Precision Measurement of the Neutron Magnetic Form Factor up to $Q^2 = 18.0$ (GeV/c)^2 by the Ratio Method

Mark Jones for

Spokespersons

Brian Quinn / Carnegie Mellon Univ.

Bogdan Wojtsekhowski / JLab

Ron Gilman / Rutgers Univ.

Collaborating institutions

Carnegie Mellon/ Jlab/ Rutgers/ William and Mary/ Santa Maria/ Norfolk/ Glasgow/ Ljubljana/ Richmond/ Kharkov/ New Hampshire/ North Carolina Central/ Saint Mary's/ Yerevan

Under review by the Hall A Collaboration

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

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Nucleon:

$G_E(Q^2)$ **and** $G_M(Q^2)$ **are Sachs Electric and Magnetic form factors.**

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

where $G_D = 1/(1 + Q^2/(.71\ \text{(GeV/c)}^2))^2$ **is empirical Dipole approximation**

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  ...a valuable test of the efficacy of lattice calculations -PAC32

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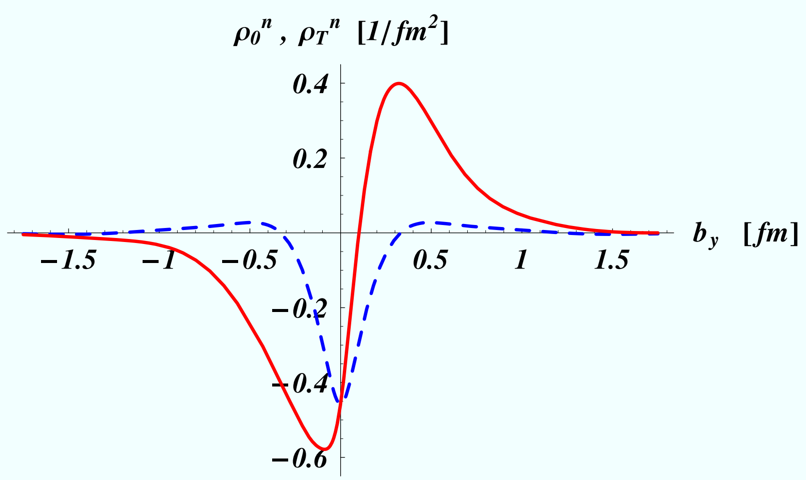
- **Quark transverse charge density (Miller, Carlson, Vanderhaeghen)**

$$\rho_0^N(b) = \int_0^\infty \frac{dQ}{2\pi} Q J_0(bQ) F_1(Q^2)$$

where: $F_1 = \frac{1}{1+\tau}(G_E + \tau G_M)$



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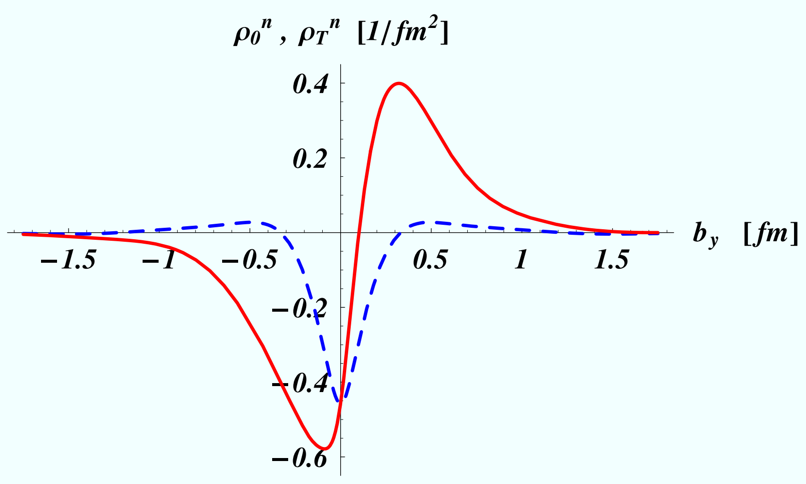
$\Rightarrow$ G_M^n **important to understanding transverse charge distribution of neutron**



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

$$\begin{aligned} G_M^p &= e_u G_M^{u,p} + e_d G_M^{d,p} \\ G_M^n &= e_u G_M^{u,n} + e_d G_M^{d,n} \\ &= e_u G_M^{d,p} + e_d G_M^{u,p} \end{aligned}$$

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- **Sets sum rules constraining GPD's (at each Q^2)**

$F_1^q(Q^2) = \int_{-1}^{+1} dx H^q(x,\xi,Q^2)$ $F_2^q(Q^2) = \int_{-1}^{+1} dx E^q(x,\xi,Q^2)$

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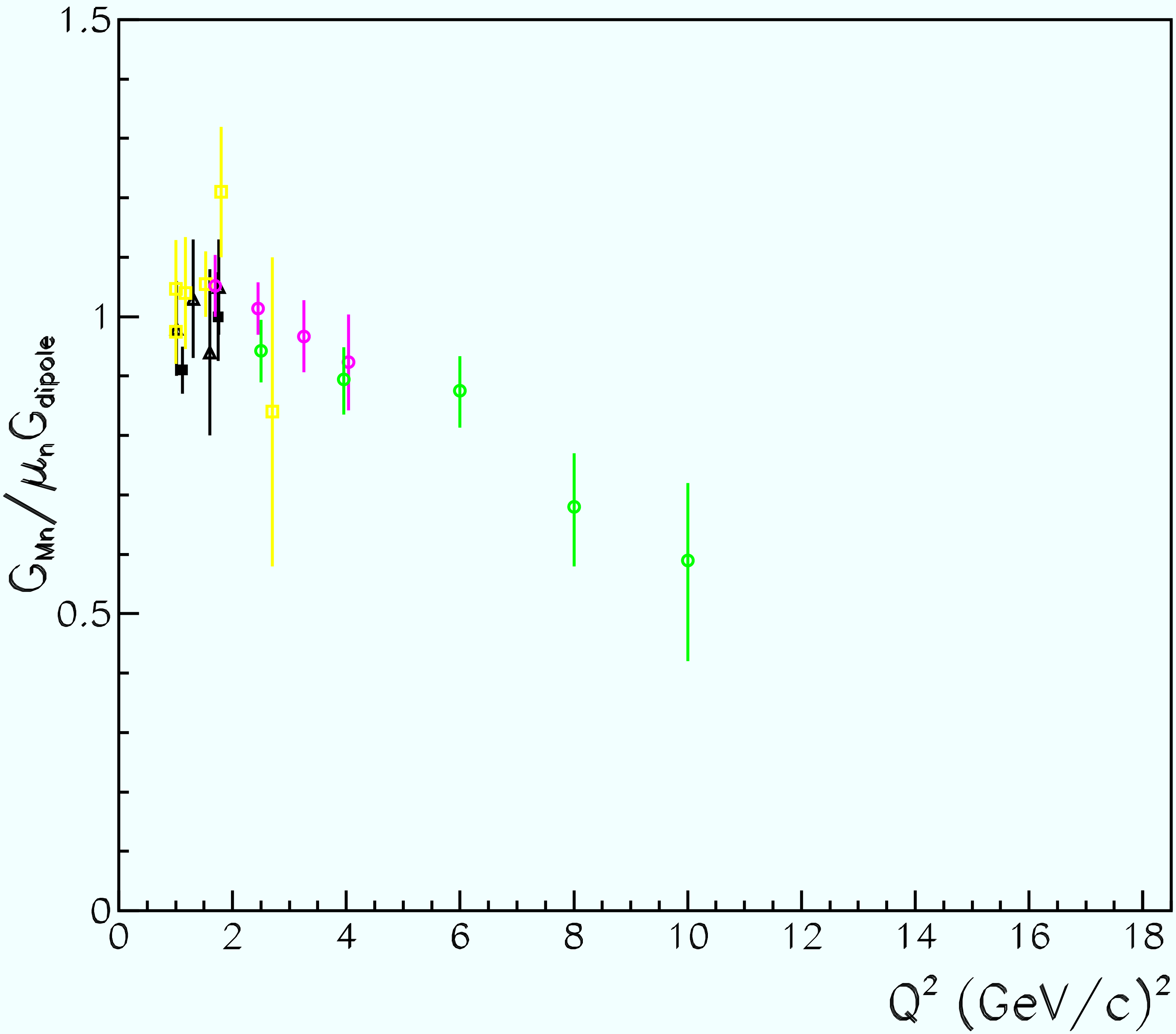
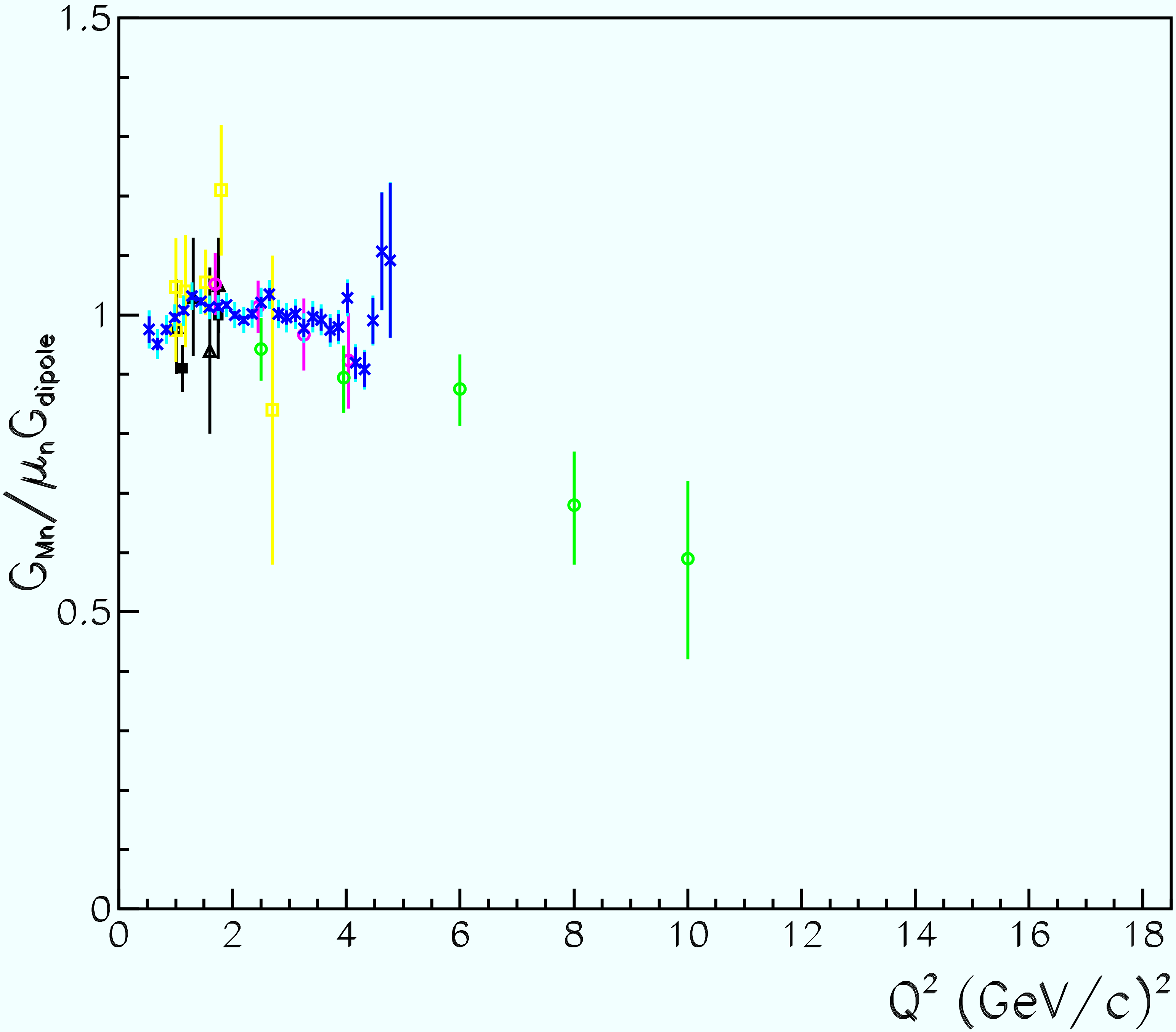
$$G_M^{u/d,p} = \int_{-1}^{+1} dx (H^{u/d}(x,\xi,Q^2) + E^{u/d}(x,\xi,Q^2))$$

