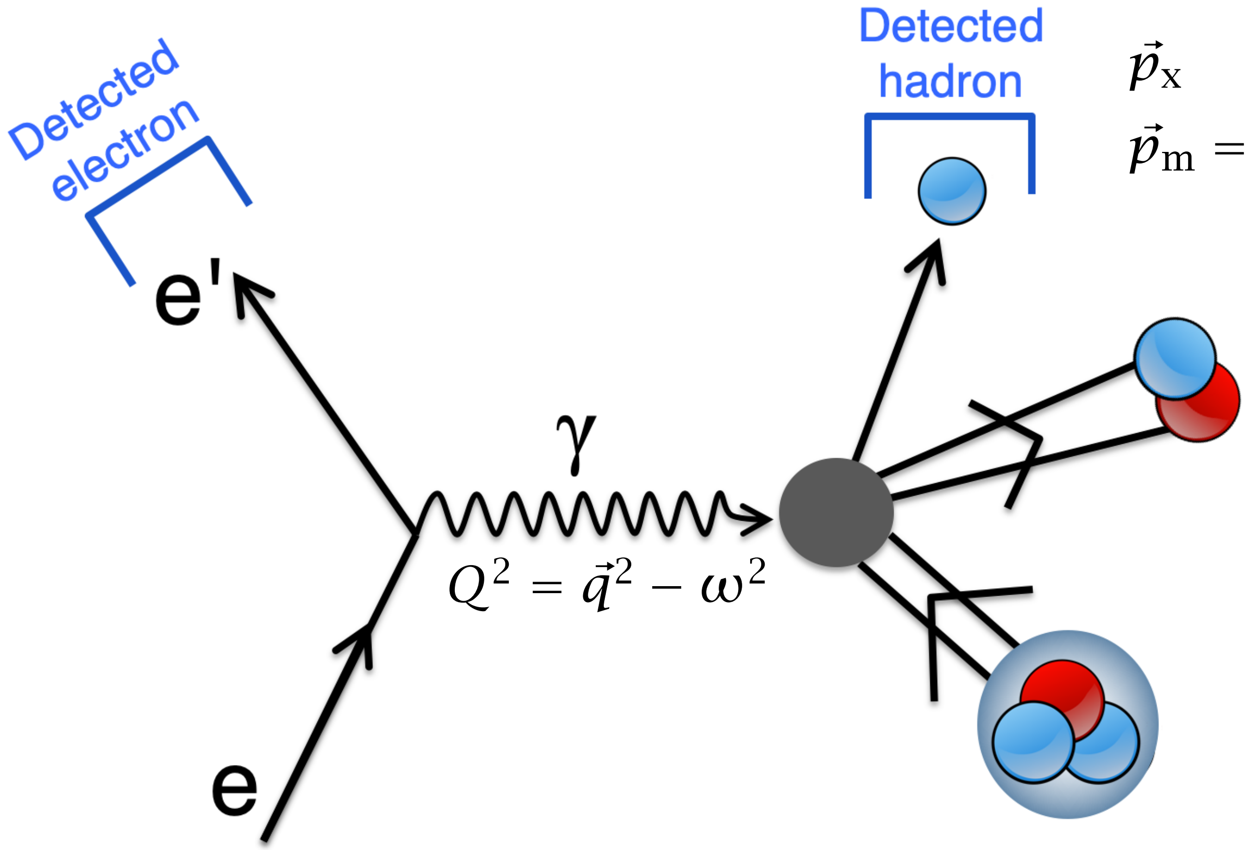
Study of light nuclei by polarization observables in electron scattering

S. Širca, U of Ljubljana, Slovenia Guildford, 6 Sep 2019

Unpolarized electron scattering

$$\omega = \vec{E}_\mathrm{e} - \vec{E}'_\mathrm{e}$$

$$\vec{q} = \vec{p}_\mathrm{e} - \vec{p}'_\mathrm{e}$$

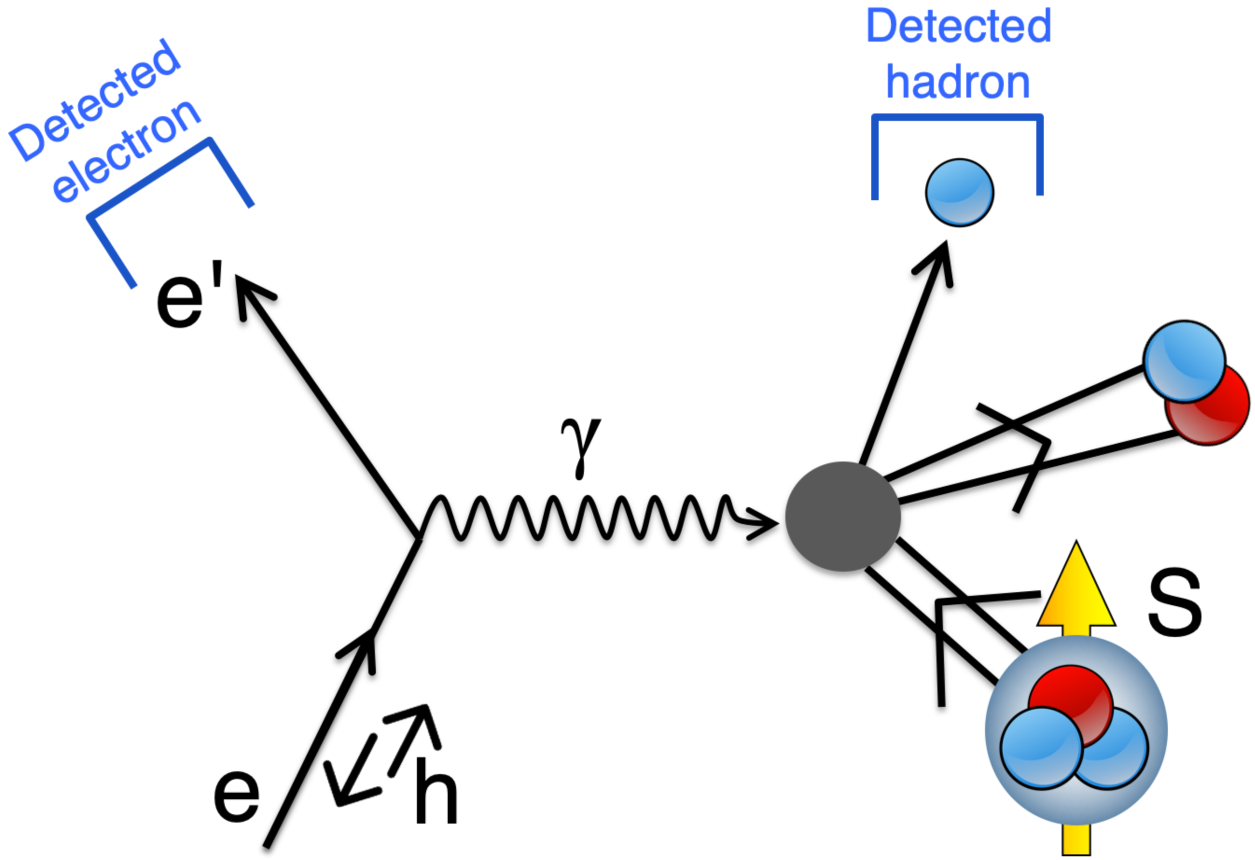


$$\vec{p}_\mathrm{x}$$

$$\vec{p}_\mathrm{m} = \vec{q} - \vec{p}_\mathrm{x}$$

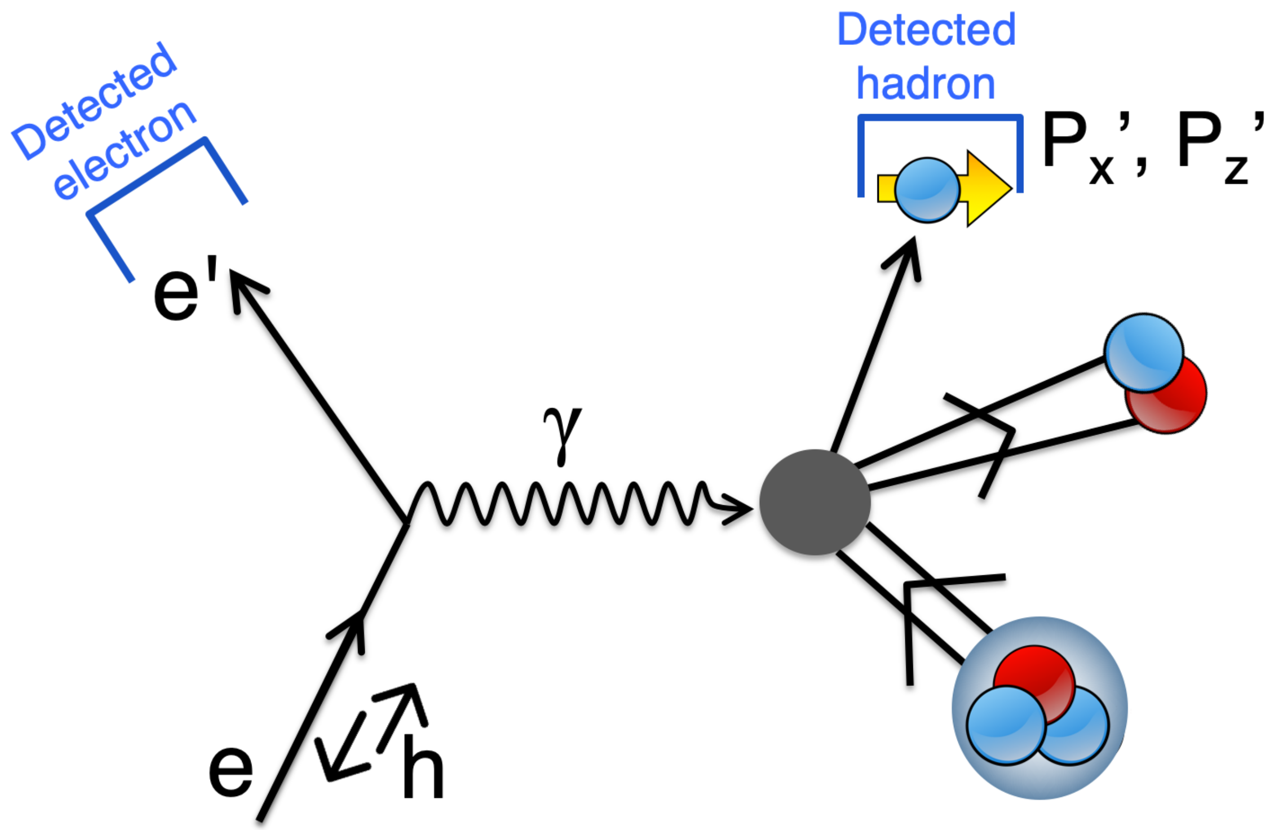
$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{e}'}\mathrm{d}\Omega_{\mathrm{e}'}\mathrm{d}E_\mathrm{x}\mathrm{d}\Omega_\mathrm{x}} = \sigma_0\left[v_L R_L + v_T R_T + v_{LT} R_{LT} + v_{TT} R_{TT}\right]$$

Electron scattering with beam and target polarization



$$A = \frac{\sigma(h_+, \vec{S}) - \sigma(h_-, \vec{S})}{\sigma(h_+, \vec{S}) + \sigma(h_-, \vec{S})} \propto v_{T'} R_{T'} + v_{LT'} R_{LT'}$$

Electron scattering with beam and recoil polarization



$$P'_z = P'_\ell \propto v_{LT'} R^{\ell}_{LT'} + v_{TT'} R^{\ell}_{TT'}$$

$$P_n \propto v_L R^n_L + v_T R^n_T + v_{LT} R^n_{LT} + v_{TT} R^n_{TT}$$

$$P'_x = P'_t \propto v_{LT'} R^{t}_{LT'} + v_{TT'} R^{t}_{TT'}$$

Experiments covered in this talk

^{3}He

- JLab E05–102
  Double-spin asymmetries in quasi-elastic $^3\vec{\mathrm{He}}(\vec{e}, e'd)p$
  $^3\vec{\mathrm{He}}(\vec{e}, e'p)d$
  $^3\vec{\mathrm{He}}(\vec{e}, e'p)pn$
- JLab E05–015
  Target single-spin asymmetry in quasi-elastic $^3\mathrm{He}^{\uparrow}(e, e')$
- JLab E08–005
  Target single-spin asymmetry in quasi-elastic $^3\mathrm{He}(\vec{e}, e'n)$
  Double-spin asymmetries in quasi-elastic $^3\vec{\mathrm{He}}(\vec{e}, e'n)$
- MAMI (Mainz) Project 'N'
  Triple-polarized $^3\vec{\mathrm{He}}(\vec{e}, e'\vec{p})$

^{2}H and ^{12}C

- MAMI (Mainz)
  Single-spin asymmetries in $^{12}\mathrm{C}(e^{\uparrow}, e')$
- MAMI (Mainz + TAU) joint recoil-polarimetry effort
  Double-spin asymmetries in $^2\vec{\mathrm{H}}(\vec{e}, e'\vec{p})$ and $^{12}\vec{\mathrm{C}}(\vec{e}, e'\vec{p})$

Physics motivation for studying processes on ^{3}He

- Knowledge of ground-state structure of ^{3}He needed to **extract information on the neutron** from $^3\vec{\mathrm{He}}(\vec{\mathrm{e}}, \mathrm{e}'\mathrm{X})$ or $^3\vec{\mathrm{He}}(\vec{\mathrm{e}}, \mathrm{e}')$.
  Examples: G_E^n, G_M^n, A_1^n, g_1^n, g_2^n, GDH.

- Complications: protons in ^{3}He partly polarized due to presence of S'- and D-state components.

- Addressing differences in $\sqrt{\langle r^2 \rangle}$ (^{3}H, ^{3}He).

- Understanding (iso)spin dependence of reaction mechanisms (MEC, IC).

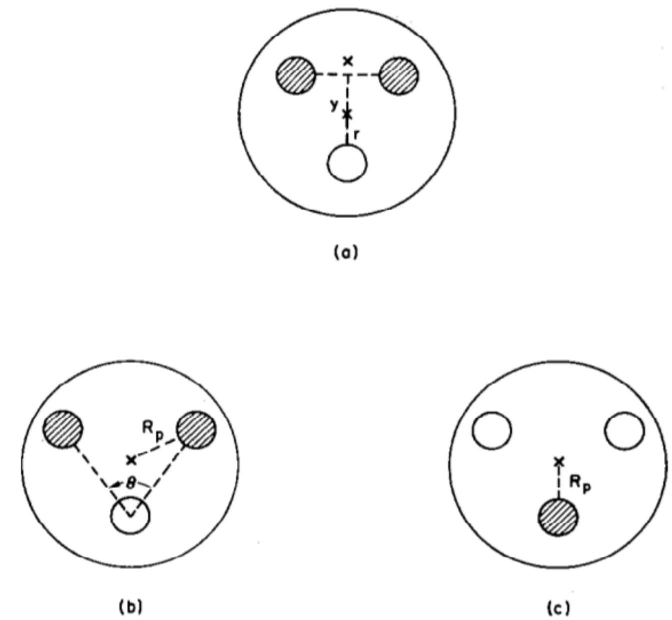
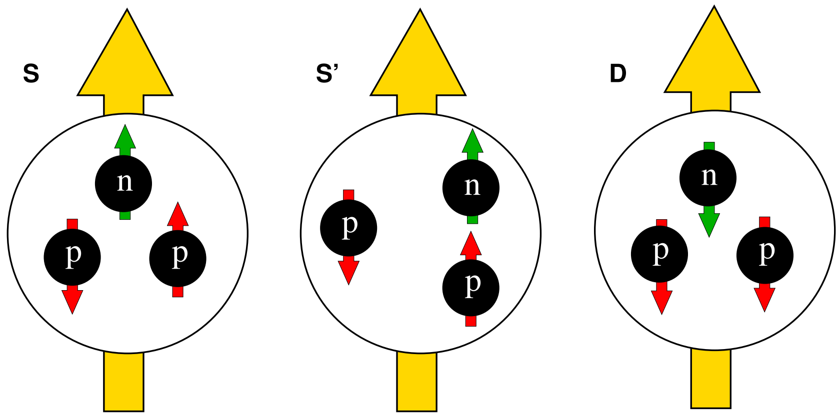


Fig. 1. Schematic picture of trinucleon when all forces are identical is shown in (a). The effect on ^{3}He and ^{3}H when the pp or nn force is weaker than the np force is illustrated in (b) and (c). R_p is the "charge radius". Shading indicates a proton.

- Understanding role of D and S' states is one of key issues in **"Standard Model" of few-body theory**.

- Persistent discrepancies among theories regarding double-polarization observables most sensitive to ^{3}He ground-state structure.

Polarized ^{3}He: it is easy to draw the cartoon ...



- S: spatially symmetric $\approx$ **90 %** of spin-averaged WF; "**polarized neutron**"
- D: generated by tensor part of NN force, $\approx$ **8.5 %** .
- S': mixed symmetry component; (spin-isospin)-space correlations, $\approx$ **1.5 %** . $P'_S \approx E_b^{-2.1}$.
- $P_n^{\text{eff}} \approx +0.86$, $P_p^{\text{eff}} \approx -0.03$

Hamiltonian	S	S'	P	D
AV18	90.10	1.33	0.066	8.51
AV18/TM	89.96	1.09	0.155	8.80
AV18/UIX	89.51	1.05	0.130	9.31
CD-Bonn	91.62	1.34	0.046	6.99
CD-Bonn/TM	91.74	1.21	0.102	6.95
Nijm I	90.29	1.27	0.066	8.37
Nijm I/TM	90.25	1.08	0.148	8.53
Nijm II	90.31	1.27	0.065	8.35
Nijm II/TM	90.22	1.07	0.161	8.54
Reid93	90.21	1.28	0.067	8.44
Reid93/TM	90.09	1.07	0.162	8.68

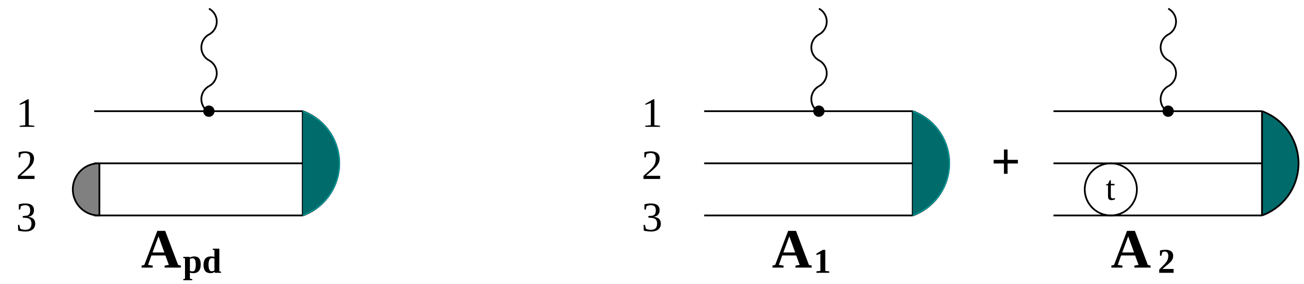
Schiavilla++ PRC 58 (1998) 1263

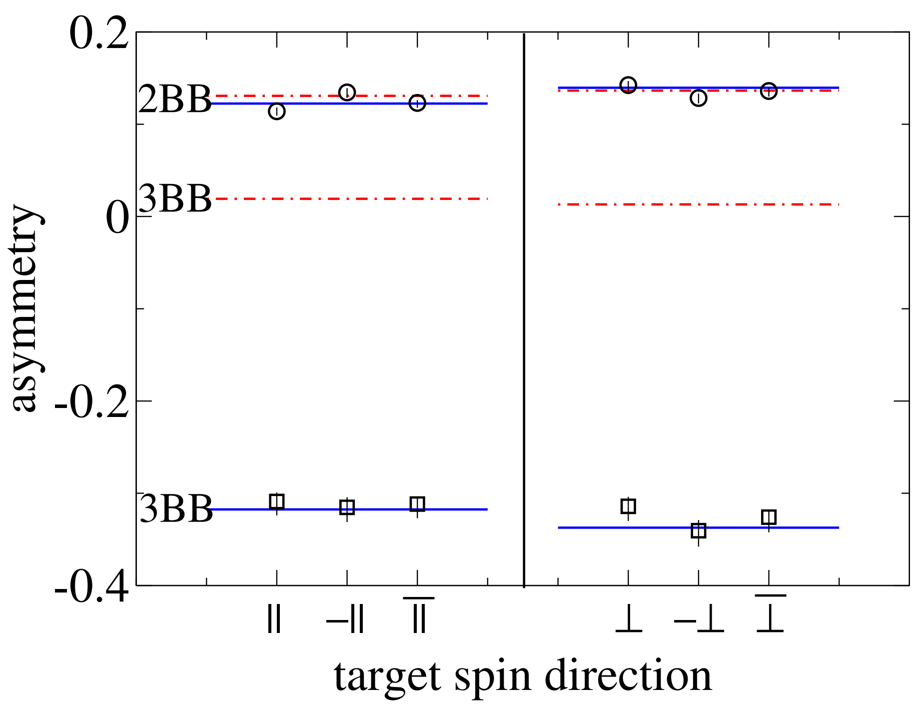
TM = Tucson-Melbourne π-π exchange 3NF

UIX = Urbana 3NF

... supported e. g. by data on $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{p})\mathrm{d}/\mathrm{pn}$ ...

