Study of ^{3}He nuclei by polarization observables in quasi-elastic electron scattering

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Experiments covered in this talk

- E05-102 (Gilad, Higinbotham, Korsch, Norum, Širca)
  Double-spin asymmetries in quasi-elastic $^3\vec{\mathrm{He}}(\vec{e}, e'd)p$
  $^3\vec{\mathrm{He}}(\vec{e}, e'p)d$
  $^3\vec{\mathrm{He}}(\vec{e}, e'p)pn$

- E05-015 (Averett, Chen, Xiang)
  Target single-spin asymmetry in quasi-elastic $^3\mathrm{He}^{\uparrow}(e, e')$

- E08-005 (Averett, Higinbotham, Sulkosky)
  Target single-spin asymmetry in quasi-elastic $^3\mathrm{He}^{\uparrow}(e, e'n)$
  Double-spin asymmetries in quasi-elastic $^3\vec{\mathrm{He}}(\vec{e}, e'n)$

Analysis work done by **Elena Long** (Kent State U)
Miha Mihovilovič (U of Ljubljana)
Yawei Zhang (Rutgers)

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).

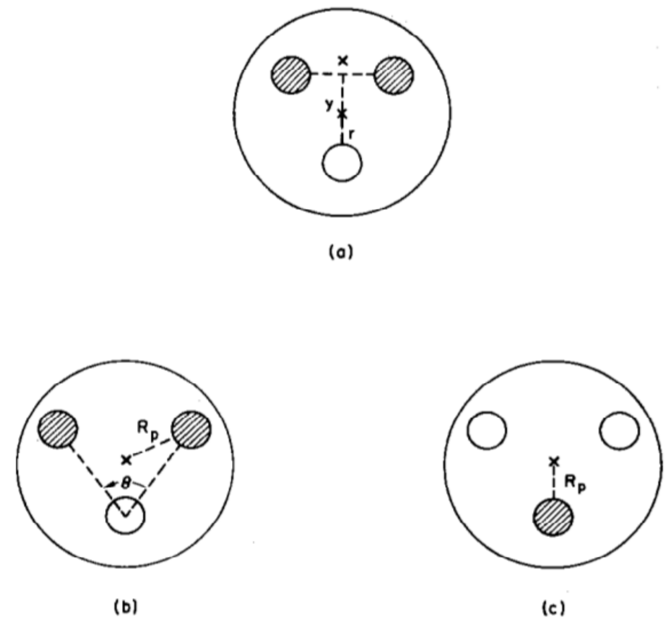
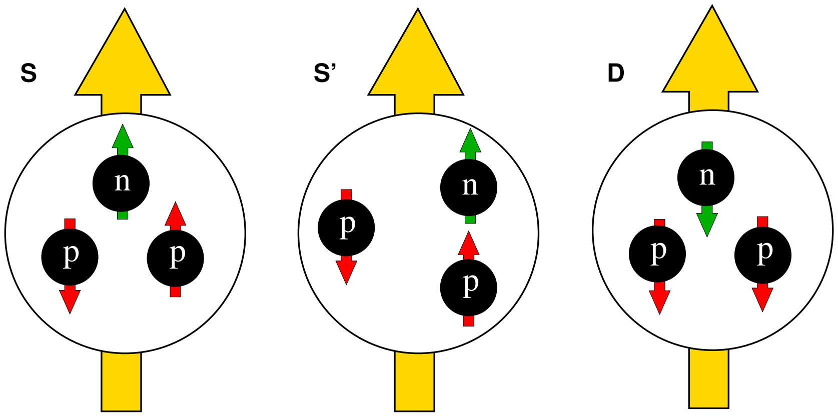


Fig. 1. Schematic picture of trinucleon when all forces are identical is shown in (a). The effect on ^{3}He and ^{3}H when the pp or nn force is weaker than the np force is illustrated in (b) and (c). R_p is the "charge radius". Shading indicates a proton.

- 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 %** . $P'_S \approx E_b^{-2.1}$.
- $P_n^{eff} \approx$ **+0.86**, $P_p^{eff} \approx$ **−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

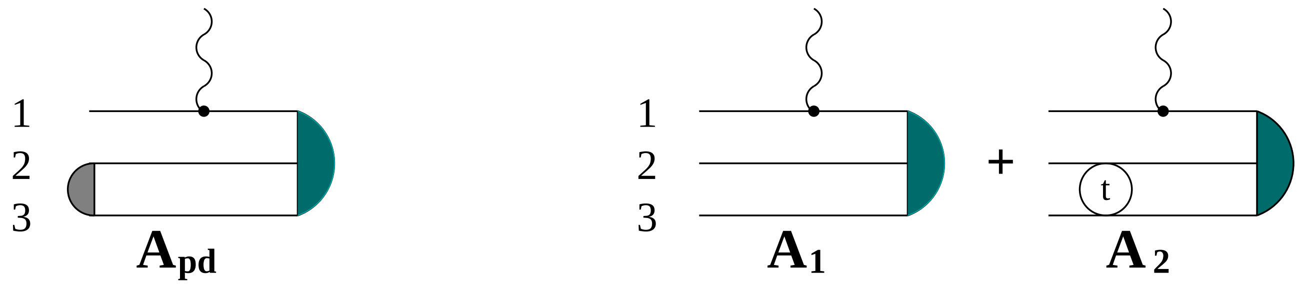
Schiavilla++ PRC 58 (1998) 1263

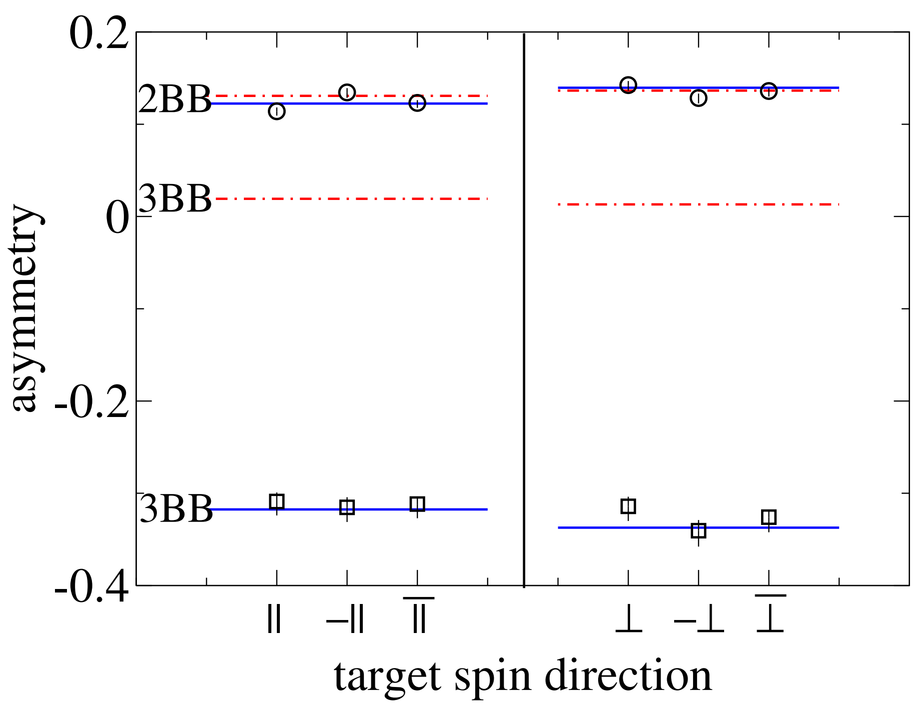
TM = Tucson-Melbourne π-π exchange 3NF

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 ↓)

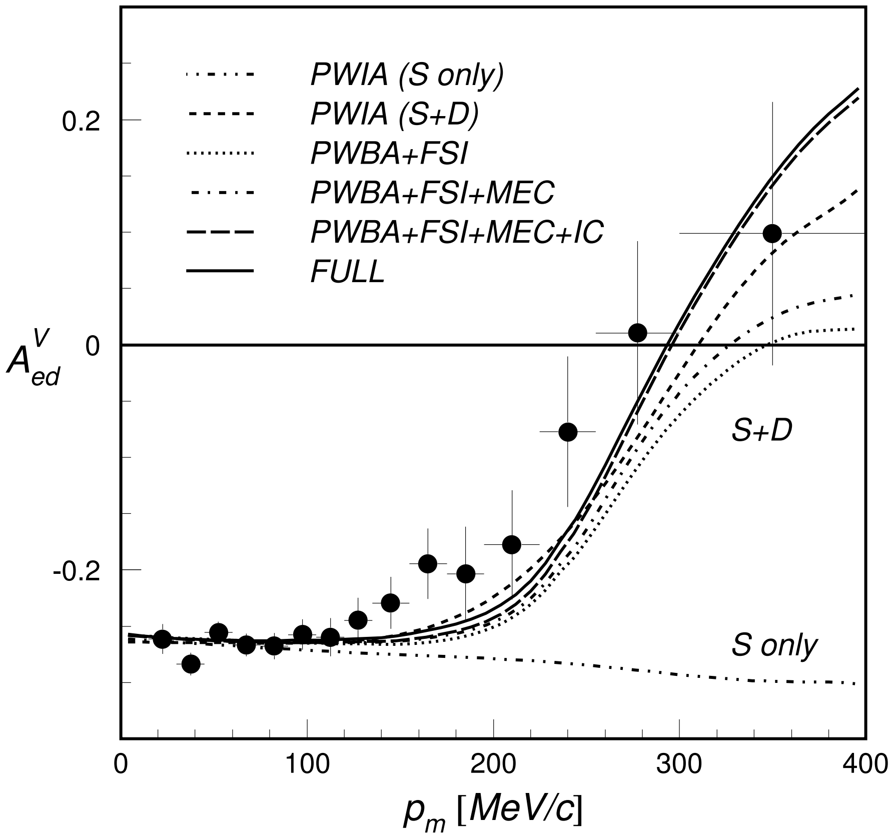
$A_{\mathrm{PWIA+FSI}}$ large & negative

