Study of ^{3}He by polarization observables

S. Širca, U of Ljubljana EMC/SRC Workshop, 26 March 2021

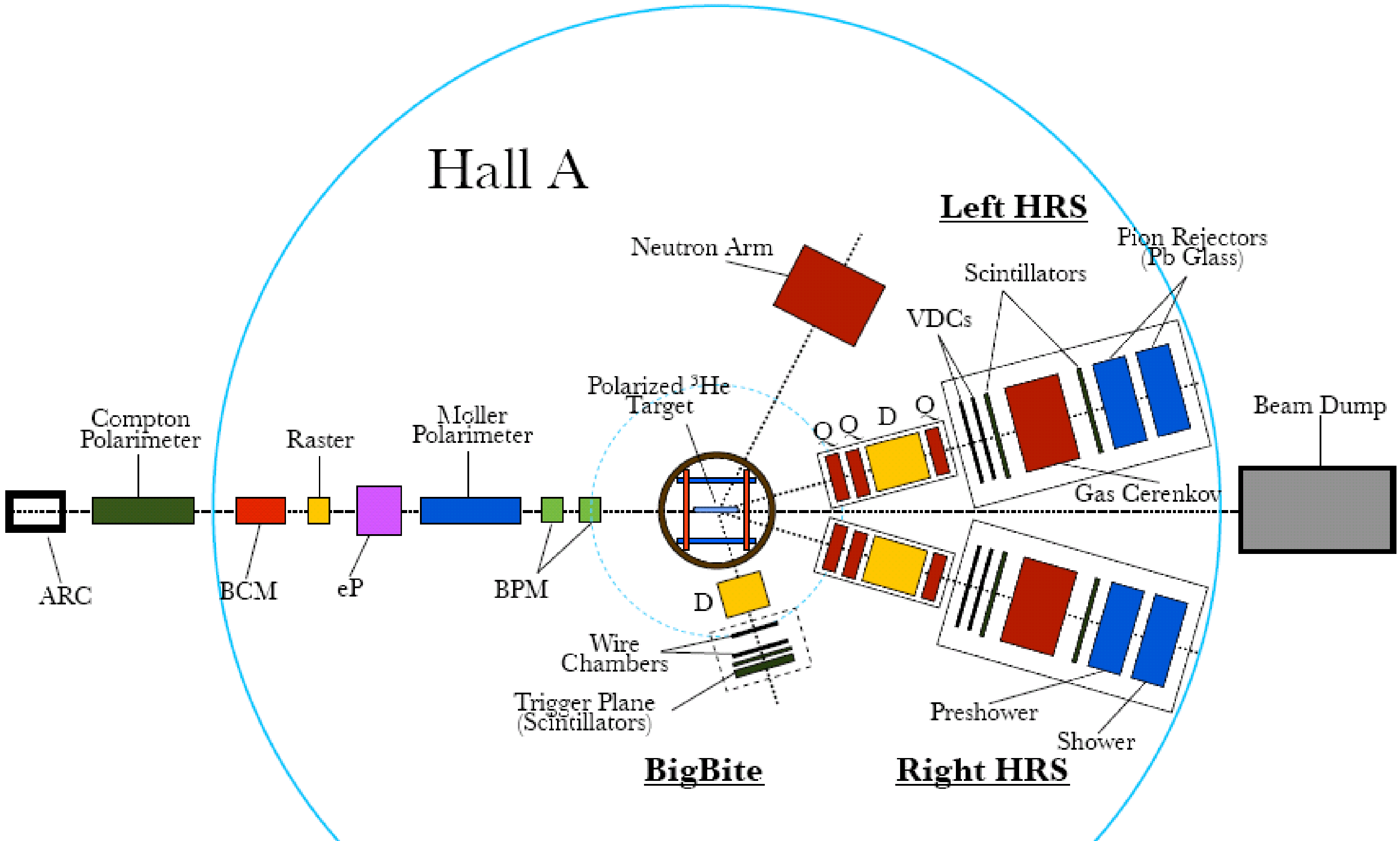
JLab Experiments covered in this talk

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

Since then:

- “Tritium” group of experiment(s) / all unpolarized
  ALREADY PUBLISHED:
  Cross-sections for $^3\mathrm{H}$ and $^3\mathrm{He}(\mathrm{e},\mathrm{e}'\mathrm{p})\mathrm{pn}$
  Proton momentum distributions via $^2\mathrm{H}$, $^3\mathrm{H}$ and $^3\mathrm{He}(\mathrm{e},\mathrm{e}'\mathrm{p})$

Experimental Setup



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

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).

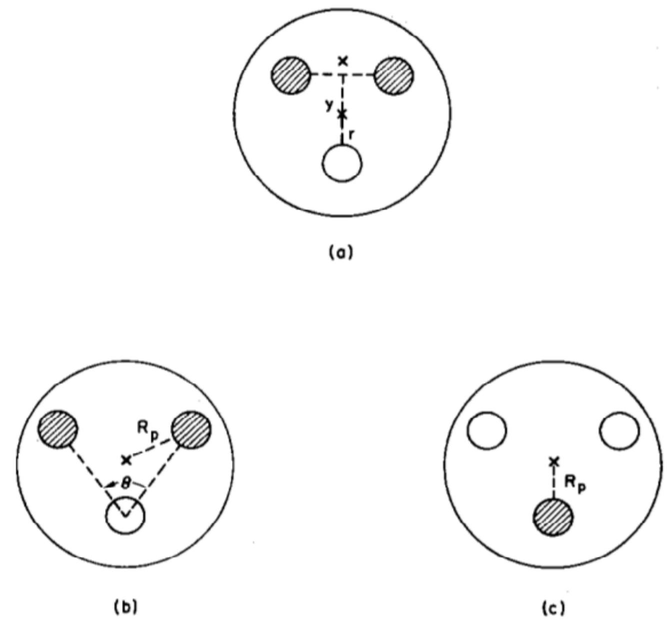
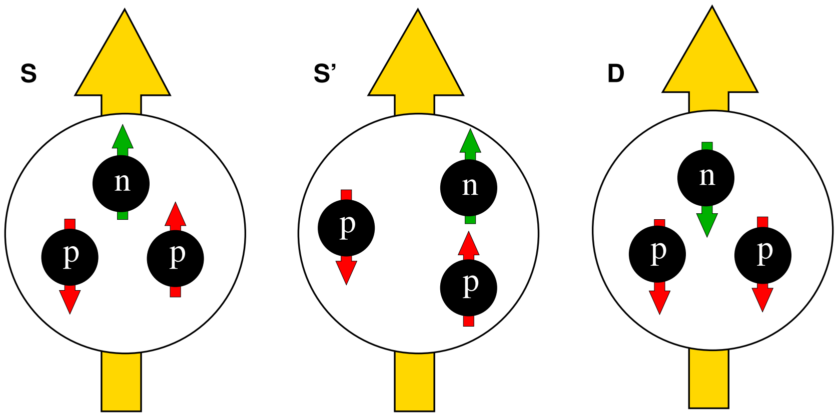


Fig. 1. Schematic picture of trinucleon when all forces are identical is shown in (a). The effect on ^{3}He and ^{3}H when the pp or nn force is weaker than the np force is illustrated in (b) and (c). R_p is the "charge radius". Shading indicates a proton.

- 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 ...



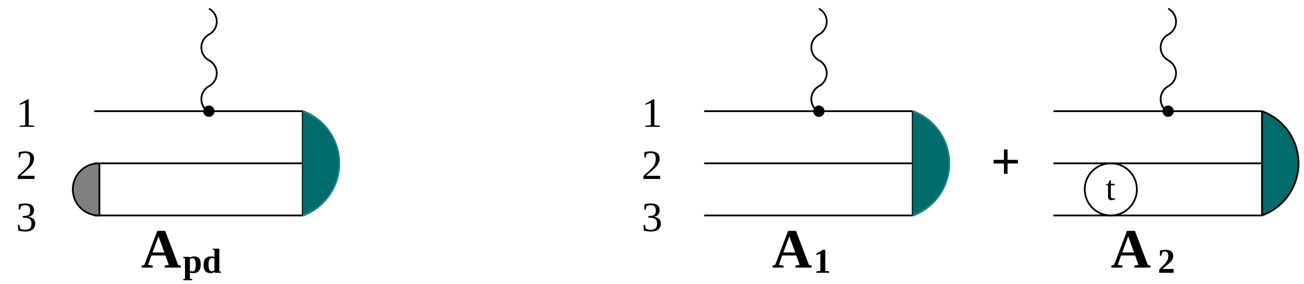
- S: spatially symmetric
  $\approx$ **90 %** of spin-averaged WF;
  "**polarized neutron**"
- D: generated by tensor part of NN force, $\approx$ **8.5 %** .
- S': mixed symmetry component; (spin-isospin)-space correlations, $\approx$ **1.5 %** . $P'_S \approx E_b^{-2.1}$.
- $P_n^{eff} \approx +0.86$,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

