Precision Measurement of the Neutron Magnetic Form Factor up to $Q^2 = 8.0$ (GeV/c)^2 by the Ratio Method

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The Hall A Collaboration

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Introduction

For spin $\frac{1}{2}$ target (one-photon-exchange approx):

$$\frac{d\sigma}{d\Omega} = \eta \frac{\sigma_{\text{Mott}}}{1+\tau} \left((G_E)^2 + \frac{\tau}{\epsilon} (G_M)^2 \right)$$

where: $\eta = \frac{1}{1+2\frac{E}{M_N}\sin^2(\theta/2)}$ $\epsilon^{-1} = 1 + 2(1+\tau)\tan^2(\theta/2)$ $\tau = Q^2/4M_N^2$

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Empirical Dipole approximation: $G_E^p \approx G_D$

where $G_D = 1/(1+Q^2/(.71\ \textbf{(GeV/c)}^2))^2$

Scaling approximation: $G_M^p \approx \mu_p G_D$ **and** $G_M^n \approx \mu_n G_D$

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Polarization-transfer measurements: $G_E^p/G_M^p \neq$ const.

...but one-photon approx. should still be valid for G_M^n.

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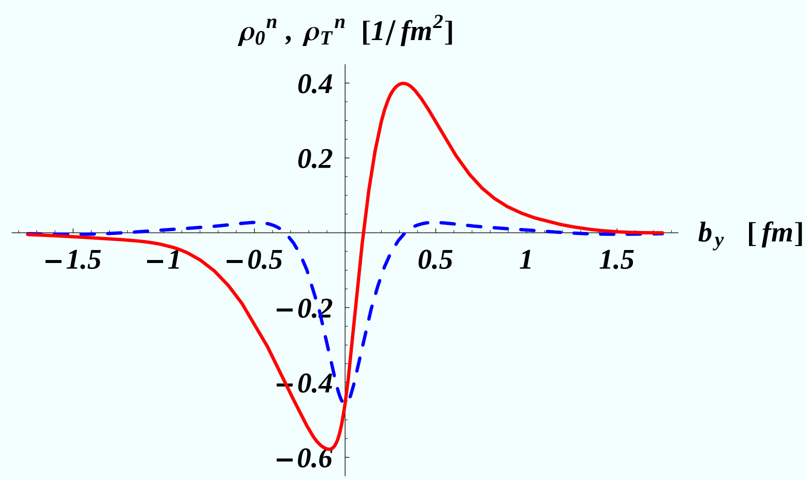
$\Rightarrow$ G_M^n **important to understanding transverse <u>charge</u> distribution of neutron**



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- **Combining G_M^n with G_M^p allows direct extraction of flavor (neglecting strange quarks)**

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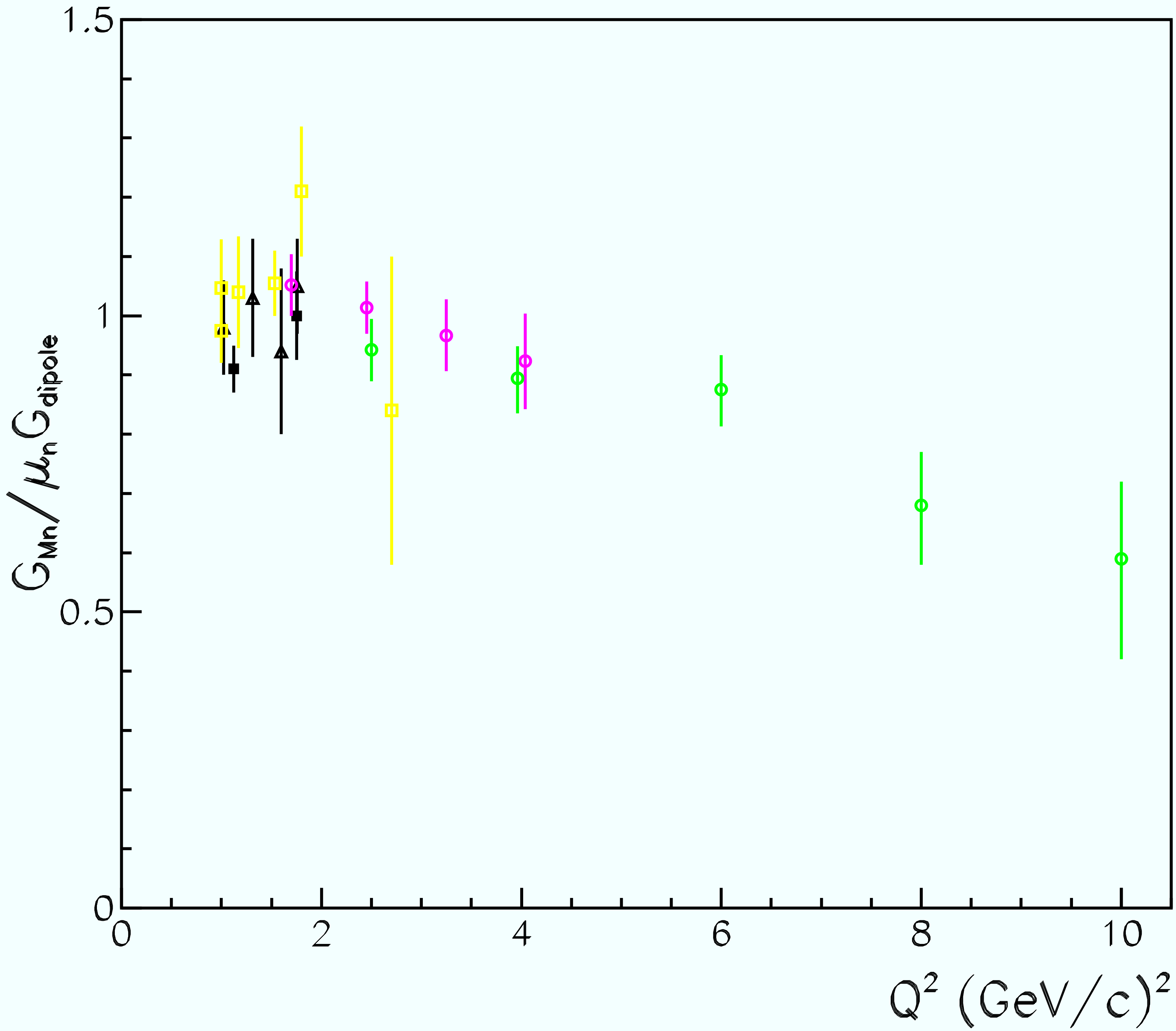
$$
G_M^{u/d,p} = \int_{-1}^{+1} dx (H^{u/d}(x,\xi,Q^2) + E^{u/d}(x,\xi,Q^2))
$$

Previous Data ($Q^2 \geq$1 (GeV/c)^2)



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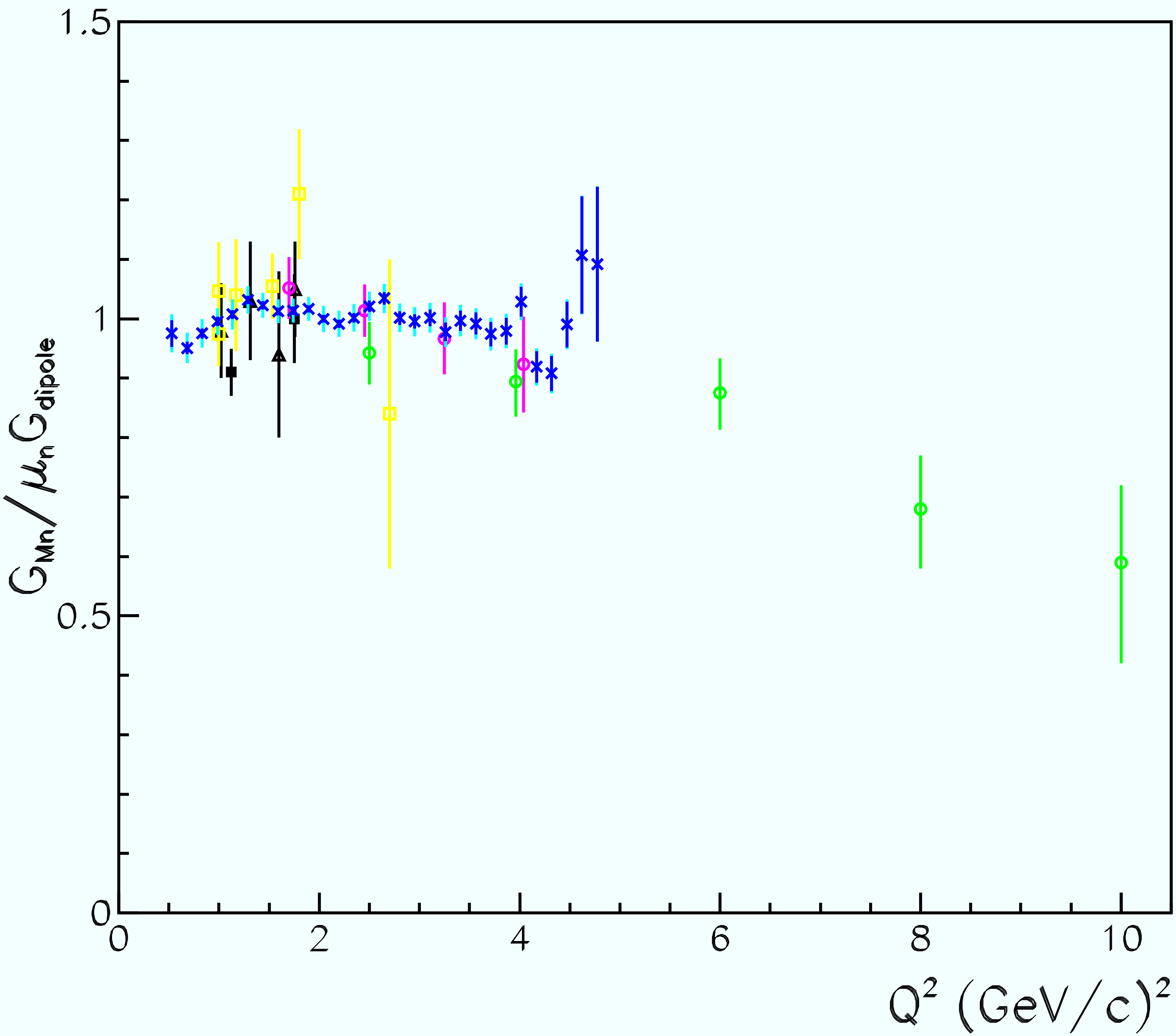
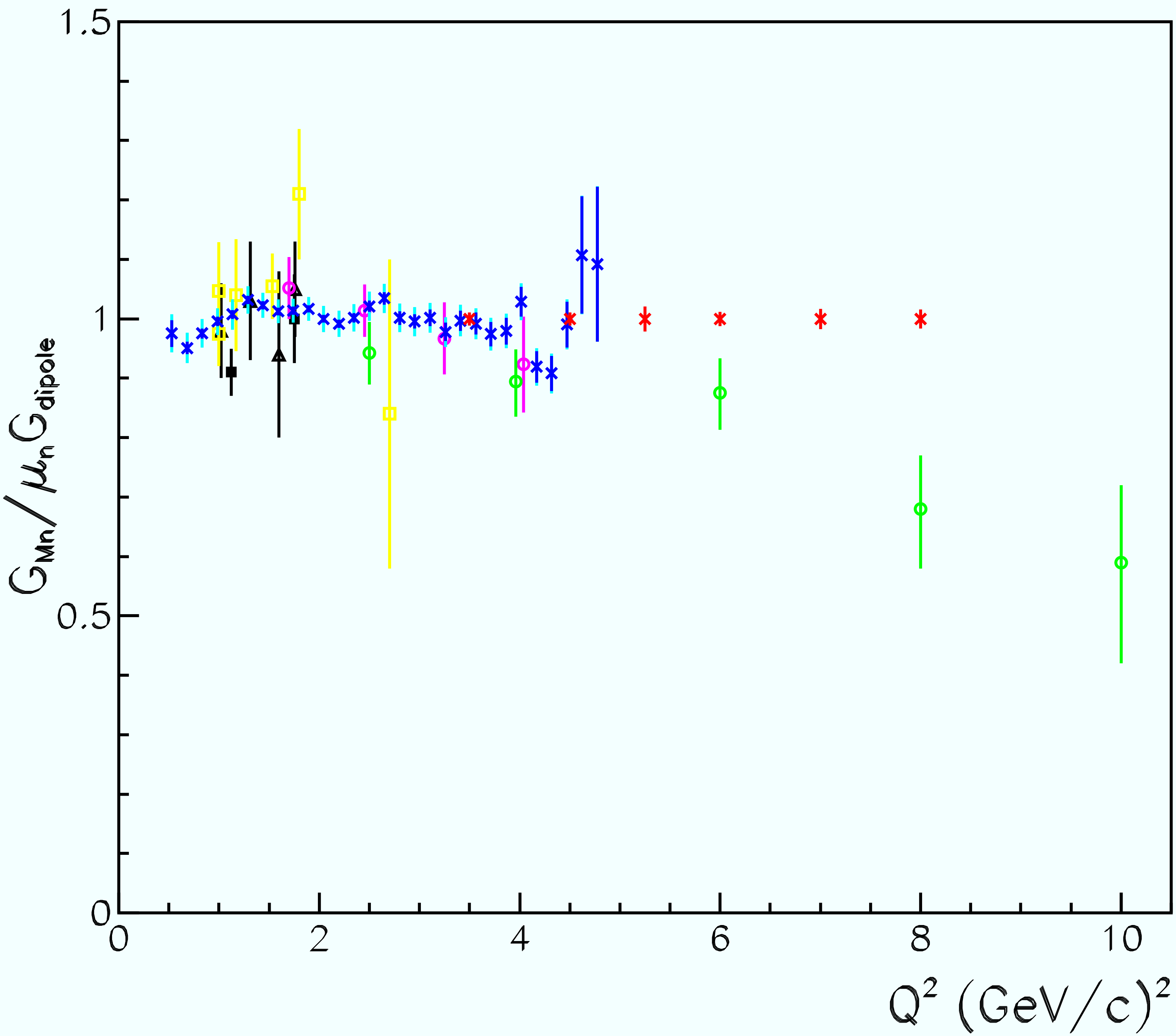