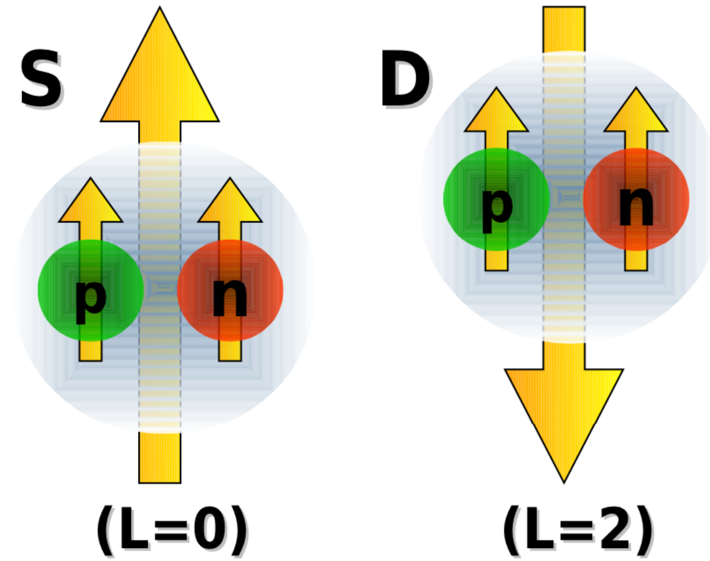
not a polarized p target

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

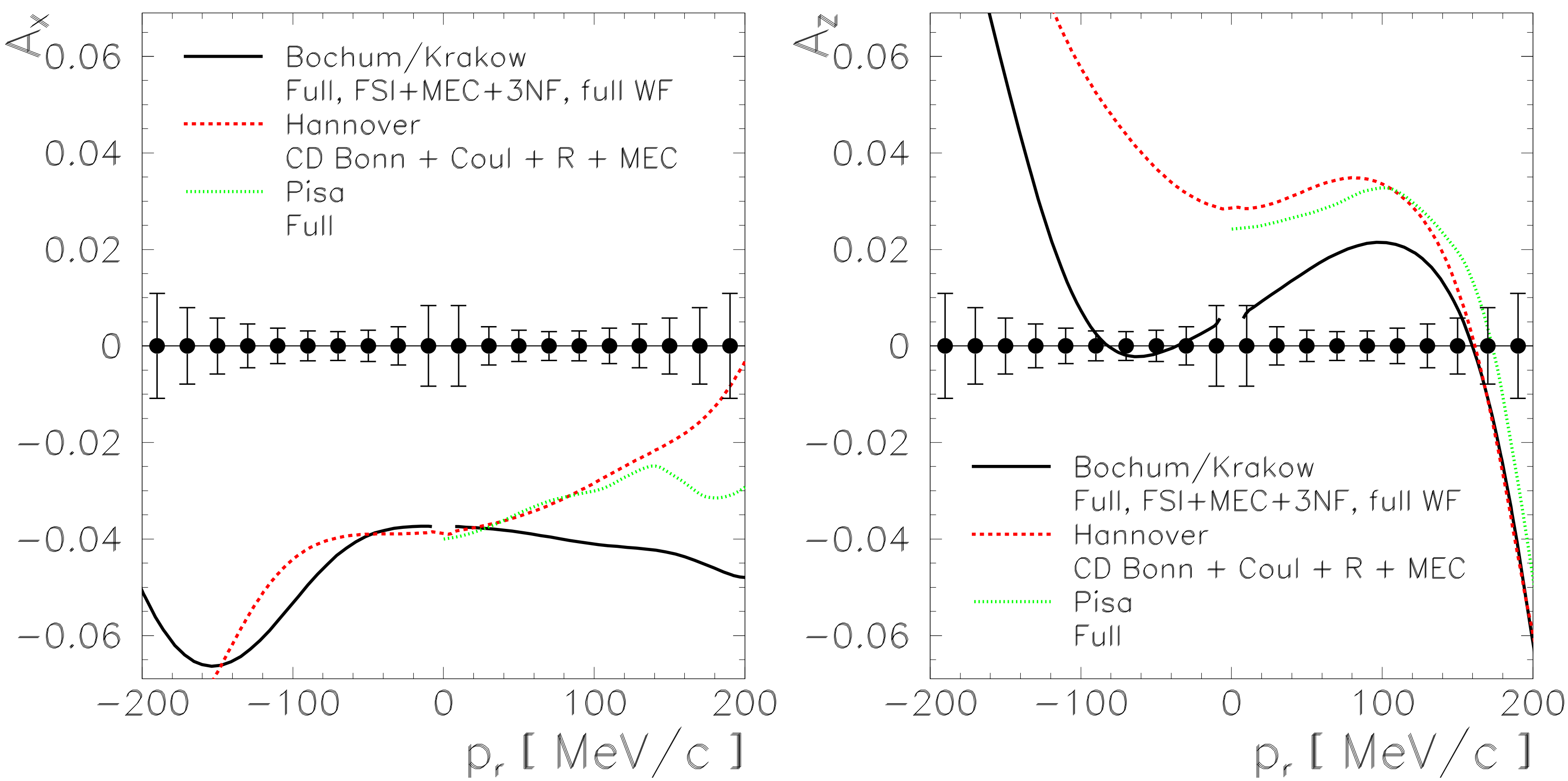
Channel number	L	S	l_α	L_α	P	K	Probability (%)
1	0	0.5	0	0	A	1	87.44
2	0	0.5	0	0	M	2	0.74
3	0	0.5	1	1	M	1	0.74
4	0	0.5	2	2	A	1	1.20
5	0	0.5	2	2	M	2	0.06
6	1	0.5	1	1	M	1	0.01
7	1	0.5	2	2	A	1	0.01
8	1	0.5	2	2	M	2	0.01
9	1	1.5	1	1	M	1	0.01
10	1	1.5	2	2	M	2	0.01
11	2	1.5	0	2	M	2	1.08
12	2	1.5	1	1	M	1	2.63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

Meeting point of theory and experiment e.g. $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{d})$

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

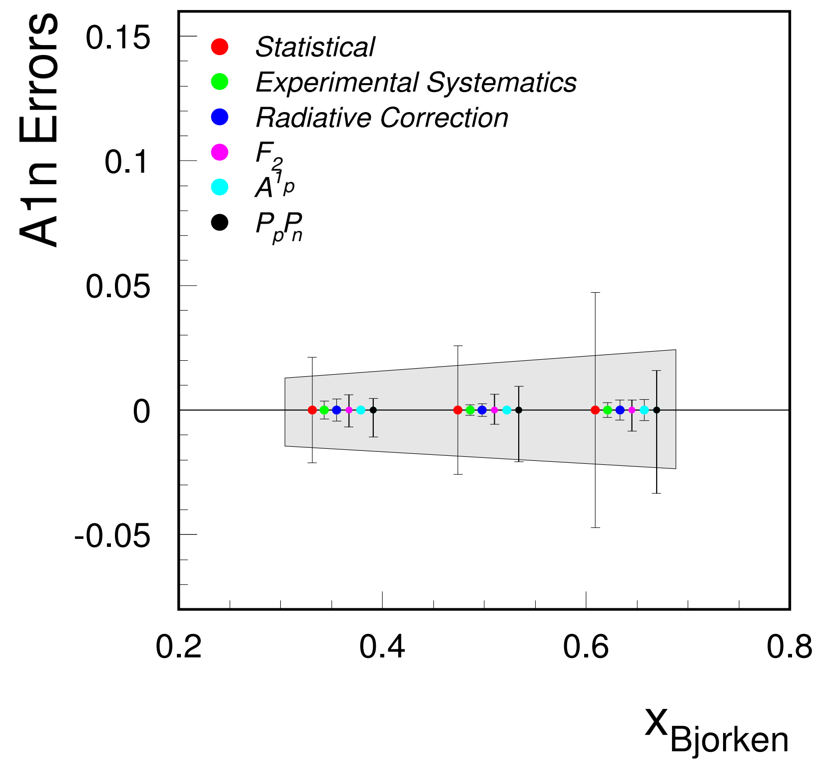
$$A_{x,z} = \frac{[\,\mathrm{d}\sigma_{++}+\mathrm{d}\sigma_{--}\,]-[\,\mathrm{d}\sigma_{+-}+\mathrm{d}\sigma_{-+}\,]}{[\,\mathrm{d}\sigma_{++}+\mathrm{d}\sigma_{--}\,]+[\,\mathrm{d}\sigma_{+-}+\mathrm{d}\sigma_{-+}\,]}$$



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 $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{n})$.

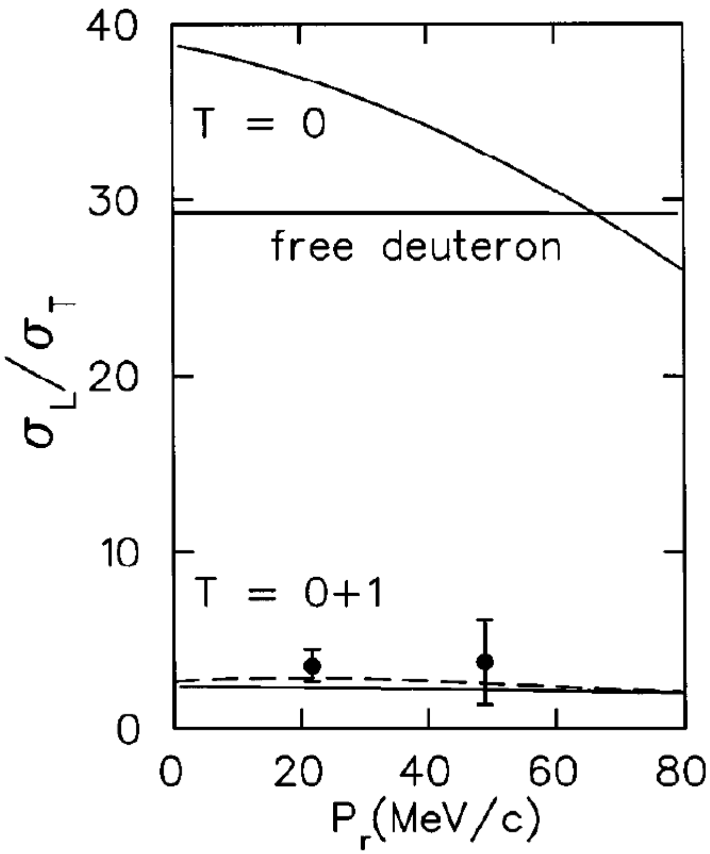
- **Better understanding of ground-state spin structure of polarized** ^{3}He — — S, S', D wave-function components. Improve knowledge of ^{3}He rather than using it as an effective neutron target. **Direct consequences for all polarized** ^{3}He **experiments**.



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

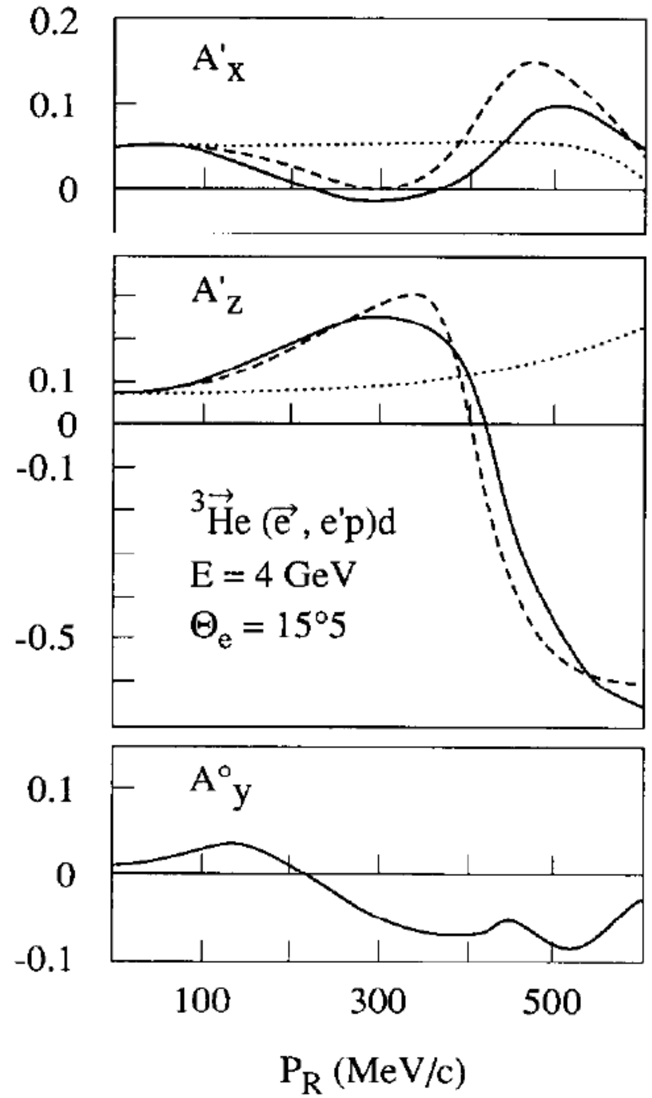
- Data at (almost) identical Q^2 for $(\vec{\mathrm{e}},\mathrm{e}'\mathrm{d})$, $(\vec{\mathrm{e}},\mathrm{e}'\mathrm{p})$, and $(\vec{\mathrm{e}},\mathrm{e}'\mathrm{n})$ simultaneously over a broad range of p_{miss} poses **strong constraints on state-of-the-art calculations**.

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



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}

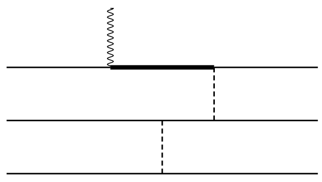
Laget PLB **276** (1992) 398

Exploiting state-of-the-art calculations

Bochum/Krakow (full Faddeev)

- AV18 NN-potential (+ Urbana IX 3NF, coming up...)
- 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

