Two photon exchange in quasi-elastic and deep-inelastic scattering

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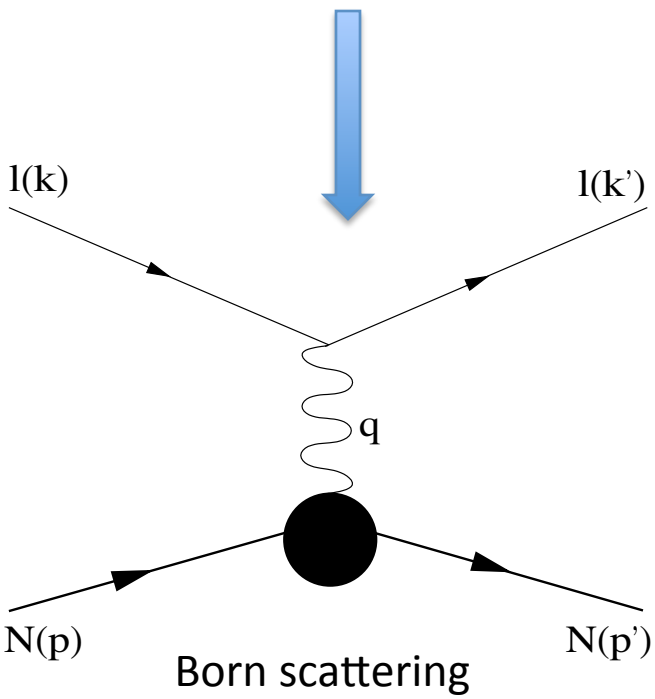
On behalf of the Jefferson Lab Hall A and polarized ^{3}He collaborations

Measure the "vertical" target single spin asymmetry A_y in:

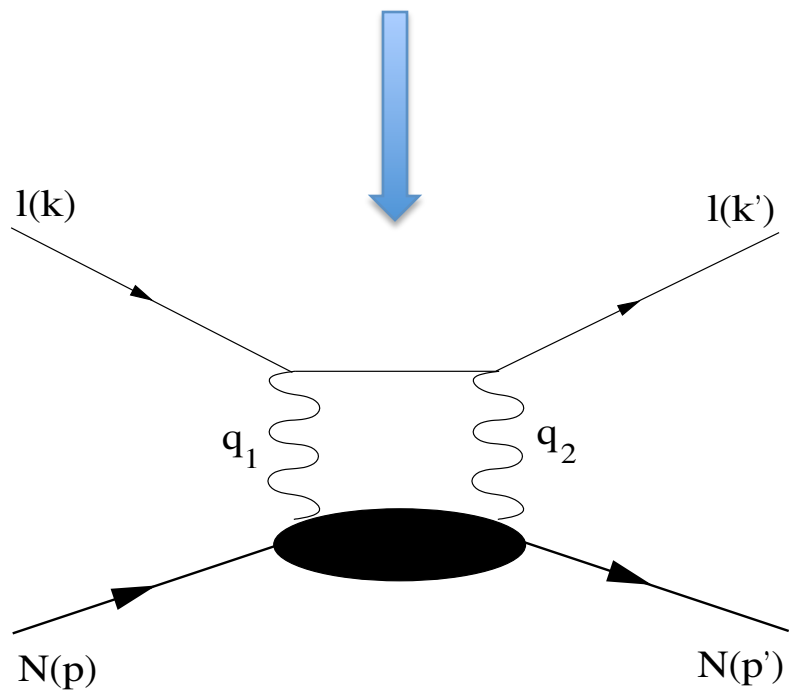
- quasi-elastic ^{3}He(e,e′)
- deep-inelastic ^{3}He(e,e′)
- quasi-elastic ^{3}He(e,e′n)

Born scattering and beyond

- JLab physicists' favorite diagram for (required for every talk):

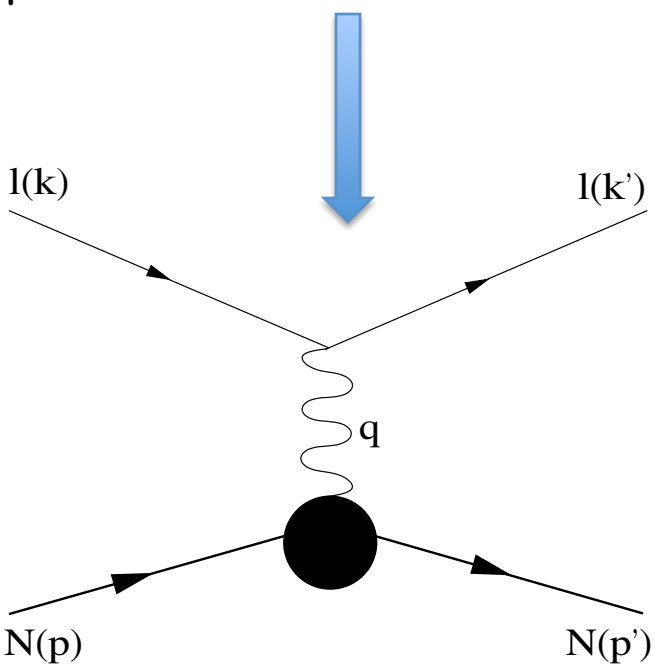


- Irritating "radiative" correction to favorite diagram. Good news —suppressed by α relative to Born diagram

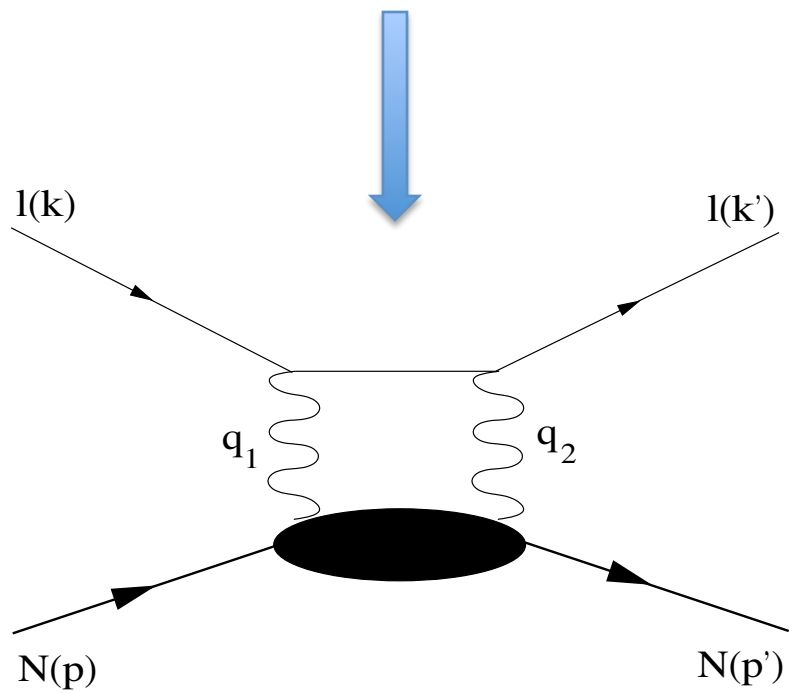


Born scattering and beyond

- Dominates unpolarized and most polarized N(e,e') scattering.
- True for N=nucleons, nuclei, quarks.



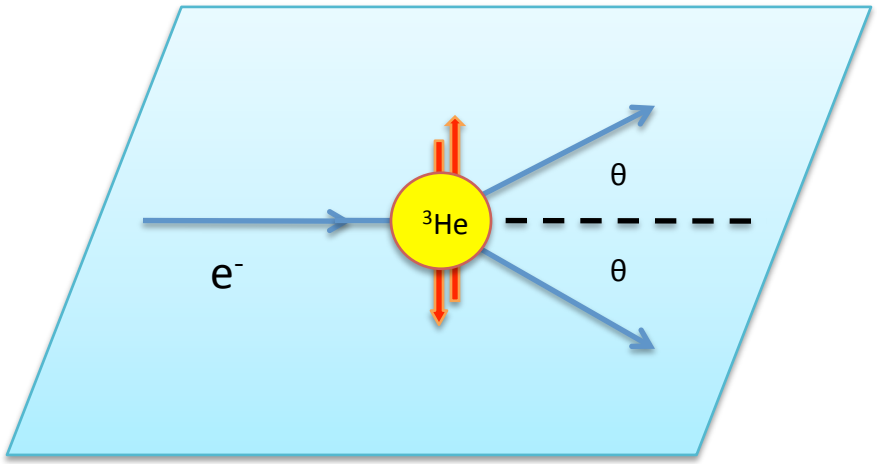
- How do we observe this?



