

# A Helium-3 polarimeter using electromagnetic interference

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12 September 2013

# OUTLINE

- Need a source of polarized down quarks to probe spin structure
- Polarized neutrons are embedded in polarized helium-3 nuclei
- Fermion polarimeters should operate over a wide energy range
  - protons: from 24 to 250 GeV, 3He: from 15 to 160 GeV/ N
  - the physics program requires precision polarimetry:  $< 5\%$
- Polarimeter calibration is frequently required at each energy
- Beam polarization profiles and lifetime or decay during store
- Measurements of P on the ramp and bunch to bunch emittance

# REQUIREMENTS

- Evaluate the level of high energy helium-3 beam polarization— polarimetry for a high energy He-3 beam may be like that for protons  
Y I Makdisi, SPIN 2012 Symposium, Dubna, Moscow
- Hadronic polarisations tend to vanish at higher collision energies making the measurement of fermion polarization a challenging problem
- A source of neutrons with oriented spin may be available for RHIC and eRHIC in the form of polarized helium-3 nuclei which, being charged, are candidates for electromagnetic hadronic interference polarimetry  
T L Trueman, AIP Conf Proc 980 (2008) 403
- Constraints on leptophobic gauge bosons can follow from using polarized helium-3 at RHIC  
P Taxil et al, Eur Phys J C **24** (2002) 149

# PROTON POLARIMETERS AT RHIC

- 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 20 Hz event rate providing better than 5% statistics in a 6-hour fill at 250 GeV
- It secures an absolute proton beam polarization measurement and additionally calibrates the proton carbon polarimeter for RHIC

A polarimeter requires a process with nonvanishing high energy polarization

- Spin one photon exchange suggests the Primakoff or a Coulomb effect
- Electromagnetic hadronic interference has proved more reliable in tests
- Helium-3 scattering reaches about  $-3\%$  asymmetry in the CNI region

A spin half hadron of mass  $m$ , charge  $Ze$ , magnetic moment  $\mu$  scattering elastically off a charge  $Z'e$  has an asymmetry that involves an interference

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

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

Including the spin averaged denominator, the asymmetry is proportional to

$$A_N \propto \frac{\sqrt{x}}{x^2 + 3}, \quad x = \frac{t_e}{t}, \quad t_e = -\frac{8\pi\sqrt{3}ZZ'}{137\sigma_{\text{tot}}}$$

the extremum value of which occurs at  $x = 1$ , that is, at transfer  $t = t_e$ .

- The optimum value of 3–4 % varies slowly with energy  $s$  as  $1/\sqrt{\sigma_{\text{tot}}(s)}$
- It is either a maximum or minimum depending on the sign of constant  $\kappa$

$$A_N^{\text{opt}} = \frac{\kappa}{4m_p} \sqrt{-3t_e}, \quad \kappa = \frac{\mu}{Z} - \frac{m_p}{m}$$

The value of  $\kappa$  is 1.793 (anomalous  $\mu$ ) for protons and  $-1.398$  for helions. Hadronic helicity flip amplitudes and two photon exchange are ignored here.

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

$$\frac{t_e^{\text{pC}}}{t_e^{\text{pp}}} = \frac{6 \sigma_{\text{tot}}^{\text{pp}}}{\sigma_{\text{tot}}^{\text{pC}}} \approx 0.74, \quad \frac{A_N^{\text{pC}}}{A_N^{\text{pp}}} = \left( \frac{t_e^{\text{pC}}}{t_e^{\text{pp}}} \right)^{1/2} \approx 0.86$$

With distinct incident fermions, by contrast, helion carbon and proton carbon scattering have extremum momentum transfer and asymmetry ratios

$$\frac{t_e^{\text{hC}}}{t_e^{\text{pC}}} = \frac{2 \sigma_{\text{tot}}^{\text{pC}}}{\sigma_{\text{tot}}^{\text{hC}}} \approx 1.0, \quad \frac{A_N^{\text{hC}}}{A_N^{\text{pC}}} = \frac{\kappa_h}{\kappa_p} \left( \frac{t_e^{\text{hC}}}{t_e^{\text{pC}}} \right)^{1/2} \approx -0.78$$

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.

