Low Q^2 Spin Moments of Neutron and ^{3}He From JLab E97-110

Jian-ping Chen, Jefferson Lab, For the JLab E97-110 Collaboration

ECT* Workshop on Nucleon Spin at Low Q: A Hyperfine View, Trento, July 2-6, 2018

- Introduction: Moments of Spin Structure Function
  - g_1: GDH Sum Rule, γ_0 Spin Polarizability
  - g_2 : B-C Sum Rule, δ_{LT} Spin Polarizability
- JLab E97-110 experiment @ Hall A :
  - Setup and Polarized ^{3}He target
  - g_1 and g_2, GDH sum, B-C Sum, γ_0 and δ_{LT} on neutron at very low Q^2
  - g_1 and g_2, GDH and g_0 on ^{3}He at very low Q^2
- Summary

Thanks A. Deur, C. Peng, V. Solkosky, … for helping with slides

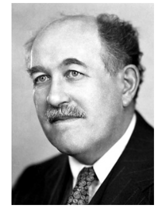
Nucleon Structure and Strong Interaction/QCD

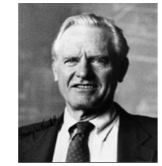
- **Nucleon Structure: discoveries**
  -- anomalous magnetic moment (1943 Nobel)
  -- elastic: form factors (1961 Nobel)
  -- DIS: parton distributions (1990 Nobel)

- **Strong interaction, running coupling ~1**
  -- asymptotic freedom (2004 Nobel)
  perturbation calculation works at high energy
  -- interaction significant at intermediate energy
  quark-gluon correlations
  -- interaction strong at low energy
  confinement

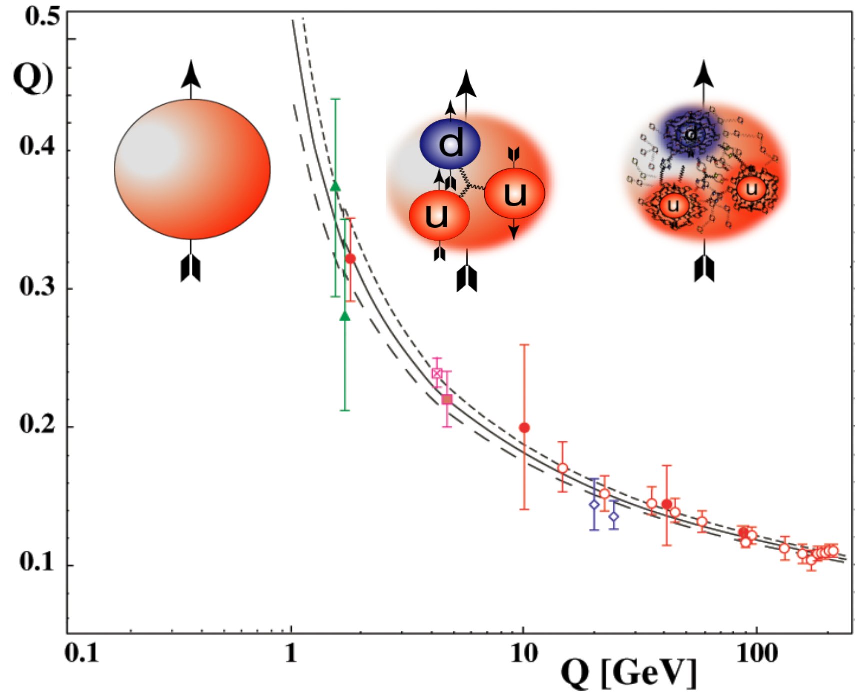
- **A major challenge in fundamental physics:**
  -- Understand QCD in all regions, including strong (confinement) region

- **Theoretical Tools:**
  pQCD, Lattice QCD, ChPT, Sum Rules, …



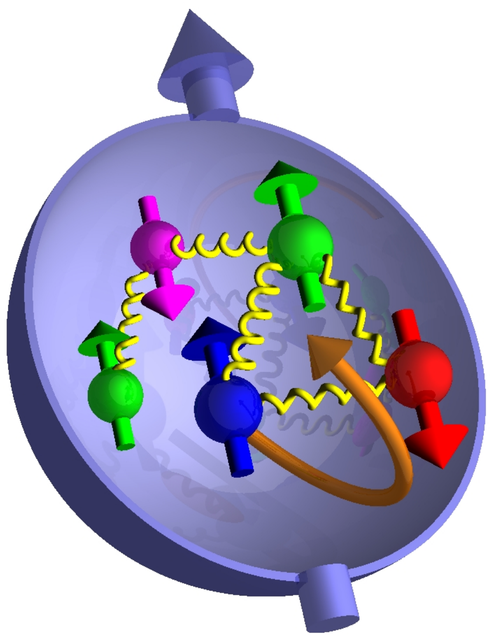




running coupling "constant"



Moments of Spin Structure Functions

Sum Rules, Polarizabilities



Sum Rules

➔

Gerasimov-Drell-Hearn (GDH) Sum Rule

$$I_{\rm GDH} = \int_{\nu_{\rm th}}^{\infty} \frac{\sigma_{\frac{1}{2}}(\nu) - \sigma_{\frac{3}{2}}(\nu)}{\nu} d\nu = -2\pi^2\alpha(\frac{\kappa}{M})^2$$

- **Circularly polarized photons incident on a longitudinally polarized target.**
- **$\sigma_{1/2}$ ($\sigma_{3/2}$) Photoabsorption cross sections.**
- **Relate spin structure to anomalous magnetic moment κ.**
- **Solid theoretical predictions based on general principles**
  - Lorentz invariance, gauge invariance → low energy theorem
  - unitarity → optical theorem
  - casuality → unsubtracted dispersion relation

    applied to forward Compton amplitude

- **Proton: verified (<10%): Mainz, Bonn, LEGS.**
- **Deuteron, ^{3}He Mainz, Bonn, LEGS, HiGS**

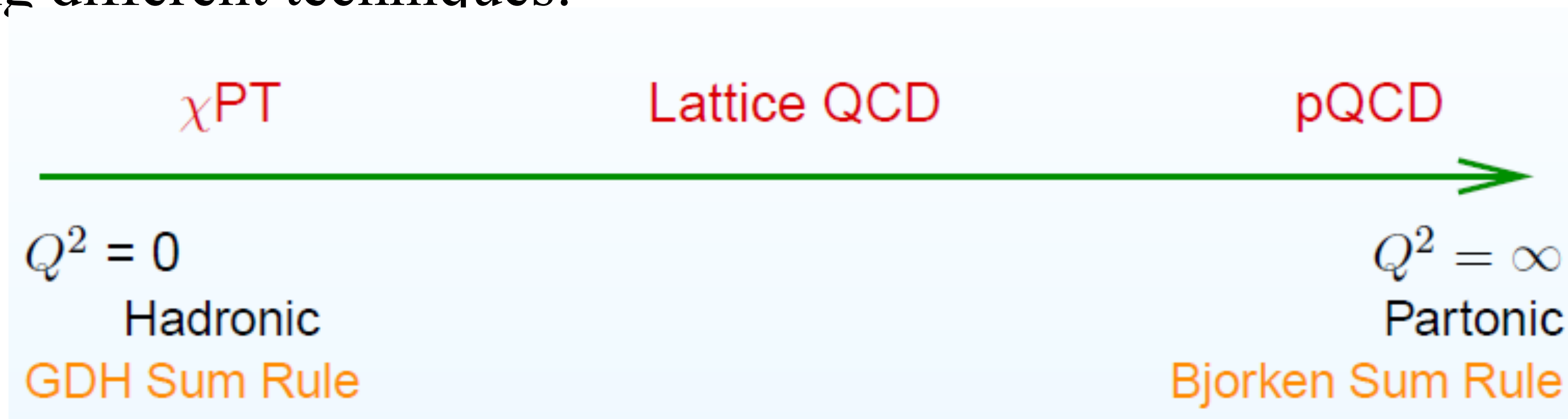
	M [GeV]	Spin	κ	$I_{\rm GDH}$ [μ b]
Proton	0.938	$\frac{1}{2}$	1.79	–204.8
Neutron	0.940	$\frac{1}{2}$	-1.91	–233.2
Deuteron	1.876	1	-0.14	–0.65
Helium-3	2.809	$\frac{1}{2}$	-8.38	–498.0

Generalized GDH sum rule

Sum rule valid at all Q^2: $$\frac{16\alpha\pi^2}{Q^2}\int_0^{1^-} g_1\,dx = 2\alpha\pi^2 S_1$$

(Ji and Osborne, …)

We can measure $\int g_1\,dx$ at different Q^2 and compute ***Compton amplitude*** using different techniques:



$\Rightarrow$ Study "strong" (non-perturbative) QCD and transition from hadronic to partonic description of strong force.

Experiment Summary ($Q^2 > 0$)

Observable	H target	D target	^{3}He target
g_1, g_2, Γ_1 & Γ_2 at high Q^2	SLAC JLAB SANE	SLAC	SLAC JLAB E97-117 JLAB E01-012 JLAB E06-014
g_1 & Γ_1 at high Q^2 COMPASS RHIC-Spin	SMC HERMES JLAB EG1	SMC HERMES JLAB EG1	HERMES
Γ_1 & Γ_2 at low Q^2	JLab RSS	JLab RSS	JLab E94-010 JLab E97-103
Γ_1 at low Q^2	SLAC HERMES JLAB EG1	SLAC HERMES JLAB EG1	HERMES
$\Gamma_1, Q^2 << 1$ GeV^2	JLab EG4	JLab EG4	JLab E97-110
$\Gamma_2, Q^2 << 1$ GeV^2	JLab E08-027		JLab E97-110

Q^2=0 **Mainz, Bonn, LEGS, HIGS**

1st Moments of Spin Structure Functions g_1 and g_2

GDH Sum Rule

Burkhardt - Cottingham Sum Rule

(Before E97-110)

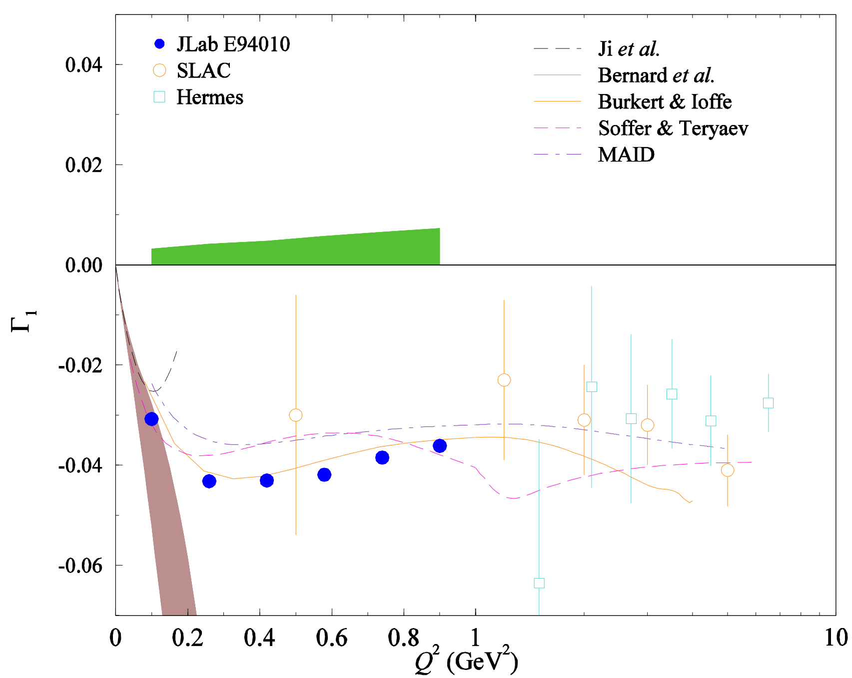
E94-010: Neutron spin structure moments and sum rules at Low Q^2

Spokespersons: G. Cates, J. P. Chen, Z.-E. Meziani

PhD Students: A. Deur, P. Djawotho, S. Jensen, I. Kominis, K. Slifer

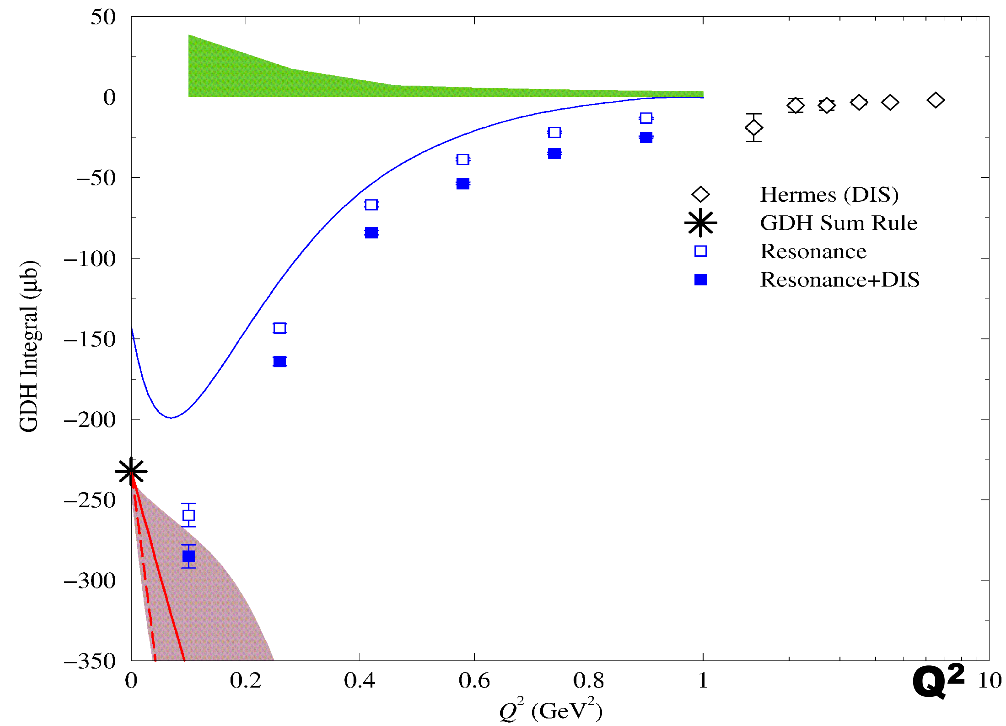
- Q^2 evolution of spin moments and generalized GDH sum, $0.1 < Q^2 < 0.9$ (GeV^2)
- transition from quark-gluon to hadron. Test χPT calculations

