B.Sc. Honours in Physics
499 Presentation

Simulations of Deep Exclusive $\pi^0,\eta,\rho,\omega,\eta',\phi$ Meson Production at Jefferson Lab Hall C

Michael Hladun
Advisors: Dr. Garth Huber, Samip Basnet

University of Regina

Presentation Outline

- Abstract: Motivations and Goals
- Deep Exclusive Inelastic Scattering Overview
- Experimental Overview
- Simulations and Data Manipulation
- Results

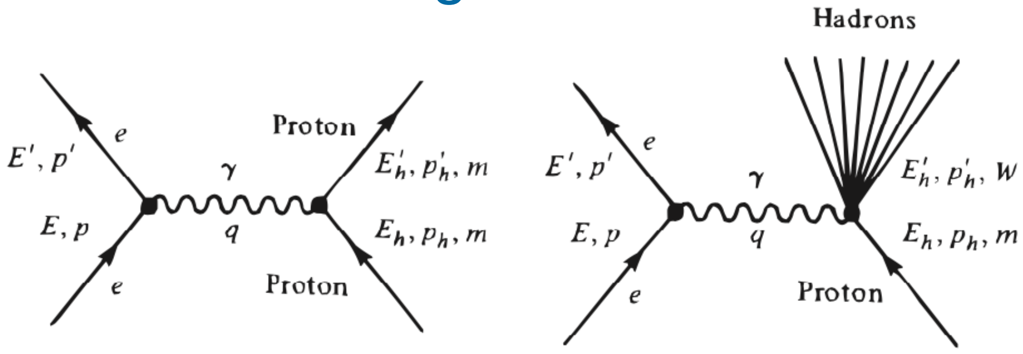
Abstract: Motivations and Goals

- $p(e,e'K^+)\Lambda,\Sigma^0$ reactions will be studied at Jefferson Labs Hall C for the first time above the resonance region in experiment E12-09-011.
- Complementary data for $p(e,e'p)\pi^0,\eta,\rho,\omega,\eta',\phi$ reactions was considered in the work.
- Study which backward angle mesons are feasible to study using complementary data from E12-09-011.

	Meson	Valence Quarks	Rest Mass (MeV/c^2)	Full Width (MeV)
Vectors: ($J^P = 1^-$)	ρ^0	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$	775.26 ± 0.25	149.1 ± 0.8
	ω	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$	782.65 ± 0.12	8.49 ± 0.08
	ϕ	$s\bar{s}$	1019.46 ± 0.019	4.266 ± 0.031
Pseudoscalars: ($J^P = 0^-$)	π^0	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$	134.9766 ± 0.0006	4.536 ± 0.0005
	η	$\frac{u\bar{u}+d\bar{d}-2s\bar{s}}{\sqrt{3}}$	547.862 ± 0.0018	0.00131 ± 0.00005
	η'	$\frac{u\bar{u}+d\bar{d}+s\bar{s}}{\sqrt{6}}$	957.78 ± 0.06	0.198 ± 0.009

Deep Exclusive Inelastic Scattering

Scattering Processes



(a) Elastic (b) Inelastic

$$\vec{q} = \vec{p}_e - \vec{p}_{e'}$$

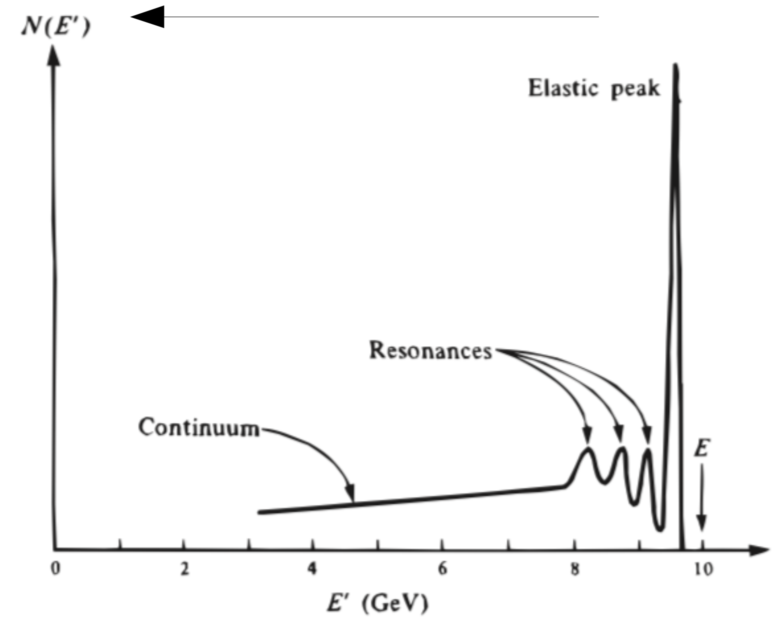
$$q^2 = q_\mu q^\mu = \omega^2 - |\vec{q}|^2$$

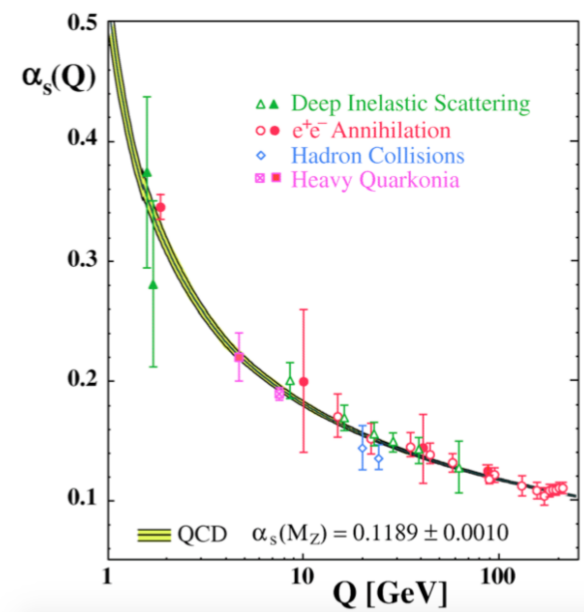
$$\text{where } \omega = (E_{e,i} - E_{e,f}) \text{ and } c = \hbar = 1$$

$$Q^2 \equiv -q^2$$

DIS Energy Region

α_s decreasing



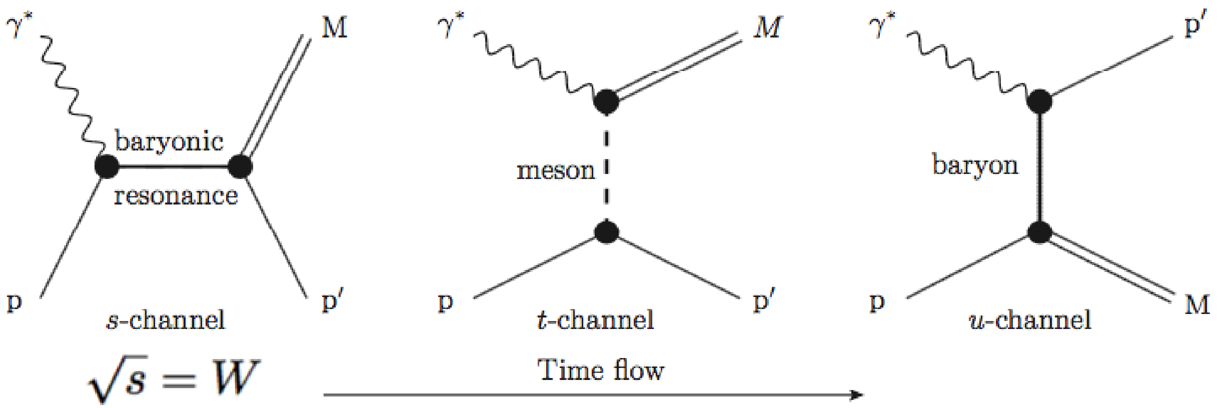


The kinematic settings in E12-09-011 range from:

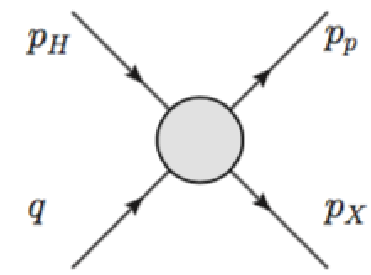
- $0.40\ \text{GeV}^2 \leq Q^2 \leq 5.5\ \text{GeV}^2$ (photon virtuality)
- $2.32\ \text{GeV} \leq W \leq 3.37\ \text{GeV}$ (hadronic invariant mass)
- $0.064\ \text{GeV}^2 \leq -t \leq 0.531\ \text{GeV}^2$ (four momentum transfer).

Deep Exclusive Inelastic Scattering

Mandelstam Processes



$$\sqrt{s} = W$$



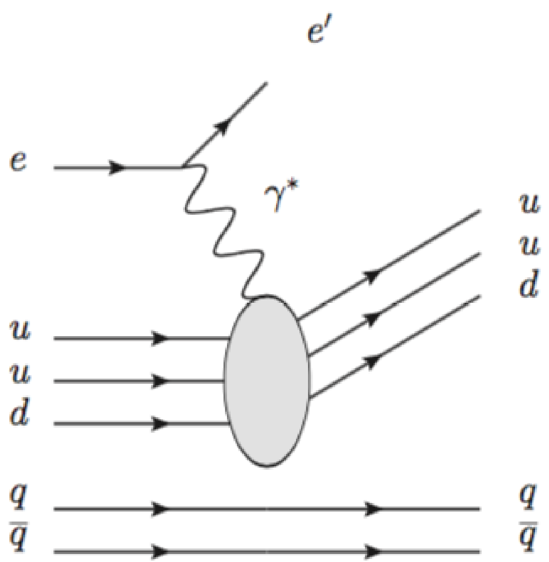
$$s = (p_H + q)^2 = (p_p + p_X)^2$$

$$t = (p_H - p_p)^2 = (q - p_X)^2$$

$$u = (p_H - p_X)^2 = (q - p_p)^2$$

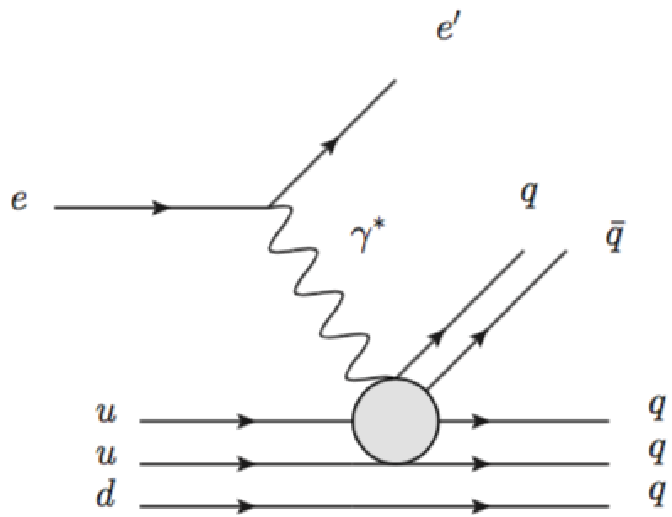
$$s + t + u = m_H^2 + m_{\gamma^*}^2 + m_p^2 + m_M^2$$

Backward Angle (u-channel)



p(e,e′p)π0,η,ρ,ω,η′,ϕ

Forward Angle (t-channel)



p(e,e'K+)Λ,Σ0

- s represents the invariant mass of the hadronic system
- t represents how forward a produced meson can go
- u represents how backward a produced meson can go

High -t interaction:
t-channel becomes a u-channel

Experimental Overview

- E12-09-011 - Extract Separated Cross Sections (L/T/LT/TT) for $p(e,e'K^+)\Lambda,\Sigma^0$ reactions above the resonance region using the Rosenbluth Separation Technique.
- Complementary data - Extract Separated Cross Sections (L/T/LT/TT) for $p(e,e'p)\pi^0,\eta,\rho,\omega,\eta',\phi$ reactions using the Rosenbluth Separation Technique.

The Rosenbluth Separation Technique Involves taking measurements at: the same Q^2, W, $-t$, x_B

but different ε

Combining lepton and hadron tensors gives us:

$$2\pi\frac{d^2\sigma}{dtd\phi} = \frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{LT}}{dt}\cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}\cos(2\phi)$$

$$x_B = \frac{Q^2}{2m_p\nu} \qquad \nu \equiv (E_e - E_e{'}) \qquad \epsilon = \left[1 + \frac{2|\vec{q}|^2}{Q^2}\tan^2\left(\frac{\theta_e}{2}\right)\right]^{-1}$$

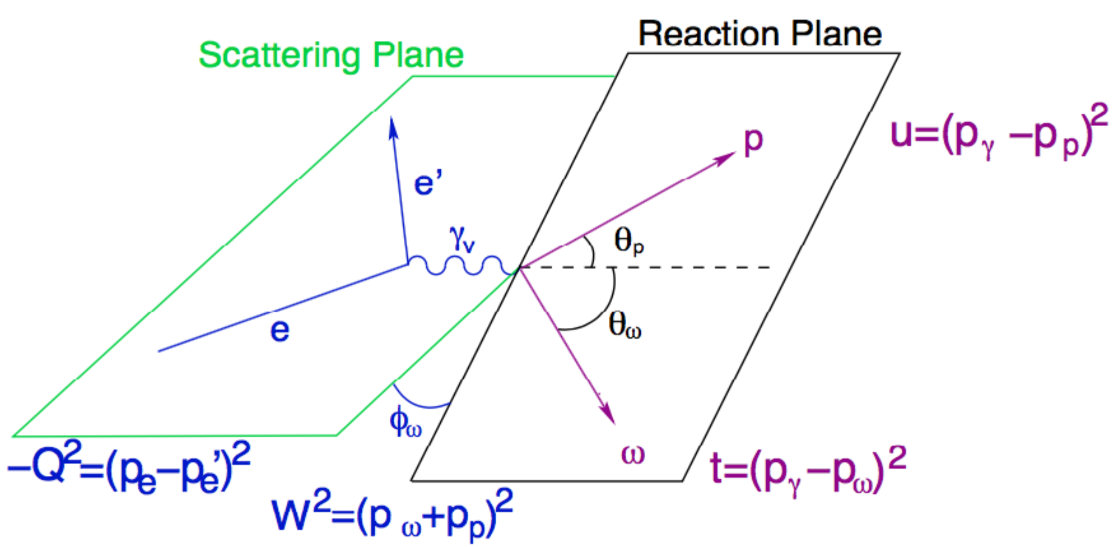
Experimental Overview

- Measurements are taken over full ϕ coverage, removing the factor of 2π as well as all ϕ dependence.
- Integration over the experimental acceptance is performed, making the cross sections free of interference terms.