- quasi-elastic ($Q^2 = 0.31$, $\omega = 135$, $q = 570$)
- 3NF, MEC negligible, FSI small in 2bbu, large in 3bbu





▷ **2bbu**

$A_{\mathrm{PWIA}} \approx A_{\mathrm{PWIA+FSI}}$

$\|$ kinematics + small p_{d}

$\Longrightarrow$ polarized p target, $P_{\mathrm{p}} \approx -\frac{1}{3} P_{\mathrm{He}}$

▷ **3bbu**

$A_{\mathrm{PWIA}} \approx 0$ (p ↑ p ↓)

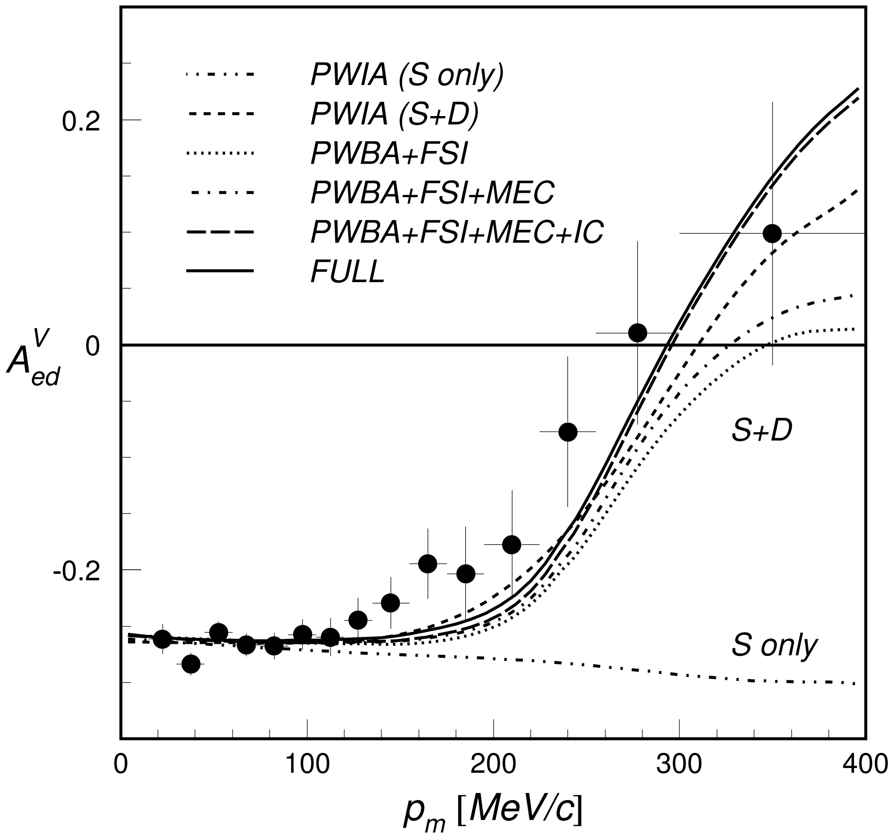
$A_{\mathrm{PWIA+FSI}}$ large & negative

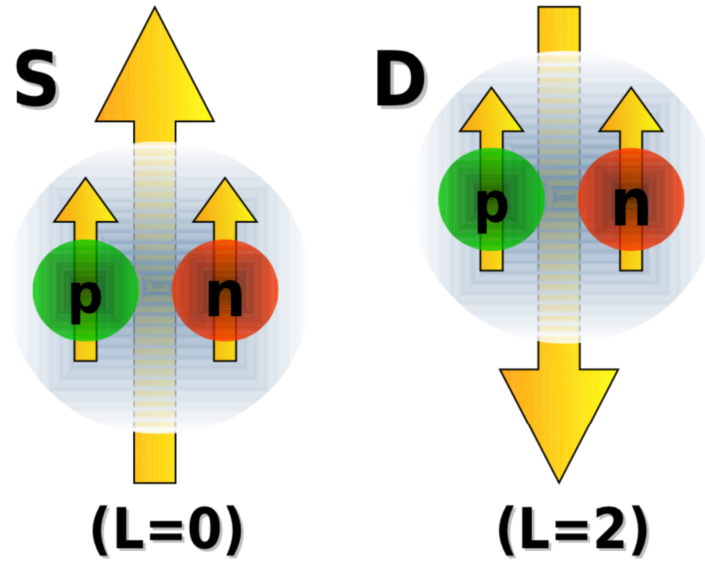
not a polarized p target

PRC **72** (2005) 054005, EPJA **25** (2005) 177

... and which has a nice analogue in the deuteron ...

$\vec{\mathrm{d}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{p})$





$$\sigma = \sigma_0 \left(1 + h P_1^{\mathrm{d}} A_{\mathrm{ed}}^{\mathrm{V}}\right)$$

$$P_z^{\mathrm{p}} = \sqrt{\tfrac{2}{3}} \left(P_S - \tfrac{1}{2} P_D\right) P_1^{\mathrm{d}}$$

Passchier++ PRL **82** (1999) 4988

Passchier++ PRL **88** (2002) 102302

... but the true ground state of ^{3}He is like lace

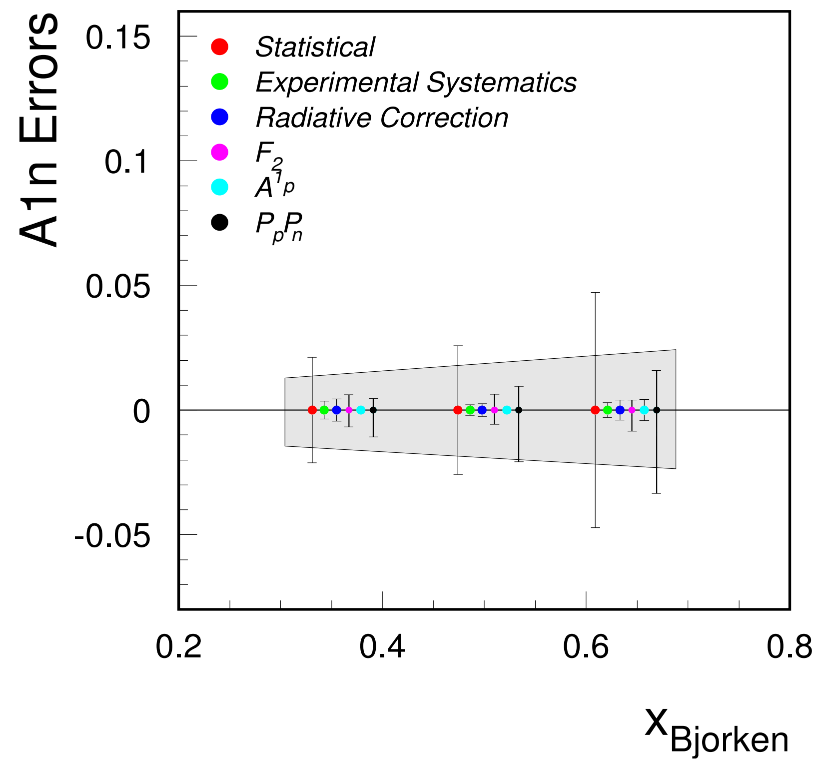
Channel number	L	S	l_α	L_α	P	K	Probability (%)
1	0	0.5	0	0	A	1	87.44
2	0	0.5	0	0	M	2	0.74
3	0	0.5	1	1	M	1	0.74
4	0	0.5	2	2	A	1	1.20
5	0	0.5	2	2	M	2	0.06
6	1	0.5	1	1	M	1	0.01
7	1	0.5	2	2	A	1	0.01
8	1	0.5	2	2	M	2	0.01
9	1	1.5	1	1	M	1	0.01
10	1	1.5	2	2	M	2	0.01
11	2	1.5	0	2	M	2	1.08
12	2	1.5	1	1	M	1	2.63
13	2	1.5	1	3	M	1	1.05
14	2	1.5	2	0	M	2	3.06
15	2	1.5	2	2	M	2	0.18
16	2	1.5	3	1	M	1	0.37

Blankleider, Woloshyn PRC **29** (1984) 538

The E05–102 and E08–005 experiments at JLab

- **Benchmark measurement** of A'_x and A'_z asymmetries in $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{d})$, $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{p})$, and $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{n})$.

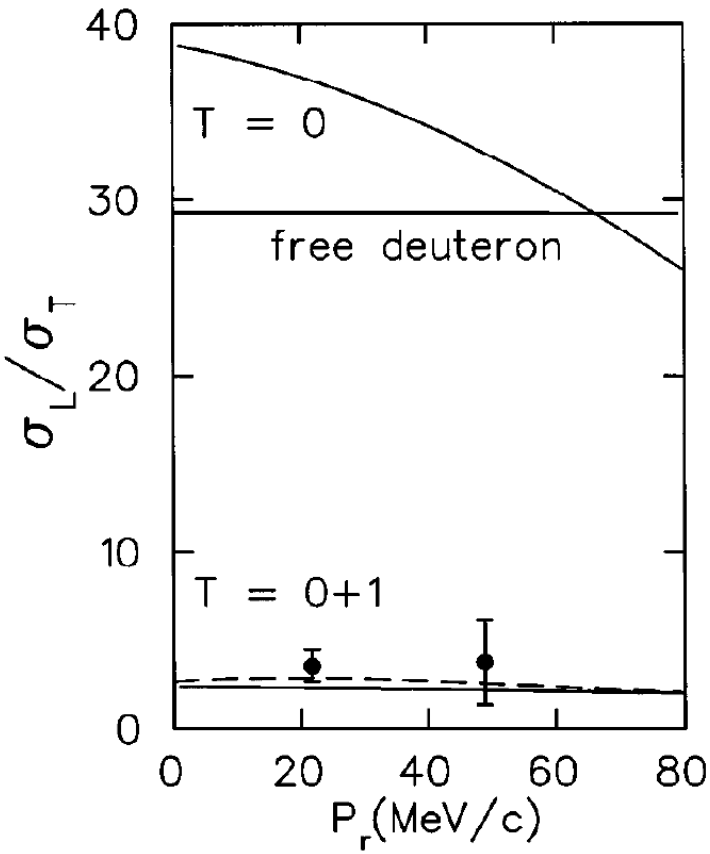
- **Better understanding of ground-state spin structure of polarized** ^{3}He — — S, S', D wave-function components. Improve knowledge of ^{3}He rather than using it as an effective neutron target. **Direct consequences for all polarized** ^{3}He **experiments**.



- Distinct manifestations of S, D, S' with changing p_{miss} in $(\mathrm{e},\mathrm{e}'\{\mathrm{p}/\mathrm{d}/\mathrm{n}\})$.

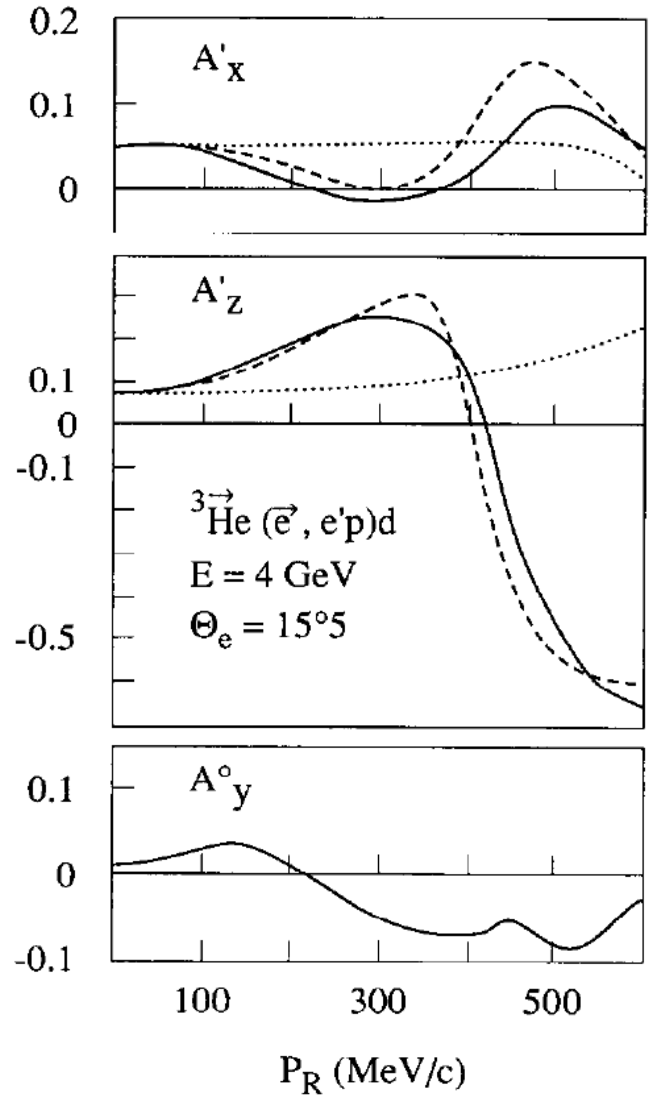
- Data at (almost) identical Q^2 for $(\vec{\mathrm{e}},\mathrm{e}'\mathrm{d})$, $(\vec{\mathrm{e}},\mathrm{e}'\mathrm{p})$, and $(\vec{\mathrm{e}},\mathrm{e}'\mathrm{n})$ simultaneously over a broad range of p_{miss} poses **strong constraints on state-of-the-art calculations**.

What is so special about ^{3}He$(e, e'd)$ and $^3\vec{He}(\vec{e}, e'd)$?



unique isoscalar-isovector interference in $(e, e'd)$

Tripp++ PRL **76** (1996) 885



in $(e, e'p)$ the D/S' effects seen only at high p_{miss}

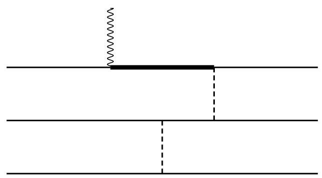
Laget PLB **276** (1992) 398

Exploiting state-of-the-art calculations

Bochum/Krakow (full Faddeev)

- AV18 NN-potential (+ Urbana IX 3NF, work in progress)
- Complete treatment of FSI, MEC

Hannover/Lisbon (full Faddeev)



- CC extension and refit of CD-Bonn NN-potential
- Includes FSI, MEC
- Δ as active degree-of-freedom providing effective 3NF and 2-body currents
- Coulomb interaction for outgoing charged baryons

Pisa PRC **72** (2005) 014001

- AV18 + Urbana IX (or IL7)
- Inclusion of FSI by means of the variational PHH expansion and MEC
- Not Faddeev, but accuracy completely equivalent to it