1^{st} moment of g_1 on neutron



PRL 92 (2004) 022301

GDH integral on neutron



PRL 89 (2002) 242301

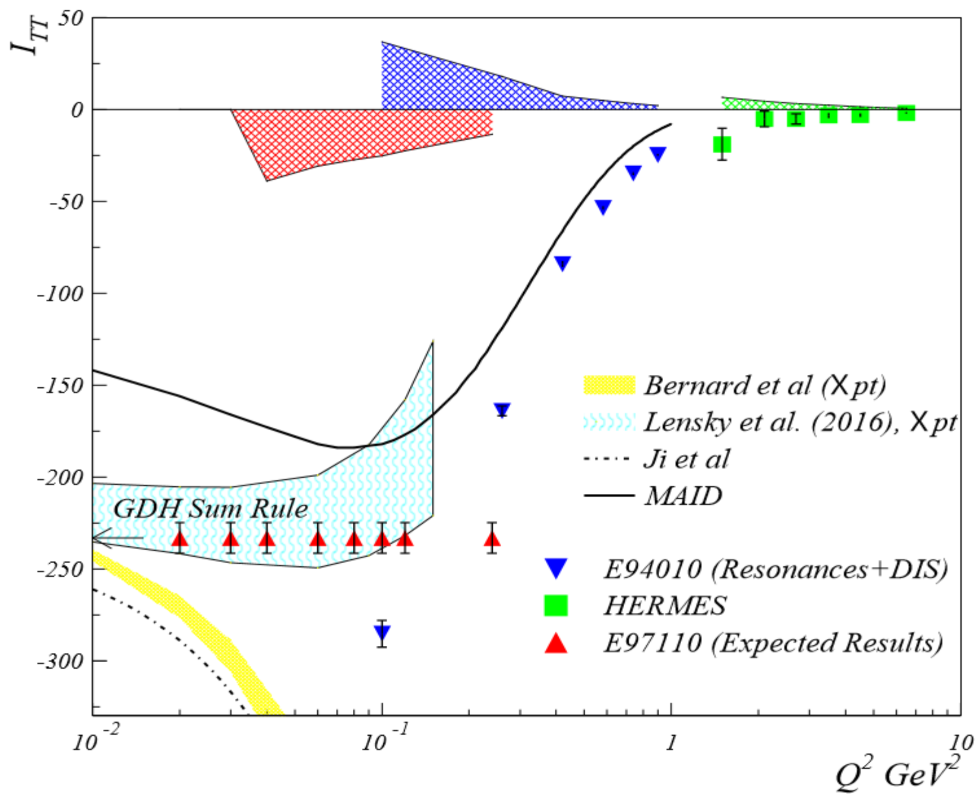
E97-110: Small Angle GDH on the Neutron (^{3}He)

Spokesmen: J.-P. Chen, A. Deur, F. Garibaldi

PhD Students:* V. Solkosky*, *J. Singh*, *J. Yuan*, *C. Peng, N. Ton

- Measurement of spin moments at low Q^2, 0.02 to 0.24 GeV^2 for the neutron and ^{3}He
- Covering an unmeasured region of kinematics to test Chiral Perturbation theory calculations
- Complements data from experiment E94-010
- Both neutron and ^{3}He results nearly finalized,

  publications in draft form
- The lowest Q^2 data (first period) still to be finalized



Experimental Considerations/Difficulties

- unpolarized proton at intermediate Q^2: easy to measure
- longitudinal polarized proton at intermediate Q^2: not too hard?

need low $Q^{2,}$ need transverse polarization, need neutron

- longitudinal polarized proton at low Q2: harder (Marco's talk)
- transverse polarized proton at low Q^2: difficult (Karl's talk)
- neutron often more difficult:

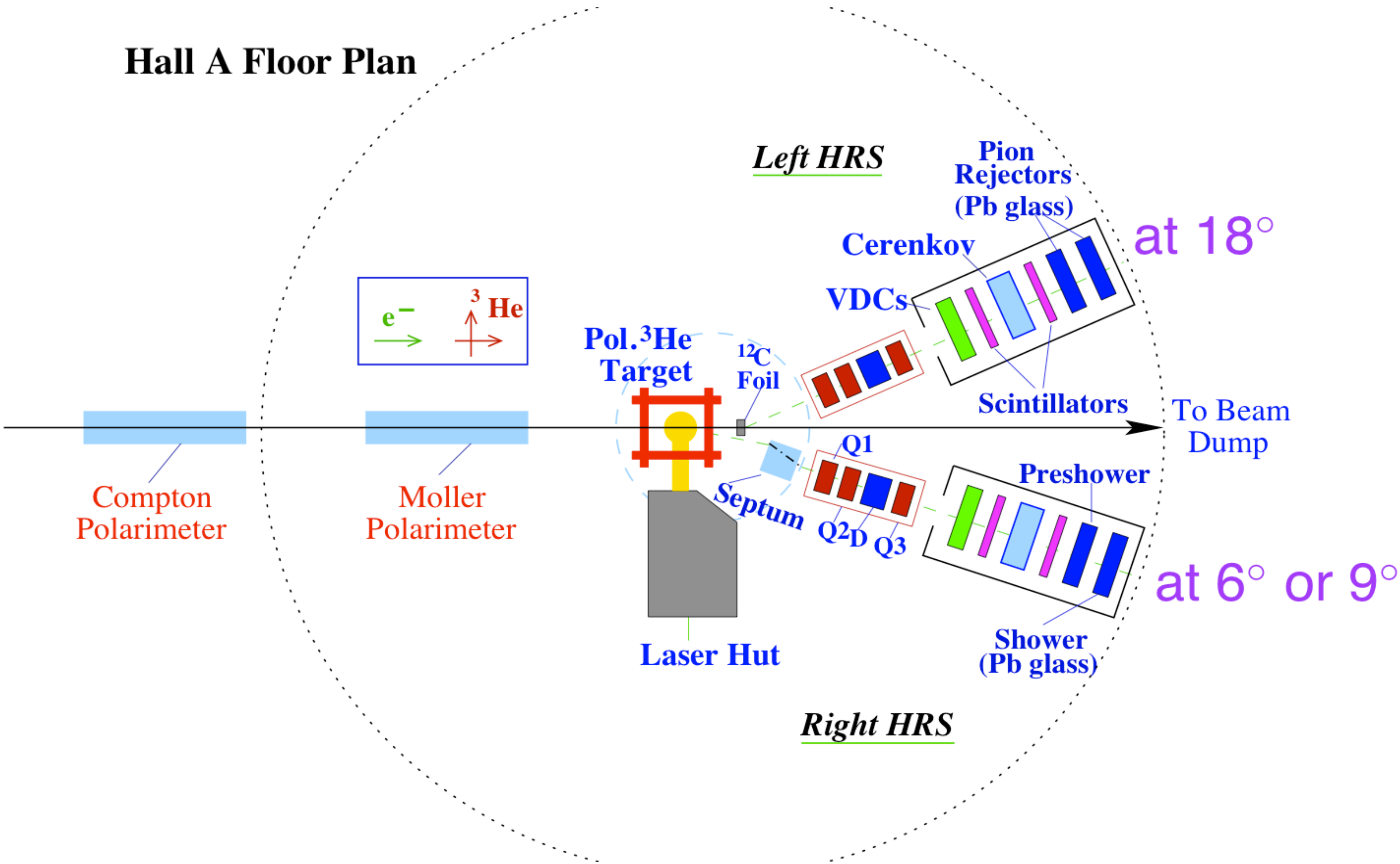
short life time → no stable neutron target

deuteron target → n ~ d – p

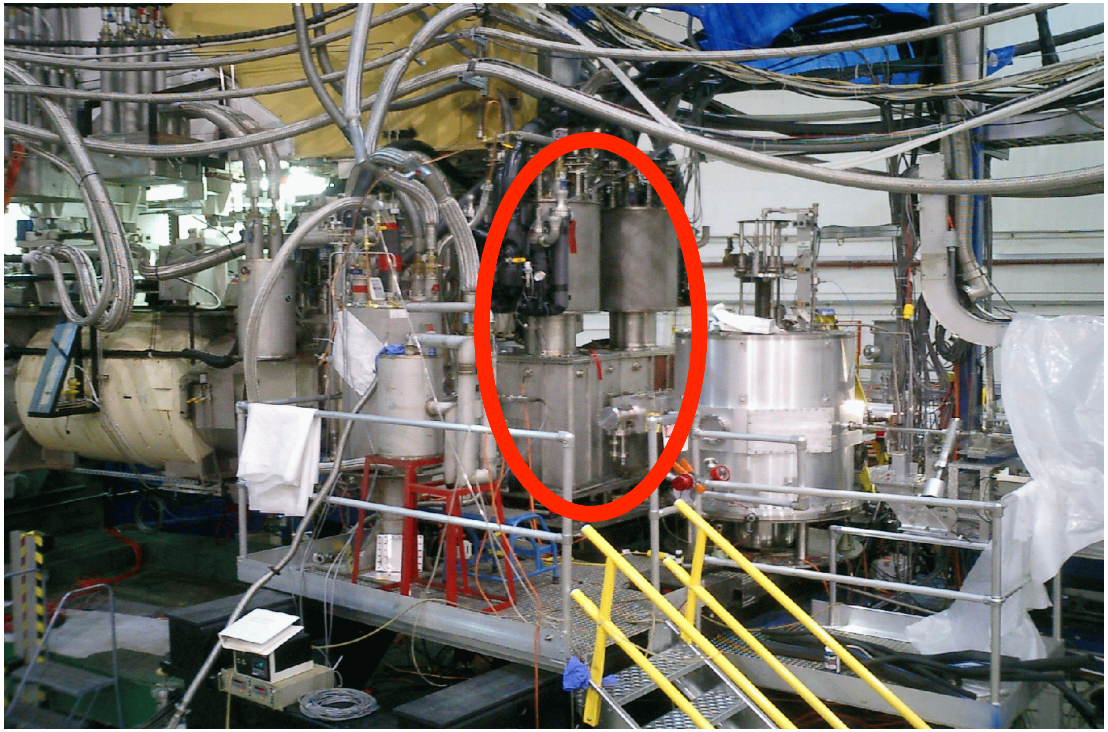
^{3}He target → n ~ ^{3}He – 2p

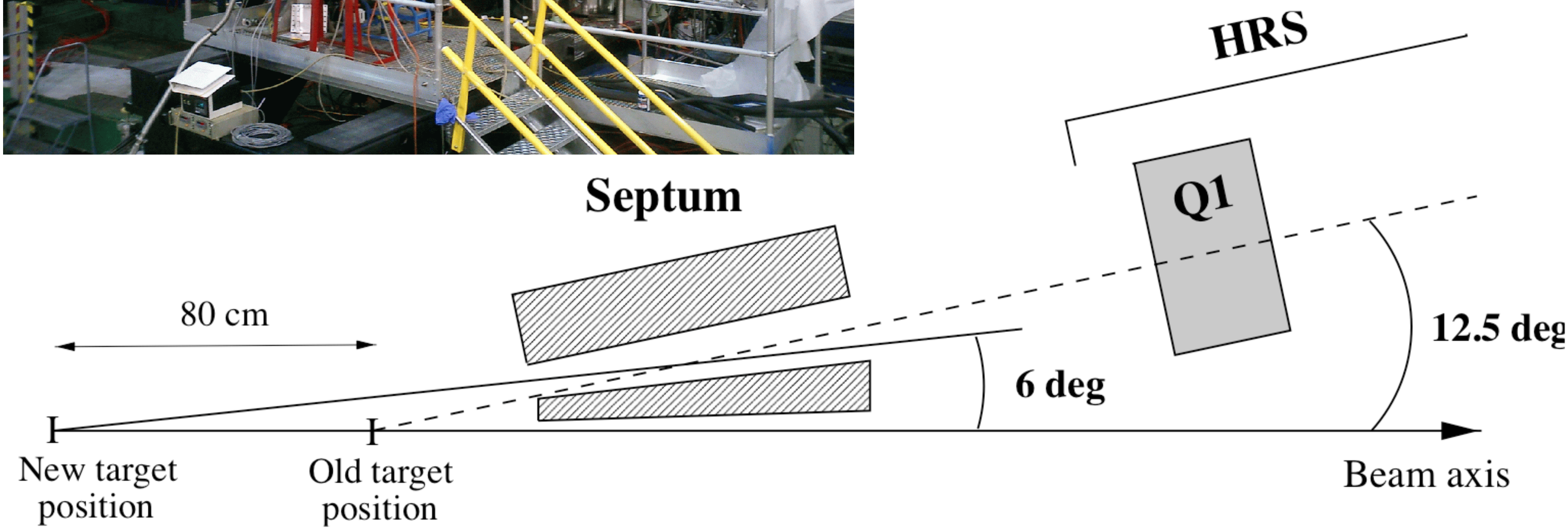
need subtract proton contributions and nuclear effect

E97-110 Experimental Setup



Low Q^2 → Reach Forward Angle: Septum Magnet





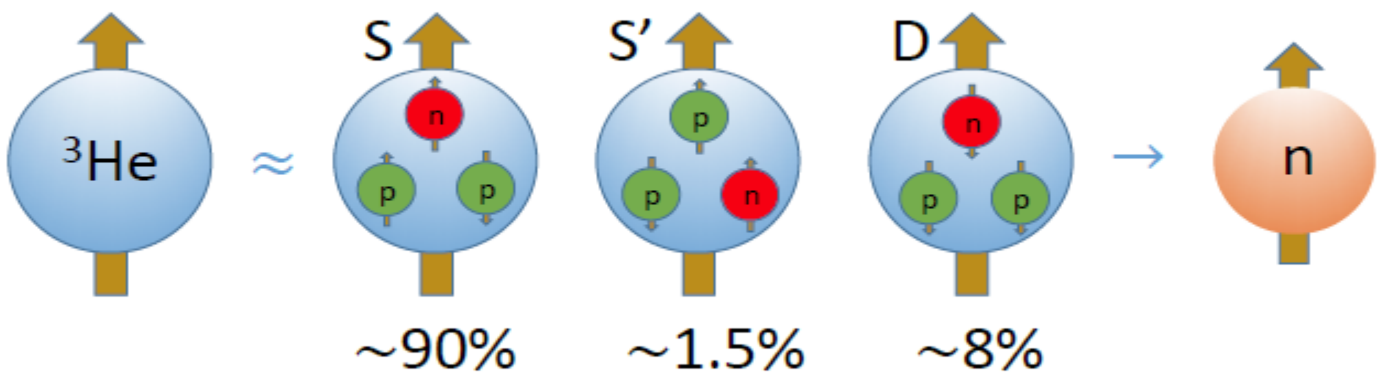
Effective Polarized Neutron Target

No free neutron target due to its short life time

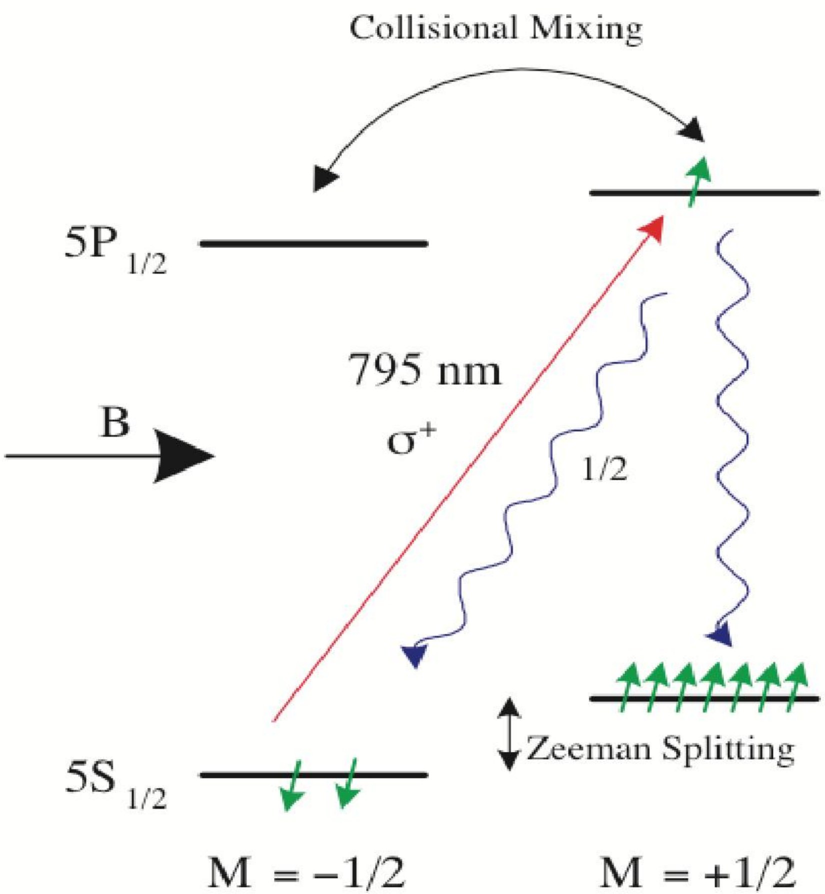
Light nuclei are used as effective neutron targets