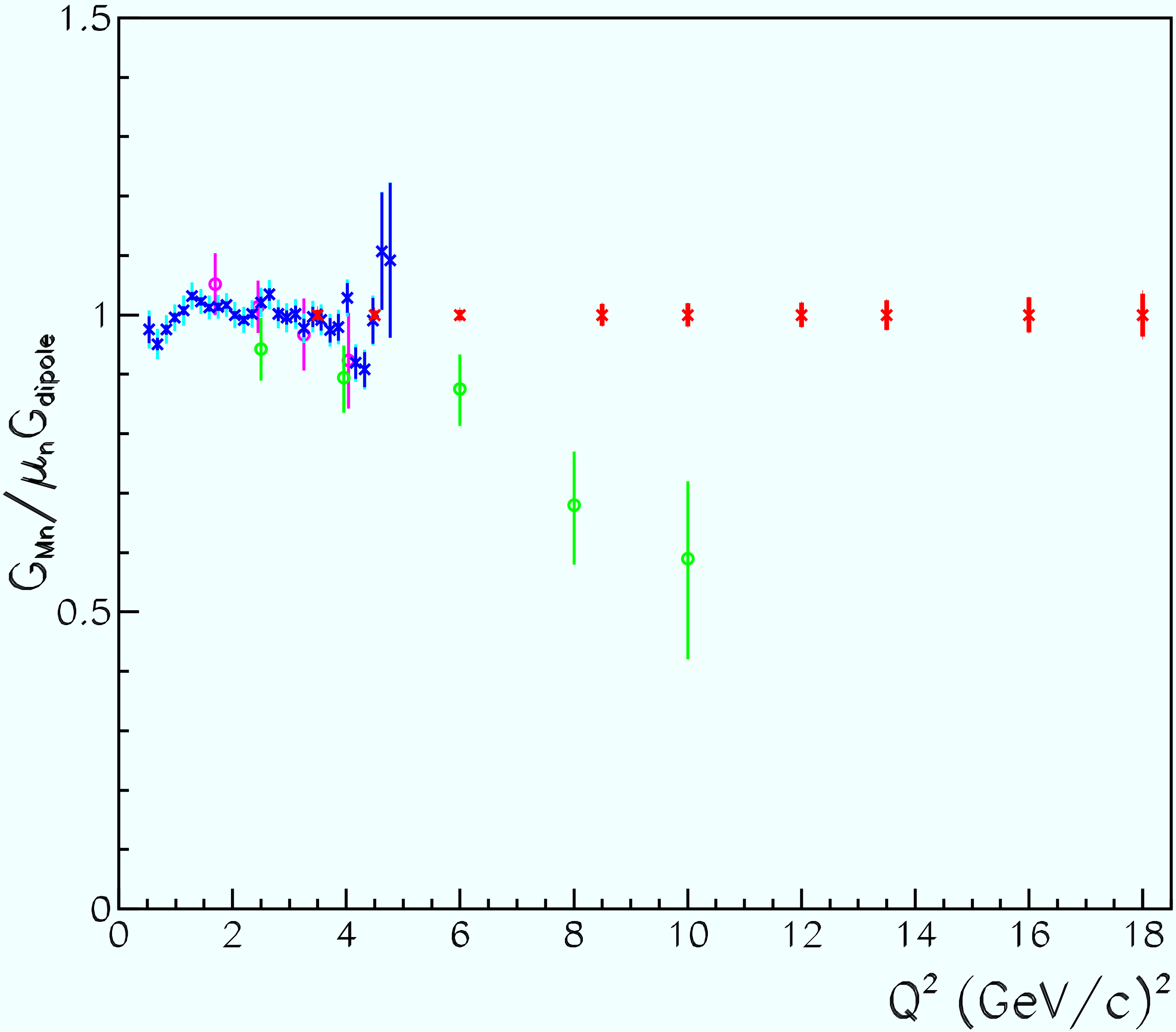
Previous Data ($Q^2 \geq$1 (GeV/c)^2)



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



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)

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

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

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$\approx$1% correction (Galster parameterization) for electric form factor

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$G_M^n \propto \sqrt{R}$ **...given proton elastic cross section**

OR

$G_M^n / G_M^p \propto \sqrt{R}$ **...with *small* corrections for proton structure**

$$R'' = \frac{\frac{d\sigma}{d\Omega}\Big|_{\mathbf{d(e,e'n)}}}{\frac{d\sigma}{d\Omega}\Big|_{\mathbf{d(e,e'p)}}}$$

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:

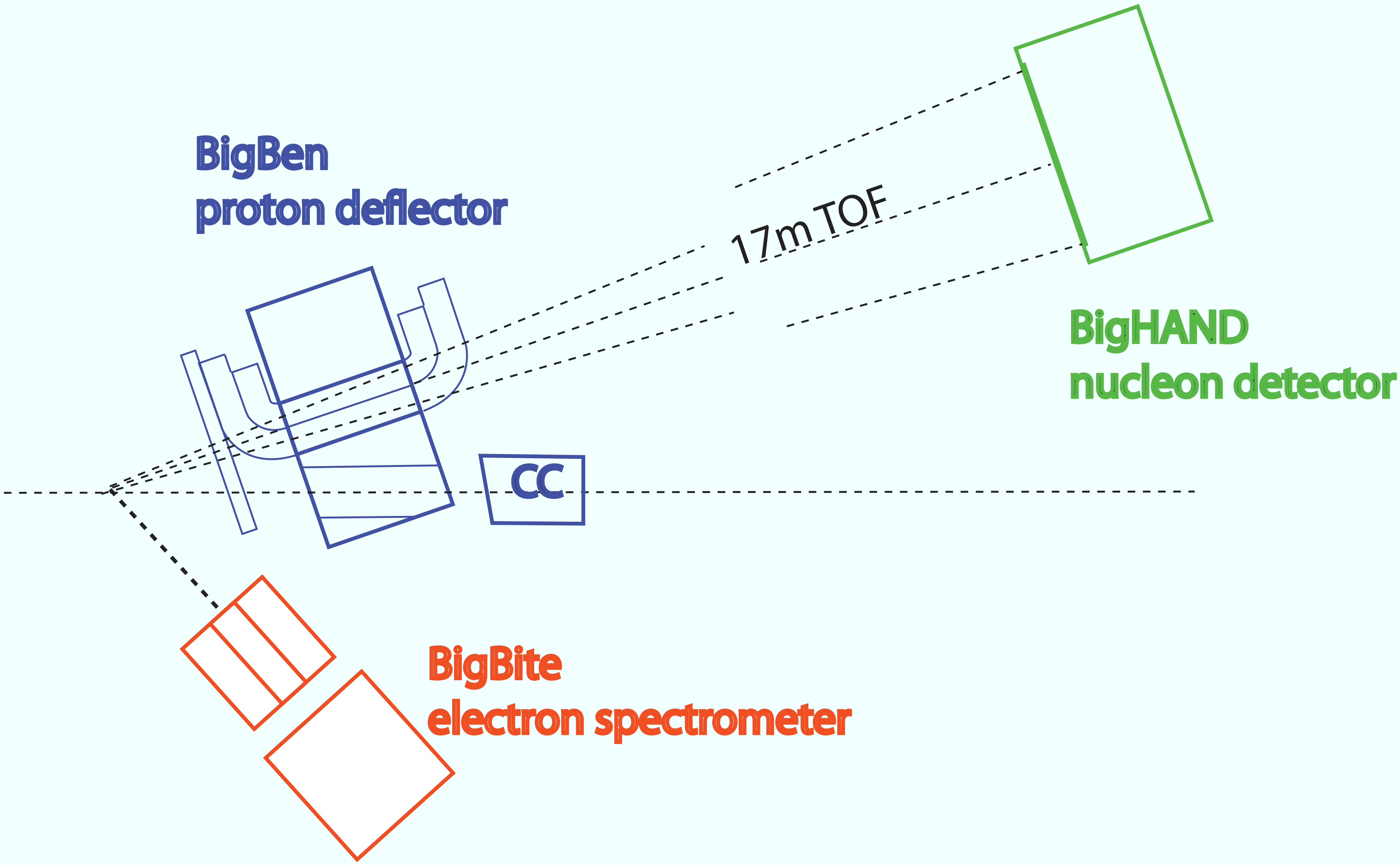
- **neutron efficiency / proton efficiency**
- **neutron acceptance / proton acceptance**

} **calibration reactions**

Kinematics

Q^2 $(GeV/c)^2$	E_{beam} (GeV)	θ_e	θ_N	E' (GeV)	P_N (GeV/c)
3.5	4.4	32.5°	31.1°	2.5	2.6
4.5	4.4	41.9°	24.7°	2.0	3.2
6.	4.4	64.3°	15.6°	1.2	4.0
8.5	6.6	46.5°	16.2°	2.1	5.4
10.	8.8	33.3°	17.9°	3.5	6.2
12.	8.8	44.2°	13.3°	2.4	7.3
13.5	8.8	58.5°	9.8°	1.6	8.1
16.	11.	45.1°	10.7°	2.5	9.4
18.	11.	65.2°	7.0°	1.4	10.5

Apparatus (Making use of *pieces* of new SBS)



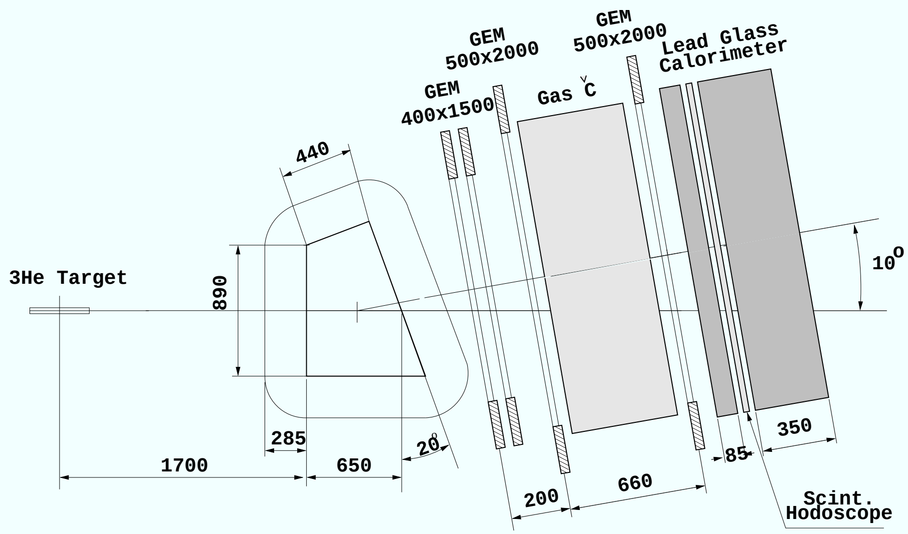
Experience from GEn experiment with BigBite/BigHAND combination

Adding "BigBen" deflector magnet

$\mathcal{L}_{\text{(per nucleon)}} = 6.7 \times 10^{37}/cm^2/s$ **(**$\approx 670 \times \mathcal{L}$ **of CLAS12)**

BigBite spectrometer

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



Reconfigured for higher momentum/higher luminosity running.

