The G_2^P Experiment and Polarized ^3He Target Upgrade

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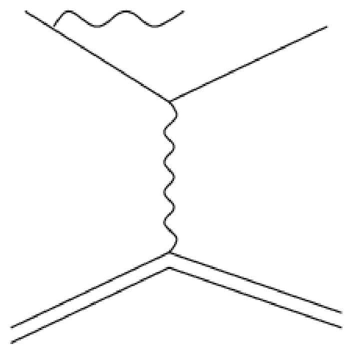
2014 Nuclear Seminar

G_2^P Outline

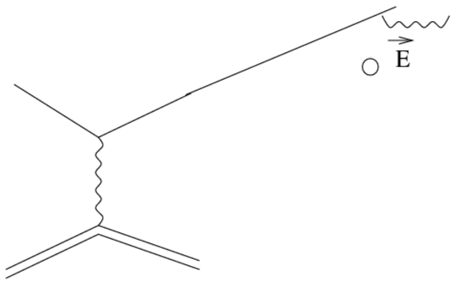
- Introduction
- Motivation
- Experiment Setup
- Analysis
- Summary

Electron Scattering

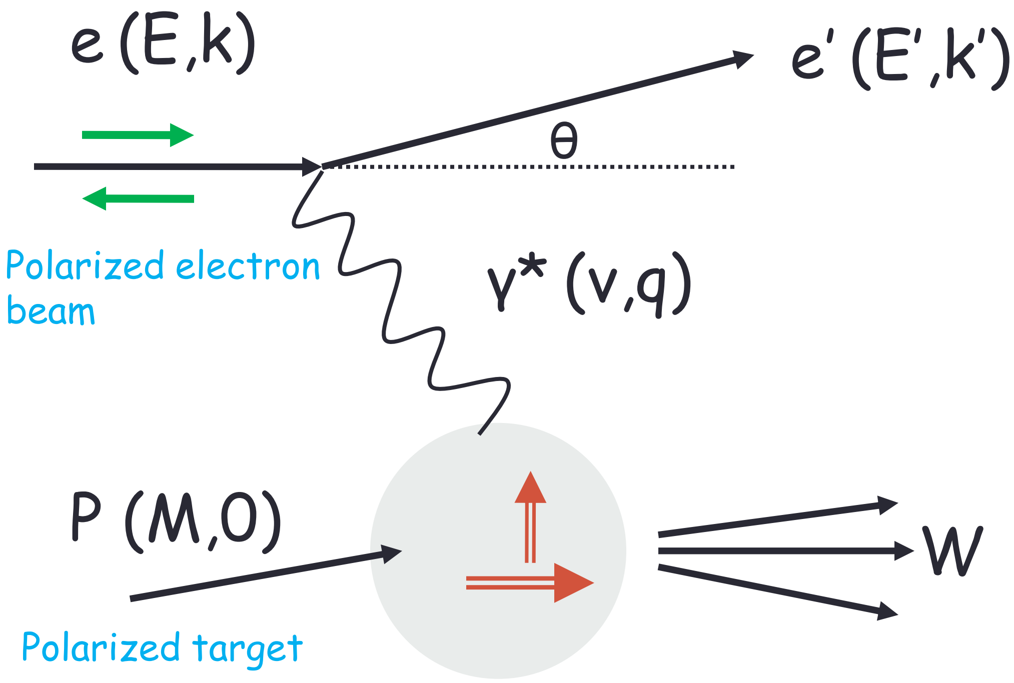
- ❑ **Why Electron Scattering**
  - ▪ Interaction well known
    - Point like
    - QED
  - Interaction is weak
  - Cross section calculable measurable



- ❑ Disadvantage
  - ▪ Cross section $\sim \alpha^2 \sim 10^{-4}$
    - high luminosity
    - thick target
    - large solid angle detectors
  - Electron is small
    - high energy
    - Radiative corrections



Inclusive Electron Scattering



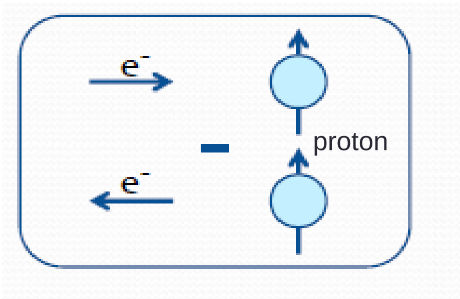
- Invariant Mass
  $W^2 = M^2 + 2M\nu - Q^2$
- Four momentum transfer squared
  $Q^2 = -q^2$
- Bjorken variable
  $x = Q^2/2M\nu$ for fixed target

g_1, g_2: polarized nucleon Spin structure function

$$\frac{d^2\sigma}{d\Omega dE'} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} (\alpha F_1(x,Q^2) + \beta F_2(x,Q^2) + \gamma g_1(x,Q^2) + \delta g_2(x,Q^2))$$

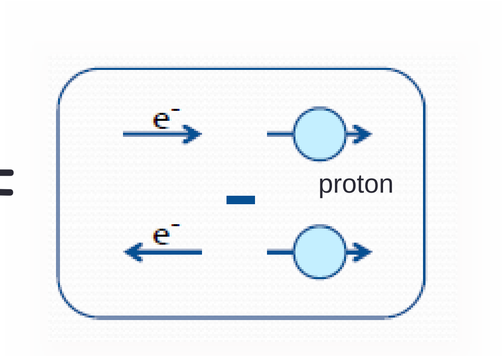
Introduction

$\Delta\sigma_{\perp} =$



$$= \frac{4\alpha^2 E'}{M\nu Q^2 E}\left[\sin\theta\left(g_1 + \frac{2E}{\nu} g_2\right)\right]$$

$\Delta\sigma_{\parallel} =$



$$= \frac{4\alpha^2 E'^2}{M\nu Q^2 E}\left[(E + E'\cos\theta) g_1 - 2Mx g_2\right]$$

g_2^P experiment measure, g_2^P essential contribution to $\Delta\sigma_{\perp}$ in our kinematic region

Hall B EG4 measure g_1^P, g_2^P experiment has one measurement to cross check

Historically more data on $\Delta\sigma_{\parallel}$, $\Delta\sigma_{\perp}$ is more difficult

Motivation

- Measure the proton spin structure function g_2 in the low Q^2 region (0.02 < Q^2 < 0.2 GeV^2) for the first time
- Benchmark test of χPT with extraction of δ_{LT}
- Examine the Burkhardt-Cottingham sum rule at low Q^2
- Crucial inputs for hydrogen hyperfine splitting and proton charge radius measurements

g_2 Structure Function

❑ At high to immediate Q^2

- g_2 can be separated into leading and higher-twist components :

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \overline{g_2}(x,Q^2)$$

- g_2 leading twist related to g_1 by Wandzura-Wilczek relation:

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 \frac{dy}{y} g_1(x,Q^2)$$

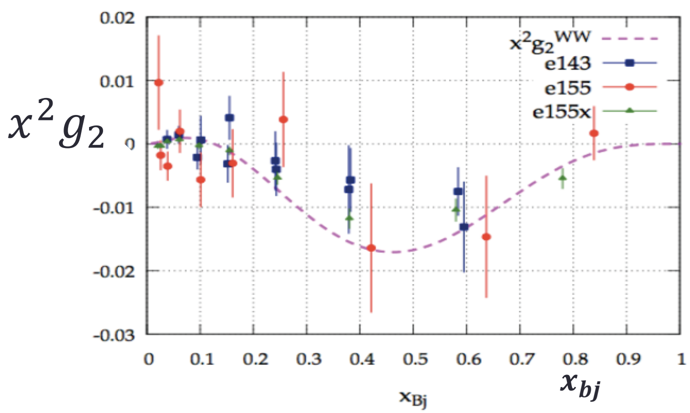
Good approximation as $Q^2 \to \infty$

- g_2 exhibits strong deviations from this leading twist behavior at typical JLab kinematics

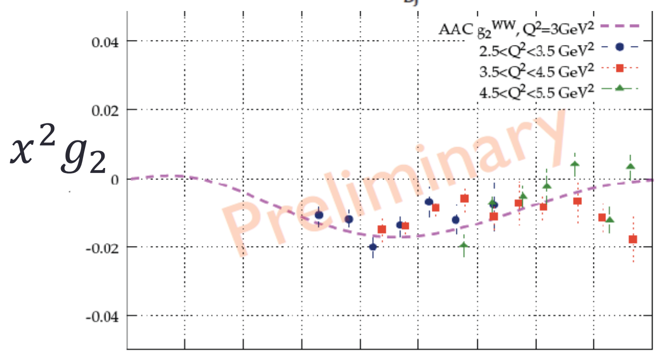
- $g_2 - g_2^{WW}$: a clean way to access higher-twist contribution, quantify q-g correlations.

g_2 Existing Data

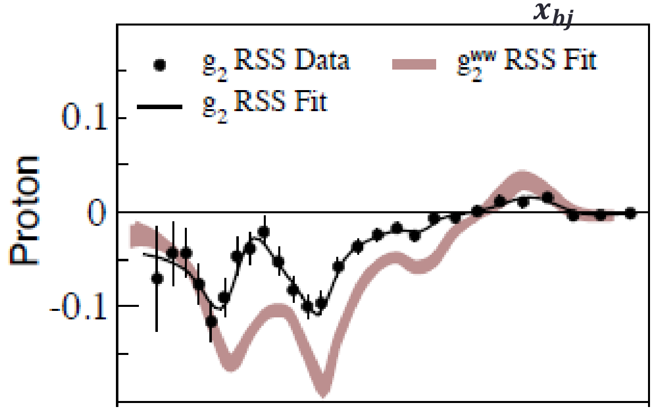
- Hard to cleanly measure g_2^P
  No much data before



Proton g_2 Data from SLAC
Averaged $Q^2 \approx 5\ GeV^2$



Proton g_2 Data from Jlab SANE
$Q^2 \approx 2.5 \sim 5.5\ GeV^2$



Proton g_2 Data from Jlab RSS
$Q^2 = 1.3\ GeV^2$

K.S., O. Rondon *et al.*
PRL 105, 101601 (2010)

BC Sum Rule

- BC Sum Rule:

$$\int_0^1 g_2(x, Q^2)\mathrm{d}x = 0$$

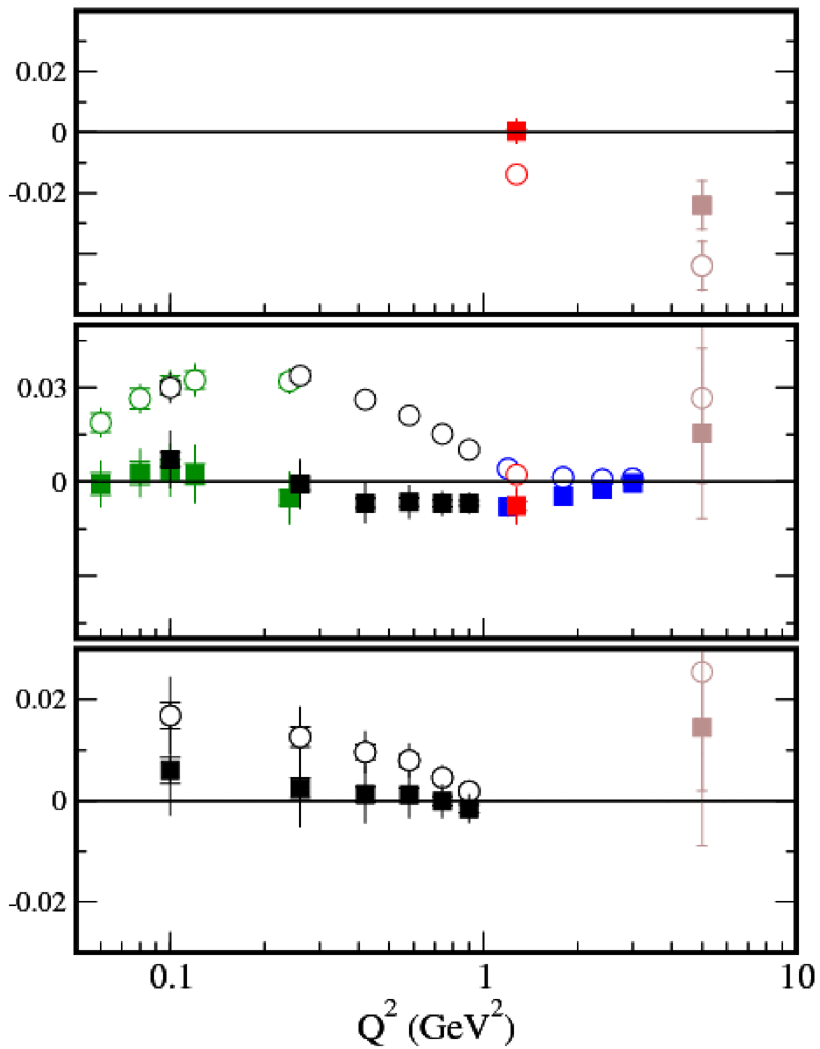
H. Burkhardt and W. N. Cottingham, Annals. Phys., 56(1970)453

- BC Sum Rule will failed if
  - exhibits non-Regge behavior at low x
  - exhibits a delta function at x = 0

R. L. Jaffe and X.-D. Ji, Phys. Rev. D, 43(1991)724

- Experiment test:
  - BC = Measured + low_x + Elastic

BC Sum Rule



- SLAC E155x
- Hall C RSS
- Hall A E94-010
- Hall A E97-110 (preliminary)
- Hall A E01-012 (preliminary)

- Open symbols: measured
- Full symbols: include unmeasured estimation
- Violation suggested for proton at large Q^2
  - Q^2 is not a constant for E155x, varies 0.8 ~ 8.2 GeV^2
- But found satisfied for the neutron & ^{3}He
- Mostly unmeasured for proton

Generalized Spin Polarizabilities

- Generalized Spin Polarizabilities:
- how nucleons respond to virtual photons

- Relate to doubly-virtual Compton scattering, with assumption: appropriate convergence and unsubtracted dispersion relation

- Generalized forward spin polarizability $\delta_0\,(Q^2)$

$$\delta_0\,(Q^2) = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} dx x^2[g_1(x,Q^2) - \frac{4M^2x^2}{Q^2}g_2(x,Q^2)]$$

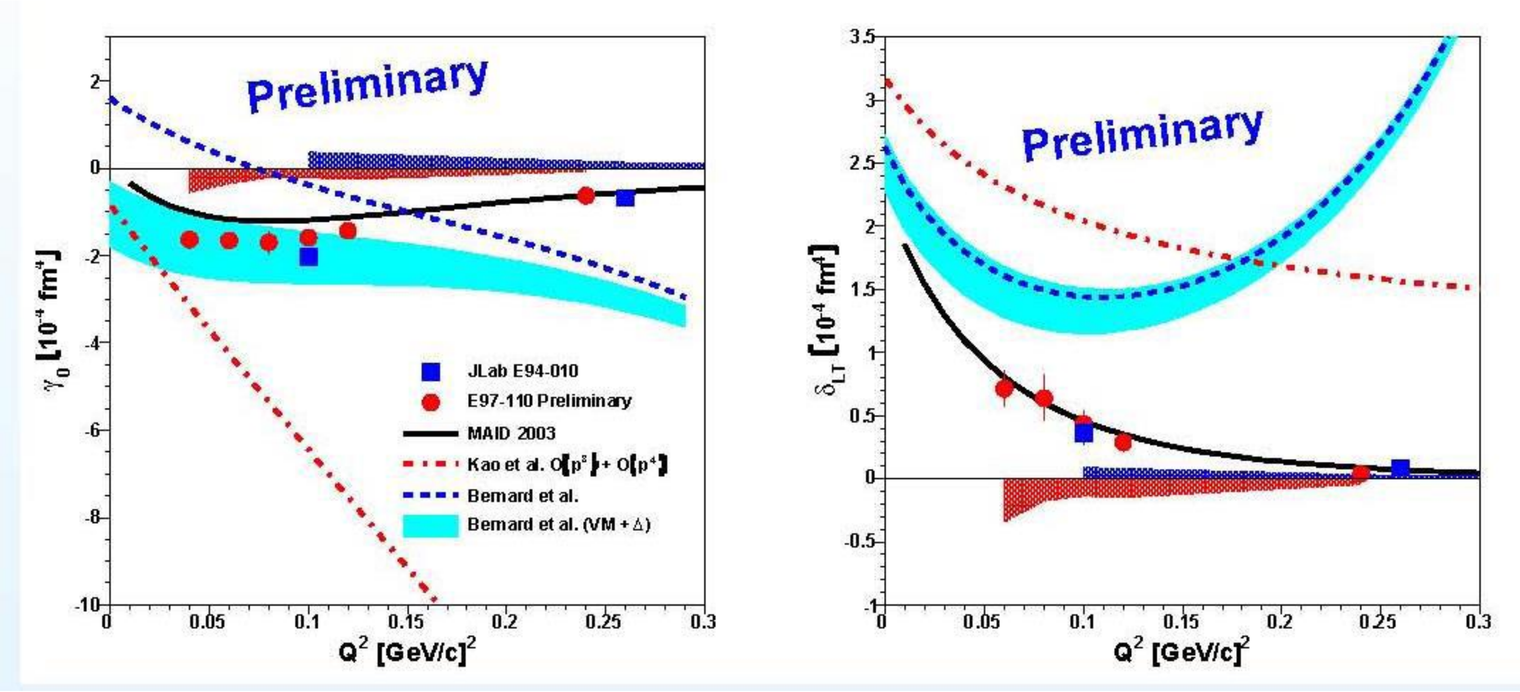
- Generalized longitudinal-transverse spin polarizability $\delta_{LT}\,(Q^2)$

$$\delta_{LT}\,(Q^2) = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} dx x^2[g_1(x,Q^2) + g_2(x,Q^2)]$$

