Accelerator

Recirculating ERL Mode
E_{max} = 105 MeV
I_{max} > 1 mA
Beam Polarization

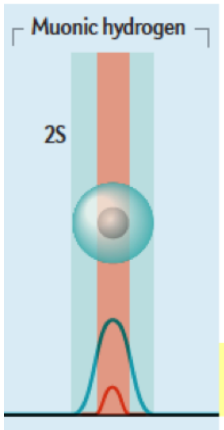
commissioning 2022

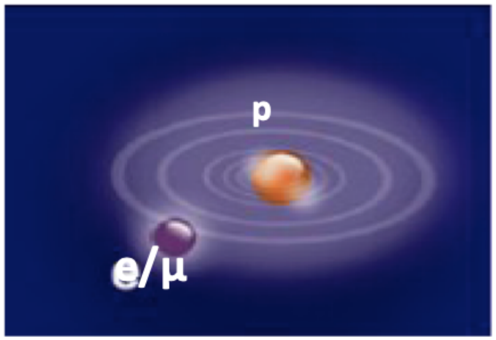


From talk of V. Pascalutsa

Proton radius puzzle

Atomic Spectroscopy
(PSI: Lamb Shift in muonic hydrogen)

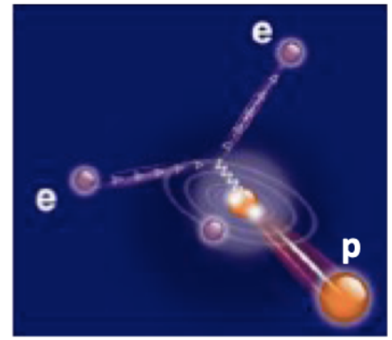




$R_E = 0.8409 \pm 0.0004$ fm

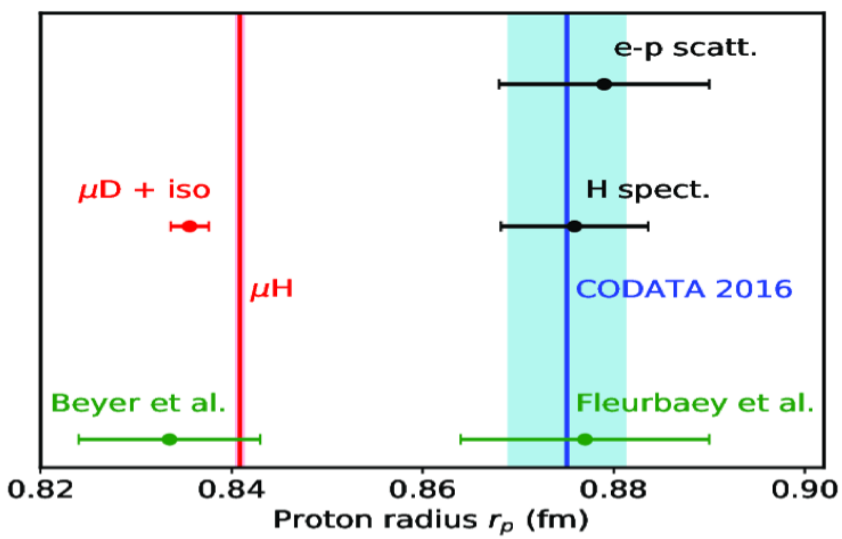
Nature (2012)
Science (2013)

Electron Scattering on proton
(EM form factor measurements)



$R_E = 0.879 \pm 0.008$ fm

PRL (2010)
PRD(2014)

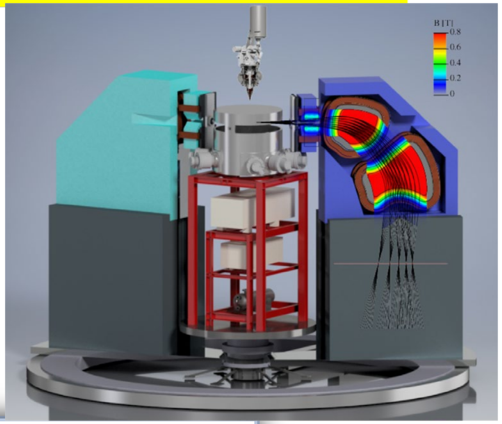


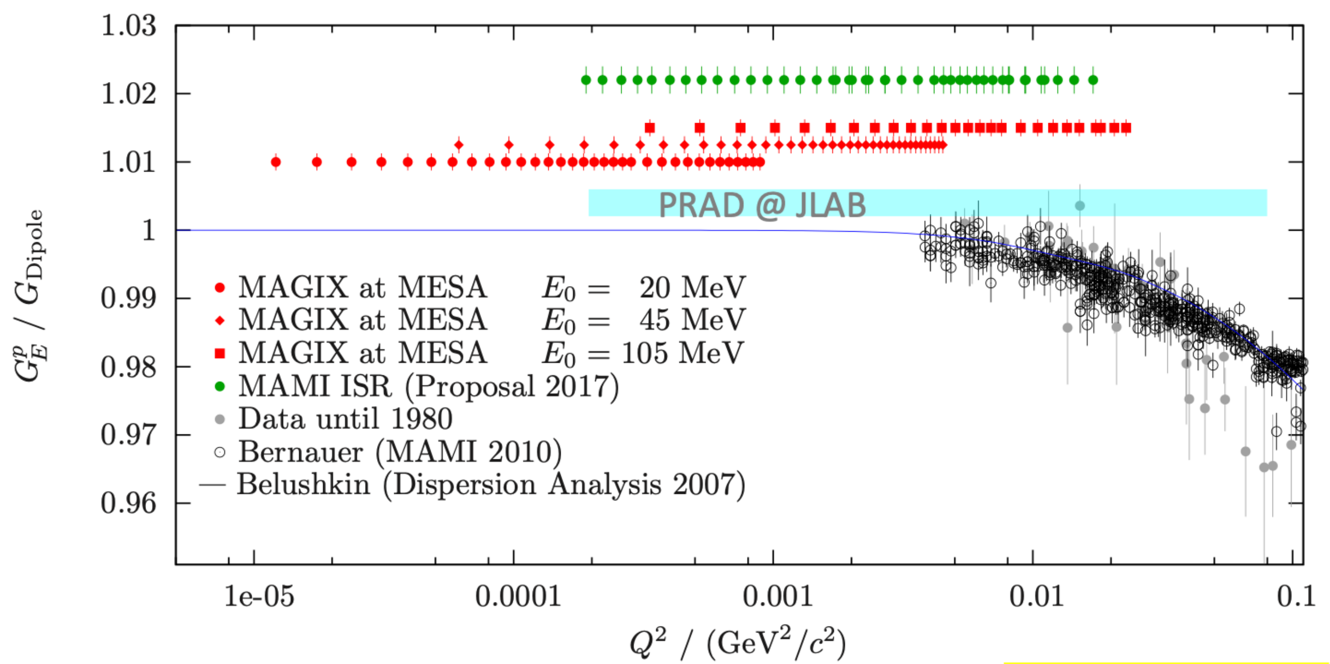
Low-Q^2 proton FF: MAGIX@MESA

Operation of a high-intensity (polarized) ERL beam in conjunction with light internal target
→ a novel technique in nuclear and particle physics

High resolution spectrometers MAGIX:

- double arm, compact design
- momentum resolution: $\Delta p/p < 10^{-4}$
- acceptance: ±50 mrad
- GEM-based focal plane detectors
- Gas Jet or polarized T-shaped target

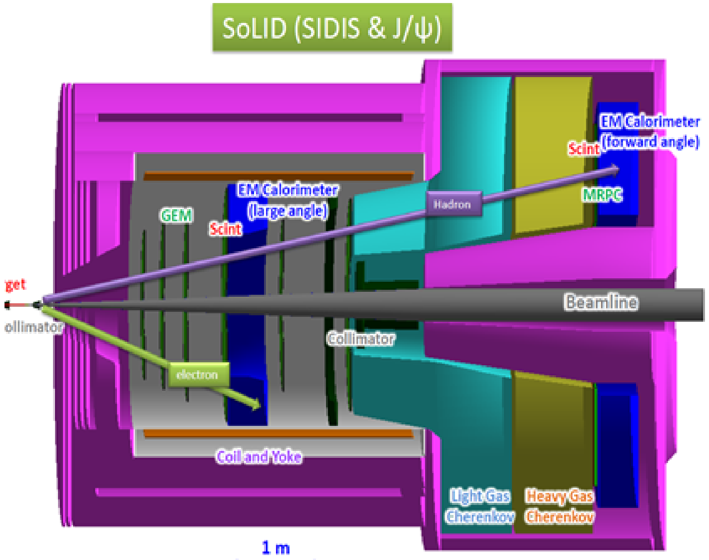


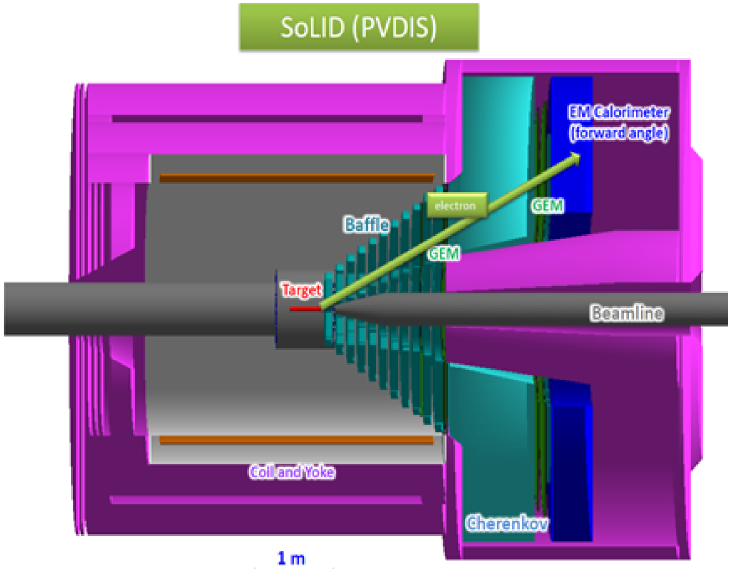


SoLID with 11 GeV at JLab

SoLID Detector

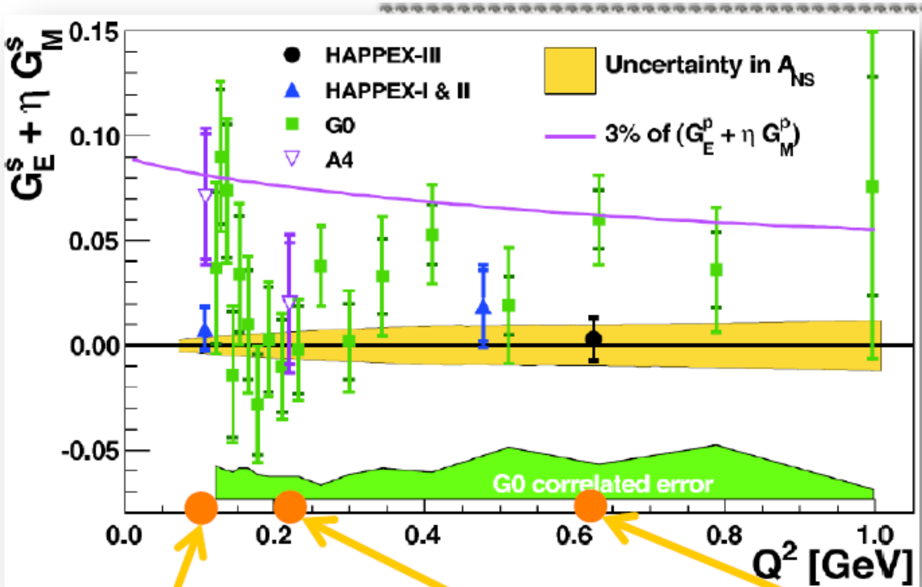
Nucleon Structure Study
JLab 12 GeV Program
SoLID: Large Acceptance and High Luminosity

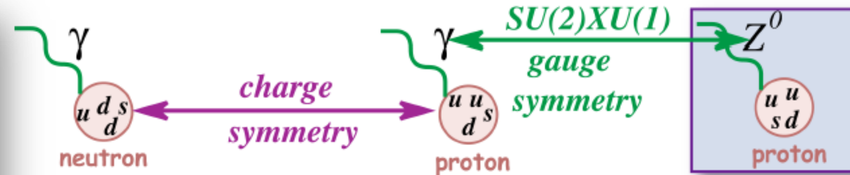




Powerful high acceptance device to handle luminosity up to 10^{39}

Elastic Scattering: s-quark Form Factors

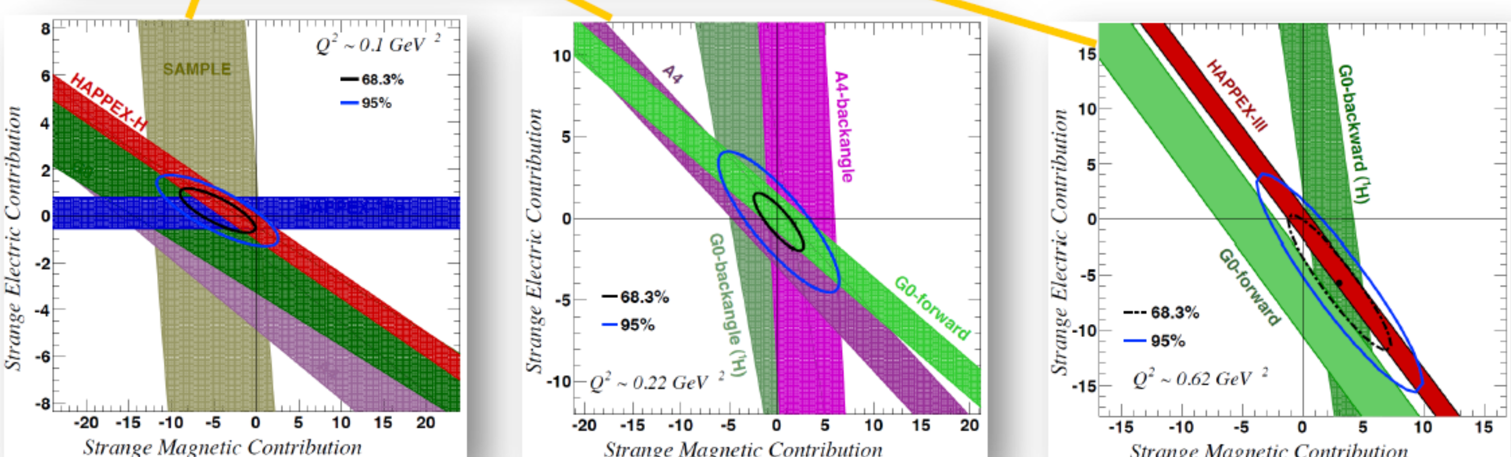




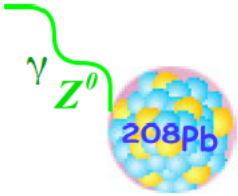
$$G_p^Z \sim (1 - 4\sin^2\theta_W)\, G_p^\gamma - G_n^\gamma - G_s$$

$\Rightarrow$ $G_E^s(Q^2), G_M^s(Q^2)$

- Sensitive Flavor separation at 3 Q^2 values
- No more than few % of EM structure
- Modern lattice QCD results in agreement



Elastic Scattering: Neutron Densities



$$M^{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2) \qquad M_{PV}^{NC} = \frac{G_F}{\sqrt{2}}\left[\left(1 - 4\sin^2\theta_W\right)F_p(Q^2) - F_n(Q^2)\right]$$

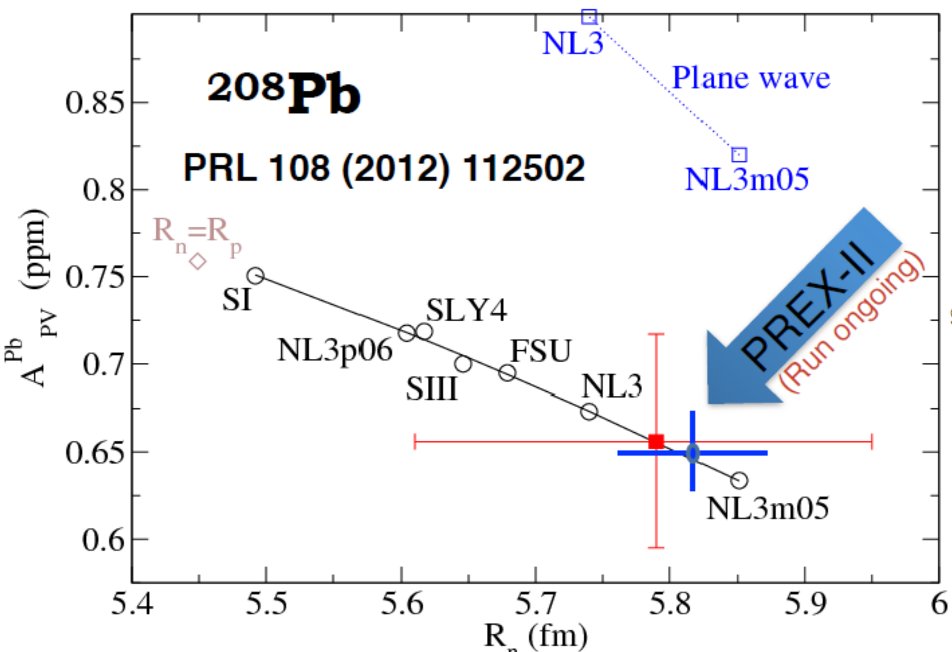
$Q^p_{EM} \sim 1$ $\quad Q^n_{EM} \sim 0$ $\quad Q^n_W \sim -1$ $\quad Q^p_W \sim 1 - 4\sin^2\theta_W$

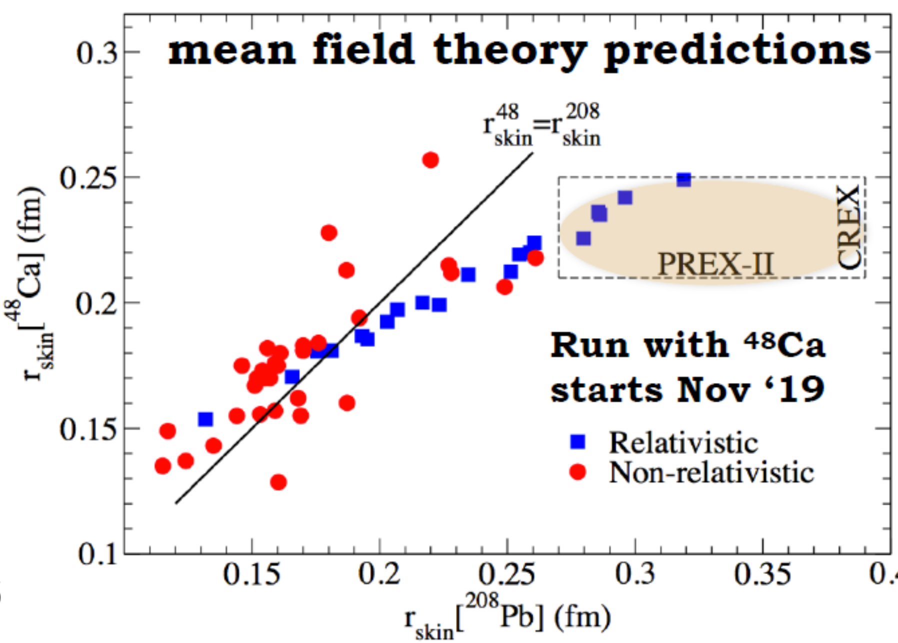
$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$$