$$\frac{d\sigma_L}{dt} = \frac{\left(\frac{d\sigma}{dt}\right)_{\text{High}} - \left(\frac{d\sigma}{dt}\right)_{\text{Low}}}{\epsilon_{\text{High}} - \epsilon_{\text{Low}}} \qquad \frac{d\sigma_T}{dt} = \frac{\epsilon_{\text{High}}\left(\frac{d\sigma}{dt}\right)_{\text{Low}} - \epsilon_{\text{Low}}\left(\frac{d\sigma}{dt}\right)_{\text{High}}}{\epsilon_{\text{High}} - \epsilon_{\text{Low}}}$$

Implications:

Each set of kinematic settings, $\{Q^2, W, -t, x_B, \varepsilon, T_{inc}, T_{e'}, \theta_{e'}, \theta_q, P_p, \Theta_{pq}\}$, we want to study has to be taken in pairs with different ε.



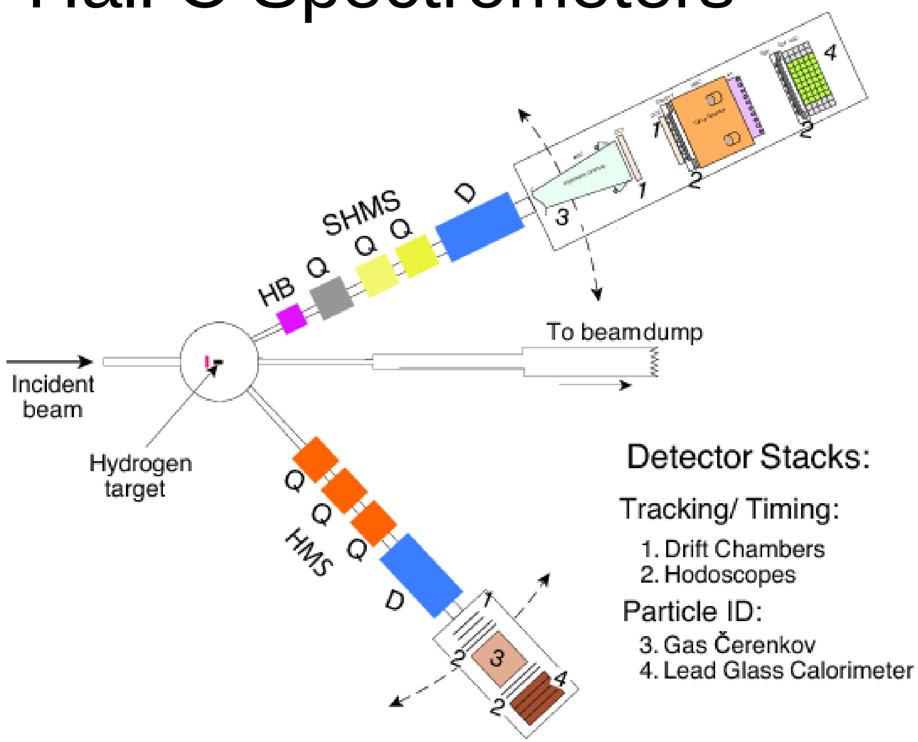
Experimental Overview

Kinematics Settings

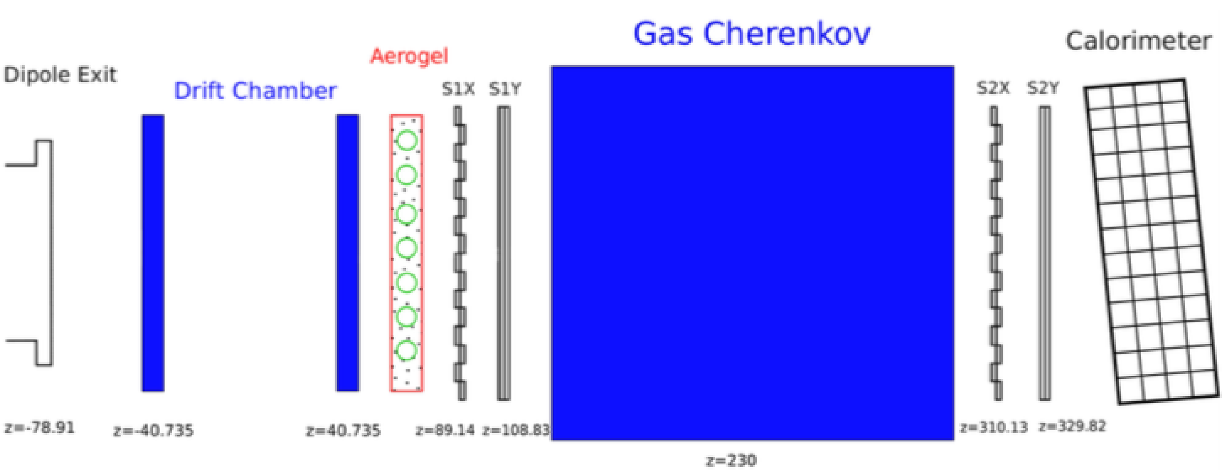
Q^2 (GeV^2)	W (GeV)	x_B	$-t$ (GeV^2)	ϵ	T_{inc} (GeV)	$T_{e'}$ (GeV)	$\theta_{e'}$ (deg)	θ_q (deg)	P_p (GeV/c)	θ_{pq} (deg)
Study of the reaction mechanism and form factor Q^2 dependence:										
0.40	2.45	0.072	0.064	0.411	3.799	0.857	20.2	-5.6	2.669	0,+3
0.40	2.45	0.072	0.064	0.685	4.951	2.008	11.5	-7.7	2.669	-2.15,0,+3
1.25	3.14	0.122	0.084	0.492	7.495	2.044	16.4	-6.0	5.189	0,+3
1.25	3.14	0.122	0.084	0.699	9.343	3.892	10.6	-7.4	5.189	-1.9,0,+3
2.00	3.14	0.182	0.138	0.395	7.495	1.645	23.2	-6.2	5.561	0,+3
2.00	3.14	0.182	0.138	0.580	8.761	2.910	16.1	-7.7	5.561	-2.2,0,+3
2.00	3.14	0.182	0.138	0.752	10.921	5.070	10.9	-9.2	5.561	-3,0,+3
3.00	3.14	0.250	0.219	0.391	8.191	1.807	26.0	-6.9	6.053	0,+3
3.00	3.14	0.250	0.219	0.691	10.921	4.537	14.1	-9.6	6.053	-3,0,+3
Scaling study at fixed x_B = 0.25, -t=0.2:										
1.70	2.45	0.249	0.239	0.595	5.647	2.012	22.3	-11.4	3.277	0,+3
1.70	2.45	0.249	0.239	0.856	8.761	5.125	11.6	-14.9	3.277	-3,0,+3
3.50	3.37	0.250	0.215	0.364	9.343	1.895	25.7	-6.1	7.122	0,+3
3.50	3.37	0.250	0.215	0.557	10.921	3.473	17.5	-7.8	7.122	-3,0,+3
Scaling study at fixed x_B = 0.40, -t = 0.5:										
3.00	2.32	0.400	0.531	0.634	6.601	2.603	24.1	-14.1	3.486	0,+3
3.00	2.32	0.400	0.531	0.888	10.921	6.923	11.4	-18.4	3.486	-3,0,+3
4.40	2.74	0.399	0.507	0.479	8.191	2.314	27.9	-10.0	5.389	0,+3
4.40	2.74	0.399	0.507	0.735	10.921	5.045	16.3	-13.1	5.389	-3,0,+3
5.50	3.02	0.400	0.503	0.372	9.343	2.021	31.3	-7.9	6.842	0,+3
5.50	3.02	0.400	0.503	0.562	10.921	3.599	21.6	-9.9	6.842	-3,0,+3

