A peek into parton confinement: Transverse polarized scattering and quark-gluon correlations in nucleons.

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Group on Hadronic Physics
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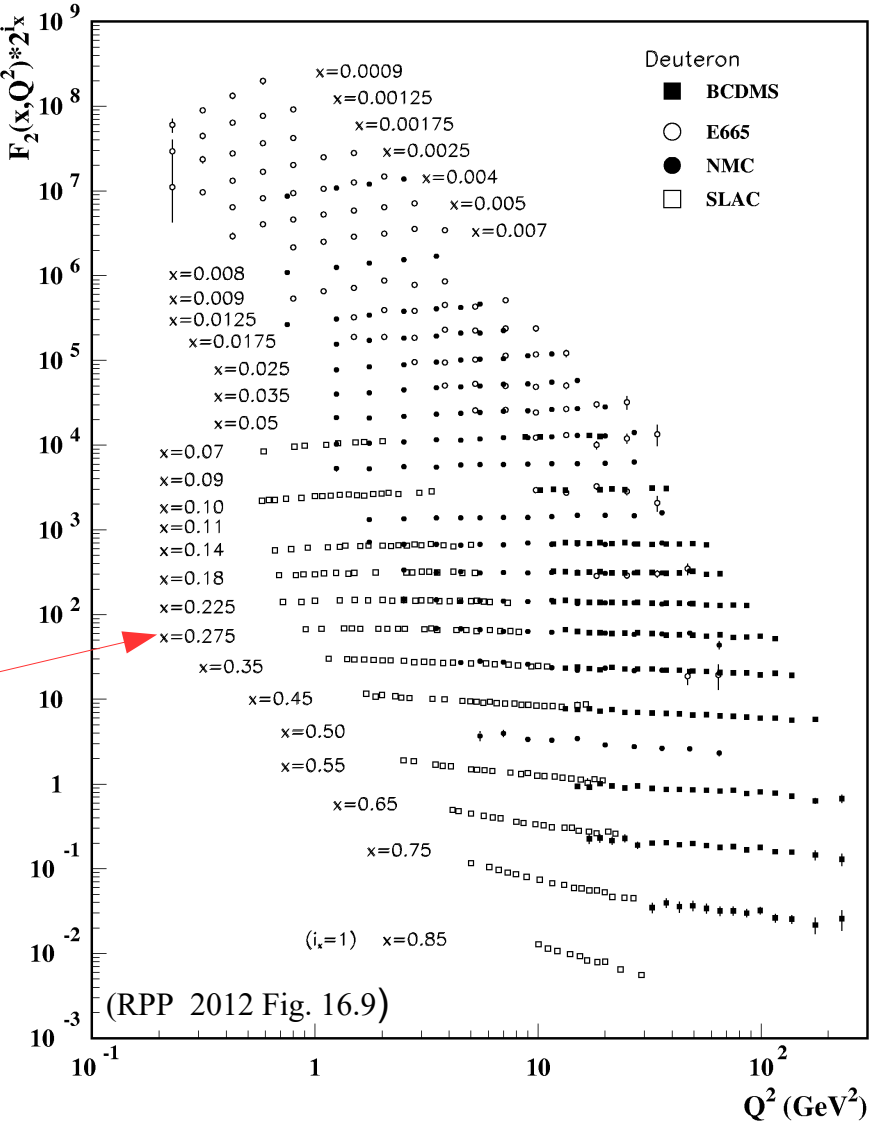
Nucleon structure from DIS

- Visible matter mostly made of hadrons (baryons & mesons)
- Hadrons, e.g. nucleons, are systems of quarks bound by gluons according to SU(3) classifications
- Nucleon structure has been probed with non hadronic probes
  - point like structures found with DIS of leptons: partons
  - partons identified with quarks
  - nevertheless, at even the highest energies/momentum transfers DIS or hadronic beams are unable to produce free quarks: confinement
  - QCD says that as quark separation increases qq potential grows linearly
  - origin of confinement still a major mystery in physics

Scaling and deviations

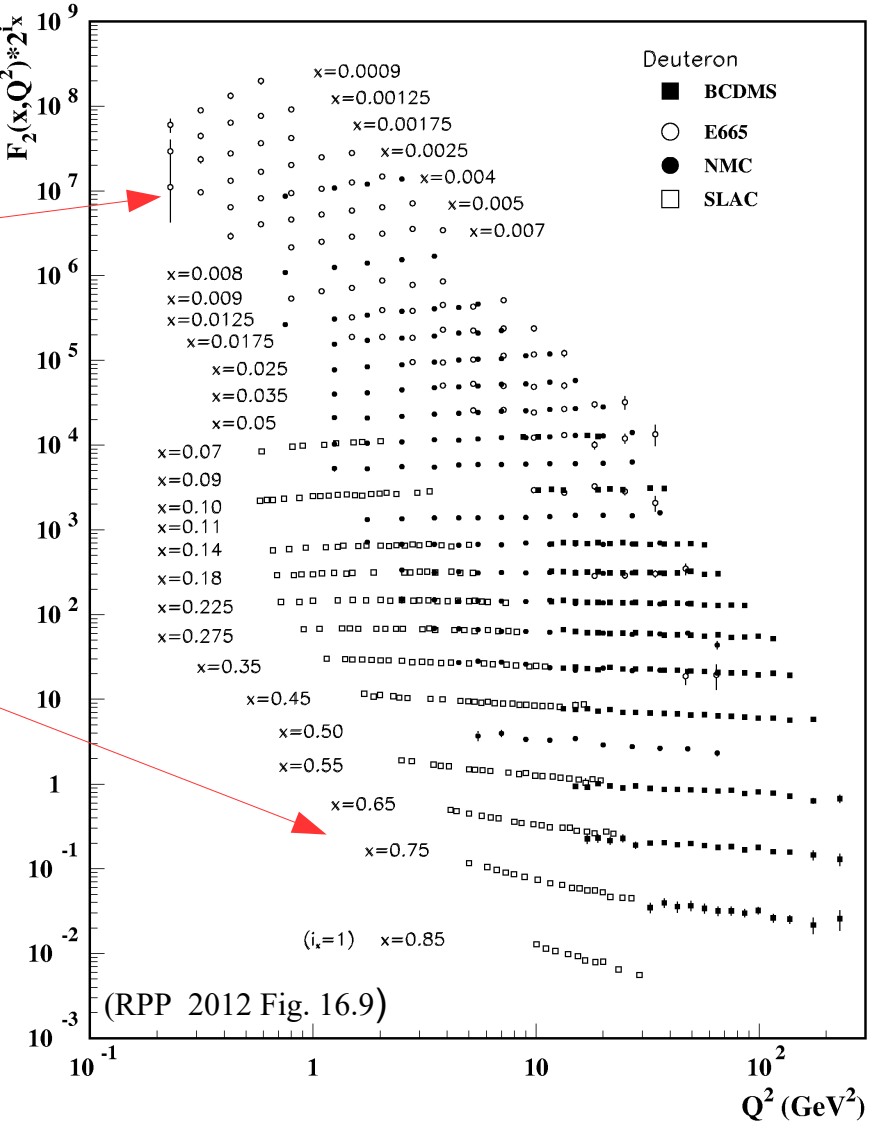
- When probing nucleon structure in DIS at small distances (= very high Q^2) partons/quarks behave as free, non-interacting objects:
  - Nucleon F_2 structure function stays constant in Q^2 at intermediate values of struck parton momentum x_B: scaling



(RPP 2012 Fig. 16.9)

Scaling and deviations

- Deviations from scaling
  - at low x_B: gluon radiation – log scaling violation
  - at x_B ~1 deviations get worse at low Q^2: increasing interactions as parton separation grows as $1/Q^2$: end of perturbative regime



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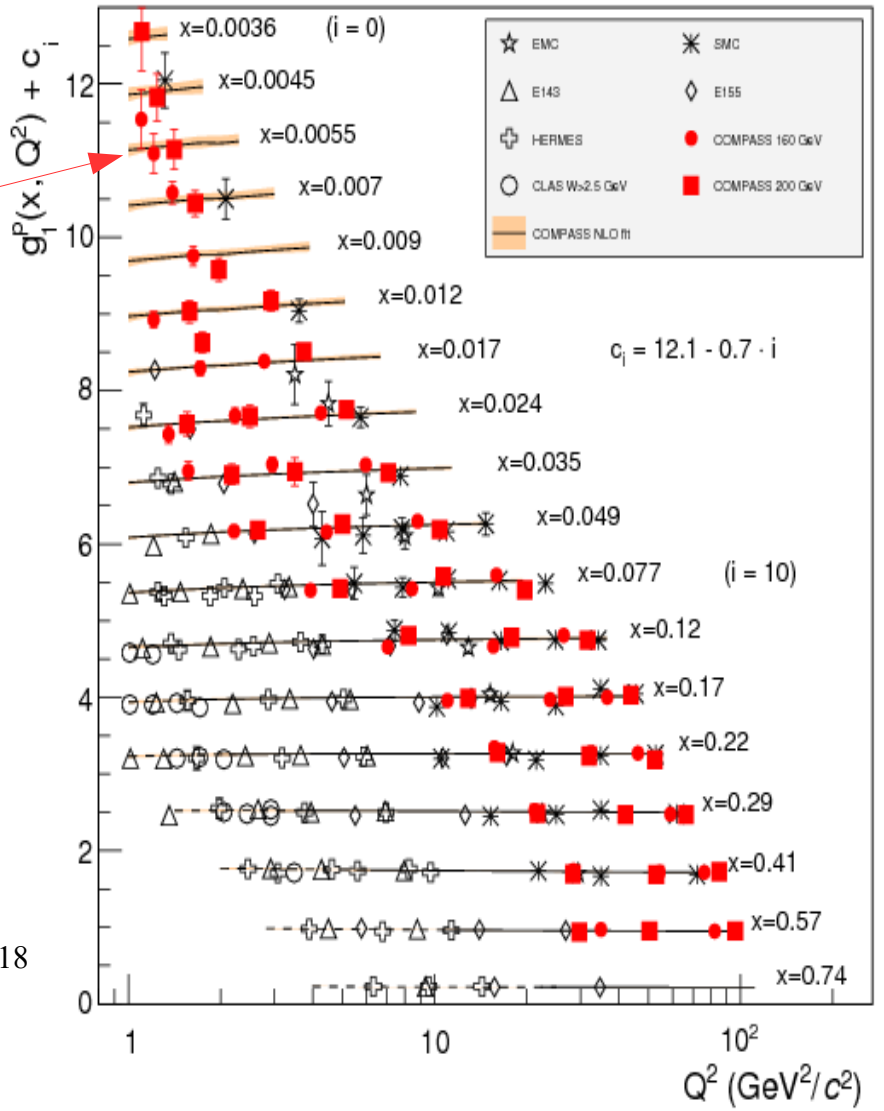
    (limited spin structure funtion g_1 data available at high x)



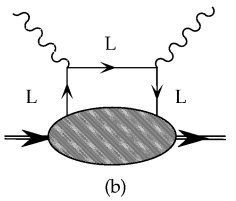
Phys.Lett. B753 (2016) 18

Moments and Higher Twists

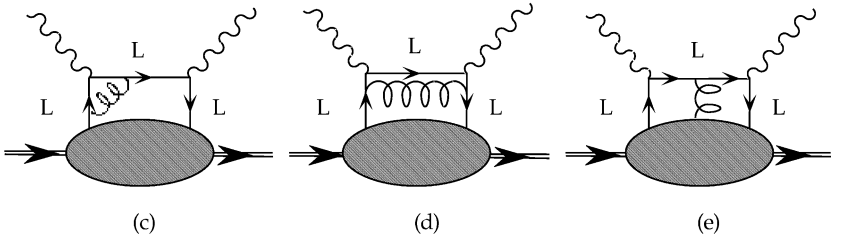
- Nucleon structure beyond log scaling violations:
  - Higher Twists (HT): inverse Q^2 power corrections to DIS structure functions (unpolarized SF's $F_{1,2}$ and spin dependent $G_{1,2}$)
  - Dynamical HT represent parton correlations beyond free quark picture: long distance behavior of quarks and gluons
- Access to HT: Moments of SF's related by OPE to matrix elements of quark operators of given twist (= *dimension – spin* of operators)
  - Moments expanded in power series of $(A(x)/ Q^2)^{(\text{twist - 2})}$
  - Moments integrate over full x range: $M_{2,3}^{(n)}(Q^2) = \int_0^1 dx\, x^n\, g_{1,2}(x, Q^2)$
    - Resonances and elastic contribute at lower energies
  - HT clouded by kinematic operators of same twist, but higher spin
    - "Target Mass" corrections required.

