Kinematics of 2N/3N knock-out mechanism

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Motivation

The starting point: plots from Fomin et al paper shown by Wim Cosyn during his seminar:

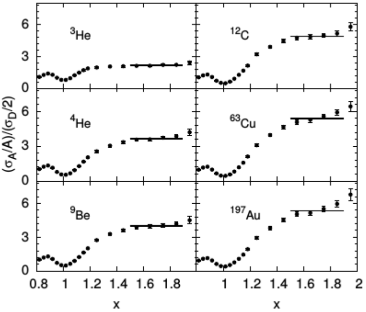


FIG. 2: Per-nucleon cross section ratios vs x at θ_e=18°.

- inclusive data
- ratio wrt deuteron
- plateau is claimed to tell us about SRC pairs

What is going on?

Fomin et al. (JLab Hall C), PRL108 092502

Kinematics of inclusive electron nucleon/nucleus scattering

We can choose among a variety of kinematic variables.
Initial and final state electron: $k^\mu = (E, \vec{k})$, $k'^\mu = (E', \vec{k}')$.

- energy transfer $\omega = E - E'$,
- momentum transfer $|\vec{q}| = |\vec{k} - \vec{k}'|$,
- 4-momentum transfer $Q^2 = \vec{q}^2 - \omega^2 \geq 0$,
- Bjorken variable $x = \frac{Q^2}{2M\omega}$,
- ...

Any two of them may be chosen as independent.

Kinematics of inclusive electron nucleon/nucleus scattering

Interesting properties of x:

- in the case of free nucleon scattering $x \leq 1$:

Invariant hadronic mass W:

$$W^2 = (M + \omega)^2 - q^2 \geq M^2 \quad \Rightarrow \quad 2M\omega \geq Q^2 \quad \Rightarrow \quad x \leq 1$$

- $x = 1 \quad \Leftrightarrow \quad$ elastic process
- $x < 1 \quad \Leftrightarrow \quad$ inelastic process

In the case of nucleus target, we may have $x > 1$.

How to *see* two-body current mechanism in the inclusive data?

The strategy

- identify kinematical region where one-body mechanism is impossible
- look for non-zero cross section in this region.

Technical details:

- use ω, q variables,
- consider Fermi motion and (constant) binding energy B
- identify a region in ω, q such that it is impossible to get $W \geq M$.

How to *see* two-body current mechanism in the inclusive data?

- The most favorable (highest W) configuration is that of antiparallel $\vec{q}$ and $\vec{p}$ (target nucleon momentum)
- $W_{max}^2 = (\tilde{\omega} + E_p)^2 - (q-p)^2 < M^2$, $E_p = \sqrt{M^2 + p^2}$, $\tilde{\omega} = \omega - B$,
- in local Fermi gas model maximal nucleon momentum in ^{12}C is ~ 270 MeV/c
- look for a maximum of $f(p) = (\tilde{\omega} + E_p)^2 - (q-p)^2$ in the region $p \in [0, 270]$ MeV/c.

How to *see* two-body current mechanism in the inclusive data?

An easy task:

- derivative $f'(p) = 2(\tilde{\omega} + E_p)\frac{p}{E_p} + 2(q - p)$
- for $q > p$ always positive
- in the whole region we solve $(\tilde{\omega} + E_p)\frac{p}{E_p} + (q - p) = 0$

$$p(\tilde{\omega} + E_p) = (p - q)E_p \Rightarrow p\tilde{\omega} = -qE_p$$

- $f(p)$ is monotonic function of p
- the maximal value is at p_F and the condition is $(\tilde{\omega} + E_F)^2 - (q - p_F)^2 < M^2$ i.e.

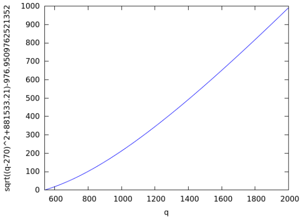
$$\boxed{\tilde{\omega} < \sqrt{M^2 + (q - p_F)^2} - E_F}.$$

How to *see* two-body current mechanism in the inclusive data?

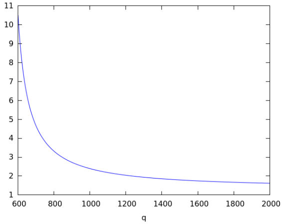
How to express this condition in terms of Bjorken x variable?
At fixed q:

$$x(\omega) = \frac{q^2 - \omega^2}{2M\omega}, \qquad x'(\omega) = \frac{-2M\omega^2 - 2Mq}{2M^2\omega^2} < 0,$$

and the minimal value of x is at the maximal ω.