Experimental Overview

Hall C Spectrometers



- The HMS and SHMS are both small solid angle magnetic focusing spectrometers
- Both have similar detector set ups:
  - Drift chambers for calculating charged particle trajectories and momenta
  - Hodoscopes measure the time-of-flight of charged particles, and allow the implementation of a trigger system
  - Heavy gas Čerenkov (HGC) detectors are used to separate pions and electrons
  - Aerogel Čerenkov detectors separate pion from protons at high momentum ($p_p > 3$ GeV/c)
  - The lead glass calorimeters are used to provide additional particle identification/separation



SIMC

The Standard Hall C Monte Carlo Package

- Takes input files with necessary physical parameters to simulate specific processes
  - Kinematic Settings
  - Target Parameters
  - Spectrometer Acceptance
  - Spectrometer Offsets

For each event:

- The coordinates of the interaction vertex, and the initial energy (E) and three-momentum ($\vec{p}$) are generated randomly within specified limits.

- The tracking of the outgoing particles are simulated with HMS and SHMS subroutines.

- Valid triggers are determined when a particle
  - is within all the spectrometer’s apertures
  - crosses the minimum number of detectors in the huts

Project Overview

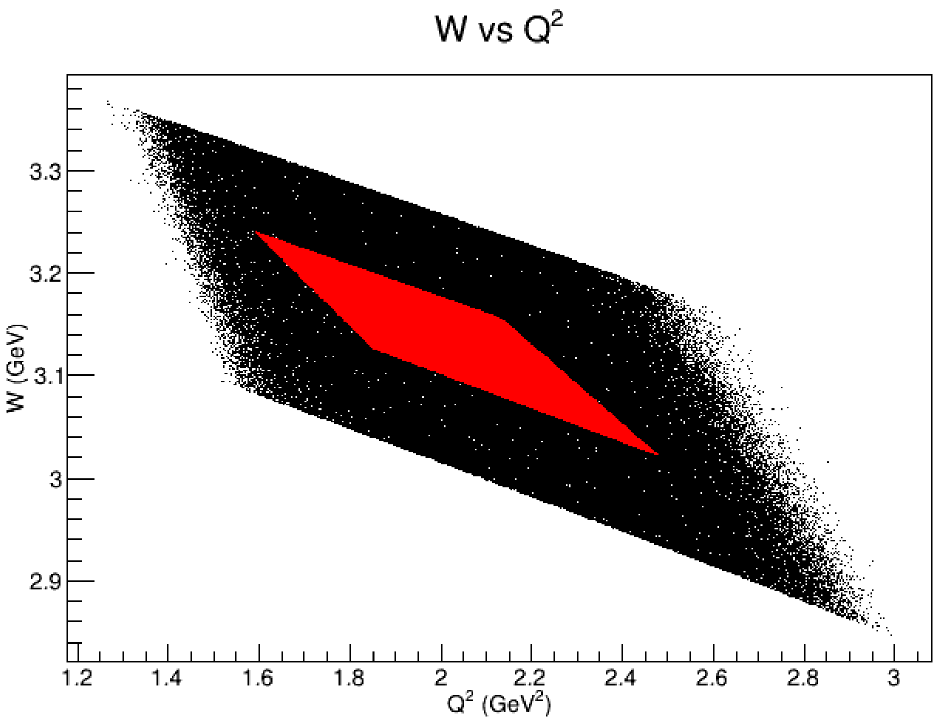
Determining the feasibility of studying $p(e,e'p)\pi^0,\eta,\rho,\omega,\eta',\phi$ reactions includes:

- Running simulations using SIMC to generate a data set of anticipated values for descriptive variables such as Q^2, W, $-t$, x_B, M_m, etc.
- Applying spectrometer acceptance cuts & W-Q^2 cuts, as well as normalization factors & weight factors, to SIMC generated data using CERN's data analysis framework, ROOT.
- Analyzing missing mass, M_m, distributions to find meson yields.

- 500,000 successful events were simulated using SIMC for all 19 kinematic settings and for each meson, $\pi^0,\eta,\rho,\omega,\eta',\phi$ ($X \equiv \{\pi^0,\eta,\rho,\omega,\eta',\phi\}$).
- Spectrometer cuts were applied to all distributions used in this work.
- Overlapping diamonds mean L-T separation is possible

Spectrometer Acceptance Cuts

Variable	Value
HMS $\lvert\delta\rvert$	$\lvert$hsdelta$\rvert$ < 8.0 %
HMS $\lvert x'_{tar}\rvert$	$\lvert$hsxptar$\rvert$ < 0.080 rad
HMS $\lvert y'_{tar}\rvert$	$\lvert$hsyptar$\rvert$ < 0.035 rad
SHMS $\lvert\delta\rvert$	$\lvert$ssdelta$\rvert$ < 15.0 %
SHMS $\lvert x'_{tar}\rvert$	$\lvert$ssyptar$\rvert$ < 0.024 rad
SHMS $\lvert y'_{tar}\rvert$	$\lvert$ssxptar$\rvert$ < 0.040 rad