$\delta(A_{PV})/A_{PV} \sim 3\%$

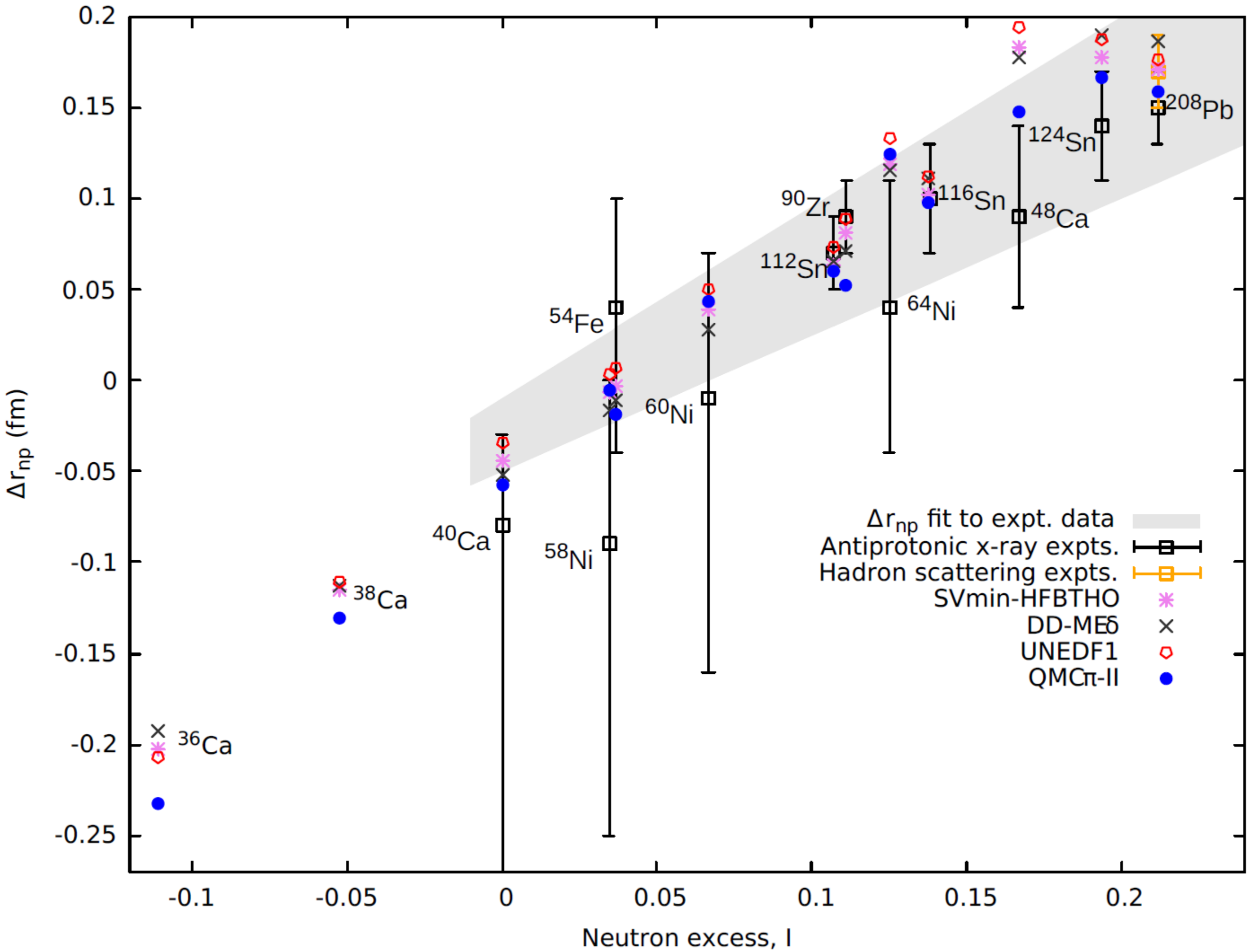
$\delta(R_n)/R_n \sim 1\%$

$\delta(R_n)$: ± 0.06 fm (^{208}Pb)
± 0.02 fm (^{48}Ca)





Neutron-proton radius difference



AWT – Quark-Meson Coupling model

^{48}Ca PVDIS

Consider PVDIS on a heavy nucleus

Neutron or proton excess in nuclei leads to a isovector-vector mean field (ρ exchange)

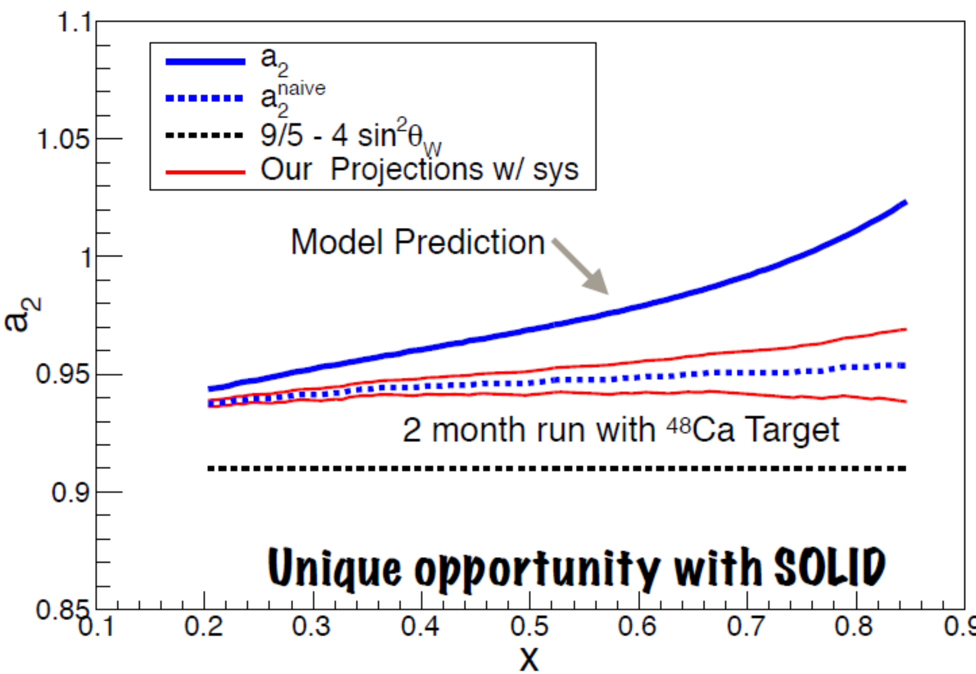
shifts quark distributions: "apparent" charge symmetry violation

Isovector EMC effect: could be responsible for at least 2/3 of NuTeV anomaly

- **new insight into medium modification of quark distributions**

$$a_2 \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+} + \dots$$

Great leverage for insight into isospin dependence of the EMC effect in an inclusive measurement

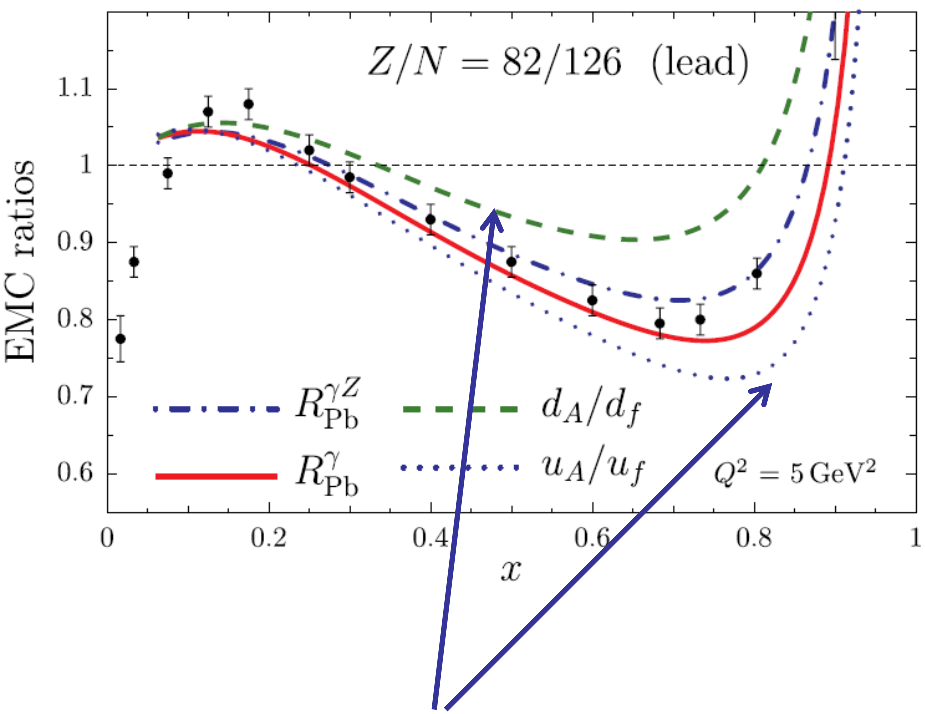


- ***methods of flavor decomposition of medium modifications challenging***
- ***must disentangle small effects (theoretically and experimentally)***
- ***Precise isotope cross-section ratios in purely electromagnetic electron scattering: MUCH reduced sensitivity to the isovector combination***

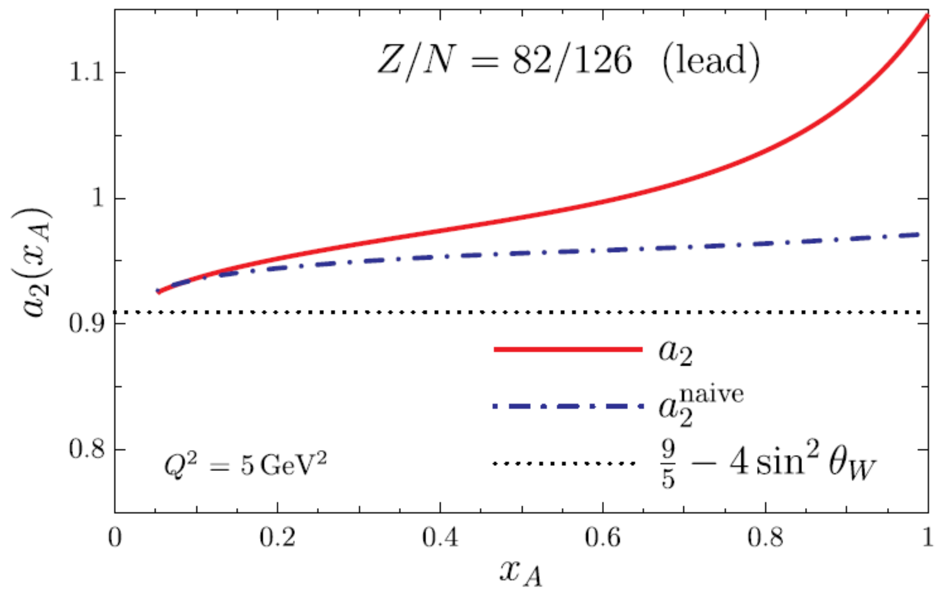
PRL 109, 182301 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

Parity-Violating Deep Inelastic Scattering and the Flavor Dependence of the EMC Effect

I. C. Cloët,[1] W. Bentz,[2] and A. W. Thomas[1]



$$A_{\rm PV} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha_{\rm em}}\left[a_2(x_A) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x_A)\right]$$



Ideally tested at EIC with CC reactions

Parity violating EMC will test this at JLab 12 GeV
- interesting to incorporate in nuclear PDF fits: Schienbein?

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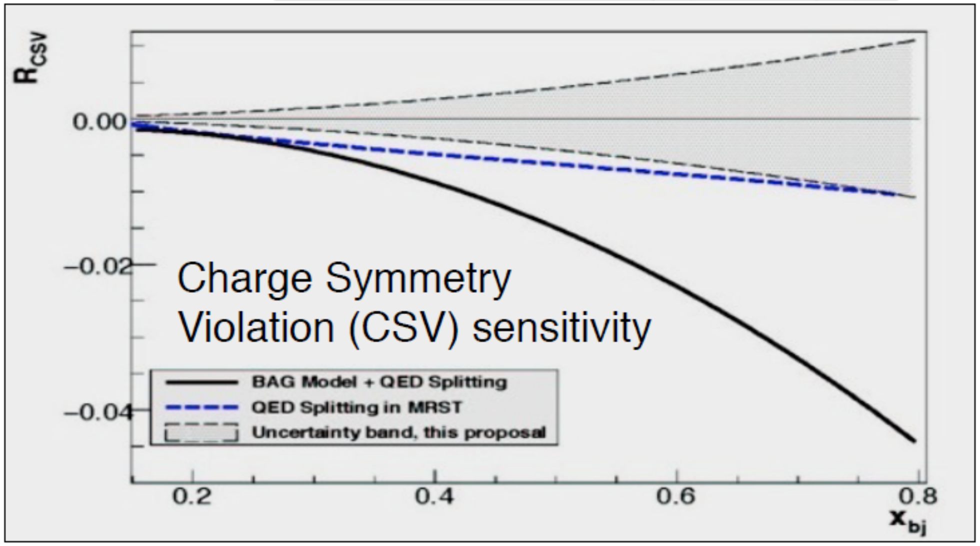
QCD Dynamics with Precision
LD_2 PVDIS

$$u^p(x) \stackrel{?}{=} d^n(x) \quad \Rightarrow \quad \delta u(x) \equiv u^p(x) - d^n(x)$$
$$d^p(x) \stackrel{?}{=} u^n(x) \quad \Rightarrow \quad \delta d(x) \equiv d^p(x) - u^n(x)$$

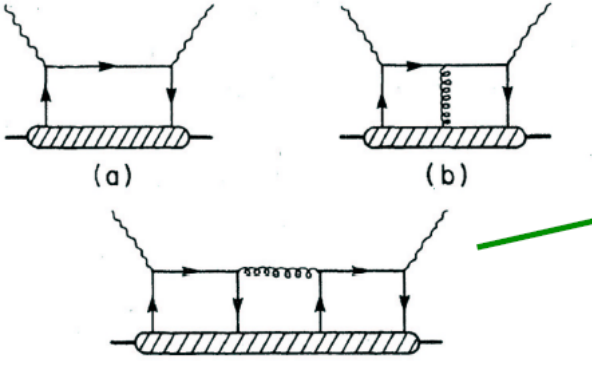
$$R_{CSV} = \frac{\delta A_{PV}}{A_{PV}} \approx 0.28 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

We already know some CSV effects:

- u-d mass difference $\delta m = m_d - m_u \approx 4$ MeV
  $\delta M = M_n - M_p \approx 1.3$ MeV
- electromagnetic effects



- Direct sensitivity to parton-level CSV
- Important implications for PDF's
- Could be partial explanation of the NuTeV anomaly



Castorina & Mulders, '84

$$\langle VV \rangle - \langle SS \rangle = \langle (V-S)(V+S) \rangle \propto l_{\mu\nu} \int \langle D \,|\, \overline{u}(x)\gamma^{\mu} u(x) \overline{d}(0) \gamma^{\nu} d(0) \rangle e^{iqx} d^4x$$

Zero in quark-parton model

Higher-Twist valence quark-quark correlation

(c) type diagram is the only operator that can contribute to a(x) higher twist: theoretically very interesting!

σ_L contributions cancel

Polarized Targets

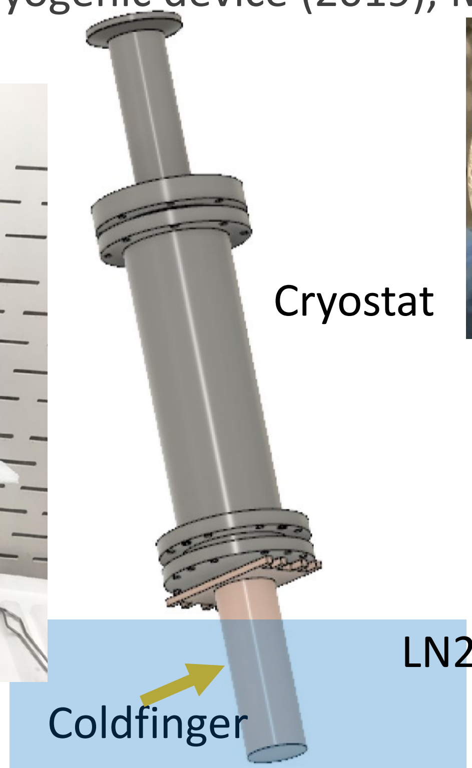
UNIVERSIDAD TECNICA
FEDERICO SANTA MARIA

News from UNH Polarized Target Lab

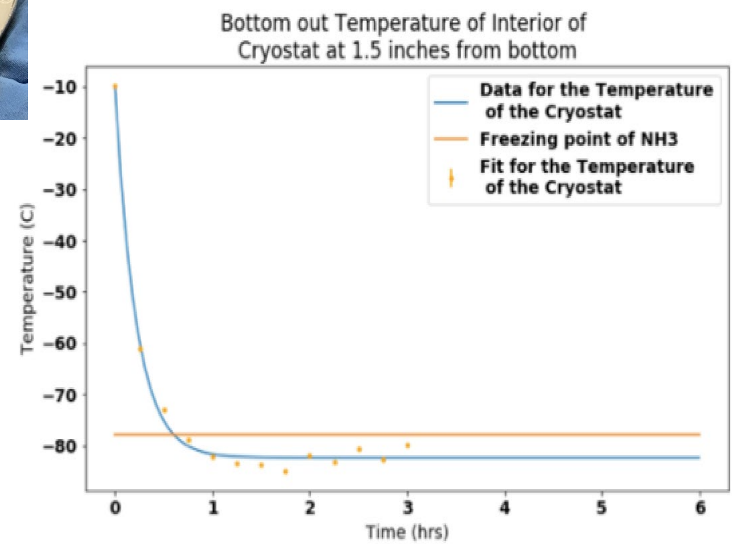
Slifer Lab

New ‘slow-freezing’ ammonia production technique: ‘Coldfinger’

- Aliaga, D. et al. Temperature-controlled crystal formation with a new prototype cryogenic device (2019), Manuscript in preparation.



Developed process to 3D print Kel-F (NIM A paper in prep.)

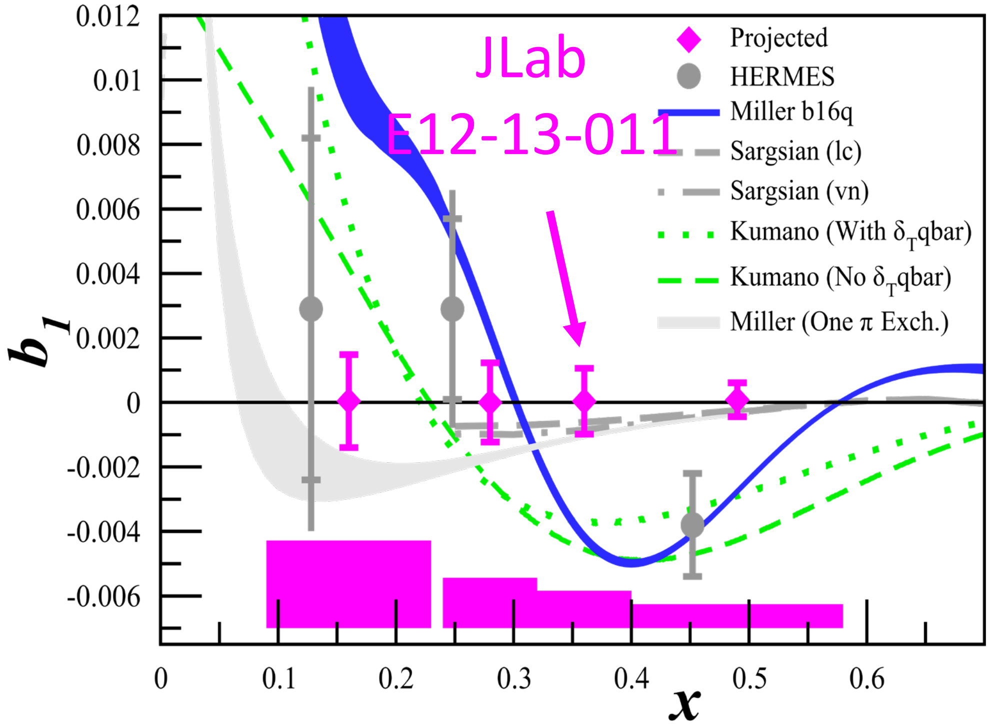


b_1 probes nuclear effects at quark resolution!