Target Single Spin Asymmetry (SSA)

- Unpolarized e^- beam incident on ^{3}He target polarized normal to the electron scattering plane

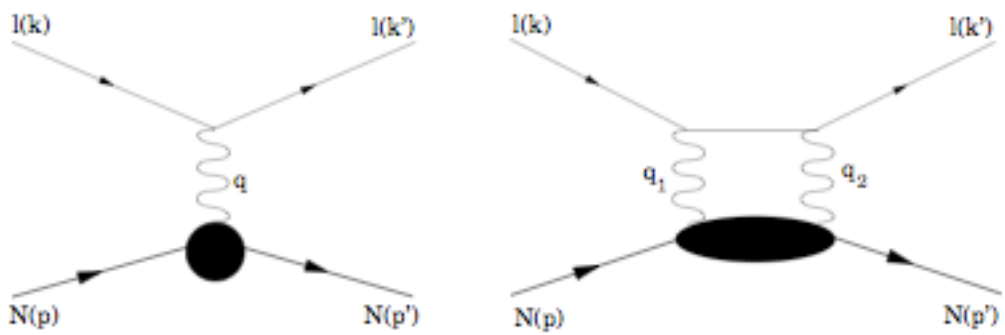
$$A_y = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$



- Note that unpolarized eN scattering and double spin asymmetries (DSA) with beam and target polarization in-plane is dominated by 1-photon exchange. e.g. measurements of G_e^n, G_M^n, F_1, F_2, g_1, g_2 <----(Born approximation)

- However, A_y=0 at Born level,
  → sensitive to physics at order α^2; two-photon exchange!

Key Points of this Experiment



- $A_y^{Born} = 0$ using Time-Reversal Invariance.
- $A_y \neq 0$ due to imaginary part of $1\gamma \otimes 2\gamma$ interference.
- Evaluation of 2γ box diagram involves *full* nucleon response to doubly virtual Compton scattering. Elastic intermediate contribution well-known. Calculate inelastic response using GPD's.

  P.A.M. Guichon and M. Vanderhaeghen, Phys. Rev. Lett. **91** (2003) 142303.
- 2γ exchange provides a unique new tool to study nucleon structure.

Topic 1: Elastic eN Scattering

Y.-C. Chen, A. Afanasev, S. J. Brodsky, C. E. Carlson and M. Vanderhaeghen, PRL **93** (2004) 122301

- For the elastic reaction $e(k) + N(p) \rightarrow e(k') + N(p')$,

$$T_{\lambda_h, \lambda'_N \lambda_N} = \frac{e^2}{Q^2}\, \bar{u}(k', \lambda_h)\gamma_\mu u(k, \lambda_h)$$

$$\times\, \bar{u}(p', \lambda'_N)\left(\tilde{G}_M\, \gamma^\mu - \tilde{F}_2 \frac{P^\mu}{M} + \tilde{F}_3 \frac{\gamma \cdot K P^\mu}{M^2}\right) u(p, \lambda_N)$$

The λ_i are the lepton and hadron helicities, P, K are kinematic factors.

- Complex functions containing nucleon structure information:

$$\begin{aligned}
\tilde{G}_M(\nu, Q^2) &= G_M^{(\mathrm{Born})}(Q^2) + \delta\tilde{G}_M(\nu, Q^2) \\
\tilde{F}_2(\nu, Q^2) &= F_2^{(\mathrm{Born})}(Q^2) + \delta\tilde{F}_2(\nu, Q^2) \\
\tilde{F}_3(\nu, Q^2) &= 0 \text{ for Born scattering}
\end{aligned}$$

- $\delta\tilde{G}_M$, $\delta\tilde{F}_2$, $\tilde{F}_3$ come from $1\gamma \otimes 2\gamma$-interference (up to $\mathcal{O}(e^4)$)

2γ-Contribution to A_y

- Assuming time-reversal invariance, A_y is related to the *Imaginary* part of the transition amplitude. Assume $T = T_{1\gamma} + T_{2\gamma}$, then,

$$A_y \propto \frac{\mathcal{I}m(T_{1\gamma}T^*_{2\gamma})}{|T|^2}$$

A. DeRujula *et al.*, Nuc. Phys. B35 (1971) 365.

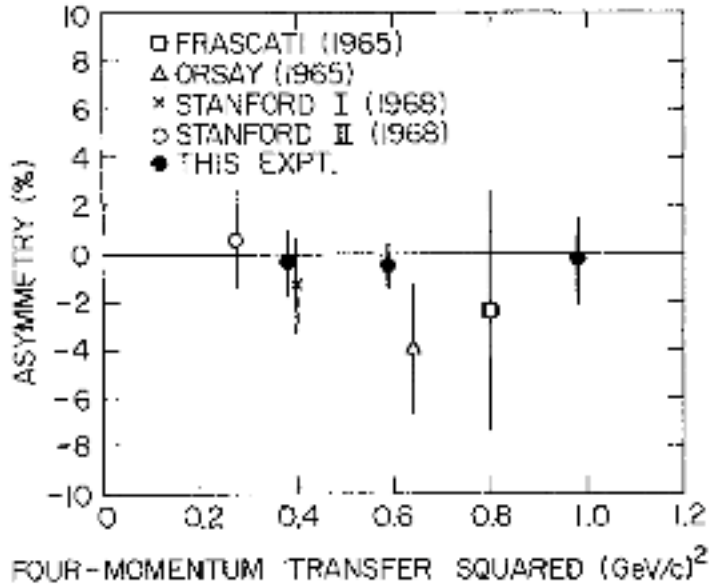
- For 1γ-exchange (assume time-reversal invariance),
  - $T_{2\gamma} = 0$, $T_{1\gamma}$ is real, $\Longrightarrow$ $A_y = 0$ for all Born processes.
- Include 2γ-exchange,
  - $T_{2\gamma}$ has absorptive (imaginary) contribution from box diagram. $\Longrightarrow$ $A_y \neq 0$

- Note that both recoil polarization and Rosenbluth separation measurements of nucleon form factors must be corrected for 2-photon exchange $\propto Re(\mathrm{T}_{1\gamma}{}^{*}T_{2\gamma})$

Existing A_y Data

- SLAC Proton Data for A_y (solid) and P_n (open); expected $A_y^p < 1\%$

  T. Powell *et al.*, PRL **24** (1970) 753.

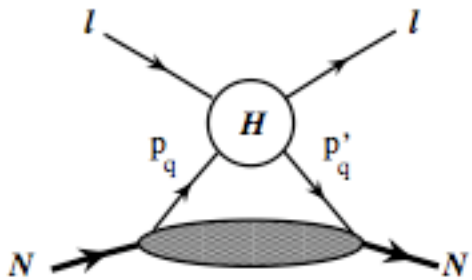


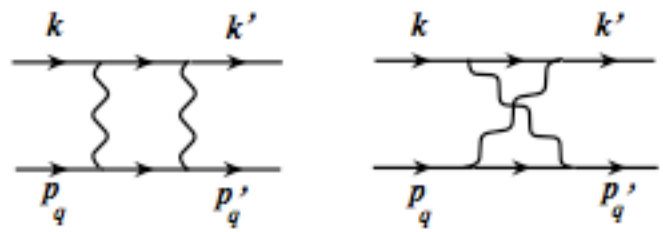
- NIKHEF QE ^{3}He$^\uparrow(e, e')$ at $Q^2 = 0.1$ GeV^2 gave $A_y = -1.0 \pm 5.4\%$.

  M. C. Harvey, Ph.D. thesis, Hampton University, 2001

- Precision measurements of A_y do not exist! A non-zero A_y never measured!

Connection with Generalized Parton Distributions (GPDs)





- Assume scattering described by hangbag diagram with box and crossed diagrams for 2γ exchange at hard vertex H.
- Only 2γ box diagram contributes to A_y.
- Elastic *intermediate state* believed well-understood, $A^n_{y,elas} \approx -1\%$

  A. DeRujula *et al.*, Nuc. Phys. B35 (1971) 365; A. Afanasev *et al.*, arXiv:hep-ph/0208060
- Full inelastic *intermediate state* described by GPD's

Connection with (GPDs) (con't)

Y.-C. Chen, A. Afanasev, S. J. Brodsky, C. E. Carlson and M. Vanderhaeghen, PRL **93** (2004) 122301