Transverse Polarized Scattering: Unlocking Twist-3

- Lowest twist-2 and twist-3 operators contribute at same order in polarized leptons scattering off transverse polarized nucleons
  - twist-2: handbag diagram
  - twist-3: *qgq* correlations
- direct access to twist-3 via g_2 SF:
  - interacting *qgq* is first step to understanding confinement
  - "*Unique feature of spin-dependent scattering*" (R. Jaffe)



twist-2



log Q^2 α_{QCD} twist-3

(twist-2 corrections)

(Comments NPP 19, 239 (1990))

(QCD evolution of g_2: singlet/non-singlet Ji et al.: many diagrams.)

OPE for Polarized SF's

- Cornwall-Norton moments of g_1 and g_2 connected by OPE to twist-2 matrix elements a_n and twist-3 d_n

$$\Gamma_1^{(n)} = \int_0^1 x^n g_1(x, Q^2)\, dx = \frac{1}{2} a_n + O(M^2/Q^2), \qquad n = 0, 2, 4, \ldots$$

$$\Gamma_2^{(n)} = \int_0^1 x^n g_2(x, Q^2)\, dx = \frac{n}{2(n+1)} (d_n - a_n) + O(M^2/Q^2), \qquad n = 2, 4, \ldots$$

  - d_n is shorthand for $\tilde{d}_n = \sum_i d_i^n(\mu^2)\, E_{i,3}^n(Q^2/\mu^2, \alpha_s(\mu^2))$, $i = spin$, $E = Wilson\ coeff.$
  - At low-moderate Q^2 Nachtmann moments are needed to obtain clean dynamic twist-3 matrix elements (no target mass effects to $O(M^8/Q^8)$)

$$d_2(Q^2) = \int_0^1 dx\, \xi^2 \left(2\frac{\xi}{x} g_1 + 3\left(1 - \frac{\xi^2 M^2}{2Q^2}\right) g_2 \right) \Rightarrow_{Q^2 \to \infty} \int_0^1 dx\, x^2 (2 g_1 + 3 g_2)$$

Brief History of g_2

- g_2 known since late 1960's:
  - $g_2 = 0$ in parton model: no transverse momentum or spin
  - $g_1 + g_2 = 0$ [1] or $= \sum (e_i^2/2) \Delta q_i^T(x)$ (transverse polarized quarks[2])
- Now g_2 is understood as having twist-2(g_1) piece[3] + twist-3 part[4]

$$g_2(x,Q^2) = -g_1(x,Q^2) + \int_x^1 g_1(x',Q^2)\frac{dx'}{x'} - \int_x^1 \frac{\partial}{\partial x'}\left[\frac{m}{M} h_T(x',Q^2) + \xi(x',Q^2)\right]\frac{dx'}{x'}$$

  - h_T is twist-2 chiral odd transversity; ξ represents qg correlations.
- $g_1 + g_2 = g_T$ is spin SF for nucleon spin transverse to virtual photon

[1] B. Ioffe et al., *Hard Processes*, 1984; [2] R.Feynman; E. Leader and M. Anselmino added m_q, k_T; [3]S. Wandzura and F. Wilczek; [4] J. Cortes, B. Pire and J. Ralston; R. Jaffe and X. Ji.

g_2 and g_T Spin Structure Functions

Inclusive SF's and TMD description

$$g_T(x) = g_1(x) + g_2(x) = \frac{1}{2}\sum e_q^2 g_T^q(x)$$

g_T^q in terms of Transverse Momentum Dependent distributions [1]

$$g_T(x) = \int d^2\vec{k}_t \frac{\vec{k}_t^2}{2M^2} \frac{g_{1T}^q(x, \vec{k}_t^2)}{x} + \frac{m}{M}\frac{h_1(x)}{x} + \tilde{g}_T(x)$$

twist-3 TMD quark mass term *qgq* interaction

Applying twist-2 Wandzura-Wilczek approximation of g_2

$$g_2^{WW}(x) = -g_1(x) + \int_x^1 \frac{dy}{y} g_1(y)$$

Twist-3 for the nucleon (neglecting quark mass)

$$\bar{g}_2 = \frac{1}{2}\sum e_q^2 \left[\tilde{g}_T^q - \int_x^1 \frac{dy}{y}\left(\tilde{g}_T^q(y) - \hat{g}_T^q(y)\right)\right]; \quad \tilde{g}_T = qg \text{ term}, \ \hat{g}_T = \text{Lorentz invariance}$$ [2]

[1] hep-ph/9408305v1
[2] JHEP 0911 (2009) 093

What else makes g_2 interesting?

- Initial interest in g_2 driven by wish to reduce g_1 systematic error
- 1st moment = BC sum rule – hard to access, no x powers supression
- d_2 twist-3 matrix element related to average color Lorentz force on struck quark:

$$F^y(0) \equiv \frac{\sqrt{2}}{2P^+} \langle P,S \left| \bar{q}(0) \gamma^+ \; G^{+y}(0) q(0) \right| P,S \rangle = -\sqrt{2} M P^+ \; S^x d_2$$

(M. Burkardt, PR D 88, 114502 (2013))

  - color field forces & polarizabilities (with twist-4 matrix element f_2)
    - magnetic $\chi_B = (4d_2 + f_2)/3$ and electric $\chi_E = (4d_2 - 2f_2)/3$.
  - test of lattice QCD, QCD sum rules, quark models
- higher twist corrections to g_1 with d_2 matrix element
- contains chiral odd twist-2 = quark transverse spin (mass term)
  - test quark masses (covariant parton models)

Model Independent Extraction of Spin Structure Functions

- G_1 and G_2 can be separated by measuring cross section differences or asymmetries for opposite beam helicities with target spins *parallel* and *transverse* to the polarized beam

$$\Delta\sigma(\theta,\theta_N,\phi)=\frac{4\alpha^2 E'}{Q^2 E}\left[(E\cos\theta_N+E'\cos\alpha)M\,G_1+2EE'(\cos\alpha-\cos\theta_N)G_2\right]$$

$$\cos\alpha=\sin\theta_N\sin\theta\cos\phi+\cos\theta_N\cos\theta,\quad (\theta,\phi: \textit{final lepton angles})$$

- *transverse* target spin $\theta_N=\pi/2$: comparable G_1, G_2 terms

$$\frac{d^2\sigma^{(\uparrow\rightarrow)}}{d\Omega dE'}-\frac{d^2\sigma^{(\downarrow\rightarrow)}}{d\Omega dE'}=\frac{4\alpha^2 E'}{Q^2 E}E'\sin\theta\cos\phi\left[M\,G_1(\nu,Q^2)+2E\,G_2(\nu,Q^2)\right]$$

$$\textit{Scaling}\ \lim_{Q^2,\nu\to\infty} M^2\nu G_1(\nu,Q^2)=g_1(x)$$

$$\lim_{Q^2,\nu\to\infty} M\nu^2 G_2(\nu,Q^2)=g_2(x)$$

Virtual Compton Asymmetries

- The spin SF's are also related to virtual photon absorption cross-sections and spin asymmetries (SA)
  - the helicity of the virtual photon-nucleon system is $^3/_2$ or $^1/_2$ for transverse photons, $^1/_2$ for longitudinal ones

- SA A_1 is defined in terms of the difference for $^3/_2$ and $^1/_2$ helicity cross sections

$$A_1 = \frac{\sigma_T^{(3/2)} - \sigma_T^{(1/2)}}{\sigma_T^{(3/2)} + \sigma_T^{(1/2)}} = \frac{1}{F_1}\left(g_1 - \gamma^2 g_2\right)$$

$$\gamma = (2xM)/\sqrt{Q^2}$$

- A_2 represents the interference between initial transverse and final longitudinal amplitudes:
  - can be obtained directly from measured $A_{\parallel}$ and $A_{\perp}$

$$A_2 = \frac{\sigma_{TL}^{(1/2)}}{\sigma_T^{(3/2)} + \sigma_T^{(1/2)}} \leq \sqrt{\frac{A_1 + 1}{2}}\, R \leq \boldsymbol{R} = \frac{\sigma_L}{\sigma_T}$$

$$A_2 = \frac{\gamma}{F_1}\left(g_1 + g_2\right) = \frac{\gamma}{F_1}\, g_T$$

Experiment

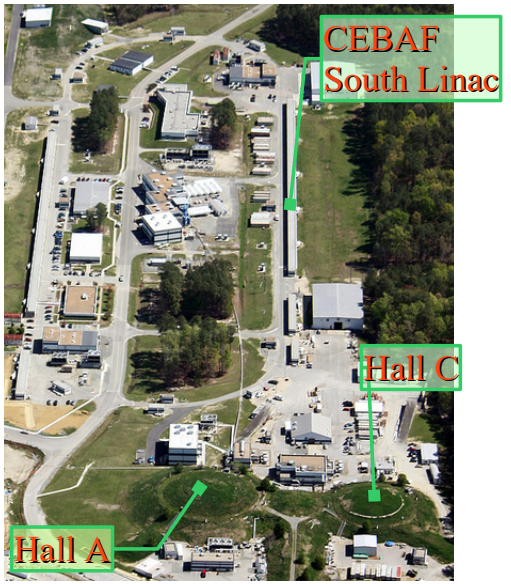
World g_2/d_2 experiments

- A quarter of a century of dedicated g_2 experiments worldwide
- g_2 obtained from beam-target asymmetries $A_{\parallel}$ & $A_{\perp}$ or cross section differences $\sigma_{\parallel}$ & $\sigma_{\perp}$
- *p* on ammonia (NH_3) solid targets or H gas (HERMES)
- *n* on ^{3}He gas and ND_3 and LiD
- Polarized *e*- beam or μ (CERN)

Lab	Experiment	Year	Target	Measured quantity	Kinematics Q^2 GeV^2
SLAC	E142	1992	^{3}He	$A_{\parallel}$, $A_{\perp}$	DIS 1.1 – 5.5
	E143	1993	NH_3,ND_3	$A_{\parallel}$, $A_{\perp}$	DIS 1 - 9
	E154	1996	^{3}He	$A_{\parallel}$, $A_{\perp}$	DIS 1.2 – 15
	E155/ 155x	1997	NH_3,LiD	$A_{\parallel}$, $A_{\perp}$	DIS 1 - 27
CERN	SMC	1994	NH_3	$A_{\parallel}$, $A_{\perp}$	DIS 1.4 – 11.8
DESY	HERMES	2003	H gas	$A_{LT}(\cos\phi)$	DIS 0.4 – 7.1
JLab	94-010		^{3}He	$\sigma_{\parallel}$, $\sigma_{\perp}$	Resonances 0.1 – 0.9
	97-103		^{3}He	$\sigma_{\parallel}$, $\sigma_{\perp}$	DIS 0.6 – 1.4
	97-110		^{3}He	$A_{\parallel}$, $A_{\perp}$	Elastic, Resonances 0.02 – 0.5
	99-117		^{3}He	$A_{\parallel}$, $A_{\perp}$	DIS 2.7, 3.5, 4.8
	01-006 (RSS)		NH_3,ND_3	$A_{\parallel}$, $A_{\perp}$	Resonances 1.3
	01-012		^{3}He	$\sigma_{\parallel}$, $\sigma_{\perp}$	Resonances 1 – 4
	06-014		^{3}He	$A_{\parallel}$, $A_{\perp}$	DIS <3>
	07-003 (SANE)		NH_3	$A_{\parallel}$, $A_{\perp}$	DIS, Resonances 1.6 – 6
	08-027 (g2p)		NH_3	$\sigma_{\parallel}$, $\sigma_{\perp}$	Resonances 0.03 – 0.3

