Precision Measurements of Electroproduction of π^0 near Threshold: A Test of Chiral QCD Dynamics

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for Jefferson Laboratory Experiment E04-007

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Introduction

- Chiral Perturbation Theory (χPT): EFT consistent with the (approximate) chiral symmetry of QCD (as well as P and C). $\mathcal{L}_{\chi PT}$ expanded as power series in (m_π/M_N) and (q/M_N). χPT → low-energy dynamics of QCD. The π is the Goldstone Boson

- HBχPT π-N interactions *V.Bernard, N.Kaiser, U.-G.Meißner, NP B383, 442 (1992), NP A607,379(1996), A633,695E(1998), Z.Phys C70, 483 (1996).*

- Pion Loop corrections → non-analytical term in m_π...old LET amplitudes smooth fn(m_π)....Taylor Series.

- Threshold γ +p →p + π^0 (SACLAY, MAINZ) showed the s-wave LET were deficient

- Constrain required range of power series by performing measurements under conditions where the factors governing the expansion are small.....soft π near threshold.

- Details of interaction are absorbed into Low Energy Constants (LECs). LECs are fitted to data (or resonance saturation or from LQCD)

- Much of the testing of HBχPT near threshold $\gamma^{(*)}$ +p →p + π^0. Virtual photons in addition give the longitudinal response.

- **Real photon results so in good agreement with HBχPT.**

- **Electroproduction data shows significant discrepancies.**

Previous $\gamma^{(*)}+p \rightarrow p+\pi$ Tests of HBχPT

Some previous work
(not an exhaustive list)

π^0 Photoproduction
SAL
J.C. Bergstrom et al., PRC53, R1052 (1996)
Mainz
A. Schmidt et al., PRL 87,232501 (2001)
CB@MAMI (Mainz)
D.Hornidge et al. 2004 - .....

π^0 Electroproduction
NIKHEF
H.B. van den Brink et al., PRL 74, 3561 (1995)
Mainz
$Q^2 = 0.1$
M.O. Distler et al., PRL 80, 2294 (1998)
Q^2 = 0.05 GeV/c dW = 0 – 4 MeV
H. Merkel et al., PRL 88, 012301 (2002)
Q^2 = 0.05 GeV/c dW = 0 - 40 MeV
M. Weiss et al., EPJ A38, 27 (2008)

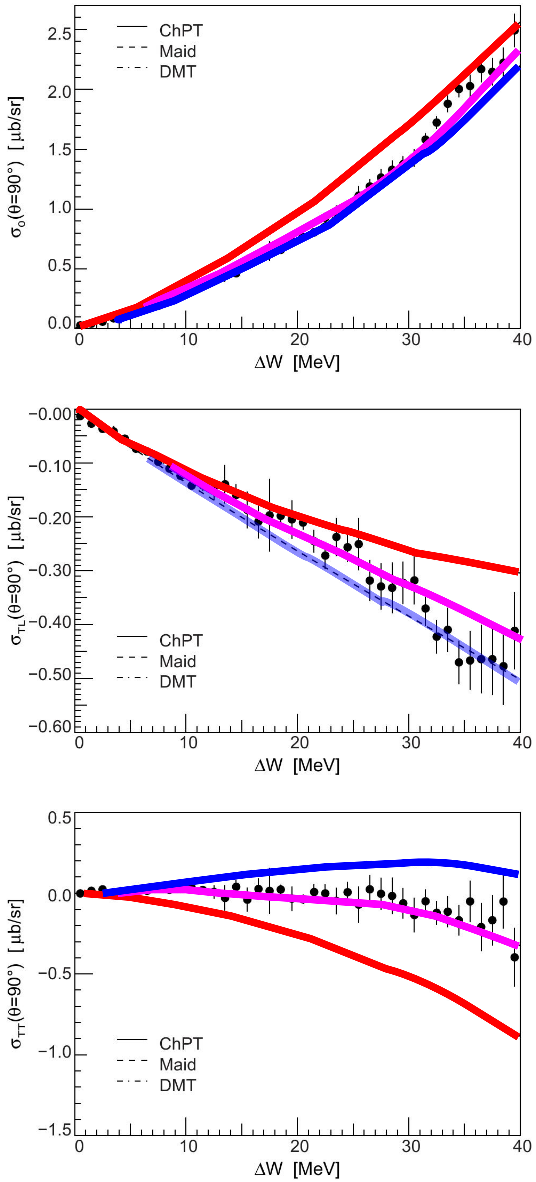
Jefferson Lab.
E04-007 1st proposed 2001, run in 2008

Photoproduction *H(γ,π^0)p*
SAL and Mainz differential cross section measurements in good agreement with HBχPT.
Mainz $\Sigma(\theta) \rightarrow P_1, P_2$ (free of LEC)
Near-threshold measurements of polarisation observables continue at Mainz using the 4π Crystal Ball & TAPS

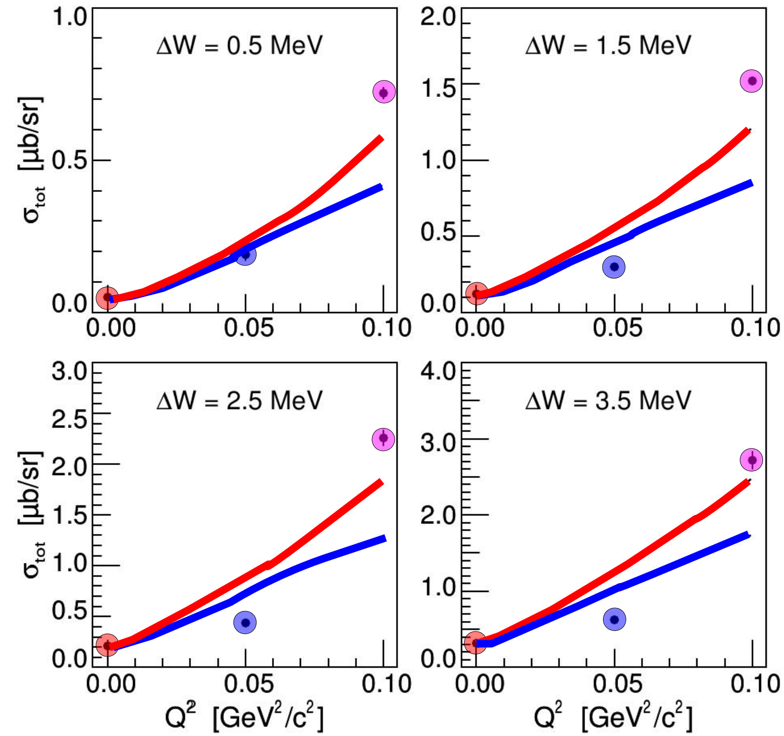
Electroproduction *H(e,e'p)π^0*
NIKHEF and 1st Mainz measurements at Q^2 ~ 0.1 $(GeV/c)^2$ HBχPT fits made on these data.
Subsequent Mainz measurement @ Q^2 = 0.05 $(GeV/c)^2$ quite steep Q^2 dependence.
Mainz (2008) beam helicity asymmetry $\rightarrow \sigma_{LT'}$ not in agreement with HBχPT

Published Results $H(e,e'p)\pi^0$ A1-MAMI

M. Weiss et al., EPJ A38, 27 (2008)



H. Merkel et al., PRL 88, 012301 (2002)



M.O.Distler et al.