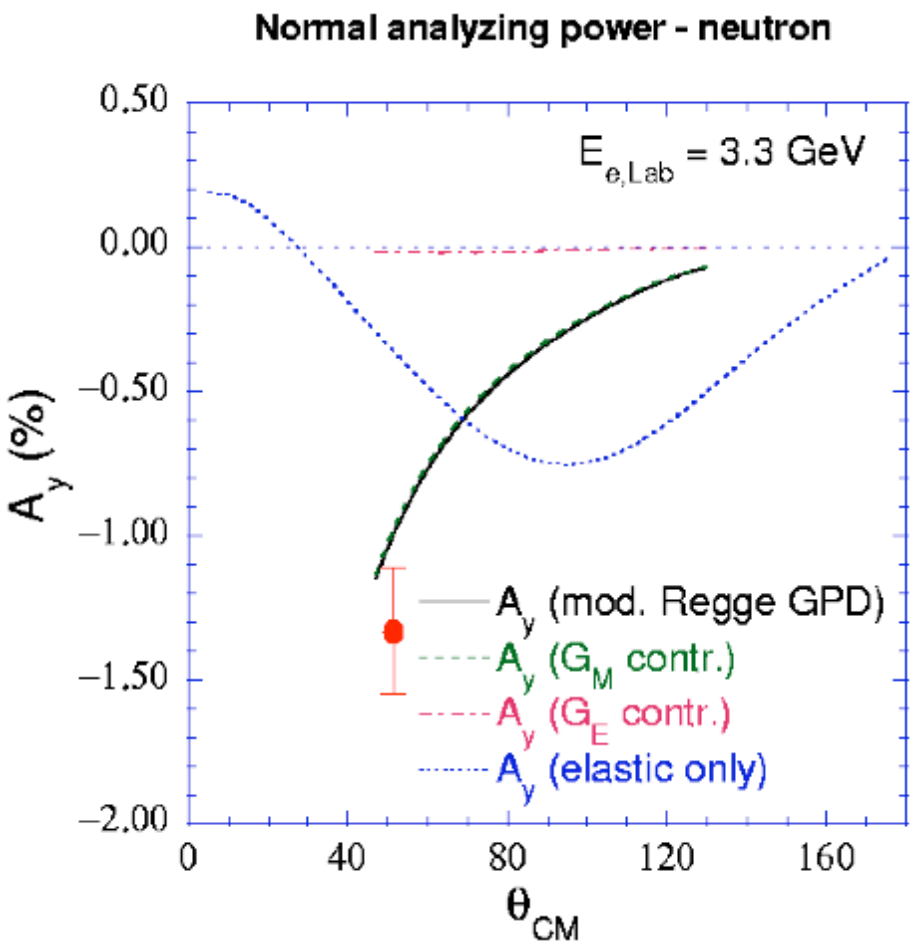
$$A_y = \sqrt{\frac{2\,\varepsilon\,(1+\varepsilon)}{\tau}}\;\frac{1}{\sigma_R}\left\{-G_M\,\mathcal{I}m\,(B) + G_E\,\mathcal{I}m\,(A)\right\}$$

$$A = \int_{-1}^{1}\frac{dx}{x}\tilde{K}\sum_q e_q^2\left[H^q(x,0,t) + E^q(x,0,t)\right]$$

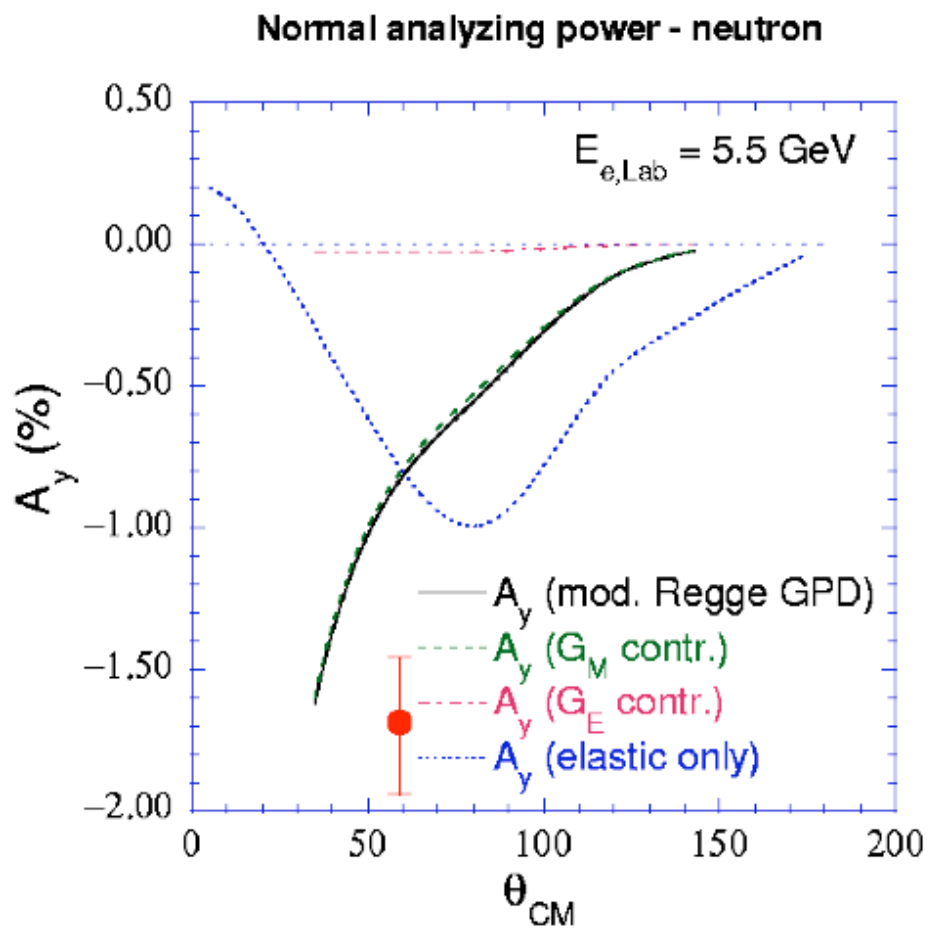
$$B = \int_{-1}^{1}\frac{dx}{x}\tilde{K}'\sum_q e_q^2\left[H^q(x,0,t) - \tau E^q(x,0,t)\right]$$

- H^q and E^q are GPD's for quarks of flavor q.
- $\tilde{K}$ and $\tilde{K}'$ contain the contributions from the hard scattering amplitudes.
- $\mathcal{I}m(A)$ and $\mathcal{I}m(B)$ are non-zero through 2γ contribution in $\tilde{K}$ and $\tilde{K}'$.
- Measuring *neutron* A_y provides new constraint on specific GPD moment.

GPD Prediction



$Q^2 \sim 1.0\ GeV^2$



$Q^2 \sim 2.0\ GeV^2$

The Experiment

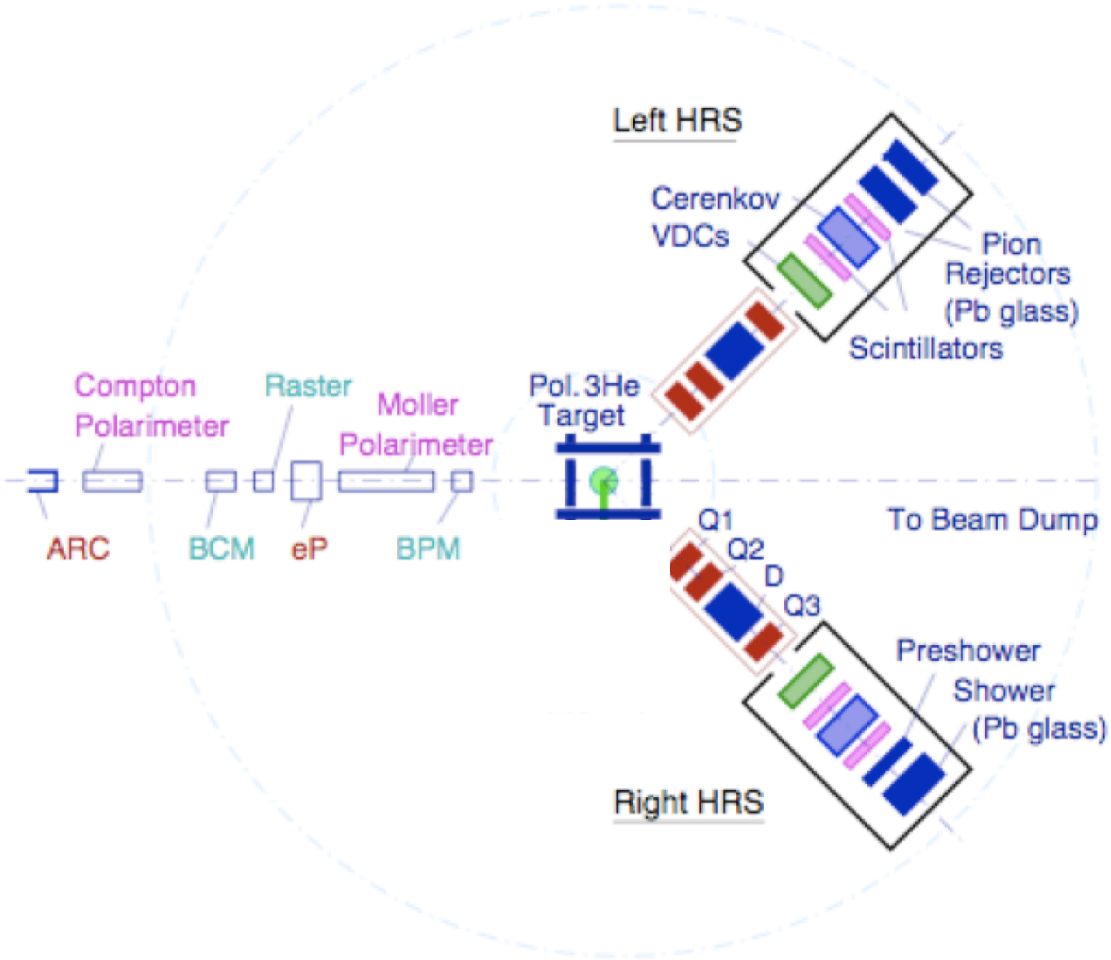
- Clearly establish the first non-zero measurement of A_y^n at Q^2=1.0 GeV^2
- Provide a new constraint on moments of GPD's.
- Measure A_y^n at Q^2= 0.2, 0.5 GeV^2 to study Q^2 dependence.
- Look for possible FSI contributions? Study parton to hadron transition.