Tools to get g_2/d_2

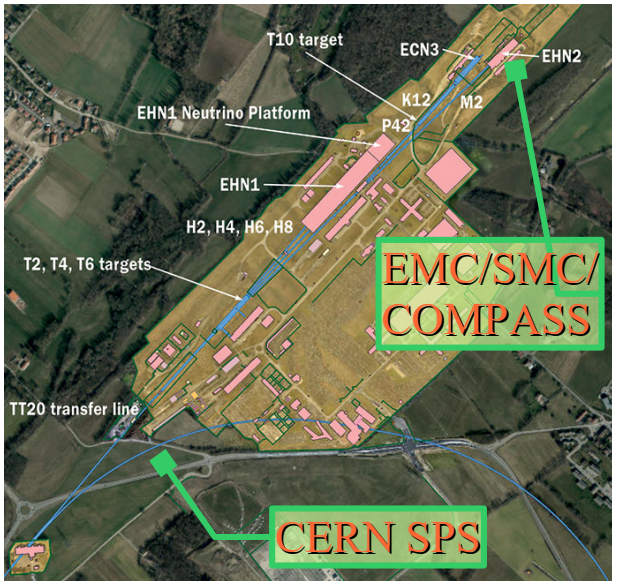
- Need
  - polarized lepton beams
    - e^- linacs (SLAC/JLab)
    - strained GaAs source

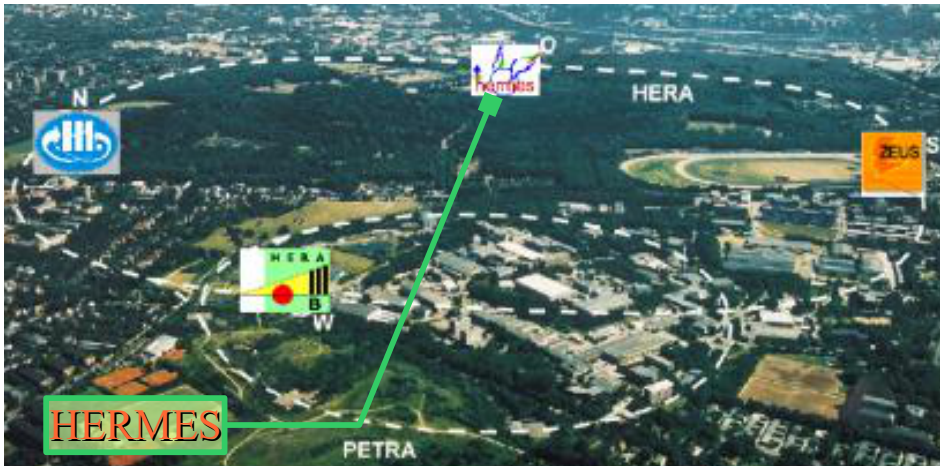


SLAC http://slac50.slac.stanford.edu/webimages/gallery/1969.jpg
JLab https://www.jlab.org/

Tools to get g_2/d_2

- Need
  - polarized lepton beams
    - $e^{-/+}$ collider (DESY-HERMES)
    - μ secondary beam (CERN SPS - SMC)

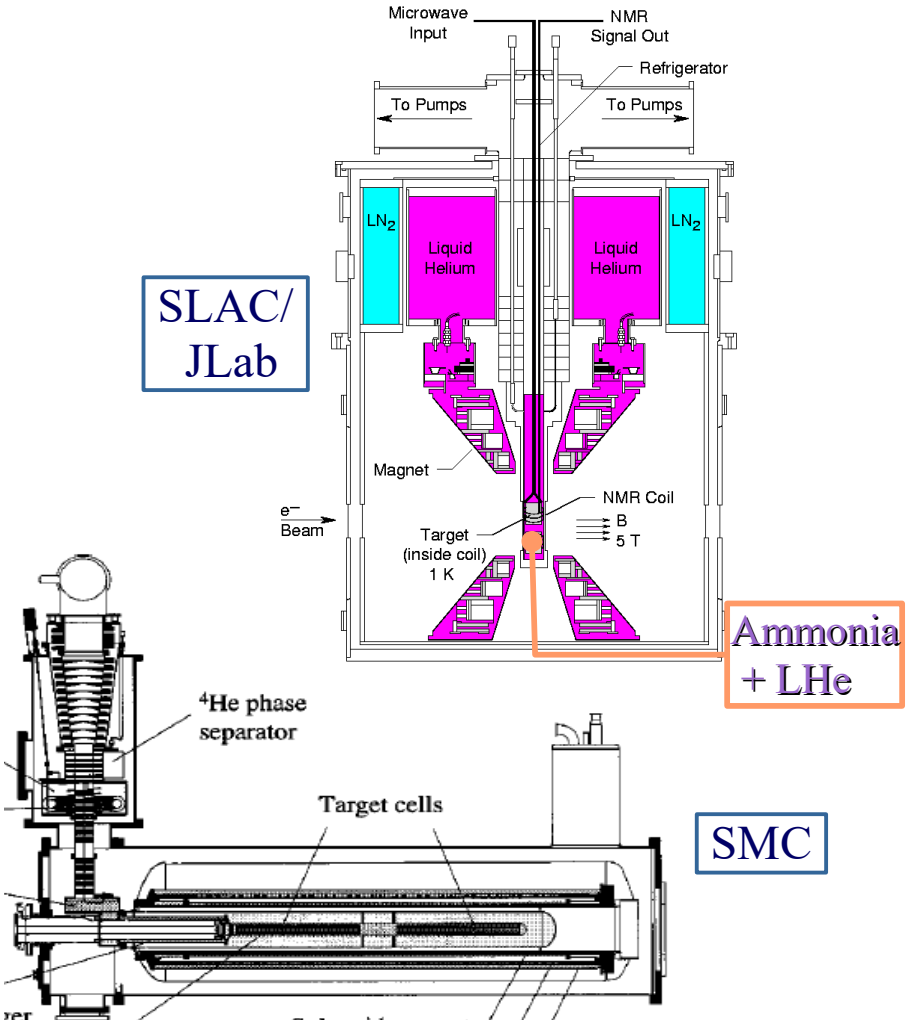




SMC CERN Courier March/April 2019
HERMES http://www-hermes.desy.de/

Tools to get g_2/d_2

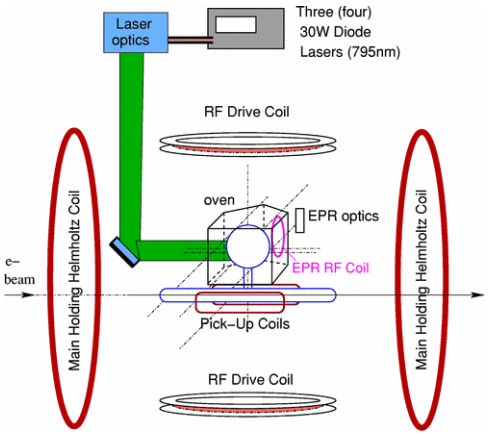
- Need
  - transverse polarized targets
    - solid (SLAC/JLab[1]/SMC[2])
      - NH_3 proton,
      - ND_3, LiD deuteron



[1]SLAC/JLab UVA polarized target group
[2] SMC NIM A 437 (1999) 23
[3]HERMES NIM A540 (2005) 69
[4]JLab 3He PR C 70, 065207 (2004)

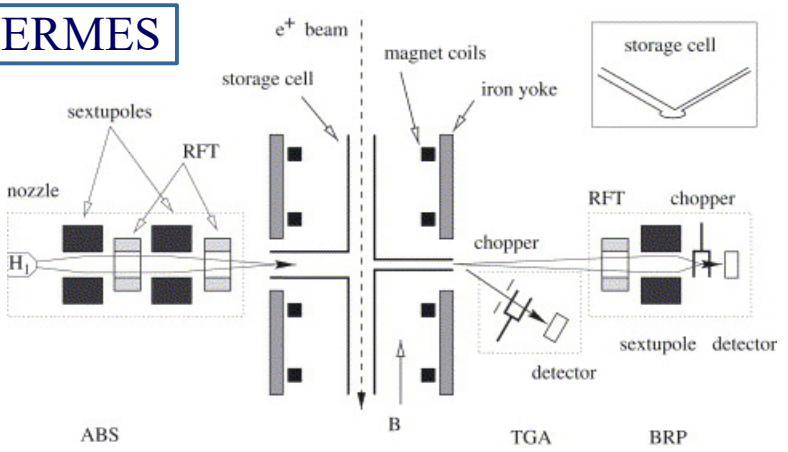
Tools to get g_2/d_2

- Need
  - transverse polarized targets
    - solid (SLAC/JLab[1]/SMC[2])
      - NH_3 proton,
      - ND_3, LiD deuteron
    - gas:
      - H (HERMES[3])
      - ^{3}He (SLAC/JLab[4])



SLAC/ JLab

HERMES



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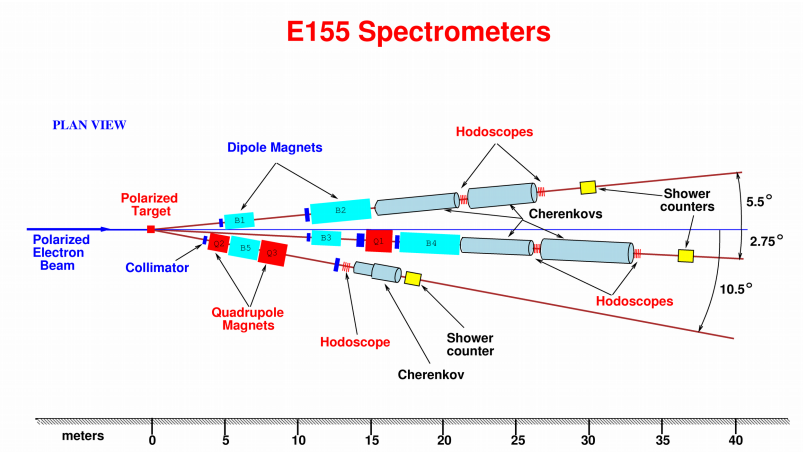
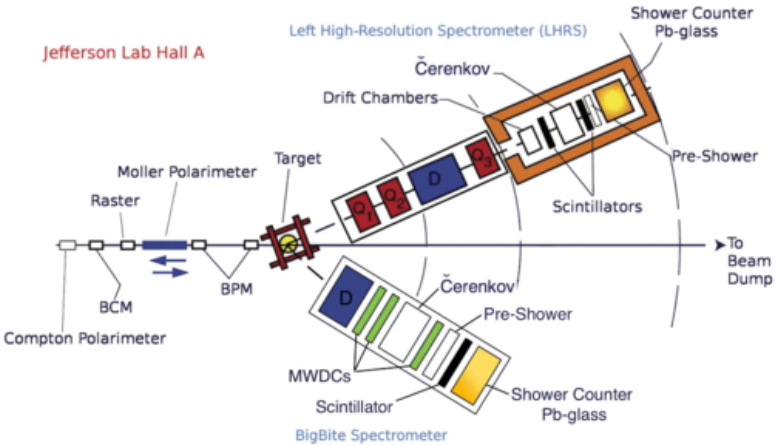
Tools to get g_2/d_2

- Need detectors
  - spectrometers
    - SLAC End Station A
    - JLab Halls A and C
    - HERMES
    - SMC NA47

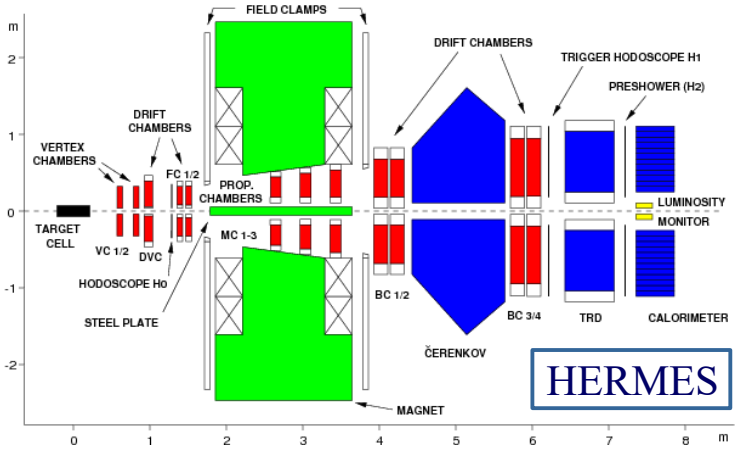


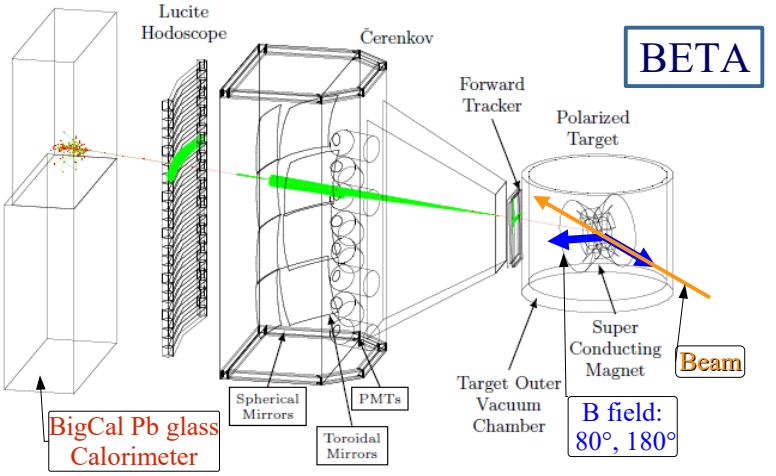


[1]SLAC E155
[2] JLab PR D 94 052003 (2016)
[3]HERMES Adv.Nucl.Phys. 26 (2001) 1
[4]SANE NIM A885 (2018) 145