Previous Data ($Q^2 \geq$1 (GeV/c)^2) and CLAS e5 and projected error bars



Technique

Ratio Method

Measure quasi-elastic scattering from the deuteron *tagged* by coincident nucleon: d(e,e′p) and d(e,e′n)

$$R'' = \frac{\left.\frac{d\sigma}{d\Omega}\right|_{\text{d(e,e}'\text{n)}}}{\left.\frac{d\sigma}{d\Omega}\right|_{\text{d(e,e}'\text{p)}}}$$

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$<$1% nuclear corrections (common factors cancel in ratio)

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Subsequent improvements...

nuclear corrections, G_E^n, $\left.\frac{d\sigma}{d\Omega}\right|_{\mathrm{p(e,e')}}$

...can be applied retrospectively to measured value of R''.

$$\frac{\sigma_{G_M^n}}{G_M^n} = \frac{1}{2}\frac{\sigma_R}{R}$$

$$R'' = \frac{\left.\frac{d\sigma}{d\Omega}\right|_{\text{d(e,e}'\text{n)}}}{\left.\frac{d\sigma}{d\Omega}\right|_{\text{d(e,e}'\text{p)}}}$$

Ratio is insensitive to:

- **target thickness**
- **target density**
- **beam current**
- **beam structure**
- **live time**
- **(electron) trigger efficiency**
- **electron track reconstruction efficiency**
- **electron acceptance ...**

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Important to understand:

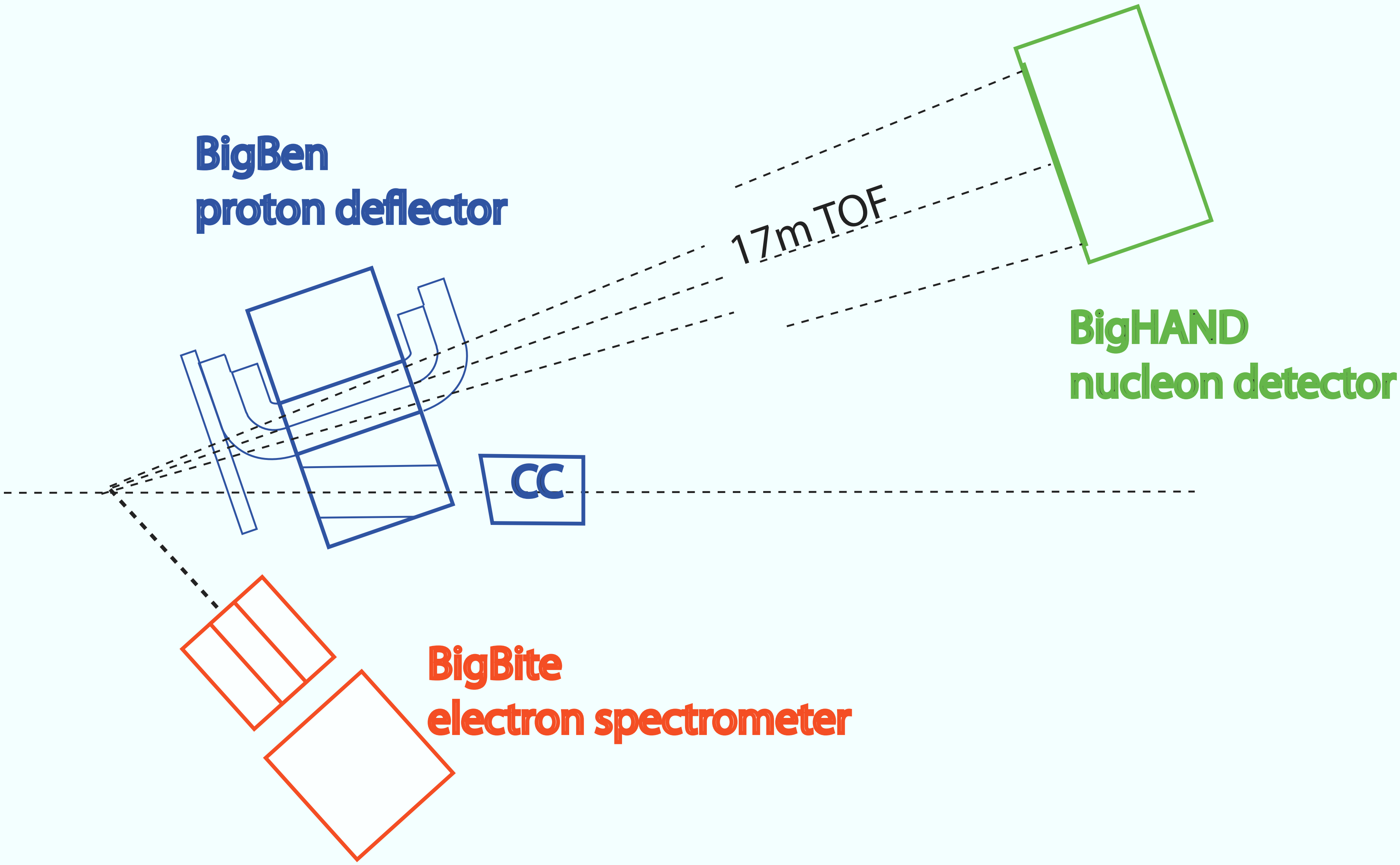
- **neutron efficiency / proton efficiency**
- **neutron acceptance / proton acceptance**

} **calibration reactions**

Kinematics

Q^2 $(GeV/c)^2$	E_{beam} (GeV)	θ_e	θ_N	E' (GeV)	P_N (GeV/c)
3.5	4	37.5°	28.7°	2.1	2.65
4.5	4	49.5°	21.7°	1.6	3.2
5.25	5	40.4°	22.7°	2.3	3.6
6	5	48.1°	18.7°	1.8	4.0
7	6	42.0°	18.7°	2.3	4.6
8	6	52.0°	14.9°	1.7	5.1

Apparatus



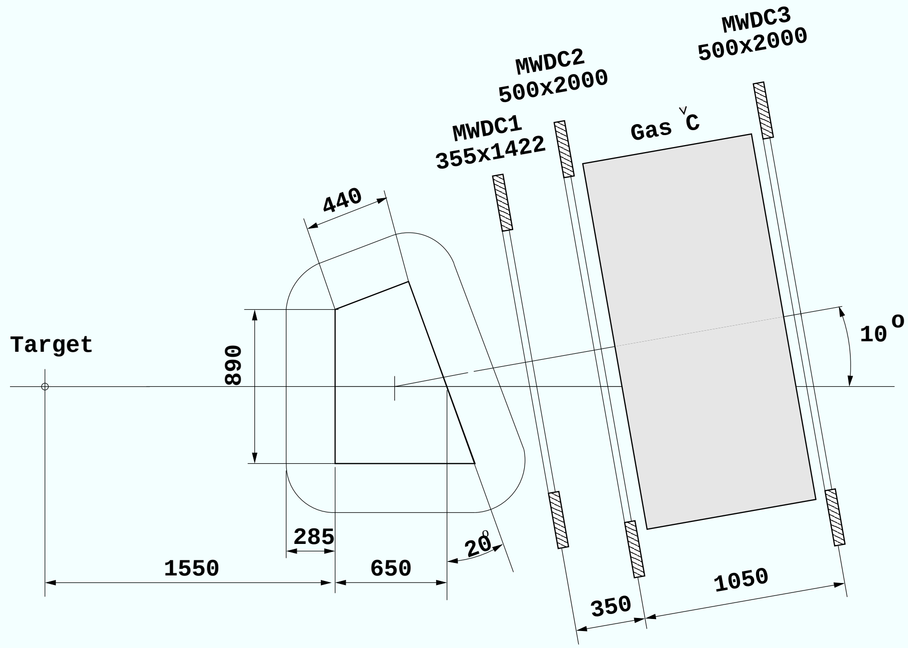
Experience from GEn experiment with BigBite/BigHAND combination

Adding “BigBen” deflector magnet

$\mathcal{L} = 10^{37}/cm^2/s$ **(100$\times\mathcal{L}$ of CLAS12)**

BigBite spectrometer

Electron arm (and π^+ for H(γ, π^+)n calibration)



Reconfigured for higher momentum running.