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

Tensor Structure Function, b_1

- All conventional **models predict small or vanishing values of b_1**
  - HERMES found something very different!
- Any measurement of $b_1 < 0$ indicates exotic physics



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

FE Close, S Kumano, PRD **42** 237

SK Taneja *et al*, PRD **86** 036008

G Miller, PRC **89** 045203

S Kumano, PRD **82** 017501 (2010)

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

K Slifer, *et al*, JLab C12-13-011

Many other polarized targets under development

- **Bonn, Jlab, INFN-Ferrara, COMPASS, LANL-Uva….**

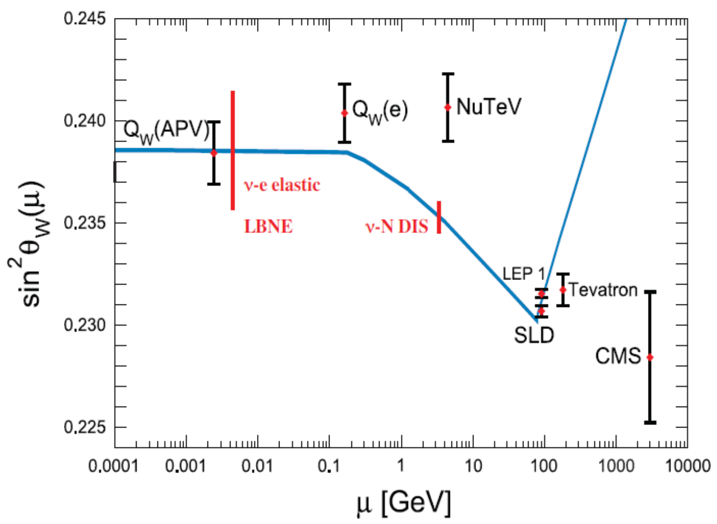
New Neutrino DIS Proposal

✦ *Novel technique to measure $\nu(\bar{\nu})$-Hydrogen by subtracting CH_2 and C targets*:

- *Exploit high vertex, angular & time resolutions of STT to locate interactions within targets;*
- *Model-independent data subtraction of dedicated C (graphite) target from main CH_2 target;*
- *Kinematic selection provides clean H samples of inclusive & exclusive CC topologies with 80-95% purity and >90% efficiency before subtraction.*

$\Longrightarrow$ *Viable and realistic alternative to liquid/gaseous H_2 detectors*

- **Much better statistics and understanding of flux**



Talk of R. Petti

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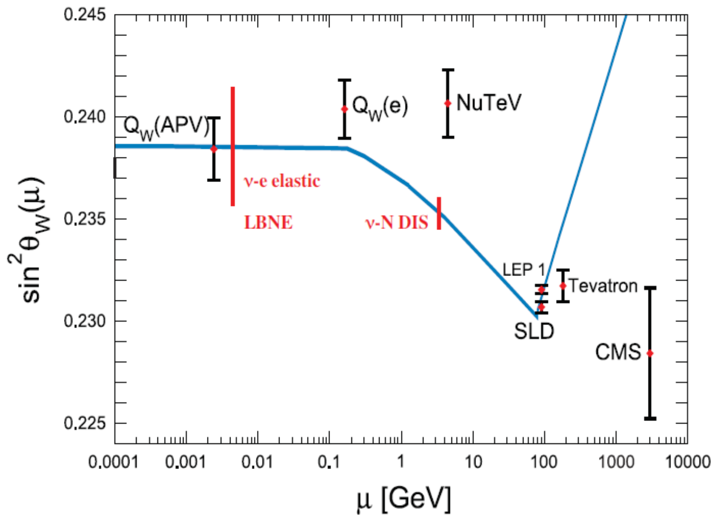
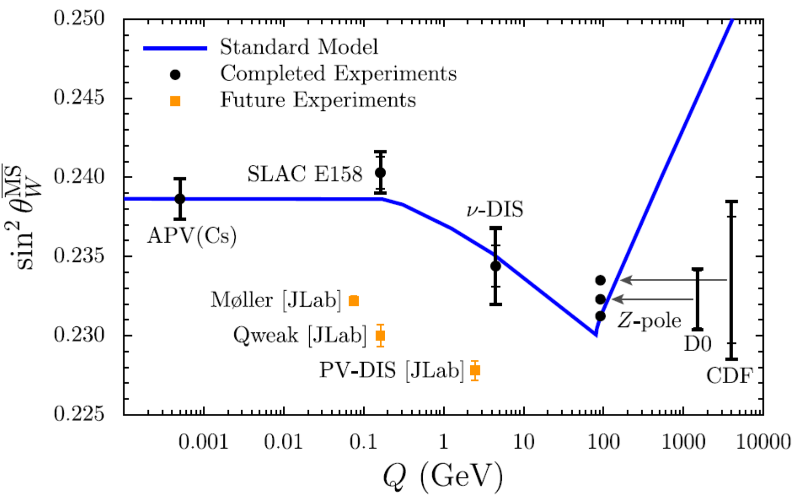
Cloët et al., Phys Lett B693 (2010) 462





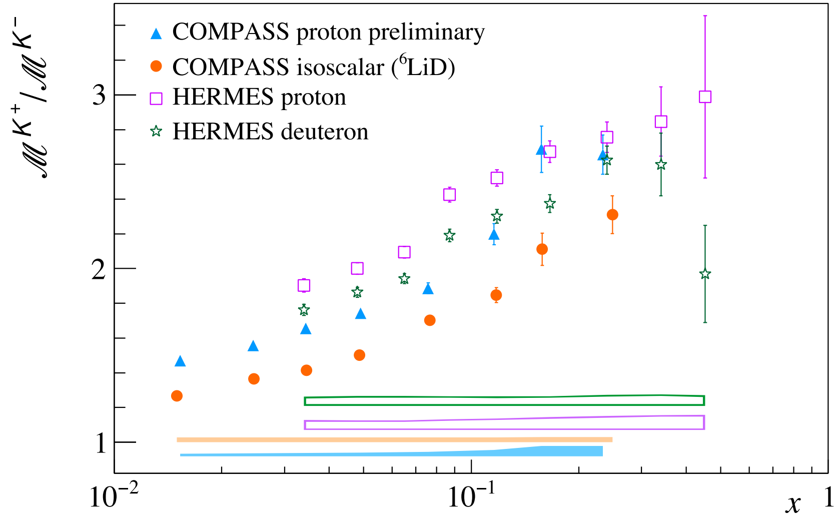
Talk of R. Petti

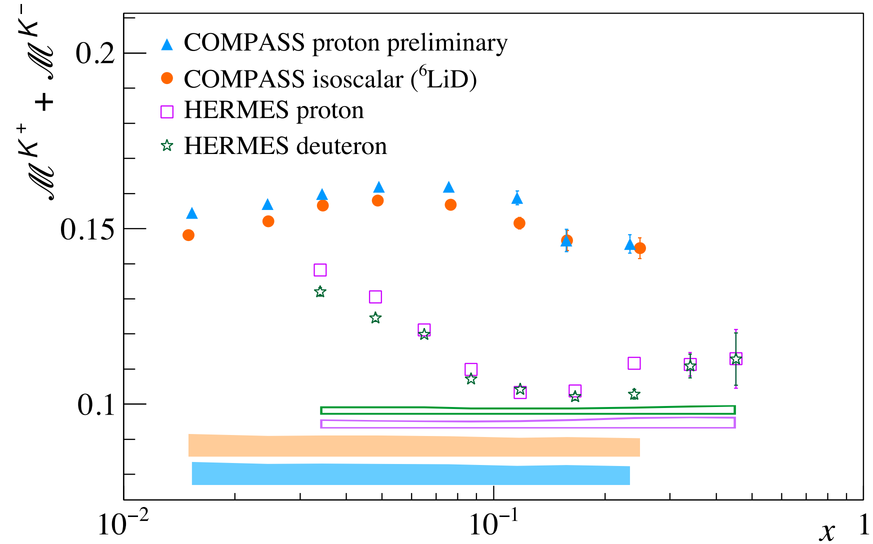
COMPASS

SIDIS multiplicities: kaons off the proton

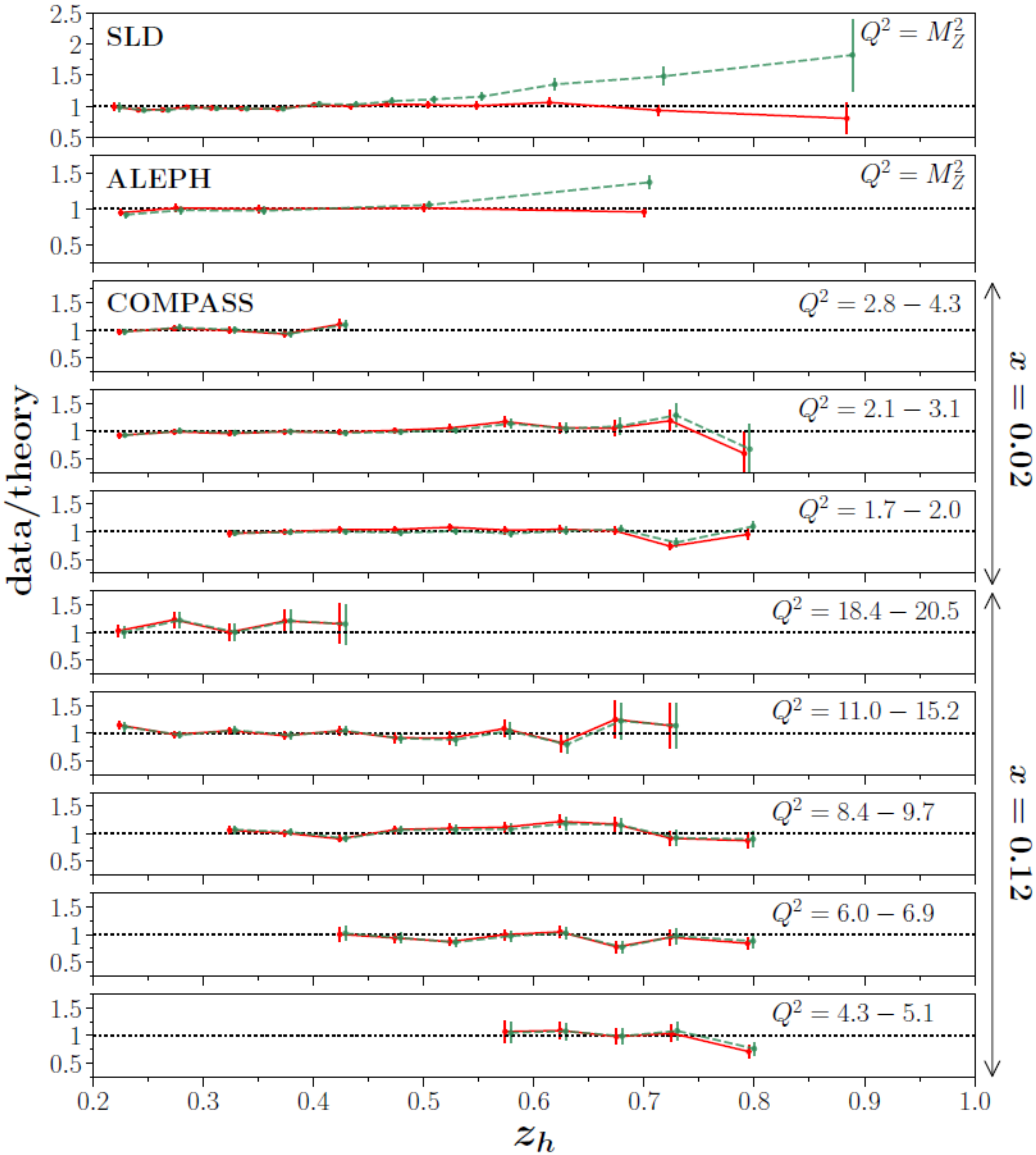
R_K of proton target
- analysis of 2016 data (l H_2 target) ongoing
- same bins as for the iso-scalar target data (integrating over z and averaging over y)
- R_K of the proton expected10-20% higher compared to the isoscalar case.

Important message: HERMES and COMPASS data are still in tension.
Can not be explained only by different Q^2 range, the discussion is going on.

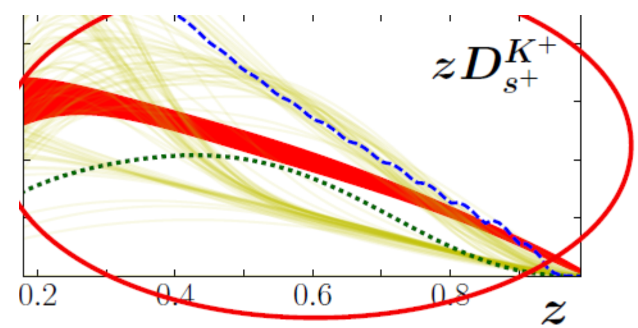




JAM 2019 analysis



← SIA data at large z strongly disfavor small strange to K FF



A NQF@M2 beam line of the SPS CERN
COMPASS++/AMBER Letter of Intent

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-SPSC-2019–003
SPSC-I-250
January 25, 2019

http://arxiv.org/abs/1808.00848

Apparatus for Meson and Baryon Experimental Research

Letter of Intent:

A New QCD facility at the M2 beam line of the CERN SPS*

COMPASS++†/AMBER‡

B. Adams[13,12], C.A. Aidala[1], R. Akhunzyanov[14], G.D. Alexeev[14], M.G. Alexeev[41], A. Amoroso[41,42],

COMPASS++/AMBER
the full “LoI” programme

Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware additions
muon-proton elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^\pm$	high-pressure H2	2022 2 years	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	10	$\mu^\pm$	$NH_3^\uparrow$	2022 2 years	recoil silicon, modified polarised target magnet
Input for Dark Matter Search	$\overline{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	liquid helium target
$\overline{p}$-induced spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\overline{p}$	LH2	2022 2 years	target spectrometer: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^\pm$	C/W	2022 1-2 years	
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	$\sim$100	10^8	25-50	$K^\pm$, $\overline{p}$	$NH_3^\uparrow$, C/W	2026 2-3 years	”active absorber”, vertex detector
Primakoff (RF)	Kaon polarisa-bility & pion life time	$\sim$100	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^\pm$ $\pi^\pm$	LH2, Ni	non-exclusive 2026 1-2 years	hodoscope
K-induced Spectroscopy (RF)	High-precision strange-meson spectrum	50-100	$5 \cdot 10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^\pm, \pi^\pm$	from H to Pb	2026 1 year	

Plan for new Drell-Yan measurments with π^+ and π^- beams at COMPASS

(using solid carbon and W targets)

Beam type (GeV)	Beam intensity (part/sec)	Target type	DY mass (GeV/c^2)	DY events
π^+ 190	1.7×10^7	100cm C	4.3 – 8.5	23000
			3.8 – 4.3	14000
			2.0 – 3.8	133000
π^- 190	6.8×10^7	100cm C	4.3 – 8.5	22000
			3.8 – 4.3	12000
			2.0 – 3.8	127000
π^+ 190	0.2×10^7	24cm W	4.3 – 8.5	7000
			3.8 – 4.3	4000
			2.0 – 3.8	40000
π^- 190	1.0×10^7	24cm W	4.3 – 8.5	6000
			3.8 – 4.3	3000
			2.0 – 3.8	39000

- This would represent a major increase for DY data with π^+ beam
- Intense kaon beams with RF-separator are also been actively considered

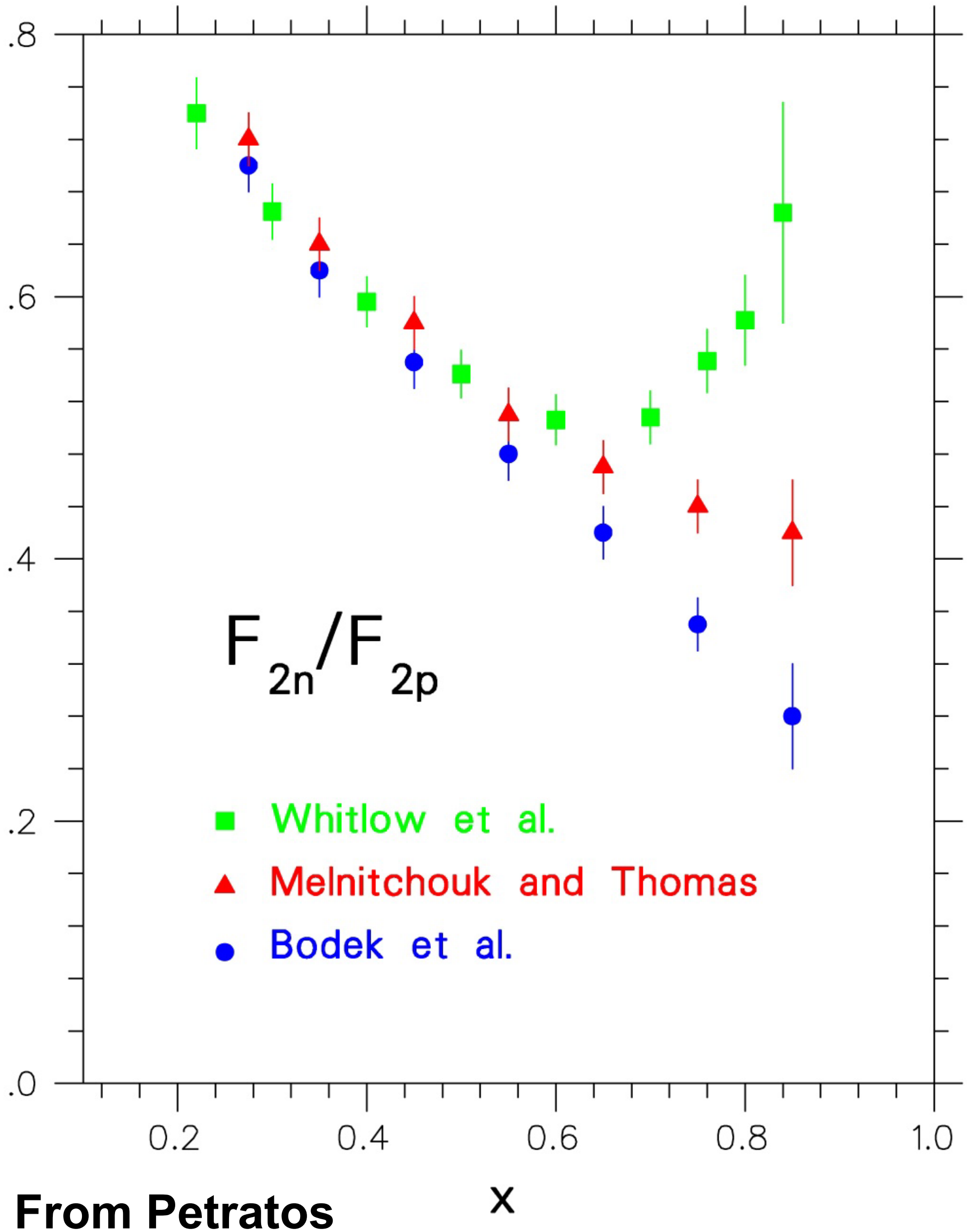
From J-C Peng

Nucleon PDFs

d/u ratio

- Fundamental to understanding non-perturbative dynamics within the nucleon – di-quarks, correlations etc….
- Many talks: Christy (BoNUS), Hauenstein, Kumar (SoLID), Malace, Melnitchouk, Nicolescu (duality), Petratos (Marathon)