$\omega_{max}(q)$



$x(q, \omega_{max}(q))$

It is clear that in the inclusive data a signal of the two-body mechanism can only be found at large Bjorken x.

How to *see* two-body current mechanism in the inclusive data?

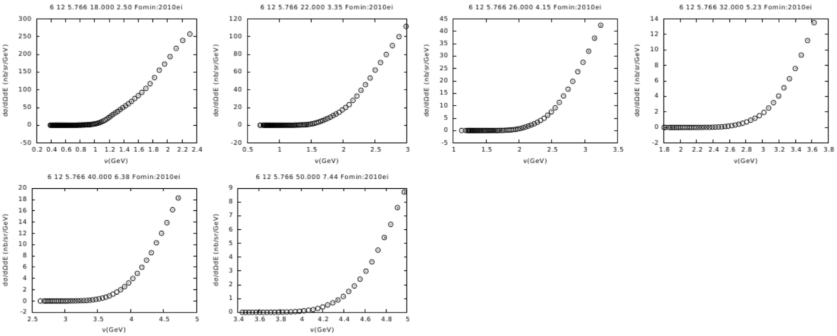
By digging in the electron scattering data e.g. on ^{12}C one can find non-zero cross section in the one-body forbidden region.

In particular we look at $E = 5.766$ GeV results at various angles.

E [GeV]	Θ (deg)	QE peak (GeV)	thr 1-body (GeV)	data (GeV)
5.766	50	3.96	3.53	≥ 3.44
5.766	40	3.4	2.92	≥ 2.63
5.766	32	2.78	2.28	≥ 1.8
5.766	26	2.21	1.72	≥ 1.13
5.766	22	1.78	1.32	≥ 0.7
5.766	18	1.33	0.925	≥ 0.39

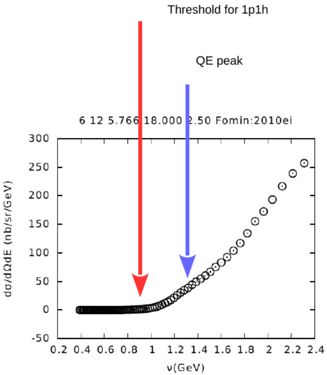
The numbers in in last three columns are values of energy transfer.

How to *see* two-body current mechanism in the inclusive data?



http://faculty.virginia.edu/qes-archive/index.html

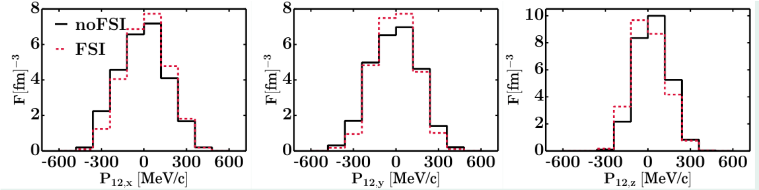
How to *see* two-body current mechanism in the inclusive data?



Constraints for 2p-2h mechanism

If 1p-1h mechanism is kinematically forbidden - what about 2p-2h?

- assume interaction occurs on correlated nucleon pairs
- nucleons move back to back in CM frame
- CM moves with a maximal momentum of $p_{max} \sim 300$ MeV/c



We treat correlated pairs as *quasi-deuterons*.

Constraints for 2p-2h mechanism

The same arguments are applied. We must be unable to get invariant hadronic mass $W^2 > 4M^2$.
Again, the most favorable configuration is that of antiparallel momentum transfer and *quasi-deuteron* momenta.
The condition is

$$\max\left((\tilde{\tilde{\omega}} + \tilde{E}_p)^2 - (p - q)^2\right) \leq 4M^2$$

with

$$\tilde{\tilde{\omega}} = \omega - 2B, \qquad \tilde{E}_p = \sqrt{(2M)^2 + p^2}.$$