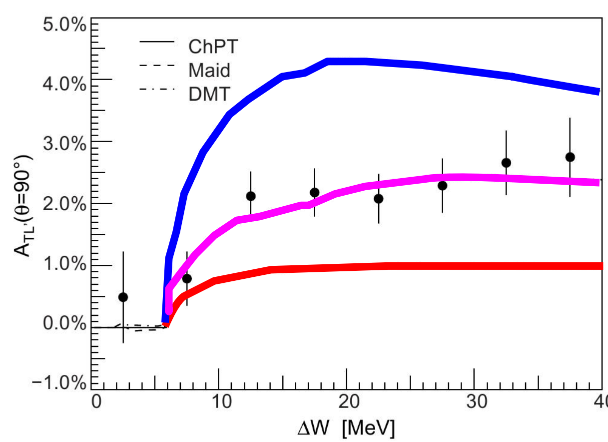
H. Merkel et al.

A. Schmidt et al.
Photoproduction

MAID
D. Drechsel et al. NPA645, 145 (1999)

HBχPT
V.Bernard et al.

DMT
S. Kamalov et al., PLB522, 27 (2001)
Meson Exchange dynamical model



HBχPT at odds with MAMI-A1 data.
DMT description rather good.

Extracted and Predicted Multipole Strength @ Threshold

Source	Q^2 $(GeV/c)^2$	E_{0+}	L_{0+}	$P_{23}^{\ 2}$	P_1	P_2	P_3	P_4	P_5
MAMI	0.00	−1.33		111.00	9.46±0.28	−9,5± 0.28	11.32±0.34		
HBχPT	0.00	−1.14	−1.70	105.00	9.30			−0.60	−0.20
MAID	0.00	−1.23	−1.29	82.00	9.07	−10.68	7.07	−3.00	2.20
DR	0.00	−1.29		86.7	9.64	−10.29	8.22		
MAMI	0.05	0.57 ± 0.11	−1.29 ± 0.02	100 ± 3.0					
AmPS	0.05		−1.57 ± 0.96						
HBχPT	0.05	0.27	−1.55	353.00	16.50			−0.72	−0.20
MAID	0.05	0.76	−1.40	250.00	15.00			−1.75	1.90
MAMI	0.10	0.58 ± 0.18	−1.38 ± 0.01	573 ± 11	15.1 ± 0.8			−2.3 ± 0.2	0.1 ± 0.3
AmPS	0.10	1.99 ± 0.3	−1.33	526 ± 7	16.4 ± 0.6			−1.0 ± 0.4	−1.0 ± 0.4
HBχPT	0.10	1.42	−1.33	571.00	20.10			−0.60	−0.10
MAID	0.10	2.20	−1.12	315.00	17.10			−1.10	1.40
DR	0.10	1.55	−1.41						

$P_1 = 3E_{1+} + M_{1+} - M_{1}$ $P_2 = 3E_{1+} - M_{1+} + M_{1-}$

$P_3 = 2M_{1+} + M_{1-}$ $P_4 = 4L_{1+} + L_{1-}$

$P_5 = L_{1-} - 2L_{1+}$ $P_{23}^{\ 2} = (P_2^{\ 2} + P_3^{\ 2})/2$

DR = Dispersion Relation Analysis

S. Kamalov et al, PRC 66, 065206 (2002)

E04-007 in Hall-A of Jefferson Lab.

Originally proposed 2001

Re-proposed 2004

Finally scheduled 2007-8, data taking April -- May 2008.

Physics Goal:

Extract high precision measurement of

H(e,e'p)π^0 differential cross section near threshold

$$\frac{d\sigma}{d\Omega_e\, d\Omega_\pi^{cm}\, dE'} = \Gamma\left\{\underbrace{\frac{d\sigma_T}{d\Omega_\pi^{cm}} + \epsilon_L \frac{d\sigma_L}{d\Omega_\pi^{cm}}}_{2\text{-}4\%} + [2\epsilon_L(1+\epsilon)]^{1/2} \underbrace{\frac{d\sigma_{LT}}{d\Omega_\pi^{cm}}}_{3\text{-}6\%} \cos\phi + \epsilon \underbrace{\frac{d\sigma_{TT}}{d\Omega_\pi^{cm}}}_{10\text{-}20\%} \cos 2\phi\right\}$$

2-4% 3-6% 10-20%

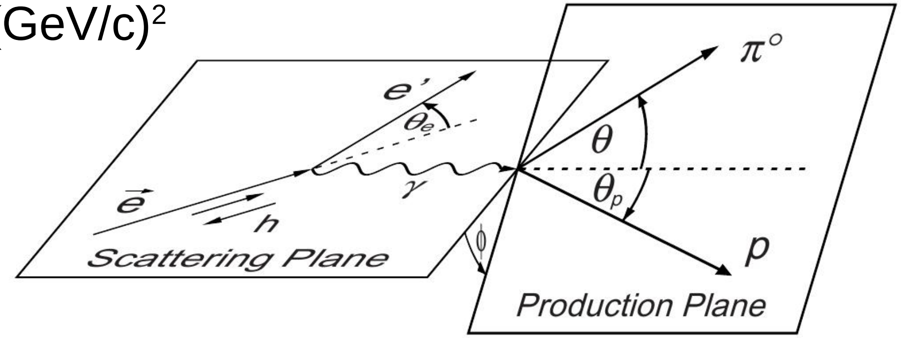
Fine grid of Q^2 and W:

Q^2 = 0.05 $\rightarrow$ 0.15 $(GeV/c)^2$, steps of 0.01 $(GeV/c)^2$

$\Delta W = 0 \rightarrow 30$ MeV, steps of 1 - 2 MeV

With complete kinematic coverage:

ΔW = 0 - 4 MeV for P_{proton} > 220 MeV/c



Polarised Electron beam

extra term $+h\sqrt{2\epsilon(1-\epsilon)}\,\sigma_{LT'}(\theta)\sin\phi$

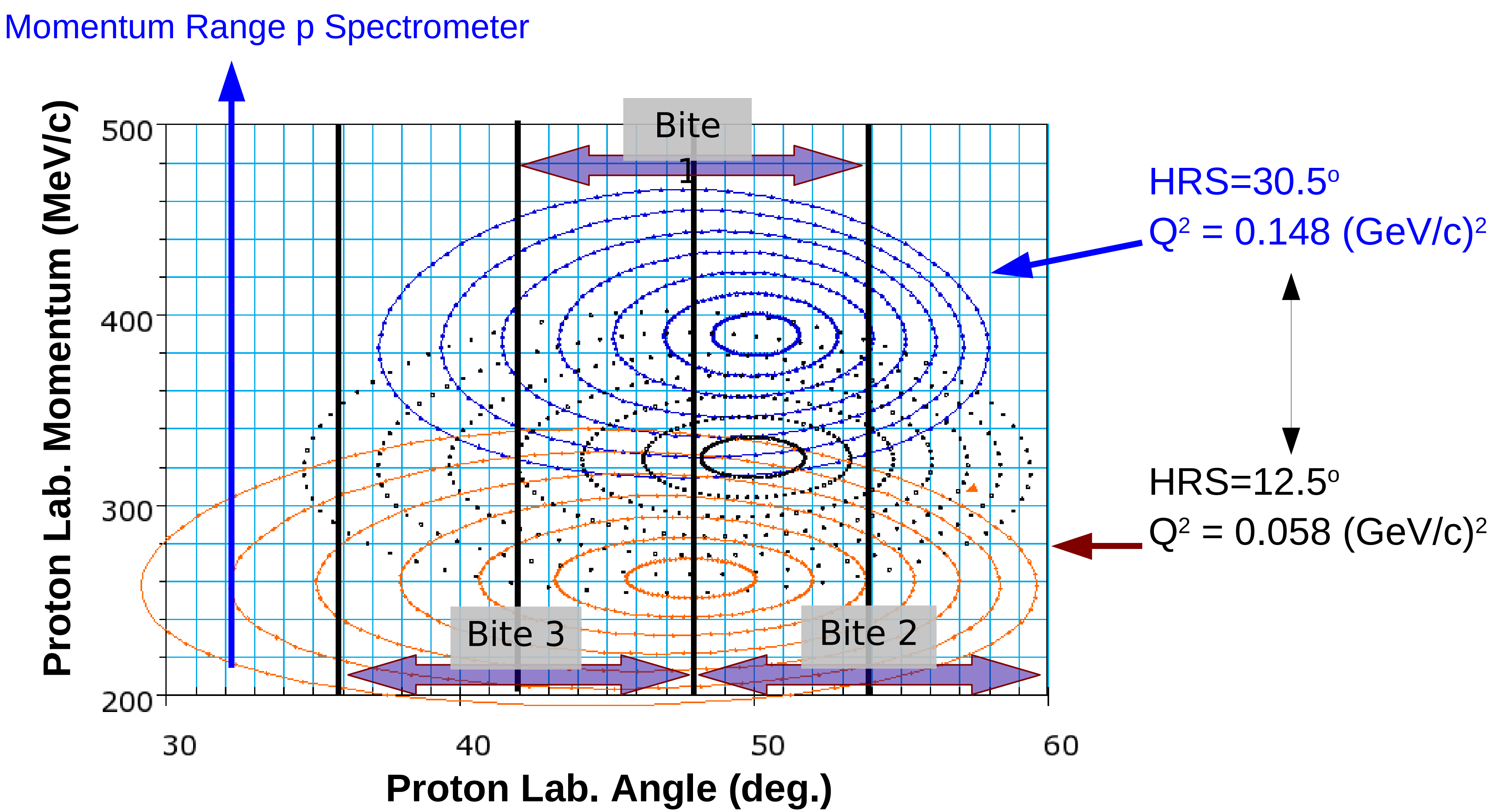
in

$$A_{LT'}(\theta) = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\sqrt{2\epsilon(1-\epsilon)}\,\sigma_{LT'}(\theta)}{\sigma_T(\theta) + \epsilon\,\sigma_L(\theta) - \epsilon\,\sigma_{TT}(\theta)}$$ $\rightarrow \sigma_{LT'} \rightarrow \mathrm{Im}(E_{0+}), \mathrm{Im}(L_{0+})$

Near-Threshold $H(e,e'p)\pi^0$ Some Experimental Considerations

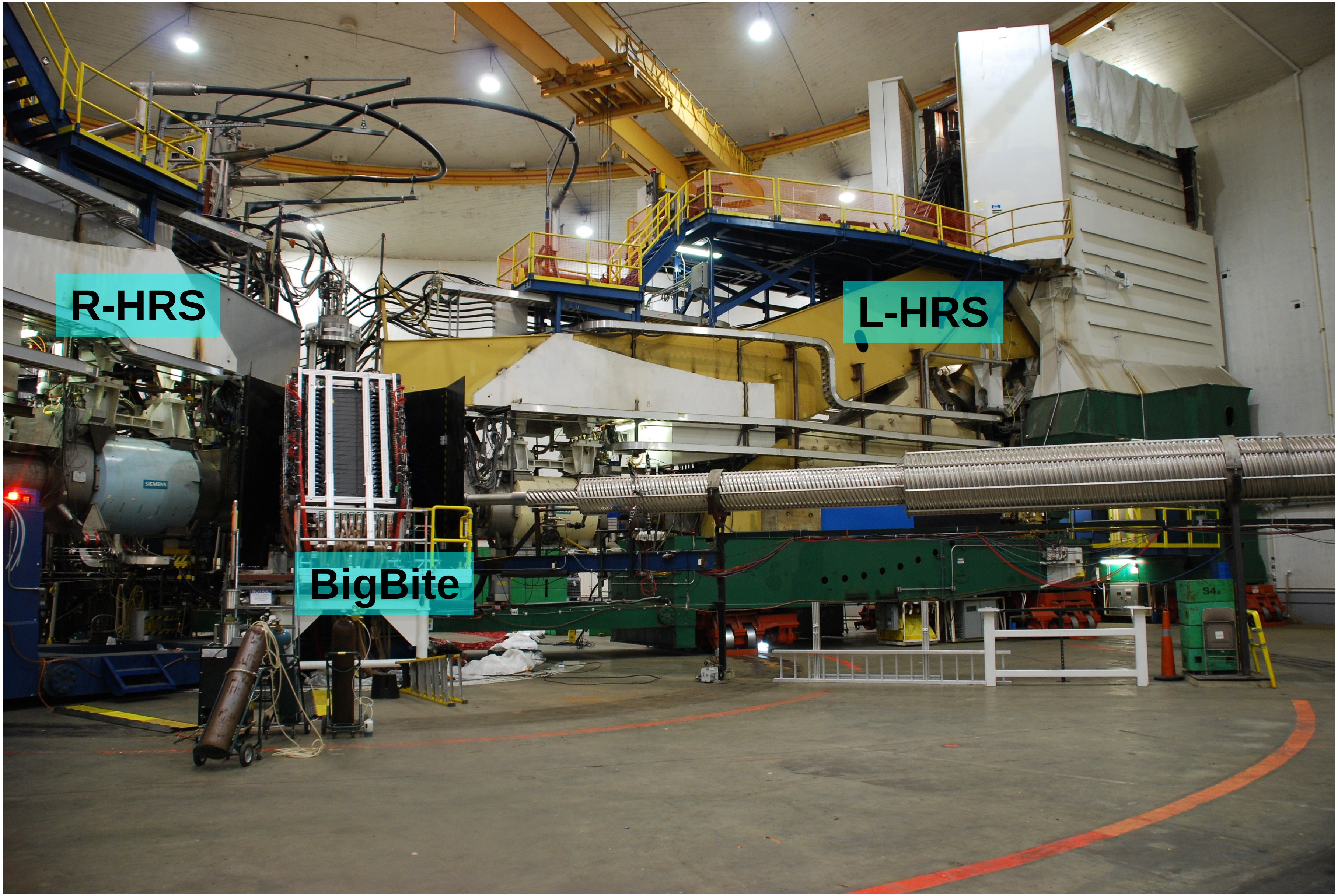
- High beam energy not required... but if e' spectrometer can reach small angles can access low Q^2 region and maximise virtual photon flux. $H(e,e'p)\pi^0$ cross section small at threshold
- Reaction identified by e' and p, π^0 not detected.
- Need sufficient energy resolution to obtain clean π^0 missing mass distribution.
- Close to threshold recoil p focused tightly about the γ^* direction. A reasonable lab. angular acceptance can catch all p.
- Low Q^2 implies low p momentum. Multiple scattering and energy loss in target and various components of the spectrometer detector stack must be accounted for carefully

