JLab Experiment
E08-007-II

Proton Electromagnetic Form Factor Ratio at Low Q^2

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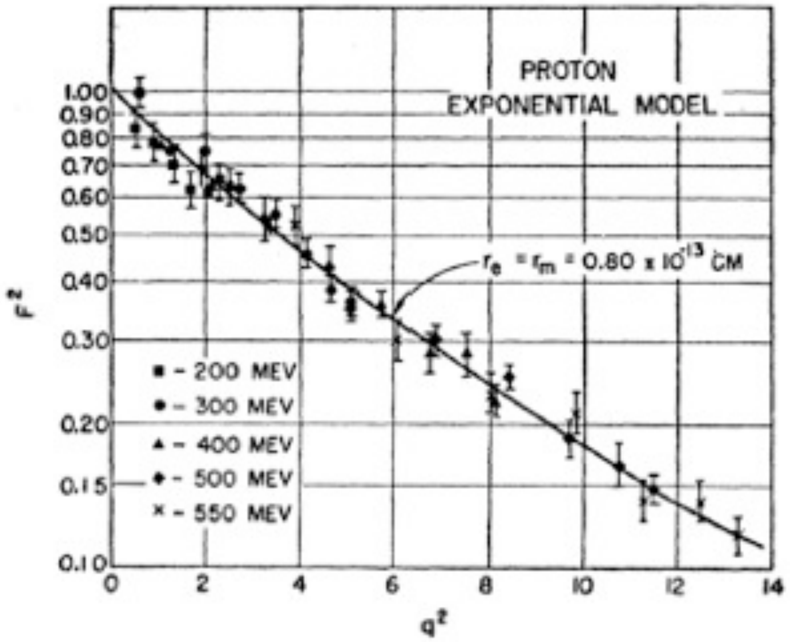
Outline

- Background
- Status
- Prospects

Hall A December 2012

Measuring proton size

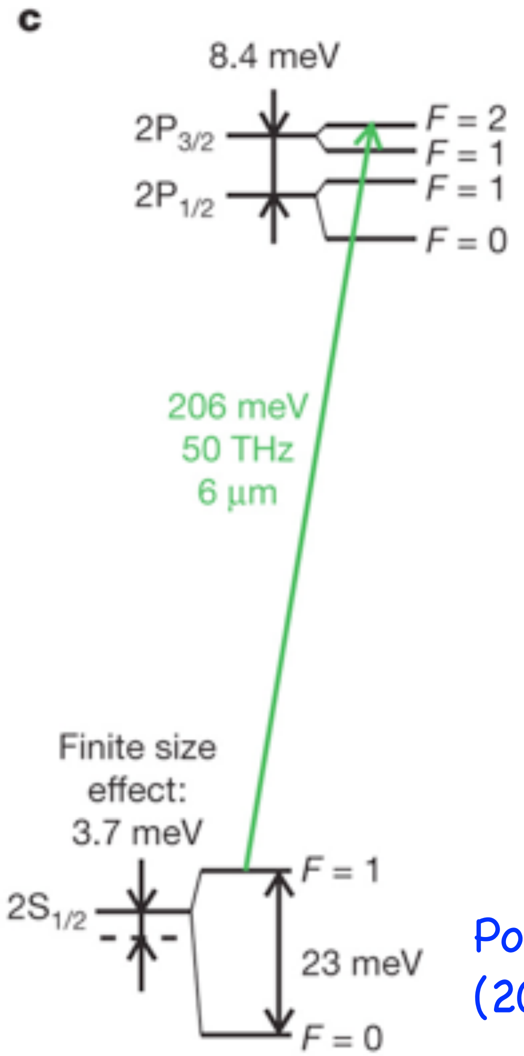
- Slope of form factor at $Q^2 = 0$
- Finite-size corrections to atomic energy levels



Chambers and Hofstadter, Phys Rev 103, 14 (1956)

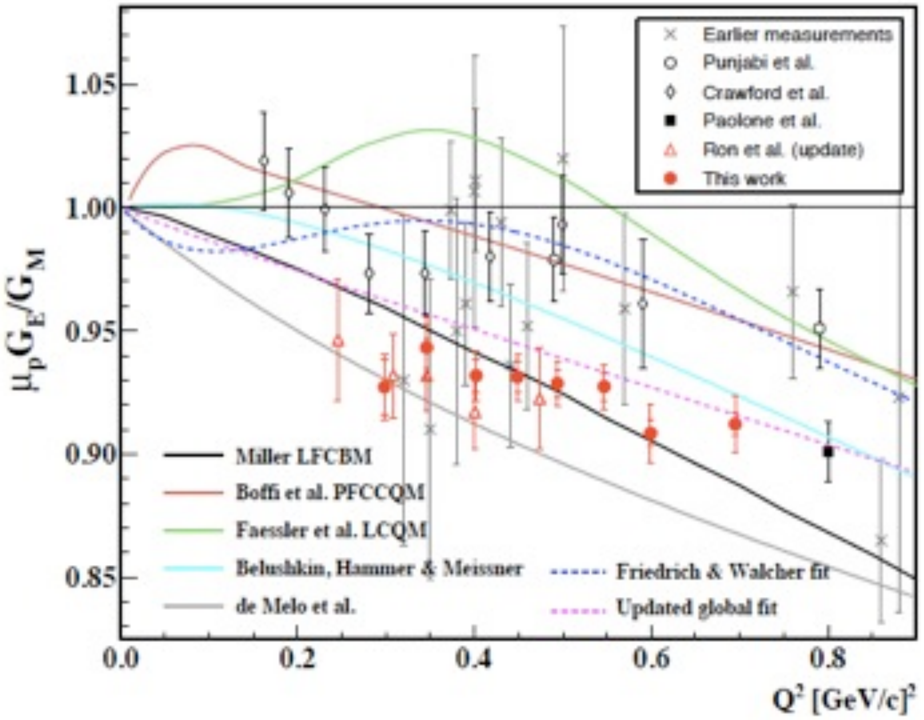
Hofstadter @ Stanford: 1950s - electron scattering

Bernauer et al., PRL105, 242001 (2010)



Pohl et al., Nature 466, 213 (2010)

Atomic physicists - precise atomic transitions in hydrogen



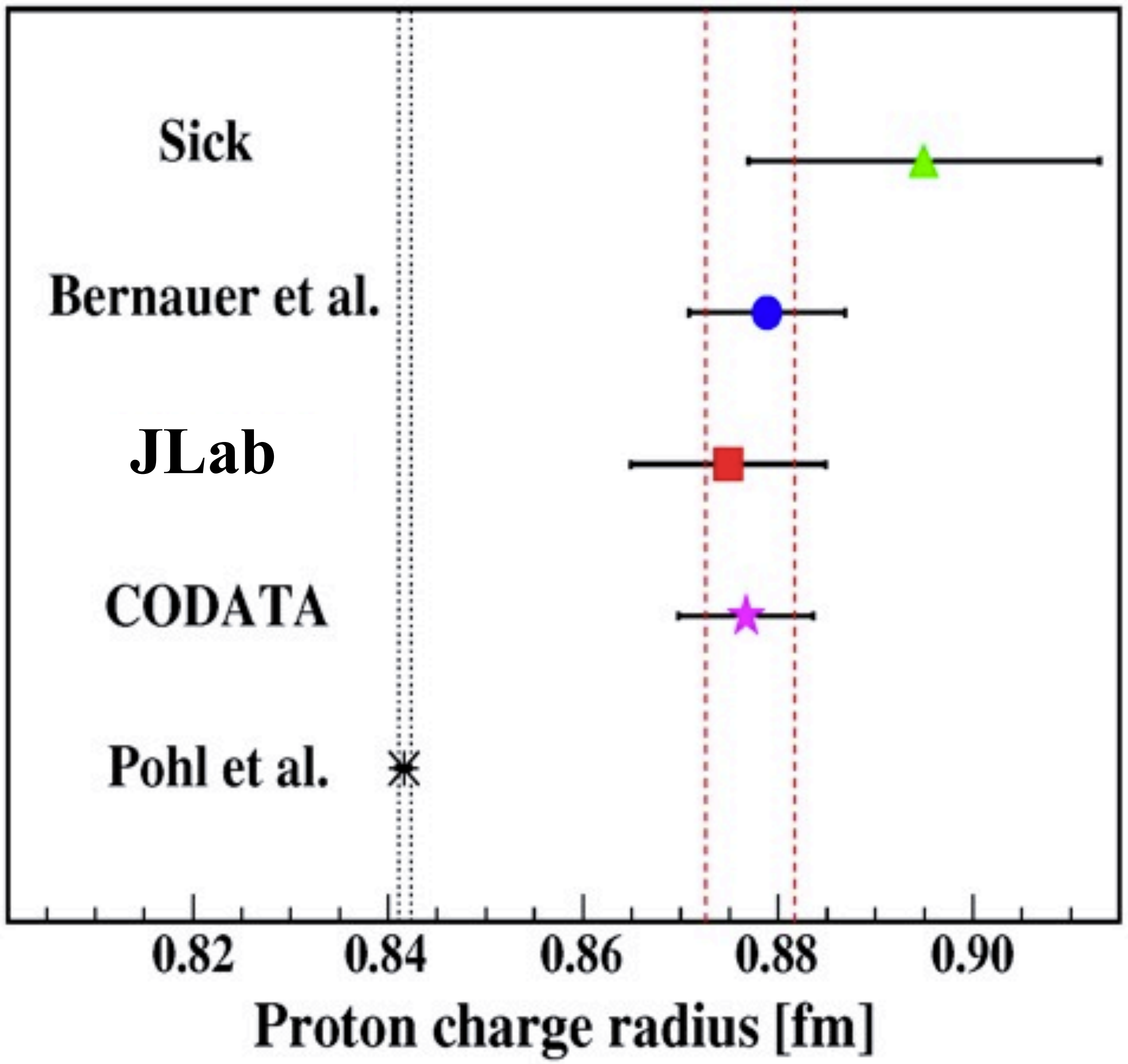
Zhan et al., PLB705, 59 (2011)
Ron et al., PRC84, 055204 (2011)

Hadronic physicists all over: 1960s-2010s - Form factors

Gilman, ECT* Workshop on the "Proton Radius Puzzle"

Proton RMS Charge Radius

Muonic hydrogen disagrees with atomic physics and electron scattering determinations of slope of G_E at $Q^2 = 0$.