- Can be calculated via Chiral Perturbation Theory

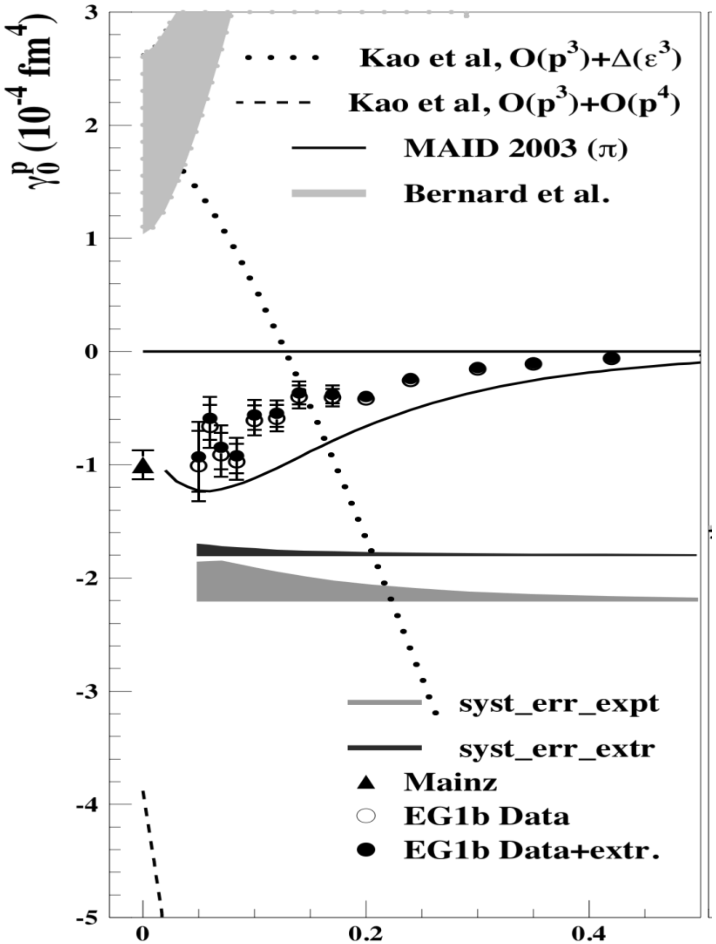
δ_{LT} Puzzle for Neutron

- Neutron data shows large deviation from χPT calculations.
- Good agreement with MAID model predictions



Plots courtesy of V. Sulkosky : Preliminary E97-110 and Published E94-010

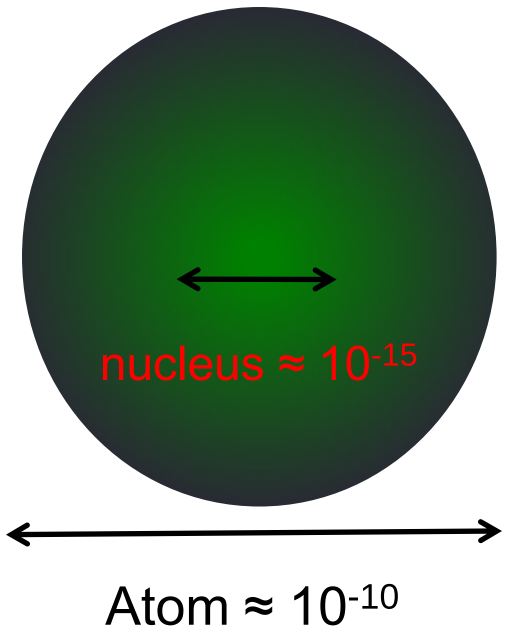
δ_{LT} Puzzle



PLB672, 12 (2009)

- χPT calculations still fails for proton γ_0
- γ_0 sensitive to resonance
- No proton data yet.
- δ_{LT} is insensitive to Δ resonance,
- more clean channel than γ_0 to test the chiral dynamics of QCD

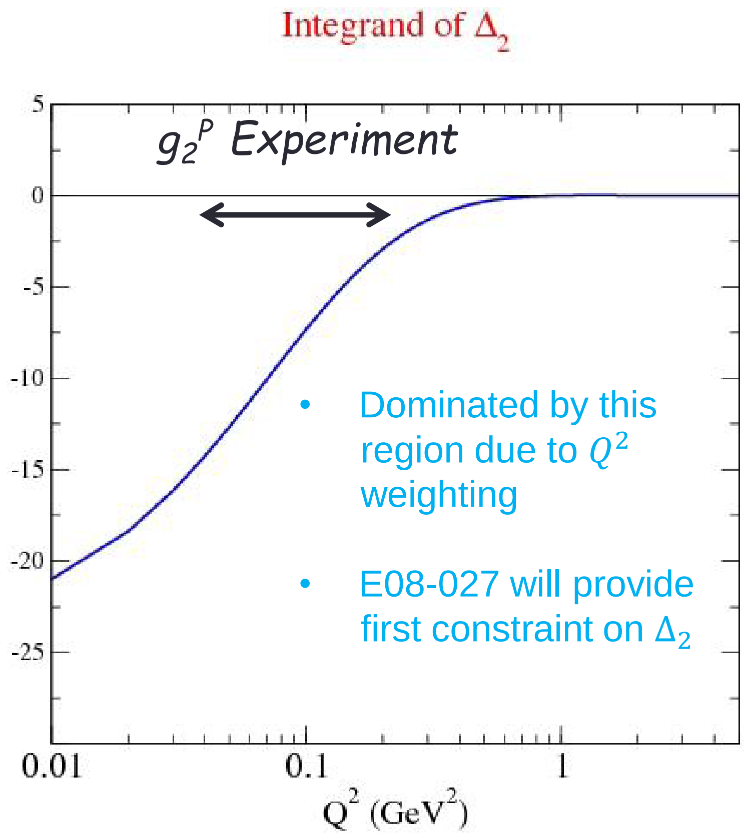
Proton Size



- Two ways to measure;
  - energy splitting of the $2S_{1/2}$-$2P_{1/2}$ level (Lamb shift)
  - scattering experiment
- Do not match when using muonic hydrogen
  - $< R_P > = 0.84184 \mp 0.00067 fm$
    Lamb shift in muonic hydrogen
  - $< R_P > = 0.87680 \mp 0.0006 fm$
    CODATA world average
  - ~6% difference

Hydrogen Hyperfine Splitting

- Hydrogen hyperfine splitting in the ground state has been measured to a relative high accuracy of 10^{-13}.



$$\Delta_E = 1420.405\,751\,766\,7(9)\ MHz$$
$$= (1+\delta)E_F$$

$$\delta = (\delta_{QED} + \delta_R + \delta_{small}) + \Delta_s$$

Δ_s : proton structure function correction

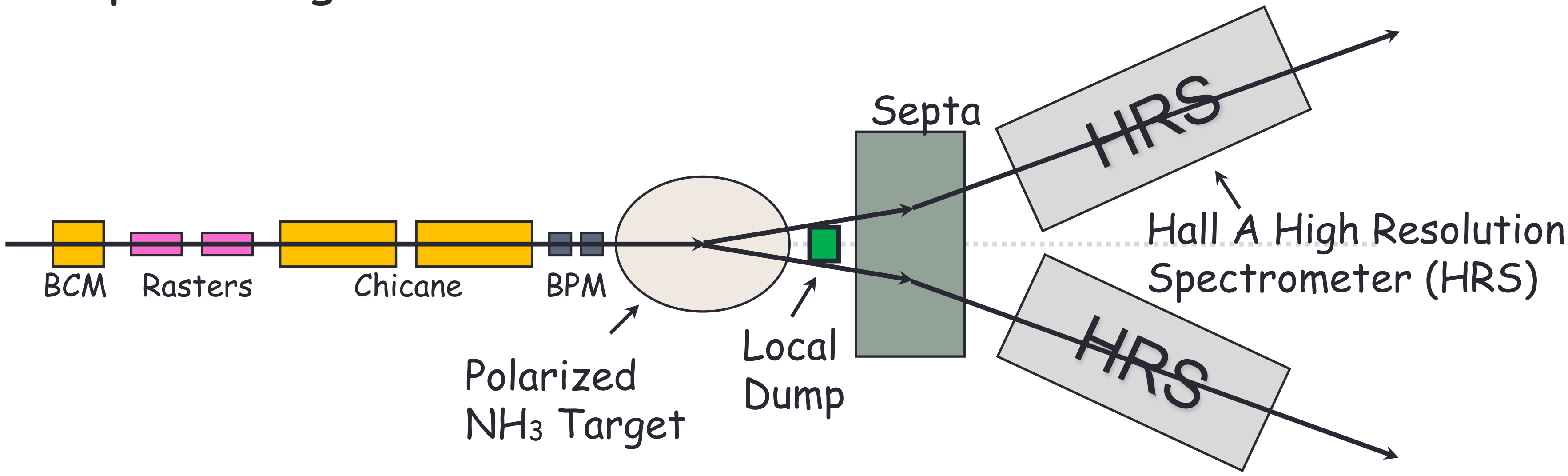
- largest uncertainty
- depends on ground state and excited properties of the proton

$$\Delta_s = \Delta_z + \Delta_{pol}$$

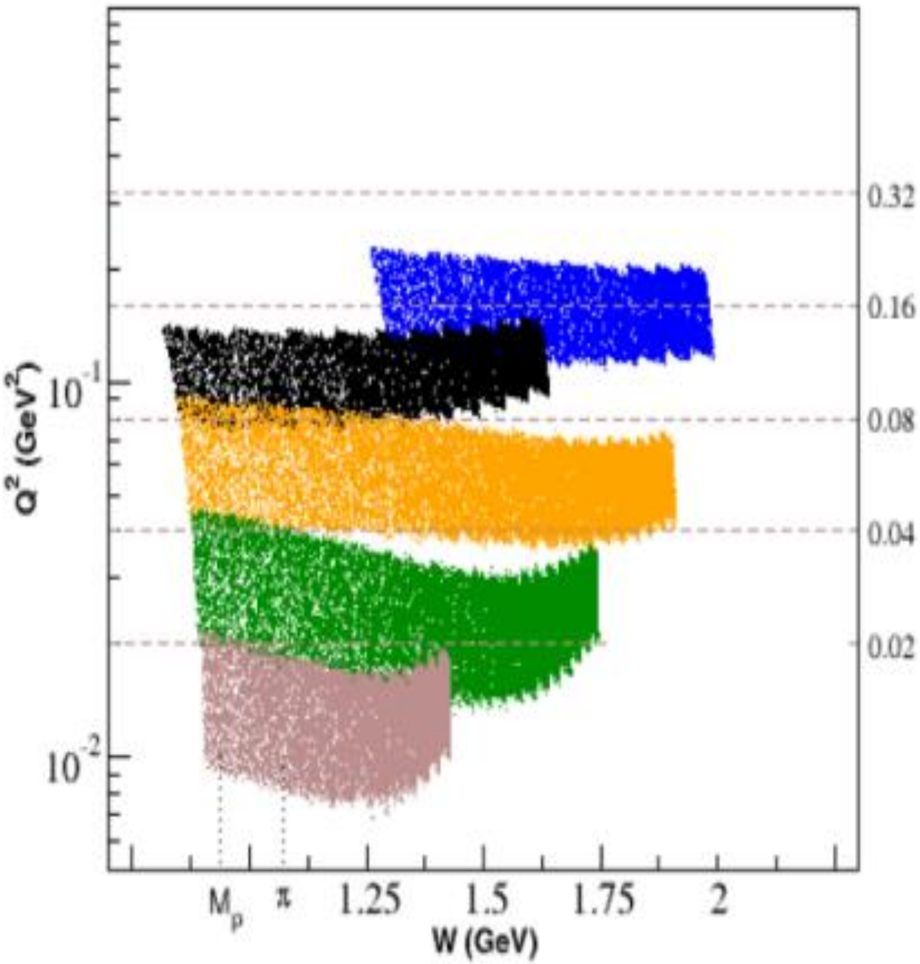
$$\Delta_{pol} = \frac{\alpha m_e}{\pi g_p m_p}(\Delta_1 + \Delta_2)$$

Experiment setup

- Transverse polarized NH_3 target (2.5T/5.0T)
- Low beam current (< 100nA)
- High DAQ rates 6~7kHz with <30% deadtime
- Rasters
- Septum magnets



Kinematic Coverage

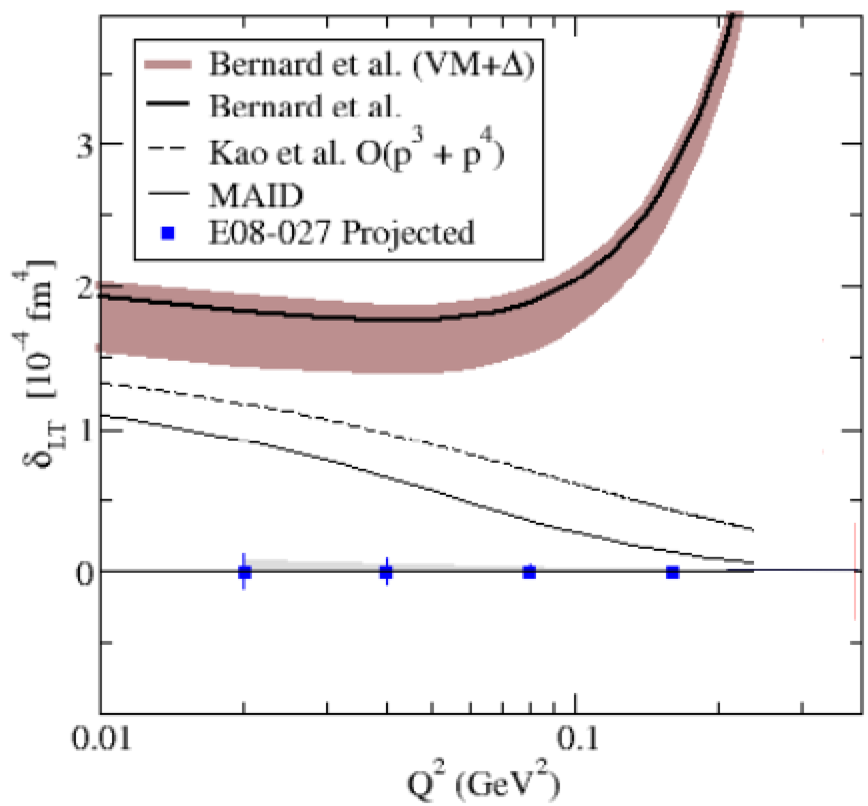


$M_p < W < 2$ GeV
$0.02 < Q^2 < 0.2$ GeV^2

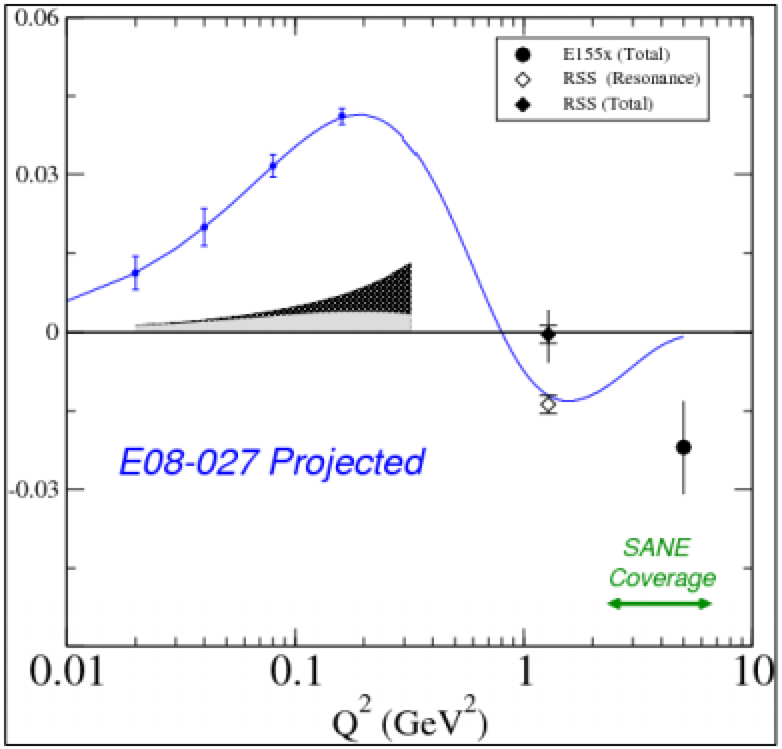
Beam Energy /GeV	Target Field /T
2.254	2.5
1.706	2.5
1.158	2.5
2.254	5.0
3.352	5.0