$\approx$ 50 msr acceptance

0.5-0.6% momentum resolution ($p \approx 2$ GeV/c)

$<$1 mr angular resolution

Gas Cerenkov $\Rightarrow$ reduced singles rates $\Rightarrow$ Single-arm trigger

“BigHAND” Hall A *Nucleon* Detector

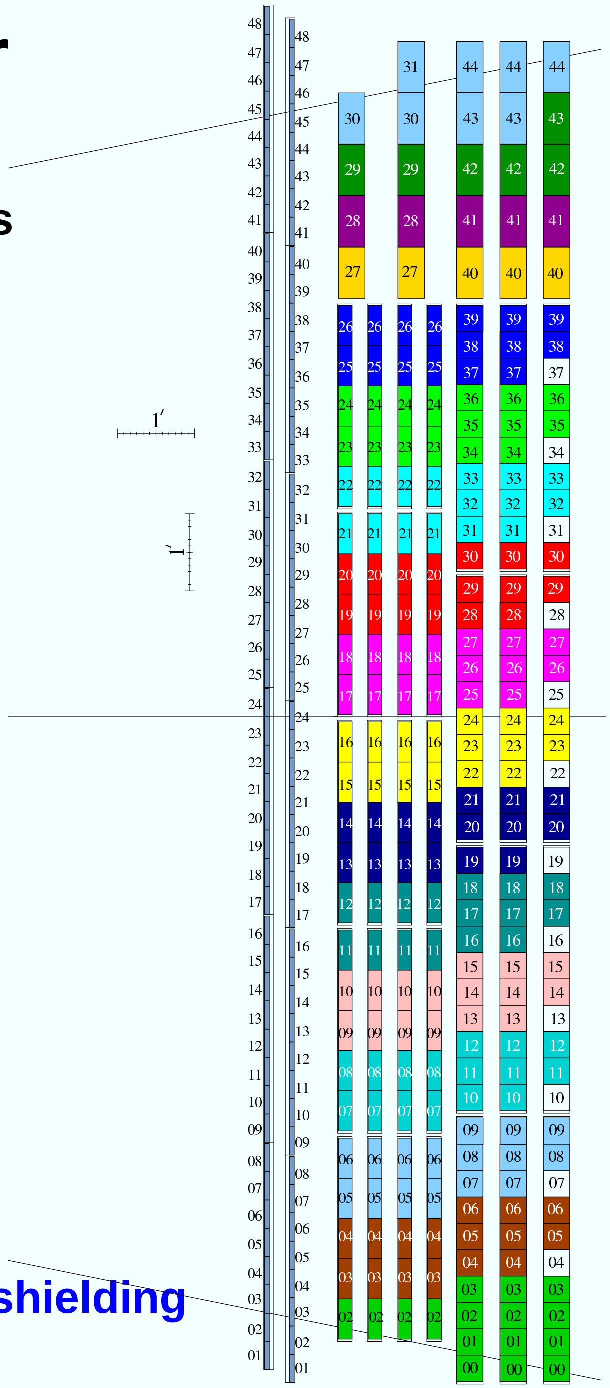
(neutron and proton arm)

244 scintillator bars in 7 layer with $\frac{1}{2}$” iron converters

Two veto layers with 2” lead and 1” iron shields

$L_{flight} = 17$ m $\sigma_\theta < .25°$

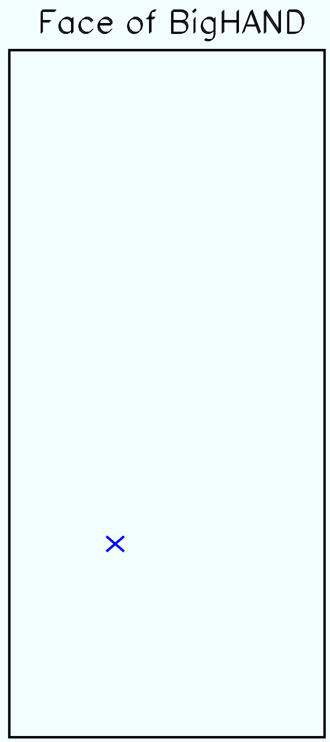
Time Resolution ≈ 0.35 ns



n vs. p PID would be complicated by hadronic interactions in shielding

Enhance neutron/ proton identifi cation

with 48D48 magnet (BigBen) on nucleon flght path



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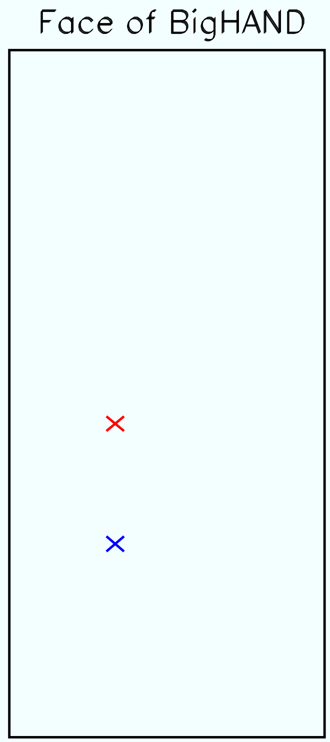

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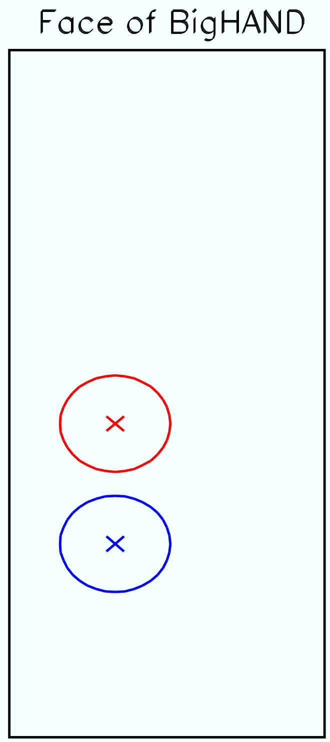

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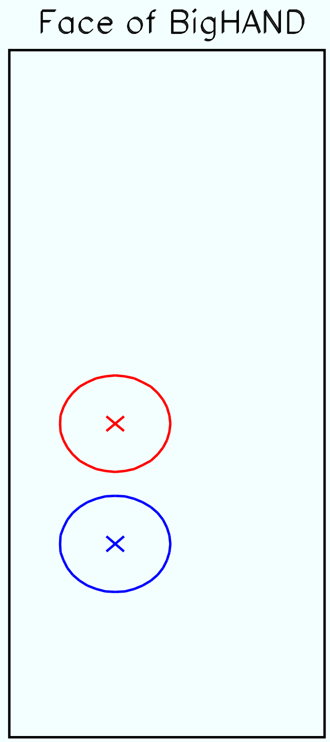

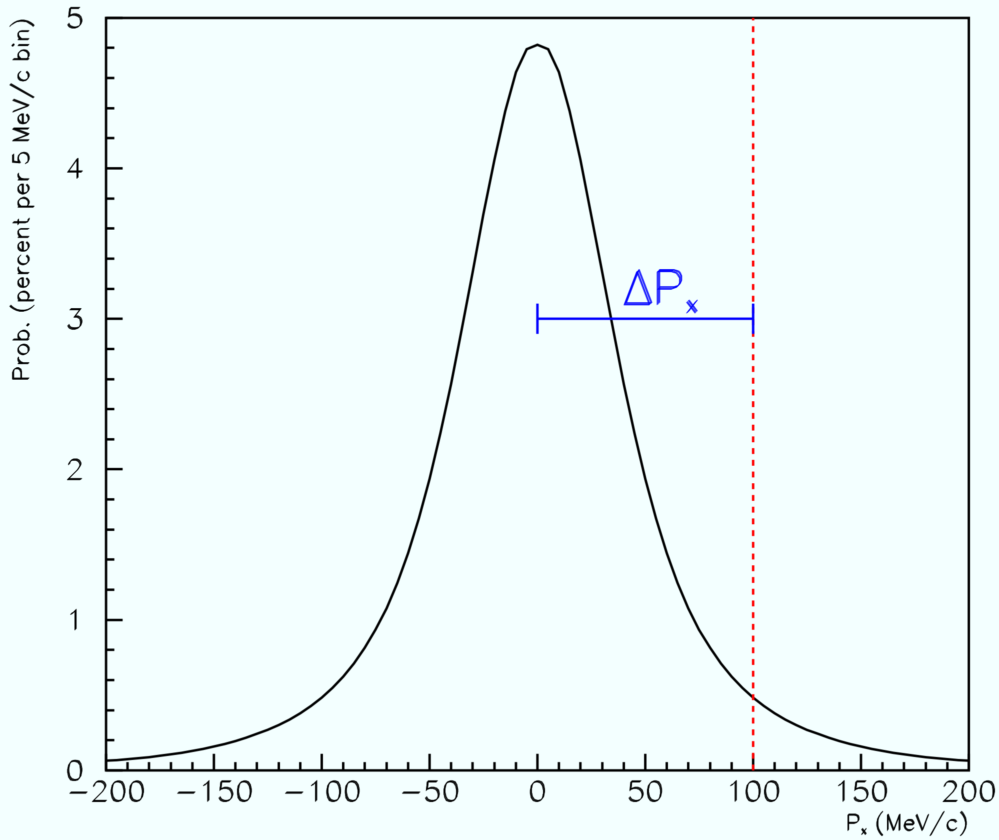

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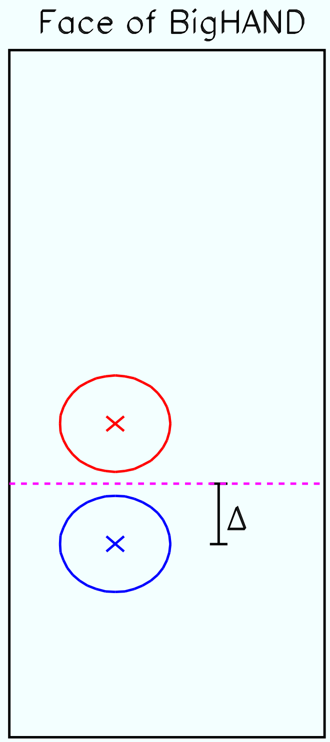
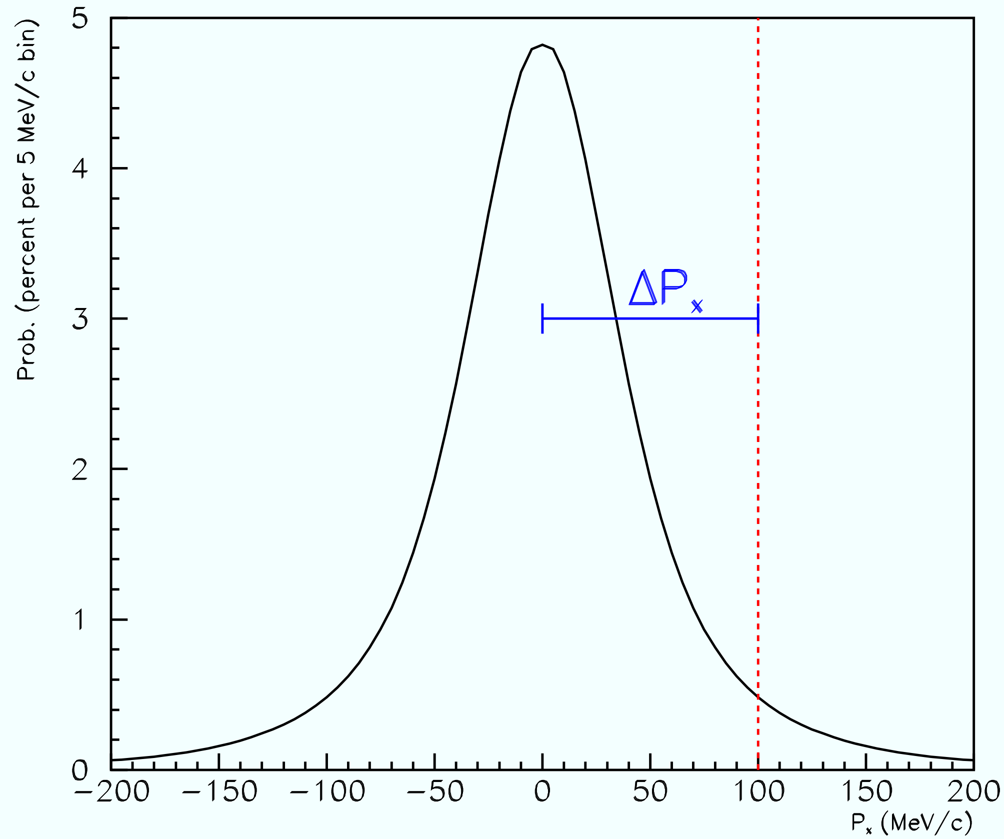