Recoil p Kinematics near Threshold

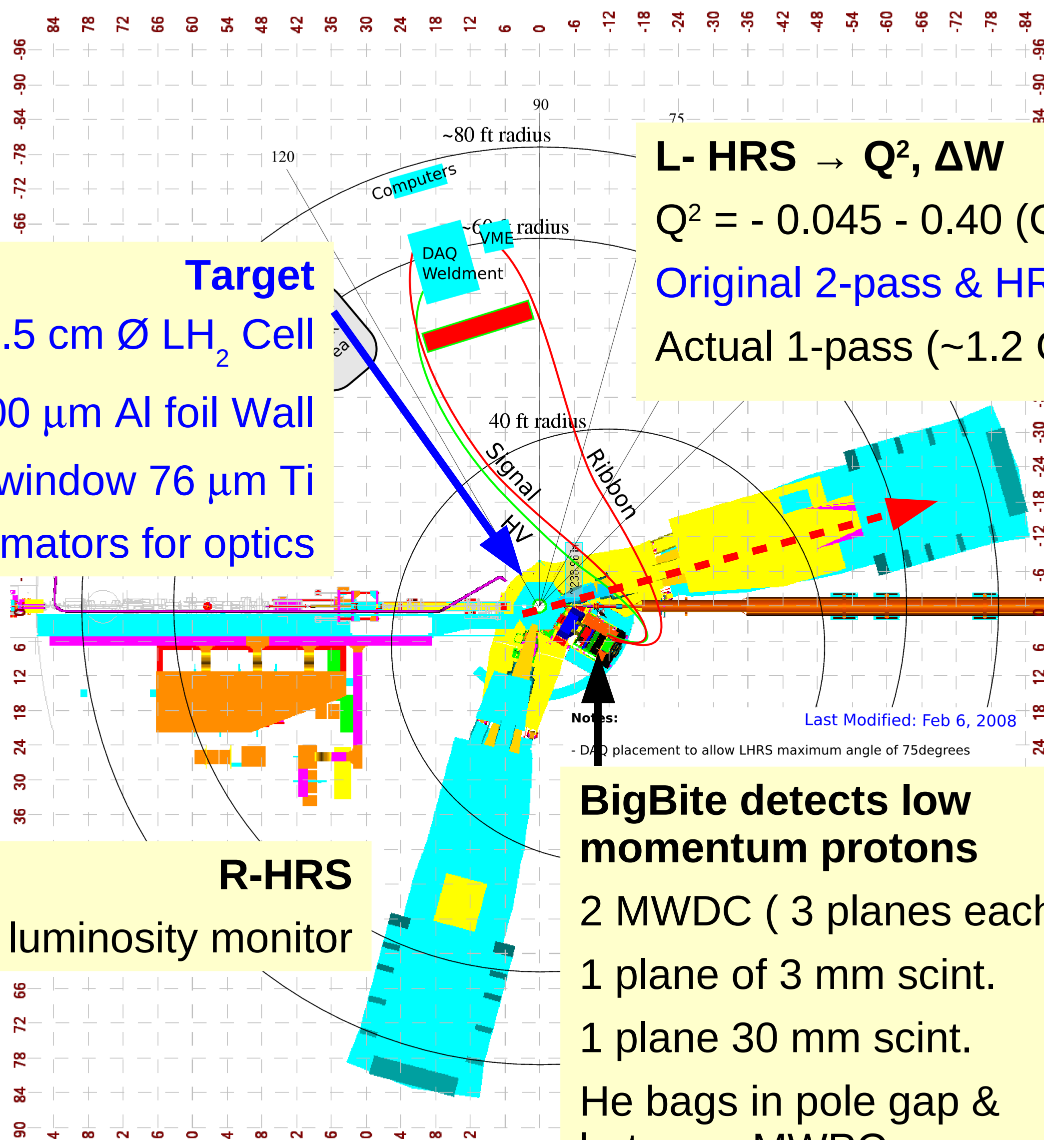


Ellipses of constant ΔW (W relative to π threshold)

$H(e,e'p)\pi^0$ @ Hall-A of Jefferson Lab



Floor Plan of Experiment



Target

6 cm long 2.5 cm Ø LH_2 Cell

200 μm Al foil Wall

Chamber exit window 76 μm Ti

Sieve-slit collimators for optics

L- HRS → Q^2, ΔW

Q^2 = - 0.045 - 0.40 $(GeV/c)^2$

Original 2-pass & HRS + mag. septum @ 6°.

Actual 1-pass (~1.2 GeV) & HRS @ 12.5°.

Electron Beam

1 - pass

1.194 GeV, 3-5 μA

L ~ 10^{37} Hz/cm^2

2 - pass

2.388 GeV

R-HRS

luminosity monitor

BigBite detects low momentum protons

2 MWDC (3 planes each)

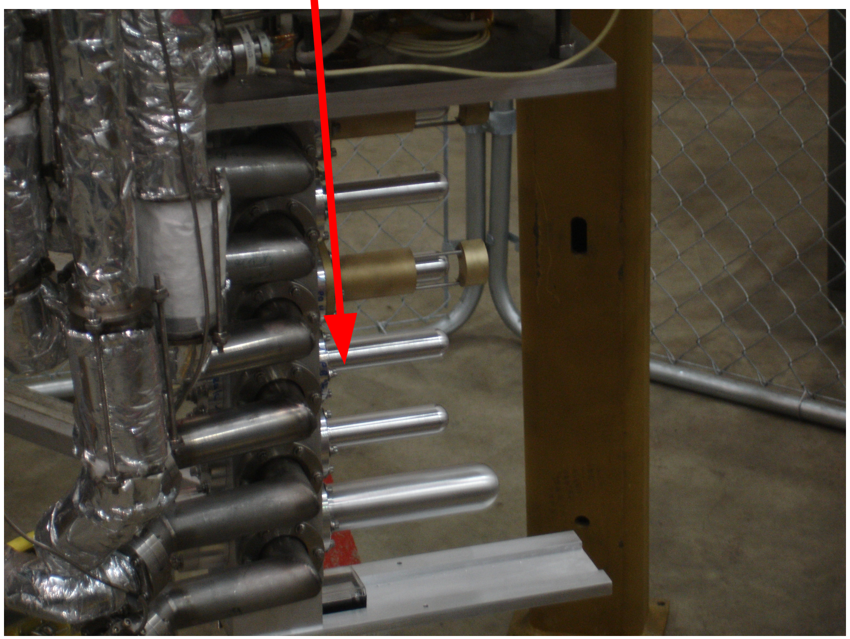
1 plane of 3 mm scint.

1 plane 30 mm scint.

