A Polarimeter for Light Ions

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OUTLINE

- Need a source of polarized up and down quarks to probe spin structure
- Polarized down quarks are available in polarized Deuterons and Helium-3
- The hadron polarimeters should operate over a very wide energy range
  - from a few tens of GeV to several hundreds of GeV per nucleon
  - physics program requires precision polarimetry of a few per cent
- Polarimeter calibration is frequently required at each energy and store
- The measurement of beam polarization profiles and lifetimes is needed

PROTON POLARIMETERS

- The p-C polarimeter uses an ultra thin carbon ribbon with a 2 MHZ event rate taken for a few minutes every few hours

- It provides an online monitor, a fill by fill beam polarization measurement, polarization profiles, and requires calibration from H-Jet data

A polarized atomic hydrogen gas jet target self-calibrates the polarized proton beam by measuring a precise analyzing power A_{N} at each energy

- The H-jet polarimeter operates continuously with around a 90 Hz event rate providing a polarization known to a few per cent every fill

- It secures an absolute proton beam polarization measurement and additionally calibrates the high energy proton carbon polarimeter

A polarimeter requires a process with nonvanishing high energy polarization

- Spin one photon exchange suggests the Primakoff or a Coulomb effect
- Deuteron scattering reaches only $-0.3\,\%$ asymmetry in the CNI region
- Helium-3 scattering reaches about $-3\,\%$ asymmetry in the CNI region

A light ion of mass m, charge Ze, anomalous mag moment κ scattering elastically off a charge $Z'e$ has an asymmetry that involves an interference

$$2\,\mathrm{Im}\left[\frac{Z\,Z'}{137\,t} + (\rho + i)\frac{\sigma_{\rm tot}}{8\,\pi}\right]^{*}\frac{\kappa\sqrt{-t}}{2\,m_{\rm p}}\left[\frac{Z\,Z'}{137\,t} + (R_{\rm S} + i\,I_{\rm S})\frac{\sigma_{\rm tot}}{8\,\pi}\right]$$

of helicity nonflip & flip amplitudes with electromagnetic & hadronic parts.

Including the spin averaged denominator, the asymmetry is proportional to

$$A_{\mathrm{N}} \;\propto\; \frac{\sqrt{x}}{x^2+3}\,, \qquad x \;=\; \frac{t_{\mathrm{e}}}{t}\,, \qquad t_{\mathrm{e}} \;=\; -\,\frac{\sqrt{3}\;Z\,Z'}{14\;\sigma_{\mathrm{tot}}(\mathrm{mb})}\;\;(\mathrm{GeV}/c)^2$$

the extremum value of which occurs at $x = 1$, that is, at transfer $t \;=\; t_{\mathrm{e}}$

- The optimum value of A_{N} varies slowly with energy s as $1/\sqrt{\sigma_{\mathrm{tot}}(s)}$
- It is a maximum or minimum depending on the sign of the moment κ

$$A_{\mathrm{N}}^{\mathrm{opt}} \;=\; \frac{\kappa}{4m_{\mathrm{p}}}\sqrt{-3\,t_{\mathrm{e}}}\;, \qquad \kappa \;=\; \frac{\mu}{Z} \,-\, \frac{m_{\mathrm{p}}}{m}$$

For protons κ is 1.793, for deuterons $\kappa = -0.143$ and κ is -1.398 for He-3

Hadronic helicity flip amplitudes and two photon exchange are ignored here

DEUTERON CARBON POLARIMETER

If the ratio between helicity flip and non flip hadronic amplitudes is denoted by τ, the analyzing power for d C elastic scattering may be written as

$$\frac{A_N}{4\pi}\frac{d\sigma}{dt} = \frac{\sqrt{-t}}{m}\,2\,\mathrm{Im}\,\left(F + F^{\,\mathrm{em}}\right)^* \left[\tau F + \left(\frac{\mu_d}{2} - \frac{m_p}{m}\right) F^{\,\mathrm{em}}\right]$$

where $F(s,t)$ refers to the hadronic part of Deuteron Carbon scattering The d C$\rightarrow$d C amplitude was obtained by Trueman using a Glauber formula

NHB & T L Trueman, SPIN 2004, Trieste, 706

The figures indicate the expected values of the analyzing power for d-C elastic scattering — with two complex values of the helicity flip parameter τ