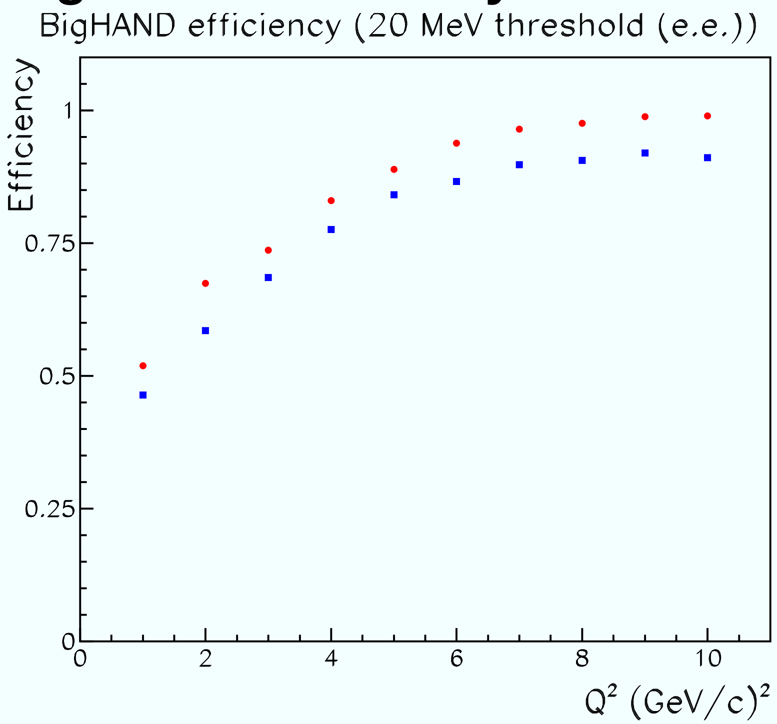
Choose $\Delta P_x = 100$ **MeV/c**

95% **probability position will be shifted by less than** $\Delta = \frac{\Delta P_x}{|\vec{q}|} L_{\text{flight}}$

Deflect proton by ≈ 200 **MeV/c for clean PID.** $\Rightarrow$ $\int B dl \approx .7$ **Tm**

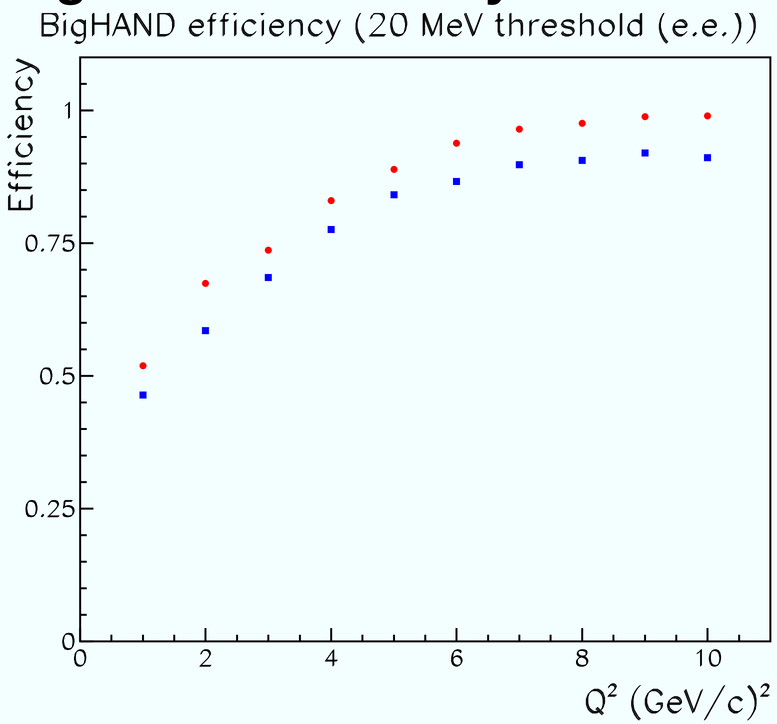
Remaining 5% corrected based on veto-based PID, opposite-side distribution

BigHAND efficiency



⇐ **Efficiency (ϵ) for neutron/proton detection with 20 MeV (electron equivalent) threshold**

BigHAND efficiency and stability



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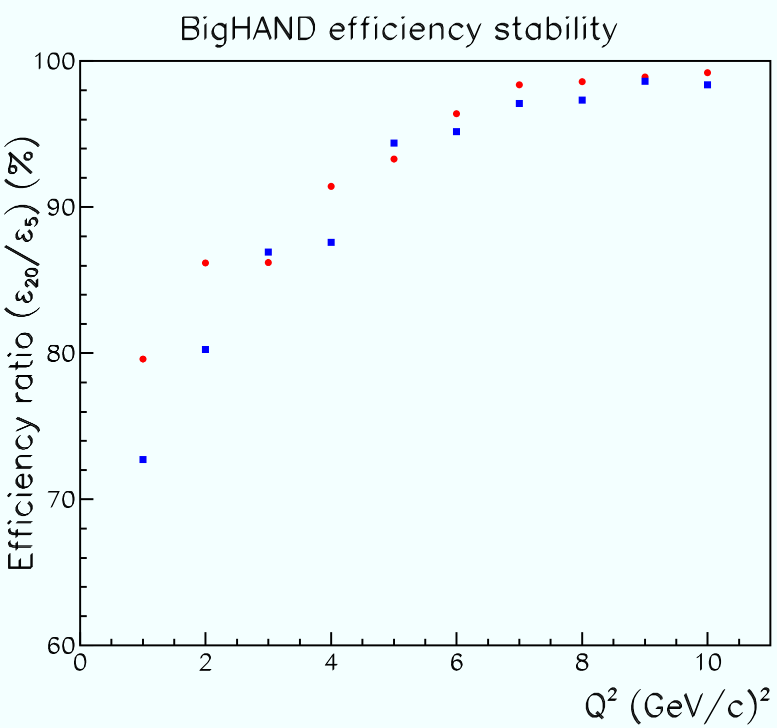


⇐ $\dfrac{\epsilon \text{ at 20 MeV (e.e.)}}{\epsilon \text{ at 5 MeV (e.e.)}}$

BigHAND calibration reactions

p(e,e′p)
p(γ,π^+n)
} $\approx$ elastic kinematics (massless e, γ, π)

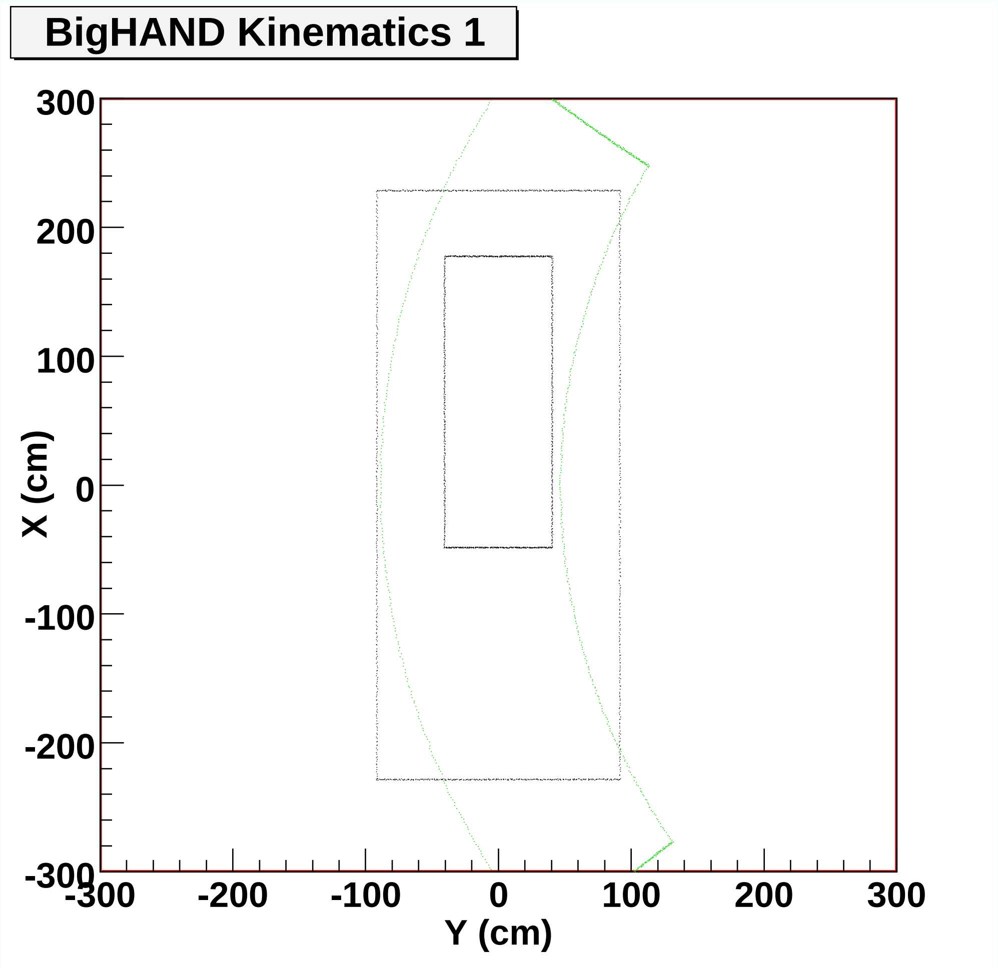
Neutron calibration p(γ,π^+n) uses bremsstrahlung end-point method

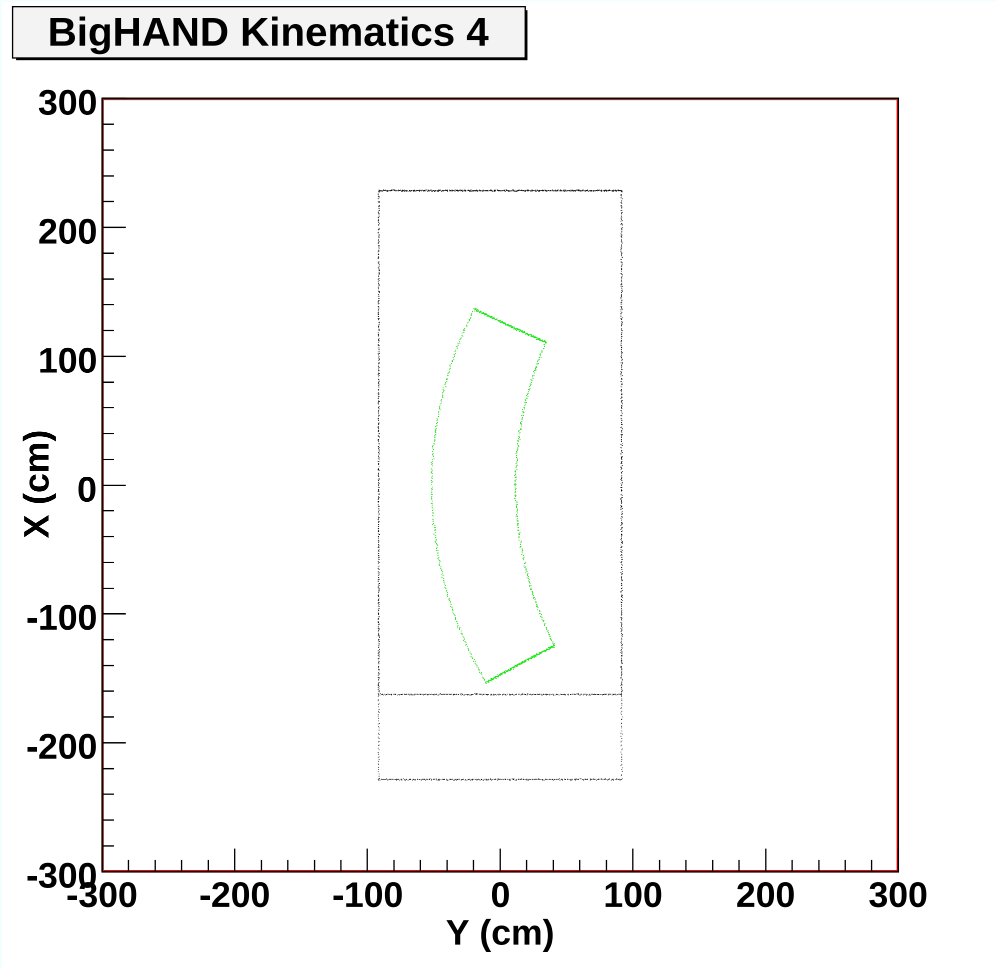
Require p_{π^+} at least 1.5% above maximum for three-body background reaction: p(γ,π)Nπ.