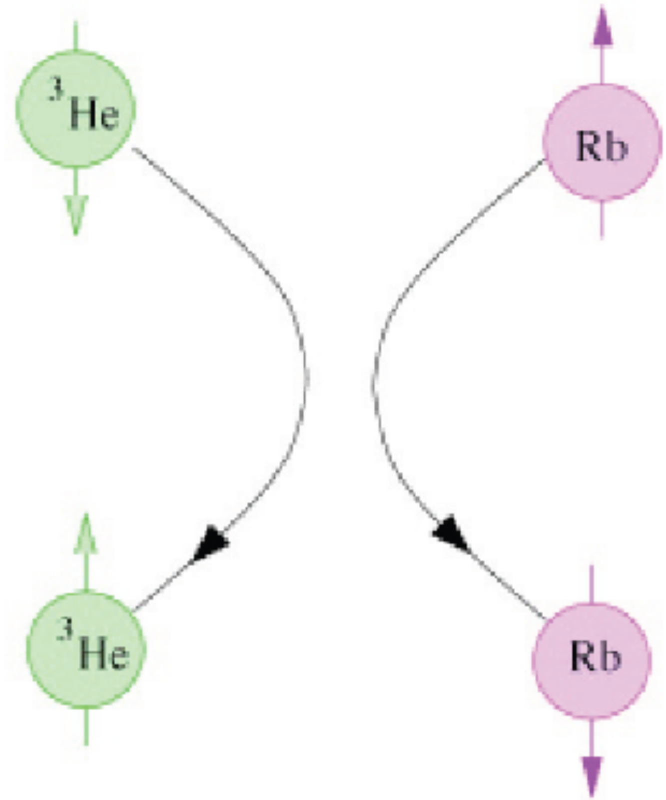
Polarized ^3He ground state is dominated by S-state

At S-state, spins of two protons cancel, 3He ~ n

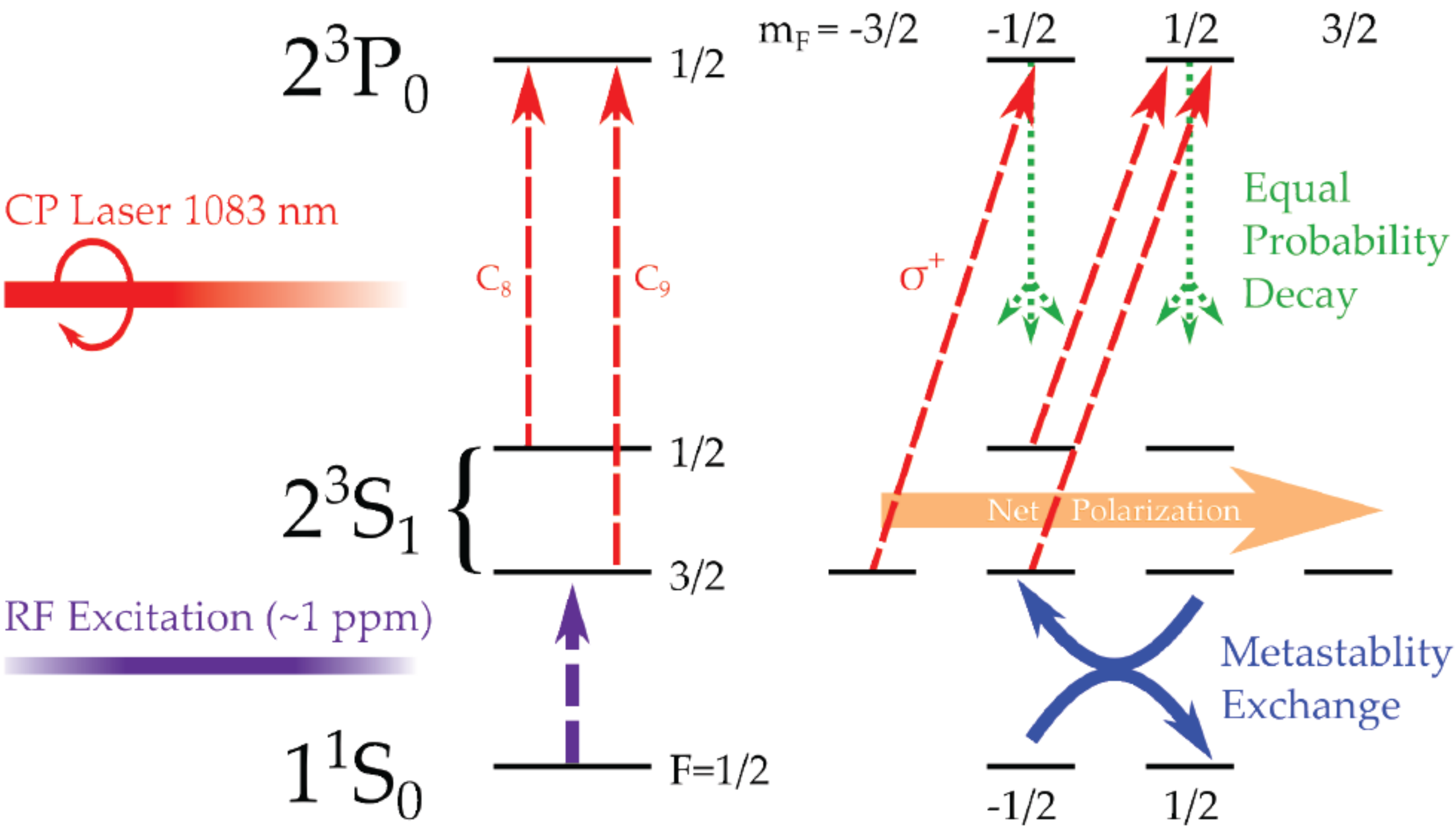


Spin exchange Optical Pumping for ^3He





Meta-stability Exchange Optical Pumping



History/Progress in Polarized ^{3}He

- Spin-Exchange Optical Pumping

1960: Bouchiat/Carver/Varnum (Princeton), PRL 5, 373 (1960)

2.8 atm ^{3}He, optically pumped 0.001 mm partial pressure of Rb, **P=0.01%**

we have observed enhancement of the nuclear polarization by a factor of 10^4 above the initial Boltzmann distribution of 10^{-8}.

Now: **10 atm ^{3}He**, Rb-K optical pumping, **P > 70% (JLab/UVa/W&M…)**

- Meta-stability Exchange Optical Pumping

1963: Colegrove/Schearer/Walters (Texas Instruments), PR, 132, 2561 (1963)

~0.001 atm ^{3}He, achieved ~40% polarization

The highest polarization measured by nuclear magnetic resonance was 40±5% in a 5 cm-diam Pyrex sphere with the He^3 gas pressure at 1 mm Hg.

Now: **~1 atm ^{3}He**, mass production with MEOP, **P > 70% (Mainz)**

Polarized Luminosity and Polarization

- Luminosity

Internal targets (storage ring)

10^{31}

Polarized external (fixed) targets

Solid (p/d) 10^{35}

Gas (^{3}He) 10^{36} (JLab)

World highest luminosity/FOM

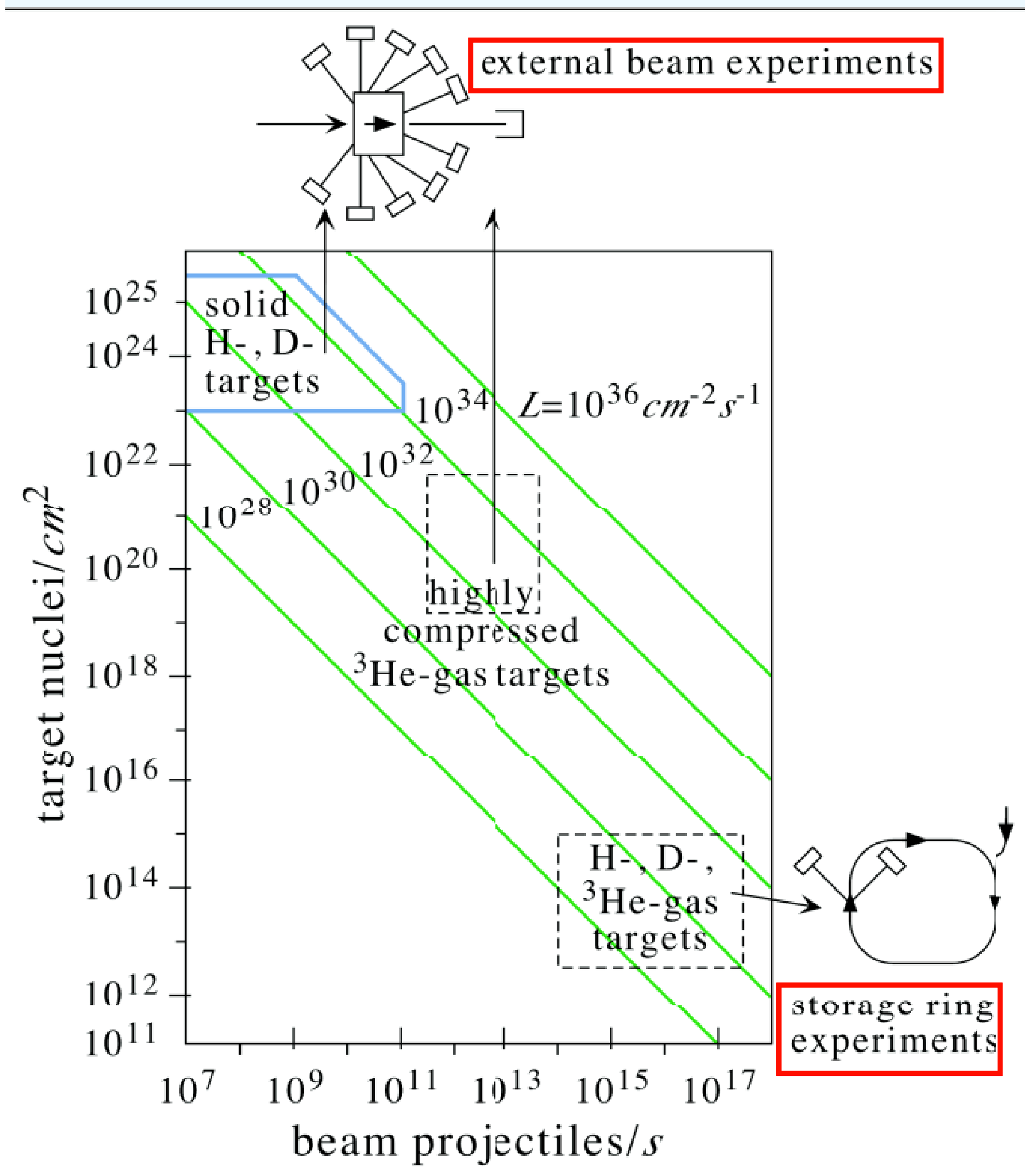
- Polarization (in-beam)

P_{3He} ~ 80% (60%) (JLab)

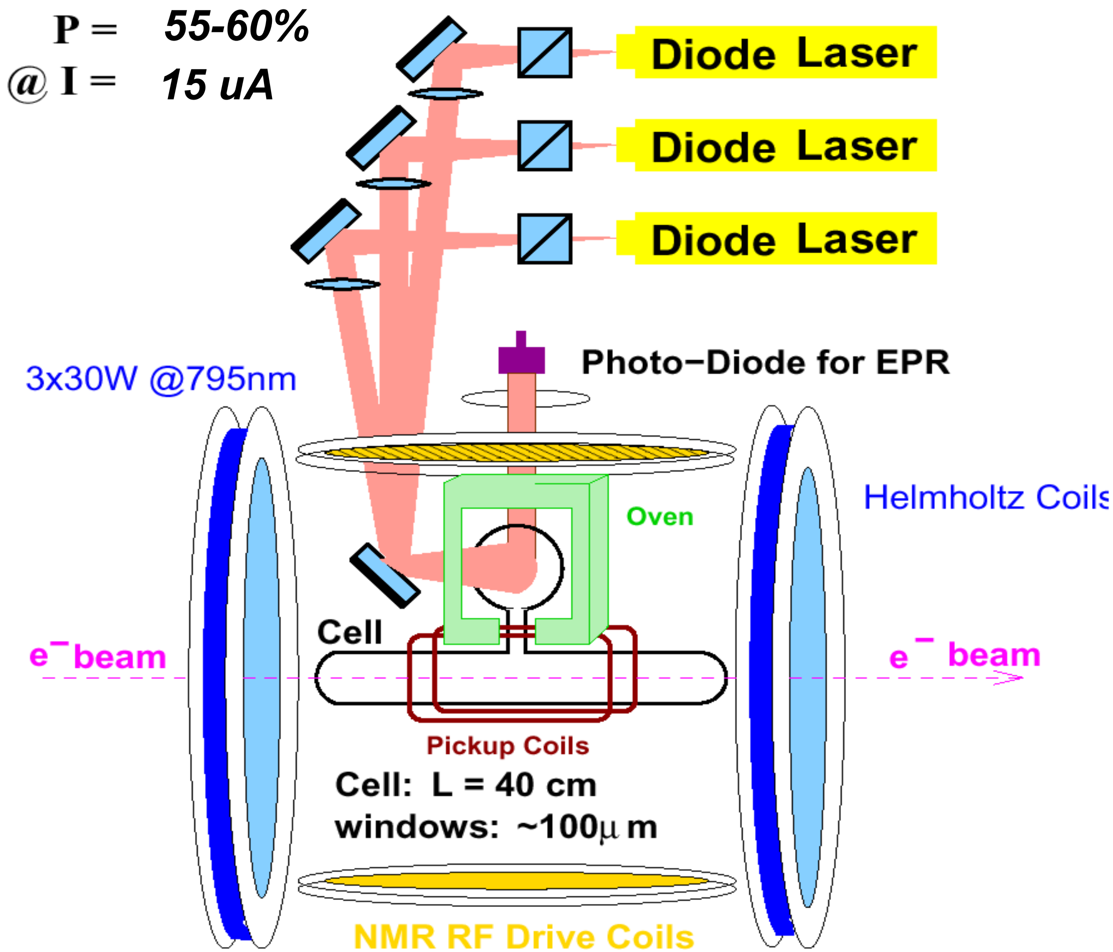
P_H ~ 90% (70%)