Trento

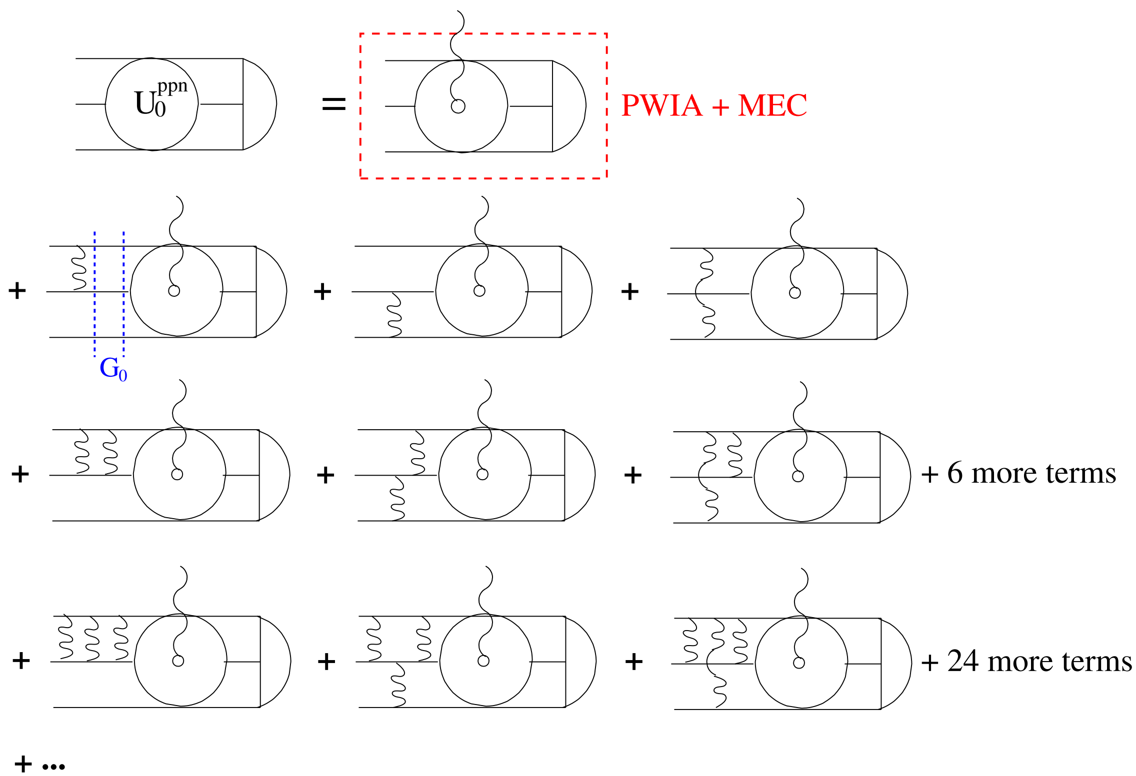
- Coming up

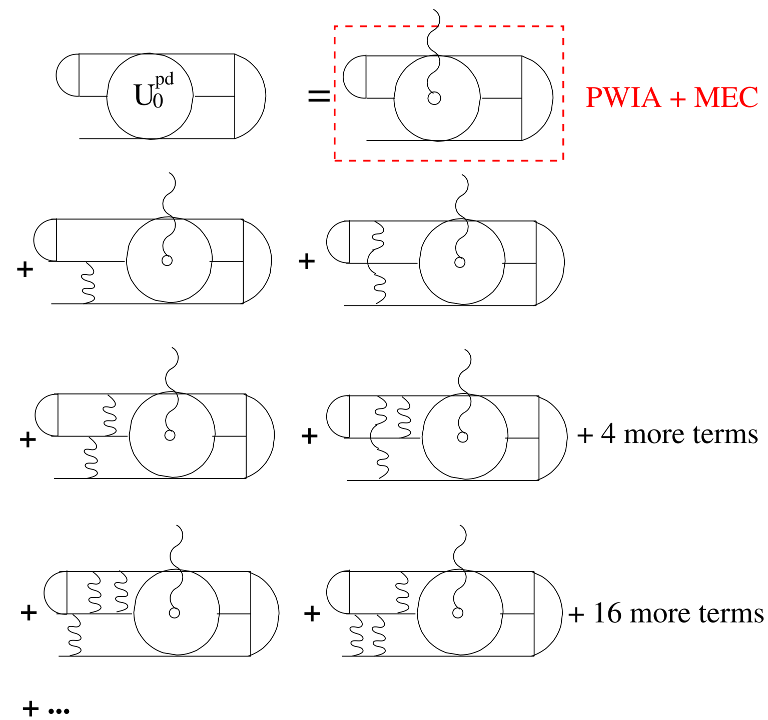
Basic machinery: Faddeev calculations

Nuclear transition current for breakup of ^{3}He: $J^\mu = \left\langle \Psi_\mathrm{f} \mid \hat{\mathcal{O}}^\mu \mid \Psi_{^3\mathrm{He}}(\theta^*, \phi^*) \right\rangle$

Photon absorption operator: $\hat{\mathcal{O}}^\mu = \sum_{i=1}^{3} \left[\hat{J}_\mathrm{SN}(i) + \hat{J}_\mathrm{MEC}(i) \right]$

Final-state interactions (auxiliary states): $\left\langle \Psi_\mathrm{f} \mid \hat{\mathcal{O}}^\mu \mid \Psi_{^3\mathrm{He}}(\theta^*, \phi^*) \right\rangle \longrightarrow \left\langle \Psi_\mathrm{f} \mid U_\mathrm{f}^\mu \right\rangle$

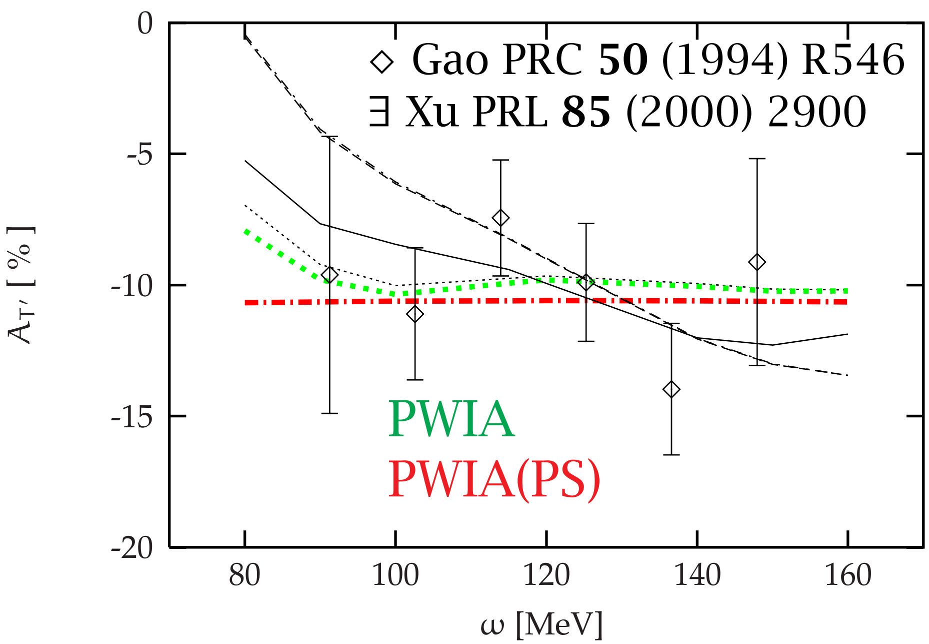


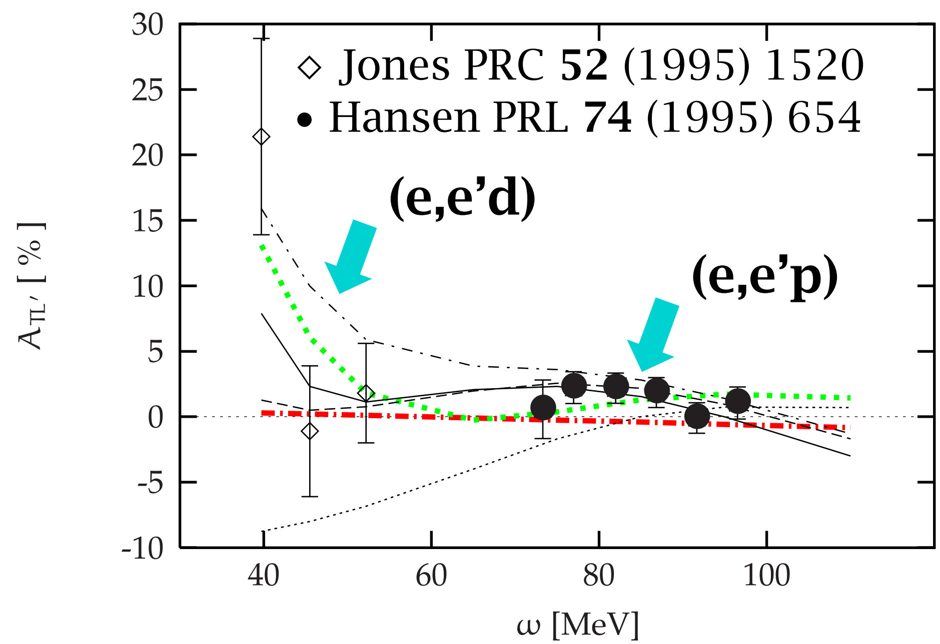


Golak++ Phys Rep **415** (2005) 89

Indication of D and S' components in $^3\vec{\mathrm{He}}(\vec{e}, e')$

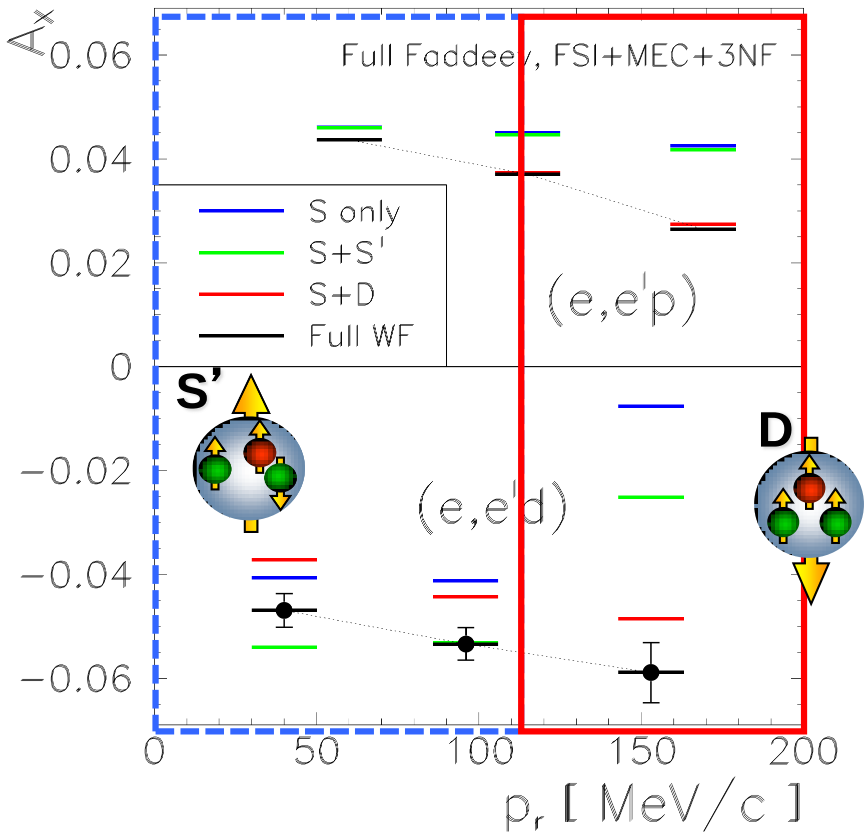
Inclusive A'_{T} ($= A_z$) and A'_{LT} ($= A_x$)

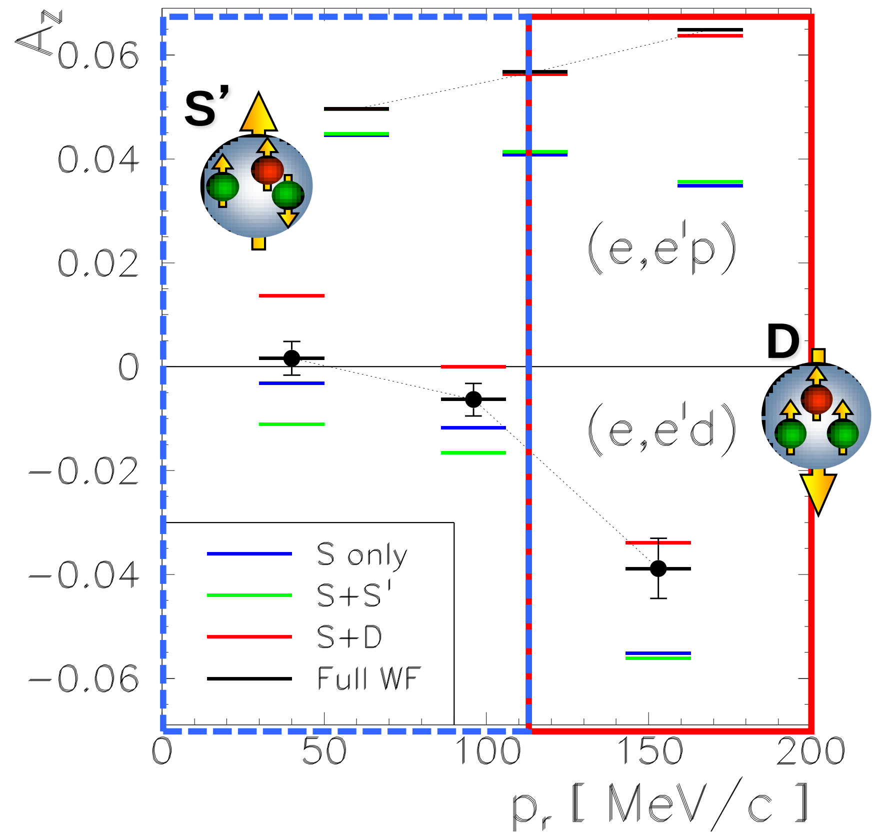




- A'_{LT} receives contributions from ingredients which go beyond most simplistic picture [$F_1^{(\mathrm{n})} = 0$]
- sensitive to replacement PWIA(PS) $\longrightarrow$ PWIA.
- S'- and D-state pieces contribute very strongly to A'_{LT}

Ishikawa++ PRC **57** (1998) 39





- S' state relevant at small p_r ($= p_\mathrm{miss}$)
- D state governs variation of A_z at large p_r

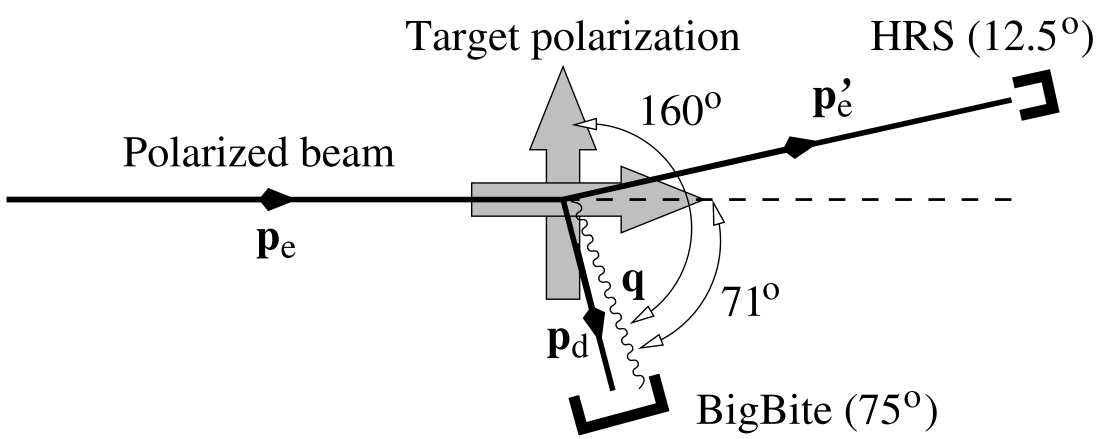
Beam-target asymmetry in QE p/d knockout from $^3\vec{\mathrm{He}}$

- Cannot disentangle effects of WF components (S, D, S') by measurement of cross-sections alone: *need polarization observables*

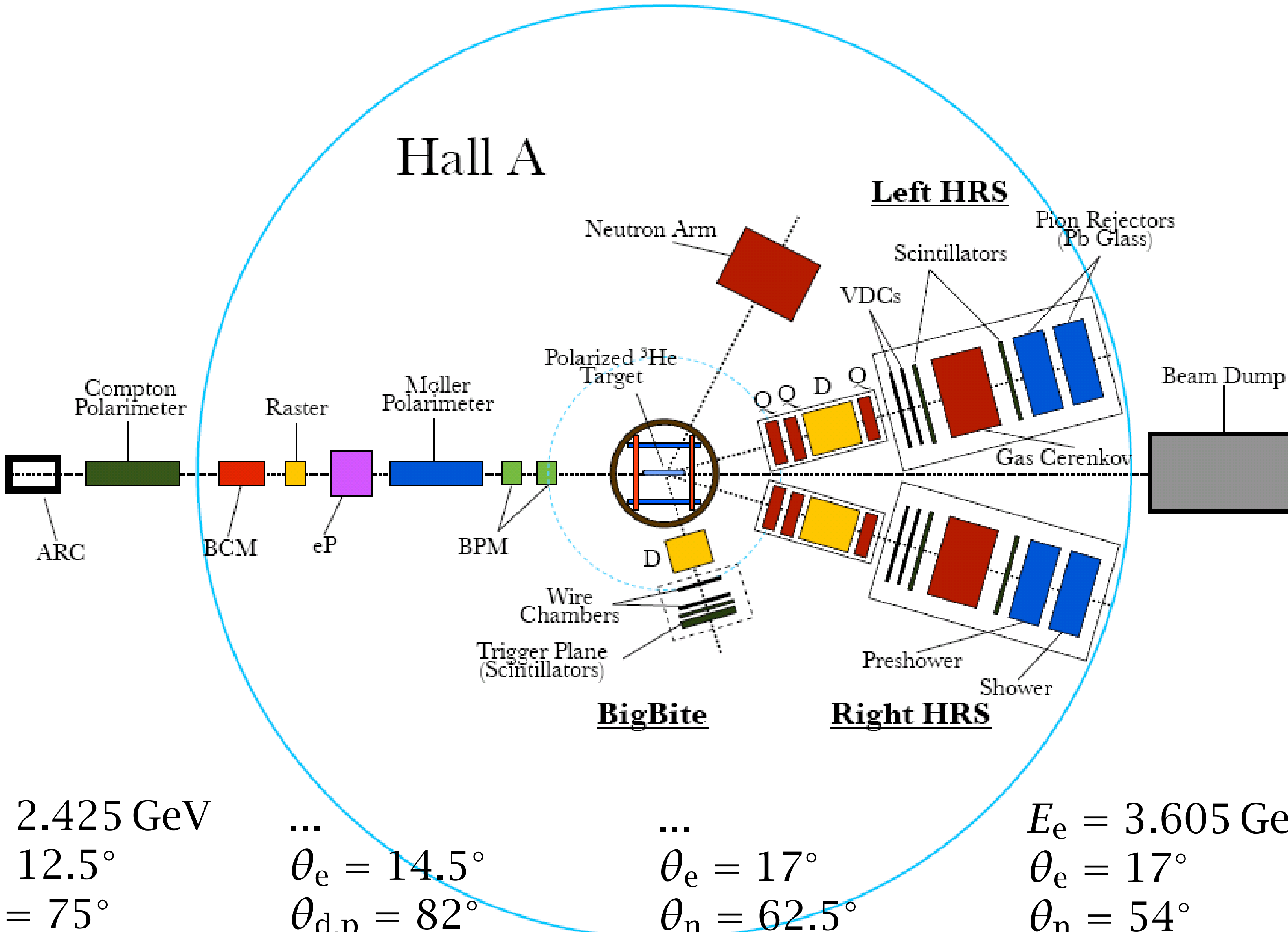
$$\frac{\mathrm{d}\sigma(h,\vec{S})}{\mathrm{d}\Omega_\mathrm{e}\,\mathrm{d}E_\mathrm{e}\,\mathrm{d}\Omega_\mathrm{d}\,\mathrm{d}p_\mathrm{d}} = \frac{\mathrm{d}\sigma_0}{\cdots}\left[\,1+\vec{S}\cdot\vec{A}^0 + h(A_\mathrm{e}+\vec{S}\cdot\vec{A})\,\right]$$

$$A(\theta^*,\phi^*) = \vec{S}(\theta^*,\phi^*)\cdot\vec{A} = \frac{[\,\mathrm{d}\sigma_{++}+\mathrm{d}\sigma_{--}\,]-[\,\mathrm{d}\sigma_{+-}+\mathrm{d}\sigma_{-+}\,]}{[\,\mathrm{d}\sigma_{++}+\mathrm{d}\sigma_{--}\,]+[\,\mathrm{d}\sigma_{+-}+\mathrm{d}\sigma_{-+}\,]}$$

- **Access to [effects of] small WF components** (D, S')
- E05–102: simultaneous measurement of all break-up channels: $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{d})\mathrm{p}$, $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{p})\mathrm{d}$, $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{p})\mathrm{pn}$ ... and also $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{n})\mathrm{pp}$