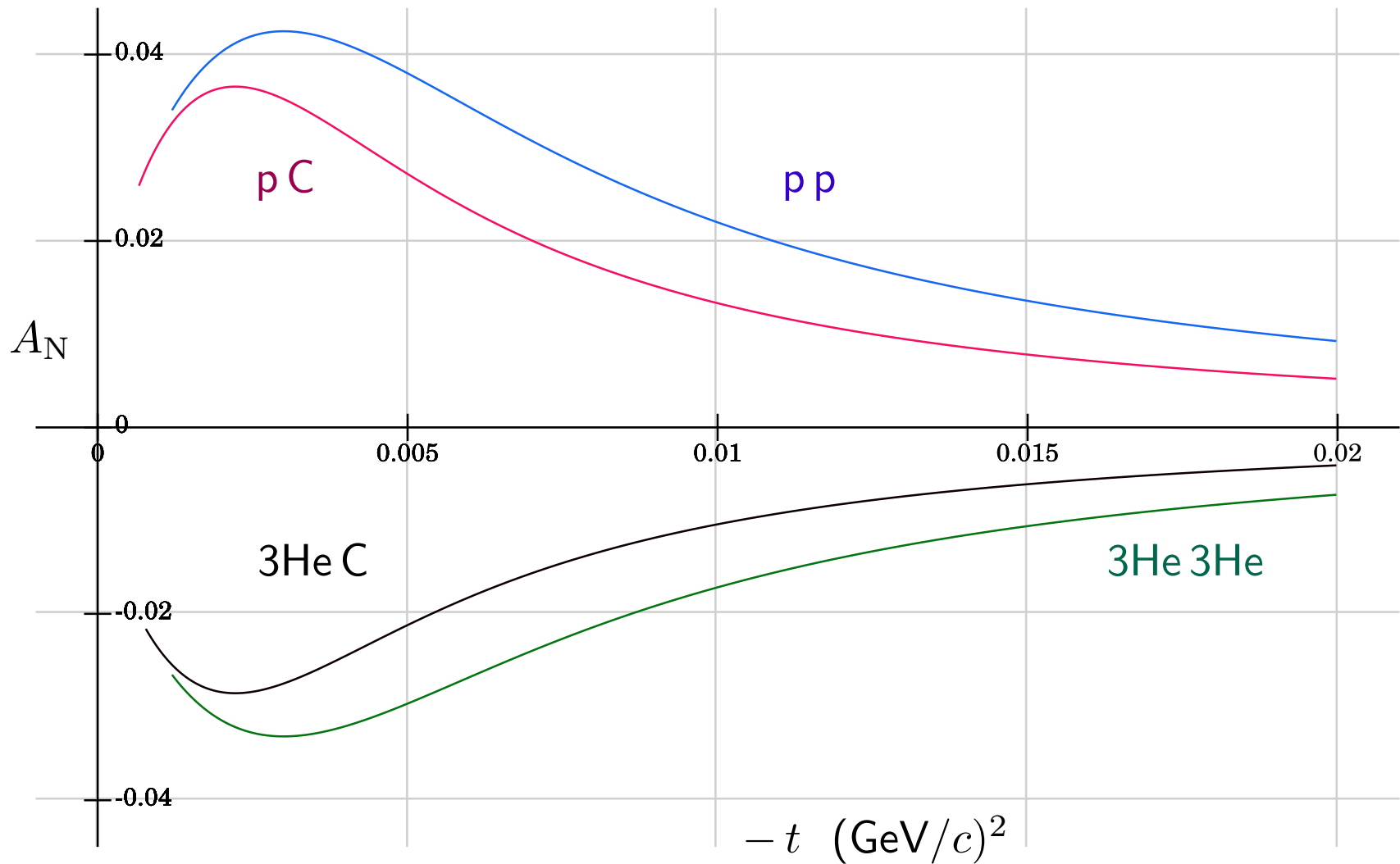


Figure 1: Analyzing power  $A_N$  versus invariant momentum transfer  $(-t)$  in  $(\text{GeV}/c)^2$  for (1) pp and ph scattering, (2) pC scattering, (3) hC scattering, (4) hh and hp scattering



The extremum value of  $t$  has first order corrections in the Bethe phase  $\delta$ , the hadronic non-flip real part ratio  $\rho$ , and the helicity-flip ratio  $R_S + iI_S$

$$t_e : 1 - (\rho + \delta)/\sqrt{3} - (R_S - \rho I_S)4/\sqrt{3}$$

Another factor with small items  $\delta$ ,  $\rho$ ,  $R$ ,  $I$ , multiplies the extremum of  $A_N$

$$A_N : 1 + (\rho + \delta)\sqrt{3}/2 - (\sqrt{3}R_S + I_S)$$

Glauber corrections provide a further factor that increases from one below extremum to about  $1 + 0.01(t - t_e)/t_e$  for helion and carbon targets.