- Use two symmetric HRS spectrometers in singles mode for electron detection.
- Check systematics using: $A_y(\theta) = -A_y(-\theta)$.
- Vertically polarized target available (E03-004); no new equipment needed.
- "The PAC believes the proposed approach has sufficient merit to warrant a test run for the two lower Q^2 values (0.5 and 1.0 (GeV/c)^2), which in itself would produce valuable results." Measurements completed at Q^2=0.1, 0.5, 1.0 GeV^2

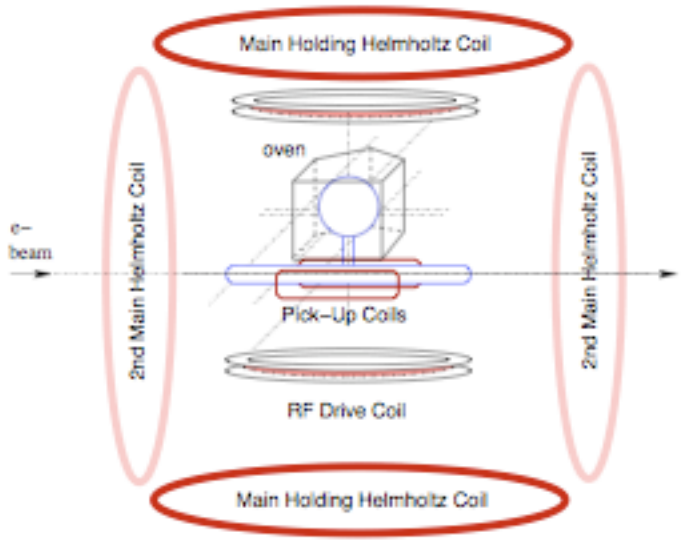
The Experimental Goals

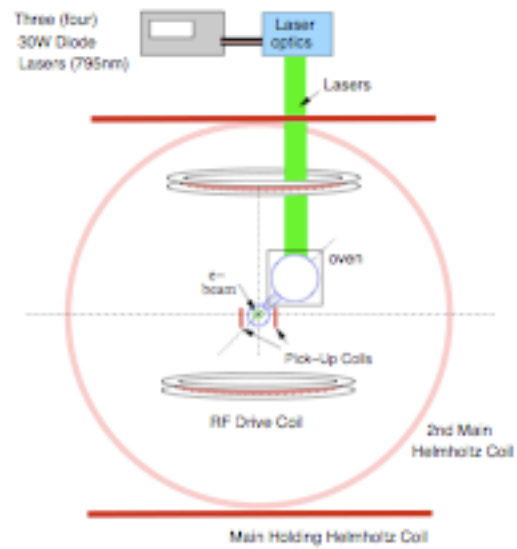
- Clearly establish the first non-zero measurement of A_y^n at Q^2=1 GeV^2
- Provide a new constraint on moments of GPD's.
- Measure A_y^n at Q^2= 0.1, 0.5 GeV^2 to study Q^2 dependence. Look for possible FSI contributions? Study parton to hadron transition.

Hall A Experimental Setup



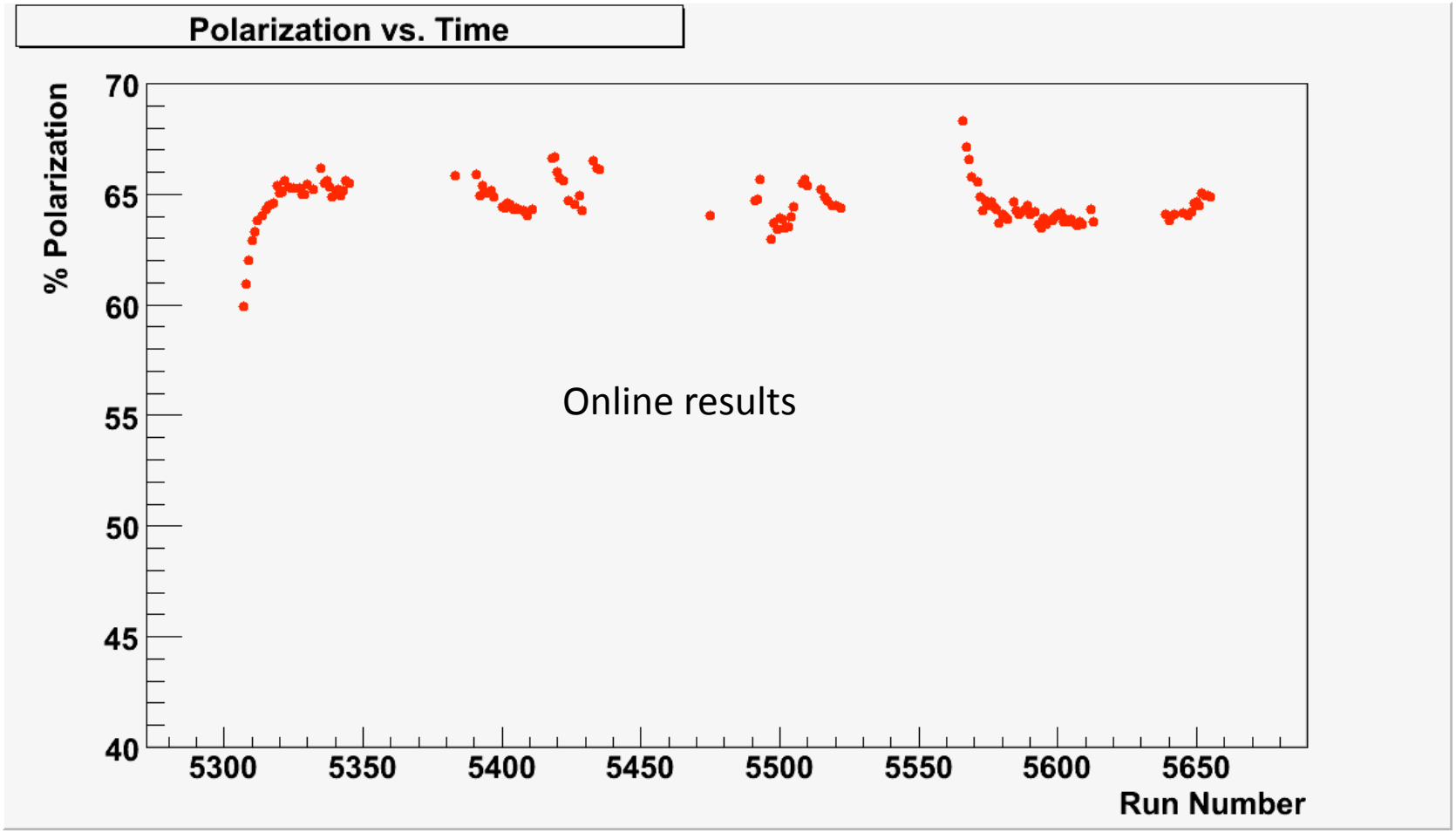
Vertically Polarized ^{3}He Target





- Spin-exchange optically-pumped gas target. Now standard technology.
- New polarized target now achieving 65% in-beam polarization due to hybrid alkali and narrowed lasers.
- Reverse target spin direction every 20 minutes or less.