Nucleon F_2 Ratio Extraction Revisited



From Petratos

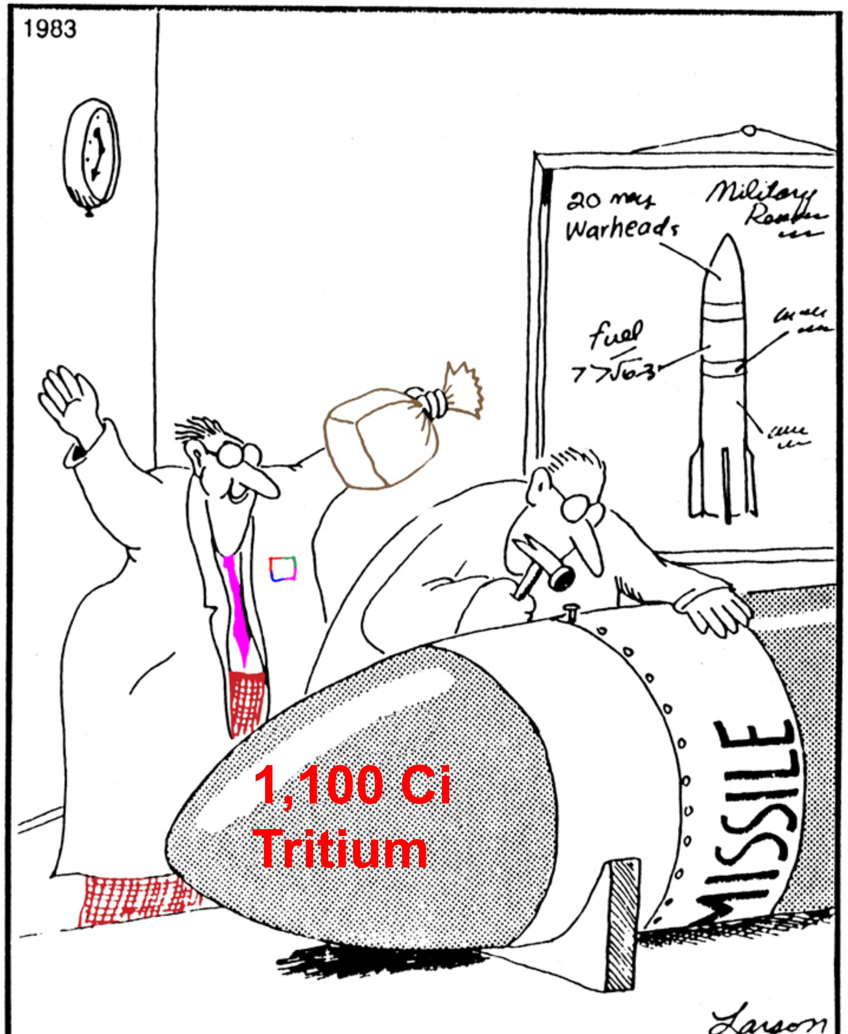
SLAC DIS Data

Whitlow (1992): Assumes EMC effect in deuteron (Frankfurt and Strikman data-based Density Model)

Melnitchouk &Thomas (1996): Relativistic convolution model with empirical binding effects

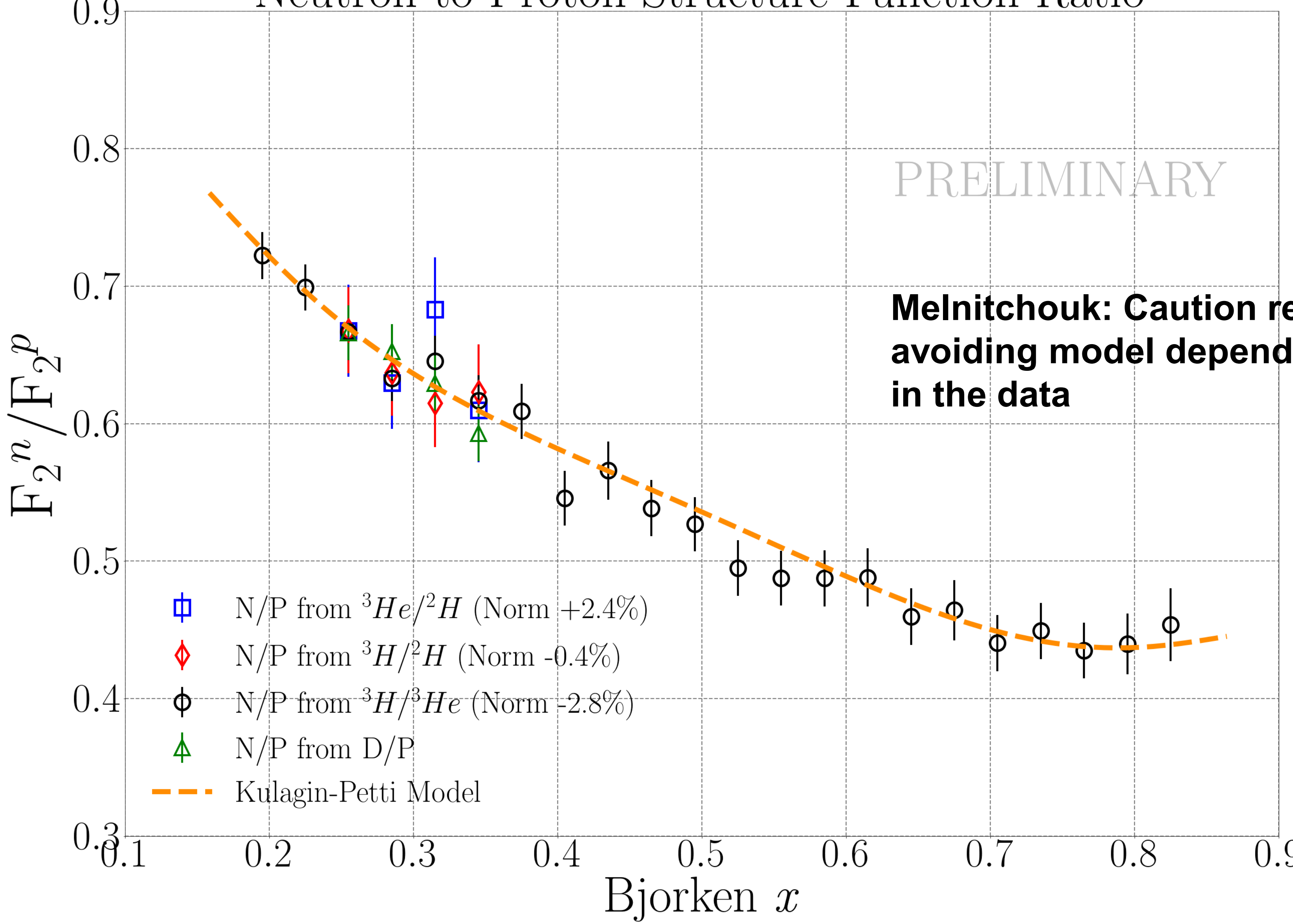
Bodek (1992): Non-relativistic Fermi smearing model with Paris N-N potential. Note: at large *x* there is significant dependence on the N-N potential used (Paris, Bonn, Argonne, etc.)

The 3H, 2H, 1H, 3He High Pressure Gas Cells Target Ladder Structure

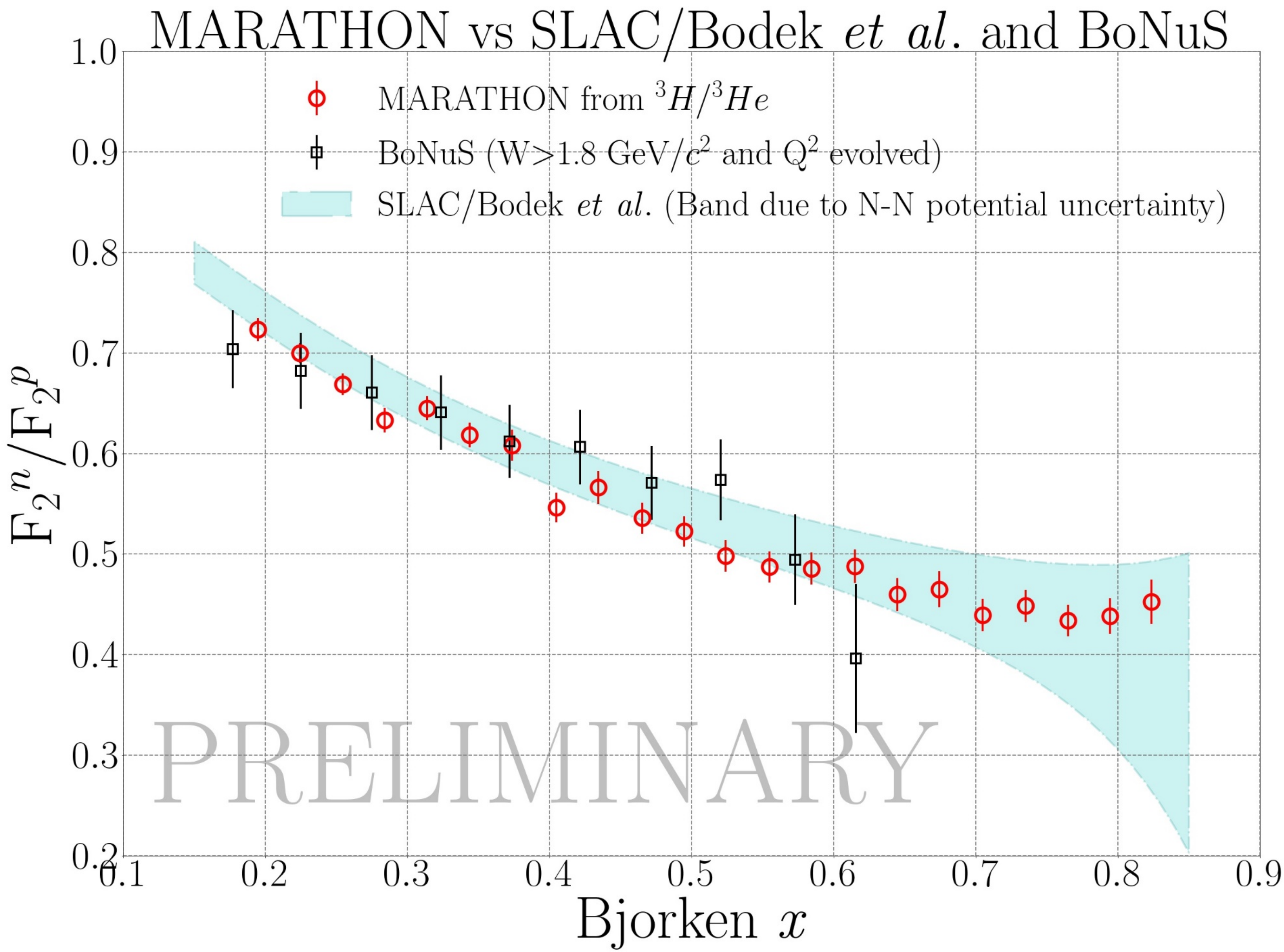


Tritium cell was filled at the Tritium Handling Facility of Savannah River National Laboratory (1,100 Curies).

Neutron to Proton Structure Function Ratio

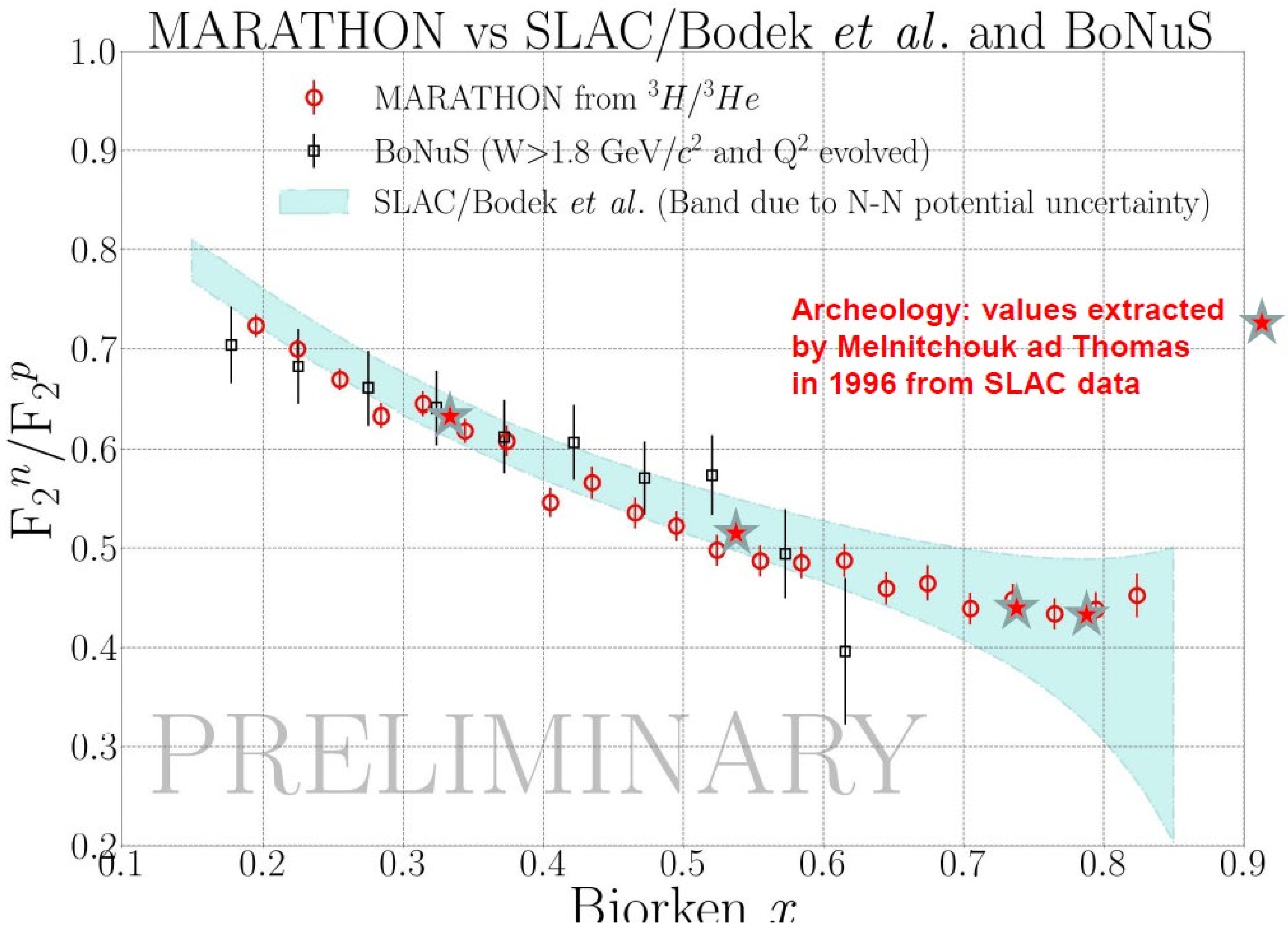


Melnitchouk: Caution re avoiding model dependence in the data



MARATHON vs SLAC/Bodek et al. and BoNuS
MARATHON from $^3H/^3He$
BoNuS (W>1.8 GeV/c^2 and Q^2 evolved)
SLAC/Bodek et al. (Band due to N-N potential uncertainty)
F_2^n/F_2^p
Bjorken x
PRELIMINARY
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

A little fun ….



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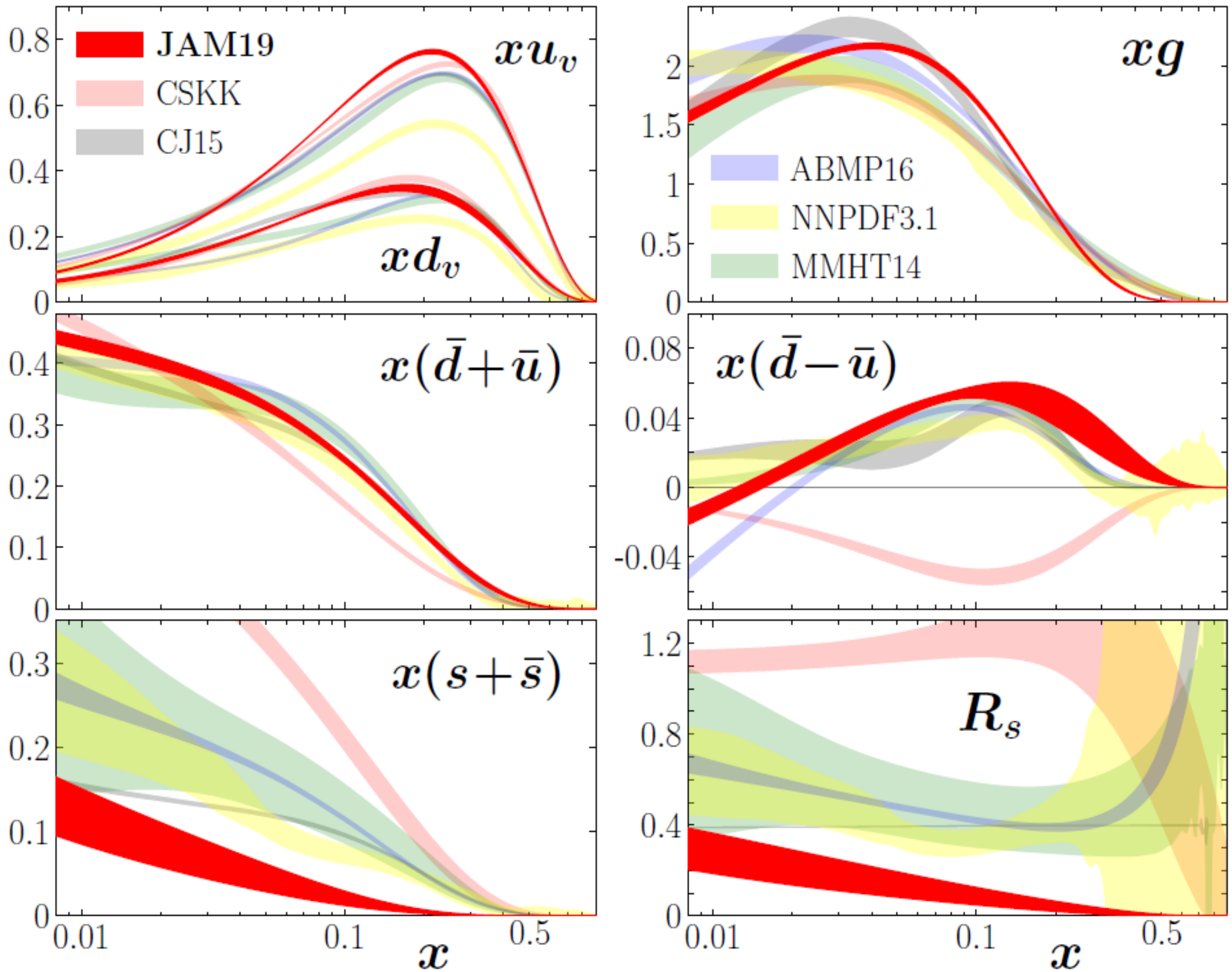
Sea quarks

JAM 2019 analysis



First simultaneous analysis of DIS plus SIDIS

mean reduced $\chi^2 = 1.3$ for all data

Sato, Andres, Ethier, WM (2019)