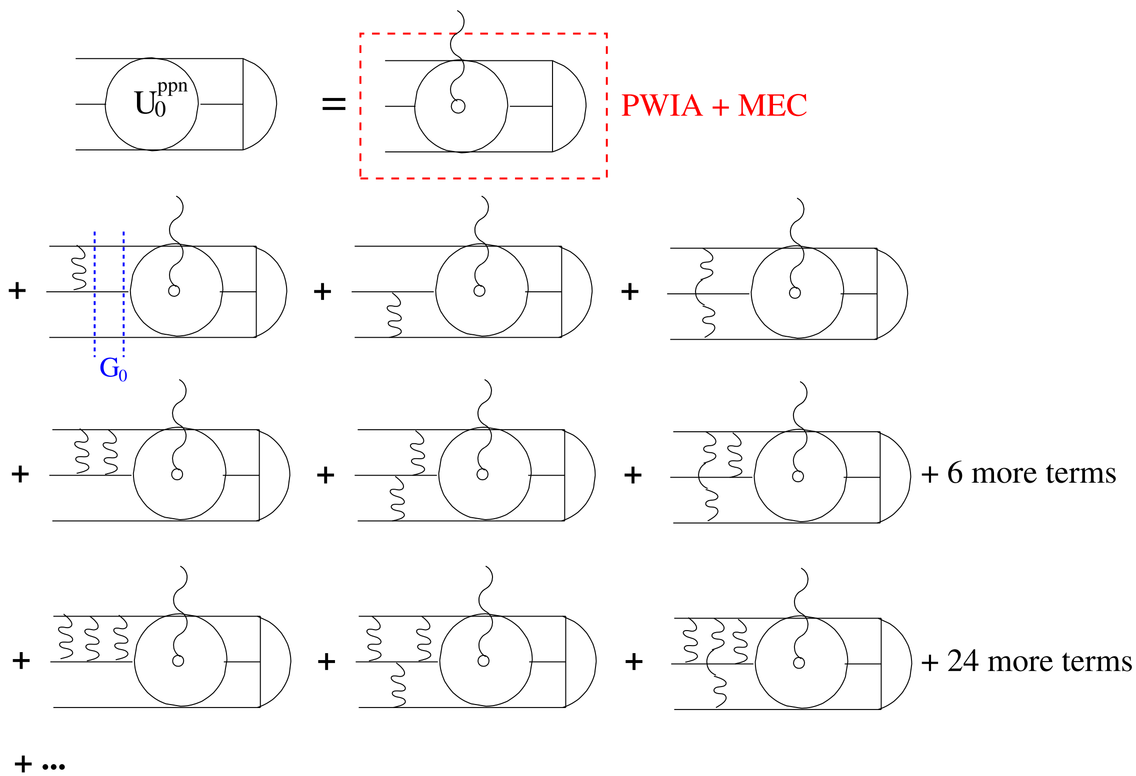
- Coming up

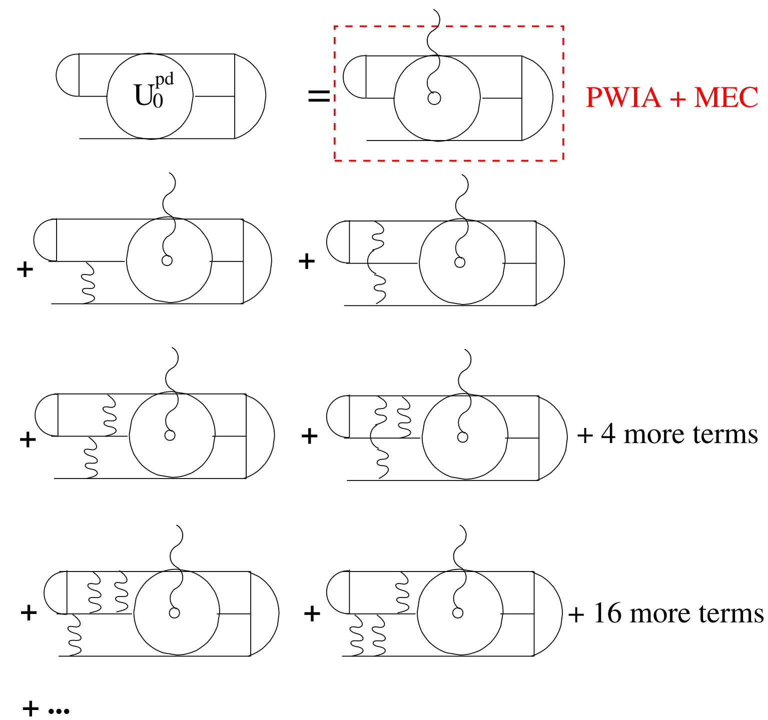
Basic machinery: Faddeev calculations

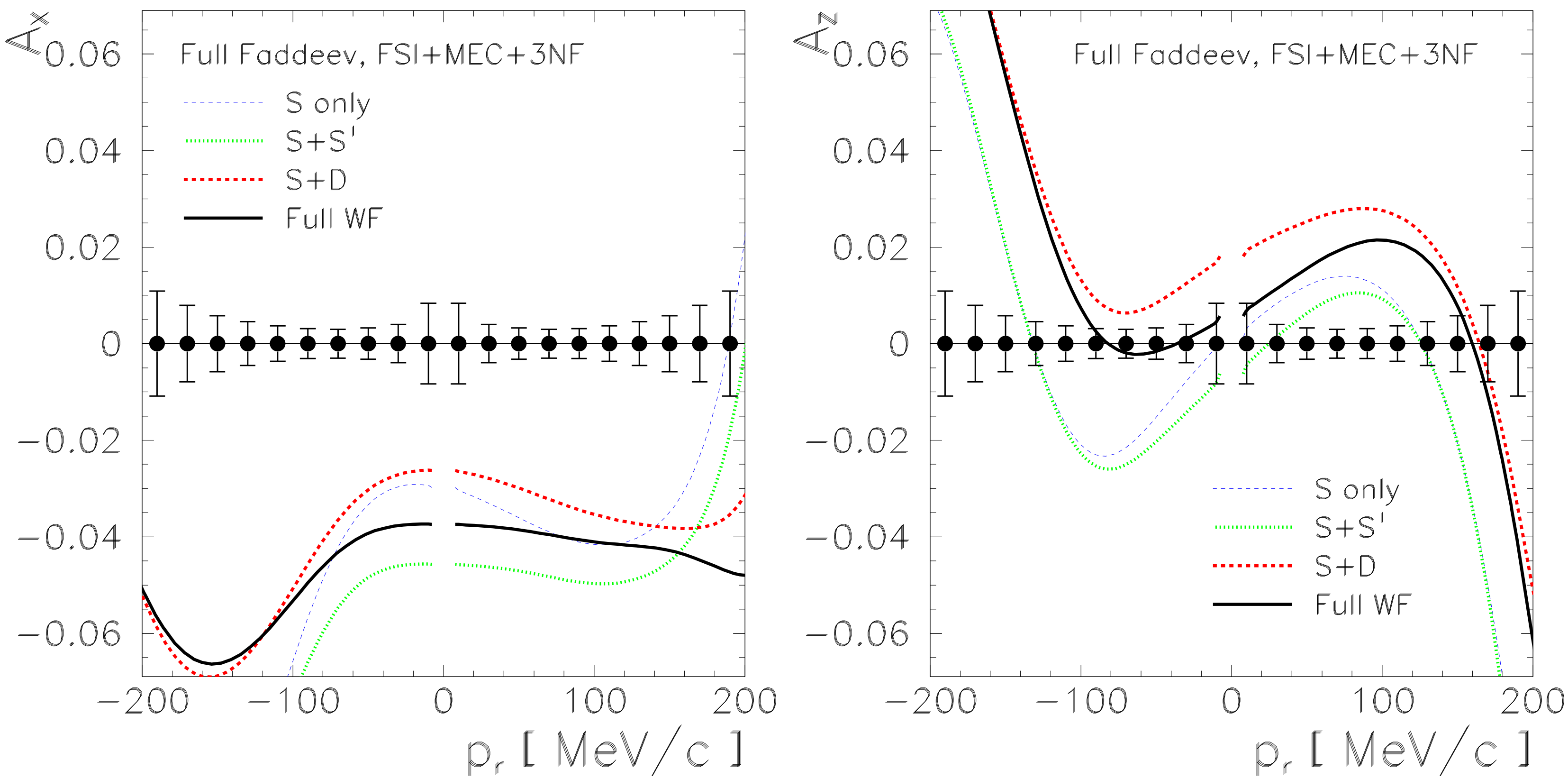
Nuclear transition current for breakup of ³He: $J^\mu = \left\langle \Psi_\mathrm{f} \mid \hat{\mathcal{O}}^\mu \mid \Psi_{^3\mathrm{He}}(\theta^*, \phi^*) \right\rangle$

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



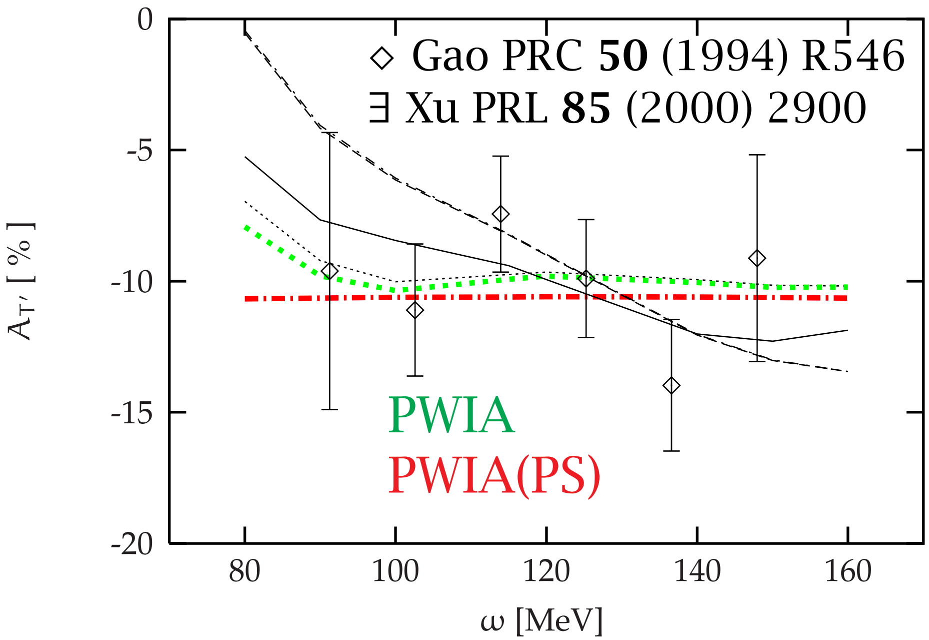


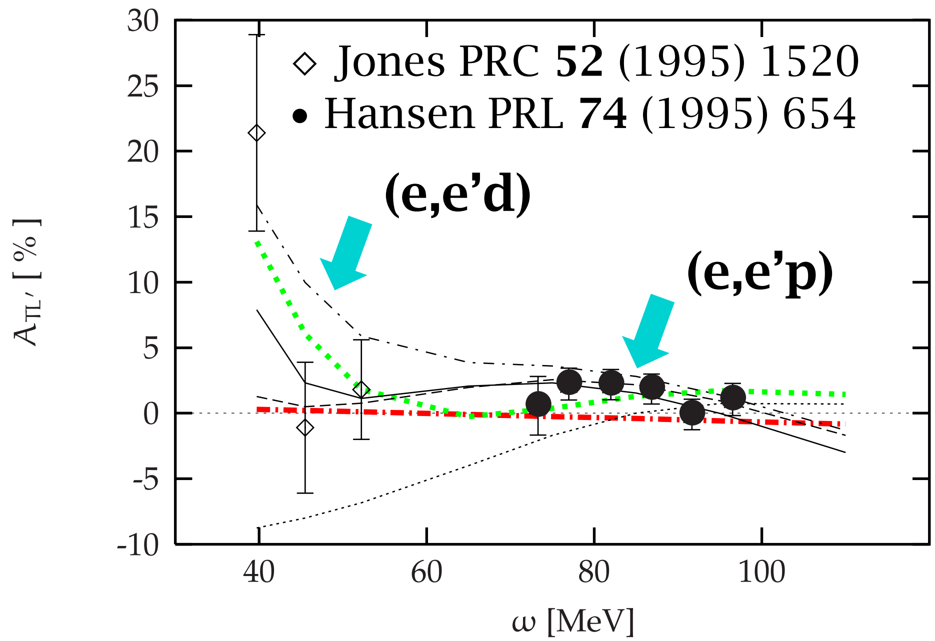


A_x
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−200
−100
0
100
200
p_r [MeV/c]
Full Faddeev, FSI+MEC+3NF
S only
S+S'
S+D
Full WF
A_z