$\approx$ **53 msr acceptance**

$<$**1 mr angular resolution**

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

GEM detectors (from SBS polarimeter) for tracking

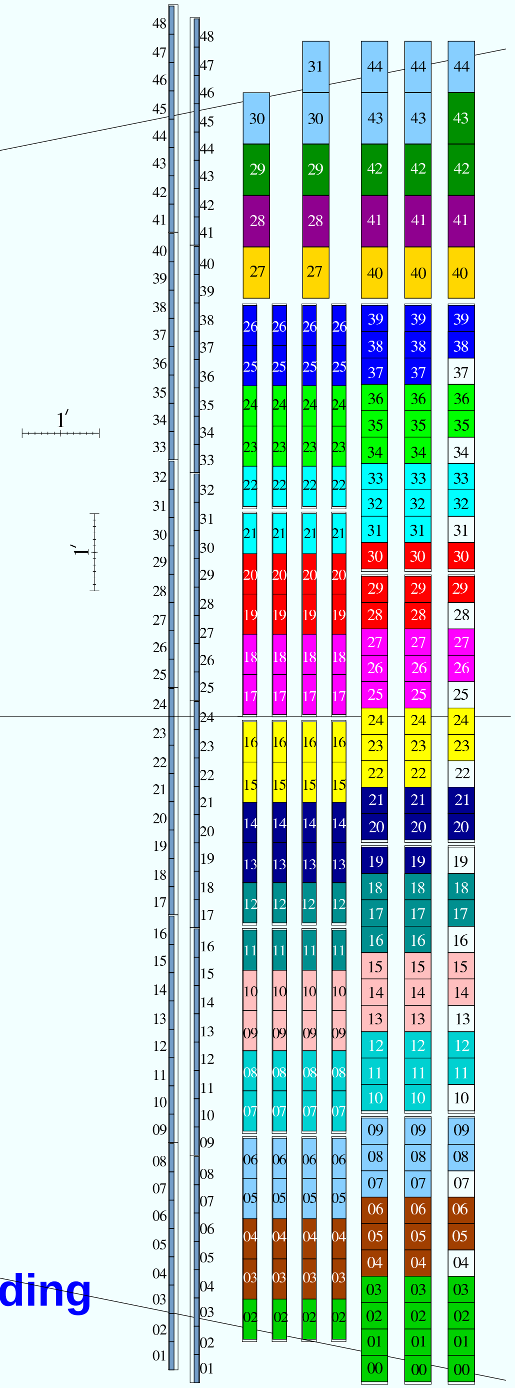
≈ 0.5**% momentum resolution**

“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



$L_{\text{flight}} = 17$ m $\quad \sigma_\theta < .25^\circ$

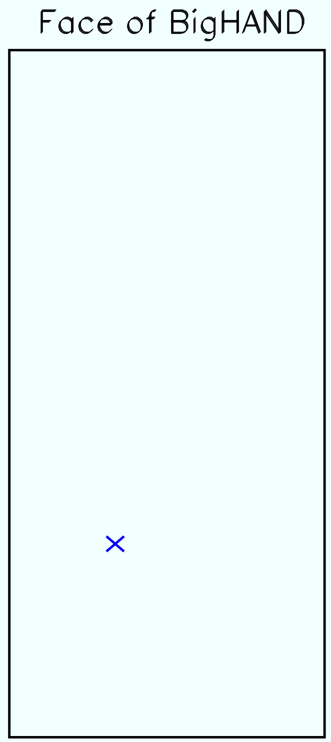
Time Resolution ≈ 0.35 ns

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

$\Rightarrow$ use SBS dipole as proton-deflector for PID

Enhance neutron/ proton identification

with 48D48 magnet (BigBen) on nucleon flight path



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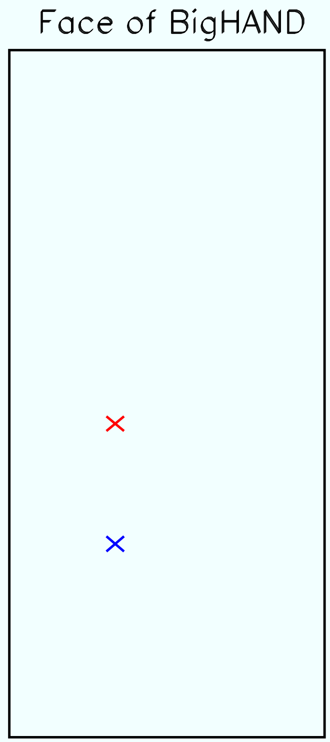

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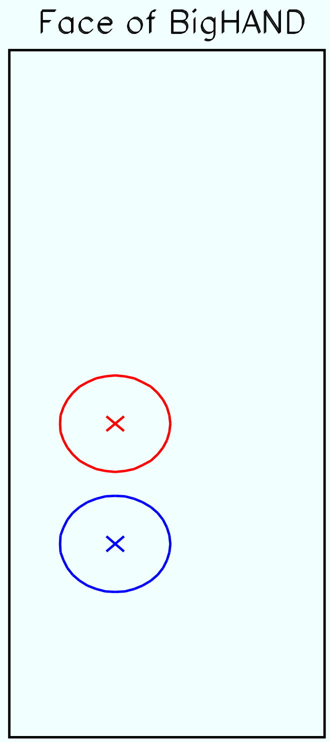

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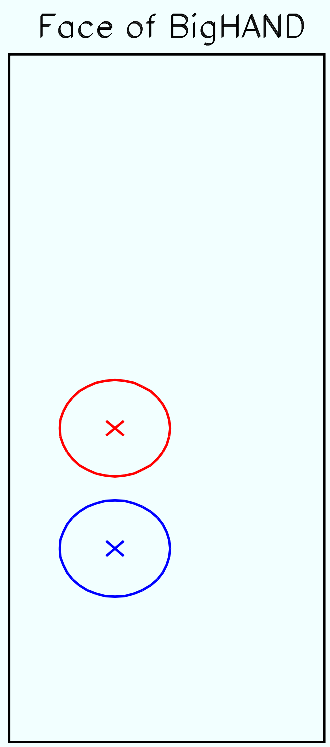

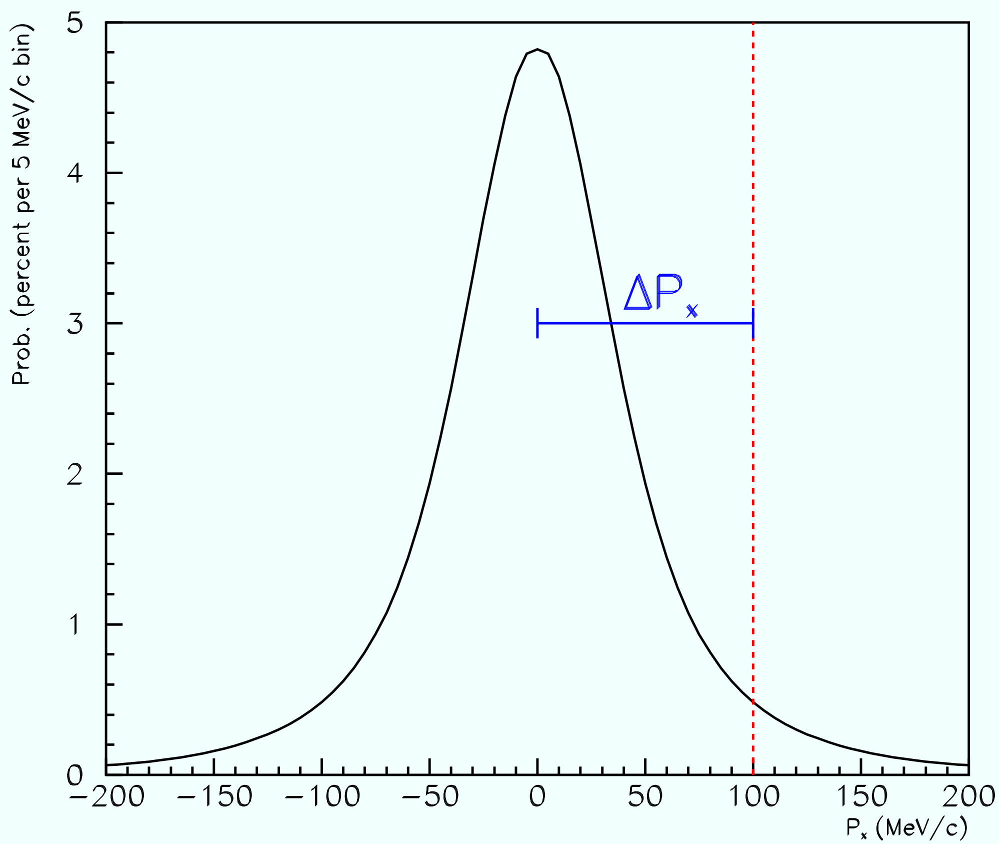

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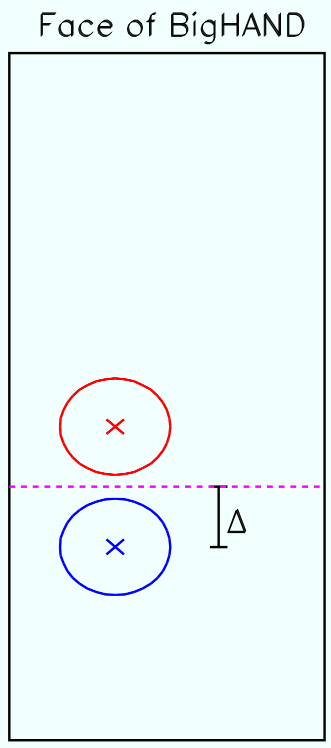
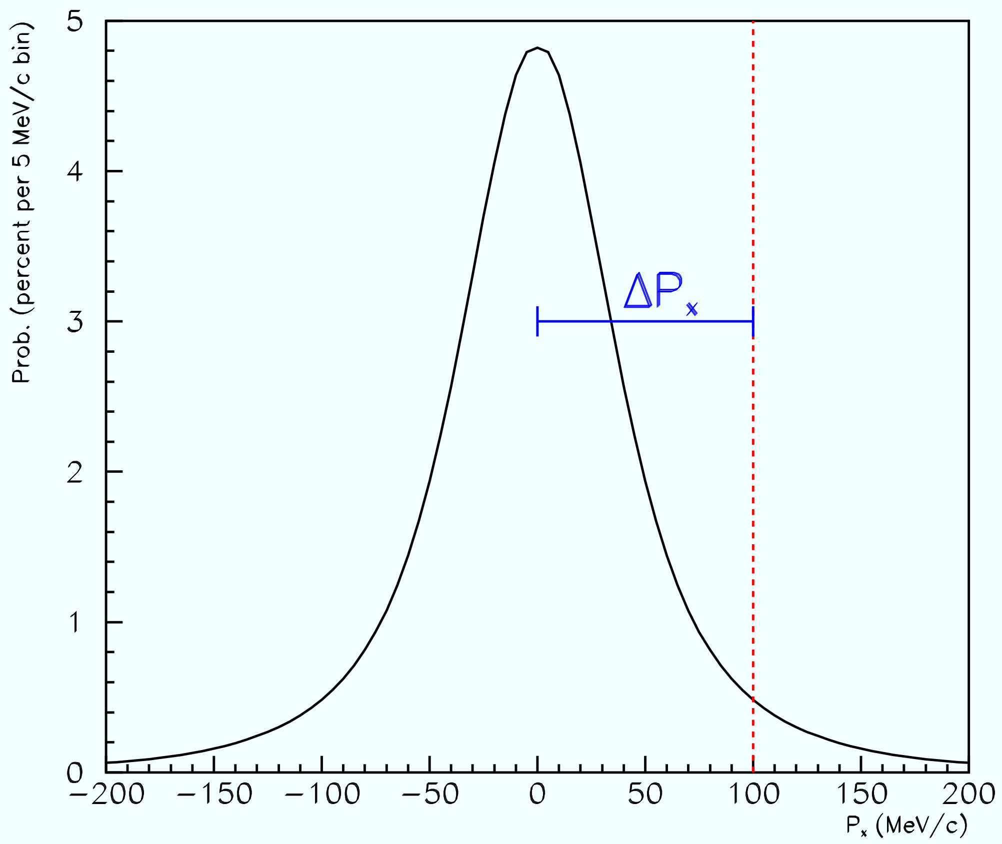