In the same way as before we get

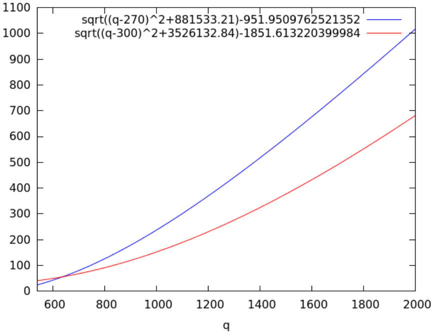
$$\boxed{\tilde{\tilde{\omega}} < \sqrt{4M^2 + (q - p_{max})^2} - \sqrt{4M^2 + p_{max}^2}}.$$

Constraints for 2p-2h mechanism

When we compare both conditions

$$\omega < \sqrt{M^2 + (q - p_F)^2} - E_F + B.$$

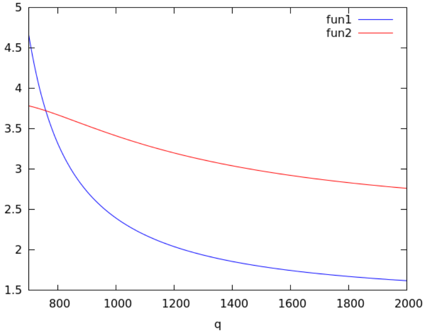
$$\omega < \sqrt{4M^2 + (q - p_{max})^2} - \sqrt{4M^2 + p_{max}^2} + 2B.$$



There is a kinematical region where 1p-1h is impossible but 2p-2h is allowed.

Constraints for 2p-2h mechanism

1p-1h and 2p-2h regions in terms of Bjorken x:



There is a lot of room for 2p-2h.

Next steps

Two natural questions:

- is that possible to identify neutrino events in 1p-1h forbidden region?
- what happens at even smaller transfers of energy?

Next steps (1)

For neutrinos the obvious problem is that the beam is wideband

- off-line trick does not improve situation because we are looking for a kinemtical veto
- most favorable situation: MinibooNE beam extending roughly to 3GeV (well there is still a small tail above, but we neglect it).

Next steps (1)

$\cos\theta_\mu$ \ T_μ (GeV)	0.2,0.3	0.3,0.4	0.4,0.5	0.5,0.6	0.6,0.7	0.7,0.8	0.8,0.9	0.9,1.0	1.0,1.1	1.1,1.2	1.2,1.3	1.3,1.4	1.4,1.5	1.5,1.6	1.6,1.7	1.7,1.8	1.8,1.9	1.9,2.0
+0.9,+1.0	190.0	326.5	539.2	901.8	1288	1633	1857	1874	1803	1636	1354	1047	794.0	687.9	494.3	372.5	278.3	227.4
+0.8,+0.9	401.9	780.6	1258	1714	2084	2100	2035	1620	1118	783.6	451.9	239.4	116.4	73.07	41.67	36.55	—	—
+0.7,+0.8	553.6	981.1	1501	1884	1847	1629	1203	723.8	359.8	156.2	66.90	26.87	1.527	19.50	—	—	—	—
+0.6,+0.7	681.9	1222	1546	1738	1365	909.6	526.7	222.8	81.65	35.61	11.36	0.131	—	—	—	—	—	—
+0.5,+0.6	765.6	1233	1495	1289	872.2	392.3	157.5	49.23	9.241	1.229	4.162	—	—	—	—	—	—	—
+0.4,+0.5	871.9	1279	1301	989.9	469.1	147.4	45.02	12.44	1.012	—	—	—	—	—	—	—	—	—
+0.3,+0.4	910.2	1157	1054	628.8	231.0	57.95	10.69	—	—	—	—	—	—	—	—	—	—	—
+0.2,+0.3	992.3	1148	850.0	394.4	105.0	16.96	10.93	—	—	—	—	—	—	—	—	—	—	—
+0.1,+0.2	1007	970.2	547.9	201.5	36.51	0.844	—	—	—	—	—	—	—	—	—	—	—	—
0.0,+0.1	1003	813.1	404.9	92.93	11.63	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.1, 0.0	919.3	686.6	272.3	40.63	2.176	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.2,-0.1	891.8	503.3	134.7	10.92	0.071	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.3,-0.2	857.5	401.6	79.10	1.947	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.4,-0.3	778.1	292.1	33.69	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.5,-0.4	692.3	202.2	17.42	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.6,-0.5	600.2	135.2	3.624	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.7,-0.6	497.6	85.80	0.164	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.8,-0.7	418.3	44.84	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.9,-0.8	348.7	25.82	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-1.0,-0.9	289.2	15.18	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

TABLE VI: The MiniBooNE ν_μ CCQE flux-integrated double differential cross section in units of 10^{-41} cm^2/GeV in 0.1 GeV bins of T_μ (columns) and 0.1 bins of $\cos\theta_\mu$ (rows).