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

The mass ratio & magnetic moments of the proton and helium-3 nuclei are

$$m_h/m_p = 2.99315, \quad \mu_p = 2.79285, \quad \mu_h = -2.1275$$

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 (RHIC 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 discusses helium-3 acceleration in C-A/AP/# 296 (2007)

[http://www.rhichome.bnl.gov/AP/ap\\_notes/ap\\_note\\_296.pdf](http://www.rhichome.bnl.gov/AP/ap_notes/ap_note_296.pdf)

Helium-3 ions 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  $A^{2/3} = 3^{2/3} = 2.08$

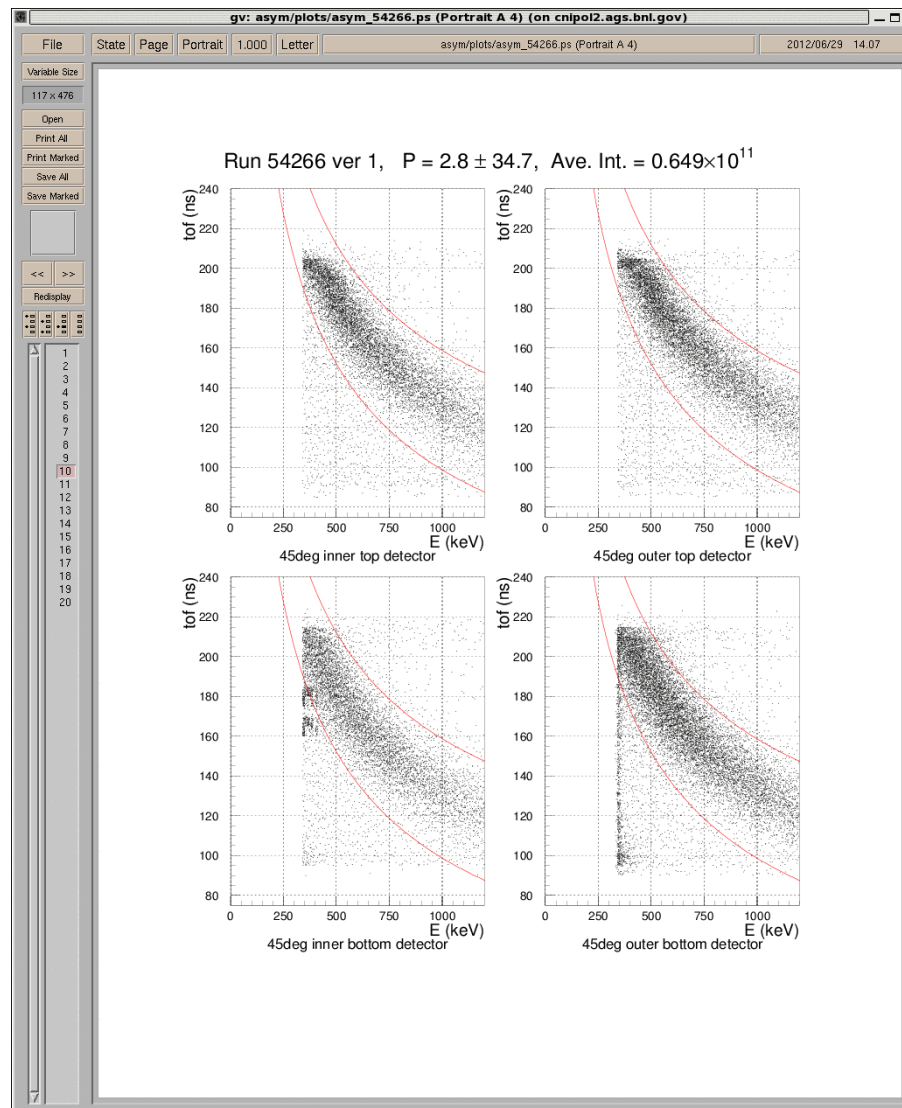


Figure 2: Time of flight of carbon recoils (on  $y$ -axis) versus the recoil kinetic energy of Helium-3 (on  $x$ -axis) as measured at the AGS. The  $3\text{He-C}$  events are double those of  $p\text{-C}$ .