Projections

LT Spin Polarizability



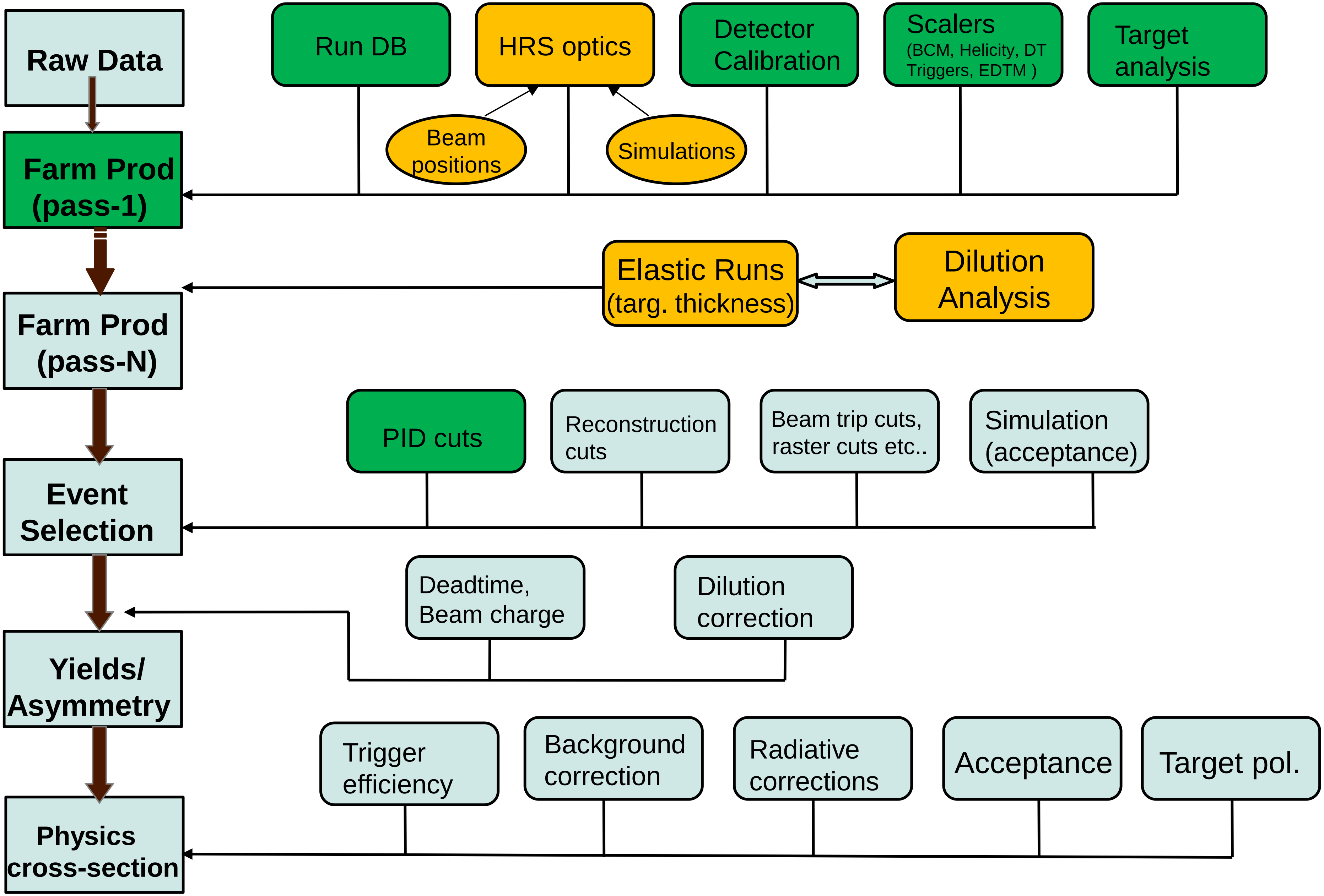
BC Sum Integral Γ_2



$$\delta_{LT}(Q^2) = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2[g_1+g_2]\mathrm{d}x$$

$$\int_0^1 g_2(x,Q^2)\mathrm{d}x = 0$$

Analysis Flow Chart



Analysis Status

Completed:

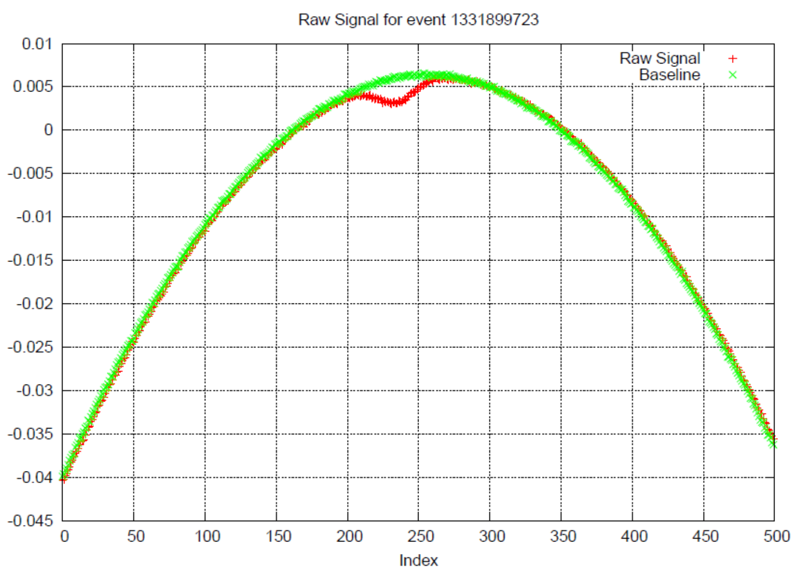
- Run DB
- HRS optics
  - Field measurement analysis
  - VDC t_0 calibration
  - Optimization of straight through runs
  - Simulation package g2psim
- Detector calibration
  - Gas Cerenkov
  - Lead Glass
  - S1 and S2m trigger efficiency
- Scalers
  - BCM calibration
  - Helicity decoding
  - Dead time calculation
- Target polarization analysis

In Progress:

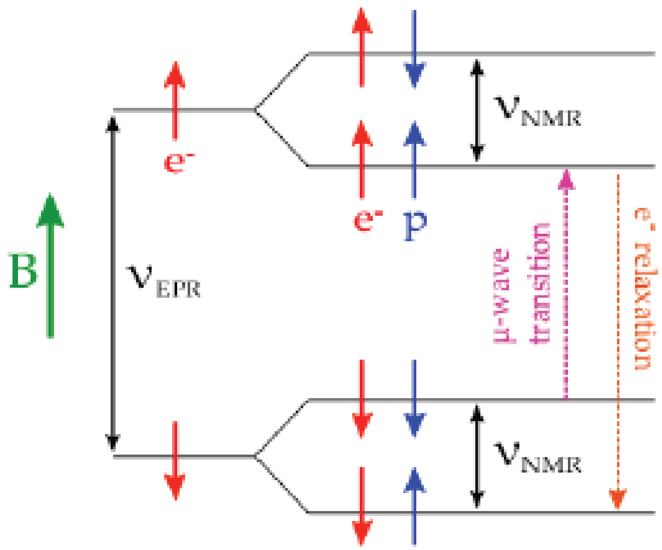
- Optics with target field
- BMP/raster calibration
- Dilution analysis
- Elastic analysis
- Yield/radiative correction

Polarized NH_3 Target

- Target polarization measured via NMR and recorded every 30s.
- Calibrated offline with TE measurements for each material