Q^2 (GeV/c)^2	E_{beam} (GeV)	θ_e	E_π^{max} (γ,π) (GeV)	E_π^{max} $(\gamma,2\pi)$ (GeV)	E_π^{limit} (γ,π) (GeV)	E_γ^{min} (GeV)	$\int \Gamma\, dk$
3.5	4	37.5°	2.12	2.043	2.074	3.83	0.0029
4.5	4	49.5°	1.603	1.540	1.563	3.78	0.0039
6	5	48.1°	1.805	1.747	1.773	4.80	0.0028
8	6	52.°	1.73	1.688	1.713	5.79	0.0025

Fiducial cut on $\vec{q}$ $\Rightarrow$ Acceptance losses $<$5%

(... and tend to cancel in ratio)

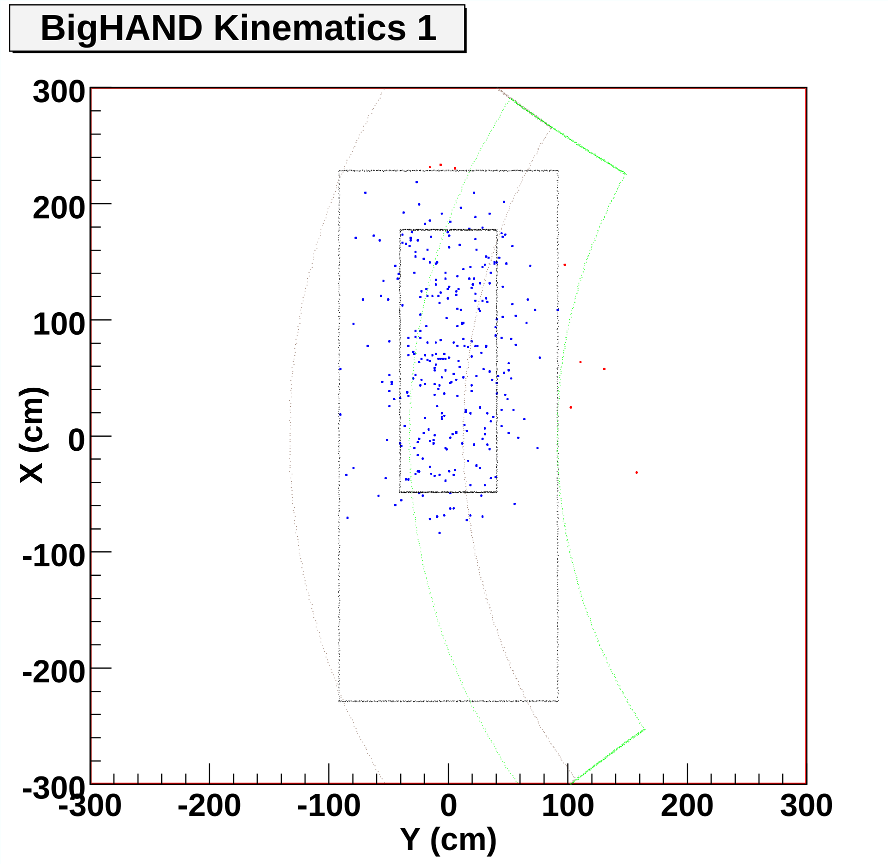




$Q^2 = 3.5$ (GeV/c)^2 $Q^2 = 8.0$ (GeV/c)^2

Fermi-motion spreads events beyond region calibrated by single BigBite position

Two calibration settings (at 4 of the 6 kinematic points)



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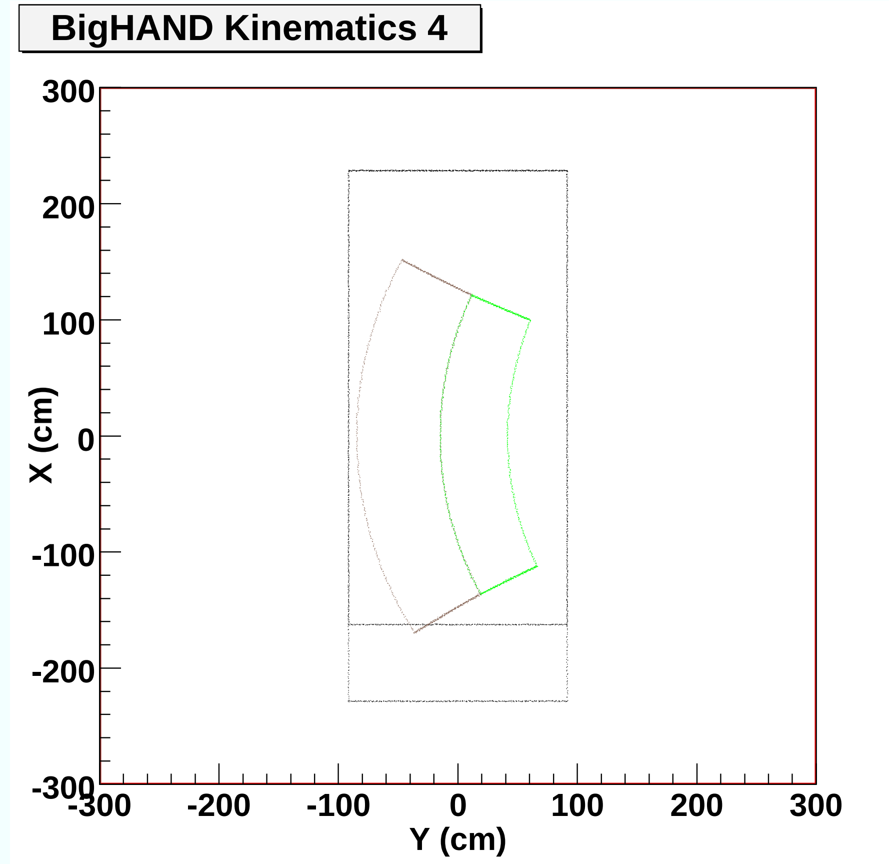
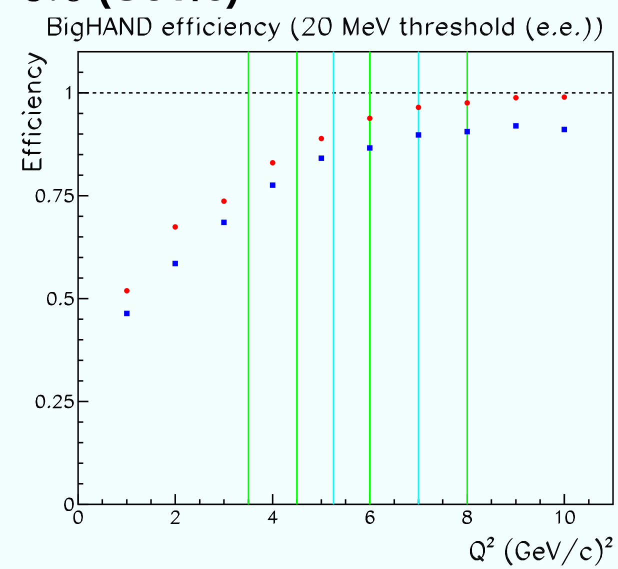


$Q^2 = 8.0$ (GeV/c)^2

Q^2 (GeV/c)^2	a) Fraction (%) in Single Cal. Zone	b) Fraction (%) in Double Cal. Zone
3.5	93.3	100.
4.5	71.1	95.3
6.0	68.4	94.4
8.0	71.7	88.6



Simulation

Quasi-elastic

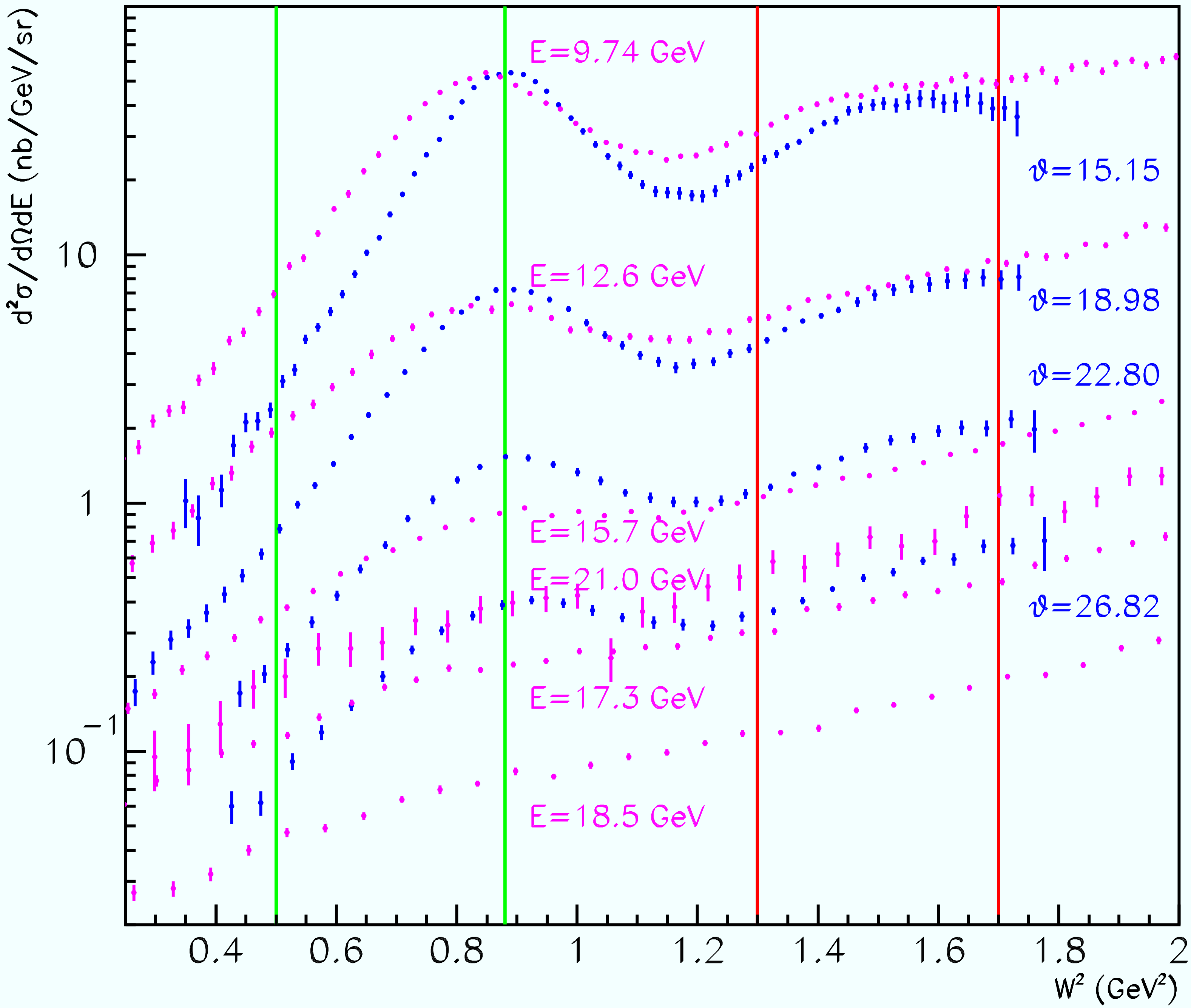
- **On shell spectator ($\Rightarrow$ Struck nucleon off shell)**
- **Boost to struck nucleon rest frame**
- **Isotropic $\cos(\theta)$, ϕ distribution**
- **Dipole (&Galster) $\rightarrow$ cross-section for weight**
- **Boost back to lab**
- **Fold in resolution, (weighted) increment of spectra**

Inelastic

- **GENEV physics Monte Carlo (Genoa/CLAS)**
- **On-shell initial nucleons ($\vec{p}_F$ and $-\vec{p}_F$)**
- **Boost to struck nucleon rest frame**
- **Generate GENEV event (with boosted beam energy)**
- **Boost back to lab**
- **Fold in resolution, increment (un-weighted) spectra**