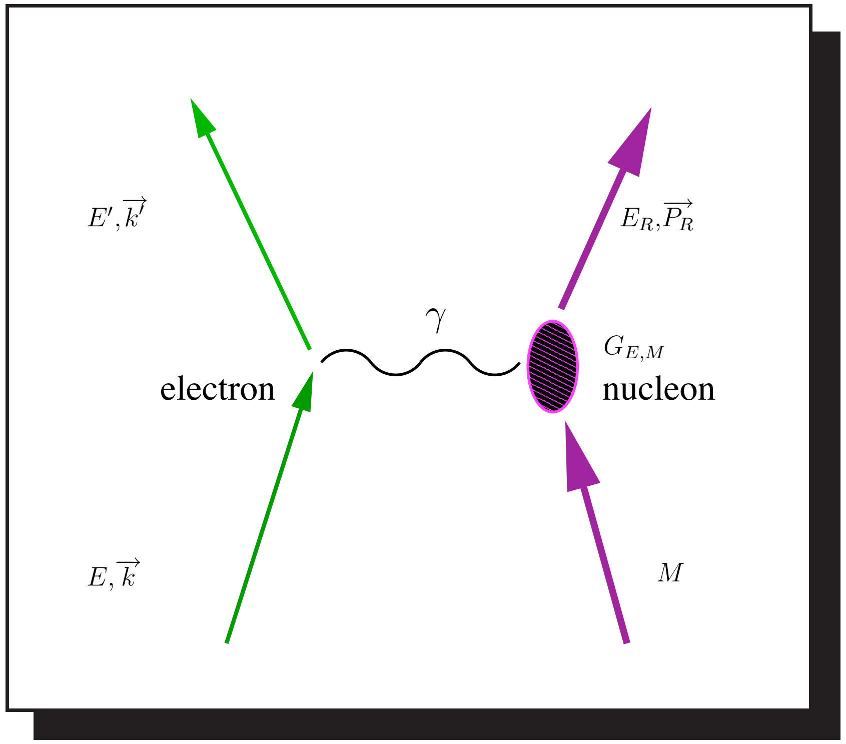


#	Extraction	$\langle R_E \rangle^2$ [fm]
1	Sick	0.8950(180)
2	Mainz	0.8790(80)
3	JLab	0.8750(100)
4	CODATA'06	0.8768(69)
5	Combined 2-4	0.8772(46)
6	Muonic Hydrogen	0.8418(7)

Arrington, ECT* Workshop on the "Proton Radius Puzzle"

Formalism

$$\frac{d\sigma}{d\Omega} = \sigma_{\mathrm{Mott}} \frac{E'}{E_0} \left\{ (F_1)^2 + \tau \left[2\,(F_1 + F_2)^2 \tan^2(\theta_e) + (F_2)^2 \right] \right\} ; \; F_{1,2} = F_{1,2}(Q^2)$$



$Q^2 = 4EE' \sin^2(\theta/2)$	$\tau = \frac{Q^2}{4M^2}$
$F_1^p(0) = 1$	$F_1^n(0) = 0$
$F_2^p(0) = 1.79$	$F_2^n(0) = -1.91$

In Breit frame F_1 and F_2 related to charge and spatial curent densities:

$$\rho = J_0 = 2eM[F_1 - \tau F_2]$$

$$J_i = e\bar{u}\gamma_i u[F_1 + F_2]_{i=1,2,3}$$

$$G_E\left(Q^2\right) = F_1(Q^2) - \tau F_2\left(Q^2\right) \qquad G_M\left(Q^2\right) = F_1\left(Q^2\right) + F_2\left(Q^2\right)$$

✓ For a point like probe G_E and G_M are the FT of the charge and magnetizations distributions in the nucleon, with the following normalizations

$Q^2 = 0$ limit: $G_E^p = 1 \; G_E^n = 0 \;\; G_M^p = 2.79 \; G_M^n = -1.91$

one-photon approx.

- In NRQM, the FF is the 3d Fourier transform (FT) of the Breit frame spatial distribution - not the rest frame!

- Boost effects in relativistic theories destroy our ability to determine 3D rest frame spatial distributions. The FF is the 2d FT of the transverse spatial distribution.

Slope of $G_{E,M}$ at Q^2=0 defines the radii. This is what FF experiments quote.

$$
\begin{aligned}
G_E^{p(n)}(Q^2) &= \frac{1}{(2\pi)^3}\int d^3r\rho(\vec{r})e^{(-i\vec{q}\cdot\vec{r})} \\
&= \int d^3r\rho(r) - \frac{q^2}{6}\int d^3r\rho(r)r^2 + \cdots \\
&= 1(0) - \frac{q^2}{6}\langle r^2\rangle_{p(n)} + \cdots
\end{aligned}
$$

$$
\boxed{\langle r_E^{p(n)}\rangle = -6\left(\frac{dG_E^{p(n)}(Q^2)}{dQ^2}\right)_{Q^2=0}}
$$

Alternatives to Rosenbluth separation

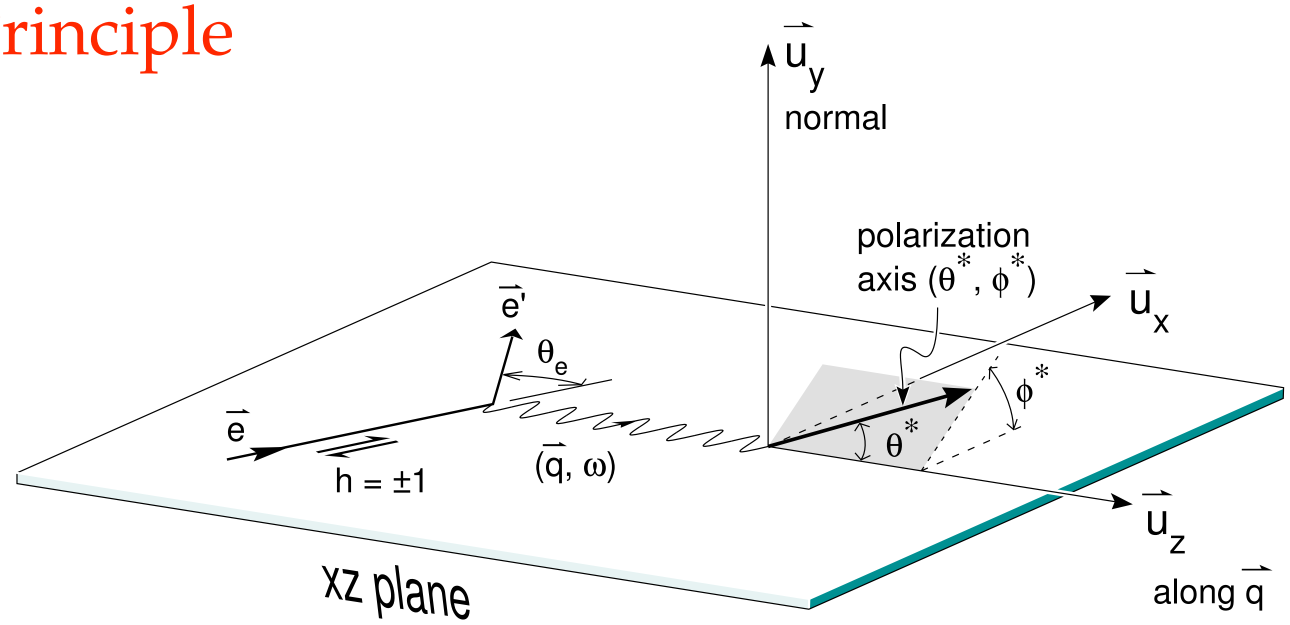
Beam–Target Asymmetry - Principle

Polarized Cross Section:

$\sigma = \Sigma + h\Delta$

Beam Helicity $h \pm 1$

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\Delta}{\Sigma}$$



$$A = \frac{\overbrace{a\cos\Theta^\star (G_M)^2}^{A_T} + \overbrace{b\sin\Theta^\star\cos\Phi^\star G_E G_M}^{A_{TL}}}{c\,(G_M)^2 + d\,(G_E)^2}; \quad \varepsilon = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} = P_B \cdot P_T \cdot f \cdot A$$

$\Theta^\star = 90^\circ \quad \Phi^\star = 0^\circ$

$$\Longrightarrow A_{TL} = \frac{b G_E G_M}{c\,(G_M)^2 + d\,(G_E)^2}$$

$\Theta^\star = 0^\circ \quad \Phi^\star = 0^\circ$

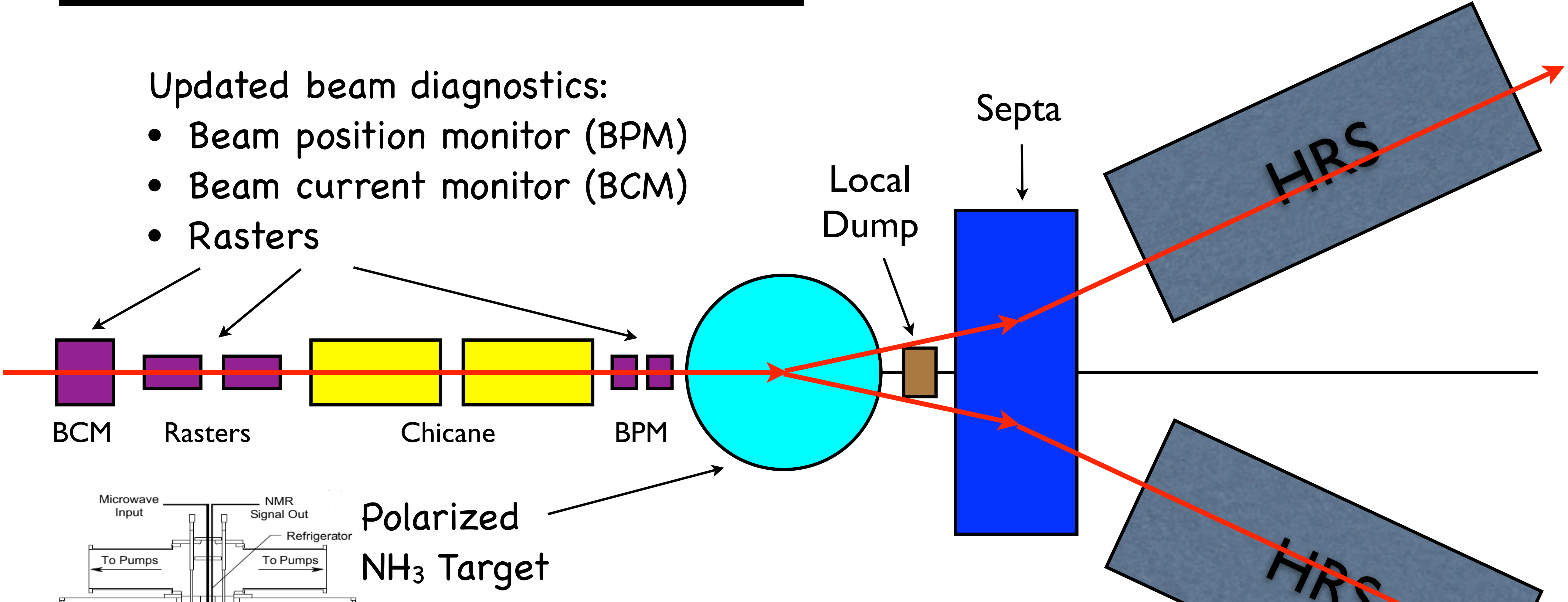
$$\Longrightarrow A_T = \frac{a G_M^2}{c\,(G_M)^2 + d\,(G_E)^2}$$

JLAB, BLAST, Mainz $\vec{H}$, $\overrightarrow{^2\mathrm{H}}$, $\overrightarrow{^3\mathrm{He}}$

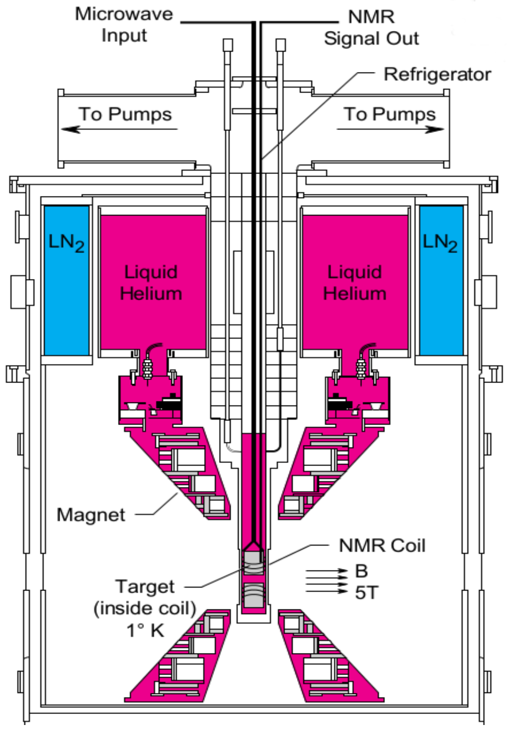
E08-027 and E08-007-II

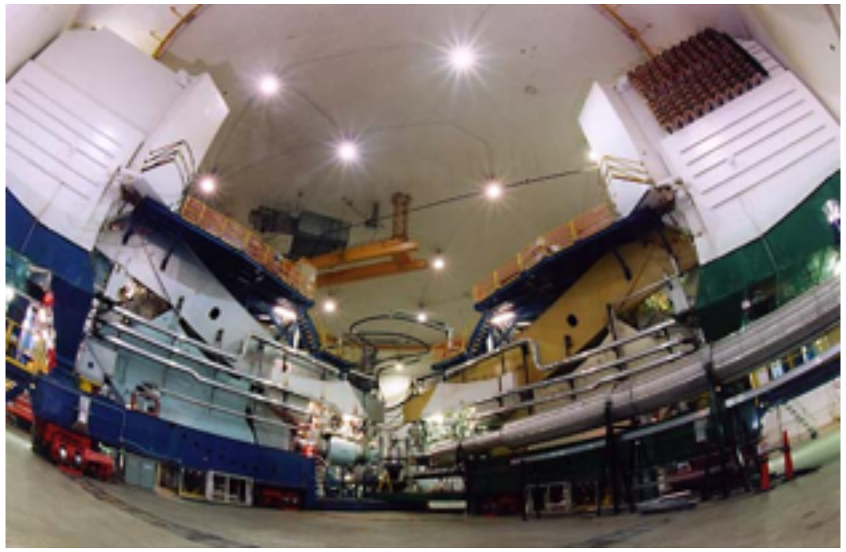
Updated beam diagnostics:

- Beam position monitor (BPM)
- Beam current monitor (BCM)
- Rasters



Polarized NH_3 Target

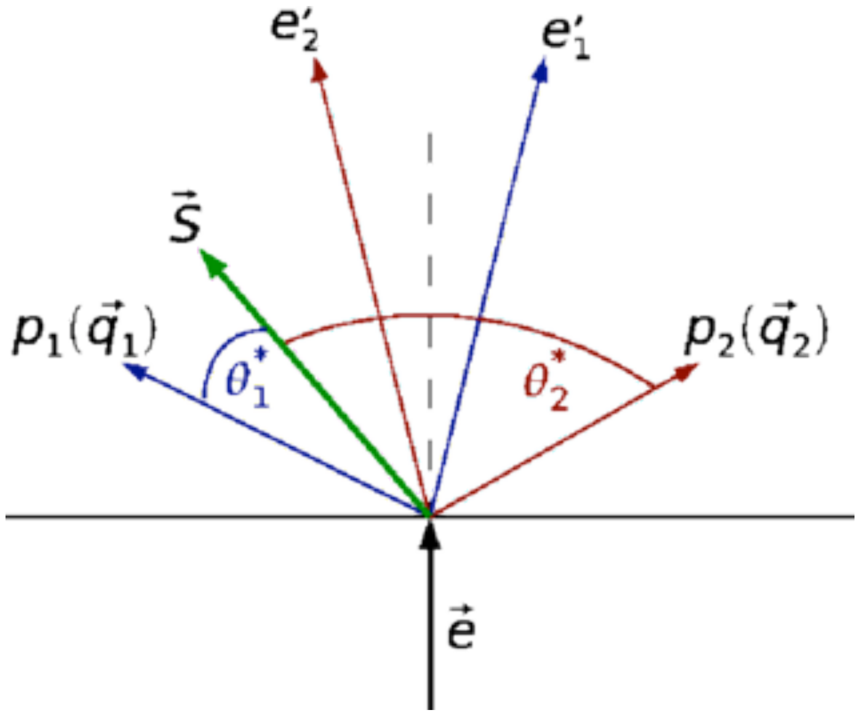




Hall A High Resolution Spectrometer (HRS)

E08007 - Part II

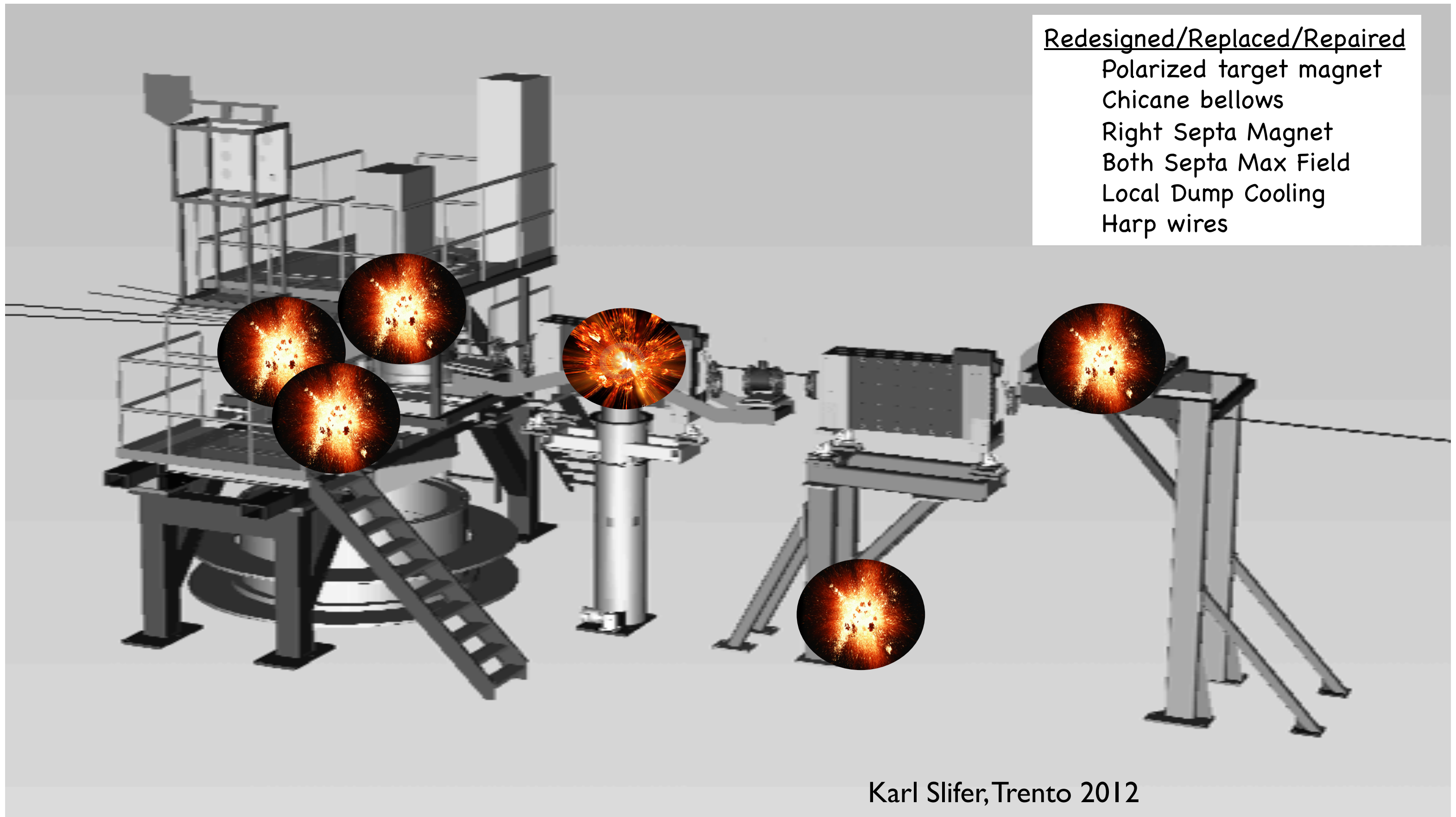
- High precision (≈1%) survey of the FF ratio at Q^2=0.01 - 0.16 GeV^2.
- Beam-target asymmetry measurement by electron scattering from polarized NH_3 target.
- Electrons detected in two matched spectrometers.
- Ratio of asymmetries cancels systematic errors → only one target setting to get FF ratio.



$$\mu_P \frac{G_E^P}{G_M^P} = -\mu_P \frac{a(\tau,\theta) cos\theta_1^* - \frac{f_2}{f_1}\Gamma a(\tau,\theta)\cos\theta_2^*}{\cos\phi_1^*\sin\theta_1^* - \frac{f_2}{f_1}\Gamma\cos\phi_2^*\sin\theta_2^*}$$

$\Gamma = A_1/A_2$

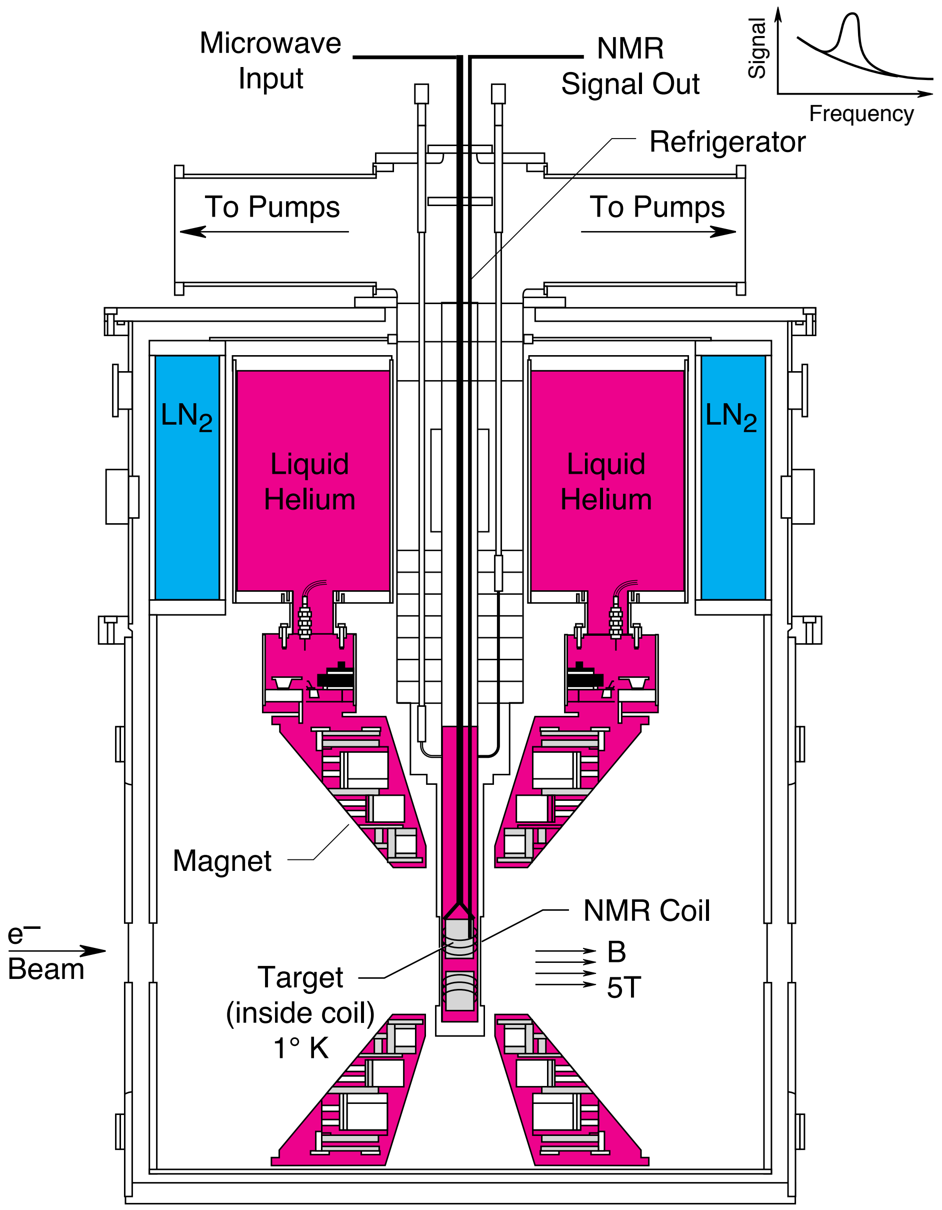
- Ran Feb-May 2012 - Moshe Friedman (HUJI) Thesis project, work in progress
- Higher Q^2 points lost mainly due to a series of difficulties with magnets