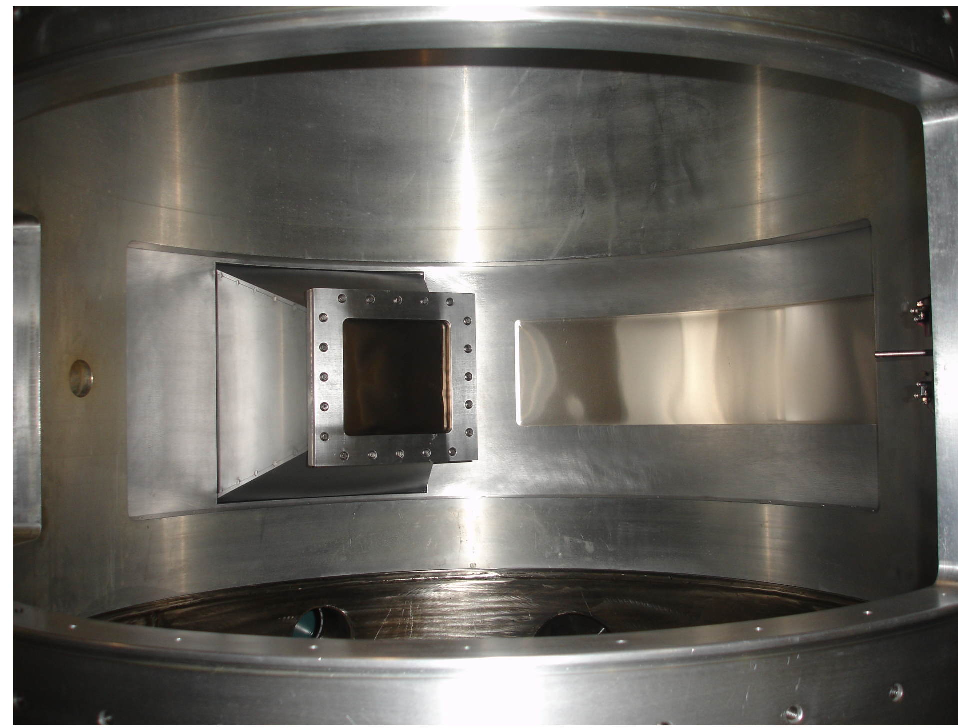
He bags in pole gap & between MWPC

Target and Scattering Chamber

6 cm long 2.5 cm Ø LH_2 Cell with 200 μm Al
Wall specially made for E04-007

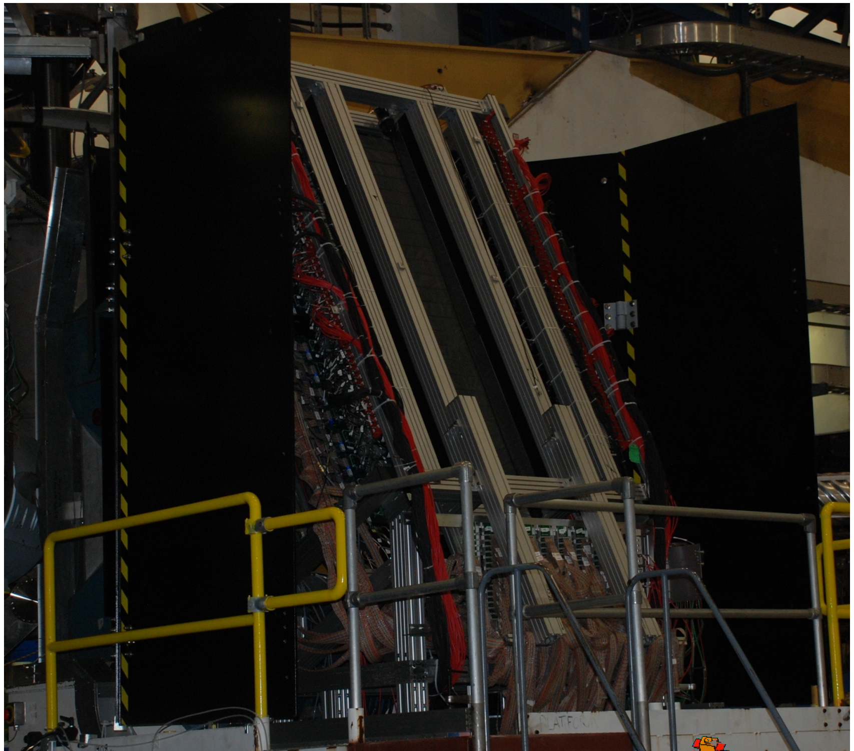


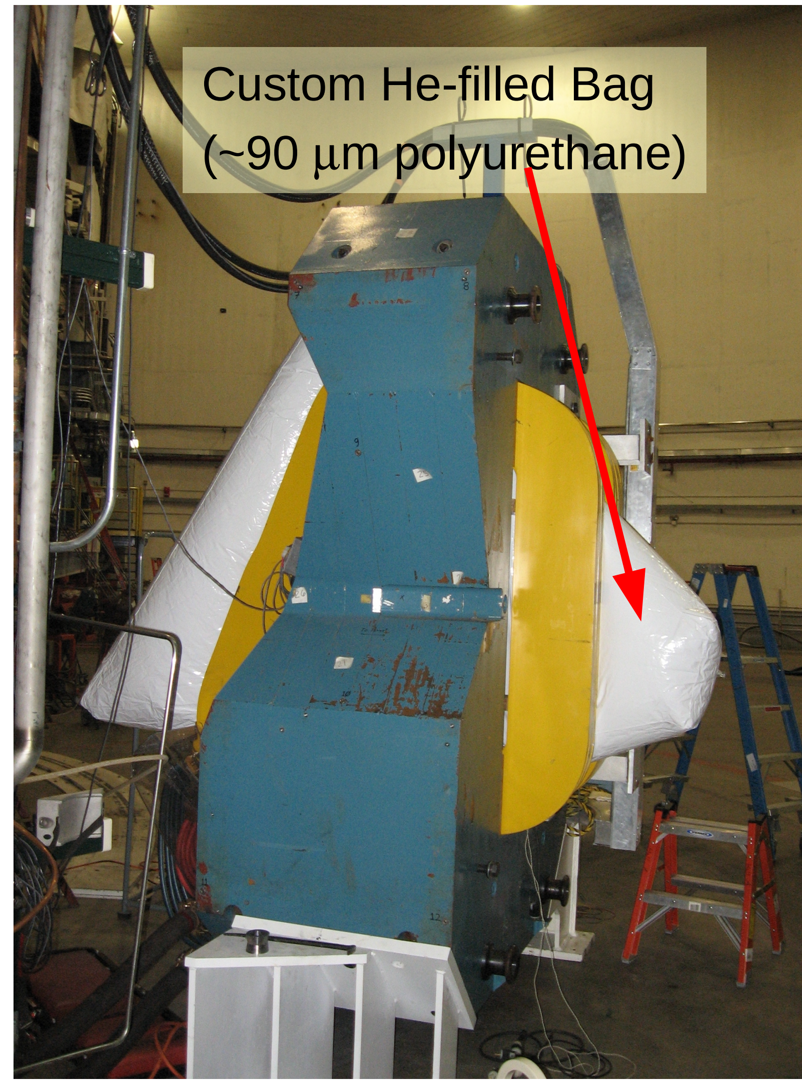
New vacuum chamber
Special flange with 76 μm Ti window
for protons exiting to BigBite



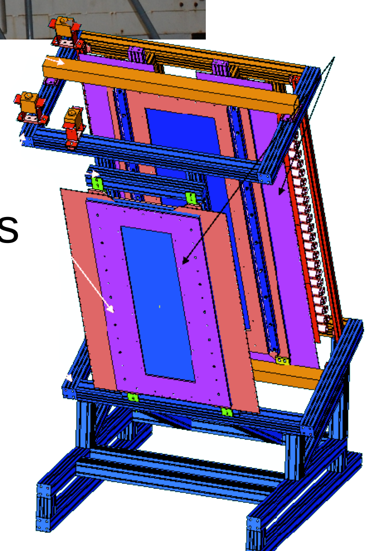
The BigBite Spectrometer

Magnet: NIKHEF/Budker
(Internal target facility AmPS)
Simple non-focusing dipole ~1 T
Momentum resolution ~ 5 x 10^{-3}





Hadron Detector stack
2 of x-u-v MWDC +
ΔE-E scintillator trigger planes



Can also be configured for e'
MWDC + ...
Threshold Cherenkov +
Shower-PreShower Pb-Glass
G_{En}, Transversity.....12 GeV

Summary of E04-007 Production Kinematics

Calibrations and Systematic Checks:

- Tantalum elastic, e' in HRS
  abs. beam energy
- Proton elastic – e' in HRS
  p in BB: cross section, optics
- Carbon elastic and inelastic
  beam energy and cross section
- HRS elastic p(e,e')
  sieve-slit optics calibration
- BigBite Sieve Slit,
  QE d(e,e'p) out-of-plane optics
- Elastic H(e,e'p) collimated target cell
- Elastic H(e,e'p) different dipole currents
  in BigBite
- Vary beam currents (1- 6 μa)
  rate effects
- MWPC high voltage and threshold.
  Efficiency for p.
- 1 KHz pulser:
  computer dead time correction

Setting	Energy (GeV)	BB (deg.)	HRS (deg.)	W_{min} (GeV)	$\langle Q^2 \rangle$ $(GeV/c)^2$	Charge (C)
A	1.19	54.0	20.5	1.074	-0.15	0.36
B	1.19	54.0	16.5	1.074	-0.10	0.31
C	1.19	54.0	14.5	1.074	-0.08	0.42
D	1.19	54.0	12.5	1.074	-0.06	0.23
E	1.19	48.0	12.5	1.074	-0.06	0.38
F	1.19	48.0	14.5	1.074	-0.08	0.55
G	1.19	48.0	16.5	1.074	-0.10	0.68
H	1.19	48.0	20.5	1.074	-0.15	0.56
I	1.19	43.6	20.5	1.074	-0.15	0.31
J	1.19	43.6	16.5	1.074	-0.10	0.36
K	1.19	43.6	14.5	1.074	-0.08	0.45
L	1.19	43.6	12.5	1.074	-0.06	0.22
M	1.19	50.3	27.2	1.194	-0.21	0.02
N	2.32	54.0	13.2	1.074	-0.25	0.22
O	2.32	54.0	15.8	1.074	-0.35	0.31
Q	2.32	54.0	18.2	1.074	-0.45	0.34

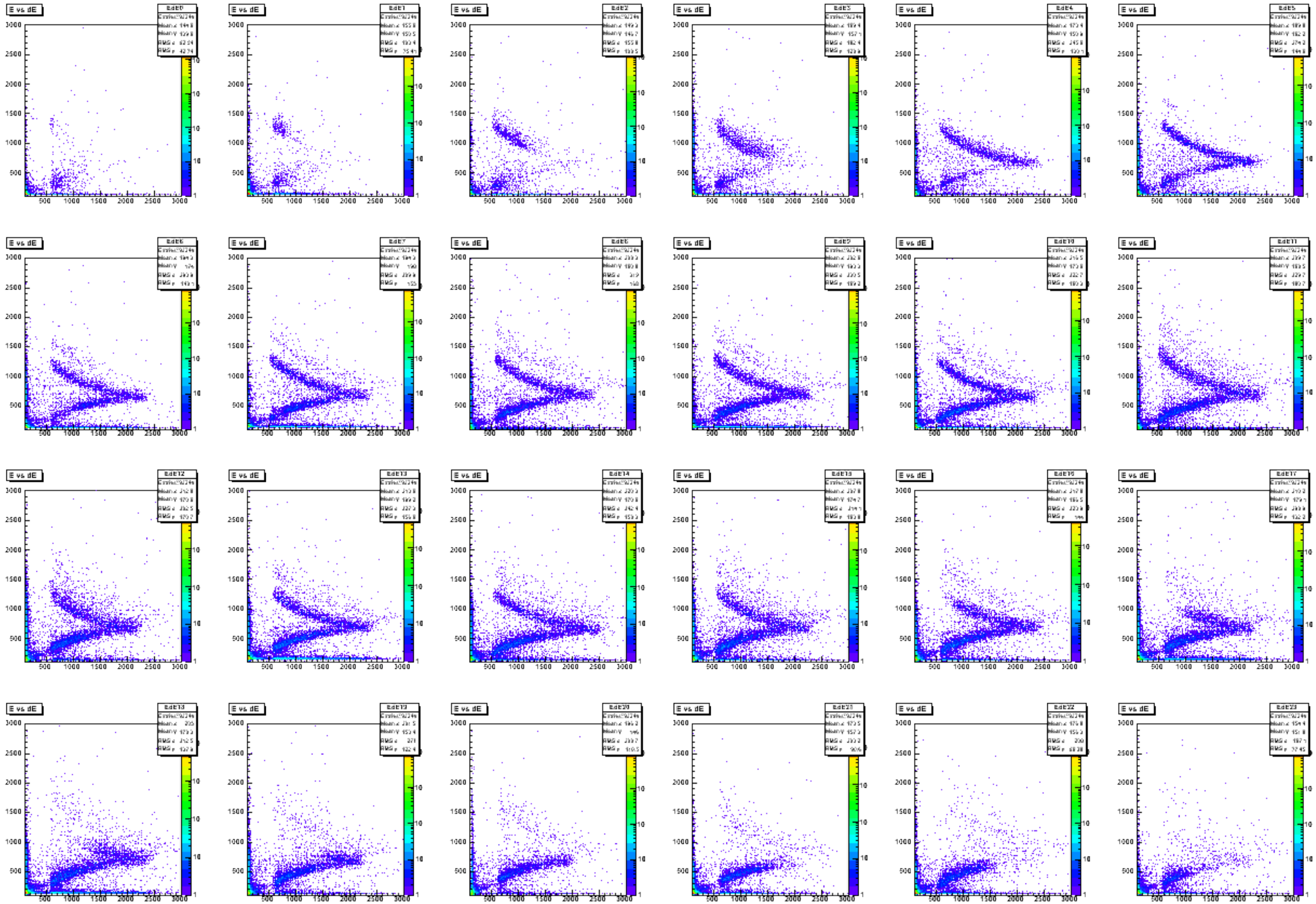
BigBite optics already reasonably well known from prior G_{En} and Transversity measurements.
Open spectrometer...detectors have direct view of target...rates in MWDC

Proton ID by δE-E (also use TOF)