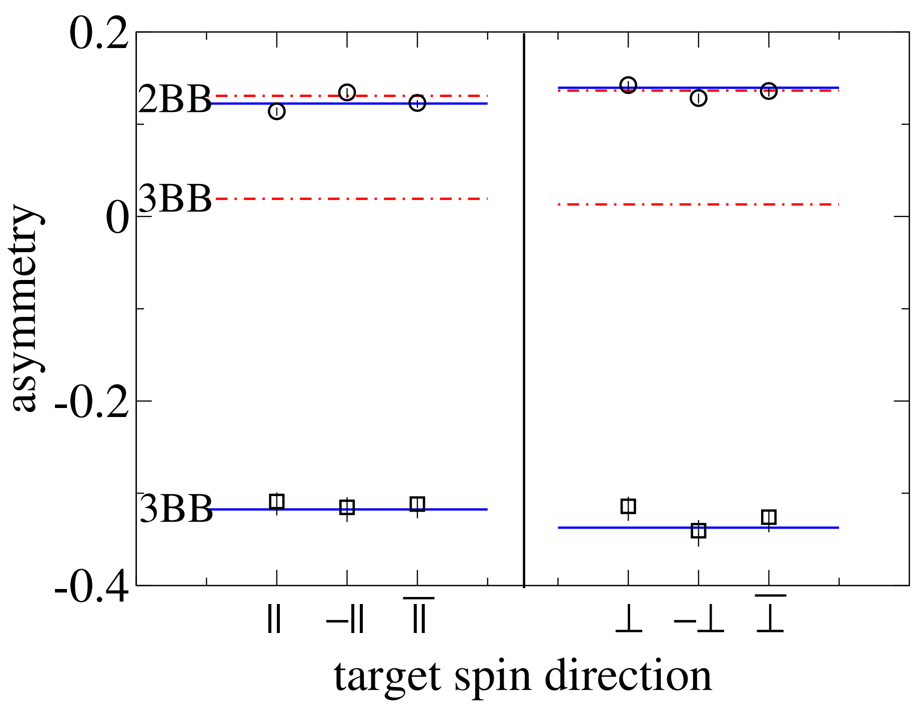
Hamiltonian	S	S'	P	D
AV18	90.10	1.33	0.066	8.51
AV18/TM	89.96	1.09	0.155	8.80
AV18/UIX	89.51	1.05	0.130	9.31
CD-Bonn	91.62	1.34	0.046	6.99
CD-Bonn/TM	91.74	1.21	0.102	6.95
Nijm I	90.29	1.27	0.066	8.37
Nijm I/TM	90.25	1.08	0.148	8.53
Nijm II	90.31	1.27	0.065	8.35
Nijm II/TM	90.22	1.07	0.161	8.54
Reid93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

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

$\parallel$ 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 ↓)

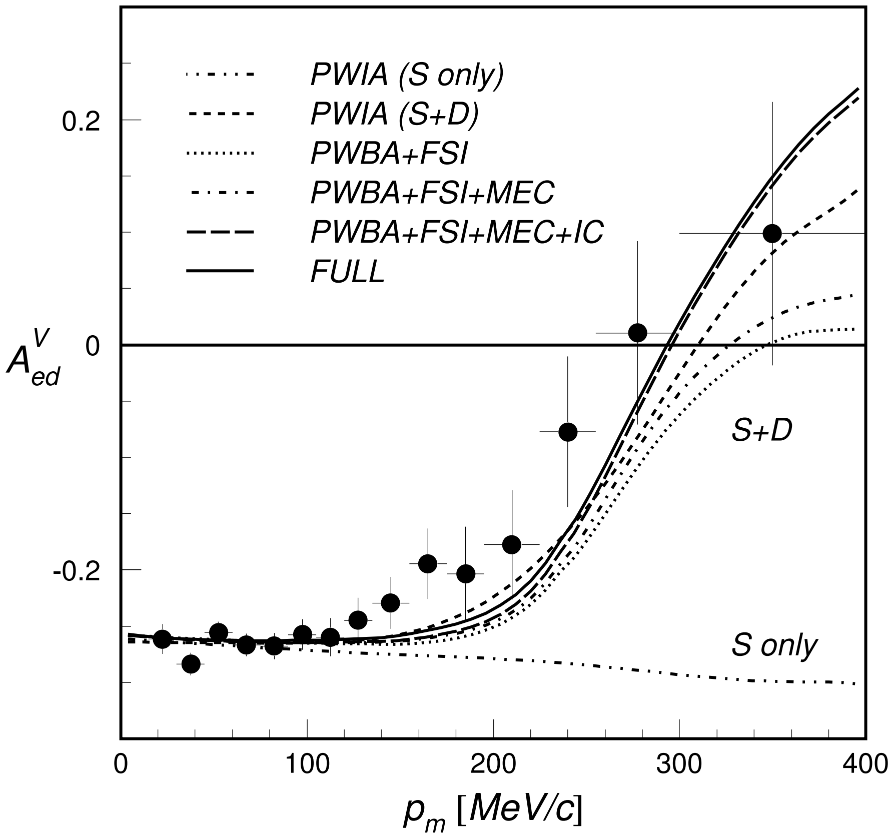
$A_{\mathrm{PWIA+FSI}}$ large & negative

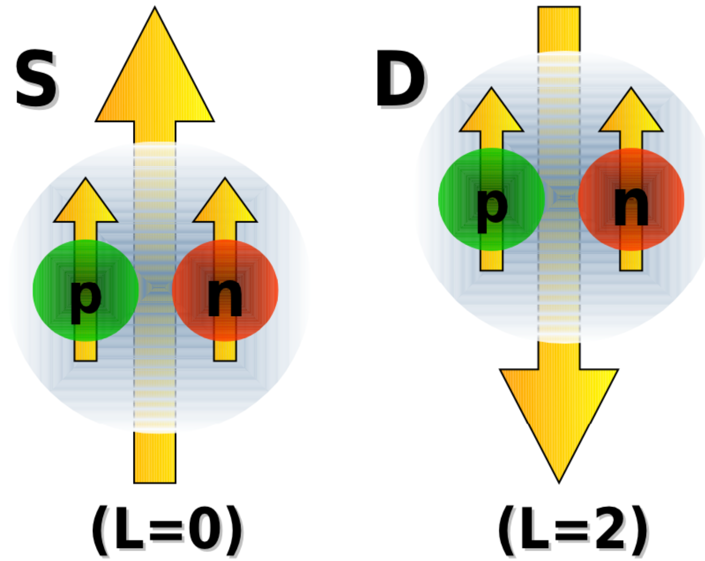
not a polarized p target

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

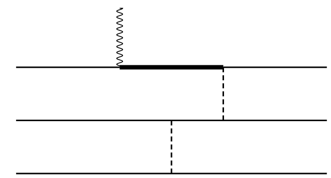
Blankleider, Woloshyn PRC **29** (1984) 538

To handle this, one needs state-of-the-art calculations

Krakow/Bochum (full Faddeev)

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

Hannover/Lisbon (→ Vilnius) (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

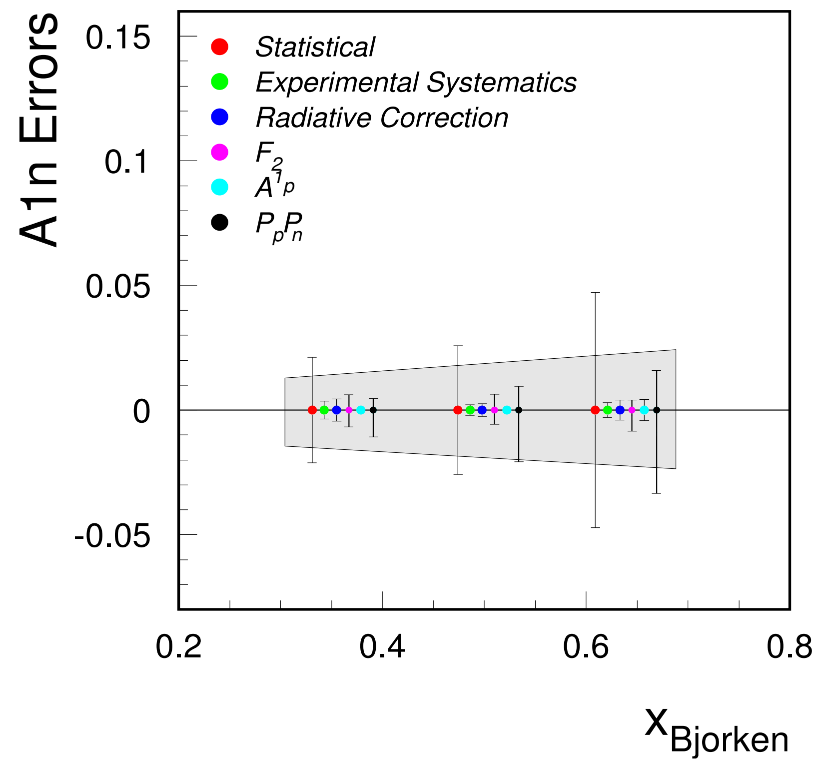
Pisa

- 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

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

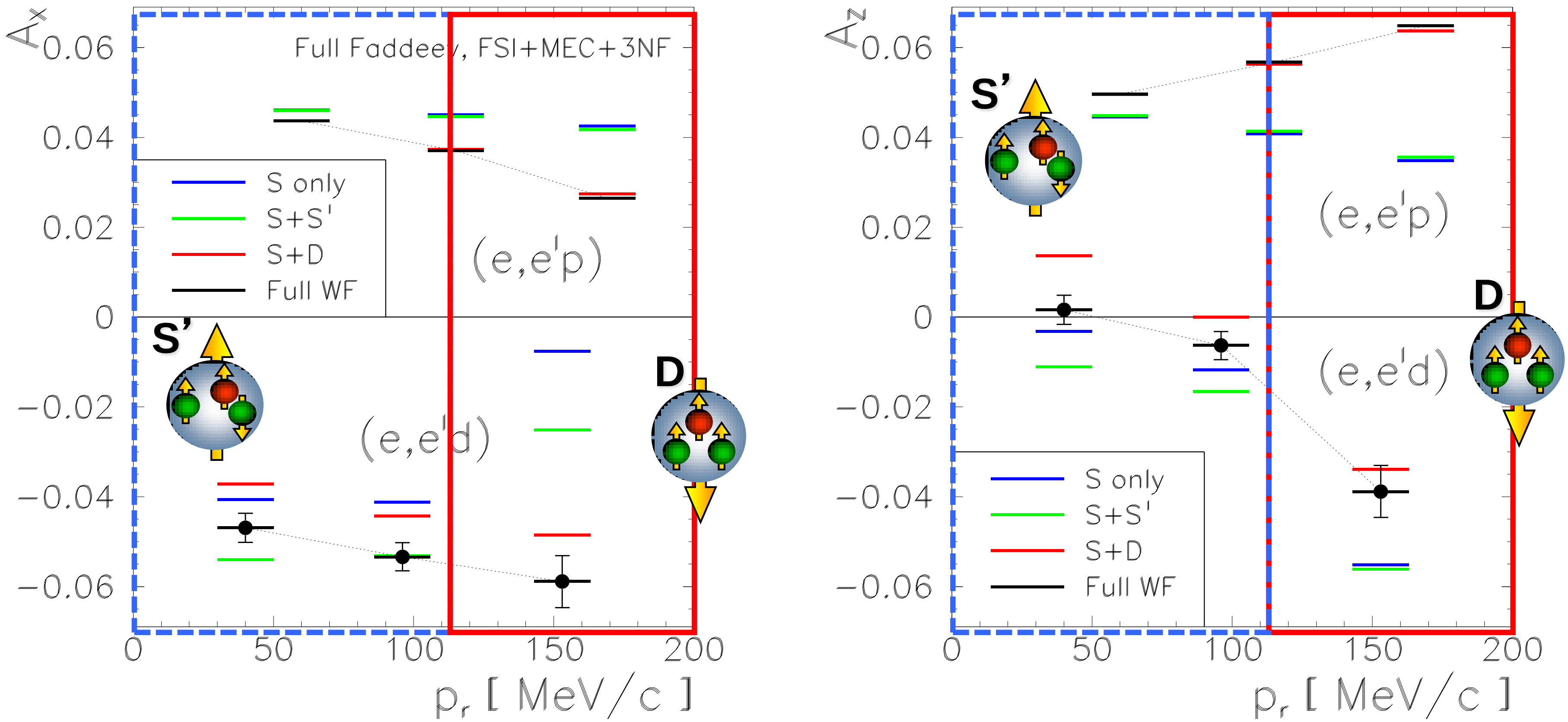
- **Better understanding of ground-state spin structure of polarized** ^{3}He — — S, S', D wave-function components. Improve knowledge of ^{3}He rather than using it as an effective neutron target. **Direct consequences for all polarized** ^{3}He **experiments**.