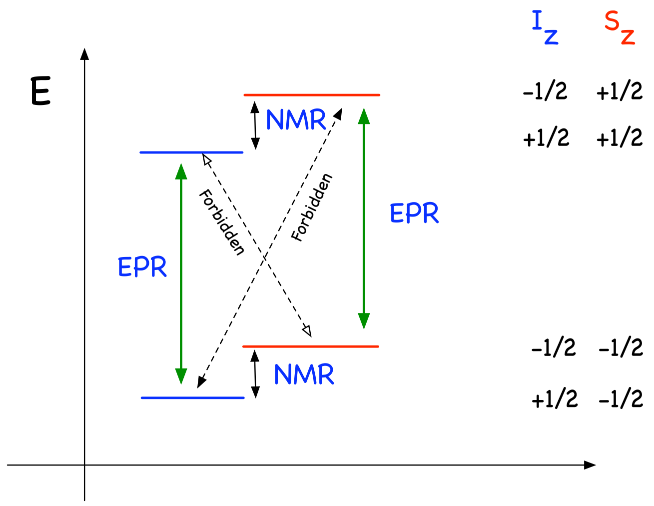


Redesigned/Replaced/Repaired

Polarized target magnet
Chicane bellows
Right Septa Magnet
Both Septa Max Field
Local Dump Cooling
Harp wires

Dynamically Polarized Solid Target





Reconfigured Hall B magnet services

Hall A Polarized Target for g2p/gep

Many Evolutionary Improvements from previous runs in Hall C

- Rotation
- Target Stick
- Target Lifter
- Software
- Cryogenics
- Cryostat

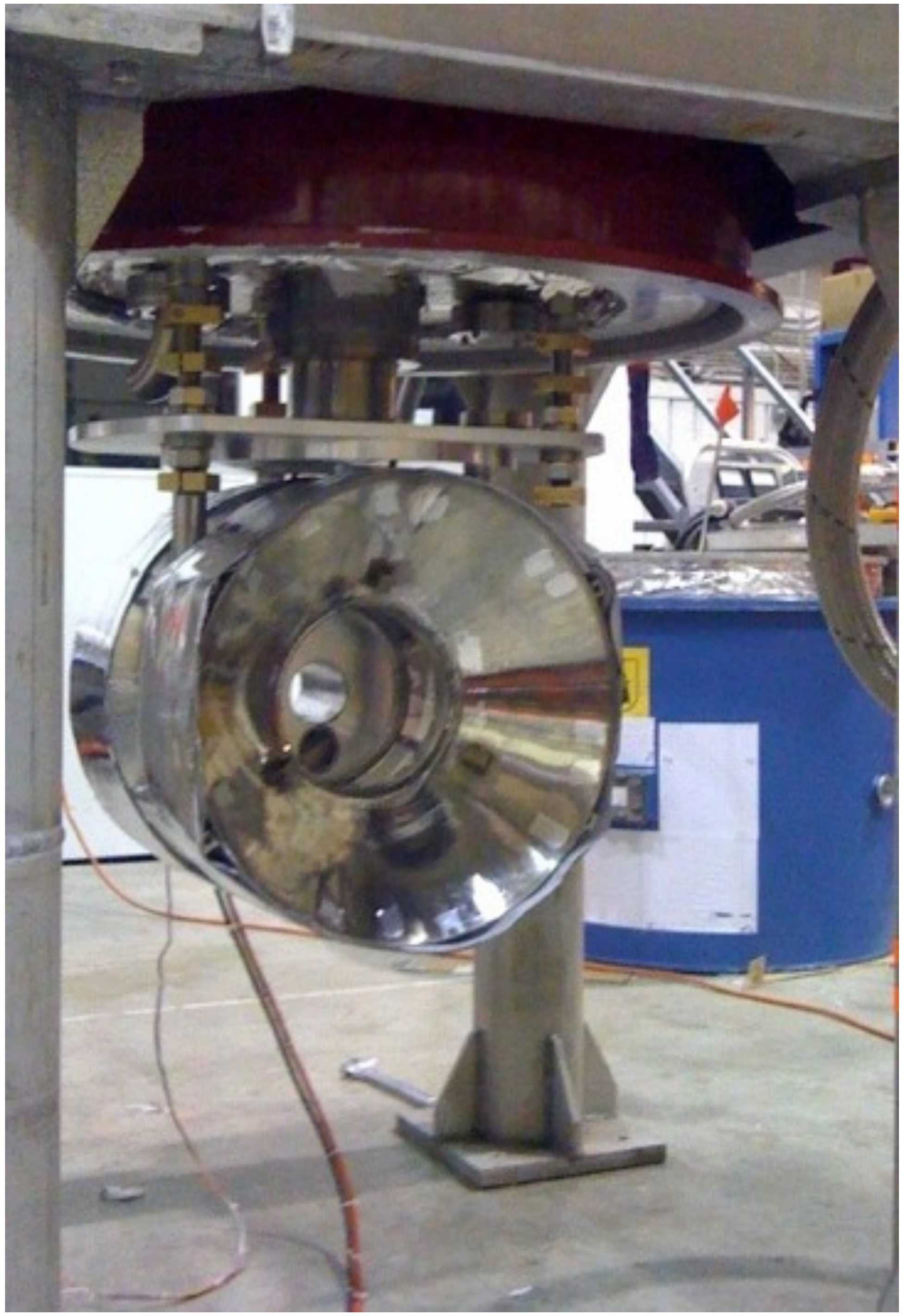
Still 5T/2.5T 140/70 GHz

- Polarization at 5T consistent with experience
- New record for irradiated NH_3 at 2.5 T
  - Polarization (same material and EIO) at UVa done without benefit of the 12000 m^3 pump at JLAB

JLAB Target scientists and technical staff did great!

UVa Target, Magnet born 1992, died 2012
SLAC - 3 experiments, Hall C - 4 experiments

Hall B Target exactly same field
parameters, born 1995, reconfigured



Only real difference is location of the quench protection circuitry, above coil package on left and upstream on the right, has implications for gep.

Cryostat also modified (and painted!), magnet from Hall B, OVC from SANE. First time in Hall A.

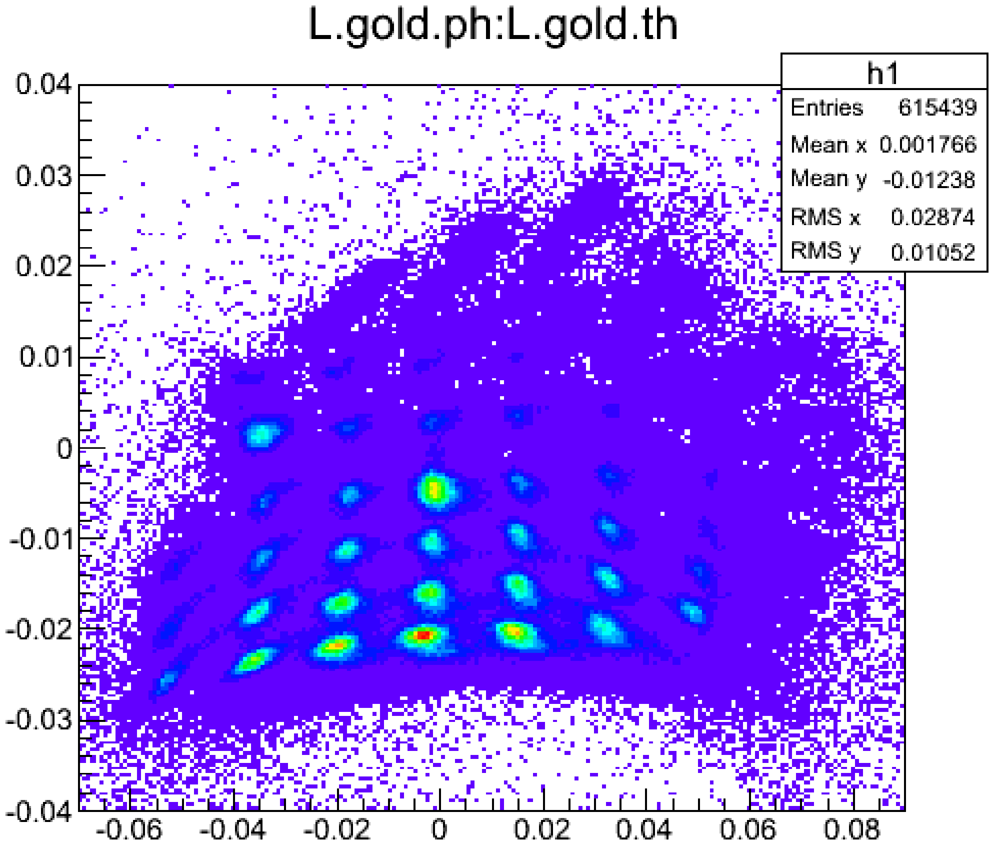
Status Report

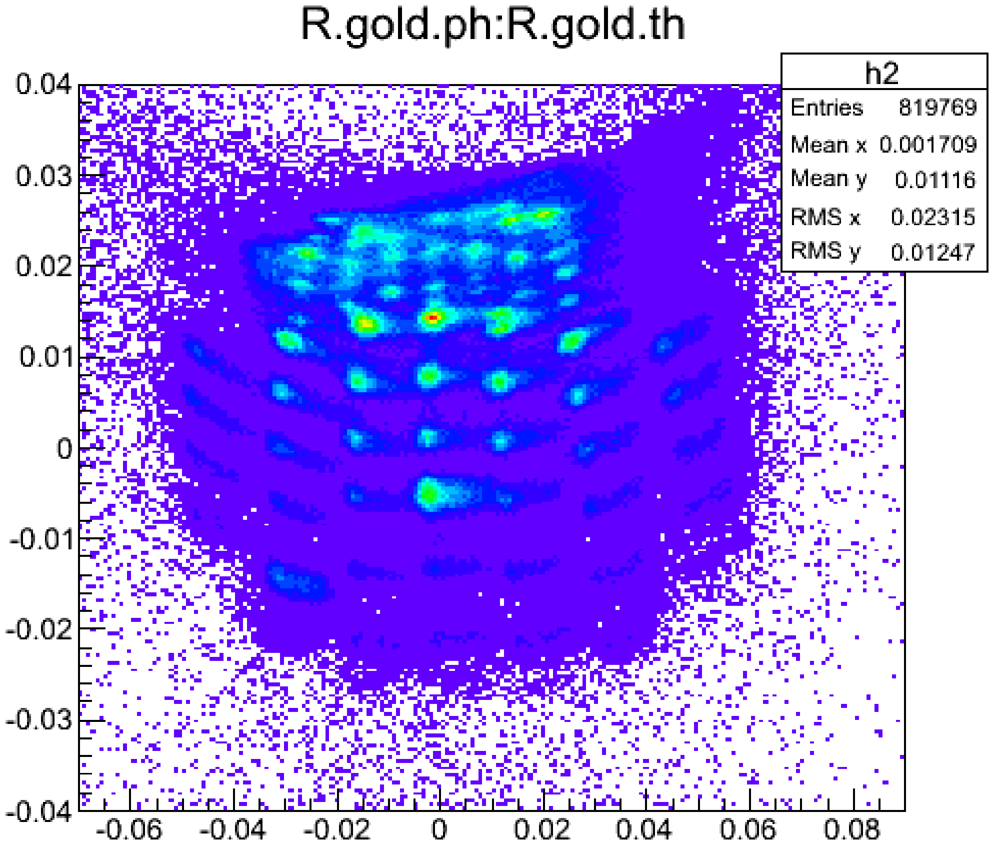
Kinematics

Q^2 (GeV^2)	E (GeV)	E' (GeV)	θ (deg)
0.013	1.157	1.150	5.7
0.020	1.712	1.701	4.7
0.030	1.712	1.696	5.8
0.034	2.253	2.235	4.7
0.052	2.253	2.225	5.8