P_D ~ 70% (40%)

$$FOM = P_b^{\,2} * P_t^{\,2} * f^2 * L$$



JLab Polarized ^{3}He Target



✓*Effective pol neutron target*

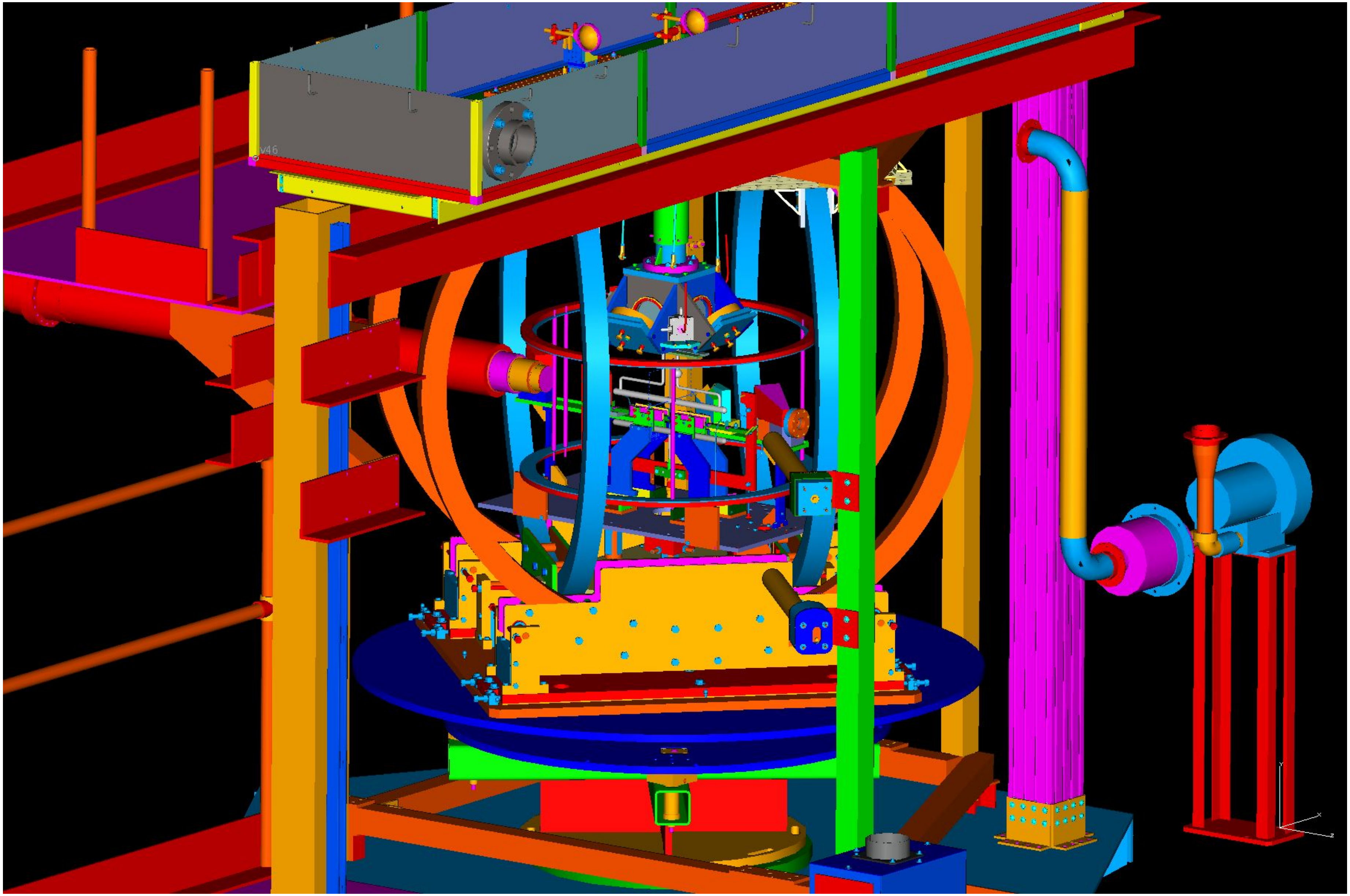
✓*longitudinal, transverse*
(and vertical)

✓*Luminosity=*10^{36} *(1/s)*
(highest in the world)
upgrade : x2 (stage I)
additional x3 (stage II)

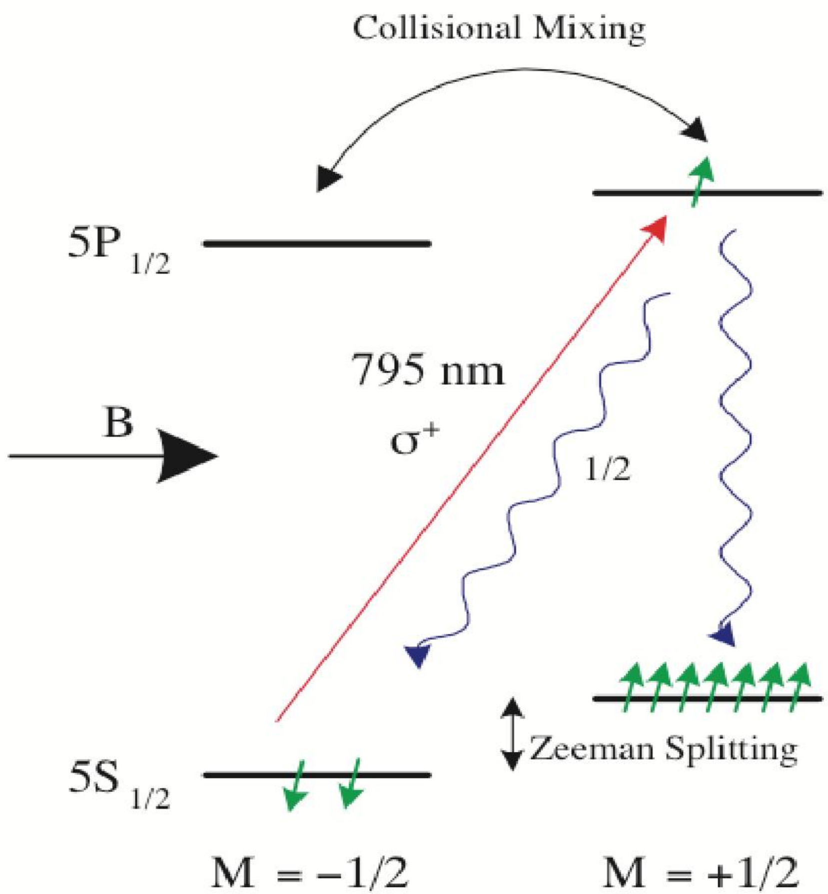
✓*High in-beam polarization*
60% (>70% no beam)

✓*13 completed experiments*
9 approved with 12 GeV (A/C)

JLab Polarized ^{3}He Target System



Rb-K Hybrid Optical Pumping for ^3He



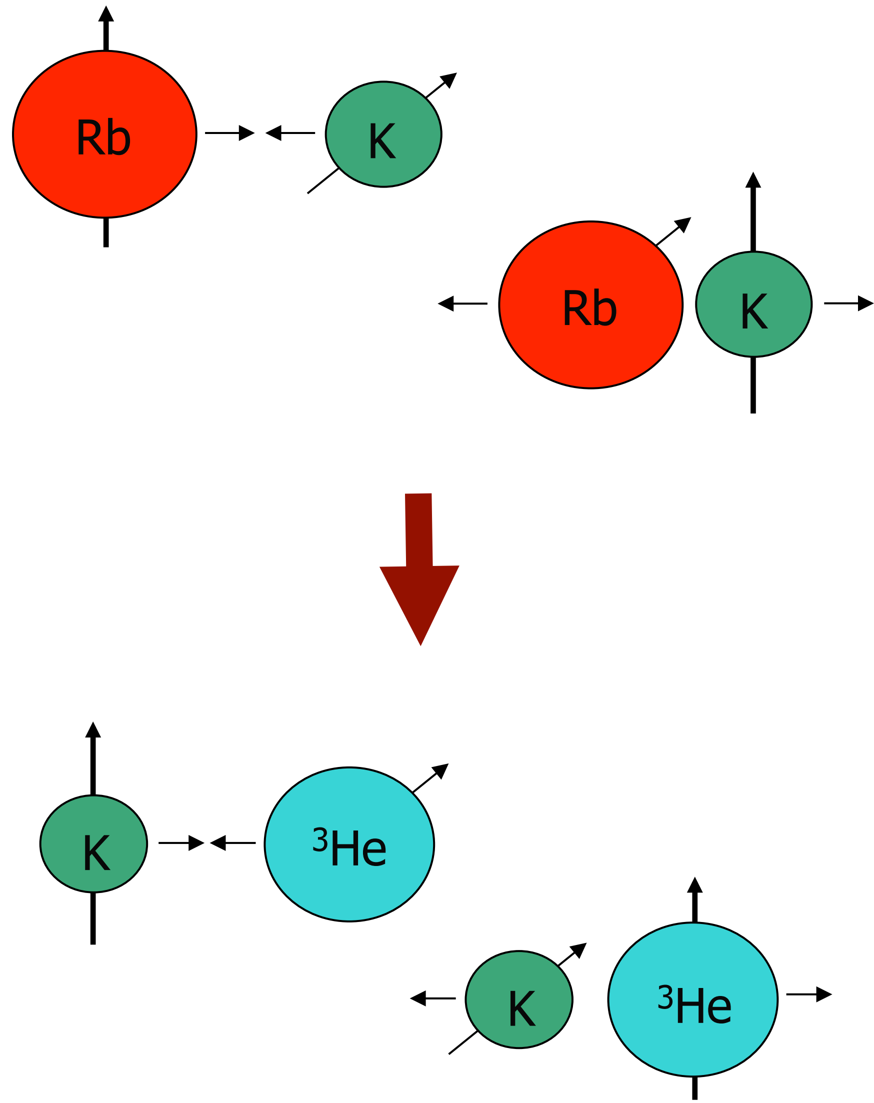
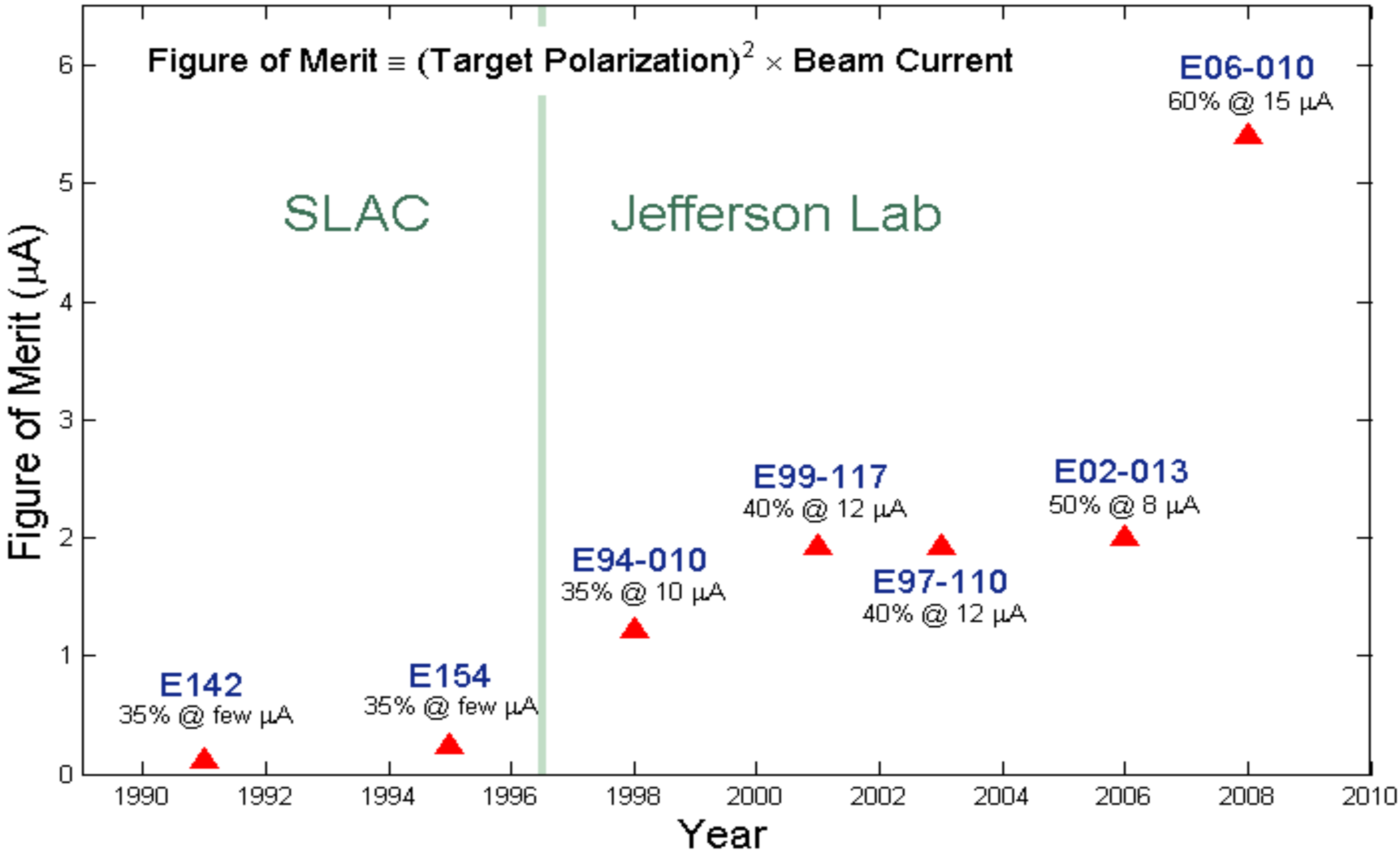


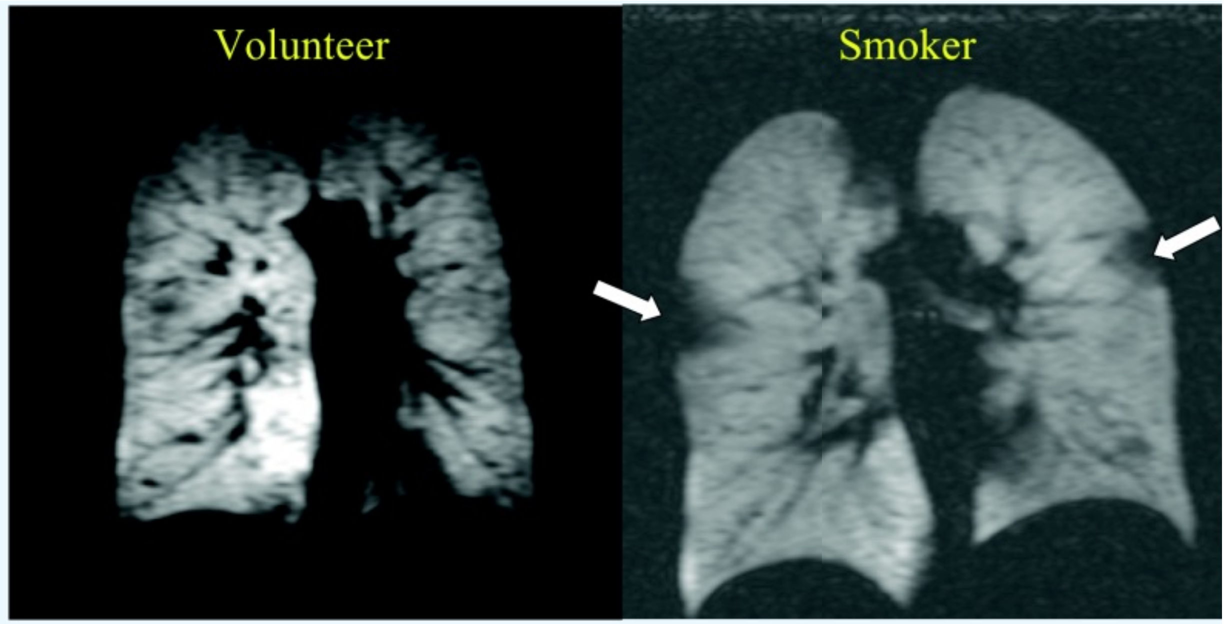
Figure-of-Merit History for High Luminosity Polarized ^{3}He