- 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**.

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



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

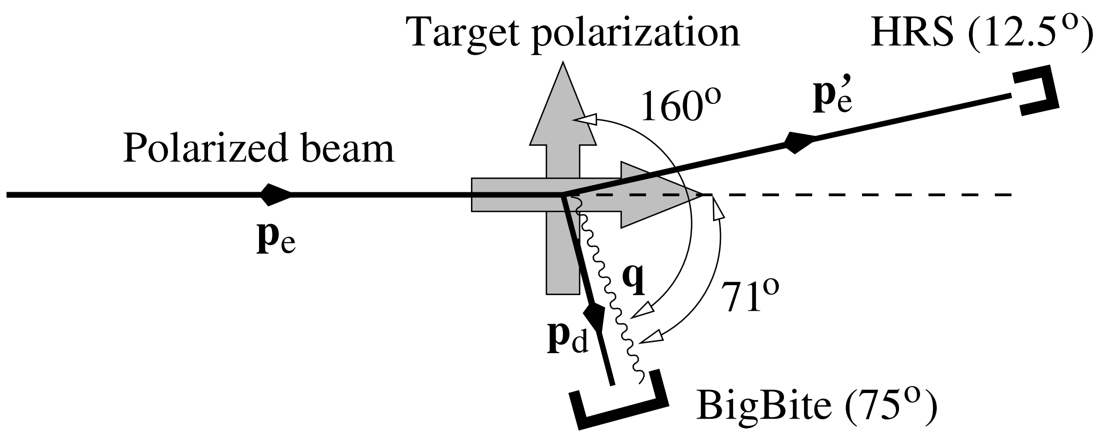
Beam-target asymmetry in QE p/d knockout from $^3\vec{\mathrm{He}}$

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

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

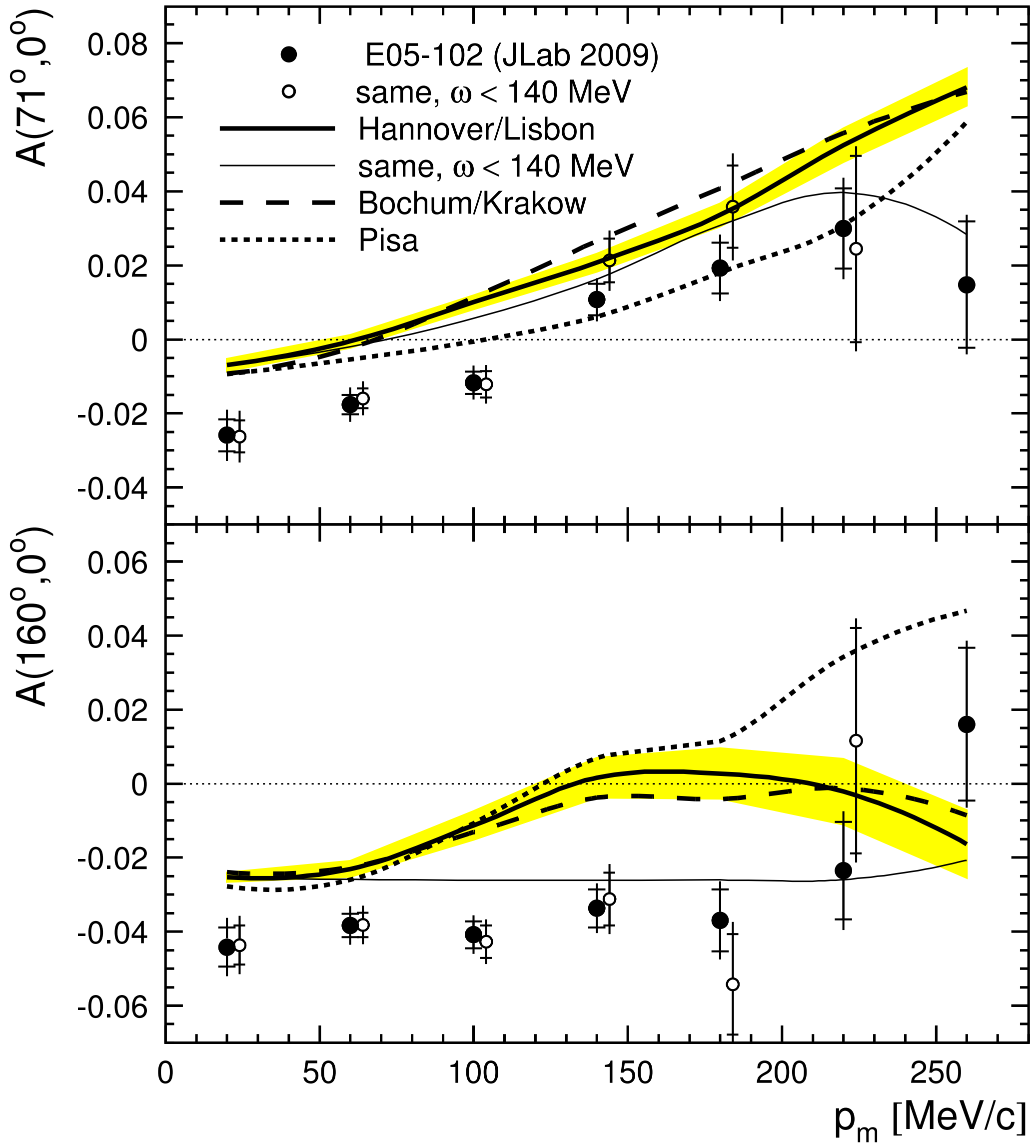
$$A(\theta^*,\phi^*) = \vec{S}(\theta^*,\phi^*)\cdot\vec{A} = \frac{[\,\mathrm{d}\sigma_{++}+\mathrm{d}\sigma_{--}\,]-[\,\mathrm{d}\sigma_{+-}+\mathrm{d}\sigma_{-+}\,]}{[\,\mathrm{d}\sigma_{++}+\mathrm{d}\sigma_{--}\,]+[\,\mathrm{d}\sigma_{+-}+\mathrm{d}\sigma_{-+}\,]}$$

- **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 $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{n})\mathrm{pp}$



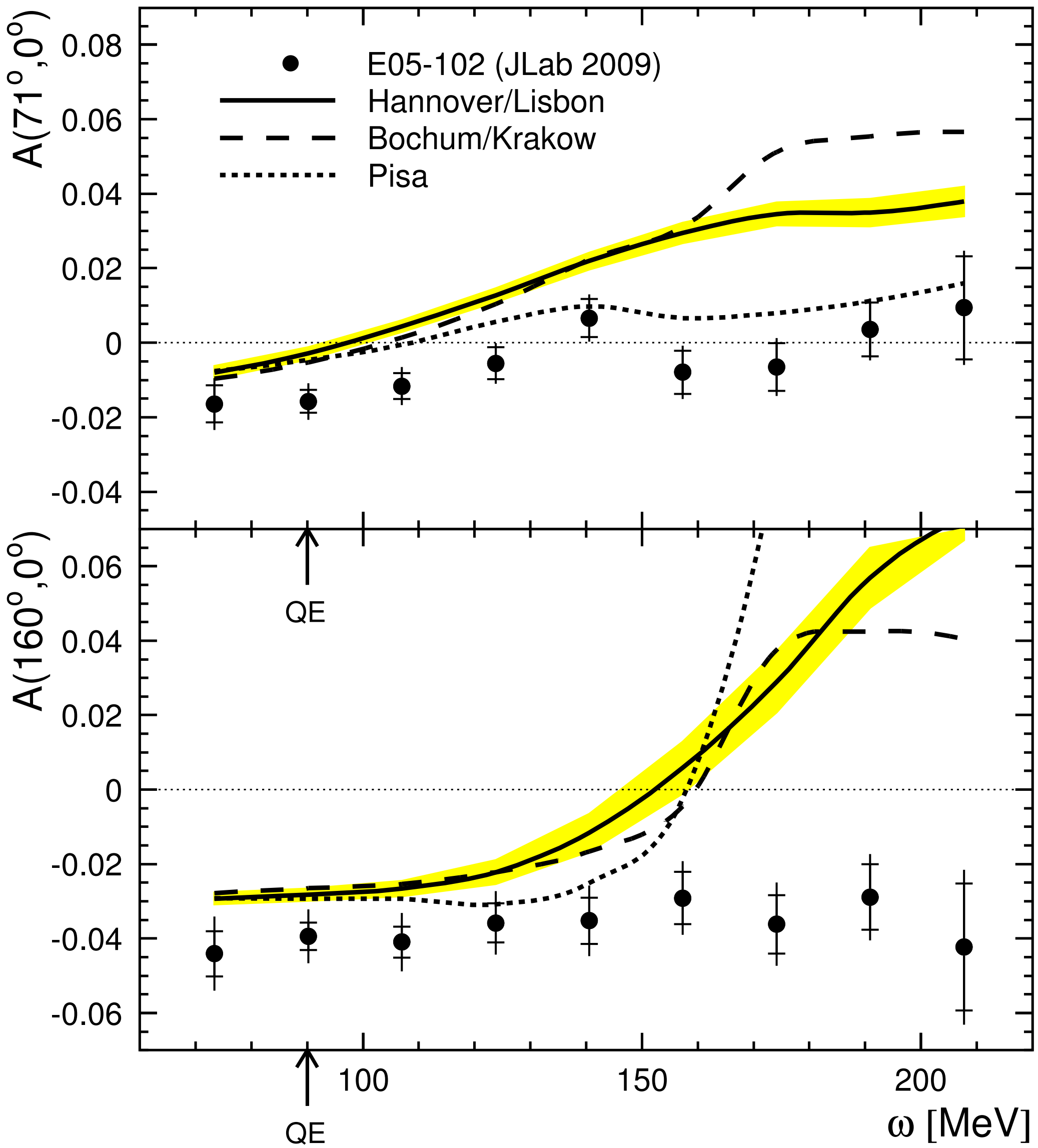
Results on $^{3}\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{d})\mathrm{p}$ — p_{m}-dependence

- 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 (?)