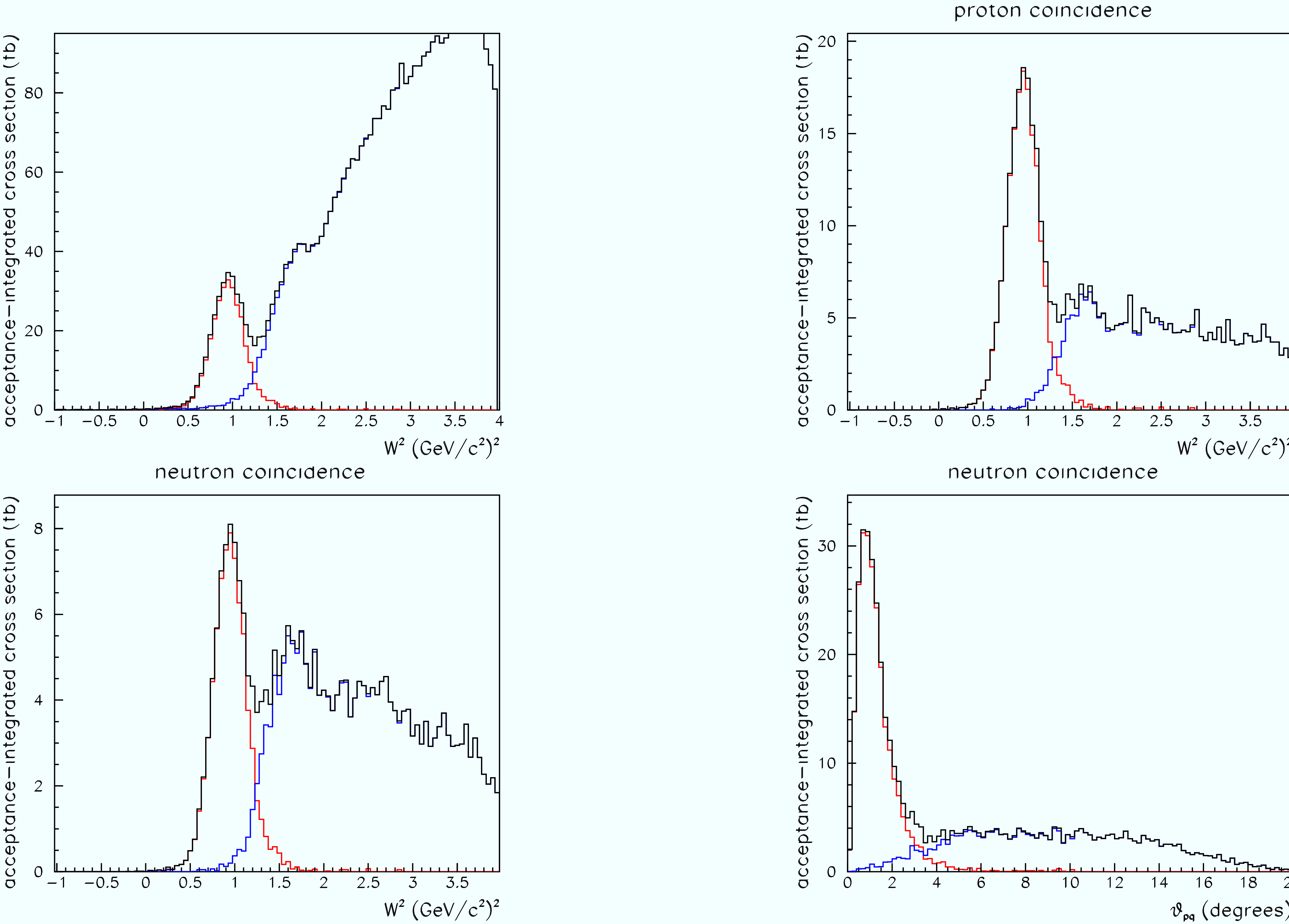
Inelastic normalized empirically to quasi-elastic

Normalization of inelastic to elastic

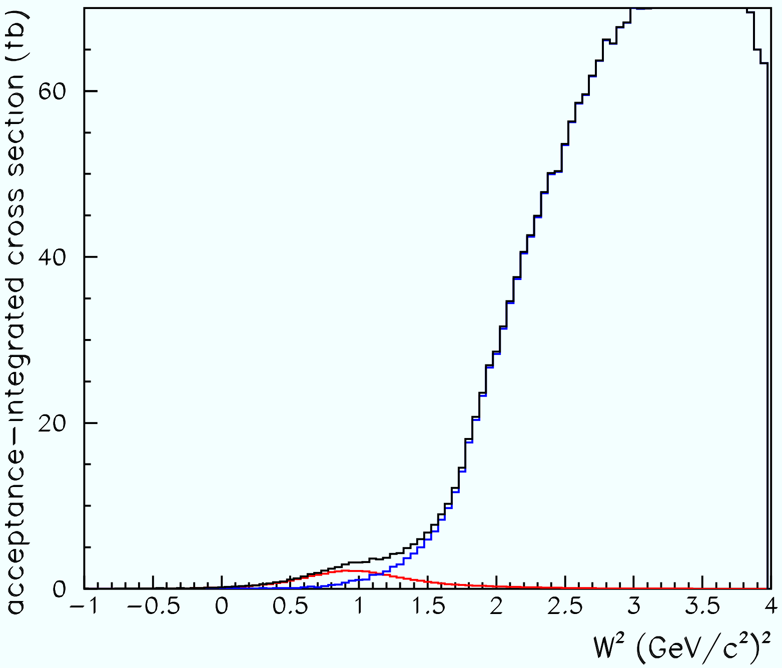


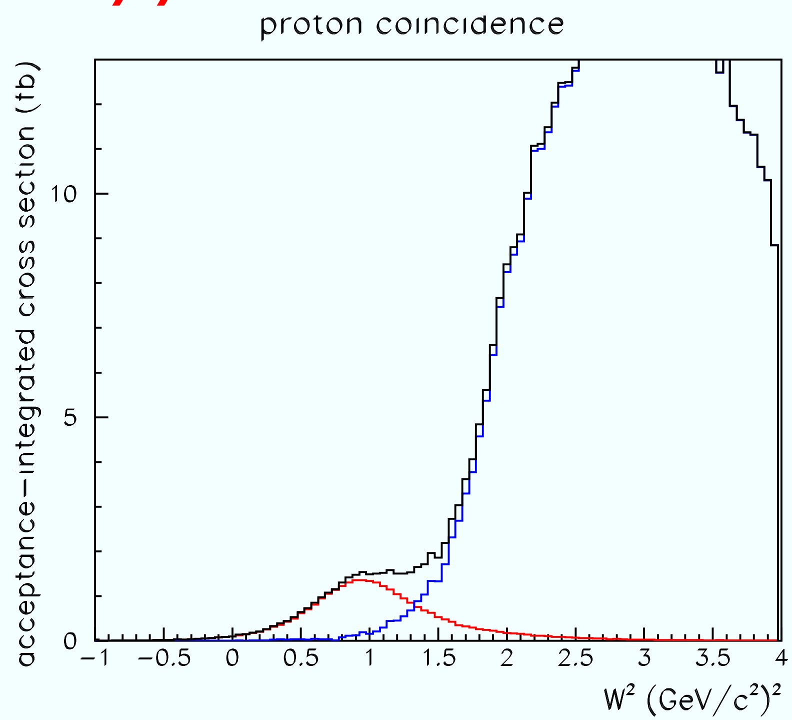
SLAC data (Stuart/Lung at E=5.5 GeV) and (Rock at $\theta = 10°$)

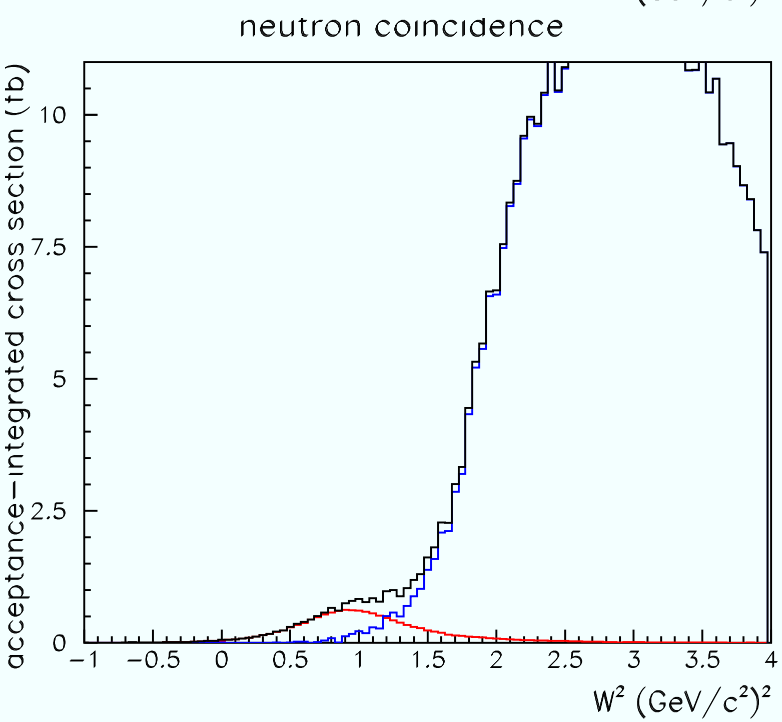
Simulation Results ($Q^2 = 3.5$ (GeV/c)^2)

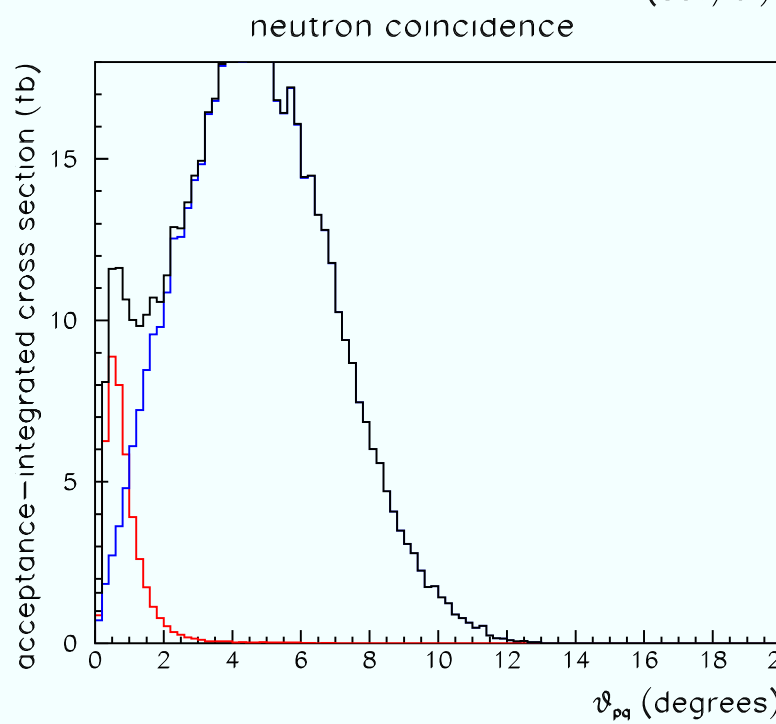


Simulation Results ($Q^2 = 8.0$ (GeV/c)^2)