Application of Polarized ^{3}He: Medical Imaging

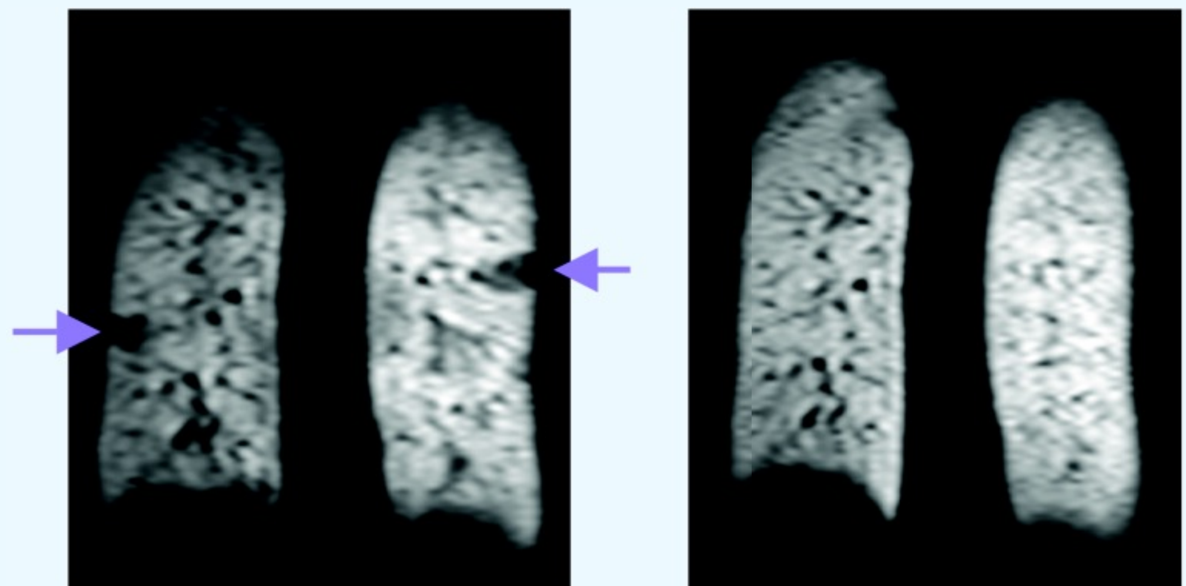
- ^{3}He Spin density MRI

Courtesy of W. Heil, Univ. Mainz

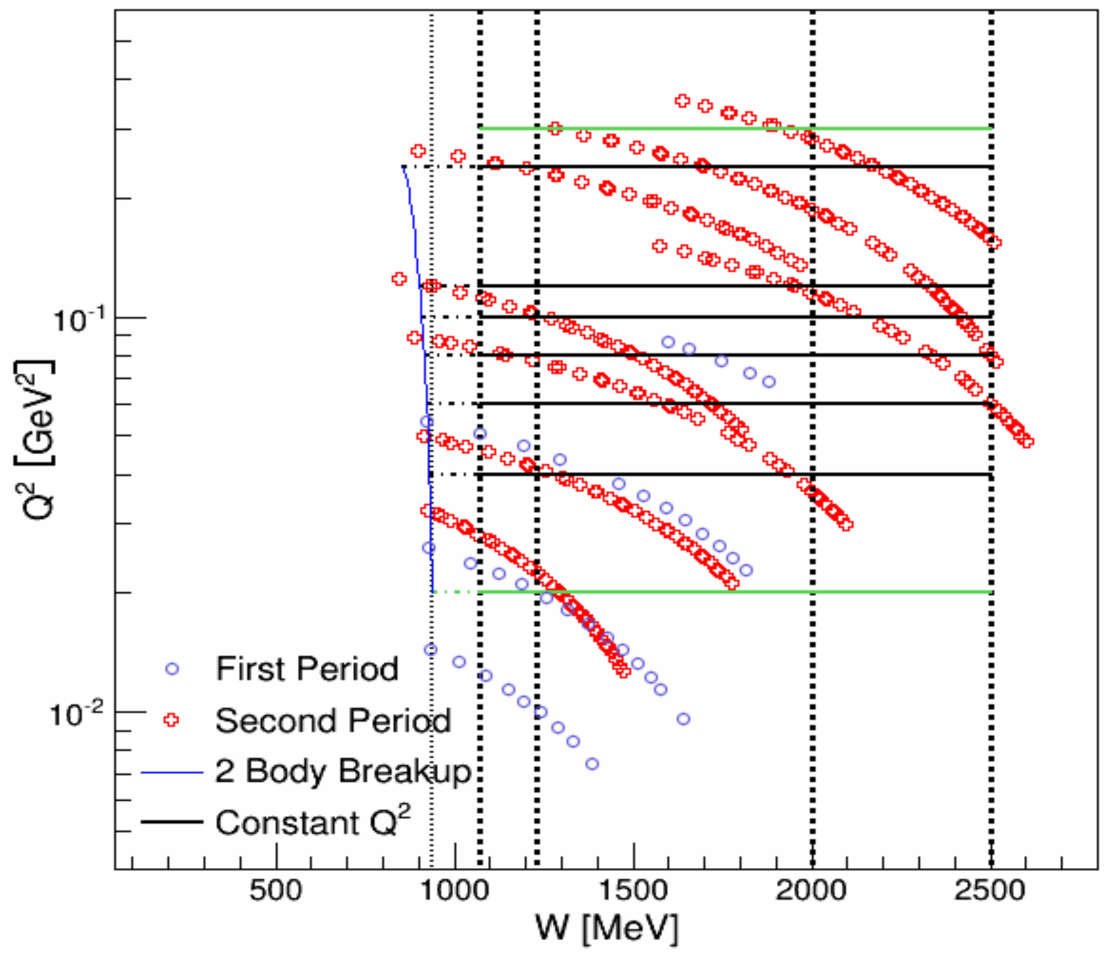


Courtesy of T. Altes et al.,
University of Virginia

Inhaled Bronchodilator
Asymptomatic Asthmatic

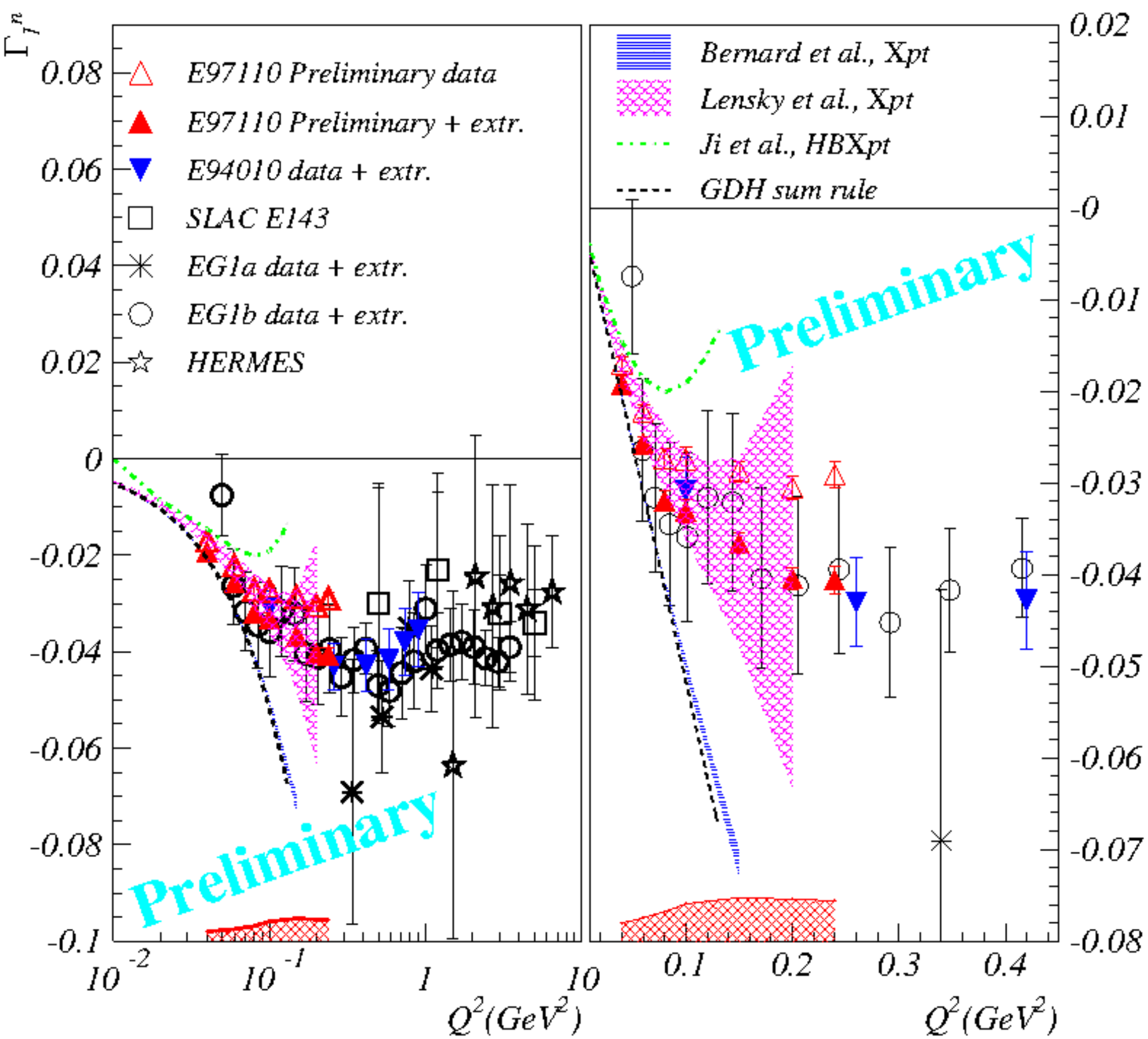


E97-110 Kinematic Coverage



Target Cell	Angle	Beam Energy (MeV)
Penelope	6.10°	2134.2
Priapus	6.10°	2134.9
Priapus	6.10°	2844.8
Priapus	6.10°	4208.8
Priapus	9.03°	1147.3
Priapus	9.03°	2233.9
Priapus	9.03°	3318.8
Priapus	9.03°	3775.4
Priapus	9.03°	4404.2

E97-110 Preliminary Results on Neutron g_1 Moment

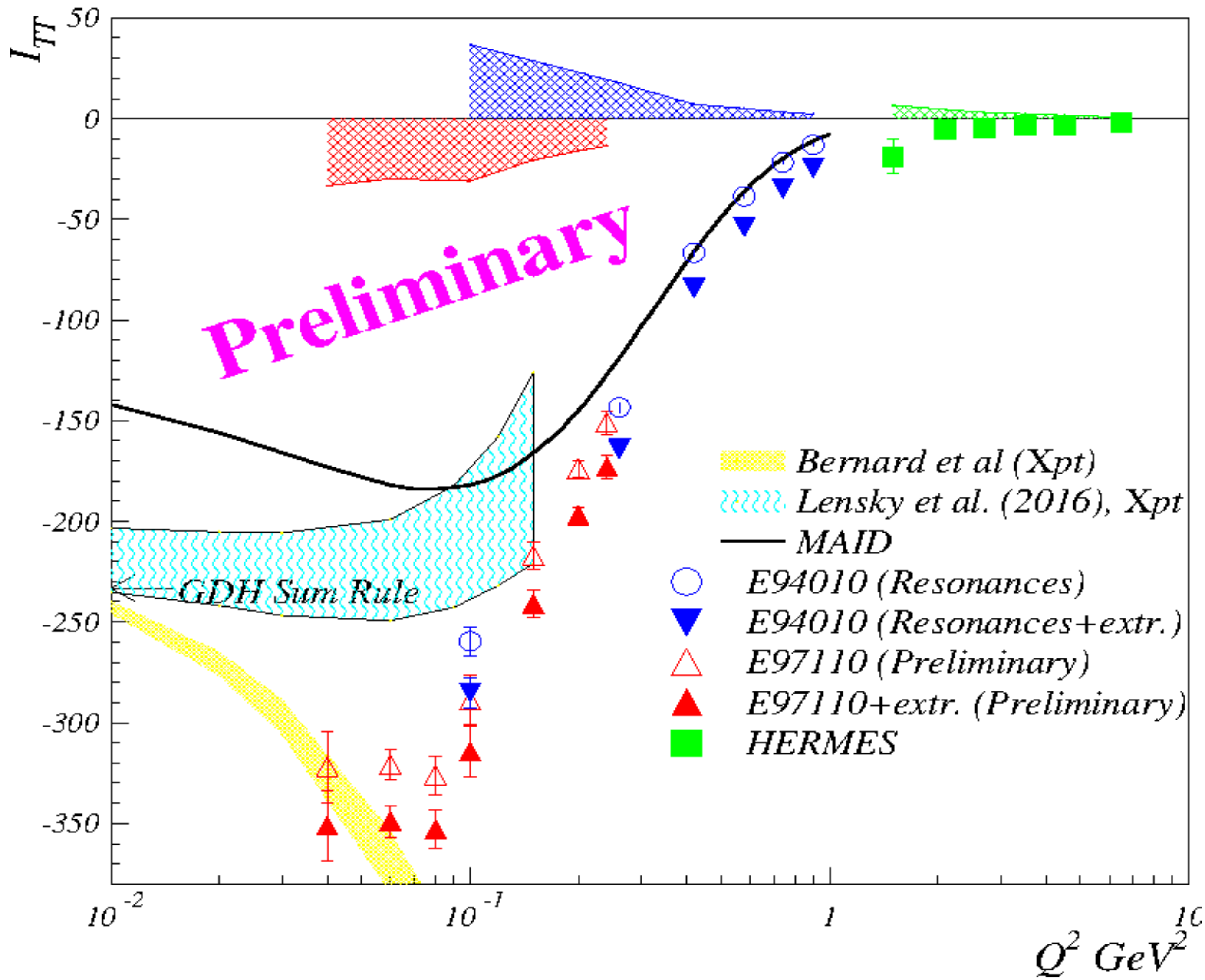


Plots by V. Sulkosky (UVa)