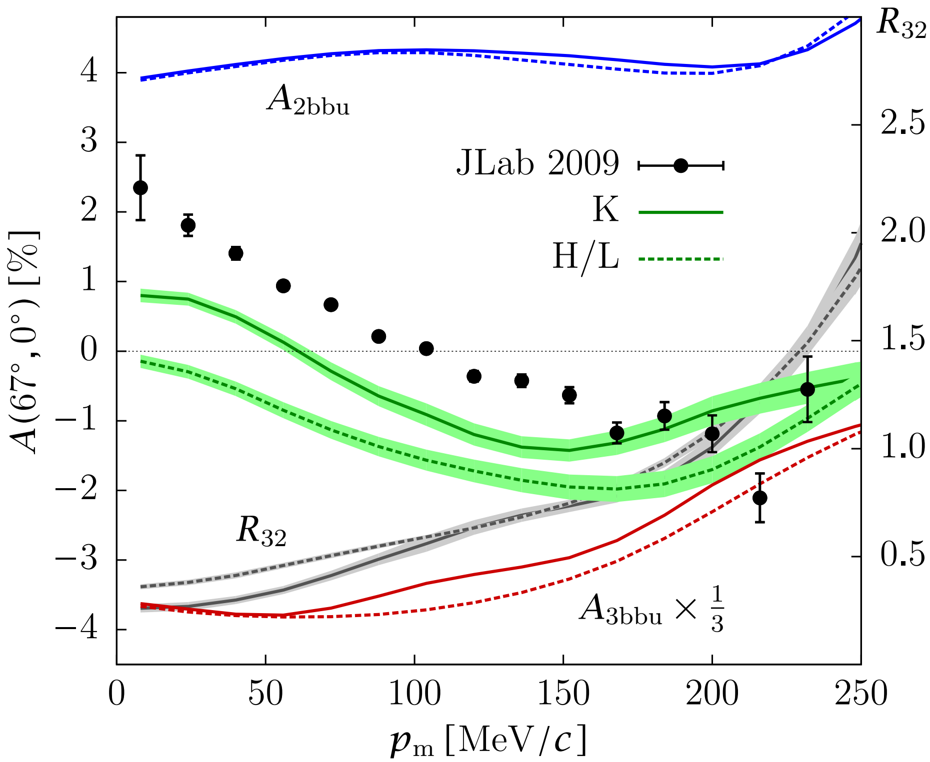
Mihovilovič++ PRL **113** (2014) 232505

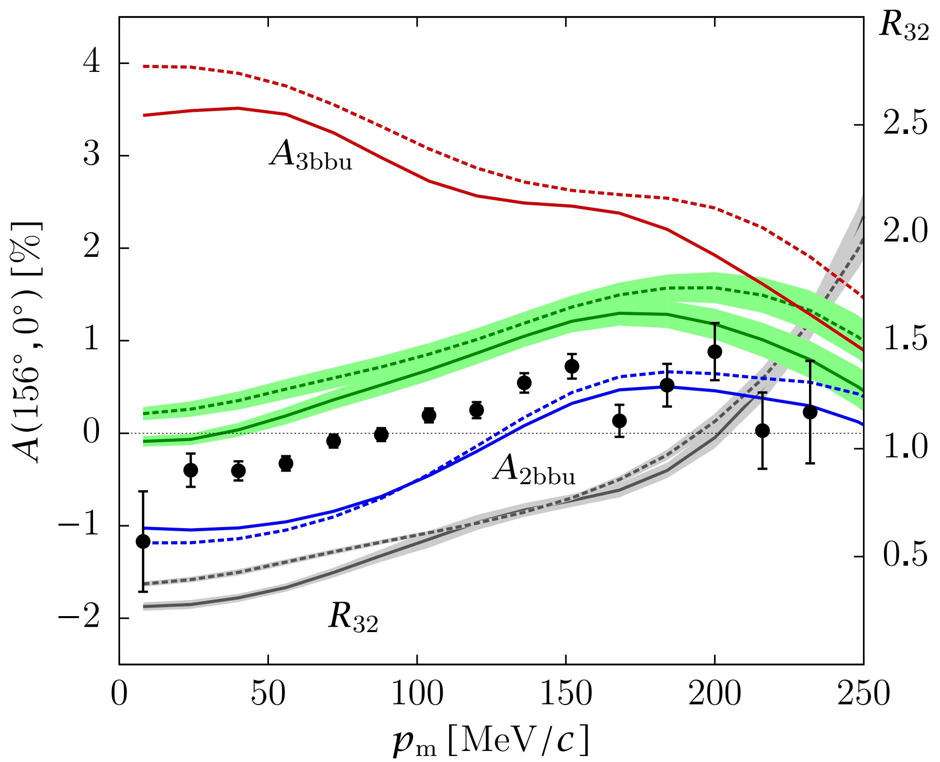
Results on $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{d})\mathrm{p}$ — ω-dependence



Mihovilovič++ PRL **113** (2014) 232505

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





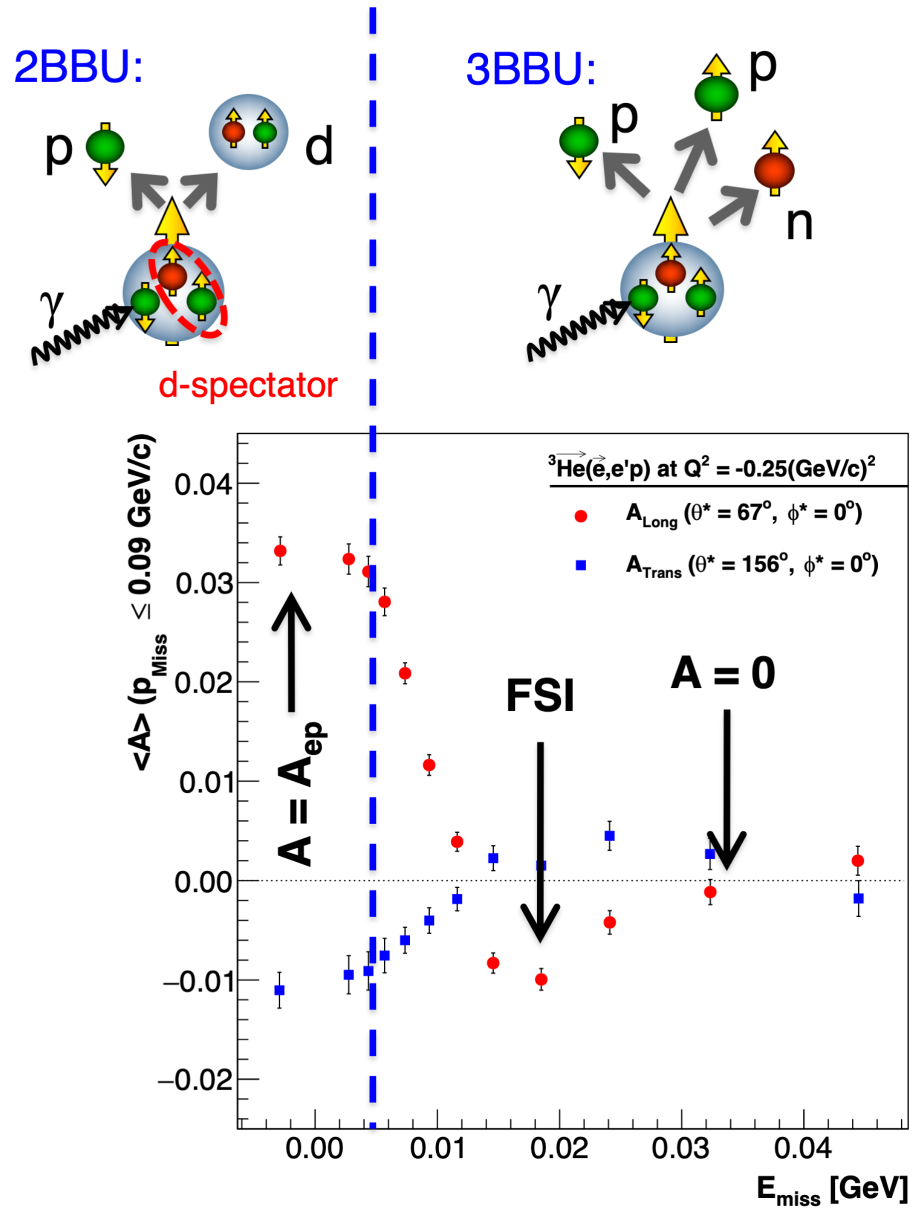
Mihovilovič++ PLB **788** (2019) 117

- 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 (?)