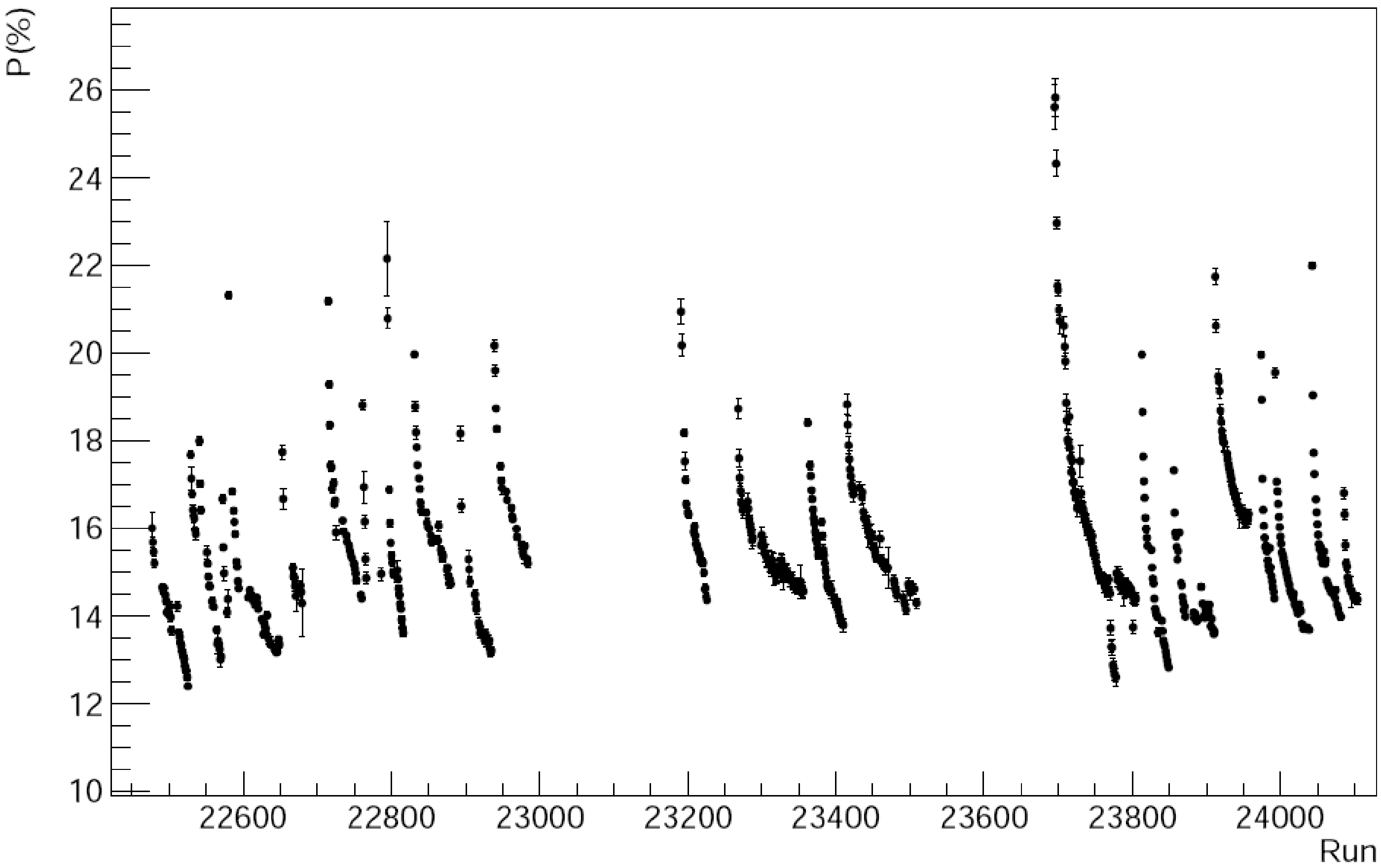
Typical NMR signal



Dynamic nuclear polarization

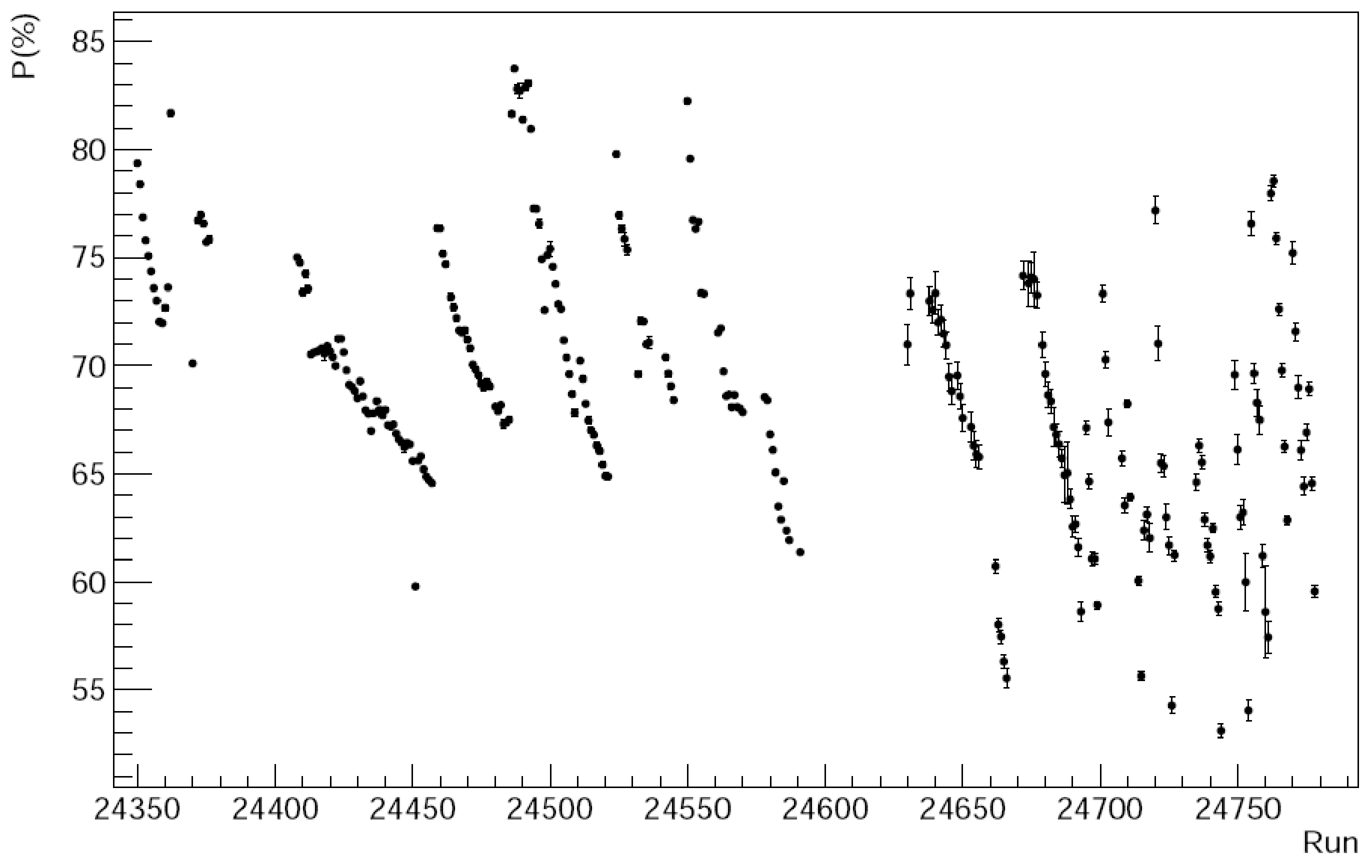
Polarized NH_3 Target

- Polarization with 2.5T



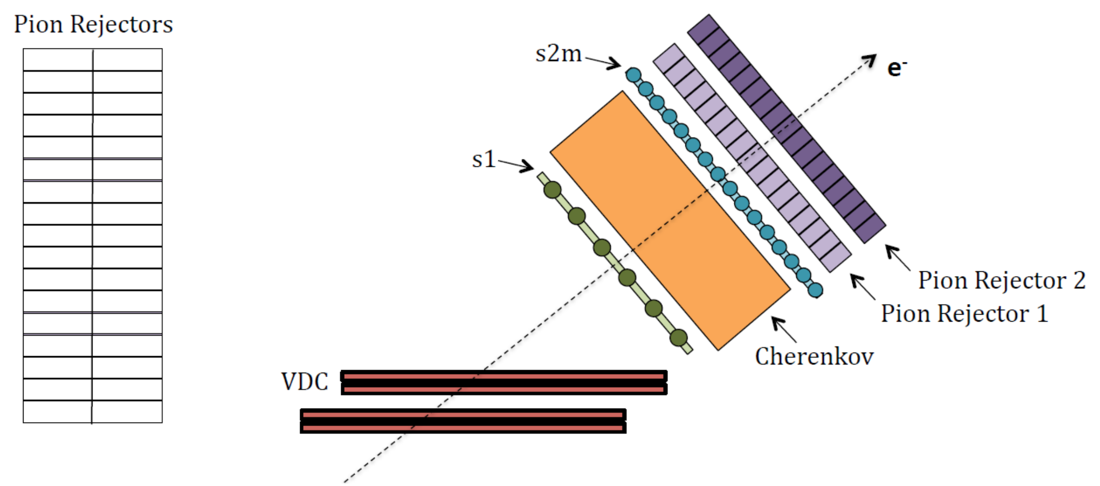
Polarized NH_3 Target

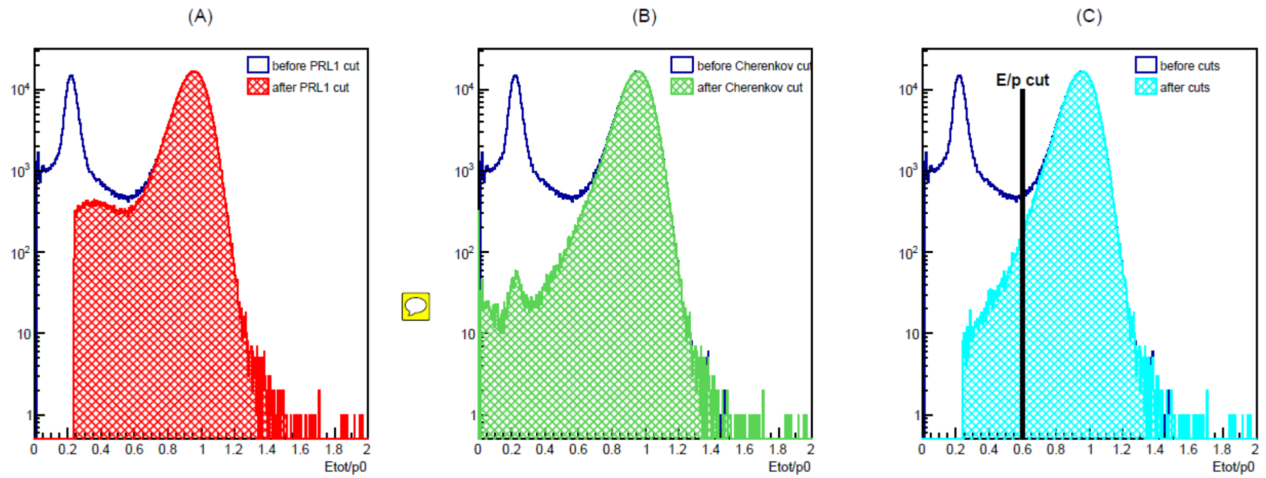
❑Polarization with 5T



Detectors Cut Efficiency

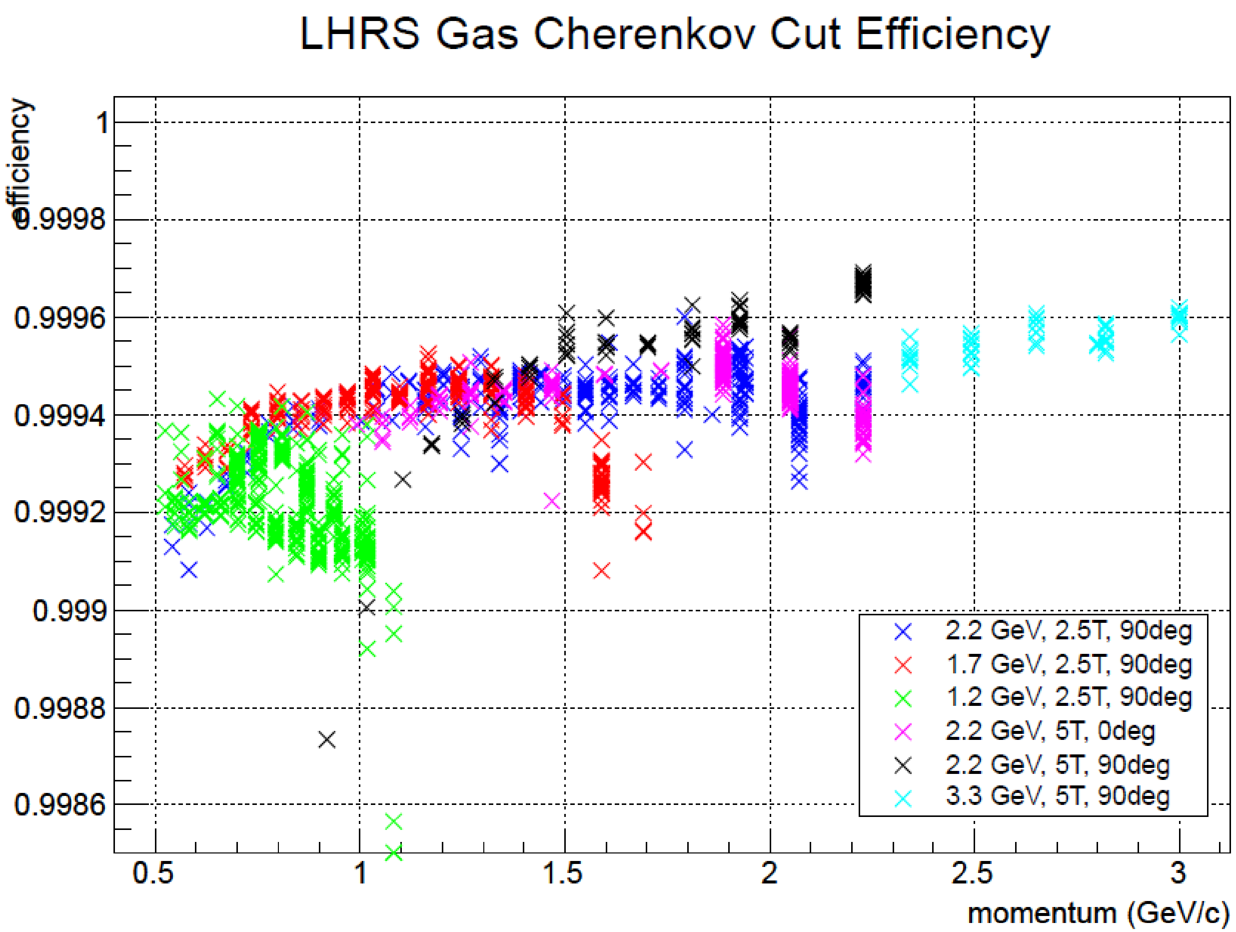
❑Detectors





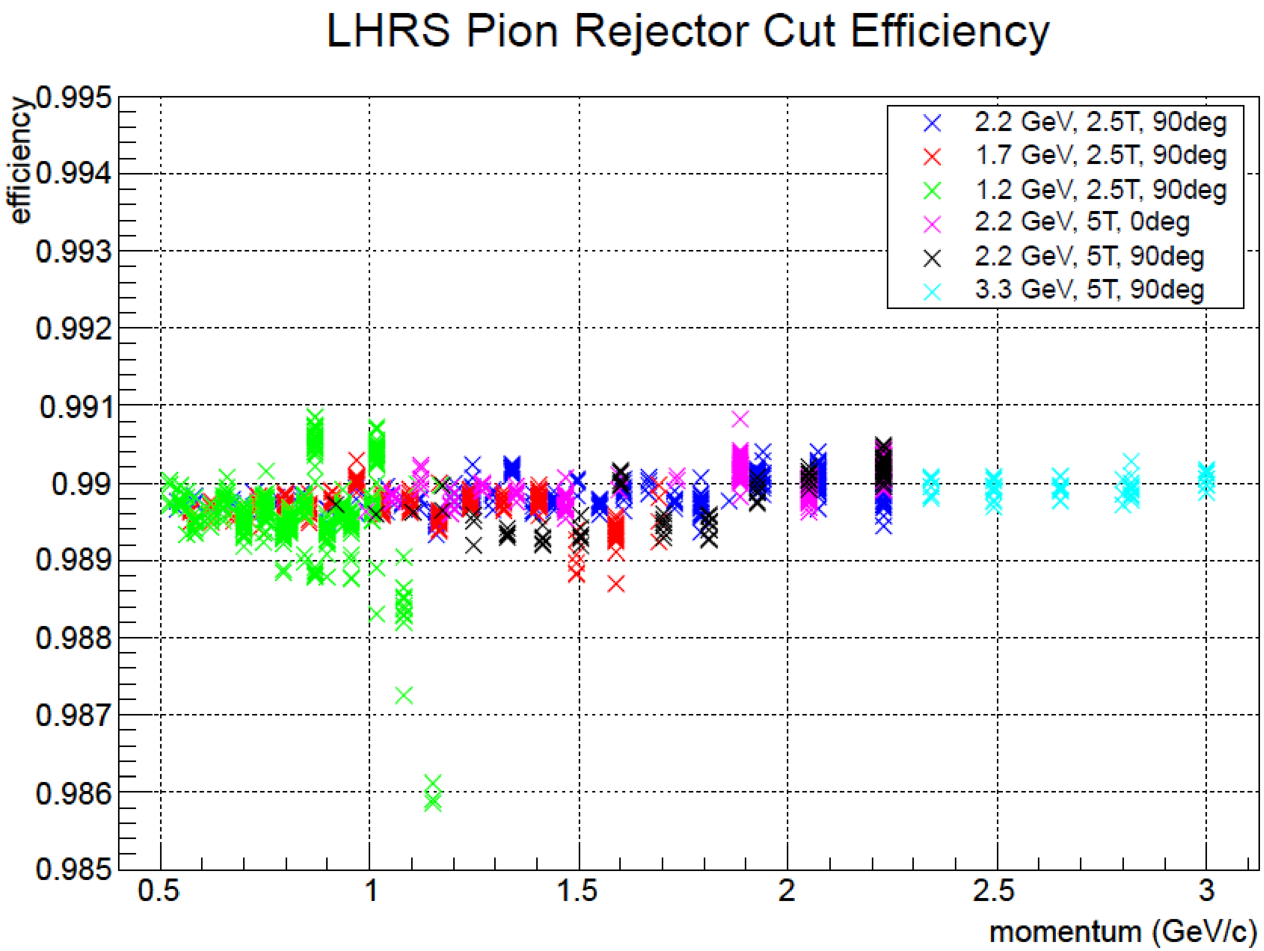
Detectors Cut Efficiency

- Detectors



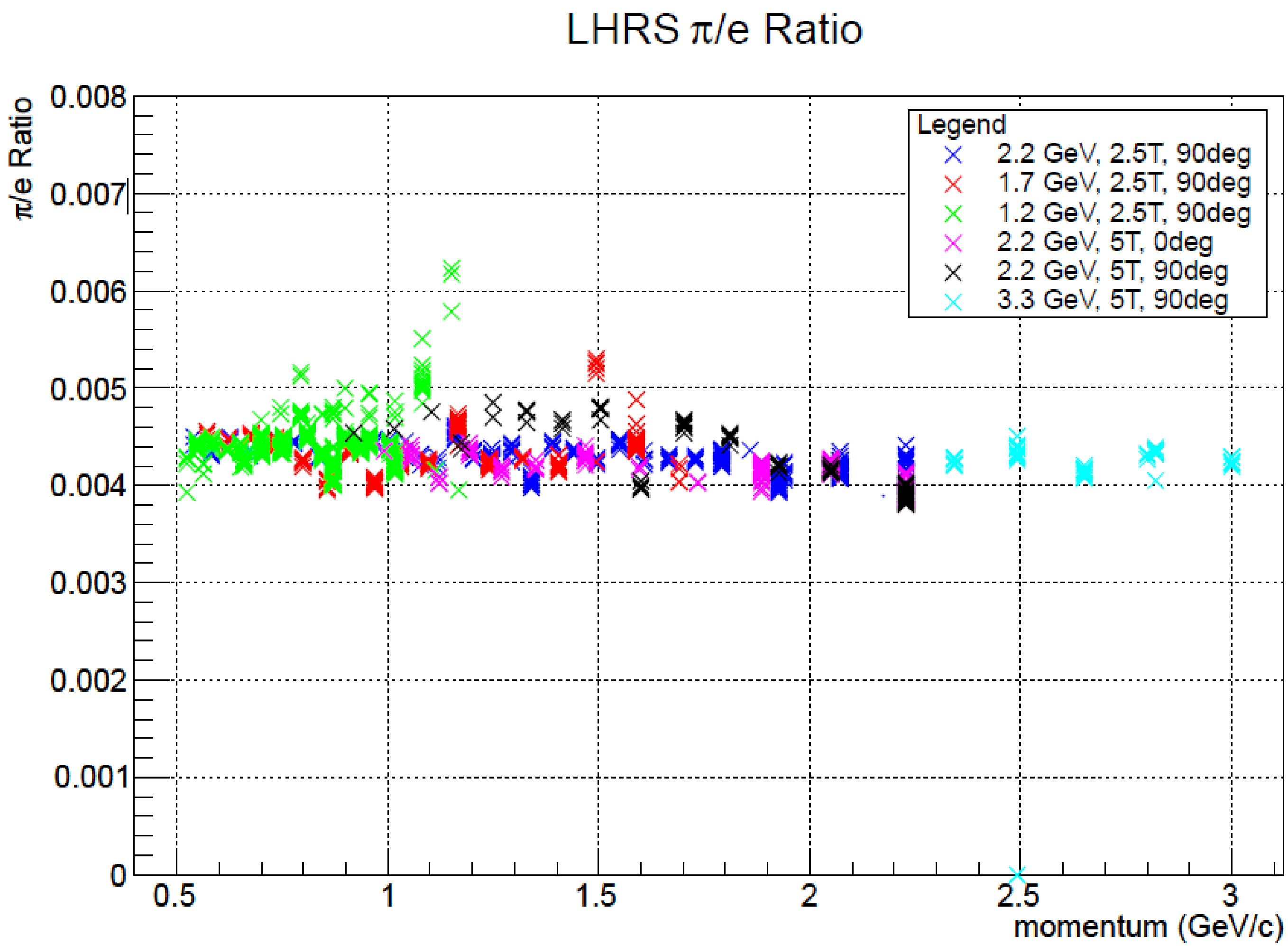
Detectors Cut Efficiency

❑Detectors



Detectors Efficiency

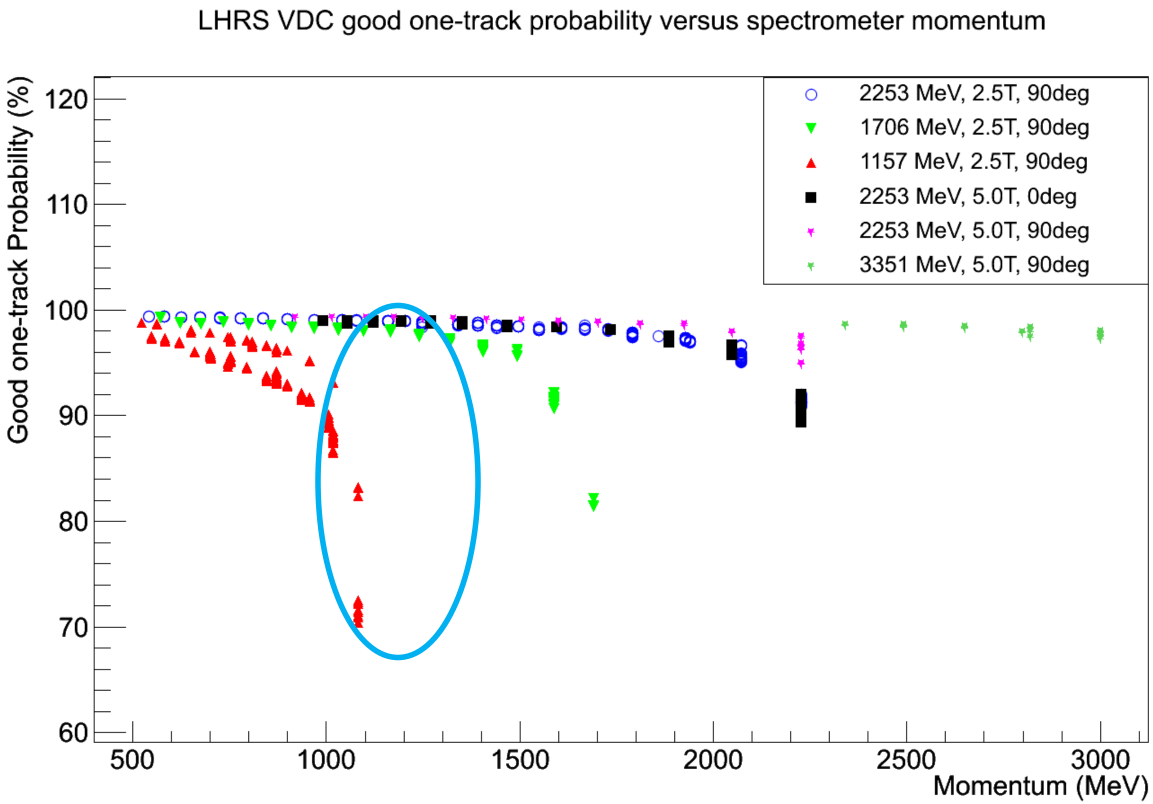
❑ Detectors



VDC Multi-track Study

❑Motivation

- VDC one track events probability gets as low as 70% around elastic region

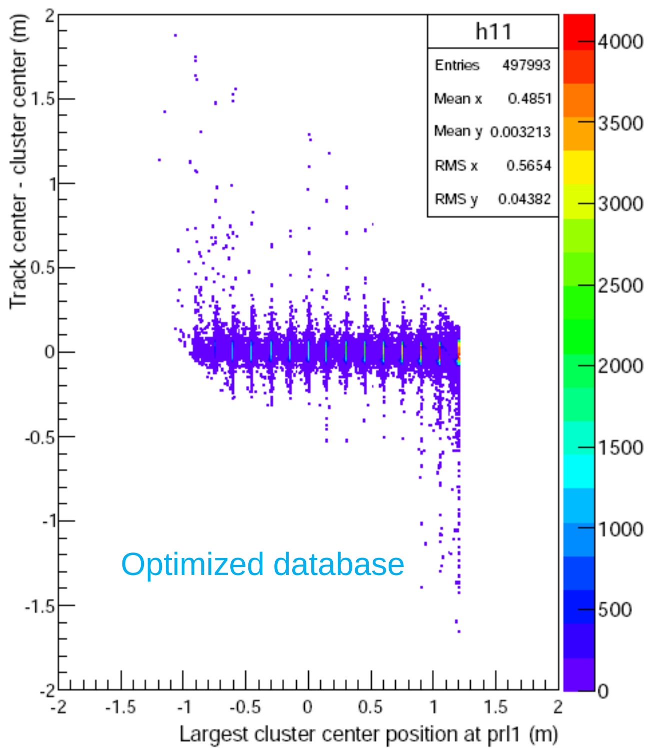


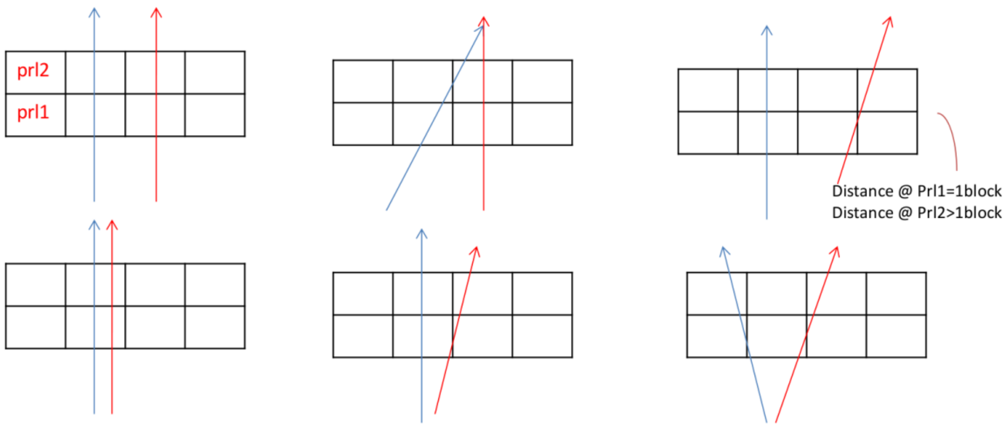
VDC Multi-track Study

- **Method**: point the track from VDC to calorimeters and sum up the total energy in the surrounding lead glass blocks.