$$\Gamma_1 = \int_0^{x_0} g_1(x, Q^2)dx$$

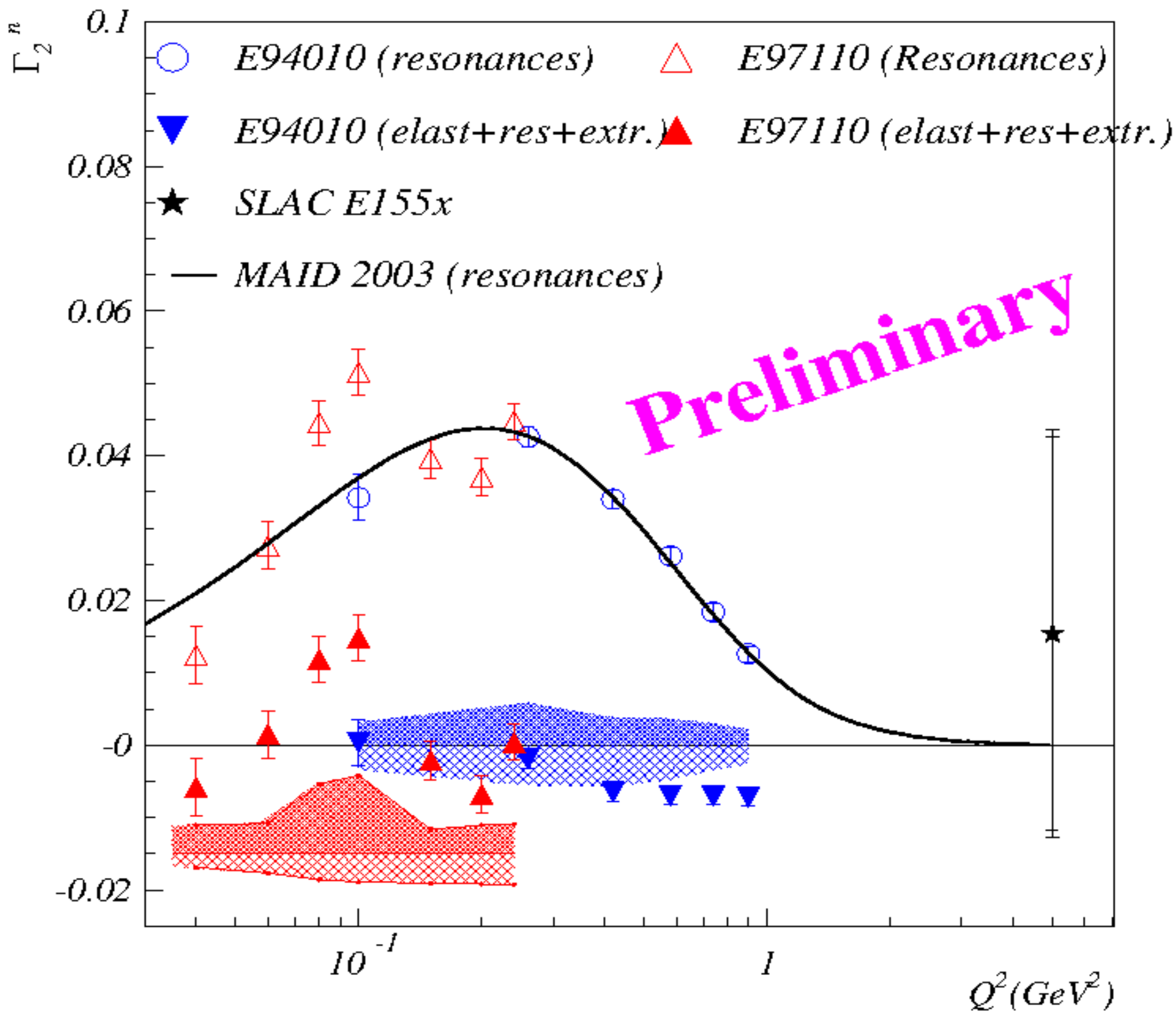
Additional data available:
Analyze the lowest Q^2 points (first period)
(on-going. N. Ton, UVa).

Generalized GDH Integral



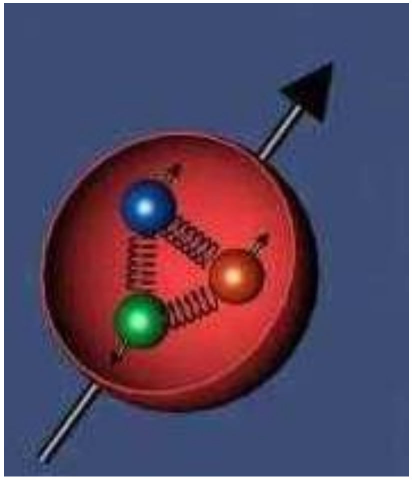
B-C Sum Rule: First Moment of g_2

$$\Gamma_2^n(Q^2) = \int_0^1 g_2(x, Q^2)dx = 0$$



Spin Polarizabilities

Higher Moments of Spin Structure Functions



Higher Moments: Generalized Spin Polarizabilities

- generalized forward spin polarizability γ_0
  generalized L-T spin polarizability δ_{LT}

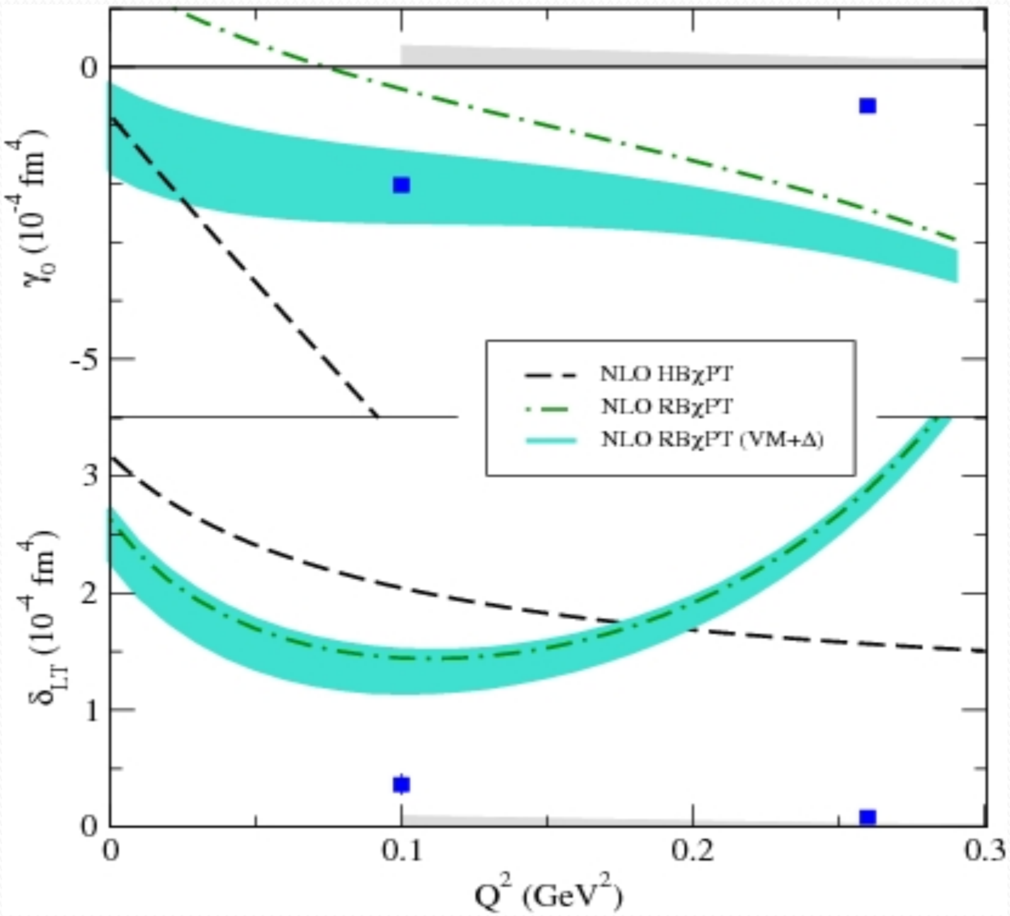
$$\gamma_0(Q^2) = (\frac{1}{2\pi^2})\int_{\nu_0}^{\infty} \frac{K(Q^2,\nu)}{\nu} \frac{\sigma_{TT}(Q^2,\nu)}{\nu^3} d\nu$$

$$= \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2[g_1(Q^2,x) - \frac{4M^2}{Q^2}x^2 g_2(Q^2,x)]dx$$

$$\delta_{LT}(Q^2) = (\frac{1}{2\pi^2})\int_{\nu_0}^{\infty} \frac{K(Q^2,\nu)}{\nu} \frac{\sigma_{LT}(Q^2,\nu)}{Q\nu^2} d\nu$$

$$= \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2[g_1(Q^2,x) + g_2(Q^2,x)dx$$

Neutron Spin Polarizabilities and the δ_{LT} Puzzle



$$\gamma_0 = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right]$$

$$\delta_{LT} = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 + g_2\right]$$

δ_{LT} not sensitive to Δ,
one of the best quantities to test χPT

E94-010, PRL 93: 152301 (2004)

Failure of χPT calculations?

Heavy Baryon χPT Calculation
Kao, Spitzenberg, Vanderhaeghen
PRD 67:016001(2003)

Relativistic Baryon χPT
Bernard, Hemmert, Meissner
PRD 67:076008(2003)

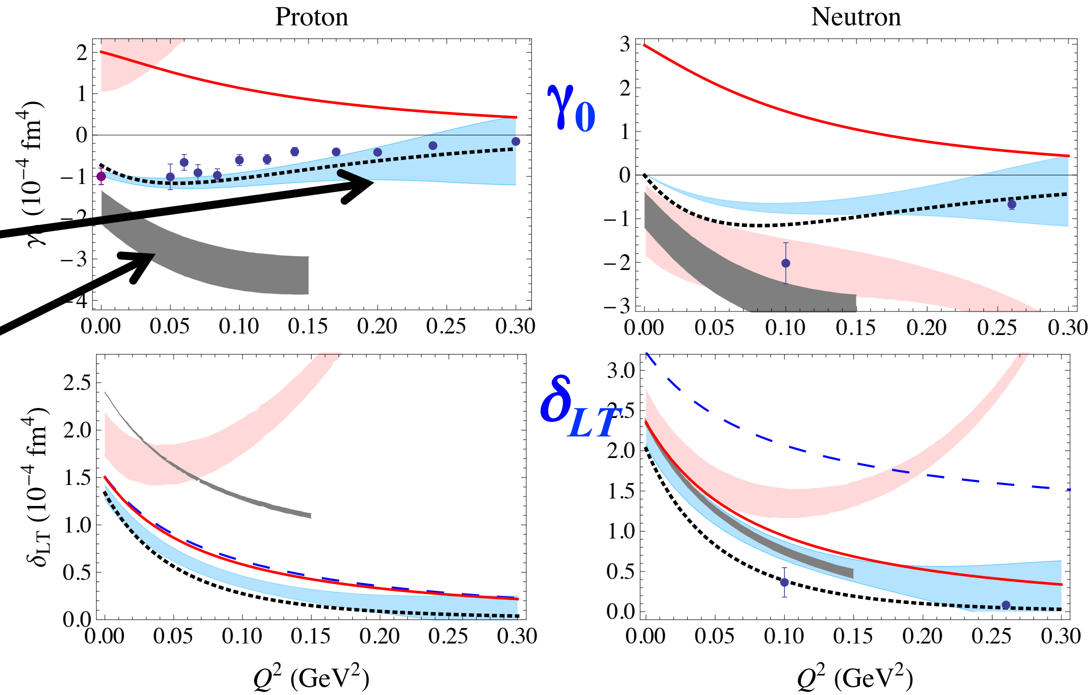
Theoretical Developments and the δ_{LT} Puzzle

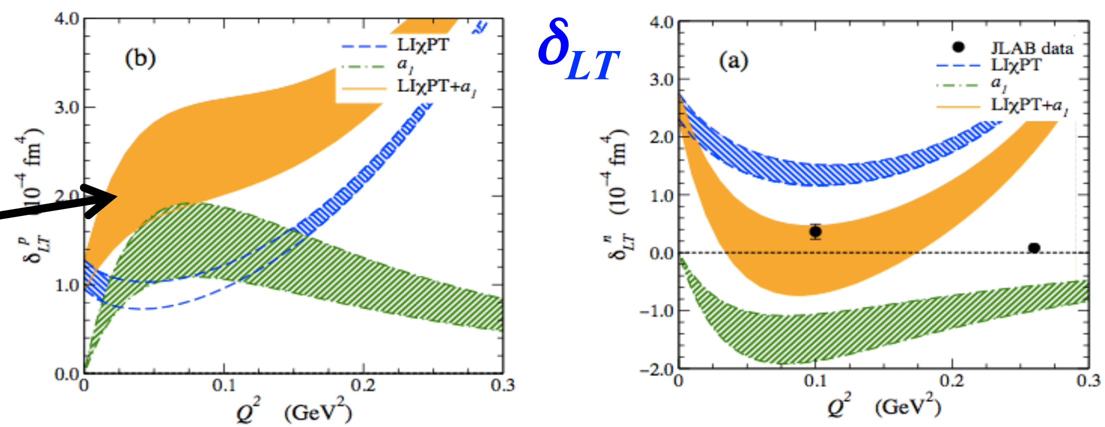
- **HBχPT**: recent: Lensky, Alarcon & Pascalutsa, PRC 90 055202 (2014)

- **RB χ PT**: properly including Δ contribution, Bernard et al., PRD 87 (2013)

- Effect from axial anomaly, N. Kochelev and Y. Oh, PRD 85, 016012 (2012)

Proton ***Neutron***





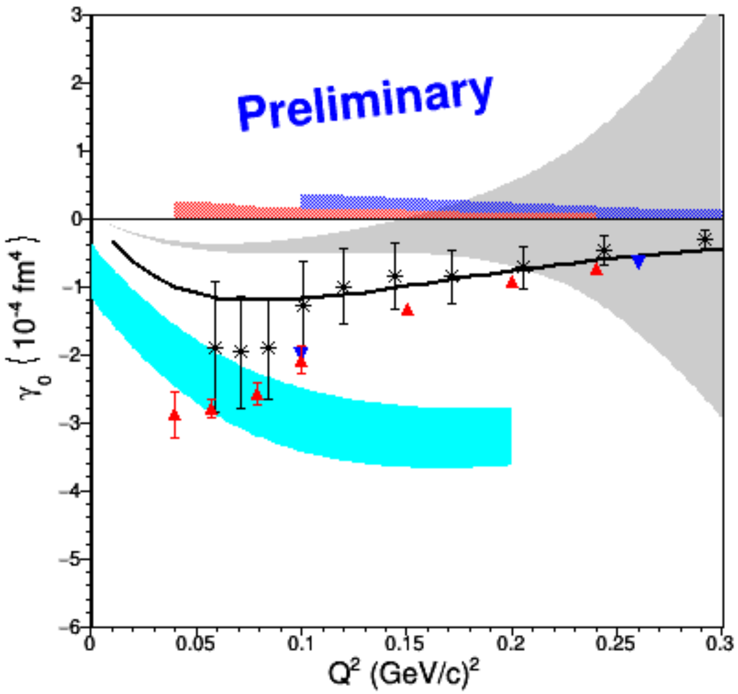
Spin Polarizabilities

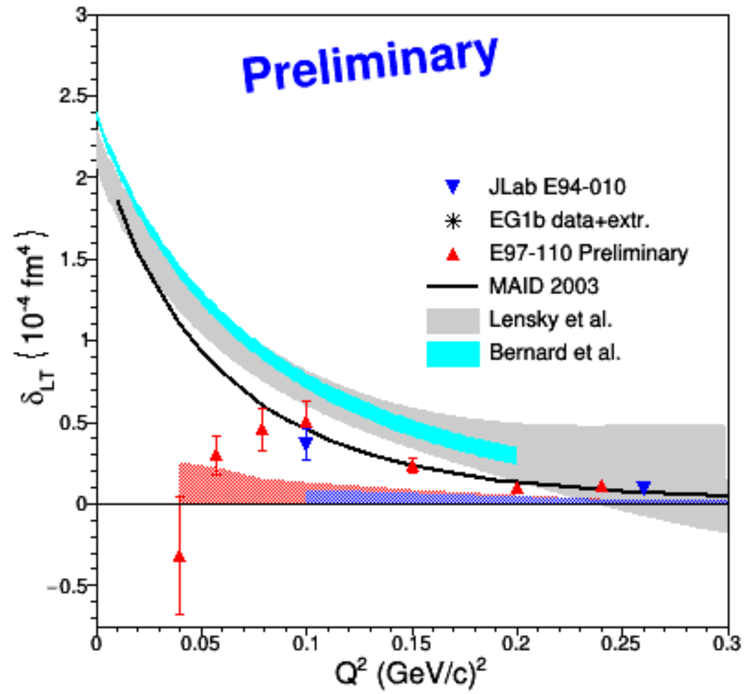
Preliminary E97-110 (and Published E94-010)