# 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

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

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  $\phi_{\text{el}}$  for elastic scattering, measured from a 90 degree point, is

$$\phi_{\text{el}} \approx \frac{E + M}{P} \sqrt{\frac{T}{2M}}, \quad \Delta\phi \approx \frac{m \Delta m}{P \sqrt{2MT}}$$

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

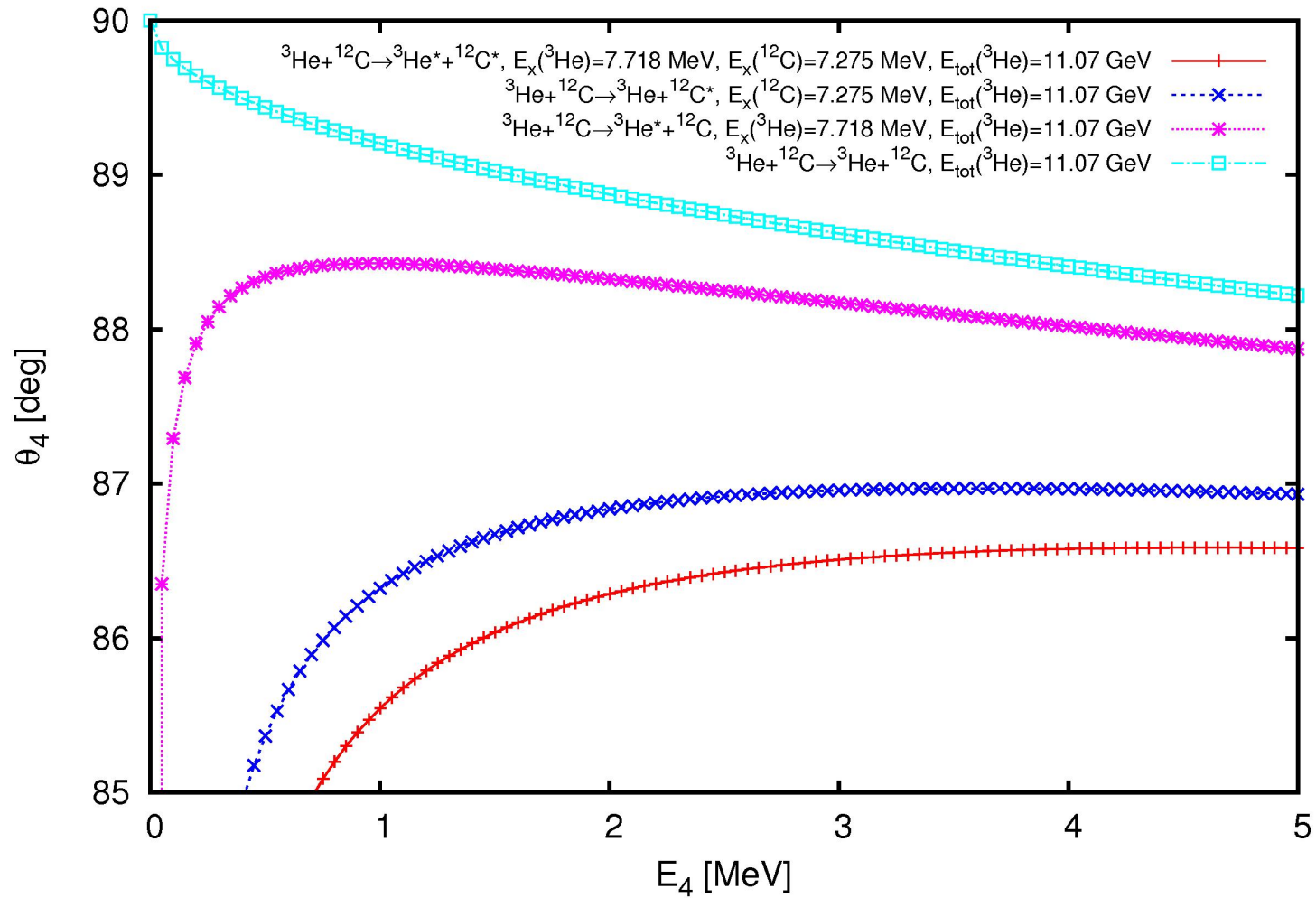


Figure 3: Carbon laboratory recoil angle versus its recoil kinetic energy for an incident helium-3 beam scattering (in)elastically to helion (break-up) or carbon (break-up) or both.