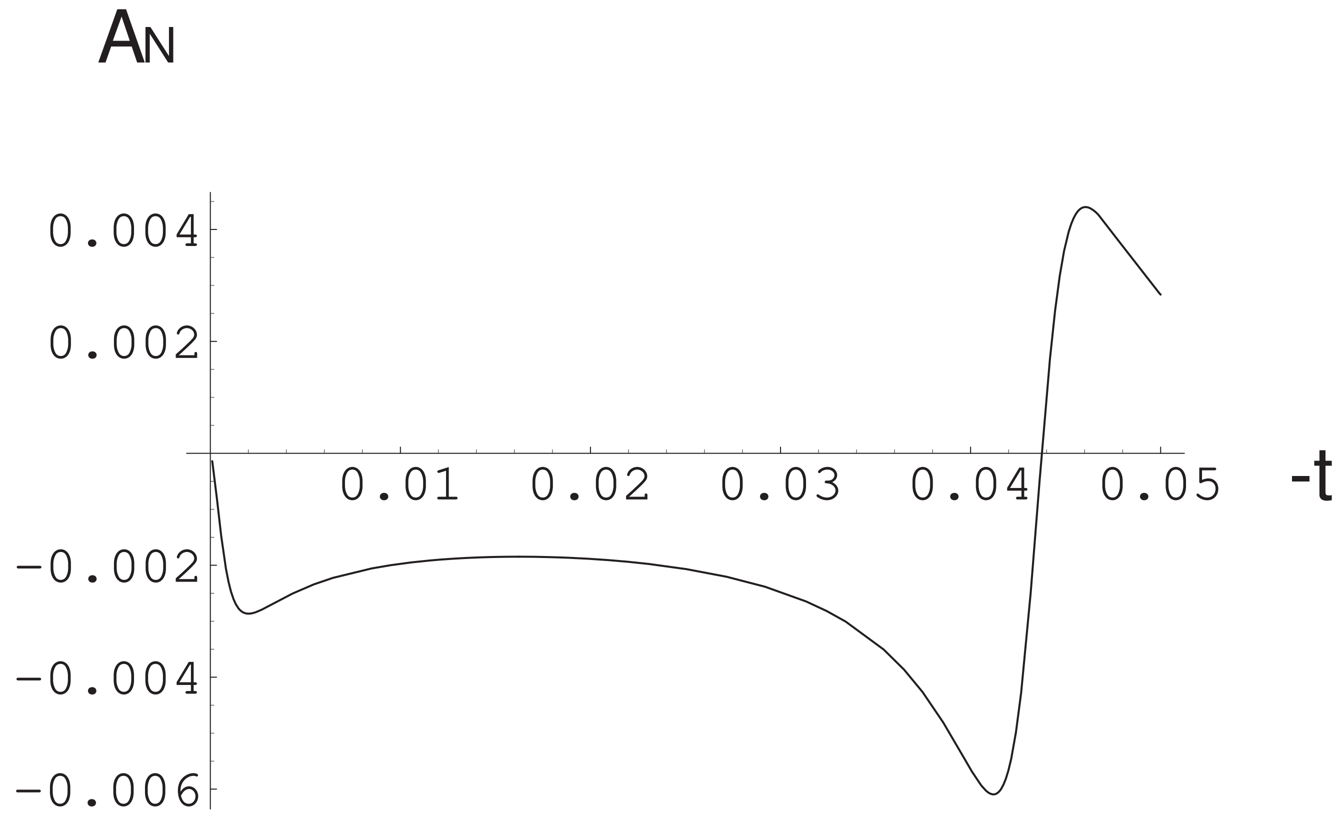

Figure 1: *The d-C analyzing power with zero hadronic flip amplitude* $\tau = 0$.

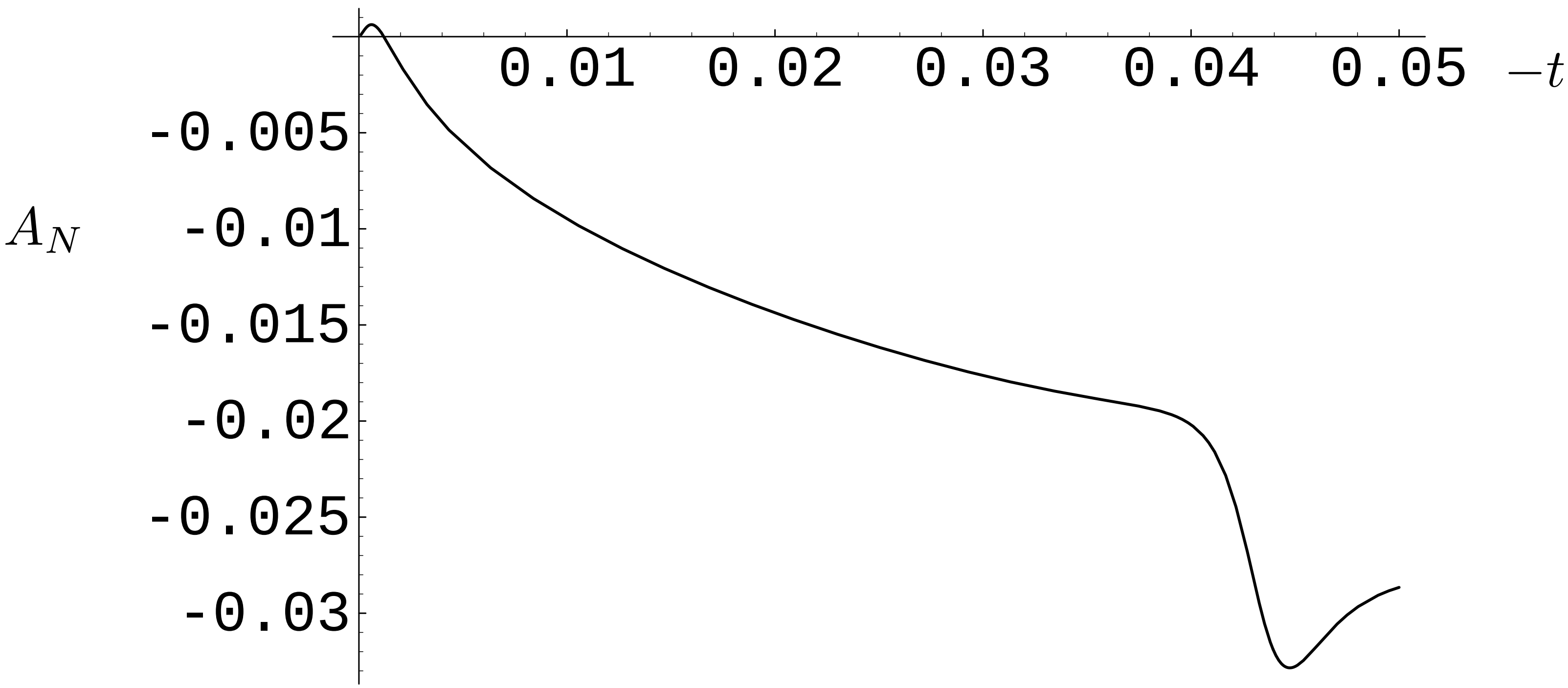

Figure 2: *The d-C analyzing power with flip factor* $\tau = -0.130 - 0.053\,i$

Quantities related to proton carbon collisions may be compared to those of the more familiar proton proton case with the same incident hadron, viz,