- **Requirements**:
  - A good position databse for lead glass (can reconstruct from data).
  - A detailed case study for cluster energy contamination between tracks.

Cluster center comparison for prl1

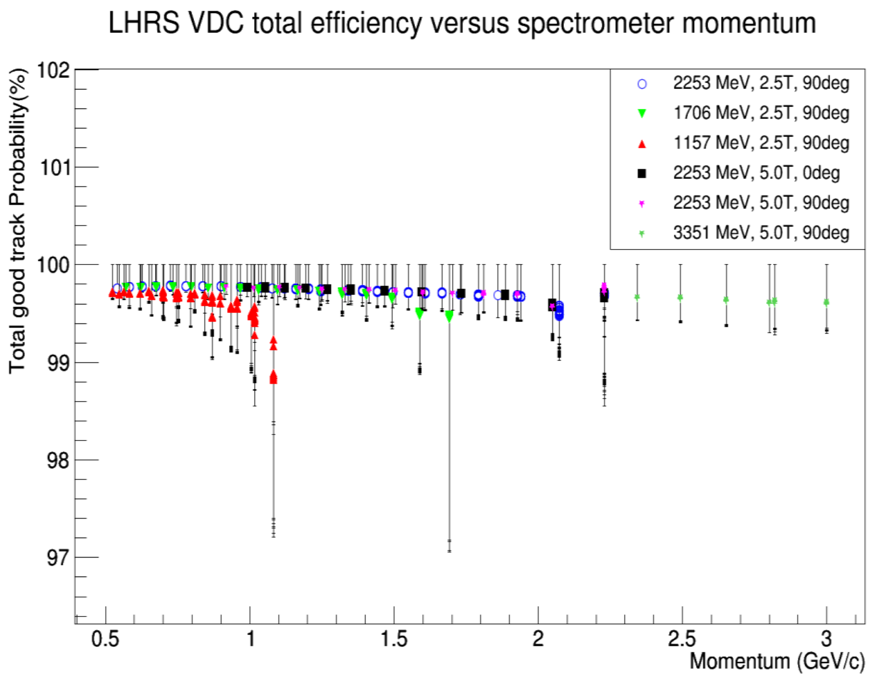


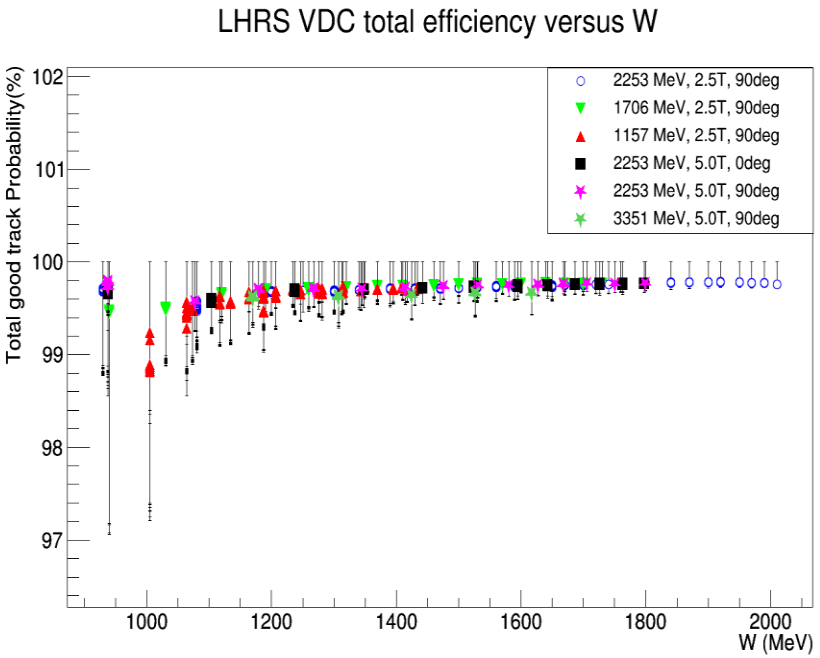


Several kinds of cluster overlap between two tracks

VDC Multi-track Study

- The VDC efficiency systematic uncertainty down to below 1% for most kinematic settings.



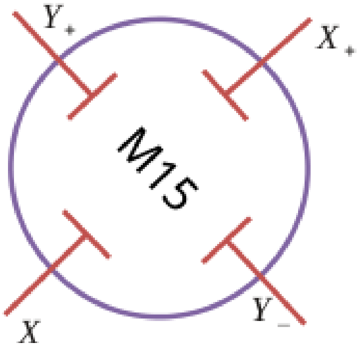


Beam Position Calibration

❑Beam Position Monitor

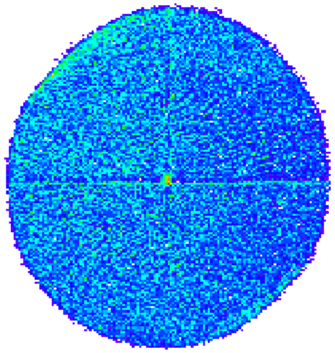
$$x_b = \frac{f(A_+ - A_{+ped}) - f(A_- - A_{-ped})}{f(A_+ - A_{+ped}) + f(A_- - A_{-ped})}$$

$$f(A - A_{ped}) = a(A - A_{ped} - b)$$

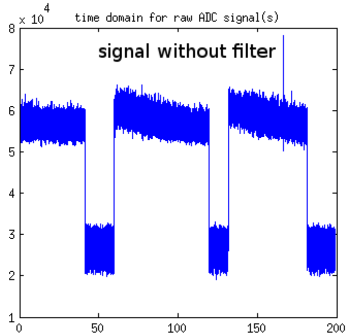


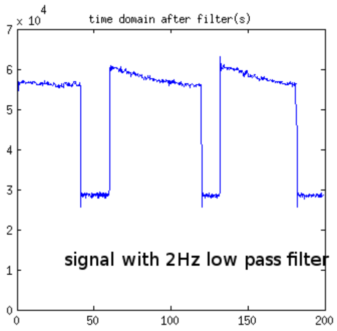
❑Slow Raster

- First time use in Hall A
- Shape about 2cm in diameter



- Software filter for better signal/noise





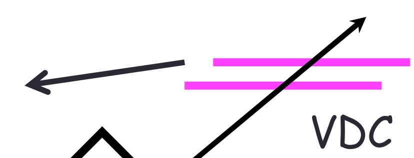
Optics

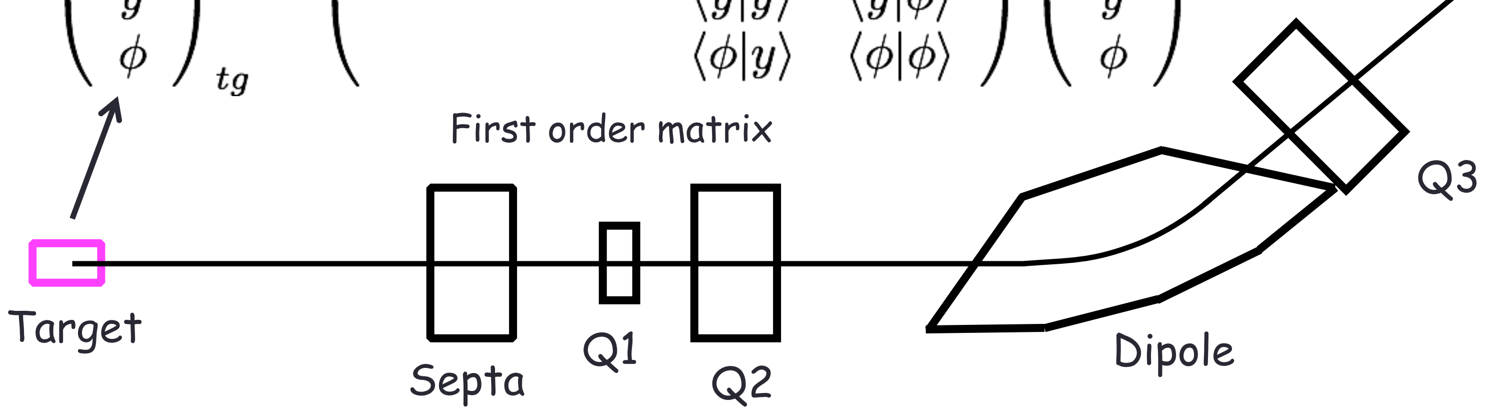
❑ Optics study:

- < 1.0% systematic uncertainty of scattering angle, which will contribute < 4.0% to the uncertainty of cross section
- Reconstruct the kinematics variables of the scattered electrons with the tracking information by a matrix

$$\begin{pmatrix} \delta \\ \theta \\ y \\ \phi \end{pmatrix}_{tg} = \begin{pmatrix} \langle\delta|x\rangle & \langle\delta|\theta\rangle & & \\ \langle\theta|x\rangle & \langle\theta|\theta\rangle & & \\ & & \langle y|y\rangle & \langle y|\phi\rangle \\ & & \langle\phi|y\rangle & \langle\phi|\phi\rangle \end{pmatrix} \begin{pmatrix} x \\ \theta \\ y \\ \phi \end{pmatrix}$$

First order matrix





Optics with No Field

❑ Performance summary:

- Beam energy 2.254 GeV, no target field, 1st & 3rd septum, carbon foil

Resolution (RMS)	LHRS (1st)	RHRS (1ST)	LHRS(3rd)
In-plane angle (mrad)	0.9	0.9	0.7
Out-of Plane Angle (mrad)	1.5	1.6	1.4
Momentum $(p_0 - p)/p_0$	$1.3*10^{-4}$	$2.0*10^{-4}$	$1.8*10^{-4}$

1st Septum: good septum with coil 48-48-16 symmetric
3rd Septum: broken twice with coil 40-00-16

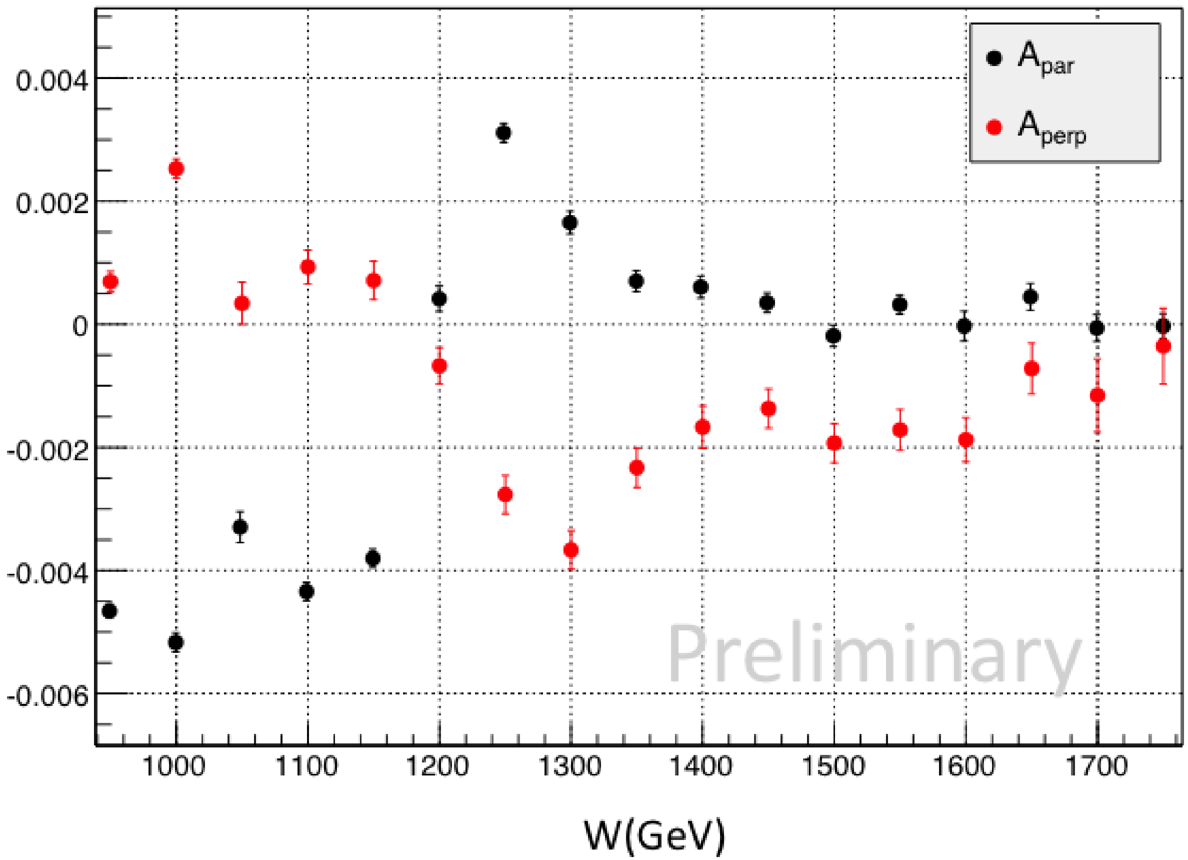
Optics with Field

- LHRS Performance summary:

Beam Energy (GeV)	Field (T)	Field Angle (deg)	Septum	Backup
2.253	0.0	90	484816	Straight through
2.253	0.0	6	484816	Straight through
2.253	5.0	0	400016	Straight through
2.253	2.5	90	484816	
2.253	2.5	90	483216	
1.706	2.5	90	400016	
1.158	2.5	90	400016	
2.253	5.0	90	400016	No full dp scan