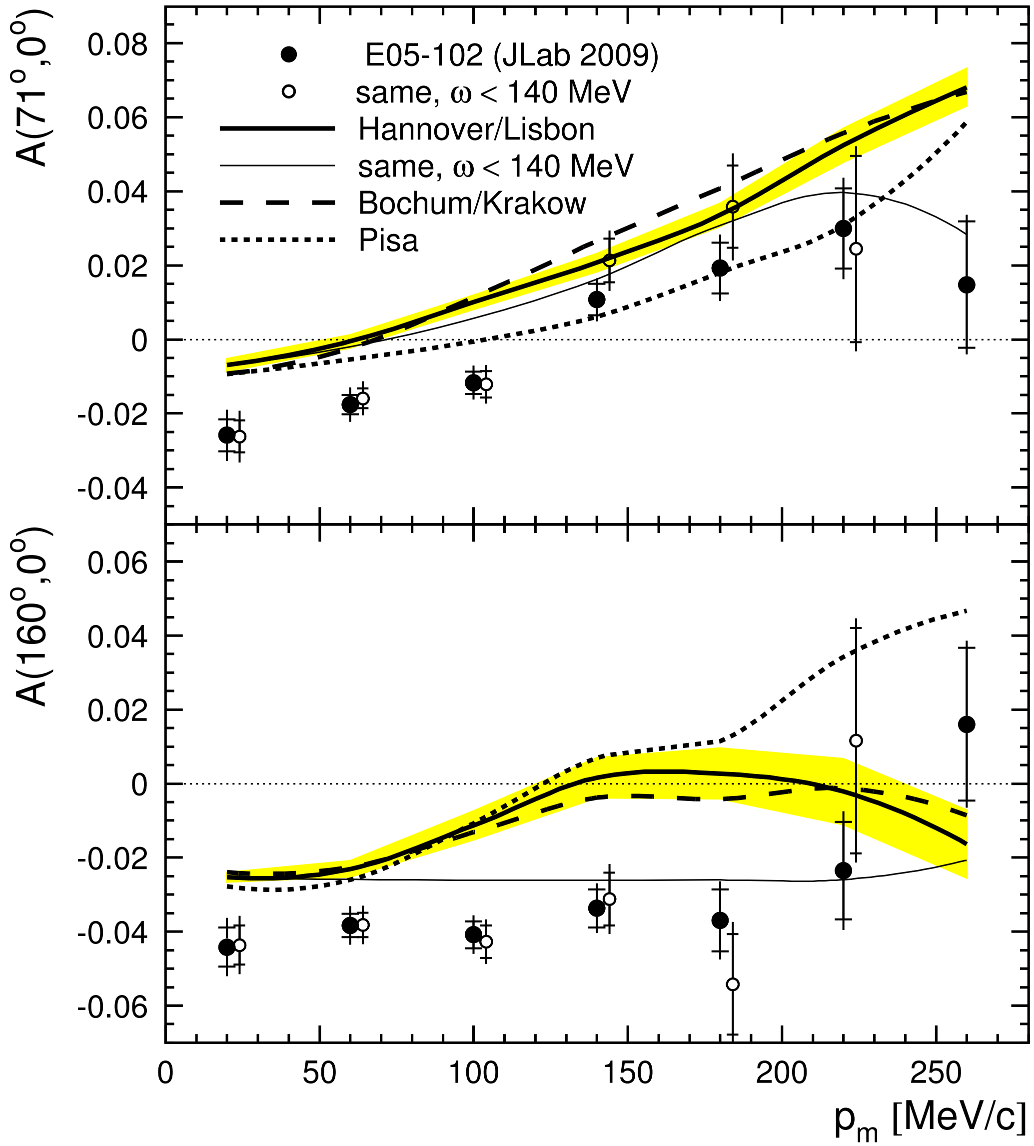
Experimental Setup



$E_\mathrm{e} = 2.425\,\mathrm{GeV}$	...	...	$E_\mathrm{e} = 3.605\,\mathrm{GeV}$
$\theta_\mathrm{e} = 12.5^\circ$	$\theta_\mathrm{e} = 14.5^\circ$	$\theta_\mathrm{e} = 17^\circ$	$\theta_\mathrm{e} = 17^\circ$
$\theta_\mathrm{d,p} = 75^\circ$	$\theta_\mathrm{d,p} = 82^\circ$	$\theta_\mathrm{n} = 62.5^\circ$	$\theta_\mathrm{n} = 54^\circ$
$Q^2 = 0.25\,\mathrm{GeV}^2$	$Q^2 = 0.35\,\mathrm{GeV}^2$	$Q^2 = 0.46\,\mathrm{GeV}^2$	$Q^2 = 0.96\,\mathrm{GeV}^2$

Results on $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{d})\mathrm{p}$ — p_m-dependence

- Asymmetries are small (typically a few %), thus hard to reproduce theoretically (cancellations)
- Good agreement on the transverse asymmetry (71°)
- Worse for the longitudinal asymmetry (160°) ... but it improves when ω is restricted to QE peak
- Discrepancy due to
  - — incomplete treatment of FSI (?)
  - — unaccounted for 3NF (?)
  - — underestimated S' component of g.s. WF (?)



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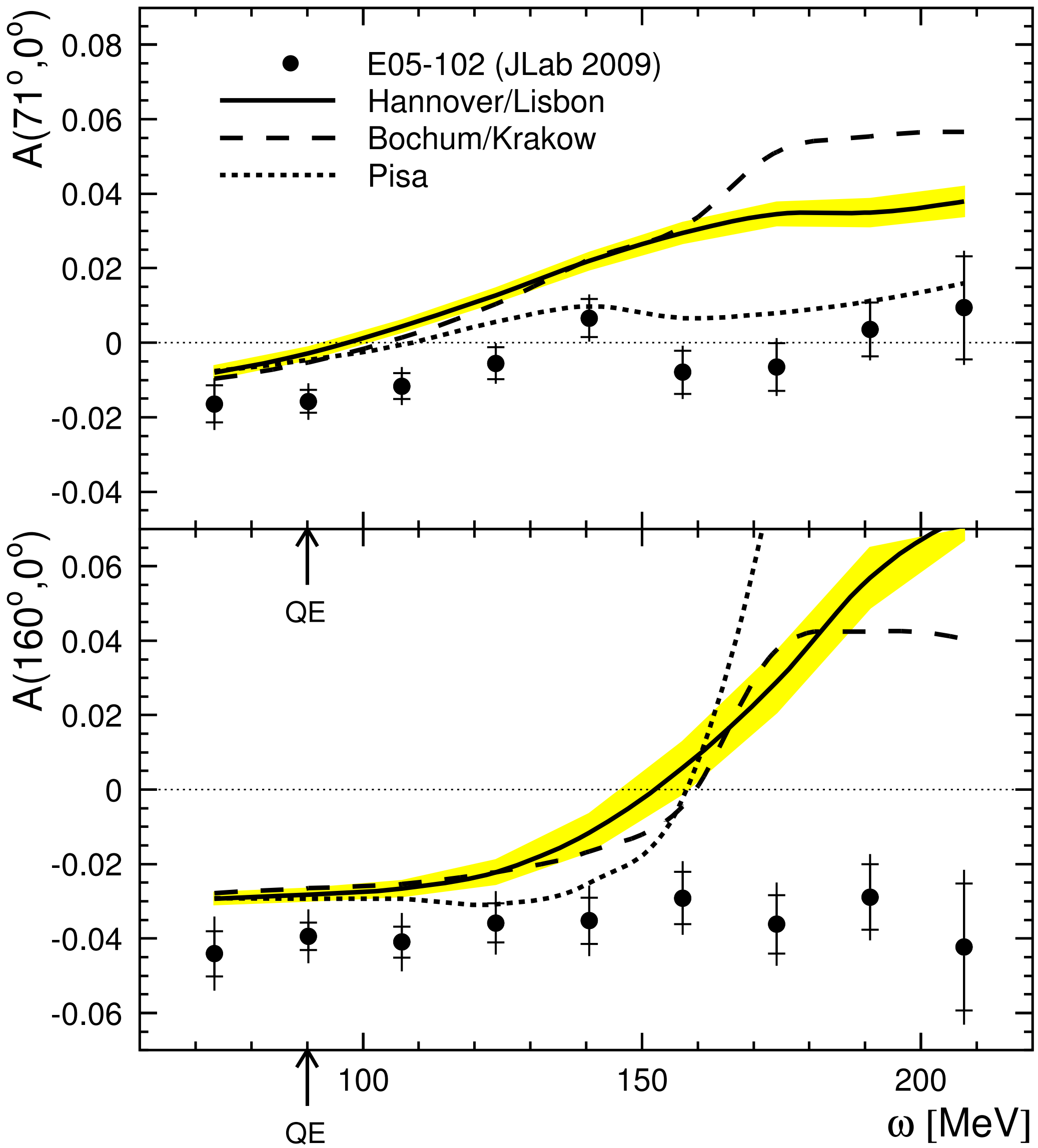
Results on $^3\vec{\text{He}}(\vec{\text{e}}, \text{e}'\text{d})\text{p}$ ω-dependence



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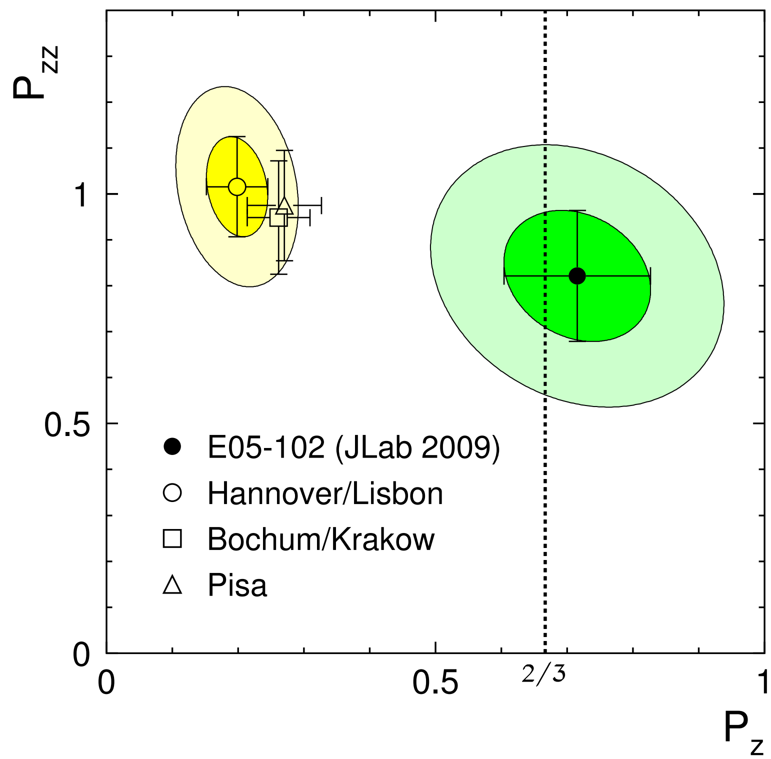
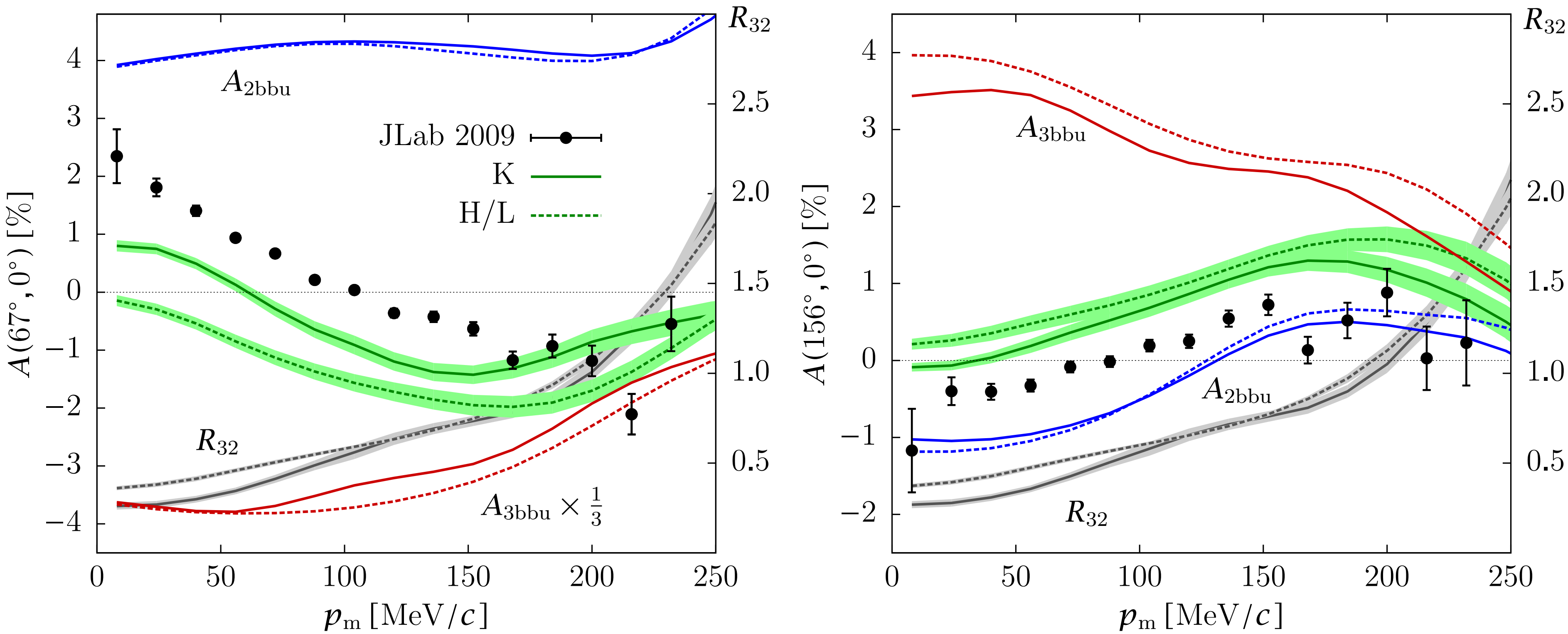
Attempt to evaluate P_z and P_{zz}

- Assume $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{d})\mathrm{p}$ at low p_{miss} is like elastic scattering off polarized d
- Use $A_x^{(^3\mathrm{He})}$, $A_z^{(^3\mathrm{He})}$ as if they were $A_x^{(\mathrm{ed})}$, $A_z^{(\mathrm{ed})}$ with appropriate deuteron FFs, and extract P_z and P_{zz}
- Toy model $|^3\mathrm{He}\rangle = |\mathrm{d}\rangle + |\mathrm{p}\rangle$
- Spin decomposition $|^3\mathrm{He}\rangle = \left|\frac{1}{2},\frac{1}{2}\right\rangle = \sqrt{\frac{2}{3}}|1,1\rangle\left|\frac{1}{2},-\frac{1}{2}\right\rangle - \sqrt{\frac{1}{3}}|1,0\rangle\left|\frac{1}{2},\frac{1}{2}\right\rangle$ gives $P_z = \langle I_z\rangle_{^3\mathrm{He}} = \frac{2}{3}$, $P_{zz} = \langle 3I_z^2 - 2\rangle_{^3\mathrm{He}} = 0$



PRL **113** (2014) 232505

Results on $^3\vec{\mathrm{He}}(\vec{\mathrm{e}}, \mathrm{e}'\mathrm{p})$ — p_m-dependence



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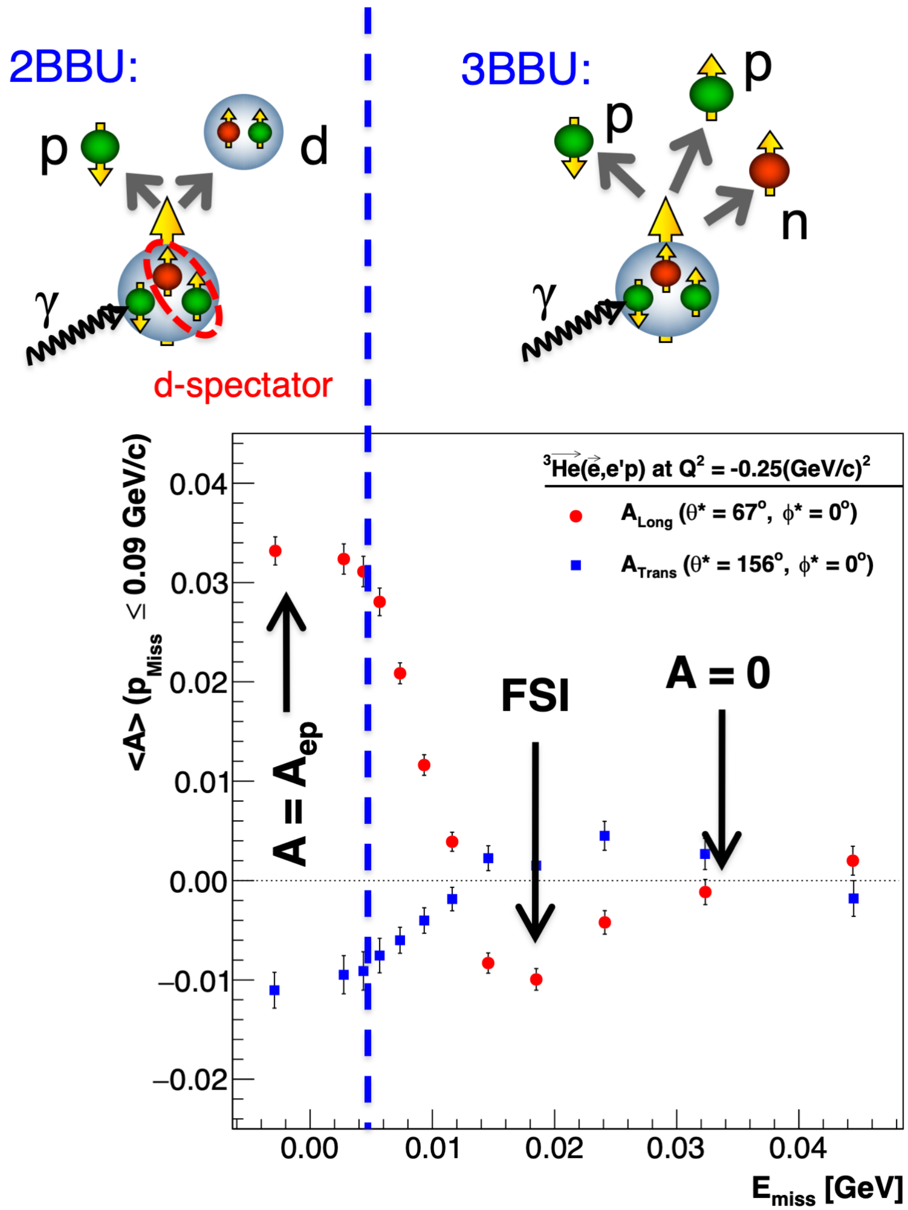
- No 2bbu/3bbu separation possible; rely on MC to disentangle $A_{2\mathrm{bbu}}/A_{3\mathrm{bbu}}$
  - ▷ Unpolarized 2bbu and 3bbu XS as well as $A_{2\mathrm{bbu}}$ well established
- Only qualitative agreement of data with theory. Issues:
  - ▷ Cancellation of 2bbu and 3bbu contributions
  - ▷ 3bbu asymmetry dominant — *possibly too much so*
  - ▷ Pertinent ingredients: Coulomb, RC, FSI, 3NF (?)