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

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

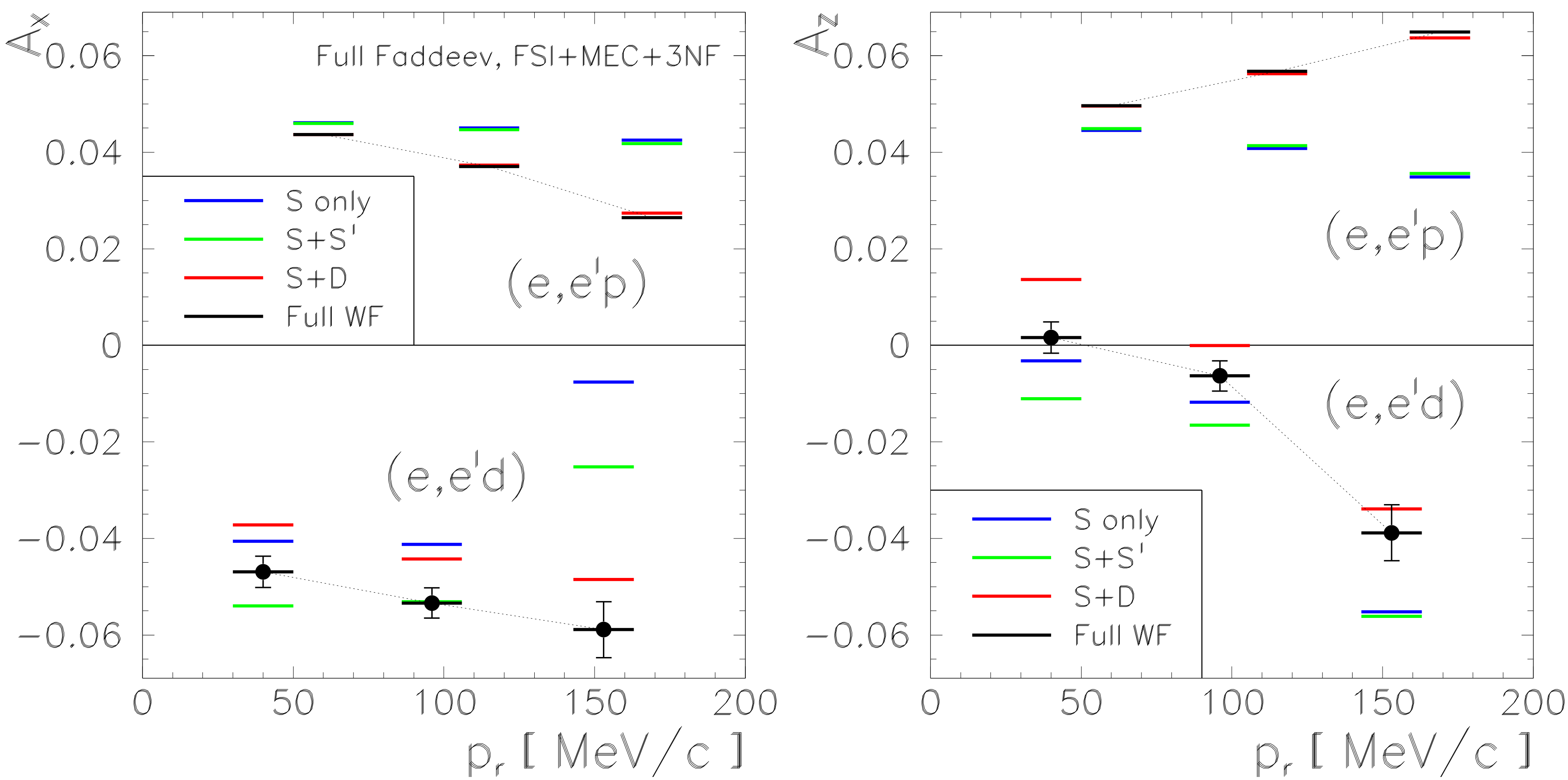


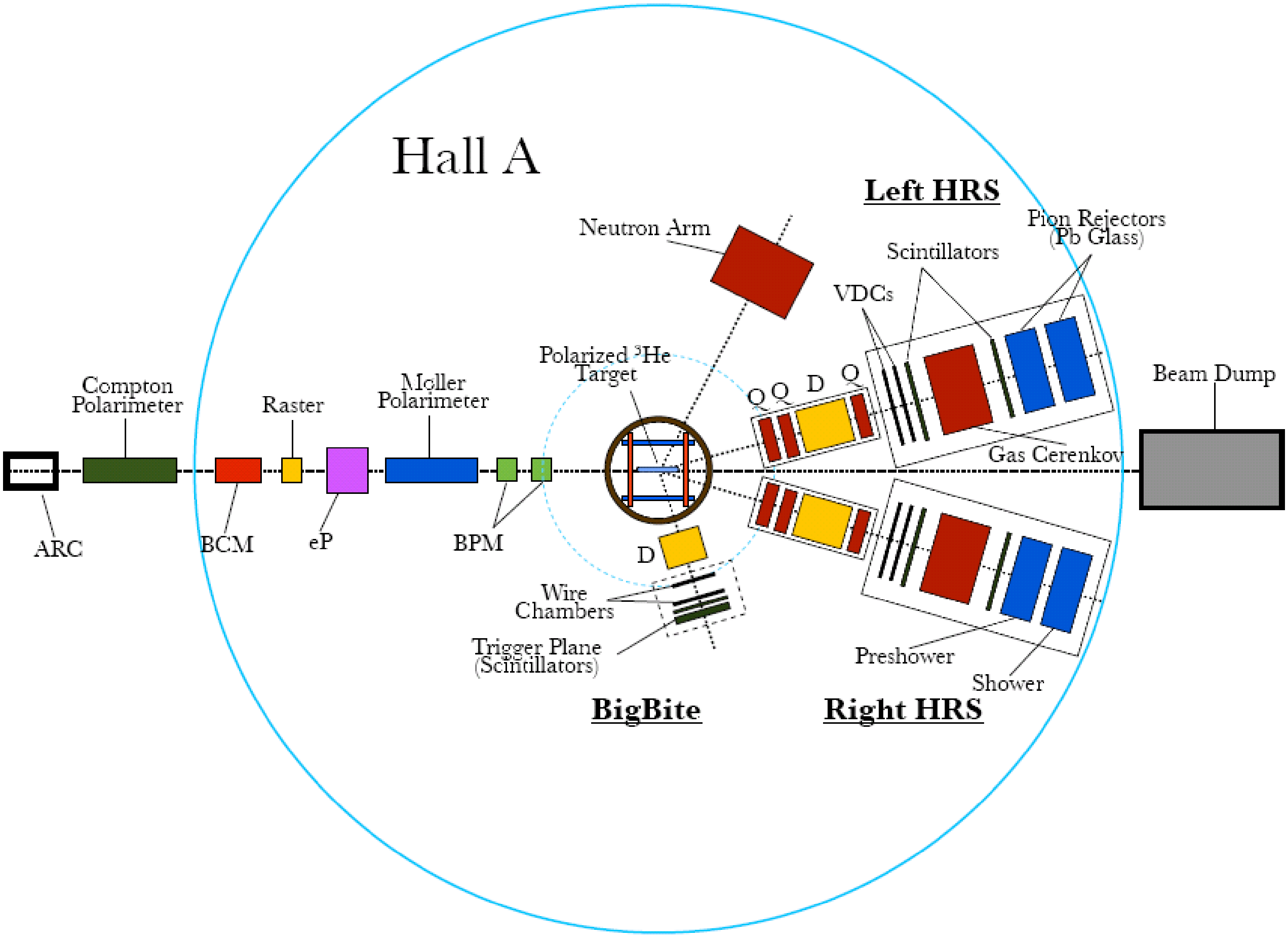


- A'_{LT} receives contributions from ingredients which go beyond most simplistic picture [$F_1^{(\mathrm{n})} = 0$]
- sensitive to replacement PWIA(PS) $\longrightarrow$ PWIA.
- S'- and D-state pieces contribute very strongly to A'_{LT}

Ishikawa, Golak, Glöckle et al. PRC **57** (1998) 39

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

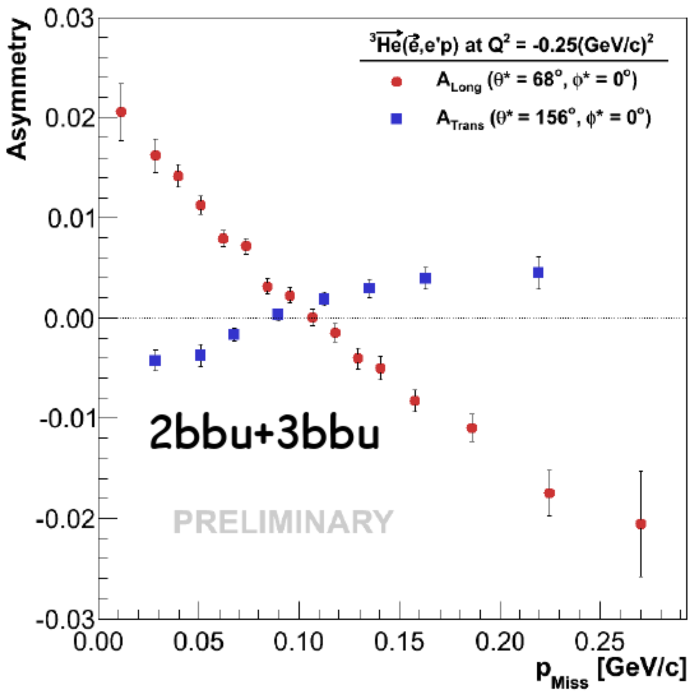


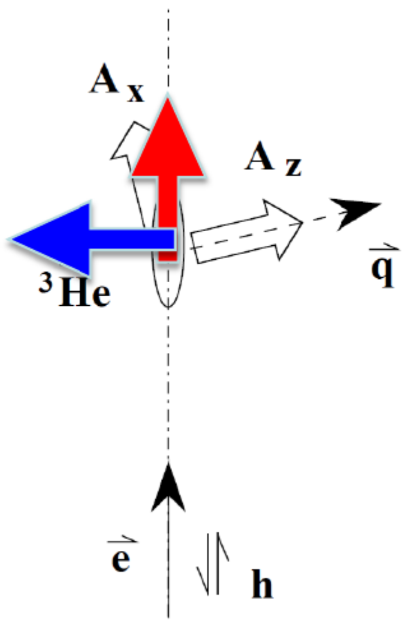

Hall A
Left HRS
Neutron Arm
Pion Rejectors
(Pb Glass)
Scintillators
VDCs
Polarized ³He
Target
Q Q D Q
Beam Dump
Compton
Polarimeter
Raster
Møller
Polarimeter
Gas Cerenkov
ARC
BCM
eP
BPM
D
Wire
Chambers
Trigger Plane
(Scintillators)
Preshower
Shower
BigBite
Right HRS

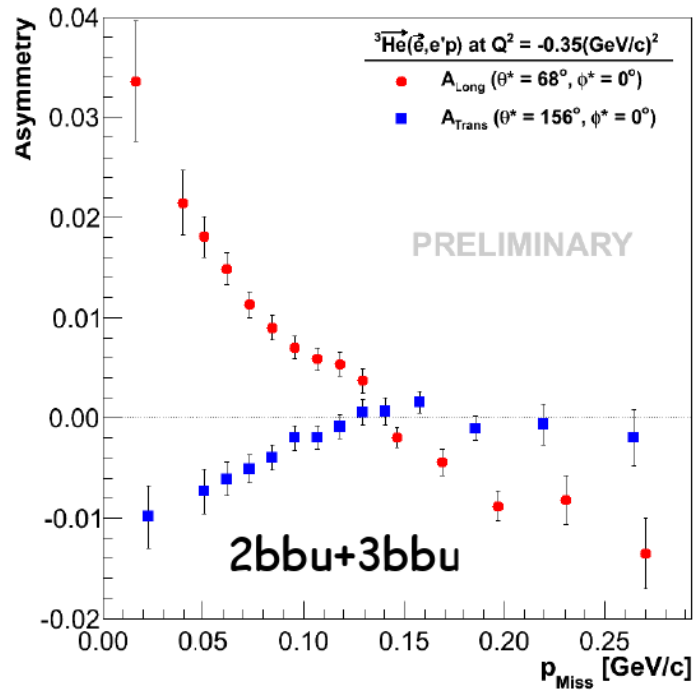
Preliminary results for asymmetries in $^3\vec{\mathrm{He}}(\vec{e}, e'p)$

$E = 2.4255\,\mathrm{GeV}$
$\omega = 100 - 200\,\mathrm{MeV}$
$Q^2 = 0.2 - 0.3\ (\mathrm{GeV}/c)^2$

$E = 2.4255\,\mathrm{GeV}$
$\omega = 150 - 250\,\mathrm{MeV}$
$Q^2 = 0.3 - 0.4\ (\mathrm{GeV}/c)^2$