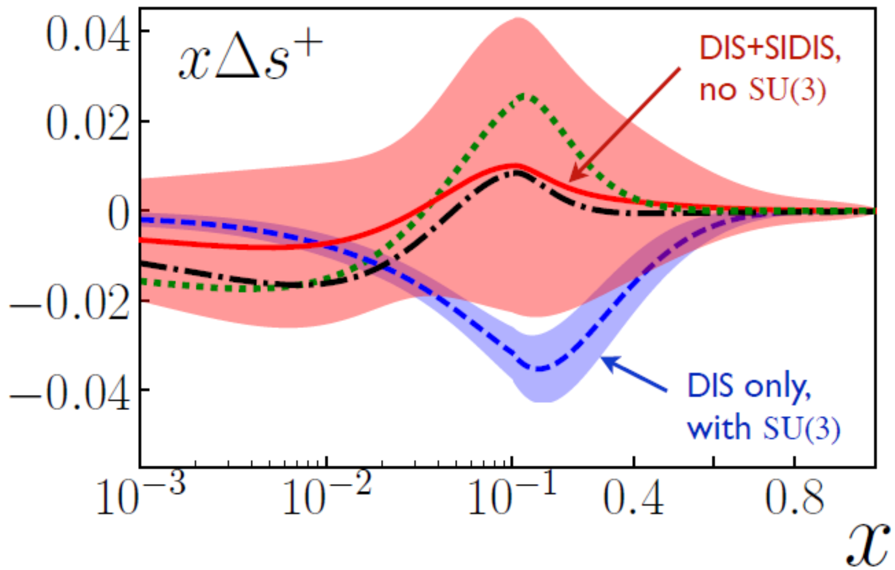
→ valence & light sea quark broadly in agreement with other groups

→ striking suppression of strange PDF compared to ATLAS extraction

Polarized Structure Functions

Simultaneous spin PDF + FF analysis

- Polarized strangeness in previous, DIS-only analyses was negative at $x \sim 0.1$, induced by $\mathrm{SU(3)}$ and parametrization bias



Ethier, Sato, WM (2017)

→ weak sensitivity to Δs^+ from DIS data & evolution

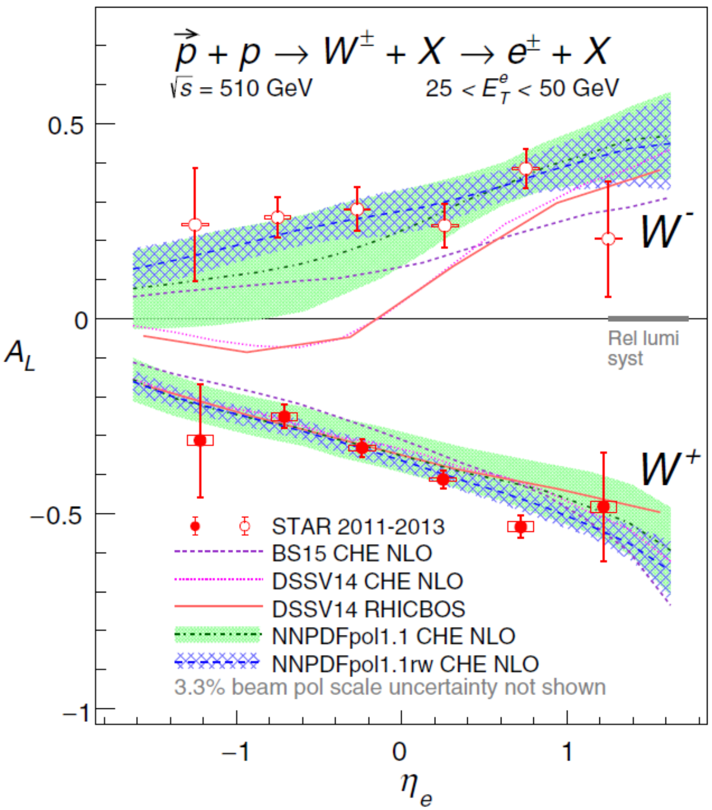
— $\mathrm{SU(3)}$ pulls Δs^+ to generate moment ~ -0.1

— negative peak at $x \sim 0.1$ induced by fixing $b \sim 6 - 8$

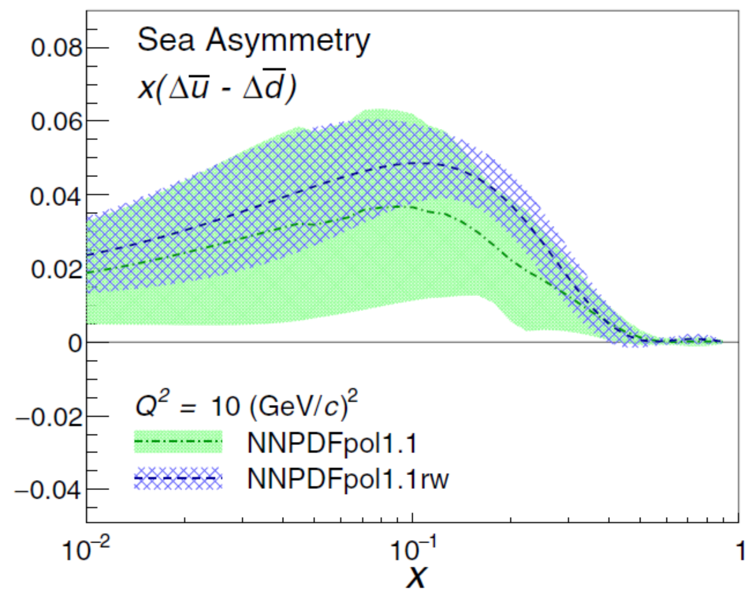
JAM analysis

Talk of C. Kim: Phenix

2. Nucleon helicity – a. $\Delta\bar{q}$ STAR, W A_L (2011-2013)



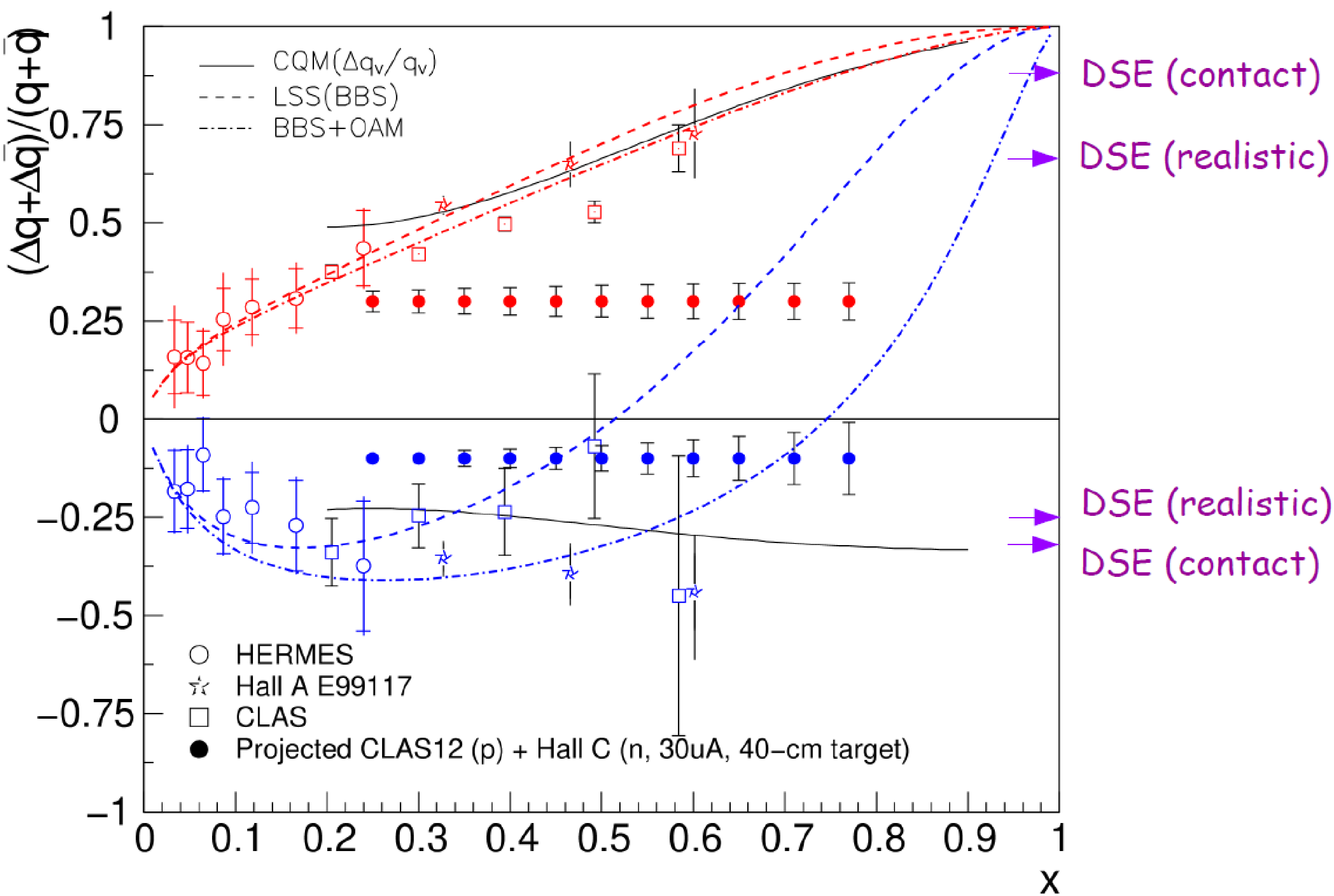
PRD99, 051102 (2019)



- **W → e A_L, $|\eta| < 1.3$**
  - Int. L = 86 (2011-2012) + 250 (2013) pb^{-1}
  - Signal extraction by $e^{\pm}$ isolation + missing energy detection + Jacobian peak
  - $0.05 < x < 0.25$
  - Sizable positive $\Delta\bar{u}$ / negative $\Delta\bar{d}$ observed
  - Clear flavor asymmetry ($\Delta\bar{u} - \Delta\bar{d}$)

Delta ubar > Delta dbar predicted in bag model then χSM in early 90's

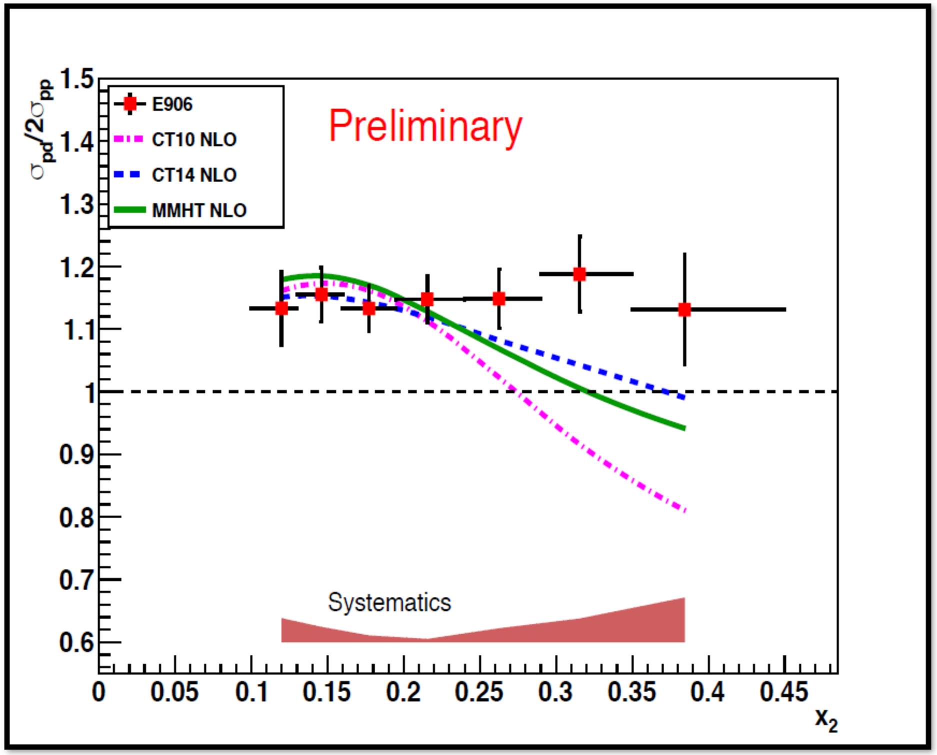
Extracting Δq/q from both proton and neutron (^{3}He) data



Extraction of Excess of dbar over ubar: SeaQuest E906

Some Results: The Cross Section Ratio

- D/H ratio, vs. PDF fits
- This result released - sea quark ratio extraction is not



$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{(x_{beam} >> x_{targ})} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_{targ})}{\bar{u}(x_{targ})}\right]$$

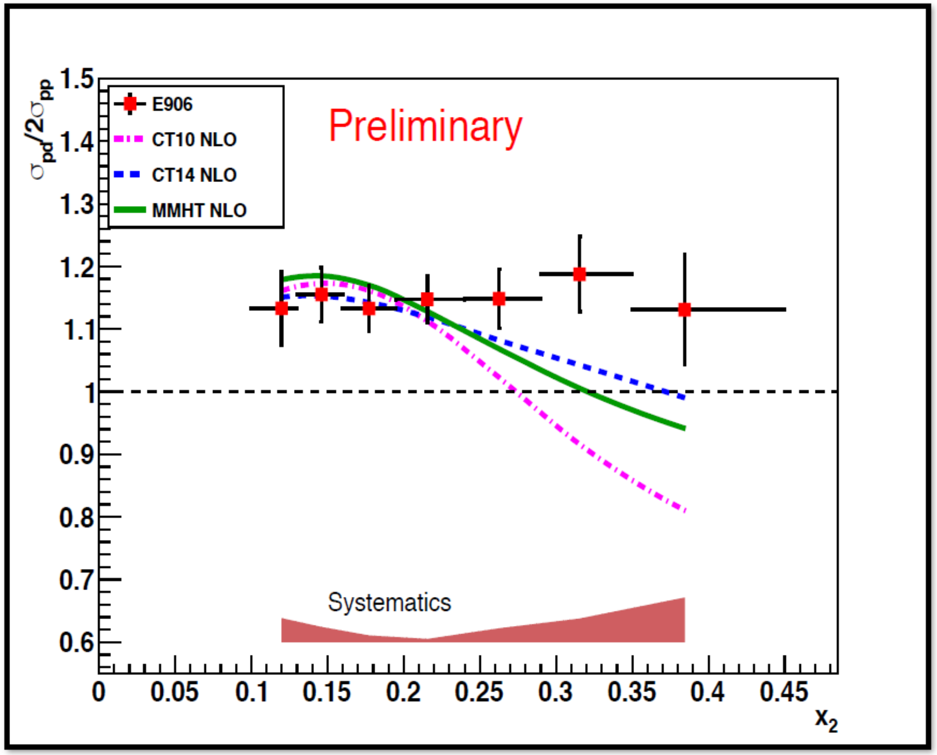
Talk of R. Gilman

Extraction of Excess of dbar over ubar:

SeaQuest E906

Some Results: The Cross Section Ratio

- D/H ratio, vs. PDF fits
- This result released - sea quark ratio extraction is not



Gotcha!

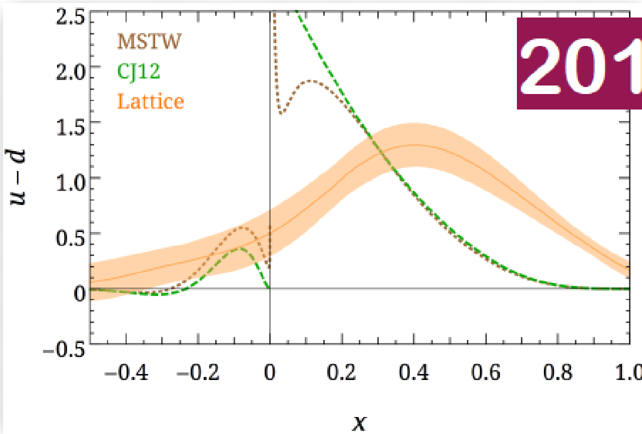
$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{(x_{beam}>>x_{targ})} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_{targ})}{\bar{u}(x_{targ})}\right]$$

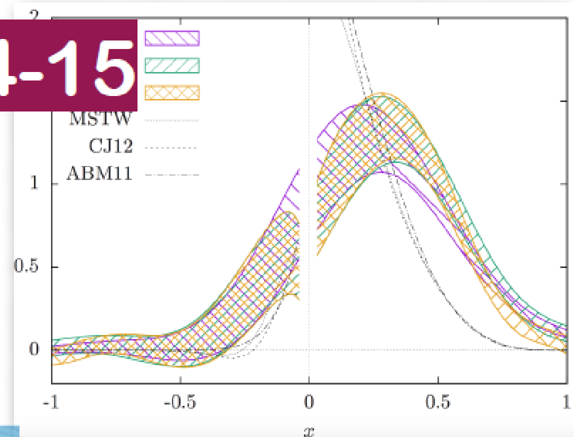
Gilman

Theory: Quasi-PDFs

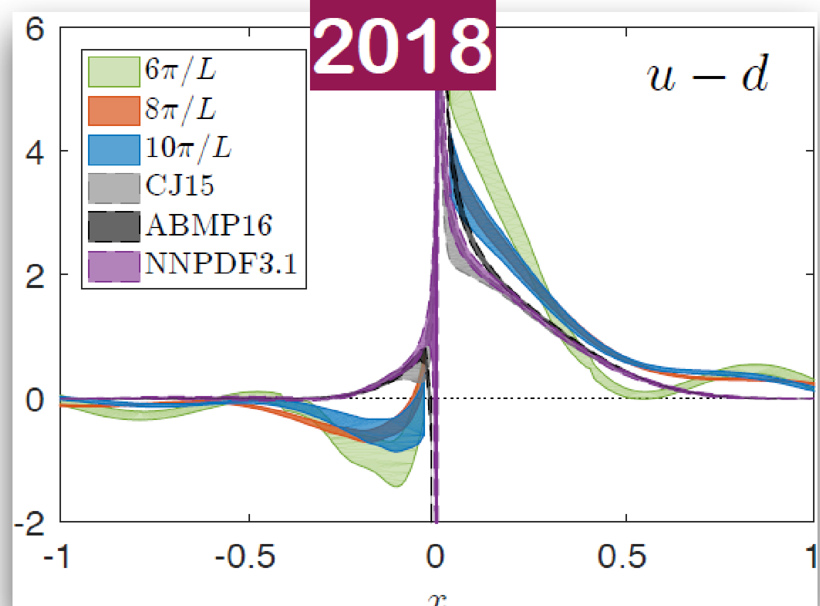
Lattice studies of quasi-PDFs

2014-15





2018



Progress due to:

- ★ Simulations at physical point
- ★ Renormalization
- ★ Matching

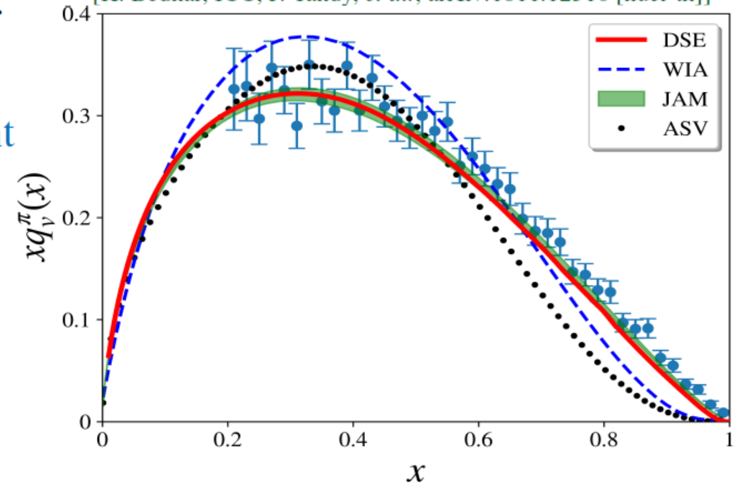
C. Alexandrou, K. Cichy, M. Constantinou, K. Jansen, A. Scapellato, F. Steffens, PRL 121 (2018) 112001, [arXiv:1803.02685]