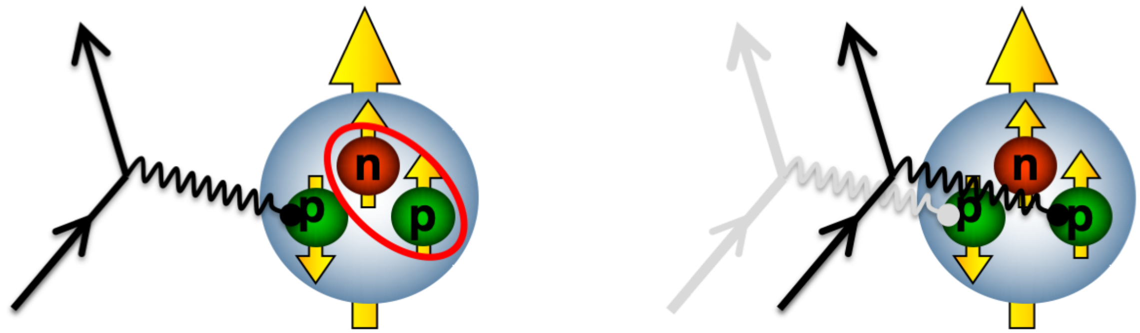
Simple interpretation of $^3\vec{\text{He}}(\vec{\text{e}}, \text{e}'\text{p})$

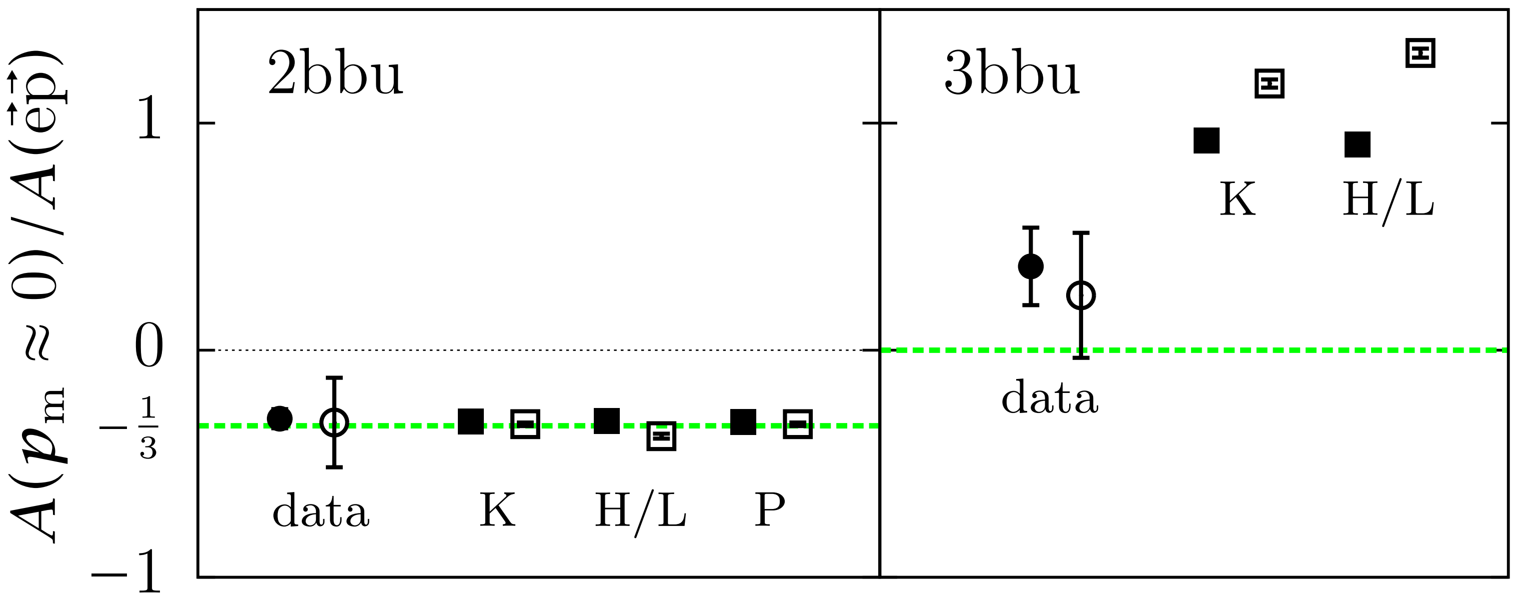
- Valid for $p_\text{m} \approx 0$
- Assume PWIA
- S-state dominates
- Missing energy:
  $E_\text{m} = \omega - T_\text{p} - T_\text{d}$

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



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





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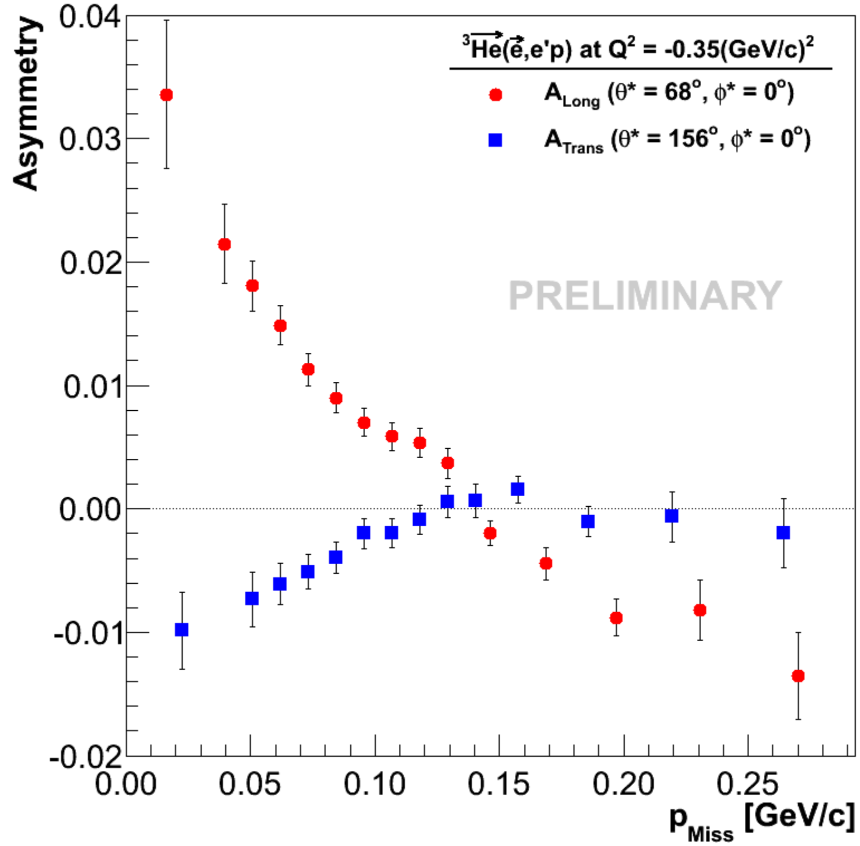
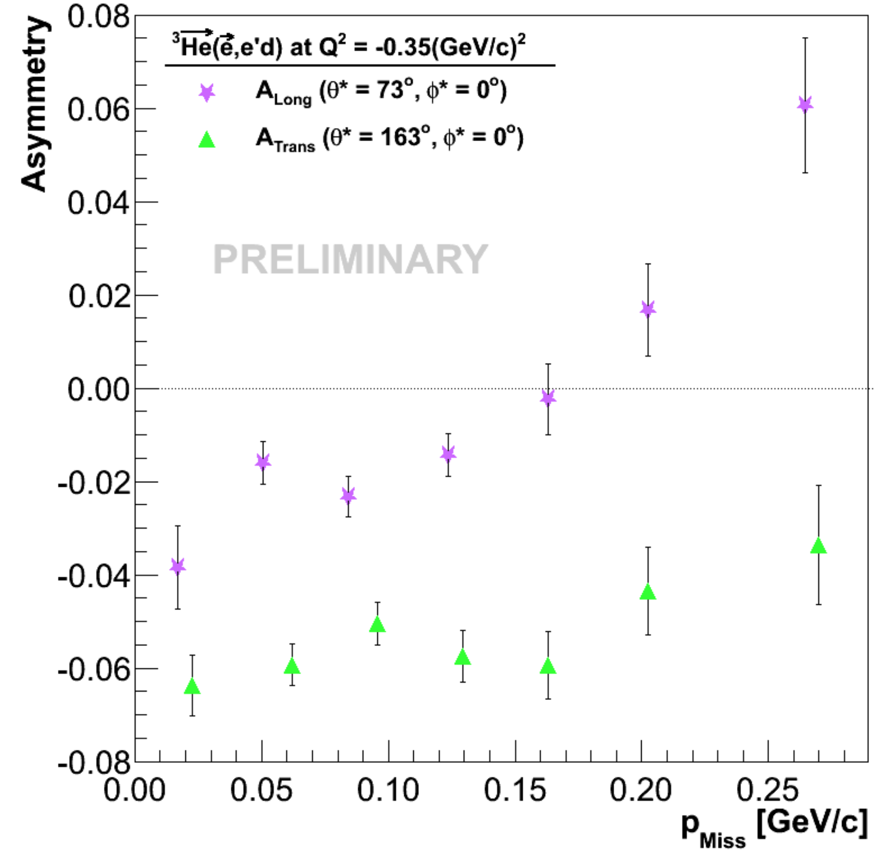
More $^3\vec{He}(\vec{e}, e'd)$ and $^3\vec{He}(\vec{e}, e'p)$ ...