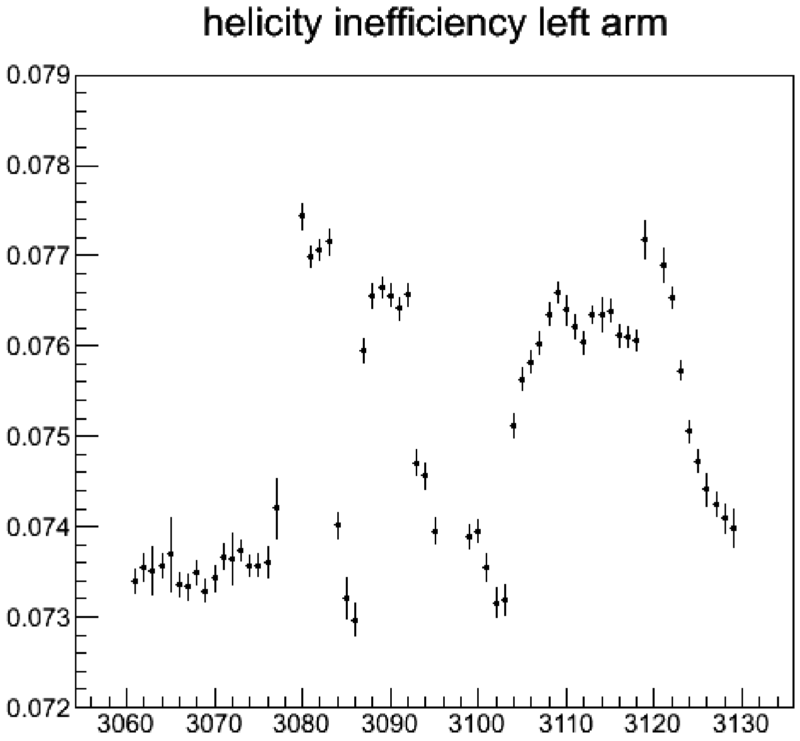
- On-line analysis - sanity checks.
- Almost all data extracted - but code is still preliminary:

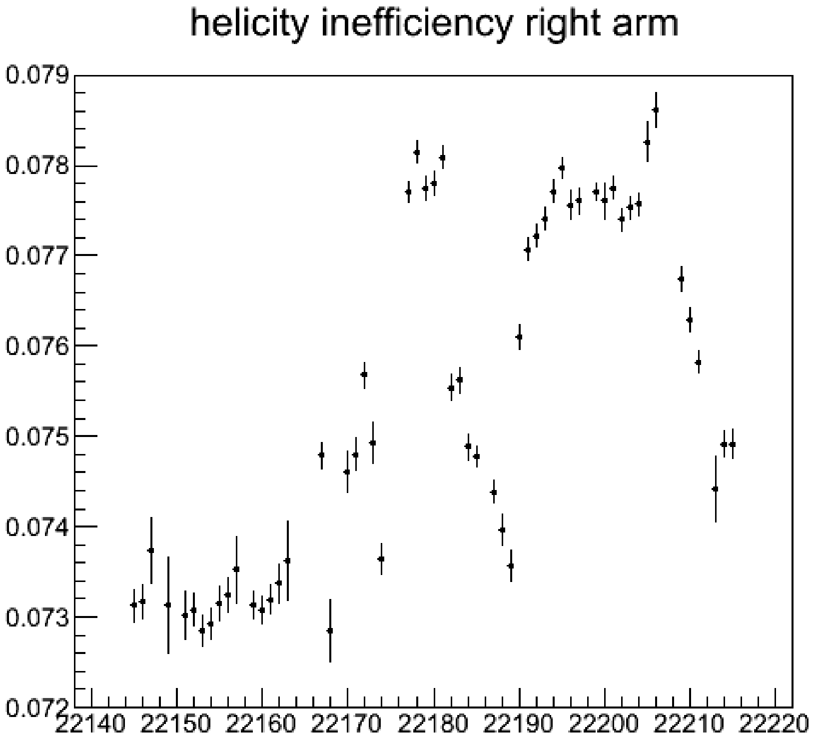
- Preliminary optics (Jixie Zhang and others)





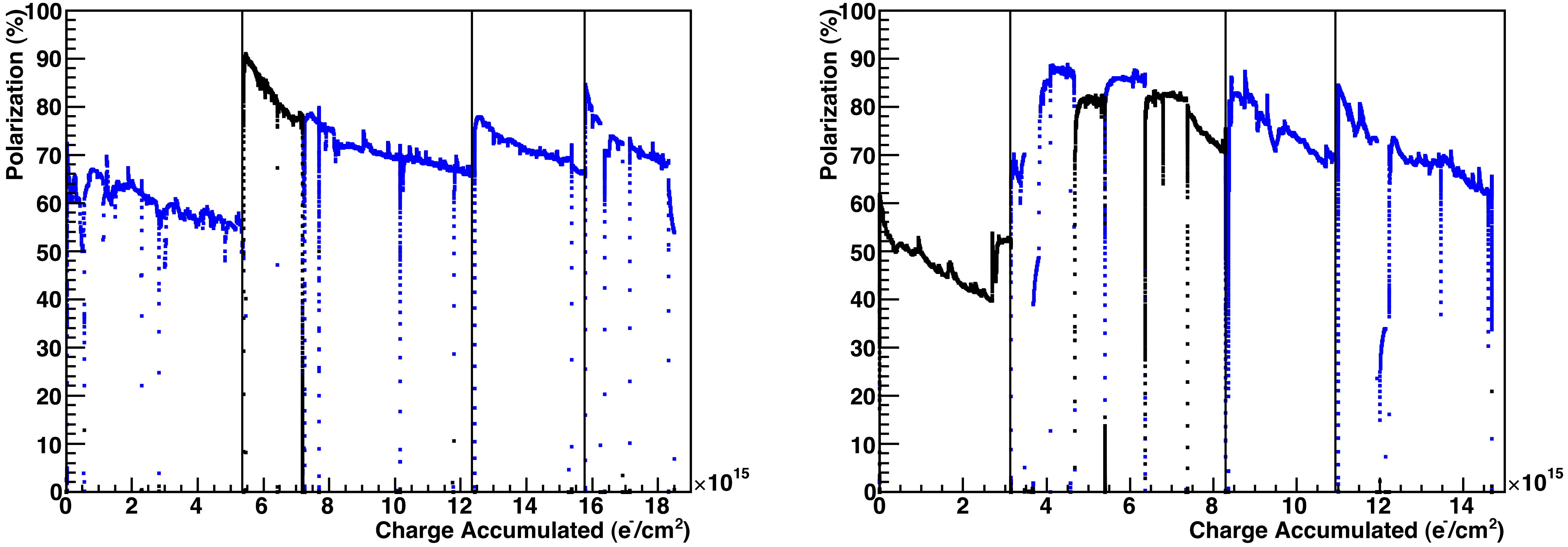
- External helicity decoder (Chau Gu).





7% helicity decoder inefficiency

Dustin Keller, Uncertainty in DNP Target Data for E08-007

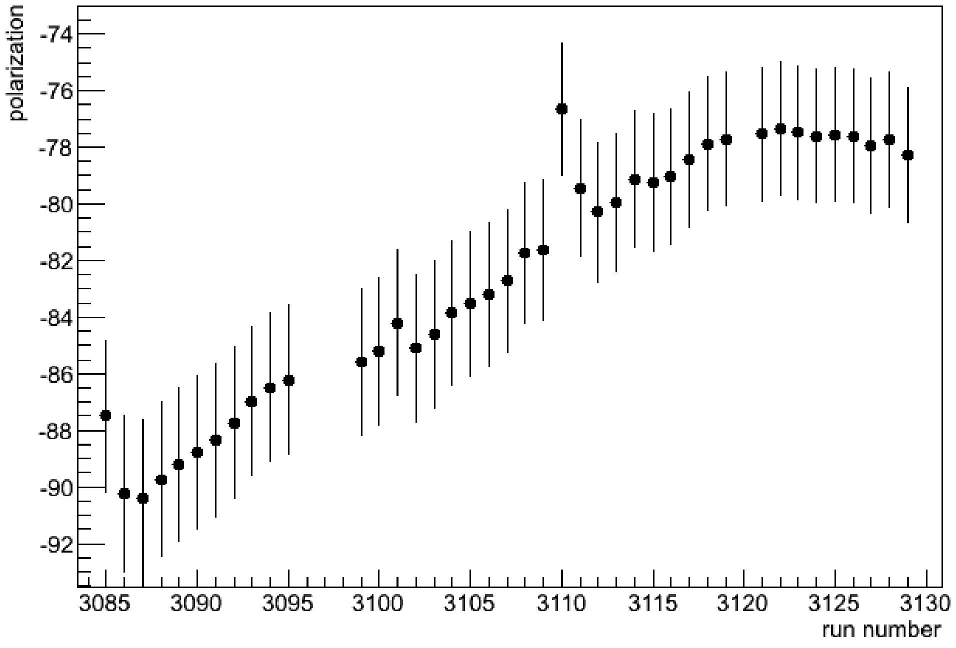


Polarization during gep

(#)	source	error (%)
(1)	ΔT	1.45
(2)	ΔA_{TE}	1.61
(3)	ΔA_{fit}	0.75
(4)	R_B	0.50
(5)	ΔV_Q	0.75
(6)	NMR-tune	0.47
(7)	ΔV_{Yale}	0.1
(8)	ΔB_{drift}	0.25
(9)	ΔP_{run}	0.53
	$\Delta P/P$	2.58

Additional uncertainties from the TE data, total error < 3.3%

Polarization vs run (3085-3130)



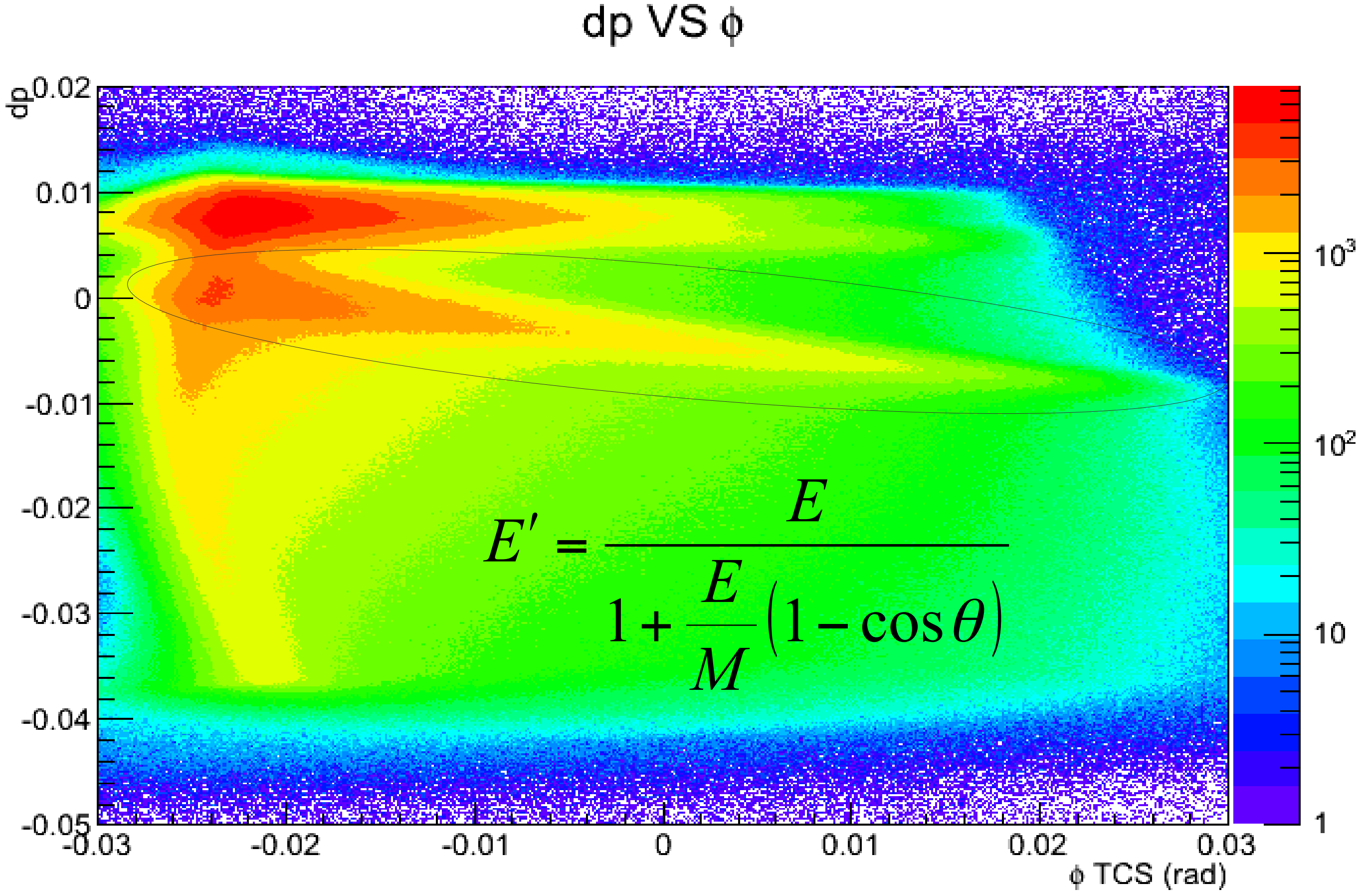
$$A = \frac{N^+ - N^-}{(N^+ + N^-)P_t P_b f}$$

Corrected for charge, inefficiencies etc.