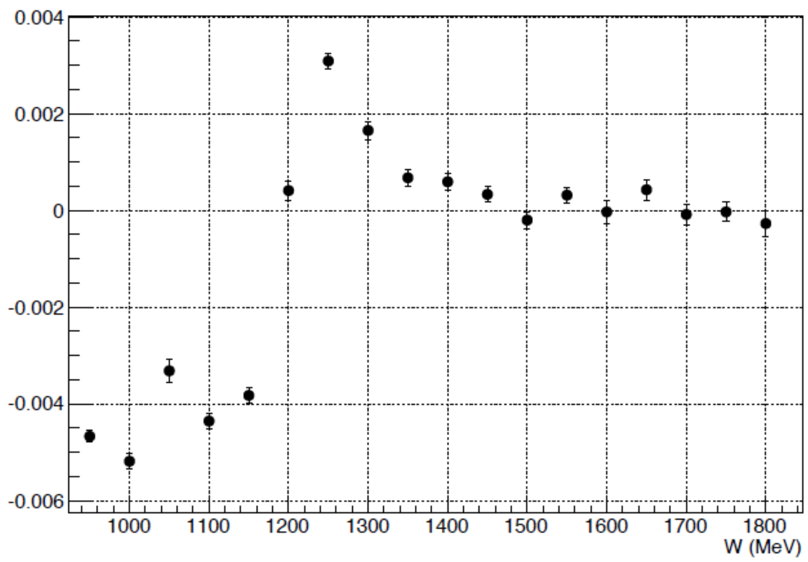
Asymmetry

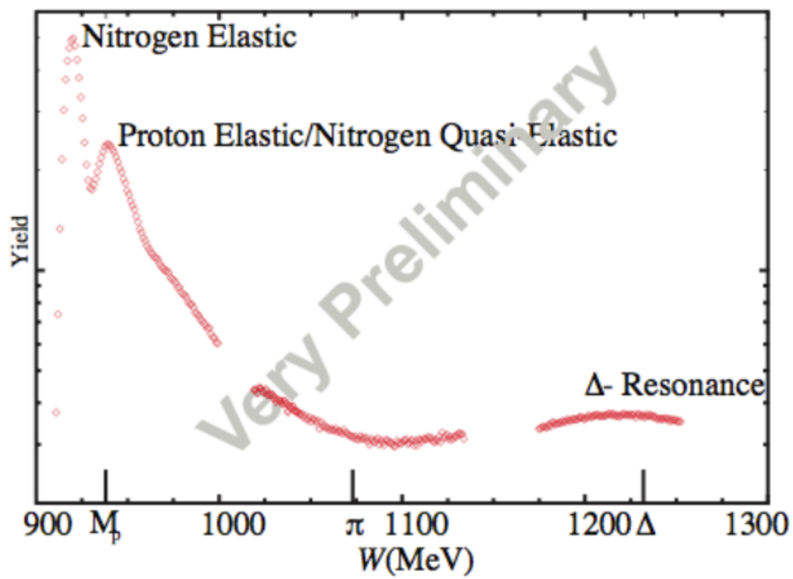
- Raw asymmetry : $A_{raw} = \frac{Y_+ - Y_-}{Y_+ + Y_-}$ yield: $Y_\pm = \frac{N_\pm}{Q_\pm L T_\pm}$
- Physics asymmetry: $A_{phys} = \frac{1}{f P_b P_t} A_{raw}$ $f = 1\ here$



G_2^P Summary

- The g2p experiment took data covering $M_p < W < 2$ GeV, $0.02 < Q^2 < 0.2$ GeV^2
- Will provide a precision measurement of g_2^p in the low Q^2 region for the first time
- Results will help to understand several physics puzzles, such as δ_{LT}





G_2^p Collaboration

- **Spokepeople**
  - Alexandre Camsonne (Jlab)
  - Jian-Ping Chen (JLab)
  - Don Crabb (UVA)
  - Karl Slifer (UNH)
- **Post Docs**
  - Kalyan Allada
  - Elena Long
  - James Maxwell
  - Vince Sulkosky
  - Jixie Zhang
- **Graduate Student**
  - Toby Badman
  - Melissa Cummings
  - Chao Gu
  - Min Huang
  - Jie Liu
  - Pengjia Zhu
  - Ryan Zielinski

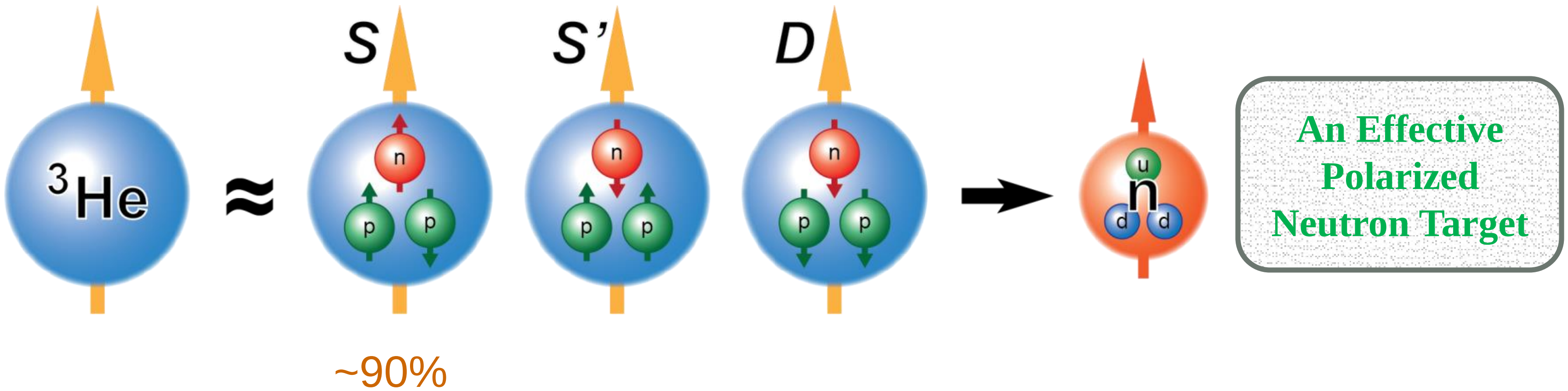
^{3}He Outline

- Introduction
- Upgrade Plan
- R&D Progress
- Summary

Introduction

- **Why Polarized ^{3}He Target**

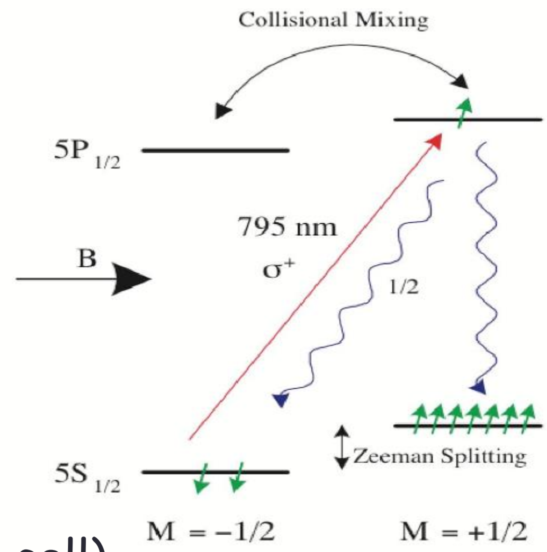
- Polarized targets essential for nucleon spin structure study
- Free neutrons, short lifetime < 15 minutes
- ^{3}He and deuteron are two good candidates for an effective neutron target.



Introduction

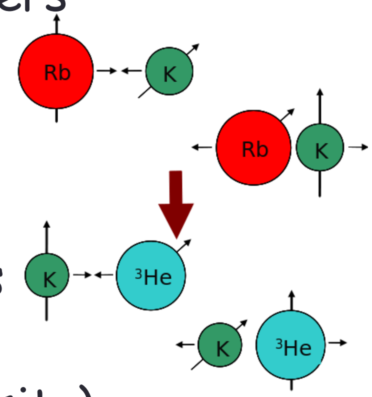
❑ How to polarize ^{3}He Target

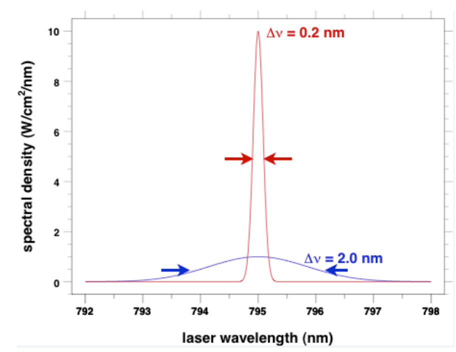
- Spin-exchange optical pumping (SEOP)
  - Polarize the alkali metal atoms
  - Exchange spin with ^{3}He



❑ Recent improvements in the SEOP:

- The change from Rb to Rb-K mixture (hybrid cell)
- The use of spectrally-narrowed diode lasers

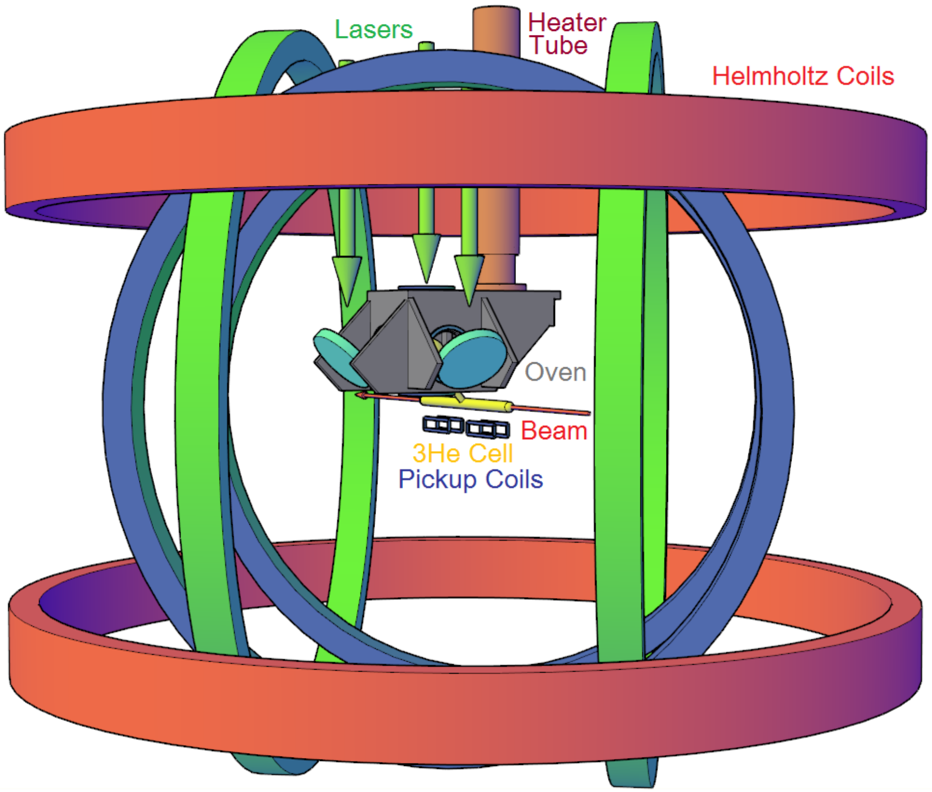




❑ Progress

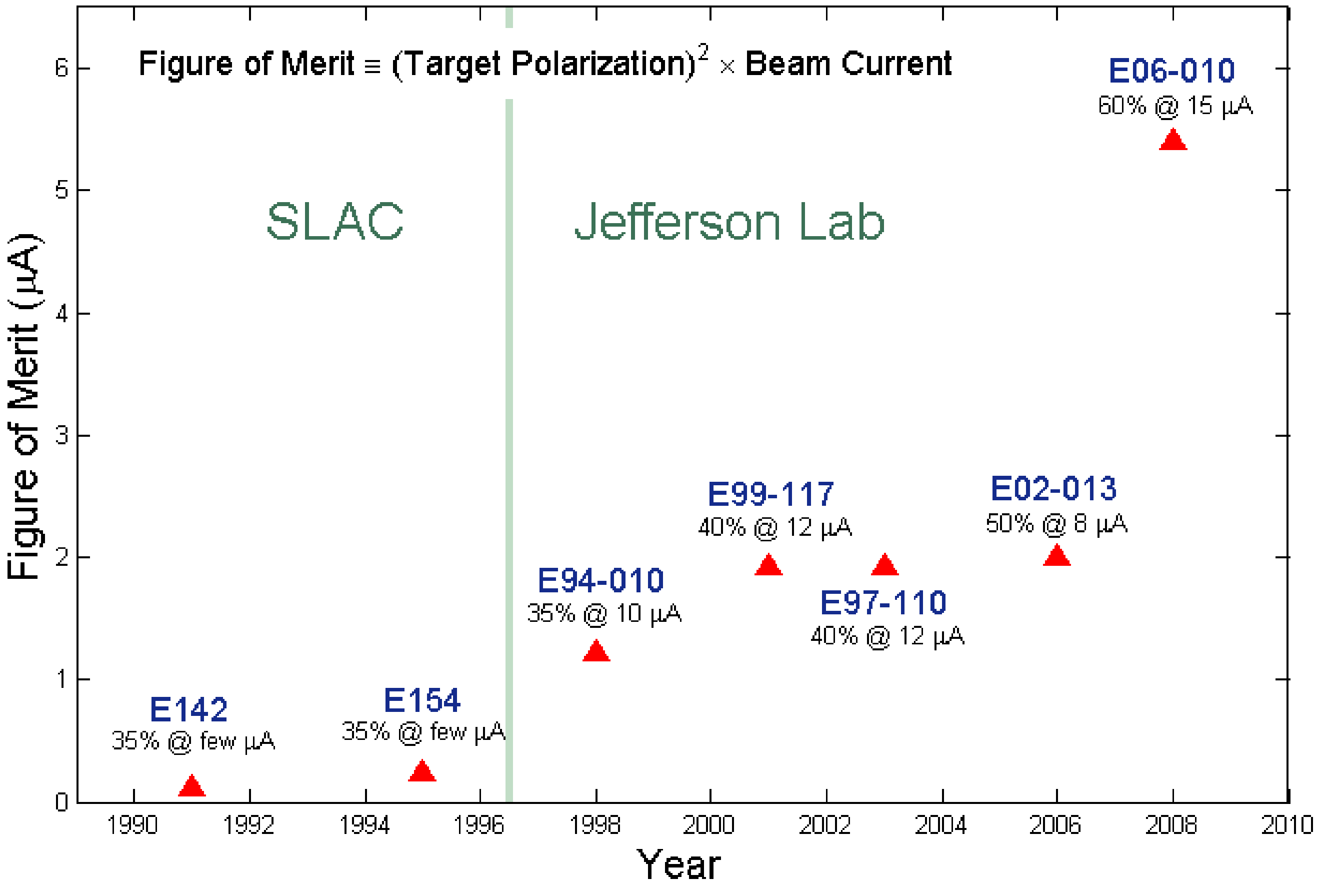
- Spin up time shorten: 10 →about 5 hours
- In-beam target polarization:
  40% → 50% (GEN) → 60% (Transversity)

JLab Polarized ^{3}He Target Overview



- ✓longitudinal, transverse and vertical
- ✓Luminosity=10^{36} ($1/cm^2/s$)
  (highest in the world)
- ✓High in-beam polarization 55-60%, maximum reached over 70% without beam
- ✓Polarimetry: NMR/water +EPR
  total uncertainty 3~5%
- ✓Effective polarized neutron target
- ✓13 completed experiments
  7 approved with JLab 12 GeV

Figure-of-Merit History for High Luminosity Polarized ^{3}He Target



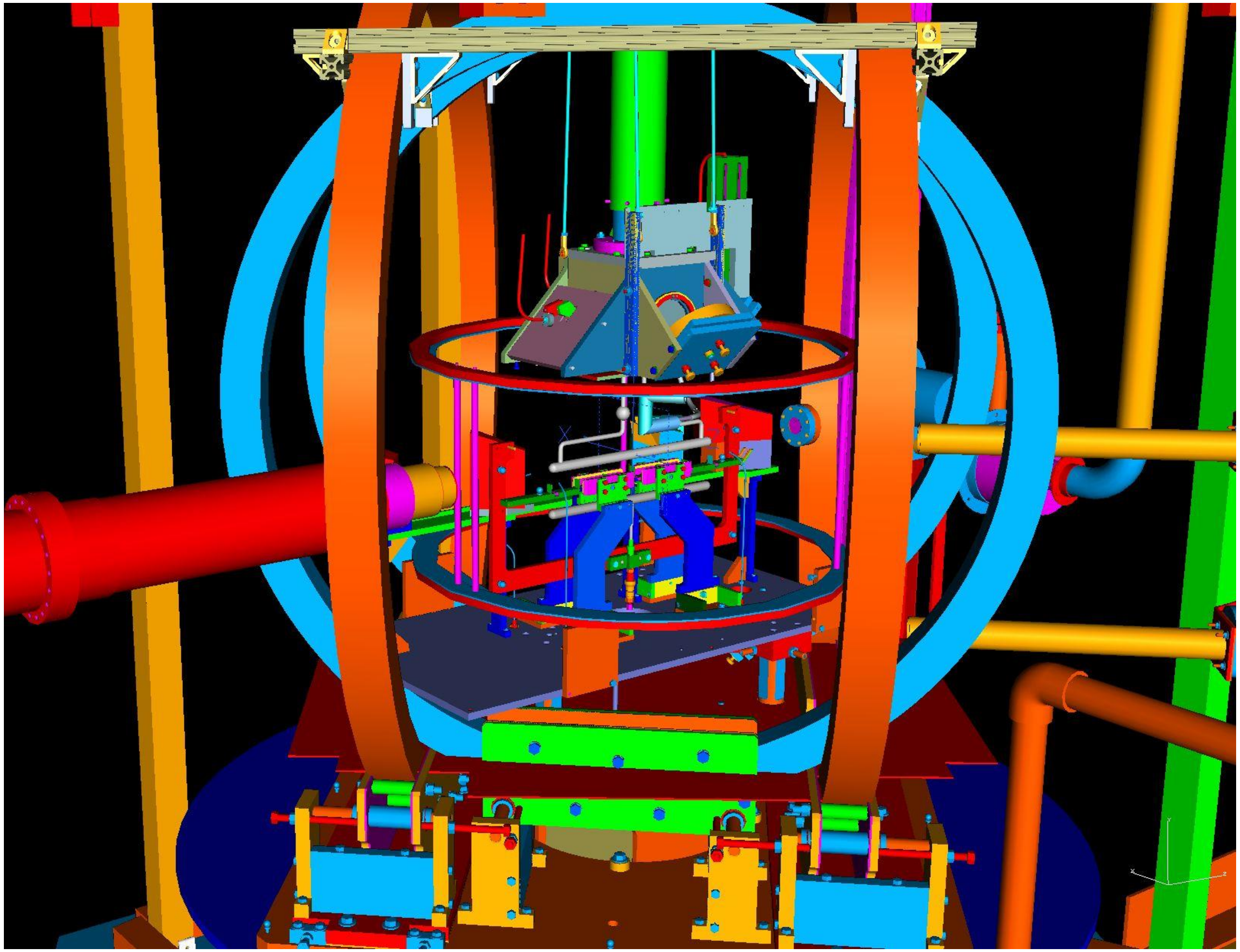
^{3}He Target Upgrade Plan

- Upgrade the target with a factor of 2~3 in FOM of the best achieved

- To satisfy A_1^n -A requirements/plan:
  - 30 uA on 40 cm convection cell, 60% in beam, 3% polarimetry
  - Use transversity setup with convection cell
    - Uniform polarization between target and pumping chambers
    - → 60% achievable
    - → Eliminate diffusion uncertainty
  - Pulsed NMR, calibrated with EPR and AFP NMR/water ,
  - k_0 measurements (users)

- R&D progress:
  - Mechanical design
  - Diffusion model test
  - Convection cell tests/transfer heater design
  - Polarization loss study (field gradient, new material, …)
  - Pulsed NMR setup and systematic study
  - Laser system study
  - Higher current study: shielding needs?