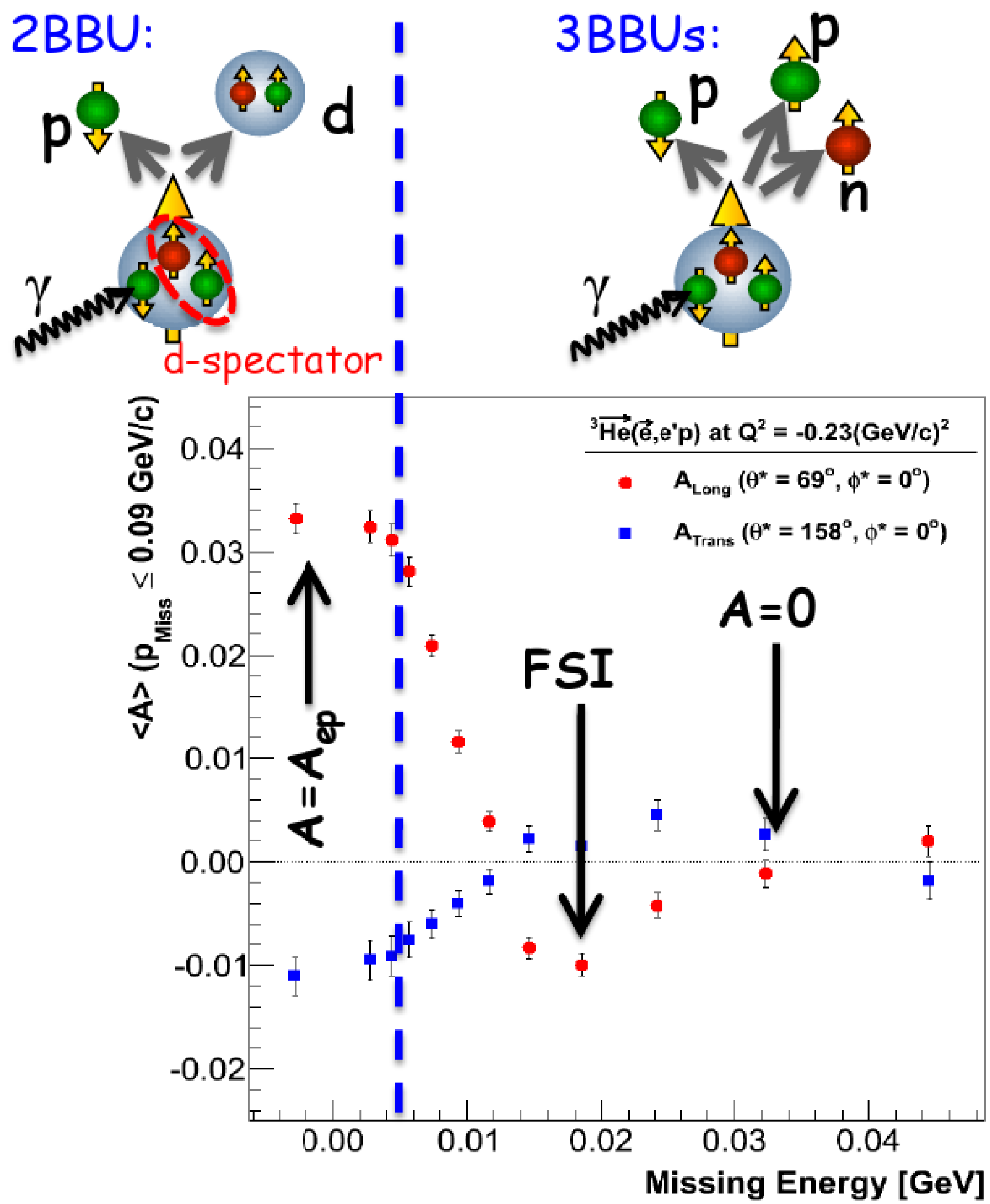






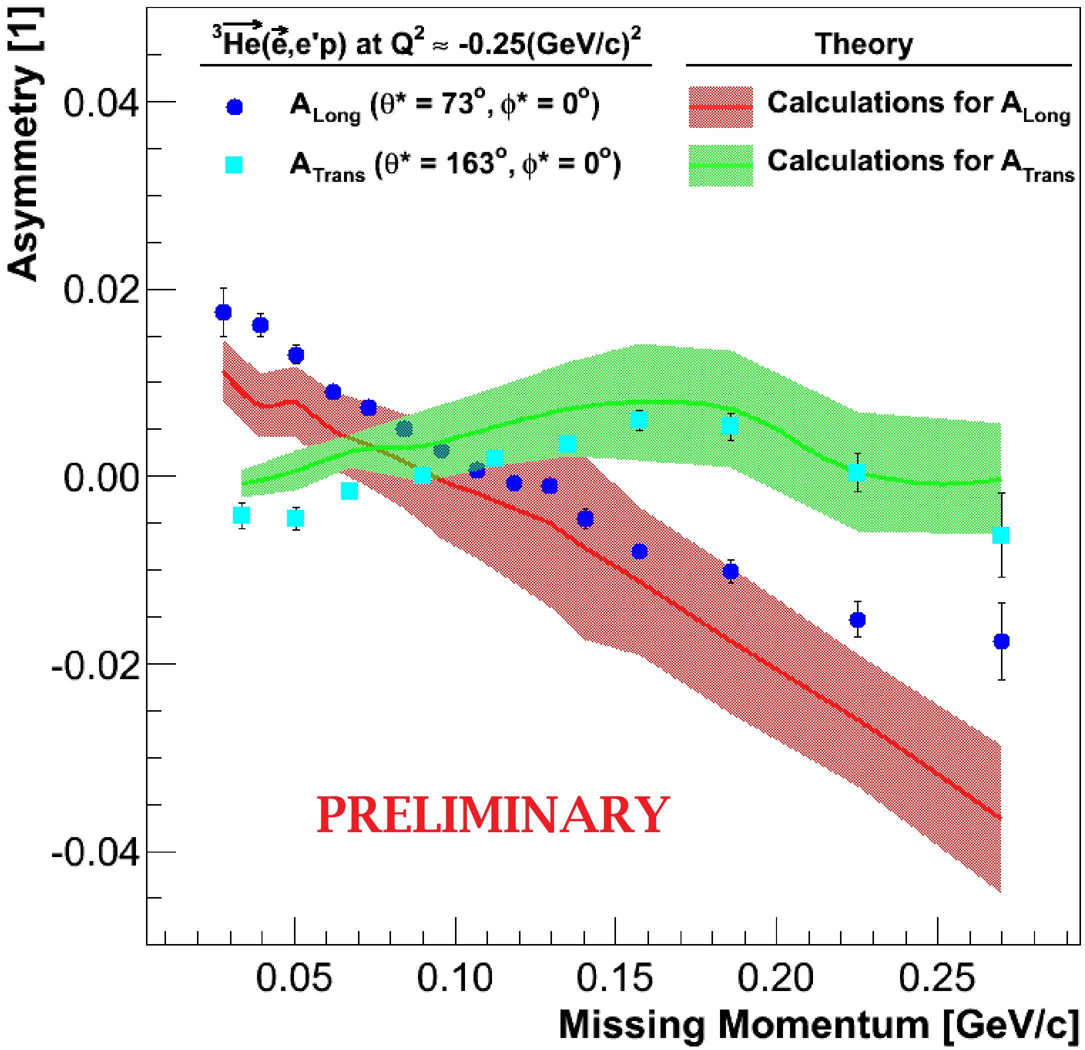
Hand-waving interpretation of $^3\vec{He}(\vec{e}, e'p)$

- Simple picture for p_{miss} ~ 0.
- S-state dominates
- Consider only tree diagram
- **Missing Energy** = $\omega - T_d - T_p$
- Negative values due to <u>resolution.</u>
- <u>Low E_{Miss}</u> region dominated by 2BBU (A->elastic e-p asym.),
- <u>High E_{Miss}</u> dominated by 3BBU (A->0).
- Non-zero asymmetry in 3BBU probably caused by <u>**FSI**.</u>