$$\frac{t_{\mathrm{e}}^{\mathrm{pC}}}{t_{\mathrm{e}}^{\mathrm{pp}}} = \frac{6\,\sigma_{\mathrm{tot}}^{\mathrm{pp}}}{\sigma_{\mathrm{tot}}^{\mathrm{pC}}} \approx 0.74\,, \qquad \frac{A_{\mathrm{N}}^{\mathrm{pC}}}{A_{\mathrm{N}}^{\mathrm{pp}}} = \left(\frac{t_{\mathrm{e}}^{\mathrm{pC}}}{t_{\mathrm{e}}^{\mathrm{pp}}}\right)^{1/2} \approx 0.86$$

With distinct incident hadrons, by contrast, Helium-3 carbon and proton carbon scattering have extremum momentum transfer and asymmetry ratios

$$\frac{t_{\mathrm{e}}^{\mathrm{hC}}}{t_{\mathrm{e}}^{\mathrm{pC}}} = \frac{2\,\sigma_{\mathrm{tot}}^{\mathrm{pC}}}{\sigma_{\mathrm{tot}}^{\mathrm{hC}}} \approx 1.0\,, \qquad \frac{A_{\mathrm{N}}^{\mathrm{hC}}}{A_{\mathrm{N}}^{\mathrm{pC}}} = \frac{\kappa_{\mathrm{h}}}{\kappa_{\mathrm{p}}}\left(\frac{t_{\mathrm{e}}^{\mathrm{hC}}}{t_{\mathrm{e}}^{\mathrm{pC}}}\right)^{1/2} \approx -0.78$$

The same would be approximately true if the target carbon particle C here were replaced throughout by another ion such as a proton p or a helion h.

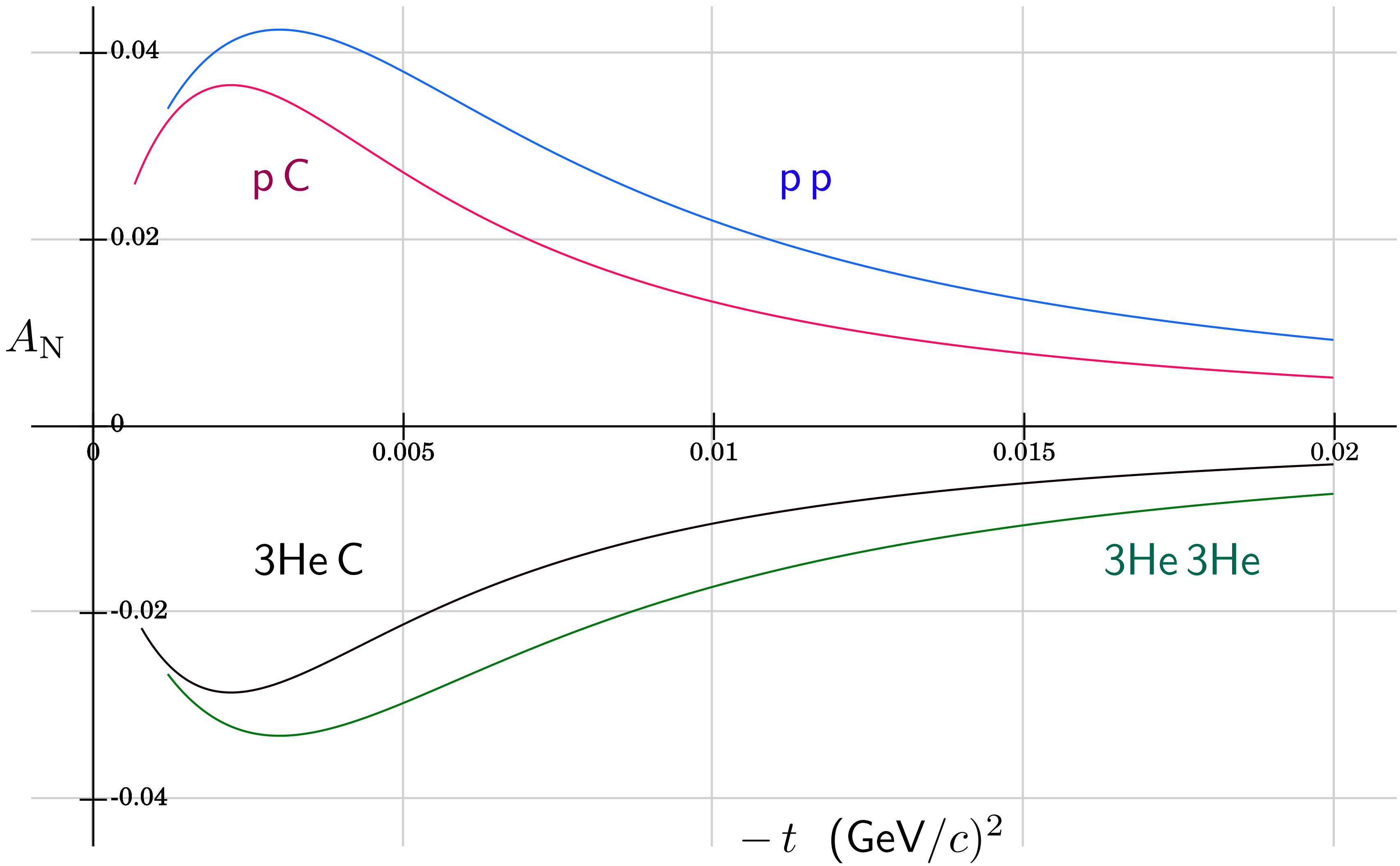

Figure 3: Analyzing power $A_{\rm N}$ versus invariant momentum transfer (-t) in (GeV$/c)^2$ for (1) p p and p h scattering, (2) p C scattering, (3) h C scattering, (4) h h and h p scattering