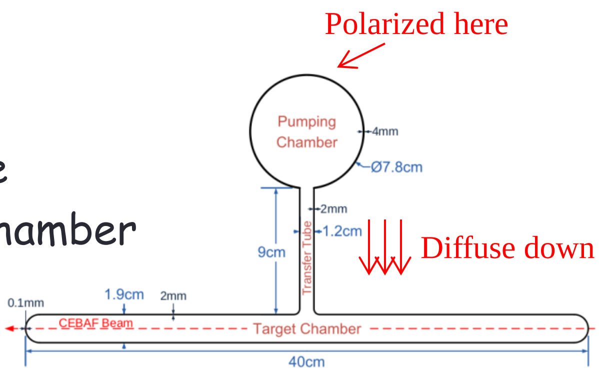
Mechanical Design

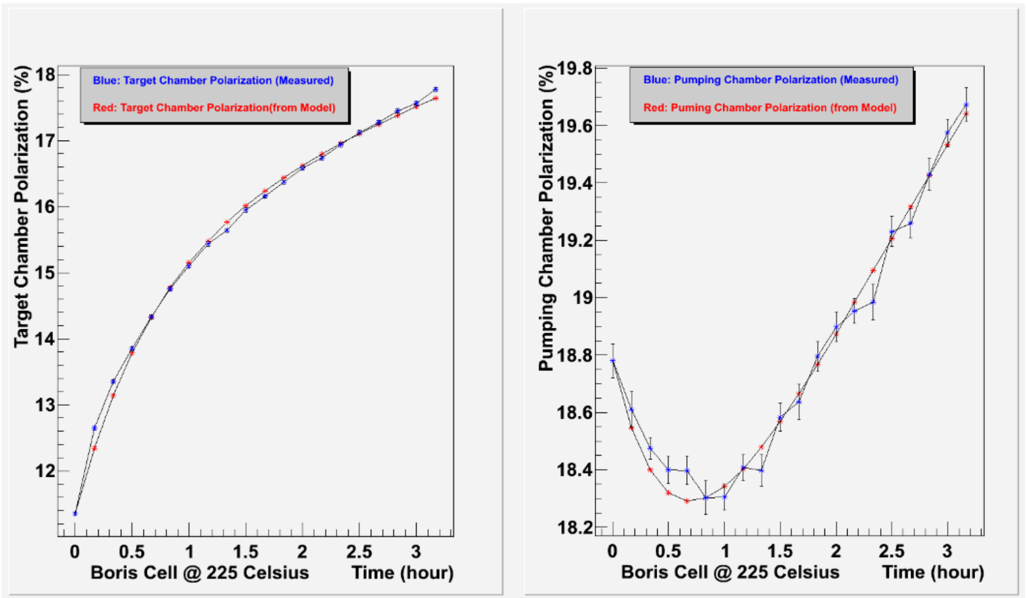


Diffusion Model Test

❑Diffusion Model Test:

- Pump up to high polarization
- Destroy spin polarization along target chamber
  Keep pumping chamber polarization as high as possible
- Record the dynamics of polarization progress in two chamber
- Water NMR calibrate the target chamber NMR signal
- EPR calibrate the pumping chamber NMR signal



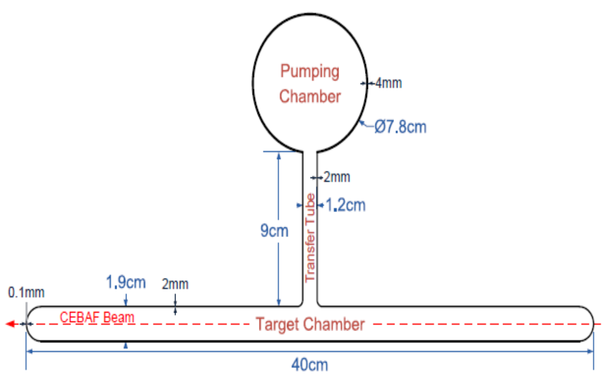


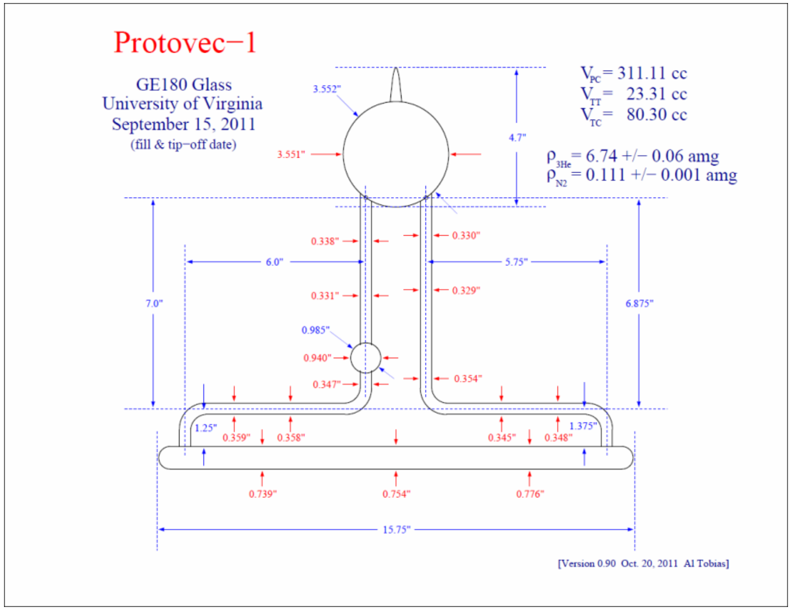
➢ **Preliminary Result:**
Diffusion time ~ 40 mins

Diffusion Cell to Convection Cell

❑New convection style cell (single pumping chamber)

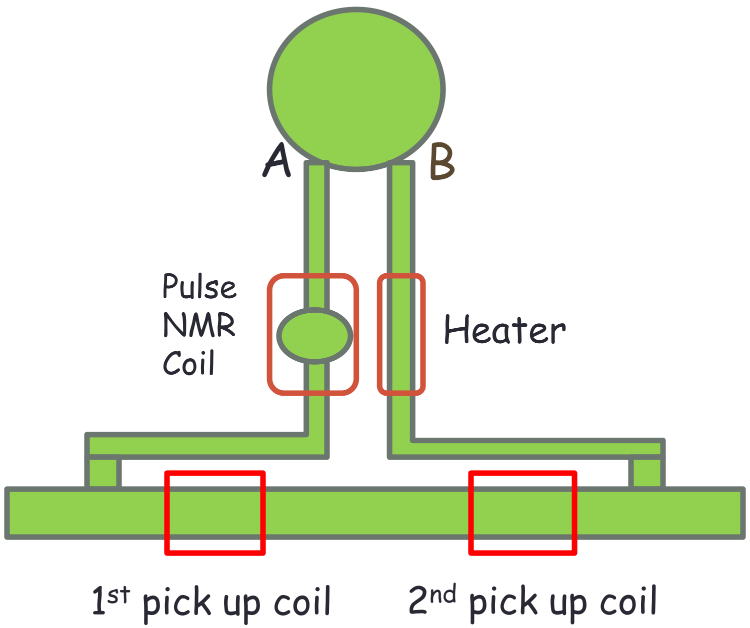
- "Protovec-I" tested at UVa, transferred to JLab a few months ago
- 3D measurement of the cell, CAD model
- Made customized mount and oven bottom piece
- Testing ongoing at JLab now





^{3}He Convection Heater

❑ **Heater choice and effects study**



Silicone Rubber Encapsulated Heating Tape

Kapton (polyimide film) heater
Excellent radiation resistance

Heater instead of convection oven?

Advantage:

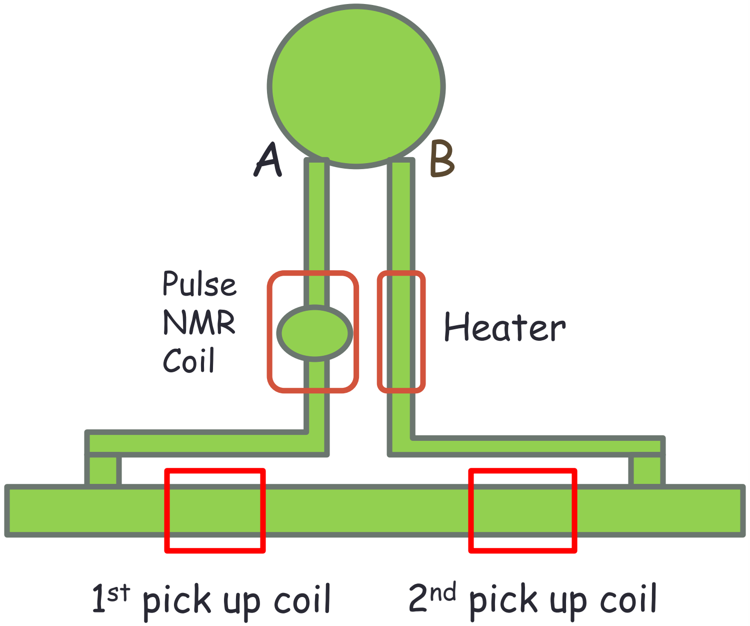
Reduce oven design labor

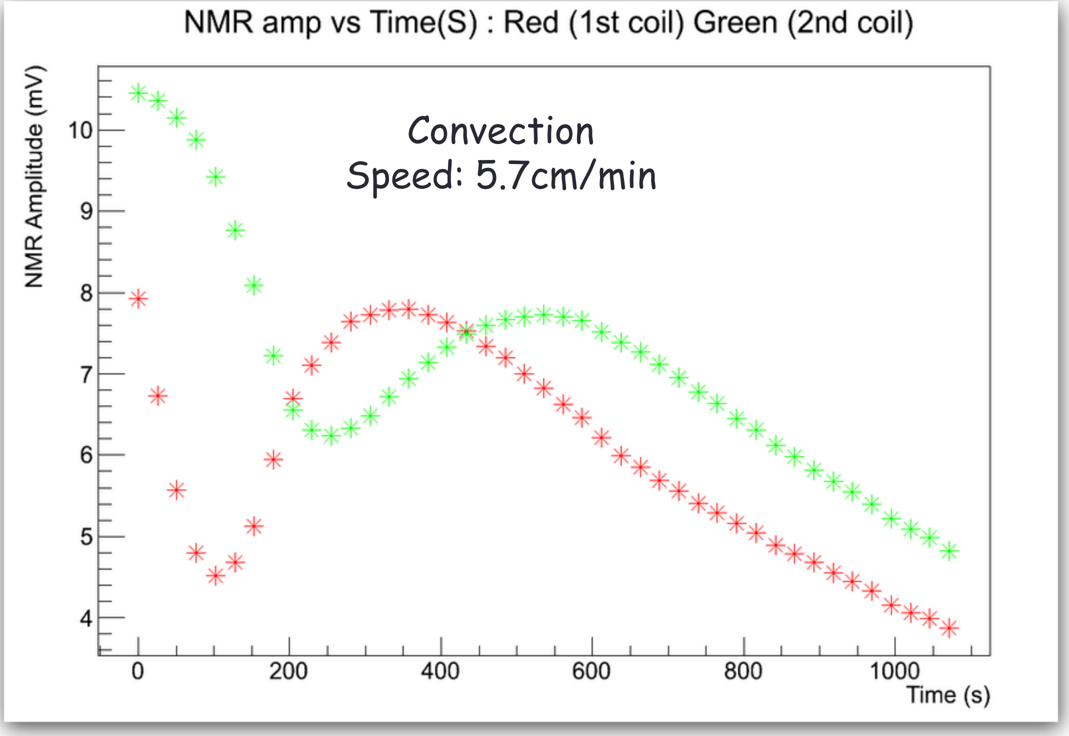
More convenient to replace cell...

Problem: Affect AFP?

^{3}He Convection Speed Test

- Convection can be much fast than diffusion (~40mins)

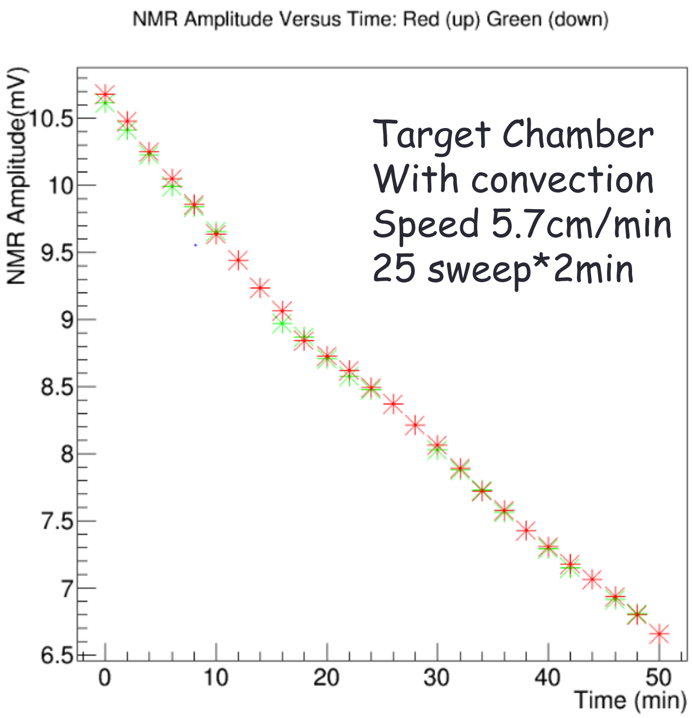


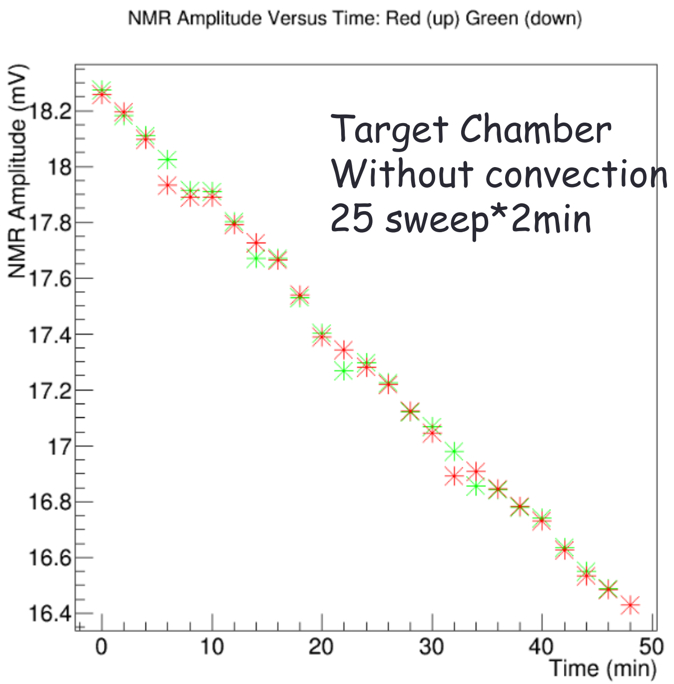


Convection from pumping chamber A to target chamber: ~1 min

Convection from pumping chamber A, through target chamber, back to B: ~8 mins

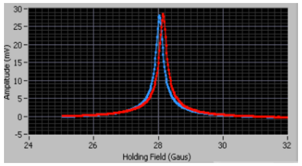
AFP Loss Study





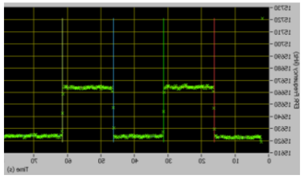
AFP Loss Per Sweep	Target Chamber	Pumping Chamber
AFP Without Convection	0.16%	0.72%
AFP With Convection	0.85%	0.87%