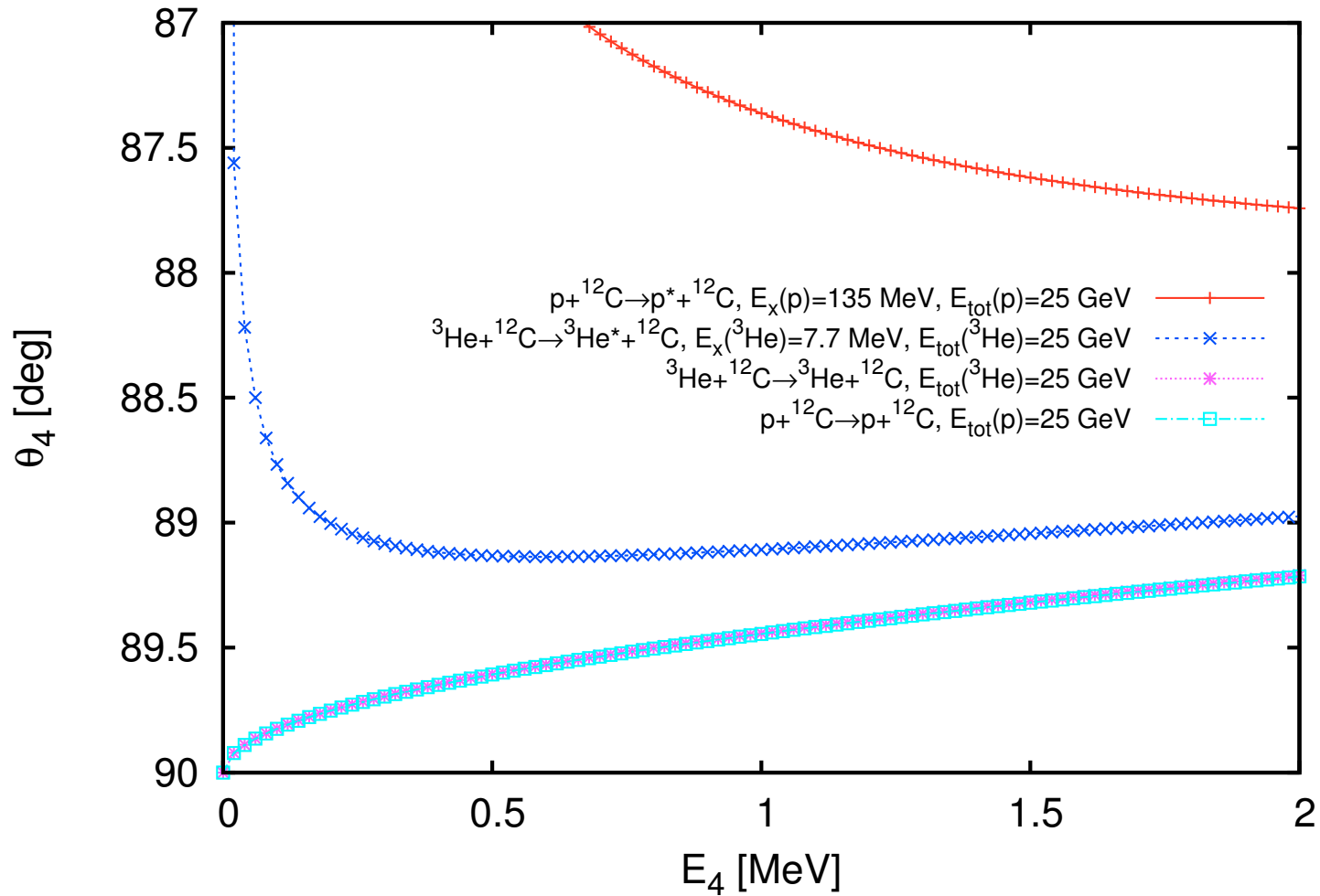


Figure 4: Carbon laboratory recoil angle versus its recoil kinetic energy for a 25 GeV proton scattering to pi-zero, or a 25 GeV helion scattering to break-up, or both elastically.