Top: low momentum p

Trigger catches low-mom. p which do not make it to E plane

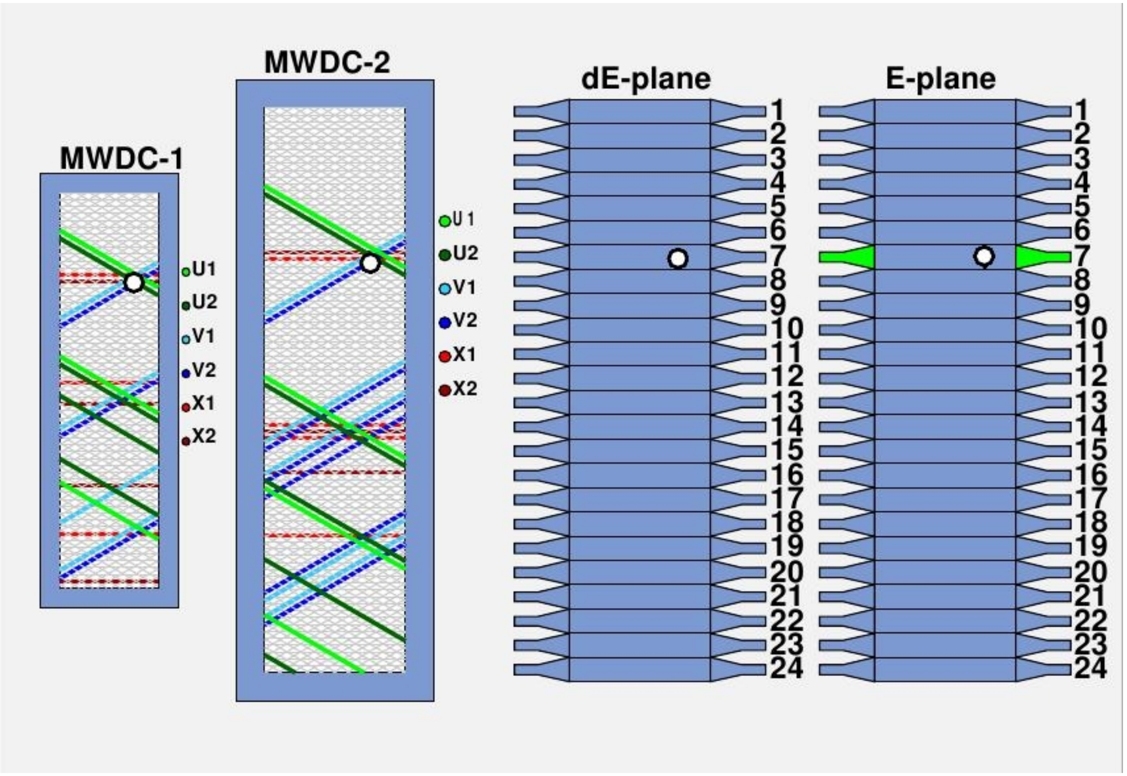
δE (3 mm thick)



E (30 mm thick)

Bottom: high momentum p

Proton Tracking in BigBite

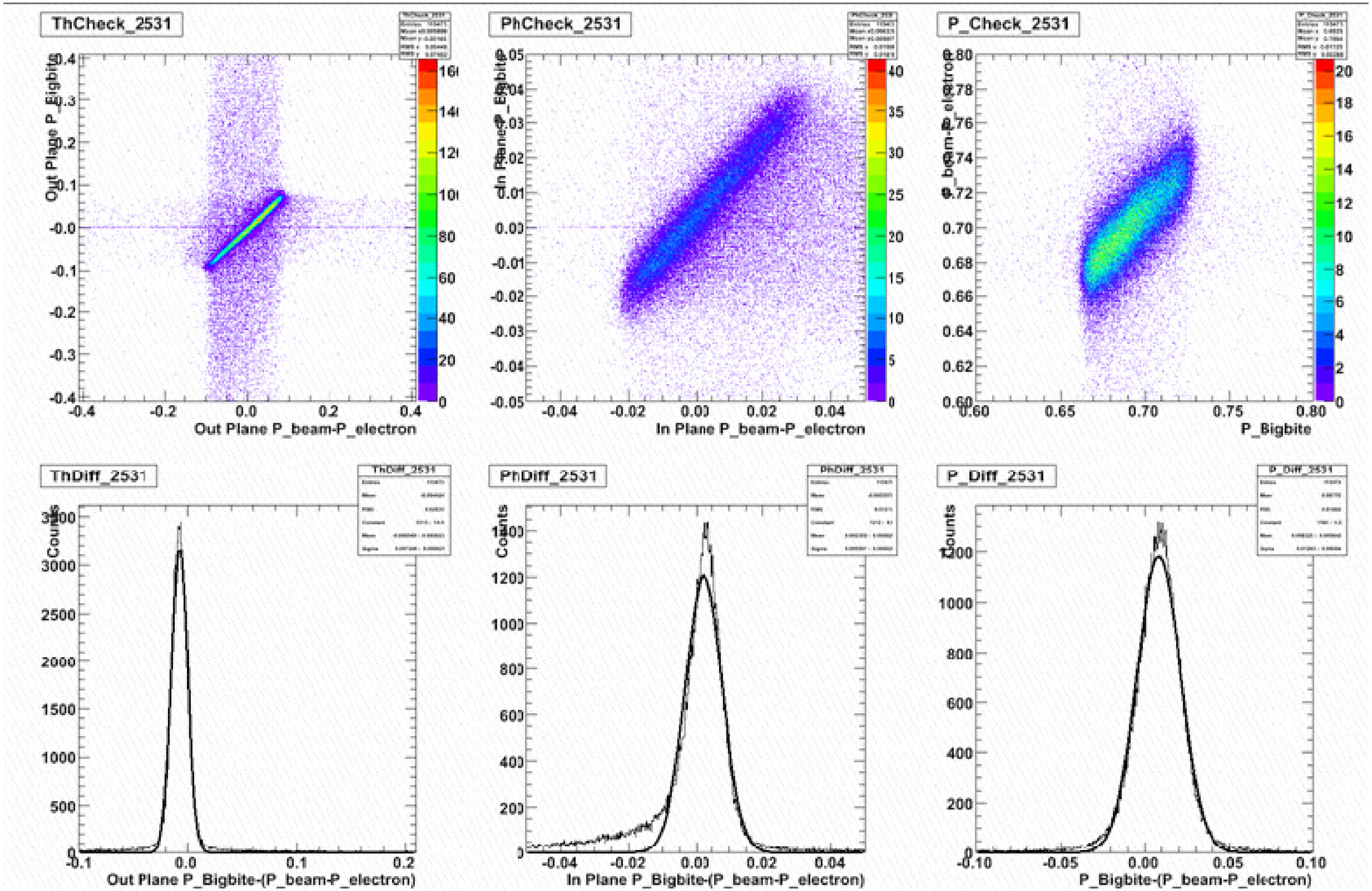


- MWDC have direct view of target
- Track reconstruction complicated by high multiplicity hits in MWDC
- Protons selected by dE-E... also have crude position resolution

- Tree Search Algorithm
  M.Dell'Orso & L.Ristori NIM A287, 436 1990
- Recursive template matching
- Fast and Efficient
- Used at HERMES