Tools to get g_2/d_2

- Need detectors
  - spectrometers
    - SLAC End Station A
    - JLab Halls A and C
    - HERMES
    - SMC NA47
  - telescopes (no ***B*** field)
    - JLab SANE BETA
      (Big Electron Telescope Array)





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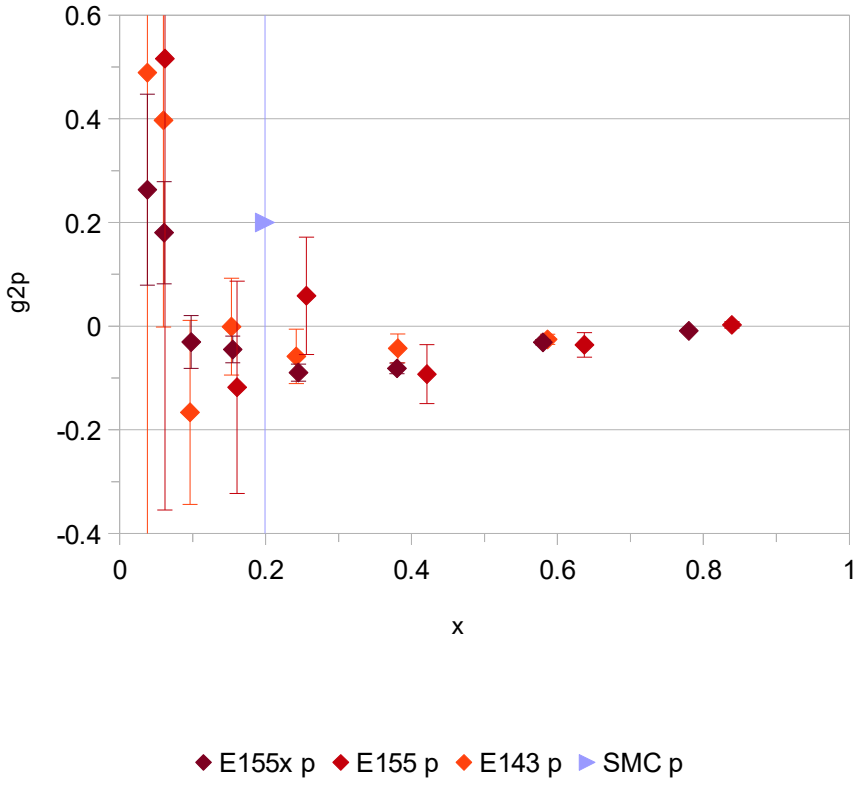
Data

g_2^p

- Proton g_2 measured on
  - solid ammonia NH_3 targets (SLAC, JLab, CERN-SMC)
  - H gas target (DESY-HERMES)
  - Mostly DIS; some high x points are resonance region but at very high Q^2

    (some points not showing are outside y axis range)



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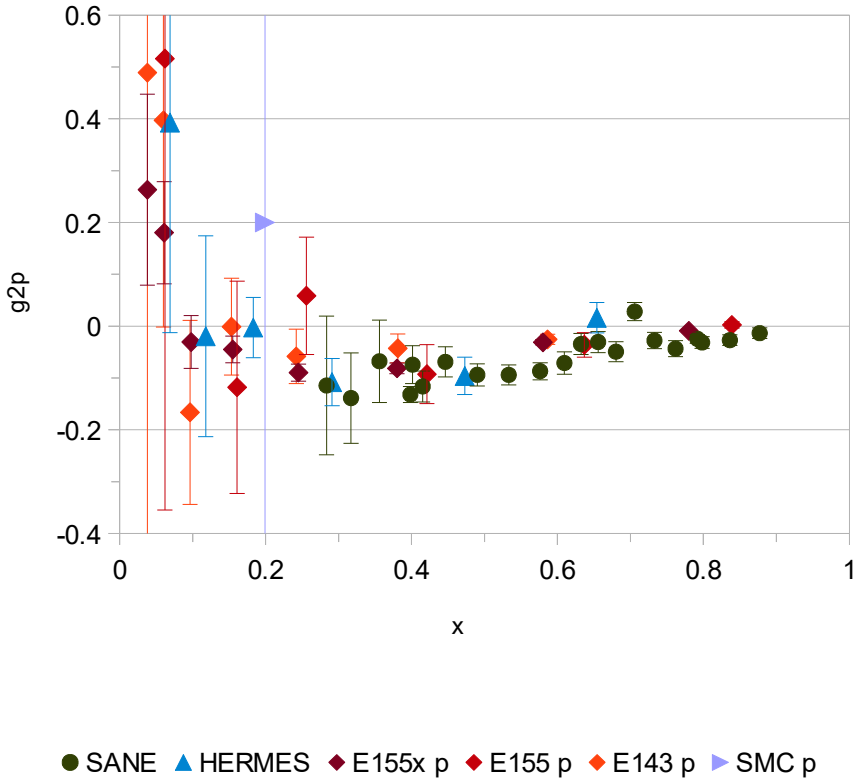

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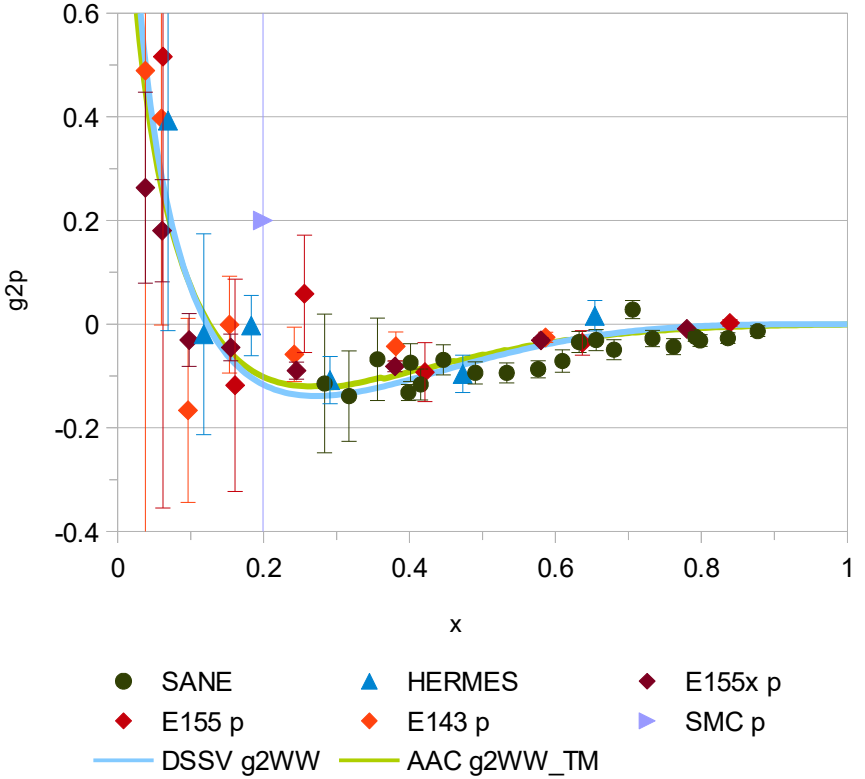
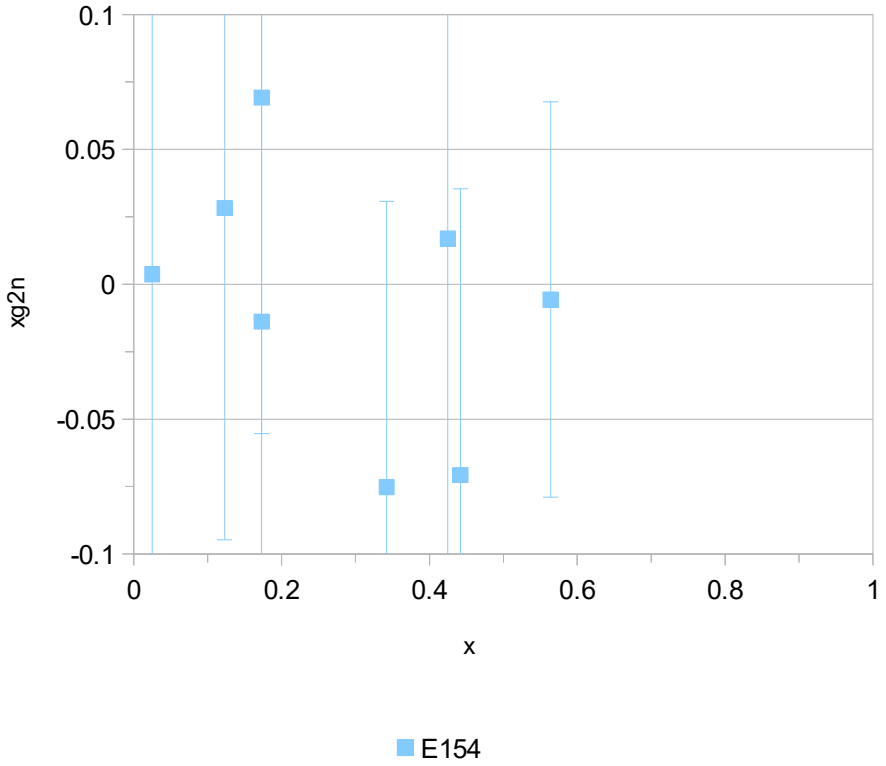


Data from Durham University HEP data repository https://www.hepdata.net/ except SANE

g_2^n

- Neutron g_2 extracted from ^{3}He, or D and *p*, target data
  - Correction for polarized *p* and effective *n* polarization in ^{3}He
  - Correction for deuteron *D*-state ~ 1/.92



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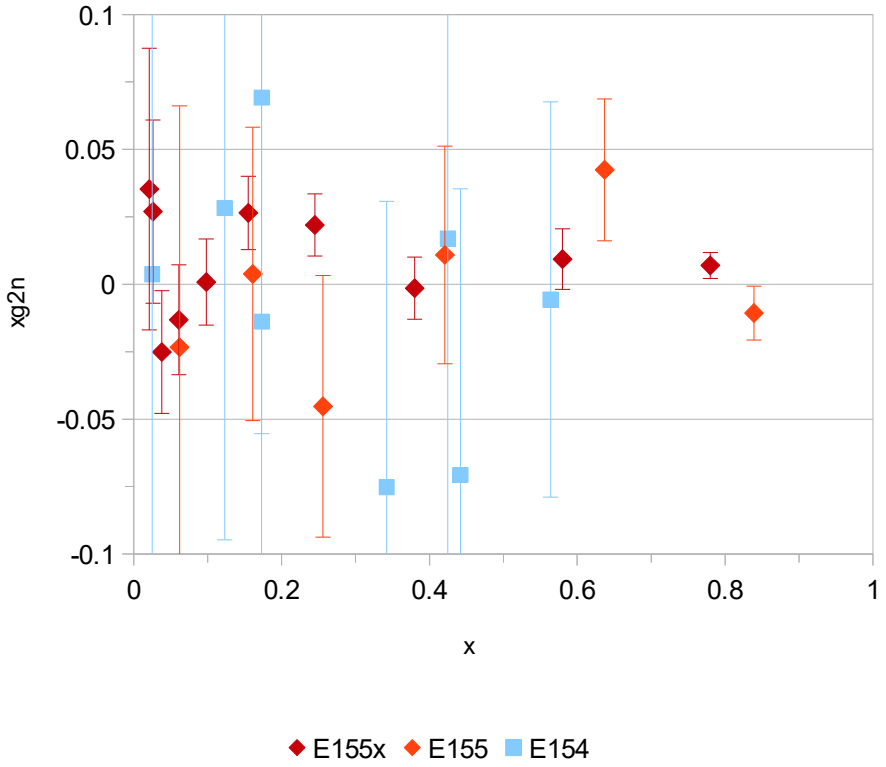