- Disagreement between data and both ChPT calculations

$$\gamma_0 = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right]$$

$$\delta_{LT} = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1 + g_2\right]$$





Q^2 Q^2

Δ resonance is supposed to be suppressed for δ_{LT} ,

More robust prediction

Summary on Spin Moments of the Neutron

- E97-110 covered $0.02 < Q^2 < 0.24$ (GeV^2)
- Results near final for $0.04 < Q^2 < 0.24$
- Comparisons with ChPT calculations

  First moments of g_1, g_2 and GDH sum

  Spin polarizabilities: γ_0 and δ_{LT}

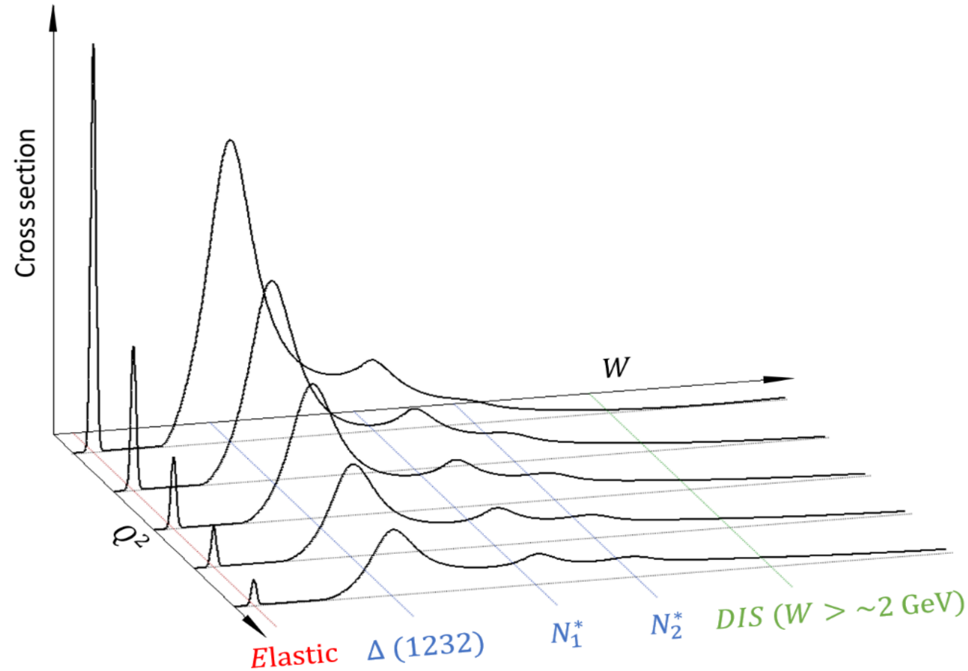
  lowest Q^2 behavior! ?

- First period data cover $0.02 < Q^2 < 0.04$, analysis not complete yet. Expect results by the end of the year.

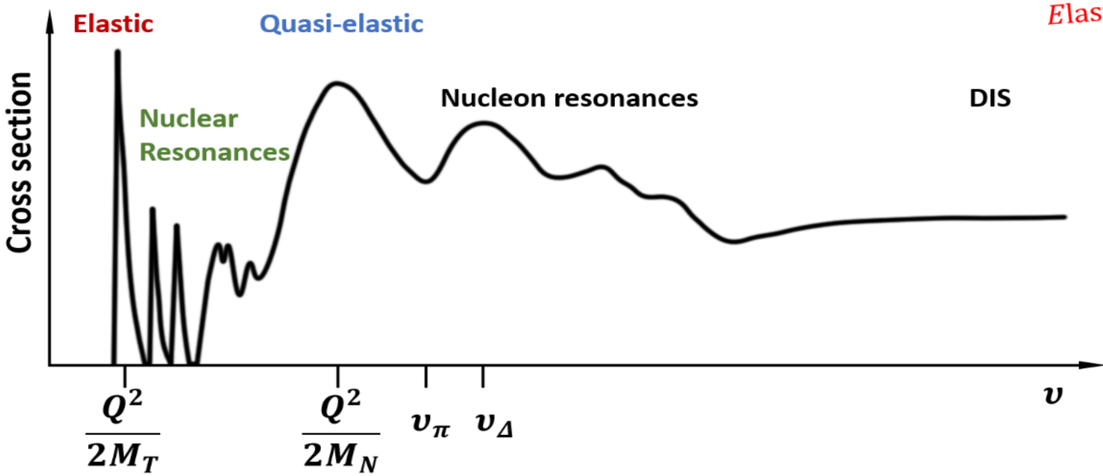
Moments of ^{3}He Spin Structure

GDH Sum and γ_{TT} for ^{3}He

Inclusive Electron Scattering Spectrum



Nucleon target
- ***elastic region***
- ***resonance region***
- ***DIS region***



Nuclear target
- ***nuclear resonances***
- ***quasi-elastic region***

Quasi-elastic Scattering

- Elastic electron scattering off a quasi-free nucleon inside the ^{3}He nucleus
  - Approximately centered at $\nu = Q^2/M_T$, with M_T the nuclear target mass
  - Broadened peak as compared to elastic peak, due to the Fermi motion
  - Final states include 2-body, 3-body
  - 2-body breakup threshold at $\nu \approx 5.5$ MeV

- Can be well calculated
  - Realistic nucleon-nucleon interaction potentials
  - Plane wave impulse approximation (high Q^2)
  - Nonrelativistic Faddeev calculations (low Q^2)

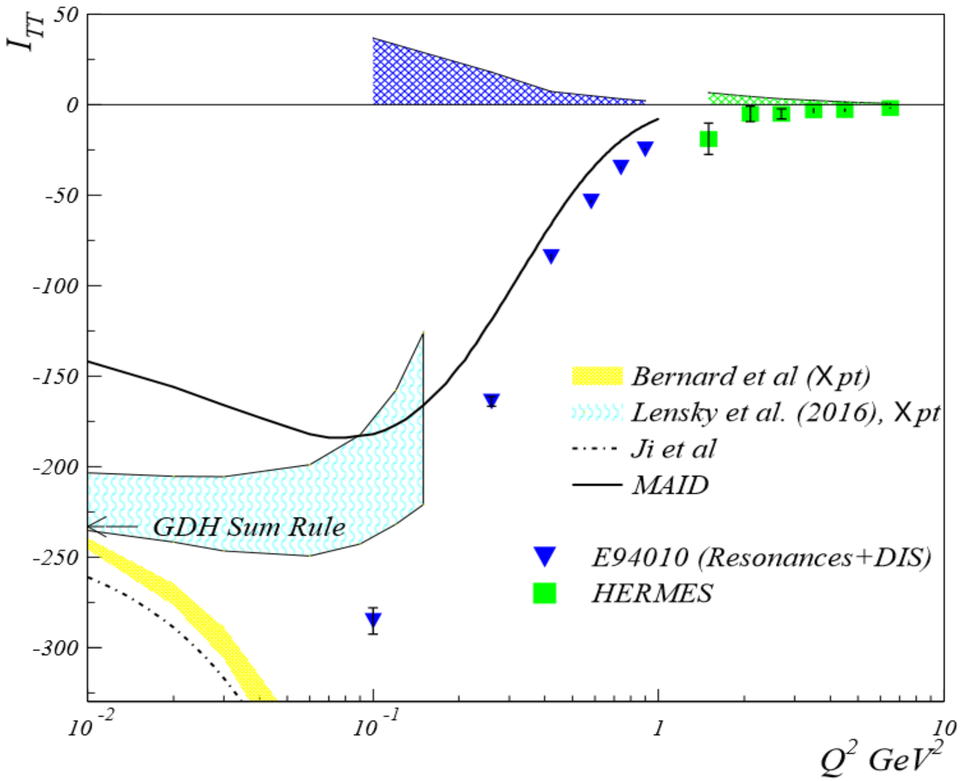
GDH (Real Photon) Measurements

- Proton, verified: Mainz, Bonn (LEGS)
- Neutron (with deuteron/^{3}He), in progress: Mainz, HIGS, …
- Measurements on Deuteron and ^{3}He

	M [GeV]	Spin	κ	I_{GDH} [μ b]
Proton	0.938	$\frac{1}{2}$	1.79	–204.8
Neutron	0.940	$\frac{1}{2}$	-1.91	–233.2
Deuteron	1.876	1	-0.14	–0.65
Helium-3	2.809	$\frac{1}{2}$	-8.38	–498.0

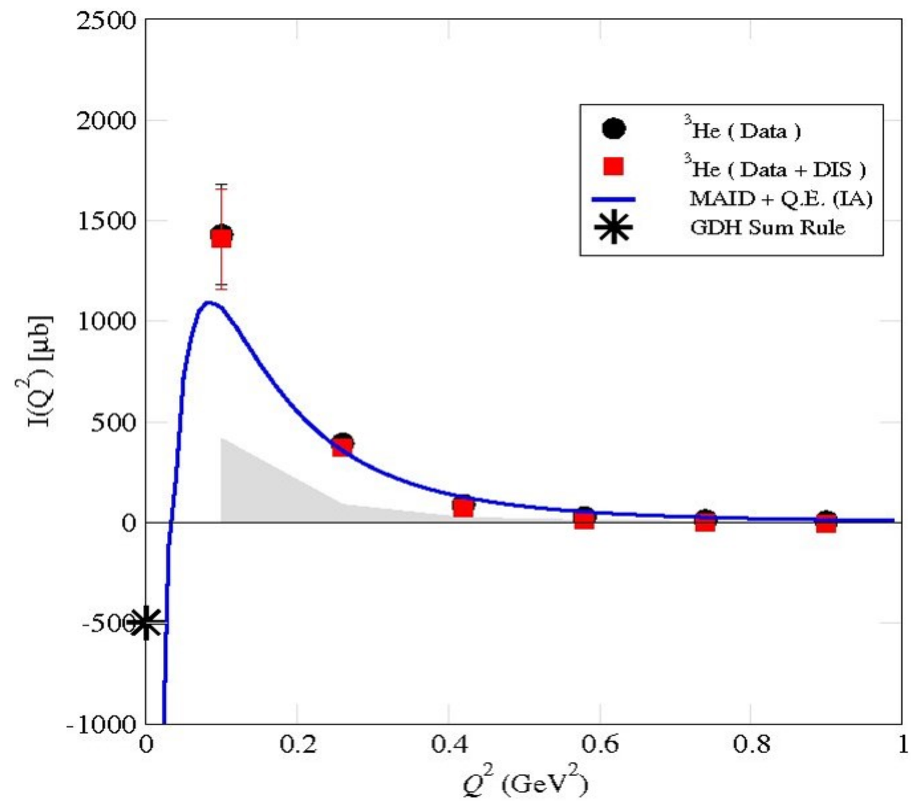
Before E97110:
E94-010 Results on Generalized GDH Sum

Neutron



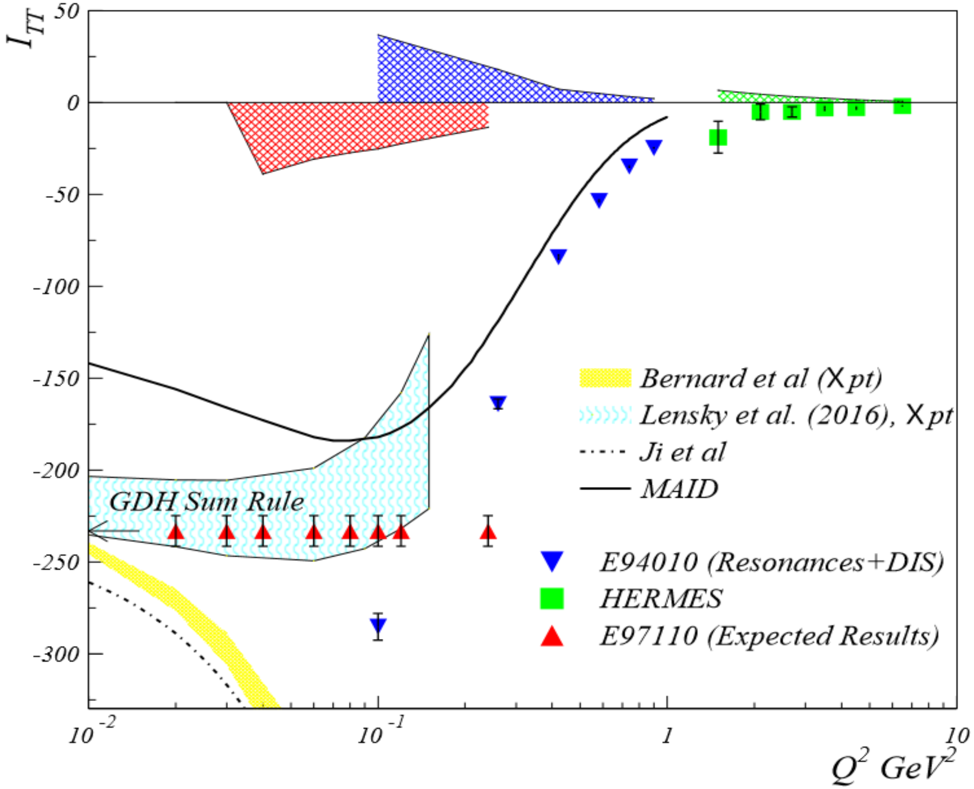
M. Amarian et al., Phys. Rev. Lett., 89:242301, Nov 2002.