The extremum value of t has first order corrections in the Bethe phase δ, the hadronic non-flip real part ratio ρ, and the helicity-flip ratio $R_{\mathrm{S}} + iI_{\mathrm{S}}$

$$t_{\mathrm{e}} \ : \quad 1 \ - \ (\rho + \delta)/\sqrt{3} \ - \ (R_{\mathrm{S}} \ - \ \rho\, I_{\mathrm{S}})\, 4/\sqrt{3}$$

Another factor with small items δ, ρ, R, I, multiplies the extremum of A_{N}

$$A_{\mathrm{N}} \ : \quad 1 \ + \ (\rho + \delta)\sqrt{3}\,/\,2 \ - \ (\sqrt{3}\, R_{\mathrm{S}} \ + \ I_{\mathrm{S}})$$

Glauber corrections provide a further factor that increases from one below extremum to about $1 + 0.01\,(t - t_{\mathrm{e}})\,/\,t_{\mathrm{e}}$ for Helium-3 and carbon targets.

B Z Kopeliovich and T L Trueman, Phys Rev D **64** (2001) 034004

The single helicity flip p p parameter r_5 has been shown to be small. Hopefully this is true for other hadronic processes. A. Poblaguev, SPIN 2018

Hadronic spin flip and Coulomb phase effects have been treated in detail in
NB, Kopeliovich, Leader, Soffer, Trueman, Phys Rev D59 (1999) 114010

The pp2pp experiment at STAR (BNL) has shown that the elastic pp

- hadronic single helicity-flip amplitude is small at $\sqrt{s} = 200$ GeV
  L. Adamczyk *et al.* [STAR Collaboration], Phys Lett B 719, 62 (2013)

W. W. MacKay has discussed the acceleration of Deuterons and Helium-3
`AIP Conf Proc 980, 191 (2008); https://doi.org/10.1063/1.2888087`

Helium-3 nuclei have been accelerated in the AGS at BNL (Haixin Huang).

The helion carbon cross section at the AGS appears to be twice that for proton carbon scattering, as expected from the factor $A^{2/3} = 3^{2/3} = 2.08$

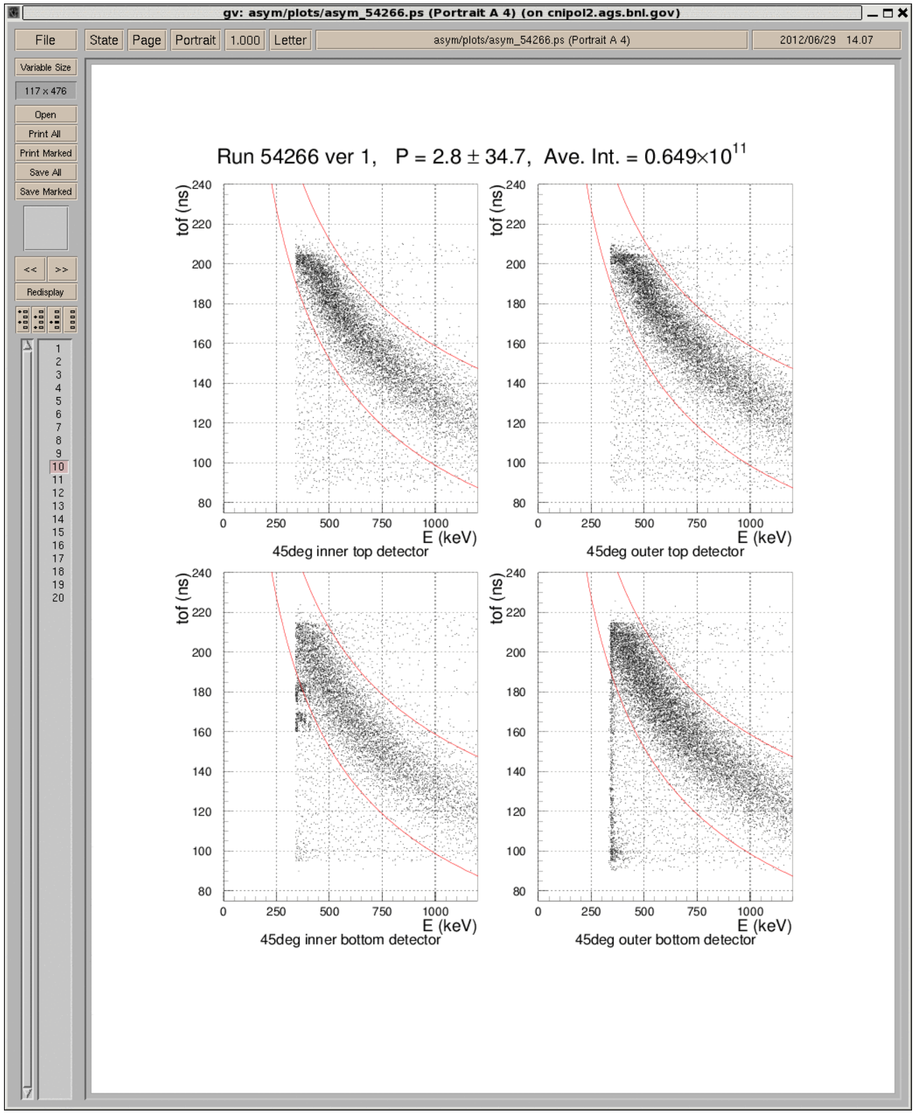

Figure 4: Time of flight of carbon recoils (on y-axis) versus the recoil kinetic energy of Helium-3 (on x-axis) as measured at the AGS. The 3He-C events are double those of p-C.