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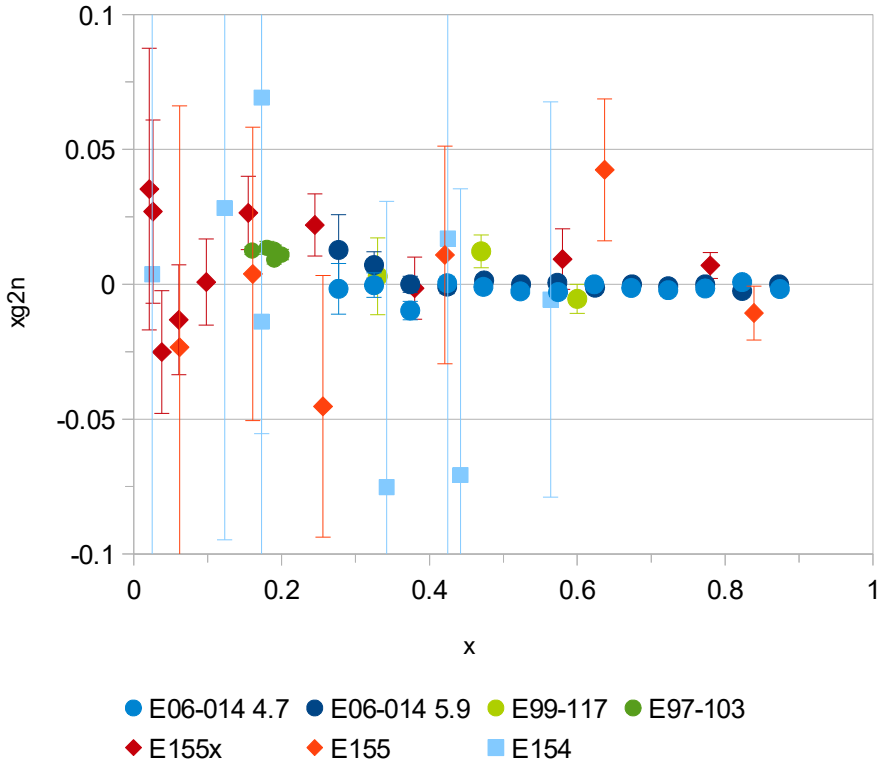
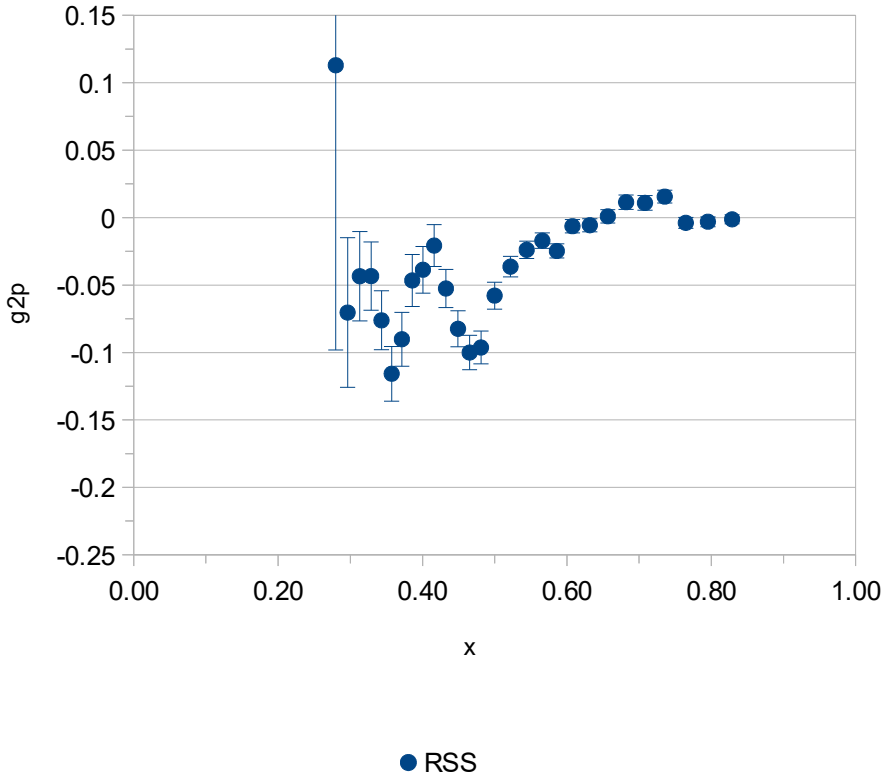


Data from Durham University HEP data repository https://www.hepdata.net/
E97-103 PRL **95**, 142002 (2005)
E99-117 PR C **70**, 065207 (2004)
E06-014 PR D **94**, 052003 (2016)

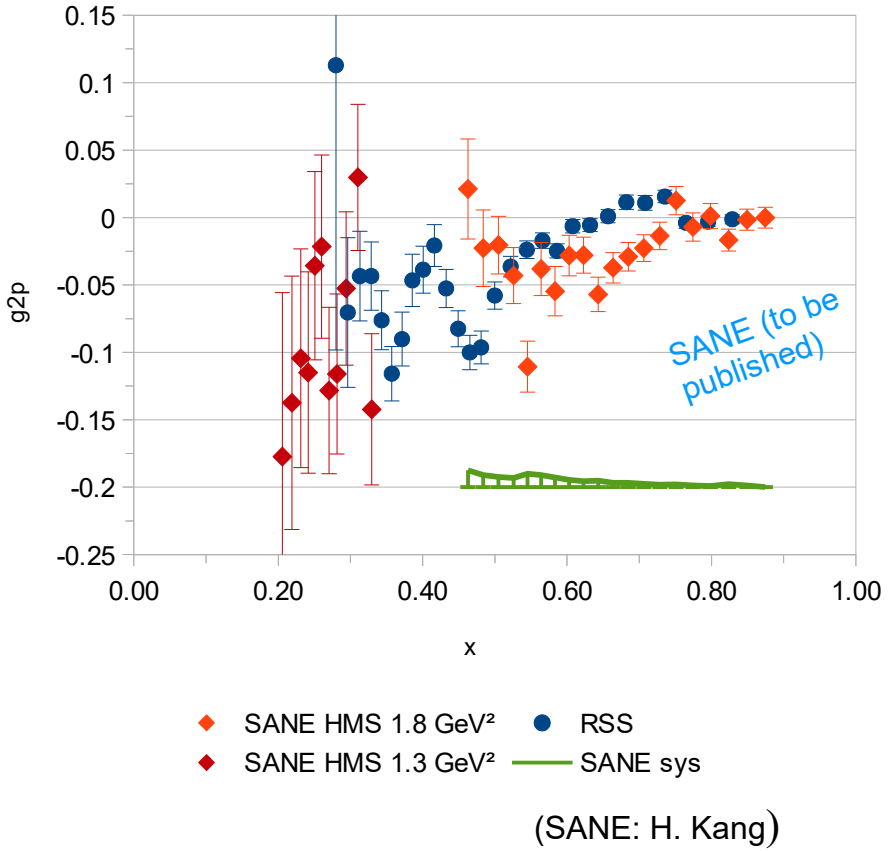
g_2 in the Resonances Region

- RSS: only published precision resonances results to date



g_2 in the Resonances Region

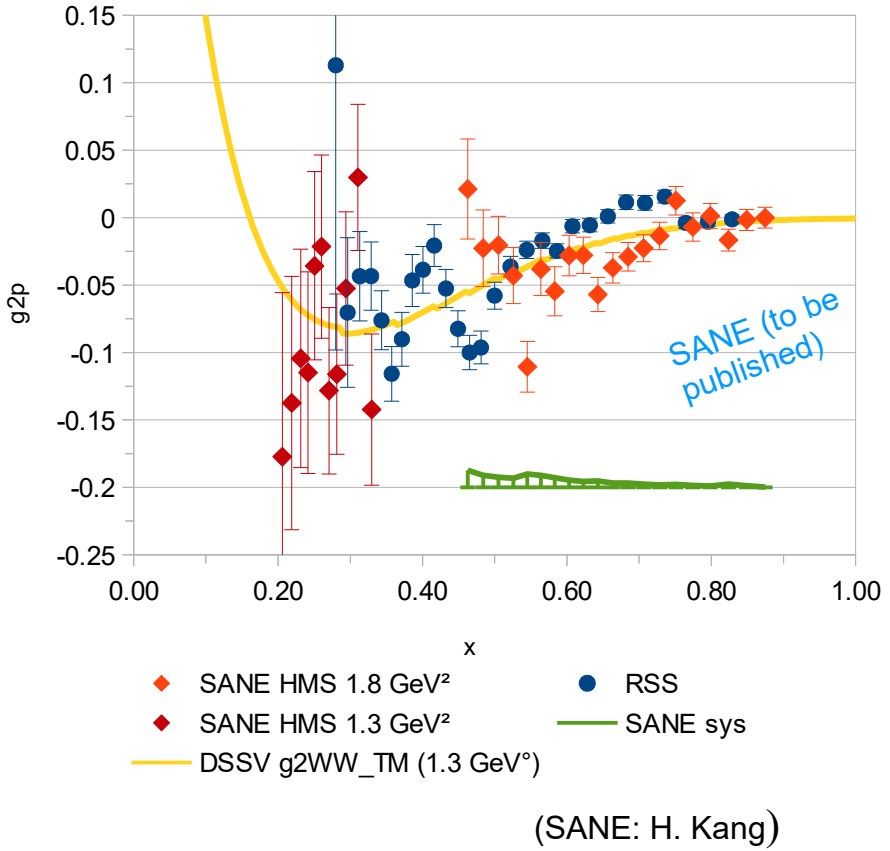
- RSS: only published precision resonances results to date
- Parasitic HMS SANE proton data:
  - new data at $Q^2 = 1.8$ GeV^2
  - extend RSS low x range at 1.3 GeV^2