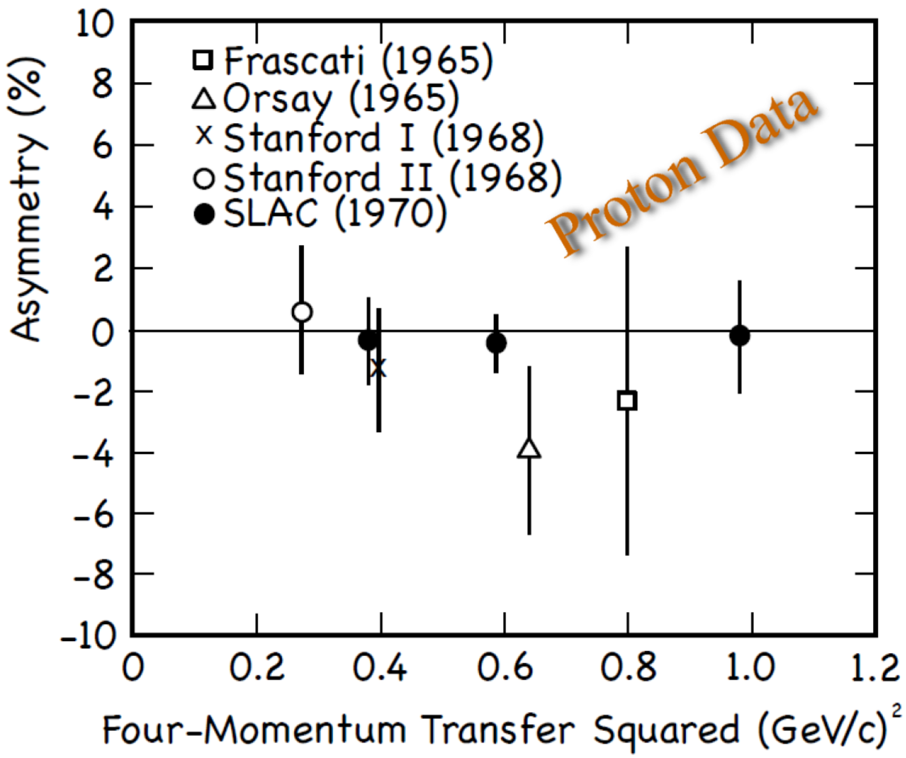
- High-statistics data also available at $Q^2 \approx 0.35\,\text{GeV}^2$ in all channels





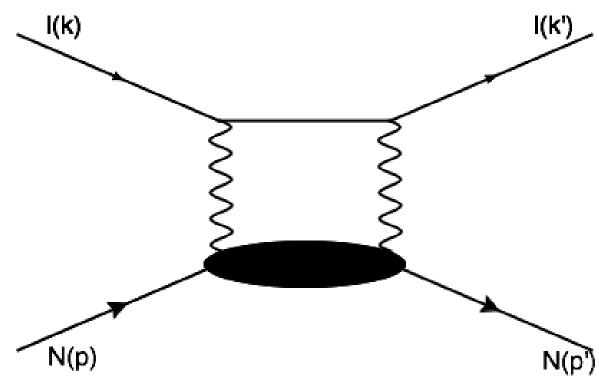
- Opportunity to study Q^2-dependence of asymmetries
- Final analysis / calculations pending

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



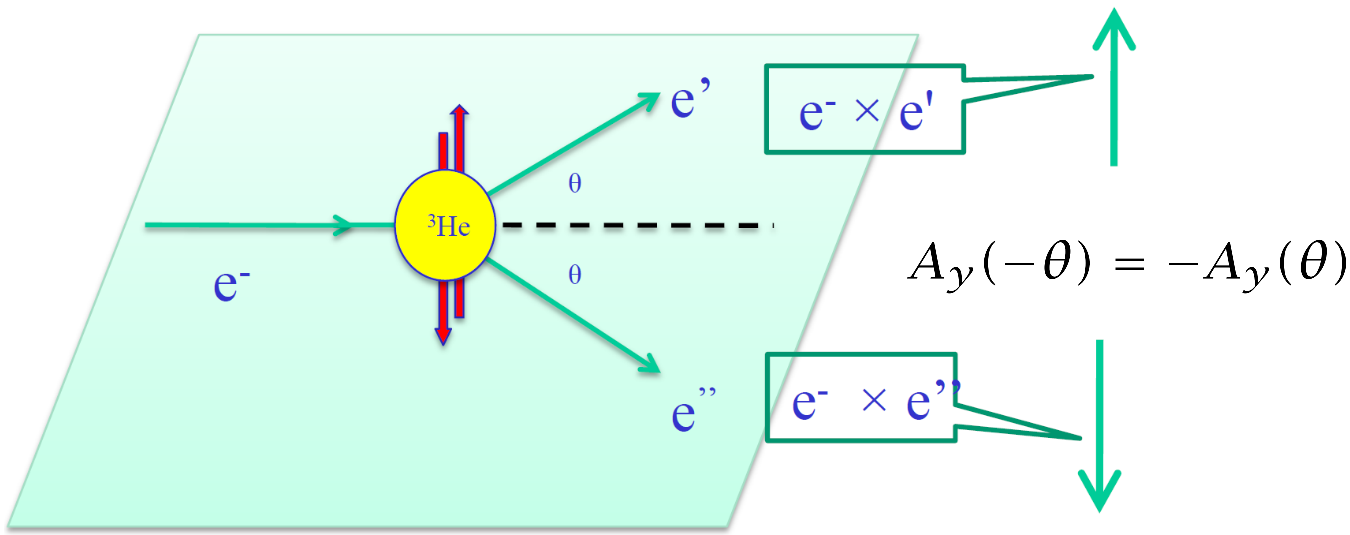
$$A_y = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

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



- $A_y = 0$ 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

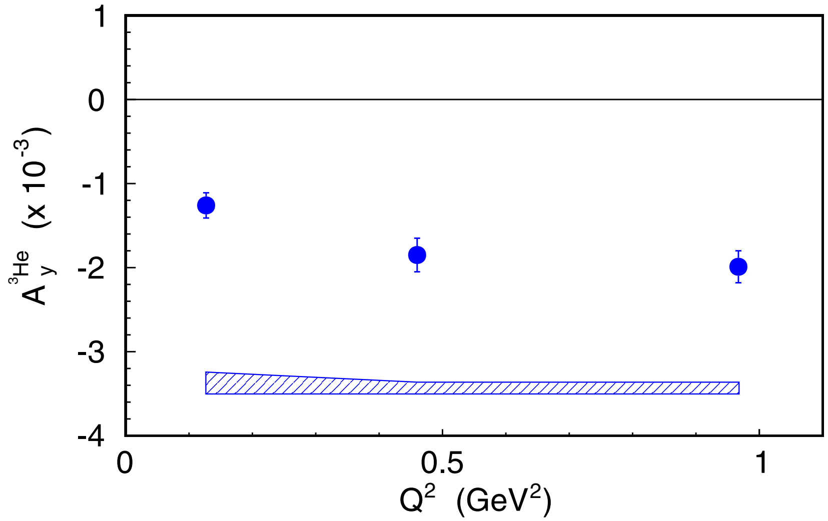


E_0 [GeV]	E' [GeV]	θ_{lab} [Deg]	Q^2 [GeV]^2	$\lvert q \rvert$ [GeV]	θ_q [Deg]
1.25	1.22	17	0.13	0.359	71
2.43	2.18	17	0.46	0.681	62
3.61	3.09	17	0.98	0.988	54

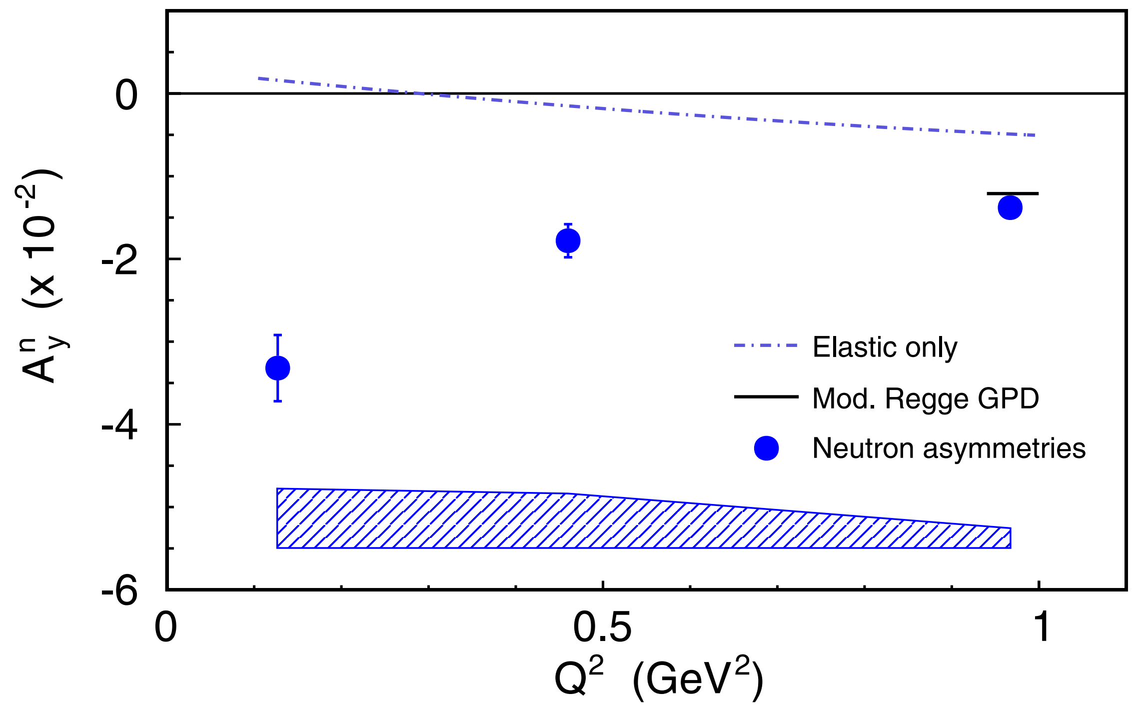
Figure & table courtesy of Yawei Zhang, Rutgers