Choose $\Delta P_x = 100$ MeV/c

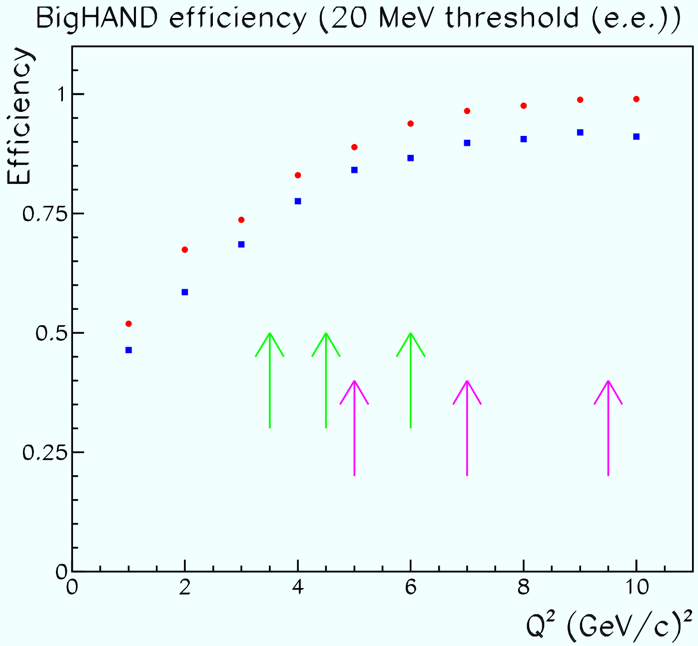
95% probability position will be shifted by less than $\Delta = \frac{\Delta P_x}{|\vec{q}|}L_{\text{flight}}$

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

('Backup plan' $\Rightarrow$ identical neutron/proton acceptances)

BigHAND efficiency

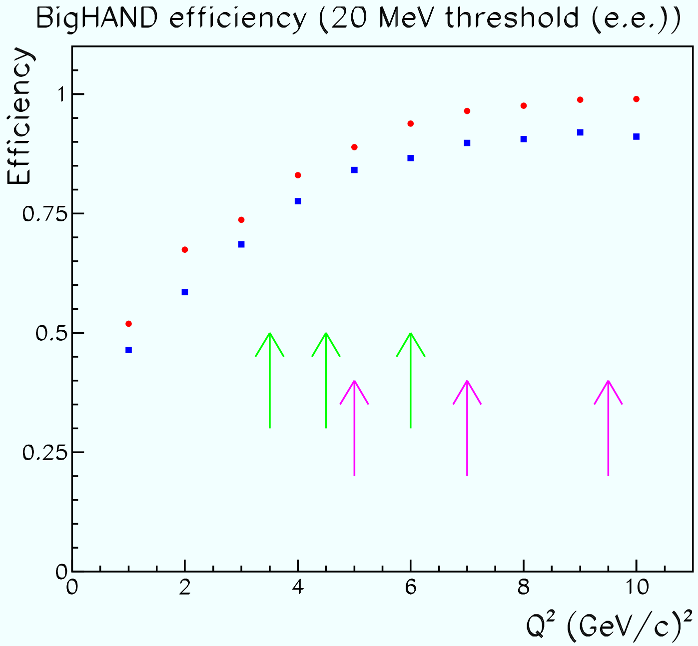


⇐ **Efficiency (ϵ) for neutron/proton detection with 20 MeV (electron equivalent) threshold**

Calibrate BigHAND at 3.5, 4.5, 6.0 $(GeV/c)^2$

Use GEN calibrations planned at 5, 7, 9.5 $(GeV/c)^2$

BigHAND efficiency and stability



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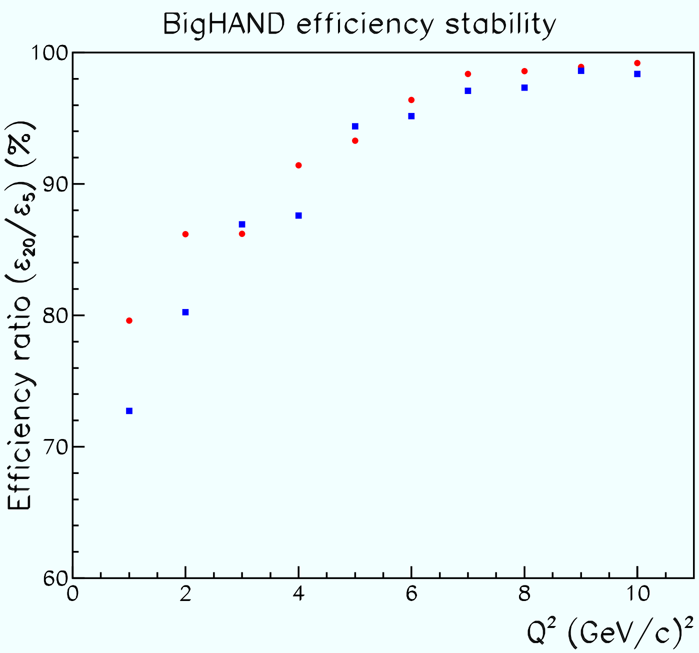


$\Leftarrow \frac{\epsilon \text{ at 20 MeV (e.e.)}}{\epsilon \text{ at 5 MeV (e.e.)}}$

Stable: No need for *simultaneous* calibration

BigHAND calibration reactions

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

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

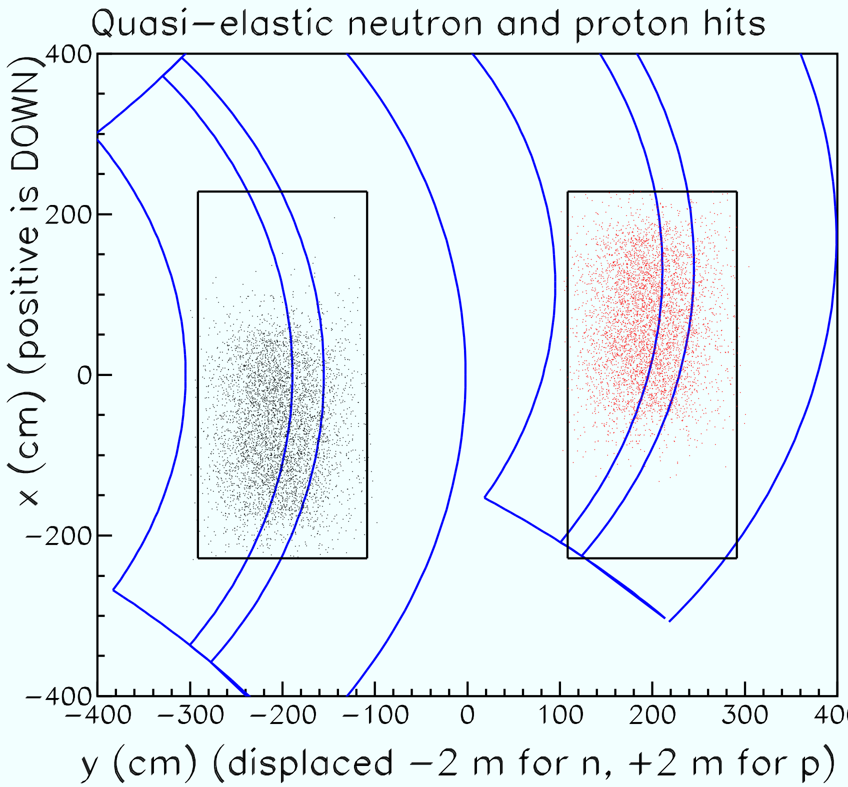
Improved relative to Bruins et al.:

- 6% radiator
- measure/subtract virtual production
- Require p_{π^+} at least 1.5% above maximum for three-body background reaction: p(γ,π)Nπ.

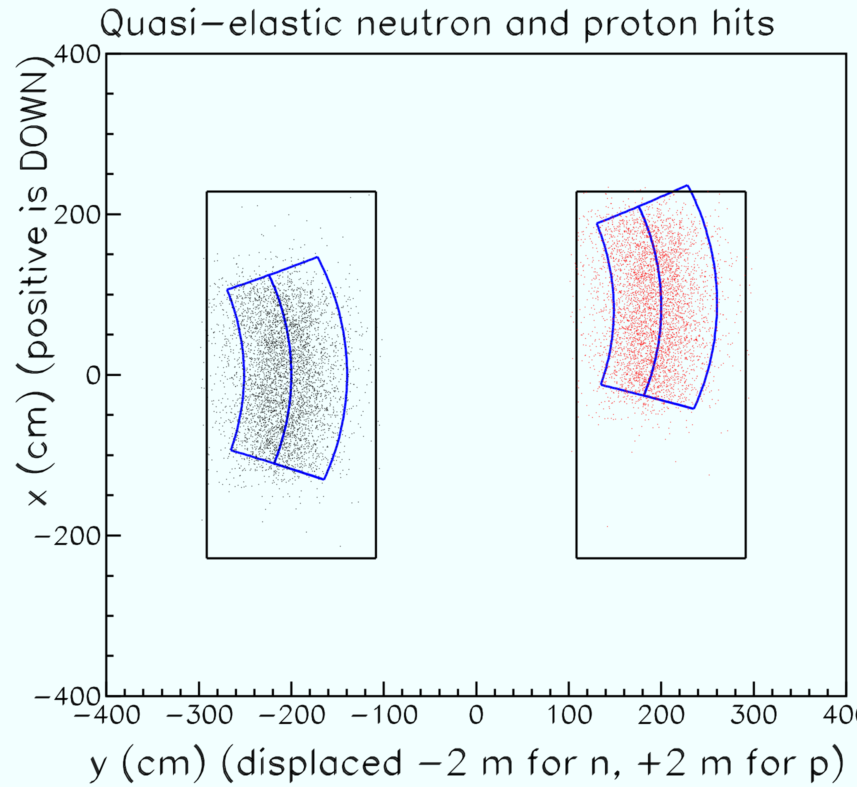
Q^2 (GeV/c)^2	E$_{beam}$ (GeV)	θ_e	E_π^{max} (γ,π) (GeV)	E_π^{max} $(\gamma,2\pi)$ (GeV)	E_π^{limit} (γ,π) (GeV)	E_γ^{min} (GeV)	$\int\,\Gamma\,dk$
3.5	4.4	32.5°	2.54	2.453	2.494	4.25	0.0023
4.5	4.4	41.9°	2.00	1.928	1.96	4.21	0.0030
6.0	4.4	64.3°	1.20	1.16	1.18	4.12	0.0046

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

⇒ Use two calibration settings.