(SANE: H. Kang)

g_2 in the Resonances Region

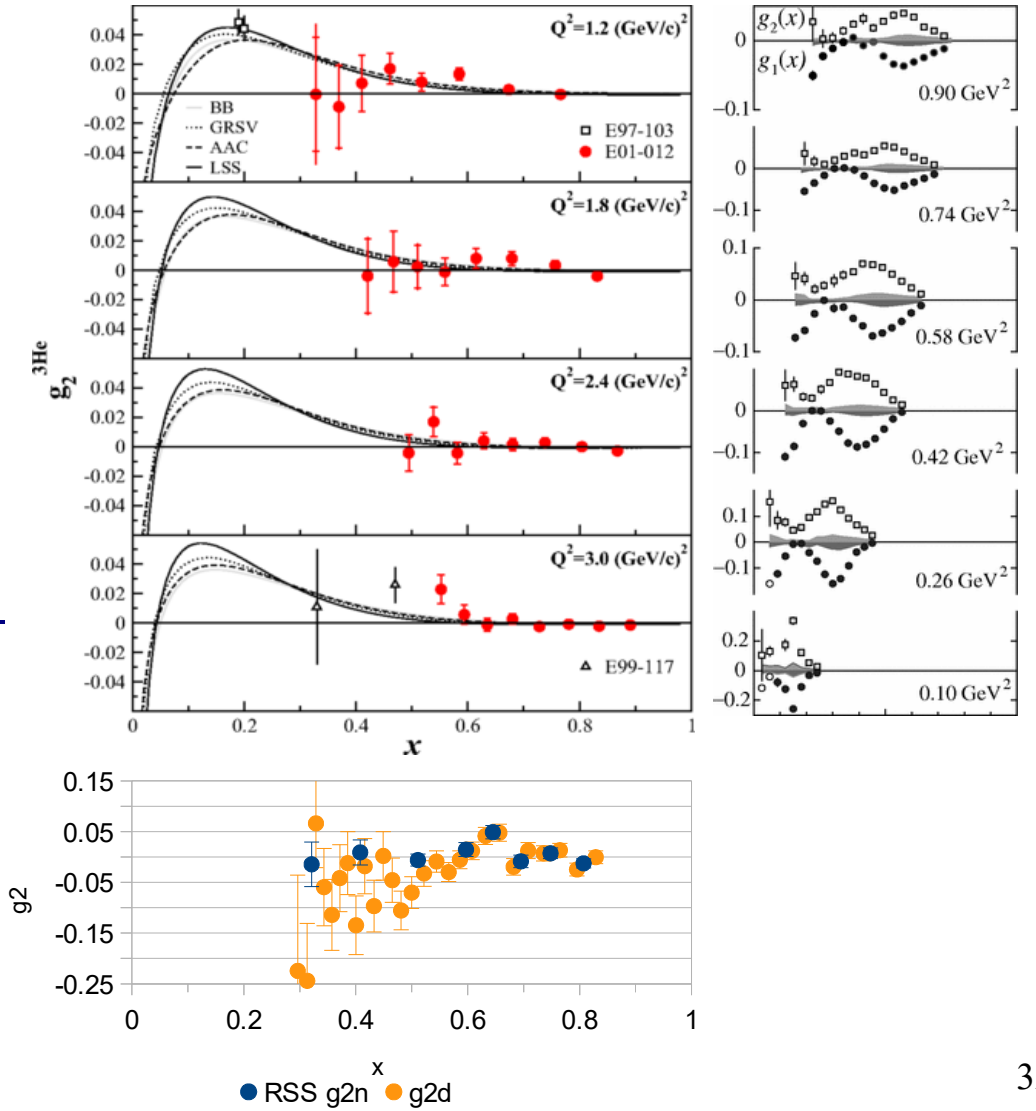
- RSS: only published precision resonances results to date
- Parasitic HMS SANE proton data:
  - new data at $Q^2 = 1.8$ GeV^2
  - extend RSS low x range at 1.3 GeV^2



(SANE: H. Kang)

g_2 in the Resonances Region

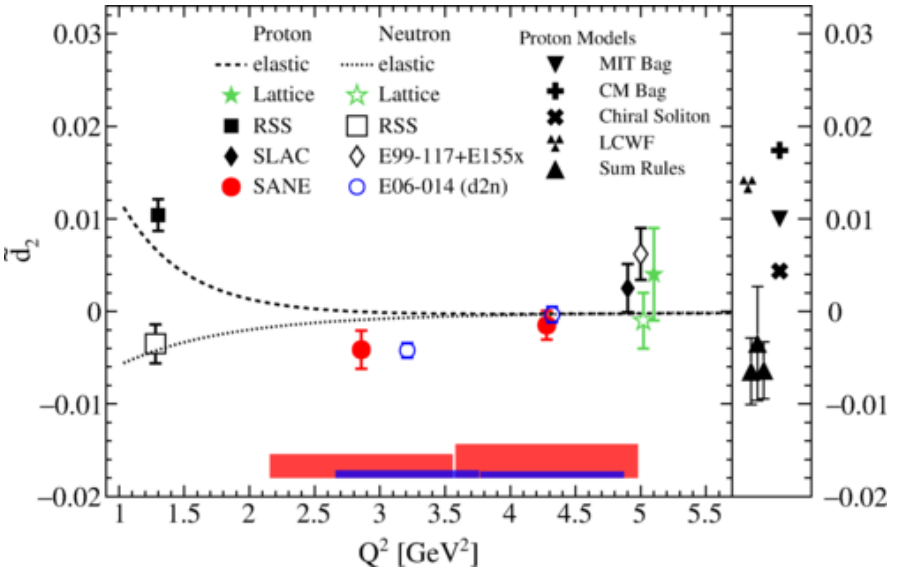
- Resonances data
  - JLab Hall A ^{3}He experiments
    - E94-010
    - E01-012
  - RSS on ammonia
    - g_2^n from g_2^d and Atwood-Watson smeared g_2^p
      (*n* result unpublished – S. Tajima)



E94-010 PRL **89**, 242301 (2002)
E01-012 PRL **101**, 182502 (2008)

d_2^p

- RSS plotted Nachtmann integral over $0 \leq x \leq 1$
  - measured only
    - $d_2^p = (37 \pm 6)10^{-4}$
    - $d_2^n = (15 \pm 12)10^{-4}$
- Unexpected SANE $d_2 < 0$
    - $d_2^p(\langle Q^2 \rangle = 3.4\ \text{GeV}^2)$ $= (-31 \pm 25)10^{-4}$ (total error)
    - consistent with d_2^n
    - no significant elastic parts



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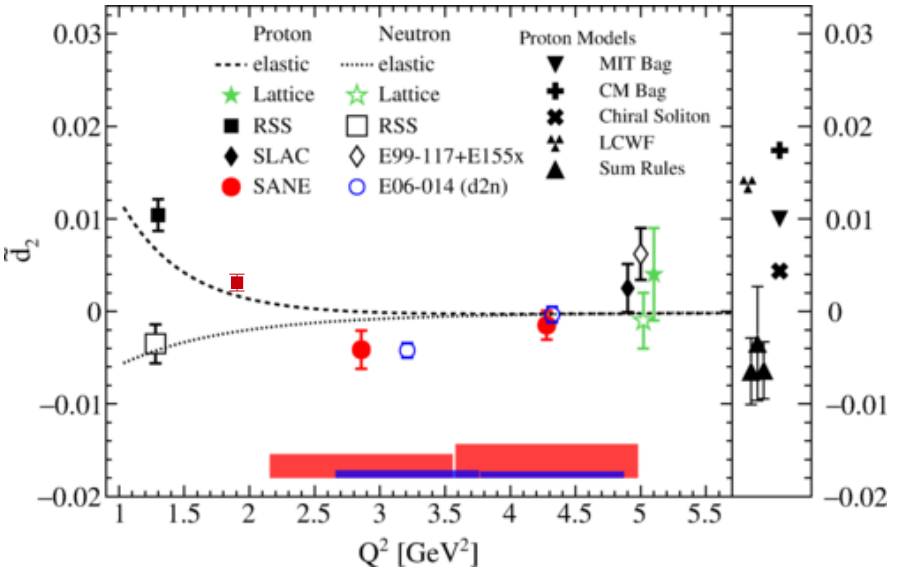
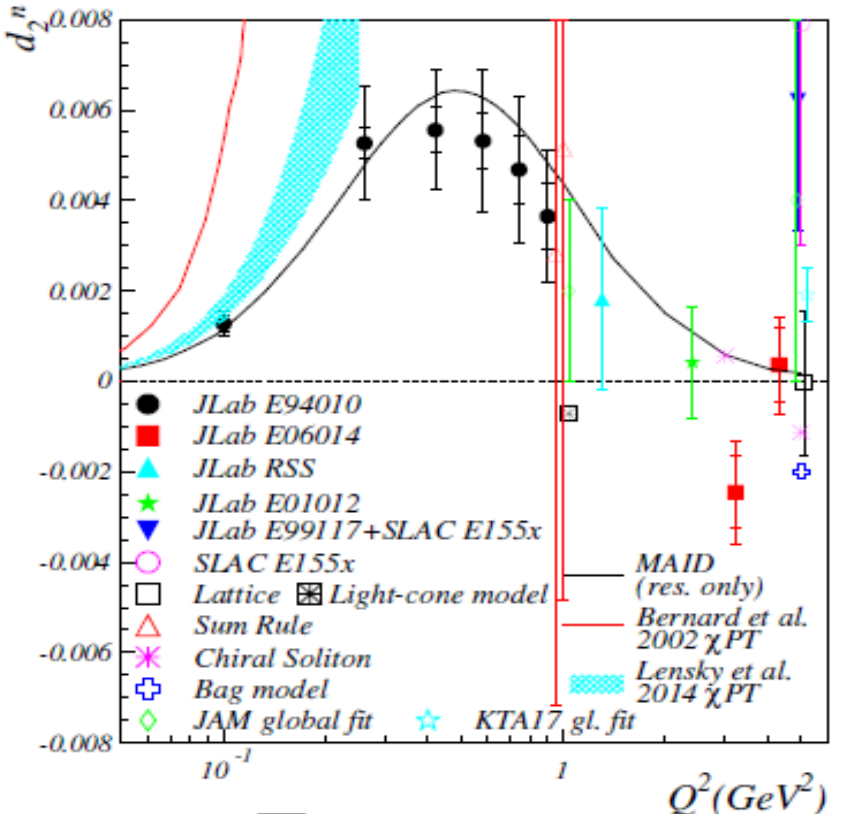
    - consistent with d_2^n
    - no significant elastic parts
  - SANE resonances 1.9 GeV^2 (preliminary)



W. Armstrong *et al.*, PRL **122,** 022002 (2019)
SANE resonances: H.Kang

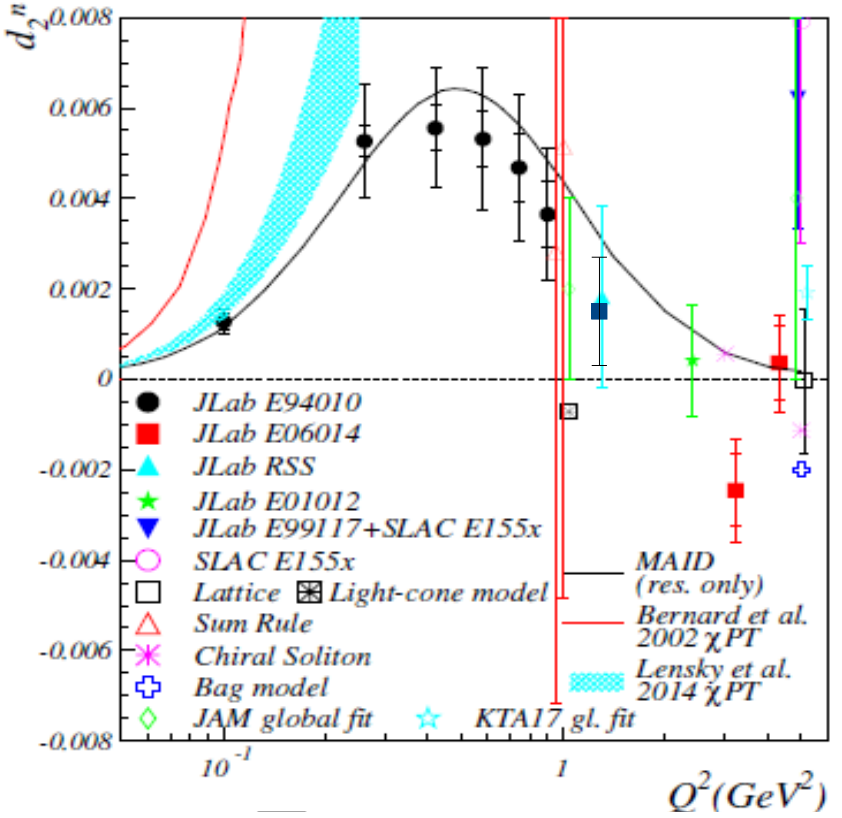
d_2^n

- Comments
  - SLAC d_2^n from $d_2^d/\gamma_D - d_2^p$
    - C-N moments only
    - γ_D =*D*-state correction



d_2^n

- Comments
  - SLAC d_2^n from $d_2^d/\gamma_D - d_2^p$
    - C-N moments only
    - γ_D =*D*-state correction
  - RSS Nachtmann moment
    - dark blue point shows resonances only
    - d_2^n from *p*, *d* moments has only *O*(1%) subtraction error (no smearing)