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

^{3}He



neutron

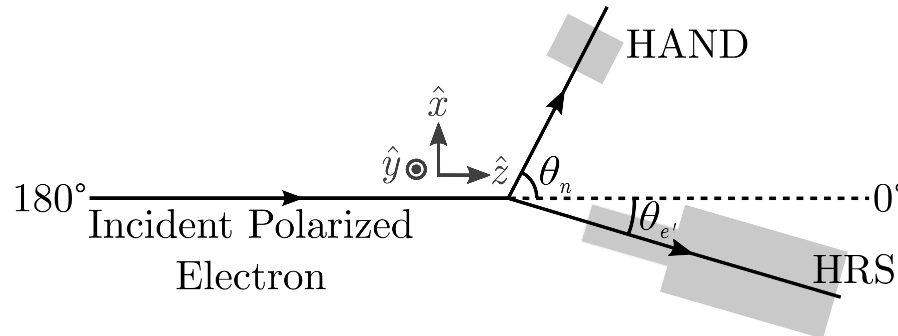


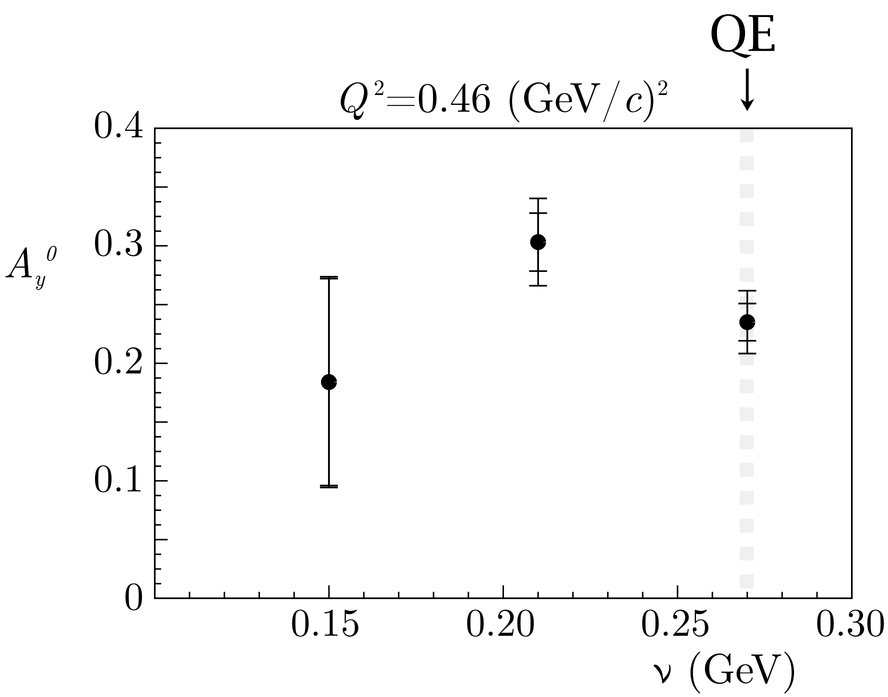
- First measurement of A_y^n (extracted from transversely polarized $A_y^{^3\mathrm{He}}$)
- Uncertainty several times better than previous proton data
- Asymmetry clearly non-zero and negative