$Q^2 = 3.5$ **(GeV/c)**^{2}



$Q^2 = 6.0$ **(GeV/c)**^{2}

Q^2 **(GeV/c)**^{2}	**a) Fraction (%) in Single Cal. Zone**	**b) Fraction (%) in Double Cal. Zone**
3.5	**97.7**	**100.**
4.5	**82.3**	**99.7**
6.0	**56.9**	**83.4**

Simulation

Quasi-elastic

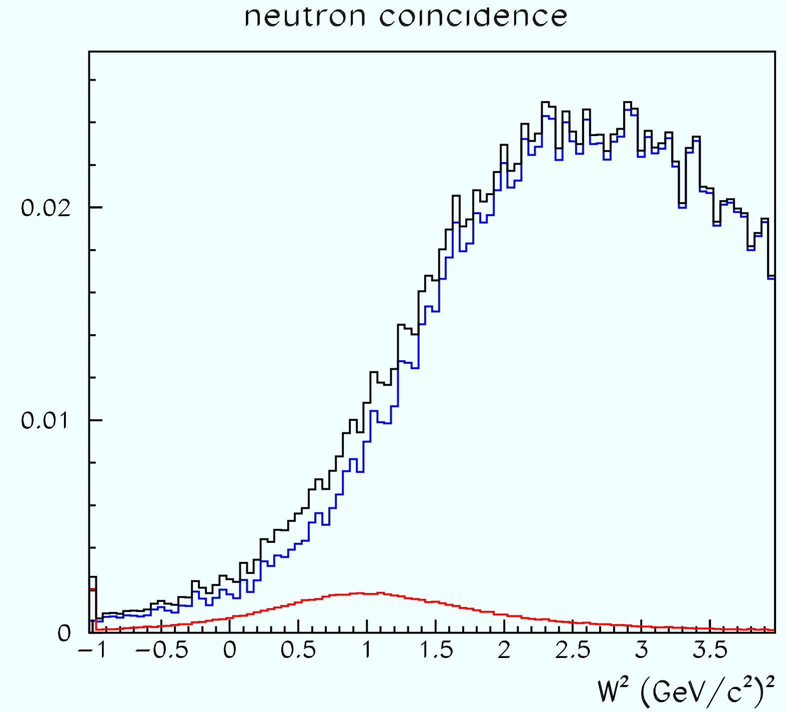
- **On shell spectator ($\Rightarrow$ Struck nucleon off shell)**
- **Boost to struck nucleon rest frame**
- **Isotropic $\cos(\theta)$, ϕ distribution**
- **Dipole (&Galster) $\longrightarrow$ cross-section for weight**
- **Boost back to lab**
- **Fold in resolution, (weighted) increment of spectra**

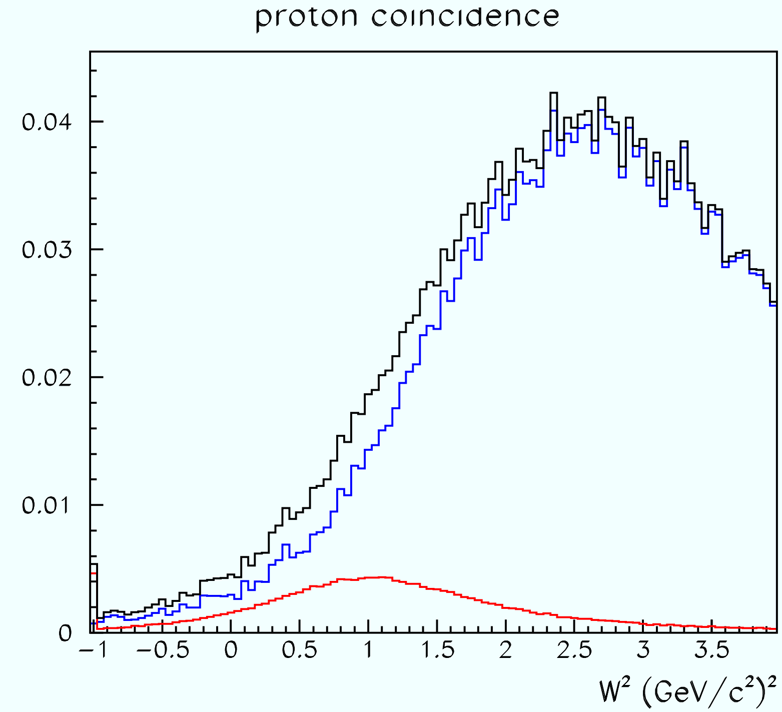
Inelastic

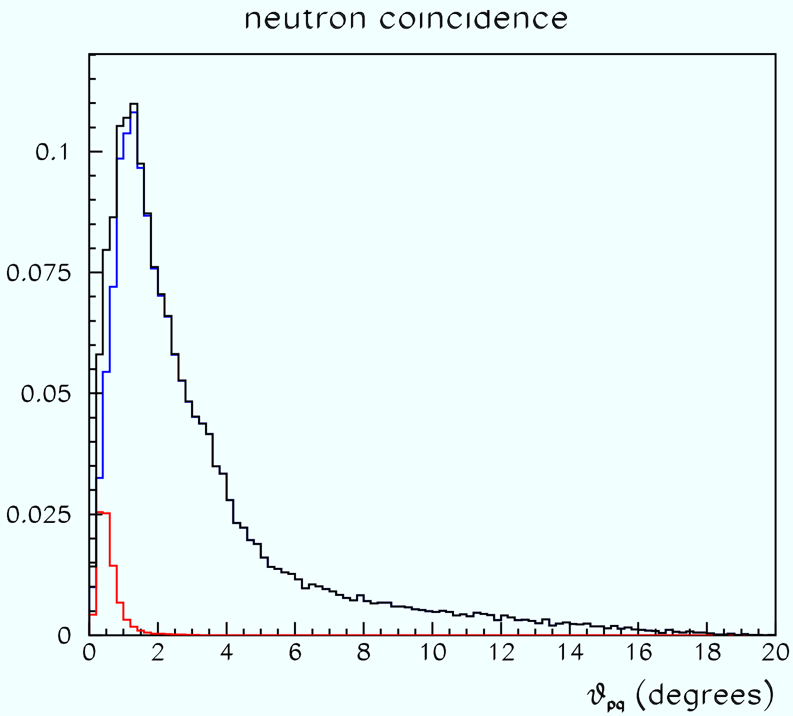
- **GENEV physics Monte Carlo (Genoa/CLAS)**
- **On-shell initial nucleons ($\vec{p}_F$ and $-\vec{p}_F$)**
- **Boost to struck nucleon rest frame**
- **Generate GENEV event (with boosted beam energy)**
- **Boost back to lab**
- **Fold in resolution, increment (un-weighted) spectra**

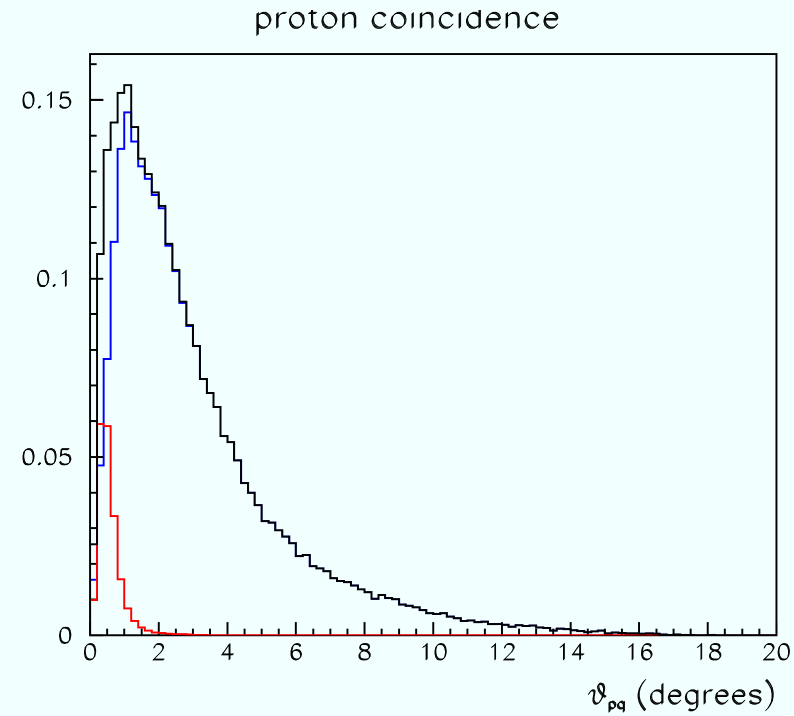
Inelastic normalized empirically to quasi-elastic

Simulation Results ($Q^2 = 18.0$ (GeV/c)^2)

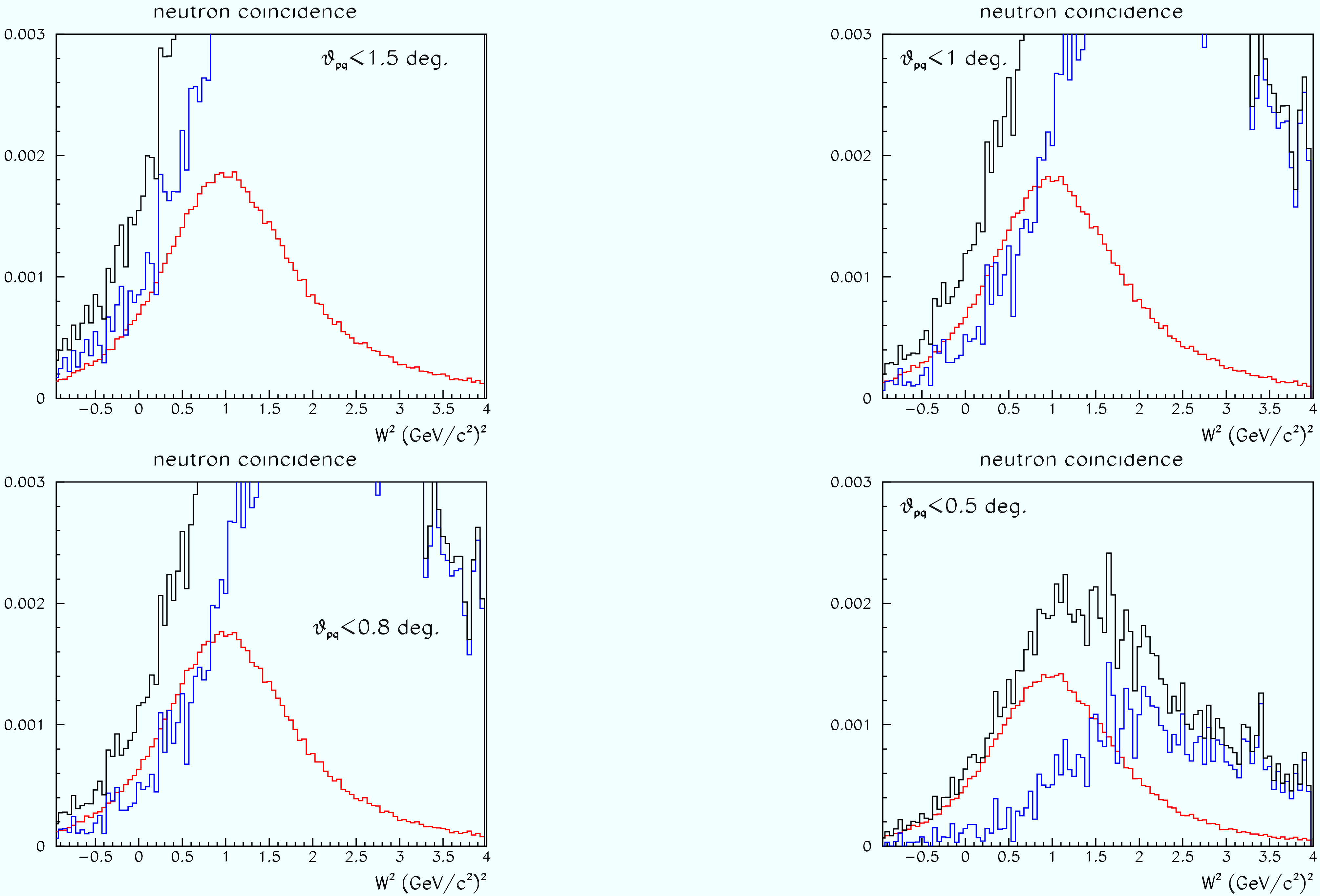








Simulation θ_{pq} cuts ($Q^2 = 18.0$ (GeV/c)^2)