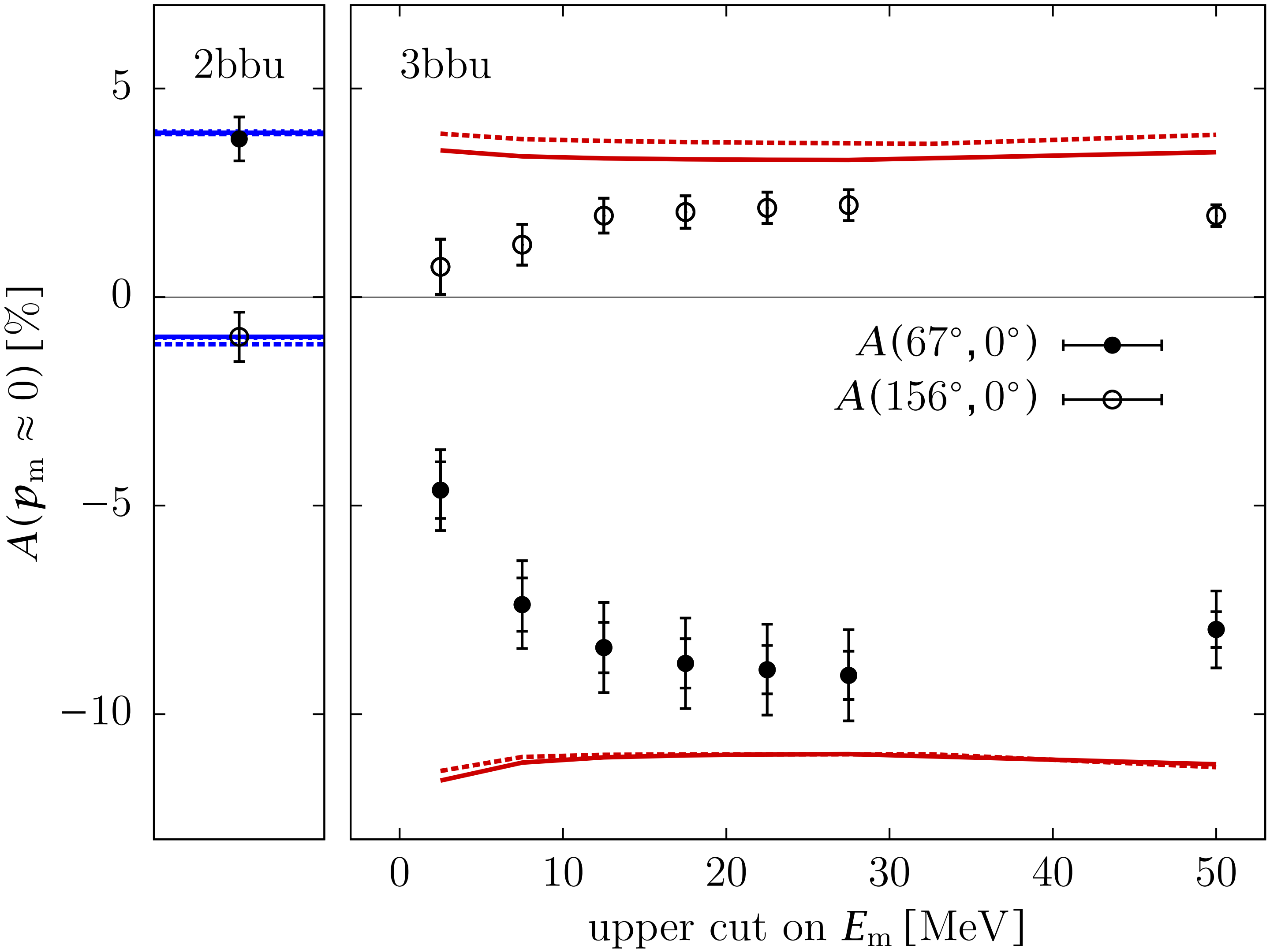
Simple interpretation of $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{p})$

- Valid for $p_\mathrm{m} \approx 0$
- Assume PWIA
- S-state dominates
- Missing energy: $E_\mathrm{m} = \omega - T_\mathrm{p} - T_\mathrm{d}$

- Low-E_m region dominated by 2bbu: $A \approx A(\vec{\mathrm{e}} - \vec{\mathrm{p}}\ \mathrm{elastic})$
- High-E_m region dominated by 3bbu: $A \approx 0$
- Non-zero asymmetry in 3bbu probably caused by FSI



Extraction of 2bbu and 3bbu asymmetries in $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{p})$



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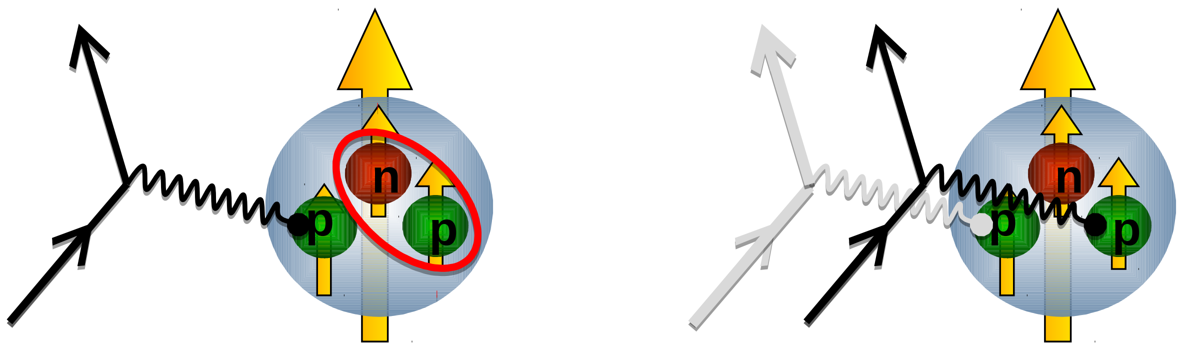
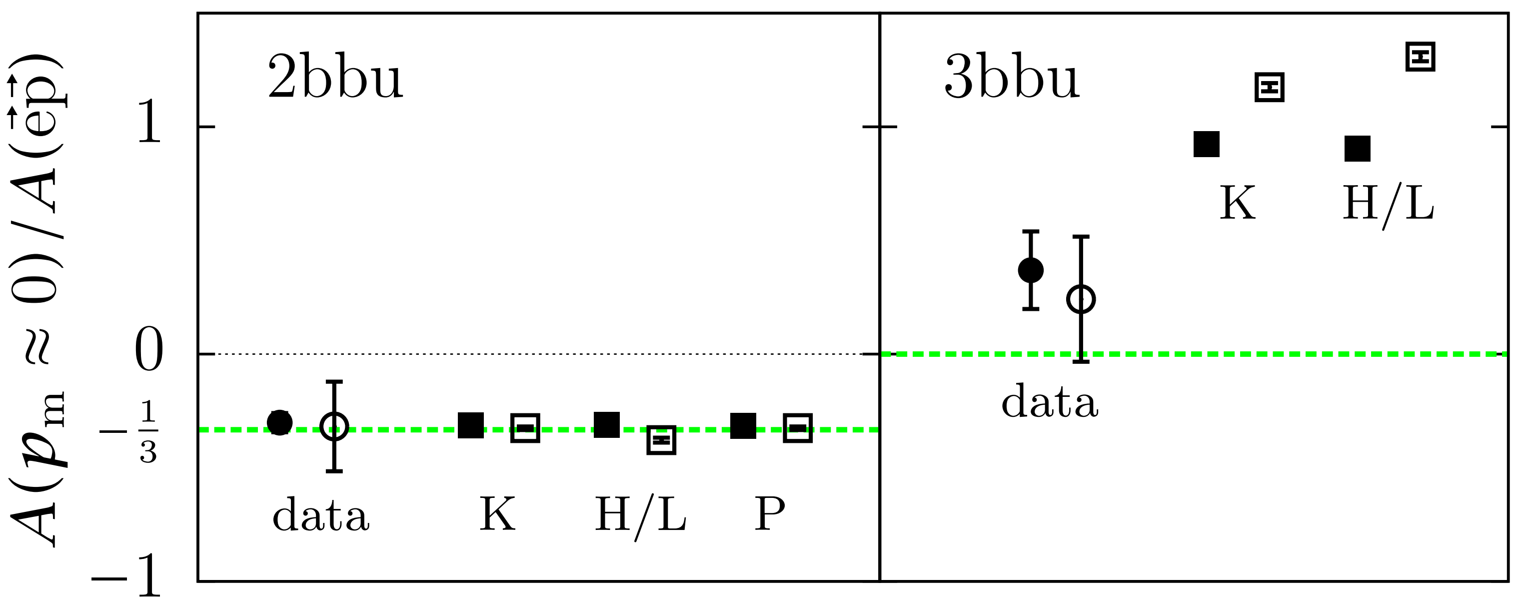
Message on 2bbu and 3bbu asymmetries in $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{p})$





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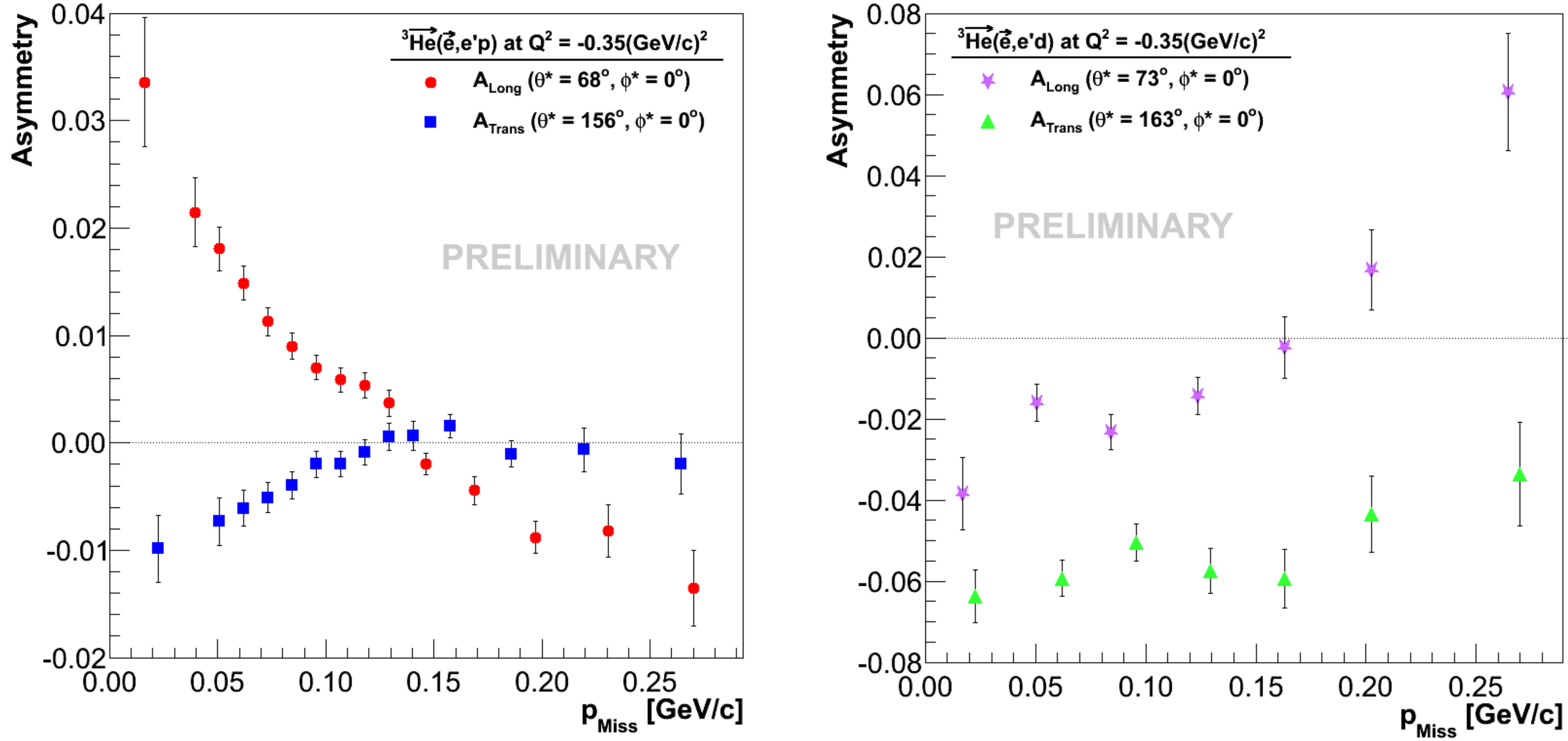
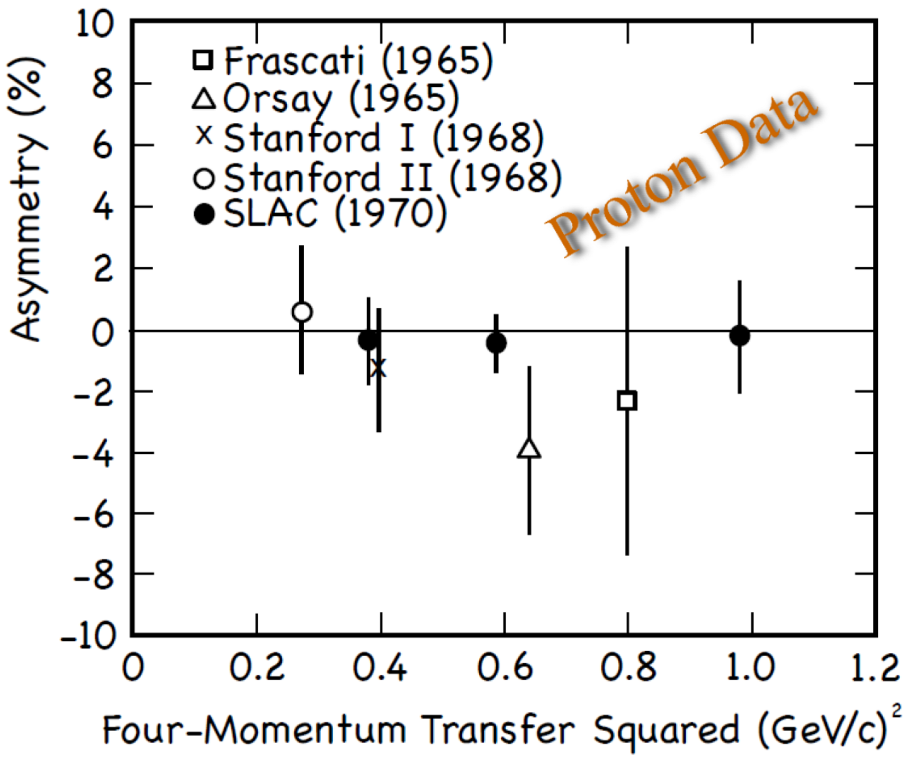
More $^3\vec{\mathrm{He}}(\vec{e}, e'd)$ and $^3\vec{\mathrm{He}}(\vec{e}, e'p)$ ...

- High-statistics data also available at $Q^2 \approx 0.35\,\mathrm{GeV}^2$ in all channels



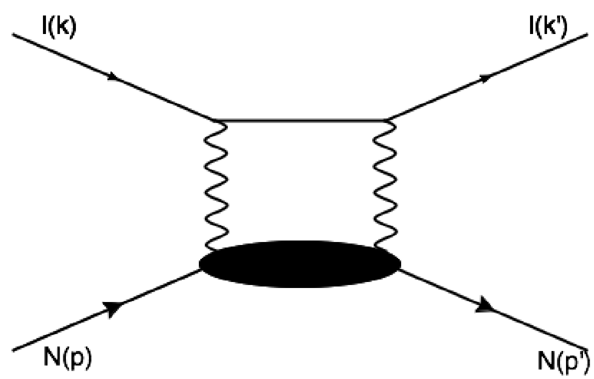
- Opportunity to study Q^2-dependence of asymmetries
- Theoretical calculations pending