Comparison with the theory

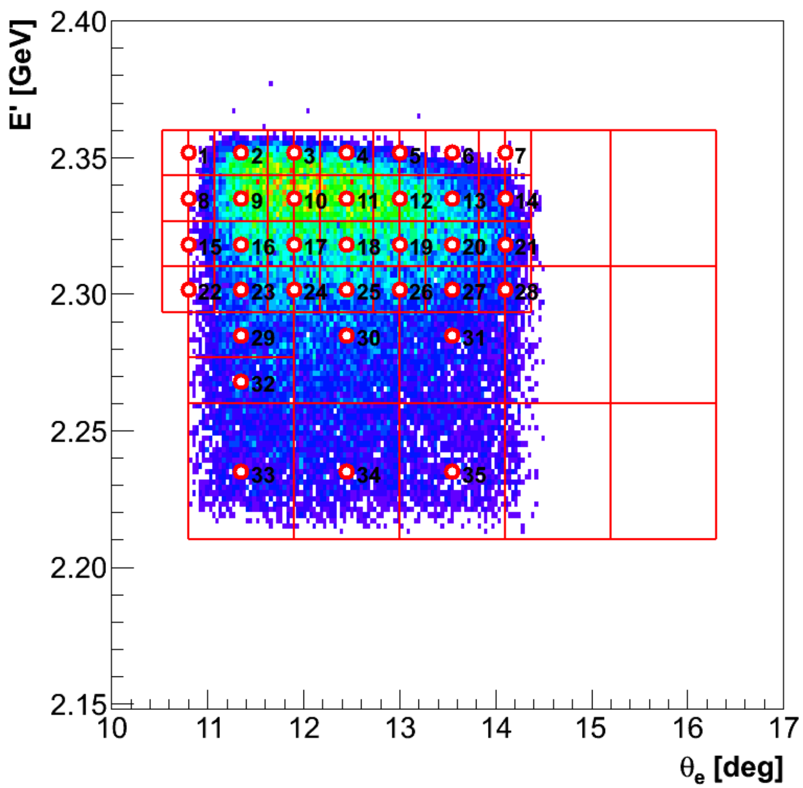
$^3\vec{He}(\vec{e}, e'p)$

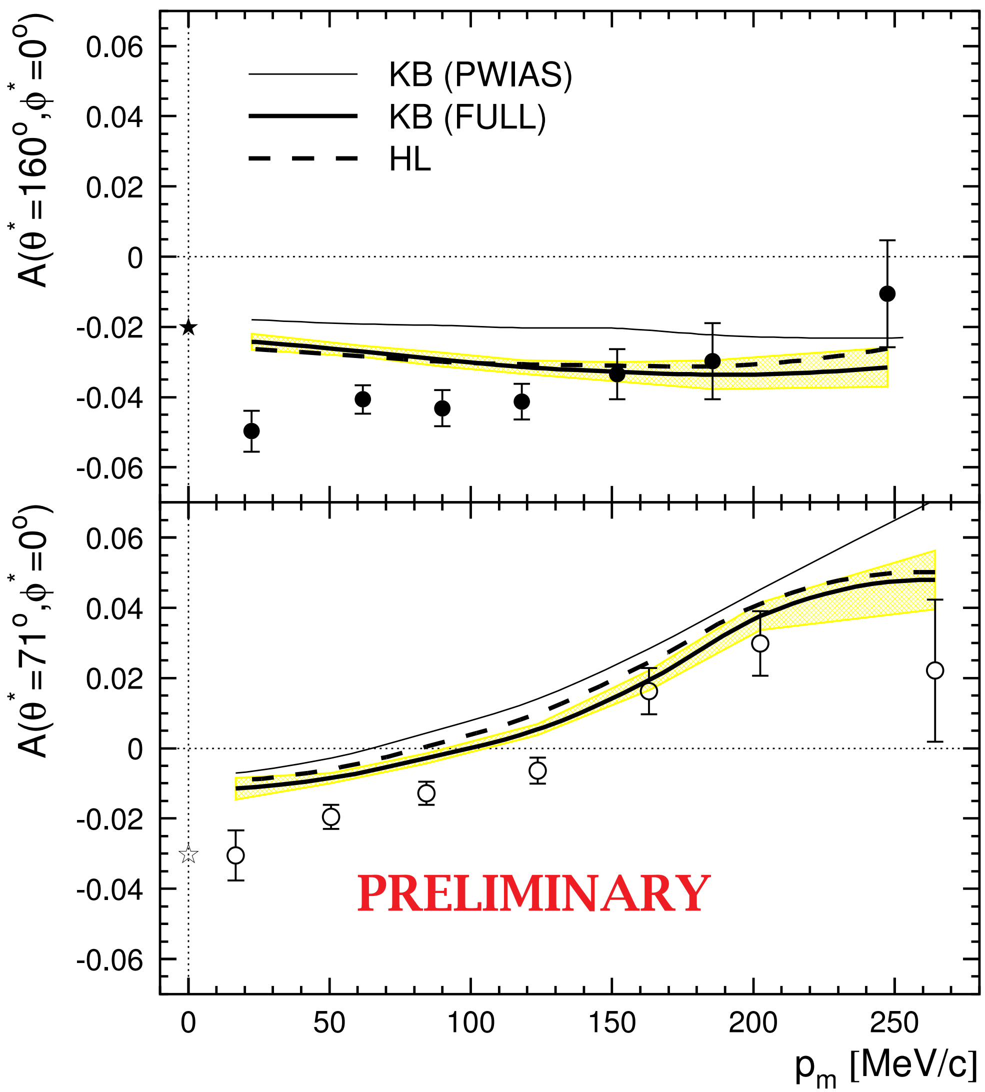


NB: 2bbu and 3bbu combined

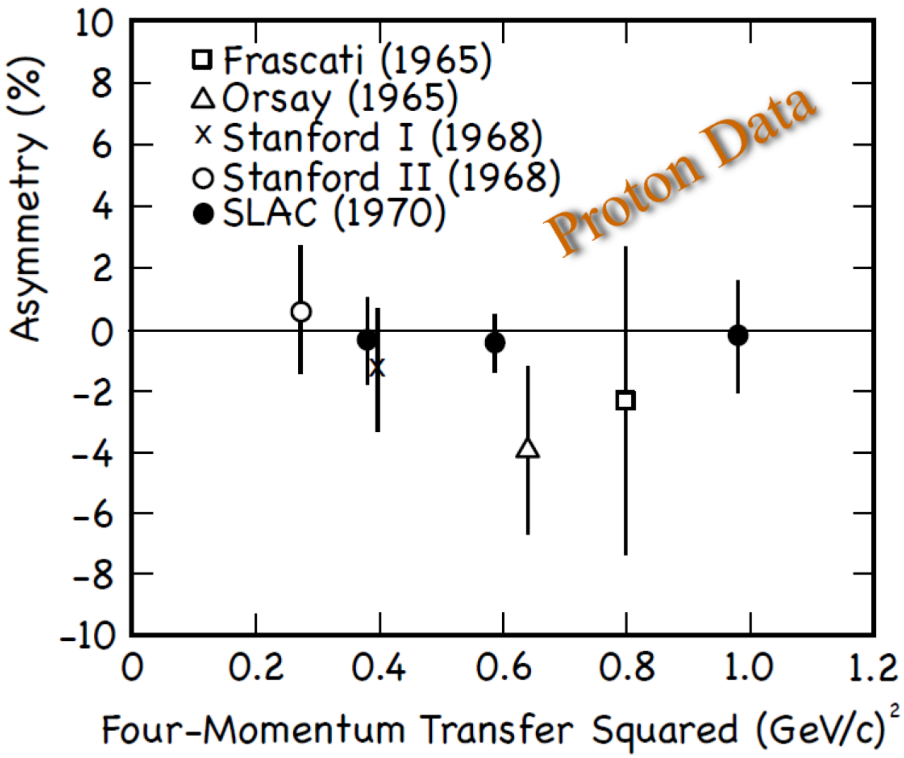
Comparison with the theory

$^3\vec{He}(\vec{e}, e'd)p$





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

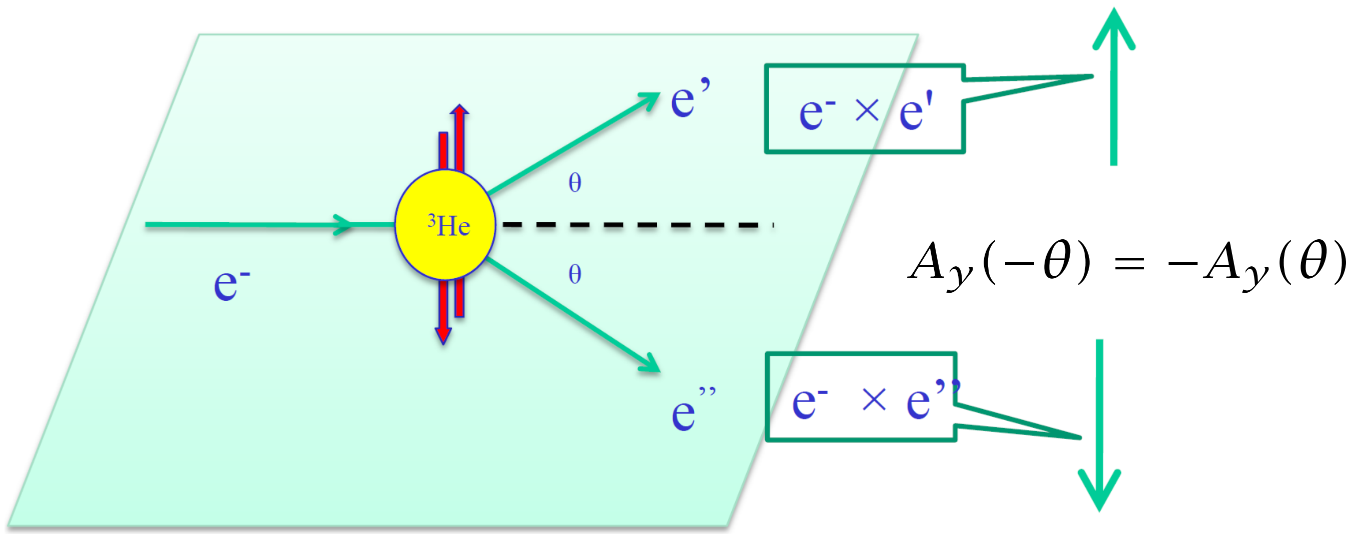


$$A_y = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

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

- $A_y = 0$ 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**

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



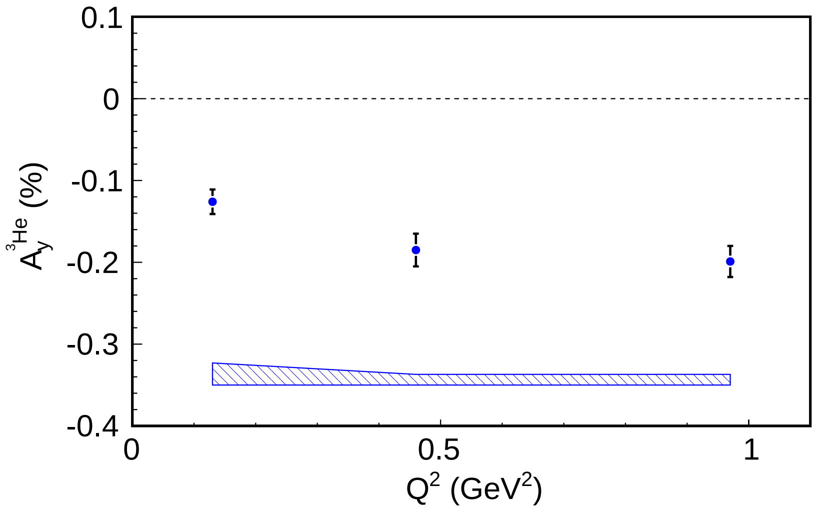
E_0 [GeV]	E' [GeV]	θ_{lab} [Deg]	Q^2 [GeV]^2	$\|q\|$ [GeV]	θ_q [Deg]
1.25	1.22	17	0.13	0.359	71
2.43	2.18	17	0.46	0.681	62
3.61	3.09	17	0.98	0.988	54

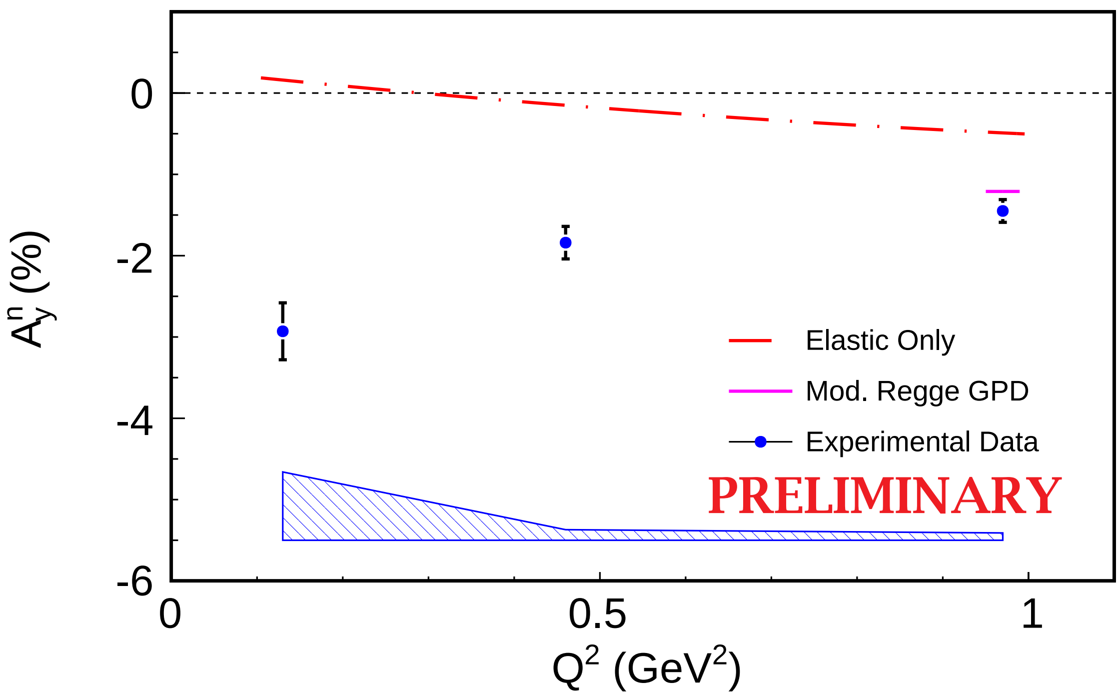
Figure & table courtesy of Yawei Zhang

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

^{3}He

neutron

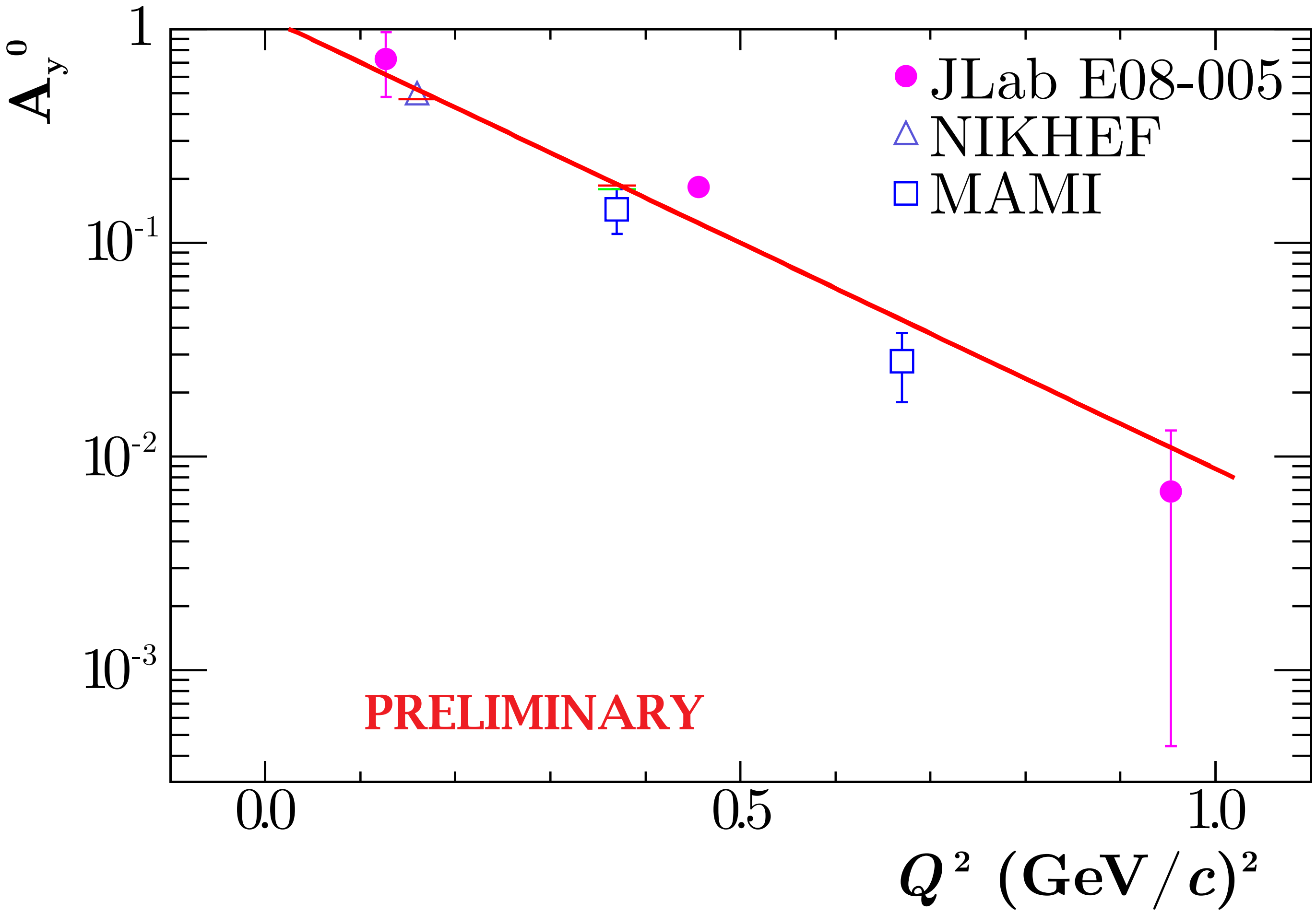




- first measurement of A_y^{n} (i.e. extraction from $A_y^{^3\mathrm{He}}$)
- uncertainty several times better than previous proton data