Rates

Q^2 (GeV/c)^2	3.5	4.5	6.0	8.5	10.	12.	13.5	16.	18.
Max. θ_{pq} (deg.)	2.5	2.3	1.9	1.1	0.9	0.8	0.7	0.6	0.6
Max. W^2 (GeV^2)	1.1	1.2	1.3	1.3	1.4	1.4	1.6	1.6	1.7

$\mathcal{L} = 6.7 \times 10^{36}$/A/cm^2/s

Predicted coincidence rates (counts per hour)

Q^2 (GeV/c)^2	3.5	4.5	6.0	8.5	10.	12.	13.5	16.	18.
$d(e,e'p)$	40700	26600	3110	1345	1240	244	56.7	47.0	7.9
$d(e,e'n)$	17600	12000	1600	627	580	114	26.5	22.0	3.72
$p(e,e'p)$	273000	82000	9300	—	—	—	—	—	—
$p(\gamma,\pi^+n)$	2920	4030	13500	—	—	—	—	—	—

Systematic Error Estimates

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

Q^2 (GeV/c)^2	3.5	4.5	6.0	8.5	10.	12.	13.5	16.	18.
proton cross-section	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	4.
G_E^n (1-4 $\times$ Galster)	1.7	1.1	0.49	0.51	0.56	0.69	0.38	.89	.39
Nuclear correction,	-	-	-	-	-	-	-	-	-
Accidentals	-	-	-	-	-	-	-	-	-
Target windows	.2	.2	.2	.2	.2	.2	.2	.2	.2
Acceptance losses	0.45	0.5	0.3	0.4	0.16	0.18	0.1	0.1	.08
Inelastic contamination	1.5	1.14	1.32	2.64	2.94	2.62	3.24	4.4	3.64
Nucleon mis-identification	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.5
BigHAND calibration	0.3	0.3	0.5	2	2	2	2	2	2
Without proton err.									
Syst. error on G_M^n/G_M^p	1.21	0.9	0.81	1.72	1.83	1.72	1.93	2.47	2.1
With proton err.									
Syst. error on G_M^n	1.48	1.24	1.17	1.92	2.02	1.91	2.11	2.61	2.9

Beam Time Request

Beam Time Request (beam hours)

Q^2 (GeV/c)^2	3.5	4.5	6.0	8.5	10.	12.	13.5	16.	18.	
E (GeV)	4.4	4.4	4.4	6.6	8.8	8.8	8.8	11.	11.	
θ_e	32.5°	41.9°	64.3°	46.5°	33.3°	44.2°	58.5°	45.1°	65.2°	
d(e, e')										
Normal $\mathcal{L}$	12	12	18	18	24	36	96	108	216	
Dummy target	2	2	2	2	3	4	8	8	16	
Half $\mathcal{L}$	12	12	12	12						
Dummy half $\mathcal{L}$	2	2	2	2						
10% $\mathcal{L}$	12	12								
Dummy 10% $\mathcal{L}$	2	2								
H(e, e')										
Normal $\mathcal{L}$	3	3	24	4	4	4	4	4	4	
Half $\mathcal{L}$	3	6	6	2	2	2	2	2	2	
10% $\mathcal{L}$	18	18								
BigBen off	6	6	6	3	3	3	3	3	3	
Dummy target	2	2	2							
H(γ, π^+)										
Radiator	24	24	12							
Dummy target	2	2	2							
No radiator	6	6	3							
Total	106	106	89	43	36	49	113	125	241	$\Rightarrow$ 908
Commissioning										72
3 Energy changes										124
15 angle changes										60
6 polarity changes										24
Beam request										1088 $\approx$45 days

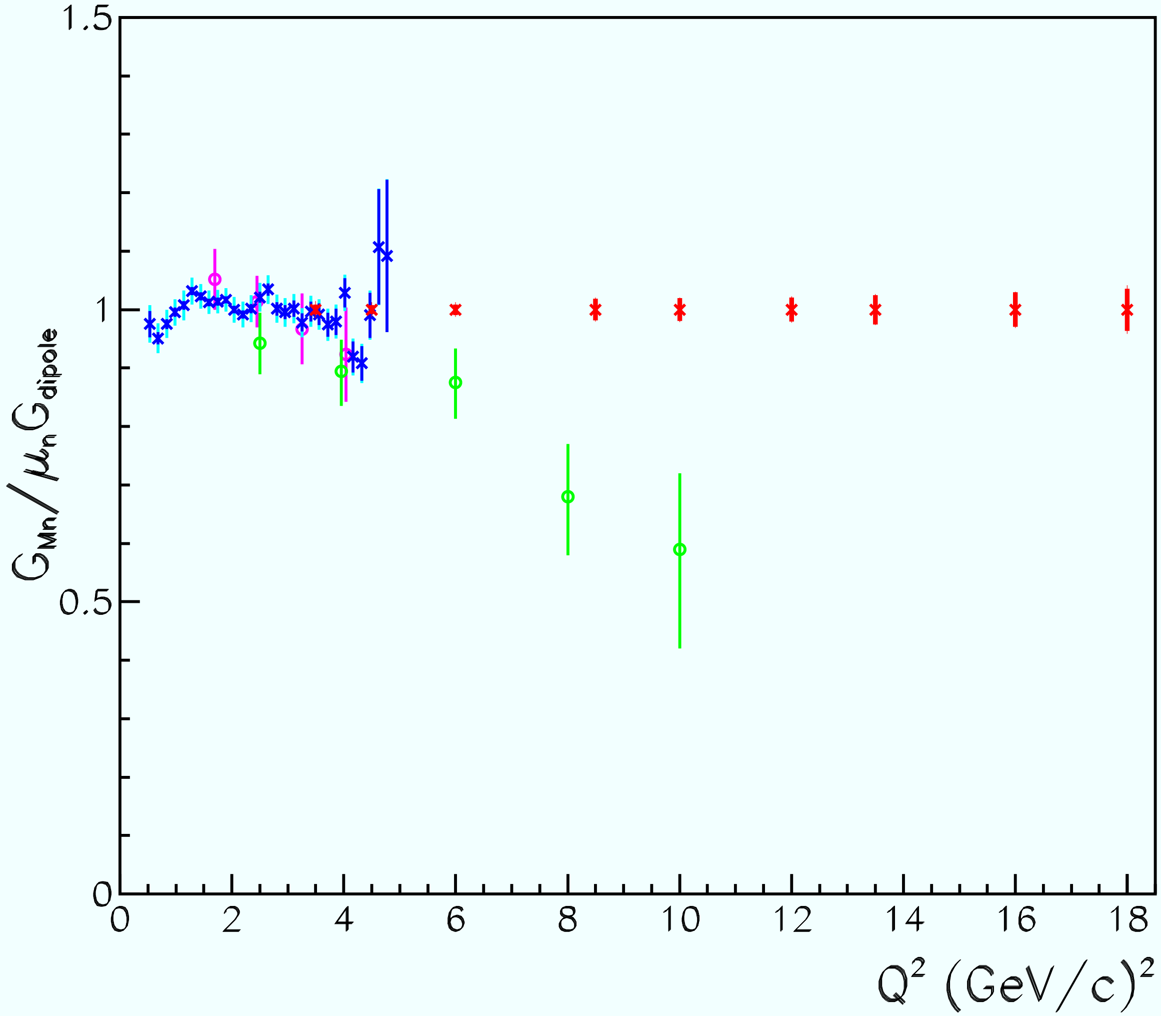
45 Days

Total errors for requested beam time

(in percent)

Q^2 (GeV/c)^2	3.5	4.5	6.0	8.5	10.	12.	13.5	16.	18.
proton cross-section	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	4.
G_E^n	1.7	1.1	0.49	0.51	0.56	0.69	0.38	.89	.39
Other syst. (quad. sum.)	1.72	1.43	1.59	3.4	3.63	3.36	3.85	4.86	4.19
Statistical error	0.3	0.3	0.8	1.4	1.3	2.4	3.2	3.4	5.9
Without proton err.									
Total error on R	2.43	1.83	1.81	3.71	3.89	4.19	5.02	6	7.25
Error on G_M^n /G_M^p	1.22	0.91	0.9	1.85	1.94	2.09	2.51	3	3.62
With proton err.									
Error on G_M^n	1.48	1.25	1.24	2.04	2.12	2.26	2.65	3.12	4.14

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



Q^2 (GeV/c)^2	CLAS12	Present proposal
2.5	1.6×10^5	—
3.5	2.3×10^6	2.1×10^5
4.5	6.6×10^5	1.4×10^5
5.5	89000	*
6.0	*	28000
6.5	35000	*
7.5	16000	*
8.5	7700	11300
9.5	4000	*
10	*	13900
10.5	2200	*
11.5	1300	*
12	*	4100
12.5	800	*
13.5	500	2550
16	—	2380
18	—	800

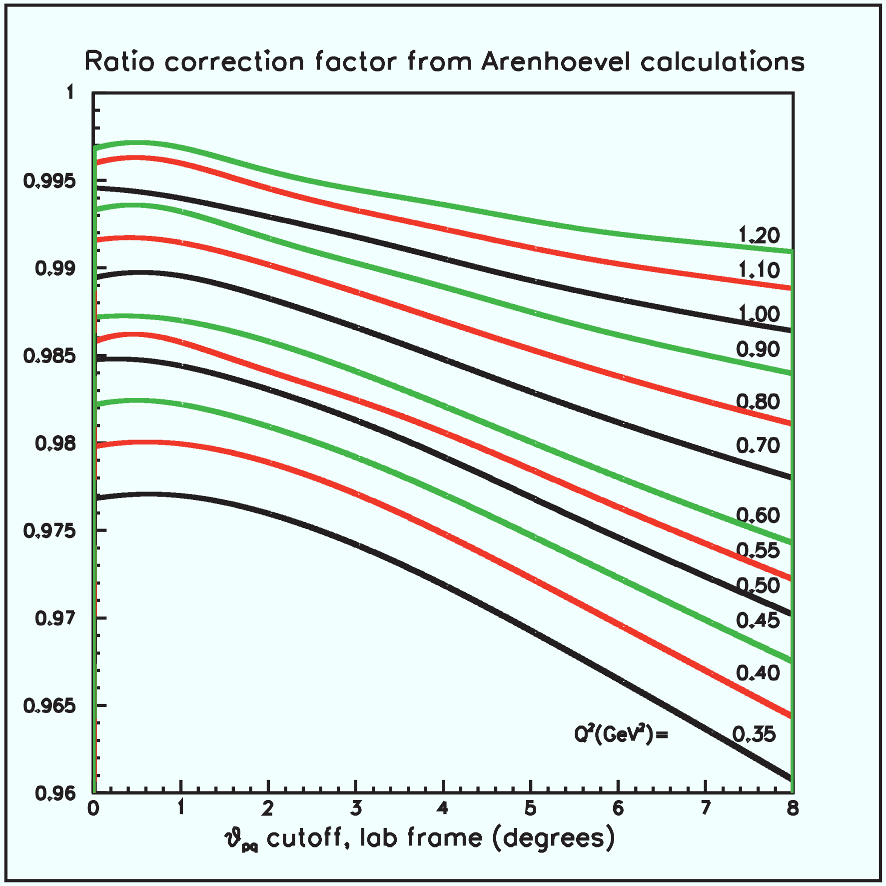
Comparison to CLAS12

(Neutron statistics)

Q^2 $(GeV/c)^2$	CLAS12	Present proposal	Hours
2.5	1.6×10^5	—	
3.5	2.3×10^6	2.1×10^5	12
4.5	6.6×10^5	1.4×10^5	12
5.5	89000	*	
6.0	*	28000	18
6.5	35000	*	
7.5	16000	*	
8.5	7700	11300	18
9.5	4000	*	
10	*	13900	24
10.5	2200	*	
11.5	1300	*	
12	*	4100	36
12.5	800	*	
13.5	500	2550	96
16	—	2380	108
18	—	800	216