Single-spin asymmetry in QE $^3\mathrm{He}^{\uparrow}(\mathrm{e},\mathrm{e}')$

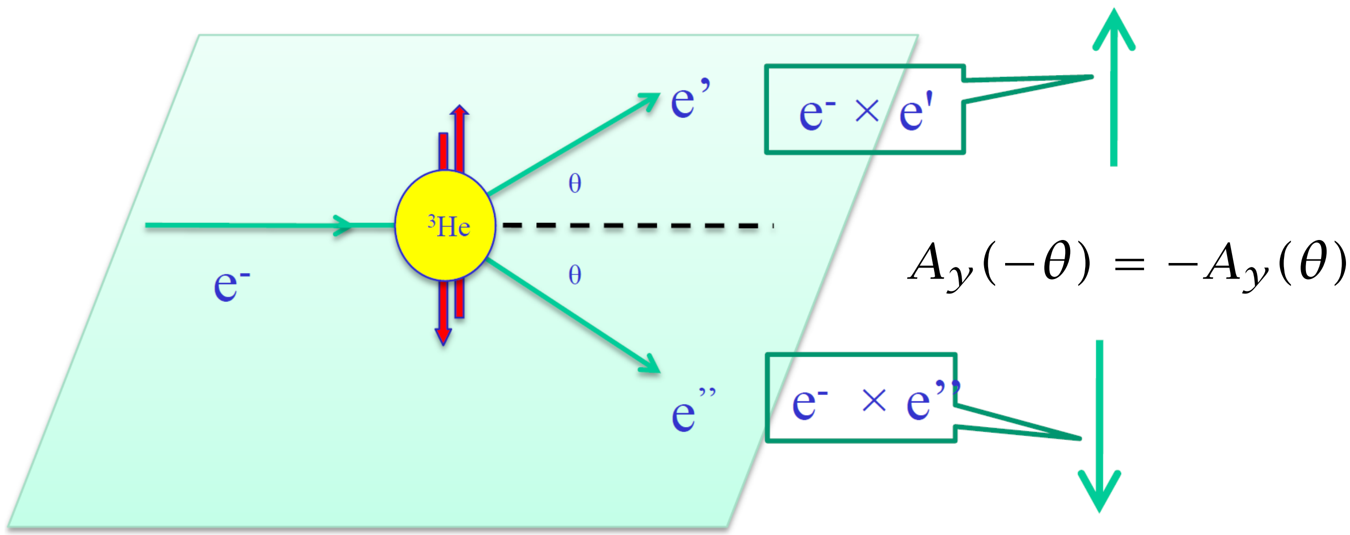


$$A_y = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

$$\propto \vec{s} \cdot (\vec{k} \times \vec{k}')$$



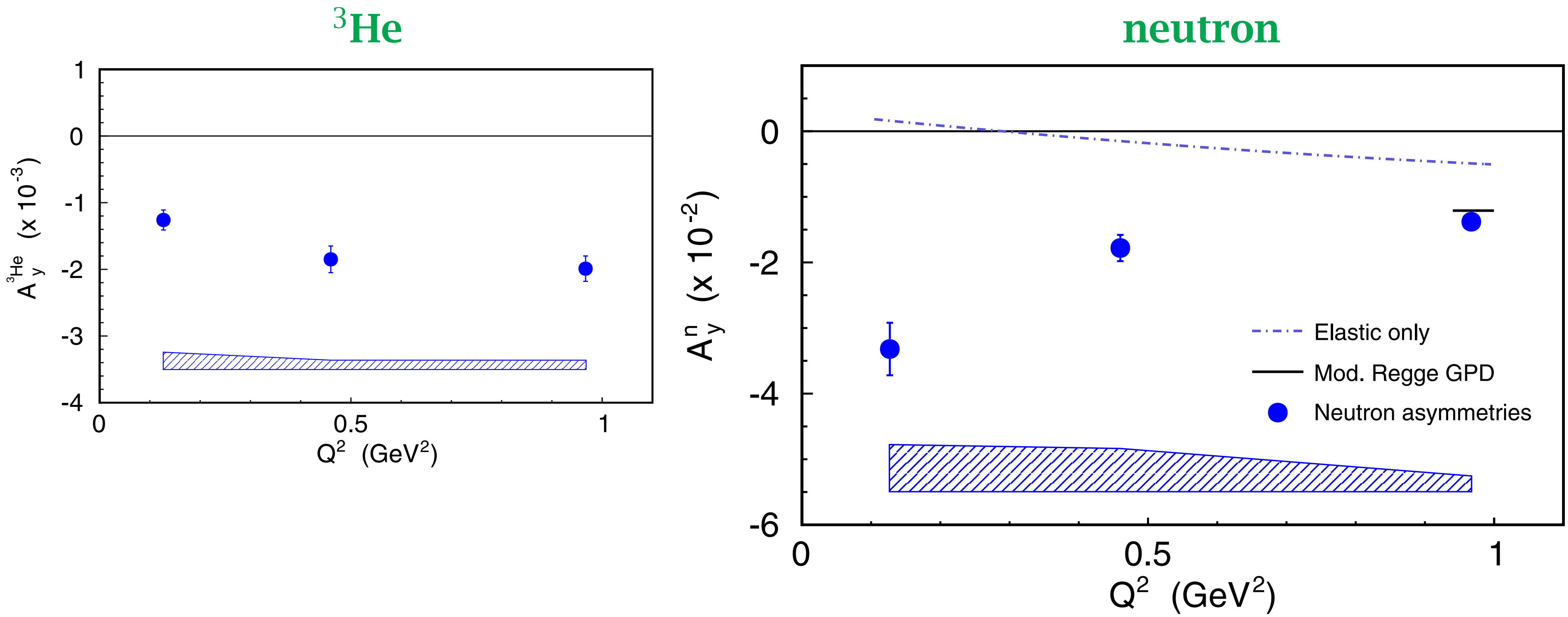
- $A_y = 0$ in Born approximation (T-invariance)
- $A_y \neq 0$ indicative of 2γ effects, $\propto \mathrm{Im}\{T_{1\gamma}T^{*}_{2\gamma}\}$ interference; relevant for G_E^p/G_M^p, GPDs
- no measurement of comparable precision on **neutron**



E_0 [GeV]	E' [GeV]	θ_{lab} [Deg]	Q^2 [GeV]^2	$\|q\|$ [GeV]	θ_q [Deg]
1.25	1.22	17	0.13	0.359	71
2.43	2.18	17	0.46	0.681	62
3.61	3.09	17	0.98	0.988	54

Figure & table courtesy of Yawei Zhang, Rutgers

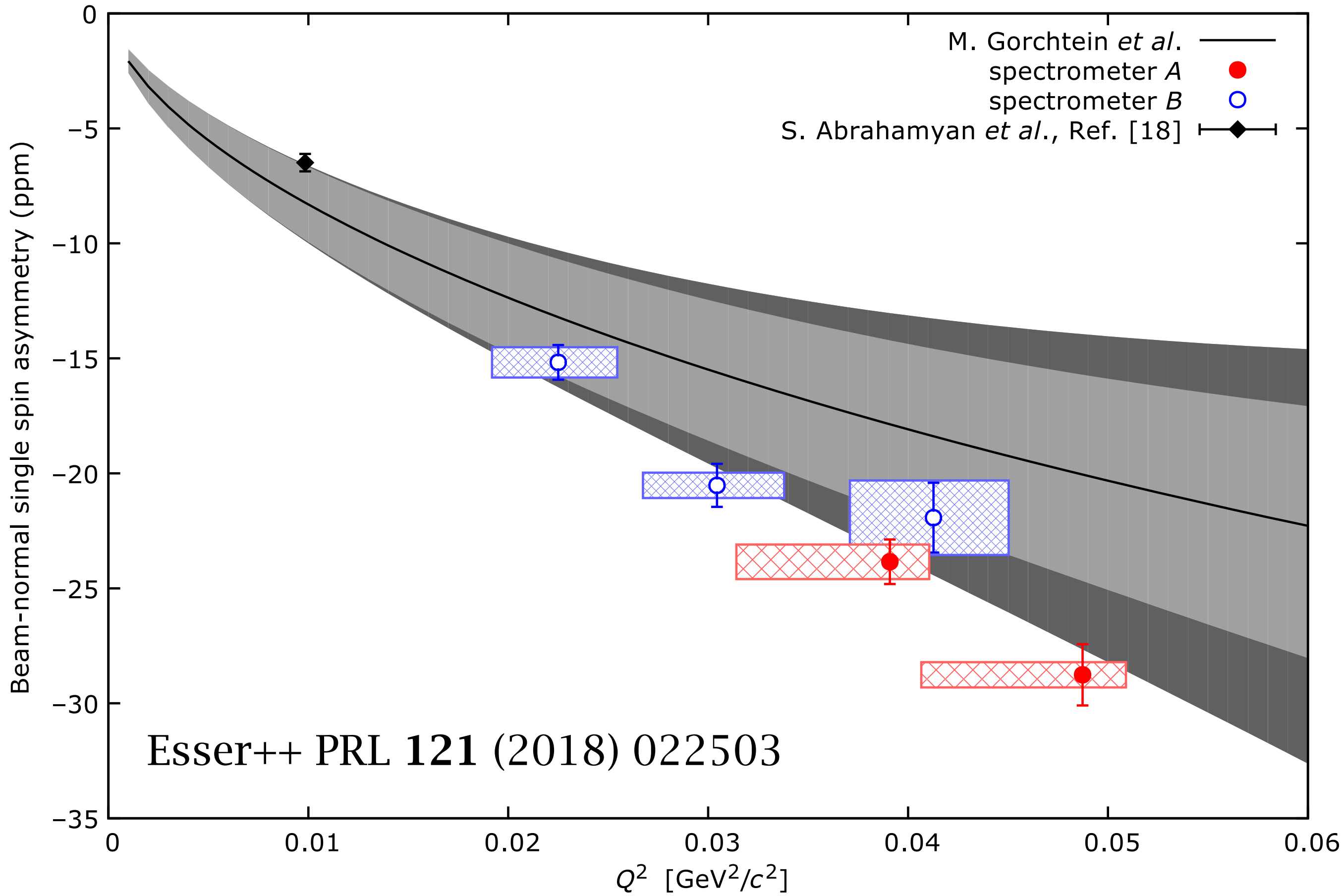
Single-spin asymmetry in QE $^3\mathrm{He}^{\uparrow}(e, e')$ E05–015



- First measurement of A_y^n (extracted from transversely polarized $A_y^{^3\mathrm{He}}$)
- Uncertainty several times better than previous proton data
- Asymmetry clearly non-zero and negative

Zhang++ PRL **115** (2015) 172502

Single-spin asymmetries in $^{12}\mathrm{C}(\mathrm{e}^{\uparrow},\mathrm{e}')$

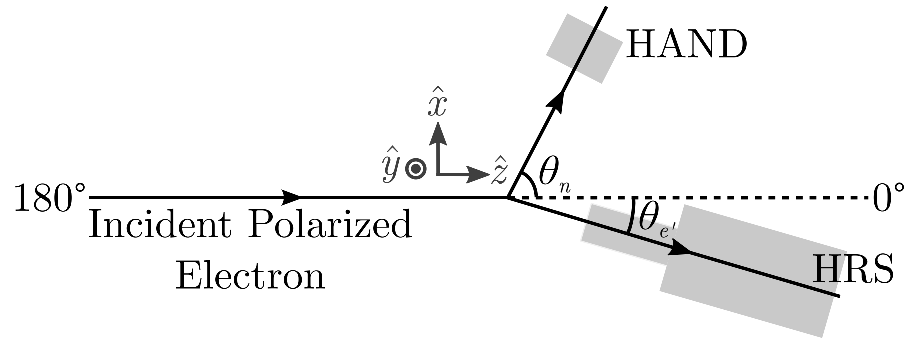


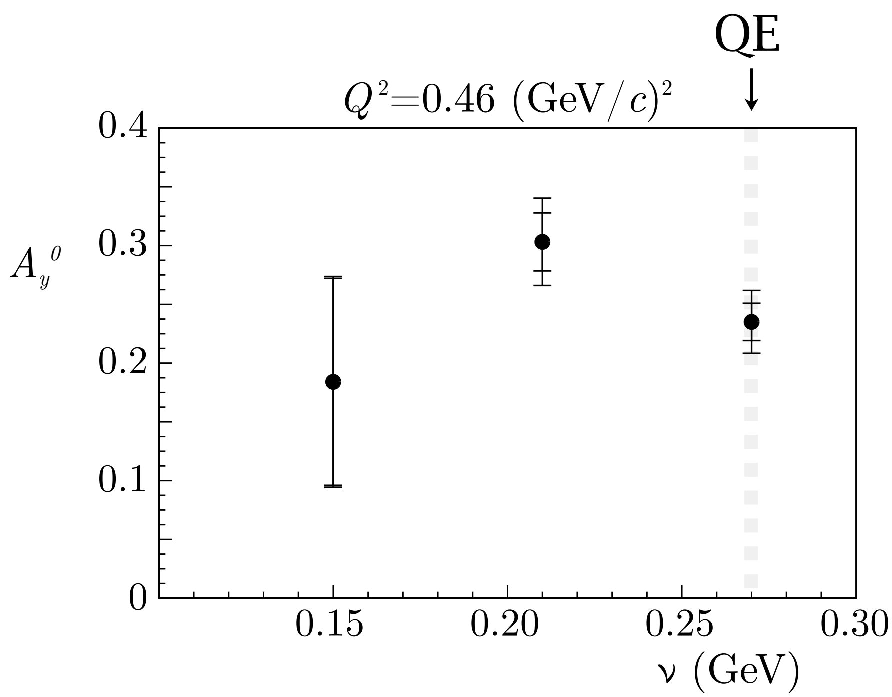
- Several calculations for A_y in $\mathrm{p}(\mathrm{e}^{\uparrow},\mathrm{e})$, very few on nuclei
- Generalization of forward inclusive model to nuclear targets:

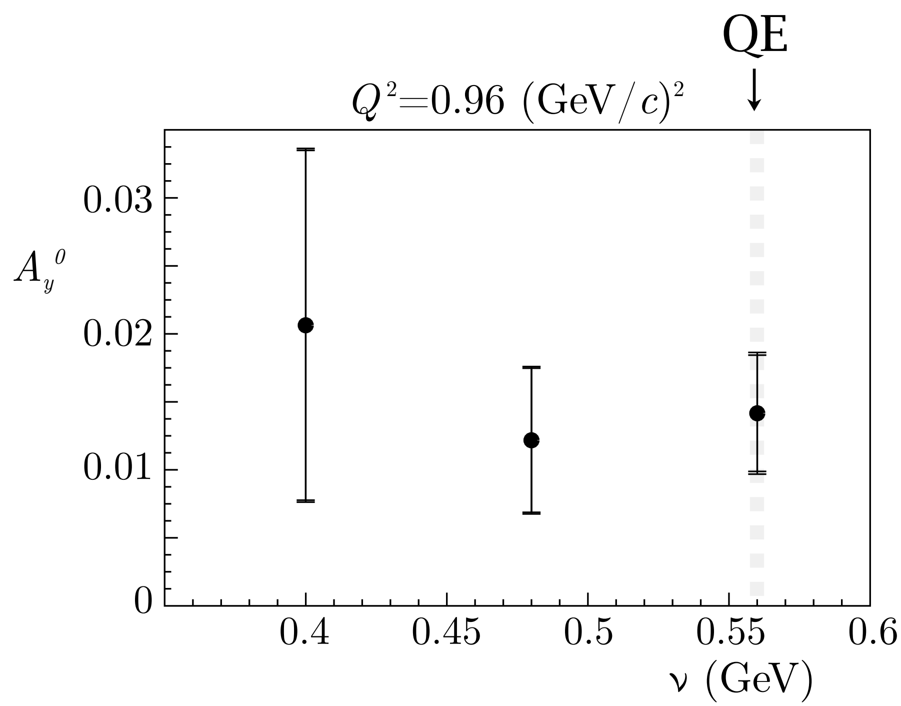
$$A_y \sim C_0 \log\left(\frac{Q^2}{m_\mathrm{e}^2 c^2}\right) \frac{F_\mathrm{Compton}(Q^2)}{F_\mathrm{charge}(Q^2)}$$

Single-spin asymmetries in QE $^3\mathrm{He}(\vec{e}, e'n)$

- Ideal probe of **FSI** and **MEC**
- Should be zero in PWIA and should die out at high Q^2
- Difficult calculations at high Q^2

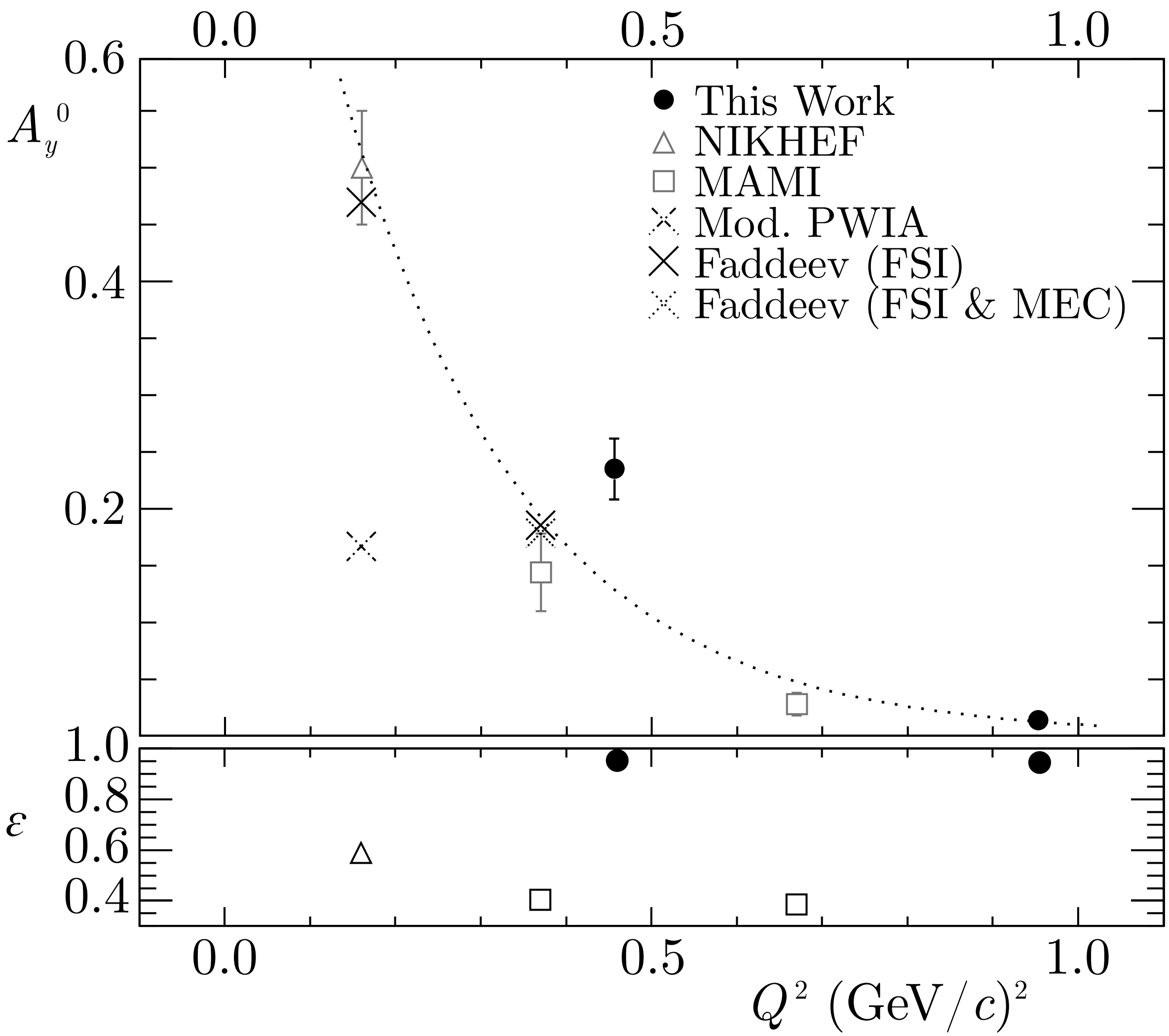






Long++ PLB (in press, 2019)

Single-spin asymmetries in QE $^3\mathrm{He}(\vec{e}, e'n)$

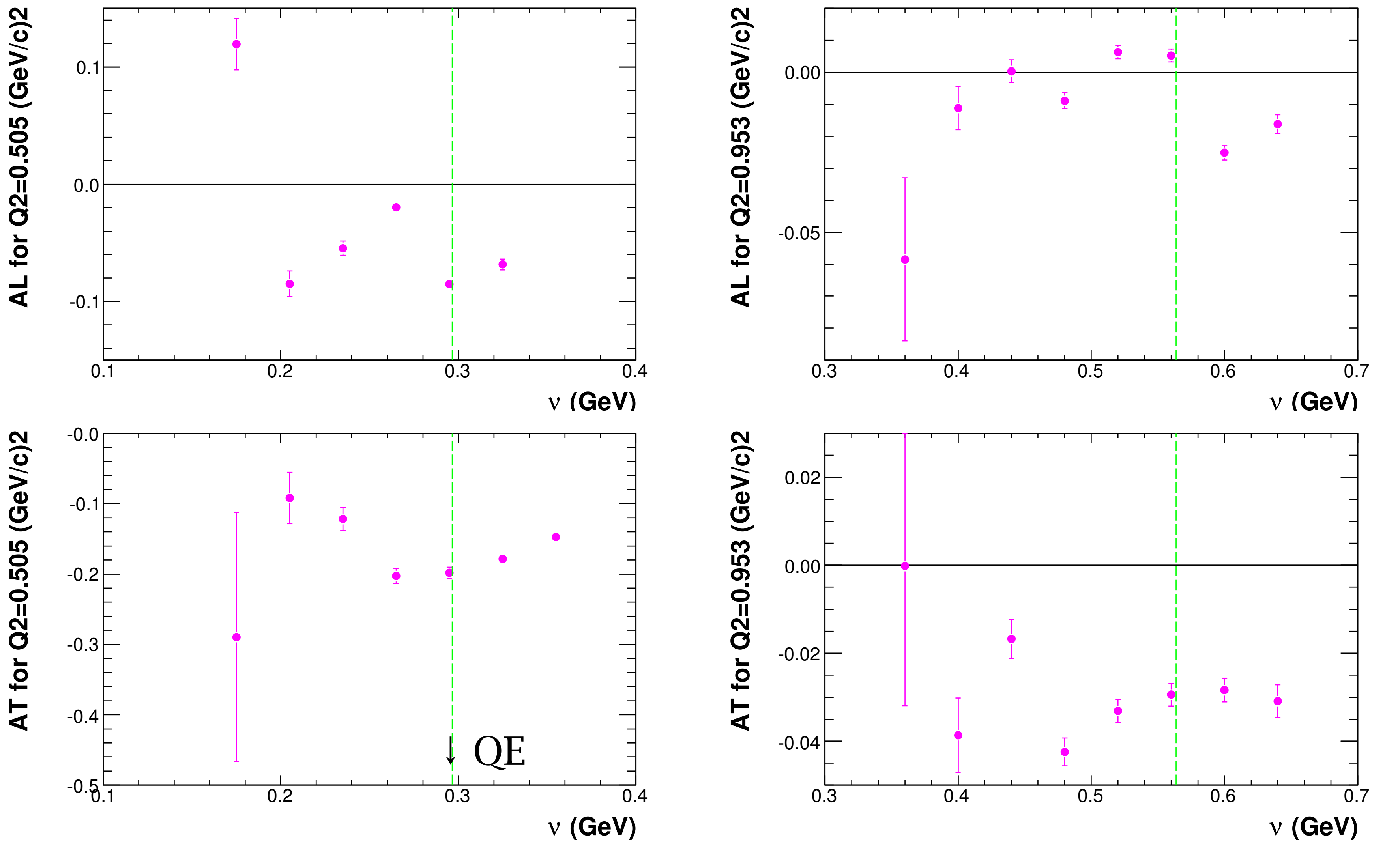


Long++ PLB (in press, 2019)

⟹ PWIA good enough for high-Q^2 experiments at JLab 12 GeV!