Helium-3



K. Slifer et al., Phys. Rev. Lett., 101:022303, Jul 2008.

E97-110 at Jefferson Lab

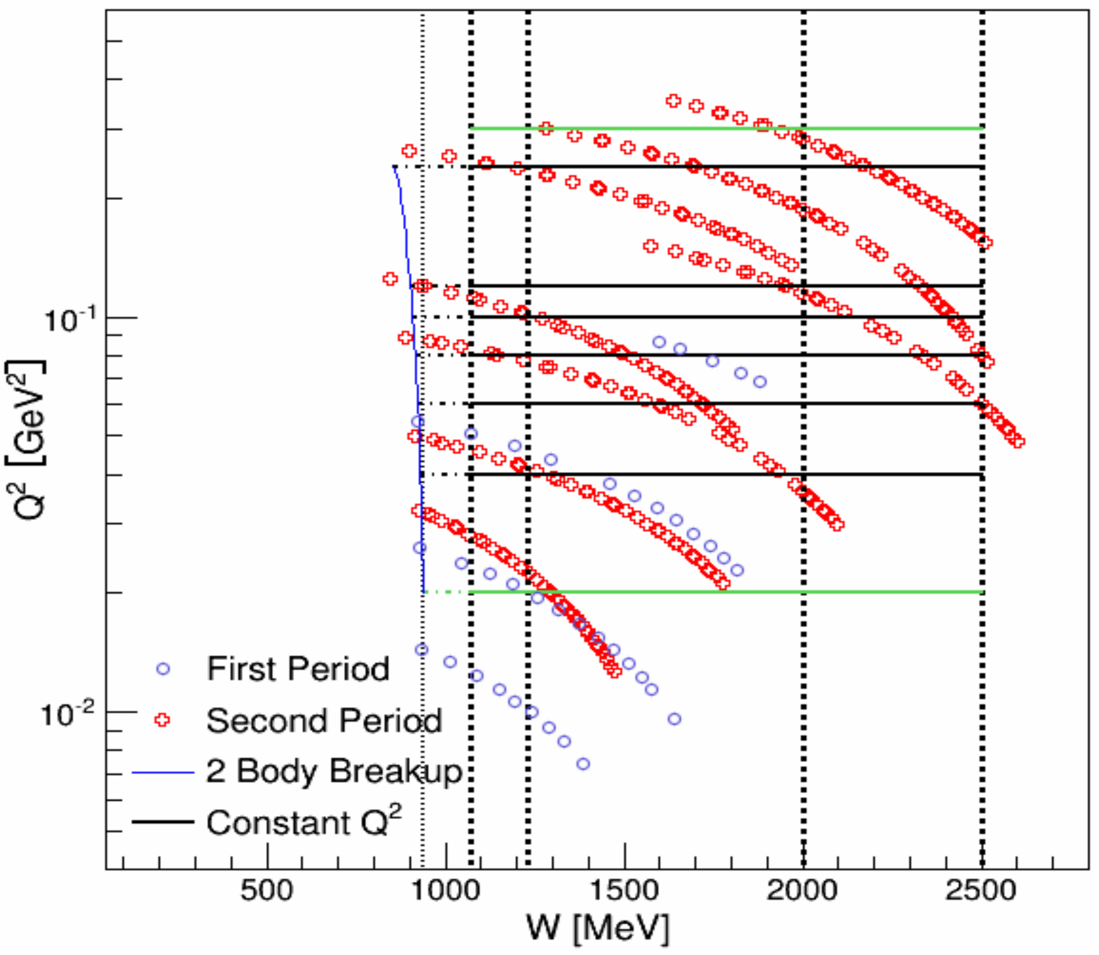


- Inclusive measurement
  - 3He $(e,e)X$ at small scattering angles
  - Focus on low $Q↑2$
- Covered quasi-elastic region and resonance region
  - Unpolarized cross sections
  - Differences of polarized cross sections (Parallel + Perpendicular)

Spokespersons: J.-P. Chen, A. Deur, F. Garibaldi

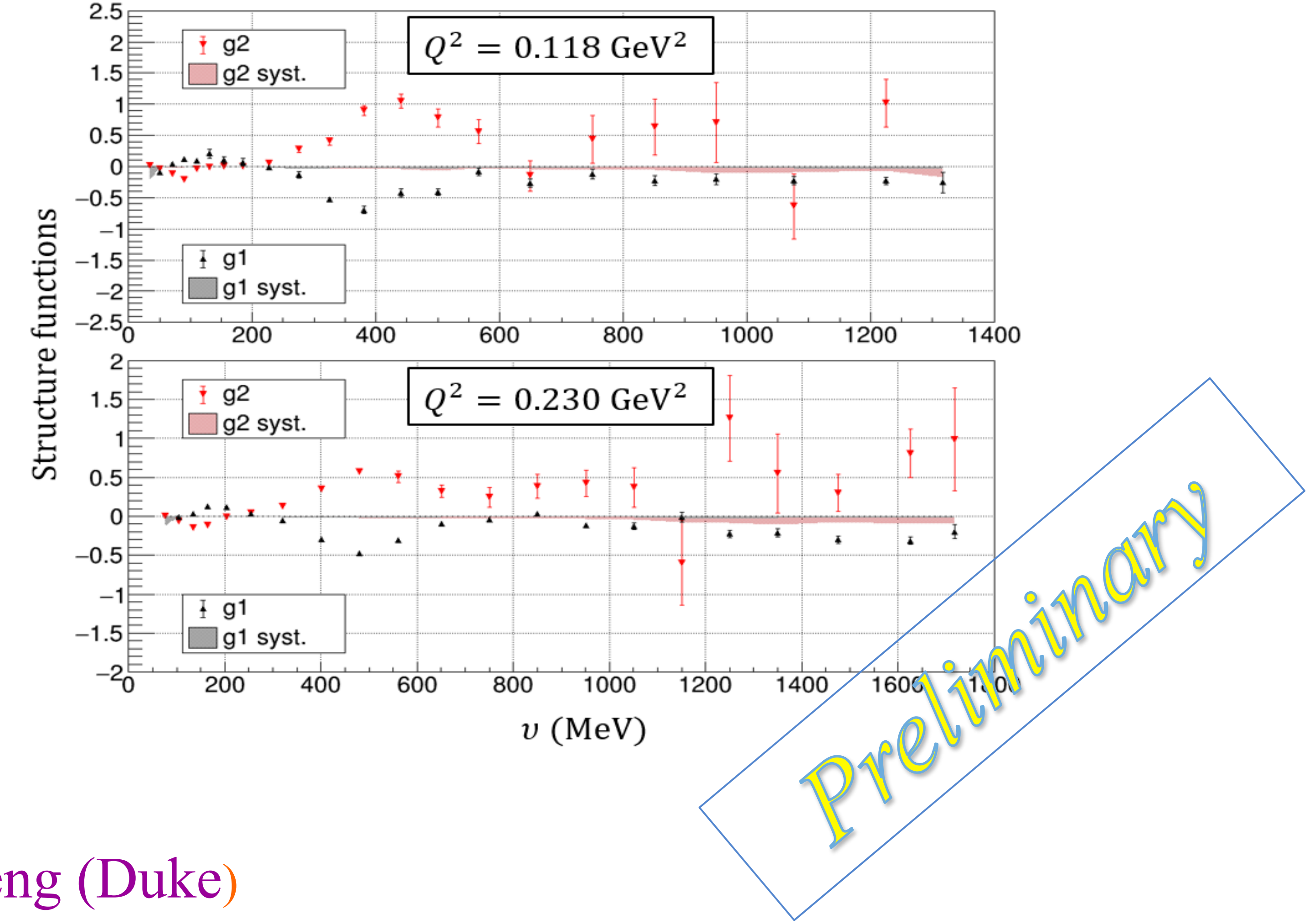
Graduate students: J. Singh, V. Sulkosky, J. Yuan, C. Peng, N. Ton

E97-110 Kinematic Coverage



Target Cell	Angle	Beam Energy (MeV)
Penelope	6.10°	2134.2
Priapus	6.10°	2134.9
Priapus	6.10°	2844.8
Priapus	6.10°	4208.8
Priapus	9.03°	1147.3
Priapus	9.03°	2233.9
Priapus	9.03°	3318.8
Priapus	9.03°	3775.4
Priapus	9.03°	4404.2

Structure Functions g_1/g_2 for ^{3}He



Plots by C. Peng (Duke)

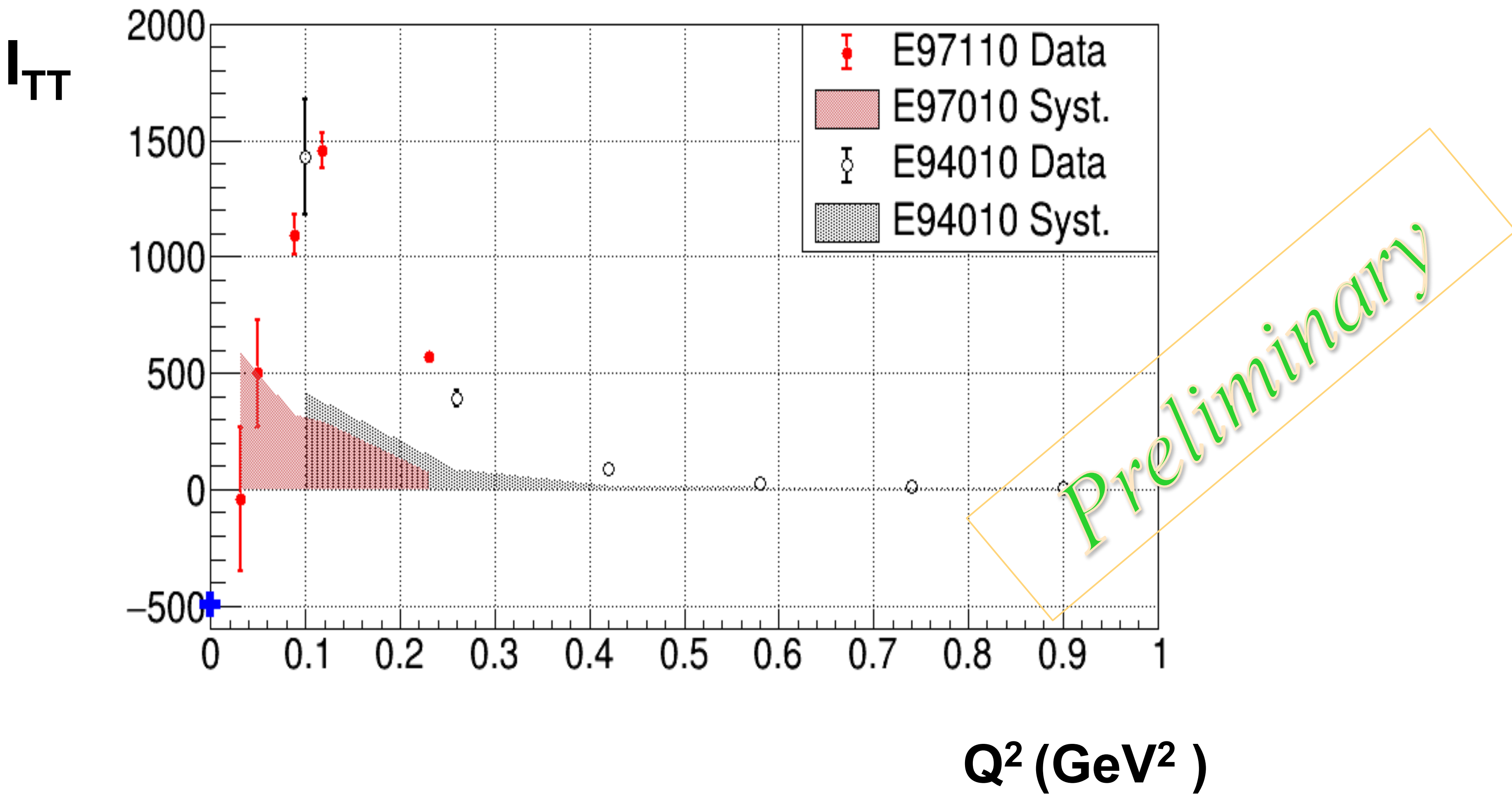
Generalized GDH Integral

- Numerical integration of the GDH integrand $$I(Q^2) = \frac{8\pi^2\alpha}{M^2} I_{TT}(Q^2),$$

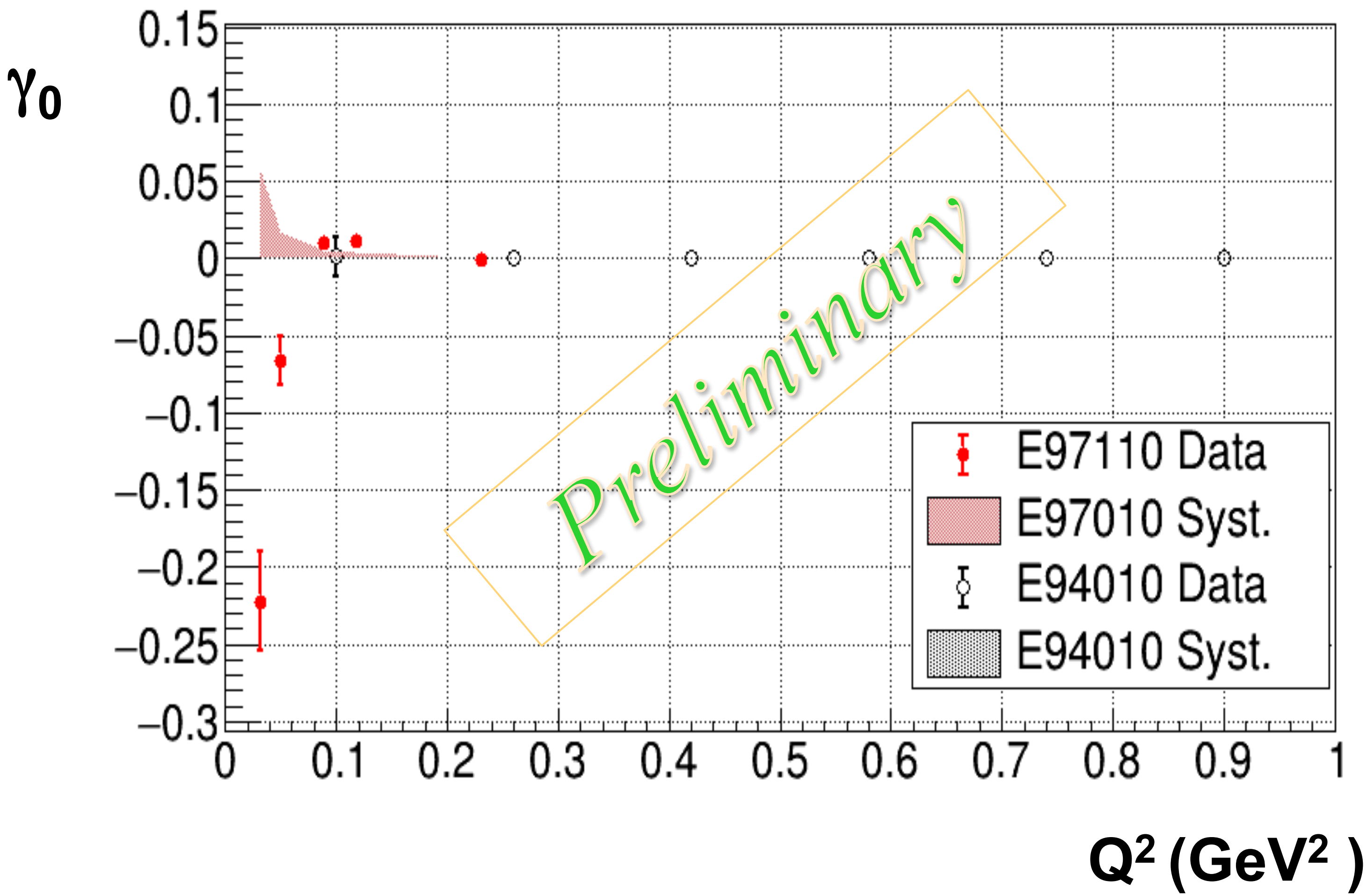
Q^2 (GeV ^{2})	W_{max} (MeV)	$I_{GDH}(Q^2)$ (μb)	σ_{stat} (μb)	σ_{syst} (μb)
0.032	1470	-17.79	295.75	604.05
0.050	1770	532.54	170.67	460.76
0.088	2000	1097.05	76.82	315.72
0.118	1790	1322.22	69.28	254.10
0.230	1950	565.71	24.66	69.84

- Systematic at lowest $Q↑2$ is dominated by the elastic tail subtraction near the threshold region
- Unmeasured contribution is estimated and added into syst.
  - MAID2007 model for W < 2 GeV
  - Regge parameterization for W > 2 GeV (E. Thomas and N. Bianchi Nuclear Physics B - Proceedings Supplements, 82:256 – 261, 2000.)
  - Negligible

Generalized GDH Integral



Generalized Spin Polarizability γ_0



Summary

- Spin structure at very low Q for the neutron
  - study "strong" QCD
  - Provide good test to ChPT calculations
  - 0^{th} moments: spin sum rules
  - 2^{nd} moments: spin polarizabilities: behavior at lowest Q region!
- Spin structure at very low Q for ^3He
  - Extracted generalized GDH sum and γ_0 for $0.03 < Q^2 < 0.23$ (GeV^2)
  - Observed "turn-around" bahavior of generalized GDH sum at very low Q^2
  - Indication when approach $Q^2=0$, recovers GDH sum rule prediction
  - Very large negative value for γ_0 at very low Q^2
  - Large uncertainty at very low Q^2 due to elastic radiative tail
  - Need theory calculation (few-body ChPT?)