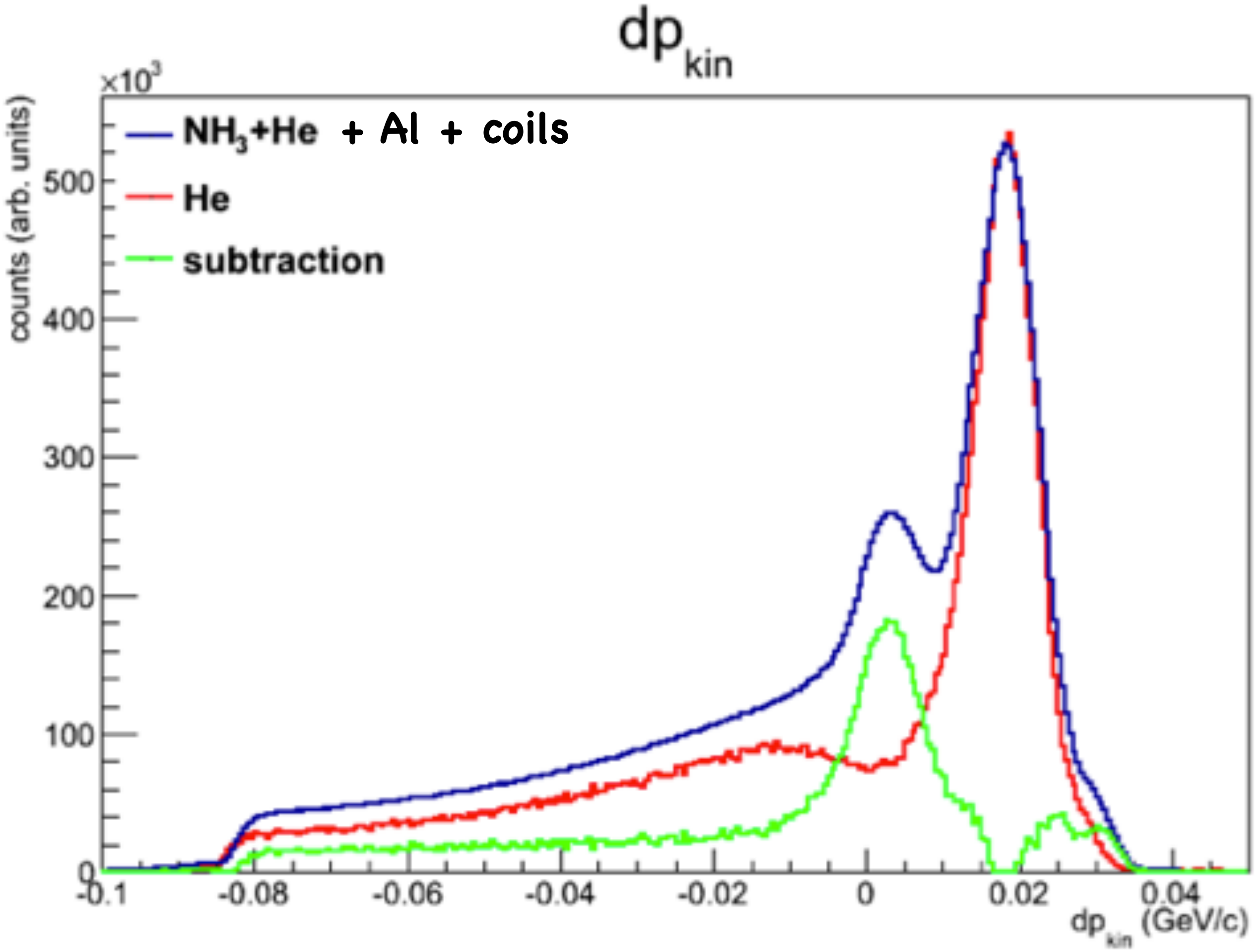
$$A^{phys} = \frac{-2\sqrt{\frac{\tau}{1+\tau}}\tan\frac{\theta}{2}\left[\sqrt{\tau(1+(1+\tau)\tan^2\frac{\theta}{2})}\cos\theta^* G_M^2 + \sin\phi^* G_M G_E\right]}{\frac{G_E^2+\tau G_M^2}{1+\tau} + 2\tau G_M^2\tan^2\frac{\theta}{2}}$$

$$A \approx -2\sqrt{\tau}\tan\frac{\theta}{2}\sin\theta^*\cos\phi^*\frac{G_M}{G_E}$$

Multiple species in target - H, N, 4He, Al, ...