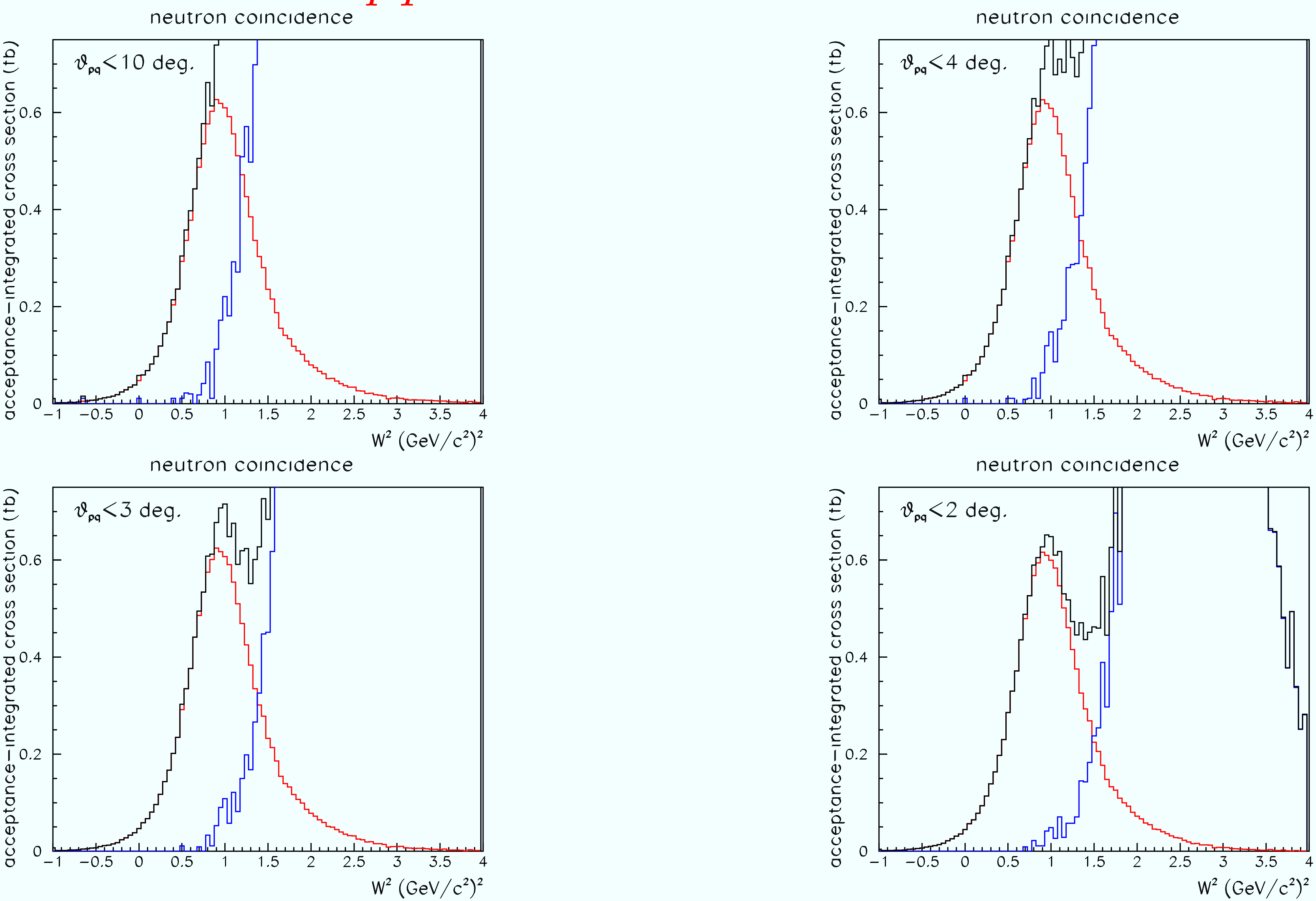








Simulation θ_{pq} cuts ($Q^2 = 8.0$ (GeV/c)^2)



Rates (inputs)

$\mathcal{L} = 10^{37}$/A /cm^2/s Livetime=80% BigBite tracking eff=75%

Q^2 (GeV/c)^2	3.5	4.5	5.25	6.0	7.0	8.0
E (GeV)	4.	4.	5.	5.	6.	6.
θ_e	37.5°	49.5°	40.4°	48.1°	42.0°	52.$^\circ$
p efficiency (%)	78.4	86.0	90.1	93.8	96.5	97.6
n efficiency (%)	73.0	80.9	84.7	86.6	89.8	90.6
Quasi-elastic						
p-coinc. $\int \frac{d\sigma}{d\Omega} d\Omega$ (fb)	172	293	228	124	85.5	27
n-coinc. $\int \frac{d\sigma}{d\Omega} d\Omega$ (fb)	74	131	102	60	40.6	12.4
W^2 cut (%)	98	92	89	84	80	77
Proton elastic (calibration)						
Full $\Delta\Omega$ (mSr)	39.5	53.6	—	53.4	—	53.2
$\frac{d\sigma}{d\Omega}_{p(e,e')}$ (pb/sr)	71.3	10.9	—	3.00	—	0.57
$p(\gamma,\pi^+)n$ (calibration)						
$\int \Gamma dk$	0.0030	0.0039	—	0.0028	—	0.0025
$\theta^*_{\gamma\pi}$	93°	110°	—	114°	—	123°
$\frac{d\sigma}{d\Omega}_{p(\gamma,\pi^+n)}$ (pb/sr)	2380	1730	—	626	—	313

Rates

Predicted coincidence rates (counts per hour)

Q^2 (GeV/c)^2	3.5	4.5	5.25	6.0	7.0	8.0
$d(e,e'p)$	1400	2500	1700	1050	710	220
$d(e,e'n)$	570	1050	830	470	315	93
$p(e,e'p)$	47000	11000	—	3200	—	640
$p(\gamma,\pi^+n)$	1100	1580	—	440	—	200

Systematic Error Estimates

Estimated contributions (in percent) to systematic errors on R.

Q^2 (GeV/c)^2	3.5	4.5	5.25	6.0	7.0	8.0
Nuclear correction, G_E^n, proton cross-section	-	-	-	-	-	-
Accidentals	-	-	-	-	-	-
Target windows	.2	.2	.2	.2	.2	.2
Acceptance losses	.5	.5	.5	.5	.5	.25
Inelastic contamination	.1	.4	.3	1.	.36	.1
Nucleon mis-identification	.6	.6	.6	.6	.6	.6
BigHAND calibration	0	.13	2.8	.16	1.5	.32
Total (quadrature sum)	.81	.91	2.9	1.3	1.7	.76

$\Rightarrow$ **Statistical error goals:**

$\leq$ **2% statistical errors on R at Q^2 =3.5, 4.5, 6.0 (GeV/c)^2**

$\leq$ **3% statistical errors on R at Q^2 =5.25, 7.0, 8.0 (GeV/c)^2**

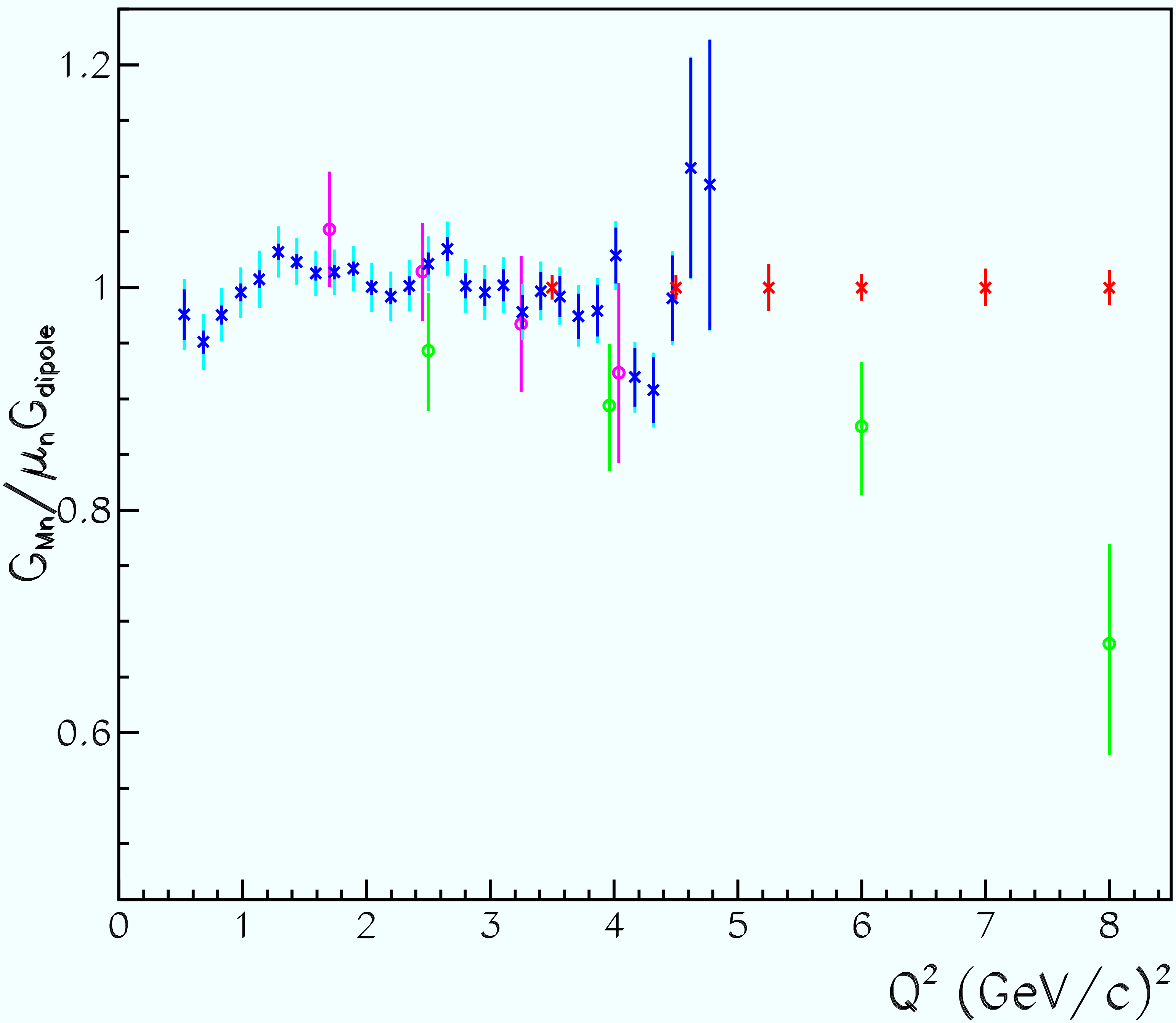
Beam Time Request

Beam Time Request (beam hours)

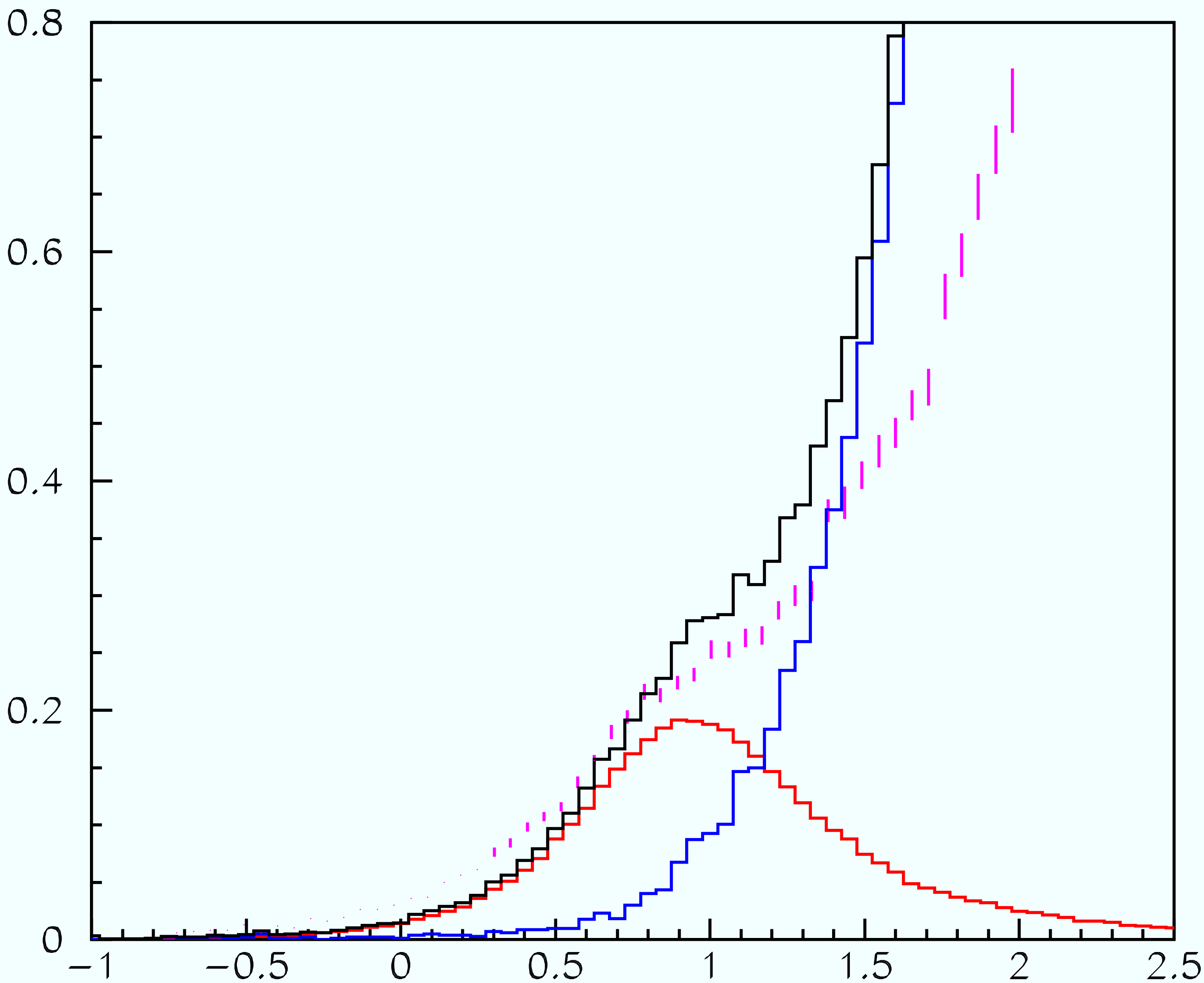
Q^2 (GeV/c)^2 E (GeV) θ_e	3.5 4. 37.5°	4.5 4. 49.5°	5.25 5. 40.4°	6.0 5. 48.1°	7.0 6. 42.0°	8.0 6. 52.$^\circ$	
d(e,e')							
Normal $\mathcal{L}$	36	24	24	48	36	80	
Dummy target	3	2	2	4	3	8	
Half $\mathcal{L}$	12	6					
Dummy half $\mathcal{L}$	2	1					
H(e,e')							
Normal $\mathcal{L}$	24	6		6		6	
Half $\mathcal{L}$	3	3		6		6	
Quarter $\mathcal{L}$	3	6					
BigBen off	6	6		6		6	
Dummy target	4	1		1		1	
H(γ,π^+)							
Radiator	24	24		12		20	
Dummy target	3	3		2		3	
No radiator	6	6		3		5	
Total	126	88	26	88	39	136	$\Rightarrow$ 502
Commissioning							72
2 Energy changes							16
13 angle changes							52
8 polarity changes							32
Beam request							674 $\approx$28 days