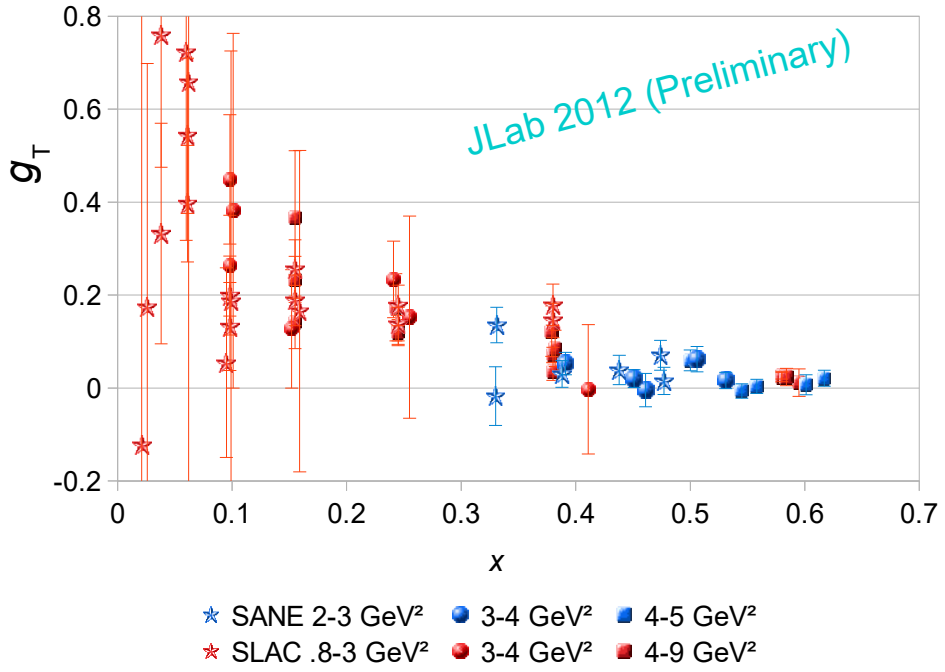
A. Deur, S. Brodsky and G. de Terramond
arXiV:1807.05250v2 [hep-ph] 19 Dec 2018
RSS PRL**105**, 101601 (2010)

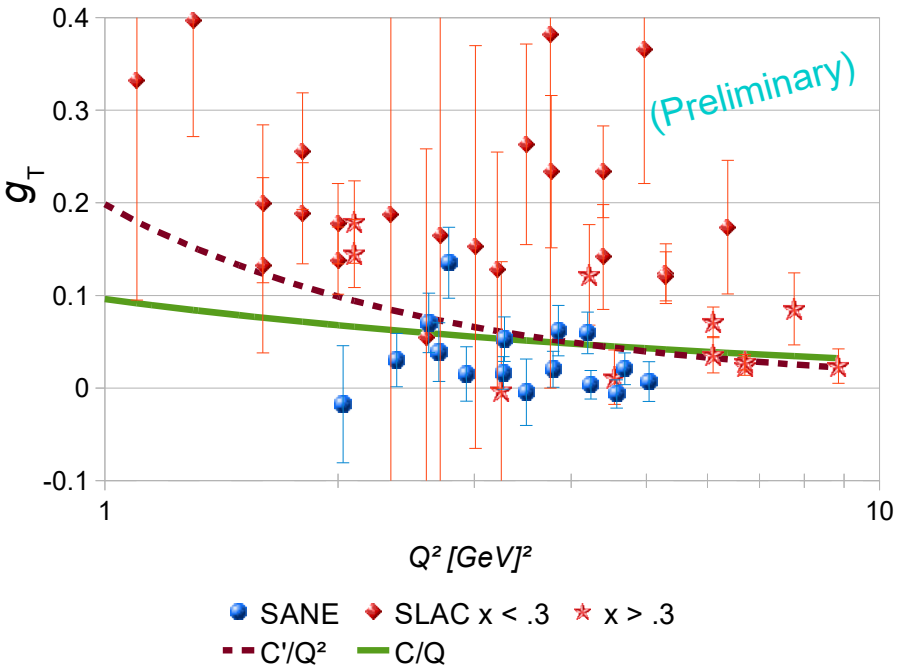
The Future

- Clear results of small but non-zero twist-3 but questions remain:
  - unexpected proton $d_2 < 0$
  - higher Q^2 neutron results have large errors
- Need updated Lattice QCD calculations: most recent is from 2005
- Use SANE results in global fits to PDF's
- Need higher precision proton g_2: SANE's goal was partially limited by experimental issues
- Need deuteron "SANE": for singlet d_2 and to compare with ^{3}He

Extras

DIS Transverse Spin SF g_T^p

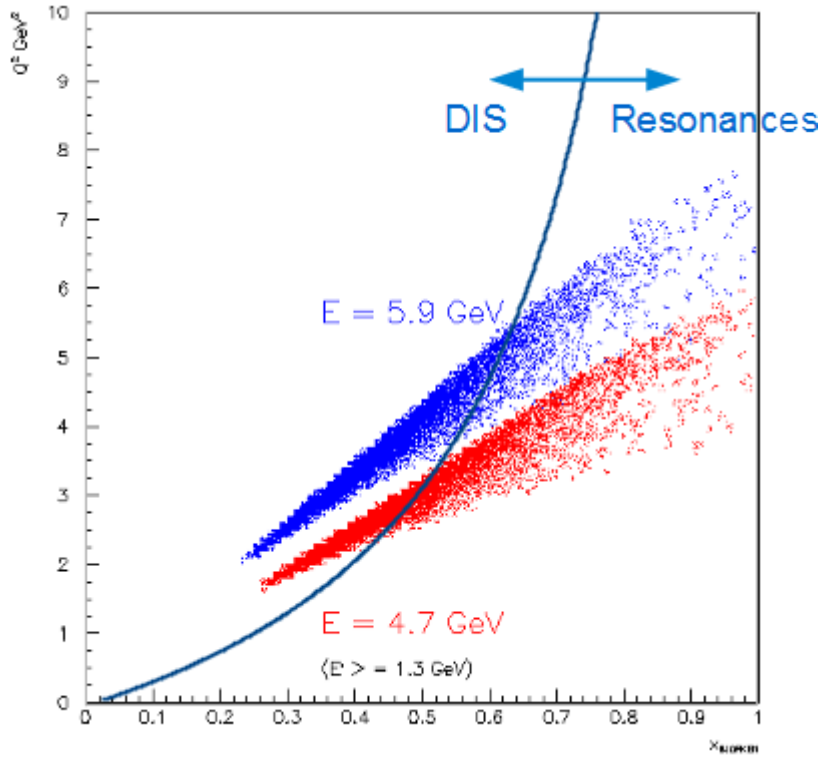


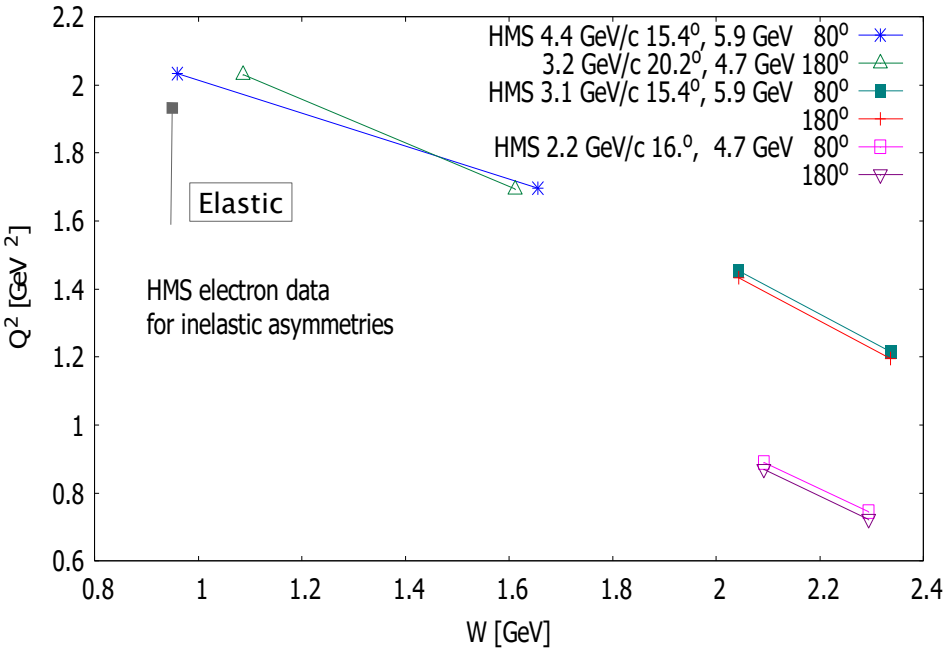


- $g_T^p = F_1 A_2/\gamma$ measures spin distribution normal to γ^*
- SANE $\langle g_T^p(x>.3)\rangle = 0.023 \pm 0.006$

- g_T evolution non-trivial: no NLO simplification (NPB 608 (2001) 235)
- d_2's pQCD evolution is known (Shuryak-Vainshtein)

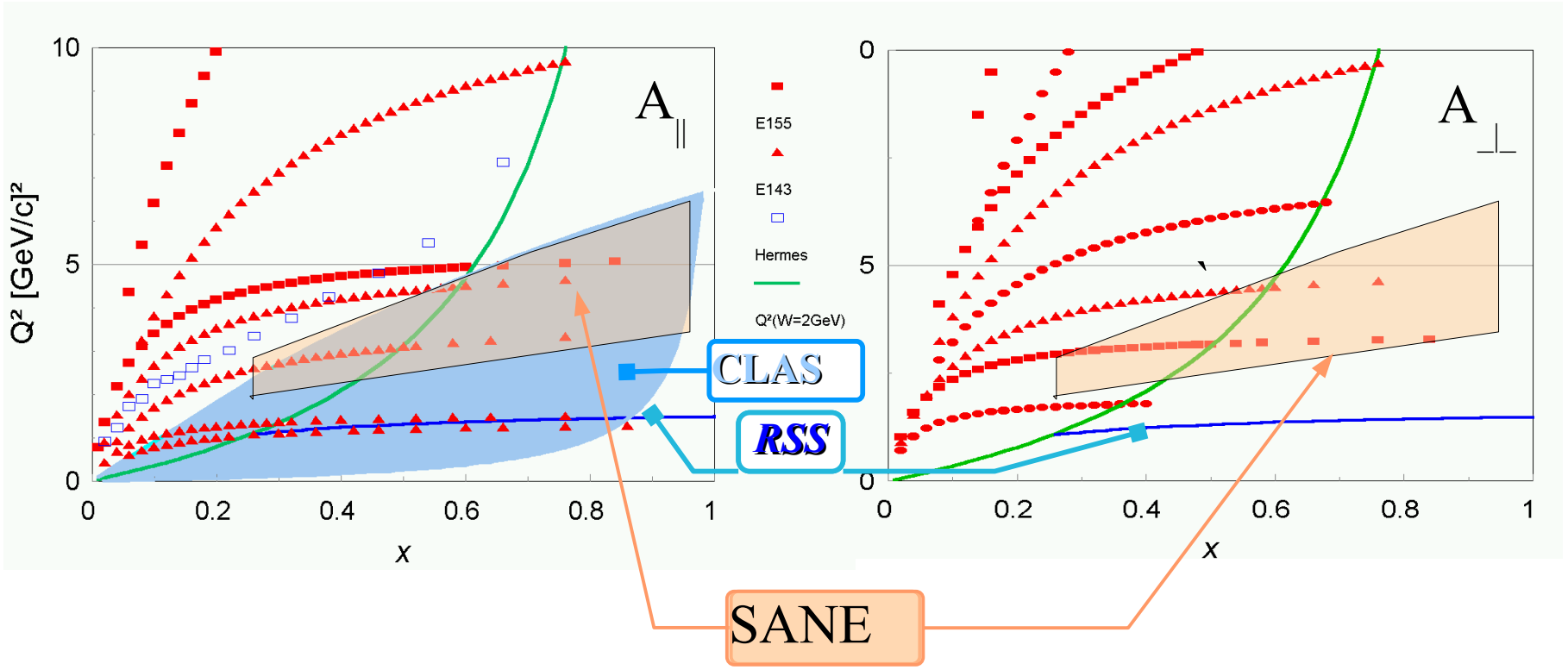
BETA and HMS data





- $Q^2 - x$ phase space of BETA's 80° data
  - cut on E' ≥ 1.3 GeV
- Central kinematics of HMS inclusive asymmetry data