Backup Slides

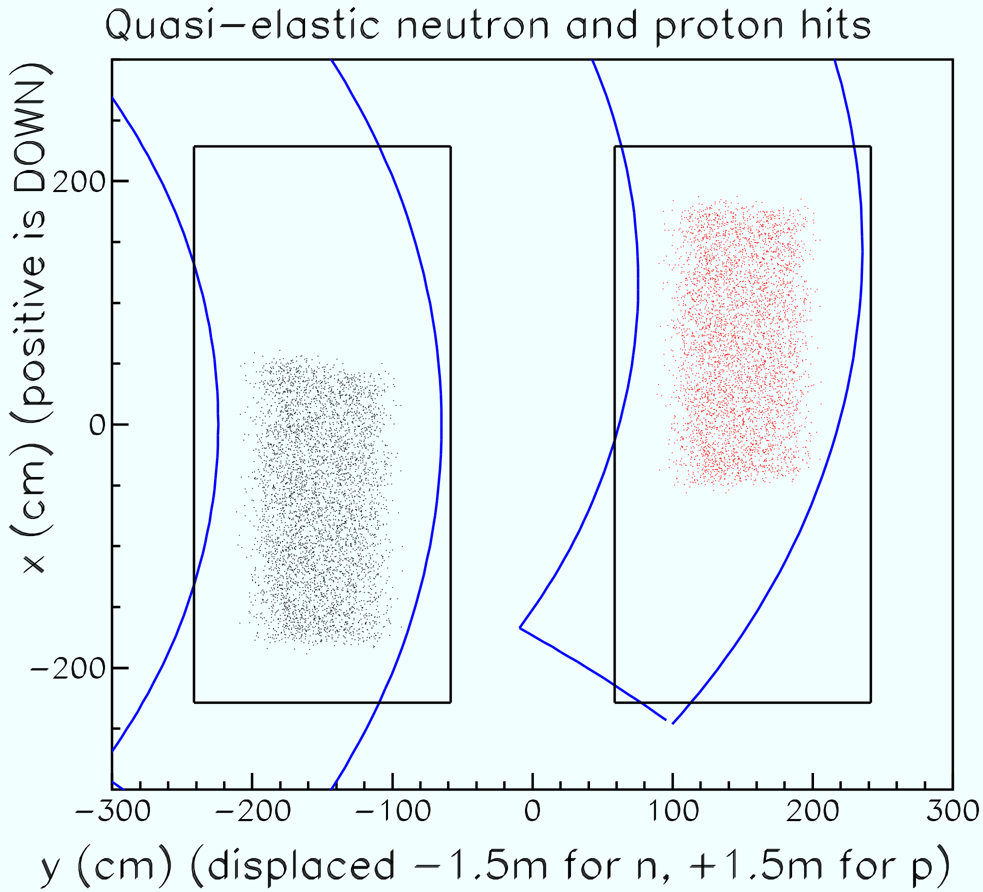
Arenhövel predictions (for low Q^2): Nuclear corrections (including FSI) small for small θ_{pq}, decrease with increasing Q^2.



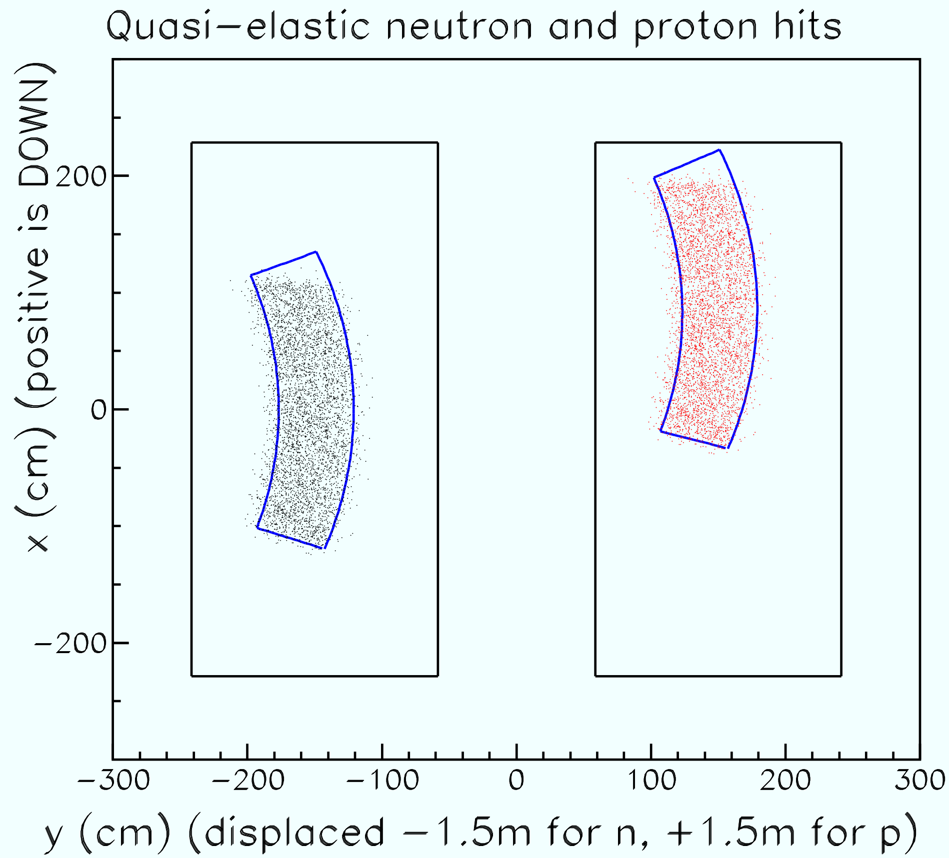
At higher Q^2 (for 4.2 GeV beam energy of CLAS e5 data) nuclear corrections calculated in Jeschonnek model with Glauber FSI corrections. Nuclear correction to ratio less than 0.1%:

Q^2	correction factor
1.0	0.9998
2.0	0.9997
3.0	0.9997
4.0	0.9996
5.0	0.9996

Fiducial cut on $\vec{q}$ **With Fermi motion turned off**



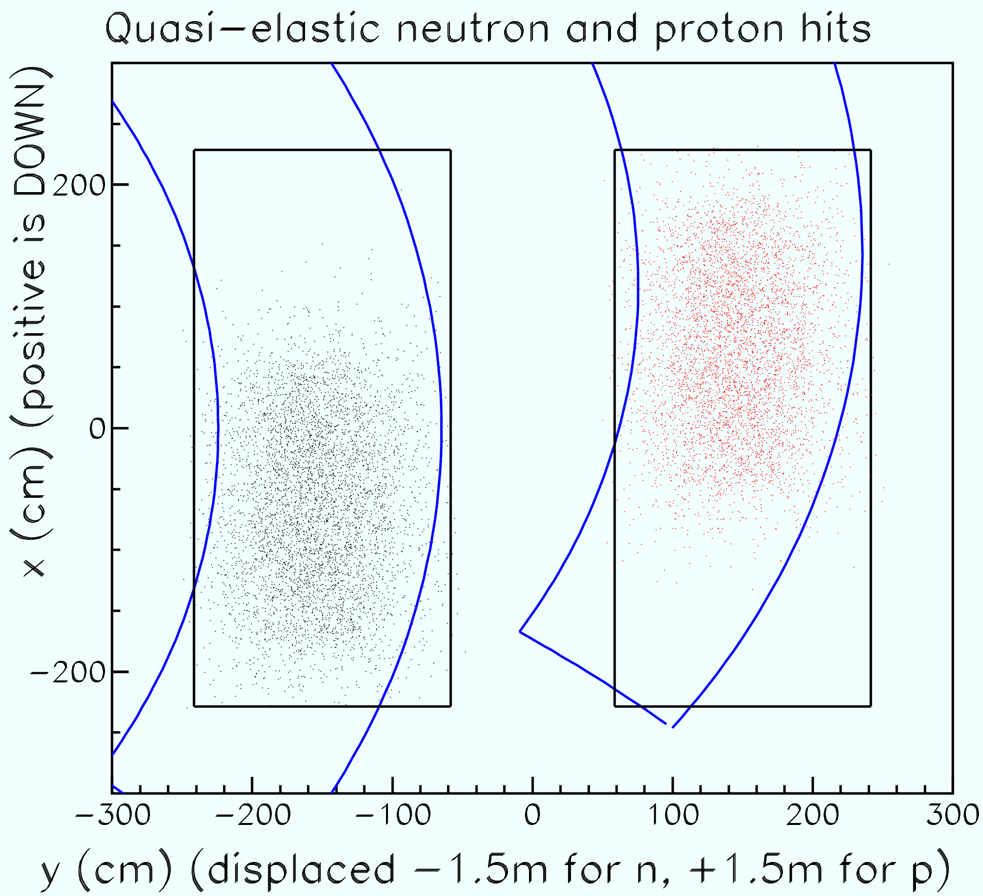
$Q^2 = 3.5$ **(GeV/c)**^{2}



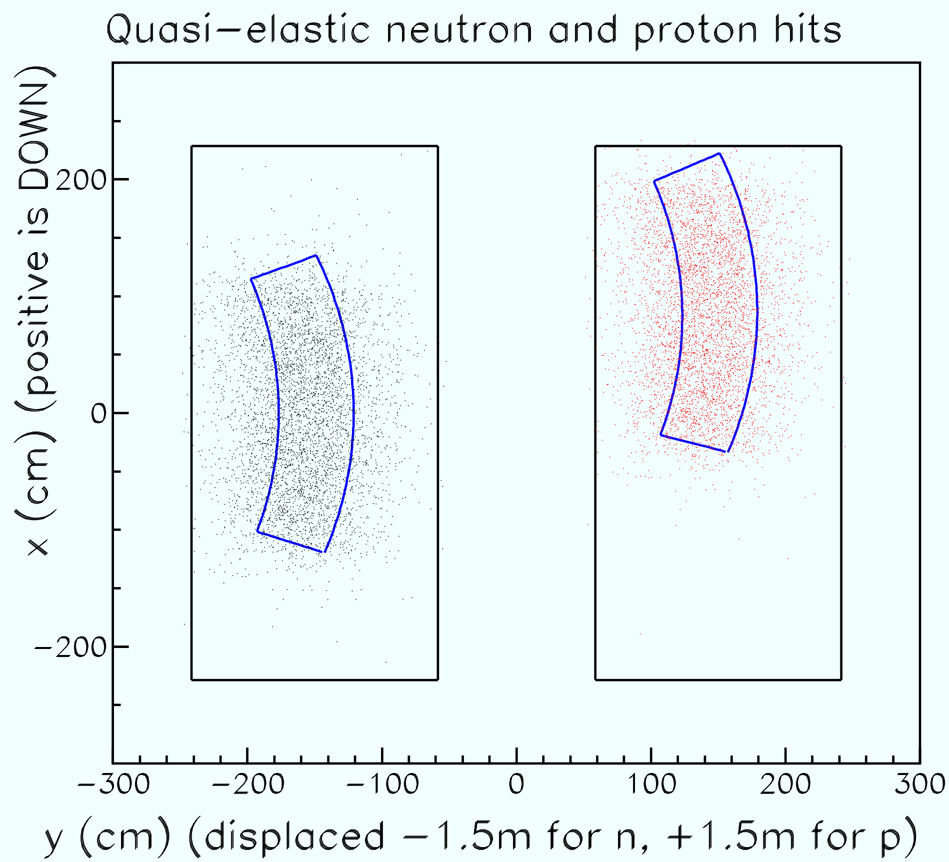
$Q^2 = 6.0$ **(GeV/c)**^{2}

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

(... and tend to cancel in ratio)