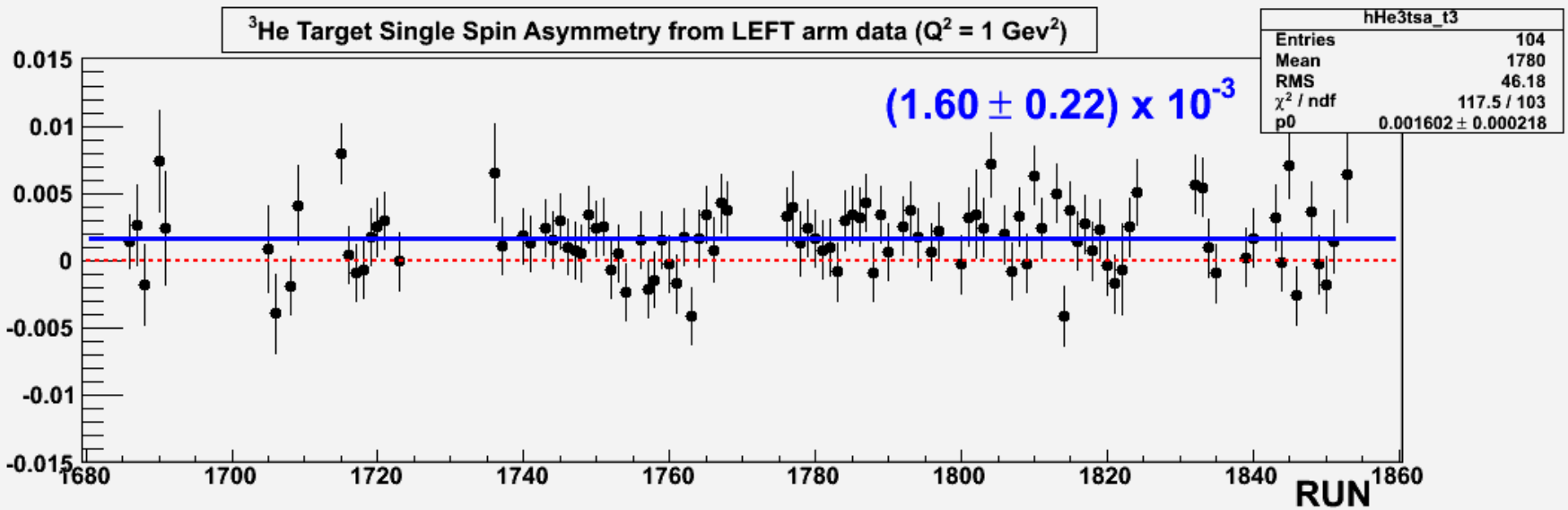
Target polarization for typical SEOP ^{3}He Hall A target

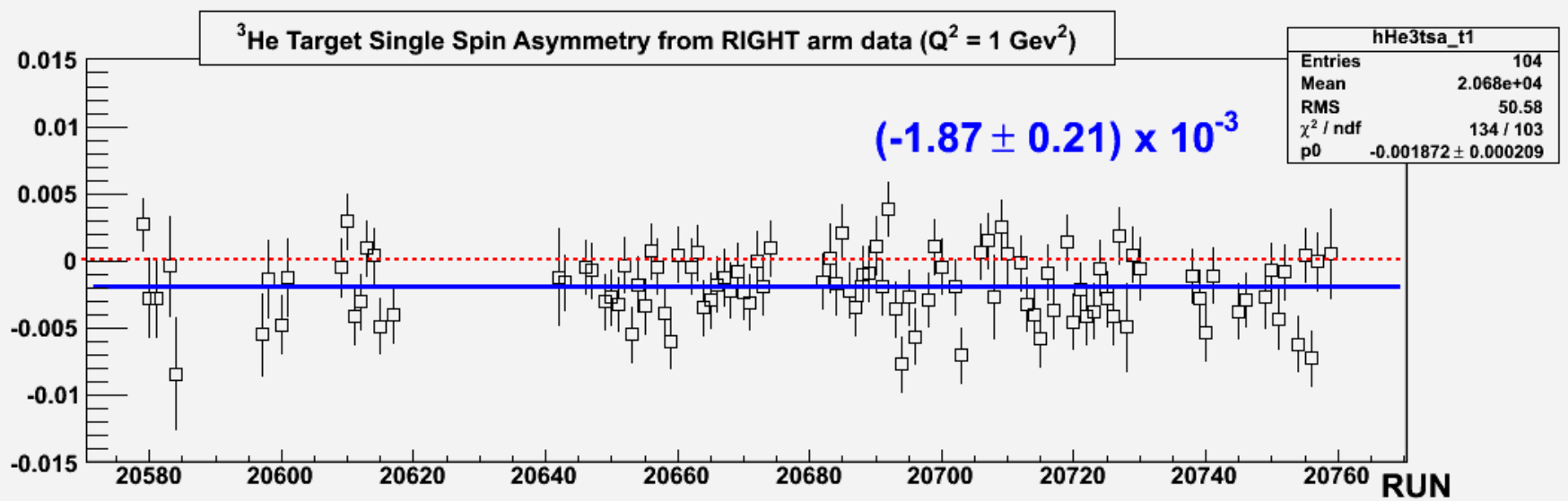


Preliminary results

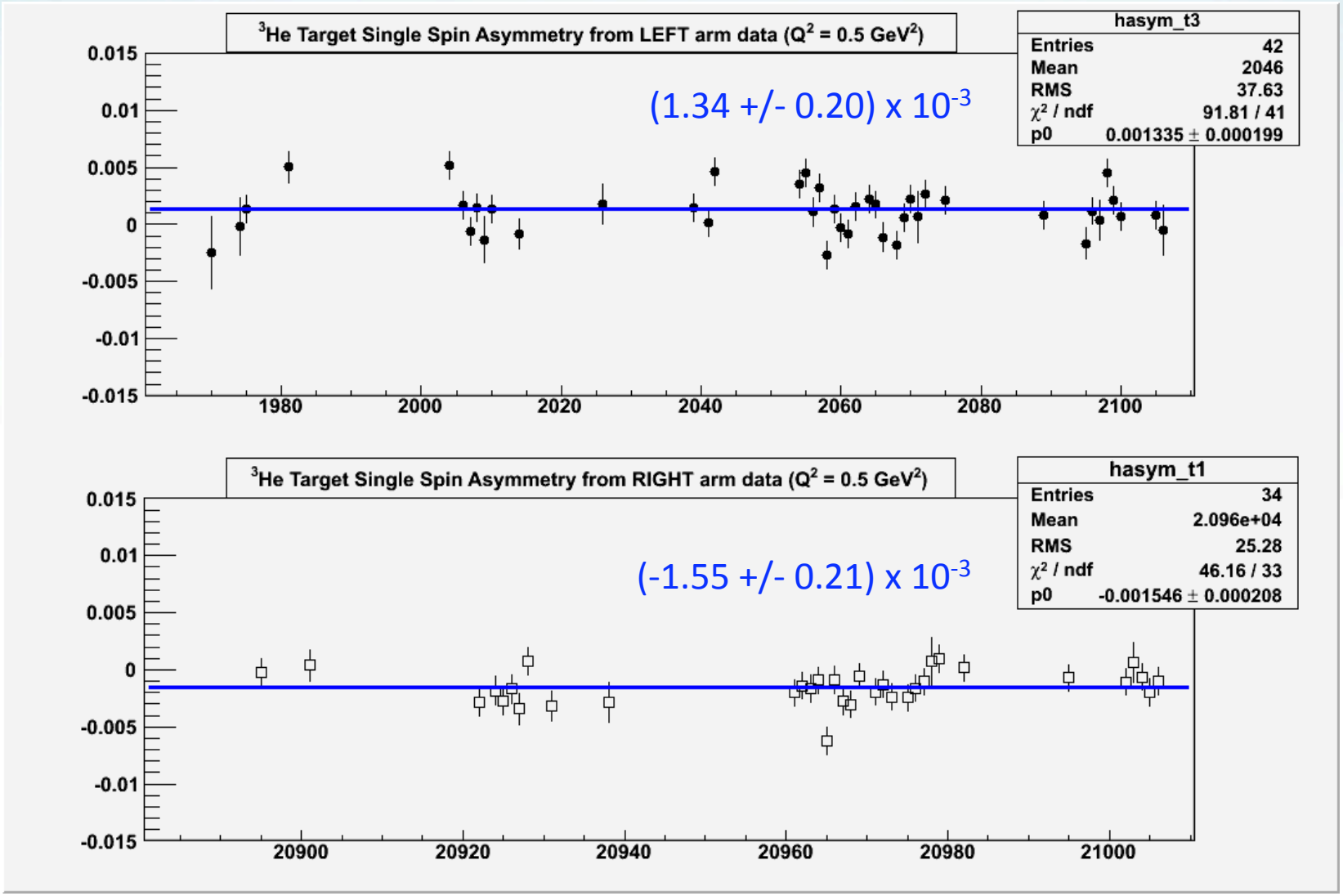
- Next two slides will show A_y for ^3He
- Preliminary results with target polarization and nitrogen dilution corrections applied.
- No radiative corrections applied
- Systematic uncertainties not finished

Preliminary results at Q^2=1.0 GeV^2





Preliminary results at Q^2=0.5 GeV^2



A_y^{3He} vs. run number

Topic 2: What about A_y for N(e,e') in DIS?

- The formalism remains the same:
  A_y=0 for 1-photon exchange

- For DIS, one assumes that the scattering is dominated by two photon exchange with a single quark.

- For non-interacting quarks, A_y=0 for two-photon exchange

- Afanasev, Strikman, Weiss (**Phys.Rev.D77:014028,2008)** predict $A_y \sim 10^{-4}$ using a model based on the quark transversity distribution.