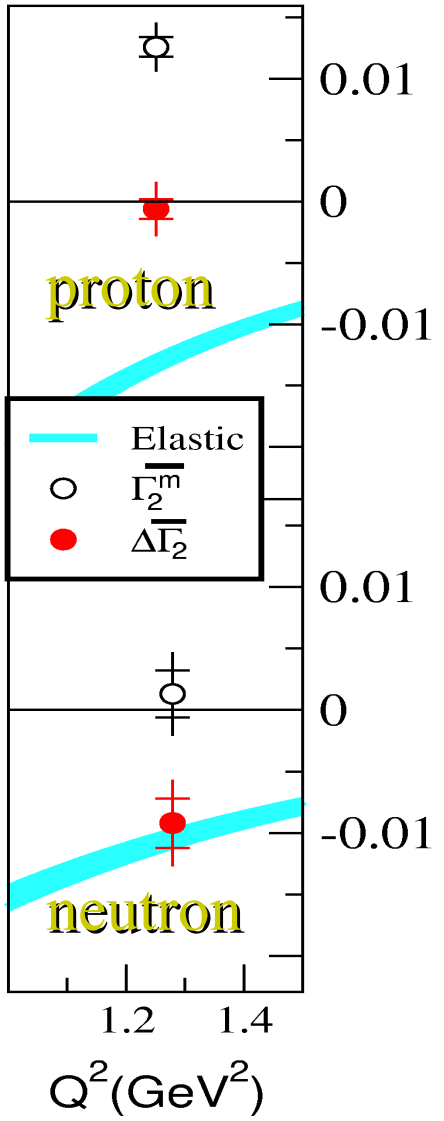
Proton world $A_{\parallel}$, $A_{\perp}$ data before SANE



- Two beam energies: 5.9 GeV, 4.7 GeV
- Very good high ***x*** coverage with detector at 40°

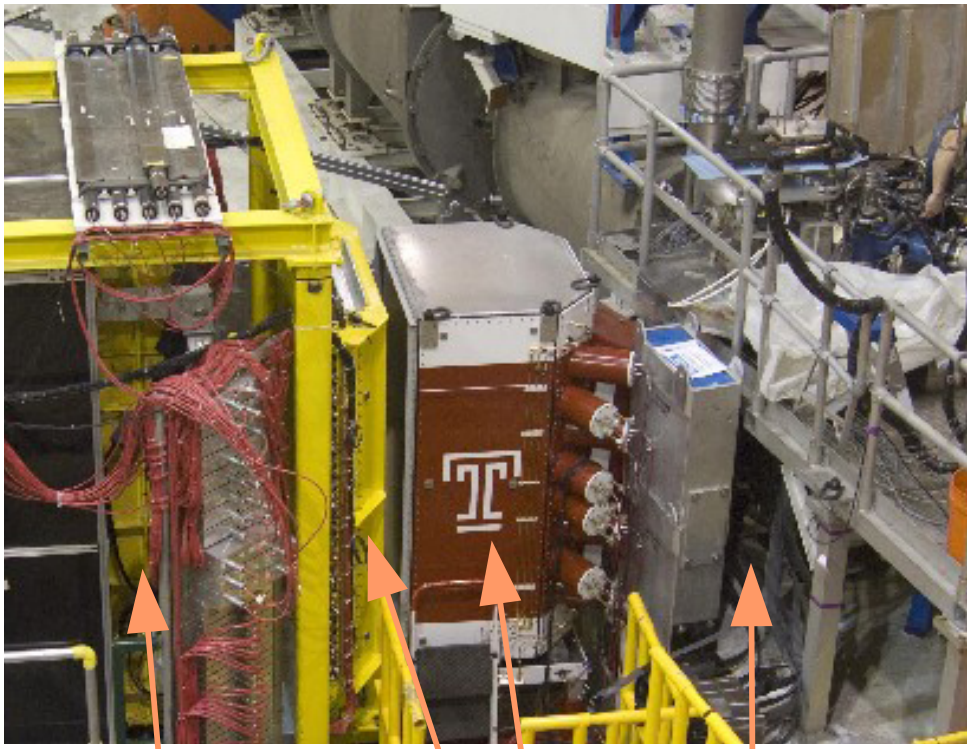
Twist-3 and the Burkhardt-Cottingham Sum Rule

- BC sum rule $\Gamma_2 = 0 = \Gamma_2^{WW} + \bar{\Gamma}_2 + \Gamma_2(\text{el})$
  - dispersion relation not from OPE, free from gluon radiation, TMC's
  - twist-2 part $\Gamma_2^{WW} \equiv 0$
- BC is higher-twist + elastic
  - $\Gamma_2 = \bar{\Gamma}_2(\text{unm.}) + \bar{\Gamma}_2(\text{measur.}) + \Gamma_2(\text{el})$
  - $\Delta\bar{\Gamma}_2 = \Gamma_2 - \bar{\Gamma}_2(\text{u}) = \bar{\Gamma}_2(\text{m}) + \Gamma_2(\text{el})$
- $\Delta\bar{\Gamma}_2 \neq 0$: assuming BC, implies significant HT at $x < x_{min}$, **or**, if twist-3 ~ 0 at low x,
  - BC fails: isospin dependence? nuclear effects?

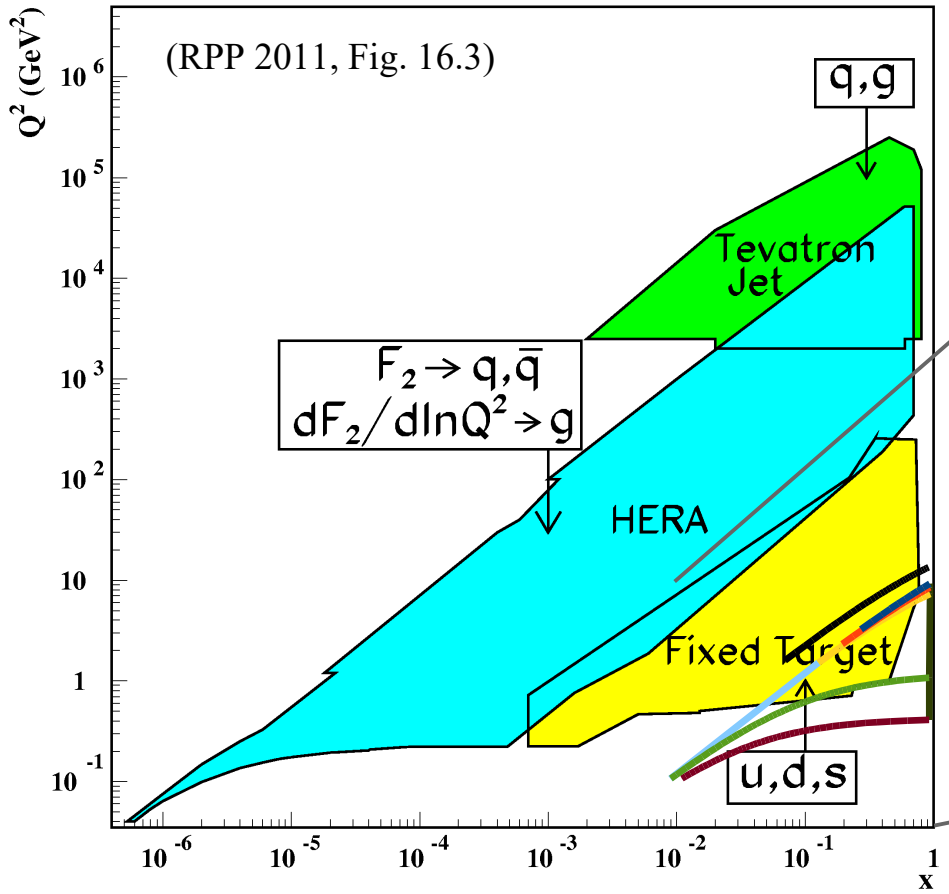


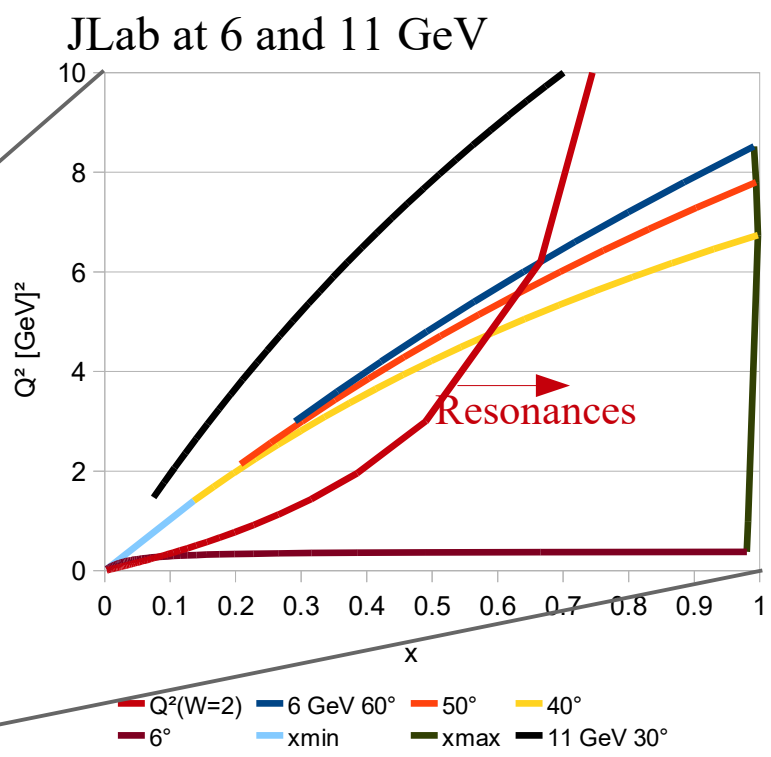
Big Electron Telescope Array – BETA

- BETA specs
  - Effective solid angle 0.194 sr
  - Energy resolution $10\%/\sqrt{E(\text{GeV})}$
  - 1000:1 pion rejection
  - angular resolution ~ 1 mr
- Non-magnetic detector
  - detects DIS e and e^+e^- pairs: need to cut on minimum E'
  - Target field helps sweep lowest E background (180 MeV/c cutoff)



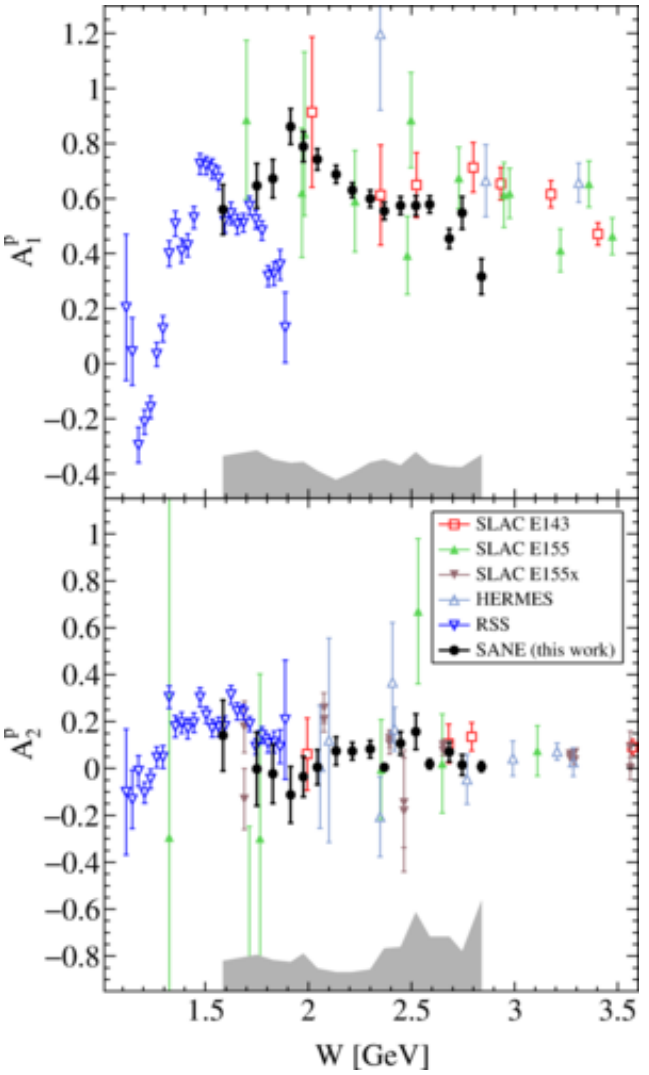
Kinematics Space at JLab





A_1, A_2

- Spin asymmetries A_1, A_2



W. Armstrong *et al.*, PRL **122,** 022002 (2019)