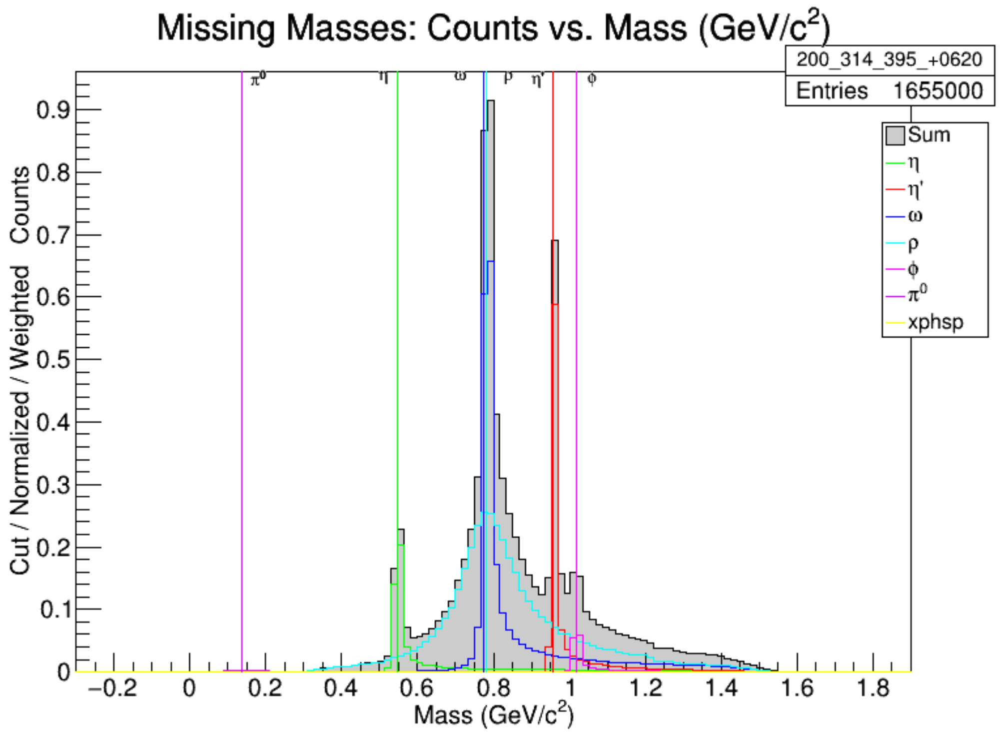


The simulation diamond plot for the p(e,e′p)ω reaction. $Q^2 = 2.00$ GeV^2, W = 3.14 GeV^2, $\varepsilon_{red} = 0.395$, $\varepsilon_{black} = 0.752$, $\theta_q = 6.20$ deg.

Anticipated Production Yields of Backward Angle Mesons

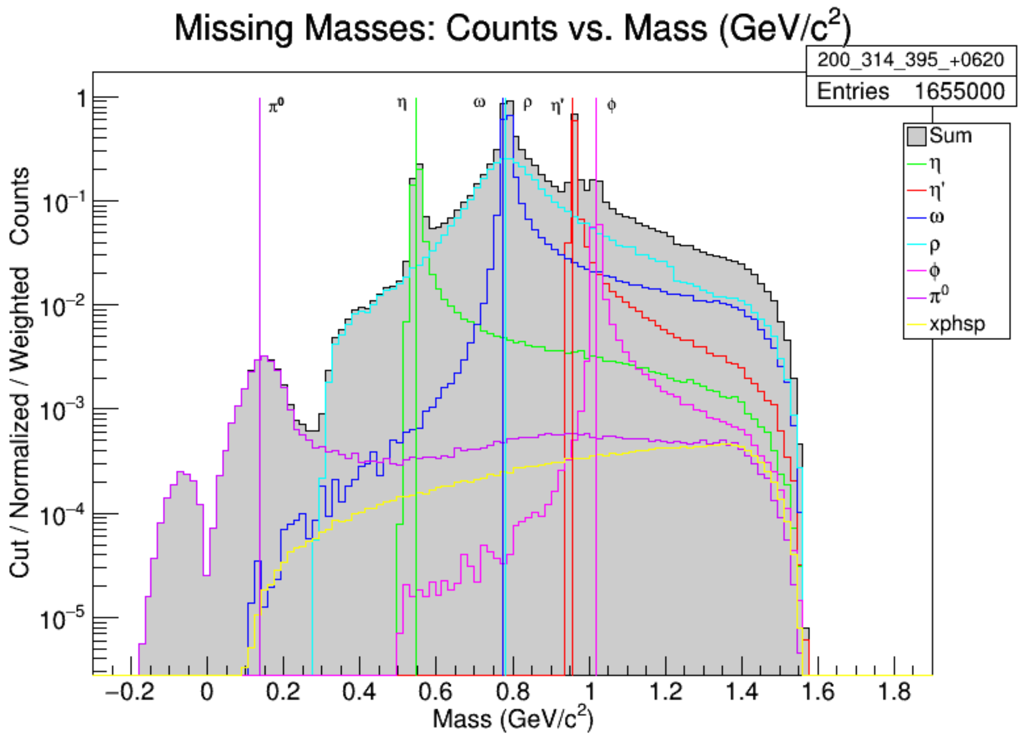
Missing Mass Plots

Used as a way of extracting production yields after cuts and factors are applied.



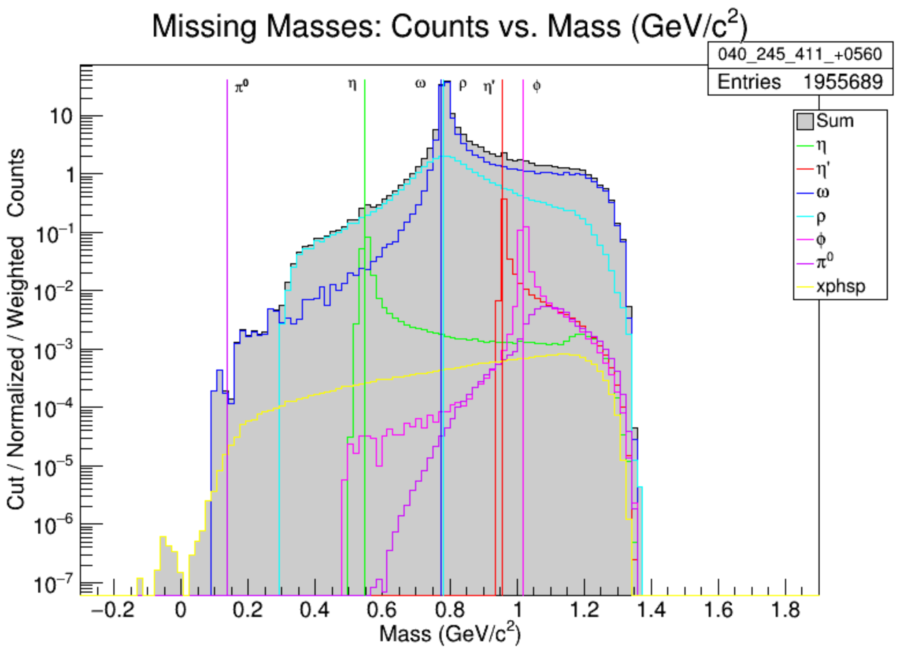
A reconstructed missing mass linear-scale plot for $Q^2 = 2.00$ GeV^2, W = 3.14 GeV, ε = 0.395, θ_q = 6.20 deg.