28 Days

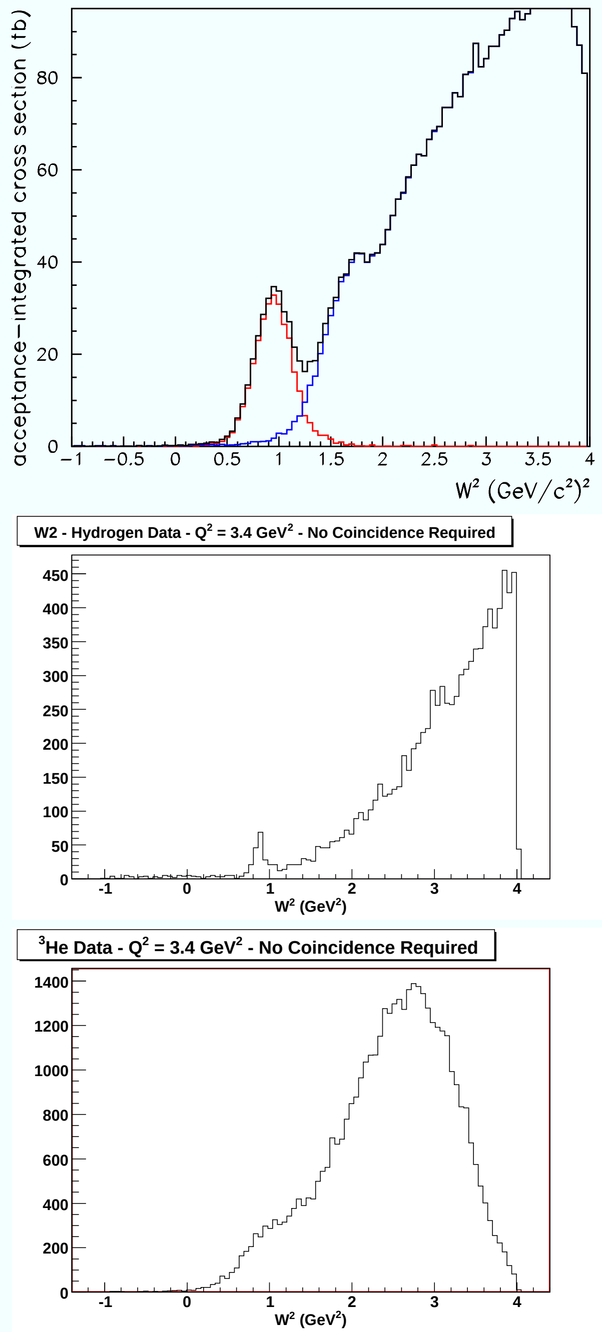
Previous Data ($Q^2 \geq$1 (GeV/c)^2) and CLAS e5 and projected error bars



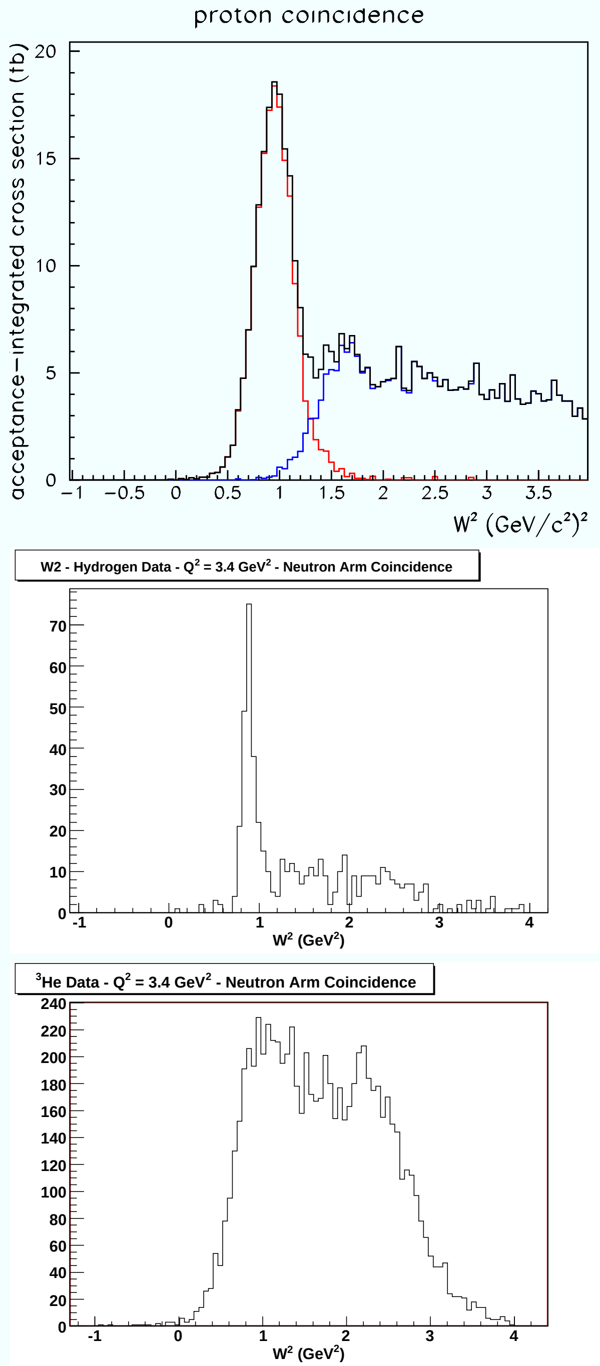
Backup Slides



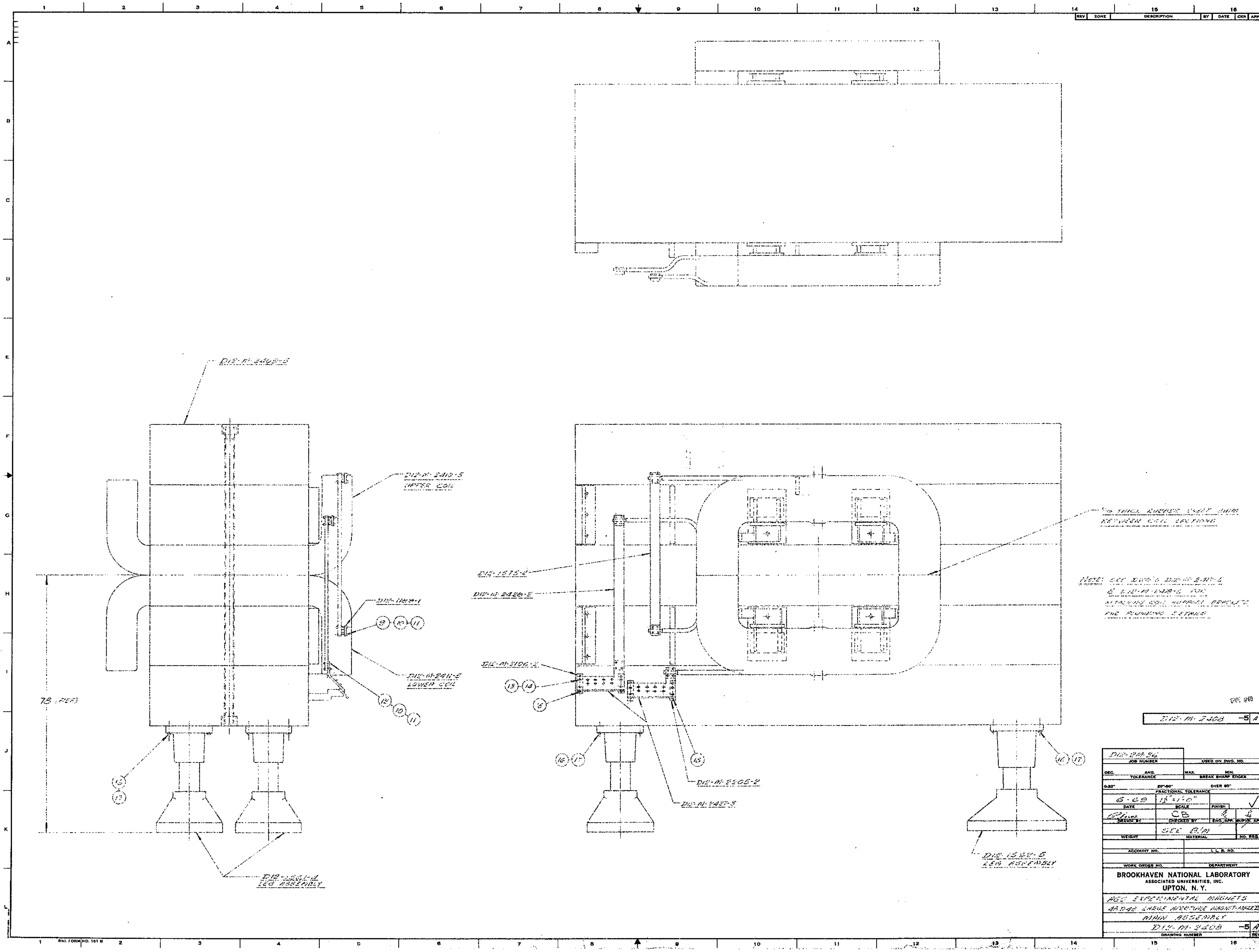
$Q^2 = 8$ **SLAC (E=18.5 GeV, $\theta = 10$) and prediction for (E=6 Gev, $\theta = 25$)**



$Q^2 = 3.5$ **prediction for d (E=4 Gev,** $\theta = 37.5$**) and GEn on p and** ^{3}**He (E=3.3 GeV,** $\theta = 51.6$**)**



$Q^2 = 3.5$ **prediction for d (E=4 Gev,** $\theta = 37.5$**) and GEn on p and** ^{3}**He (E=3.3 GeV,** $\theta = 51.6$**)**



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MATERIAL
NO. REQ.
ACCOUNT NO.
L. L. R. NO.
WORK ORDER NO.
DEPARTMENT
BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
UPTON, N. Y.
AGS EXPERIMENTAL MAGNETS
MAIN ASSEMBLY
D12-M-2408 -5
DRAWING NUMBER
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