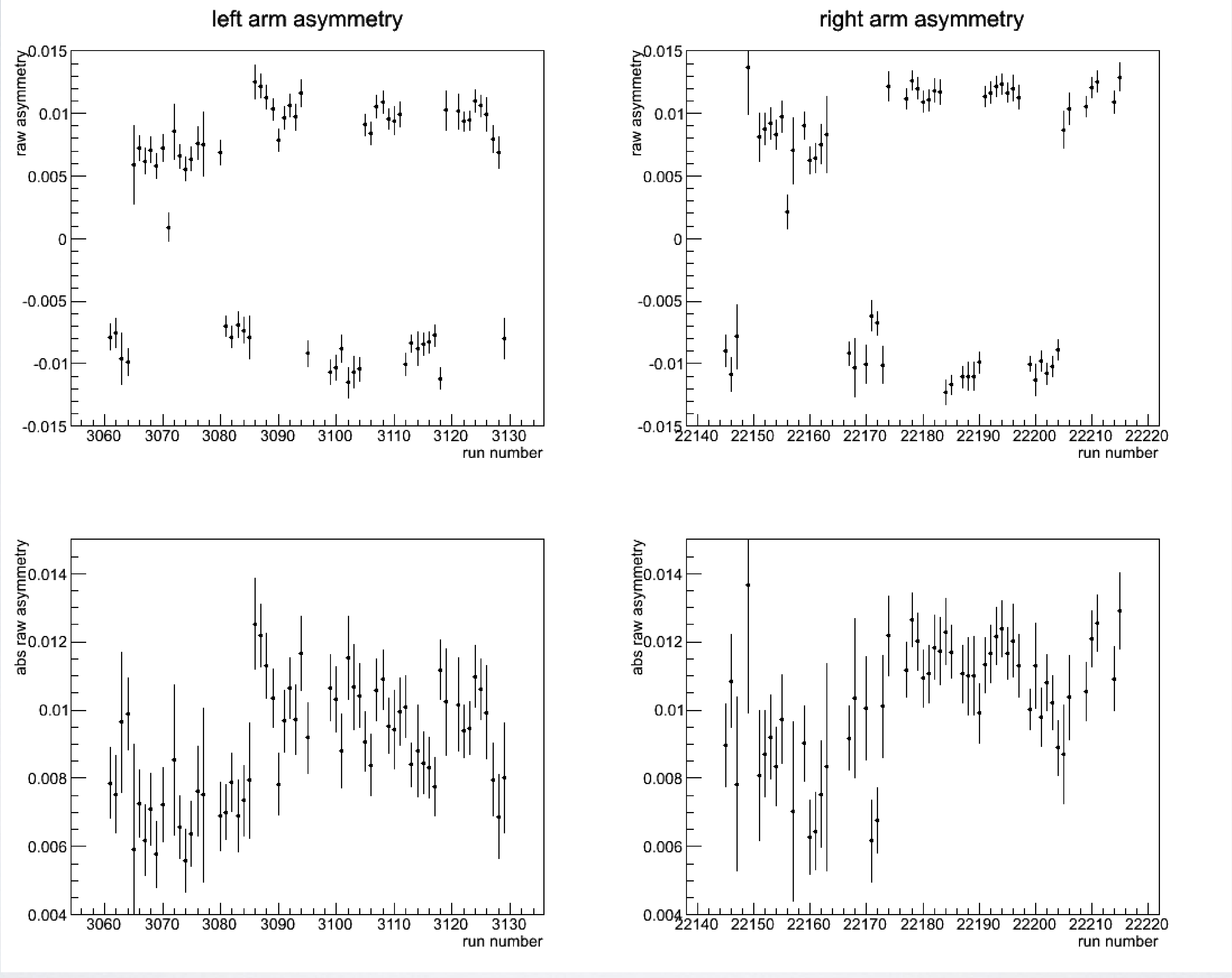


$$E' = \frac{E}{1 + \frac{E}{M}(1-\cos\theta)}$$

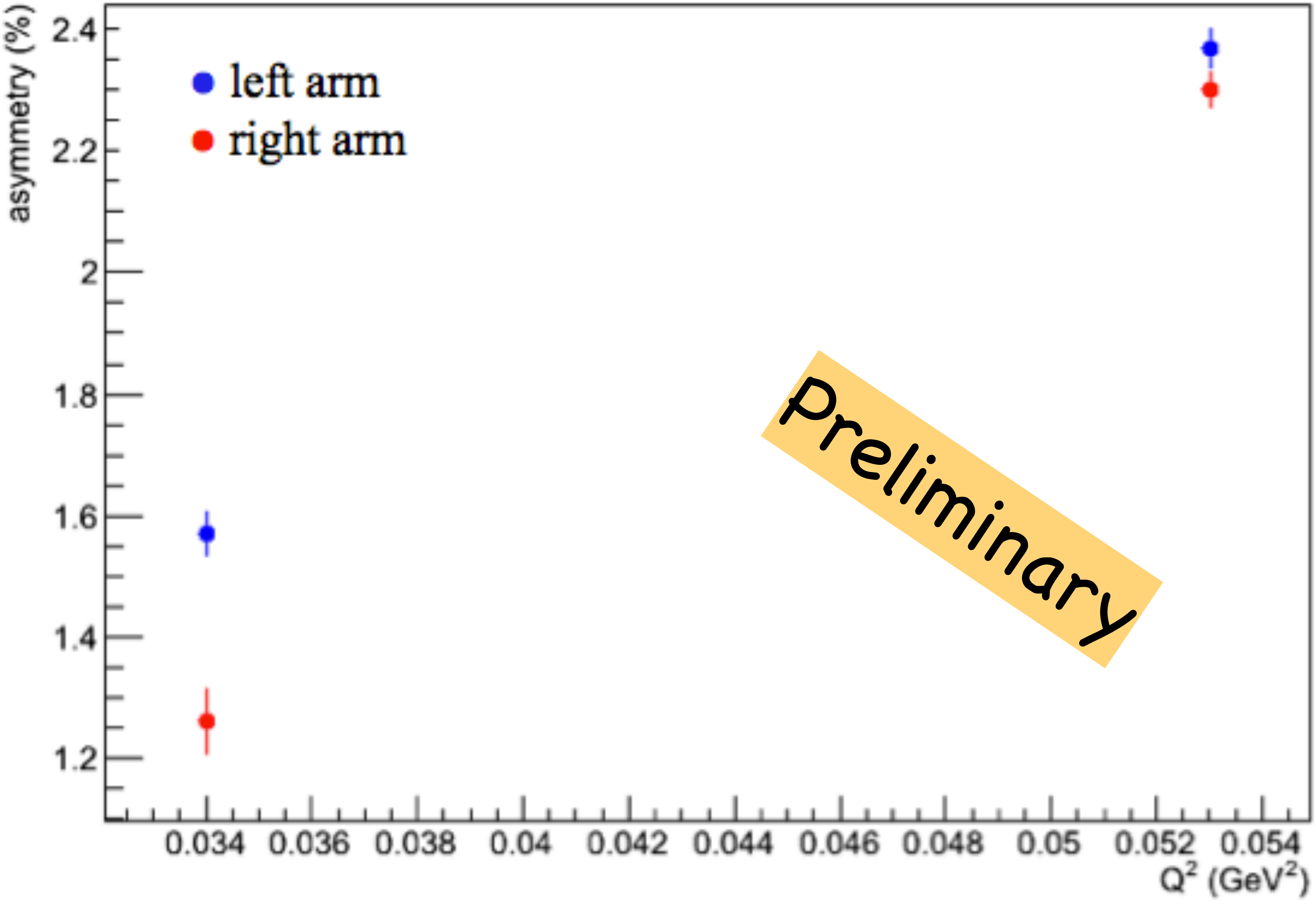


Raw Asymmetries

uncorrected for beam or target polarizations



- •Asymmetries consistent under both target and beam polarization flipping
- •Random tests for the 1.7 and 1.1 GeV data gives similar results

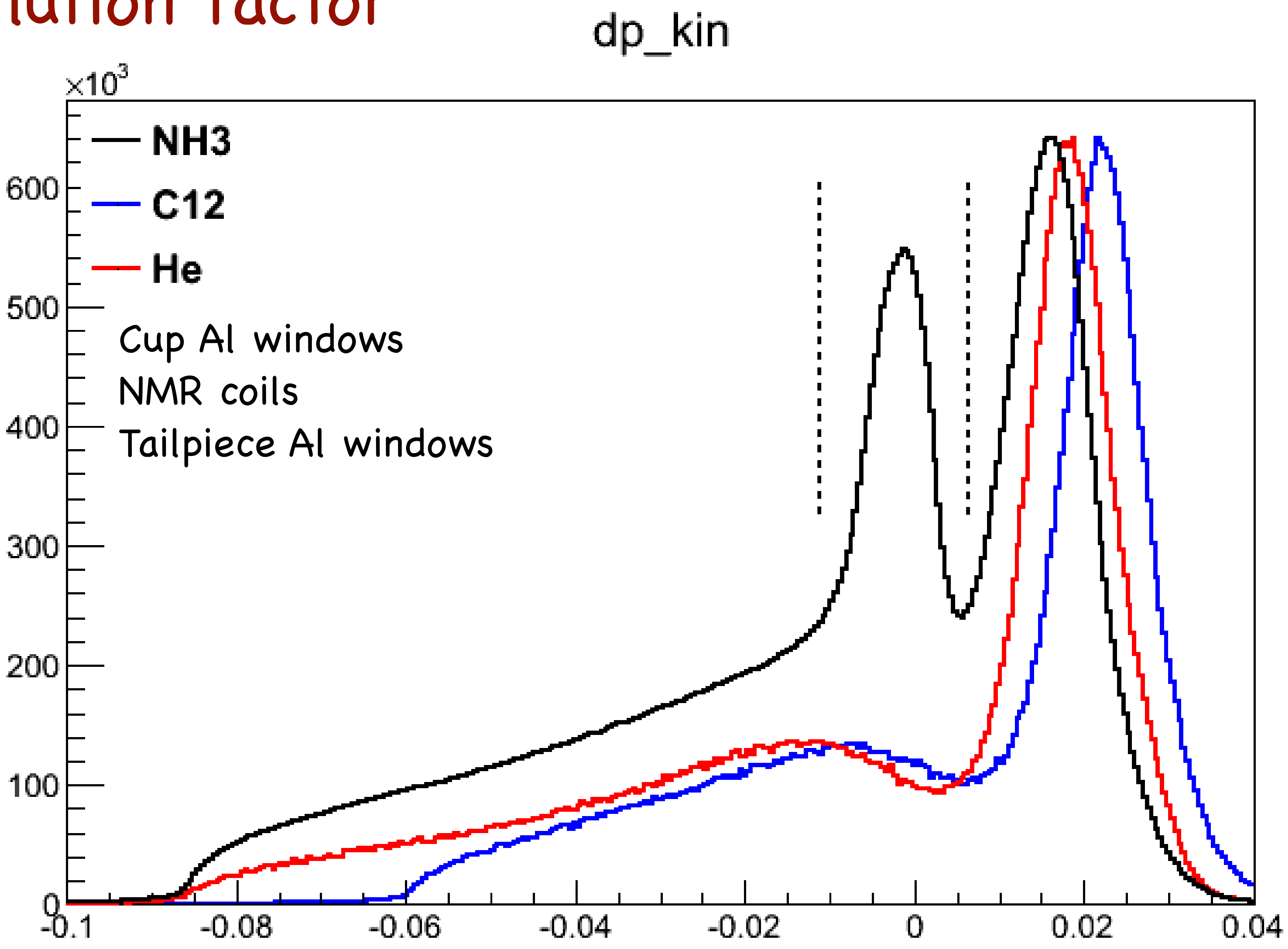


On line polarization, rough estimate of the dilution factor.

Moshe Friedman, “the asymmetries are far below anything that make sense”

D. Day, “Situation normal”

•Dilution factor



$$f_p = \frac{N_1 \sigma_p}{N_{14}\sigma_{14} + N_1 \sigma_p + \sum N_A \sigma_A}$$

To know f, one needs to know the packing fraction, pf, the amount of material in the cup (by volume)

•Dilution factor and packing factor

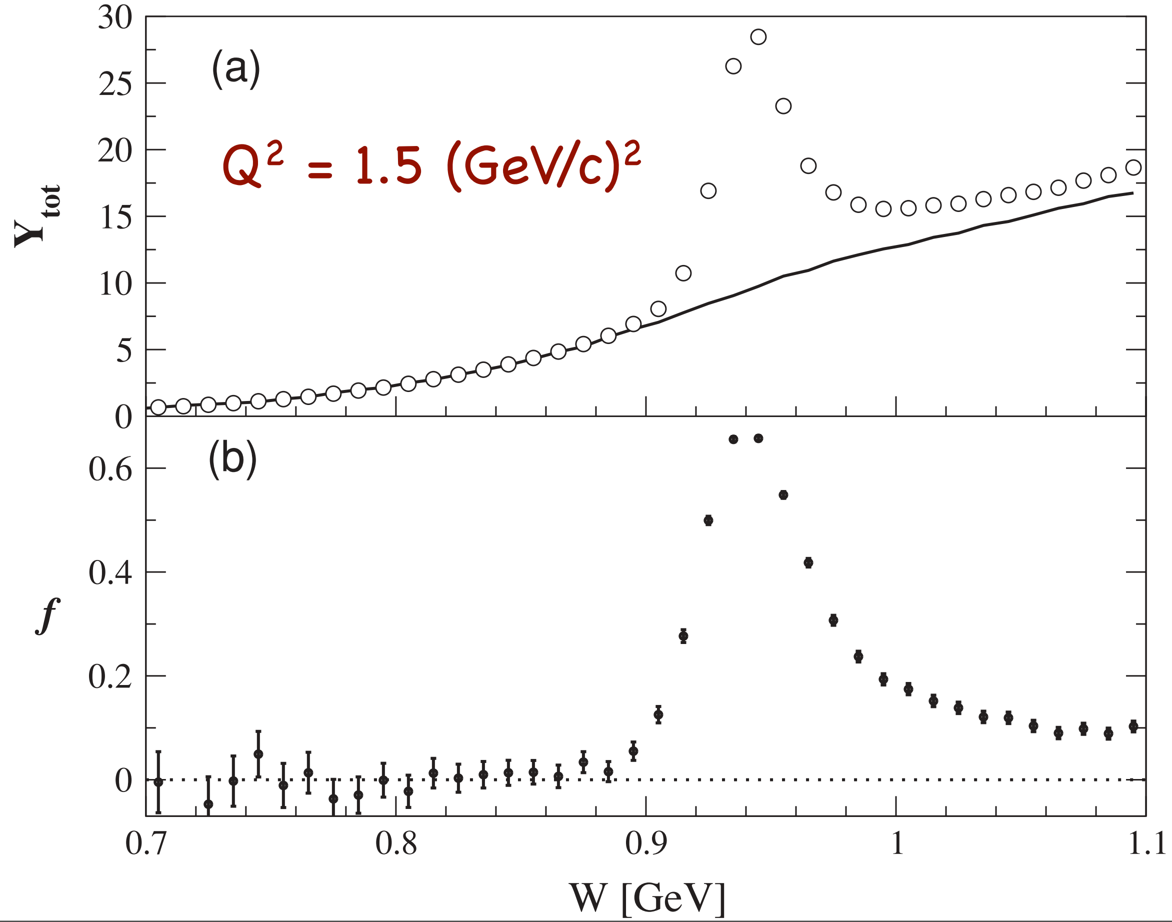
RSS

$$f = \frac{\frac{3\rho_{NH_3}3pf}{M_{NH_3}}\sigma_1}{\frac{3\rho_{NH_3}3pf}{M_{NH_3}}\sigma_1 + \frac{\rho_{NH_3}3pf}{M_{NH_3}}\sigma_{15} + \frac{\rho_{He}3(1-pf)}{M_{He}}\sigma_4 + \frac{\rho_{He}z'_{He}}{M_{He}}\sigma_4 + \frac{\rho_{Al}z_{Al}}{M_{Al}}\sigma_{27}}$$

$$= \frac{\frac{3\rho_{NH_3}}{M_{NH_3}}\sigma_1}{\frac{3\rho_{NH_3}}{M_{NH_3}}\sigma_1 + \frac{\rho_{NH_3}}{M_{NH_3}}\sigma_{15} + \frac{\rho_{He}}{M_{He}}(\frac{1}{pf} - 1)\sigma_4 + \frac{\rho_{He}z'_{He}}{M_{He}3pf}\sigma_4 + \frac{\rho_{Al}z_{Al}}{M_{Al}3pf}\sigma_{27}}$$

$$= \frac{3}{3 + \frac{\sigma_{15}}{\sigma_1} + \frac{\rho_{He}M_{NH_3}}{\rho_{NH_3}M_{He}}(\frac{1}{pf} - 1)\frac{\sigma_4}{\sigma_1} + \frac{\rho_{He}M_{NH_3}z'_{He}}{\rho_{NH_3}M_{He}3pf}\frac{\sigma_4}{\sigma_1} + \frac{\rho_{Al}M_{NH_3}z_{Al}}{\rho_{NH_3}M_{Al}3pf}\frac{\sigma_{27}}{\sigma_1}}$$

Done by comparing MC (incorporating well-tested model of the scattering processes (elastic, QED, DIS) to data with varying pfs