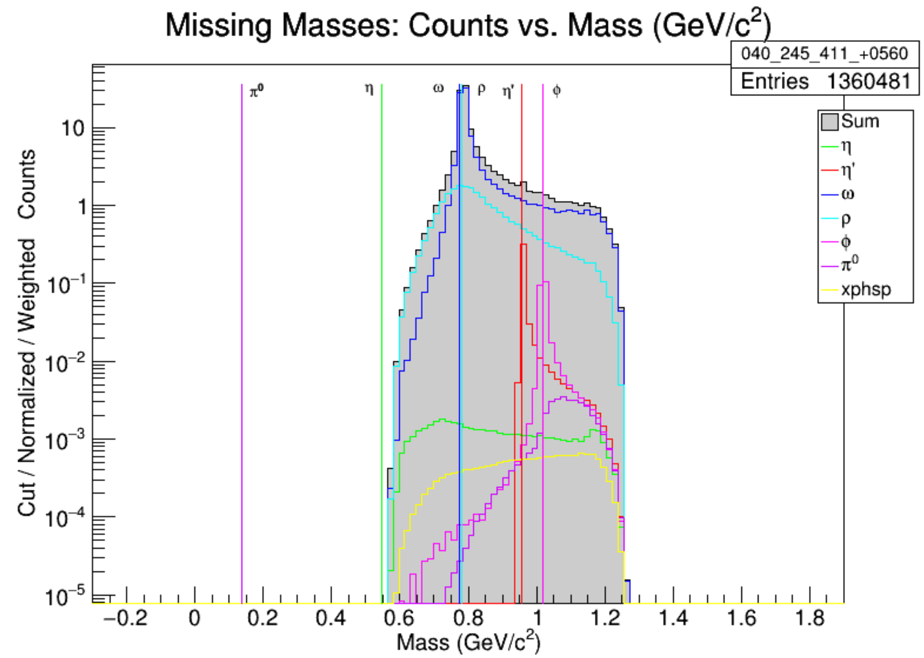
Linear-scale



A reconstructed missing mass linear-scale plot for $Q^2 = 2.00$ GeV^2, W = 3.14 GeV, ε = 0.395, θ_q = 6.20 deg.

Log-scale

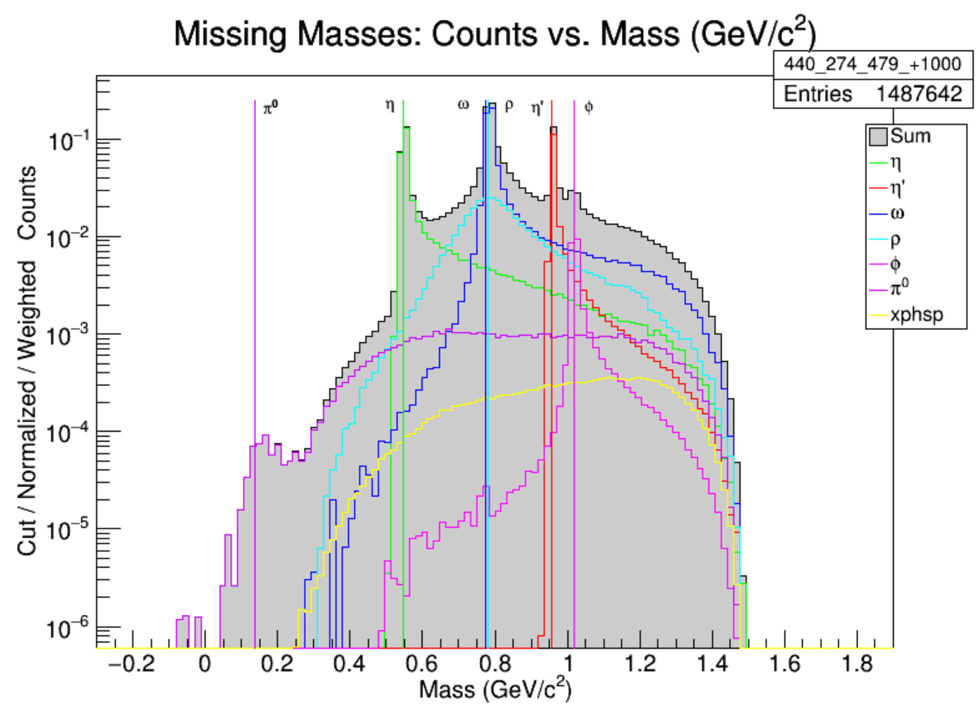




A reconstructed log-scale missing mass plot for $Q^2 = 0.40$ GeV^2, W = 2.45 GeV, ε = 0.411, $\theta_q = 5.60$ deg without spectrometer acceptance cuts (left) and with spectrometer acceptance cuts (right). This demonstrates how the width of the distribution is effected by spectrometer acceptance cuts. This distribution is much wider than the same distribution with spectrometer acceptance cuts

Mesons were deemed not feasible to study if their missing mass distributions did not have adequate coverage

- Missing mass distribution has peak that aligns with accepted mass value
- Healthy yield characteristics



Q^2 (GeV^2)	W (GeV)	ϵ
1.25	3.14	0.492
1.25	3.14	0.699
2.00	3.14	0.395
2.00	3.14	0.580
2.00	3.14	0.752
3.00	3.14	0.391
3.00	3.14	0.691
3.50	3.37	0.364
3.50	3.37	0.557
4.40	2.74	0.735
5.50	3.02	0.372
5.50	3.02	0.562

A table of settings with adequate missing mass coverage for mesons, *X*. The main limiting factor was the π^0 meson not having yields above 10^{-3} events/mC for each of the missing settings from our list of 19 settings.

Observation:

If we disregard π^0, and η at $Q^2 = 0.40$ GeV^2, we have adequate missing mass coverage for each meson at each setting.

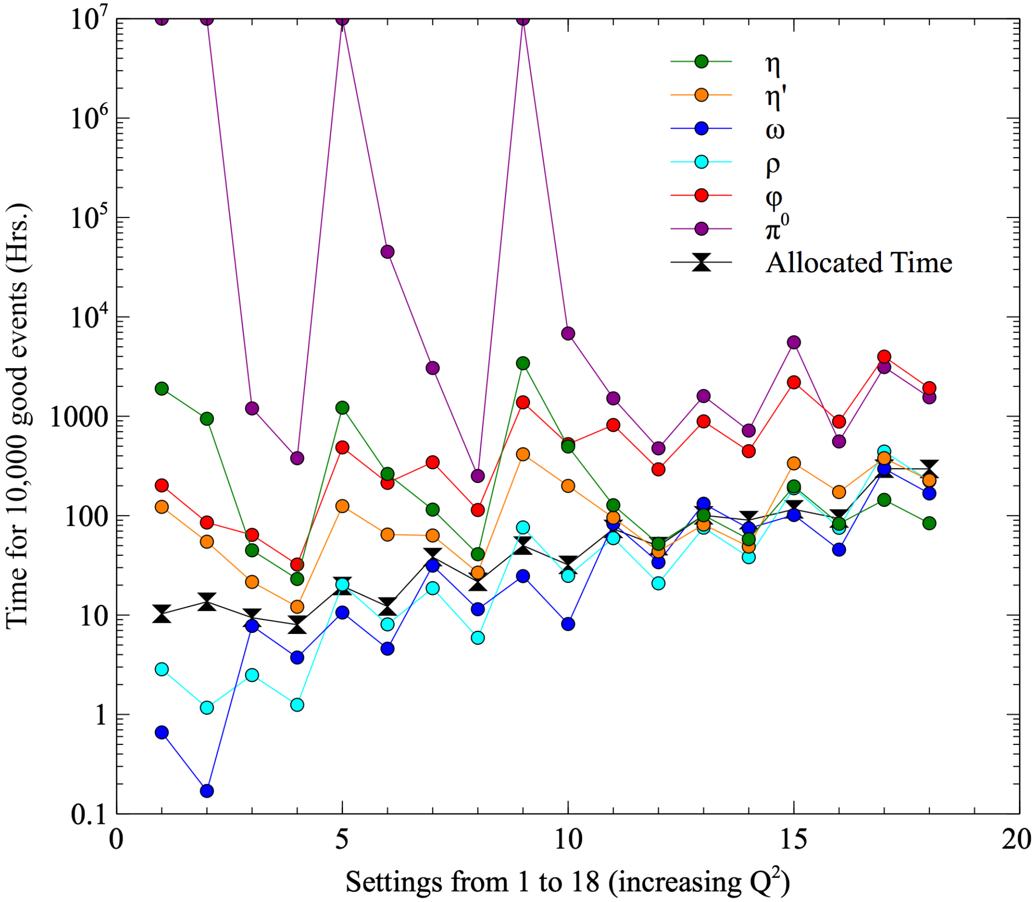
To summarize, these missing mass plots provide us with information that tells us which kinematic settings, and for which backward-angle mesons, complementary data from experiment E12-09-011 is feasible.