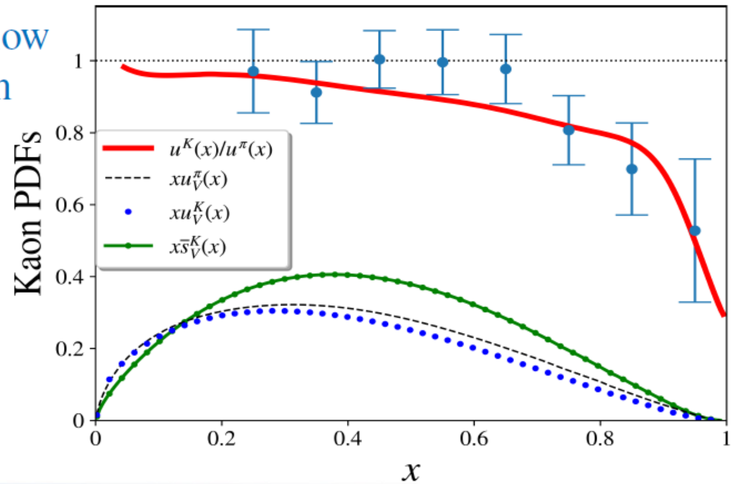
Pion Structure – DSE and Drell-Yan

Self-Consistent DSE Results

- For pion and kaon PDFs included for first time gluons self-consistently
  - correct RL-DSE pion PDFs in excellent agreement with Conway *et al.* data and recent JAM analysis
  - agrees with $x \to 1$ pQCD prediction
- Treating non-perturbative gluon contributions correctly pushes support of $q_\pi(x)$ to larger x
  - gluons remove strength from $q_\pi(x)$ at low to intermediate x – baryon number then demands increased support at large x
  - cannot be replicated by DGLAP – DSE splitting functions are dressed
- *Immediate consequence of gluon dressing is that gluons carry 35% of pion's and 30% of kaon's momentum*

[K. Bednar, ICC, P. Tandy, *et al.*, arXiv:1811.12310 [nucl-th]]





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From talk of I. Cloët

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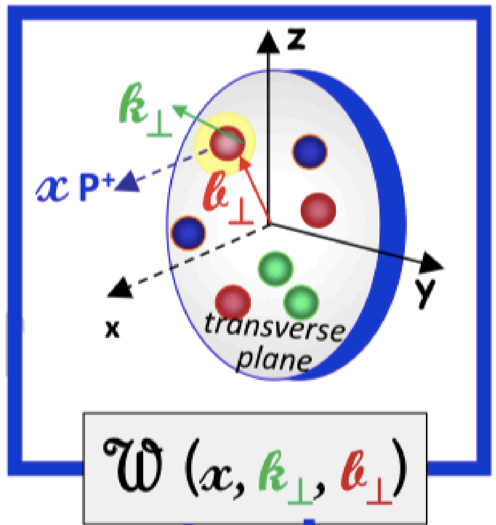
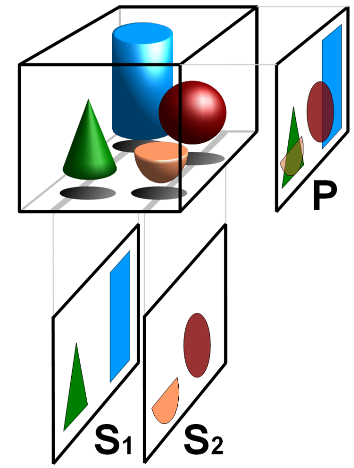
A Three-dimensional Picture of the Nucleon

Toward a more complete description of the nucleon



Quantum tomography of the nucleon

Ji, PRL91 (2003)
Belitsky, Ji, Yuan, PRD69 (200
Lorcé et al, JHEP1105 (2011)



$\int db_\perp$ $\int dk_\perp$

Transverse momentum

f $(x, k_\perp)$
8 TMDs

accessible
in SIDIS *and* Drell-Yan

$\int dk_\perp$

Transverse position

q $(x, b_\perp)$
8 GPDs

$\int dx$ → **Form Factors**

$\int db_\perp$

PDFs (x)

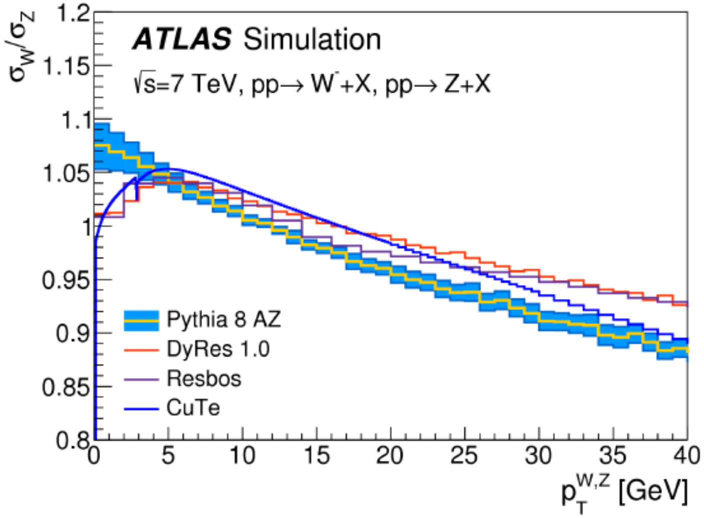
DVMP: Deeply Virtual Meson Production
DVCS: Deeply Virtual Compton Scattering
HEMP: Hard Exclusive Meson Production

Slide from N. d'Hose, APS-April meeting 2019.

GPDs and TMDs

PREDICTIONS THAT REQUIRE TMDS

from A. Apyan's talk at LHC EW Precision sub-group workshop
https://indico.cern.ch/event/801961/



also
ResBos2
Radish
SCETlib
...

There is an entire industry of tools that make predictions for observables that involve TMDs. Most of them neglect important effects (especially at low p_T) coming from nonperturbative TMD components.

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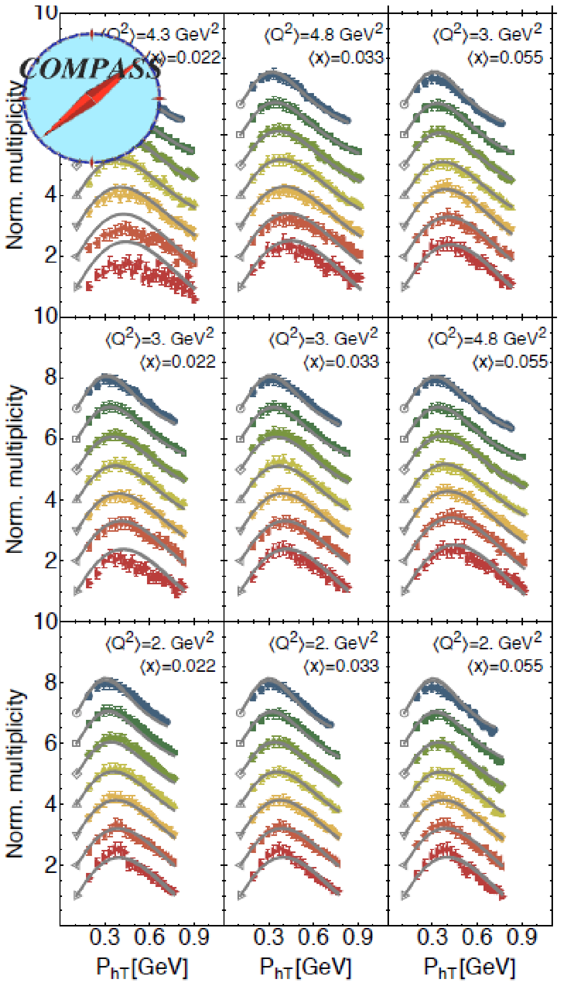
From talk of A. Bacchetta

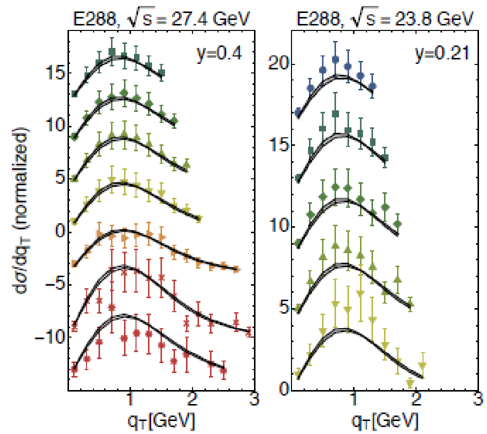
FIRST TMD GLOBAL FIT

SIDIS

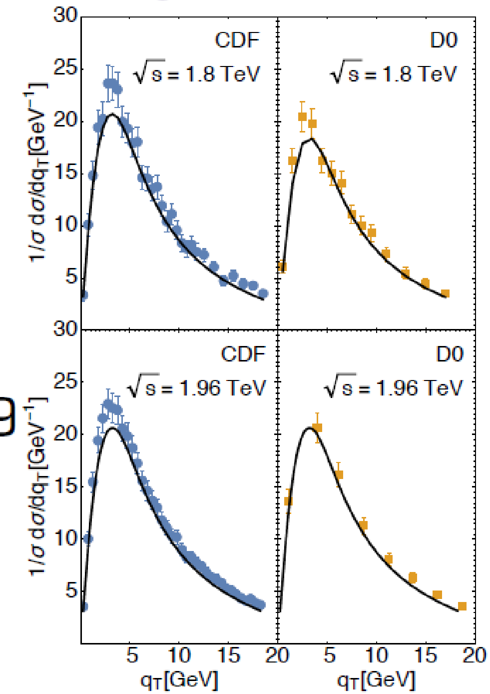


Drell-Yan

Fermilab



Z production

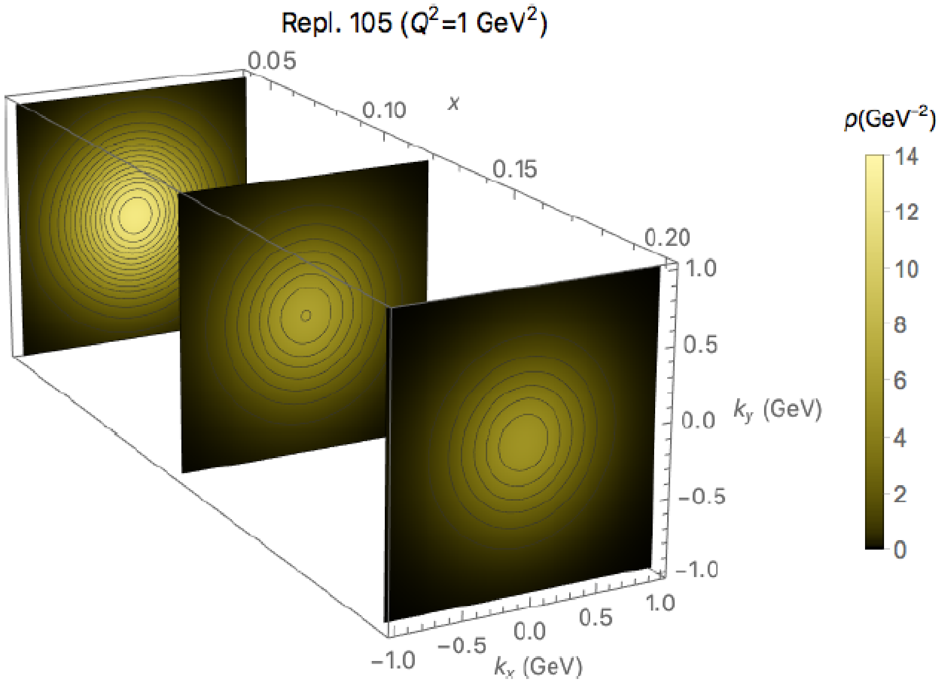


Number of data points: 8059

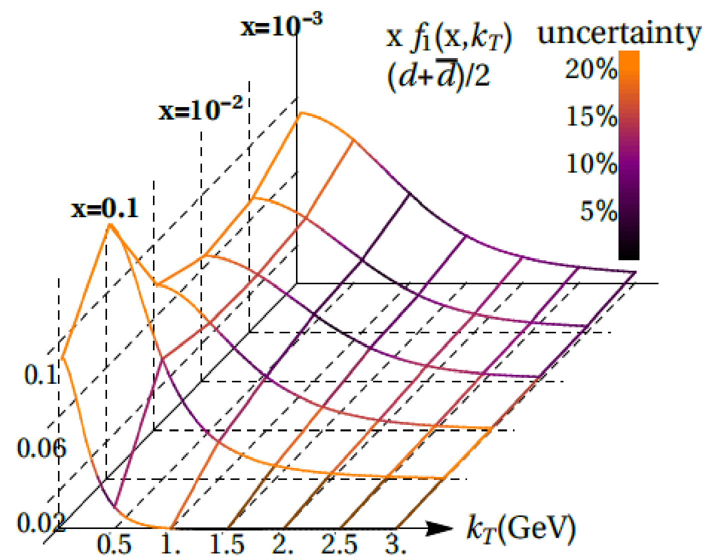
Global $\chi^2/\mathrm{dof} = 1.55$

Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

3D DISTRIBUTIONS EXTRACTED FROM DATA



Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157



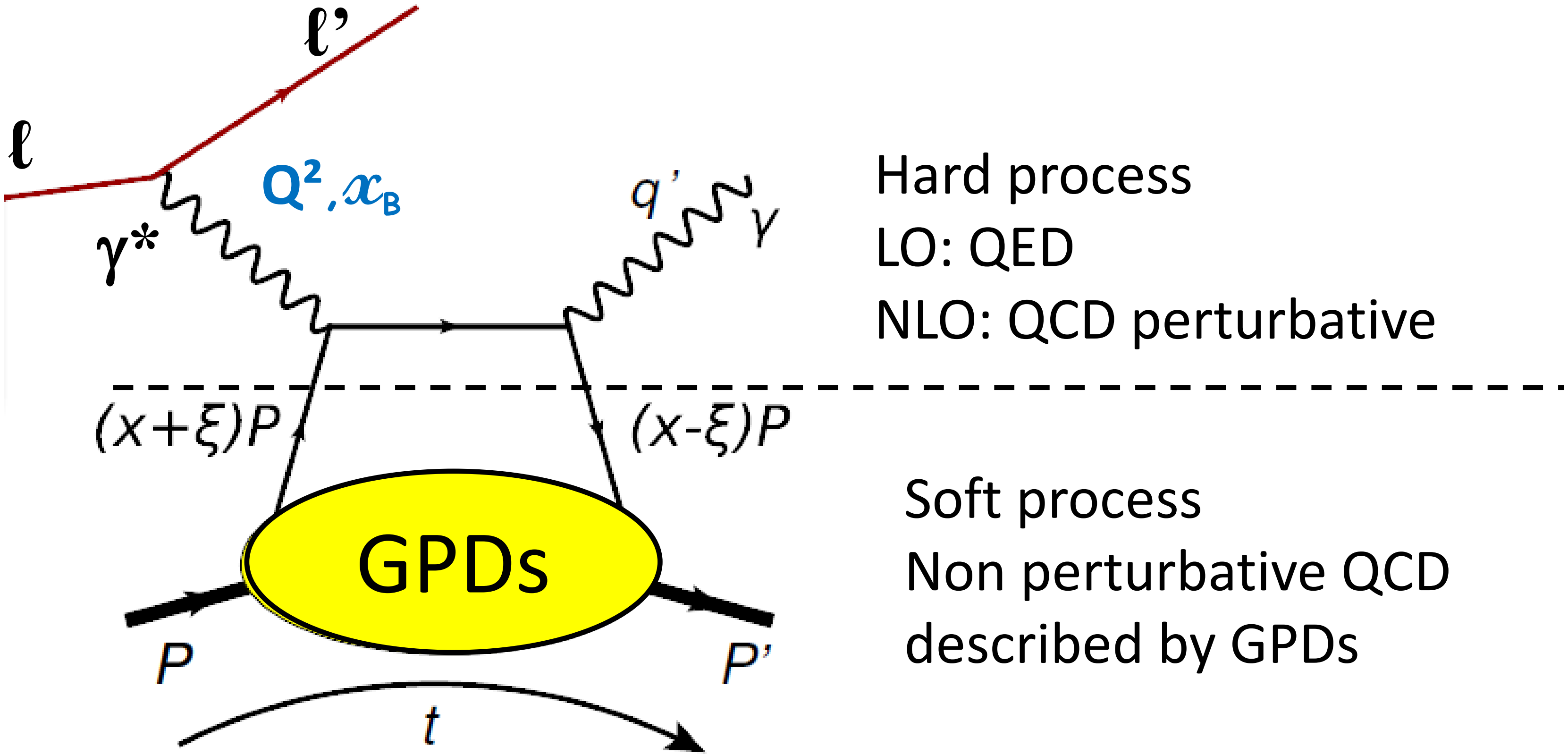
Bertone, Scimemi, Vladimirov, arXiv:1902.08474

GPDs and factorization

D. Mueller *et al*, Fortsch. Phys. 42 (1994)
X.D. Ji, PRL 78 (1997), PRD 55 (1997)
A. V. Radyushkin, PLB 385 (1996), PRD 56 (1997)

- Talk of J. Roche

In the Bjorken limit: $\left.\begin{array}{rcl} Q^2 = -q^2 & \rightarrow & \infty \\ \nu & \rightarrow & \infty \end{array}\right\} \quad x_B = \frac{Q^2}{2M\nu} \quad \text{fixed}$



Hard process
LO: QED
NLO: QCD perturbative

Soft process
Non perturbative QCD
described by GPDs

The minimal Q^2 at which the factorization holds **must be tested** and established by **experiments**

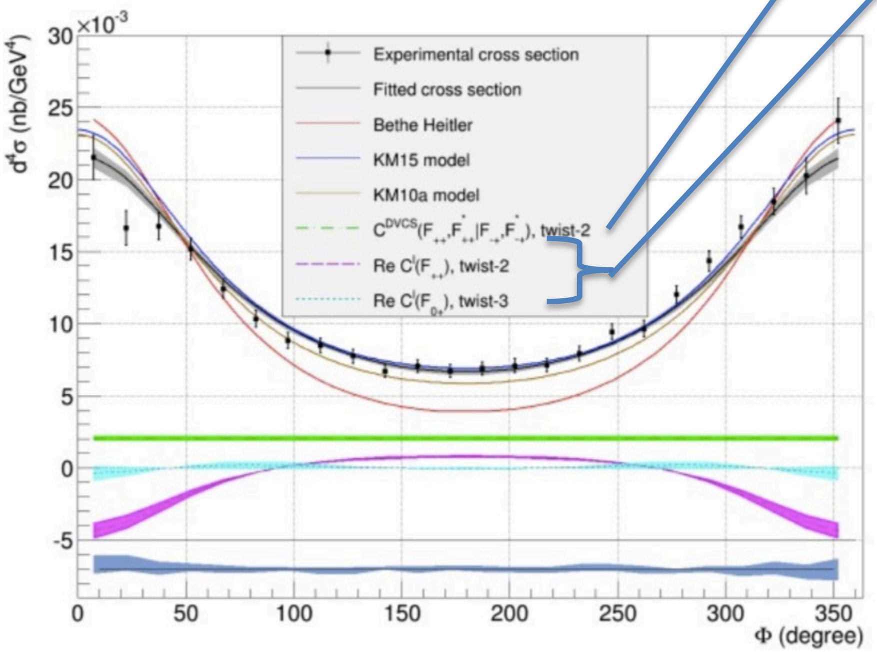
DVCS Hall A@Jlab12 3rd generation

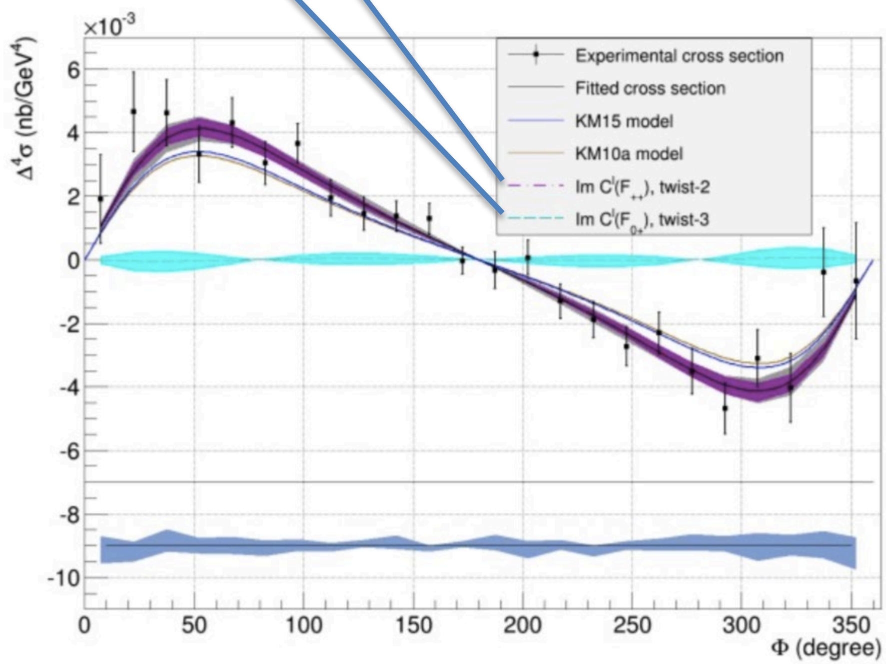
Among the first experiments to take data at Jlab 12