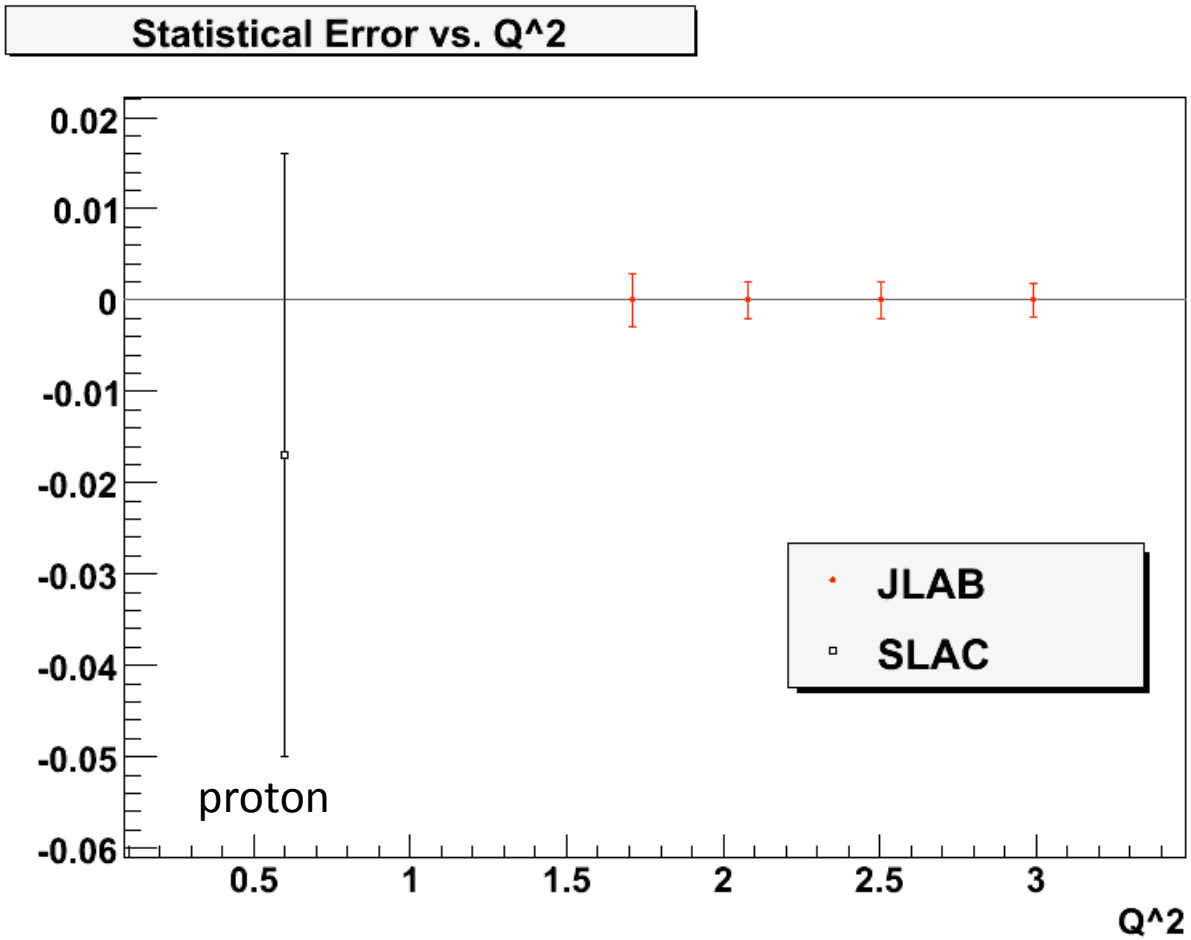
- This means *the SSA should change by two orders of magnitude from DIS to QE kinematics.* This is a direct study of the "transition" from hadron-like to parton-like behavior.

- This was measured in Hall A during the transversity experiment, using the BigBite Spectrometer in singles mode.