Q^2 = 1.5 (GeV/c)^2

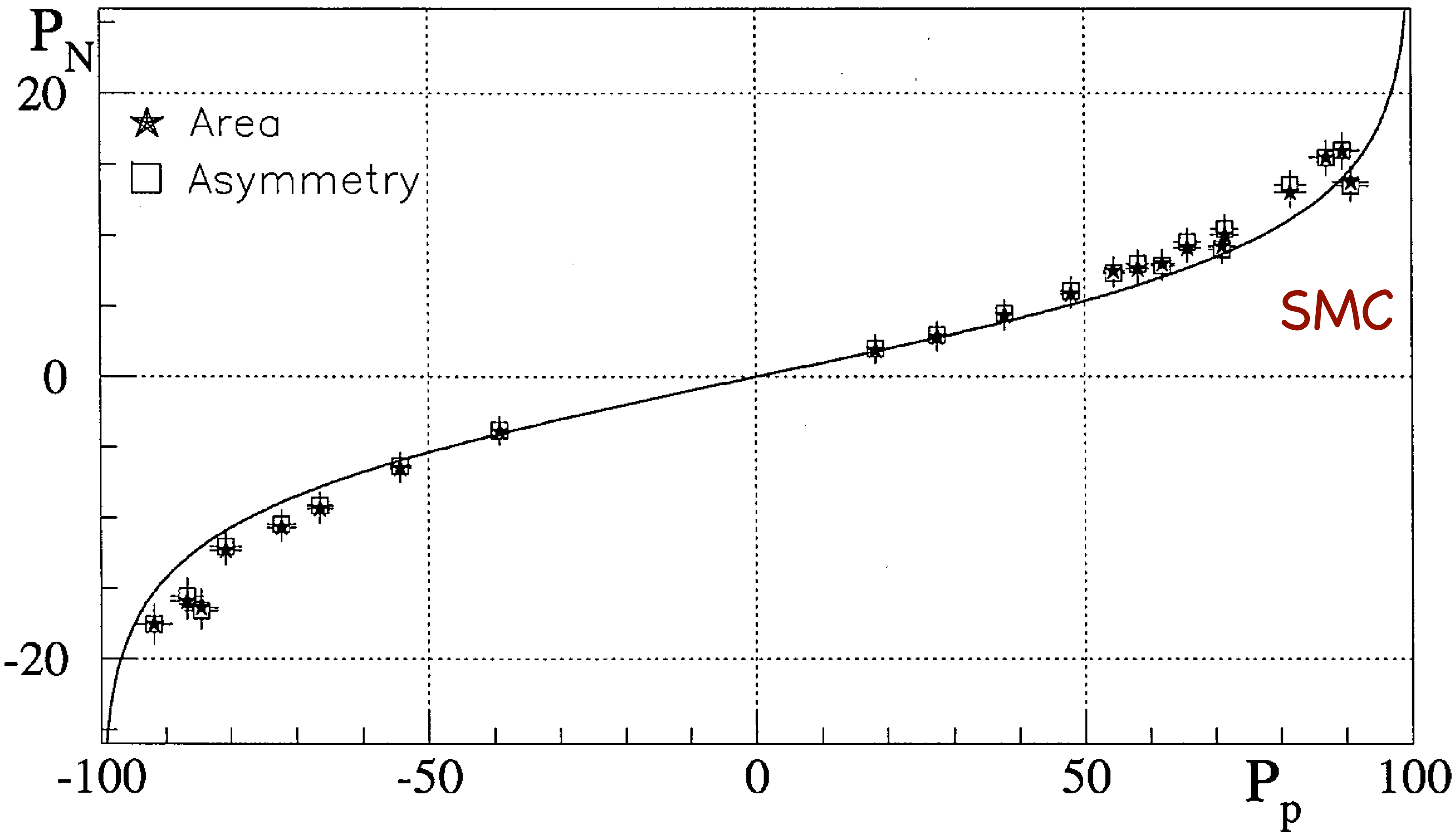
RSS

Nitrogen polarization

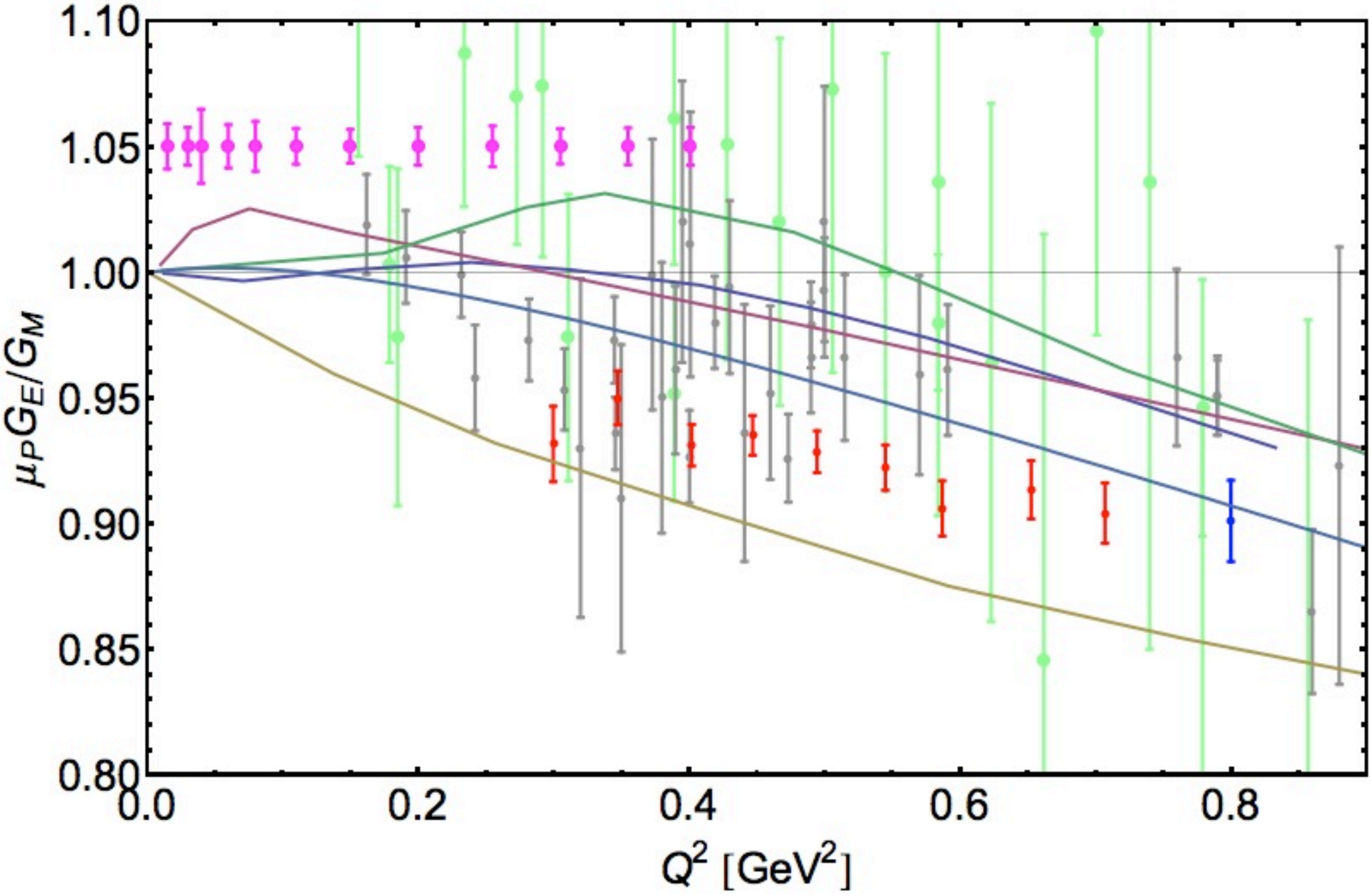
Nitrogen is polarized and contributes to the asymmetry

Should be small.

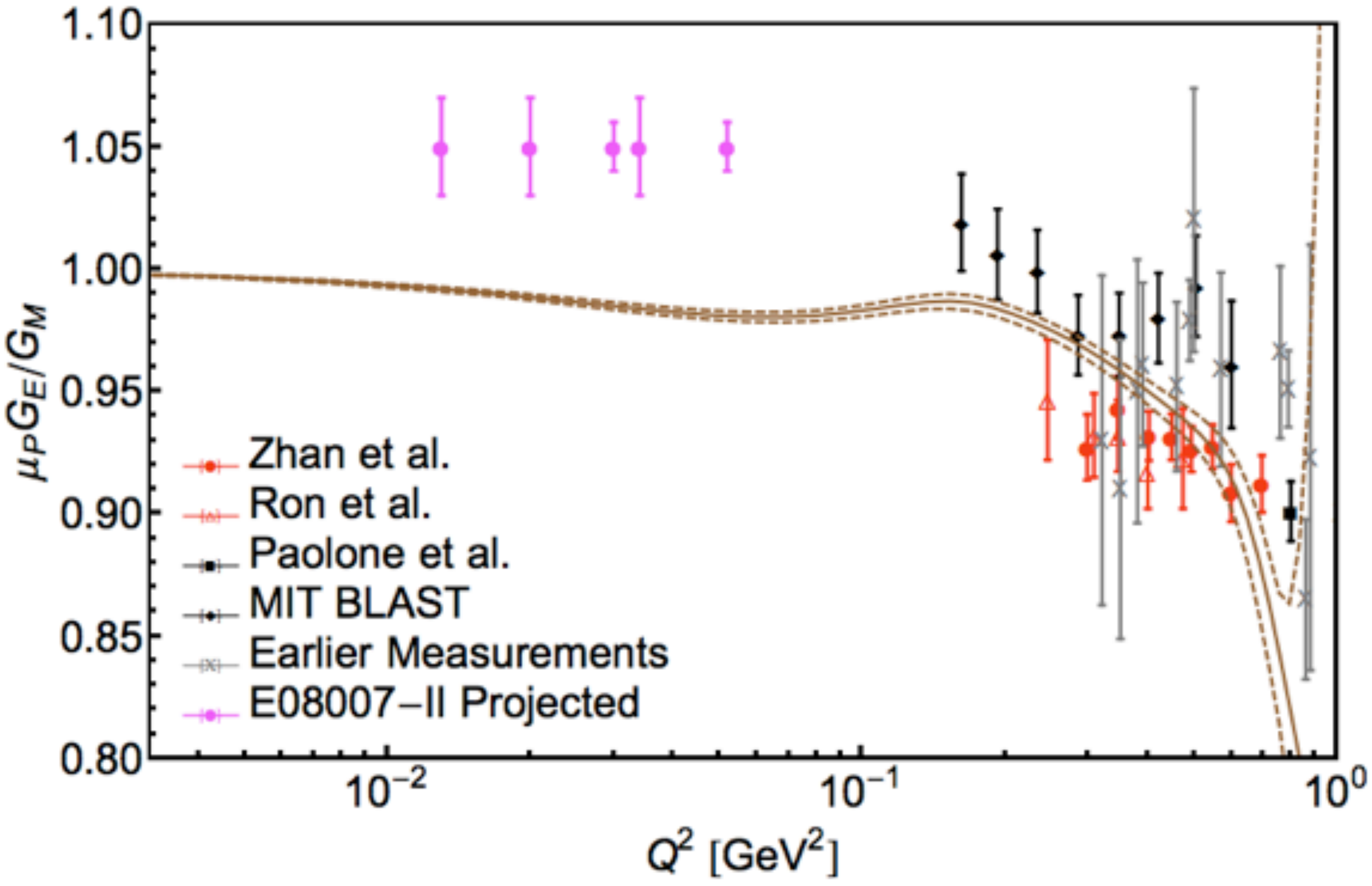
Nuclear Instruments and Methods in Physics Research A 437 (1999) 23}67



E08007 - II Projected uncertainties in proposal



E08007 - Part II Projected uncertainties



Much to do

- Optics - elastic peak is 15 MeV wide!
- Packing fraction
- Dilution factor
- Radiative corrections
- Nitrogen polarization
- Final beam polarizations
- Systematics

Compare ratio method with results from each arm independently

Regular interactions with g2p would be beneficial