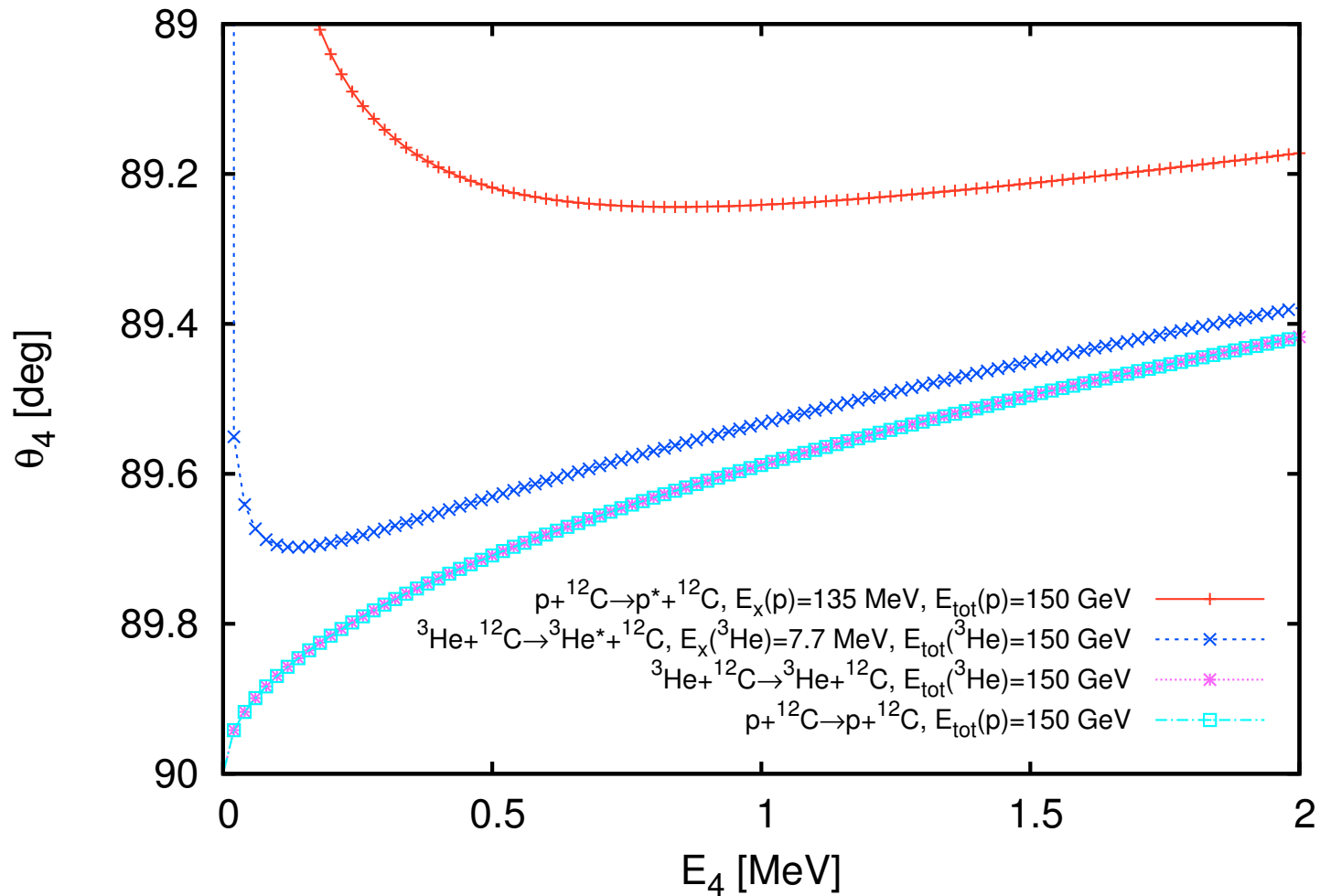


Figure 5: Carbon laboratory recoil angle versus its recoil kinetic energy for a 150 GeV proton scattering to pi-zero, or a 150 GeV helion scattering to break-up, or both elastically.