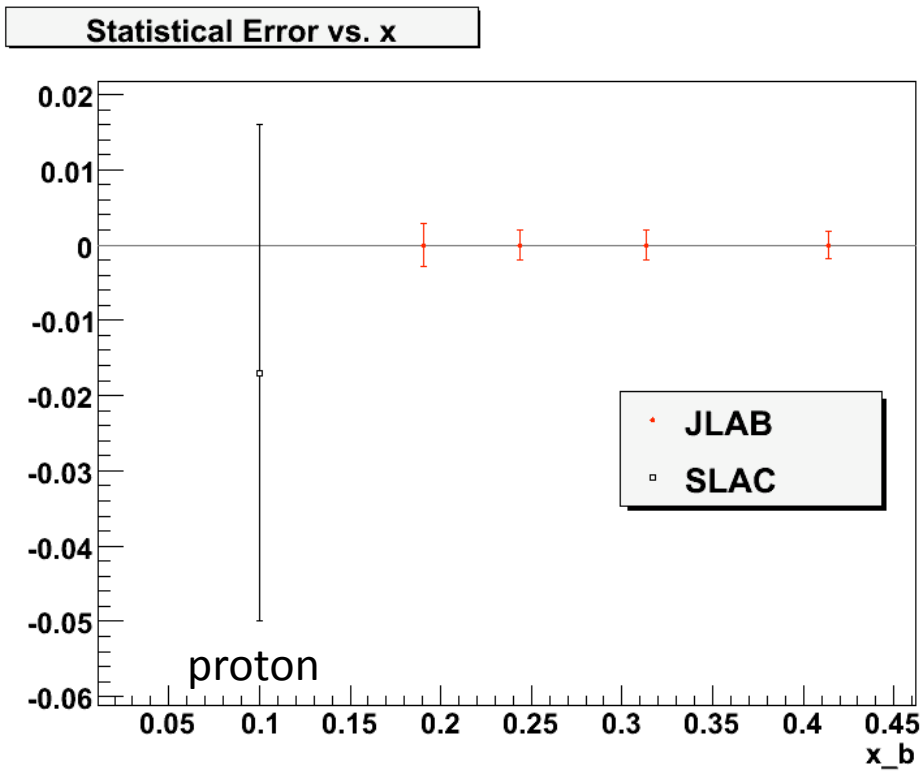
- Joe Katich-WM graduate thesis student

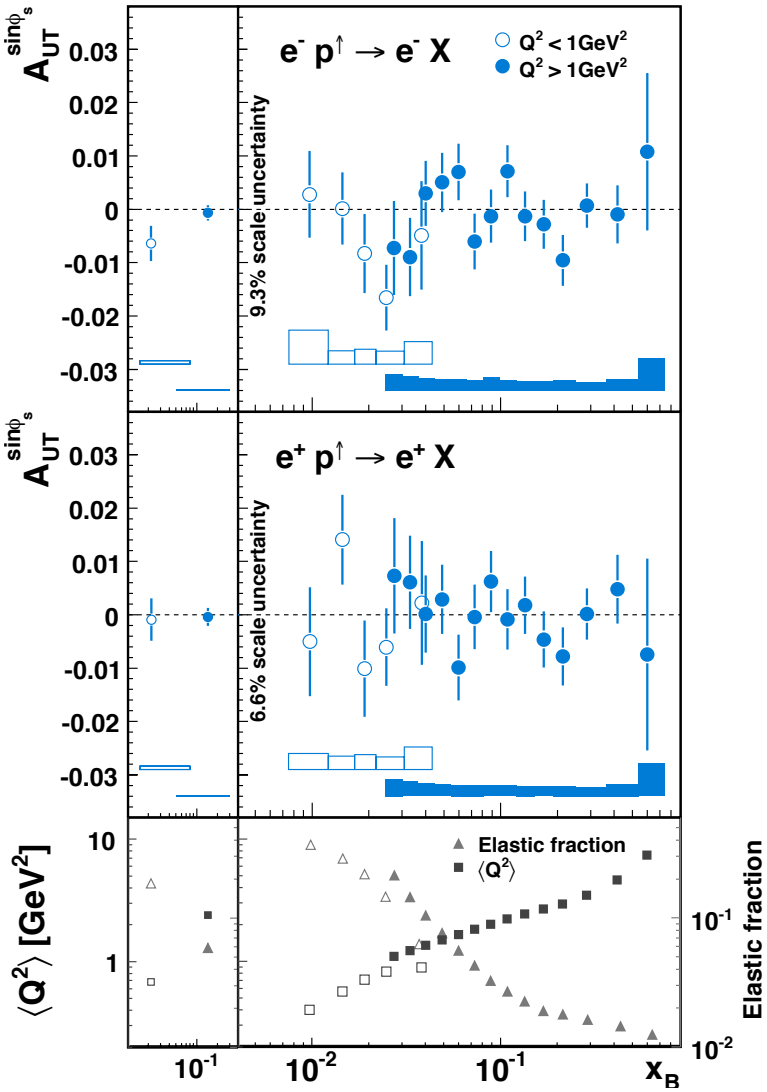
A_y for ^3He versus Q^2

Preliminary statistical uncertainties only



HERMES proton DIS data

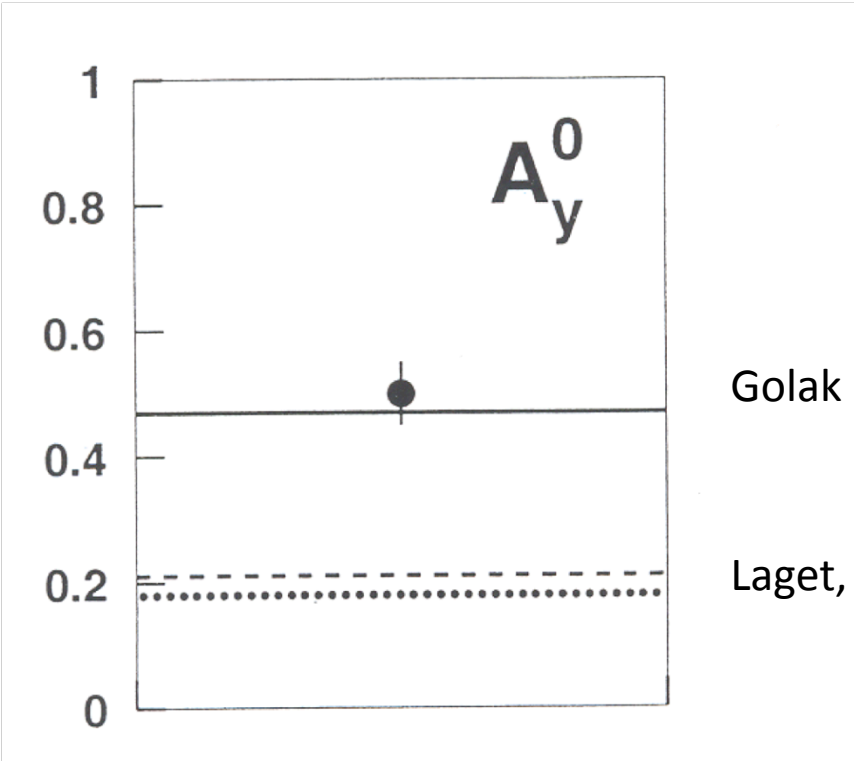




A. Airapetian et al,
Phys. Lett. B682, 351 (2010)

Topic 3: SSA in quasi-elastic ^{3}He(e,e'n)

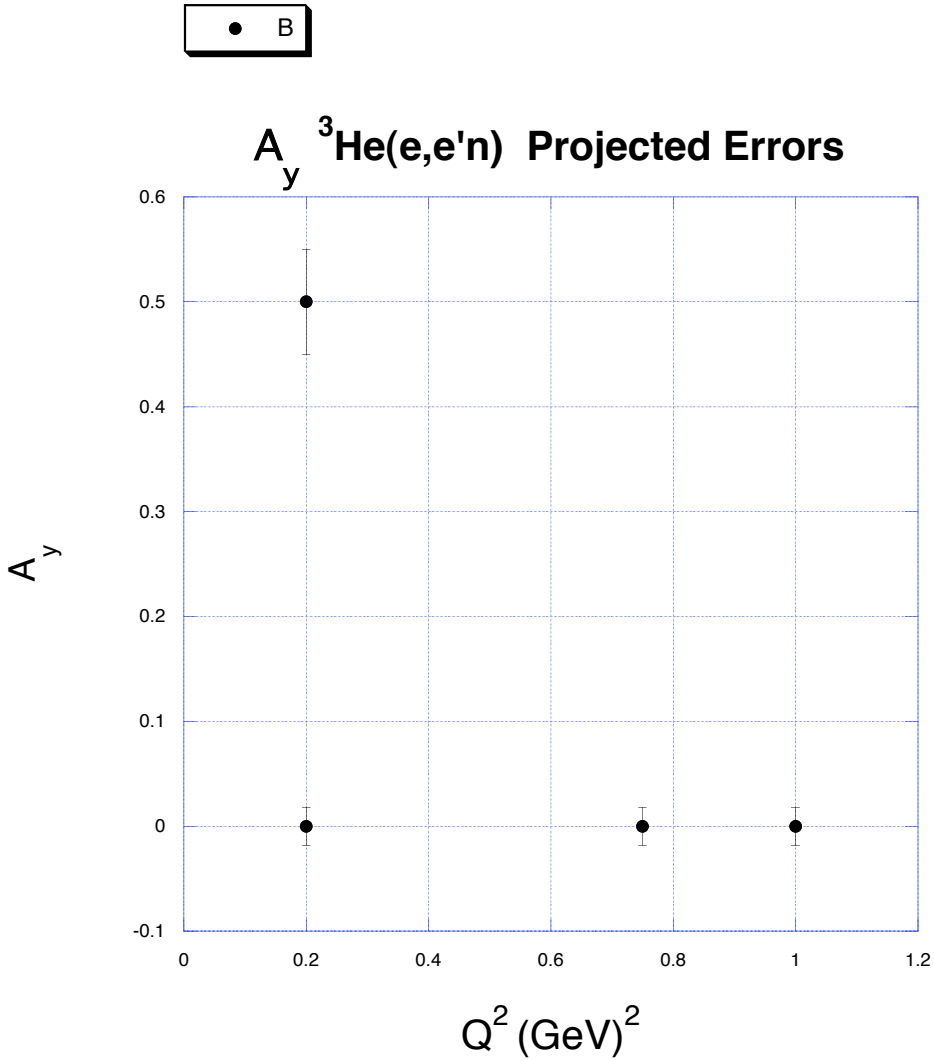
- By detecting the outgoing neutron, the SSA is sensitive to FSI
- PWIA Calculations predict A_y=0
- Theoretical models with FSI, 3He wavefunction, etc predict A_y=20-45%
- Unpublished measurement at NIKEF measured large A_y~50% at Q^2=0.2 GeV^2!!!

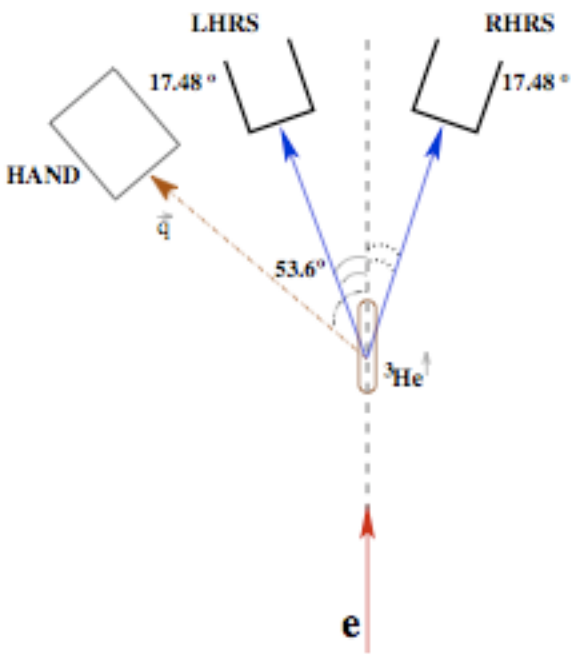


Golak

Laget, Nagorney

Recoil neutron measurement





Summary

- First measurements of the target SSA using vertically polarized ^{3}He

- Precision results obtained in the quasi-elastic and DIS regions.

- Provides sensitive tests of GPDand hadronic models of nucleon structure.

- Preliminary QE results for A_y on ^{3}He at Q^2=0.5 and 1.0 GeV^2.
    - Clearly non-zero, no apparent Q^2-dependence
    - Data at $Q^2 \sim 0.1$ GeV^2 coming soon.

- First DIS results for A_y on ^{3}He at Q^2=1.5-3.0 GeV^2.
    - Precision comparable to HERMES proton results.

- Detection of recoil neutron in QE measurement of $A_y$expected to be huge due to FSI

QE

Backgrounds

- Inclusive reaction; Hadronic final states are integrated over

  $\Longrightarrow$ no contribution to A_y from hadronic FSI.

  N. Christ, T.D. Lee, Phys. Rev. **143** (1966) 1310

- There are no channels which contribute to A_y at Born-level.