Which bins are kinematically forbidden for 1p-1h?

Next steps (1)

$\cos\theta_\mu$ \ T_μ(GeV)	0.2,0.3	0.3,0.4	0.4,0.5	0.5,0.6	0.6,0.7	0.7,0.8	0.8,0.9	0.9,1.0	1.0,1.1	1.1,1.2	1.2,1.3	1.3,1.4	1.4,1.5	1.5,1.6	1.6,1.7	1.7,1.8	1.8,1.9	1.9,2.0
+0.9,+1.0	190.0	326.5	539.2	901.8	1288	1633	1857	1874	1803	1636	1354	1047	794.0	687.9	494.3	372.5	278.3	227.4
+0.8,+0.9	401.9	780.6	1258	1714	2084	2100	2035	1620	1118	783.6	451.9	239.4	116.4	73.07	41.67	36.55	—	—
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+0.6,+0.7	681.9	1222	1546	1738	1365	909.6	526.7	222.8	81.65	35.61	11.36	0.131	—	—				—
+0.5,+0.6	765.6	1233	1495	1289	872.2	392.3	157.5	49.23	9.241	1.229	4.162	—			—	—	—	—
+0.4,+0.5	871.9	1279	1301	989.9	469.1	147.4	45.02	12.44	1.012	—	—		—	—	—	—	—	—
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0.0,+0.1	1003	813.1	404.9	92.93	11.63	—	—	—	—	—	—	—	—	—	—	—	—	—
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-0.7,-0.6	497.6	85.80	0.164		—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.8,-0.7	418.3	44.84	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.9,-0.8	348.7	25.82	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-1.0,-0.9	289.2	15.18	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Forbidden bins are far away from those with non-zero cross section.

Next steps (2)

Look again carefully at the Cosyn seminar plot:

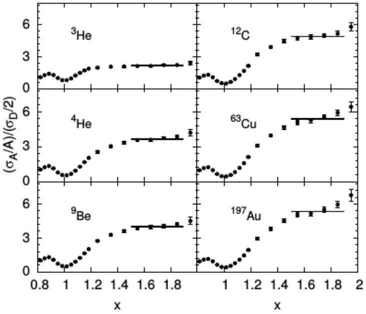


FIG. 2: Per-nucleon cross section ratios vs x at θ_e=18°.

Fomin et al. (JLab Hall C), PRL108 092502

What happens at $x \sim 2$?

Next steps (2)

Cosyn answer is: We are approaching a threshold for deuteron 2p-2h mechanism; the denominator goes to zero. In fact $M \to 2M$!

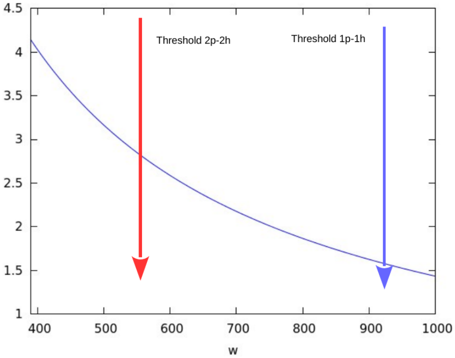
We add an extra column in our table:

E [GeV]	Θ (deg)	QE peak	thr 1p-1h	thr 2p-2h	data (GeV)
5.766	50	3.96	3.53	2.63	≥ 3.44
5.766	40	3.4	2.92	2.05	≥ 2.63
5.766	32	2.78	2.28	1.45	≥ 1.8
5.766	26	2.21	1.72	1.05	≥ 1.13
5.766	22	1.78	1.32	0.76	≥ 0.7
5.766	18	1.33	0.925	0.555	≥ 0.39

Great! For 18^o we are sensitive to mechanism beyond 2p-2h! 3N correlated triple?!

Next steps (2)

Final look. Fomin 18° data from the Bjorken x point of view.



In fact, 1p-1h forbidden region starts at $x \sim 1.5$. For SRC pairs threshold is moved because pairs are moving.

At larger x one can investigate $\frac{\sigma(A)}{\sigma(^3\mathrm{He})}$ searching for 3N correlated configurations.

Conclusions

Kinematical studies can be very instructive.