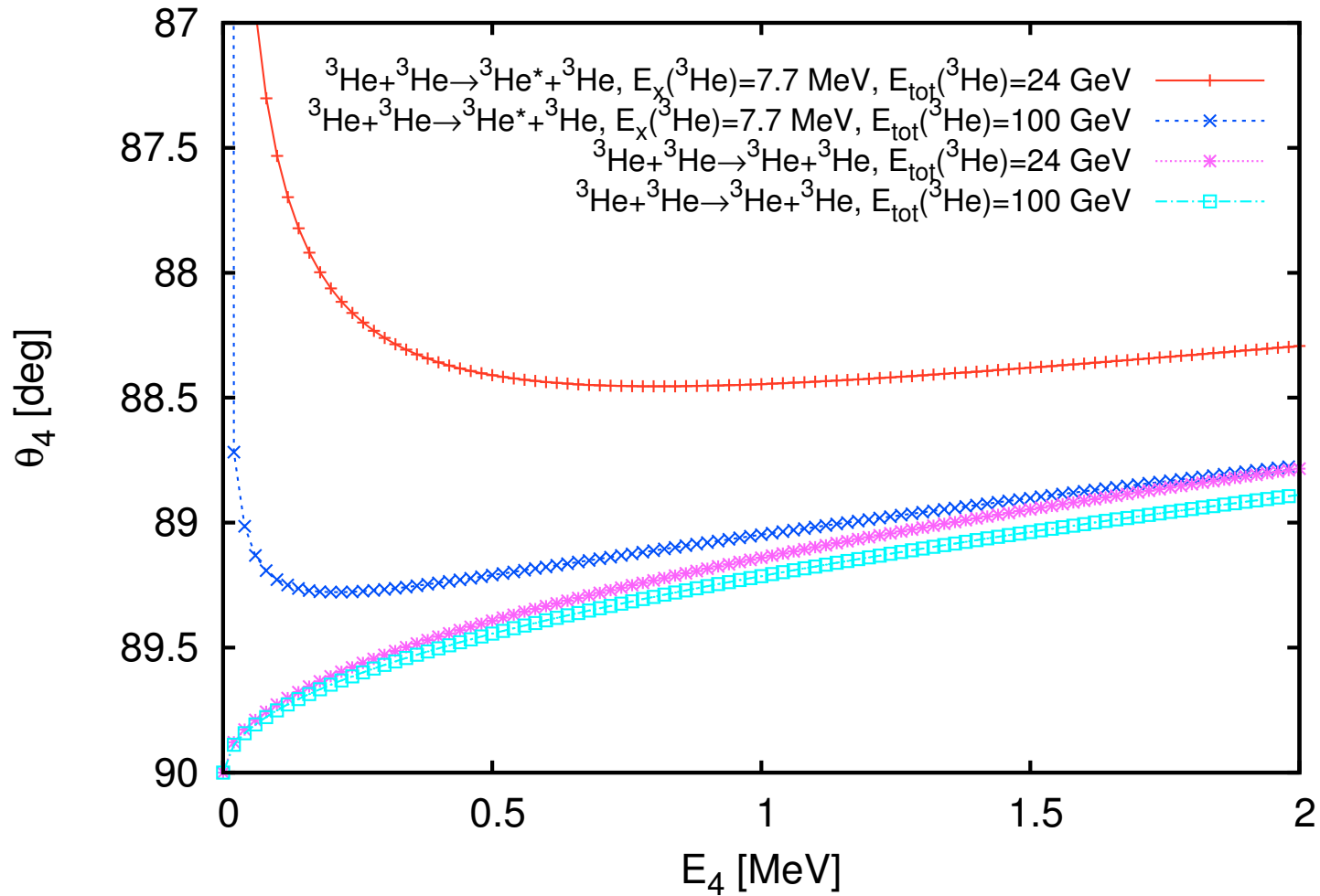


Figure 6: Helion laboratory recoil angle versus its recoil kinetic energy for an incident 24 GeV and 100 GeV helium-3 beam scattering to a break-up state or elastically to a helion.