ELASTIC KINEMATICS

Excited states of the incident mass m, $(+\Delta m)$, are more important than those of the target mass M, $(+\Delta M)$, for laboratory energies E such that

$$E \quad > \quad m\,\Delta m\,/\,\Delta M$$

For pC scattering with $\Delta m = 135$ MeV and $\Delta M = 7.3$ MeV, $E > 17$ GeV
For hC scattering with $\Delta m = 7.7$ MeV and $\Delta M = 7.3$ MeV, $E > \ 3$ GeV.
If P is the laboratory momentum of the incident particle of mass m, the recoil angle $\phi_{\rm el}$ for elastic scattering, measured from a 90 degree point, is

$$\phi_{\rm el} \;\approx\; \frac{E+M}{P}\sqrt{\frac{T}{2\,M}}\,, \qquad \Delta\phi \;\approx\; \frac{m\,\Delta m}{P\,\sqrt{2\,M\,T}}$$

Inelastic collisions occur beyond the angle $\phi_{\rm el} + \Delta\phi$, a function of the recoil kinetic energy T above, where the analyzing power $A_{\rm N}$ may become diluted.

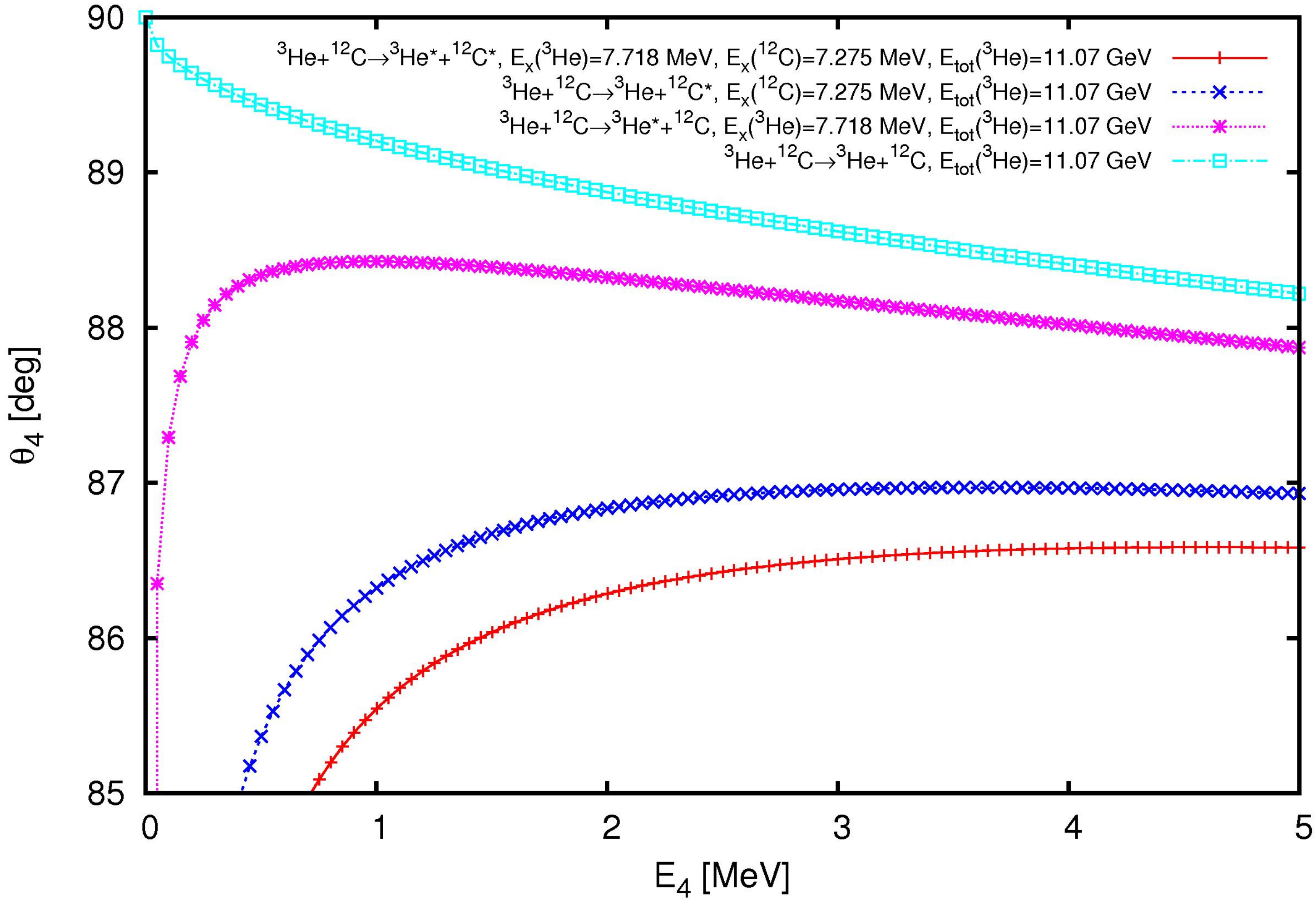

Figure 5: Carbon laboratory recoil angle versus its recoil kinetic energy for an incident helium-3 beam scattering (in)elastically to helion (break-up) or carbon (break-up) or both.