Figures courtesy of Yawei Zhang

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

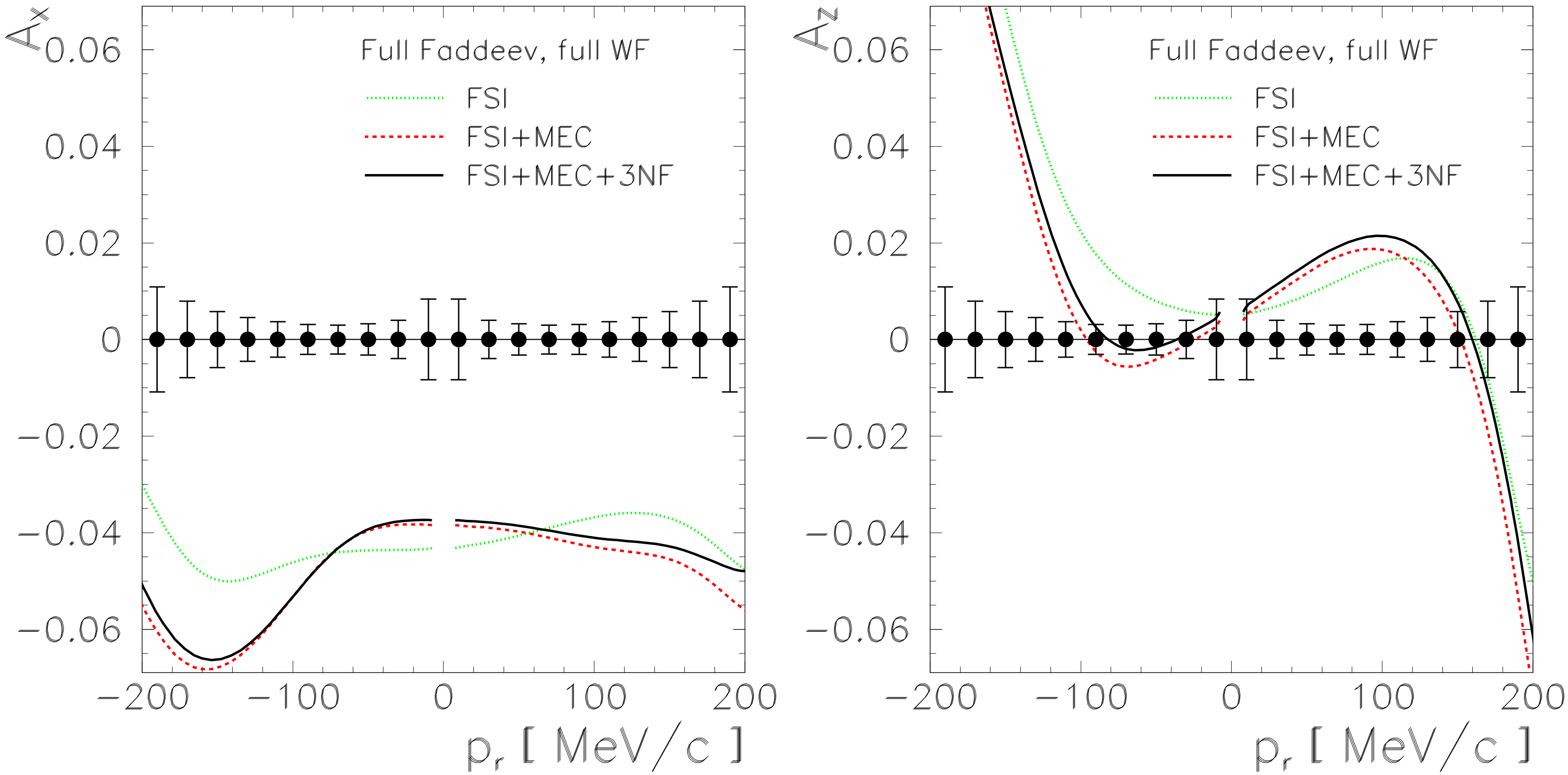


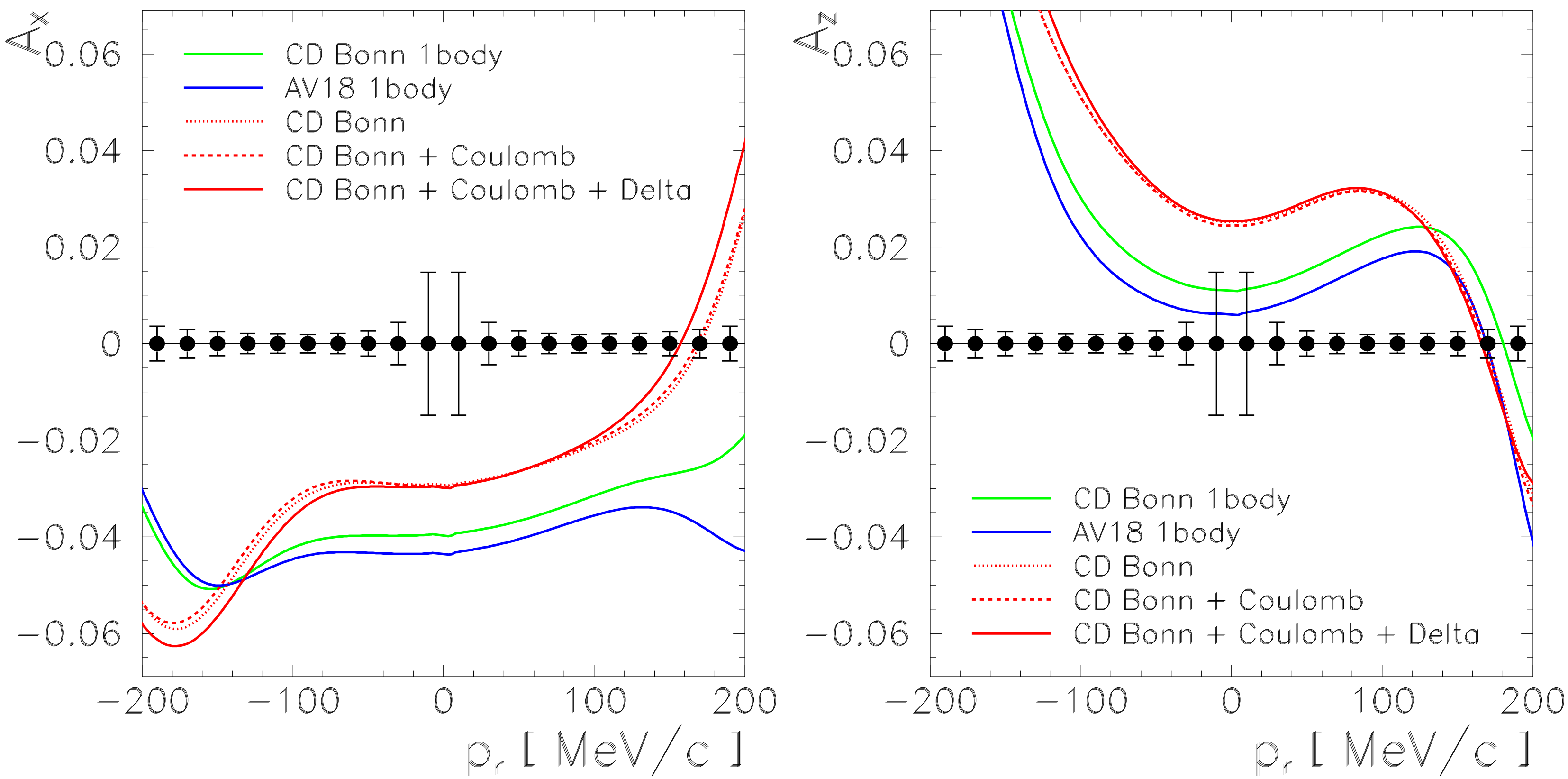
Double-spin asymmetries in QE $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{n})$ coming up!

Figure courtesy of Elena Long

Thank you!

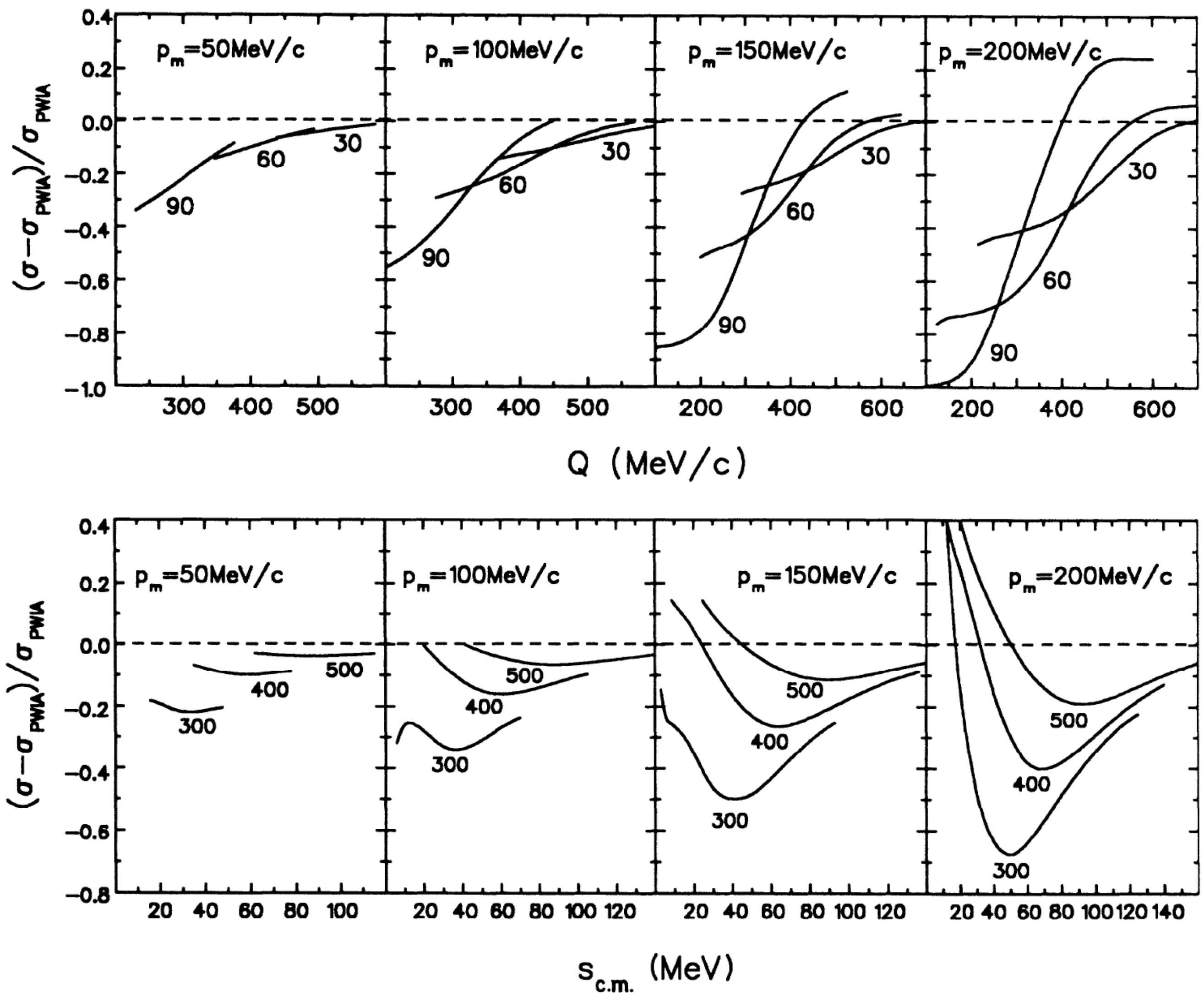
Dynamics ingredients $^3\vec{He}(\vec{e}, e'd)$





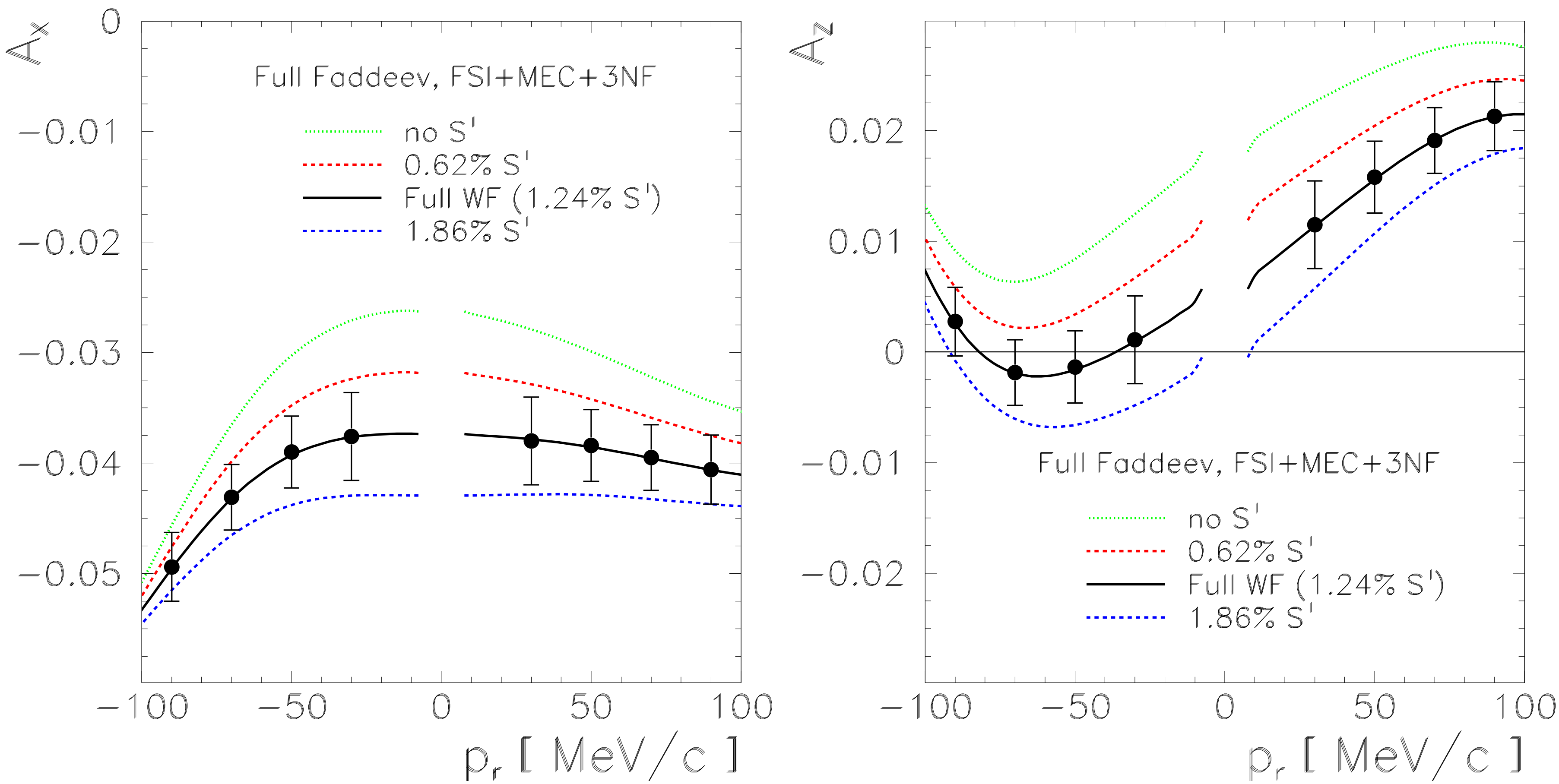
A_x
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
CD Bonn 1body
AV18 1body
CD Bonn
CD Bonn + Coulomb
CD Bonn + Coulomb + Delta
−200
−100
0
100
200
p_r [MeV/c]
A_z
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
CD Bonn 1body
AV18 1body
CD Bonn
CD Bonn + Coulomb
CD Bonn + Coulomb + Delta
−200
−100
0
100
200
p_r [MeV/c]