^{3}He Target Polarimetry



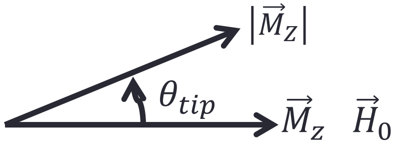
❑Adiabatic Fast Passage (AFP) - NMR

- AFP-NMR works for both 3He and water
- AFP loss significant for longer/larger cell due to field gradient
- Will not work for metal target chambers or hybrid glass/metal cells



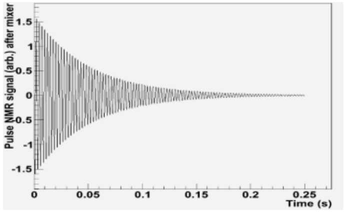
❑Electron Paramagnetic Resonance (EPR)

- EPR will still work



❑Pulsed NMR

- Send a pulse tuned at Larmor Frequency
- Spin presses tipping from holding field
- $\theta_{tip} = \frac{1}{2}\gamma H_1 t_{pulse}$
- Spin components orthogonal to holding field,
- Have free-induction-decay, Amplitude$\propto M_z \sin(\theta_{tip})$

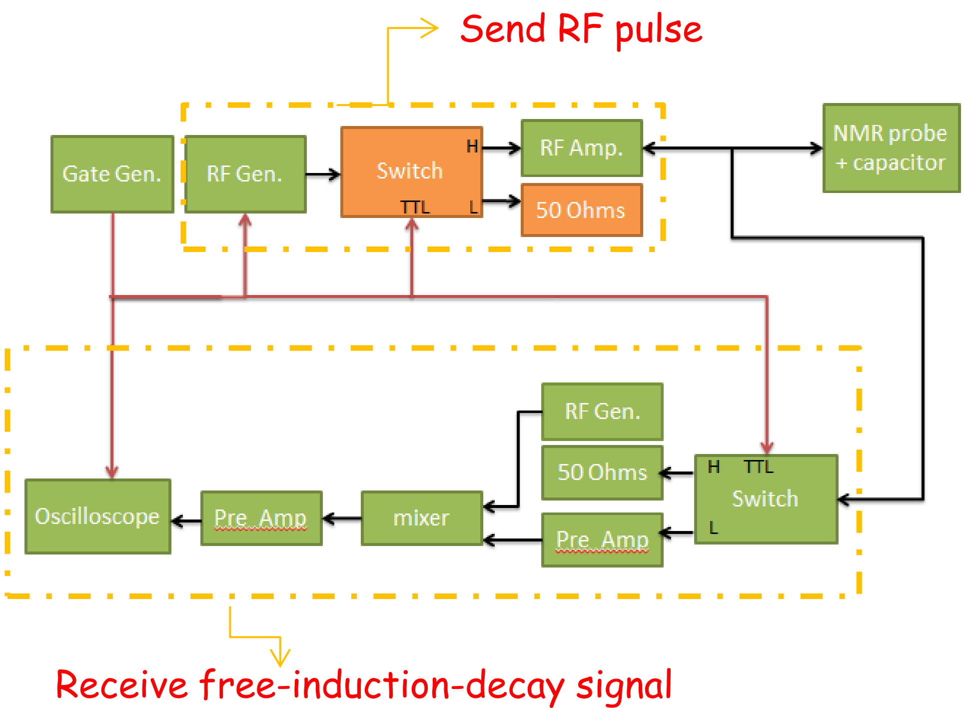


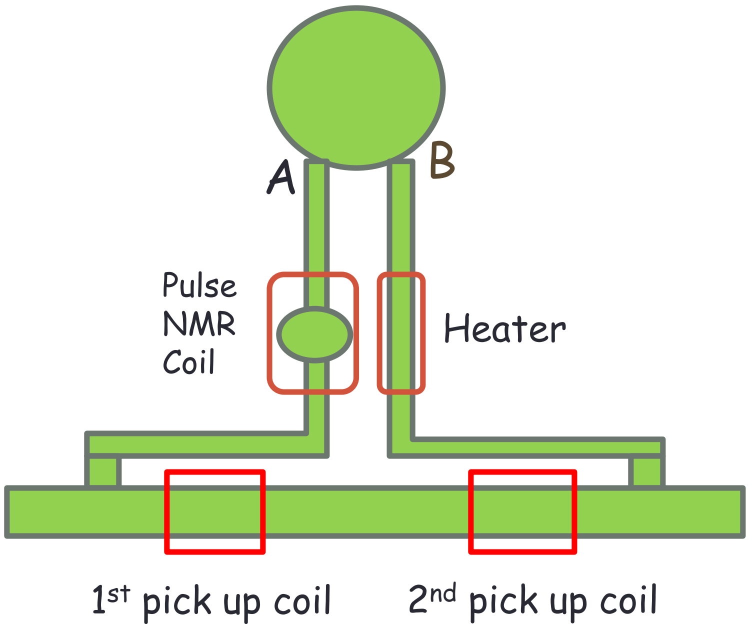
Theory:
S$\propto M_z \sin(\theta_{tip}) e^{-t/T_2} \sin(wt)$

AFP-NMR will not be suitable for measurement on target chamber of glass/metal cell. Pulsed NMR can work on transfer tube

Pulsed NMR @JLab

- Pulsed NMR Set Up

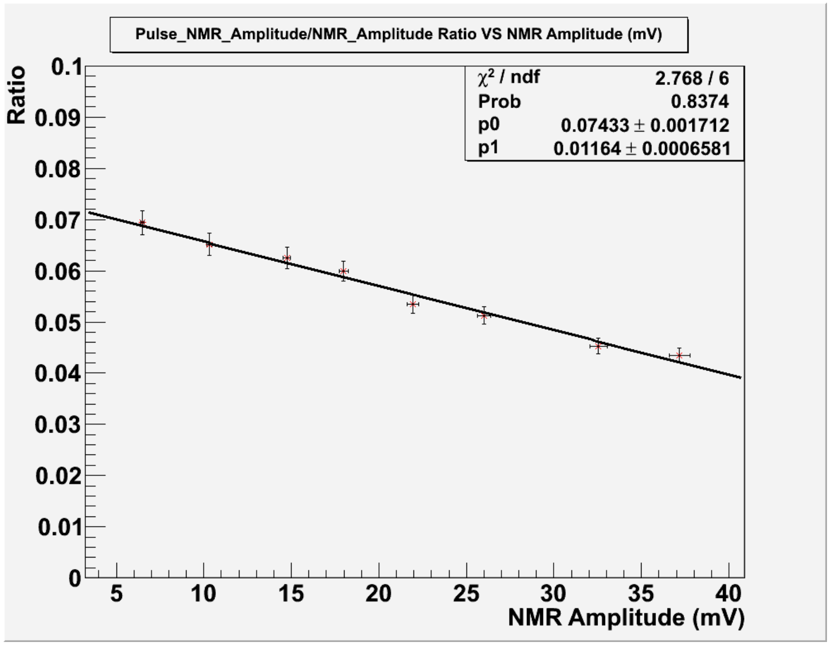


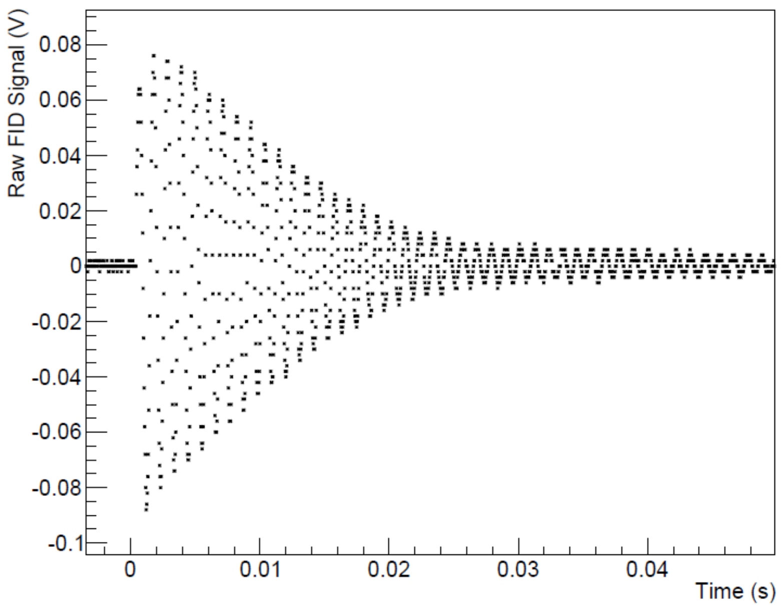


Pulsed NMR monitor polarization locally around the 1-inch bulb

Pulsed NMR

- Pulsed NMR compared with regular NMR

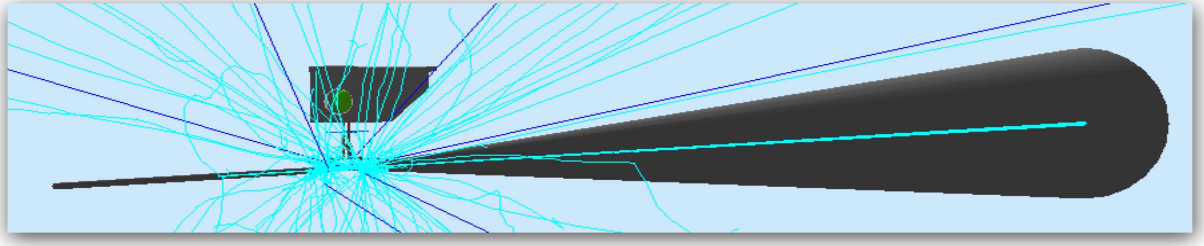


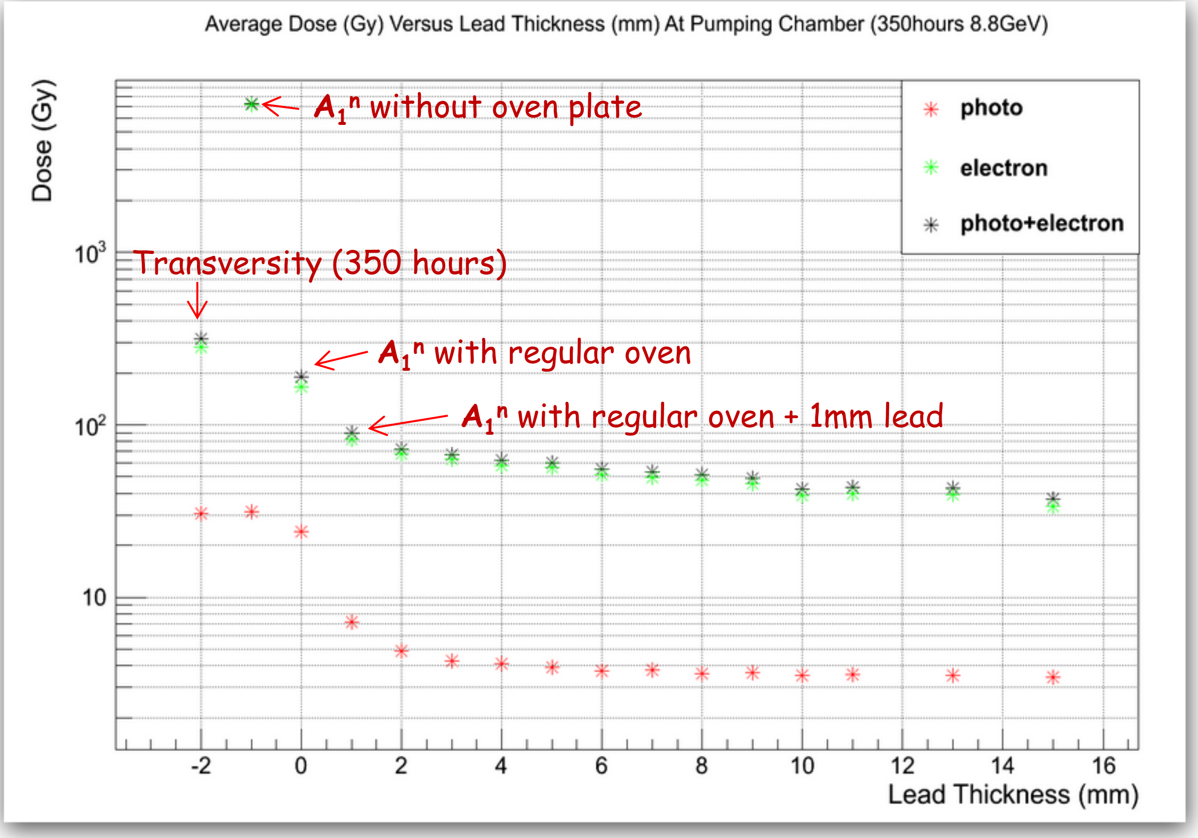


Systematic study continuing

Challenge: to improve S/N

^{3}He Target Radiation Shielding Study

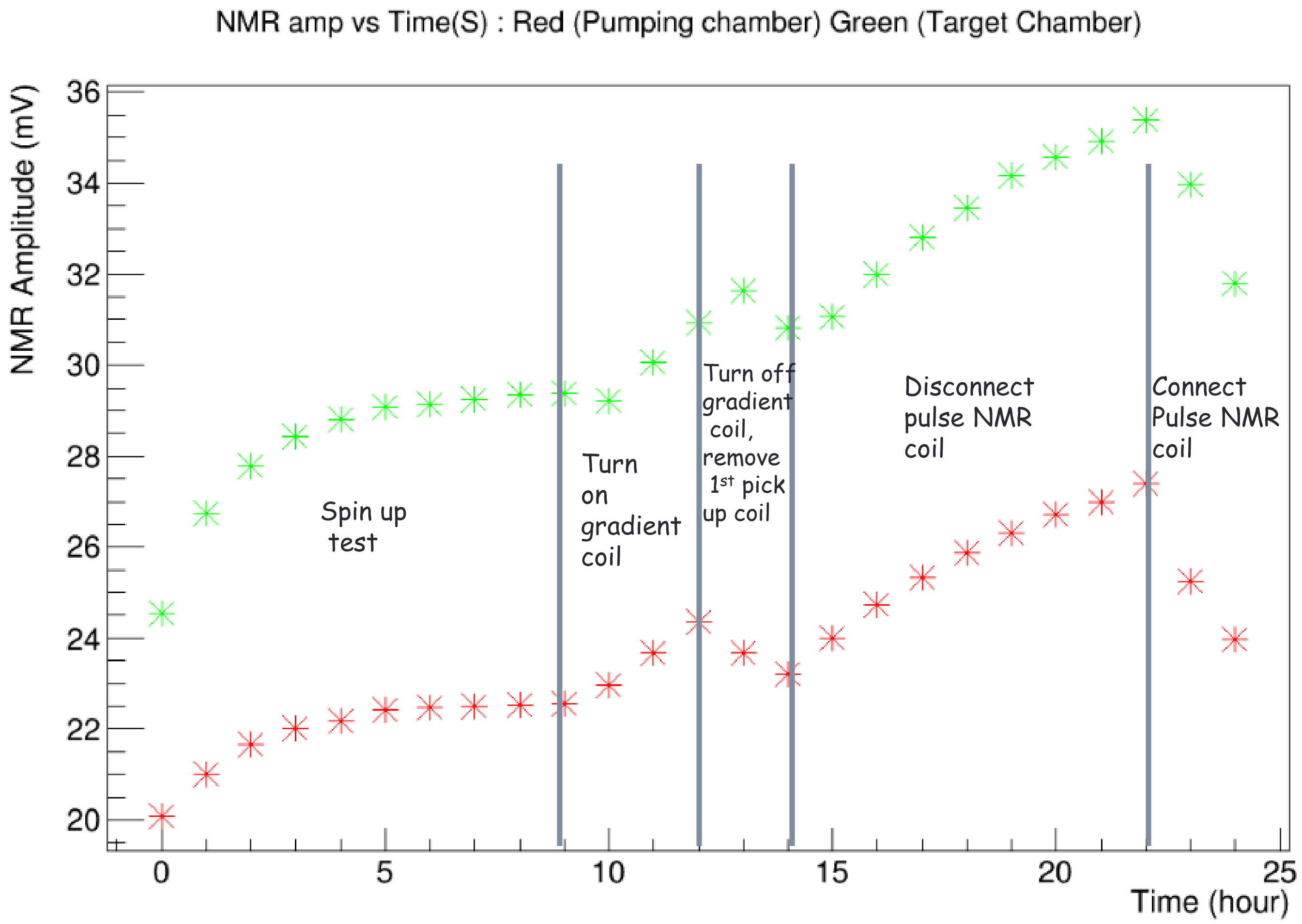




- Study shielding of pumping chamber from radiation damage
- Most of the radiation shielded by the oven
- A_1^n will not bring radiation to pumping chamber as much as Transversity

Masing Effect

- **Masing Effect:** non-linear coupling between coil/closed loop and spin



Target Upgrade Summary

- Polarized 3He target world-record performance for 6 GeV experiments

- 12 GeV R&D in progress

- Future Plan

- Near term: ~6 month
  - Pulsed NMR systematic study
  - Full polarization test

- Goal: full system ready for A_1^n -A exepriment