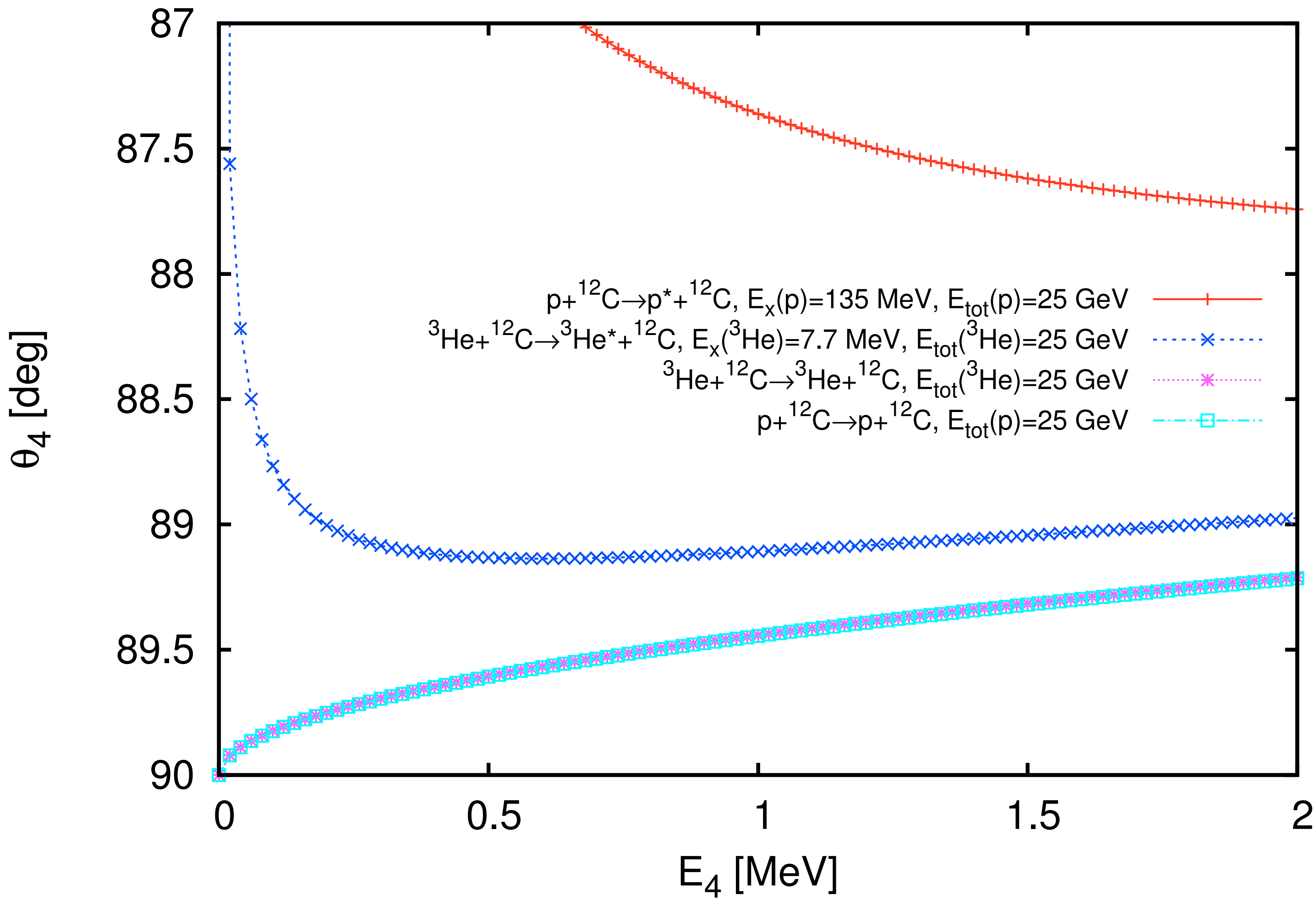

Figure 6: Carbon laboratory recoil angle versus its recoil kinetic energy for a 25 GeV proton scattering to pi-zero, or a 25 GeV helion scattering to break-up, or both elastically.