# Double-spin asymmetries in QE $^3\vec{\mathrm{He}}(\vec{e}, e'n)$ 	E08-005

$Q^2 \approx 0.5$ 	$Q^2 \approx 0.95$



- Calculations?

*** PRELIMINARY *** Figures courtesy of Elena Long, UNH

Triple-polarized $^3\vec{\mathrm{He}}(\vec{\mathrm{e}}, \mathrm{e}'\vec{\mathrm{p}})$

- PWIA: σ_L, σ_T, $\sigma_{T'}$ yield spin-dependent momentum distribution
- FSI, MEC preclude direct access except at $p_d \lesssim 2\,\mathrm{fm}^{-1}$
- Rich interplay ▷ **final-state symmetrization:** large effect in C_3
  ▷ **FSI:** largest in C_2
  ▷ **MEC:** most prominent in C_1

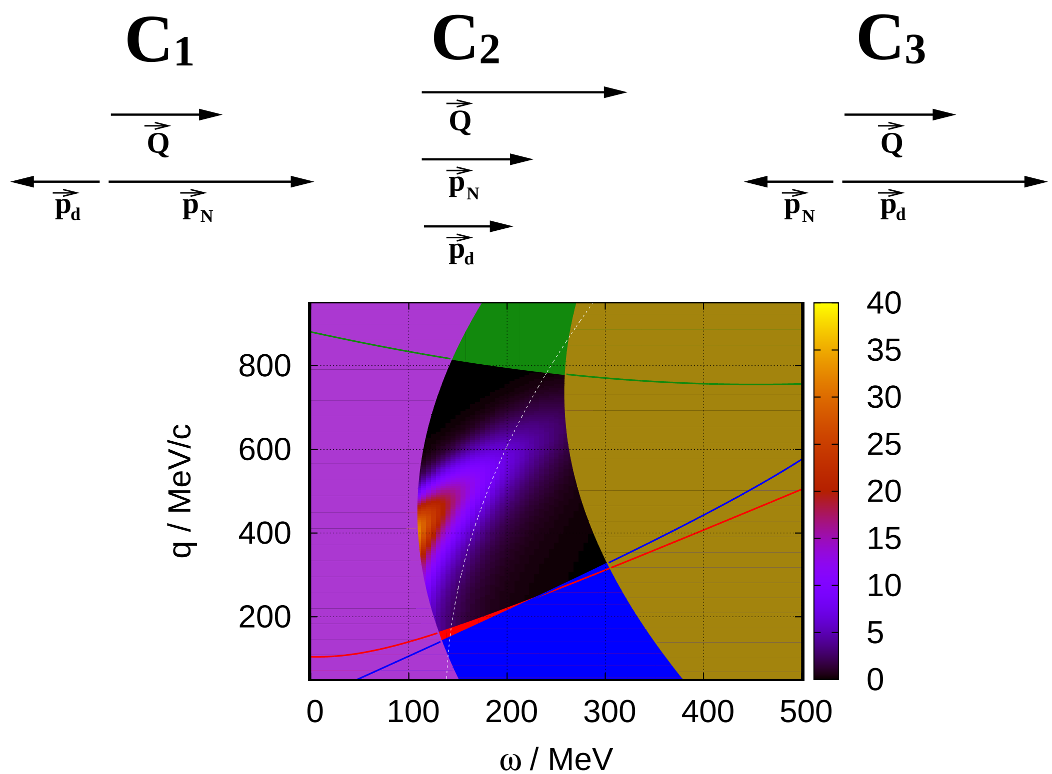


Fig. courtesy of M. Distler, JGU Mainz

Triple-polarized $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\vec{\mathrm{p}})$ MAMI/A1

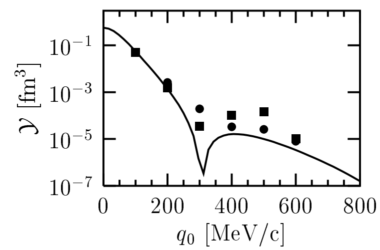
- Spin-dependent momentum distributions of $\vec{\mathrm{p}}\vec{\mathrm{d}}$ clusters in polarized ^{3}He
  Golak++ PRC **65** (2002) 064004

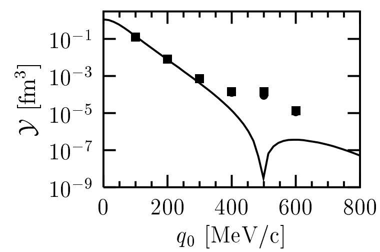
$$N_\mu = \left\langle \Psi^{(-)}_{\mathrm{pd}} M_{\mathrm{d}} m \,|\hat{j}_\mu(\vec{q})|\, \Psi M \right\rangle$$

$$\mathcal{Y}\left(M=\frac{1}{2}, M_{\mathrm{d}}=0, m=+\frac{1}{2}\right) \propto \left| N_{-1}^{\mathrm{spin\ PWIA}}\left(\frac{1}{2},0,-\frac{1}{2}\right)\right|^2$$

$$\mathcal{Y}\left(M=\frac{1}{2}, M_{\mathrm{d}}=1, m=-\frac{1}{2}\right) \propto \left| N_{+1}^{\mathrm{spin\ PWIA}}\left(\frac{1}{2},1,+\frac{1}{2}\right)\right|^2$$

$$A = \frac{\mathcal{Y}(1/2,0,1/2) - \mathcal{Y}(1/2,1,-1/2)}{\mathcal{Y}(1/2,0,1/2) + \mathcal{Y}(1/2,1,-1/2)}$$

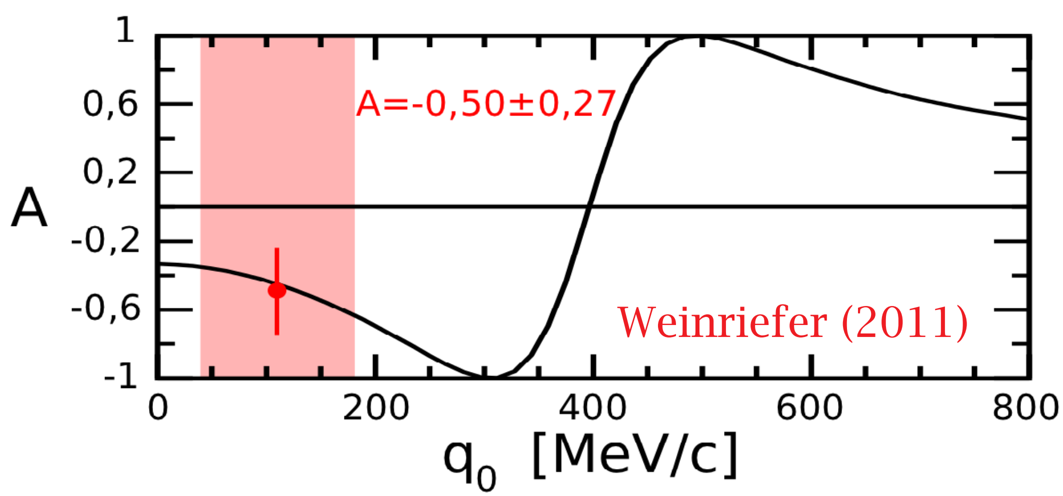




$$\sigma_{\mathrm{L}} \propto |N_0|^2$$

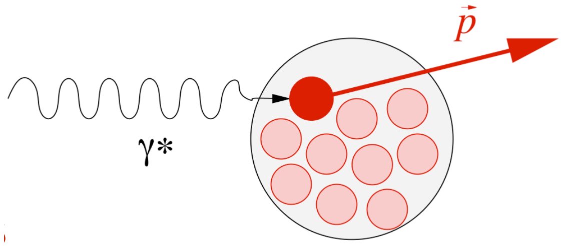
$$\sigma_{\mathrm{T}} \propto |N_{+1}|^2 + |N_{-1}|^2$$

$$\sigma_{\mathrm{T'}} \propto |N_{+1}|^2 - |N_{-1}|^2$$

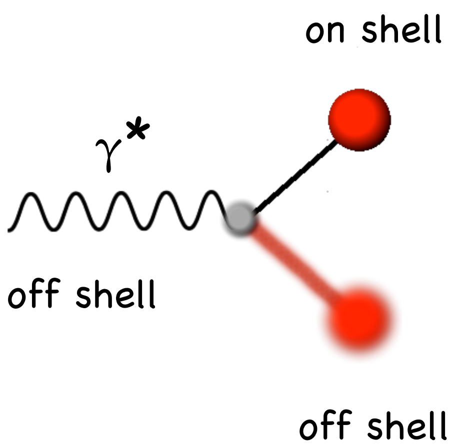


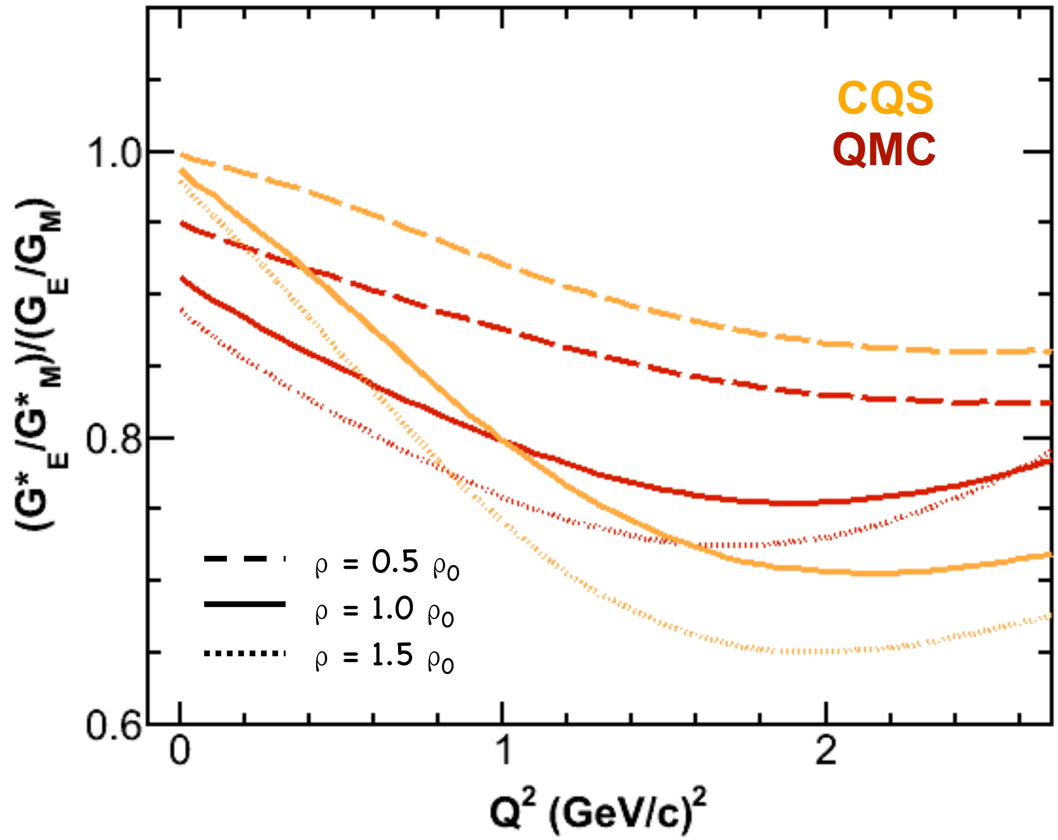
Form-factor modification in medium

Figs by S. Strauch



$$^{A}X(\vec{e},e'\vec{p})^{A-1}X$$



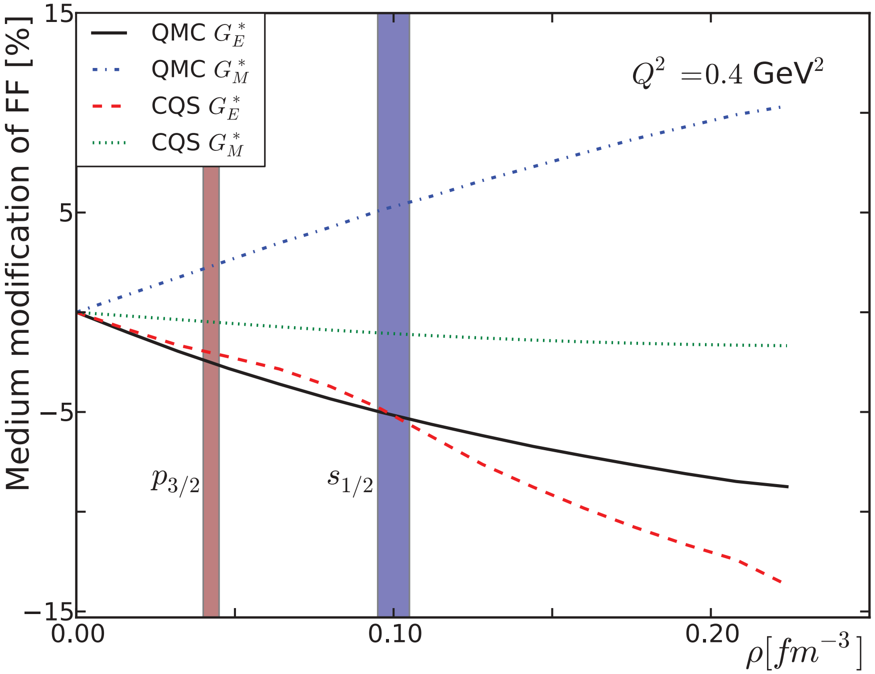


- Observable Q^2– and ρ–dependent effects predicted by various models
- Exploit polarization-transfer technique in ≈ QE proton knock-out:

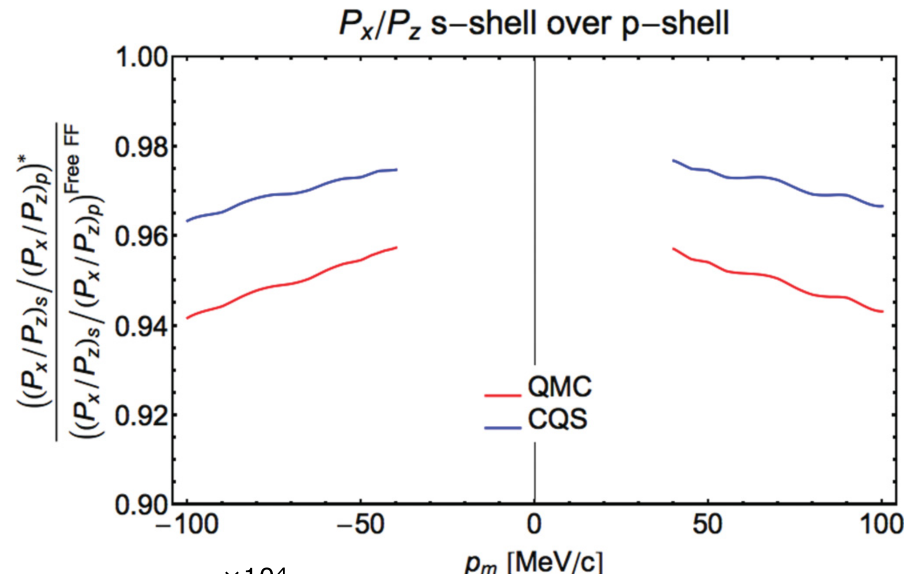
$$\frac{G_E^p}{G_M^p} = -\frac{P'_x}{P'_z}\frac{E_e + E'_e}{2M_p}\tan\frac{\theta_e}{2} \qquad \Longrightarrow \qquad \left(\frac{P'_x}{P'_z}\right)_A \Big/ \left(\frac{P'_x}{P'_z}\right)_p$$

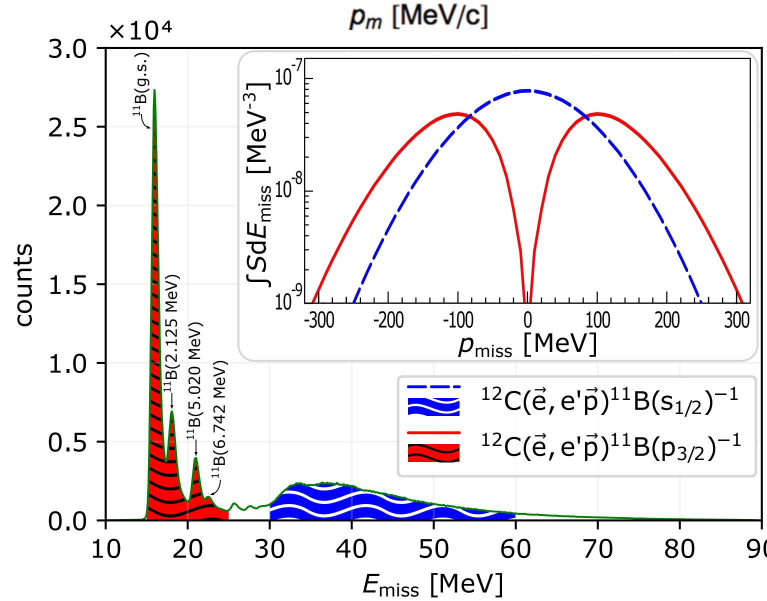
Form-factor modification: calculations for ^{12}C