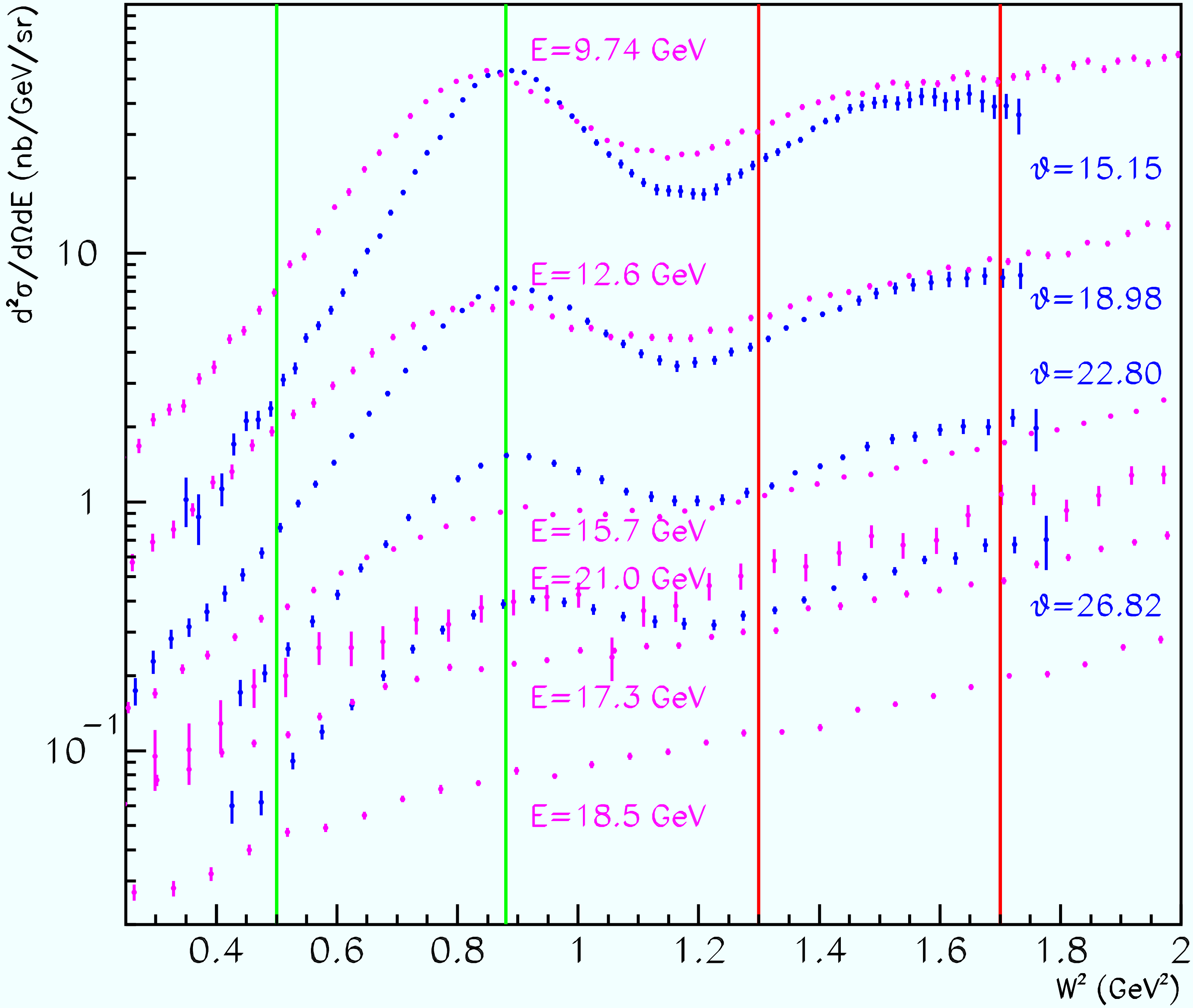


$Q^2 = 3.5$ **(GeV/c)**^{2}



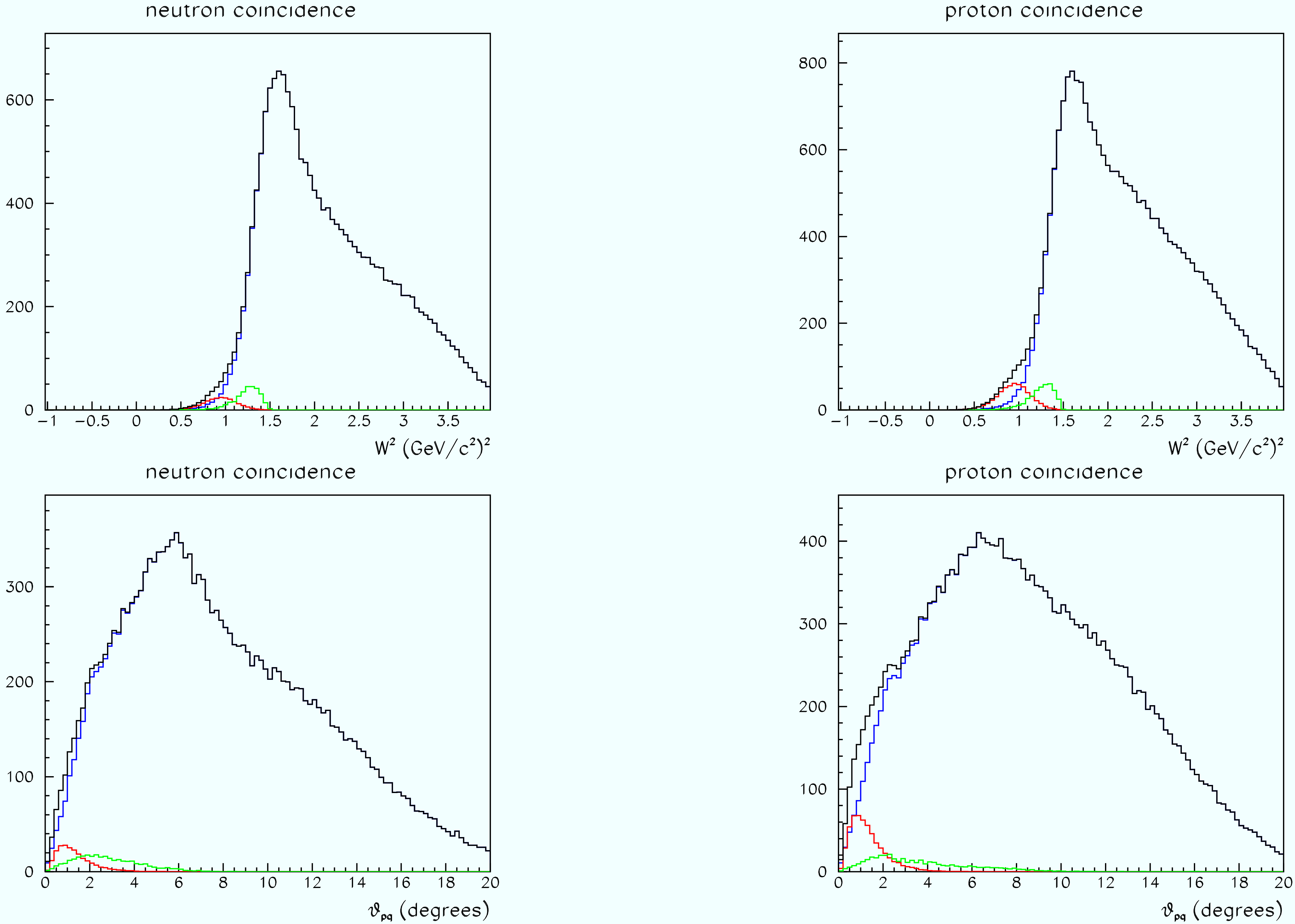
$Q^2 = 6.0$ **(GeV/c)**^{2}

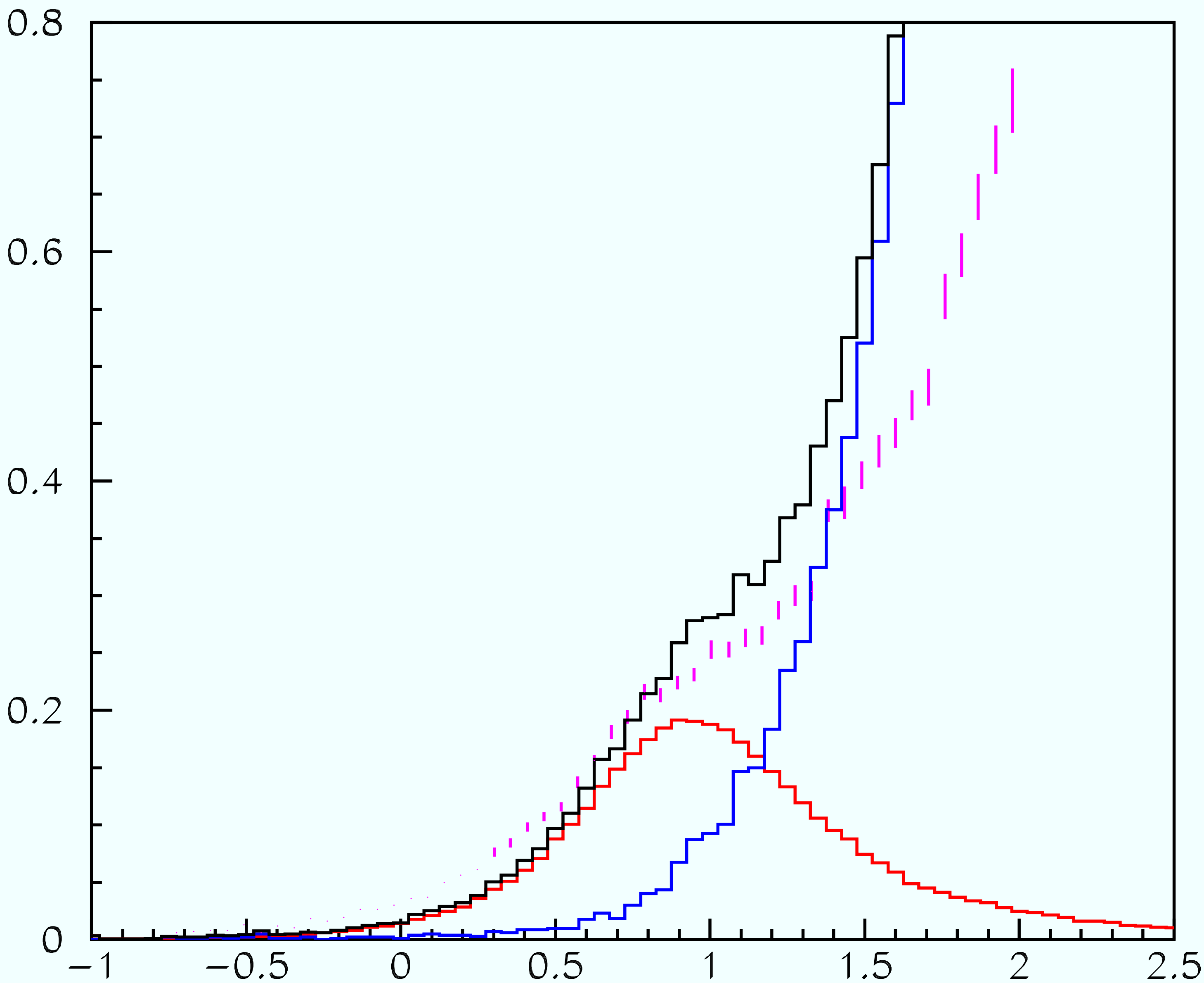
Normalization of inelastic to elastic



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

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





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