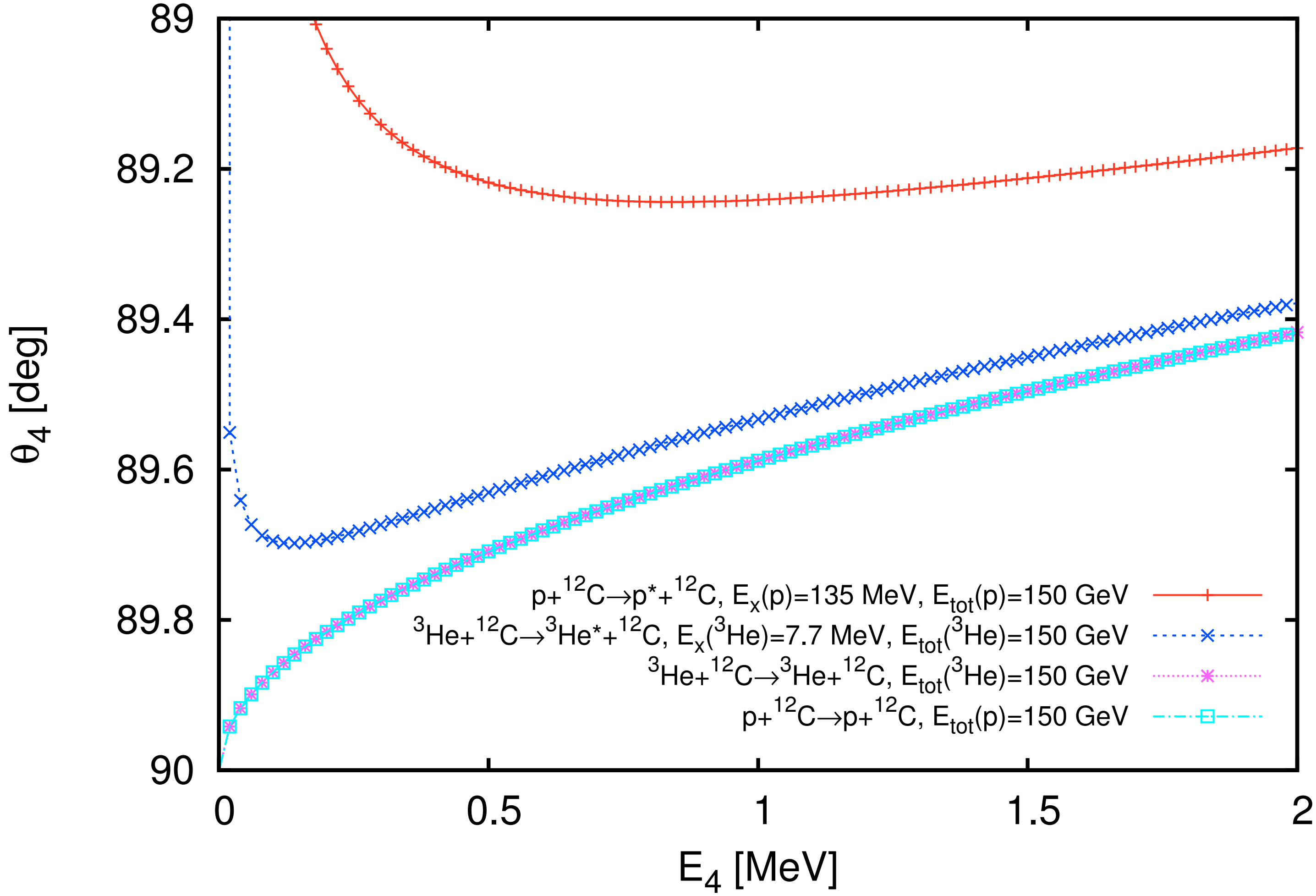

Figure 7: Carbon laboratory recoil angle versus its recoil kinetic energy for a 150 GeV proton scattering to pi-zero, or a 150 GeV helion scattering to break-up, or both elastically.