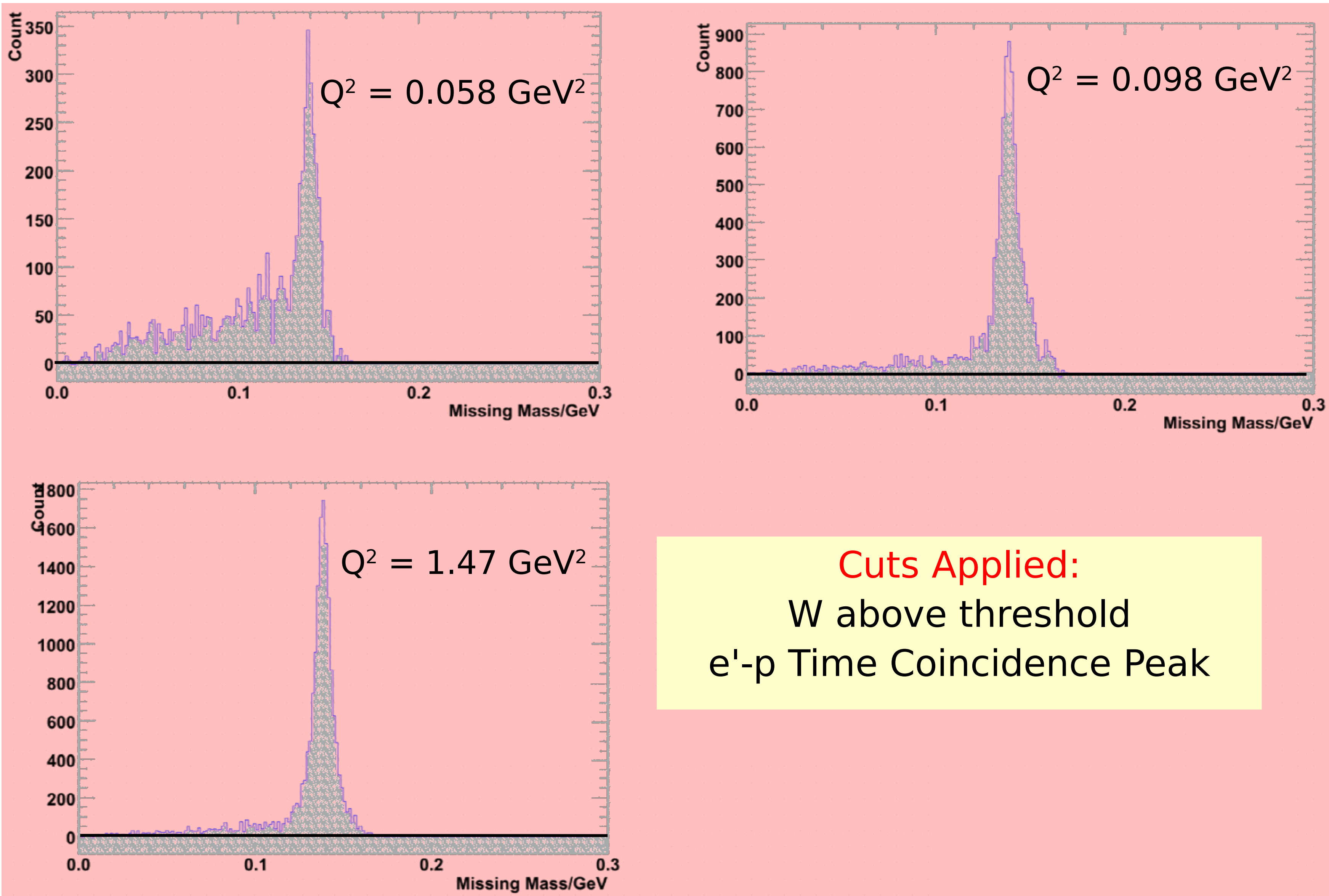
Open spectrometer: direct view of target....high rates

BigBite Optics Calibration: Online Analysis

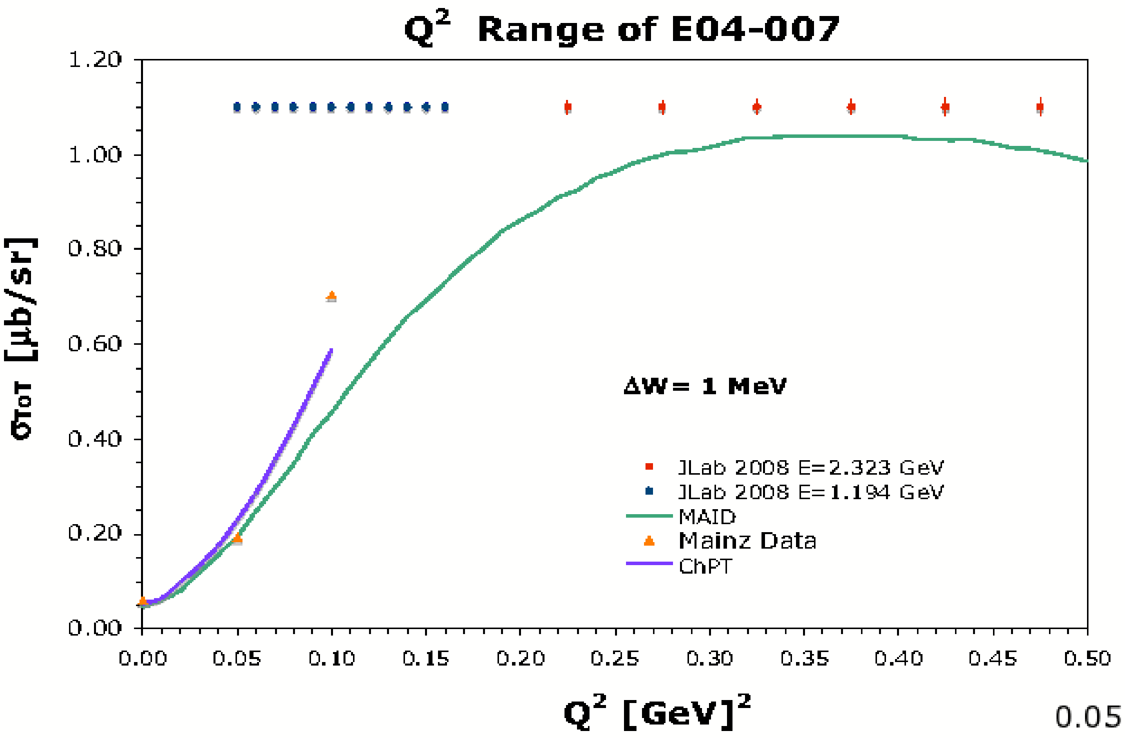


Elastic e-p scattering with BigBite coil @ ~400A

π^0 Missing Mass for a range of Q^2

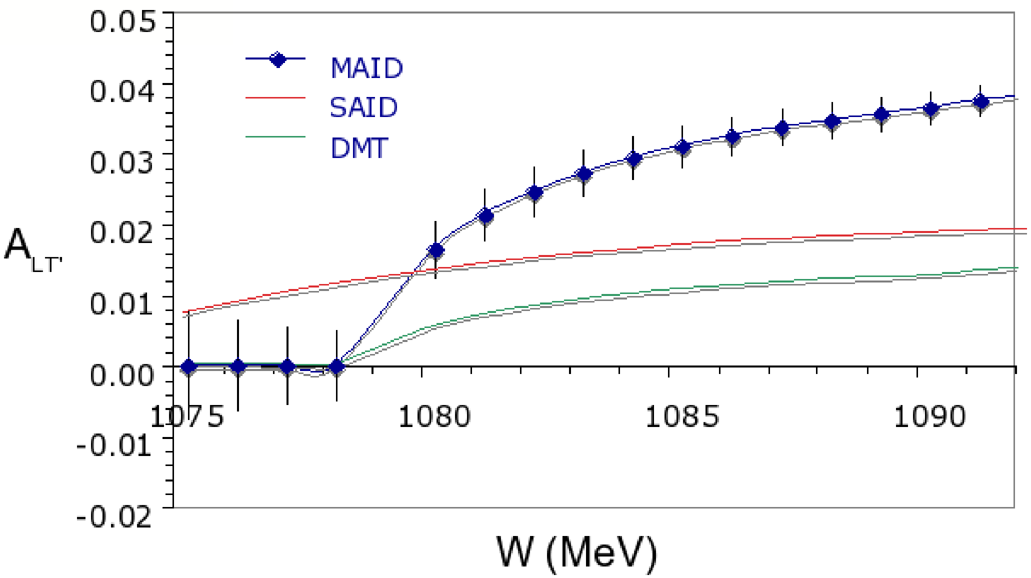


Expected Data Precision



- Highly successful experiment 2008...
- in terms of range of Q^2 covered
- accumulated statistics
- fine binning of data points
- In addition have helicity asymmetry $A_{LT'}$

- Analysis of Data Progressing (*festina lente*)
- Will have relative cross sections fairly soon
- Absolute cross section values...a bit longer
- Helicity asymmetry should be relatively fast



HRS Optics: Sieve-Slit Collimator