50% of the proposed data were taken

$$
\begin{aligned}
d\sigma^{BH} &\propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi \\
d\sigma^{DVCS}_{unpol} &\propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi \\
d\sigma^{DVCS}_{pol} &\propto s_1^{DVCS}\sin\phi \\
\mathrm{Re}\, I &\propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi \\
\mathrm{Im}\, I &\propto s_1^I\sin\phi + s_2^I\sin 2\phi
\end{aligned}
$$

HT NLO LT/LO





Talk of J. Roche

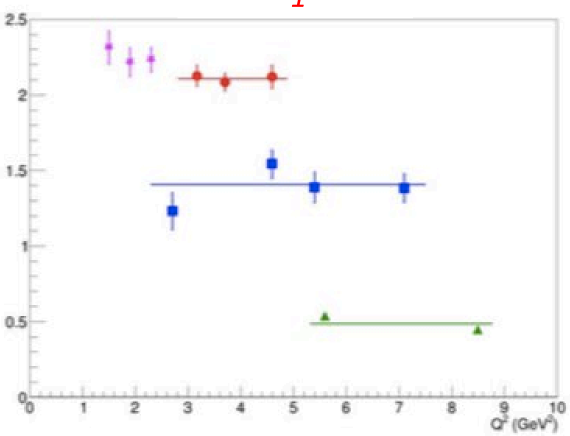
E=8.5, Q^2 = 3.6, x_B=0.36, $t - t_{min}$ [-0.186, -0.124]

DVCS Hall A@Jlab 3rd generation (12 GeV data)

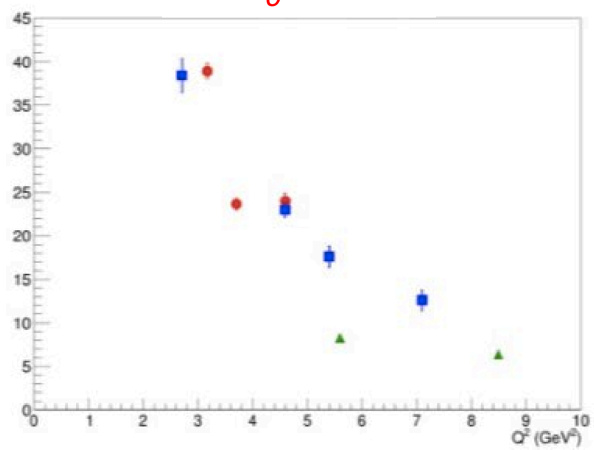
Analysis by F. Georges, INP Orsay

$$
\begin{aligned}
d\sigma^{BH} &\propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi \\
d\sigma^{DVCS}_{unpol} &\propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi \\
d\sigma^{DVCS}_{pol} &\propto s_1^{DVCS}\sin\phi \\
\mathrm{Re}\, I &\propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi \\
\mathrm{Im}\, I &\propto s_1^I\sin\phi + s_2^I\sin 2\phi
\end{aligned}
$$

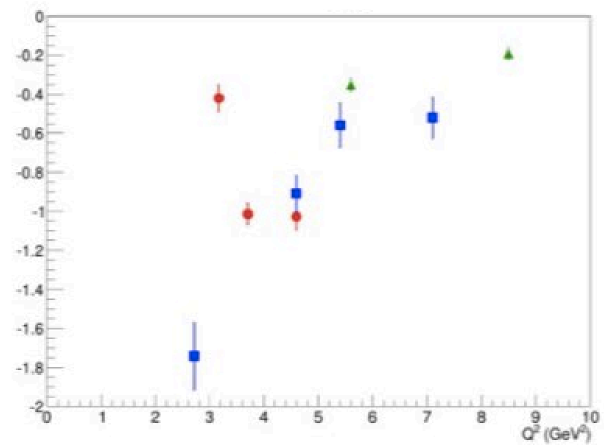
$S_1{}^I$



$C_0{}^{DVCS}$



$C_1{}^I$



$X_B = 0.36$, $<t> = -0.35$ | $X_B = 0.60$, $<t> = -1.06$

$X_B = 0.48$, $<t> = -0.47$ | $X_B = 0.36$, $<t> = -0.27$

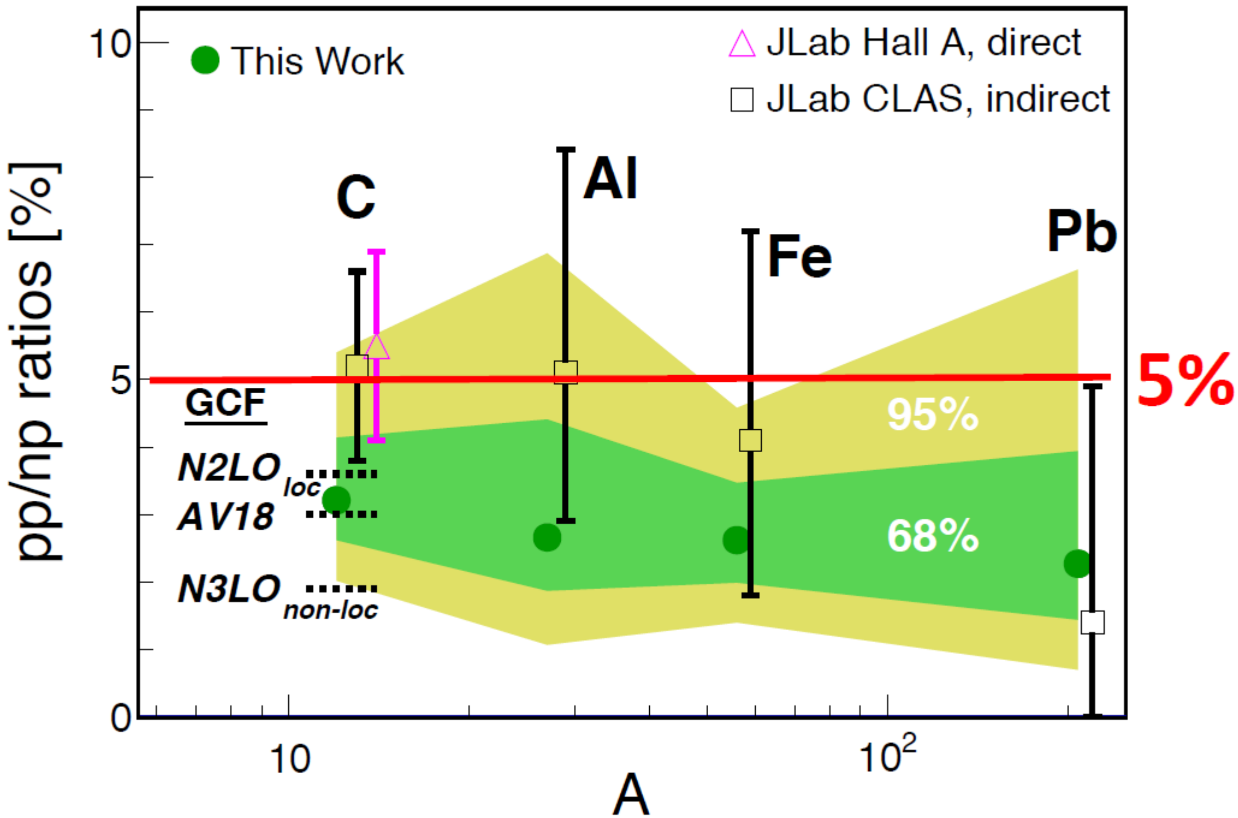
In depth study of trigger efficiency delayed the publication:
Could not resolve a 5% systematic inefficiency.

Nuclei

- **SRC and tensor force**
- **EMC effect**
- **x>1**
- **PDF analysis (not discussed – c.f. I. Schienbein)**

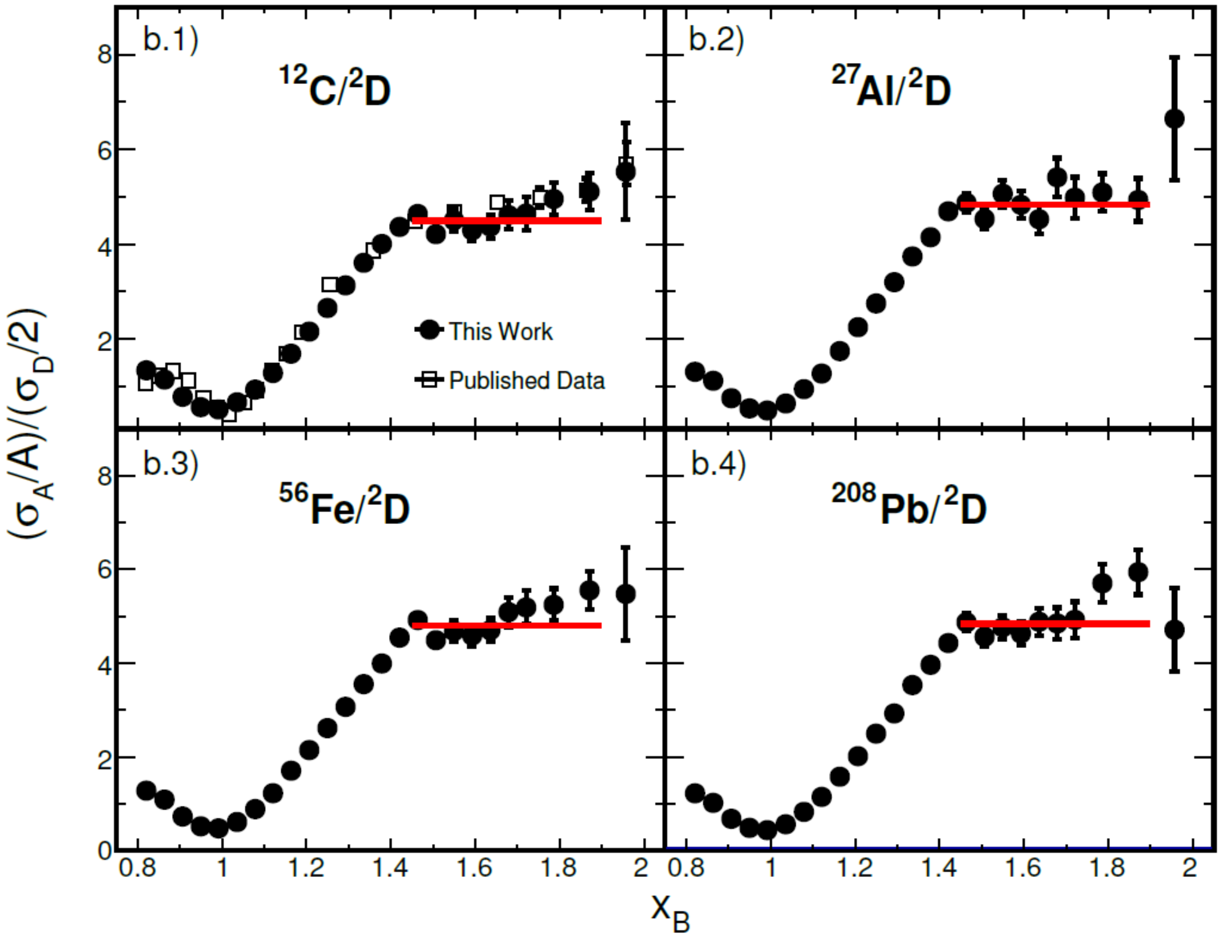
Role of Tensor Force in SRC – Talk of O. Hen

- **Established in beautiful series of experiments at Jlab**
- **Resolves a decades old dispute – with Arima's group as the winner**



x>1: New CLAS results

B. Schmookler *et al.*, Nature **566** (2019) 354-358.

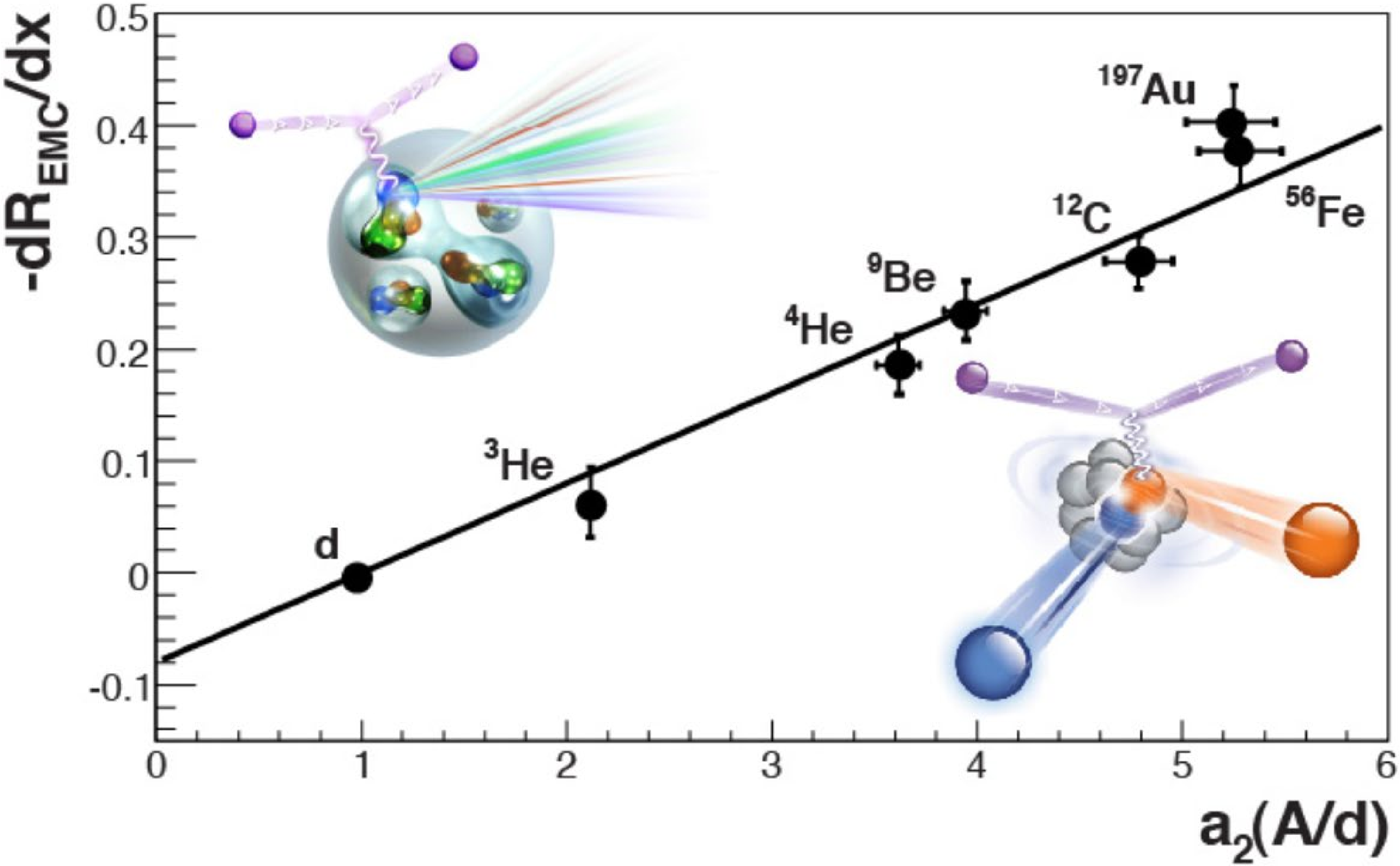


HiX 2019

From talk of D. Higinbotham

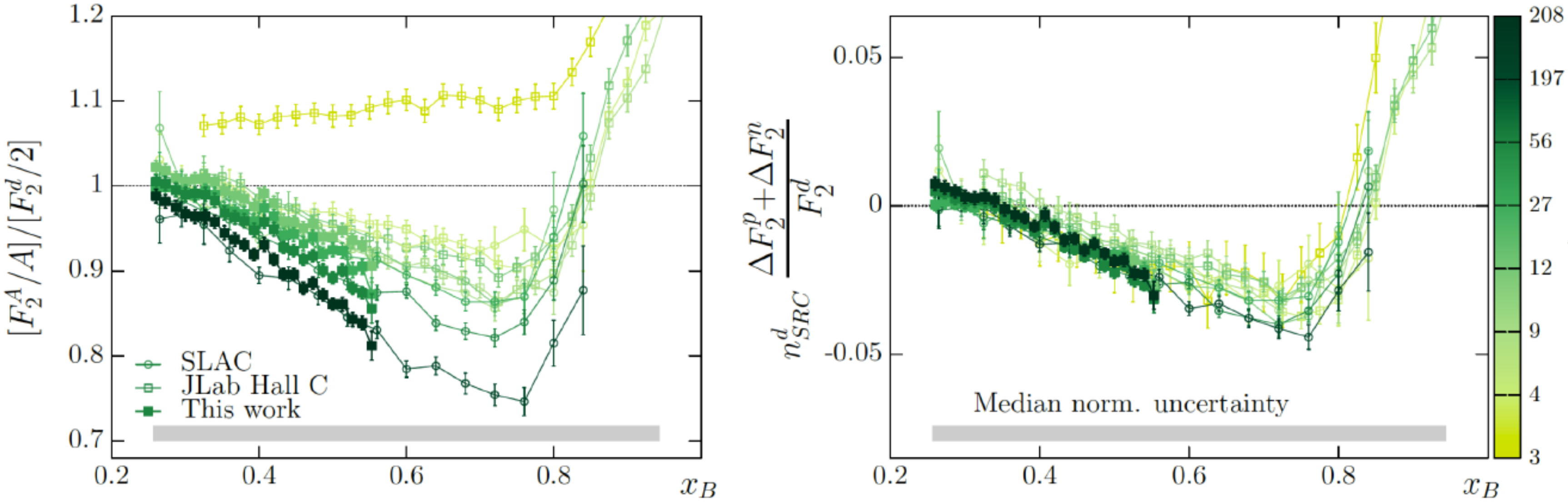
x>1 Ratios and EMC Slope Correlation

L. Weinstein *et al.*, Phys. Rev. Lett. **106** (2011) 052301.



Linear relation proposed as evidence that SRC explain the EMC effect

B. Schmookler *et al.*, Nature 566 (2019) 354-358.



$$F_2^A = (Z - n_{SRC}^A)F_2^p + (N - n_{SRC}^A)F_2^n + n_{SRC}^A(F_2^{p*} + F_2^{n*})$$
$$= ZF_2^p + NF_2^n + n_{SRC}^A(\Delta F_2^p + \Delta F_2^n),$$