Relative size of FSI effects for $^{3}\mathrm{He}(e, e'd)$

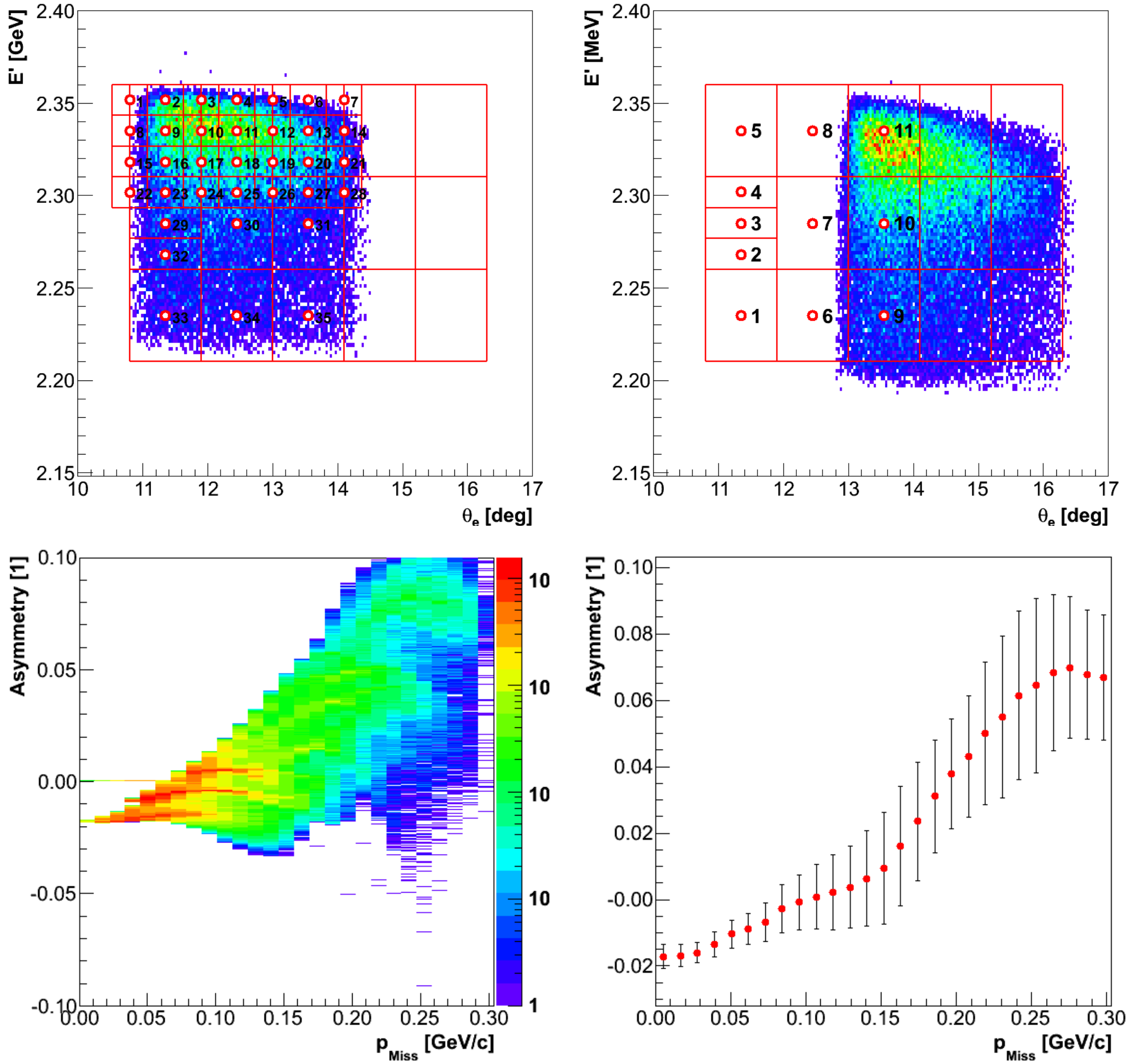


Meijgaard, Tjon PRC **42** (1990) 96

Sensitivity to the S' component



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



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:

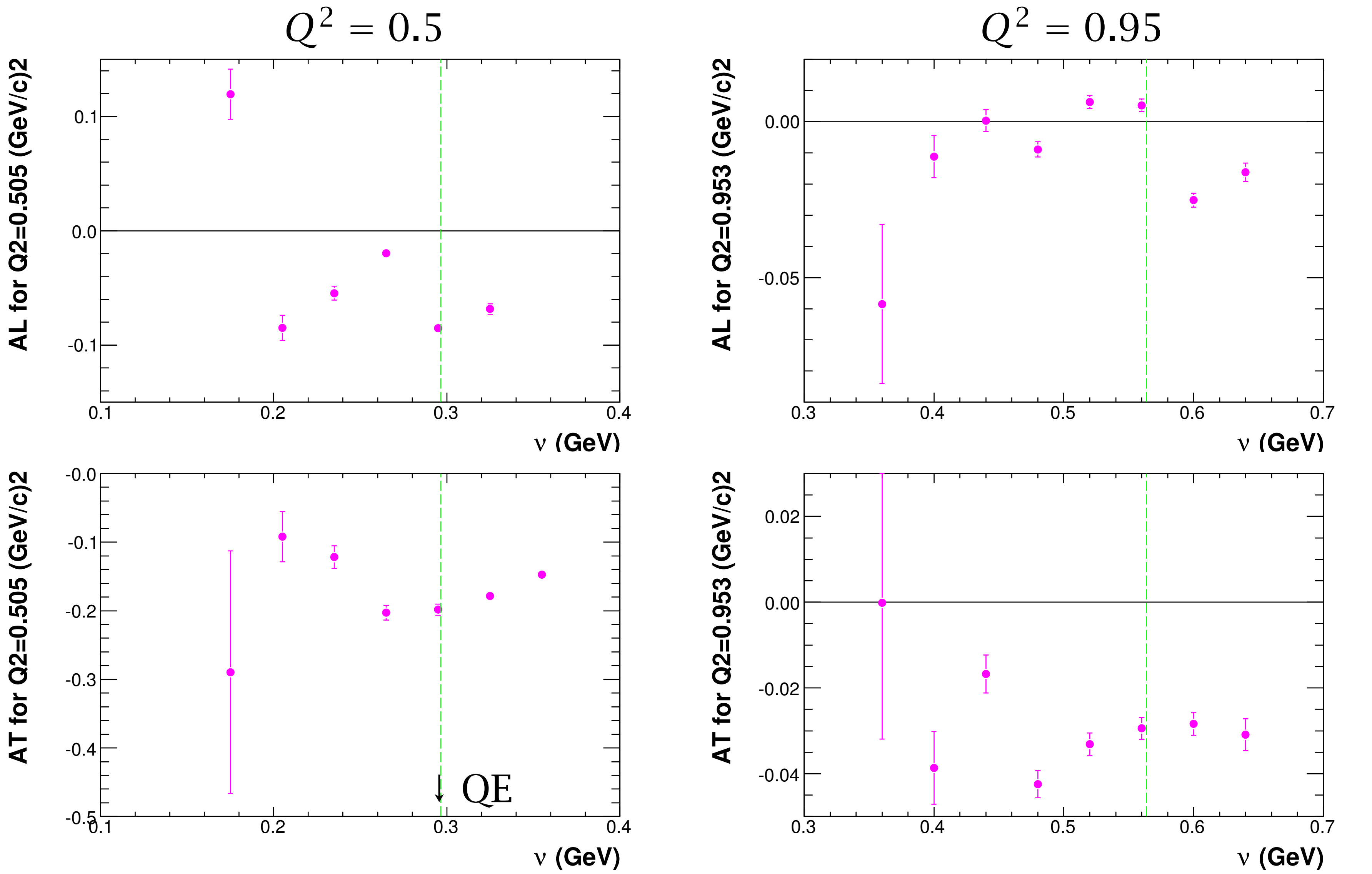
$$A_y^{^3\mathrm{He}} = P_{\mathrm{n}} f_{\mathrm{n}} A_y^{\mathrm{n}} + P_{\mathrm{p}} (1 - f_{\mathrm{n}}) A_y^{\mathrm{p}}$$

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

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

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.

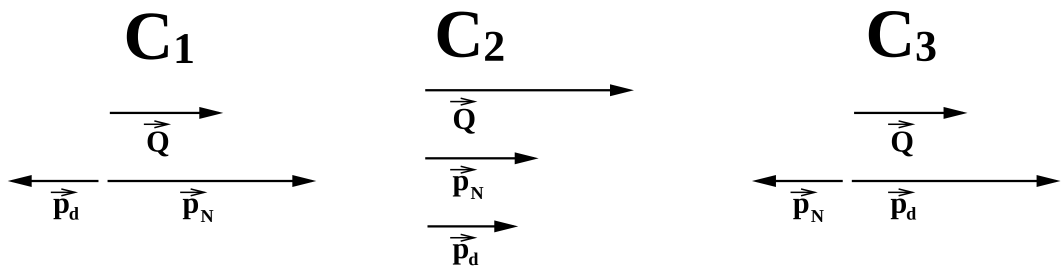
Double-spin asymmetries in QE $^3\vec{\mathrm{He}}(\vec{e}, e'n)$ E08-005



VERY PRELIMINARY Figures courtesy of Elena Long

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

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



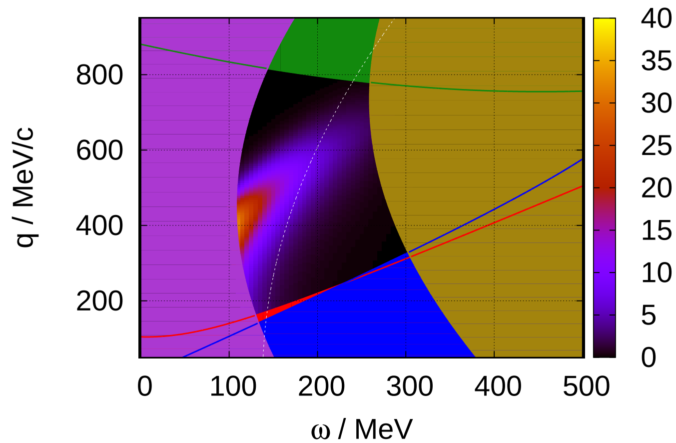


Figure courtesy of Michael Distler, JGU Mainz

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

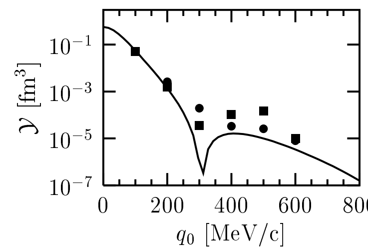
- spin-dependent momentum distributions of $\vec{\mathrm{p}}\vec{\mathrm{d}}$ clusters in polarized ^{3}He

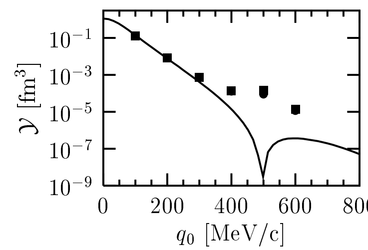
$$N_\mu = \left\langle \Psi^{(-)}_{\mathrm{pd}} M_{\mathrm{d}} m \,|\hat{j}_\mu(\vec{q})|\Psi M \right\rangle$$

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

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

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

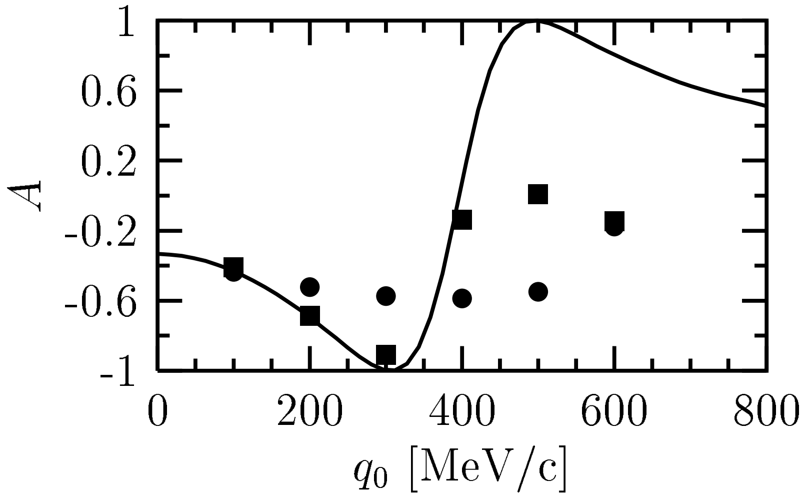




$$\sigma_{\mathrm{L}} \propto |N_0|^2$$

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

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



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Experiment E05-102 in Hall-A