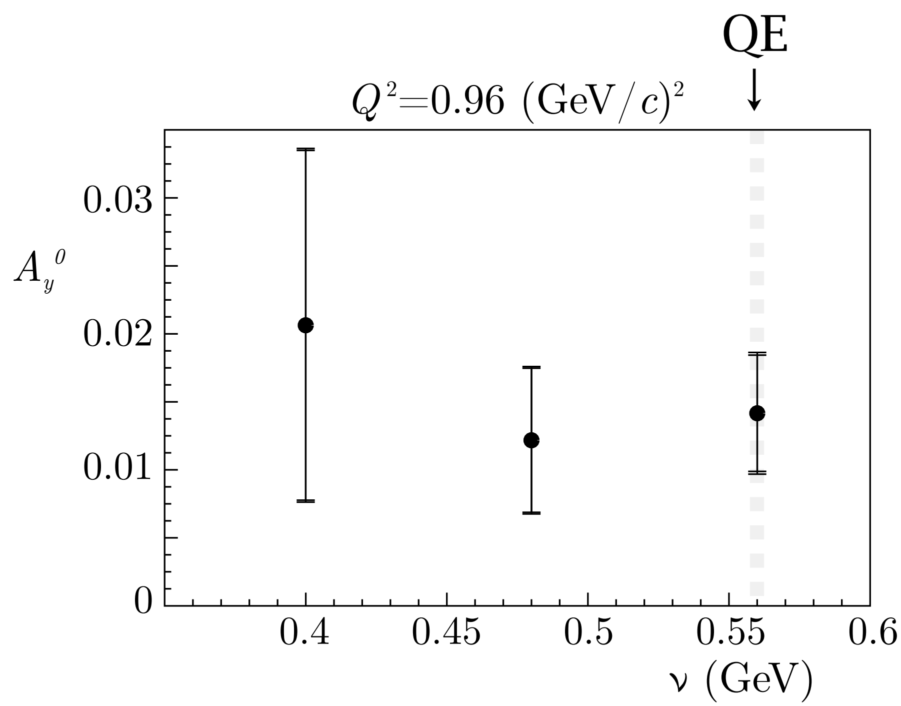
Zhang++ PRL **115** (2015) 172502

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

- 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

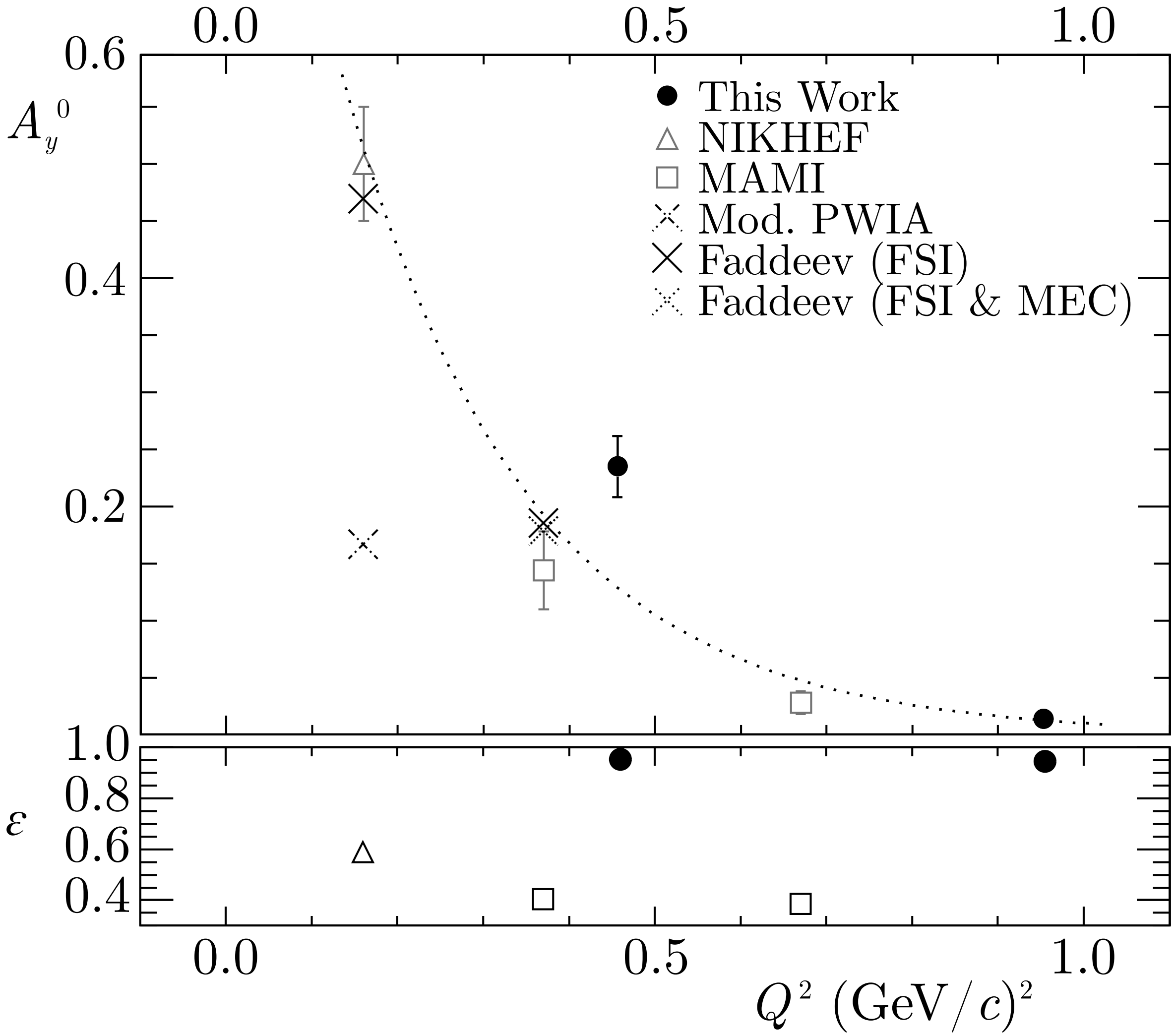






Long++ PLB **797** (2019) 134875

Single-spin asymmetries in QE $^3He^\uparrow(e, e'n)$ E08-005

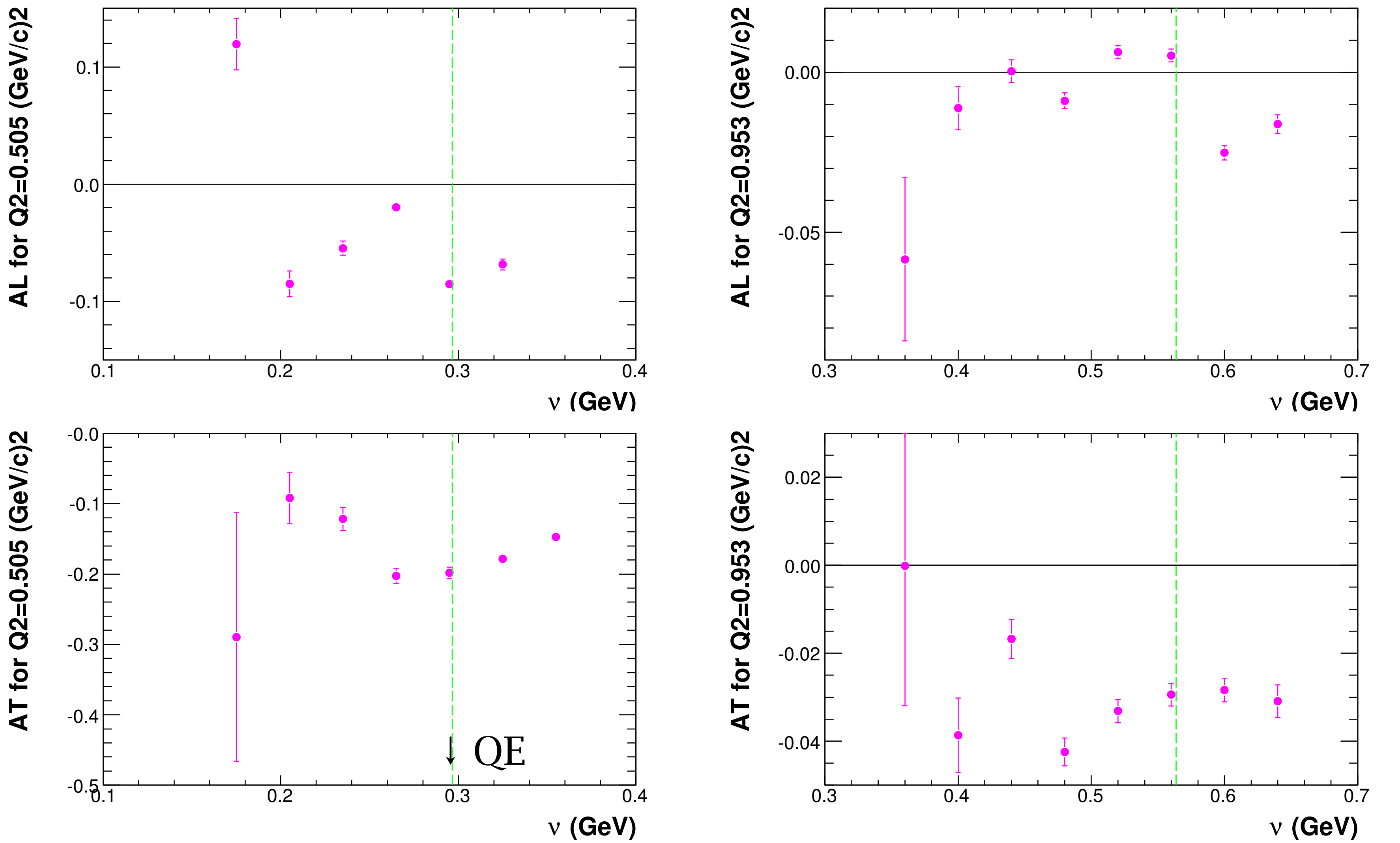


Long++ PLB **797** (2019) 134875

$\Longrightarrow$ PWIA good enough for high-Q^2 experiments at JLab 12 GeV!

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

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



- Calculations?

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

Perspective instead of Conclusion

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Date: Sun, 28 Aug 2005 04:35:13 +0200 (MEST)
From: Eddy Jans <eddy@nikhef.nl>
To: doug@jlab.org, gilad@mitlns.mit.edu, simon.sirca@fmf.uni-lj.si
Subject: E05-102

Hi all,

[...] So now to you the nice task to make the community happy
with three new nice datasets on 3He: (e,e'p), (e,e'd) and GEn.
Good luck,

        eddy jans
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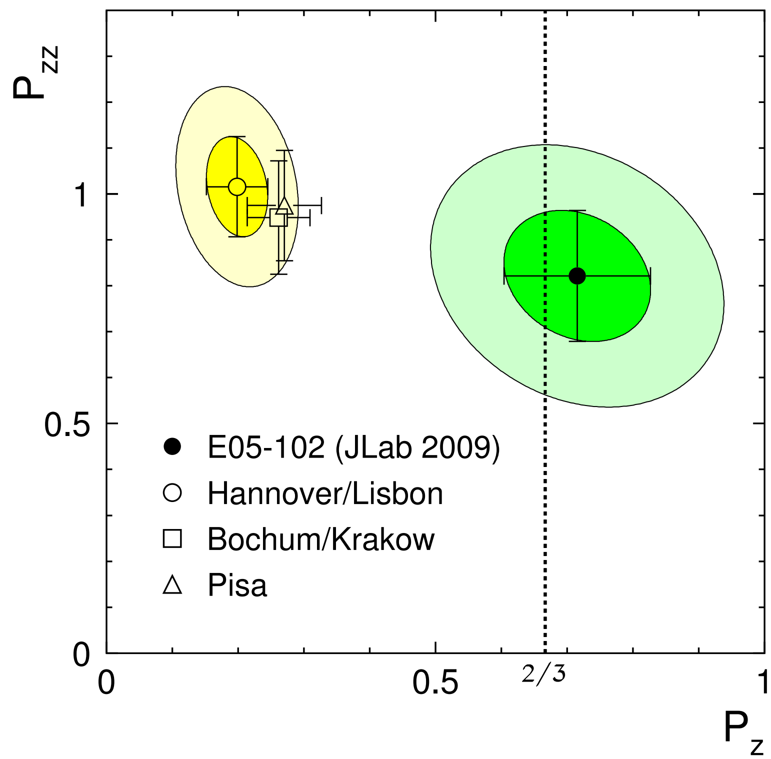
The data sets are here, but ... we still don't know [well enough]:

- the true nature of the ^{3}He ground state (S vs. D vs. S');
- the effective neutron (deuteron, proton?) polarization in ^{3}He.

It's not that we haven't tried ⟶

Toy model 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 $P_z = \langle I_z\rangle_{^3\mathrm{He}} = \frac{2}{3}$, $P_{zz} = \langle 3I_z^2 - 2\rangle_{^3\mathrm{He}} = 0$



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Perspective cont'd

- Polarized $^3\vec{\mathrm{He}}$ target (e.g. at CLAS12) still has work to do!
- $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{d})$ remains "golden channel" as 2bbu/3bbu separation likely impossible at 12 GeV
- Asymmetries hint at zero-crossings at high p_{miss}
  Indication of D-state kicking in as in the deuteron case?
  $\Longrightarrow$ Extend measurements to higher p_{miss}
- Failure of theories away from the QE peak (dip and above)
  Could be due to anything: tails of Δ, MEC, FSI, 3NF.
  $\Longrightarrow$ Measure at several Q^2 to capture appropriate evolution
- Still unable to quantify the role of ground-state WF components
  $\Longrightarrow$ Need calculations that will be able to tune or switch on/off individual components ... which is a problem $\longrightarrow$
  $\Longrightarrow$ Need calculations capable of handling high(er) energies

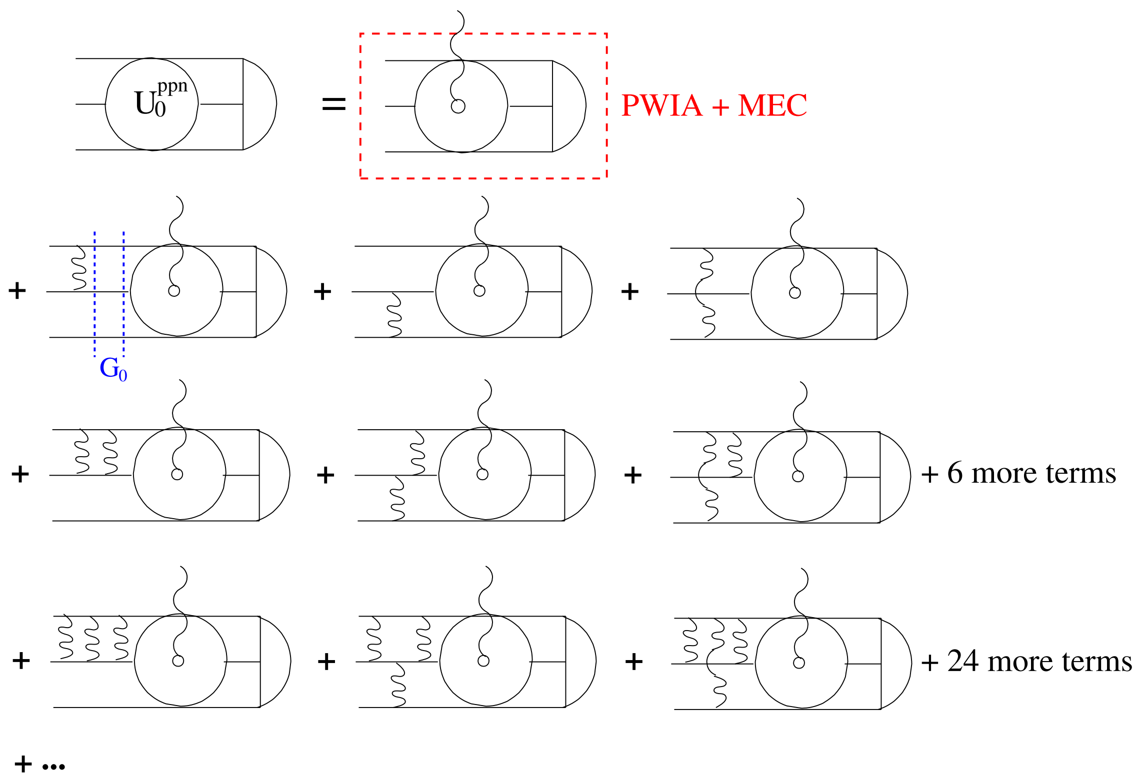
- Similar show-stoppers with high-Q^2 single-spin asymmetries etc.

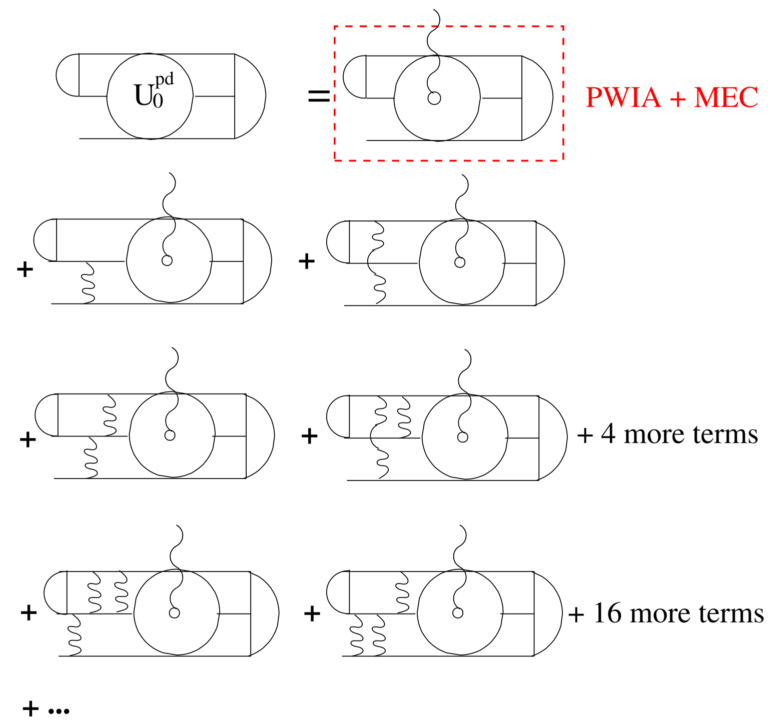
Strange final slide: Faddeev calculations

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

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

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





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This is it ...


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