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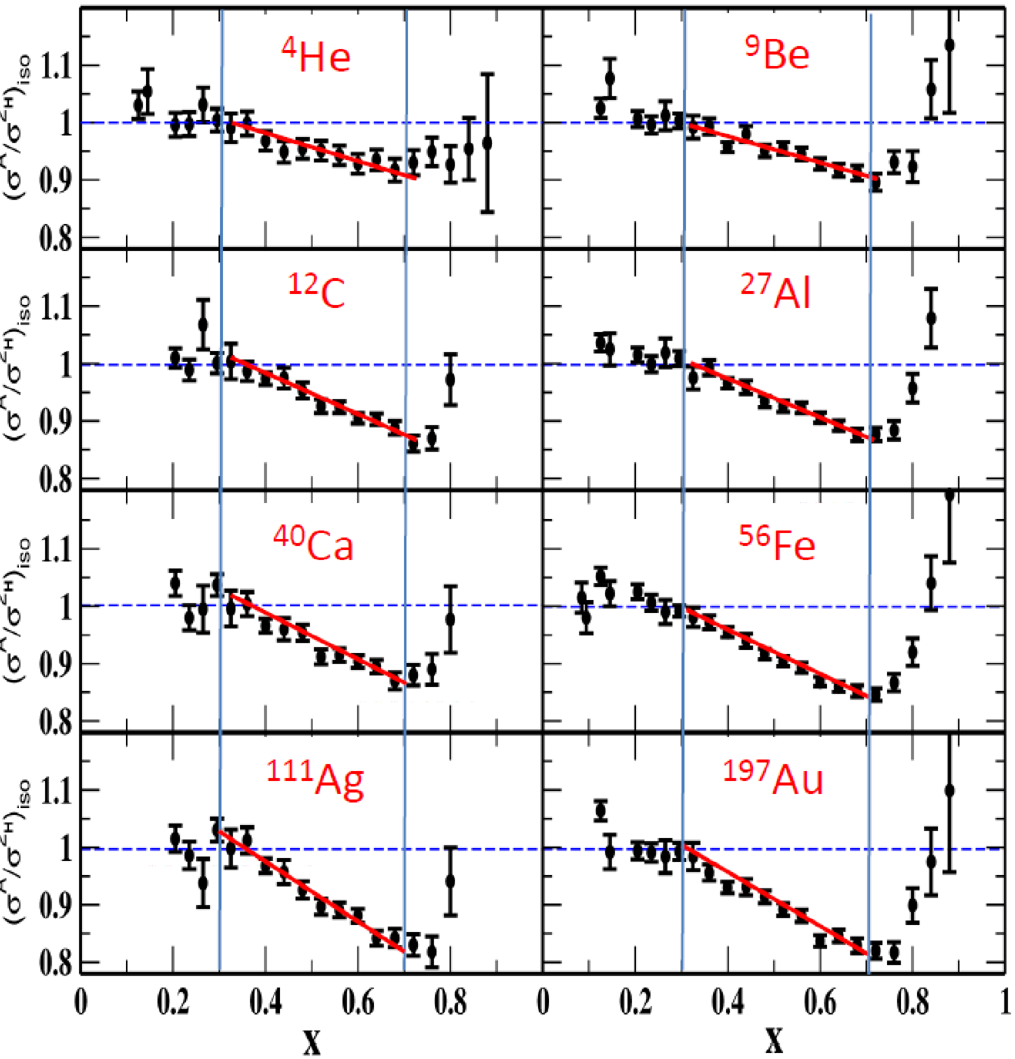
From talk of D. Higinbotham

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

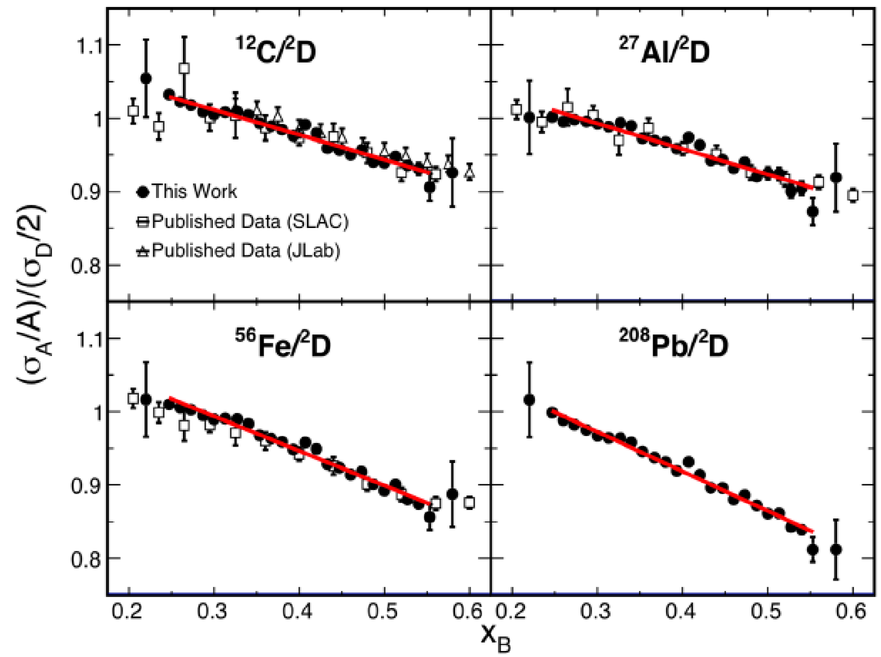
‘Global’ EMC Data



Gomez PRD (1994)

SLAC (1994)

JLab (2018)



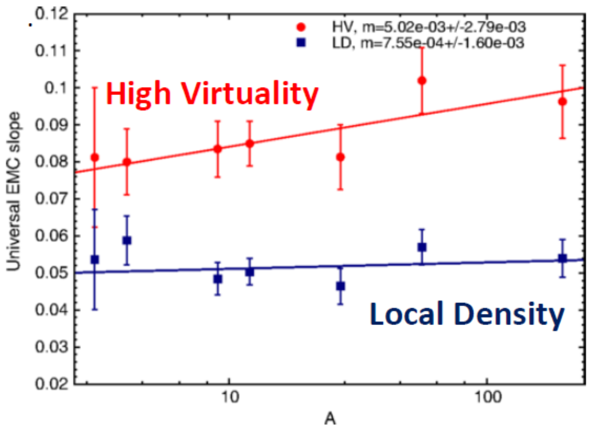
Schmookler,
Nature (2019)

From talk of O. Hen

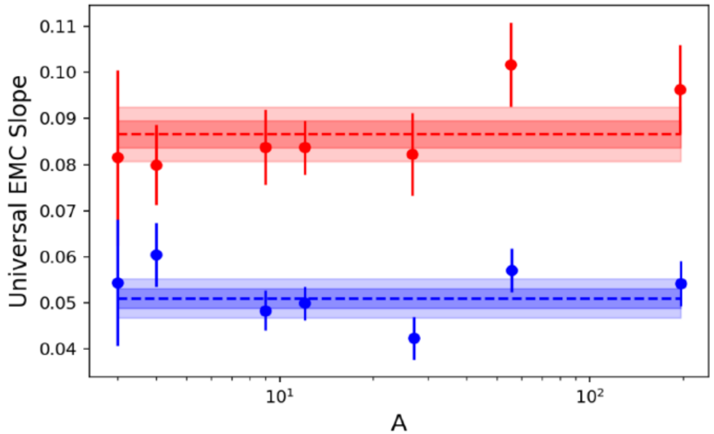
Origin of the EMC Effect

High Virtuallity vs. Local Density

J. Arrington and N. Fomin, Phys. Rev. Lett. 123 (2019) 042501



O. Hen et al., arXiv:1905.02172.



The plots on the left and right side are exactly the same data.

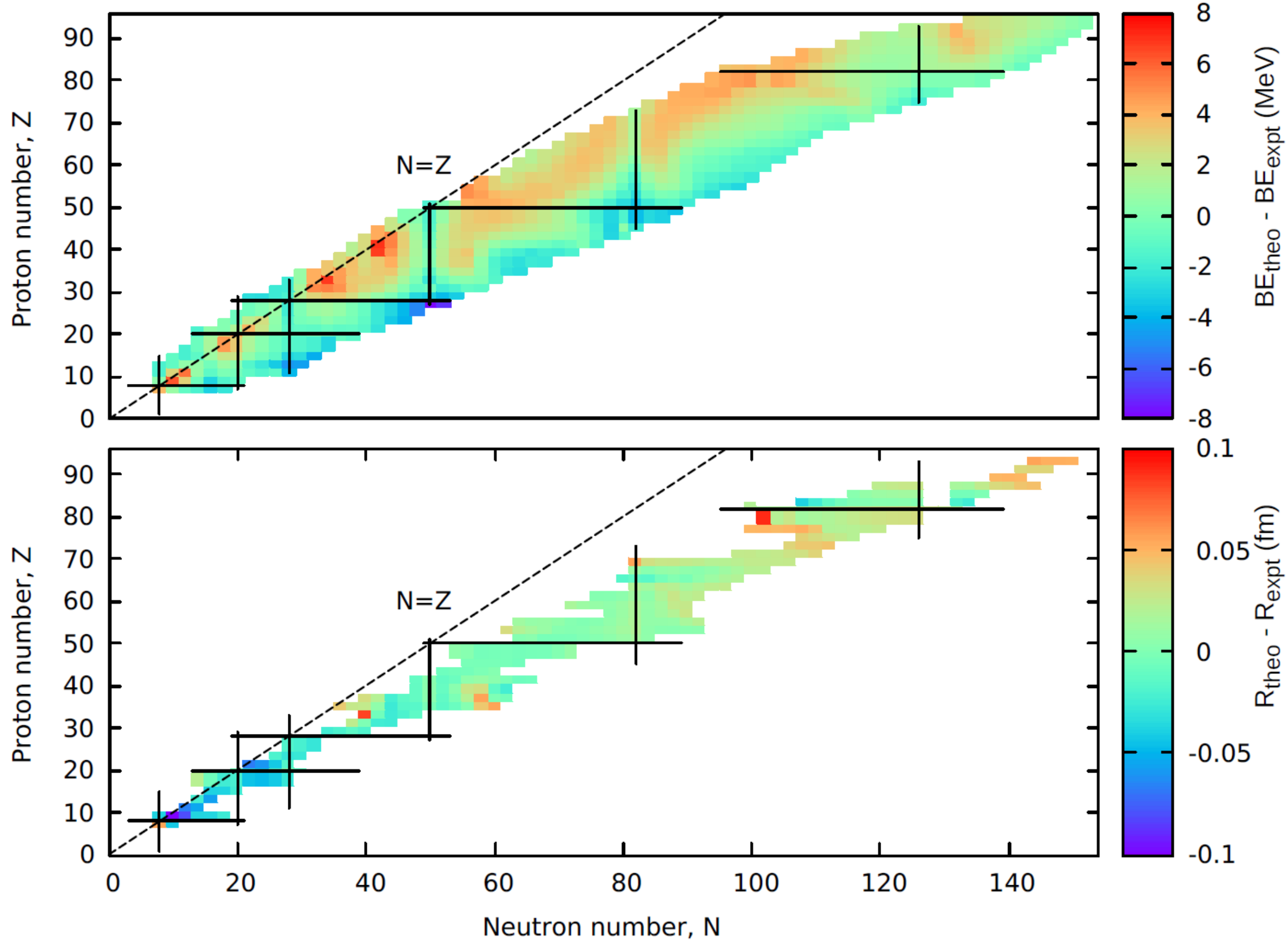
The simpler model (i.e. a constant) is consistent with both universal functions.

One should define there criterion for adding parameters to a regression.
(see Higinbotham *et al.*, Phys. Rev. C. 93 (2015) 055207 for examples)

NOTE: When handled consistently, HV and LD give exactly the same 'a2' values.
https://arxiv.org/abs/1907.03658

Alternate Explanation Based Upon Quark-Level Description of Nuclear Structure

Overview of 739 even-even nuclei



Martinez et al., arXiv:1811.06628

Summary: Finite Nuclei

- **The effective force was *derived* at the quark level *based upon changing structure of bound nucleon***
- **Has many less parameters but reproduces nuclear properties at a level comparable with the best phenomenological Skyrme forces**
- **Looks like standard nuclear force**
- **BUT underlying theory also predicts modified internal structure and hence modified**
  - **DIS structure functions**
  - **elastic form factors......**

Theoretical Understanding

- Still numerous proposals but few consistent theories

- Initial studies used MIT bag[1] to estimate effect of self-consistent change of structure in-medium
  − but better to use a covariant theory

- For that Bentz and Thomas[2] re-derived change of nucleon structure in-medium in the NJL model

- This set the framework for sophisticated studies by Bentz, Cloët and collaborators over the last decade

[1] Thomas, Michels, Schreiber and Guichon, Phys. Lett. B233 (1989) 43
[2] Bentz and Thomas, Nucl. Phys. A696 (2001) 138

EMC Effect for Finite Nuclei

(There is also a spin dependent EMC effect - as large as unpolarized)

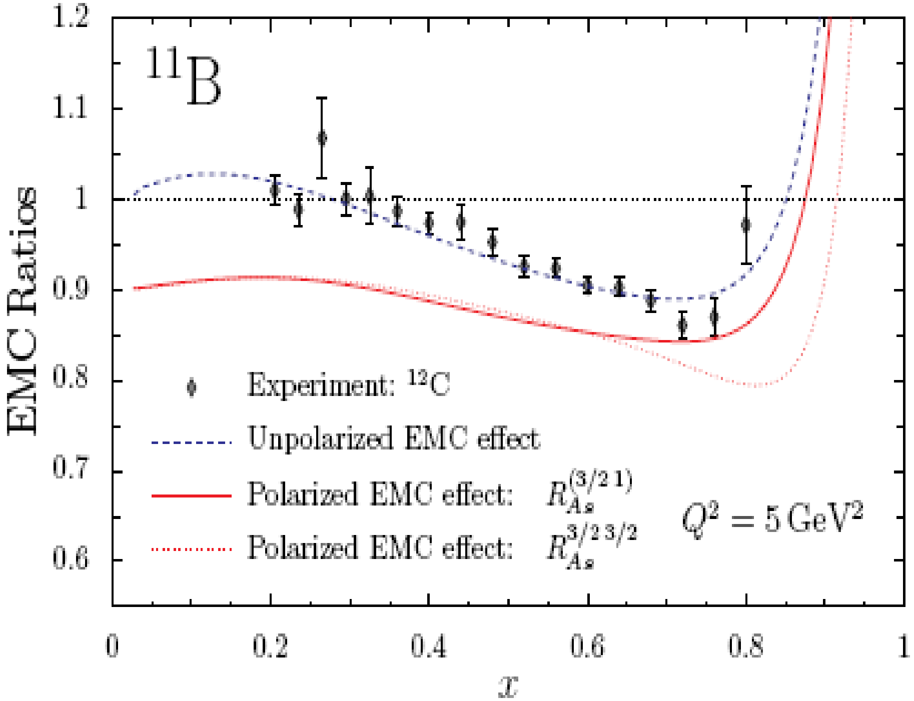


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

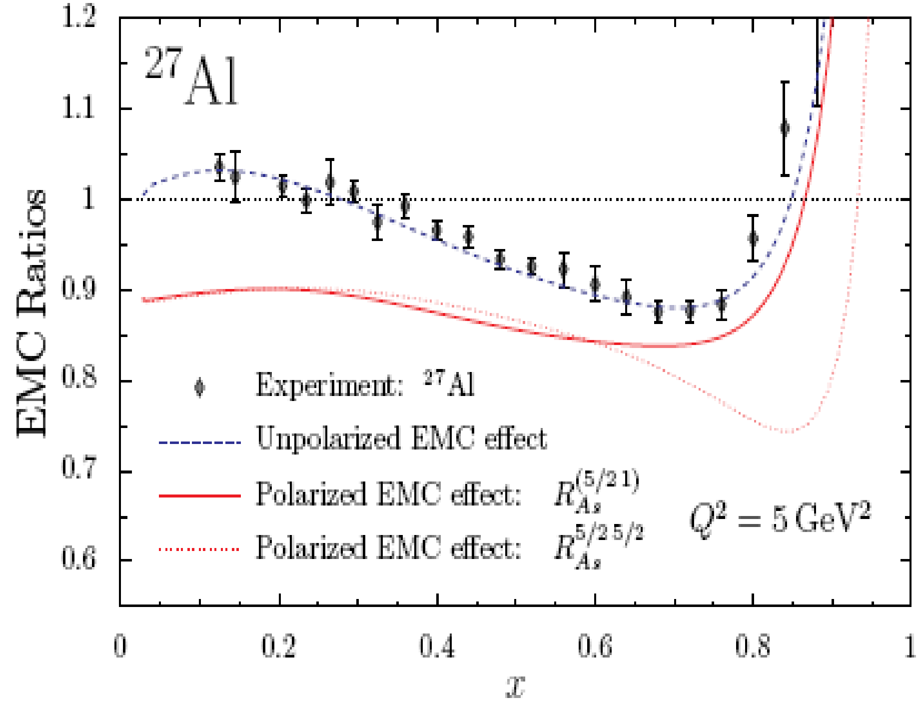


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

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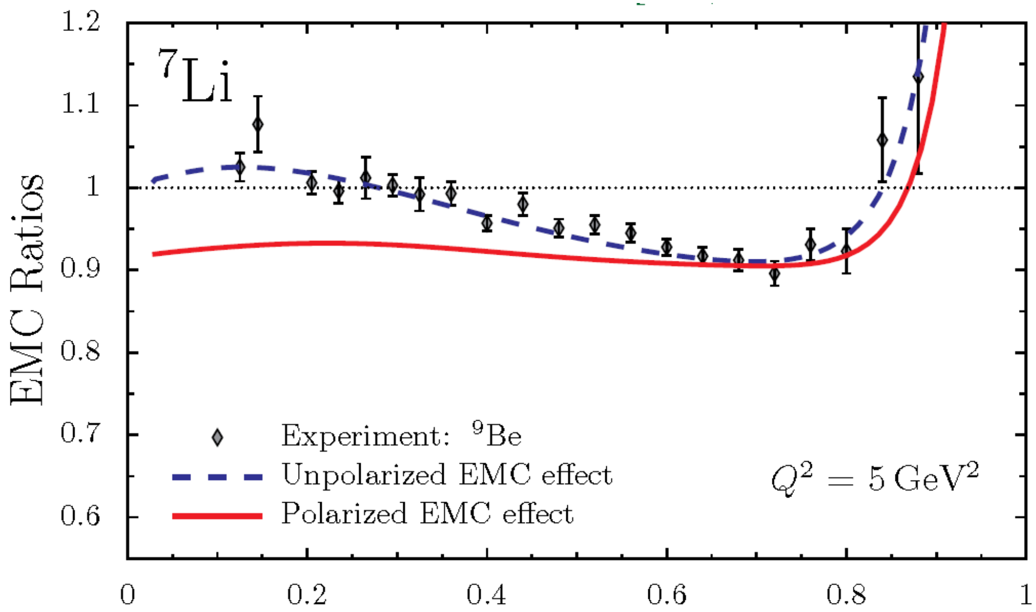
Cloët, Bentz &Thomas, Phys. Lett. B642 (2006) 210

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Approved JLab Experiment

- Effect in ^{7}Li is slightly suppressed because it is a light nucleus and proton does not carry all the spin (simple WF: $P_p = 13/15$ & $P_n = 2/15$)
- Experiment now approved at JLab [E12-14-001] to measure spin structure functions of ^{7}Li (GFMC: $P_p = 0.86$ & $P_n = 0.04$)
- *Everyone with their favourite explanation for the EMC effect should make a prediction for the polarized EMC effect in ^{7}Li*



Other tests (e.g. Isovector EMC effect)

Spin-EMC Effect is a crucial test

- Tensor correlations leading to high momentum components in nuclear wave function have been proposed as an alternate explanation of the EMC effect

- The tensor force scatters $^3S_1$ pairs almost entirely into $^3D_1$ at high momentum (~84% at p > 400 MeV/c)

- Nucleons in SRC are depolarized – simple Clebsch-Gordan coefficients - and cannot contribute to spin-EMC effect

- That is SRC predicts essentially NO spin-EMC effect

AWT - Int J Mod Phys 27 (2018) 1840001 (Ernest Henley Memorial)

Apologies to those I missed and for any errors of fact or judgement