ρ-dependence



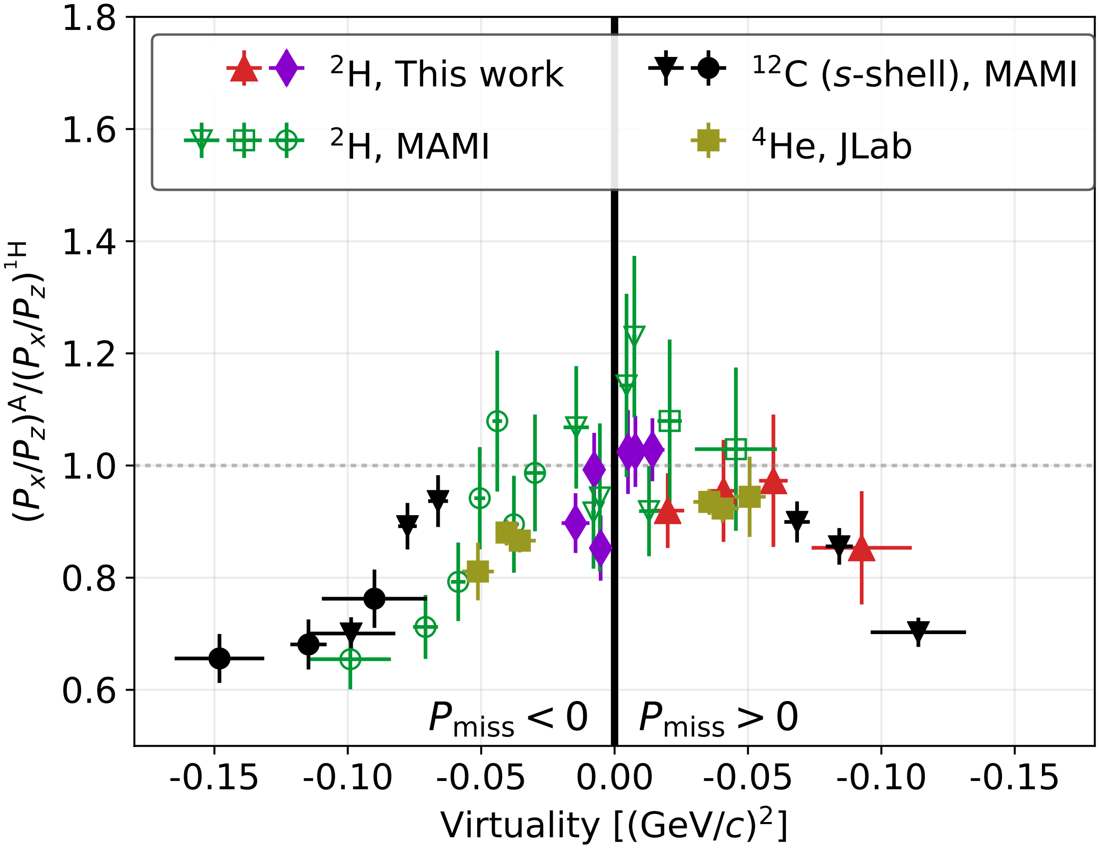
$p_{\rm m}$-dependence

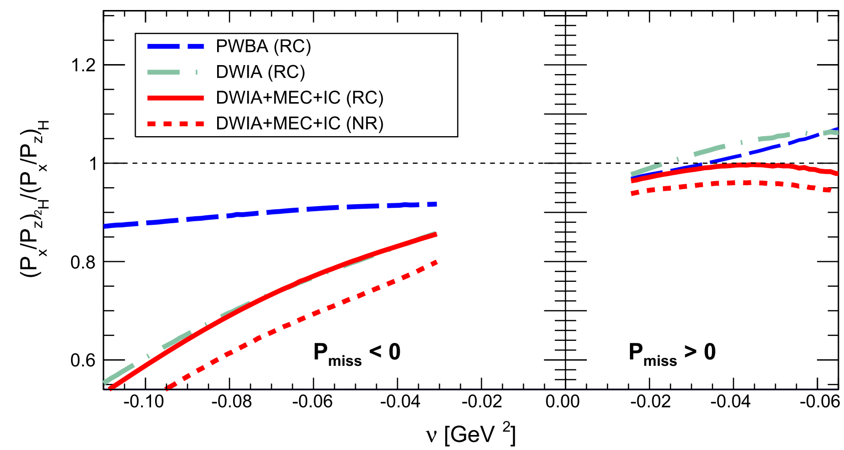




- Different shells ⇔ different local densities // Ron++ PRC **87** (2013) 028202
- Disentangle via $E_{\rm m}$ cuts
- Need to explore $\pm p_{\rm m}$ and $\pm\nu$ regions (no a priori symmetry)

Form-factor modification in medium: “universality”

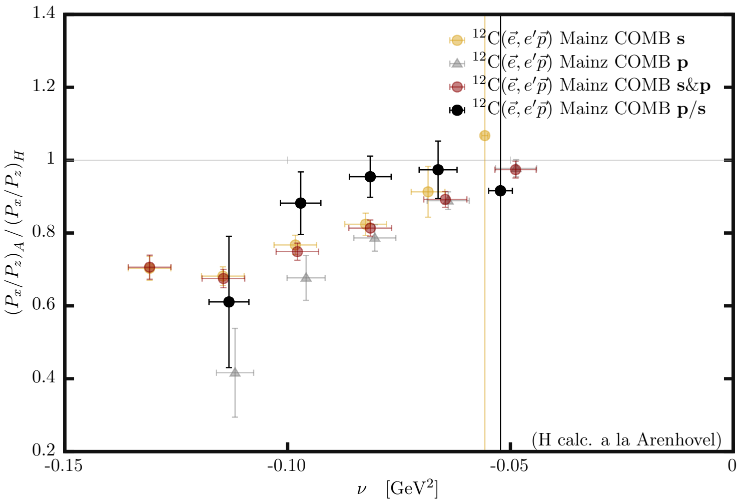


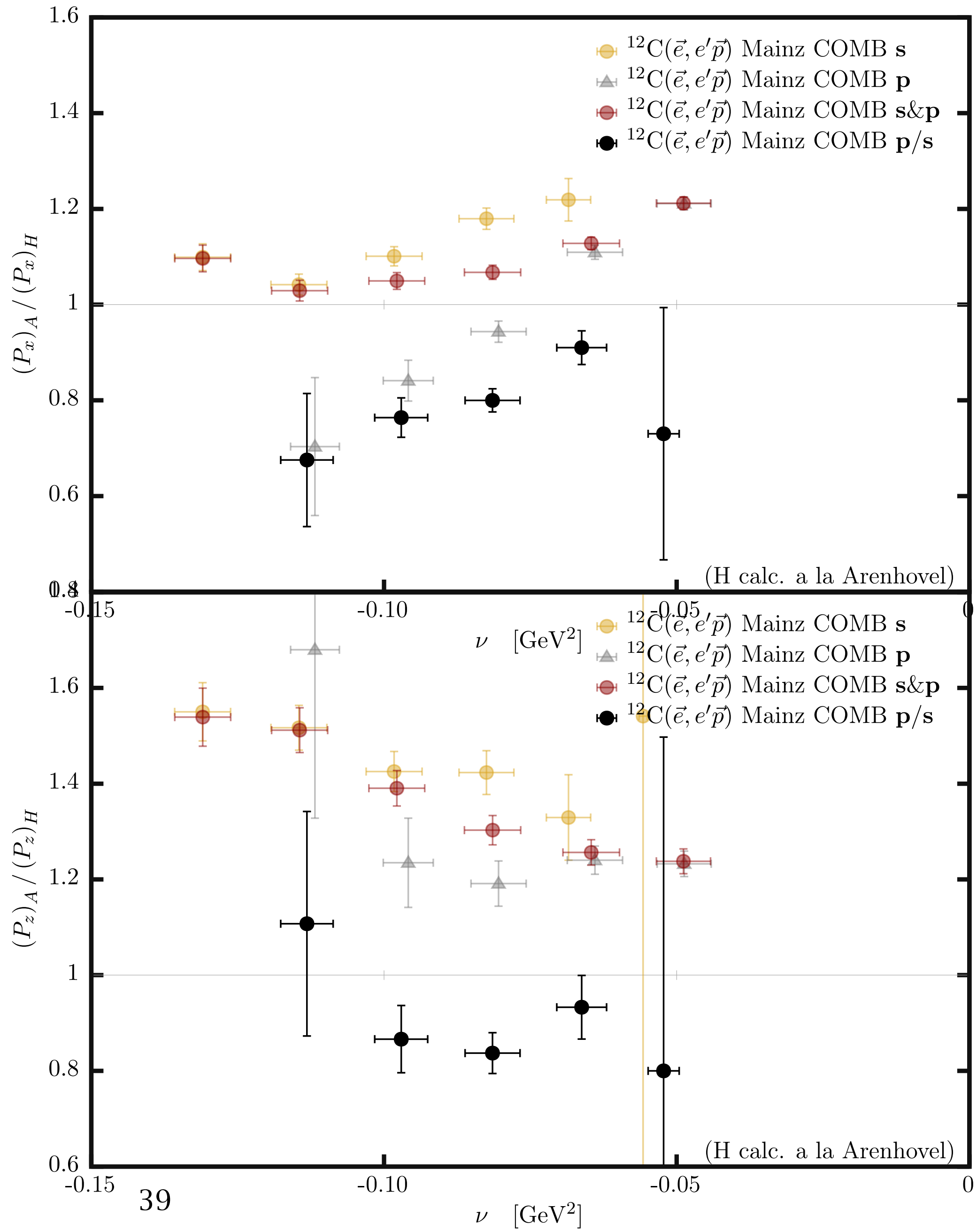


Paul++ PLB **795** (2019) 599

- Virtuality: $\nu = p^2 - m_p^2$ or, better, $\nu = \left(m_A - \sqrt{m_{A-1}^2 + p_{\mathrm{m}}^2}\right)^2 - p_{\mathrm{m}}^2 - m_p^2$
- Relevant variable: ν. No A-dependence (“universality”)
- Largest effects due to FSI and WF of proton in nucleus, not due to FF modification — hard to disentangle $\Longrightarrow$ new JLab proposal at higher Q^2

Preliminary results on ^{12}C $\qquad$ P'_x and P'_z (not ratios)



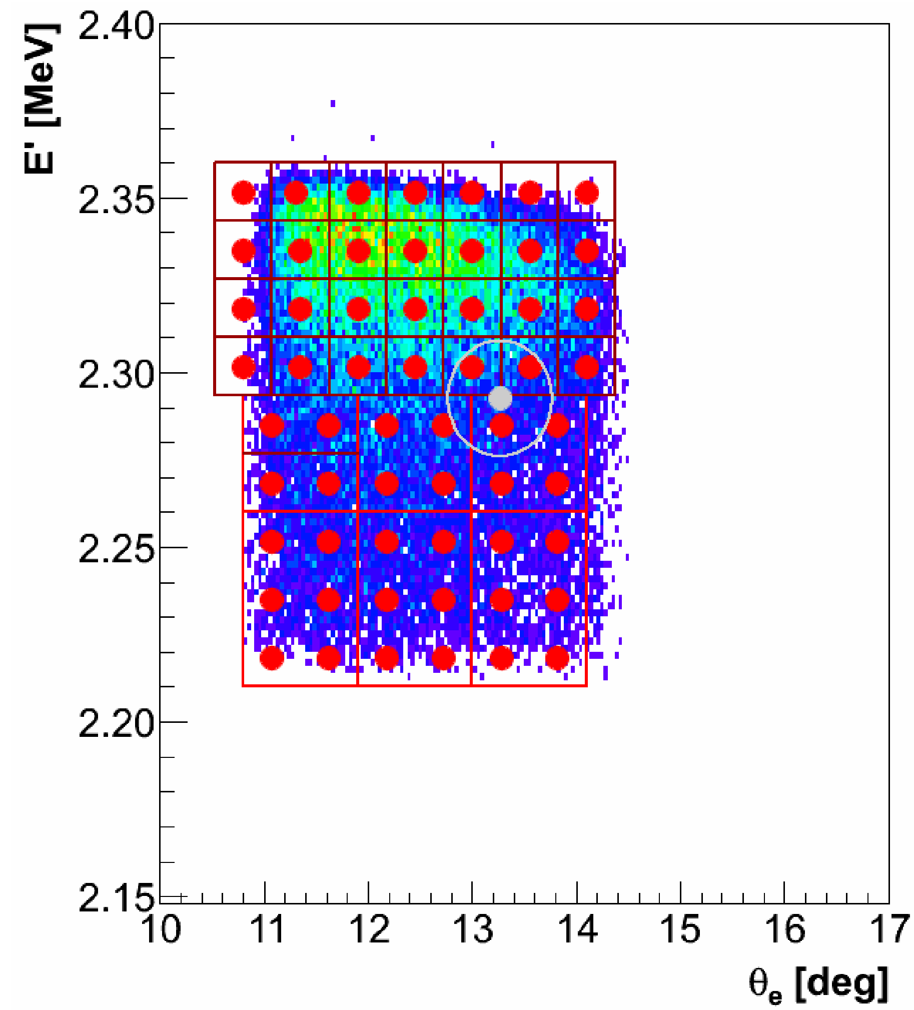


Figs courtesy of T. Kolar


Any Questions ?

Acceptance-averaging of $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{p})$ and $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{d})\mathrm{p}$

- Calculations available only on a discrete kinematic mesh acceptance averaging needed
- Decision: Manipulate calculations — not data
- Asymmetry for each (E', θ_e) at each $(p_\mathrm{m}, \theta_{\mathrm{x}q})$ determined by calculating the weighted mean of the nearest points
- Weak dependence on cell size
- Data at $Q^2 = 0.25$ and $0.35\,\mathrm{GeV}^2$, only first set published: PRL **113** (2014) 232505

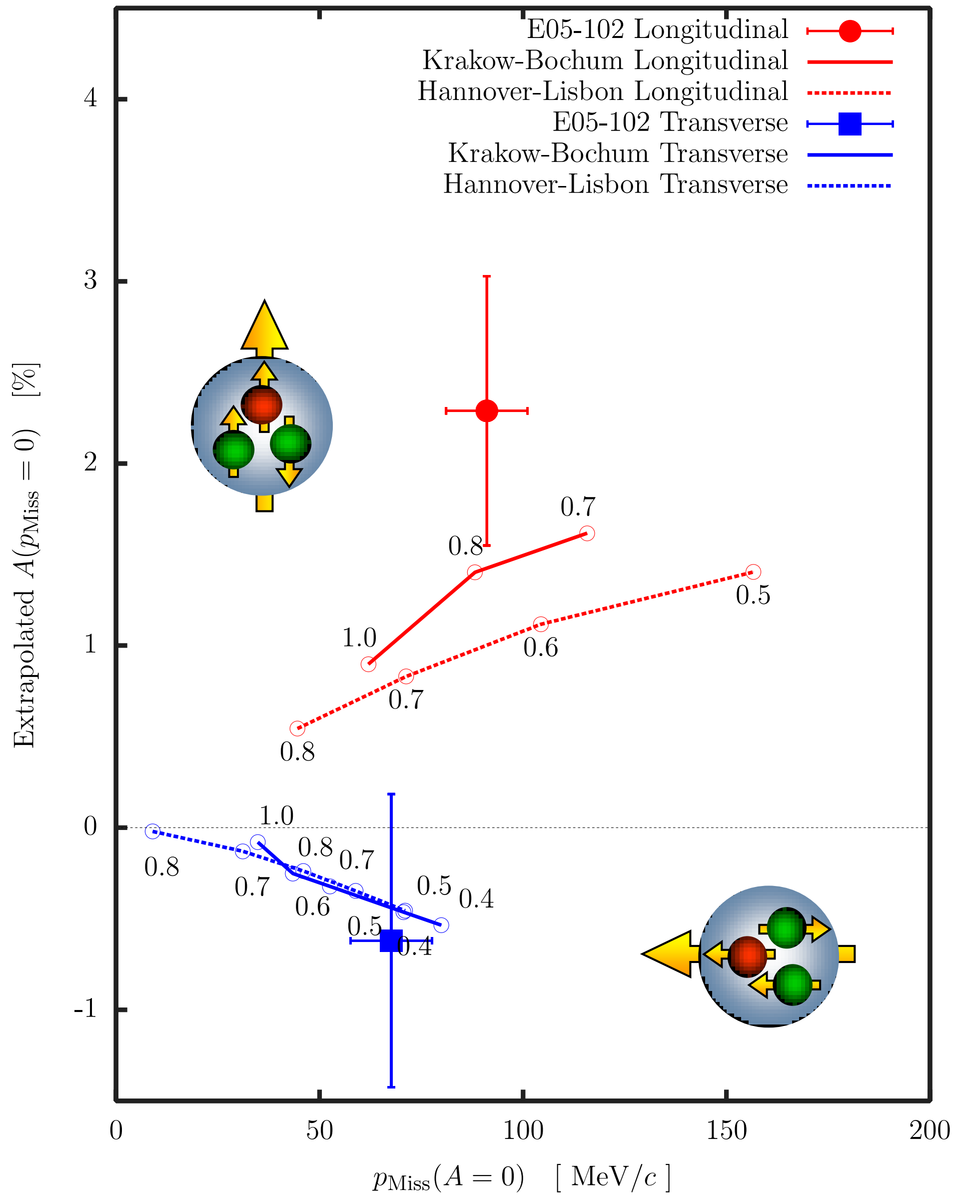


“Fine-tuning” the calculations for $^3\vec{\mathrm{He}}(\vec{e}, e'p)$

- Rescale 3bbu calculations
  to roughly match magnitude
  and zero-crossing of A

- $A = \dfrac{\sigma_2 A_2 + \sigma_3 A_3}{\sigma_2 + \sigma_3} = \dfrac{A_2 + A_3 R_{32}}{1 + R_{32}}$

- ≈ 30–40 % reduction needed



SSA in QE $^3\mathrm{He}^{\uparrow}(\mathrm{e},\mathrm{e}')$ (details) E05-015

Extraction of A_y^{n} from $A_y^{^3\mathrm{He}}$ — effective polarization approximation:

$$A_y^{^3\mathrm{He}} = P_\mathrm{n} f_\mathrm{n} A_y^\mathrm{n} + P_\mathrm{p}(1 - f_\mathrm{n}) A_y^\mathrm{p}$$

$$f_\mathrm{n} = \frac{\sigma^\mathrm{n}}{\sigma^{^3\mathrm{He}}} = \frac{\sigma^\mathrm{n}}{2\sigma^\mathrm{p} + \sigma^\mathrm{n}}$$

$$P_\mathrm{n} = 0.86 \pm \cdots \qquad P_\mathrm{p} = -0.028 \pm \cdots$$

high Q^2: f_n computed with Kelly's parameterization of nucleon FFs
low Q^2: theoretical estimate (due to FSI): $f_\mathrm{n} = 0.042$ (A. Deltuva)
A_y^p computed by Afanasev et al.