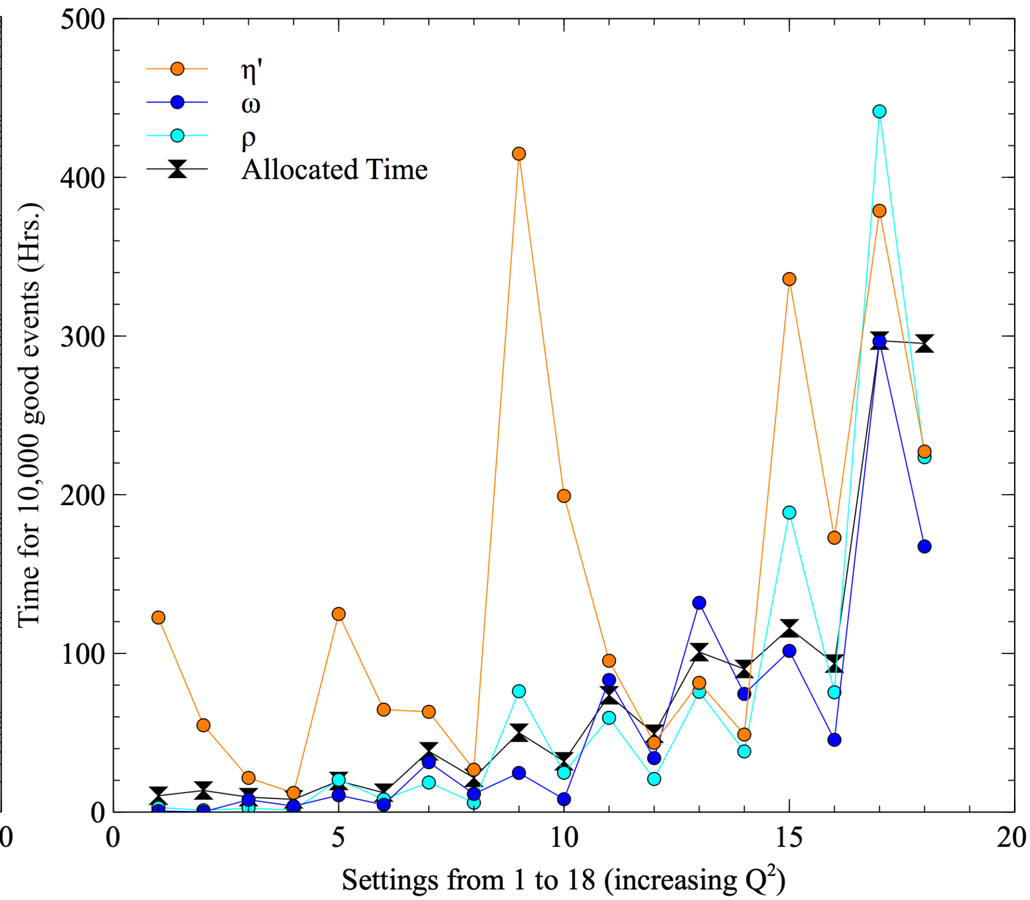
However, we still have to consider the production rates.

The time required to produce 10,000 successful events with the specified kinematic settings assuming 70 μA beam current on a 10 cm LH2 target. The "Allocated Time (Hrs.)" is the updated beam time estimates for E12-09-011.

Setting Number	Q^2 (GeV^2)	W (GeV)	ϵ	Allocated Time (Hrs.)	Time (Hrs.) η	η'	ω	ρ	ϕ	π^0
1	0.40	2.45	0.411	10.3	1898.4	122.6	0.7	2.9	201.66	inf
2	0.40	2.45	0.685	13.6	943.9	54.7	0.2	1.2	85.34	inf
3	1.25	3.14	0.492	9.4	44.8	21.6	7.8	2.5	64.06	1199.98
4	1.25	3.14	0.699	8.0	23.1	12.1	3.7	1.3	32.24	378.68
5	1.70	2.45	0.595	19.6	1219.5	124.9	10.6	20.3	486.16	inf
6	1.70	2.45	0.856	12.2	263.0	64.6	4.6	8.1	213.74	45225.70
7	2.00	3.14	0.395	38.3	115.1	63.2	31.4	18.6	344.49	3060.01
8	2.00	3.14	0.752	21.6	41.0	26.7	11.5	5.9	114.01	250.86
9	3.00	2.32	0.634	50.0	3416.9	414.9	24.7	76.2	1381.28	inf
10	3.00	2.32	0.888	32.0	496.7	199.2	8.1	24.8	524.57	6807.34
11	3.00	3.14	0.391	73.6	127.4	95.4	83.2	59.4	816.85	1515.39
12	3.00	3.14	0.691	49.4	52.1	43.7	34.0	20.9	292.43	475.85
13	3.50	3.37	0.364	100.8	101.0	81.4	131.9	75.8	889	1598.83
14	3.50	3.37	0.557	90.2	58.0	48.9	74.5	38.2	445.49	718.10
15	4.40	2.74	0.479	115.8	196.9	335.9	101.6	188.8	2196.72	5547.05
16	4.40	2.74	0.735	93.6	83.0	172.9	45.6	75.5	883.88	558.03
17	5.50	3.02	0.372	297.1	144.2	378.9	296.6	441.6	3981.87	3126.93
18	5.50	3.02	0.562	295.3	83.9	227.2	167.4	223.6	1920.19	1552.63

Illustrating the difference between time required for 10,000 good events...





Log-Plot

Linear-Plot

Removing the settings not in the allocated beam time...