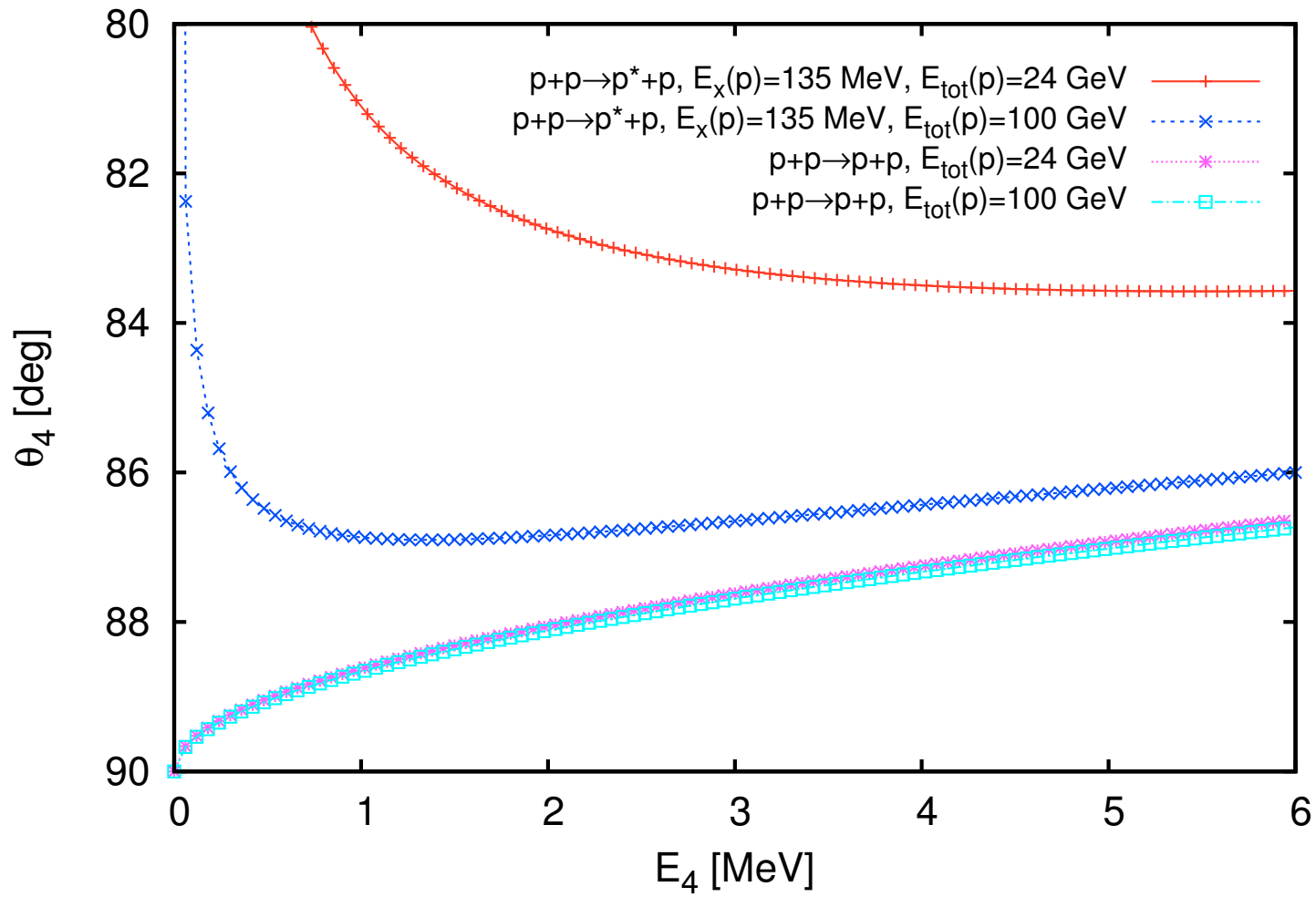


Figure 7: Proton laboratory recoil angle versus its recoil kinetic energy for a 24 GeV and 100 GeV incident proton beam scattering to a proton and pi zero or elastically to a proton.

# CONCLUSIONS

Probing the spin structure of hadrons increases the understanding of QCD

- The  $^3\text{He}$ -C analyzing power is  $\approx -78\%$  of  $A_N$  for p-C in the CNI region
  - The  $^3\text{He}$  elastic scattering window is much less than that for protons
- Interest in  $^3\text{He}$  nucleus scattering may speed  $^3\text{He}$  beam development
  - A polarized helium-3 jet target permits helium-3 beam calibration

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