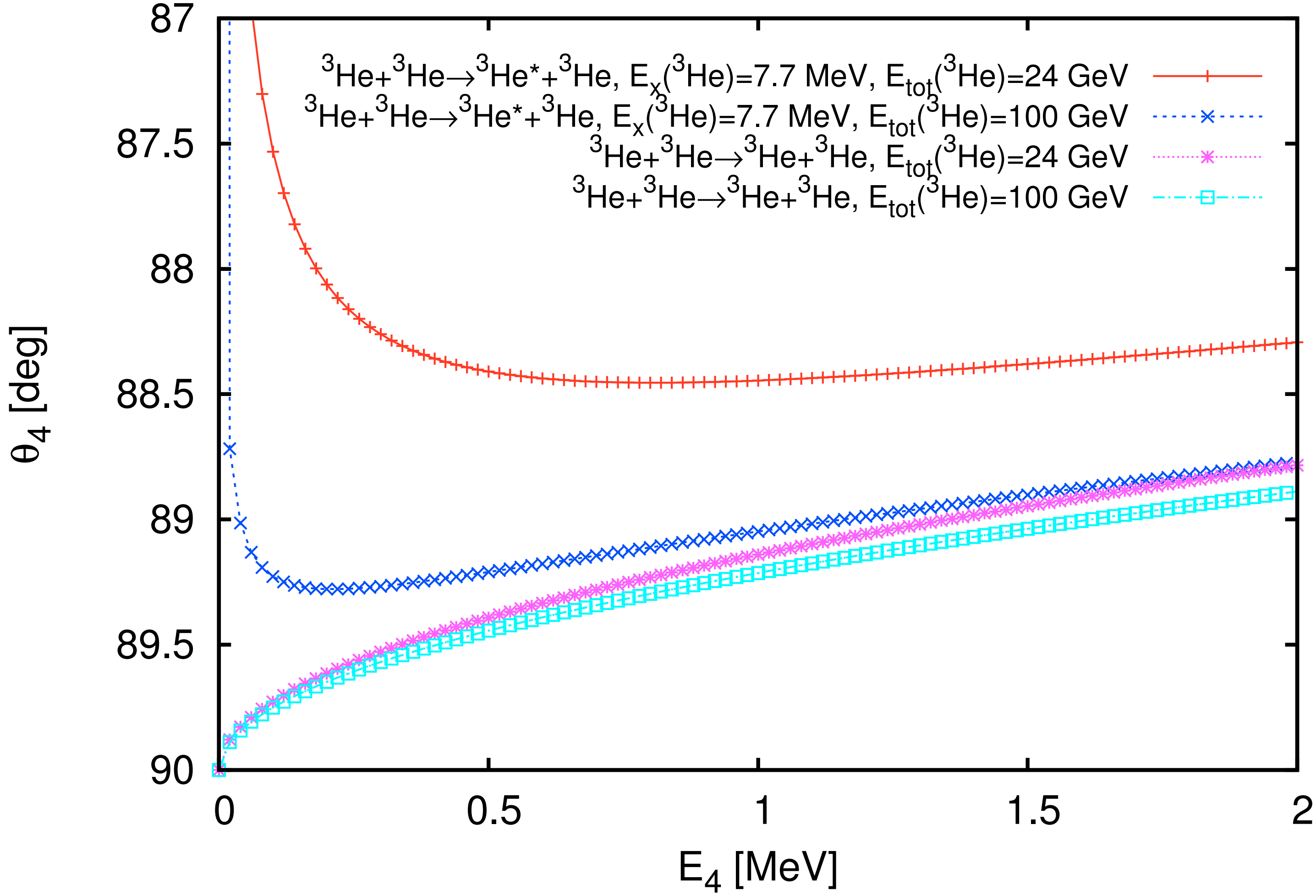

Figure 8: Helion laboratory recoil angle versus its recoil kinetic energy for an incident 24 GeV and 100 GeV helium-3 beam scattering to a break-up state or elastically to a helion.

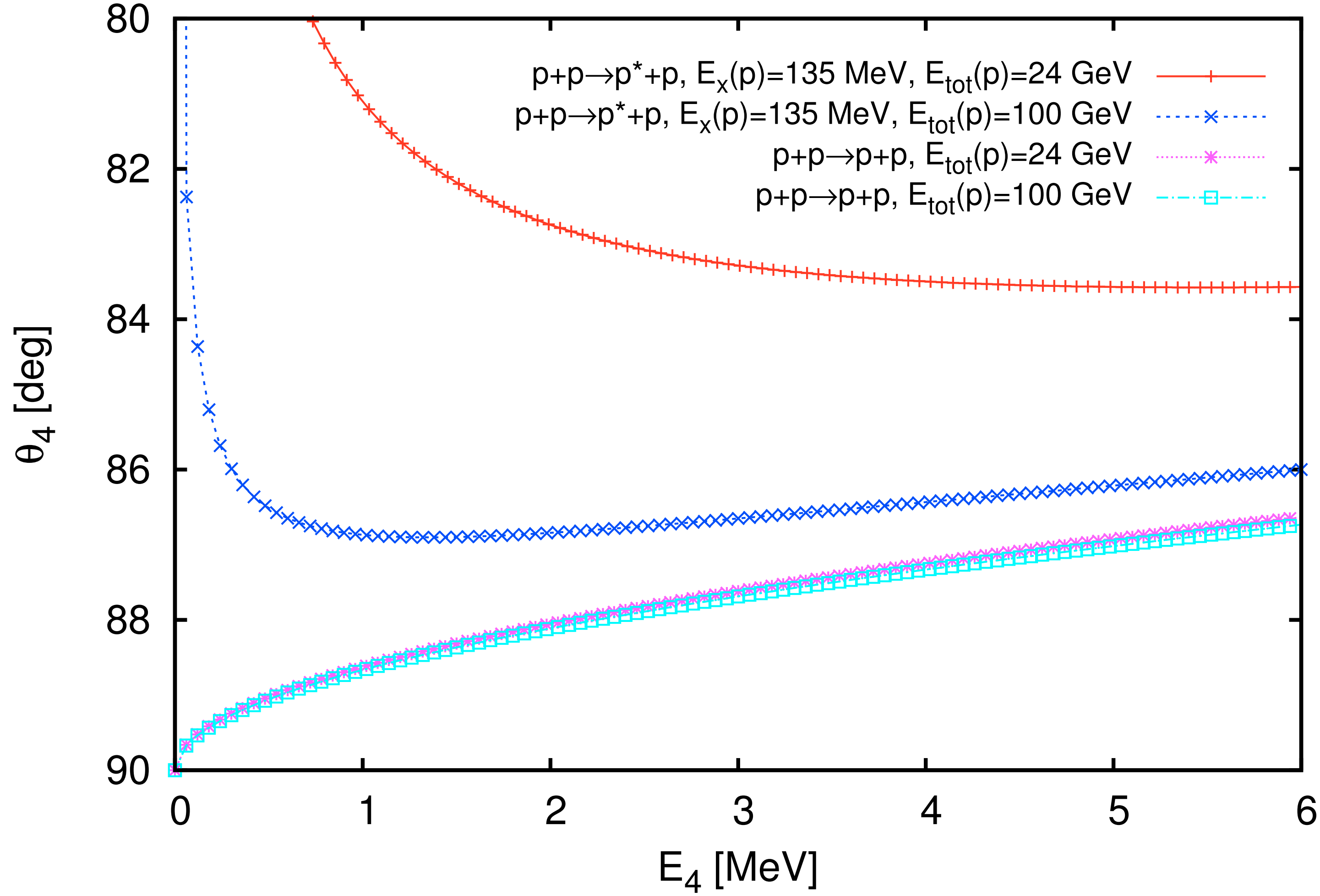

Figure 9: Proton laboratory recoil angle versus its recoil kinetic energy for a 24 GeV and 100 GeV incident proton beam scattering to a proton and pi zero or elastically to a proton.

CONCLUSIONS

Probing the spin structure of hadrons increases the understanding of QCD

- The ^{3}He–C analyzing power is $\approx -78\%$ of $A_{\rm N}$ for p-C in the CNI region
  - The d–C CNI analyzing power is about one tenth of that for ^{3}He–C
- Much more d–C data would be required to achieve good d polarimetry
  - Absolute polarized ion calibration needs the same polarized ion jet
- A study of recoiling ion kinematics may help avoid polarization dilution

There is great potential for studies employing polarized up and down quarks.