Setting Number	Q^2 (GeV^2)	W (GeV)	ϵ	Allocated Time (Hrs.)	Time (Hrs.) η	η'	ω	ρ	ϕ	π^0
1	0.40	2.45	0.411	10.3			0.7	2.9		
2	0.40	2.45	0.685	13.6			0.2	1.2		
3	1.25	3.14	0.492	9.4			7.8	2.5		
4	1.25	3.14	0.699	8.0			3.7	1.3		
5	1.70	2.45	0.595	19.6			10.6			
6	1.70	2.45	0.856	12.2			4.6	8.1		
7	2.00	3.14	0.395	38.3			31.4	18.6		
8	2.00	3.14	0.752	21.6			11.4	5.9		
9	3.00	2.32	0.634	50.0			24.7			
10	3.00	2.32	0.888	32.0			8.1	24.8		
11	3.00	3.14	0.391	73.6				59.4		
12	3.00	3.14	0.691	49.4		43.7	34.0	20.9		
13	3.50	3.37	0.364	100.8		81.4		75.8		
14	3.50	3.37	0.557	90.2	58.0	48.8	74.4	38.2		
15	4.40	2.74	0.479	115.8			101.6			
16	4.40	2.74	0.735	93.6	83.0		45.5	75.5		
17	5.50	3.02	0.372	297.1	144.2		296.6			
18	5.50	3.02	0.562	295.3	83.9	227.2	167.4	223.6		

References

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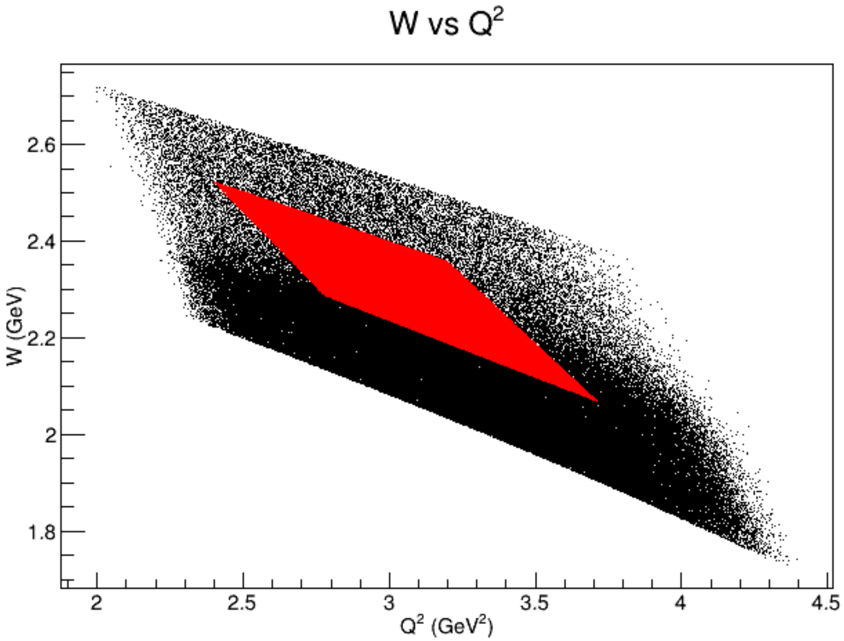
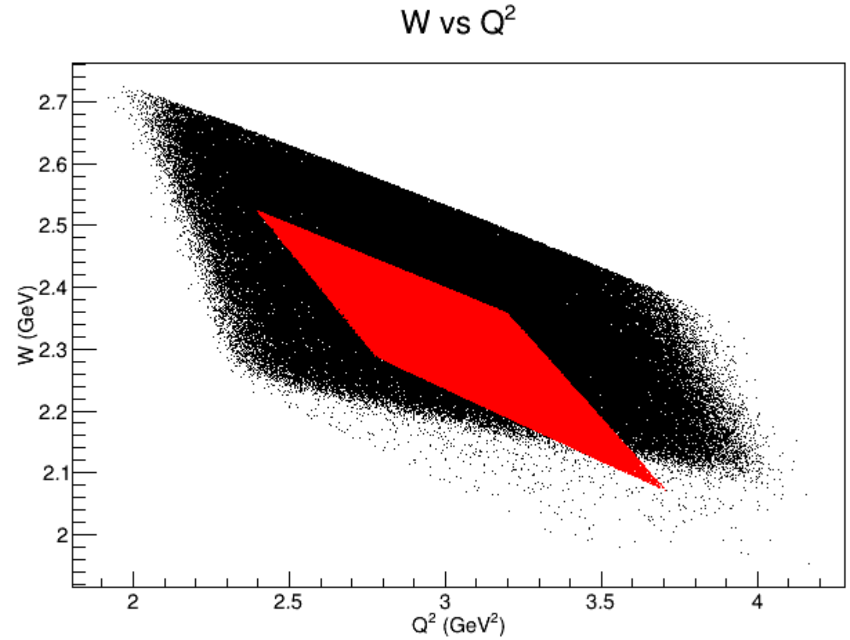
Thank You!

Questions

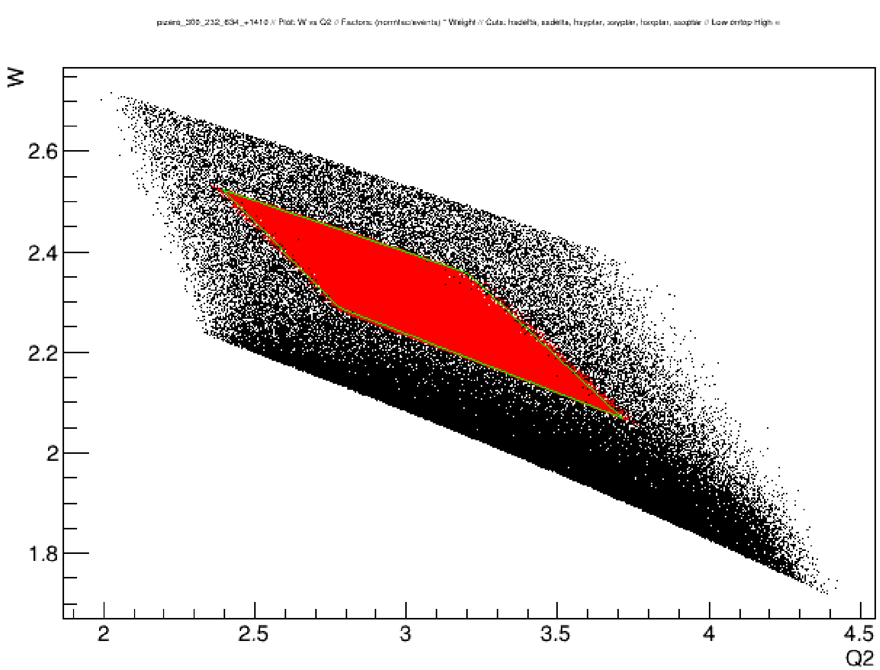
Extra Slides



η-meson diamond plot with Q2 = 3.00 GeV2, W = 2.32 GeV, εred = 0.634, εblack = 0.888, θq = 14.1 deg.



φ-meson diamond plot with Q2 = 3.00 GeV2, W = 2.32 GeV, εred = 0.634, εblack = 0.888, θq = 14.1 deg



Quantity	**Specifications**	
	HMS	**SHMS**
Dipole Bend Angle (^{o})	25.0	18.4
Central Momentum Range (GeV/c)	0.5-7.5	2.0-11.0
Path Length (m)	26.0	18.1
Scattering Angle Range (^{o})	12.5-90	5.5-40.0
Momentum Acceptance ($\delta p/p$)	$\pm$10.0%	-10% $< \delta <$ +22%
Momentum Resolution	$< 0.1\%$	$0.03 - 0.08\%$
Solid Angle Acceptance (msr)	6.7	4.0
Horizontal Acceptance (mrad)	$\pm$27.5	$\pm$24.0
Vertical Resolution (mrad)	$\pm$70.0	$\pm$40.0
Horizontal Resolution (mrad)	0.8	0.5-1.2
Vertical Resolution (mrad)	0.9	0.3-1.1
Maximum DAQ Rate (events/second)	$\sim$10000	$\sim$10000