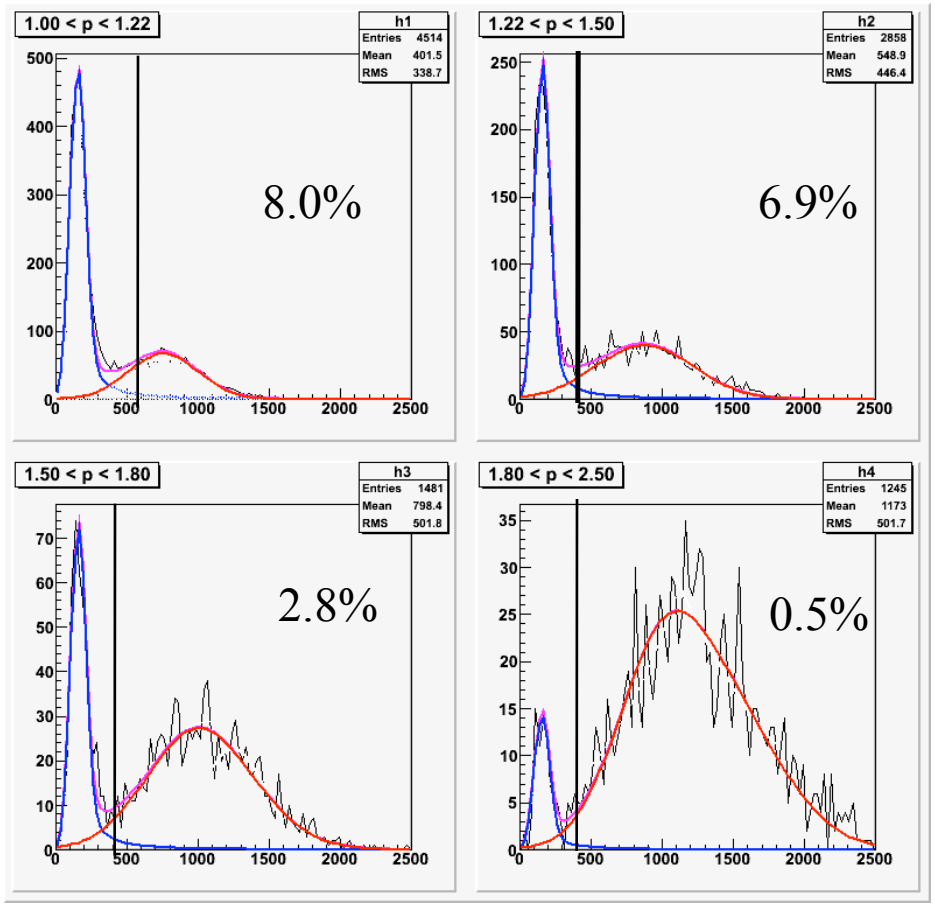
  Time Reversal Invariance, A. DeRujula *et al.*, Nucl. Phys. B **53** (1973) 545

- 2γ backgrounds:
  - Elastic tail negligible at these kinematics.
  - Inelastic contamination (DIS and resonances) under control.
  - For DIS $A_y \propto m_q/Q \sim 0$.

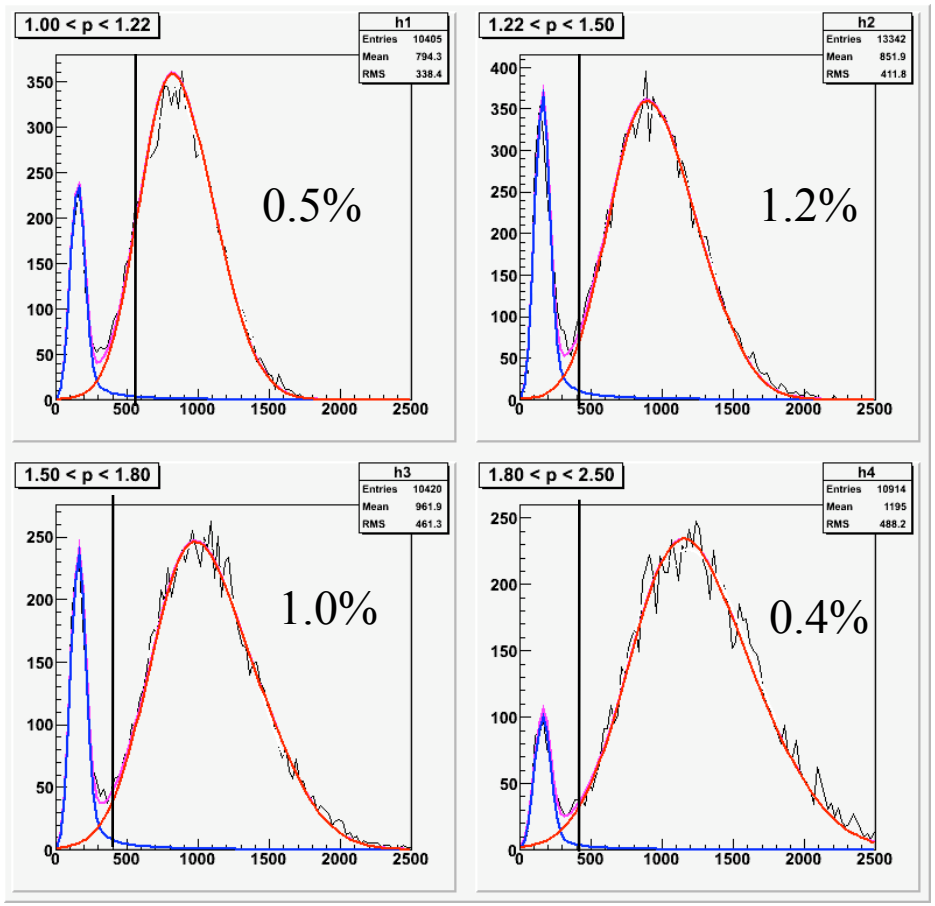
    A. O. Barut and C. Fronsdal, Phys. Rev. 120 (1960) 1871.

Final pi- Contamination

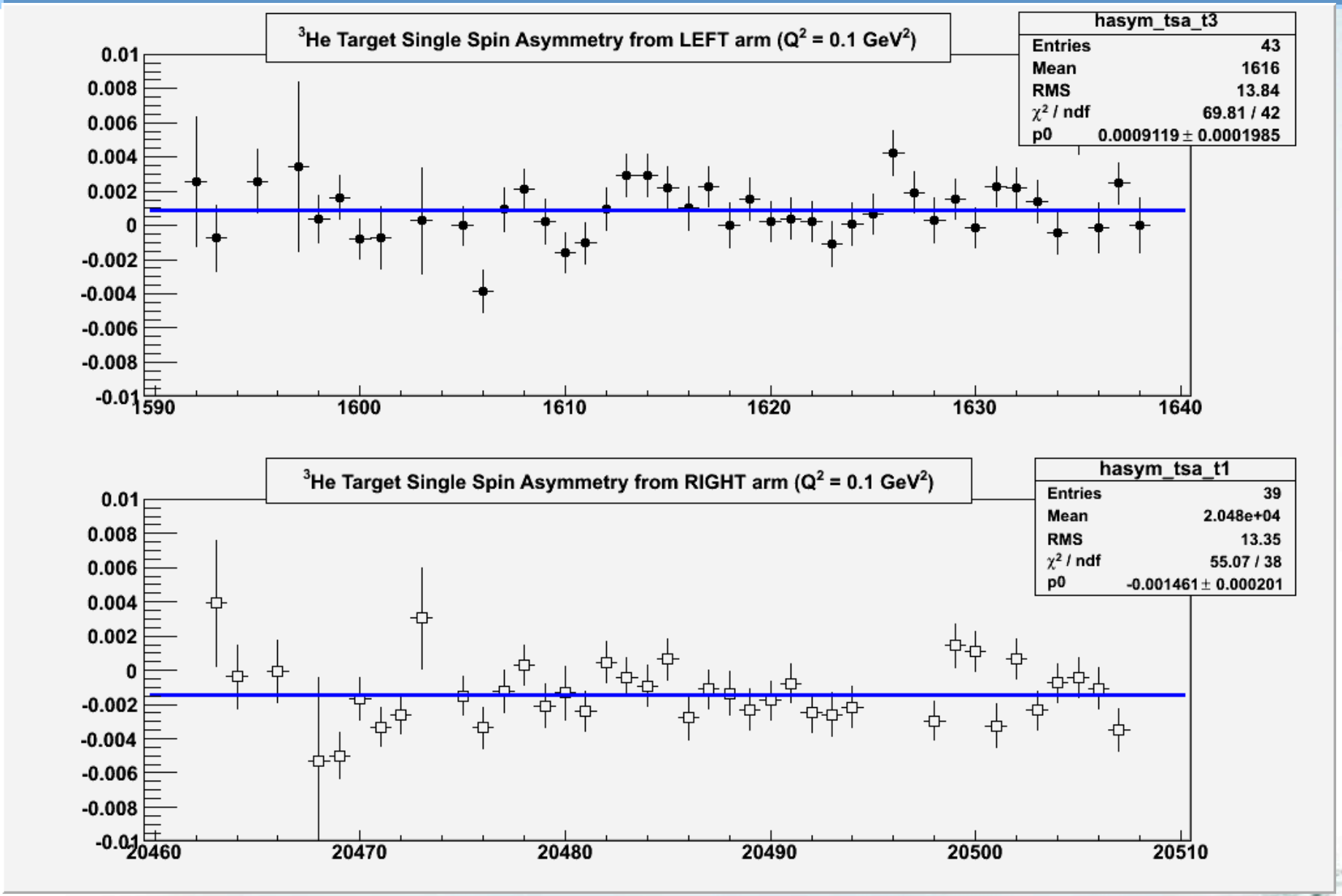
T1



T6



Prelim. He3 SSA (QE for 1-pass vertical data)



f_{N2} ~ 95% and <Pt> ~ 60%